SCOR WORKING GROUP 38 (WITH SCAR) OCEAN PROCESSES IN THE ANTARCTIC

Final Report – April 1977

1. Introduction

The objectives of the SCOR Working Group 38 – Ocean processes in the Antarctic – are given in the terms of reference, i.e.:

"To recommend observational and theoretical studies to facilitate the design of a major study of the circulation of the Antarctic oceans. The group will take into account the findings of Working Groups 34 and 48 and integrate their recommendation with the plans of Working Group 47."

WG 34:	Internal Dynamics of the Ocean.
WG 47:	Oceanographic Programmes during FGGE.
WG 48:	The Influence of the Ocean on Climate.

After the first brief meeting held in Buenos Aires (July 1974) the group members have expressed their ideas on pertinent programmes in letters which have been circulated among the group members. These documents formed the background for the discussion during the meeting held in Grenoble, 1 September 1975. A final meeting of the group was held at I.O.S. Wormley, 15-16 March 1977.

After considering the growing number of national and international plans for work in the southern oceans, the group felt that many problems remained, but the group was not able to comply satisfactorily with the terms of reference as given above. It seemed apparent that a comprehensive study of the circulation of the Antarctic oceans would not be possible in the foreseeable future because of the limitation of available resources.

The group agreed that the descriptive studies should be completed, but in the future more emphasis should be placed on theoretical and special problem-oriented programmes It was furthermore recommended that all field programmes should be based on sound theory in order to ensure sampling on proper time and space scales.

Due to the large scales in space and time involved in the processes in the Antarctic oceans, it is convenient to list the recommended programmes under four different headings, with no priority to the sequence:

1. Antarctic Circulation
2. Frontal Zones
3. Water masses
4. Special processes

1.(a) There is already an existing programme to measure drift paths of icebergs which is a step towards understanding the coastal water transport on a large scale. The group recommends a continued and expanded programme, including measurements of air pressure, air temperature and if possible wind speed and direction. Both theory and observations are needed to determine the response of icebergs to air and water movements. This programme should also be coordinated with programmes on katabatic wind investigation.

1.(b) Drifting buoys (preferably with drogues) have potential capacity to give information on water movements. Therefore considerable study should be made to determine both the behaviour of the buoys and the appropriate time and space scales for their deployment. More work is needed on interpretation of data from drifting buoys.

The following measurements from buoys are considered important:

1. Air pressure
2. Air temperature
3. Sea surface temperature
4. Subsurface temperatures
5. Salinities

1.(c) There are indications that the circulation in the area 30° – 60° E south of 50° S may be associated with or part of the Weddell Sea gyre. It is possibly also important to the distribution of krill.

The Antarctic Circumpolar Current has been the subject of many investigations and is currently being intensively studied in the Drake Passage region. The role of the gyres to the south of the Antarctic Circumpolar Current has not been thoroughly investigated. In particular, the large gyre in the Weddell Sea may play an important part in the Antarctic circulation and in bottom water formation. Two aspects of the Weddell Sea gyre are of particular interest: the total transport in the gyre, and the eastern extent of the gyre. It is suggested that a line of current meters across the Weddell Sea from the South Orkney Islands to Cape Norwegia be set out for a one-year period. These current measurements should be supplemented by hydrographic surveys along the section at both ends of this period. Hydrographic surveys and current measurements should also be made in the eastern end of the Weddell Sea gyre believed to extend to about 30° to 60° E south of about 50° S.

1.(d) Extensive monitoring programmes and plans exist for studies on the circumpolar current. The long term variability of the circumpolar current is considered to be of importance to the total global circulation. We therefore consider it important to continue the existing monitoring programmes and encourage long term monitoring of additional sections. This should be an appropriate supplement to the FGGE programme.

2. Frontal Zone studies

The frontal zones in the Antarctic regions have shown considerable variability in space and time. We encourage the continuation of the several pertinent existing and planned programmes. In addition we encourage development of observation programmes using aircraft, satellites and possibly supply ships. Using all these methods would provide information on a variety of time and space scales.

3. Water masses

The Working Group 38 encourages the existing and future programmes designed to study the following topics related to the water masses:

A. Processes leading to the formation of water masses.
B. The continuity and the variability in time and space of water mass formation and movement.

Very few oceanographic winter data from the Antarctic regions exist, mainly due to severe ice conditions which make these areas inaccessible for a large part of the year. In order to understand water mass formation a much broader based year round data base is required, especially from the regions assumed to be of importance to bottom water formation (such as Weddell Sea, Ross Sea and other shelf regions). We suggest that serious consideration should be given to the following techniques for obtaining winter data:

A. Manned drifting stations.
B. Telemetering ice station equipped with oceanographic sensors.
C. Aircraft, either to bring manned stations to the ice, or equipped with remote sensors.
D. Automatic stations moored under the ice cover.
E. Satellite imagery.

