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Weddell Sea Exploration from Ice Station

Arnold L. Gordon and Ice Station Weddell Group of Principal Investigators and Chief Scientists

On January 18, 1915, the *Endurance* and Sir Ernest Shackleton and his crew were stranded in the ice of the Weddell Sea and began one of the most famous drifts in polar exploration. Shackleton turned a failure into a triumph by leading all of his team to safety [*Shackleton*, 1919]. The drift track of the *Endurance* and the ice floe occupied by her stranded crew after the ship was lost on November 21, 1915, at 68°38.5′S and 52°26.5′W, carried the group along the western rim of the Weddell Gyre, representing a rare human presence in this region of perennial sea-ice cover.

Seventy-seven years later, in 1992, the first intentional scientific Southern Ocean ice drift station, Ice Station Weddell-1 (ISW-1), was established in the western Weddell Sea by a joint effort of the United States and Russia. ISW-1 followed the track of the *Endurance* closely (Figure 1) and gathered an impressive array of data in this largely unexplored corner of the Southern Ocean, the western edge of the Weddell Gyre.

The Weddell Gyre is the largest of the cyclonic-flowing gyres occupying the region south of the Antarctic circumpolar current. Its environmental setting makes it an active element of the global climate system. Ekman-induced regional upwelling of the relatively warm saline deep water leads to brief residence time of the cold, fresher surface layer—about 2 years, compared to 5 years for the Arctic surface water—and a somewhat stable water column. Coupling of the Weddell waters with the cold polar atmosphere across a highly variable sea-ice cover forces vigorous vertical fluxes of heat and moisture, salinity, dissolved gases, and nutrients. These fluxes initiate feedbacks with the atmosphere and ice cover, influence the biology, and ventilate the world ocean with cold, oxygenated water. A central product of the ventilation is the cold Antarctic Bottom Water (AABW) that is carried by the western boundary current of the Weddell Gyre into the circumpolar belt to flood and chill the lower kilometer of the world ocean. In the 1980s, a series of winter and spring expeditions (*Somov*–1981; *Polarstern*–1986, 1989; *Fedorov*–1989; see *Gordon and Huber* [1990]) provided a more precise view of the coupling of the deep water with the winter mixed layer and its control of the seasonal sea ice distribution and thickness.

During the winter, nearly all of the Weddell Gyre is covered by sea ice. In the gyre's western rim, however, there is a high concentration of perennial sea ice that has hindered even basic exploration of this important region. Observations from ships are nonexistent in the western Weddell between 65° and 70°S west of 50°W, leaving a vast region unexplored except by satellite-borne sensors, recent aircraft-based geophysical observations, and instrumented drifters placed on the ice. Basic questions remain that can only be addressed with detailed in-situ observations. These include: Why is

