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USSR Report

EARTH SCIENCES

(FOUO 1/81)

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CONTENTS

OCEANOGRAPHY

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PHYSICAL PRINCIPLES FOR THE MODIFICATION OF ATMOSPHERIC PROCESSES

Leningrad FIZICHESKIYE OSNOVY VOZDEYSTVIYA NA ATMOSFERNYYE PROTSESSY (Physical Principles for the Modification of Atmospheric Processes) in Russian 1978 signed to press 17 Nov 78 pp 5-14, 169-177, 216-229, 263-273, 412-442, 451-455

[Excerpts from monograph by L. G. Kachurin entitled "Fizicheskiye Osnovy Vozdeystviya na Atmosfernyye Protsessy," Gidrometeoizdat, total copies and pages unknown]

[Text] Introduction.

In the not distant future the science of modification of atmospheric processes will unquestionably become one of the leading sciences. This is attributable to the following circumstances.

Hurricanes, thunderstorms, hail, heavy showers, fogs and other dangerous atmospheric phenomena in many cases inflict significant losses on the national economy of even the most economically well-developed countries. Accordingly, it is natural that science is seeking possibilities not only for predicting these phenomena, but also preventing them. At the same time, an improvement in climatic conditions (such as timely additional moistening of the soil by precipitation artificially induced from clouds) can be an effective means for increasing the yields of agricultural crops.

The first real steps in weather control were taken in the middle of the current century. They were taken to a considerable degree because atmospheric researchers have received new technical equipment: high-altitude aircraft, radars and rockets.

The opinion exists that with the development of technology the power of natural forces over man will progressively decrease. However, this is not entirely true.

To be sure, a modern airliner cannot be compared with aircraft of the 1930's-1940's. The power of the engines and the strength of aircraft have increased sharply but the energy of atmospheric turbulence, exerting a destructive effect on the aircraft, in the atmosphere on the whole has remained as before. At first glance it appears that man in his single combat with nature has received enormous advantages. But aircraft, making flights at great altitudes, in many cases enter jet streams which are characterized by great velocities and very strong turbulence. In addition, the modern aircraft has become more sensitive to weather caprices, especially during takeoff and landing.

A light-motor aircraft, even with aerodynamic qualities greatly deteriorating as a result of icing or thunderstorm activity, or with cessation of communications, can continue flight and make a landing. A modern airliner is equipped with means for contending with icing and static electrification. However, as a result of great speed and size it is charged in the clouds to a far greater degree, which increases the probability of thunderstorm discharges in a cloud disrupting the operation of radionavigational apparatus, as well as the probability of a direct strike of lightning on the aircraft. The probability of heavy icing of a high-speed aircraft in supercooled clouds has decreased sharply, but its sensitivity to a change in aerodynamic qualities has increased sharply. The icing of turbines is more dangerous than the icing of propellors. It must also be remembered that the pilot of a light aircraft makes an endeavor to bypass the region of thunderstorm activity or wait at the airport for an improvement in the weather, whereas a modern liner in many cases is forced to take off in a thunderstorm situation and when there is a threat that a fog will occur at the airport of destination. And however perfect the instruments may be, at the moment of landing the pilot must see the ground and the distance must be the greater the greater the speed of the aircraft. A completely automated "blind" landing under any weather conditions for the time being is not guaranteed at any airport in the world.

The intensity of air traffic at the present time is so great that a disruption in the schedule for the takeoff and landing of aircraft at large airports, the most common reason for which is a marked deterioration of weather, can create an emergency situation in the air space over the airport where aircraft awaiting their turn for landing "pile up."

A fog on a landing strip was always a reason for additional difficulties in the takeoff and landing of aircraft, but the progressive increase in the size of aircraft and their flight speed causes a disproportionately large increase in the danger of catastrophes. In 1977 a fog at an airport in the Canaries resulted in a collision of two airliners, as a result of which 811 persons died in an instant.

In the same year, 1977, after a lightning strike on an electric power transmission line, the city of New York, with 10 million inhabitants, was plunged into darkness. It was possible to correct the results of the damage only on the next day, as a result of which the losses sustained amounted to several millions of dollars.

The implementation of mining work with the use of directed explosions involves a danger of premature detonation under the influence of thunderstorms which are relatively weak and not observable visually. This is one of the examples when a new, technologically progressive production method was in greater dependence on atmospheric processes than the methods preceding it and brought to life a new direction in the methods for passive and active protection against atmospheric effects.

An important circumstance stimulating the necessity for search for means to control the weather is the increasing highly negative influence of man in the course of atmospheric processes, at the present time already very significant. In order to confirm this it is sufficient, for example, at dawn in calm and cloudless weather to approach in an aircraft to a large industrial city and observe the dome of highly contaminated (and warmer) air covering the city and its neighborhood.

In carrying out production and in the course of his daily life man introduces into the atmosphere impurities which are not characteristic of it (for example, freons). These impart to the atmosphere new properties: now sunrise not only disperses the morning fog in the streets of a large city, but at the same time favors the photochemical transformation of the introduced impurities into others, considerably more harmful for man and the animal and plant world surrounding him.

The rate of such an artificial transformation of atmospheric properties is constantly increasing and this now forces one to think of the inevitable consequences and also the countermeasures because the possibilities of man (and the animal and plant world surrounding him) to adapt to the deteriorating conditions of existence are limited. An increase in the number of diseases associated with contamination of the environment and characteristic for the current century is evidence of this. Even now we are forced to begin a planned regulation of the anthropogenic effect on the atmosphere in order to prevent a calamitous deterioration of atmospheric properties, which can lead to irreversible changes in the balance of heat and impurities in the earth-atmosphere system capable of making our planet ill-suited for man's habitation.

Ideas on to what degree man can control atmospheric processes and become a master of the weather have changed periodically with time. If one mentally constructs a curve and plots time along the x-axis and the possibility of control along the y-axis (at the top -- hopes, at the bottom — disappointments), the graph will have the form of a slowly attenuating periodic curve with high maxima and low minima, but nevertheless with a gradually increasing mean value. Now we will trace the shape of this curve for the current century.

Between 1899 and 1902 several international scientific conferences were held on the subject of contending with hail, after which the governments of France, Italy and Austria, foreseeing the success, appropriated great sums for carrying out experiments with the cannonading of hail clouds. Over a series of years, under the direction of leading scientists, such experiments were actually carried out. They were unsuccessful.

However, the very idea of controlling the weather was not abandoned. In September 1910, at the British Society for Applied Knowledge, a report was presented on the influence of electricity on the weather. In a discussion of this report the well-known scientist J. J. Thomson declared that according to his computations it was sufficient to use a moderate amount of electricity in order to change the weather over a significant area and that the difficulties along these lines were more of a political than a scientific character. Unfortunately, the results of Thomson's calculations remained unknown and Thomson himself did not return to the subject. However, it is known that in the 1920's electrically charged sand figured as one of the principal reagents in investigations of the possibilities of artificially inducing precipitation.

In 1931 Feraat (Netherlands) for the first time was able to induce artificial rain by dumping ground solid carbon dioxide from an aircraft into supercooled clouds. However, at that time his experiments were not evaluated with respect to validity. It is true that the vertical extent of the clouds subjected to modification and accordingly, the intensity of precipitation from them, were relatively small.

The theory of control of atmospheric processes advanced greatly in the 1930's. In those years much was done in the Soviet Union under the direction of V. N. Obolenskiy and in Bulgaria by L. K. Krystanov and his colleagues. The first scientifically sound computations of condensation processes in the atmosphere were made and there were a great number of experiments in laboratories and under natural conditions. However, on the basis of these materials it was impossible to formulate practical recommendations, although great hopes were laid on their basis. It is not without reason that in the tense prewar period the Soviet state went to great expense for those times, creating the Institute of Experimental Meteorology, its main task being the artificial inducing of precipitation; artificial rain was regarded as one of the most important potentially possible means for contending with drought.

However, it should be noted that at that time not everyone felt optimistically with respect to the fundamental possibilities for weather control. We can quote Marvin, the director of the United States Weather Bureau: "...droughts cannot be stopped, that is, abundant or even appreciable quantities of precipitation cannot be produced either by aerial bombardment or by introducing insignificant quantities of any substances into clouds. All the means and forces which man possesses constitute only a negligible and insignificant fraction of that inexhaustible reserve of energy which is required and expended by nature in order to induce or maintain an individual rain over a limited space."

Today it can be said very definitely that the arguments expressed by Marvin are without validity. However, it must be stated that at that time there was still no basis for considering artificial rain to be a real means for contending with drought in the immediate future.

The Second World War in all countries stopped work on the control of atmospheric processes. All attention was concentrated on the weather forecasts necessary for the support of military operations. But immediately after the end of World War II the problem of modifying atmospheric processes became one of the most important in atmospheric physics. As early as 1946 Langmuir and his associates in the United States carried out a series of effective experiments for inducing artificial showers. Aircraft with a maximum ceiling for that time were used in dumping reagents into clouds. These made it possible to rise to the level of the tops of well-developed cumulus clouds. New and effective means for cloud crystallization were also found. Descriptions of the experiments filled the pages of many journals throughout the world. Terms like "commanders of the weather" appeared. It began to seem that control of the weather, at least control of precipitation, was already in man's hands.

In actuality, during this period no unexpected results were obtained affording fundamentally new possibilities for cloud modification, but they were accompanied by correct computations and by laboratory experiments. These were carried out by authoritative scientists and this, probably, to a not lesser degree than the results of the experiments themselves, favored advertisement of the new achievements in work on the modification of clouds and precipitation. This was more than a claim. In the late 1940's and in the early 1950's specialists in the USSR, Australia and other countries carried out experiments which reliably confirmed the possibility of artificially inducing precipitation from supercooled clouds. However, the reproducibility of these experiments was not very high and precipitation was obtained only from those clouds which by the time of modification were sufficiently well developed.

In 1954 a group of experts of the World Meteorological Organization, summarizing the results of this period, indicated the unconditional reliability of artificial inducing of precipitation from supercooled clouds and recommended, "sparing no efforts," that work be continued primarily for "evaluating the limits of applicability of the developed modification method and their economic significance." In response to this call, work developed on the construction of new meteorological polygons in a number of countries; aircraft-laboratories were outfitted; special radars were developed, etc. The "hope curve" climbed sharply upward.

The successes of modification attracted the attention of the lovers of the arms race. A new term, "meteorological war," appeared in the arsenal of the "cold war." For example, as early as 1953 the Bulletin of the American Meteorological Society carried a paper by one Gugenheim concerning the possibilities, taking advantage of the geographical location of the Soviet Union, of artificial creation of a drought over our country, or, on the other hand, of inundating its territory with rains, without risking anything similar in response.

However, the very idea of using clouds as a weapon was not new. As early as 1750 Maria Theresa, empress of Austria, was forced to publish a law forbidding the cannonading of hail clouds or driving them away by the tolling of a bell. The purpose of this law was the cessation of the "malicious directing of hail clouds toward agricultural fields in adjacent provinces."

On the borderline between the 1950's and the 1960's the term "meteorological war" temporarily disappeared from the horizon. But also the prospects for the peaceful use of methods for controlling clouds no longer seemed so bright as a decade before. A report of a special commission on weather and climate control of the Committee on Atmospheric Research in the United States is characteristic in this respect: it states that "for checking the hypothesis that the seeding of clouds exerts an appreciable positive influence on the formation of precipitation there have been many statistical investigations based on experimental data. Almost all the results of these investigations have been negative: they could not prove the hypothesis of a positive influence of the seeding of clouds by reagents on the falling of precipitation. Moreover, it can be asserted that the more careful the investigations have been, the lesser has been the assurance that they have yielded positive results."

"Fifteen years of complex and costly investigations, for the time being yielding only an insignificant result, represented an attempt at rapid learning how to control the weather. Not one scientist could expect such a result 15 years ago."

A complete disappointment, it seemed: "the curve of the possibility of weather control" dropped sharply downward. But the science of weather control had already entered the stage of scientific maturity. New problems arose in the weather control field; new aspects of old problems from this same field have appeared. New, more modern means appeared for the modification of cloud development processes, and what was extremely important, new means and methods for monitoring the results of modification.

In the USSR rockets, antiaircraft artillery and radars have already appeared as antihail protection for enormous areas. The protection results for the most part have been successful, although in individual situations the hail has burst through the protective gun and rocket fire, regardless of real intensity. At the present time a number of airports are being systematically cleared of supercooled fogs and low clouds, cumulus clouds are artificially created and local air basins are cleared of impurities. All this has now become a reality, having a solid scientific base, which precludes the possibility of compromising the weather control idea.

Even now, using theory and model laboratory experiments, it is possible with a great degree of reliability to evaluate in advance what is fundamentally possible and what is impossible in weather control. It is precisely to this subject that this book is devoted.

The book examines the fundamental principles of modification of atmospheric processes, not only those in practical use, but also those which, it can be assumed quite soundly, will have prospects for use in the future. But it is not impossible that new technical means for weather control will appear which today are unknown or which simply have not come to our attention. In particular, new possibilities may appear when methods are really feasible for the transmission of powerful energetic and ionizing pulses over great distances in any direction. Proposals of this sort will be carried out in the foreseeable future.

However, as indicated by history, the long-range prediction of the development of science in many cases is erroneous. In the 1930's a commission which included outstanding American scientists attempted to make a prediction of the development of science for 30 years in advance. This prediction did not foresee electronic computers, nuclear energy, radars, transistors, or even, however strange this may be, rockets.

At the present time predictions of the development of science and technology are becoming systematic. They are considerably more perfect and objective than the predictions of the 1920's and 1930's, but even now predictions in the field of science and technology are sometimes based to a considerable degree on the intuition of scientists.

It must be remembered that the significance of scientific and technical predictions has considerably increased in our time. This is understandable, because the development of science, based on scientific and technical predictions, has become one of the most important problems in national policy and international relations.

In the preparation of predictions of the development of the sciences and in the planning of their development in a number of cases the proposed cost of investigations and the anticipated economic effect of introduction are decisive factors.

But the science of atmospheric control as a whole for the time being is still in a somewhat special position in this respect because without question not all the fundamental ideas of control are yet known and have an adequately sound physical-mathematical basis on which it would be possible to formulate a scientifically sound prediction of economic or other consequences of their realization.

Moreover, the mechanism of a number of atmospheric processes which it is proposed be controlled and which to some degree are already controlled remains unclear, allowing different, sometimes mutually exclusive variants of interpretation. And nevertheless, and possibly specifically because of this, the planning of artificial intervention in the course of atmospheric processes, the relative sequence of theoretical, laboratory and field investigations here is still more necessary than for other sciences which are more "established" and which have a more solid basis.

The history of the rise and fall of our hopes for weather control, mentioned above, is evidence of the uselessness of vigorous attacks on the forces of nature not backed up by solid scientific and technical findings.

The First International Conference on the Modification of Atmospheric Processes was held in 1973 and the second was held in 1976. They were attended by scientists of all five continents, most of them from the countries of Europe and America. They presented the results of the latest investigations with the use of the most modern experimental and analytical techniques and computer technology. And nevertheless when discussions arose at the conferences concerning the prospects and fundamental possibilities of modification, as well as the degree of reliability of presently available methods, they frequently acquired the nature of enlivened combat among the supporters of opposite, mutually exclusive points of view. Stories of illustrious victories over nature were mixed with reports of failures under seemingly similar situations. To some degree this is attributable to the fact that existing modification methods to a considerable degree provide for "frontal attacks" on nature. However, the energy of atmospheric movements is enormous and whatever have been the successes in the artificial freeing of energy, such as atomic, the forces of nature will still for a long time be greater than man can cope with. Therefore, an approach "from a position of strength" in solving the problems relating to atmospheric control in most cases cannot lead to success. However, atmospheric processes are closely interrelated with one another, with direct and inverse, positive and negative relationships. In some situations in definite links of this chain of processes conditions are created for unstable equilibrium and the relationship between the links is such that intervention in one of them, in some cases of little importance in energy respects, results in a change in the other links which is far more significant and sometimes truly catastrophic. In planning modification it is necessary to know in advance how close the atmosphere is to such situations. In other words, in nature there are some, for the time being still only partially understood control channels by ably using which it is sometimes possible, with insignificant energy expenditures, to bring into action an atmospheric machine of enormous power. Here there is a direct analogy with atomic energy. The energy gain, if one speaks in orders of magnitude, in both cases is approximately identical.

There is an analogy in another respect. Weather control requires a very precise analysis of the state of the atmosphere and its possible evolution and also a careful choice of means and methods of modification. In some cases an insignificant miscalculation not only can negate the modification itself, but even cause an undesirable effect either immediately directly in the experimental region or in the remote future and even in another region of the planet. As a result, there is a particular need for the international cooperation of scientists in the field of control of weather and climate. In this connection it is fitting to recall the words of Ye. K. Fedorov that the "global nature of weather phenomena and the principal characteristics of climate are least of all suitable for individual intervention in their state."

However, in the 1970's the problem again came to the forefront of the need for including weather as well in the list of fields banned for military purposes and subject to international monitoring, together with nuclear energy, space, the ocean depths and bacteriology.

During recent years, in connection with the creation of new technology for the modification of atmospheric processes, publications appeared on modern methods for meteorological war as a means for mass annihilation. The stratosphere came to be considered as an arena for the modification (advertent and inadvertent) of atmospheric processes, having the purpose of annihilation of life on earth. All this cannot but cause alarm, especially since the very thought of the possibility of waging a meteorological war exerts a psychological effect on people, especially aggravated by the existence of weather anomalies characteristic for the modern period in development of the solar system, still not having an adequately precise scientific explanation.

The control of atmospheric processes for peaceful purposes can and should become one of the important means for the development of the productive forces of human society. Collective efforts in this direction should bring together all the peoples of the earth and not constitute a threat of annihilation of life.

References: [17, 21, 23, 24, 25, 31, 36, 44, 45, 48, 55, 64, 69, 70, 72, 74, 77, 78, 79, 101, 107, 108, 115, 118, 127, 132, 135, 137, 138].

CHAPTER 4

CONTROL OF THERMODYNAMIC PROCESSES IN CLOUDS

In this chapter we will discuss the modification of thermodynamic processes in clouds, excluding electrical processes, which are considered in Chapter 6. In general, electrical processes are inseparable from the others; in particular, all phase transitions are accompanied by electrical phenomena. But applicable to the problems which are examined in this chapter it is assumed that they play a secondary role and therefore methodologically it is feasible to separate the materials into Chapters 4 and 6.

4.1. Means for Delivery of Reagents into Clouds

At the present time the principal means for the delivery of reagents into clouds are uncontrolled rockets (of the "ground-air" class) launched from the ground and anti-aircraft shells. But in addition, reagents are dumped into clouds from aircraft or clouds are cannonaded by airborne rockets (rockets of the "air-air" class). Sometimes reagents are introduced into a cloud from the ground by ascending currents, either natural or artificially created (see Chapter 3). The most promising means for the delivery of reagents are rockets launched from the ground and anti-aircraft shells.

At the present time the most perfect Soviet anti-hail rockets are the "Oblako" and "Alazan'." The first Soviet rocket was the PGI (protivogradovoye izdeliye — anti-hail object). The PGI was created in 1957 and constitutes a turbojet shell of the caliber 82.5 mm.

The rocket (Fig. 4.1.1) consists of a solid-fuel rocket engine (RE) 1 and a nosecone 2. The nosecone holds a smokepot 3 (active smokepot — ASP), during whose combustion the reagent is released in an aerosol state. The reagent emerges through radial openings 4. The nosecone also holds a remote device 5 ensuring ignition of the ASP at a stipulated distance, to be more precise, upon the elapsing of a stipulated time. The remote device consists of a firing-pin mechanism, distance-setting mechanism and ignition device. The distance-setting mechanism ensures actuation of the fuse at a stipulated distance. It has a curved channel into which the fuel mixture is pressed. The length of the working part of the channel is regulated by turning the cap 6 relative to the nosecone of the rocket housing. On the cap there is a zero graduation 7 and on the housing a scale 8, graduated for time. With turning of the cap, the firing-pin mechanism turns together with it and its displacements along the curved channel determine its working length. The ignition device is used in igniting the ASP.

In another design of the PGI the distance-setting device is situated completely within the cap. In such rockets the setting for distance is accomplished within the cap in an inactive state.

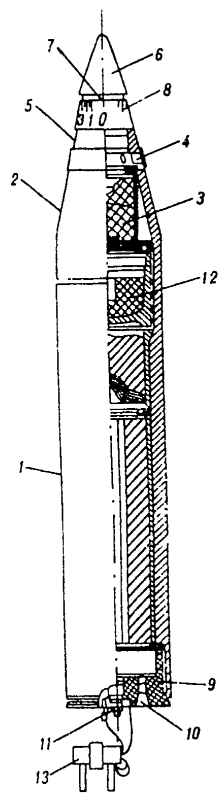

Fig. 4.1.1. Design of the PGI rocket.

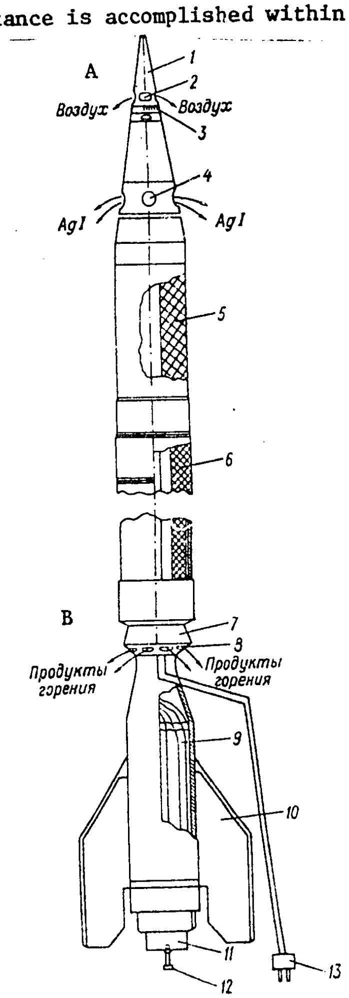

Fig. 4.1.2. Design of "Oblako" rocket.

KEY:
A) Air
B) Combustion products

The engine ensures translational motion of the rocket and rotation which stabilizes its flight as a result of gyroscopic effects. The engine housing is made of light nonmetallic materials. A jet assembly 9 is attached to its lower part. It has jet channels 10 arranged in a circle which are somewhat slanted relative to the circumference. All are slanted in the same direction (beveled). The fuel combustion product of the rocket engine is gases which burst through the jet openings and impart to the rocket a translational motion. The slant of the channels ensures rotation of the rocket, being a necessary condition for its in-flight stability. At the center of the jet assembly is a screwed-in electrocapsular element (percussion cap) 11 which is used in igniting the rocket engine fuel.

The explosive charge 12 of the fragmentation element ensures fragmentation of the rocket into safe fragments; it is situated between the rocket engine and its nosecone. The fragmentation unit is triggered after burn-out of the ASP. In addition, it has an autonomous igniting mechanism which is actuated after a fixed time interval if the circuit of the main fragmentation element has not been triggered by this time due to failure of the distance-setting fuse or preliminary cessation of ASP combustion.

The PGI rocket with an aerosol reagent operates in the following way. After the rocket, by means of the launching apparatus, is imparted the necessary angle of elevation, it is aimed in the firing azimuth, the distance-setting mechanism is set for the stipulated distance, the electric current generator is cut in. From there an electric pulse is fed through the plug 13 to the percussion cap mechanism, causing ignition. The thermal pulse from the percussion cap is transmitted to the fuel engine, which is fired and imparts a translational-rotational motion to the rocket. As soon as the rocket goes into motion the wires connecting the plug and the electric detonator are broken off. Then the rocket leaves the launcher.

When the rocket attains a definite velocity of rotation the centrifugal firing pin of the distance-setting fuse and the duplicating firing pin of the fragmentation element are activated. After the firing pin is triggered the fuel mixture of the distance-setting fuse is ignited. After its combustion along the entire working length of the curved channel the flame is transmitted to the ASP, during whose combustion the smoke of the reagent 4 passes through the openings and is scattered in the cloud along the flight path of the rocket.

After combustion of the ASP the flame is transmitted to the fragmentation element, shattering the body of the rocket. If the fuse fails or the ASP ceases to burn, at a definite time after rocket launching the duplicating circuit of the fuse is triggered and the rocket is destroyed.

Cannonading by rockets can be accomplished both with individual firings and in a salvo (with a short time between firings). A blocking device prevents the simultaneous firing of two or more rockets from a multibarrel launcher. If a rocket does not leave the launcher or after launching assumes a low velocity due to some malfunction it is not detonated because the firing pins of the fuse and fragmentation element are not activated.

The finned "Oblako" rocket (Fig. 4.1.2), created in 1964, has a greater firing range than the PGI and carries a greater quantity of reagent. Its basic specifications are as follows: caliber 125 mm, length 2,110 mm, mass 35 kg, maximum altitude attained 8.6 km, maximum flight range 12 km, length of path of active smoke up to 8 km.

The crystallizing reagent is either an aerosol (of the AgI type) or carbon dioxide. If AgI is used, with a temperature in the cloud of $-10^{\circ}C$ with the triggering of one rocket (weight of pyrotechnic mixture 5 kg) about 10^{16} ice nuclei are formed in the atmosphere. The rate of rocket descent by parachute is 8 $m \cdot sec^{-1}$. The "Oblako" rocket is a finned jet-propelled shell which consists of the following principal parts: nosecone, situated in the middle of the engine, and a parachute compartment. The nosecone is made in two variants, depending on what reagent is used — an aerosol (of the AgI type) or solid carbon dioxide.

The rocket has two distance-setting fuses: head fuse 3 and bottom fuse 11, functioning autonomously. Both fuses prior to rocket launching are set for a stipulated time, in dependence on the distance to the cloud, its size and the modification tactics. The head fuse ignites the ASP or fires the explosive charge, scattering the solid carbon dioxide. The bottom fuse activates the parachute system. It is duplicated by a second fuse triggered a fixed time (30 or 60 sec) after rocket launching for the purpose of decreasing the probability of parachute system failure.

As in the PGI rocket, the mechanisms ensuring triggering of the nosecone of the "Oblako" rocket are activated only when the rocket attains a definite velocity of motion.

The sensor of the velocity of rocket motion is a small air turbine 1 activated by air with a velocity which is the greater the greater the flight velocity of the rocket. The small turbine communicates with the atmosphere through an aperture at the tip of the rocket and a system of outlets 2. A mechanism connected to the small turbine triggers the distance-setting fuse and prepares it for operation only after the small turbine makes a definite number of revolutions and is twisted along its axis (the small turbine is held on the axis on a helical groove). An additional safety device is triggered when the limiting dynamic overload on the rocket attains a definite, prestipulated value.

The "Oblako" rocket operates in the following way. With the feeding of an electric pulse through the plug 13 the percussion cap is "triggered" and this ignites the fuel 6 and this thereby brings the rocket engine into operation. The fuel combustion products are expelled through the openings 8 in the jet assembly 7.

When the force developed by the engine attains a definite limit the rocket is freed from its connection with the locking mechanism of the guiding launcher and begins to move through the guide. The plug 13 is detached, the pin 12 of the bottom distance-setting fuse is pulled and from that moment is actuated. Then the duplicating circuit of the distance-setting fuse is activated.

During motion in the launcher the rocket assumes a rotational component of motion, but considerably less than for turbojet rockets. In-flight stabilization is created for the most part by the finning 10.

When the rocket assumes a definite velocity the mechanism of the head distance-setting fuse is actuated. After flying a stipulated time after triggering of the head distance-setting fuse the rocket begins to eject the reagent (either because the ASP begins to burn or as a result of explosion of a briquette with CO_2). Then the bottom distance-setting fuse is actuated, a slide charge opens the cover of the parachute compartment and ejects a braking parachute. Entering into the air flow, the braking parachute is filled with air and brings into action the mechanism setting free the main canopy of the parachute 9 by which the rocket is lowered to the ground.

Depending on the relationship of the stipulated times of triggering of the distance-setting fuses — main and bottom — the release of the reagent by the ASP method can enter before or after deployment of the parachute. In the second case, descending, the rocket will continue to discharge reagent.

In one of the variants of the "Oblako" rocket provision is made for discharge of the reagent by means of expulsion of reagent by means of a magazine which successively expels one packet of reagent after another.

Figure 4.1.3 shows the launching of the latest anti-hail turbojet rockets which have been assigned the name "Alazan'." They are smaller in size than the "Oblako" rocket. These rockets have no parachute system. After the reagent is expended the rocket self-destructs as a result of an explosion whose timing is set by the distance-setting fuse. It is also important that the "Alazan'" has a uniformity of discharge of reagent and a greater rate of fire than the other rockets, which ensures a greater maneuverability in the seeding of clouds, especially in the variant of automatic programmed telecontrol from the central command point in the polygon.

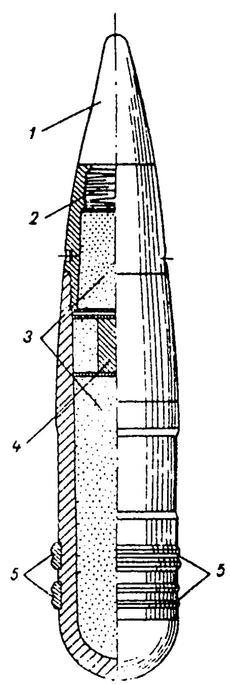

Fig. 4.1.4. 100-mm anti-hail shell "El'brus-2."

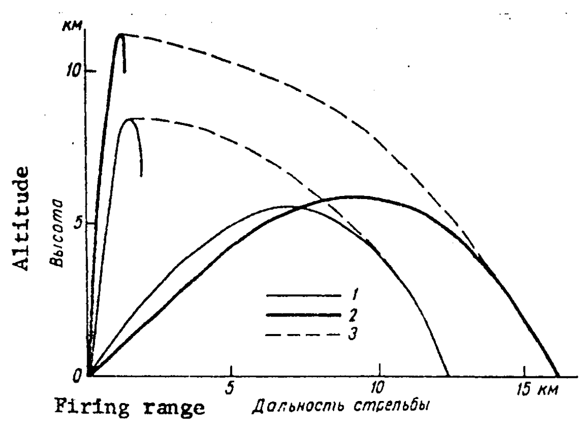

Fig. 4.1.5. Trajectories of flight of "Oblako" rocket (1), "El'brus-2" shell (2) and envelopes of trajectories corresponding to different angles of elevation (3).

A Japanese "ground-air" anti-hail rocket carries 400 g of pyrotechnic mixture to an altitude of 6-7 km. After ejection of the reagent the rocket is automatically ignited and burns up.

An American rocket carried aboard an "Aztec" aircraft is an anti-hail rocket of the "air-to-air" class. The launcher is situated in the tail part of the aircraft. The launcher launches rockets containing silver iodide or other reagent in a stipulated direction (usually upward). Cannonading by rockets can be accomplished either successively or in a salvo.

The rocket body is fabricated from fiberglass; it carries rocket fuel, reagent and distance-setting fuse. The caliber of the rocket is 42 mm, its length is 21 cm and the mass is about 500 g. The rocket is propelled in the launcher.

When launched from an aircraft at an altitude of 3 km the rocket attains altitudes of 5-6 km. A merit of the aircraft rocket variant is the possibility for routine use over extensive territories not limited by the firing range. However, flights of modern aircraft under meteorological conditions characteristic for hail situations usually involve considerable risk and sometimes are forbidden.

Cannonading of hail clouds was also used in the last century. At that time hail-combatting mortars and guns were used. No reagent was present in the shell. It was assumed that the bursting of the missile in the cloud favored its transformation from a hail to a rain cloud.

The "El'brus-2" is a modern anti-hail, fragmentless shell with a caliber of 100 mm; it is shown in Fig. 4.1.4. The shell weighs 12.25 kg and its initial velocity is 850 $m \cdot sec^{-1}$. It holds a reagent which at a temperature of -10°C is capable of forming 10^{13}-10^{14} ice-forming particles.

The body of the shell, with a screwed-on upper part, is fabricated from a material ensuring strength of the shell when fired from a launcher but scatters in small fragments when it is detonated in the air. Briquettes of explosive 3 and reagent 4 are situated within the shell.

The shell is topped-off by a head fuse 1 with a distance-setting mechanism 2. The shell is held in a sleeve filled with a powder charge. A percussion cap is situated in the lower part of the sleeve.

At the time of firing the hammer strikes the percussion cap, which ignites the powder charge. A high pressure is developed in the sleeve, the shell bursts from the sleeve and moves translationally in the barrel. The shell slips along the grooves in the barrel by means of the elements 5, fitting into the grooves and thereby acquires a rotational component of motion, imparting to it stability during flight in the atmosphere.

At the time of firing the main fuse is actuated and when the stipulated time has elapsed the distance-setting device forces triggering of the head fuse, and thereafter the explosive in the shell. An explosion occurs and the reagent is scattered. At this time the shell and fuse scatter into small pieces which can cause no harm to people or animals.

The "El'brus-3" shell is similar in design. It is intended for anti-aircraft guns with a caliber of 130 mm.

In the proposals for along-path anti-hail shells which have now been developed provision is made for ejecting the reagent gradually along the entire flight path, not at a single point (instantaneous point source). On the approach to the modification zone the pyrotechnic mixture situated in the nosecone of the shell is ignited as a result of the first triggering of the distance-setting fuse. The second triggering (with a delay) of the fuse is transmitted to the central part of the shell where the reagent is situated.

The dispersed reagent, together with the smoke forms a track behind the shell. The track can be regarded as a linear source, and with respect to its time curve, a finite-action source, that is, intermediate between instantaneous and continuous. The detonation of the shell occurs automatically when a stipulated time has elapsed after triggering of the distance-setting fuse.

In order to evaluate the possibility of using anti-hail missiles -- uncontrolled rockets and shells -- it is important to know their trajectory and payload. The quantity of reagent which they hold has been discussed above.

A diagram of flight of the "Oblako" rocket and the "El'brus-2" shell is given as Fig. 4.1.5.

Within the limits of the information which is of interest to us, the flight diagrams for rockets and shells are similar to one another, but as indicated by Fig. 4.1.5, the range and altitude of the shells now used are greater than for rockets. On the other hand, the rockets carry substantially more reagent and are better adapted for gradual discharge of the reagent along the flight path; this is very important in any segment of the trajectory.

4.4. Control of Processes in Convective Clouds

Convective clouds in their development attain the cumulonimbus stage when they have sufficiently great vertical thickness and liquid-water content, ensuring enlargement of cloud particles to such a size that with their falling under a cloud they cannot evaporate. However, in many cases clouds pass through the entire cycle from generation to decay without developing to the stage of cumulonimbus (Cb).

What are the possibilities for intervention in this process for the purpose of artificial transformation into a rain cloud of a cloud which in its natural evolution would not reach the rain stage? We will enumerate them, first of all giving attention to the degree that they are feasible.

First of all this is the possibility of intensification of convection for the purpose of increasing the vertical thickness of the cloud. The factors favoring the development of convection were examined in Chapter 3. Atmospheric stratification is an important factor. However, by direct modification we cannot change the temperature, humidity and wind in the atmosphere at scales comparable to the dimensions of Cb.

An increase in the horizontal dimensions of a cloud (increase in R, see Section 3.1) and a decrease in entrainment would favor the development of convection. The horizontal movement of clouds for the purpose of bringing several clouds together would sharply increase the possibility of their vertical development, but we do not know how to do this. It is true that the considerations relating to R force us to reflect on whether it would not be more advantageous to employ the meteotron (see Chapter 3) to intensify the development of existing clouds than to create new ones. With respect to an artificial decrease of entrainment, this undoubtedly is an unrealistic approach for modifying cloud development.

Thus, at our disposal we have only one other parameter -- cloud temperature $T'(z)$ -- whose control in supercooled clouds by use of crystallizing reagents is entirely realistic. Chapter 3 examined the possibilities and consequences of heating of the lower part of the cloud. There we brought attention to the dependence of the effect of heating on atmospheric stratification. The atmosphere must be prepared if the heating is to lead to an intensification of convection. In the case of strong atmospheric stability or a strong wind shear no realistically possible heating of the air can change the situation.

In Chapter 3 there was a discussion of the artificial introduction of heat into the atmosphere. Now we will consider the control of the phase transitions in which there is a release of heat, which can also be used in increasing temperature in a cloud for the purpose of intensifying convection. The control of phase transitions for the purpose of intensification of condensation-coagulation processes of growth of individual droplets in a cloud will be discussed at the end of this section. However, here we will give several model computations by the method considered in Chapter 3.

We will stipulate two variants of temperature stratification: to an altitude of 5 km identical, but aloft more stable in the first variant and less stable in the second variant. We will also vary the vertical wind profile in the atmosphere:

in the main variant the wind velocity does not change with altitude (v = const), in the other variant the wind velocity increases with altitude with a constant gradient $dv/dz = 1.5\ m \cdot sec^{-1} \cdot km^{-1}$. Mean characteristic meteorological conditions are stipulated at the condensation level.