Plans and programmes exist which will provide information on the formation of deep water and bottom water in the Weddell Sea. It is recommended that a programme be developed to determine their formation rates. Studies on long time variability are important and measurements should be carried out over periods of years.

Bottom water is believed to form in the Weddell Sea in the region near the shelf break west of somewhere between 30°W and 40°W. In order to investigate the mixing processes leading to bottom water formation, it is proposed that a multi-ship expedition carry out detailed hydrographic surveys of this area in successive years and the currents and temperature fields should be monitored between surveys.

4. Special processes

4.(a) Ice shelf/seawater ineraction

The Antarctic ice shelves provide unique thermodynamic conditions by acting as substantial heat sinks at water depths to about 500 m. There are studies on the effect of the ice shelves on the ambient water masses. It is furthermore believed that processes near the ice shelves are important to the vertical circulation. We therefore encourage the continuation of such studies.

4.(b) Mixing processes and dynamics near the continental margins

The processes at the continental slope region are thought to have an influence on water mass formation and deep circulation in general. We recommend the implementation of appropriate programmes in selected regions.

5. Conclusions

Although a number of important problems have been identified, dealing with ocean circulation, climate and living resources, none of them are likely to be tackled by existing SCOR Working Groups.

The group therefore recommends that SCOR should appoint a convenor and a small nucleus of scientists with wide interests in the Southern Ocean to organize periodic workshop meetings on different topics. This proposal is dealt with in the report of meeting 15-16 March 1977 at I.O.S. Wormley, UK.

T. Kvinge
Chairman WG 38

SCOR WORKSHOP ON IDENTIFYING PROBLEMS OF THE SOUTHERN OCEANS

Wormley, UK

15-16 March 1977

Participants:

T. Kvinge (convenor), G.E.R. Deacon, T.D. Foster, P. Tchernia, P.M. David, A de C. Baker, J.C. Swallow, V.T. Neal, P.D. Killworth

On 15-16 March 1977 a group of oceanographers, including members of the former SCOR Working Group 38 met at the Institute of Oceanographic Sciences, Wormley, UK, with the purpose to promote investigations of important aspects of Antarctic Oceanography.

Because of the importance of the Antarctic circulation to the other oceans and to world climate, as well as to the marine living resources, and growing pressure for their exploitation, the group recommends that SCOR should find the mechanism for keeping Antarctic problems permanently in mind.

It was felt that an efficient method would be to maintain a small group of scientists with wide and active interests in the Southern oceans. This might best be done by appointing a convener or small nucleus of scientists whose function would be to identify and recommend important problems which would profit from SCOR attention.

During the meeting discussions of this type were initiated and the following emerged:

1) Studies of the Antarctic circulation by tracking icebergs by means of satellite transponders. This project requires studies of factors such as: geometry of the icebergs, wind, current, pack ice and bathymetry which may determine the movements of the icebergs.

2) The Weddell Gyre project. This is a multidisciplinary approach to the problems of a large part of the southern ocean between the eastern side of the Antarctic Peninsula and the Kerguelen Plateau. Because of the large area involved the problems require international cooperation.

3) Studies of the polar front region with the view to determine the meridional and zonal transport and the mechanisms involved. This would necessitate both long term monitoring of currents and water masses in a few selected locations and also short term detailed studies of the exchange mechanisms.

The projects selected are representative of problems of interest in the Antarctic. We believe that SCOR can contribute to their success.

These problems represent three different stages of progress, and therefore require three different timescales of action.

Project No. 1 has been in progress since 1972, international cooperation is urgently needed for continuation and expansion of this programme.

Project No. 2 Because of the long time needed to obtain logistic support an early meeting of a planning workshop to formulate the scientific programmes is a matter of urgency. We suggest that SCOR support such a workshop.

Project No. 3 This is an ongoing project and a large extension is desirable. We recommend an early meeting to discuss the feasibility of such an operation.

If SCOR finds that such suggestions are helpful, it may wish to continue to support informal meetings (such as this) in which Antarctic problems can be discussed.

OCEAN SCIENCE IN THE ANTARCTIC

Presented to SCOR by Sir George Deacon

The problems are wide ranging. Many of them are summarized in planning documents such as those of the National Academy of Sciences. The purpose of the present draft is to make out a case for some fairly approachable biological and physical problems likely to prove immediately rewarding, mainly to do with krill.

