The growth, structure and properties of Antarctic sea ice

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ABSTRACT The Weddell Gyre Region (60°W to 20°E longitude) is one of the more complex areas of sea ice processes in Antarctica. In the western part of the region, the pack ice persists year-round, caused by a vigorous generation and circulation of the ice, controlled by the atmospheric and ocean current forcing that is turned northward by the topographic boundary of the Antarctic Peninsula. The dynamical character of the pack ice affects the ice thickness characteristics, with the oldest, thickest ice appearing in the northwest outflow region of the western pack ice. In the eastern part, the pack is seasonal rather than perennial. The primary origin of the pack ice (0.6 m of mean ice thickness) is the rapid formation of pancake ice, controlled by the temperature and ocean wave regime at the ice edge during the advance period.

INTRODUCTION

Ice-atmosphere-ocean interaction

Ice-atmosphere-ocean processes and the budgets of heat, momentum, salt and trace constituents (e.g. CO₂) related to these processes provide a fundamental setting for the role of the Southern Ocean in global oceanic and atmospheric climate. The South Polar heat sink undergoes drastic changes in its seasonal cycle primarily because of the growth and decay of the sea ice cover. Sea ice area increases by a factor of ten between summer and winter and encompasses about half the area south of the Polar Front at winter maximum. Crucial to oceanography is the interaction of the abyssal waters of the ocean directly with the atmosphere at high latitudes of the Southern Ocean.

From the atmospheric perspective, the region between 40°S and 60°S latitudes is the location of the most vigorous large-scale circulation feature in the world, the circumpolar low pressure trough, and its surface manifestation, the Southern Hemisphere westerly winds. An interesting characteristic of most general circulation
models (GCMs) of the atmosphere is their relatively poor representation of these features (Schlesinger, 1983). If the models are "tuned" to give a better representation to the actual Southern Hemisphere, the Northern Hemisphere circulation becomes less realistic, i.e. too vigorous. In a qualitative sense, this implies inadequately represented Southern Hemisphere processes by reliance on Northern Hemisphere analogs. A better understanding of the exchange processes in the Southern Hemisphere by field studies and experiments would probably improve these simulations. The improved models can then increase our understanding and lead to better predictions of the global climate system as it undergoes natural and anthropogenic changes.

Antarctic sea ice

The sea ice region around Antarctica provides the greatest variability in the climate system on short time scales (Weller, 1982). The properties of greatest impact on the climate system are the extent and concentration of the ice cover, followed by the ice thickness and the depth and properties of the snow cover. Weller (1980) points out that the extent of open water in the pack ice can vary the midwinter energy loss by an order of magnitude. The amount of thin ice can also give a large effect on the energy balance. The interannual variability of the energy balance in the Southern Hemisphere is, to a large extent, controlled by these variations in the sea ice cover. Since the variations in the ice cover are governed by changes in the atmosphere (winds and temperatures) and in the ocean (ocean heat flux and currents), there is strong coupling in the system which significantly alters the mass and energy flow between the components. How this process operates and regulates the flow is complex and presently undetermined, yet crucial to the explanation of the role of the Polar heat sink in global climate.

SEA ICE PROCESSES IN THE WEDDELL GYRE

Western Weddell pack ice

Drift of the ice The Western Weddell pack ice is of particular interest in the general context of Antarctic sea ice. It is one of the major regions of perennial (year-round) pack ice in Antarctica (Zwally et al., 1983). The pack ice in the western region persists throughout the year primarily as a result of the diverting influences of the Antarctic Peninsula on the winds and ocean currents. The general westward movement near the coast of Antarctica of winds, ice and water is bent northward to parallel the Peninsula in the Western Weddell. This movement, along with the mountain topography of the Peninsula produces relatively colder conditions of the Weddell Sea side and
FIG. 1 Drift of the Endurance and Deutschland and drifting buoys in the Weddell Sea.
essentially creates the perennial sea ice pack on this side of the Peninsula. The general movement northward is indicated in Fig. 1 which shows the ice drift pattern from the trapped ships Endurance and Deutschland when they were locked into the ice (Ackley, 1979) as well as later data from drifting buoys placed in the pack ice (Ackley & Holt, 1984).

FIG. 2 Summer extent of pack ice in the Western Weddell Sea.

The areal distribution of summer pack ice indicates the importance of drift and advection in maintaining the ice in this region. The summer extent of pack ice is generally west of 45°W longitude from the Antarctic continent in the south to 64°S latitude in the northern part (Fig. 2). North of 67°S (i.e. north of the Antarctic circle) corresponds to other regions in the seas around Antarctica that are free of ice in the summer. The presence of the pack, consistent with the drift
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information, is therefore caused by the export of ice from the higher latitudes. This export region, off the Filchner-Ronne Ice Shelf, combines low temperature and high winds, conducive to ice formation and advection, throughout the year.

