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Sea Ice Feedbacks Observed in Western Weddell Sea

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The western Weddell Sea is the largest region of perennial sea ice in the Southern Ocean. Although poorly explored, earlier studies suggest that it hosts important sources for deep and bottom water ventilating of the global abyss. Ocean structure limits ice melt because the oceanic heat flux is only a few watts per square meter, and wind change in summer prevents the large-scale northward movement of the pack ice [*Hunke and Ackley,* 2001]. As the ice melts, the absence of melt ponds and the development of gap-like porous internal layers with extremely high amounts of algal standing stocks have large implications for primary productivity and biogeochemical cycles.

The field experiment Ice Station Polarstern (ISPOL) was designed to observe, at the transition from austral spring to summer, the physical and biological atmosphere-ice-ocean processes, thus completing investigations of the seasonal sea ice-ocean cycle initiated (over fall to winter) by Ice Station Weddell 1 (ISW-1) [*Gordon et al.,* 1993]. Data from this experiment will be used to better understand the seasonal carbon flux in ice covered oceans, to narrow down the variability inherent to water mass formation, and to improve the sea ice component in climate models.

The German research icebreaker *Polarstern* drifted within the western Weddell Sea pack ice from 27 November 2004 until 2 January 2005 (Figure 1), anchored to an initially 10 by 10 kilometer-sized floe. ISPOL covered a distance of 290 kilometers with a net south-north displacement of 98 kilometers due to various loops in the drift. The average northward drift of less than three kilometers per day is less than the approximately seven kilometers per day observed in other seasons [*Gordon et al.,* 1993], reflecting a different dominant wind direction.

For 36 days, the *Polarstern* served as accommodation, laboratory, and platform for field and water column studies for an interdisciplinary scientific team from 10 countries. Helicopters supported sea ice thickness and ice dynamic measurements, iceberg marking, and water column sampling on both sides of the trajectory. The results obtained so far affirm that ISPOL provided invaluable information about the internal structure and forces of the pack ice and its interaction with the atmosphere above, the biology within and at its base, and the ocean underneath.

Atmosphere

Despite the time of year—spring—and the relative low latitude, measurements of the local fluxes of momentum and heat, radiation, and sea ice thermodynamics in the study area revealed a mean surface heat balance of just a few watts per square meter into the snow. Strong snow melting was observed during only a few events, but most of this melt refroze within the remaining snowpack, causing snow settling and the formation of internal ice layers. Therefore, snow thickness decreased by not more than 0.1–0.2 meters during the entire drift. The weak thinning resulted from cooling of the snow by cold and dry air, which caused sensible

