# Energy Exchange Over Antarctic Sea Ice in Late Winter

**G. König-Langlo**
*Alfred-Wegener-Institute, Bremerhaven, Germany*

**B. Ivanov and A. Zachek**
*AARI, Leningrad, USSR*

## ABSTRACT

In September and October 1989 during the "Winter Weddell Gyre Study" energy balance measurements were performed from the Soviet ice-breaker *Akademik Fedorov*. The average radiation balance of the sea ice surface turned out to be zero, i.e., short-wave radiation gains were fully compensated by long-wave radiation losses. Due to turbulent fluxes of sensible and latent heat the atmosphere received about 25 W $m^{-2}$ energy from the ice/ocean system. Since no significant ice melting or freezing was observed, the latter must originate mainly from warm deep water which is entrained into the oceanic mixed layer.

## INTRODUCTION

Sea ice covers only 4% of the earth's surface but it is nevertheless believed to play an important role in the climate system through its coupling with the ocean and the atmosphere. For a review see Walsh [1983].

Thus a hierarchy of sea ice models has been developed [e.g., Maykut et al., 1971; Hibler, 1979; Lemke et al., 1990]. They all use parameterization schemes for the exchange between ice, atmosphere and ocean. For the antarctic regions there is very little in situ data to verify and improve these models. Especially in remote areas, such as the Weddell Gyre, and during strong ice conditions at the end of winter, nearly no field observations exist.

The multinational Winter Weddell Gyre Study 1989 (WWGS89) offered a good opportunity to take surface measurements in the antarctic sea ice belt during the period of maximum ice extent. The data collected may help to improve the parameterization schemes describing the physical processes which control the sea ice development as well as its interaction with the ocean and the atmosphere. Subsequently we present some observational results of the surface heat and radiation balance of the Weddell Sea ice area.

## CRUISE

The WWGS89 was carried out by the research vessels *Akademik Fedorov* (Leningrad) and *Polarstern* (Bremerhaven). Both ships operated for about six weeks in the sea ice–covered Weddell Gyre.

The energy balance measurements were performed on the *Akademik Fedorov*. The ship reached the rather sharp ice edge (60°20'S, 34°25'W) on 18 September 1989 (see Figure 1). The ice edge was well pronounced. Within several meters the ice cover changed from 0% to nearly 100% 50 cm of thick first-year ice.

Heading southeast, some multi-year ice floes of up to 200-cm thickness were observed. After crossing the polar circle (24 September, 20°W) and heading eastward to Maud Rise, first-year ice with thicknesses between 60–100 cm was dominant. West of Maud Rise the ice thickness dropped to 30–40 cm for about 50 km. This coincided with a shallow mixed layer of only 40 m depth and a mixed layer temperature 0.2°C above freezing. This local phenomenon can be interpreted as an orographic effect of Maud Rise.

After several days of measurements near Maud Rise *Akademik Fedorov* stopped on 6 October for a 12-day drifting station. During this period the ship drifted together with the ice more than 100 km from 65°46'S, 1°50'W to 65°21'S, 4°8'W. First-year ice of 60 cm thickness was mainly observed. Heading northward *Akademik Fedorov* left the ice on 24 October (58°3'S, 25°15'W).

With some exceptions during the last few days of the cruise the ice coverage was always well above 90%. The observed cracks and leads were frequently filled with thin new

