PROBLEMS OF SEA ICE RESEARCH*

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ABSTRACT. Sea ice research has reached a critical point in its development. In place of a geographical statistical trend there is now a geophysical approach. Whereas the main problem has been the explanation of the phenomena of sea ice in space and time, more and more attention is being devoted to the connexion between the state of the ice and the changing conditions in the water and the air.

ZUSAMMENFASSUNG. Die Meereisforschung ist an einem entscheidenden Wendepunkt angelangt. An Stelle der geographisch statistischen Arbeitsrichtung tritt die geophysikalische Arbeitsmethode. Während bisher das räumliche und zeitliche Vorkommen des Meereises das Hauptproblem war, gewinnen jetzt die Untersuchungen über die Zusammenhänge zwischen dem Eisvorkommen und den Zustandsänderungen von Wasser und Atmosphäre an Bedeutung.

THE problems of sea ice research were frequently discussed before the war at the Baltic Hydrological Conferences. The papers published by the Permanent Bureau of the Baltic Hydrological Conference are evidence of this. Although only the problems of the Baltic Sea were discussed, the publications include many suggestions which are of importance beyond this region for the formulation of problems in other seas. Not long before the war, J. Blüthgen[1] tried to point out the ice formation problems of sea regions in general.

In accordance with the then state of the researches, the Baltic Conferences dealt primarily with its geographical problems. The special scientific demands of the war, however, halted the preliminary developments of modern research, since scientific results for immediate practical use were needed. At the same time, auxiliary means not normally available were placed at the disposal of those working on the subject. After the war, J. Büdel[2] summarized the scientific results acquired to date and pointed out new lines of development for sea ice research.

In comparison with other branches of science, for example the study of glaciers, sea ice research is still far behind the times. In the German language alone, there are, up to date, four scientific handbooks on the study of glaciers, but there is no single complete work on sea ice with the possible exception of a work by Josef Zukriegel dating from 1935[3]. In other languages, so far as the author knows, a similar situation prevails. Only in the U.S.S.R. has the subject been pursued with the utmost care as a matter of practical necessity, but the Russian publications are not easily obtainable; moreover, only a comparatively small number of persons have a sufficient knowledge of Russian to be able to make use of such publications. Comparing the size of the areas covered by sea ice with the size of those covered by glacier ice, the difference in the progress of the two branches of ice research becomes still more striking.

According to Büdel [2] glacier ice covers about 2 million km. of the northern hemisphere, while the polar sea ice covers about 8·2 million km. in September (minimum distribution) and about 16·4 million km. in March (maximum distribution). A glacier is relatively easy of access, and a great number of studies can be made of it with comparatively modest means. With the exception of ice near the coast, sea ice is accessible only to aircraft or to specially constructed ships, both of which are costly. Moreover, sea ice very frequently undergoes a rapid change of structure and distribution, being more exposed to the effects of temperature and wind than glacier ice. In addition, sea ice is subjected to the influence of ocean currents. All these difficulties explain the fact that, in contrast to glacier research, sea ice research has not yet succeeded in producing the uniform terminology or the uniform formulation of problems which its vast extent seems to demand.

Yet sea ice is of great practical importance; in this connexion, the great influence which it exerts on climate may be remembered. The most obvious evidence of its importance is, however, the obstruction it causes to navigation. Sea ice paralyses the transit trade in Arctic waters, so important if only the water were ice-free. It is a navigational risk on the Northern Sea Route

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and on fringes of Arctic waters along the Siberian coast; it obstructs or impedes the approach to coasts, and, even in temperate latitudes, to cite Granqvist[4], it converts parts of the sea into mainland for a certain period, thus transforming commercial towns and sea-ports of the summer coast into inland places.