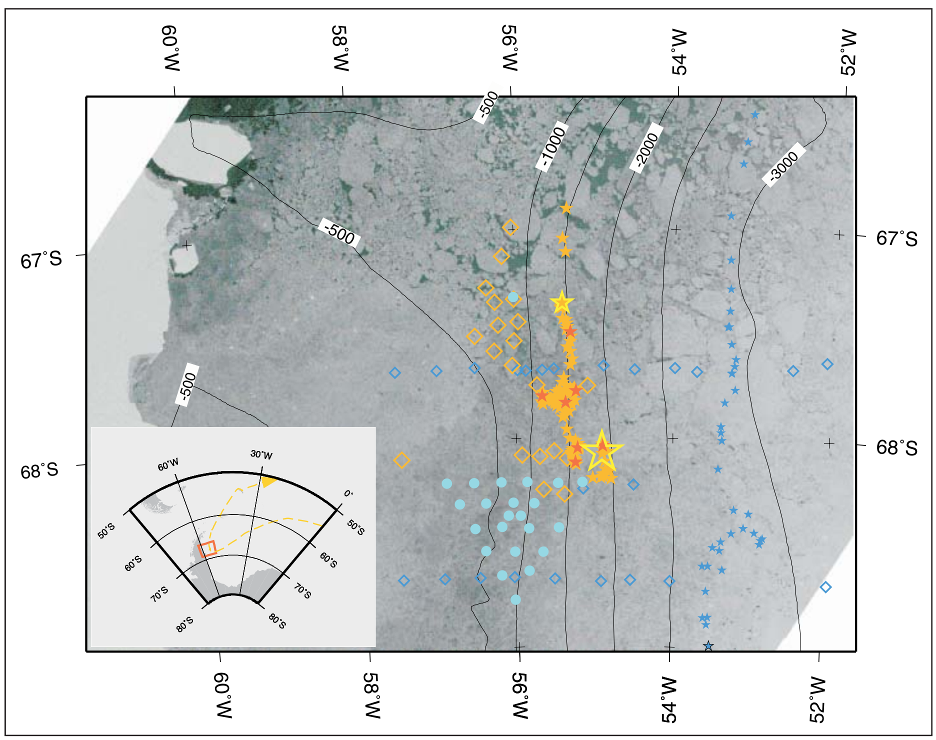

Fig. 1. Envisat synthetic aperture radar image acquired on 30 November 2005, showing the Ice Station Polarstern (ISPOL) study area in the western Weddell Sea (inset, plus cruise track) and the start (27 November 2004, large yellow star) and end points (2 January 2005, small yellow star) of the drift. The western border coincides with the Larsen-C ice front; the northern boundary is close to the sea ice edge. Black contours show water depth in meters. Orange symbols indicate locations of ISPOL ship-CTD (solid) and helicopter-CTD stations (open). Light blue circles represent locations of deployed International Program for Antarctic Buoys. For reference, dark blue symbols show 1992 locations of Ice Station Weddell 1 floe (solid) and helicopter based CTD stations (open). Red stars indicate locations of measurements presented in Figure 2. Note the north-south extent of a dark appearing band of first-year sea ice at about 56°W.

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and latent heat fluxes to be predominantly upward, confirming earlier results of *Andreas and Ackley* [1982].

The albedo, or reflectivity of the snow, decreased slightly from 0.87 to 0.73, not enough to trigger significant snow melt-albedo feedbacks. The automatic measurements of the surface energy balance were hampered by the problem of determining snow surface temperature under conditions of strong radiation, a prerequisite for accurate estimates of the turbulent bulk fluxes. Compared to a reference station 100 kilometers farther north, the ISPOL measurements indicate a large meridional delay in the onset of sea-ice melting.

Sea Ice Physics

In contrast to the Arctic, radar backscatter of Antarctic sea ice increases [*Haas*, 2001] and microwave emissivity decreases [*Willmes et al.*, 2006] during melt onset. This is due to a strong snow metamorphosis, forming ice layers and superimposed ice—snow melt refrozen on top of sea ice—[*Haas et al.*, 2001] in the absence of very wet snow. This change in snow surface properties agrees with the observed low atmospheric energy fluxes, hardly sufficient to heat more than the upper 0.3–0.4 meters of snow to the melting temperature of 0ºC.

Satellite radar imagery by backscatter differences revealed the presence of three major ice regimes, interpreted as second-year ice from the central Weddell Sea, first-year ice formed off the Filchner-Ronne Ice Shelf in the southwestern Weddell Sea during the preceding winter, and heavily deformed first- or second-year ice along the Antarctic Peninsula (Figure 1). Helicopter-borne electromagnetic (EM) ice thickness sounding and ruler stick snow thickness measurements showed that the ISPOL floe consisted of two-meter-thick second-year ice, covered by 0.8 meters of snow, interspersed by locally formed and advected first-year ice with modal thicknesses of 0.9 and 1.8 meters, respectively, and 0.3 meters of snow on top. With modal thicknesses between three and five meters, the deformed ice along the peninsula is among the thickest sea ice on the globe. The EM surveys revealed only a reduction of 0.1–0.2 meters of total (ice plus snow) thickness during the observation period, due mostly to the thinning of the snow layer.

The breakup of large floes into smaller ones and their consecutive crushing to brash ice with floe diameters less than two meters during the spring-summer transition were documented by repeated downward looking aerial photo surveys along the same flight tracks. Floe breakup and brash ice melting is assumed to dominate ice disintegration in the absence of strong atmospheric and oceanic energy fluxes. The brash ice often appeared brownish due to high diatom concentrations, indicating its importance for primary production in the otherwise thick and compact ice cover.