Using the method presented in Chapter 3 we will first compute two variants of a naturally developing cloud 1 and 2 (curves a) corresponding to temperature stratifications 1 and 2 with v = const (Fig. 4.4.1). The figure shows the profiles of the vertical wind velocity component w and liquid water content q. In order not to burden the figure the liquid water contents are given only for variant 2.

As might be expected, in the second t(z) variant the cloud developed to a considerably greater altitude than in the first.

Now we will artificially crystallize part of the cloud, introducing reagent into it. The results of such an operation will be examined in greater detail below, but now we will give attention only to the new w profiles for both t(z) variants (curves b).

First we will examine variant 2. What occurred after introduction of the reagent? The artificial crystals appearing in the cloud grow and coagulate with supercooled droplets. This process additionally affects an almost 2-km layer (compare the curves for the natural process and after modification). The heat of crystallization is released in this layer, as a result of which the cloud receives an additional thermal momentum and with a velocity comparable only to a sufficiently maneuverable aircraft rises upward and attains an altitude of 9.5 km.

But repetition of the experiment with a more stable atmosphere (with the temperature stratification 1) leads to a far lesser effect: the upper boundary rises only 200 m.

A comparison of variants 2 with v = const and dv/dz = const shows to what extent the convection intensification effect in this case attenuates as a result of an increase in the wind with altitude.

The model computations, whose results are illustrated in Fig. 4.4.1, show that the convection intensification effect caused by artificial crystallization is highly dependent on the state of the atmosphere and it makes no sense to carry out modification experiments without preliminary computations of the artificial transformation of clouds.

Experiments under natural conditions confirm that in actuality the intensification of convection is usually maximum in the artificial crystallization of those clouds above whose tops there is atmospheric instability. In accordance with theory it is necessary to differentiate two cases. The first is when over the cloud the atmosphere is stable with respect to the condensation process but is unstable with respect to the sublimation process. Then crystallization assists in overcoming the barrier existing between them. The second is when the cloud in its natural development has reached the level of stability with respect to condensation processes (a moist-stable stratification is noted directly over the cloud), but somewhat above there is a quite thick layer with strong instability. Then the artificial crystallization, provided that it assists the cloud in breaking through the stability layer, causes vigorous convection in the unstable layer.

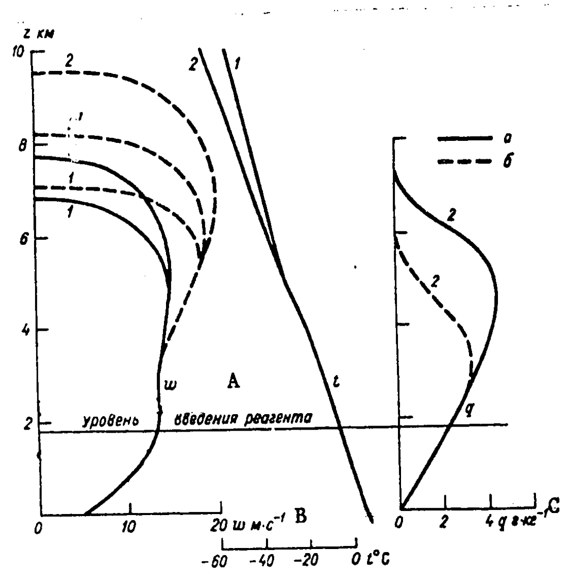

Fig. 4.4.1. Transformation of cloud under influence of artificial crystallization: vertical profile of ascending currents in the cloud w(z) and liquid water content q(z) for different variants of the vertical profile of temperature t(z) and wind velocity v(z) in the atmosphere. a) naturally developing cloud, b) artificially crystallizing clouds; curves 1 and 2 for w and q correspond to temperature stratifications 1 and 2; curve 2' corresponds to a wind profile dv/dz = const, the remaining curves are for v(z) = const.

KEY:

A) Level of introduction of reagent
B) w $m \cdot sec^{-1}$
C) q $g \cdot kg^{-1}$

In addition to the intensification of convection directly due to the release of the heat of crystallization there are secondary effects accompanying the crystallization of a cloud and exerting an influence on the dynamics of its development: expansion of a cloud in a horizontal direction and an intensification of condensation-coagulation processes of droplet growth in the cloud.

An increase in the horizontal dimensions of the cloud favors an intensification of convection and thus it leads, as we pointed out in Chapter 3, to a relative decrease in the role of the entrainment effect which as a rule impedes the development of convection.

As a result of intensification of condensation-coagulation processes in a crystallizing cloud there can be falling of precipitation and as a result the cloud can receive an upward-directed additional acceleration proportional to the mass of falling precipitation. At the same time the opposite effect occurs: large particles in the cloud create an appreciable aerodynamic resistance to the ascending air currents whose value is proportional to the cross section of the particles and their number.

However, the intensity of formation of precipitation should also be different in dependence on whether the cloud was overseeded with nuclei during modification or their concentration in the experiment is such that the conditions for the growth of the ice particles in the supercooled cloud are optimum. In the first case no precipitation will fall; in the second case the effect of "washing out" of the cloud may be so great that the cloud begins to decay.

It must be remembered that for the time being there is no sufficiently complete method for computing the mentioned secondary processes.

Now we will discuss the results of observations of the effects of artificial crystallization of cumulus clouds in two experiments.

Figure 4.4.2 shows the evolution of a cumulus cloud penetrated by rockets with AgI. Prior to modification the cloud extended to a considerable altitude, but there was no crystallization in it. The left margin of the cloud was subjected to modification first. Five minutes after entry of the reagent it was completely crystallized. Then the topmost part of the cloud was modified. After 10 minutes the entire upper part of the cloud was crystallized. A photograph taken 21 minutes after the onset of modification shows that the upper part of the cloud was destroyed and transformed into an ice "shroud."

In the experiments described above the principal object of observation was the upper part of the clouds and observations of precipitation from clouds from an aircraft were made only incidentally, and visually at that.

In experimental polygons with a dense network of rain gages the modification of cumulus clouds, which will be discussed below, was carried out primarily for the purpose of inducing precipitation. It was necessary to determine with what parameters of the cumulus clouds artificial crystallization of the upper part of the cloud causes precipitation and with what parameters it does not.

Figure 4.4.3 shows the results of a series of experiments for inducing precipitation from cumulus clouds subjected to modification with solid carbon dioxide in the Ukrainian Experimental Meteorological Polygon. The vertical thickness of the cloud Δz and the temperature at the level of introduction of the solid carbon dioxide into the cloud (t°C) are plotted along the axes. The figure shows four regions corresponding to four groups of clouds: I) clouds from which precipitation reached the earth in all cases; II) same, in 50% of the cases; III) light precipitation reaching the ground in 10% of the cases; IV) not even a zone of falling under the cloud was observed.

The mean value of the altitude of the lower boundary of the investigated clouds was 1.7 km over the ground level (minimum mean monthly altitude 1.5 km, maximum 1.9 km). The mean temperature at the lower boundary was +7°C (minimum mean monthly temperature +5.1°C, maximum +7.9°C).

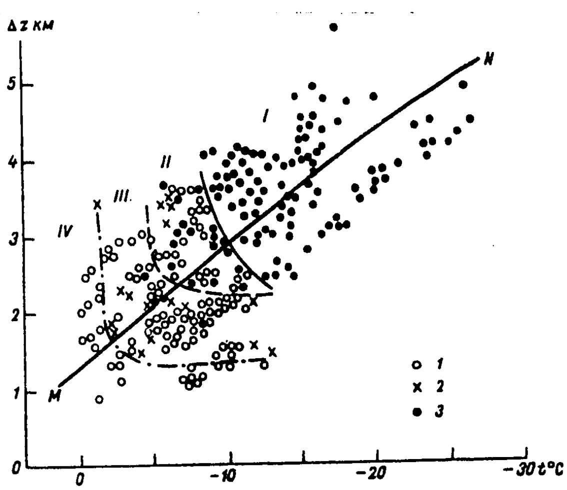

Fig. 4.4.3. Results of experiments for inducing precipitation from cumulus clouds with modification by solid carbon dioxide. 1) no precipitation, 2) light precipitation, 3) heavy precipitation.

Using the standard dependence of the moist adiabatic temperature gradient on pressure and temperature, we obtain the curve MN. This curve indicates a completely obvious relationship between the vertical extent of a cloud and the temperature of its upper part. It must be remembered that in constructing the MN curve use was made of averaged temperature values, as well as averaged temperature gradient and altitude of the lower cloud boundary. Precisely this is primarily responsible for the scatter of points near the MN curve in Fig. 4.4.3.

The relative position of regions I, II, III, IV is evidence that in accordance with the theory considered in Chapter 2 the success of artificial inducement of precipitation from supercooled clouds was the greater the greater the vertical extent of the cloud.

It follows from a more detailed analysis, in addition, that the success will be the greater the greater is the liquid water content of the cloud, the closer the temperature of the upper part of the cloud is to the temperature of natural crystallization and the poorer the conditions are for the evaporation of precipitation under the cloud (that is, the lower the lower boundary of the cloud and the greater is the air humidity under the cloud).

The line separating regions I and II in accordance with the theory of condensation-coagulation consolidation of droplets in clouds developed in Chapter 2 is evidence that in these regions the higher the temperature of the supercooled part of the cloud the greater is the vertical extent and the greater is the time required for the forming of precipitation (both artificial and natural).

Now we will carry out three typical computations of the consolidation of small ice particles introduced into the cloud applicable to the results shown in Fig. 4.4.3. The first should characterize region IV, the second and third -- region I. In the computations it is necessary to know such parameters of the cloud as vertical extent, temperature and liquid water content (and in precise computations, also the size of the cloud droplets), the velocity of ascending currents, position of the lower boundary of the cloud and the humidity below it, and also the concentration of artificial ice particles. Then, using the method developed in Chapter 2, it is possible to compute the consolidation of droplets artificially crystallized in the upper part of the cloud and their evaporation under the cloud.

The results of computations of the growth of ice particles in a cloud and their evaporation under a cloud are shown in Fig. 4.4.4.

We will assume that the temperature and position of the cloud boundaries are the same as in Fig. 4.4.3 (we will use the line MN). In addition, in all three cases we will use the characteristic profiles of the vertical velocities (shown in Fig. 4.4.4) and liquid water content (not shown). We will limit ourselves to a case when the concentration of artificially introduced particles is small and therefore they, first of all, do not compete with one another, and second, the heat of crystallization is not reflected in the values for the vertical currents (we recall that in Fig. 4.4.1 this effect, on the contrary, is the main one). Bearing in mind that the computations are approximate, we will operate with the mean capture coefficient. Then the computations can be carried out without allowance for the size of the cloud droplets. The humidity under the cloud is assumed equal to 60%. The crystallizing reagent is introduced at the optimum altitude in such a way that the ice particles, growing larger and rising upward (as long as they are small), do not emerge from the limits of the cloud.

In case I the particles grew to 0.5 mm, but completely evaporated under the cloud; in case II there was falling of large rain droplets forming as a result of the melting of large ice particles. In case III the artificial ice particles were transformed into graupel or hailstones. The main flaw in the figure is that no allowance has been made for natural crystallization, which in this case should play a substantial role (for more details see Section 4.5).

Figures 4.4.3 and 4.4.4 once again confirm that cumulus clouds with a supercooled upper part usually pass into the rain stage after the onset of crystallization (natural or artificial) if their vertical extent is sufficiently great.

The model computations which we made can be considerably improved by introducing more detailed dependences of vertical velocity on vertical thickness of the cloud and on altitude above its base and also the dependence of liquid water content on temperature and vertical thickness. It is also possible to upgrade the method for computing the enlargement of droplets, the cloud parameters can be varied, etc. All this will make possible a more detailed explanation of the results presented in Figures 4.4.3 and 4.4.4. However, this is not rational. It is more reasonable to carry out such computations applicable to specific clouds, for which the principal "input" parameters are known.

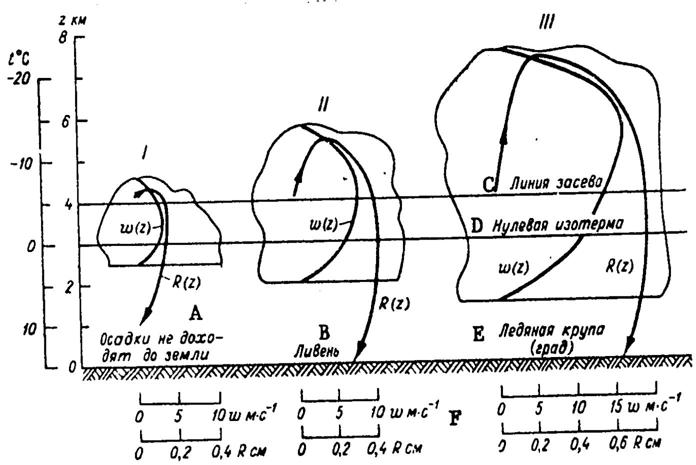

Fig. 4.4.4. Growth and evaporation of ice particles forming in cloud after introduction of crystallizing reagents. I) corresponds to region IV in Fig. 4.4.4; II and III) correspond to region I in Fig. 4.4.3.

KEY:
- A) Precipitation does not reach ground
- B) Shower
- C) Seeding line
- D) Zero isotherm
- E) Graupel (hail)
- F) $m \cdot sec^{-1}$

A typical example of successful artificial inducing of precipitation in the Ukrainian Experimental Meteorological Polygon on 17 June 1967 at 1707 hours is illustrated in Fig. 4.4.5. The left part of the cumulus cloud, in the development stage, was modified by the crystallizing reagents. Prior to seeding the top of the cloud was sharply defined, as is characteristic for purely water clouds (see right part of Fig. 4.4.5a, part not subjected to modification). The cloud parameters, whose values were taken from the experimental program and the weather bulletin, are indicated in the figure. The liquid water content (q) and the vertical currents (w) were not measured in this experiment and therefore were taken as the mean characteristic values for such clouds. At 1730 hours there was visual observation of crystallization of the upper left part of the cloud; now a fibrous structure of the top is visible, as is characteristic for Cb; the falling of precipitation has begun.

The intensity of natural crystallization ($\mathring{W}$) was evaluated using formula (2.3.3). The rate of natural crystallization does not exceed $\mathring{W} = 10^{-10}$ sec^{-1} at any level. The results of computations of the enlargement of particles passing through the entire cloud from top to bottom, taking into account their evaporation in the layer under the cloud, are shown in Fig. 4.4.5b. The computations of the enlargement of water (prior to modification) and ice (after modification) particles were made using equations (2.2.9) and (2.2.10).

The water droplets, which under the influence of this process increased to 400 μm at the lower boundary of the cloud, as a result of evaporation in the layer under the cloud, to all intents and purposes do not reach the ground.

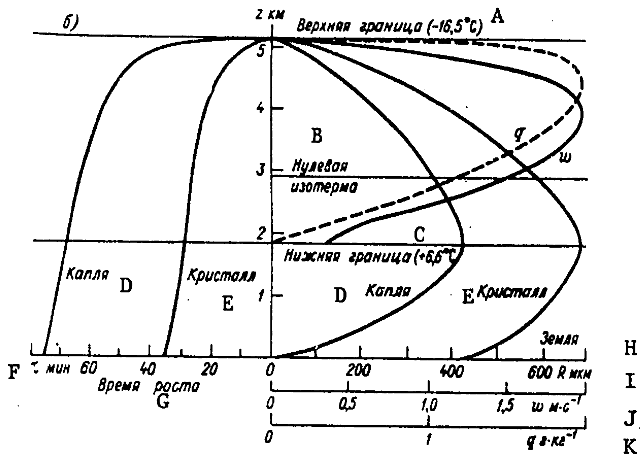

Fig. 4.4.5. Modification of cumulus cloud by crystallizing reagents for purpose of inducing precipitation. 17 June 1967 (Ukrainian Experimental Meteorological Polygon). a) [not reproduced here] photograph 23 minutes after introduction of reagents into left part of cloud; b) computation of enlargement and evaporation of cloud particles before and after modification.

KEY:

A) Upper boundary
B) Zero isotherm
C) Lower boundary
D) Droplet
E) Crystal
F) min(utes)
G) Time of growth
H) Ground
I) μm
J) $m \cdot sec^{-1}$
K) $g \cdot kg^{-1}$

The situation changed with introduction of the reagent. Ice particles are enlarged in the cloud more energetically than droplets and precipitation reaches the ground surface. The time necessary for the passage of particles of natural precipitation along the path from the upper to the lower boundary is 70 minutes. The particles of precipitation forming as a result of modification overcome this path twice as rapidly. Artificial precipitation generated at the lower, rather than the upper boundary of the cloud, falls to the ground still more rapidly.

This example is close to the case of maximum success in modification. However, if one were to be objective, it would be necessary in evaluating the success of modification to be able to precompute the natural development of a cloud and be sure that the cloud in the course of natural development does not reach the Cb stage. In the case considered heavy precipitation was not observed in the polygon region before the end of the day. But this became known after ending of the experiments and on a practical basis this must be known in advance, at the time of adoption of a decision concerning modification.

Data are available on the results of experiments for the artificial inducing of precipitation from cumuliform clouds carried out in Canada, Australia and South Africa. Their results are similar to those shown in Figures 4.4.4-4.4.5. The thicker the cloud is and the closer the temperature of its upper part is to the temperature of natural crystallization, the more probable is its transformation into a rain cloud.

Thus, only in a case when the supercooled cloud in its natural development is sufficiently prepared for its rain stage will artificial crystallization be highly productive.

Strictly speaking, above we have examined two processes induced by artificial crystallization: intensification of convection and intensification of the process of enlargement of cloud particles. In the event that the effects intensify one another (that is, there is a positive feedback between them), the total effect will be maximum.

In order to end our examination of the problem of inducing precipitation from supercooled clouds it remains to tell of the so-called norms for the seeding of clouds with crystallizing reagents. Experience shows that with a great vertical extent and great horizontal dimensions of the cloud the excess of the reagent (overseeding) is not counterproductive in reasonable limits. In this case "too many cooks do not spoil the broth." If in the upper part of the cloud there is "overseeding" (see Chapter 5), the largest ice particles, falling downward more rapidly than the others, at altitudes below the level of introduction of the reagent an optimum concentration is formed and precipitation is nevertheless formed. Relatively small ice particles, propagating in different directions, also at some distance from the seeding site, create an optimum concentration. However, if the cloud has a small thickness, the excess concentration of introduced particles leads to their mutual competition, as a result of which the cloud becomes iced, but yields no precipitation. Accordingly, the lesser the size of the cloud, the more critical are the conditions for the formation of precipitation from it with respect to the quantity of reagent. In this case the concentrations of artificial ice nuclei should be computed with great certainty.

Experiments seemingly confirm this: for clouds of great volume the result of modification is not dependent on the seeding norm; there is such a dependence for small clouds. Some mean norm is optimum. It is true that this conclusion was drawn on the basis of a small number of experiments and requires confirmation.

We have discussed clouds having a supercooled part. However, with large vertical extent and liquid water content so-called warm clouds (such is the name given to clouds not having a supercooled part) develop to the stage of warm clouds. There are also cases when the cloud does not quite reach the rain stage and artificial intervention in the course of the process can yield results. As in the case of supercooled clouds, here there are two fundamentally possible intervention variants: intensification of convection or intensification of condensation-coagulation enlargement of selected droplets in the cloud.

In conclusion we point out that during recent years attempts have been made to seed thick cumulus clouds forming over forest fires for the purpose of extinguishing the latter. As follows from the material in Chapter 3, the success of such measures is determined primarily by the extent to which the atmosphere is prepared for the creation of a "meteotron" under the influence of heating of the air over the fire. With a great stability and dryness of the atmosphere, which, unfortunately, is often characteristic in the case of large forest fires, small cumulus clouds are formed whose effectiveness against fires is small. However, the loss from forest fires is so great that even the slightest possibility of using clouds against them cannot be neglected.

There are many cases when large forest fires arise in the presence of frontal cloud cover or during its propagation over a territory affected by forest fires. In such cases the artificial expansion of zones of heavy precipitation from clouds is an effective means for contending with the centers of forest fires or restricting the possibilities of their expansion.

4.6. Dynamic Methods for Cloud (Fog) Dispersal

In this section we examine methods for the dispersal (scattering) of clouds (fogs) in which use is made of directed descending movements either created by flight vehicles (aircraft, helicopters) or arising as a result of the discharge of reagent into the cloud or fog.

A flight vehicle, moving over a cloud or fog, creates a descending current. The aircraft creates a momentum which is particularly strong if the aircraft rises steeply upward — pitches. A helicopter, moving slowly or hovering above a definite point, creates a quasistationary descending air current.

First we will examine the action of a stationary descending current. As a simplification we will assume that the cloud is monodisperse and in computing its evaporation we will use the approximate formula (2.1.31), which makes it possible to estimate the time of evaporation of a cloud particle with $dT'/d\tau>0$, where T' is cloud temperature (we note that in Chapter 2 it is denoted T).

Assuming

$$\frac{dT'}{d\tau}=\gamma w \qquad (4.6.1)$$

and assuming that the change in $E\gamma w/T'^2$ in the segment of motion of the air particle is relatively small, from (2.1.31) we obtain the time of total evaporation of the cloud particle

$$\tilde{\tau}=\frac{4\pi\rho_{в}nkNT'^2Mpr^3}{3LE\mu^2\gamma w}, \qquad (4.6.2)$$

where ρ_{water} is the density of water.

If the liquid water content of a cloud (in $g\cdot cm^{-3}$) is introduced into consideration

$$q=\frac{4}{3}\pi r^3 n\rho\rho_{в}, \qquad (4.6.3)$$

then

$$\tilde{\tau}=\frac{qkNT'^2Mp}{LE\mu^2\rho\gamma w}. \qquad (4.6.4)$$

Accordingly, the total evaporation path is

$$\tilde{z}=w\tilde{\tau}=\frac{qkNT'^2Mp}{LE\mu^2\rho\gamma}. \qquad (4.6.5)$$

Stipulating w, q, T', we obtain the characteristic time of total evaporation of a cloud particle (Fig. 4.6.1). The temperature gradient γ is stipulated without taking mixing into account, that is, is somewhat exaggerated, to the greater degree the lesser the cross section of the current (see Chapter 3).

Figure 4.6.1 shows that nonconvective clouds (they are characterized by currents of about 1 $cm\cdot sec^{-1}$) decay naturally very slowly: this requires several hours; however, they are formed equally as slowly. At the same time the figure shows that an artificially created descending flow, having a velocity of only a few meters per second, is capable of very rapid local scattering of a nonconvective cloud regardless of its stage of development.

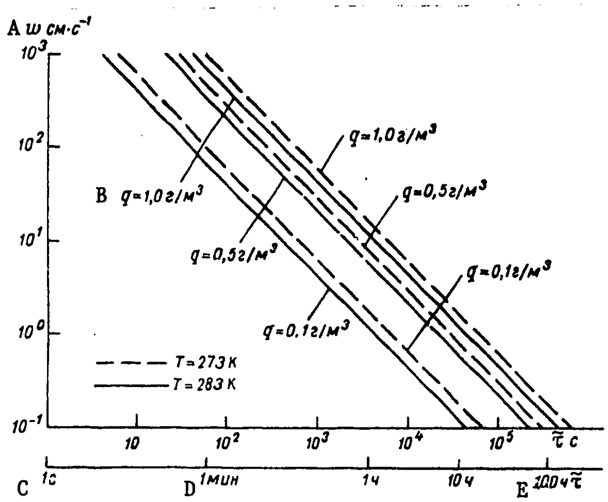

Fig. 4.6.1. Time of total evaporation of cloud as function of velocity of descending flow.

KEY:
- A) cm·sec^{-1}
- B) g/m^3
- C) sec
- D) min
- E) hours

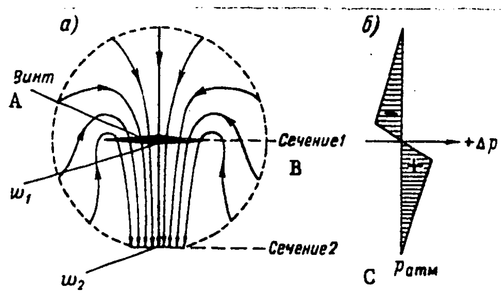

Fig. 4.6.2. Descending air current from helicopter propellor operating "in place." a) flow lines; b) pressure curve

KEY:
- A) Propellor
- B) Section 1, 2
- C) P_{atm}

We should also point out the circumstance that with a change in vertical velocity there is an inverse proportional change in dispersal time but the path covered by the cloud particle prior to its evaporation remains approximately the same.

We will assume that a helicopter has appeared over a cloud or fog. A descending air current is formed under it. The currents near the propellor are shown in Fig. 4.6.2. The propellor forms a vertical current. Its velocity in the section in which the propellor is situated (section 1), the so-called characteristic velocity of the descending current of the helicopter, can be computed using the approximate equation

$$w_1 = \left(2 \frac{\mathcal{P}}{S\chi\rho}\right)^{1/2}, \qquad (4.6.6)$$

where $\mathcal{P}$ is the per-second thrust momentum, S is the area swept by the propellor, χ is the coefficient of end losses. Here reference is to velocity averaged over the area of the current section.

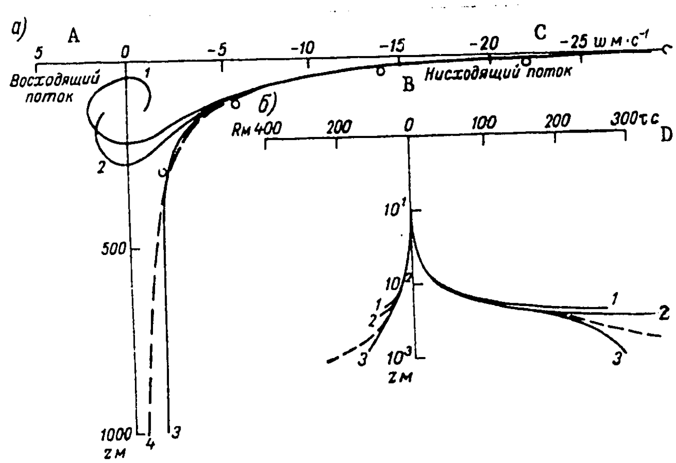

Fig. 4.6.3. Velocity of descending movements w (a), radius of current R and time of total evaporation of cloud τ (b) in current from helicopter. 1) γ = 1°C/100 m, 2) γ = 0, 3) γ = 1°C/100 m, 4) computation without allowance for stratification; dots -- results of measurements under conditions of moderately unstable atmosphere.

KEY:
- A) Ascending current
- B) Descending current
- C) m•sec^{-1}
- D) sec

Formula (4.6.6), with an accuracy to the factor χ expresses the correlation between flow velocity and dynamic pressure

$$\frac{\mathcal{P}}{S}=\rho\frac{w_1^2}{2}. \qquad (4.6.7)$$

In section 2 (Fig. 4.6.2), where the pressure becomes equal to atmospheric pressure, the vertical velocity w_2, as indicated by theory, is approximately twice as great as in section 1, whereas the area of section 2 is twice as small as the area of section 1. The distance between sections is approximately equal to the diameter of the rotor blades.

The dashed line in Fig. 4.6.3 shows the velocity of the descending flow under the helicopter and the radius of the isothermic current, computed for an Mi-1 craft.

We will assume that the helicopter hovered directly over the cloud. Judging from the computations, it is capable of "breaking through" a cloud of considerable vertical thickness. Hovering over the cloud, whose vertical thickness is 1 km, the helicopter "breaks" in the cloud a conical window with a radius of about 5 m in the upper section directly under the helicopter and 220 m in the lower section.

Above the computations were made for an isothermic current. However, the theory presented in Chapter 3 indicates that even for short distances the nonisothermicity of the current in the real atmosphere can substantially change the pattern of vertical currents in the flow, and accordingly, the results of computations of the rate of cloud evaporation.

Descending into a region of higher pressure, the air is heated; at the same time, as a result of evaporation of cloud droplets a heat loss develops. A temperature difference arises between the currents and the surrounding air, even if it was not at first directly below the helicopter; the flow experiences Archimedean acceleration, and as a result, is either slowed down or is additionally accelerated.

It was demonstrated in Chapter 3 that this effect is essentially dependent on the temperature stratification in the cloud (or fog). It is taken into account in the theory developed in Chapter 3. Using the theory, we obtain the possibility for repeating the computations of cloud dispersal, but now already with allowance for change in the temperature of the current in the process of its movement in the cloud. Three examples were considered, differing with respect to the degree of atmospheric stability (inversion, isothermy, decrease of temperature with altitude).

It appears that already at a distance of 100-200 m below the helicopter the temperature stratification begins to exert its influence (Fig. 4.6.3). Both the size of the window and the evaporation time in examples 1, 2 and 3 are substantially different and differ from the computed values under the condition of isothermicity of the flow.

Allowance for stratification considerably changed the results of the computations. In an unstable atmosphere the current reaches the ground. However, in the case of isothermy the current descends downward only 250 m, then is imparted an acceleration which is directed upward, experiences several upward-downward cycles of movement and then attenuates. In an inversion all this occurs in a still higher cloud layer. The branch of the line w with the "+" sign is conditional. In actuality, an air particle, imparted an acceleration directed upward, collides with a particle moving in a downward direction and as a result there will be a "spraying" of the current to the sides and downward. A so-called air cushion is formed below this level and the current does not penetrate through it.

As a comparison, this same Fig. 4.6.3 shows the results of measurement of the descending flow beneath the helicopter with similar parameters under conditions of a moderately unstable atmosphere.

The axial velocity was measured, and for conversion to the mean velocity in the section use was made of the universal profile of excess velocity in the main segment of a free axially symmetric air current, which is usually used in gas dynamics:

$$\frac{w(r)}{w(0)}=\varphi\left(\frac{r}{R}\right),$$

where R is the radius of the current, r is the momentary radius ($0<r<R$). Taking (4.6.2) into account

$$\frac{\bar{w}}{w_0}=\frac{2\pi}{\pi R^2}\int\limits_0^R r\frac{w(r)}{w(0)}dr=2\int\limits_0^1\frac{r}{R}\varphi\left(\frac{r}{R}\right)d\left(\frac{r}{R}\right).$$

The accuracy of the comparison is low because the helicopters were different and the positions of the measurement points were inadequately determined relative to the axis of the current, but nevertheless the comparison makes sense in the upper part of the current where the role of atmospheric stratification is small.

Figure 4.6.3 indicates the possibility of use of helicopters for "breaking" windows in clouds and fogs, but the degree of success of this measure is highly dependent on atmospheric stratification.

Figure 4.6.3 shows velocities averaged along the section of the current. In more detailed computations it is necessary to take into account the radial distribution of the parameters of the current. The descending flow along the axis of the current can considerably exceed the mean velocity. This excess is the greater the lesser is the section of the current.

Experiments with the dispersal of fogs using helicopters were carried out in 1968 in the United States (in western Virginia) and then were repeated many times.

Figure 4.6.4 illustrates a successful experiment in which after five helicopter passes the landing strip was freed of fog. The spatial scale of clearing can be judged from the landing strip, whose length was 2 km. In this case the spatial corridor was maintained for approximately an hour. The dynamics of regeneration of the scattered fog is illustrated by an experiment carried out on the next day (Fig. 4.6.5). Three or four minutes after ending the clearing operation the airport was again covered by a fog.

For practical purposes it is necessary to know at what rate the cleared region (window) in the fog or cloud disappears. This region is gradually drawn in because of two factors: diffuse (turbulent) flow of fog from the surrounding space into the window and the simultaneous condensation of water vapor in the window if the cloud (or fog) as a whole develops. Both can be computed if the thermo-pressure field of the atmosphere and the tendency of its development are known.

Figure 4.6.6 shows the track which remained in the cloud after the flight of two aircraft over it. It is probable that the descending component of the "wakes" which were created by the aircraft penetrated for a small depth in the cloud. According to the observer's report, the width and depth of the track was about 250 m; the track from the aircraft was 3 km in length.

The "wake" behind the aircraft has a rather complex structure. Eddy currents, which with increasing withdrawal of the aircraft gradually expand and attenuate, develop at the ends of the wings. A descending flow is created directly under the aircraft and a compensating ascending flow is created along the sides. The rate of decay of eddy currents is dependent on the degree of atmospheric turbulence. Under average conditions the descending flow of more than 1 $m \cdot sec^{-1}$ can persist in them for several minutes so that the "wake" can extend several kilometers behind the aircraft. In accordance with the theory developed above, a clearing can be formed in the wake in the region of descending movements in the case of adequate instability. The depth of penetration of the descending flow behind the aircraft (or helicopter) into the lower-lying layer of the atmosphere is dependent not only on the degree of atmospheric stability, but also on the flight speed of the flightcraft. This circumstance is graphically illustrated in Fig. 4.6.7, which schematically shows the results of typical computations of the current in an unstable atmosphere for different speeds of horizontal movement of a helicopter.

If the aircraft pitches over a cloud decaying or developing when there is little instability, the effect of its modification input is small. However, if the cumulus cloud is vigorously developing, this is evidence of strong thermal instability of the atmosphere and then the pitching can lead to the decay of the cloud.

Corresponding experiments were carried out in the USSR in the 1960's. They confirmed the ideas developed above. Several minutes after modification there was a substantial decrease in the upper boundary of cumulus clouds with a thickness up to 5-6 km or they disappeared completely. The experiments also confirmed that the more unstable the atmosphere, the stronger and more rapid was the destruction of the cloud. Thus, the more favorable the conditions for cloud development, the more effective is their modification by descending currents.

A similar effect can be achieved by detonating sufficiently powerful charges in the cloud. The cannonading of clouds with explosive shells, especially if it is thereby possible to create a directed explosion, is a rather effective means for destroying clouds in an unstable atmosphere.

The dumping of heavy particles into a cloud creates forces in it additional to those which were examined in Chapter 3. This can lead to deformations in the vertical velocities in the cloud and thereby exert an influence on its fate. In order to take this into account it is now necessary to introduce into formula (3.1.5) the additional force of aerodynamic resistance F', related, like F, to the per-second mass.

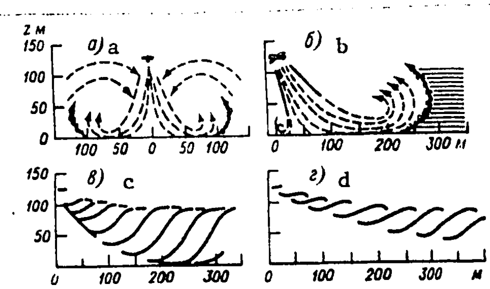

Fig. 4.6.7. Diagram of descending air flow for different speeds of helicopter movement in absence of wind. a) 0 km·hour^{-1}, b) 10 km·hour^{-1}, c) 30 km·hour^{-1}, d) 60 km/hour.

If the particles are distributed uniformly in the volume of the current, then

$$F' = S'wn\rho \int_0^\infty C_a r^2 \frac{w_r^2}{2} \eta(r)\, dr, \tag{4.6.8}$$

where the following are new parameters: n is the concentration of particles dumped into the cloud, $\eta(r)$ is the function of their distribution along the radii r, w_r is the rate of falling of particles, C_a is the drag coefficient.

If the concentration of dumped particles is great their drag is less than the sum of the resistances of individual particles. If the concentration is small, it is evidently possible to assume that the movement of the dumped particles does not differ very greatly from steady movement and the drag force can be replaced by the equivalent gravitational force

$$F' = S'wmg, \tag{4.6.9}$$

where m is the mass of the dumped particles, related to a unit air volume (g·cm^{-1}).

Then, summing (3.1.5) and (4.6.9), we obtain the equation

$$\frac{1}{g}\frac{dw}{d\tau} = \frac{T'-T}{T} - \frac{m}{\rho} - \frac{w^2}{g}\frac{C}{R}\frac{T'}{T}, \tag{4.6.10}$$

which makes it possible to evaluate the relative role of superheating of the cloud in relation to the atmosphere (first term), mixing (third term) and dumping (second term). The dumping, which can change the sign of acceleration of the current, is determined if we assume that the left-hand side in (4.6.10) is equal to zero. Then in dimensional units

$$\frac{m}{\rho} = \frac{T'-T}{T} - \frac{w^2}{g}\frac{C}{R}\frac{T'}{T}. \tag{4.6.11}$$

As might be expected, the dumping effect is highly dependent on the state in which the cloud is situated.

If prior to dumping (with m = 0) at some level there is satisfaction of the condition $dw/d\tau = 0$, after dumping a downward-directed acceleration of the current appears regardless of how small a quantity of matter is dumped. However, in the active part of the cloud, where the first term in (4.6.10) is considerably larger than the third, this acceleration is capable of appreciably changing the velocity if the left-hand side of (4.6.11) is of the same order of magnitude as each of the terms on the right-hand side:

$$\frac{m}{\rho} \approx \frac{T' - T}{T} \gtrless 10^{-3}, \qquad (4.6.12)$$

or with $\rho \approx 10^{-3}$ g·cm^{-3} the value m$\geqslant 10^{-6}$ g·cm^{-3} = 1 g·m^{-3}. In order by means of the dumping of particles in a small concentration to attempt to decrease the ascending flow it was necessary to introduce into the cloud an enormous quantity of substance, not less than the mass of water in that part of the cloud to be modified.