![Ice edge advance around Antarctica. Note the northeast movement of the ice edge in the Weddell Sea.](image)

Several interesting aspects of the drift of the ice exist for this region. Trapped ships (Ackley, 1979) and buoy data (Ackley, 1981; Ackley & Holt, 1984; Limbert et al., 1989) show a generally broad northern flow across the entire western region. However, the ice edge advance in the early winter is directed northeast at rates considerably higher than the observed drift. This behavior was shown markedly by the emplacement of several buoys in 1980. Two were placed near the summer ice edge while two others were placed further to the west in the perennial pack. All buoys tracked to the north while the observed ice edge, seen from satellite imagery, moved rapidly northeast (Fig. 3). This difference between the drift of the ice and the ice edge growth or advance leads to some contrasts in the ice properties as discussed below.

In the far western portion, some anomalies in the drift behavior have been noted. Hibler & Ackley (1983) in a modeling study of the Weddell Gyre pack ice, used a dynamic formulation to predict ice drift based on
geostrophic winds. Comparisons with buoy data showed that this worked well, except for regions in the western portion. Here the ice drift was underpredicted by the geostrophic winds compared to actual buoy drifts for the region. This behavior was corrected in an ad hoc way by increasing the winds in this region. In a meteorological study of the region, Schwerdtfeger (1979) suggested a physical basis for this behavior due to the damming of cold air by the mountains of the Peninsula. This process would lead to a barrier wind enhanced by the temperature gradient in the cold air, essentially a thermal wind, that accentuated the winds due to the normal pressure gradients. Stossel (in press), who used a coupled sea ice-oceanic mixed layer model, showed that the computed ice drift and ice thickness distribution, compared to actual values, responds more effectively to surface winds, including the barrier winds, than to winds calculated from a higher reference level. In the absence of additional field data, however, this behavior could also be caused by some modification of the ice response or by ocean currents which were only estimated from sparse data.

Up on the continental shelf in the Western Weddell some additional features were observed (Ackley, 1981). Fig. 4 shows the track of a buoy air dropped into the region for the first four months of 1979. In contrast to buoys placed off the continental shelf, this buoy underwent a sharp southern motion for the first month of
drift and then rotated for about 28 days with little net displacement, finally heading north at the end of February. As a result, the net northern speed is about half that for the offshore buoys during the same period. The rotation may indicate the buoy was trapped in an eddy at the time of its maximum southward drift. These observations indicate that ice forcing on the continental shelf may be different than that observed offshore, but the relative contributions of the atmosphere, ocean or the ice response itself to that behavior has not been determined.

![Graphs showing ice thickness distribution](image)

**FIG. 5 Ice thickness distribution from the Western Weddell Sea.**

**Ice thickness characteristics**  Ice observations were made in the fall period during the cruises when the ice edge buoys were emplaced. It was observed that the rapid movement of the ice edge to the northeast was a result of new pancake ice growth rather than advection of older ice from the west. The ice edge typically moved out, as a freezing front, at rates of 100 km day\(^{-1}\) (directed northeast), far in excess of the drift of the ice which is averaged about 5 km day\(^{-1}\) (northward). Wadhams *et al.* (1987) noted this type of advancing ice edge was also observed for the eastern Weddell region. Because of this behavior, the summer ice edge, usually in the region of 45°W longitude, marks a boundary in ice thickness during the winter as well. Lange & Eicken (in press) and Gow *et al.* (1987) find that the Western Weddell pack ice to have significant
percentages of ice thicknesses from 2 m to 5 m (Fig. 5) while ice in the eastern portions, formed only during the fall-winter ice advance, is typically only 0.6 m thick (Wadhams et al., 1987; Lange & Eicken, in press). Given that the drift data indicates the ice in this area is generally less than two years old, the significant amounts of thick ice are somewhat surprising. Several causes are possible, the primary suspected one is enhanced deformation, but direct measurements of the ice thickness changes over time with associated deformation and energy balance (thermodynamic) behavior would provide the best answer.

FIG. 6 Ice and snow thickness profile from the Weddell Sea showing the below sea level nature of much of the ice surface.

An additional phenomenon, flooding of the top surface, has been recently observed in significant areas of the Weddell pack ice (Fig. 6) (Ackley et al., 1990; Wadhams et al., 1987; Lange & Eicken, in press; Lange et al., in press). Flooding of the ice cover affects several processes including ice thickness changes and heat flux. The heat flux problem is intriguing since flooding would produce heat flux to the atmosphere as the flooded water freezes, but the salt flux usually accompanying ice freezing would not be available since the ice is formed on the top of the existing ice cover. Flooded surfaces also affect the microwave emissivity (Comiso et al., 1989) and the sea ice biology (Ackley & Sullivan, in press). Both the details of the flooding process and its regional effects are unknown in the Western Weddell.