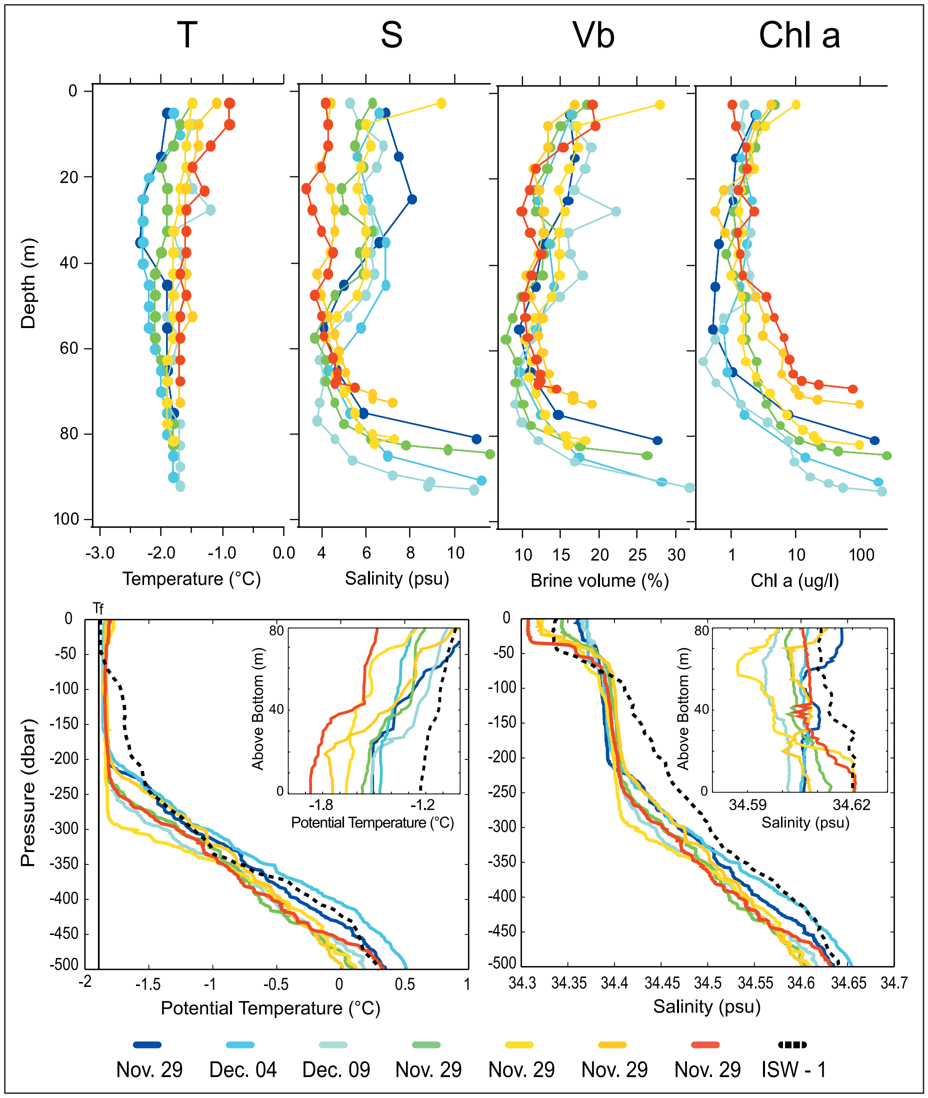

*Fig. 2. Evolution of temperature, salinity, brine volume, and chlorophyll-*a *in thin first-year sea ice with its surface below the ocean surface and slush layer (zero level represents the solid ice surface) together with upper and bottom (insets) ocean temperature and salinity during the course of the experiment inferred from discrete samples in time (colored bars). For comparison, characteristic ISW-1 profiles (dashed black curves) from the ISPOL area (see Figure 1) are added. T_f marks the surface freezing temperature using the lowest ISPOL surface salinity. Spatial variability is inherent in the oceanic profiles due to drift into different oceanic regimes.*

As a contribution to the International Program for Antarctic Buoys (IPAB), 23 buoys were deployed at the beginning of the experiment in a triangular grid of 70 kilometers per side (Figure 1) to study mesoscale ice deformation, complemented by repeated aerial surveys for sea ice thickness, sea ice coverage (percent per unit area), and type. The drifts revealed strong shear, with the eastern buoys closely following the ship's northward drift and the westernmost buoys moving slightly south. The meteorological and sea ice measurements provided new data for modeling sea ice dynamics and deformation, particularly at high temporal and spatial frequencies, to resolve subdaily tidal and inertial forcing. These new data and better models allow an improved estimate of the Southern Ocean's response to climate change.

Sea Ice Biology and Biogeochemistry

Ecological and biogeochemical studies focused on the dynamics and temporal development of sea ice assemblages and biogeochemical processes on, within, and below the ice, as well as on the exchange of carbon dioxide (CO_2), oxygen, and dimethylsulfide (DMS) between the under-lying water column, sea ice, and atmosphere. Recording devices for temperature and oxygen were deployed at different sites, and cores were extracted for analyses ranging from biota biomass and biogeochemical parameters to iron concentrations. The under-ice environment was sampled by means of sediment traps, divers, and a small remotely operated vehicle.

The measurements of chlorophyll-*a* and primary production using radiolabeled isotopes and oxygen optodes showed a continuous increase with time in biomass and primary production in all ice categories. Time series cores revealed a pronounced bottom assemblage with mean chlorophyll-*a* concentrations being one order of magnitude higher in the bottom 10 centimeters than in other core segments (Figure 2).