Above reference was to particles which, upon entering into the cloud, do not change their size.

The situation is considerably improved if the particles dumped grow in the cloud. Then the m value, and accordingly the dumping effect, can increase by many times; in this case the dumping effect is dependent on both the degree of dispersivity of the particles and on their surface properties. A powerful descending flow which destroys the cloud appears in a considerable part of the cloud. Sometime later it is replaced by another cloud, since, in annihilating a cloud, we did not eliminate the factors which led to its appearance, but time is required for the appearance of a new cloud. In some cases such a temporary freeing of space from cumulonimbus clouds makes sense.

If a cloud has already formed, for the creation of a descending flow it is necessary to overcome the ascending flow. It is possible to create a descending flow in a thermally unstable atmosphere in a place where for the time being there is still no ascending flow by the dumping of a small quantity of substance. Then, much as is shown in Fig. 4.6.3, a descending flow will develop, drawing the energy of thermal instability from the atmosphere.

Then the property of air continuity exerts its effect: either the development of the descending movements leads to the disappearance of ascending movements in surrounding space, and accordingly, in clouds, or, despite the energy reserve of instability, the artificially created descending flow attenuates.

In evaluating the results of computations it must not be forgotten that we are considering the "fate" of the flow, a flow isolated from other vertical and horizontal movements in space.

In the 1960's a series of experiments was carried out in the USSR with the dumping of pulverized cement into cumulonimbus clouds. The experiments were successful. Several tens of kilograms of cement particles with a diameter of several tens of microns in many cases led to the decay of clouds.

As already mentioned above, a downward-directed momentum can be created by an aircraft. Diving into the cloud from above, it changes the momentum in the current by a force proportional to the mass of the aircraft and the acceleration of diving; pitching, it sends toward the cloud flow a powerful high-velocity descending flow created by the turbines of its engines. An estimation of the diving effect can be made much as was done in the case of dumping of particles. An evaluation of the pitching effect involves solution of the countercurrents problem.

References: [1, 5, 7, 10, 12, 14, 15, 16, 20, 21, 22, 25, 39, 40, 42, 52, 64, 65, 70, 72, 84, 85, 87, 93, 95, 99, 104, 105, 117, 119, 124, 125, 129, 132].

CHAPTER 8

MODIFICATION OF THE HIGH LAYERS OF THE ATMOSPHERE

8.1. Fundamental Principles

The high layers of the atmosphere are those layers situated above 10-15 km. The field of aeronomy is concerned with investigation of these layers.

The atmosphere at great altitudes differs fundamentally from the surface layer both with respect to its properties and with respect to the role which it plays in the earth's life. The ozonosphere and ionosphere have been investigated most completely. Both these layers are filters blocking a large part of the short-wave part of the solar spectrum and cosmic ionizing radiation acting on the animal and plant world. The ionosphere, in addition, is an important element in systems for global radio communications. In the upper layers of the atmosphere there are such phenomena as auroras, magnetic storms, meteorites, etc.

The role of the high layers of the atmosphere in the formation of weather and climate on the earth is less known. Considerable efforts have now been directed to study of their role. In addition, there is basis for suspecting that some phenomena in the upper atmosphere exert a direct influence on the biological rhythms of life on earth.

Figure 8.1.1 shows the principal molecular-kinetic parameters of the high layers of the atmosphere.

The troposphere is characterized by an intensive turbulent mixing of air masses as a continuous medium and therefore the troposphere contains no stationary, clearly expressed layers with specific properties. The molecular composition of the air is virtually constant. In the stratosphere the turbulent mixing of air as a continuous medium attenuates, but on the other hand in the higher layers the length of the free path of air molecules and accordingly, kinematic viscosity, governed by the thermal motion of molecules, become so great that they are predominant in diffusion processes. Gradually, with upward ascent, mixing becomes free molecular, different air components behave independently and for each of them the vertical distribution is determined, this being governed by their molecular mass and accordingly the rate of molecular diffusion. In this sense one can speak of the diffuse separation of air components at great altitudes.

Precisely for this reason the molecular mass of air as a whole (this parameter, as is well known, is conditional) is an index of the intensity of diffuse separation of its component parts.

The criterion for conversion from motion of a continuous medium to free molecular motion is the Knudsen number

$$\mathrm{Kn}=\frac{l}{R}, \tag{8.1.1}$$

where l is the length of the free path of molecules in the medium, R is the characteristic dimension of the body around which the flow occurs.

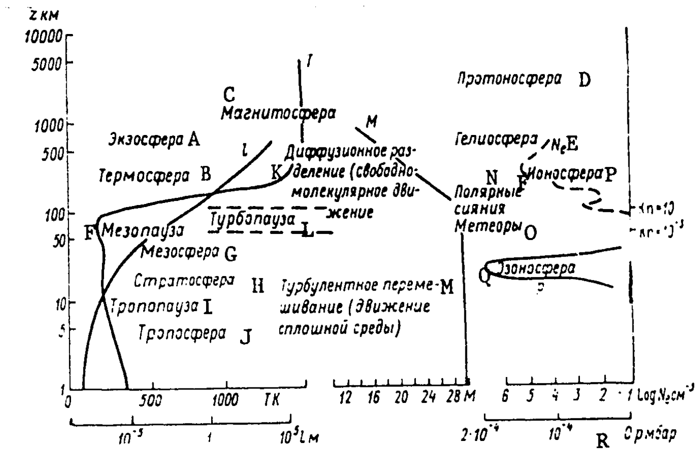

Fig. 8.1.1. Principal layers and molecular-kinetic parameters of the atmosphere. Vertical profiles: T -- temperature, l -- length of free path (Knudsen number with characteristic dimension of body 1 m), M -- molecular mass, N_e -- ionospheric electron concentration, p -- ionospheric ozone content.

KEY:

A) Exosphere
B) Thermosphere
C) Magnetosphere
D) Protonosphere
E) Heliosphere
F) Mesopause
G) Mesosphere
H) Stratosphere
I) Tropopause
J) Troposphere
K) Diffuse separation (free molecular motion)
L) Turbopause
M) Turbulent mixing (motion of continuous medium)
N) Auroras
O) Meteors
P) Ionosphere
Q) Ozonosphere

If it is assumed that R = 1 m, the length of the free path and the Knudsen number coincide numerically. Figure 8.1.1 shows the region of transition from motion of the continuous medium to free molecular motion (with R = 1 m). This region is limited by Knudsen numbers 10^{-3} and 10; it is called the turbopause (the name was given by analogy with the tropopause).

In the region of free molecular motion the coefficient of molecular diffusion (molecular kinetic viscosity) is computed using the formula

$$\nu = \frac{1}{3} lV. \tag{8.1.2}$$

Here l is the mean length of the free path of air molecules, V is the mean velocity of their thermal motion, which is determined from the expression

$$\frac{1}{2}\frac{MV^2}{N} = \frac{3}{2}kT, \tag{8.1.3}$$

where M is the molecular mass of air, N is the Avogadro number, k is the Boltzmann constant.

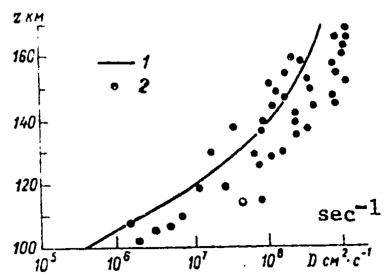

Fig. 8.1.2. Coefficient of molecular diffusion, computed for standard atmosphere (1) and from observations of diffusion of trimethyl aluminum, sodium, lithium and other artificial clouds (2). 1961-1965 (United States).

Figure 8.1.2, for the stratosphere (above the turbopause), shows the results of observations of artificial aerosol clouds; on the basis of the rate of their dispersal it was possible to determine the diffusion coefficient (see Chapter 3), which was also computed using formula (8.1.2) for the standard atmosphere.

The figure shows that in actuality at such altitudes diffusion of the impurity is for the most part determined by molecular processes and formula (8.1.2) is entirely suitable for approximate computations, although it is known that in actuality both the self-diffusion of the component parts of the air and the diffusion of impurities at such altitudes have a more complex nature. This is attributable to the fact that a considerable percentage of the molecules is ionized and in the process there is "intervention" of electrical forces. The charged particles move under the influence of electric and magnetic fields. Different kinds of electro- and magnetohydrodynamic effects of different scales arise. Their examination is beyond the scope of this book. Accordingly, in the text which follows in the estimates of diffuse mixing in the high layers of the atmosphere, both at the altitudes to which Fig. 8.1.2 pertains, and at greater altitudes, as the coefficient of diffusion of impurities we will use only kinematic molecular viscosity of electrically and magnetically neutral air.

The vertical distribution of ozone and free electrons will be discussed below. In Fig. 8.1.1 it is shown for completeness of the picture (here the characteristic daytime concentrations of ozone and electrons are given).

In order to estimate the rate of diffusion of impurities in the high layers we will recall (see Chapter 3) that the rate of propagation of the maximum concentration of matter from the source is determined by formulas in the form

$$r^2 = KD\tau, \qquad (8.1.4)$$

where K is a numerical coefficient varying in the range of several units in dependence on the specific properties of the source; D is the diffusion coefficient; τ is the time during which the maximum concentration of impurities is attained at the distance r from the source.

Assuming in (8.1.4) that r = 100 km and assuming that the diffusion coefficient is equal to the coefficient of kinematic viscosity of air ($D = \nu$), we obtain the time τ of propagation of the impurities, measured for an altitude of 200 km (in days), for an altitude of 400 km (in minutes), and for an altitude of 700 km (in seconds).

Thus, at altitudes characteristic, for example, for the ionospheric F layer, impurities can be propagated as a result of molecular-atomic thermal motion with an enormous velocity horizontally and upward, but with a considerably lesser velocity downward, toward the earth.

In other words, propagating globally through the stratosphere, impurities can persist for a long time in the stratosphere, accumulating in it, without penetrating into the troposphere. This is one of the circumstances explaining why contamination of the high layers is a special danger. The second circumstance is related to the fact, as will be clear from the text which follows, that the ozone and ion layers are exceedingly sensitive to the impurities playing the role of catalysts of ozone and ion formation or decay; therefore, even an insignicant quantity of catalyst-impurities can have serious consequences. Impurities can penetrate into the stratosphere from the lower layers of the atmosphere, but with each passing year they are directly entering into the stratosphere in increasing quantities. Even now supersonic aircraft have assumed flight altitudes of 15-20 km, that is, altitudes where the ozone layer is situated.

In the years immediately ahead the number of aircraft and their flight altitude will increase. True, the progress of technology should result in a decrease in the harmful effluent of aircraft and rocket engines, but the total quantity of discharged impurities, according to available estimates, will increase, although not so quickly as the number of aircraft flights.

We will cite two figures in order to obtain some idea concerning the quantity of impurities which can be discharged into the atmosphere by supersonic aircraft. The engine of a "Boeing 2707-300" aircraft, during a flight at an altitude of 20 km with a Mach number 2.7, according to computations in one hour of flight should, among other combustion products, discharge 18.6 tons of water vapor and 0.65 ton of carbon monoxide.

Considerable quantities of impurities are discharged by rockets. For example, the "Saturn" carrier-rocket, which on 14 May 1973 was used for putting the "Skylab" space laboratory into orbit, in the final stage, at an altitude of 440 km, as a result of combustion of hydrogen in an oxygen medium in the engines of the second stage, discharged into the atmosphere $3 \cdot 10^{28}$ molecules of water and 10^{28} molecules of hydrogen per second. With a flight velocity of the rocket of 7.3 $km \cdot sec^{-1}$ this corresponds to a discharge of approximately 10^{27} molecules of H_2O

and H_2 per kilometer of path. Assuming in formula (П.64) that $Q' = 10^{27}$ km^{-1} and in accordance with Fig. 8.1.1 $D = 10^7$ m$^2\cdot$sec^{-1}, at a distance r = 1,000 km, under the condition of a maximum of the concentration, during the time

$$\tau = \frac{r^2}{4D} = 420 \text{ minutes}$$

we obtain the concentration of H_2O and H_2 molecules

$$c = Q' \frac{1}{\pi r^2 l} = 10^{11} \text{ м}^{-3}. \qquad (8.1.5)$$

This value is of the same order of magnitude as the electron concentration in the ionosphere at this altitude and therefore is entirely adequate for an appreciable acceleration of the reactions of disappearance of electrons in the ionosphere.

The reactions of formation and disappearance of electrons and ions themselves in the iono- and ozonosphere will be discussed below. Now we note that some of them have become known quite recently and it was found that the rates of such reactions, measured under ordinary laboratory conditions, are difficult to extrapolate into the region of stratospheric conditions. For the time being direct measurements of the rates of reactions directly in the stratosphere are impossible due to lack of appropriate instrumentation.

8.2. Modification of Ionosphere

The ionosphere is the layer of the stratosphere from approximately 50 km to several hundred kilometers in which there is an adequate quantity of ionized particles capable of exerting a substantial influence on radio wave propagation. In the first approximation in the ionosphere it is possible to discriminate the D, E and F regions, within which there are narrower regions.

The ionosphere is formed under the influence of solar irradiation (UV, X- and corpuscular radiation), as well as fluxes of cosmic ionizing radiation. The principal charge carriers in the ionosphere, exerting an influence on radio wave propagation, are electrons. Therefore, the electron concentration in the ionosphere is usually considered.

The properties of the ionosphere are subject to regular and irregular variations. Until recently the ionospheric regime was considered exclusively in relation to the solar and cosmic effect on it. However, investigations of recent years have indicated that the stratosphere also sensitively reacts to processes transpiring in the troposphere, hydrosphere and lithosphere. Volcanic activity, tsunamis, earthquakes, cyclones, thunderstorms, launching of large flight vehicles, transmission of adequately powerful radio signals, acoustic and thermal signals — all these processes find a response in the ionosphere.

In order to understand what is involved, first of all we will examine transformation of an acoustic signal during its movement from the earth to the ionosphere. As is well known, the flux density of a plane acoustic wave (this is also called sound intensity) is equal to

[ЗВ = sound]
$$I = \frac{1}{2} \rho c_{\text{зв}} \omega^2 A^2, \qquad (8.2.1)$$

where ρ is air density, c_{sound} is the speed of sound, ω and A are the angular frequency and amplitude of the acoustic signal. The flux density of the acoustic wave (Umov vector) is a vectorial parameter.

The speed of sound in the air is determined using the formula

$$c_{sound} = \sqrt{\gamma \frac{KNT}{M}}, \tag{8.2.2}$$

where γ is the ratio of specific heat capacity at a constant pressure to the specific heat capacity for a constant volume.

If there are no losses of acoustic energy (I = const), the signal amplitude with motion of the signal upward would increase approximately proportionally to the decrease in the square root of air density (with altitude the speed of sound varies far more weakly -- proportional to $\sqrt{T/M}$). But in actuality the signal experiences attenuation in the atmosphere at great altitudes primarily due to losses in molecular viscosity, thermal conductivity and radiation.

The first two factors are most important for not excessively great signal intensities. Accordingly, the attenuation of intensity of an acoustic wave in the stratosphere is registered in the form

$$dI = -I\mu\, dz. \tag{8.2.3}$$

Here μ is the attenuation coefficient, related to a unit path (upward) and

[3B = sound]

$$\mu = \frac{\omega^2}{c_{3B}^3}\left[\frac{4}{3}\nu + \lambda\frac{(\gamma-1)}{c_p\rho}\right], \tag{8.2.4}$$

where ν is the coefficient of molecular kinematic viscosity of air, c_p is heat capacity at a constant pressure, λ is the thermal conductivity coefficient, ρ is density (the first term is the coefficient of sound attenuation as a result of losses in friction, the second term is the coefficient of sound attenuation as a result of losses in thermal conductivity).

Replacing ν and λ by corresponding expressions, we obtain

$$\mu = \frac{\omega^2}{c_{3B}^3} lV\left[\frac{2}{3} + \frac{1}{3}\frac{\gamma-1}{\gamma}\right] \approx \frac{\omega^2}{c_{3B}^3} lV \approx \frac{\sqrt{3}\,\omega^2 lM}{KN\gamma^{3/2}T}, \tag{8.2.5}$$

from which it can be seen that the coefficient of sound absorption in the atmosphere is determined by the frequency ω of the acoustic signal, and also by the length of the free path of air molecules l, since the parameter $V/c_{sound}^3 \propto M/T$ varies with altitude far more weakly than l. Thus, the coefficient of attenuation of the acoustic signal at great altitudes increases with altitude as a result of an increase in the length of the free path of molecules rather rapidly (see Fig. 8.1.1) and becomes significant the more rapidly the greater the frequency of the acoustic signal.

In accordance with formulas (8.2.1)-(8.2.4) the signal amplitude increases with propagation of the acoustic wave upward from the earth's surface as long as the coefficient of sound absorption is small and the signal propagates virtually without losses. Then, with an increase of the attenuation coefficient μ with altitude, the signal amplitude A begins to decrease (see formula (8.2.3)).

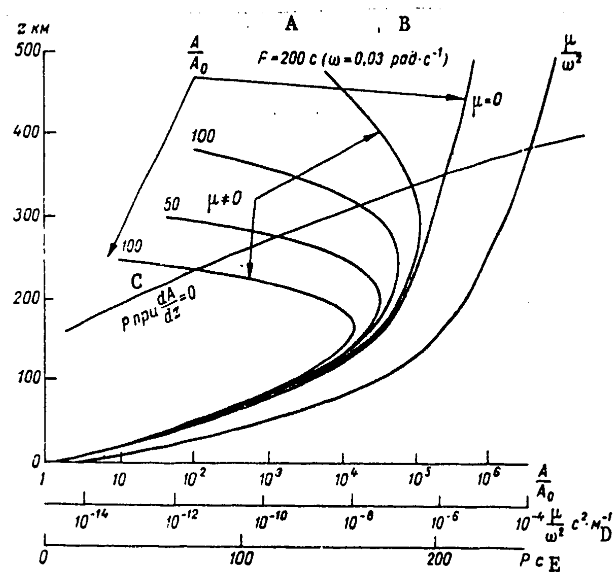

Fig. 8.2.1. Vertical change in curve of sound attenuation μ/ω^2 and relative amplitude of acoustic signal A/A_0 without allowance for attenuation ($\mu = 0$) and real attenuation for different periods of acoustic signal, and also isoline of altitudes, where $dA/dz = 0$ for different periods (frequencies) of acoustic signals.

KEY:

A) sec
B) rad·sec^{-1}
C) with
D) sec^2·m^{-1}
E) sec

When the acoustic signal contains components of different frequencies we obtain the picture represented in Fig. 8.2.1; it shows the curve of sound attenuation μ/ω^2 and the altitudinal change in the relative amplitude of the acoustic signal A/A_0, taking into account both its increase as a result of a decrease in air density and attenuation. The greater the period of the acoustic signal (the lower its frequency), the lesser are the altitudes which it attains. The altitude at which the signal amplitude begins to decrease can be found from the condition of a maximum of the amplitude of the acoustic signal:

$$\frac{dA}{dz} = 0. \qquad (8.2.6)$$

Combining (8.2.1) and (8.2.3), we obtain

$$I_0 \exp(-\mu z) = \frac{1}{2} \rho c_{зв} \omega^2 A^2.$$

Taking the logarithmic derivative of z (in this case neglecting the change in the speed of sound with altitude), we have

$$\mu + \frac{1}{\rho}\frac{d\rho}{dz} + \frac{2}{A}\frac{dA}{dz} = 0. \quad (8.2.7)$$

The amplitude of the acoustic signal begins to decrease with altitude, where the third term is equal to zero:

$$\mu + \frac{1}{\rho}\frac{d\rho}{dz} = 0.$$

Figure 8.2.1 shows that the atmosphere is an extremely effective amplifier of acoustic signals and at the same time is a singular filter sorting out by altitudes the components of different frequencies (periods), as a result of which a possibility appears for observing the response of different layers of the ionosphere to acoustic signals of different frequencies (periods).

It becomes understandable why the ionosphere reacts (responds) appreciably to relatively weak acoustic disturbances arising in the low layers of the atmosphere (explosions, cyclones, tsunamis, etc.).

Observations of ionospheric fluctuations are made by radio methods. As the principal metric property we will use the plasma properties of the ionosphere: the concentration of free electrons and the dielectric constant caused by them.

The fundamental formulas for the dielectric properties of plasma were given in Section 1.8; we will supplement them with the following:

1) the phase velocity of propagation of a monochromatic radio wave

$$V_{ph} = c\left[\frac{\varepsilon_0}{\varepsilon}\right]^{-\frac{1}{2}} = c\left[1 - \left(\frac{\omega_п}{\omega}\right)^2\right]^{-\frac{1}{2}}; \quad (8.2.8)$$

2) the group velocity of a wave packet forming as a result of dispersion, which is different from the phase velocity,

$$V_{gr} = c\left[\frac{\varepsilon_0}{\varepsilon}\right]^{\frac{1}{2}} = c\left[1 - \left(\frac{\omega_п}{\omega}\right)^2\right]^{\frac{1}{2}}. \quad (8.2.9)$$

In the ionosphere, with upward propagation of the sounding radio signal, in the region of high concentrations of electrons, the signal frequency gradually approaches the local plasma frequency; the phase velocity increases, gradually more and more exceeding the speed of light, whereas the group velocity, on the other hand, decreases. Upon reaching the altitude where the frequency of the sounding signal and the local plasma frequency coincide

$$V_{ph} \to \infty, \quad V_{gr} \to 0, \quad (8.2.10)$$

the sounding radio signal experiences complete reflection.

With a frequency of the sounding radio signal less than the plasma frequency ($\omega < \omega_{pl}$) the signal will all the more be completely reflected from the boundary of the ionized medium. With $\omega > \omega_{pl}$ the signal will penetrate into the ionized medium to a depth which will be the greater the higher the frequency of the sounding signal in comparison with the plasma frequency.

If, for example, $n_e = 5\cdot10^{11}$ $m^{-3} = 5\cdot10^5$ cm^{-3} (typical electron concentration in the daytime in the F layer), the critical angular frequency of the sounding radio signal is

$$\omega = \omega_{pl} = 41.84.10^6 \ sec^{-1},$$

which corresponds to the linear frequency

$$f = \omega/2\pi = 6.66\cdot10^6 \ Hz = 6.66 \ MHz.$$

With lesser frequencies the signal will be reflected from the ionized layer of the atmosphere; with greater frequencies the signal will penetrate into it.

It is possible to measure the electron concentration by selecting the minimum frequency of the radio signal at which it is reflected from the investigated layer of the ionosphere. The altitude of this layer is determined by the travel time of the radio signal from the transmitter to the reflection level and back to the receiver.

When measuring the total (integral) quantity of electrons in the ionosphere it is customary to use a method based on measurement of the Faraday rotation of the polarization plane of a high-frequency radio signal, which is directly proportional to the quantity of electrons along the signal path. The plane-polarized high-frequency radio signal, during passage through the ionosphere, rotates by some angle which is dependent on the parameters of the signal itself, the ionosphere and the geomagnetic field. If the direction of propagation of such a radio signal coincides with the geomagnetic field vector, the Faraday angle of rotation in an isotropic segment of the length L is equal to

[π = pl(asma)]

$$\Omega = \frac{L}{2c} \frac{\omega_\pi^2}{\omega^2} \omega_H, \tag{8.2.11}$$

where c is the velocity of propagation of the electromagnetic wave, ω_H is the Larmor frequency of rotation of an electron in the magnetic field (in formula (8.2.11) it is assumed in advance that $\omega \gg \omega_{pl}$, ν).

If ω_{pl} is replaced by its value, and in addition,

$$\omega_H = \frac{e}{m_e} \mu_H H, \tag{8.2.12}$$

where H is geomagnetic field strength, μ_H is space permeability, we obtain the Faraday angle of rotation in the form

$$\Omega = \frac{Ln_e}{\omega^2} \frac{\pi e^3 \mu_H H}{c\varepsilon_0 m_e^2}. \tag{8.2.13}$$

Measuring Ω, with a known geomagnetic field strength it is possible to determine Ln_e -- the integral quantity of electrons on the radio signal path.

If the electron concentration varies along the radio signal path, in (8.2.13) it is necessary to convert to $d\Omega$ and dL and then integrate the equation along the radio signal path.

If the vectors c and H do not coincide, it is necessary that this be taken into account in computing the integral quantity of electrons. However, during vertical sounding of the ionosphere in many cases use is made of formulas which do not take this circumstance into account.

Now we will proceed to an examination of intentional and unintentional modification of the ionosphere.

Response of ionosphere to launching of space systems. An example is the "Saturn-Skylab" system. The "Saturn-5" rocket, launched from Cape Canaveral on 14 May 1973, put the "Skylab" space laboratory into orbit. This caused a considerable disturbance of the ionospheric F layer. The launching was accomplished at 1230 hours EST. The laboratory was put into orbit at an altitude of 442.2 km with a flight velocity of 7.3 $km \cdot sec^{-1}$ at 12 hours 39 minutes 59 seconds.

Five ionospheric stations observed the change in the quantity of electrons on the path to them of polarized radio signals from the two geostationary satellites ATS-5 and ATS-3.

Figure 8.2.2 is a diagram of the observations. It can be seen that the trajectory of the radio signal on the path ATS-3 - Sagamore Hill approached closest to the trajectory of the "Saturn-5" rocket in its final stage. Figure 8.2.3 shows how the integral quantity of electrons on the path from the ATS-3 satellite to this station changed after launching of the space system.

It is easy to see a sharp dropoff of the curve approximately 10 minutes after the launching at a time close to the time of the maximum convergence of the rocket and sounding signal trajectories. Figure 8.2.2 shows that the distance between them at this time was less than 100 km. Judging from the estimates, the impurities discharged by the rocket engines in a fraction of a minute are propagated to such a distance at the altitude of the ionospheric F layer that it cannot be noted due to the scale of this figure.

At stations for which the paths of radio signals from satellites passed farther from the rocket trajectory the lag in response is more conspicuous and the response is accordingly weaker.

Figure 8.2.4 shows the characteristic diurnal variation of the integral electron concentration and its diurnal variation on the day of launching of the space laboratory 14 May 1973. Their comparison was difficult because precisely on 13 and 14 May there was a strong magnetic storm which exerted an influence on the Faraday rotation of the polarization plane (see formula (8.2.11)). However, the scale of response of the ionosphere to launching of the space system can nevertheless be seen clearly.

The mechanism of disappearance of electrons in the ionospheric F region is a two-stage process. The first stage is ion-atom exchange in the reaction

$$O^+ + N_2 \xrightarrow{k_1} NO^+ + N \qquad (8.2.14)$$

or charge transfer in the reaction

$$O^+ + O_2 \xrightarrow{k_2} O_2^+ + O. \qquad (8.2.15)$$

Recombination reactions occur in the second stage

$$NO^{+}+e^{-}\xrightarrow{k_1}N+O, \quad (8.2.16)$$

$$O_2^{+}+e^{-}\xrightarrow{k_1}O+O. \quad (8.2.17)$$

Here k_1 is the rate of the corresponding reaction.

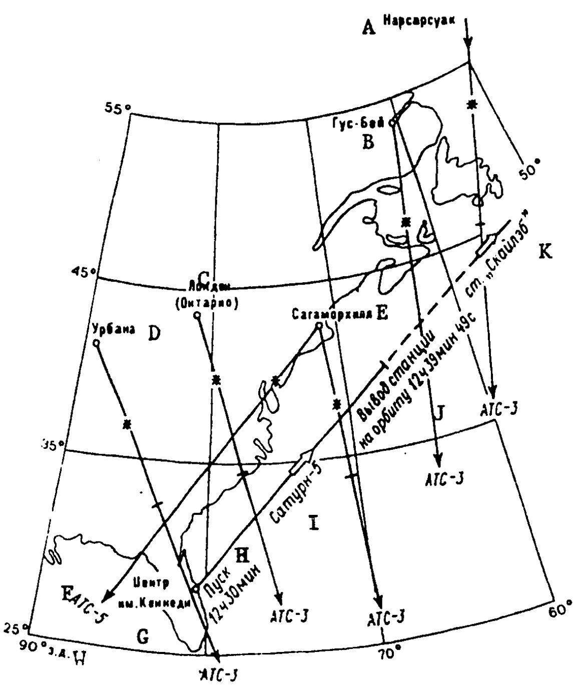

Fig. 8.2.2. Horizontal projections of the trajectory of the "Saturn-Skylab" space system and lines of sight of ionospheric stations to ATS geocentric satellites. The asterisks on the lines of sight indicate the projections of their intersection with the surface z = 420 km and the short transverse lines indicate the projections of their intersection with the surface z = 1,000 km. 14 May 1973 (United States).

KEY:

A) Narsarsuak	G) Center Cape Kennedy
B) Goose Bay	H) Launching 1230 hours
C) London, Ontario	I) Saturn-5
D) Urbana	J) Putting of station into orbit 12 hours 39 minutes 49 seconds
E) Sagamore Hill	K) Skylab station
F) ATS-5 (ATS-3)	

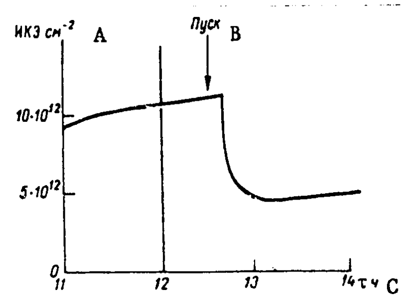

Fig. 8.2.3. Integral quantity of electrons (record of polarimeters measuring Faraday rotation) with direction of sounding to ATS-3; according to data for Sagamore Hill station. 14 May 1973. (United States).

KEY:
- A) Integral quantity of electrons
- B) Launching
- C) hours

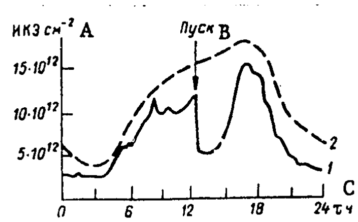

Fig. 8.2.4. Variation of integral quantity of electrons on 14 May 1973 (1) and its characteristic diurnal variation (2) according to data for Sagamore Hill station (United States).

KEY:
- A) Integral quantity of electrons
- B) Launching
- C) hours

The rate of reactions (8.2.14) and (8.2.15) is approximately 100 times less than the rate of reactions (8.2.16) and (8.2.17). Accordingly, the rate of disappearance of electrons on a practical basis is determined by the rate of reactions (8.2.14) and (8.2.15). If the concentration of nitrogen molecules is $n(N_2)$, of oxygen is $n(O_2)$ and of electrons is $n(e^-)$, the rate of disappearance of electrons is equal to:

$$\frac{dn(e^-)}{d\tau} = -[k_1 n(N_2) + k_2 n(O_2)]\,n(e^-) \quad (8.2.18)$$

or

$$\frac{1}{n(e^-)}\frac{dn(e^-)}{d\tau} = -\beta(z), \quad (8.2.19)$$

where $\beta(z)$ is the coefficient of losses of electrons at a given altitude (the expression for $\beta(z)$ is obvious from a comparison of (8.2,18) and (8.2.19)).

With the introduction of molecules of hydrogen H_2 and water H_2O into the ionosphere by a rocket ion-atom exchange transpires in the reactions

$$O^+ + H_2 \xrightarrow{k_5} OH^+ + H, \quad (8.2.20)$$

$$O^+ + H_2O \xrightarrow{k_6} H_2O^+ + O. \quad (8.2.21)$$

In the second stage this is followed by dissociative-recombination reactions

$$OH^+ + e^- \rightarrow O + H, \quad (8.2.22)$$

$$H_2O^+ + e^- \rightarrow H_2 + O, \quad (8.2.23)$$

$$H_2O^+ + e^- \rightarrow OH + H. \quad (8.2.24)$$

The rate of reactions (8.2.20) and (8.2.21) is approximately 10^3 times greater than the natural reactions, similar in sense (8.2.14) and (8.2.15). Accordingly, the rates of natural and artificially induced disappearance of electrons in the F layer have the same order of magnitude even at those distances from the source of impurities where the H_2 and H_2O admixtures in their concentration are only 1/1000 of the natural N_2 and O_2 impurities.

Using an equation of the type (Π.64) for computing the concentration of admixed H_2 and H_2O molecules at different distances from the trajectory of their discharge into the stratosphere, then using an equation of the type (8.2.19), it is possible to compute the rate of artificially induced disappearance of electrons. Those regions where the role of artificially induced reactions of disappearance of electrons is greater than for natural reactions are of practical interest. There it is possible to assume that

$$\beta(z) = k_5 n(H_2) + k_6 n(H_2O). \quad (8.2.25)$$

For comparison with experimental data, that is, in order to obtain an artificially induced change in the integral quantity of electrons, it is necessary to integrate $dn(e^-)/d\tau$ along the trajectories of the sounding signals.

Evidently it is possible to detect artificial impurities even more energetic than H_2 and H_2O favoring the decay of ionospheric layers. It is important to know their properties along these lines in different stages in the development of new space technology so that their harmful effect is not expected.

Response of ionosphere to tsunamis. Two types of surface seismic waves arise in the earth's body during earthquakes, and also at its surface: horizontal shear waves (Love waves) and waves with a vertical component (Rayleigh waves). If the epicenter is situated in the ocean, the earthquake is accompanied by ocean waves. If these waves attain a great size and a great destructive force they are called tsunamis.

It is considered established that Rayleigh waves and tsunamis are caused by the release of potential energy as a result of vertical subsidence of sectors of the earth's crust. The Rayleigh wave is propagated with a velocity approximately 20 times greater than the destructive tsunami wave and therefore it reaches great distances considerably earlier than the tsunami wave. Accordingly, a warning concerning the approach of a tsunami can be obtained by analyzing the vertical component of the Rayleigh wave, to be more precise, its long-period components.

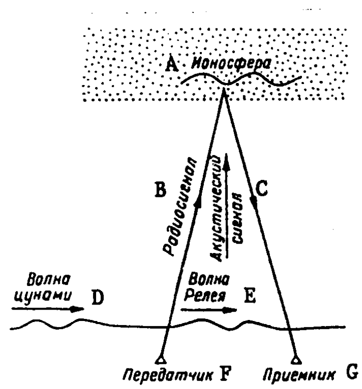

Fig. 8.2.5. Diagram of warning of approach of tsunami on basis of ionospheric response.

KEY:
- A) Ionosphere
- B) Radio signal
- C) Acoustic signal
- D) Tsunami wave
- E) Rayleigh wave
- F) Transmitter
- G) Receiver

The vertical component of the Rayleigh wave at the ocean surface or at the ground surface forms an acoustic signal which under corresponding conditions can attain the high layers of the atmosphere.

Observing the ionospheric response to acoustic surface signals, at the point for observing the ionosphere it is possible to obtain an idea concerning the frequency spectrum of the vertical component of the tsunami ahead of time, prior to the approach of the tsunami wave.

A diagram explaining detection of ionospheric response to tsunamis is shown in Fig. 8.2.5.

On two islands in the ocean there is a radio transmitter and radio receiver with a continuously adjustable frequency which are synchronously tuned to the plasma frequency of that layer of the ionosphere whose oscillations are caused by an acoustic signal of a stipulated frequency and from which it is necessary to obtain reflection of the radio signal.

If the ionosphere is continuously sounded, at each moment it is possible to know the vertical concentration of electrons, and accordingly, also the plasma frequency of the ionosphere, which makes it possible to select the necessary radiosonde frequency. By gradually changing the frequency it is possible to obtain reflected signals from different layers of the ionosphere, modulated by acoustic oscillations of different periods.

Direct measurements are made of the Doppler frequency shift of a radio signal reflected from the ionosphere caused by acoustic oscillations of the ionosphere and also the travel time of the signal from the transmitter to the ionosphere and then to the receiver. The Doppler frequency shift is caused by both the direct vertical displacement of the ionosphere and by change in the concentration of electrons as a result of acoustic change in air density at the ionosphere level.