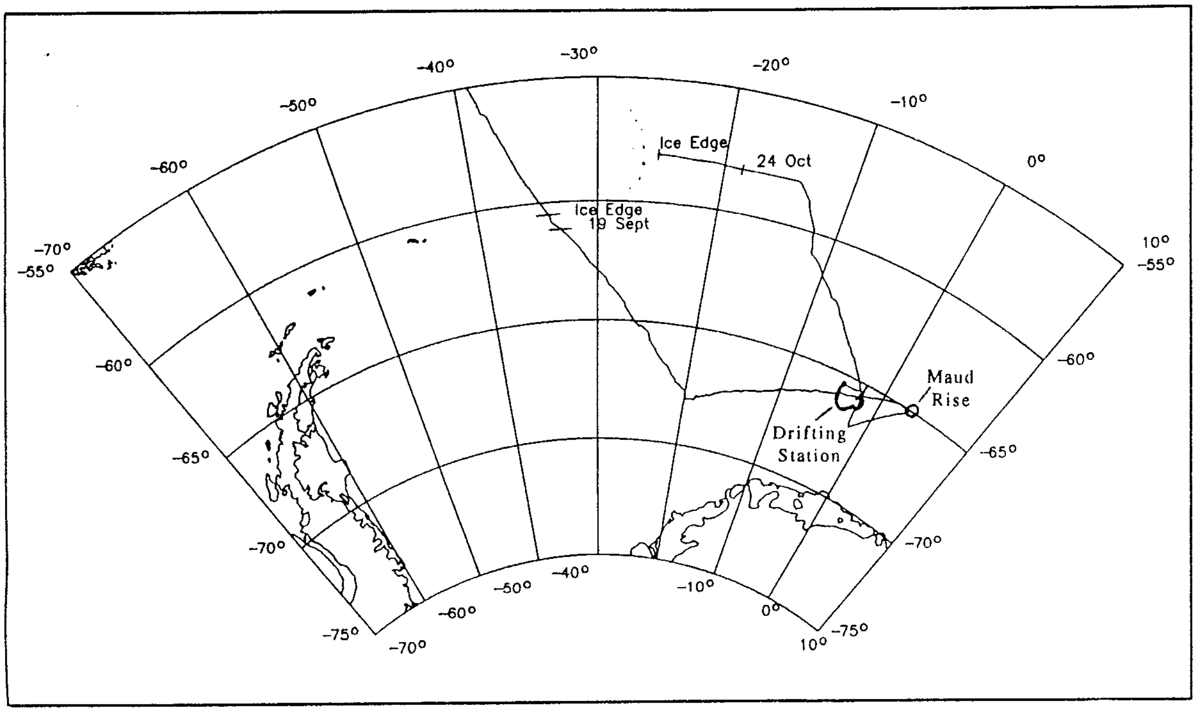


**Figure 1.** Cruise of *Akademik Fedorov.*

ice and nilas. Ice ridging was low to moderate. The sea ice was always covered by snow with a depth of about 20 cm. Except in newly opened cracks and leads no significant ice formation or melting was observed until the end of the drifting station.

Weather conditions were quite variable. The air temperature was always below freezing (minimum=-24°C, mean=-12°C), and the wind speed ranged between 1–21 m $s^{-1}$ (mean=10 m $s^{-1}$). From the ice edge to the drifting station westerly winds prevailed. Later on winds from east and south were more common. Frequently the sky was totally overcast and snow fell several times.

The cruise can be divided into three parts. Along the first part from the ice edge to the drifting station *Akademik Fedorov* stopped every 30 or 60 miles for a 2- to 6-hour hydrological station and experiments on the ice. During the two weeks drifting station, part two, ice work was done continuously. The last part from the drifting station to the ice edge was organized similarly to part one.

## INSTRUMENTATION

The following components of the surface energy balance were measured:

- global radiation ($K\Downarrow$)
- reflected solar radiation ($K\Uparrow$)
- downward long-wave radiation ($L\Downarrow$)
- upward long-wave radiation ($L\Uparrow$)
- turbulent flux of sensible heat (H)
- turbulent flux of latent heat (LE)

Additionally weather and ice observations were carried out routinely. To achieve accurate and reliable data all components were measured using different methods and instruments wherever possible.