It was this practical aspect of sea ice research which gave it its original impulse and caused it to be of general interest. However advantageous this may be, it still hides a great danger; the limiting of the research to exclusively practical aims will necessarily lead to a neglect of scientific development. However, our knowledge of sea ice would be far less had the practical demands not existed. These have led to the establishment of specific ice departments at institutes of practical sciences, such as the International Ice Observation and Ice Patrol Service, U.S.A., the ice departments of Sveriges Meteorologiska och Hydrologiska Institut and of the Merentutkimuslaitos Institute of Oceanography, Finland, and the Eisdienst of the Deutsches Hydrographisches Institut. While these services work under scientific management, those in other countries are restricted to a mere description of ice conditions and of the obstructions to navigation caused thereby. Even with regard to the ice services under scientific management, the word "service" in various languages (*e.g.* Ice Patrol Service, Eisdienst) characterizes the nature of the work.

During one of the Baltic Conferences, Granqvist drew an illuminating picture of the work carried out by one of these offices. According to his description, the work-room of the service, with its noisy telephones and typewriters, incoming and outgoing telegrams, and the constantly manned radio station, bears more resemblance to a business office or to the editorial office of a newspaper than to a quiet work-room for scientific research.

The great scientific merit of these services which have mainly practical aims resides in the collecting and sifting of observation material. Were there no ice service offices, only isolated and more or less accidental observations would be available. As with weather services, the establishment of a special network of observation stations and the exchange of messages gave rise to a considerable collection of observational material which constitutes the basis for all further research. During the war, the network was considerably extended. With the exception of the North Atlantic sea route, ice observations made before 1939 were restricted to coastal areas, and little was known of ice conditions in the open sea. It was supposed that in temperate latitudes, the winter ice sheets did not extend beyond the coastal margin, although they would be considerably broader in severe winters. It was commonly believed, however, that the open sea would always remain free of ice; but the German war-time ice reconnaissance flights made it clear that in severe winters (such as those of 1941/42 and 1946/47) the whole of the Baltic Sea is ice-covered, and that even its south-eastern section, where conditions are unfavourable to the formation of ice, is then frozen up.

The extension of German ice reconnaissance flights, complemented by ice reconnaissance cruises of submarines into the North Atlantic and Arctic waters, further increased our knowledge of sea ice. Reconnaissances were made in that area extending from south of Cape Farvel to Proliv Borisa, Vil'kitskogo (Boris Vil'kitski Strait, between Severnaya Zemlya and the Soviet mainland) and northwards to lat. $82\frac{1}{2}^{\circ}$ N. in the vicinity of Spitsbergen. The information obtained by these war-time patrols covered an area which had previously been obtained only from occasional ships' observations or expedition reports. These ice reconnaissance flights or cruises became particularly valuable by the fact that they were even undertaken throughout the winter, the season during which such reports were seldom obtained previously.

Other belligerent states, besides Germany, likewise undertook ice reconnaissances of this kind. Thus the war, while it disrupted the constantly growing international cooperation in sea ice research, helped to procure observations even from the remotest places which would never have been gathered in such abundance in peace-time. If science is to profit from this abundance of observational material, it is necessary that all the countries concerned should cooperate on an international scale in the working up of this material and in the adoption of a uniform working

scheme. This would enable us to record the ice conditions in the sea areas concerned far more completely than ever before. In view of the wide spatial distribution of sea ice, cooperation of individuals will also be necessary in times to come if a uniform advance in knowledge is to be achieved. Before the war, the North Sea and the Baltic Sea were already the concern of the Baltic Hydrological Conference. A closer connexion between individuals studying sea ice all over the world might be achieved under the auspices of the International Commission on Snow and Ice.