The phase path of the sounding radio signal vertically propagating in the ionosphere, with allowance for dissipation, is determined as

[Γ p = group, Π = pl(asma)]

$$P=\int_{z_0}^{z}\frac{c}{V_{\Gamma\Pi}}dz=\int_{z_0}^{z}\left[1-\left(\frac{\omega_\Pi}{\omega}\right)^2\right]^{\frac{1}{2}}dz, \qquad (8.2.26)$$

where integration is carried out along the path of movement of the sounding signal from z_0 to z. Accordingly, the Doppler shift of the angular frequency of the sounding radio signal in the ionosphere is

$$\frac{\Delta\omega}{\omega}=-\frac{1}{c}\frac{dP}{d\tau}. \qquad (8.2.27)$$

Substituting (8.2.6) into (8.2.27), we obtain

[Π = pl(asma)]

$$\frac{\Delta\omega}{\omega}=-\frac{1}{c}\frac{dP}{d\omega_\Pi^2}\frac{\partial\omega_\Pi^2}{\partial\tau}=-\frac{1}{2c}\int_{z_0}^{z}\left[1-\left(\frac{\omega_\Pi}{\omega}\right)^2\right]^{-\frac{3}{2}}\frac{\omega_\Pi^2}{\omega^2}\frac{\partial\ln n_e}{\partial\tau}dz. \qquad (8.2.28)$$

If in (8.2.28) we convert to the derivative of the vertical concentration, making the replacement

[Φ = ph]

$$\frac{\partial\ln n_e}{\partial\tau}=V_\Phi\frac{\partial\ln n_e}{\partial z},$$

we obtain

[Π = pl(asma)]

$$\frac{\Delta\omega}{\omega}=-\frac{1}{2}\int_{z_0}^{z}\left[1-\left(\frac{\omega_\Pi}{\omega}\right)^2\right]^{-2}\frac{\omega_\Pi^2}{\omega^2}\frac{\partial\ln n_e}{\partial z}dz.$$

The continuous registry of the relative Doppler shift $\Delta\omega/\omega$ at several frequencies makes it possible at the observation point to reproduce the frequency spectrum of the vertical component of tsunamis prior to the arrival of the destructive ocean wave.

Vertical movements with a period from several seconds to several tens of seconds are of practical interest in connection with the tsunami problem.

Modification of the ionosphere by the radiation of powerful short-wave transmitters. In the irradiation of the ionosphere by powerful radio radiation, under corresponding conditions it experiences considerable absorption, as a result of which the electron temperature of the ionosphere increases. As a result of heating it will be possible to observe local peculiarities of the properties of plasma, which can lead to the appearance of plasma instability, expressed, in particular, in the generation of plasma waves and turbulent movements of different scales, as well as the transformation of radiation by the ionosphere itself, etc.

Artificial ionospheric disturbances are capable of reflecting radio waves at frequencies exceeding the local plasma frequencies under undisturbed conditions. Accordingly, they are used for distant communications at high frequencies. In addition, they are also of interest in connection with the possibility of carrying out of direct experiments with plasma, which are difficult to carry out under laboratory conditions, where the scales of the investigated space are always limited. In contrast to other methods for the disturbance of ionospheric plasma, associated with the introduction of chemical admixtures into the stratosphere or atomic explosions, etc., this method is attractive in that the ionosphere is not contaminated and the experiments themselves can be reproduced without harmful residual effects.

The radio signal, passing through the ionosphere, experiences particularly strong absorption in those layers of the ionosphere where its frequency is close to the local plasma frequency, that is, where its group velocity is close to zero. The absorbed energy, related to a unit volume of plasma and a unit time, is approximately equal to

$$Q=\frac{1}{2}\sigma E_0^2=\frac{\pi}{2}\frac{\omega_n^2}{\omega^2}\varepsilon_0 E_0^2\nu, \qquad (8.2.29)$$

where E_0 is the amplitude of electric field strength, σ is the conductivity of plasma for the particular signal, ν is the frequency of the mutual collisions of electrons; as above, it was assumed that $\omega^2 > \nu^2$.

Some part of the energy is also lost due to the collisions of electrons with ions, but this part is relatively small. A greater role is played by energy losses in the excitation of plasma turbulence at different scales. It is still inadequately clear under what conditions it arises.

It goes without saying that formula (8.2.29) is correct only when $\omega > \omega_{p1}$, since signals with lesser frequencies do not penetrate into plasma. Thus, in actuality $Q \to max$ when $\omega \to \omega_{p1}$ from the direction of greater ω values.

In a more detailed examination of the problem it is necessary to discriminate two radio signal components into which the electromagnetic wave in the ionosphere is split as a result of the presence of the geomagnetic field: one rotates clockwise (ordinary, or O-wave) and the other rotates counterclockwise (extraordinary, or X-wave). They differ with respect to velocities of propagation, and accordingly, also with respect to trajectories, and therefore by virtue of the difference in properties they exert a different effect on the ionosphere. For example, ionospheric radiation at a wavelength of 6300 A, which owes its origin to excited oxygen atoms, can be modulated by powerful radio pulses. The extraordinary wave causes a decrease in the intensity of radiation (luminescence), whereas the extraordinary wave, on the other hand, intensifies luminescence.

Figure 8.2.6 illustrates modulation of ionospheric radiation at a wavelength of 6300 A using an ordinary radio wave of a surface transmitter operating at a frequency of 5.3 MHz and having a power of 1.6 MW. The transmitter operated cyclically (switched on and off each 6 minutes) and strictly synchronously with this there was also a change in ionospheric luminescence. The figure shows that against a background of a monotonic decrease in the characteristic luminescence of the atmosphere there are artificially induced radiation bursts.

In the ionosphere particularly powerful directed radiation can cause a substantial decrease in the electron concentration as a result of direct heating and dynamic transformation of the ionospheric layer caused by it. There were cases when under the influence of one or more sufficiently powerful short-wave pulses the electron concentration decreased to such an extent that the subsequent pulses penetrated through the ionosphere.

Figure 8.2.7 shows the results of observations of the reflection of radio signals from the ionosphere made using an ionosonde (ionospheric station), which is a pulsed radar with measurement of a signal carrier frequency discretely changing in space.

The ionosonde makes it possible to determine the apparent range (virtual height) of the ionospheric echo at different signal sounding frequencies. The virtual height is determined from the signal travel time to the reflection level and back (to the sounding apparatus) on the assumption that the velocity of its propagation is equal to the speed of light. The true height is less because in actuality as the signal advances into the region where the electron concentration is high the group velocity of movement of the signal decreases (see Section 1.8).

Figure 8.2.7 shows ionograms; signal frequency is plotted along the x-axis and virtual height is plotted along the y-axis. The upper ionogram, for the undisturbed ionosphere, clearly shows the tracks of the O- and X-waves. At an altitude of approximately 300 km, with an increase in the carrier frequency, the signal tracks (signals of the O-wave, and then the X-wave) move sharply upward. At the critical frequencies the signals penetrate the ionosphere. On subsequent ionograms (after cutting in the powerful transmitter operating at a frequency of 5 MHz) it can be seen how the region of signal reflection is broadened and the tracks become more blurred (a rather complex phenomenon is observed). An artificially induced blurring of ionospheric structure appears; it is called "artificial diffusivity." It is precisely this which is the main reason for broadening of the tracks.

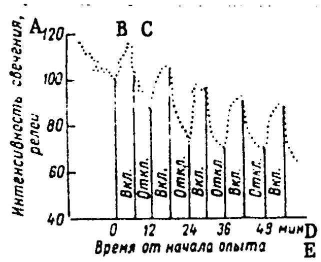

Fig. 8.2.6. Modulation of intensity of luminescence of red line of atomic oxygen in the ionosphere caused by O-waves with cyclic operation of radio transmitter at a frequency of 5.3 MHz (beginning of experiment 2030 LT; 1 rayleigh = 10^6 photons$\cdot$cm$^{-2}\cdot$sec^{-1}). 25 September 1970. (United States)

KEY:

A) Intensity of luminescence, rayleighs
B) On
C) Off
D) minutes
E) Time from onset of experiment

With prolonged heating of the ionosphere additional, clearly expressed tracks can appear, as well as an additional sharp signal attenuation in a broad frequency band near the frequency of the modifying transmitter, atmospheric luminescence (see Fig. 8.2.6) and other phenomena still inadequately fully investigated.

The ionospheric absorption of radio waves is also considered in relation to the problem of transmission of electromagnetic energy through space. The high-energy beam must be sufficiently high-frequency in order to ensure high directivity and minimum absorption in the ionosphere. In accordance with the examples considered above it is necessary to be oriented on a frequency of 10^2–10^3 MHz. An attempt is made to solve the problem precisely at such frequencies.

A geostationary satellite situated in an equatorial orbit carries solar cells. They are illuminated by the sun almost continuously, except for short time intervals (each 1 hour 14 minutes) for 22 days before and accordingly after the days of the spring and autumn equinoxes when the satellite enters a region of solar eclipse.

The solar energy is converted into electrical energy. The d-c current produced by the cells supplies SHF generators. The powerful SHF signals emitted by them are transmitted to the earth and there can be converted into those more convenient for practical use.

In the plans for such a system, called a satellite solar power station (SSPS), provision is made for super-powerful sources (10^3–10^4 MW) which can compete even with large-scale atmospheric formations. Therefore, the sporadic use of SSPS for the modification of atmospheric processes at the times of critical situations will be entirely realistic in the future. SHF beams with stipulated parameters can be formed on SSPS and directed to objects to be modified by signals from the earth or from orbital stations.

Semiconductor d-c converters, producing a high-frequency current by means of solar cells, are extensively used in cosmonautics. In the future plans call for the use of powerful magnetrons for this purpose; in such cases they are usually called amplitrons. Their efficiency is high and can attain 0.8–0.9.

The electromagnetic energy is focused into a narrow beam by different methods. The most perfected method is based on the use of horn emitters and ellipsoidal dishes, as in radars (see Section 4.2). Phased antenna arrays (passive or active) are more suitable for space systems. However, the difficulties in use of SSPS are not related to technology alone. The schematic diagrams for energetic control of atmospheric processes for the time being have not yet been adequately developed, although the ideas themselves are clear (they have been examined to one degree or another in all preceding chapters).

Ionospheric phenomena caused by nuclear explosions. Nuclear explosions cause a number of geophysical phenomena. They have not all been studied sufficiently that definite judgments could be drawn concerning their effects -- near and distant. For this reason nuclear explosions must be regarded as a completely unsuitable tool for geophysical investigations and it is to be hoped that experiments with nuclear explosions will not be repeated in either scientific work or for any other purposes, particularly since the most interesting geophysical phenomena which were studied with them can be reproduced even without atomic bombs.

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The first geophysical result of such an explosion (underground or atmospheric) is acoustic waves, which in accordance with what has been said above must cause oscillations of the ionosphere. Such ionospheric oscillations have actually been observed.

Only sufficiently low-frequency components of acoustic signals, whose absorption coefficients are relatively small (see formula (8.2.4)), travel great distances. For example, over points situated at a distance of several thousands of kilometers from the site of a nuclear explosion there were observations of acoustic signals with periods of $10-10^2$ sec and simultaneously oscillations of ionospheric layers with the same periods. They were registered using the Doppler shift of the sounding radio signal of ionospheric stations.

A direct consequence of high-altitude nuclear explosions is the formation (as a result of β-decay) of a large number of relativistic electrons. The electrons set free in the geomagnetic field are entrained into motion around the magnetic lines of force, and in addition, are displaced eastward, gradually forming a thin electron shell -- an artificial ionosphere -- around the earth.

The fission reaction in a detonating bomb with a 1-megaton power gives about 10^{26} β-decays. If it is assumed that only one of the relativistic electrons, forming as a result of each decay, is trapped by the geomagnetic field, this means that only one such explosion is already capable of creating a significant electron concentration in the earth's atmosphere. In order to appreciate this it is sufficient to recall that the earth's volume is 10^{27} cm^3, whereas the volume of the atmosphere is considerably less.

As a result of Coulomb interaction with atoms of air gases the electron fluxes gradually attenuate, but this effect, naturally, is the weaker the more rarefied the air, that is, the greater the altitude above the earth. As demonstrated in Chapter 6, the path of the relativistic electrons is inversely proportional to air density. Using formula (6.5.7) and substituting the parameters of the standard atmosphere into it, for great altitudes we obtain paths of kilometers (Table 8.2.1). As a comparison, for altitudes of 50 and 100 km the table gives the ratios of the electron path to the length of the circumference of the earth's equator, equal to $4 \cdot 10^4$ km (second line).

The table shows that at altitudes for which auroras are characteristic (auroras are relatively well-studied geophysical phenomena) relativistic electrons can travel global distances and accordingly can cause artificial auroras at a time inopportune for natural processes. This was observed, in actuality, at the time of atomic explosions. Ionizing the atmosphere at altitudes of about 10^3 km, the electrons induced a characteristic luminescence. It was observed visually, photographed and also investigated by more precise spectroscopic and radar methods.

However, electrons can be introduced into the atmosphere at any altitudes and by other means more suitable for this purpose, more controllable, and not causing any direct danger of radiation damage. Computations show that after the detonation of a 1-megaton nuclear bomb the radiation in surrounding space becomes commensurable with the lethal dose for man.

Modern technology of acceleration of elementary particles makes possible the direct installation of electron generators on satellites and rockets for the purpose of their direct introduction into the atmosphere. Such Soviet-French experiments have been carried out successfully during recent years. Small accelerators (see Chapter 6) make it possible to obtain electron fluxes adequate for creating thousand-kilometer curtains of artificial auroras.

Table 8.2.1

Path of Relativistic Electrons in Atmosphere at Different Altitudes

Altitude, km	Electron energy, MeV				
	1	10	100	500	1000
25	0.13	1.3	8	19	25
50	4.6	49	300	720	910
	$1.1 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$0.75 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$
100	$9.2 \cdot 10^{3}$	$9.8 \cdot 10^{4}$	$6 \cdot 10^{5}$	$1.4 \cdot 10^{6}$	$1.9 \cdot 10^{6}$
	0.23	2.4	15	35	48

8.3. Stratospheric Ozone as a Biological Shield. Anthropogenic Effects on Ozone

The element oxygen in a free state can exist in the form of molecular allotropic modifications of more stable ordinary O_2 and less stable ozone O_3. With respect to its physicochemical properties ozone is characterized by a high chemical activity. The characteristics of its absorptive properties in the short-wave biologically active part of the solar spectrum are most important for further consideration.

The total ozone content in the atmosphere is measured as the thickness of the layer which would be formed by all the ozone reduced to normal conditions. The measurement unit is centimeters or their thousandths, a unit which has been given the name "dobson." The total ozone content in the atmosphere varies in the range 0.16–0.45 cm. The main mass of ozone is situated in a relatively narrow layer of the atmosphere from 10 to 50 km with a maximum between 20 and 25 km. At greater altitudes the concentration of O_2 is small; its dissociation serves as a beginning of the ozone formation reaction. There is a small concentration of catalysts of this process. A small part of the ultraviolet radiation, under whose influence O_2 dissociation occurs, penetrates to lesser altitudes.

The ozone concentration at the maximum level is only 10^{12}–10^{13} molecules per cubic centimeter. The quantity of ozone in the earth's atmosphere is small, but its role is great. In the creation and penetration of the ozone layer the biologically active part of the UV radiation is attenuated by many times. Virtually all forms of life on earth to one degree or another react to variations in UV radiation. A normal intensity of UV radiation exerts a favorable influence on them, whereas a high intensity exerts a destructive effect. Accordingly, there is basis for assuming that life on the earth did not develop until the ozone stratospheric layer had formed.

For the time being the consequences of variation in the intensity of UV radiation have not been adequately studied. It was established that a decrease in the ozone shielding from UV radiation can cause an increase in allergic diseases, skin cancer, different kinds of mutations in the animal and plant world. With respect to the influence of variation of UV radiation on climate and weather, for the time being there is no clarity in this problem, as is the case, however, in other problems relating to the influence of physicochemical processes in the upper layers of the atmosphere on the surface weather. It has been postulated that such an influence is quite strong. For example, an attempt has been made to demonstrate the presence of direct correlations between the intensity of UV radiation and the quantity of polar ice, ocean plankton, etc.

Figure 8.3.1 shows the relationship between UV radiation at the upper boundary of the atmosphere and at the earth and also gives the coefficient of absorption of radiation by ozone μ. The μ coefficient is usually related to the elasticity of ozone, equal to 1 mm Hg. The characteristic elasticity of ozone in the ozonosphere is 10^4 times less. This same figure shows the corresponding path of photons

$$\Lambda = \frac{1}{\mu}.$$

If it is taken into account that the characteristic thickness of the ozone layer is 20-30 km, it becomes understandable why at the earth's surface UV radiation is virtually absent in the region λ = 2700-3000 A (Fig. 8.3.1).

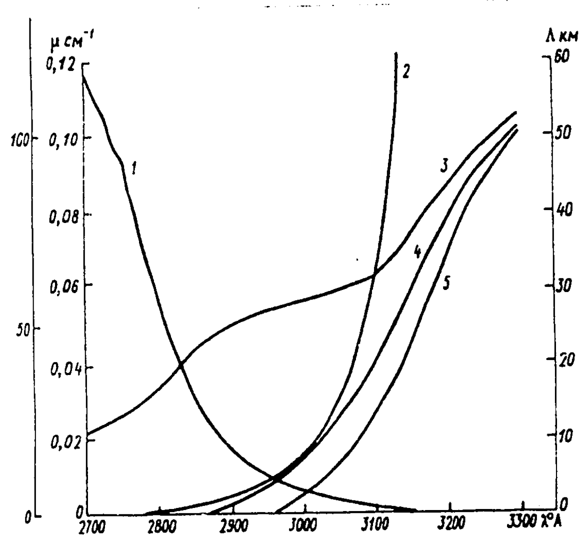

Fig. 8.3.1. Ultraviolet radiation at the upper boundary of the atmosphere and at the earth's surface (characteristic values). 1) coefficient of absorption of UV radiation by ozone, related to an ozone pressure of 1 mm Hg; 2) path of photons at partial pressure of ozone 10^{-4} mm Hg; 3) UV radiation at upper boundary of atmosphere; 4) UV radiation at ground level; 5) UV radiation at ground level corresponding to a 50% decrease in the ozone content.

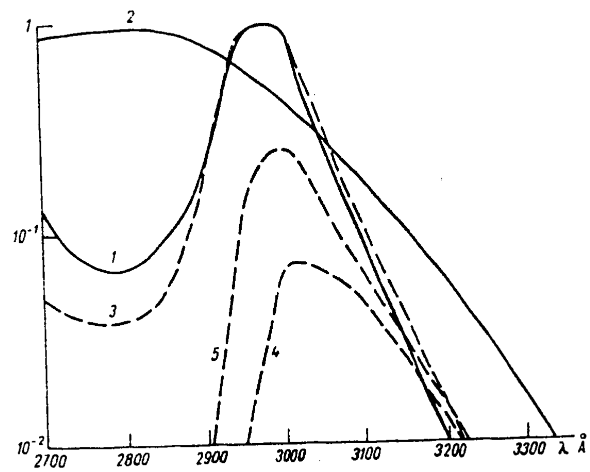

Fig. 8.3.2. Biological effect of ultraviolet radiation. 1) relative sensitivity of human skin to erythema (UV burn); 2) relative rate of protein decay; 3, 4, 5) relative spectra of erythemic biological effect of UV radiation at upper boundary of atmosphere, at ground under ordinary conditions and at ground with a 50% decrease in ozone content.

The decrease in ozone content is proportional to the increase in the photon path and displaces the boundary of total absorption of UV radiation in the direction of shorter waves (harder radiation).

In an approximate estimate of the change in intensity of radiation reaching the earth it can be assumed that a decrease in the ozone content in the ozonosphere by a factor of k will lead to an increase in the intensity at the earth from I to I':

$$\frac{I'}{I_0}=\left(\frac{I}{I_0}\right)^{\frac{1}{k}},$$

where I_0 is the intensity of UV radiation at the upper boundary of the atmosphere.

Figure 8.3.2 illustrates the natural shielding of life on earth against UV radiation.

The sensitivity of human skin to UV radiation in different parts of the spectrum is different. The maximum of UV burning, as indicated by Fig. 8.3.2, falls in the region near 2980 A. The maximum of the rate of protein decay is in a still shorter-range region. Thus, in the region of the maximum of harmful biological activity (UV burning, protein decay, etc.) a completely insignificant part of the UV radiation reaches the earth.

By multiplying the functional intensity of UV radiation and the relative sensitivity to erythema, we obtain the so-called spectrum of the erythemic biological effect in relative units. Its value, especially in the region of maximum sensitivity, determines the real degree of the UV burn. The spectrum of the biological effect of UV radiation on protein can be determined in a similar way.

Figure 8.3.2 shows the spectrum of the erythemic biological effect of UV radiation at the upper boundary of the atmosphere and at the earth, and also at the earth with a hypothetical two-fold decrease in the ozone content in the ozonosphere. The change caused by a decrease in the absorption of UV radiation was considerable, and as it is easy to understand, the harm from UV radiation increases far more strongly than the intensity of UV radiation with a decrease in the quantity of ozone in the atmosphere. The variations in the spectrum of erythemic biological effect as a result of the hypothetical weakening of ozone shielding of the atmosphere fall in the limits between curves 3 and 4.

Photochemical reactions in the stratosphere, in particular leading to the formation or decay of ozone, have still been poorly studied. This is attributable to imperfection of methods for making measurements in the stratosphere and the difficulty in reproducing stratospheric reactions in the laboratory. Therefore, the relative role of particular reactions of ozone formation and destruction must not be regarded as finally established, particularly since for the time being they still are not all known.

The principal ozone formation reaction in the stratosphere is considered to be the combining of ordinary molecular oxygen with atomic oxygen. The rate of this reaction is essentially dependent both on the quantity of atomic oxygen which is formed as a result of the dissociative decay of oxygen molecules into atoms and on how intensively catalysts intervene in the ozone formation process. In the stratosphere these catalysts are nitrogen, oxygen, water vapor, etc.

The energy of dissociation of O_2 molecules is A = 5.08 eV. Such an energy is characteristic of a light quantum with the frequency

$$\nu = \frac{A}{h}, \qquad (8.3.1)$$

where h is the Planck constant.

The corresponding wavelength of light is

$$\lambda_d = \frac{c}{\nu} = \frac{ch}{A}, \qquad (8.3.2)$$

where c is the speed of light.

Substituting $A = 5.08$ eV $= 8.13 \cdot 10^{-12}$ erg, we obtain $\nu = 1.23 \cdot 10^{15}$ Hz, $\lambda_d = 2441$ A. Such a wavelength belongs to the UV part of the solar spectrum. The solar energy in the region of shorter wavelengths $\lambda > \lambda_d$ is all the more intensively absorbed by molecular oxygen and favors its dissociation (with the formation of atomic oxygen in an excited state).

In the region of longer wavelengths the dissociation of oxygen molecules attenuates, but to $\lambda = 3100$–3200 A it is still significant (see Fig. 8.3.1). With $\lambda > \lambda_d$ a single-event encounter of a photon with an oxygen molecule does not result in its dissociation, but a stepped dissociation can be observed: with the first encounter with a photon the molecule passes into an excited (metastable) state; in the second (or subsequent) encounter the molecule passes from a metastable state into a dissociated state. Using the terminology in Section 5.11, it must be said that when $\lambda > \lambda_d$ the quantum yield of the dissociation reaction is less than unity. Here reference is to relatively low-intensity radiation fluxes. In intensive fluxes, in addition to multistep photoionization, it is possible to observe multiphoton photoionization, when one molecule absorbs two (or more) photons simultaneously (see Section 6.3).

Ozone is destroyed as a result of direct combination with free atoms of oxygen

$$O_3 + O \rightarrow 2O_2.$$

However, ozone is destroyed most energetically in a catalytic cycle of interactions with nitrogen oxides:

$$\begin{array}{c} NO + O_3 \rightarrow NO_2 + O_2 \\ O_3 + h\nu \rightarrow O_2 + O \\ \underline{NO_2 + O \rightarrow NO + O_2} \\ 2O_3 + h\nu \rightarrow 3O_2 \end{array}$$

in interaction with atomic hydrogen H, hydroxyl OH, HO_2, both directly, for example in the reaction

$$H + O_3 \rightarrow OH + O_2,$$

and as a result of exclusion from the reaction of ozonization of atomic oxygen, for example, in the reaction

$$OH + O \rightarrow H + O_2$$

and evidently as a result of other still unknown mechanisms.

The anthropogenic increase in the content of such components of stratospheric air as nitric oxide or water vapor favors the decay of ozone, but the penetration of other more energetic destroyers of ozone into the stratosphere is especially dangerous in this respect. For example, atomic chlorine, which is virtually absent in a natural unimpaired state in the stratosphere, but which is introduced into the stratosphere as a result of human activity, is a more energetic catalyst of ozone decay than are nitrogen oxides.

The corresponding catalytic cycle of reactions has the following form:

$$\begin{array}{c} Cl + O_3 \rightarrow ClO + O_2 \\ O_3 + h\nu \rightarrow O_2 + O \\ \underline{ClO + O \rightarrow Cl + O_2} \\ 2O_3 + h\nu \rightarrow 3O_2 \end{array}$$

Among the presently known still more energetic catalysts of ozone decay is bromine. It can enter the atmosphere, for example, due to the combustion of ethyl gasolines and from the use of methyl bromide.

The inadvertent impairments in the mobile, poorly stable photochemical equilibrium between ozone and other components of the stratospheric medium are associated with the gradual penetration and accumulation of impurities in the stratosphere, which is attributable, in particular, to the flights of supersonic aircraft, rockets, nuclear explosions and industrial sources.

In discussing the consequences of nuclear explosions in the atmosphere the main emphasis is usually on the direct effect of the explosion and radioactive contamination. In comparison with this, the effect of explosions on ozone may be of little importance. However, the high temperatures accompanying an explosion so favor an intensification of the dissociation of nitrogen with the formation of its oxides that even in the case of a limited nuclear war this could substantially (or even irreversibly) disrupt the ozone equilibrium, that is, could favor the breakdown of the ozone protective layer on a global scale. Such a process transpires relatively slowly: the maximum ozone decrease should be attained 10^6-10^7 sec after a nuclear explosion. During this time the dissociation products can be propagated for distances commensurable with the dimensions of the earth. Such phenomena were seemingly discovered in the 1970's after French and Chinese nuclear tests. The observations were made using the "Nimbus-4" satellite, which carried appropriate instrumentation. However, information of the opposite character is available; specifically, after a nuclear explosion in China along the track of the radioactive cloud over Japan a number of ozonometric stations observed a considerable increase in the total ozone content.

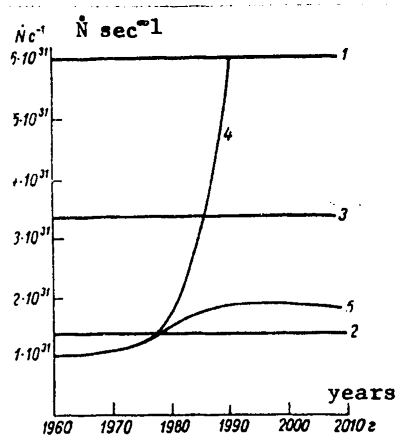

Fig. 8.3.3. Rate of natural appearance of ozone in atmosphere (1) and its decay as a result of the influence of oxygen (2), nitrogen oxides (3) and also rate of decay of ozone as a result of anthropogenic effect of chlorofluoromethanes for two variants: their production will increase (4) and their production will cease (5).

With the improvement of engines and other flight vehicles even now attention is being given to the need for decreasing substances favoring the decay of ozone. International norms will evidently be introduced along these lines in the future.

With respect to the intentional destruction of the earth's ozone shield, this is theoretically possible, unfortunately, rather realistic. The principal obstacle to this should be man's reasoning and conscience.

Figure 8.3.3 gives some idea concerning the degree of reality of the anthropogenic destruction of the ozone layer. It shows the ratio between the natural rate of appearance of ozone and the rate of its decay. Ozone decays as a result of combination with pure oxygen and nitrogen oxides, usually present in the stratosphere; however it also decays not less intensively as a result of the reaction with chlorine atoms forming during the decay of chlorofluoromethanes, primarily $CFCl_2$ and $CFCl_3$, which enter the stratosphere as a result of flights of vehicles with jet engines, the operation of different kinds of surface refrigerating apparatus, etc.

The figure shows the results of computation of the rate of appearance and decay of ozone for two variants of use of chlorofluoromethanes, differing from one another with respect to the prospects of their use in the future. In the first variant the production of chlorofluoromethanes is constantly increasing — doubling each 3.5 years; in the second variant such production completely ceases.

The natural processes of appearance and decay of ozone are considered constant during the entire period of analysis.

It follows from the figure that already in the next decade the situation can become threatening as a result of the entry of only one destroyer of the ozone layer into the atmosphere -- chlorofluoromethane.

In constructing Fig. 8.3.3. the losses of chlorofluoromethane on the path from the earth to the ozonosphere were not taken into account.

Until recently it could be assumed that in actuality impurities of surface origin cannot without considerable transformation reach the altitudes of the ozonosphere. However, the experiments carried out in American test polygons with the use of ground instrumentation, radiosondes and satellites have shown that this is not so: chlorofluoromethanes, retaining their chemical inertia, reach the stratosphere where they decompose under the influence of UV radiation, setting free chlorine atoms which also destroy ozone molecules.

The accumulation of another impurity in the atmosphere -- carbon dioxide -- has been studied more thoroughly. Observations of CO_2 have long been made and at the present time rather detailed data are available. Attempts are being made to predict accumulations of carbon dioxide for decades in advance.

The results of observations and prediction can be used as a base in the prediction of the accumulation of other impurities, the behavior of which has been studied to a lesser degree.

The influence of carbon dioxide on the thermal regime of the atmosphere is considered known, but its influence on other properties of the atmosphere, its participation in general gas exchange processes, the catalytic role in ozone formation and decay, all this is known only in its most general outlines.

The strong dependence of the rate of ozone-forming processes on the concentration of known, and also still unknown catalysts, makes it necessary to seek effective methods for observing the content of impurities in the stratosphere -- natural and anthropogenic. A method has been developed for tracking the global distribution of hydrochloric acid in the stratosphere and is in use. It is based on measurement of the absorption of solar radiation by HCl in the narrow band near $3.5\mu m$. The absorption bands of other air components are situated in this same region and therefore it is necessary to have instrumentation with a high spectral resolution.

Changes in the absorption spectra of solar radiation on slant paths at the time of a solar eclipse of an artificial earth satellite make it possible to determine the HCl content (and the content of some other absorbing components) with a high sensitivity -- to a ten-billionth of the total mass of the air components on the path from a satellite to the horizon. This is approximately 0.1 of the mean HCl content in the stratosphere.

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MONOGRAPH ON DYNAMICS OF THE EQUATORIAL ATMOSPHERE

Leningrad DINAMIKA EKVATORIAL'NOY ATMOSFERY (Dynamics of the Equatorial Atmosphere) in Russian 1980 signed to press 31 Mar 80 pp 5-7, 288

[Foreword and Table of Contents from book by Ye. M. Dobryshman, Gidrometeoizdat, 1000 copies, 288 pages]

[Text] Foreword. In global models of general circulation of the atmosphere the peculiarities of the processes transpiring in a narrow equatorial zone with a width of approximately 1,000 km are usually not taken into account or in the best case are taken into account very approximately. This occurs for three reasons. The zone is small and within it the variations of the principal meteorological parameters are 10-20 times less than in the middle latitudes. Moreover, in numerical models of general circulation for a hemisphere it is simpler to "set" a wall at the equator; in global models (of which there are few for the time being) it is simpler to "stride" across the equator. Finally, the methods for analysis of the equations of hydrothermodynamics customary for the entire remaining atmosphere do not reflect the specifics of the processes near the equator; for the zone itself it is not easy to formulate models of physical processes and it is difficult indeed to relate them or tie them in to the processes transpiring outside the zone. In addition, the intertropical convergence zone exists at the boundary of the equatorial zone. Typhoons develop a little beyond the boundary of this zone and in the process of development of necessity "flee" from the equator. Not one typhoon has crossed the equator. This can scarcely be attributed only to the β-effect. Indeed, some hurricanes (Carlotta 2-11 July 1975, Denise 4-15 July 1975), arising at latitude 8-10°, rose to latitude 17-18° and then dropped down to 13°. But Denise on 10 July made a loop at latitude 13° [193]. The narrow equatorial zone with a very small variability of meteorological parameters "frightens off" typhoons. Why? We are far from an answer to this question. First it is necessary to carry out a careful analysis of processes in the equatorial zone. A number of difficulties are involved here. One of them is related to a detailed calculation of heat influxes. Therefore, as usual, in the first approximation the heat influxes are considered either stipulated or such as will ensure a "background." Then it remains only to consider the dynamics.

In order to reveal the specifics of processes in the equatorial zone more clearly, we will first briefly present the results of a study of the interaction of the pressure and wind fields in the atmosphere, then we will describe the characteristic features in the transition zone 15-5° latitude and only thereafter will we consider processes in the zone itself. It is to be understood that the choice of material and the interpretation to a considerable degree reflect the points of view of the author and are not always indisputable and clearly substantiated to an identical degree. The style of exposition of different subjects is not the same, this reflecting the tastes of the author.

Unfortunately, the volume of the book did not make it possible to include detailed calculations, which sometimes are long and not always obvious. Insofar as possible, one and the same method is used in solving different problems and in simple cases it is in principle easy to trace the calculations.

I would hope that the monograph will help in drawing attention to the difficult but interesting and important problems involved in the dynamics of the atmosphere in the low latitudes on the part of the greatest range of specialists "sensitive" to meteorology. It is more difficult to become indoctrinated in the field of meteorology than to learn to use different mathematical methods for the solution of problems and nevertheless the physicists most frequently are able to give a correct interpretation of the result.

The book makes no pretense at complete coverage of the problems involved in the dynamics of the equatorial atmosphere. The interaction and regime in the boundary layers, the processes of radiation transfer, the circulation mechanism in the stratosphere and a number of other problems have remained almost untouched.

Very little attention has been devoted to thermodynamic processes. But here there is justification for the weak discussion of the problem because the recently published monograph of A. I. Fal'kovich [178] analyzed extremely carefully many of the principal problems relating to the intertropical convergence zone.

The bibliography as well in no way gives a proper idea concerning the numerous articles directly or indirectly pertaining to the considered problems. But the principal GATE problems are now being published in special numbers of the GATE BIBLIOGRAPHY. At the time of publication of this monograph two such numbers have appeared. The preliminary results of analysis of TROPEX-72, TROPEX-74 and GATE have been published in the form of collections [169, 170, 207, 263 (28*-50*)], where there is an extensive bibliography. [The references to the literature marked with an asterisk are cited in the appendix to the list of basic literature.]

The table of contents gives some idea concerning the content of the book and accordingly there is no need for a brief description of each chapter.

The numbering of the formulas in each section is independent. Therefore, references to a formula in the same section are indicated simply by the sequence number of the formula; if a figure precedes the number of the formula, this refers to the number of the section in this same chapter. In the case of references (rare) to formulas from another chapter, the latter is indicated by a Roman numeral at the very beginning of the citation. There is an introductory part at the beginning of each chapter; in citations to formulas from these introductory parts the number of the formula is preceded by an "0." In citations to formulas from the "Introduction" a "V" is indicated. The numbering of the figures is independent in each chapter. The tables are numbered in sequence throughout the book.

In an era of an exceptionally fast pace of life the affording of the necessary and adequate conditions for writing a book on a "related" field of specialization is a task not less than the writing of the book itself; this accounts for the appreciation which I express to my wife. The thankless task of a very rigorous, but also very objective reviewer, A. I. Fal'kovich, won my deep appreciation. This applies to a still greater degree to the work of the exacting and attentive scientific editor M. A. Petrosyants.

The book deals with many matters, set forth in implicit or explicit form, constituting problems for which there is no solution; in any case these solutions are unknown to the author. One of the purposes of the book is a deep desire to bring important and interesting problems in tropical meteorology to the attention of the scientific community. Any criticism, reviews, wishes and comments will be received with sincere appreciation.

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METEOROLOGY

AERIAL METHODS FOR STUDY OF THE OCEAN AND ITS FLOOR

Leningrad PROBLEMY ISSLEDOVANIYA I OSVOYENIYA MIROVOGO OKEANA in Russian 1979 signed to press 30 Oct 79 pp 135-165

[Article by V. V. Sharkov]

[Text] In the study of the earth's surface, the surfaces of the oceans and their deep layers extensive use is made of survey materials obtained employing different types of instrumentation (detectors) which are carried aboard aircraft, helicopters and other aerial or space carriers. These methods have come to be known as remote aerial methods.

Aerial methods, in contrast to other methods in oceanology, observations with which are made at individual stations at different times, make it possible to obtain information on features and phenomena over extensive expanses of the ocean virtually simultaneously or during a relatively short period of time.

Such phenomena and features can be studied only in parts and over a long time when using other methods. After first interpreting the materials from aerial surveys it is possible to plan the use of other oceanological methods.

The possibilities of different aerial methods in the study and special mapping of the oceans are still far from clarification. Without question, the improvement of existing aerial methods, as well as the further development of new (laser, luminescent, ultraviolet, geochemical surveys, etc.) methods considerably increase the effectiveness of study of the ocean and make it possible to solve many scientific and practical problems in oceanology.

1. Classification of Aerial Methods

[Most of these methods are also used in surveys from space carriers.]

Modern highly sensitive detectors carried in flight vehicles are capable of registry of the radiation of the ground and water surface in narrow zones of almost the entire spectrum of electromagnetic waves.