*Short-wave Radiation.* The global radiation ($K\Downarrow$) was measured with three redundant pyranometers (CM11, Kipp + Zonen). During the drifting station the reflected solar radiation ($K\Uparrow$) was determined directly using a fourth CM11 instrument mounted on a sledge 500 m away from *Akademik Fedorov.* In all other cases $K\Uparrow$ was calculated using $K\Downarrow$, albedo values obtained periodically from a hand-held albedometer and ice observations. The absolute error of the mean short-wave balance can be expected to be less than 3 W $m^{-2}$ according to the small scatter of the redundant instruments, the rather low global radiation and rather high albedo.

*Long-wave Radiation.* The downward long-wave radiation ($L\Downarrow$) was measured with a pyrgeometer (Eppley PIR) and an instrument (P2-30) developed recently in Leningrad. A built-in filter compensation and heating prevents the P2-30 from being affected by hoar-frost. With a measuring angle less than 180° a second P2-30 and an infrared thermometer (KT4) determined the upward long-wave radiation ($L\Uparrow$) while the ship was in motion. Furthermore a second Eppley PIR supplied $L\Uparrow$ data during the drifting station. Comparing these data derived from quite different instruments, the mean deviation was less than 3 W $m^{-2}$.

*Radiation Balances.* The German net pyrradiometer of the type Schulze–Lange mounted on the ship provided the total downward radiation ($Q\Downarrow=K\Downarrow+L\Downarrow$). This instrument was mounted on a sledge during the drifting station and measured additionally the upward radiation balance ($Q\Uparrow=K\Uparrow+L\Uparrow$). The Soviet net pyrradiometer BP_1 also fixed on the radiation sledge determined the radiation balance ($Q^*=Q\Downarrow+Q\Uparrow$) directly.

$Q^*$ could therefore be estimated from several independent instruments (Figure 2). The good agreement is expressed by the low standard deviation of 3 W $m^{-2}$. Adding all errors of the single radiation components $K\Downarrow$, $K\Uparrow$, $L\Downarrow$ and $L\Uparrow$ leads to much greater uncertainties in $Q^*$. Due to the high albedo and frequently overcast sky the errors in the downward components were often compensated by the errors of the upward components.

Despite the fact that the net pyrradiometers offered reasonable radiation balances, all derived quantities like $L\Downarrow=Q\Downarrow-K\Downarrow$ show systematic errors and were excluded from analysis.

*Turbulent Fluxes.* While the ship was in motion the turbulent fluxes were estimated continuously on the basis of an algorithm established by Ivanov and Makshtas [1986] based on the Monin–Obukhov method. During the drifting station and at some hydrographic stations additionally a small gradient tower and a sonic anemometer–thermometer (Kaijo Denki DAT 300) erected on the ice were used. The mean difference between tower data and sonic data was less than 30%. The error for the mean turbulent fluxes was assumed to be within the same order.

## RESULTS

From the radiative and turbulent fluxes the surface energy balance

$$B = K\Downarrow + K\Uparrow + L\Downarrow + L\Uparrow + H + LE$$

was computed. Positive values indicate a gain, negative values a loss of energy at the surface. The component B comprises all energy fluxes below the surface, i.e., B depends on changes in heat storage of the ice, phase changes and energy supplied by the ocean. Figure 3 shows some time series from the first part of the cruise.

The surface gained energy mainly by the short-wave balance ($K^*=K\Downarrow,+K\Uparrow$). The long-wave balance ($L^*=L\Downarrow,+L\Uparrow$), generally negative, significantly depended on cloud coverage. Thus the radiation balance ($Q^*$) did not follow the daily cycle as strictly as $K^*$. Generally, the mean short-wave gain was about compensated by the mean long-wave loss.

When $Q^*$ distinctly exceeded +50 W m$^{-2}$ the turbulent fluxes transported most of this energy into the atmosphere, thus preventing ice melting or ocean warming. The analogous mechanism for cases with $Q^*$ lower than -50 W m$^{-2}$ was less pronounced. Due to the reduced turbulence under stable atmospheric conditions the surface radiation loss could not be compensated by the atmosphere. Thus the mean surface energy balance was negative. Figure 4 shows the same data as Figure 3 but averaged over 17 days of part I of the cruise.