1. Krill

In spite of what is sometimes written, a good start has been made – sufficient to give direction and promise to new work. The principal features which distinguish the successive stages of krill, from egg to adult, have been described. We also have broad outlines of their distributions, and reasonable working hypotheses about how the population is maintained. The *Discovery* reports give a clear indication that krill reproduce most successfully in the east wind drift, along the Atlantic continental margin, but grow to largest size where they are carried northwards by branches of the current, particularly by the Weddell Sea current, but also near the Kerguelen-Gaussberg ridge and north of the Ross Sea. It has been suggested that the distribution of pack ice may determine that of the krill, but this may only be so because the ice distribution runs parallel to that of the cold water of the east-wind drift and its northward branches. In winter the main areas of krill distribution are frozen over, except for parts of the northern fringe, but later on the krill is left in open water. The ice may give some protection again predators: divers see krill sheltering in cavities in its under surface; a ship ploughing through pack, up-ending small floes, throws out krill, or makes them jump out, so that they land kicking on the ice, well above the water surface. They may also congregate below the ice to feed on the phytoplankton which seems to be concentrated there, possibly because there is a fairly stable environment and just enough light. The main phytoplankton outburst required to support growth and spawning seems to occur when the ice melts, letting in more light; the outburst must also be helped by stable surface layering promoted by the release of fresh water.

Full understanding of the spawning and hatching of the krill eggs, and development of the larval stages, is clearly essential to a general picture of the krill distribution and its apparent relationship to the currents and water masses. The comprehensive summary by Marr (1962) leaves little doubt that the gravid and spent females are found mostly near the surface, at least within the first 100 m or so, and that their eggs are laid there. The number of eggs collected is small in relation to the number of nets hauled, and remarkably small in relation to the astronomical abundance of krill, but collecting is not easy. The eggs appear to sink to great depth, developing as they go, so that the first nauplius, – the first larval stage – is hatched at great depths, perhaps 2,000 – 3,000 m if the water is deep enough. It took some time to realize this, and most of the *Discovery* nets were fished at shallower depths, usually down to 1,000 m and occasionally 1,500 m. The very few first nauplii, and most of the eggs, that have been collected were taken near the continental slope or in regions of upwelling, where the shallow sea floor, or upward water movement, kept them within range of the nets. Probably more would have been taken near the slope if the nets had been fished specially close to the bottom to sample possible concentrations, but the modern techniques, using acoustic telemetry to keep gear close to the bottom were not known, nor was the possibility that more eggs might be found there. The later stages of larval development occur at higher and higher levels, till the transition from non-feeding to the first feeding stage, the first calyptopis, occurs in the Antarctic surface layer.

One of the most remarkable outcomes of the krill sampling is the strikingly small number of eggs taken in the well-sampled, krill-rich, area near South Georgia – only 11 from 880 *Discovery* net hauls. This may be because the eggs were mostly below the depths to which the nets were fished, but Marr (1962) found it difficult to avoid the conclusion that the eggs spawned near South Georgia fail to mature, and therefore contribute little or nothing to the annual recruitment of the population. Complete absence of the early larval stages – which can be expected to come within range of the nets – afforded further evidence that eggs did not hatch successfully. Such failure might result from the eggs sinking too deep to allow the usual development ascent to succeed; perhaps the water movements and densities also may be unfavourable. This is only surmise, but whatever the cause, it seems that the rich population near South Georgia, and possibly those in other northern areas of abundance, spring from incursions of larvae from higher latitudes rather than successful local hatching.

Such hypotheses linking krill distribution to water movements cannot be fully acceptable till we know more about the speeds and directions of transport in the surface layer, in the bottom current, which may influence the distribution of the early larval stages, and in the intervening warm deep layer, where there must be a general southward trend. Within the east wind drift such a trend might help to maintain the krill distribution near the continental slope, where there seem to be conditions favourable for reproduction. In the Atlantic sector, where there is a rich population in the Weddell Sea outflow, the southward movement might be instrumental in replenishing the east wind population from the apparently unfavourable northern region, though it seems fairly certain that once the larvae reach the surface layer they remain there. There is no evidence of a mass descent into the warm deep layer in winter like that demonstrated for some other species. Water movements in 20°E to 30°E may be of special interest because, while there is massing of the older larvae in the eastward flow of water from the Weddell Sea in about 55°S, there seem to be relatively few in the same latitude farther east. A strong southward movement near 20°E to 30°E might replenish the southern population, though from our present knowledge of the water movements and krill depths it seems unlikely. The absence, or virtual absence, of *Euphausia superba,* as distinct from *crystallorophias,* from extensive areas of shelf water – at the head of the Ross Sea, for example – was attributed by Marr to the failure of warm deep water to penetrate far on the shelf.