The collected data can be represented in the form of two-dimensional images (photographs) or one-dimensional profiles or curves [4].

Depending on the range of electromagnetic waves and registry apparatus employed, it is possible to define different types of aerial surveys, the comparative characteristics of which are given in Table 1. [Table 1 uses data from [1] and [9].]

In addition, surveys are classified as passive, registering the characteristic radiation of features or reflected solar radiation, and active, in which there is irradiation of the earth's surface, with subsequent reception of reflected radiation. Most of the active methods can be employed at any time of day or night, and a radar survey can be made in virtually any weather.

Passive surveys, except for an IR survey, can be made only in the daytime.

Most frequently in the study of natural features use is made of photographic, television, multizonal and spectrometric methods (scanner, IR and also aerial radar and airborne magnetometer, aerospace surveys). Laser surveys are already used in measuring distances and depths of the sea within the limits of shallow seas.

The materials from aerial surveys, and accordingly, the information obtained from them, are tied in to geographic coordinates by means of radiogeodetic equipment. Angle-measuring, range-finding and mixed systems are available. The greatest accuracy in determination (up to ±20 m) is attained using a range-finding system.

In those cases when radiogeodetic apparatus cannot be used, the tie-in of features is accomplished using navigational methods in which an allowance is made for the course of the aircraft and the time expended on reaching a definite point. When working near a shoreline aerial survey routes are calculated directly from shore landmarks.

2. Materials from Photographic, Television and Scanner Aerial Surveys

In the process of the above-mentioned surveys there is registry of reflected solar radiation primarily in the visible zone of the spectrum (0.4-0.74 μm) in the form of two-dimensional images -- aerial photographs. The principles for an aerial photographic survey are widely known.

Aerial television surveys (with nonscanning apparatus) differ from aerial photographic surveys in that the image is formed on a conducting target -- a vidicon, and not on a photographic film. The images from the vidicon are transmitted to receivers (on the ground) in a regime of phototelegraphic transmission or are registered on an aircraft on magnetic tape.

Aerial photographic and aerial television images are constructed on the central projection principle.

A scanner image is obtained as a result of scanning of the terrain perpendicular to the flight direction using an oscillating mirror or a rotating drum to whose lateral walls are attached mirrors showing a narrow terrain band in the form of a line. With the motion of the aircraft and synchronous movement of the photographic film on which the line is registered the individual lines are "put together," as a result of which there is formation of a two-dimensional terrain image in an equiangular projection [4].

The materials of these surveys are used extensively in a study of both the ocean surface and the surface water layer and also for study of the structure of the floor of shallow seas.

In order to obtain aerial photographic images of the water surface use is made of panchromatic, isopanchromatic or infrachromatic films. In order to obtain images of the sea floor, taking into account the strong absorption of long-wave and the scattering of the short-wave part of the spectrum by the water layer, use is made of films sensitized to the yellow-green (in the case of turbid coastal waters) and blue-green (in the case of transparent waters of the open sea) range of the electromagnetic spectrum. For this reason, in a survey of the sea floor in coastal shallow waters it is recommended that use be made of isochromatic and isoorthochromatic films.

The use of multizonal (photographic, television) and multichannel (spectrometric or scanner) surveys is common. A multizonal survey is made using several synchronously operating or multiobjective cameras with films of different types or on one film with different light filters. The images are obtained in relatively broad spectral ranges. A multichannel survey makes it possible to obtain images in both broad and narrow spectral ranges.

Thus, surveys of an ocean area and the sea floor can be made in optimum spectral ranges. When there is a set of multizonal and multichannel photographs in the course of their interpretation it is possible to have a more reliable separation of images of the sea floor or features in the water thickness from features on the sea surface, since the first are registered better in the blue-green and green, whereas the second are registered better in the red spectral range. Photographs taken in different ranges of the electromagnetic spectrum, with availability of the corresponding equipment can with a high accuracy be matched on a single screen.

Using different light filters, from black-and-white images it is possible to obtain color images reflecting the natural or conventional coloration of images.

Such images are characterized by a high information content, which considerably simplifies and accelerates interpretation and increases its reliability.

The photograph scale I/m is of considerable importance for the interpretation of aerial photographic images; it is dependent on the ratio of the camera focal length f and survey altitude H, specifically: $I/m = f/H$.

The materials of aerial surveys, on the basis of scales, are arbitrarily classified as large-scale (larger than 1:15,000), medium-scale (1:15,000-1:70,000), small-scale (1:70,000-1:250,000) and ultra-small scale (smaller than 1:250,000). The scale of these surveys is selected in dependence on the formulated problems.

Recently there has been a tendency to carry out aerial surveys at smaller scales, especially from space. This is attributable to several factors.

First, photographs taken from great altitudes, and especially from space, are better in quality because on the camera focal plane there is no incidence of scattered light of the atmosphere, which in this case can be regarded as a natural light filter. In the course of a survey of the sea floor from great altitudes over a considerable area the light rays pass through the atmosphere and water layers at more vertical angles than in the case of a survey from low altitudes. This predetermines a lesser absorption and scattering of light by the water.

Table 1

Comparative Characteristics of Types of Remote Surveys

Parameters	Types of surveys							
	gamma survey	ultraviolet		luminescent	spectrometric	TV	photographic	laser
		far	middle					
Wavelength	0.03A	100–300A	3000–4000A	0.3–1.2 μm		0.4–0.76 μm		0.3–11.0 μm
Frequency, MHz	10^{14}	$3 \cdot 10^{10}$ $3 \cdot 10^{9}$	$8 \cdot 10^{8}$			$5 \cdot 10^{8}$		
Nature of survey method	Passive	Passive and active		Passive and active		Passive		Active
Atmospheric absorption	Very strong	Almost full	Strong			Weak		
Instrument carriers	Air from altitude of less than 200 m		Air				Air and space	
Time of survey	In any weather	Day and night			Day and night		Day	In any weather

Continuation of Table 1

Para-meters	Types of surveys							
	gamma survey	ultraviolet		luminescent	spectrometric	TV	photographic	laser
		far	middle					
Depth in solid rocks	To 50 cm	Micrometers						
Depth in water	Several -- more than 1 m	Water surface				To 100 m		
Form of collected data	Curve	Signal, curve, TV image		Photograph, signal, curve	Curve, spectrometric curve	TV image	Photograph	Curve, in future, photograph
Purpose	Search for radioactive ores, breakdown of rocks	Study of features with specific UV radiation		Search for luminescent features	Study of geological-geomorphological and geographic features			

Continuation of Table 1

Parameters	Types of surveys: IR near	IR middle	IR far	radar: radiothermal	radar: radar	electric prospecting	magnetometry	geochemical	gravity
Wavelength	0.74-1.35 μm	1.35-5.5 μm	5.5-1000 μm	0.3	-1000 cm	100's and 1000's km			
Frequency, MHz	10^8	10^7	10^6	$2 \cdot 10^4$	$3 \cdot 10^3$	$10-10^8$			
Nature of survey method	Passive				Active	Passive and active		Passive	
Atmospheric absorption	Individual atmospheric "windows"; main: 0.74-1.35; 3.5-5.5; 7.5-14.0; 20.0-1000.0 μm			Weak	Very weak	None	None	-	None
Instrument carriers	Air and space			Air		Air	Air and space	Air	Air & space
Time of survey	Day and night			In any weather				Day and night	

Continuation of Table 1

Parameters	Types of surveys: IR, near	IR, middle	IR, far	radar, radiothermal	radar, radar	electric prospecting	magnetometry	geochemical	gravity
Depth in solid rocks				Centimeters		To 300 m	kilometers	surface	kilometers
Depth in water		Water surface				To 10-15 km	Same	Water surface	
Form of collection of data	IR photographs to 1 μm, image more than 1 μm	Thermal photographs	Photographs, curves, TV image			Signal, curve			Curve
Purpose	Study of geological-geomorphological and geographic features					Detection of conducting bodies	Detection of magnetic complexes of rocks and geological mapping	Search for some elements	Determination of gravity field of large geological features

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Second, such aerial photographs with a high resolution can be multiply enlarged to the necessary scale without a substantial loss in quality.

Third, in the case of a small-scale survey it is possible to cover a great area simultaneously, which reduces the time expended on the processing of materials and their interpretation.

The special interpretation of aerial photographic, aerial television and scanner photographs in principle does not differ in any way.

2.1. Interpretation of Aerial Images of Surface of Water, Features and Phenomena in its Layer

On aerial photographs of the water surface at the present time it is already possible to identify a number of features and phenomena, specifically waves, currents, water color and transparency, Langmuir circulations, etc.

Sea waves show up clearly on aerial photographs. In their interpretation it is possible to detect all systems of waves and determine their characteristics [10].

Stereoscopic measurements from overlapping aerial photographs, taken from two aircraft with synchronously operating cameras, make it possible to compile maps of isohypses of the wave-covered surface of the oceans. All the wave parameters can be read from such maps.

Using individual photographs (taken with a single camera) it is easy to measure the wavelength of swell. The use of cylindrical lenses or rotating screens facilitates the study of different wave systems. This is achieved by the diffraction method, in which an aerial photograph with images of waves is regarded as an imperfect diffraction grating. Wave systems are determined from the position of the maxima in the diffraction pattern obtained using special apparatus.

On small-scale aerial photographs with images of the wave-covered sea surface with three-dimensional waves it is possible to note ordered waves, not observed from ships or on large-scale photographs.

On the basis of materials from an aerial photographic survey it is possible to make a detailed study of the refraction and diffraction of waves (Fig. 1) and use these data for clarifying the characteristics of bottom relief, and sometimes (on the basis of wave refraction) also for making an indirect determination of the sea depth [12].

Sea currents in many cases are easily recognized on ordinary aerial photographs on the basis of image tone. This is possible if the water layers moved by the currents, depending on their properties, differ from the surrounding water expanses, and also from the waters transported by other currents. For example, to the east of the Japanese islands there is a cold (Oyashio) and a warm (Kuroshio) current. The first is enriched with nutrient substances, and accordingly, is saturated with plankton, which imparts a yellowish-brownish color to the waters. The warm Kuroshio Current is characterized by a water transparency of a dark aquamarine color. Accordingly, on the aerial photographs these currents are represented in different tones.

An improved method for studying surface currents from an aircraft for the coastal parts of ocean areas has been developed in the Aerial Methods Laboratory of the USSR Geology Ministry [8]. In accordance with one of the variants of the method the water surface is marked by means of floats, impregnated with fluorescent salts, dropped from an aircraft and forming bright spots. Then an aerial photographic survey of the marked ocean area is carried out twice at definite time intervals. After orientation of the aerial photographs measurements are made of the direction and degree of displacement of the spots relative to fixed reference marks (features on shore, structures above the water or the photoimages of bottom contours). Thus, it is possible to make a detailed study of the structure of currents.

In another variant of the method, in order to mark the water surface a bottom indicator is dropped from an aircraft; from this bottom indicator two floats with dyes are successively released by means of special devices at a rigorously set time interval and these float to the sea surface. After floating-up of the second float aerial photographs are taken in such a way that on a single photograph there is immediately an image of dye spots from both floats. The direction of movement of the dye spots and the distance between them, with allowance for the survey scale, are determined on the aerial photographs. By knowing the time interval between the surfacing of the two floats and the distance between them, it is possible to compute the velocity of their movement, that is, the velocity of drift under the influence of the currents. The position of the floats can be registered in the course of radiogeodetic measurements.

Water color is recognized on black-and-white aerial photographs from the tone, and on synthesized color photographs is recognized from definite colors. On black-and-white aerial photographs turbid waters, having yellowish or gray-brown hues, are relatively light, whereas transparent waters have dark hues. Using these criteria, it is possible to ascertain, and map on the basis of the relatively light tone of the aerial photographic image, the areas of propagation of river runoff waters; turbid waters, forming after storms in the limits of coastal shallows or over sand banks; waters enriched with suspended material from eruptions of underwater lava and mud volcanoes; sectors of upwelling of bottom waters to the surface, usually having a brownish color as a result of their enrichment with phytoplankton, etc. The discharge of ground or juvenile water at the sea floor is sometimes manifested at the sea surface in the form of spots of transparent water, corresponding to darker sectors on aerial photographs. On the basis of the change in the tone or color of the image of the water layers within the limits of coastal shallows (when homogeneous ground is present) it is possible to make a photometric determination of the sea depth, since under these conditions the image tone on black-and-white photographs and the color on color aerial photographs are dependent on the latter [11].

Langmuir spiral-like circulations (eddies). These, as is well known, predetermine on the surface the concentration of floating objects (surface-active substances, foam, vegetation, etc.) in the form of long and relatively narrow bands. These bands, formed by a surface-active substance (Fig. 2,a) and foam (Fig. 2,b), can be seen clearly against the background of the wave-covered sea surface. An analysis of photographs in combination with an analysis of hydrometeorological data at the time of an aerial photographic survey can be of substantial assistance in an investigation of a still inadequately studied phenomenon -- a Langmuir circulation, and will make it possible to determine the interrelationship between the distribution of bands and wind directions and the directions of the principal systems of waves and sea depths and ascertain the dependence of the distance of the bands and their structure on the above-mentioned factors, and also internal waves.

Internal waves are formed in the water layer at the boundary of layers of different density. At the crests of these waves the turbid surface water is of a lesser thickness than in the troughs and therefore the latter on the photographs have lighter tones than the first [13].

In addition, it can be expected that at the boundary of water layers with different density there is an accumulation of dead valves of plankton and other fine particles, and this, with the high transparency of the upper water layer, assists in discriminating internal waves on photographs [14].

An analysis of images of internal waves makes it possible to evaluate their parameters: period, phase velocity, direction of propagation.

Discontinuous currents disrupt the system of coastal wind waves and the surf zone, as is manifested on the aerial photographs. In addition, the mass of water of discontinuous currents is usually distinguished on the basis of color as a result of the great quantity of suspended material. This can be seen clearly on the photographs. Their analysis makes possible a detailed study of this phenomenon.

Plankton colors water in yellowish-brownish or greenish tones. Such sectors are clearly discriminated on the photographs (their tone differs from the tone of the remaining sea surface).

As already mentioned, the high productivity of plankton organisms is frequently associated with upwellings or the presence of cold currents.

Turbid water, as already noted, on aerial photographs is lighter in tone than pure sea water. The mapping of the propagation of turbid water is of substantial importance for clarifying the conditions of modern sedimentation at the limits of the shelf.

2.2. Indirect Indicator of Local Change in Water Temperature

American astronauts [19] discovered clouds of a special form whose formation was associated with the presence of eddylike circulations of cold water, such as amidst the warm Yucatan Current. Over cold water eddies they observed a clear sky, whereas along the edges of the eddies, that is, at the boundary of cold and warm waters, there was a powerful sickle-shaped form of the cloud cover. Thus, on the basis of the form of the cloud cover it is possible to make an indirect determination of local areas of propagation of cold water (such as upwellings) amidst the relatively warmer surface waters of the ocean. An analysis of the characteristics of structure of the cloud cover in the case of a relatively quiet synoptic situation can assist in a study of temperature anomalies of surface waters of the ocean, sea currents, etc. The greatest effect for study of the cloud cover over the ocean is from materials of aerial and space surveys.

2.3. Interpretation of Features on the Sea Floor

Modern technical equipment makes it possible to obtain an aerial photographic image of the sea floor at depths from several meters to several tens of meters in dependence on water transparency. As a result, the width of the band of the underwater shore slope, within whose limits it is possible to survey the sea floor, varies from several hundreds of meters to tens of kilometers. In addition, the sea floor shows up on aerial photographs within the limits of isolated banks both in the open sea and on the shelf.

On such aerial photographs it is possible to identify many underwater features whose office and field interpretation favors their detailed study and mapping [2, 3].

At the present time the materials from aerial surveys of the sea floor are already in use for geological-geomorphological investigation and mapping, engineering-geological field work, search for minerals, study and mapping of underwater vegetation, compilation of sea and landscape maps of coastal shallows, etc.

Geological-geomorphological study and mapping. On aerial photographs of the sea floor in coastal shallows it is common to see clearly both rocks and unconsolidated sea bottom material, whose photopatterns frequently differ sharply in dependence on their mineralogical composition, texture and structural characteristics [2, 3]. This can be seen clearly in the cited aerial photograph of the sea bottom (Fig. 3). In this same photograph it is easy to make out disjunctive dislocations in the form of straight or curved lines bounding individual tectonic blocks.

The interpretation of such aerial photographs makes it possible to obtain extensive geological information: determination of the bottom propagation of different rock complexes, including those to which various minerals can be related; measurement of horizontal thicknesses (that is, the width of outcropping on the bottom) of individual strata, layers, suites, etc.; determination of the bedding elements of strata (azimuths and dips); clarification of stratigraphic and angular unconformities; recognition of different accumulative and abrasional relief forms, etc., and also geological structures and their elements (Fig. 4), the clarification of which is of considerable importance in the search for marine petroleum and gas deposits.

Due to this, as well as the clear image of the boundaries between the features, it is possible to compile geological, geomorphological, bottom material and other special maps of the sea floor which with respect to reliability and detail are in no way inferior to maps of the land.

Geological engineering field work. The materials of aerial photographic surveys can be used for study of the geological engineering characteristics and compilation of geological engineering maps of the underwater shore slope and the coastal parts of the land which are necessary for the designing of hydroengineering structures. These materials have great importance in clarifying and predicting the dynamics of shore processes. In particular, on the basis of the character of the image of shore and bottom accumulative and abrasional relief forms it is possible to determine the direction of along-shore movement of flows of sediments and their relative thickness, sectors of abrasion or accumulation of unconsolidated deposits, etc.

Allowance for the dynamics of these processes is important in predicting the possible erosion of shores, or, on the other hand, the silting-up of hydroengineering structures during the period of their operation.

Search for minerals. Aerial photographs of ocean areas show a number of features, phenomena or processes which can be used as criteria in the search for some minerals. This makes it possible to localize sectors of ocean areas promising for the formulation of more detailed exploration and reconnaissance work. Thus, sectors of ocean areas beneath which petroleum and gas are present can be discovered from the aerial photographic images of rocks which contain petroleum (Fig. 3); anticlinal folds (see Fig. 4,a); constantly renewable films of petroleum floating on the sea surface are identified on aerial photographs from a specific aerial photographic pattern of a light tone, under which the image of the sea floor can be seen (Fig. 5); underwater mud volcanoes, identifiable from their characteristic shape (Fig. 4,b); gas eruptions (Fig. 6), etc.

Sectors promising for coal deposits or iron ores of sedimentary origin, etc. can be discriminated from the characteristic images of underwater outcrops of coal-bearing, iron ore and other suites and strata. The left part of Fig. 7 shows a coal-bearing suite represented by rocks of a clayey-silty composition with strata of sandstones, coal and coaly shales. It is characterized by a clearly expressed bedding and a strong warping of the rocks represented on the photograph. These indicators make it possible to establish the presence and distribution of such suites on the sea floor.

Coastal-marine placers of minerals are detectable from the change in the photographic density (image tone), reflecting the coloration of beach sands enriched with minerals; on the basis of the images of elements of accumulative forms of relief above and below the water it is possible to localize sectors within which there is separation of heavy fraction minerals.

Construction materials within the limits of the sea floor and the coastal part of the land are represented primarily by unconsolidated sediments making up different accumulative forms of relief or filling in U-shaped valleys. These forms, like the unconsolidated deposits themselves, show up clearly on aerial photographs. Thus, the latter give exhaustive information on their distribution on the bottom and the possible conditions for their exploitation without impairment of the dynamics of shore processes, that is, without disruption of the dynamic equilibrium of the shore. [It must be remembered that the production of construction materials along the coasts frequently leads to disruption of the dynamics of shores and their destruction. The collection of unconsolidated material can be accomplished in the upper parts of submarine canyons without damage to the dynamics of shores.]

Underwater vegetation is easily identifiable on aerial photographs. Sometimes it is possible to identify not only different algae, including useful algae (sea kale, grass wrack, etc.), but also to determine the limits of their distribution and to calculate the reserves (Fig. 8).

Compilation of sea charts. Stereophotogrammetric measurements of the local relief of the sea floor are made for compilation of sea charts when the bottom contours are visible on the photographs. In the absence of contours use is made of the already considered (2.1) photometric method, making it possible, on the basis of the image tone or color of the water layer (in the case of homogeneous ground) to determine sea depth. Sometimes stereoscopic measurements are combined with data from depth measurements made with echo soundings or lasers and by the photometric method. The materials of an aerial photographic survey considerably facilitate the carrying out of hydrographic work and the compilation of sea charts, especially in the region of shallows, since they give a relatively precise and objective idea concerning underwater relief.

Compilation of landscape maps. The detailed and objective representation of underwater features on aerial photographs makes them indispensable for landscape study and mapping of the sea floor. In the interpretation of aerial photographic images it is possible to identify not only different landscape components and elements, but in many cases ascertain their interrelationship and interdependence.

Study of the dynamics of processes transpiring on the bottom of shallow seas. When there are repeated aerial surveys within the limits of one and the same ocean area it is possible to judge the changes in the landscapes of the sea floor occurring during a rigorously determined time period. By such a method it is possible to determine changes in the forms of bottom relief, rate of formation of new or destruction of already existing coastal relief forms, overgrowth of the bottom with underwater vegetation, etc. A comparison of materials from repeated aerial surveys is one of the most modern and reliable methods for the study of the dynamics of processes transpiring within the limits of the bottom of coastal sea areas, making it possible to obtain both a quantitative and qualitative description of these processes.

2.4. Obtaining Information on Features on the Sea Floor Using Indirect Criteria

The materials of aerial photographic surveys of the sea floor can be used in solving many scientific and practical problems. However, their use to a considerable degree is restricted to a relatively narrow band of the coastal part of the oceans and individual shallow-water banks. Only the image of the water surface is obtained on aerospace photographs of very extensive areas of the open sea and oceans.

The assumption of some researchers [5, 6, 18] that in a survey from great altitudes and from space it is possible to observe and photograph the sea floor with depths of several hundreds or even thousands of meters is improbable. The attenuation of light by the water layer is so great that for practical purposes, as demonstrated by experimental studies, there is no possibility, using modern technical equipment, to obtain photographs of the sea floor at depths more than 100 m. This is also confirmed by numerous visual observations of divers, who have noted a rapid attenuation of light with depth and by measurements of the light flux at different depths in the sea with different water transparencies. The maximum sea depth at which a photoimage of the sea floor was obtained was 70 m.

In connection with what has been said above it can be concluded that the photographing of the sea floor beyond the limits of the underwater shore slope and individual shallow-water banks is impossible over the areas of the seas and oceans.

Nevertheless, the materials from aerial photographic surveys and space photographs of the surfaces of the seas and oceans can be used for obtaining information on some characteristics of structure of the sea floor. This is becoming possible due to the fact that definite features and phenomena, present or developing at the water surface and in its layer, are interrelated to the structure of the sea floor and also to processes transpiring in its deep layers. Such interrelationships can be used as indicators of some characteristics of its structure.

The first attempt at study of the sea floor with the use of such indicators was undertaken at the Aerial Methods Laboratory [14].

Indicators of underwater volcanic eruptions. Volcanic eruptions are manifested in the form of a change in the optical properties of the water due to the ejection of ash material; presence of local sectors of swirling water or strong and irregular waves amidst the calm sea surface; ejections of ash, smoke and the release of steam above the water surface; concentrations of floating fragments of pumice, and sometimes also the formation of temporary or permanent volcanic islands.

Indicators of underwater mud volcano eruptions. These eruptions are manifested in the form of small fountains and waterspouts, emanations of gases (see Fig. 6), making the water foamy, water turbidity due to the ejection of pelitic material, and sometimes in the form of hot flares of hydrocarbon gases. Temporary or permanent islands are also formed in many cases.

Indicators of discharge of ground fresh, thermal and juvenile waters. The discharge of these waters at the bottom in the case of a calm sea surface is manifested in the form of sectors of swirling water, and when waves are present, in the form of sectors of relatively smooth water; sometimes powerful underwater springs form sectors of more transparent water at the sea surface.

Indicators of possible petroleum and gas deposits. The presence of petroleum in the deep layers of the sea floor is sometimes manifested at the sea surface in the form of spots of petroleum constantly renewed at one and the same places and eruptions of gas, usually making the water foamy.

The following indicators can be used for clarifying the forms of bottom relief:

Waves. These sensitively react to positive relief forms present at sea depths less than 1/2 of their length. Beginning with this depth the waves experience deformations, specifically, there is a decrease in the length and an increase in height and velocity. Such a deformation of the waves can be reflected on aerial photographs and on the basis of the change in the nature of the photoimage of the wave-covered sea surface it is possible to detect positive relief forms on the bottom, sometimes at considerable sea depths. For example, Yu. M. Shokal'skiy notes that "...even at such great depths as are present in the Wyville Thomson Ridge, between the Faeroe Islands and Scotland, that is, at depths of 400-500 m, there was a shortening of the waves" [16, p 277].

In the coastal parts of the sea, on the basis of the change in the nature of the wave-covered surface, it is possible to detect submarine valleys, within which at the time of a storm, due to the considerable depths, the waves experience a lesser deformation in comparison with the shallow-water sectors separating the submarine valleys.

Wave destruction. In shallow waters it is observed with a decrease in sea depth approximately (on the average) up to 3/4 of the wave height. At the time of wave destruction breakers can be observed and an aerated (foamy) zone is formed which can be seen clearly on the aerial photographs. A particularly energetic destruction of waves occurs over obstacles. Specifically from photographs of breakers it is possible to ascertain the presence and number of underwater bars, underwater ridges, rocks and reefs, shoals, etc. For example, breakers were observed along the shores of Syria over underwater reefs with sea depths as great as 84 m [16].

Refraction of sea waves. This shows up clearly on aerial photographs. It is possible to ascertain the angles of approach of waves to the shore, measure the length of waves, and under certain conditions ascertain the steepness of their slopes and even the velocity of propagation. The latter is determined as the ratio of displacement of the characteristic points of waves on adjacent photographs, determined relative to corresponding fixed landmarks on the shore or at sea, to the time intervals between adjacent exposures.

Knowing the length λ and the velocity v of waves at a definite point, it is possible to determine sea depth as well [12]. For this we use the Stokes formula, establishing the correlation between H, v and λ, specifically:

$$v^2 = g\lambda/2\pi \,\mathrm{th}\, 2\pi H/\lambda,$$

where g is the acceleration of gravity; H is sea depth at a particular point.

In addition, from the curves of the refraction waves it is possible to make out elements of relief of the underwater shore slope -- troughs, rises, etc.

Upwellings, that is, a rise in deep waters to the sea surface, in the open parts of the seas and oceans are often manifested over banks, underwater mountains and ridges. [Upwellings can also be caused by the wind driving the water away from the shore and by divergent currents; they can arise along the leeward sides of islands, etc. However, in the open sea, if there are no divergent currents, they are usually associated with bottom relief forms.] As already noted above, waters rising from the bottom predetermine the fluorishing development of plankton and a change in the optical properties of the water. An attentive analysis of aerial and space photographs makes it possible to detect local changes in the image tone, from which it is possible to judge bottom relief, and if the underwater ridges are genetically related to faults, also determine their position.

Turbid waters. These arise after storm waves in areas of shallow waters and show up clearly on aerial photographs. The systematic renewal of turbid water in the form of isolated areas, sometimes observed far from the shore, can be evidence of the presence of underwater sand banks. Thus, turbid water marks a shallow-water zone along sandy and silty shores, and also sandy-silty banks considerably distant from the shore.

Transport of turbid water by rivers. This sometimes occurs along submarine valleys (canyons) and thereby marks the continuation of the latter into the sea.

3. Infrared (IR) Aerial Survey

An IR aerial survey is based on the registry of reflected solar radiation and the characteristic thermal radiation of features on the earth's surface in the form of electromagnetic waves in the range from 0.74 to 1,000 μm. It was established experimentally that for the IR radiation in the atmosphere there are three principal atmospheric windows of transparency, determini ; the aerial survey in three ranges: 0.74-1.35; 3.5-5.5; 7.5-14.0 μm.

In the first atmospheric window (0.74-1.35 μm) use is made of reflected solar radiation and therefore use is made of ordinary methods of aerial photographic surveying on films sensitized to this wavelength range (to be more precise -- to 0.74-1.2 μm). Such an aerial survey can be called infraphotographic.

An IR aerial survey in the second and third atmospheric windows 3.5-5.5 and 7.5-14 μm makes it possible to register the characteristic thermal radiation of the earth and the thermal anomalies of features arising as a result of heating by solar radiation (induced thermal anomalies). It is carried out by scanning apparatus -- television sets, making it possible to obtain two-dimensional images (thermal aerial photographs) or using IR radiometers registering changes in the temperature of the earth's surface along the aircraft flight axis. Instrumentation has also been developed which operates in narrow spectral IR zones. The synthesis of photographs taken with this equipment makes it possible to reproduce color IR images. Such an aerial survey is called a thermal survey.

3.1. Infraphotographic Aerial Survey

The near-IR spectral zone, in comparison with the visible zone, is characterized by a lesser scattering of rays during propagation through the atmosphere. This increases the range of the survey, and the differences in the reflection and transmission coefficients favor an increase in the contrast of individual features and their details.

An IR aerial photographic survey is not used for obtaining an image of the sea floor because the first meters of the water layer already completely absorb all the long-wave part of the spectrum. However, as a result of the difference in the reflection coefficients of this part of the spectrum and the visible part on the IR photographs there is a clear representation of the boundary between the water surface and the land. This is determined by the property of the water to absorb IR-red radiation, as a result of which there is a sharp contrast in the reflection of rays in the IR range from the land and water surface. Accordingly, an IR aerial photographic survey can be used for study and mapping of shorelines, maximum and minimum positions of sea level during incoming and outgoing tides, wind-driven level changes, etc.

3.2. Thermal Survey

A thermal survey, carried out using IR radiometers, makes it possible to register the temperature of the water surface along the flight profile. In oceanology it is used for determining one of the most important and spatially and temporally variable characteristics of the ocean — water temperature at the surface.

A thermal survey made using thermal sensors makes it possible to register thermal contrasts (anomalies).

It is used for the clarification of hydrodynamic processes, underwater volcanic and mud volcano eruptions, contaminations of the sea surface, etc.

Hydrodynamic processes cause a nonuniform distribution of temperature at the sea surface and therefore on thermal aerial photographs there is a clear representation of warm and cold currents, their structural characteristics, zones of convergence and divergence of currents, and also cold waters of upwellings, great discharges of ground or juvenile waters, fronts of cold and warm waters, convective cells, Langmuir circulations, etc.

Underwater eruptions of volcanoes can increase the water temperature over them either as a result of direct heating in the case of a close position of the funnels of volcanoes to the sea surface or due to the rising of bottom heated water to the surface together with the solid products of volcanic ejecta during an eruption occurring at great sea depths. These "traces" also can be registered on photographs.

Discharge of ground water at the bottom of the oceans usually causes local thermal anomalies at the sea surface. During the discharge of fresh ground water the latter rises to the surface and reduces water temperature. On the other hand, during the discharge of thermal waters the water temperature at the sea surface over these sectors increases. Thus, a thermal aerial survey can be used in the search for fresh and thermal waters. Taking into account that the discharge of the latter is frequently associated with faults, the mapping of thermal waters can be of assistance in the tracing of large disjunctive dislocations within the limits of ocean areas.

The contamination of the sea surface by petroleum products is clearly registered on thermal photographs. Petroleum products reduce the evaporation of water, as a result of which in such sectors of the sea surface there is no cold layer, to a considerable degree arising due to evaporation. This situation can also be applied, evidently, in the sectors of the sea contaminated by wastes of anthropogenic origin.

Within the limits of coastal shallow waters, using a thermal survey, it is possible as well to register wave and discontinuous currents, river runoff, sandy and rocky drained areas, vegetation, etc. Due to the different heating of water over shallower and deeper sectors, it is possible to see underwater valleys, shoals, underwater bars and other features in shallow-water sectors of the underwater shore slope.

4. Radar Aerial Survey

A radar survey is an active research method [7]. The terrain surface is irradiated from an aircraft by radio waves, whose reflected signals are registered by receiving apparatus. The survey can be made in virtually any weather, during daytime or nighttime.

Radar photographs show only the surface of the oceans. If the water surface is smooth, there is a mirror reflection of radio rays in the direction away from the antenna (receiver), as a result of which the water surface on the photograph shows up as a uniform dark color. Accordingly, a radar survey must be carried out when there is a wave-covered surface, when the rays reflected from the slopes of the waves, and also radio rays scattered from the foamy water, are incident on the receiver. In this case the radar photographs make it possible to obtain information on sea waves, different circulations and other phenomena at the surface of the oceans.

The radar photographs clearly show petroleum films because the latter "quench" capillary waves. The sectors of the smoothed sea surface forming here, from which radar rays are mirror-reflected in the direction of the receiving apparatus, appear dark on the photographs.

On the basis of the image of waves which are breaking up (bands of foamy water) in the coastal shallow-water parts on the radar photographs it is possible to identify some forms of bottom relief (underwater bars, shoals, individual ridges or underwater rocks). Radar photographs are also used successfully for the evaluation of ice conditions in polar ocean areas because they make it possible to detect leads and fissures amidst the pack ice; sometimes it is even possible to estimate the relative thickness of the floating ice.

5. Laser, Luminescent, Ultraviolet Surveys

As already mentioned, laser, luminescent and UV surveys are in the stage of testing or development.

5.1. Laser Survey

Experimental investigations indicate that in transparent waters, using a laser operating at a wavelength of 0.55μm with a zone width of 0.003μm, it is possible to measure sea depths of several tens of meters. By combining the interpretation of aerial photographs of the sea floor and measurement of sea depths by means of a laser it is possible to carry out a hydrographic survey of shallow waters [17].

5.2. Luminescent Survey.

[Sections 5.2, 5.3, and also 6 were written using materials supplied by A. V. Dolivo-Dobrovol'skiy.]

A luminescent survey is based on the fact that during irradiation the atoms of some substances enter an excited state which is then unstable. The return of the electrons to the former level is accompanied by the emission of a quantum of energy in the form of rays of a greater length than the irradiating radiation. This is nonthermal luminescence. A strong luminescence is characteristic of petroleum and gases, chlorophyll. Evidently, this survey can be used not only for registry of petroleum films on the water surface, but also plankton.

In the active method there is irradiation of the ground surface by artificial UV rays which in the presence of luminescent substances can cause a nonthermal luminescence. It is registered on film in the visible range. This survey can be made only at nighttime and from low altitudes.

In a passive luminescent survey use is made of special apparatus making it possible to register the deviations of the constant of the ratio between the intensity of solar radiation near the Fraunhofer line and directly at its center, caused by luminescent objects. On the basis of this method, proposed in the Soviet Union by A. N. Kozyrev, as well as in the United States, a special instrument of the radiometer type was created.

5.3. Ultraviolet Survey

At the present time work is proceeding on the development of effective instrumentation for carrying out an UV survey. In such a survey use must be made of special types of aerial films whose light-sensitive layer includes luminophors which during the transmission of UV rays give a burst of light registered by the light-sensitive layer. Such a survey can be useful in a study of contamination of the sea surface by petroleum and the detection of hydrocarbons reaching the water surface from deep layers beneath the bottom.

The measurement of the spectrum of reflected sunlight emanating from the sea also makes it possible to study phytoplankton and estimate the chlorophyll concentration. The latter in the visible part of the spectrum absorbs violet-blue (0.42-0.46 μm) and red (0.66-0.70 μm) light. However, these studies, made from an aircraft, are complicated by the influence of the atmospheric transfer function, allowance for which makes possible the use of aerospectrometric measurements for the study of chlorophyll, determining photosynthesis.

6. Aerogeochemical Survey

An aerogeochemical survey makes it possible to register areas of scattering of gases or fine suspended particles in the air. On a practical basis it is accomplished in a suction process with the pumping of outside air into the aircraft.

The outside air is passed through a system of absorbents selectively absorbing the sought-for components and is analyzed by means of a counter measuring the radioactivity of the air. Suspended particles can be collected my means of grids of artificial polymers, etc. Specialists have also developed procedures based on the spectrometric study of atmospheric composition under and over the aircraft by means of the Fraunhofer lines method.

The appearance of new lines in the surface profile of an atmospheric column of air is evidence of the presence of aureoles of some substances.

For the time being an aerogeochemical survey is virtually not used at all for an investigation of ocean areas. It evidently can be used in detecting hydrocarbon gases arriving at the sea surface from deep layers beneath the sea floor and indicative of the presence of petroleum and gas deposits.

The practical use of aerogeochemical methods is difficult due to the absence of a method for the tie-in of observations to the features responsible for the presence of areas of scattering of different gases because it is difficult to take into account the motion of air masses.

7. Aerogeophysical Survey

Among the aerogeophysical methods for study of the geological structure of the floor of sea areas use is being made of an aeromagnetic survey and an aerogravity survey is in the development stage.