An energy imbalance of B=-24 W m$^{-2}$ corresponds to a sea ice growth of about 12 cm within 17 days. But no significant ice formation was observed. The same imbalance over the same period could decrease the mean ice temperature within the order of 10°C. But no significant changes in heat storage of the ice were observed. Thus B can be interpreted as primarily energy supplied by the ocean.

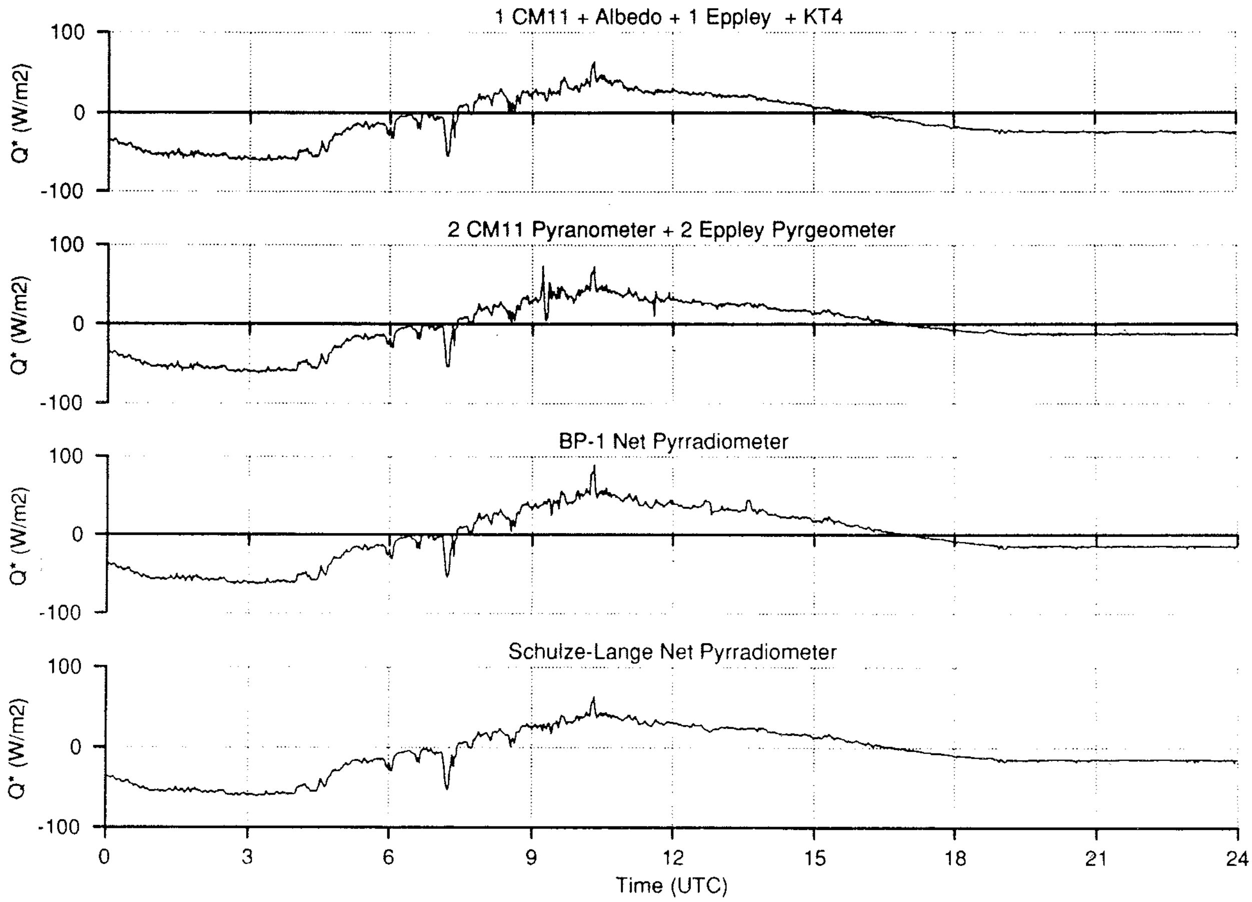


**Figure 2.** Example of radiation balances from 12 October measured with four different instrument systems.

Similar data analyses were carried out also for parts II and III of the cruise. Figure 5 shows the daily averaged values.

The data obtained during the drifting station are quite similar compared to the data described above. Again K* and L* are nearly equal but opposite. The surface energy balance is slightly more negative because of stronger turbulent fluxes. During the 9 days analyzed from the drifting station the ice thickness was constant at 60 cm. The energy imbalance of B=-34 W $m^{-2}$ could readily change it by about 10 cm. But the observations indicated no ice thickness change. Thus B can be interpreted as a heat flux from the ocean. Only during the last part of the cruise was the surface energy balance positive, indicating the arrival of spring.

## DISCUSSION

The results described above can be compared with data from the *Michail Somov* expedition in 1981 and the *Polarstern* cruise in 1986.

Energy balance measurements were made north of Maud Rise from 20 October to 14 November on *Michail Somov*. The last days of the *Akademik Fedorov* cruise covered the same area during the same time of the year as the *Somov* expedition. But in the mean *Akademik Fedorov* activities were more concentrated on the interior of the Weddell Gyre and took place about one month earlier.