The striking feature of the CO_2 measurements was the strong undersaturation within the ice with values between 28 and 135 parts per million by volume (ppmv), as opposed to values from both the atmosphere (374 ppmv) and seawater (368–400 ppmv). Within their range, the sea ice values probably reflect the imbalance between CO_2 pumping through primary production of the sea ice biota and limited replenishment through exchange with underlying water and diffusion processes at both the ocean-ice and air-ice interfaces.

DMS concentrations in sea ice were one to two orders of magnitude higher than those measured in seawater, and dimethylsulfoniopropionate (DMSP, an algal precursor of DMS) concentrations were up to three orders of magnitude higher. Although the bulk seawater concentrations increased steadily, they stayed relatively low throughout the drift. On the ice surface and under conditions of high light intensities, elevated rates of DMS photodegradation were observed, indicating that the ice surface is a major sink for DMS, thereby reducing its potential flux to the atmosphere.

Because of the high productivity, dissolved organic matter (DOM) concentrations in the brine were among the highest measured in polar oceans. Since the biogeochemistry of sea ice is largely unknown, it is unclear whether sea ice DOM can survive downward ocean convection. The combination of several molecular tracer techniques will soon allow quantification of the concentration of ice-algal derived DOM in the different water masses and their modification on a large scale. These techniques should answer the question of whether ice-covered oceans act as a DOM pump to the abyssal ocean and sequester carbon from active cycles, and also establish any broader significance of sea ice derived DOM.

ISPOL provided the first evidence of large swarms of adult krill grazing the under-ice algal community deep in the pack (Figure 1). This was also reflected in the sediment trap samples, which contained fecal pellets from zooplankton, particularly krill. In addition, the traps provided evidence of a high diatom flux from the sea ice, indicating a continuous release of ice algae months ahead of enhanced sea ice decay.

Physical Oceanography

The 136 conductivity/temperature/depth (CTD) casts, including 20 profiles with a helicopter CTD, from the continental shelf (Figure 1) revealed wintertime conditions until the end of the drift with little freshening due to brash ice melting and minor warming of the surface water above freezing temperature (Figure 2). Compared to ISW-1, the winter water layer (upper 200 meters) was thicker and fresher, thus increasing the stability of the water column, and the bottom water cooled by 0.5°C.

The continuous layer of bottom water at approximately −1°C, which covered the continental slope in 1992 [*Gordon*, 1998], has been replaced by a patch of bottom water at even lower temperatures with no obvious connection to the continental shelf. The analysis of the 480 helium/neon samples—which were taken from the whole water column using a 24-bottle rosette—revealed that this bottom water originated from water modified by ocean-ice shelf interaction farther upstream. Vertical profiles of thermal microstructure reflected lateral intrusions of upper continental slope water above the topography following density currents. Density flows, intrusions, and the thermocline separating the upper from the deep ocean were accompanied by vertical shear in the horizontal currents, contributing to vertical mixing and therefore to deep water ventilation.

Turbulence instrument clusters mounted not more than 12 meters below the ice base showed different stress and heat flux scenarios superposed by diurnal variation, possibly related to the dominant diurnal tide. With the exception of one strong event (20 watts per square meter), the mean ocean heat flux into the ice was small—between two and five watts per square meter—supporting the results of the sea ice observations. The ratio of ice drift speed to ship wind speed was only approximately 1.36 percent, surprisingly low for early summer conditions but reflecting the high sea ice concentration.

Implications of the Drift Experiment

The comparison of preliminary results—at the first ISPOL scientific workshop in Tvärminne Zoological Station, Finland (9–13 March 2006)—showed that low atmospheric and oceanic energy fluxes in combination with complex ice dynamics maintain a perennial sea ice cover in the western Weddell Sea. Despite its compactness, this ice is home for high amounts of algal standing stocks, which play a significant role in the carbon dynamics of the ice covered ocean and provide the food for krill prior to ice decay. This pack also covers an ocean in which deep and bottom water is formed, but with a higher spatial and temporal variability than previously assumed. Therefore, the ISPOL results significantly contribute to our understanding of the role of sea ice in the climate and ecosystems.

All metadata according to the Global Change Master Directory (GCMD), updated information on scientific progress, and future activities are available at http://www.ispol.de. A photographer (I. Arndt) and writer (C.-P. Lieckfeld) joined ISPOL and published a book (in German) entitled *Logbuch Polarstern: Expedition ins antarktische Packeis* (ISBN 3-89405-654-1).

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Author Information

Hartmut H. Hellmer, Christian Haas, Gerhard S. Dieckmann, and Michael Schröder, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; E-mail: hhellmer@awi-bremerhaven.de