7.1. Aeromagnetic (Airborne Magnetometer) Survey

An aeromagnetic survey is intended for study of the characteristics of the magnetic field of the seas and oceans, which are predetermined by the rocks making up the deep layers of the bottom of the seas and oceans. The survey is made using airborne magnetometers carried aboard flightcraft. Magnetometer investigations of the oceans made it possible to reactivate the mobilistic theory of the earth's development and served as a basis for creating a theory of the new global tectonics; by means of these investigations it was possible to determine deep and transformed faults on the floor of the oceans which can be traced for many hundreds and even thousands of kilometers. On the basis of magnetic susceptability of different rocks it is possible to use aeromagnetic measurements in geological mapping for the tracing of individual geological suites (strata, bodies, etc.). On the basis of the detected magnetic anomalies it is possible to speak of the deep geological structure of layers beneath the sea floor, in particular, concerning the presence of intrusions of basic and ultrabasic rocks and even concerning geological structures which are promising for petroleum and gas.

7.2. Aerogravity (Airborne Gravimeter) Survey

An aerogravity survey, together with gravity investigations made from ships at sea, facilitates the detection of gravity anomalies. This type of survey for the time being is of an experimental character. An analysis of gravimetric maps makes it possible to determine the deep structure of layers beneath the sea floor, the presence of intrusions, and sometimes anomalies indicating the presence of anticlinal structures. This makes it possible to use materials from gravity surveys for determining ocean areas promising with respect to petroleum and gas.

The use of materials from aerial surveys in a study of the ocean for all practical purposes has only begun, but already at this stage it is obvious that it is necessary for solving both scientific problems and some practical problems in mastery of the ocean.

Taking this into account, it can be expected that the interpretation of materials from aerial surveys of ocean areas will make it possible to obtain extensive information on the physical phenomena transpiring in the ocean, on some of its biological characteristics and geological structure of the bottom. The multisided use of different types of aerial methods, together with other oceanographic methods, can substantially refine our ideas concerning the laws of the nature of the oceans and seas, as is necessary for more effective use of its resources.

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SYSTEMS FOR THE CONTROL OF INDUSTRIAL ROBOT COMPLEXES

Leningrad PROBLEMY ISSLEDOVANIYA I OSVOYENIYA MIROVOGO OKEANA in Russian signed to press 30 Oct 79 pp 343-359

[Article by Ye. P. Popov]

[Text] In many branches of the national economy and scientific fields extensive practical use is being made of manipulators (industrial robots), as well as master and slave manipulators, remotely controlled by a man-operator. In particular, master and slave manipulators are being used with manned and unmanned underwater vehicles and structures.

However, extensive problems in mastery of the world ocean cannot be solved using existing simple manipulators. There is a need for more universal, multipurpose industrial robot manipulator complexes with unmanned working craft controlled by a combined man-computer system.

A whole series of considerations dictates the need for them.

First, an unmanned craft when performing a great volume of work at depth can continuously over a prolonged period of time be located near an object, whereas a manned vehicle or a diving complex, due to the limited operating time of its life-support system, is forced to go through several cycles of submergence and surfacing. This considerably protracts and increases the cost of the entire operation.

Second, the mass of a manned vehicle will always be much greater than the mass of an unmanned vehicle intended for the very same operations. This results in a considerable increase in the weight of the raising and lowering apparatus on the surface carrier-ship, and this means also an increase in the minimum admissible tonnage of the latter, which reduces the easy operability of the system and also increases the cost of the operation.

Third, in order to carry out a whole series of jobs at depth there is a need for universal manipulators with a number of degrees of freedom not less than six (similar to the human arms, not counting the wrists). They can be multipurpose with a simple readjustment to different operational cycles. This is one of the advantages of manipulation robots over traditional automatic devices. In many cases they can completely replace the heavy and dangerous work of divers.

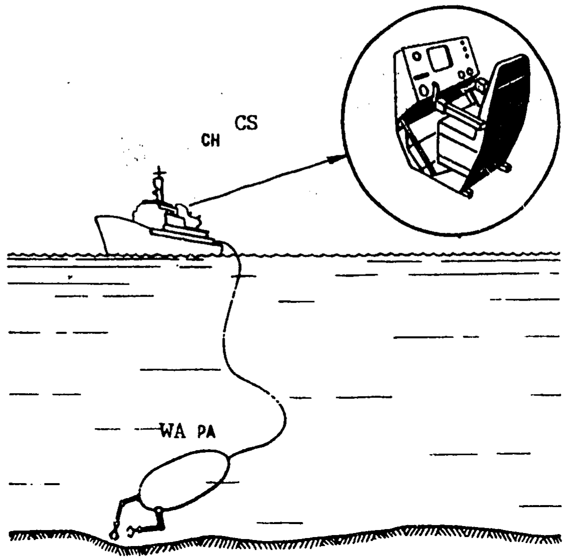

Figure 1. Biotechnical system for control of manipulators from carrier-ship. CS -- carrier-ship; WA -- working apparatus.

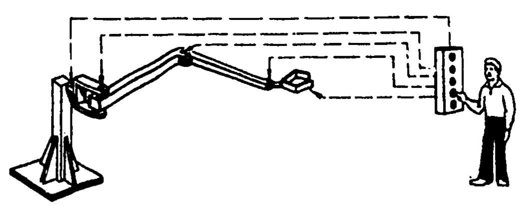

Figure 2. Diagram of operation of command control system.

Fourth, a manipulation system must have a sufficiently "intelligent" control system, adapting itself to the actual circumstances in the place of operation of the manipulators, similar to the human brain, controlling the purposeful motion of the arms during the work process. For this it is necessary that the manipulators be "sensitized" and that a digital computer or specialized computer be included in the control circuit. As a result of the complexity of the operation and the "unpredictability" of underwater conditions for the total automation of operation of a manipulation robot it is necessary to create elements of an artificial intellect. However, it is still premature to speak of solution of the latter problem at the present level of development of science and technology. Accordingly, it is inevitable that a man-operator, located aboard the surface carrier-ship, be included in the process of control of underwater manipulators. In such cases control signals must be transmitted remotely along the supporting and electric cable from the ship to the underwater craft, whereas in the opposite direction, from the vehicle to the ship, there must be transmission of television and other information for the representation of underwater conditions on a TV screen (reception panel).

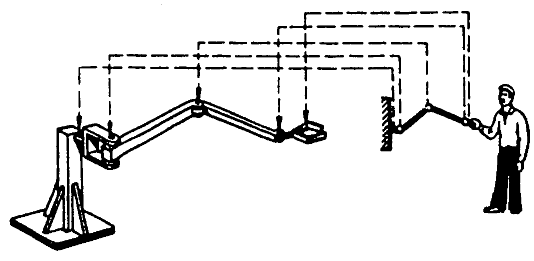

Figure 3. Diagram of operation of slave control system.

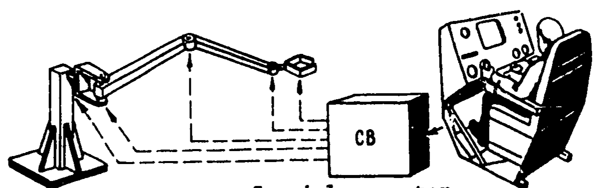

Figure 4. Diagram of operation of semiautomatic control system. SC designates the special computer employed.

Thus, the intellect of a man-operator is used in the recognition of undetermined and changing underwater circumstances and conditions and in controlling the motion of the manipulators. Different ways for designing such a control system are possible.

In the simplest variant the system is designed in such a way that the operator at all times controls each motion of the manipulators, using his hands on the control mechanisms and on the screen observing the underwater conditions near the underwater object (Fig. 1). Such systems are called biotechnical. These biotechnical systems can be divided into three principal types: master, slave and semiautomatic.

In master control systems the operator by means of buttons, toggle switches or levers with buttons brings about the motion of the manipulators, corresponding to different degrees of freedom, separately. In this case there is simply remote activation of individual drives in the manipulator (Fig. 2).

In slave control systems there is a master mechanism near the operator completely similar to the underwater manipulator. The operator takes these controls in his hand or simply moves just the end of the controls with his hand. Then the manipulator will precisely duplicate the motion of the controls in all its degrees of freedom. This occurs because each degree of freedom of the manipulator corresponds to a degree of freedom of the controls in accordance with the servosystem principle (Fig. 3). The manipulator includes the actuating part of the servosystem whereas the control unit is at the operator's post. Thus, the total number of servosystems is equal to the number of degrees of freedom of the manipulator. The servosystems are closed. Accordingly, two signals -- direct and return -- pass through each of them through the ship - vehicle communication channel.

As is well known, two-directional slave systems are in use. In these systems both the controls and the manipulator have motors for transmitting to the hands of the man-operator, at some scale, the forces arising during the operation of the manipulator. Then man, as a link in the control system, receives two feedback signals: visual through the television channel (on the screen) and tactile (reflection of work forces), which considerably increases the effectiveness of his actions.

In semiautomatic systems there is a control lever at the operator's control post which has several degrees of freedom (in a general case -- six). Small movements are possible for each degree of freedom. In this case man's pressure on the lever for each degree of freedom creates a movement proportional to it, which is converted into an electric signal.

Thus, the operator, pressing on the control lever and rotating it, thereby imparts the desired movement to the end of the underwater manipulator (gripping device or tool) in six space coordinates (linear movements and angular orientation) simultaneously. In order to execute this the signals received from the control lever in all degrees of freedom are sent to a special computer (Figures 4 and 5). The latter scales them in such a way that the control commands for all the drives formed as a result will bring about the combined motion of the drives, under whose influence there will be the desired linear movement and angular orientation at the end of the manipulator.

Semiautomatic systems have a number of advantages: first, their control devices are more compact, and second, there is a lever convenient for operation, in the planning of whose kinematics, independently of the kinematics of the manipulator, it is possible to take advantage of convenience of work with it.

There are three principal methods for the control of such semiautomatic systems: speed, force and position, and also combinations of these.

The speed method for semiautomatic control. In this method when the operator presses on the control lever the special computer shapes such control commands for the drives so that the velocity of movement (linear or angular) at the end of the manipulator will be proportional to the displacement of the control lever or the pressure imparted to it.

The force method of semiautomatic control. In this method there is formation of an effort (forces or moments) at the end of the manipulator proportional to the compressive force on the lever. It is desirable that it be used in a case when the gripping device or tool on the end of the manipulator is in contact with the object in the work area. The free motion of the manipulator when using the force method using a special computer is formed as if its end point is drawn with a force proportional to the operator's compressive force on the control lever. However, the force control method is undesirable for the free motion of the gripping apparatus because the imparted force does not directly determine the direction of motion.

Finally, the position method for semiautomatic control differs in that in this method the man-operator by means of a control lever sets the momentary coordinates of the end point of the manipulator and the momentary angular position of gripping, that is, the trajectory of motion and the angular orientation of the gripper or tool at the end of the manipulator. The special computer in this case shapes control signals for the drives of all degrees of freedom of the manipulator in such a way that the above-mentioned motion is realized.

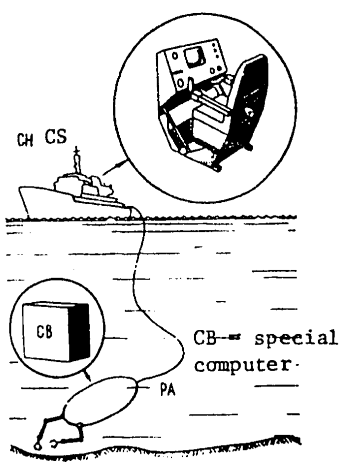

Figure 5. Automated system with special computer aboard working apparatus.

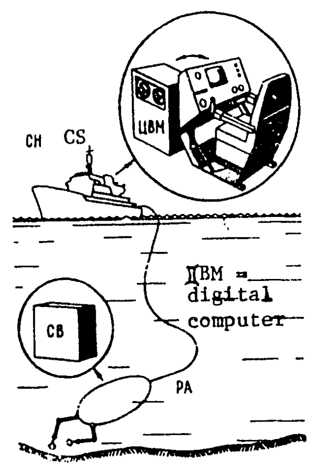

Figure 6. Automated system with digital computer aboard carrier-ship.

It is desirable to construct a combined semiautomatic control system in which for transfers (transport movements) of the end of the manipulator use is made of the speed control method, whereas the position method is employed for local small movements with precise positioning of the gripper or tool and the force method of semiautomatic control is used for carrying out working operations in contact with objects. Such a combined system can be designed with a single control lever with a single special computer with the addition of only a simple switching device connected to this lever. The effectiveness of operation of the entire system is increased if the control lever is "sensitized" for signals from sensors placed on the underwater manipulator.

Thus, the three principal types of remote control systems (master, slave and semiautomatic) are biotechnical, since the operator in these systems, watching the screen and instruments for the motion of the manipulator and the prevailing conditions, continuously imparts control signals with his hands. Human hands at all times control operation of the manipulator.

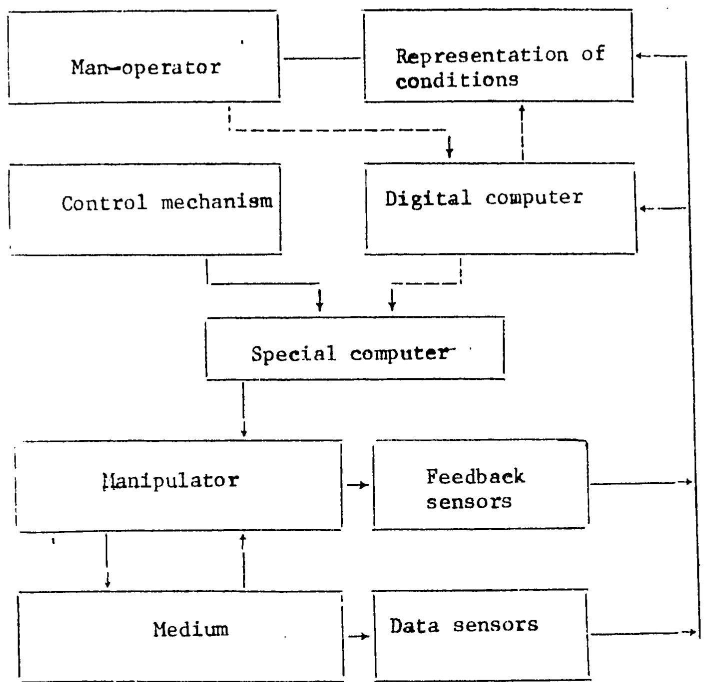

Figure 7. Functional diagram of automated control system.

With such a continuous work load, creating a stressed work regime, the operator cannot continue a long time. In order to increase the effectiveness of carrying out the operation it is necessary to reduce the operator's load considerably and increase the duration of his work considerably by a reduction in fatigue. This can be achieved in part, true, to an inadequate degree, by shifting from slave to semi-automatic control.

The effectiveness of operations of the underwater manipulation robot increases if some of the operation, subject to rigorous programming or flexible programming -- with very simple adaptation, is carried out in an automatic regime. The control system for this part of the operation can be completely placed on the working apparatus (WA) itself; in this case it is possible to use either an on-board special computer in the WA (Fig. 5), that is, without loading of the information channel of the electrical and supporting cable, or a shipboard digital computer (Fig. 6).

On the screen and instruments at his post the man-operator observes the conditions and operations of the underwater manipulators in an automatic regime, and in dependence on this, one or another automatic regime is cut in or cut out, and in case of necessity can take control into his hands (changeover to one of the biotechnical regimes described above) (Fig. 7).

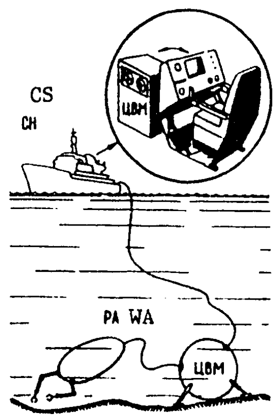

Figure 8. Industrial robot system with intermediate master apparatus.

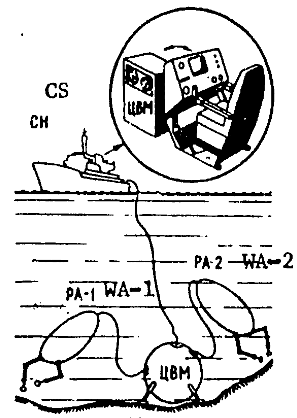

Figure 9. Industrial robot system with several working apparatuses.

Such a combined system, which can be called automated, is extremely promising. It makes possible a considerable increase in the productivity of labor (due to automatic regimes), facilitates the work of an operator (frees him from continuous manipulations with his hands) and thereby increases the duration of his effective operations.

The autonomy of operation of the working apparatus, without an increase in its weight, can be increased by introducing an additional master apparatus which includes an on-board digital computer (Fig. 8). Then the actuating level for control of the drives with a very simple computer will be placed in the vehicle and the digital computer for the next hierarchical level of the control system -- the adaptive level -- will be situated in the master apparatus. We note that two or more working apparatuses can operate simultaneously with such a master apparatus (Fig. 9).

It is desirable that this master apparatus be used in working at great depths. First of all, the light working apparatus cannot contend with the oscillations of the long electrical and supporting cable by means of its own motors (see Fig. 6) if it is not strengthened. In this case the master apparatus (see Fig. 8) serves as an anchor from which a relatively short electrical and supporting cable will run to the working apparatus.

Second, such a master apparatus will serve as an intermediate power unit. Power is transmitted from the carrier ship to the master apparatus along a long electrical and supporting cable in a form most advantageous for transmission. On the master apparatus there are current converters in different forms. The current is then fed to the users on the working apparatus along a short cable. In addition, storage batteries can be installed on the master apparatus as extra power sources.

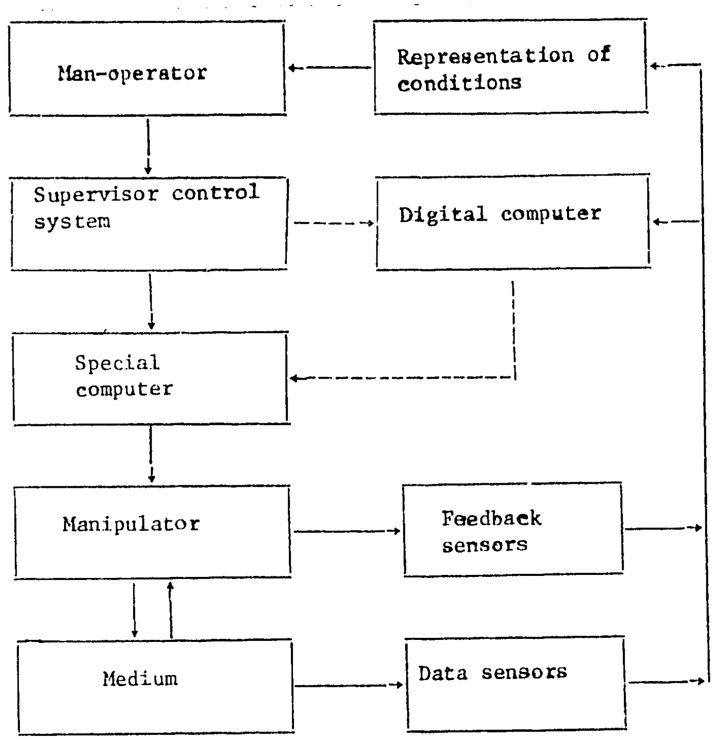

Figure 10. Functional diagram of "supervisor" control.

Third, the master apparatus can be supplied with measurement and recording apparatus for the registry of different properties of the medium along the entire line of descent from the carrier-ship and at the ocean floor.

The descent of the working apparatus from the ship is carried out in stages: first it is lowered together with the master apparatus to the necessary depth and then moves with it toward the stipulated work object.

The already described automated control system, including automatic and biotechnical regimes (see Fig. 7), is a very simple type of system with interactive control. The latter assumes active interaction between man and machine. Control in a "supervisor," and also in the most perfect "dialogue" regime, is included under the term interactive control.

In the "supervisor" control regime all the individual elements of the operation are programmed. The elements of the operation are performed by manipulators, each individually, automatically under the control of a digital computer or special computer.

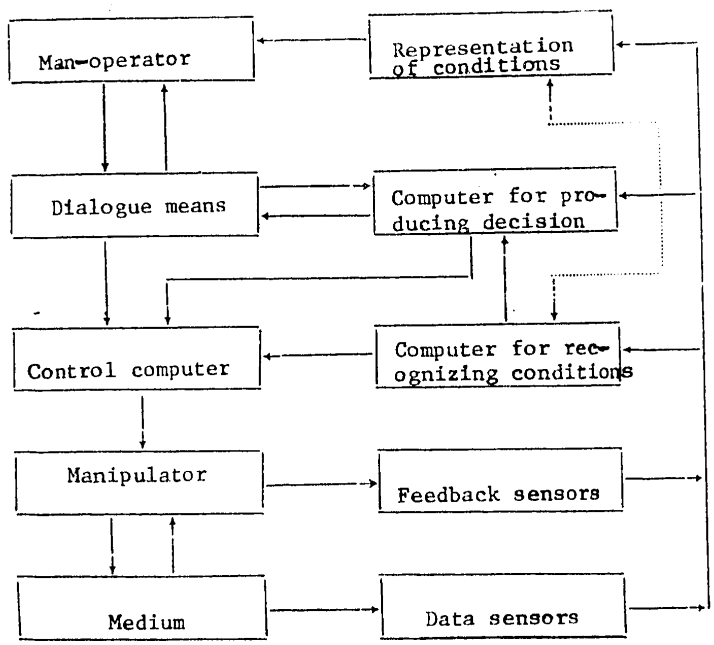

Figure 11. Functional diagram of "dialogue" control system.

The man-operator, by means of feeding of a designated command (with a "light pen" on a screen, using a lever or other method) gives the machine an order to carry out a definite element of the operation (Fig. 10). Thus, the recognition of the conditions and the strategy of actions of the manipulation robot is the task of the operator. Observing the conditions on the screen and using the instruments, he determines the sequence for activating different elements of the operations and their direction in the developing circumstances. Within the elementary operation there can be not only rigid programs, but also very simple adaptation, such as homing and search regimes.

In a dialogue control regime in the most complete form there is active interaction between the digital computer and the man-operator. The digital computer participates jointly with man in the recognition of conditions and formulating a decision concerning further actions of the manipulation robot (Fig. 11). In this case the digital computer is a "creative" partner of the operator in the observation and control processes. For this purpose the manipulation robot must be supplied with corresponding sensitization (visual, tactile, sonic, etc.), that is, with a definite set of sensors of different information and perception apparatus, and means for the primary processing of this information. The control computer must be supplied with corresponding devices for the input of such initial data, as well as apparatus for the graphic representation to the man-operator of the results of his perception and recommendations on further actions. It is also necessary to have means for dialogue interchange, input of the control object and feeding of the control commands by man.

In general, the system will have a hierarchical structure with three levels, separated with respect to tasks and territory:

a) an actuating control system with drives with a special computer aboard the working apparatus (see Fig. 8);

b) a digital computer in the master apparatus for the primary processing of information and adaptive control of the manipulators;

c) a digital computer and operator post on the carrier-ship for interactive recognition of conditions, adoption of a decision and dialogue control.

It is very important to solve the problem of the desirable separation of functions between these three levels, taking into account the loading of the information channels of the electrical and supporting cable in both sectors (WA-MA and MA-CS). The observation and control apparatus must be tested, taking into account the discreteness of transmission of information along the electrical and supporting cable in a rather narrow frequency band.

Then it is necessary to solve the problem of visualization of the place of operation of the underwater robot at the operator's post. The fact is that in underwater work the water medium is turbid. Television information is unreliable; it must be supplemented by ultrasonic, laser and tactile information. In this case all four types of information together must give a three-dimensional representation. Only the complex representation of these types of information with output to a common display will make it possible, under different conditions, to represent the underwater conditions more satisfactorily than when using each of them separately. But this problem still remains unsolved.

We have already considered underwater telecontrolled manipulation robots with a combined man-machine control system. Even now it is possible to speak of the creation of autonomous working apparatuses with a control system based exclusively on an on-board digital computer, without cable connection with the carrier-ship. They can be used for carrying out simple manipulation operations and the collection of information.

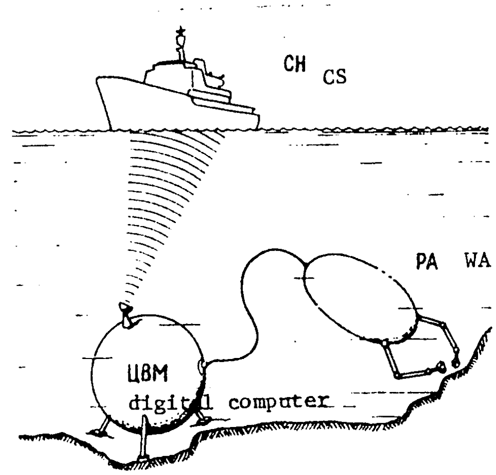

Fig. 12. Diagram of industrial robot complex.

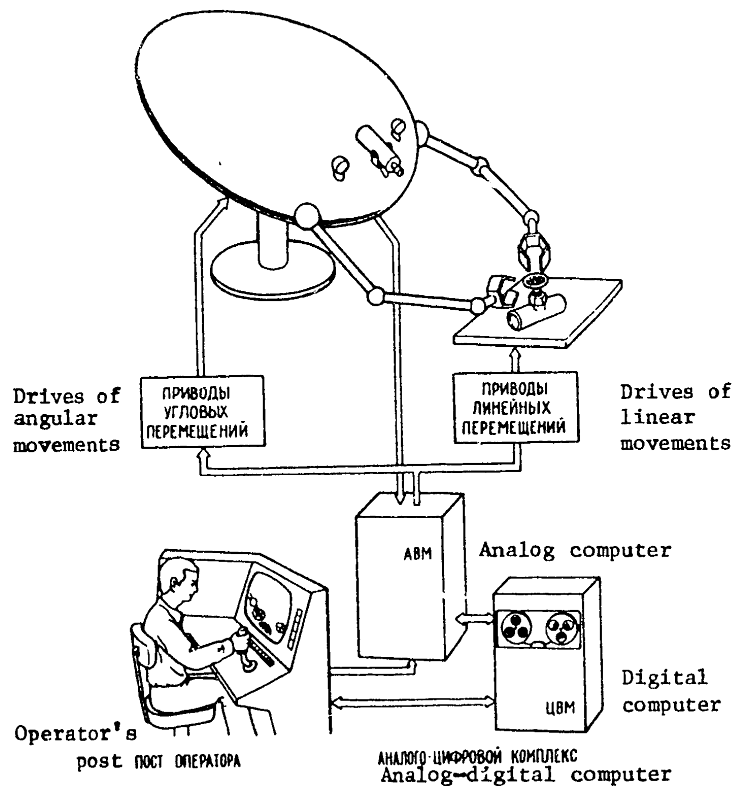

Figure 13. Diagram of complex laboratory stand for semireal modeling.

In this case the industrial robot complex (Fig. 12) consists of a master apparatus and a working apparatus, joined by a short cable. The principal digital computer controlling and processing information is placed in a master apparatus and the simpler special computer is placed in the working apparatus. The hierarchical principle for constructing the control system of the manipulator is retained, but with purely automatic regimes, programmed and adaptive, and in the future -- with elements of an artificial intellect, as described above.

Now we will examine key problems in the designing of remote man-machine systems for the control of unmanned manipulation robots.

As we see, the system includes a large complex of technical apparatus, diverse in content and scattered territorially, but nevertheless constituting a single whole. All links in this system are interconnected in the work process. Accordingly, there is a need not only for a detailed planning of these as individual technical devices, but also a systemic designing with a tie-in of the principal parameters of these elements on the basis of the general requirements imposed on effectiveness, quality, accuracy and dynamic properties of the entire system.

The first stage in such planning is a determination of the actuating level of the system for controlling the manipulators within the working underwater apparatus. Proceeding from an analysis of the operations which must be performed, we will ascertain the principal requirements on the servicing zone, the kinematics of the manipulators, energetics and dynamic qualities of the drives and algorithms for operation of the special computer. It is necessary to ascertain the necessary set of sensors for "sensitizing" the manipulator and the information sensors concerning the properties of the medium.

The dynamics of the manipulator as a whole is described by a complex system of differential equations whose investigation for the synthesis of a control system is possible only using universal computers. This investigation is complicated in a case when provision is made for operation of the manipulators with a floating apparatus (in a hovering regime without attachment). In this case all the movements and working forces of the manipulator play the role of disturbing effects on the system for control of the apparatus itself. This makes difficult its stabilization in the process of functioning of the manipulation system. In order to solve the problem it is necessary to investigate the dynamics of the apparatus jointly with the manipulators and sometimes it is necessary to install an additional mechanical arm for attachment of the apparatus to the body of the object. It is possible that in this case the system for control of the motion of the working apparatus must be interrelated to the system for the control of motion of the links of the manipulator so that as a result of their joint actions the necessary manipulation operation will be performed. This introduces a definite contribution to the algorithms for operation of the on-board special computer in dependence on the signals of the sensors for sensitizing the manipulator.

Such are the principal problems in designing the actuating control level aboard a working underwater apparatus.

Then the communication line between the underwater working apparatus, the master apparatus and the surface carrier-ship enters into operation as a link in the control system. The communication line is necessarily multichannel and has a limited frequency band. The transmission of a considerable number of information signals (including TV) in one direction, and also command and control signals in the other direction, leads to a substantial discreteness in the transmission of signals, and as a result there can be a time lag. This exerts a substantial influence, first of all, on the effectiveness and dynamic qualities of the adaptive automatic part of the system for control of the manipulators, including the digital computer for the master apparatus. Second, this exerts a substantial effect on the quality of operation of the observation and control circuit passing from the working underwater apparatus through the operator's panel on the surface ship.

Accordingly, in the second stage of systemic planning it is necessary, on the one hand, to take into account the characteristics of the communication line when determining the effectiveness and dynamic qualities of the general control contour, and on the other hand, impose requirements on the communication line (within the possible limits), proceeding on the basis of the necessary effectiveness of operation of the general control circuit. In this case it is necessary to take into account the noise and distortions of the information and command signals, for which it is necessary to make corresponding statistical computations of the control system both with respect to the units directly related to the communication line and with respect to the total effectiveness and dynamics of the control system as a whole.

In order to cut such a communication line into the control circuit it is also necessary to be concerned with the serious development of elements for the coupling of the outputs of this line to the main units of the control system. All these elements must be minimized, taken together, with respect to mass and size characteristics and with respect to power requirements, and at the same time an effort must be made to achieve maximum reliability.

In the third stage of systemic planning it is necessary to construct the upper levels of the man-machine interactive control system with the use of a digital computer, special computer, and with allowance for all the characteristics and properties of the already considered actuating level, communication line and sensitizing system.

In the fourth stage it is necessary to represent the information on underwater conditions in a form convenient for man, and in the last, fifth planning stage carry out biotechnical testing of the technical means for observation and control, that is, match them with the physiological characteristics of man. In this case the control system as a whole, like the interactive system, must automatically perform the maximum possible number of elements of manipulation operations with the minimum use of manual labor of the man-operator at the control panel. This requires the use of all modern technical means and man must be drawn into the control process only when his active participation is really necessary. However, during the entire period of operation of the underwater manipulation robot, including in automatic regimes, the man-operator makes continuous observations of the screen and instruments to ascertain its actions and if necessary, at any moment in time can take control into his hands.

Thus, the automated, "supervisor" and "dialogue" interactive control systems, supplemented by semiautomatic biotechnical systems with a control lever and a special computer, must be regarded as the most promising.

We note that all the tasks of systemic planning considered above are closely related to one another and in the last analysis are solved jointly.

In order to carry out systemic planning of remote control with success when using underwater manipulation robots it is necessary to create special complex laboratory stands for semireal modeling, including an analog-digital computer complex, an oscillating model of a working apparatus with real manipulators, a model of the work objects, an operating model of the operator's post with instrumental representation of conditions and control units (Fig. 13). The model of the post must be situated in the next room beyond direct visibility of actions of the manipulators.

In the analog-digital complex there is modeling of the equations of motion of the apparatus, taking into account hydrodynamics, the properties of the measuring instruments and the motive-rudder complex, the effects of the electrical and supporting cable, etc., and also algorithms for control of the motion of the vehicle and the manipulation system, taking into account the properties of the communication line and interference, must also be employed.

Such a stand makes it possible, under laboratory conditions, first of all, to check how correctly the preceding computations of the control system were made for all the tasks of systemic planning, including the results of computer planning with preliminary purely mathematical modeling. Second, it makes it possible to test the control algorithms, taking into account the real representation of the manipulators and post of the man-operator in the stand. Third, it makes it possible to introduce the necessary changes into these real parts of the system for increasing the effectiveness of operation of the entire system. Fourth, it makes it possible to test the ergonomic and biotechnical characteristics of the system.

In addition, such a stand can be used in laboratory tests of different remote systems for control of manipulation robots, and also become the principal training complex for the teaching, selection and breaking-in of operators.

Such a stand for semireal modeling is a powerful universal means for the planning and laboratory testing of a system making it possible, in a well-prepared state, to proceed to real tests at sea.

It must be said that it can be used for laboratory perfecting and testing of any other remotely controlled industrial robot complexes, intended, for example, for unmanned operation in mine shafts or under other extremal conditions, including in space.

We note in conclusion that in a similar way it is possible to carry out planning and laboratory testing of systems for the remote control of manipulators for manned underwater and space vehicles. In this case the man-operator can be within the oscillating apparatus in the already described stand for the purpose of bringing the conditions of his activity closer to real, in particular, for putting his vestibular apparatus into operation.

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MAN'S HABITATION OF THE SEA DEPTHS. LIFE SUPPORT SYSTEMS

Leningrad PROBLEMY ISSLEDOVANIYA I OSVOYENIYA MIROVOGO OKEANA in Russian 1979 signed to press 30 Oct 79 pp 391-403

[Article by P. A. Borovikov]

[Text] Man's habitation of the sea depths can be dictated by both economic and social factors. The first are related primarily to the search for new food, mineral and energy resources and the second to the search for living space as a result of overpopulation of the land.

As of now, it is possible to speak, with allowance for the foreseeable future, only of the economic mastery of the ocean, about transformation into a day-to-day inhabited medium, that is, for the time being there can be no talk of a social expansion because this problem has simply not been considered in depth. Accordingly, henceforth the sea depths will be regarded as an arena of man's productive activity. Thus, man's presence underwater is restricted to weeks, possibly months, but no more.

The engineers and physicians concerned with the problem of habitation of sea depths must successively solve three interrelated problems: man's maintenance of life, health and performance under water. In order to understand more clearly the essence of the problems to be solved, their nature and scope, we will discuss the specifics of the underwater medium.

First, water does not support the respiration of man, developing as a biological species under conditions of an air, gas medium. Accordingly, independently of all other conditions, for breathing under water it is necessary to use a gas mixture ensuring normal vital functioning of the human body, that is, depending on submergence conditions having a very definite composition and parameters. When working under water it is necessary to use means for the individual or collective protection of man as a whole, or at least, his respiratory passages, from the effect of water on them.

Second, the water layer exerts a pressure on the body greatly exceeding atmospheric pressure. In this case all the conditions for man's life change sharply. True, it has been experimentally demonstrated that man's vital functions, when he is uniformly subjected to exposure to increased pressure (from 0.3 to 60 atm or more), are not disrupted when there is an appropriate composition of the breathing mixture. He experiences such pressure when submerging under water to a depth of 600 m or more.

However, in general, the problem of man's life support in hyperbaric conditions, many times over the course of many days and even weeks, is new and by no means solved.

At the present time there are two methods for carrying out underwater work.

Method of total isolation from the surrounding water. People are in submarines, working in underwater structures, working chambers, etc., that is, in structures whose solid housing receives increasing water pressure. In such structures conditions to the greatest degree are close to ordinary terrestrial conditions. The pressure acting on the body is kept equal to or extremely close to atmospheric pressure, the breathing mixture is air and comfort zones are not deformed.

Method of prolonged, multiday presence of man under pressure. This method is receiving increasing recognition because diving training is now assuming secondary importance and is becoming only a means for adaptation to the water medium in which definite work is performed. The principal task of a man submerging under water is the performance of different operations in the assembly of equipment, its repair, underwater welding, and also inspections, expert examinations, etc. The present-day objects of underwater work are at depths of 200-300 m or more; the volumes of work attain tens and hundreds of man-hours of underwater time. In such cases it is necessary to be concerned not only with the safety of people, but also the effectiveness of their work under water.

In order to put man under water, afford him the possibility of working under water on a project and returning him to the surface alive and healthy it is necessary to meet a number of requirements. Thus, rigorously in accordance with the depth of submergence and the rhythm of descent it is necessary to change the pressure of the breathing mixture, and in accordance with pressure -- the composition of the breathing mixture, its temperature and humidity. In addition, these characteristics are also dependent on time of presence under pressure under specific conditions, and also on the class of technical apparatus used.