Andreas and Makshtas [1985] reported albedo values typically between 50–60%. On the *Akademik Fedorov* generally higher values were observed (Figure 5). Obviously the albedo is less in spring than in late winter when surface melting is uncommon and cracks and leads are covered with thin ice.

The long-wave radiation balance (L*) measured in 1981 accounts for a mean loss of 10–15 W $m^{-2}$. On the *Akademik Fedorov* the loss was about two times larger, reflecting the fact that the sky was not as predominantly overcast as was observed in 1981. Under clear sky conditions the ratio of $L\Downarrow$ to $L\Uparrow$ ranged between 0.65–0.75. Due to the very clean and dry air these values are 10–15% lower than similar data from the Arctic Basin.

In the austral winter 1986 *Polarstern* activities were concentrated on oceanographic work along the Greenwich Meridian. Gordon and Huber [1990] reported a mean bulk mixed layer temperature 0.08°C above the freezing point leading to a mean heat flux to the ice of 22 W $m^{-2}$. This value fits quite well with the data obtained from the surface energy balance measurements on *Akademik Fedorov*.

Values for the oceanic heat flux found in the literature range between 2–20 W $m^{-2}$. Sea ice models such as that of Lemke et al. [1989] show that this uncertainty has only a minor effect on sea ice extent but a major effect on sea ice volume. Regarding the observations described above, 20 W $m^{-2}$ seems to be more realistic than 2 W $m^{-2}$. Our result