The swarming habits of krill (which seem to make them more vulnerable to the larger predators) are little understood. As far as we know they spring from a lifelong habit of the species. Analysis of net hauls and of the contents of whale stomachs show that a swarm generally contains individuals of much the same age, though sometimes they may be more mixed near the surface and augmented by younger stages. Marr found that deep, and east wind drift, swarms tend to be more homogenous than surface, west wind drift swarms, possibly because of wider time and space separation of the different stages. He thought that each swarm tends to keep together from hatching onwards. The movements of a swarm seem to depend on remarkable uniformity of individual action. There is clearly a lot to learn about variations in size, depth and density of swarms, and how they are affected by nets, ships, storms and varying light intensity. The physical processes that cause patchiness everywhere in the sea may also have some significance.

2. Water movements

To gain the information needed to further the krill studies needs some long-term basic studies of the water movements as well as those immediately related to plankton problems. It would, for example, be useful to know more about the basic physical processes that maintain the permanent surface, deep and bottom layers, and their meridional circulation – northwards in the surface and bottom layers and southwards in the intervening warm deep layer – that is superposed on their eastward and westward movements. Assessments of the northward and southward movements are based on budgetary estimates of the transports needed to maintain the observed temperatures and salinities in face of loss of heat, freezing, excess of precipitation and drainage from the continent. Averaged over the extent of each layer, and all round the continent, the speeds of the north and south movements seem likely to be of the order of 0.1 cm sec, though the activity of the meridional circulation must vary sufficiently from one sector to another to make 1.0 cm sec, and perhaps a little more, possible in some places.

The west and east wind drifts are better known, especially the west wind drift in the Drake Passage. The International Southern Ocean Studies programme, largely conducted by USA scientists, shows that it is not the broad, steady, flow we have imagined. It consists of bands of strong current separated by bands of little or no current, with variations over space and time scales of about 75 km and 15 days. It probably varies in much the same way everywhere else, though the bands of varying current may be wider in the less restricted ocean outside the relatively narrow Drake Passage. Much of our information from the rest of the ocean is based on ships' observations, drift bottles, drift cards, and timing of the drift of a large quantity of pumice produced by an underwater disturbance near the South Sandwich Islands. The average surface speed is of the order of 10-15 km a day, about the same as in the Drake Passage. The wind that drives it is not a broad, continuous air flow, but a succession of changes, mainly between NW and SW, dependent on depressions travelling along tracks that usually lie farther south. The east wind drift, driven by the NE and SE winds that prevail south of the storm tracks, has been said to be somewhat faster than the west wind drift. We know something of its speed and variability from the work of Tchernia, who used the *Eole* satellite, and later the *Nimbus 6,* to follow the movements of icebergs fitted with transponders. Along the continental margin south of the Indian Ocean the average speed of the icebergs was 15 km a day with a maximum of 46 km, and with sometimes backward loops to the east. The iceberg movements indicate a strong northward branching of the current near the Kerguelen-Gaussberg ridge – where one of the northern krill-rich areas occurs. The deep and bottom currents appear to flow east and west like the surface currents, though the measurements made so far, in the Drake Passage, the Weddell Sea and south of Australia, suggest average speeds less than half the surface speeds.

Although, even in the early days, it was clear that water movements and current boundaries varied with the changing winds, it seemed reasonable to think of them – the sinking of Antarctic water into the lower part of the subantarctic water column, for example – as fairly steady processes. Newer, closely spaced, observations emphasize the variability, though it is remarkable how closely the zone across which the transition between the two water masses wavers, agrees with the old maps, and how there is always evidence of the lower salinity and temperature of sinking Antarctic water near the bottom of the well-mixed subantarctic water. Fuller understanding of what goes on in such transition areas, and special investigation of the exchange between surface, deep and bottom waters, near the continental shelf seem essential to further progress.

3. **Immediate opportunities**

While advantage should be taken of every opportunity to make new observations, it is clear that very good use can still be made of earlier work, particularly of existing plankton collections. Krill samples have probably been worked over thoroughly, though perhaps not exhaustively, and sufficient has been done with plankton species other than krill to gain useful information about their relationships with each other and with the water movements. There are some objections to putting young men beginning their careers on to such work unless they are able to go to sea to try out new ideas and methods, but time and effort will be lost unless the old collections, analysis sheets, unpublished studies and experience, are kept alive and used in conjunction with the new ideas and observations. Further study of earlier work would undoubtedly strengthen the biological and physical background and planning of new work.