Eastern Weddell pack ice

Drift of the ice The Eastern Weddell Region is an area of seasonal rather than perennial ice cover with the length of the ice season shortening as the distance from the Western Weddell, north and east, increases (Ackley, 1979). As mentioned earlier, the primary origin of the ice
cover is the rapid formation in the winter period of pancake ice. At the northwest boundary with the Western Weddell, however, advection of perennial pack ice contributes significantly to the total coverage of pack ice as the drift turns east north of 65°S (Ackley, 1979; Ackley & Holt, 1984). Pancake ice is produced when a wave field propagates on the ocean where freezing conditions exist. Small ice crystals, frazil ice, are produced in the freezing water. The wave action herds these crystals together and pushes them into contact, forming floes or pans consisting of stuck together small ice crystals (Lange et al., 1989; Ackley et al., 1986; Wadhams et al., 1987) (Fig. 7). While this initial formation process is dominated by thermodynamic processes, the high winds generally found in this region cause the ice to drift once it is formed. Differential drift leads to deformation in the ice cover and, if it is diverging, open water is created in leads and polynyas which then freeze over to modify the existing structure of the ice. Hoeber (in press) described the Eastern Weddell with its characteristic easterly drift in the north and westerly drift in the south as exhibiting large-scale shear behavior. However, individual storms, on smaller scales, cause more localized convergence and divergence of the ice as well. Because the ice cover is relatively thin, the deformational behavior exhibits both free drift and behavior governed by some resistive ice stress, depending on the history and local forcing at the time of measurement.

FIG. 7 Formation of pancake ice in a wave field.
Ice thickness characteristics. Wadhams et al. (1987) showed the ice thickness distribution for the area near the Greenwich Meridian based on the Winter Weddell Sea Project cruises, conducted in 1986. We found the ice thickness dominated by the pancake ice thickness accreted during the initial ice advance which was generally about 0.6 m. Subsequent ice growth was inferred to be small, dominated by the freezing of open water in deformationally created cracks and leads. This ice also averaged around 0.6 m in average thickness. Little north-south gradient in ice thickness was found, (Fig. 8) and where thicker ice existed, its origin was determined to be a higher percentage of deformed ice in rafts and ridges.

![Graph](image)

FIG. 8 Mean ice thickness vs latitude for the Eastern Weddell Sea taken from a transect approximately along the Greenwich Meridian.

The relatively small growth, after the initial ice edge formation, was found to be associated with flooding of the ice and building of a snow-ice layer on top of the existing sheet (Ackley et al., 1990; Lange et al., in press) (Fig. 9). No evidence was found structurally for an increase in ice thickness, after the ice initially formed in the ice edge advance, from bottom accretion onto existing pancake ice. The presence of a thin ice cover and little to no additional growth is attributed to the presence of significant vertical exchange in the ocean water. High ocean heat flux (tens of W m\(^{-2}\)) results and the conduction of heat through the existing ice necessary to overcome this value is not sufficient to add additional ice to the bottom of the existing ice cover. The stability of this thin veneer is also questionable, since the Weddell Polynya, observed for three consecutive years in the 1970s, was free of ice over an area of 100 000 km\(^2\). This feature was apparently maintained by convective
overturning, bringing up sufficient heat from 2000 m of water column to prevent ice from forming. The initiation of the condition and the possible role of sea ice formation in maintaining the polynya remains undetermined. A possibility also exists that the polynya condition was eventually destroyed by ice advection, which initially melted enough to establish a stable surface layer and shut down the deep convection.

![Image of schematic formation of flooded snow and ice.](image)

**FIG. 9** Schematic formation of flooded snow and ice.

**Sea ice scientific problems in the Weddell Gyre**

The background discussed above leads to the following summary of the characteristics which are posed as specific problems worthy of further investigation by field measurements, satellite data analysis and modelling.

(a) Ice drift in the Western Weddell Sea does not respond to geostrophic wind forcing in the same way as other sea ice regions. The differences between wind forcing, ocean currents and sea ice response in this region than that in other regions remains to be resolved.

(b) Ice drift and deformation on the continental shelf in the Western Weddell are apparently affected by mesoscale processes that are different from the forcing and response in the offshore regions. The relative contributions of atmospheric and oceanic forcing to this response are not known.

(c) Ice thickness in the Western Weddell Sea is transformed during transit from its initial thickness in the southern and eastern Weddell Sea to the ice of 2 m to 5 m thickness found in the northwest region. The importance of ice deformation and ice thermodynamics in making this transformation are presently unknown.

(d) Ice mass balance is dominated by horizontal advection in the Western Weddell, by *in situ* freezing (vertical convection) in the Eastern Weddell (eastward of the summer minimum ice edge), and by some combination of
these two in the north-west. Ice deformation contributes substantially to this process, probably in varying degrees in the three regions. The deformation contribution and quantification of the horizontal (drift) and vertical (freezing) contributions of the ice mass balance remain to be specified.

(e) Vertical heat exchange apparently limits the ice thickness in the Eastern Weddell to thicknesses less than about 1 m. The regional variation in vertical heat flux and the mechanisms controlling it are important parameters in initially forming and then maintaining the Weddell Polynya ice-free. The role of sea ice formation in initiating or preventing, and then maintaining and eventually destroying these large-scale features is presently undetermined.

REFERENCES

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