The need for working up the observational material has been stressed; much work remains to be done, and there is a lack of the specialists required for the task. The few specialists working in the different ice services will not be able to undertake a great part of it. During the ice season, the practical service almost entirely absorbs their energies, and the time between the ice seasons is almost too short for the observations of the past winter to be worked up thoroughly. Nevertheless, the results thus obtained have been comparatively important. The principal work achieved up to now is, above all, the derivation of statistics from the existing observations. These elaborations have yielded many new scientific results, which do not, however, extend far beyond the establishment of the basic elements of sea ice geography. Even so, it is already possible to calculate the distribution of ice in all ice-producing oceans from the mean values as well as from the extreme variations. This work has resulted in the publication of several ice atlases. In addition, it has been possible to distinguish specific types of ice cover proper to certain characteristic phenomena. This was necessary because, in comparing the ice conditions in different regions, it was found that besides the individual forms of the ice cover peculiar to each part of the ocean and incapable of identical reproduction elsewhere, there also exist types common to all regions. Büdel[2], who made a special study of this question, distinguished between the types of ice in the polar seas and oceans from that in adjacent seas. Within these two main types, subordinate types can be recognized, the differences being due to topographical features of the coasts as far as the polar and oceanic type is concerned, and to the climatic gradient between sea and continent for the subordinate type. With the aid of a classification of types of ice cover, and in conjunction with a strictly geographical method it will be possible to define the boundaries of individual sea areas according to their type of ice and to separate them from neighbouring areas. At this point, a comparison with the classification of types in climatology comes to mind. Only by defining the various ice forms (the detailed classification can be left open to further discussion) can a general view of the ice conditions in large areas be obtained. Whereas formerly there were only isolated monographs describing limited areas, it is now possible to incorporate these into a harmonious, comprehensive picture.

The determination of the different ice types is about as much as can be obtained from the observational material gathered by the practical ice services by the statistical method. It should, however, be borne in mind that as yet, only the bare outlines of a scheme have been established and many details still wait to be worked out.

Another difficulty is the lack of a really uniform terminology for all that has to do with sea ice. This can only be understood by considering the historical development of sea ice research. Before its scientific study began, mariners had produced a terminology based on their practical experience and corresponding to their requirements. For the seaman ice is an obstruction to the passage of his ship, and it is therefore necessary that the extent of the obstruction should be clearly seen from the nomenclature employed. If sea ice terminology had been evolved by scientists, the kind of ice formation, its stages of metamorphosis, and similar attributes would have been expressed by specific terms. The adoption of the existing ice terminology of the seaman for scientific research was, however, unavoidable. A second terminology more suited to scientific purposes was developed for the designation of the various types of ice. Unavoidable difficulties arose from this dualism, paralysing the efforts made towards the establishment of a uniform terminology. Moreover, confusion arose because every seafaring nation had its own names for the different types of ice[4]. The attempt[5] of the International Hydrographic Bureau (Monaco) to define and reconcile the different polyglot expressions is indeed a great help, but is no final solution.

The demand for a uniform terminology was the subject of discussion at several Baltic Conferences. In 1937 Granqvist [4] proposed that an inventory should be made of the existing terminology and that exact definitions of sea ice phenomena should be laid down to obtain a basis for a standardized and complete terminology. This question was raised again in 1952 by the World Meteorological Organization, and an approach to a solution was made[6]. It seems that the time is right for such action. The old seaman's terminology was partly created in the days of sailing vessels and of ships with low-powered engines. For modern ships, with their powerful engines and increased resistance to ice, ice is no longer the same obstruction as in earlier times. For this reason, the old terminology is partly obsolete, and should therefore be replaced. This could be done without causing too much confusion among those concerned with navigation.

The problems of sea ice research have so far been geographical problems. Now it is entering a new stage of development, using in the main geophysical methods. Thus it is taking the course that meteorology and oceanography have already taken, a course which poses new problems and calls for new methods.

During the period of transition to geophysical working methods, it is not possible to make a clear distinction between the two aspects of research. From a geophysical point of view, the different types of ice formation may be attributed to changes in the physical condition of the water and to changes in the atmosphere. To obtain a correct conception of the processes of growth and melting, it is necessary to study the specific conditions obtaining in water and air independently of one another, with regard to the part they play in the occurrence and the condition of ice. Only thus can a uniform synthesis result. The vast scope of the studies still to be undertaken is indicated by citing some of the many factors which affect sea ice, *e.g.* for sea water, the temperature, salinity, pattern of density variations, currents, tides, depths, coastal configuration, proximity of great land masses; or for the atmosphere, the temperature variations, the persistence and origin of the air masses concerned, wind, precipitation and humidity. These investigations, too, will have to be based on the existing observations of the practical ice services. While, as explained above, this material alone was sufficient for showing the spatial distribution of ice, the use of simultaneous meteorological and oceanographical observations is now necessary.