In modern diving technology there are three classes of equipment intended for the creation of conditions necessary for man's presence under pressure: shipborne pressure chambers, diving bells and individual diving equipment. They differ with respect to the level of comfort afforded and the time people are present in them.

Divers live for days and weeks in the pressure chambers carried on ships operating on and under the water. Such a prolonged presence of people in a closed volume under pressure of tens of atmospheres requires the maintenance of the necessary living conditions of the crew at a high level and in the most complete volume.

Diving bells are used in practical work for several hours a day and then the bell is either inactivated or a second crew is sent down to replace the first. Naturally, the life support system in them is considerably simpler and the living conditions are less comfortable.

Individual diving equipment is used continuously for only two or three hours and therefore it can be used to create the minimum necessary conditions for man's presence underwater.

On the whole, a life support system must satisfy the following requirements.

First, it must maintain a working pressure of the respiratory mixture with an accuracy to ± 0.25 m H_2O.

Second, there must be a change in the composition of the breathing mixture with an increase in the working depths and therefore pressure. For example, with submergence to 60 m or more the inert component of the air -- nitrogen -- must be replaced by helium. The presence of helium in the breathing mixture sharply changes all its properties and accordingly there is a change in the requirements on habitation conditions.

Third, there must be precise regulation of the content of oxygen and carbon dioxide, whose presence in the breathing mixture is important for the normal vital functioning of the human body.

At the present time researchers feel that a biological effect is not exerted on the human body by the relative percentage content of the biologically active component, but by its absolute mass content in a unit geometric volume of the compartment. In addition, regardless of the pressure of the breathing mixture the mass content of the oxygen and carbon dioxide in a unit geometric volume can remain approximately at the "surface" level. Life support systems are planned with these two considerations in mind.

In the course of vital functioning the human body releases into the surrounding medium a whole series of gaseous products, so-called anthropotoxins. The presence of these gases in the breathing mixture in large quantities can lead to poisoning of the body. Among physiologists up to the present time there is no clear idea concerning the nature of prolonged, multiday exposure of the human body to anthropotoxins under conditions of increased pressure.

It is usually assumed that their mass content in a unit geometric volume of a compartment will be acceptable for hyperbaric complexes as well.

Fourth, it is necessary that the heat and moisture characteristics of the breathing mixture be maintained in the necessary range. They are maintained by means of special equipment externally not connected to systems for regulating the composition of the breathing mixture. It has been demonstrated in repeated experiments that with an increase in the pressure of the breathing mixture, especially with the replacement of nitrogen in the mixture by helium, the zones of heat and humidity comfort are deformed. For example, at a depth of 200-300 m a temperature of 30-32° (±1°) and a humidity of 40-50% are considered comfortable. However, strictly speaking, for each breathing mixture, for each pressure, and especially for each life support system, the comfort zone will be different. This is attributable to the fact that the concept of comfort is based on the processes of heat and moisture exchange between the body and the external medium. Naturally, these processes are also influenced by the thermophysical characteristics of the breathing mixture, the moisture content, the organization of its flows through the chamber and the velocity of these flows. The problem of the heat and moisture balance of the human body under hyperbaric conditions nevertheless is in need of careful investigation, especially with the practical introduction of new equipment and gear in diving work.

Existing life support systems usually handle the complex processing of the breathing mixture, eliminating carbon dioxide and anthropotoxins from it, adding oxygen and maintaining the temperature and humidity of this mixture within the necessary range.

However, this is by no means a full listing of the tasks assigned to the life support system. It must purify the breathing mixture of the microflora constantly emanating from crew members; this microflora, under the conditions of a closed volume, is accumulated at an extremely significant rate. Moreover, the presence of microflora in a manned compartment is especially dangerous because the resistance of the human body under hyperbaric conditions is sharply reduced. Usually prior to the onset of work there is careful disinfection of the pressure chamber and equipment. The crew members also undergo disinfection. The disinfection is periodically repeated. In addition, special filters are installed in the system through which the breathing mixture circulates. These filters trap not only microflora, but ordinary dust as well.

Finally, in the life support system provision must be made for supplying food to the people under the water or under pressure. Under conditions of normal pressure -- within solid hulls -- the feeding problem presents no special difficulties. In solving this problem for divers exposed for many days under pressure it must be remembered that their taste sensations are different from the sensations arising under ordinary surface conditions. Researchers must ascertain how food is assimilated in hyperbaric media, in order to devise a ration.

Thus, at the present-day stage of knowledge concerning the characteristics of vital functioning of the human body under underwater hyperbaric conditions our information is of a semi-empirical nature and is obviously inadequate. It is evident that the most important task is a maximum expansion of the volume of fundamental research in the field of diving and underwater physiology. Only then will practical recommendations be based on the results of scientific studies, and not on the trial-and-error method.

Today man's habitation of the sea depths involves the use of shipboard diving complexes: movable unit and stationary complexes. Deep-water variants of both types of complexes are intended for supporting multiday work under pressure and differ from one another with respect to the number of divers occupying the compartment and accordingly the volume of work. Movable complexes hold two or three divers and are employed in carrying out random work in small volume, such as checking on the condition of bottom equipment or small repairs. Stationary complexes can hold 8-12 divers simultaneously and these carry out work of considerable volume, such as the assembly of underwater equipment, pipelines, etc.

The requirements on the conditions of habitation in the pressure chambers of diving complexes of both classes in general are similar and their technical solutions in general are similar.

The pressure of the breathing mixture is on a practical basis maintained in the necessary range by means of feeding into the pressure chamber (through lines) the gas stored in cylinders in compressed form or by discharge of the excess breathing mixture from the pressure chamber. In the circuit for regulating pressure it is customary to include devices for the collection of the mixture released from the compartments, separating out the helium from this mixture (if the mixture contains it) in pure form and the pumping of the purified helium again into the cylinders for repeated use. The circuits for regulating pressure are usually controlled manually, especially in the stage of reduction of pressure -- decompression. Variants of automated circuits for compression, stabilization of pressure and decompression are being considered, but for the time being they are in the stage of experimental checking.

The monitoring of the composition of the breathing mixture and its maintenance in stipulated limits are accomplished by means of circuits regulating the breathing medium parameter or the parameters of several media at the same time. Each circuit consists of a device for measuring the values of the parameter to be regulated (temperature, humidity or oxygen content) -- a unit for shaping a control signal and an actuating mechanism, which also regulates the value of the stipulated parameter.

It is very important that measurements of the composition of the breathing mixture and its parameters -- temperature and moisture content -- be highly precise in the entire pressure range. We have already stated that with a change in pressure the composition of the breathing mixture changes: relative, percentage content of the components (other than the inert component) decreases proportionally to the pressure increase. For example, whereas in air the normal oxygen content is 20%, at a depth of 100 m the normal content will already be 1.8%, at a depth of 300 m -- 0.65%, and a depth of 500 m -- 0.39%.

Accordingly, any gas analyzer measuring the relative, volumetric content of the breathing mixture components should have a fantastic accuracy, especially for great depths unattainable at the present time. Therefore, as was already mentioned above, it is possible to make a sufficiently precise analysis of the composition of the breathing mixture only by the method of measuring the absolute content of the component in a unit geometric volume of the compartment (the measurement must be made directly in the compartment, under the working pressure of the medium being analyzed). In this case the accuracy of the measurements may be relatively low, but, most importantly, it must not change with an increase in the depth of submergence because there must not be a change in the mass content of components of the breathing mixture (other than the inert component). Thus, the problem of increasing the accuracy of the gas analysis in shipboard pressure chambers, and especially in diving bells, and also breathing apparatus, is still not solved.

The measurement of the temperature and moisture content of the breathing mixture is a somewhat simpler problem than the analysis of composition of the mixture, but in this case as well the method used for the measurement must be insensitive to a change of both pressure and the composition of the breathing mixture.

The unit for shaping the control signal, comparing the readings of the measuring instrument (sensor), determines to what extent the value of the parameter to be monitored has deviated from the stipulated value, and cuts in (or cuts out) the corresponding actuating element. In automatic regulation systems this unit is designed in the form of a special instrument.

It should be noted that an increase in the depth of submergence of a diver results in an intensification of intracircuit, cross-connections between individual, seemingly unrelated parameters. It is very difficult to take all these relationships into account when shifting the life support system from one regime to another when a man-operator is involved, and during recent years work has begun on the many-sided automation of a diver's descent and the inclusion of a specialized control computer in the system as the unit for shaping the control signal.

The actual actuating elements regulating the content of different components of the mixture or its parameter operate by commands from the unit for shaping the control signal.

Oxygen for compensating for that expended by the crew in respiration is fed into the breathing mixture usually from an external source through lines and through a dosing unit. The latter is the principal element of the circuit for the feeding of oxygen, since the quality of its operation to a considerable degree governs the quality and reliability of operation of the entire circuit. There are two variants of dosing units. In one the oxygen is fed into the compartment at a constant rate (for example, dose-by-dose) and the quantity of supplied oxygen is regulated by the feeding time; in the second the oxygen is fed into the compartment in ready-prepared doses. Both these variants have their merits and shortcomings and are used to an equal degree in diving systems.

In creating a circuit for the delivery of oxygen into the compartment it is necessary to contend with oxygen "flares" -- jets of pure oxygen flowing from the dosing unit. The velocity of the flowing oxygen, its quantity, point of delivery and parameters of the mixer at the output of the dosing unit must be selected in such a way that the oxygen entering the compartment is already mixed with the breathing mixture and its concentration in the breathing mixture constitutes no danger of fire.

In actual practice use is usually made of several types of oxygen sources: cylinders with compressed gaseous oxygen, containers of liquid oxygen, electrolyzers producing oxygen by decomposing water into oxygen and hydrogen, and finally, solid chemical compounds releasing excess oxygen in the course of one reaction or another.

All the units for purifying the breathing mixture of carbon dioxide and anthropotoxins are usually combined into a single circuit, including units for absorbing impurities and a device pumping the breathing mixture through these units -- a so-called stimulator of mixture discharge.

The breathing mixture is usually purified of carbon dioxide either by its chemical bonding with some substance -- an absorbent, or using physical adsorption by substances of the zeolite type or its freezing-out using deep-cold apparatus. Most commonly use is made of quite simple, reliable and inexpensive chemical absorbers of carbon dioxide. The principal shortcoming of chemical purification of the breathing mixture from carbon dioxide is a very great expenditure of the absorbent, attaining 10-30 kg or more per person per day, depending on operating conditions. In the case of multiday and even multiweek exposures of crews of four, six or more men the expenditure of absorbents attains many tons. This quantity must be delivered to the work site, stored, loaded into capsules, all of these operations involving definite difficulties. Precisely for this reason an intensive search is being made of absorbents of carbon dioxide of the adsorption type which can be regenerated or nonexpendable means of purification of the cryogenic apparatus or molecular sieves type.

The breathing mixture is purified of gaseous anthropotoxins also by special absorbers in the course of pumping the breathing mixture through them. The filters-absorbers of harmful impurities usually are adsorbents of the activated carbon type or compounds similar to it, included in a single circulation circuit with catalysts, ensuring the oxidation of products of the carbon monoxide type to carbon dioxide and subsequent elimination of oxidation products in corresponding filters-absorbers. The filters are quite capacious with respect to absorptivity, are relatively small in size, and, it can be said, satisfy practical purposes. In order to create the necessary heat flow, heating the breathing mixture, electric, steam and water heaters are cut into the circuit for circulating the mixture. It is necessary to maintain the temperature of the mixture in stipulated, frequently extremely narrow limits. Experience shows that in helium-oxygen hyperbaric media the temperature fluctuations must not exceed a fraction of a degree and the maintenance of this degree of fluctuations, especially in an automatic regime, is a complex technical problem.

The regulation of the moisture content of the respiratory mixture involves the elimination from the mixture of the water vapor entering it due to breathing, from food, showers and sanitary units. Moisture can be absorbed from the breathing mixture by different methods. One of the principal methods is the condensation of water vapor by cooling of the breathing mixture to the dew point, corresponding to a stipulated regime, and the expulsion of the condensate beyond the limits of the chamber. For this purpose a heat exchanger is cut into the circuit for circulating the breathing mixture. A coolant with a temperature ensuring the necessary cooling is fed into the heat exchanger. Beyond the heat exchanger and droplet trap there is a unit for the heating of the breathing mixture cooled in the heat exchanger to the initial temperature. The condensation method for the absorption of moisture is in the most common use since it is sufficiently reliable and simple in operation. However, for its application there is a need for refrigerating units, heat exchangers, pumps for pumping coolant through the heat exchangers, etc. In addition, this method requires exceptional energy expenditures -- there is double thermal processing of the respiratory mixture: first it is cooled, and then it is heated. It should be noted that the energy expenditures on condensation absorption increase with an increase in the pressure of the breathing mixture.

The second method for the absorption of moisture used in diving practice is adsorption drying. Water vapor is eliminated from the breathing mixture by adsorbents of the silica gel type, by zeolite, etc. Energetically this method is more advanrageous, since for its implementation there is no need for thermal processing and technically it is simpler. Its shortcoming is the need for a periodic regeneration of the adsorbent, which complicates the operation of the system and increases the operating losses of breathing mixture, and this, taking into the cost of helium, is of more than a little importance. Adsorption drying is not sensitive to an increase in pressure and therefore at the present time it is regarded as the most promising, especially for the drying of breathing mixtures at pressures of several tens of atmospheres.

Finally, it is necessary to mention the need for careful organization of flows of breathing mixture in the chamber. Usually this breathing mixture is collected for regeneration in one of the ends of the compartment, and processed, returns to the other end. Thus, there is a constant movement of breathing mixture from the "clean" to the "dirty" end, that is, the required mixing in the compartment itself. However, in this case, on the one hand, in the compartment there should be no formation of stagnant zones in which there is no constant exchange of breathing mixture, and on the other hand, the rates of movement of the flow, the velocity gradients and the drops of temperature and humidity along the flow must be limited and cannot exceed comfortable values.

All the manned pressure chambers of diving complexes include sanitary-suction units. Cold and hot water are usually supplied to the sanitary units and fecal-suction system water and waste are expelled from the chamber. Naturally, for a chamber experiencing a pressure of 30 atm, for example, it is necessary to supply water under a pressure exceeding by several atmospheres the pressure within the chamber. This is usually done using an intermediate pressure tank which is filled with water at normal pressure and then a counterpressure of a definite level is created in this tank ensuring the entry of water into the chamber. This system is simple in design but creates some additional operating difficulties: it is necessary to monitor the water level in the tank and the counterpressure in the tank, regulate pressure during filling of the tank, etc. In addition, the water supply in the pressure tank is limited and it usually runs out at the most inconvenient time. Recently high-pressure water pumps have been included in the water delivery lines and by means of these pumps it is possible to replenish the water in the pressure tank and thus ensure an unrestricted water supply.

The fecal-suction system water is collected by special units (shower trays, washstand basins, commodes); through a line the collected water is removed from the chamber into a strong storage tank and from there it passes into the ship's general system. The shut-off valves installed along the outlet line must reliably close the line even with the passage of foreign objects through it.

In examining the habitability of hyperbaric compartments it is impossible not to mention the acoustic communications. The great speed of sound in helium, the different density of the breathing mixture, lead to a shift in the resonance frequencies of voice communications of man into the region of higher frequencies. This shift increases with an increase in pressure, and at depths of 200-300 m or more the human speech is understandable only after its processing in special electronic instruments -- speech correctors. Their creation is a still unsolved problem.

Up to this point we have examined the problems arising in ensuring the normal vital functioning of the crew when it is in the manned pressure chamber of a diving complex on a submarine or surface vessel. Approximately the same problems must be solved in ensuring the entry of a diver in individual gear into the water. As a result of the brief presence of a diver in the water (up to several hours) there has been solution of a number of problems, such as conformity to the comfort zone with respect to humidity, the consumption of food and satisfaction of natural needs, as well as the control of microflora. On the other hand, the remaining problems are becoming still more acute. First, direct contact of man with the water is creating an additional load on the physiological systems of the body. Second, the individual gear for a diver is a far more dynamic problem than a manned pressure chamber.

In the case of failure of the apparatus for purification of the breathing mixture, feeding oxygen or heating the diver spends minutes on eliminating the irregularity. Virtually any irregularity can be eliminated only in a diving bell or even at the surface. All this imposes very rigid requirements on the reliability of individual diving gear.

Thus, a breathing apparatus must supply the diver a mixture for breathing in precise accordance with the pressure of the surrounding medium.

An equality is achieved between the pressures of the breathing mixture and the medium surrounding the diver by means of including a highly sensitive element in the breathing channel of the gear in the form of a rubber bag, from which the diver breathes, or a fine rubber membrane which brings the gas-feeding mechanism into operation.

Regulation of the composition of the breathing mixture in individual gear is ensured by two methods. In the first the diver receives a fresh breathing mixture through a hose from the surface or from a diving bell and the mixture which he exhales is returned through another hose to the surface or to the bell for regeneration and repeated use. In the second the diver uses a self-contained breathing apparatus, that is, one not connected to the surface or bell. Such an apparatus automatically replenishes the oxygen expended by the diver during breathing and eliminates the carbon dioxide from the mixture.

In diving practice it is most common to use hose breathing apparatus as being more reliable in operation, light and less unwieldy than self-contained apparatus. The principal difficulty is determination of the composition of the breathing mixture in the apparatus. Until now no one has created an industrial model of sensors for registering the content of oxygen and carbon dioxide in the breathing mixture of a self-contained apparatus, although individual variants of such sensors have already appeared.

The problem of keeping the diver warm under the water must be regarded as more acute. In the pressure chamber the diver is in an atmosphere with a comfortable temperature and breathes it; in the water he is surrounded by a water medium with a temperature reaching as little as -2° and breathes a gas mixture from an apparatus having a temperature close to the water temperature. Thus, a normal feeling of well-being of the diver can be ensured by heating his body to a comfortable temperature and at the same time heating the gas mixture breathed by him in order to avoid respirator heat losses. The problem of maintaining the thermal comfort of the diver for the time being has not been satisfactorily solved because the available gear either does not ensure the necessary heat transfer or is unwieldy and restricts the actions of the diver. At the present time the most widely used gear is that with heating by hot water fed through a hose from the surface or from a diving bell, but it is far from perfect.

An individual but important problem in ensuring the normal vital functioning of a diver in the water at depths of hundreds of meters is monitoring of his feeling of well-being. Experience has shown that the self-monitoring of a diver is inadequate because not all the symptoms of increasing impairments will be sensed and in particular the diver cannot properly evaluate the degree of his danger.

Several systems have been created for monitoring the state of the principal indices of well-being of the diver, such as the respiration rate, frequency of cardiac contractions and body temperature, but they are still in the stage of experimental checking.

In examining the problem of habitation of sea depths by man we should particularly dwell on the problems relating to rendering the necessary medical assistance to a diver in trouble (sick or who has experienced an accident).

First, there can be "purely" divers' maladies: all kinds of compression and decompression disorders, the consequences of deviations in the composition of the breathing mixtures, etc. These diseases in general are quite well studied; methods have been developed for their prevention and treatment.

Second, when carrying out work under water there can be accidents on the job. And even a small trauma, absolutely safe for man's life on the land, can lead to a lethal outcome under water. For example, if a man loses consciousness on the land it is 100:1 that he will be saved, whereas for a diver this ratio decreases to 4:1.

Third, during prolonged work under water and under pressure (to several weeks or more) any diver can fall ill with ordinary, "everyday" diseases, catch cold, appendicitis can occur, ulcers can be aggravated, etc. It is impossible to bring the victim out from pressure at once; he must undergo decompression with an average rate of reduction of pressure of 1 m/hour, that is, beginning with a depth of 300 m a man, regardless of the severity of his state, can be brought out only after 300 hours or after 12.5 days.

The treatment of a patient under pressure is also complicated by the fact that the diagnosis is made at a distance -- doctors are not sent down to a chamber at great depths and for the time being the nature of the effect of medicines and the consequences of surgical intervention on a body under pressure are unclear. At present it is not even known how to decompress a person who has undergone a surgical operation.

As long as the volume of diving work in a particular region is small in scale, accordingly the number of diseases or injured divers is also small and the problem of rendering them medical specialized assistance is not so acute as when carrying out large-scale diving work in a restricted region. As a model of such an aggravation of the situation it is possible to cite the petroleum and gas deposits of the North Sea where about 2,000 divers are working at the present time; the mortality among them is 1% per year. [See S. A. Warner, "Diving Fatalities Lead to Corrective Action," OCEAN INDUSTRY, Vol 12, No 4, pp 124-126, 1977.]

A specialized hospital is now being established in the North Sea basin. It will have a barooperations unit (pressure 30 atm), intended for the therapeutic or surgical treatment of afflicted divers. In this region about 2,000 persons are engaged in underwater work. The afflicted divers will be delivered from the work place to the hospital by helicopter and placed in single-patient movable-mobile pressure chambers, that is, at the same pressure at which they were under at the time of the illness or accident.

The depth of submergence is becoming greater and greater. Depths of 610 m have been attained under laboratory conditions; in real dives into the sea men have reached a depth of 501 m. Practical work on the servicing of petroleum wells at sea is being carried out at depths of about 300 m and the average working depth for divers today is 100 m. Researchers anticipate that soon depths of 600-800 m will become the realistic working depths -- possibly 1,000 m. The duration of presence of a crew of divers is increasing. The maximum working time for divers in a regime of prolonged presence under pressure is, according to data from foreign diving firms, 100 days a year or more.

An increase in the depth and time of man's work under water will be dependent on the quality of the life support system, creating comfortable and safe conditions for his existence.

As we see, an indispensable task is a fundamental medical-physiological investigation of the behavior of the body under the extremal conditions of the hydrosphere, the collection of information concerning the postponed aftereffects of increased pressure, because the process of man's habitation of the world ocean is becoming more intensive with each passing day.

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TOWED MEASURING SYSTEM FOR INVESTIGATING INTEGRAL TEMPERATURE VARIABILITY IN THE UPPER LAYER OF THE OCEAN

Moscow OKEANOLOGIYA in Russian Vol 20, No 5, 1980 pp 937-942

[Article by A. N. Paramonov, N. A. Grekov and A. F. Ivanov, Marine Hydrophysical Institute Ukrainian Academy of Sciences, Sevastopol']

[Text]

Abstract: The "Shleyf" towed measuring system with a distributed temperature sensor has been developed and came into extensive use in the hydrophysical investigations aboard the scientific research ship "Akademik Vernadskiy." The article describes the structure of the system, gives its principal technical specifications and presents the characteristics of calibration of the integral temperature measurement channel.

The use of antenna systems consisting of distributed temperature sensors (DTS) has made it possible to obtain new data on the structure of internal waves from a drifting ship [4]. Interesting material on the variability of heat and salt component and the mean weighted speed of sound on a run along 35°N, determined using the "Istok" STD probe [salinity-temperature detector], was collected during the 14th voyage of the scientific research ship "Akademik Vernadskiy" [3]. In this work the need arose for developing towed instruments for measuring the integral characteristics (temperature $\bar{T}$, conductivity $\bar{\chi}$, speed of sound $\bar{C}$, density $\bar{\rho}$) in the surface layer of the ocean. Such measuring systems are most effective in investigations over extensive areas of the ocean, including the range of synoptic scales; this makes possible a routine search for eddy formations, a study of their dynamics and spatial structure.

Making use of the great experience of the Marine Geophysical Institute Ukrainian Academy of Sciences in the development and operation of towed instrumentation at sea [1, 2, 5], the automation detachment on the 17th voyage of the scientific research ship "Akademik Vernadskiy" tested a method for using a system for measuring the integral temperature $\bar{T}$ for investigations of the surface layer of the ocean while the ship is underway. The integral temperature of the layer from the depth z_1 to z_2 is determined by the expression

$$\bar{T} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} T(z)\, dz.$$

The investigations were made using the towed "Shleyf" measuring system. A diagram of the towing and a structural diagram of this system are shown in Fig. 1.

The system consists of submergible and on-board components. The submergible unit includes primary converters of integral $\overline{T}$, surface T_0 and deep T_{deep} temperatures, as well as a primary pressure converter P_{deep} (at depths) on the end of the DTS. In addition to the primary converters T_{deep} and P_{deep} the hermetically sealed capsule of the submergible unit contains: a temperature - frequency converter and a channel commutator, alternately sending data on deep temperature and pressure into the communication channel. The hermetically sealed capsule is submerged using a streamlined, drop-shaped hydrological weight (100 kg).

As the primary converters of deep T_{deep} and surface T_0 temperature use was made of quartz plates with a temperature cutoff, placed in protective housings. The accuracy of temperature - frequency conversion (F_{deep}) is determined for the most part by the stability of the reference quartz oscillator, which in the range of working temperatures -2 - +32°C is equal to $\pm 1 \cdot 10^{-5}$ with a useful operating time of 2,000 hours. In measuring the depth of submergence of the capsule use is made of a primary pressure converter (PDV-50A) with an accuracy class 0.25.

The primary integral temperature ($\overline{T}$) converter is a three-strand electrical and supporting cable of the KTB-6 type with rubber insulation of the copper strands and with a length of 3,000 m. The sensing element of the distributed temperature converter consists of two internal copper strands of cable connected with one another and hermetically sealed at the submerged end. The third strand of the electrical-supporting cable and its external braiding serves as a communication line between the submergible capsule and the converters and the on-board unit of the towed system.

Information from the primary and measuring converters of the submergible unit is fed into the on-board unit of the system. The primary integral temperature converter is cut into the arm of a precise bridge which is housed in a thermostat and fed a stabilized d-c voltage. In addition to a resistance box, a compensator, constituting a segment of the KTB-6 electrical and supporting cable, is connected to the other arm of the bridge. An electronic automatically recording potentiometer of the KSP-4 type is cut into the bridge diagonal; this potentiometer is simultaneously for measuring and recording the integral temperature $\overline{T}$. The frequency signal from the deep temperature T_{deep} and pressure P_{deep} converters is fed through a LF-filter to a frequency meter, from whose output, in the form of a parallel binary-decimal code, it is fed to a code-analog converter and then to the input of a KSP-4 automatic recorder. The surface temperature is also measured and registered using an automatic recorder. In addition to data on temperature $\overline{T}$, T_0 and T_{deep} and pressure P_{deep}, the tapes of the automatic recorders carry automatically applied LAG (coordinate) and time marks.

The calibration of the primary temperature (T_0 and T_{deep}) converters is accomplished in the laboratory using sample equally graduated thermometers of the TR-2 type, whereas the calibration of the primary hydrostatic pressure (P_{deep}) converter is accomplished using a piston-type manometer (MP-600, class 0.05).

The principal technical specifications of the "Shleyf" towed system are:

-- response of device for measuring integral temperature ($\Delta\overline{T}$) 0.02°C;
-- response of device for measuring surface temperature (ΔT_0) 0.005°C;
-- response of device for measuring deep temperature (ΔT_{deep}) 0.005°C;
-- time constant of device for measuring integral temperature (τ) 16 sec;
-- time constant of device for measuring deep temperature (τ_{deep}) 18 sec;
-- time constant of surface temperature (τ_0) 3 sec;
-- working length of distributed primary temperature converter (L) 3,000 m;
-- depth of towed end with ship's speed of 15 knots -- 220 m;
-- accuracy in determining depth -- ±1 m.

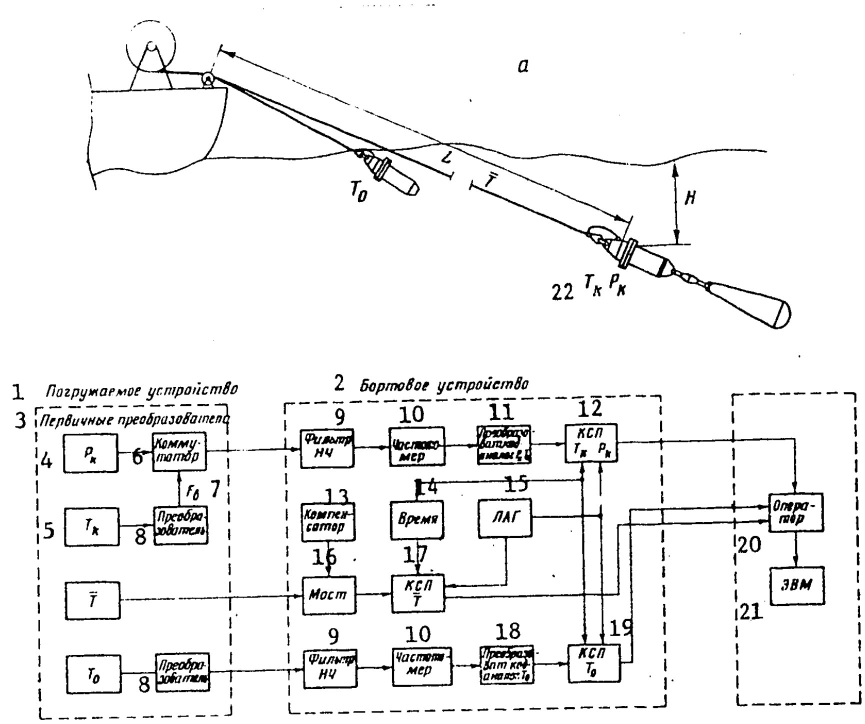

Fig. 1. Diagram of towing (a) and structural diagram (b) of "Shleyf" measurement complex.

KEY:

1. Submergible apparatus
2. On-board apparatus
3. Primary converters
4. P_{deep}
5. T_{deep}
6. Commutator
7. F_{ship}
8. Converter
9. LF filter
10. Frequency meter
11. Code-analog converter $P_{deep}T_{deep}$
12. Autorecorder $T_{deep}P_{deep}$
13. Compensator
14. Time
15. Coordinate(s)
16. Bridge
17. Autorecorder $\overline{T}$
18. Code-analog converter T_0
19. Autorecorder T_0
20. Operator
21. Electronic computer
22. $T_{deep}P_{deep}$

KEY:
- A) Supporting and electrical cable
- B) Bridge
- C) KSP automatic recorder
- D) On-board instrumentation

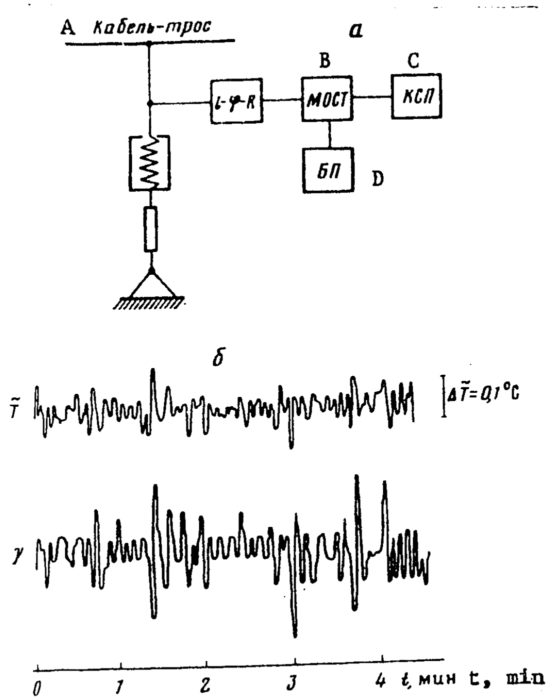

Fig. 2. Structural diagram of device for measuring tension on supporting and electrical cable (a); samples of records of integral temperature $\tilde{T}$ and tension on supporting and electrical cable γ (b).

On the 17th voyage of the scientific research vessel "Akademik Vernadskiy" a great volume of work was carried out for investigating the metrological and operational characteristics of the "Shleyf" complex. During the voyage specialists tested a method for letting out and bringing in the towed line of the complex while the ship was proceeding at normal speed (15 knots).

As a result of this testing it was established that the records of integral temperature $\tilde{T}$ contain high-frequency oscillations. A unit was fabricated for clarifying the nature of these oscillations. It makes it possible tc register the tension on the supporting and electrical cable. Its structural diagram is shown in Fig. 2a. The unit consisted of a primary converter of linear movement l into an electric parameter -- resistivity R, which was cut in to the measuring bridge. The signal was fed from the bridge to the input of a KSP-4 automatic recorder. The integral temperature and tension on the supporting and electrical cable were registered synchronously. The experiment revealed that the high-frequency fluctuations of integral temperature and the tension on the supporting and electrical cable correlate with one another. Samples of the records of these parameters, registered with a high speed of KSP tape movement (2400 mm·hour^{-1}), are represented in Fig. 2b.

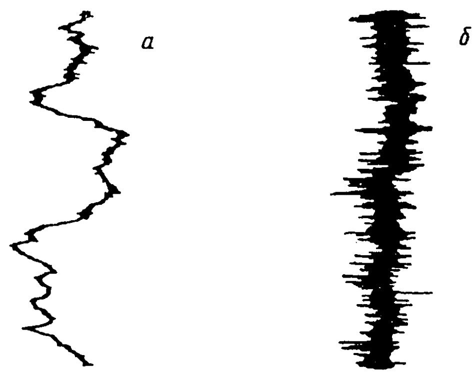

Fig. 3. Records of integral temperature under calm conditions (a) and with waves of class 7 (b).

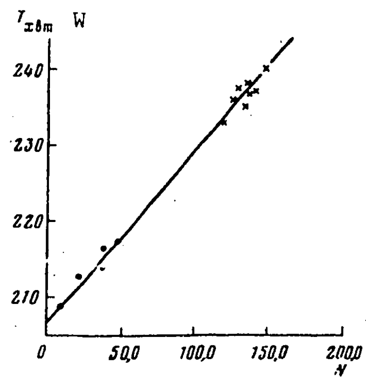

Fig. 4. Calibration curve for integral temperature channel. Dots — data from the 17th voyage; crosses -- data from the 18th voyage of the scientific research vessel "Akademik Vernadskiy."

Figure 3 shows samples of records of integral temperature $\overline{T}$ made under calm conditions and with waves up to class 7. A comparison of the records indicates a considerable increase in the level of high-frequency oscillations in stormy weather. These oscillations, caused by the tensometric effect of the cable strands, have a periodic character; they can be filtered out and do not reduce the overall response of the device for measuring integral temperature.

An evaluation of the accuracy characteristics of the channel for measuring integral temperature in the "Shleyf" complex was made under field conditions. Two methods were used in calibrating the distributed primary temperature converter: static and dynamic. The first method was used on drifting stations. The distributed temperature sensor was fully or partially lowered over the side of the ship. The readings of integral temperature, temperature in the winch cabin and the length of the towed supporting and electrical cable were registered synchronously. Soundings with the "Istok" salinity and temperature apparatus were made in order to obtain the standard integral temperature values. These data were used in computing the calibration coefficients.

The distributed temperature sensor was calibrated in a dynamic regime while the vessel was proceeding on course. Virtually the entire supporting and electrical cable, which was arranged as indicated in Fig. 1a, was lowered over the side. The readings of integral, surface and deep temperature and the depth of the end of the distributed temperature sensor were recorded simultaneously. During the course of the towing "breakaway" thermobathysondes were dropped overboard. Their data were used in computing sample integral temperature values. Calibrations in a dynamic regime were carried out during the 17th and 18th voyages of the scientific research vessel "Akademik Vernadskiy." The results of the processing are given in Fig. 4. The dots represent data from the 17th voyage and the crosses correspond to data from the 18th voyage. The calibration curve is approximated well by the straight line $\bar{T} = a + bN$ with the coefficients $a = 20.68°C$ and $b = 0.0125°C\cdot unit^{-1}$, which were determined by the least squares method, N are the readings of the integral temperature channel of the "Shleyf" complex. The standard deviation of the computed data from the standard values was ±0.053°C. This error is attributable to the static errors of the unit for measuring integral temperature and sample measures (thermobathysondes) and the dynamic error of the unit for measuring integral temperature, whose calibration was carried out in the frontal zone of the circulation where the horizontal temperature gradients were $2\cdot 10^{-3}$ °C·mile^{-1}.

In addition to study of the metrological characteristics of the towed "Shleyf" complex on the voyages of the scientific research vessel "Akademik Vernadskiy" it was employed in carrying out systematic investigations of the temperature field of the upper 200-m layer in the ocean. The measurements were made both on runs for obtaining the background characteristics of the field and ascertaining the regions of anomalous distribution of integral temperature and in the POLIMODE polygon with respect to detection, study of structure and determination of the kinematic characteristics of individual eddy formations. The simplicity of the electrical and mechanical construction of the "Shleyf" complex, its high reliability in operation under complex weather conditions and in different climatic zones during the 17th and 18th voyages of the scientific research vessel "Akademik Vernadskiy," made it possible to carry out extensive investigations of the upper layer of the ocean for a distance of more than 15,000 km, which was 750 hours of continuous observations. The high results of these investigations make it possible to draw the conclusion that it is necessary to introduce a complex of the "Shleyf" type on scientific research ships.