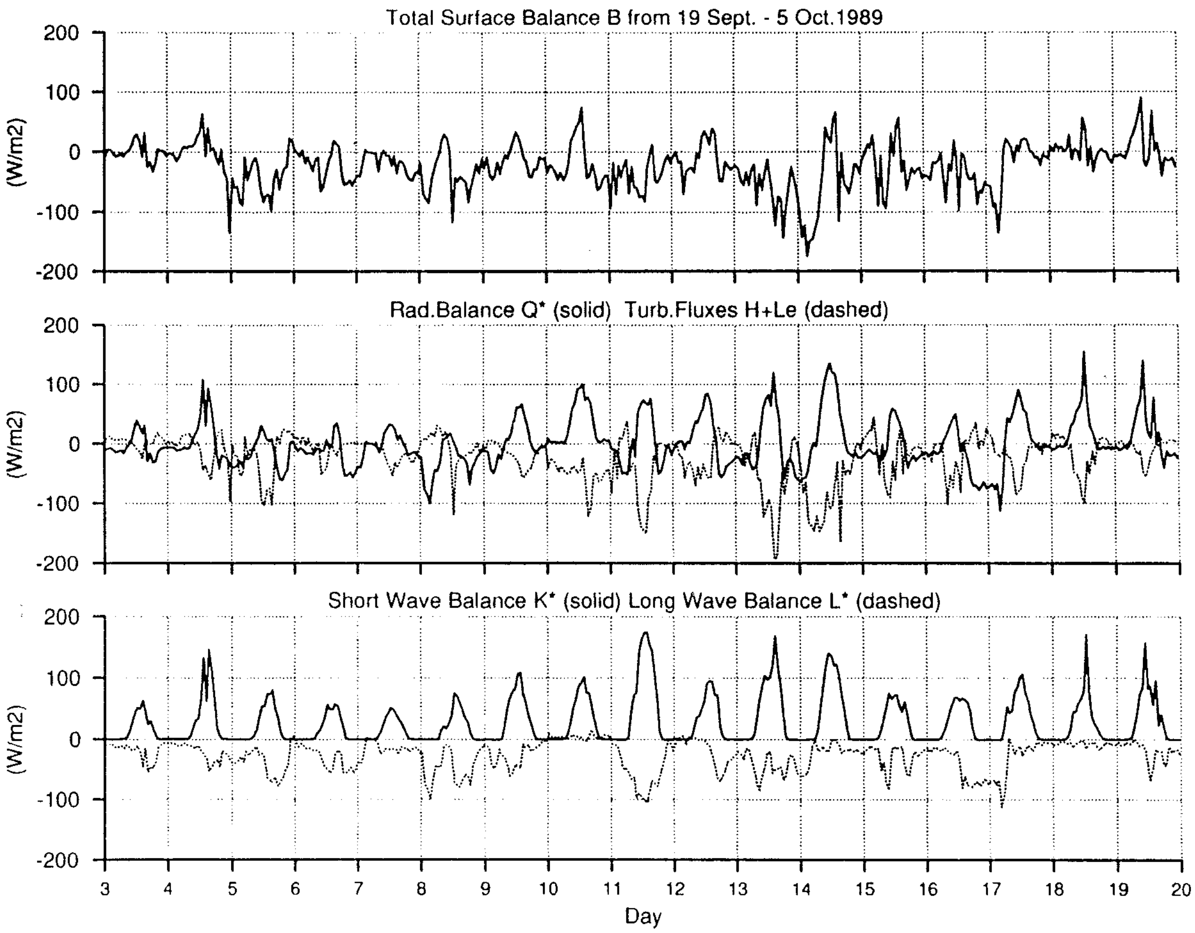


**Figure 3.** Time series of some components of the energy balance measurements made during part I of the cruise.

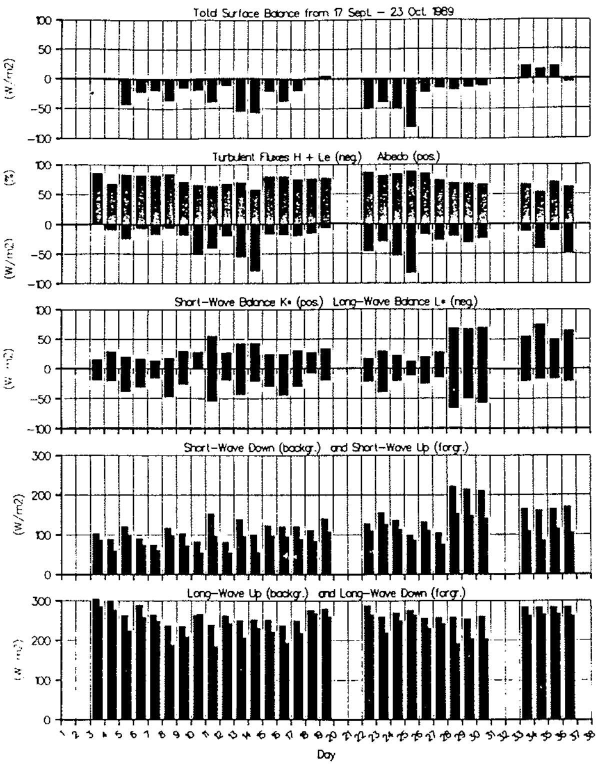

Figure 4. Mean energy balance components during part I of the cruise.

agrees with the annual heat flux of 19 W m-2 that Gordon and Huber [1990] derived from an analysis of a depression of oxygen saturation under the sea ice found in 1986.

## CONCLUSION

Zero ice production and zero mean radiation balance can be regarded as a special feature of late winter in the area where the measurements took place.

The instantaneous radiation imbalances can amount to ±100 W m-2 (see Figure 3) but they are largely compensated by turbulent heat fluxes. A mean oceanic heat flux larger than 20 W m-2 seems to be more realistic than smaller values often used in numerical models.

Until now energy balance measurements have been carried out in the Weddell Gyre in late winter and in spring. Observations during ice formation seasons are still needed to achieve a better understanding of the physical processes controlling one of the most sensitive components of our climate system.

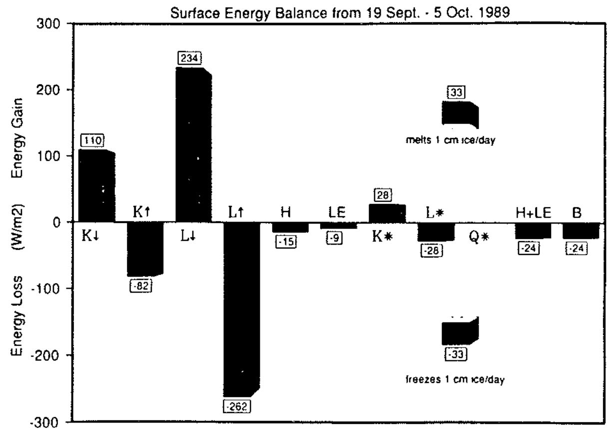


Figure 5. Daily averaged components of the energy balance for all three parts of the cruise.