In spite of the many attempts already made, the scientific approach has not yet advanced beyond its beginning. The results already obtained show the importance of following the new trend of research. Such results include the discovery of the fact that the ice masses in the Labrador and East Greenland currents depend on the distribution of atmospheric-pressure over neighbouring areas; the possibility of telling two years in advance the degree of decrease in ice in the Barents Sea from the condition of the water masses off the south-western coast of Norway and the knowledge that for ice to form in waters not permanently ice-covered the main point is not how many degrees the air temperature stands below zero, but whether the cold air persists over a long period or occurs intermittently during several short periods, and whether the cold is due to radiation or to advection. The relationship between specific large-scale weather situations and the formation of ice, and also the influence of the summer heat store of the water on the first occurrence of ice have, as a result of the new methods, yielded a deep insight into the behaviour of sea ice.

The future development of this new outlook is important not only from a scientific but also from a practical viewpoint. It will no longer be sufficient to provide navigation with a mere description of ice conditions; navigation is asking for ice forecasts. It is comparatively easy to forecast ice for coastal regions because there the reaction of ice to thermal variations of the atmosphere and the water is slow. It is more difficult to forecast ice conditions in open sea areas, because, owing to the influences of wind and current, the situation there is apt to undergo complete and rapid changes. If the practical ice service is to make a great number of correct forecasts, it must adopt these new methods. The mean and extreme values obtained by the statistical method are no longer sufficient, and the application of the synoptic method is essential. Neither scientific

research nor the practical ice services can now forgo the combined use of synoptic weather maps and synoptic oceanographical charts in conjunction with the use of ice charts.

The difference between the older working methods and the new course followed by sea ice research now becomes clear. The causality of phenomena gradually gains in importance. In consequence of the new course new problems and new methods are appearing. Specific laws governing the formation of ice are established, and a specific terminology will necessarily follow. With greater knowledge of the internal relationship between ice formation and ice metamorphosis, a uniform terminology will be evolved and scientifically based ice forecasts will provide additional security for navigation. With the establishment of specific laws and concepts, sea ice research will attain equality of status with glacier research as a special branch of science.

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OBSERVATIONS IN A COLD ICE CAP

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(Continued from Vol. 2, No. 18, 1955, p. 571–81)

PART II

IV. Relationships of Stress and Temperature

The stress, movement, temperature and viscosity conditions in cold ice affect each other very closely.

1. *Stress Relationships*

In the purely schematic illustration in Fig. 11 (p. 625) some of the prominent features of stress and temperature variations in the ice cap are indicated in general terms in connection with the progress of movement. On examining the normal vertical and horizontal stresses σ_y and σ_z, a distinction must be made between states of stress before and after the formation of longitudinal crevasses. Before the formation of cracks, the distribution of horizontal stresses σ_y along a vertical in the region of the division of movement should be qualitatively similar to Diagram 4 (Fig. 11). The horizontal tensile stresses in the centre of the cap are influenced both by the specific boundary conditions and by the variations of viscosity in a vertical direction.

The concentration of tensile stresses in the central zone of the cross-section leads to the observed formation of longitudinal crevasses, whereupon the picture of stress is radically altered; the horizontal tensile stress is in places reduced to zero, so that in certain zones a bi-axial state of compression arises (σ_x and σ_z) with σ_z as the overburden pressure and σ_x the compressive stress perpendicular to the plane of the figure. The gradual filling up of the cracks with water gives a lateral water pressure, which produces yet another radical alteration in the state of stress and deformation of the cold ice, and also gives periodic fluctuations, depending upon the height of the water level.

Technically the possibility now arises of draining the cracks, as was done during the construction of the cross-tunnels, and thus of influencing the state of stress and movement in the cap in a particular manner and of slowing down the horizontal movement to both north and south.