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THERMAL EFFECT OF INTERNAL GRAVITATIONAL WAVES AT THE FREE SURFACE OF THE OCEAN

Moscow IZVESTIYA AKADEMII NAUK SSSR, FIZIKA ATMOSFERY I OKEANA in Russian Vol 16, No 10, 1980 pp 1077-1081

[Article by Yu. A. Volkov and Yu. M. Kuftarkov, Institute of Physics of the Atmosphere USSR Academy of Sciences and Marine Geophysical Institute Ukrainian Academy of Sciences]

[Text]

Abstract: Within the framework of the international JASIN-78 program an experiment was carried out for ascertaining the interrelationship between internal waves of the seasonal thermocline and temperature fluctuations at the free surface of the ocean. The article gives the results of observations made on an expedition carried out during the 18th voyage of the scientific research ship "Akademik Vernadskiy." The measurements of the parameters of internal gravitational waves were made using distributed temperature sensors. Observations of temperature of the ocean surface were made using an infrared radiometer from shipboard. The nature of the coherence and phase shift indicate the presence of a correlation between fluctuations in the thermocline and at the ocean surface.

Despite extensive investigations for study of the spatial-temporal structure of the field of internal waves in the ocean, the possibilities of their indication by remote methods have still been poorly studied. It is only possible to mention a few studies [1, 2] in which the first steps have been taken for observations in the optical range of internal waves from artificial earth satellites and from aircraft.

In this article we give the preliminary results of investigation of the possibility of indicating (sensing) internal gravitational waves from the characteristic thermal radiation of the free surface of the ocean in the IR spectral region.

It is well known that the IR radiation of the ocean is formed in the thin surface layer (several tens of micrometers) and is determined by its thermal structure. It is also known that at the free surface there is almost always a cold inversion layer in which the temperature drop from tenths of a degree to a degree is concentrated in several millimeters. The thermodynamic parameters of this layer are formed under the influence of processes transpiring both at the discontinuity of the ocean and the atmosphere itself and in the upper boundary layer of the ocean.

Under definite conditions internal waves can exert an appreciable influence on some parameters of the spectrum of surface waves [2, 3], whose high-frequency part evidently makes the maximum contribution to formation of the thermal structure of the inversion layer. As demonstrated in [4], it is short capillary waves which exert the greatest influence on the temperature drop and the heat flow in the inversion layer.

Thus, the effect of internal gravitational waves in the temperature of the ocean surface can be manifested, for example, through the reaction of the field of capillary waves to the variable current induced by internal waves, which in the long run leads to variations in the temperature of the free surface.

In September-October 1978, during an expedition on the 18th voyage of the scientific research ship "Akademik Vernadskiy" in the North Atlantic, carried out under the direction of B. A. Nelepo and A. M. Obukhov, with investigations under the international JASIN-78 program, an experiment was carried out whose objective was a clarification of the possibilities of existence of the above-mentioned correlation. Methodologically the experiment was carried out in several variants.

In the first of these variants observations of the field of internal gravitational waves were carried out from the drifting ship using a system of three spatially separated distributed temperature sensors (DTS) [5].

In the second variant, which we will discuss in greater detail, the ship was anchored to a depth of 120 m in the neighborhood of Ampere Bank (near Gibraltar). [We note that the observational data obtained at drift and at anchor are identical with respect to the effect of the interrelationship of temperature fluctuations in the upper thermocline and at the ocean surface; therefore, below we will give only some results of the experiment carried out on Ampere Bank.] The steep slopes of this bank (horizontal scale along the 2,500-m isobath -- 30-40 km) make it a natural generator of internal waves. Observations of the field of internal waves were made using a system of distributed temperature sensors. This system included two groups of sensors which were formed of elements of different scales and occupied almost the entire thickness of the water from the surface to the top of Ampere Bank. The time constant of the entire measuring system was 15 sec. The response was better than 0.06°C. The depth distribution of the sensors was as follows: first (DTS-100) -- lowered from the prow of the vessel, occupied the water layer from the surface to the depth of 100 m; on this same vertical there were six other decimeter sensors (DTS-10), arranged successively one after the other, beginning with a depth of 10 m; three sensors (two -- 10 m and one -- 50 m) were lowered from the stern of the vessel.

Measurements of the temperature profile were made with an "Istok" (STD) instrument for computing the mean profile of the Brent-Väisälä frequency, characterizing the field of internal waves. At the same time the "Istok" data were used for calibrating the distributed sensors. Measurements of the radiation temperature of the ocean surface were made using an IR-radiometer (in the range 8-12 μm) with a time constant of 3 sec and a response not less than 0.03°C. The radiometer was mounted on a boom at the ship's prow and was directed vertically downward. The angle of view of 5° ensured averaging of the radiation temperature in a circle with a radius of 1 m.

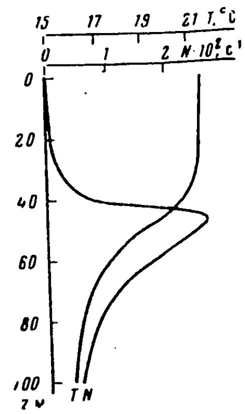

Fig. 1. Vertical distribution of water temperature T and Brent-Väisälä frequency N in region where experiment was made.

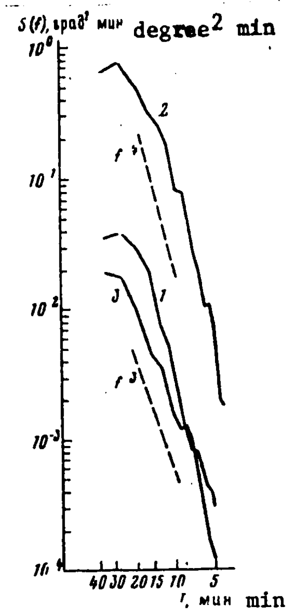

Fig. 3. Initial records of effective water temperature for series 1, 2, 3 for depths indicated in table.

Table 1

Time Series of Temperature Fluctuations

Instrument	Number of series	Depth, m	Duration, T, hours	Discreteness t, min	Number of terms in series
IR radiometer	1	0	7.8	0.62	760
DTS-10	2	50–60	7.8	0.62	760
DTS-100	3	0–100	7.8	0.62	760

In the analysis we used data from an 8-hour measurement interval in the evening and nighttime as the most favorable for observations of radiation temperature of the ocean surface.

Below we give some results of observations for investigation of temperature fluctuations in the upper thermocline and at the ocean surface, and also present their cross statistical analysis.

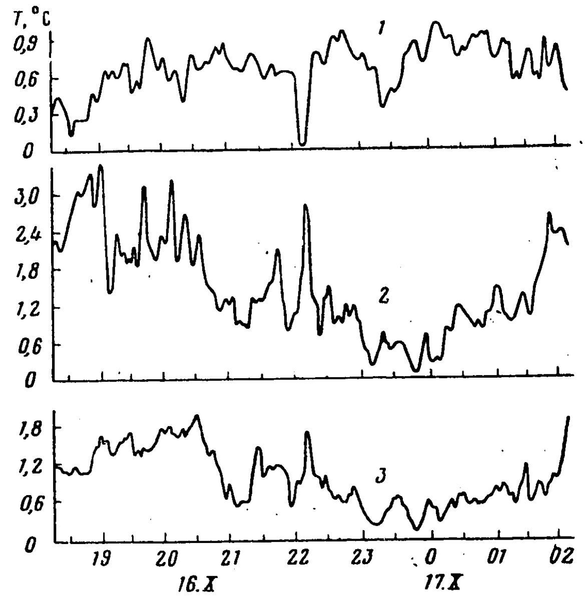

Fig. 3. Spectral densities of temperature fluctuations for series 1, 2, 3.

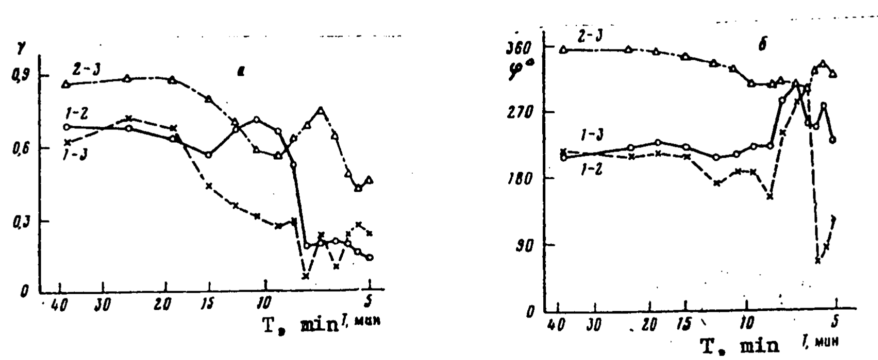

Fig. 4. Cross spectral analysis of series 1,2,3: a) coherence γ, b) phase shift φ.

The depth distribution of temperature and the Brent-Väisälä frequency in the region where the experiment was carried out, as can be seen from Fig. 1, indicates the existence of a sharply expressed thermocline and a quite well-developed quasi-homogeneous layer. During the time of the measurements there was a weak wind (0.5-4 m/sec) and poorly developed waves (class 2).

The characteristics of some series of measurements subjected to statistical processing are given in the table for the period of observations from 1820 hours on 16 October to 0208 hours on 17 October.

Figure 2 shows the initial records of water temperature fluctuations (series 1-3) for the 8-hour measurement period. Thereafter the derived series were filtered using a cosine-filter; the value of the maximum shift of the correlation function when carrying out the spectral and cross spectral analysis was assumed equal to 1/12 of the length of the entire initial series, which gave 30 degrees of freedom and the statistically supported evaluations of the spectral characteristics.

A preliminary analysis of the primary results of observations, obtained using six 10-meter distributed sensors arranged on one vertical, indicated that the temperature fluctuations in different water layers at almost all the considered frequencies are cophasal. In addition, the maximum amplitude of the fluctuations was registered by sensors situated in the layer of observed maximum temperature gradients. In our opinion this is already adequate for identifying temperature fluctuations in the thermocline as internal waves.

Figure 3 shows the spectral densities of temperature fluctuations of series 1, 2, 3. Figure 3 shows that the spectral densities for time scales from 5 to 40 min for series 1 and 3 were close in value, indicative of a comparability of fluctuations of the effective temperature of the upper 100-m layer and the temperature of the free surface of the ocean. The intensity of the temperature fluctuations for series 2, registered by the sensor situated in the layer of maximum temperature gradients, at all the considered frequencies was an order of magnitude greater than the spectral densities of series 1, 3. Common for all the spectra is a rather steep (f^{-3} and f^{-4}) decrease from the low to the high frequencies; this can serve as an indirect confirmation of the wave nature of the investigated process.

The cross spectral analysis of series 2 and 3 made it possible to ascertain the coherence and phase shifts between the indicated series. Figure 4,a shows that the evaluation of the coherence between the temperature fluctuations in the thermocline and in the 100-m upper layer of the ocean is very high, considerably greater than the coherence values for confidence values at the 95% level. The insignificant dependence of phase shift on frequency (Fig. 4b) and the high coherence of series 2 and 3 not only confirm the wave nature of the investigated process, but also make it possible to assume that in this case there is a predominance of internal fluctuations of the first mode.

The coherence and the phase shift between series 1-2, 1-3, represented in Fig. 4, were computed for an evaluation of the field of internal gravitational waves (series 2, 3) and temperature of the ocean surface (series 1). It can be seen that the values of the coherence evaluations in the range of time scales from 35 to 15 min considerably exceed the limiting level $\gamma = 0.36$, attaining values 0.66 and 0.7 re-respectively. If series 1-2 and 1-3 are uncorrelated ($\gamma = 0$), with a number of degrees of freedom equal to 30 the value of the coherence evaluations will not exceed the level 0.36. In analyzing the phase spectra one should note the stability of the phase shift in periods from 35 to 15 minutes, which also indicates a high level of correlation of the field of internal gravitational waves and temperature of the ocean surface.

It can be seen from Fig. 4,b that for series 1-2, 1-3 in periods 35-15 min the phase shift is close to 200°, that is, the fluctuations of effective temperature in the thermocline (with an accuracy to the registry and processing of data) are in antiphase with the radiation temperature of the ocean surface. This important result merits great attention and special theoretical analysis.

Thus, the stability of the phase shift and the high coherence level in periods from 35 to 15 min indicate an interrelationship of temperature of the ocean surface and the field of internal waves of the upper thermocline. The cited cross statistical analysis makes it possible to assume that on the basis of the IR thermal radiation of the free surface of the ocean it is possible to carry out a remote investigation of internal gravitational waves of the seasonal thermocline.

In conclusion the authors express appreciation to K. D. Sabinin and G. G. Khundzhua for assistance in preparing the experiment.

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EFFECT OF FILMS OF SURFACE-ACTIVE SUBSTANCES ON CHANGES IN THE SPECTRA OF WIND WAVES UNDER THE INFLUENCE OF INTERNAL WAVES

Moscow IZVESTIYA AKADEMII NAUK SSSR, FIZIKA ATMOSFERY I OKEANA in Russian Vol 16, No 10, 1980 pp 1068-1076

[Article by S. A. Yermakov, Ye. N. Pelinovskiy and T. G. Talipova, Institute of Applied Physics USSR Academy of Sciences]

[Text]

Abstract: A study was made of the mechanism of formation of slicks of surface-active substances. The authors give an analysis of the attenuating properties of real sea films. The redistribution of the matter in the film in the field of the internal wave and the modulation of the coefficient of attenuation of ripples associated with this redistribution were analyzed. On the basis of a linear model of wind waves it was possible to compute the changes in the spectra of wind waves in the centimeter range under the influence of an internal wave.

Introduction. As is well known, the investigation of internal waves (IW) in the ocean by traditional oceanographic methods and instrumentation involves great difficulties. However, the methods of aerial photographic surveying, optical and radio oceanography make it possible to study IW directly on the basis of their manifestations at the sea surface. Some of these manifestations of IW are the slicks frequently observed at the ocean surface: sectors with a relatively small intensity of the surface waves. The slicks can be caused by different factors (for example, petroleum contaminations, convective cells in the surface layer, etc.), and depending on the mechanism of their formation can have the most different structure [1]. In this study we examine slicks caused by IW; they have the form of long parallel bands separated from one another by a distance of a hundred meters. There are now a great number of observations of such bands from ships and aircraft and from space in both the optical and in the radio ranges [2-11]. The relationship between slick bands and IW was demonstrated in [3, 4, 9-11], where the observations of slicks were accompanied by simultaneous registry and measurements of the parameters of IW.

Now we will enumerate the principal results of these observations. It was established that slicks are observed, as a rule, when there is a weak wind (wind speed $W \sim 2$-4 m/sec); with an increase in wind speed their width decreases. The rate of movement of the slick bands coincides with the phase velocity and the distance between bands coincides with the length of the IW. According to data in [3] slicks were situated over the bottoms of waves, but according to [4] the greatest number of slicks was displaced toward the rear slope of the internal waves. The reason for the discrepancy in observed data with one another at the present time is not clear. The amplitudes of the jump-forming internal waves, according to the data in [3, 4, 9, 10] assumed values in the range from 1.5 to 7.5 m; the corresponding values of the horizontal velocities of fluid particles in a wave, as can be easily estimated, is of the order of 5-10 cm/sec; the same velocities were registered directly in [11].

With respect to changes in the spectrum of surface waves under the influence of IW, they can be judged only on the basis of radio and optical images and also on the basis of measurements [11] which for the time being are few in number. Available optical images of slick bands are evidence of change in the mean square slope of wind waves in slicks; synchronous radio images of slicks in the SHF range [7] show that this change is caused, in particular, by changes in the high-frequency part of the spectrum -- the range of ripple waves. [As is well known, the radio and optical image of the sea surface is essentially determined by the spectrum of surface waves; in radar when working in the SHF range -- by the spectral component of ripples with a resonance wavelength [12]; in optical measurements -- by the integral characteristic of the spectrum -- the mean square slope [13].] Thus, in a slick there should be a "smoothing-out" in the centimeter waves and possibly in the longer-wavelength range. These conclusions are confirmed by the data in [11], according to which the value of the spectral components is essentially less than the undisturbed values. This effect is strongest for the meter waves (0.5 m $\lesssim \lambda \lesssim$ 2 m) and in the centimeter range ($\lambda \lesssim$ 10 cm).

The formulation of the theory of interaction of IW with wind waves involves fundamental difficulties. One of these is that at the present time the mechanism by which the spectrum of wind waves is established is unknown and existing theories of wind waves in a general case are unsatisfactory. However, in some cases this difficulty can be avoided. It is natural to assume that depending on the length of the surface waves their interaction with internal waves occurs differently. For example, in the meter range (lengths of surface waves $\lambda \gtrsim$ 1 m) the lengths of the fetch and attenuation of waves are of the order of hundreds of meters, that is, greater than the length of the IW; therefore, the effect of the wind and dissipation cannot be taken into account here, regarding surface waves as free waves. In this case it is possible to formulate a theory of adiabatic transformation of the wave spectrum in stipulated large-scale currents caused by IW [14-16] (also see the bibliography in [11] and [17]). In the shorter wavelength, decimeter (1 m $\gtrsim \lambda \gtrsim$ 10 cm) and centimeter ($\lambda \lesssim$ 10 cm) ranges the scales of excitation and attenuation of waves are comparable and less than the lengths of IW; accordingly, allowance for the effect of wind and dissipation is fundamental here. The first attempt at such an allowance was made in [11], where to the equation for the spectrum, similar to that used in [14-16], the source of wave generation (the Miles generation mechanism with a nonlinear limitation of the increment) has been added. As a result of the computations made in [11] there was found to be a fair coincidence with the experimental data in the first two ranges. In the range of centimeter waves the transformation of the wave spectrum under the influence of IW should be computed with allowance for films of surface-active substances (SAS), almost everwhere present at the sea surface (especially in the coastal waters) and exerting a strong attenuating effect on surface waves. The important role of surface-active substances was already pointed out in the first studies of slicks [2, 3] (also see [1, 4]), where their origin was associated with the effects of a redistribution of the matter of the film in the field of IW and the modulation of the coefficient of absorption of surface waves caused by this redistribution, although there have been no computations of the effect. Since attenuation due to the presence of surface-active substances is important for relatively short waves, the region of the effect of this mechanism of formation of slicks should be limited to the range of centimeter and partially decimeter waves (range of ripple waves).

As already noted, at present there is no sufficiently general theory of wind waves; however, the situation is simplified for the case of quite weak waves. As is well known, the Miles mechanism of wave generation begins to operate when there is surpassing of some critical wind velocity; for pure water it was 1.3 m/sec; for water covered by an undilatable film it was 5.7 m/sec [18]. However, with lesser wind velocities it is the Phillips mechanism which is decisive: resonance excitation of waves by fluctuations of atmospheric pressure. In this case it is possible to write a balance equation for the wave spectrum (as was done within the framework of the linear model in [19]) and then analyze the influence of IW on the steady spectrum in the presence of surface-active substances.

This article is devoted to an investigation of the mechanism of formation of slicks in the centimeter range under the influence of internal waves in the presence of surface-active substances. In the article, on the basis of known experimental data, we have analyzed the attenuating properties of real sea films and have determined the redistribution of concentrations of surface-active substances in the field of IW and the modulation of the coefficient of attenuation of ripples associated with this. Then, using the results, on the basis of a linear model of wind waves, we computed the variability of the spectra of wind waves in the centimeter range under the influence of an internal wave. A comparison was made with available experimental data.

Attenuation of Surface Waves by Sea Films

Films of surface-active substances are formed on the sea surface by fatty acids, fatty alcohols, esters, etc., reaching the water surface as a result of the decomposition and vital functions of marine organisms, and also as a result of the contamination of coastal waters by wastes of industrial production and populated places [20].

First we will examine the properties of films of chemically pure surface-active substances. The principal characteristic of such films, determining their attenuating properties, is the elasticity coefficient

$$P=-\frac{\Gamma}{\sigma}\frac{d\sigma(\Gamma)}{d\Gamma}, \tag{1}$$

where Γ is the concentration of the surface-active substance; $\sigma(\Gamma)$ is the surface tension of the water covered by a film of surface-active substance. Depending on the type of film and its state (degree of compression) the P value can vary from zero to quite large values $P \to \infty$, which corresponds to the case of an absolutely undilatable film. The attenuation of the surface wave for the case of an undilatable film is easily estimated in the following way [18]. It is evident that the horizontal velocity u of the particles in the wave at a surface covered by an undilatable (and not slipping) film becomes equal to zero: the particles due to viscosity "stick" to the film. Near the surface a boundary layer is formed whose thickness b is dependent on the coefficient of molecular viscosity ν and the wave frequency ω. The value $b \sim (\nu/\omega)^{1/2}$ for not excessively short waves (wavelength $\lambda \lesssim 1$ mm) is small in comparison with the characteristic vertical scale of the surface wave $\lambda = 2\pi/k$; therefore the vertical velocity gradients u in the boundary layer are considerably greater than outside it and precisely they determine the energy losses due to viscosity. The decrement γ, determined as the ratio of energy losses per unit area $d\mathcal{E}/dt \sim \nu\rho\int(\nabla u)^2 dz \sim \nu\rho b^{-1} u^2_{max}$ to the total energy $\mathcal{E} \sim \rho\int u^2 dz \sim \rho k^{-1} u^2_{max}$, is of the order of $(\nu k^2 \omega)^{1/2}$.

For films with a finite elasticity the γ value was found in [21, 22] and is given by the following expression:

$$\gamma = 2\theta\omega \frac{2\theta - \sqrt{2\theta}\,\chi + \chi^2/\sqrt{8\theta}}{2\theta - \sqrt{8\theta}\,\chi + 2\chi^2}, \qquad (2)$$

where $\omega^2 = gk + \sigma k^3/\rho$ is the frequency of gravitational-capillary waves; the parameter $\theta = \nu k^2/\omega \ll 1$; $\chi = (k^3/\omega^2)P/\rho$.

With an increase in P from zero to $P_m = (\rho/\sigma k^2)\sqrt{2\nu/\omega^3}$ the decrement increases from the value $2\nu k^2$, corresponding to pure water, to the maximum value $\gamma_m = \sqrt{\nu k^2 \omega/2}$; with $P > P_m$ there is an asymptotic approximation of γ to the value $\gamma_\infty = \gamma_m/2$, which corresponds to the already considered case of a nondilatable film.

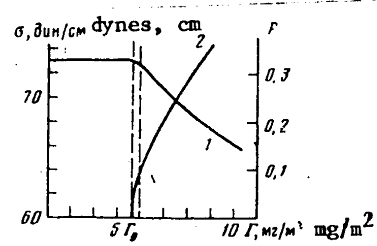

Fig. 1. Dependence of coefficient of surface tension σ (curve 1) and elasticity P (curve 2) on concentration of surface active substance of sea film sample.

Now, in greater detail, we will examine the isotherms of films of chemically pure surface-active substances -- the dependence of σ on Γ. On the basis of the type of isotherm it is possible to distinguish gaseous, vaporous-dilatable, fluid-dilatable and condensed films [23]. In a free (uncompressed) state the films of the first two types spread out without limit, on the water surface forming a gas of molecules which exerts virtually no influence on the surface waves. Fluid-dilatable and condensed films spread out to a monomolecular layer, attaining some extreme minimum value of the concentration Γ_0 at which the surface tension of the water covered by the film virtually does not differ from the tension of pure water. With $\Gamma > \Gamma_0$ on the isotherm of these films there is a transition region (its width is about $0.1\,\Gamma_0$) in which the derivative $d\sigma/d\Gamma$, and accordingly, also the elasticity P, and the decrement γ increase sharply. [A jumplike change in the decrement γ near the critical value Γ_0 was confirmed in laboratory experiments [25,

[26]]. Beyond the limits of the transition region begins the so-called active sector of the isotherm, where P changes considerably more slowly than in the transition region.

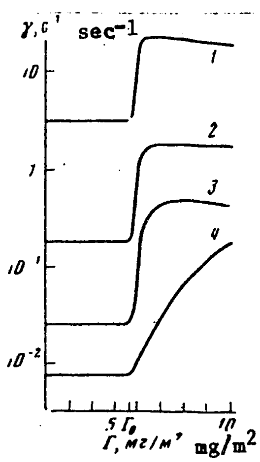

Fig. 2. Coefficient of attenuation of ripples γ as a function of the concentration of surface-active substance: 1) with wavelength $\lambda = 0.5$ cm, 2) $\lambda = 2$ cm, 3) $\lambda = 5$ cm, 4) $\lambda = 10$ cm.

Sea films constitute a mixture of different surface-active substances of a rather complex composition. The behavior of such mixtures with application to the water can differ substantially from the behavior of chemically pure surface-active substances. In particular, they do not spread out to monomolecular layers; their thickness usually is of the order of several sizes of molecules; however, the thicknesses of the petroleum films attain still greater values (to 10^{-1}–10^{-2} mm) [24].

At the present time the elastic properties of sea films have been studied rather poorly; only scattered experimental data are available. For example, in [25] a study was made of 17 samples of films taken from different sectors of the world ocean with simultaneous observation of the state of the sea surface (the presence or absence of slicks was noted). In general, the resulting isotherms resemble the isotherms of chemically pure surface-active substances. Some of them are close to the isotherms of gaseous films and their elasticity in the transition region is extremely small; in other cases, however, there are limiting concentrations and quite narrow transition regions in which the elasticity parameter increases rather sharply. One of these isotherms, corresponding to a slick-forming film, is shown in Fig. 1, which shows the dependence of elasticity P on the concentration of surface-active substances. As for pure surface-active substances, we will compute the attenuation of ripples on sea films using formula (2). An example of such computations for a selected sample of a film for different lengths of surface waves is given in Fig. 2. It can be seen that as for films of pure surface-active substances the attenuation in the sea film in the transition region increases: the value of the decrement at centimeter waves changes on the average by an order of magnitude. We note that the nature of the dependence of γ on Γ for other slick-forming films is qualitatively the same; there is a change only in the values and extent of the transition region.

Redistribution of Concentration of Surface-Active Substance and Modulation of the Coefficient of Attenuation of Ripples in Field of Internal Wave

The problem of the distribution of surface-active substances in the wave field, in general, should be solved as a self-consistent problem. However, as follows from [21], the inverse influence of the film at wavelengths with lengths of 1 m or more can be neglected. Accordingly, the film of surface-active substance in the IW field can be regarded as a passive impurity and one can describe changes in concentration of surface-active substances, using as a point of departure the equation for the conservation of matter, which, with allowance for the smallness of the horizontal velocity U of the particles in the internal wave and the changes in the concentration Γ_1 near the mean value Γ_0 caused by it, can be written in a linearized form (a one-dimensional case is examined as a simplification)

$$\frac{\partial \Gamma_1}{\partial t}+\Gamma_0\frac{\partial U}{\partial x}=0. \tag{3}$$

For a wave U(x-ct) travelling with the velocity c, from (3) we have

$$\Gamma_1=\Gamma_0\frac{U}{c}. \tag{4}$$

The Γ_1 value can also be expressed directly through the displacement of the pycnocline. Using the continuity equation $\partial U/\partial x = -\partial w/\partial z$ and taking into account that $w = \partial \xi/\partial t$ (w is the vertical velocity of the particles, ξ is the level displacement in the internal wave), it is easy to obtain

$$\Gamma_1=-\Gamma_0\frac{\partial \xi}{\partial z}\bigg|_{z=0}. \tag{5}$$

Thus, by knowing the vertical structure of the IW mode it is possible to relate Γ_1 directly to the displacement of the pycnocline $\xi_m(x,t) = \max_z \xi(x, z, t)$. For the first mode with a wavelength exceeding the characteristic depth h of the depth of the pycnocline

$$\frac{\partial \xi}{\partial z}\bigg|_{z=0} \sim \xi_m/h,$$

and therefore the maxima of the concentration of surface-active substance fall at the bottom of the IW, that is, the film is compressed to the greatest degree at the bottoms. On the other hand, the film is dilatated to the greatest degree over the crests. These computations confirm the conclusions drawn concerning the distribution of surface-active substances in the field of the standing and travelling IW presented in [3] on the basis of a qualitative examination of the motion of fluid particles in the wave. If an allowance is made for diffusion in equation (3) (see [27]), then it is easy to demonstrate that the Γ_1 maxima are displaced to the rear slope of the wave. This displacement with values of the coefficient of turbulent diffusion $D \sim 10^2 - 10^3$ cm/sec are of the order of 10^{-2} rad; therefore, they can be neglected, although it is not excluded that in regions of increased turbulence the phase shift can be more significant.

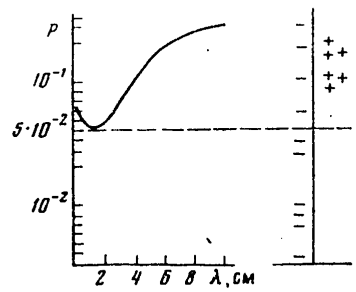

Fig. 3. Dependence of P_* on λ; film elasticities computed using data in [25] (at right).

In accordance with the distribution of surface-active substances there is also modulation of the decrement γ: it increases under the bottom of the IW and decreases with approach to the crest. It follows from an analysis of [3, 9-11] that for slick-forming IW the ξ_m/c (or U/c) values were of the order of 0.1, that is, the characteristic values of the relative changes in the concentration Γ_1/Γ_0 are comparable to the values of the transition region of isotherms of sea films. The role of the film in the formation of a slick is evidently substantial if in the mentioned range of change in the concentration the decrement γ varies quite strongly. For greater clarity we will assume that the γ value in the slick should exceed γ_∞; for the elasticity parameter this condition can be rewritten in the form

$$P \geqslant P_* = \frac{\rho}{\sigma k^2}\sqrt{\nu\omega^3/2}. \tag{6}$$

The dependence $P_*(\lambda)$ with σ = 70 dynes/cm, $\nu = 10^{-2}$ cm/sec^2 is shown in Fig. 3. It can be seen that with $\lambda \sim 1$ cm the $P_*(\lambda)$ curve attains its minimum value, equal to 0.05. Accordingly, if with changes in the concentration Γ_1 due to IW the parameter P does not exceed a value of the order of 0.05, it can be assumed that no appreciable "smoothing-out" occurs at any wavelength, that is, condition (6) is a necessary condition for the formation of slicks. This conclusion is also evidently confirmed by field observations. In actuality, if the P parameter is computed in the transition region along the isotherms of the sea films cited in [25], by expanding them along the P axis it is possible to see (see Fig. 3) that for all samples of films with $P < 0.05$ there are no slicks (in Fig. 3 the "+" denotes the existence of slicks, whereas the "-" denotes their absence).

Thus, if the IW changes the concentration of surface-active substance by values comparable to the magnitude of the transition region, and with a given length of ripples λ the condition (9) is satisfied for the film, the coefficient of attenuation of ripples at this wavelength behaves in the following way: over the crests of IW it virtually does not differ from the attenuation for pure water, equal to $2\nu k^2$, whereas over the depressions there is an almost jumplike increase to a value of the order of γ_∞, similar to what is shown in Fig. 2. Stipulating the U(x, t)/c value and finding from the isotherm the P value corresponding to $\Gamma_1 = \Gamma_0 U/c$, using the inequality (6) it is possible to find the range of lengths of "smoothed-out" waves for each IW point. As follows from (6) and Fig. 3, the smoothing-out begins with lengths 1-1.5 cm, propagating with approach to the bottom of the internal wave to both shorter and longer waves.

Variability of Spectra of Surface Waves Under Influence of Internal Wave

As already mentioned in the introduction, for computing the changes in the spectrum of wind waves applicable to the case of weak winds it is possible to use the linear theory of wind waves, according to which the surface waves are excited by fluctuations of atmospheric pressure and are stabilized by viscous dissipation. From the balance equation for the energy spectrum of displacements of the sea surface [19] we have the following expression for a steady spectrum E(k, U) in the presence of a current U(r, t), caused by the internal wave:

$$E(\mathbf{k}, \mathbf{U}) = \frac{\Pi(\mathbf{k}, \Omega) k^2}{8\rho^2 \gamma[k, \Gamma(\mathbf{U})] \Omega^2}, \qquad (7)$$

where $\Pi(k, \Omega)$ is the spatial-temporal spectrum of fluctuations of atmospheric pressure at the resonance frequency $\Omega = \sqrt{gk + \frac{\sigma}{\rho} k^3} + \mathbf{kU}$.

The variability of the spectrum will be described by the relative value K(k, U) = E(k, U)/E(k, 0) — the hydrodynamic contrast. As can be seen from (9), K(k, U) is expressed in the form of the product of three parameters:

$$K_{sp} = \frac{\Pi(\mathbf{k}, \Omega)}{\Pi(\mathbf{k}, \omega)}, \quad K_{\omega} = \frac{\omega^2}{\Omega^2} = \left[1 + \frac{U \cos(\mathbf{k}, \mathbf{U})}{c_g(k)}\right]^{-2}, \quad K_{\gamma} = \frac{\gamma[k, 0]}{\gamma[k, \Gamma(\mathbf{U})]} \qquad (8)$$

We will analyze each of them. The contrast K_{ω} is governed by the Doppler frequency shift of ripples on the current U. Depending on the angle α between the velocity U and the wave vector k it can be both greater than unity, which corresponds to an intensification of ripples, and less than unity -- the "smoothing-out" of waves. The K_{ω} value as a function of k for the velocity value U = 5 cm/sec is shown in Fig. 4,a. It can be seen that the contrast K_{ω} varies slightly with a change in the wavelength of the ripples and its value is relatively small (the spectrum changes by a value of the order of 20-30%).

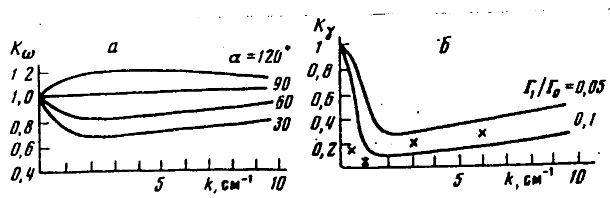

Fig. 4. Contrasts K_{ω}(a) and K_{γ}(b) as functions of wave number k of ripples.

The contrast K_{sp} is determined by the type of spatial-temporal spectrum of atmospheric pressure. It can be expected that if the wind velocity W is greater than the velocity of the ripples $c_g(k)$ ($W > c_g(k) > U$), then the changes in the K_{sp} value are determined by the ratio U/W and accordingly are less than the K_{ω} values, dependent on U/c_g. As a result, the contrast K_{sp} changes slightly and it can be assumed equal to unity. Unfortunately, there are presently no experimental data which could confirm (or refute) this hypothesis.

Now we will examine the contrast K_γ governed by the presence of the film. We first of all note that K_γ cannot exceed unity, that is, the film can lead only to a "smoothing out" of the waves, not to their attenuation. The dependence of the K_γ parameter on the wave number for ripples for values $\Gamma_1/\Gamma_0 = 0.05$, 0.1 is shown in Fig. 4,b. It can be seen that changes in the spectrum caused by surface-active substances are more significant than the changes due to the Doppler frequency shift; the maximum variability of the waves falls at a wavelength 2-3 cm. Thus, the mechanism of formation of slicks by an internal wave, associated with the presence of a film of surface-active substance, leads to a rather considerable contrast in the high-frequency part of the spectrum of surface waves.

Now we will compare the determined values of the contrasts with the experimental data in [11]. First of all, it can be seen from a comparison of the undisturbed spectrum of surface waves and the spectrum in the presence of an internal wave that in the range of centimeter waves the waves are "smoothed out," that is, the contrast is less than unity (in the meter range there is both a smoothing out and intensification of the waves). The contrasts, according to [11], in order of magnitude are rather close to the computations made above, based on a linear model. These experimental values were noted by dots in Fig. 4,b. We note that in the experiment the wind was quite weak ($W \approx 2$ m/sec), which corresponds to the condition of applicability of the linear model; the U/c values on the average were about 0.1. The agreement between theory and experiment which was obtained is evidence in support of the considered smoothing mechanism, related to the film of surface-active substance, although, it goes without saying, it cannot be regarded as proof of its correctness, since, first of all, in [11] no study was made of the surface film, and second, available experimental data for the time being are scattered.

Summary

1. On the basis of known experimental data [25] it was possible to analyze the attenuating properties of sea films. The coefficient of attenuation of waves in the centimeter range in the limits of the transition region increases sharply to maximum values.

2. It is demonstrated that disturbances in the concentration of surface-active substances are proportional to the displacement of the level of the fundamental mode of the internal wave. For the waves observed under actual observation conditions these disturbances are of the order of magnitude of the transition regions of isotherms of sea films, as a result of which (with satisfaction of condition (6)) the decrement over the bottom of the wave increases sharply.

3. The necessary condition was obtained for the formation of slicks associated with a film of surface-active substance and this is confirmed by the results of observations [25].

4. On the basis of a linear model of wind waves and the results of computations of the redistribution of the decrement γ in the field of an internal wave it was possible to compute the variability of the spectra of waves. The position of the slick corresponds to the bottoms of the IW (which agrees with [3], but diverges with the data in [4]), and the value of the spectrum in the slick can be an order of magnitude less than the undisturbed value of the spectrum. Comparison of the computed contrasts with the data in [11] gave satisfactory agreement.

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