## ACKNOWLEDGMENTS

The data collection and analysis was supported by the Alfred-Wegener-Institute for Polar- and Marine Research (Bremerhaven, FRG) and the Arctic and Antarctic Research Institute (Leningrad, USSR). We thank all members of these institutes who made this joint expedition as successful and enjoyable as it was.

## REFERENCES

Andreas, E. L., and A. P. Makshtas, Energy exchange over antarctic sea ice in the spring, *J. Geophys. Res.*, *90*, 7199–7212, 1985.

Gordon, A. L., and B. A. Huber, Southern ocean winter mixed layer, *J. Geophys. Res.*, *95*, 11655–11672, 1990.

Hibler, W. D., A dynamic thermodynamic sea ice model, *J. Phys. Oceanogr.*, *9*, 815–846, 1979.

Ivanov, B., and A. P. Makshtas, On the estimation of surface air parameters over sea ice by observation from moving vessel, *AARI Proceedings*, *406*, 139–145, 1986.

Lemke, P., W. B. Owens, and W. D. Hibler, A coupled sea ice–mixed layer–pycnocline model for the Weddell-Sea, *J. Geophys. Res.*, *95*, 9513–9525, 1990.

Maykut, G. A., and N. Untersteiner, Some results from a time dependent thermodynamic model of sea ice, *J. Geophys. Res.*, *76*, 1550–1575, 1971.

Walsh, J. E., The role of sea ice in climate variability: Theory and evidence, *Atmos. Ocean.*, *21*, 229–242, 1983.