The most pressing need for new observations is to confirm and extend our understanding of the krill's life history, distribution, abundance and swarming habits. A ship supplied with modern nets, water sampling instruments, current meters and acoustic equipment, and worked by a team strong enough to pick out the different stages and interpret the other measurements, could make substantial progress in a very short time. Remaining more or less stationary in one of the northern areas of krill abundance, east of South Georgia, for example, she could, at the right time of year, follow the development of the adult females, the spawning and subsequent history of the eggs, look for the first nauplius, and test the whole hypothesis of the non-productiveness of a northern area. At the same time enough physical observations could be made to further our understanding of the water movements, and acoustic measurements would help with the studies of the size, structure, movements and continuity of krill swarms. A single well-equipped research vessel would achieve a great deal, several would ensure success. If fuel is available in South Georgia the work could be done within a 3-month cruise from South Africa or South America. Fish studies might be added to the list.

A similar study in the neighbourhood of the continental slope would give further information about the processes of spawning, hatching and larval development. It would also allow measurements of size and growth rates for comparison with those found in warmer water farther north. Physical measurements would give useful information about exchanges and mixing between the surface, deep and bottom layers, and allow investigation of the possible effects of water movements, particularly the meridional circulation on the distribution of eggs, larvae and adults. Studies of the krill swarms made there would also allow useful comparison with similar observations made in one of the northern areas. The continental slope north of the Soviet Antarctic station at Mirny would be a promising site, especially if arrangements could be made for ships to re-fuel.

Another prominent requirement is for study of over-wintering populations in the east wind drift. The *Discovery* sometimes reached latitudes where krill were present, and was sometimes kept out by the ice and freezing extending too far north. An icebreaker could penetrate further into the krill habitat, but net hauls and physical measurements become very difficult in low temperatures and ice cover. It is also hard to see how, with our foreseeable resources, the problem could be attacked from the south, even where there are sometimes patches of open water close to the land.

The area between longitudes 20°E and 30°E is particularly interesting because of the sharp transition from the Weddell Sea current, well-populated with krill larvae, to the relatively barren conditions found in the same latitude farther east. It raises the question whether the krill can migrate southwards, to help make up for the great outpouring from the western part of the Weddell Sea, possibly assisted by a southward trend of the surface current or by a particularly strong southward movement in the warm deep layer.

Physical studies are already being very effective in and near the Drake Passage, but they may soon have to be supplemented by a long-term current measurements in wider parts of the ocean where the meridional circulation is less likely to be constrained by a northern as well as southern boundary. Much more information about the variability of surface currents is likely to be obtained from satellite-monitored drifting buoys during the GARP experiment in 1978-79, when there should also be unique meteorological coverage. To learn more about northward transfer of water from the east wind drift may prove particularly useful. Long-term deep-current measurements would be valuable everywhere; it should now begin to be possible to get current meter moorings laid and recovered from the supply vessels that make regular voyages to the continent.

Another topic deserving special study is the effect of increased stability of the near surface water column due to surface inflow of fresh water on phytoplankton growth. Many authors have suggested such a possibility near melting sea-ice and near land. The effect of the fresh water, and some shelter by the ice or land is likely to lessen vertical mixing. Farther from ice or land, wind action is likely to stir the water and circulate the phytoplankton to much greater depths, so that it must spend some of its time at depths where the light intensity is too weak to maintain active growth. The rich phytoplankton growth found at the bottom of sea ice is probably due to porous ice providing a fairly stable environment with just enough light.

4. Other problems

Studies of the effect of the ocean on world climate and on the weather of the neighbouring continents require physical observations of much the same kind as those needed for krill studies. Recent work indicates that in the North Atlantic Ocean northward transport of heat is greater in the ocean than in the atmosphere. The Southern Ocean, a relatively narrow zone between climatic extremes, seems likely to be of special importance.

Marine geophysical studies are providing new information about the processes that have shaped and structured the Antarctic and neighbouring continents. The Antarctic continental shelf, though little known, seems to have some unique features. It is abnormally deep and often contains depressions that tend to run parallel to the coast. It has been suggested that these depressions may be due to cracking of the crust during downwarping, due to the heavy load of ice on the continent, but there is the further possibility that morainic activity has been responsible, as with similar formations close to the coast of Norway.

There is great scope for other studies, particularly the fish, squid and benthos, waves, tides and other physical processes, and there can be no doubt that many problems basic to marine science would be furthered by study in the Antarctic.