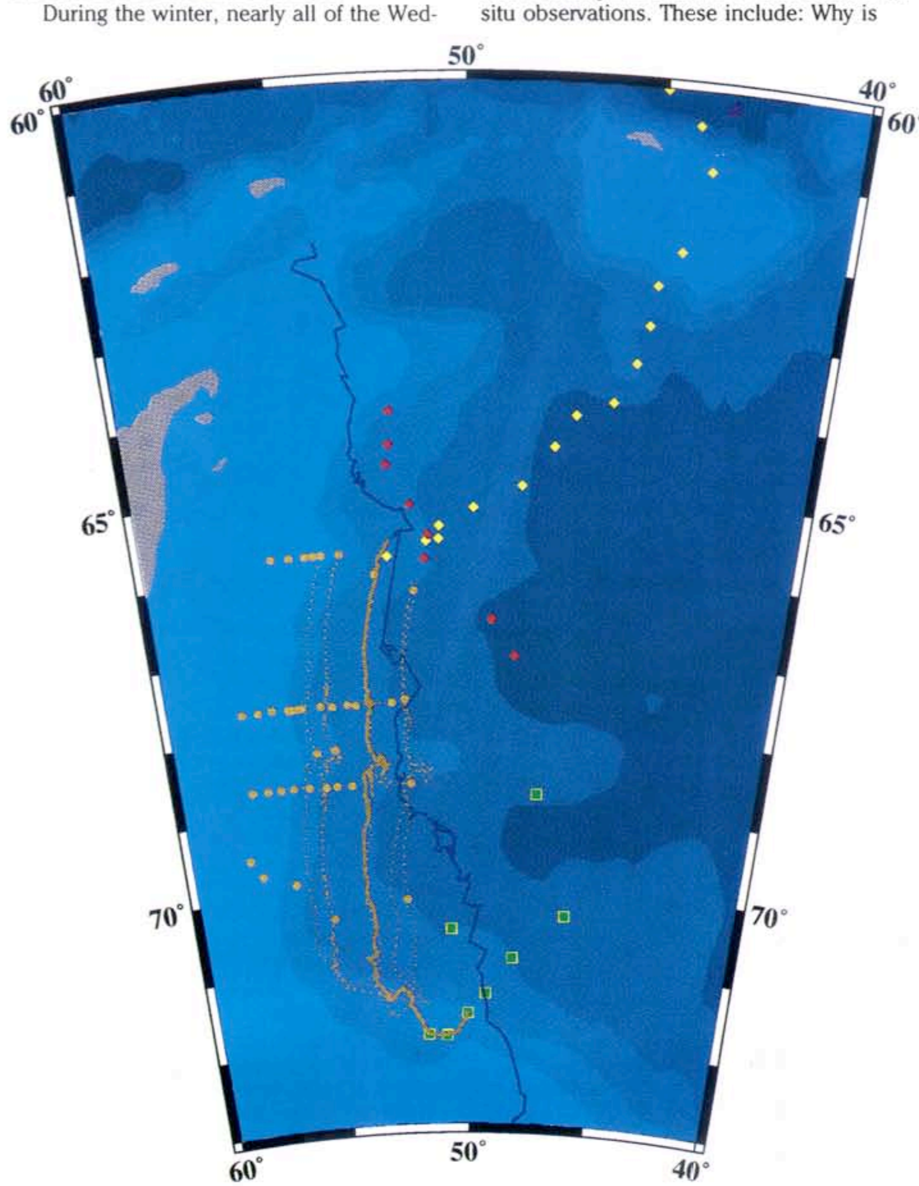

Fig. 1. Map of activities of Ice Station Weddell-1 with the track of the Endurance *and bottom topography. The solid orange line is the drift of the ISW ice floe; the dotted orange line shows the drift of the five ice buoys; the larger orange circles mark the position of the helicopter-based CTD stations; the green squares are CTD stations obtained from* Fedorov *during the deployment phase; the red diamonds are CTD stations obtained by* Palmer *cruise 92–1 (the April 1992 rotation cruise); and the yellow diamonds are* Palmer *cruise 92–2 CTD stations obtained during the recovery phase. The track of the* Endurance *and subsequent ice station occupation are shown as a dark blue line.*

Arnold L. Gordon, Lamont-Doherty Earth Observatory, Palisades, NY 10964

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there an extensive perennial ice cover in the western Weddell?, how climatically stable is it?, do ocean processes along the western rim of the Weddell Gyre contribute to the formation or further modification of AABW?, and, what is the structure of the western boundary current that delivers Southern Ocean products to the world ocean? Even the location of the continental slope has not been firmly established.

An effective way to gather extensive observations in the ice-cluttered western Weddell is to borrow a successful method from the Arctic: deployment of a scientific station on a drifting ice floe. In 1988, the concept for ISW-1 was initiated by scientists of the Arctic and Antarctic Research Institute in St. Petersburg and U.S. scientists sponsored by the National Science Foundation's Division of Polar Programs. Detailed planning followed from 1989 to 1991 with field deployment in February 1992. The extensive experience of the two nations in ice station operation helped meet the challenges of establishing a scientific ice station in an unexplored part of the Southern Ocean.

In the spirit of basic exploration of an unknown region, the science program spanned many disciplines. Included were measurements of thermohaline and tracer fields, currents, and turbulent fluxes within the oceanic and atmospheric planetary boundary layers; the study of the physical, chemical, and biological characteristics of sea ice; sea-ice dynamics; and water column biology. U.S. and Russian science programs complemented each other to yield a more complete picture of the environment. Observations were made at the ISW-1 site and from remote instrumented drifters, helicopters, and ships associated with the various phases of the work (Figure 1).

Drift of the ISW-1 floe from February 12 (71.4°S) to June 4, 1992, (65.8°S) was 750 km at a mean speed of 6.6 km/day. The smoothed drift distance and direction is nearly 700 km and 357°, respectively. The maximum drift per day was 25 km on May 24 and the minimum was 0.5 km on February 27. The drift track was relatively smooth and, in general, was determined by the wind. Figure 2 shows a general drift to the left of the wind vector as expected from Ekman dynamics. After a warm spell in February, the noon air temperatures were mostly in the −20°C range but reached as low as −35°C (Figure 2).

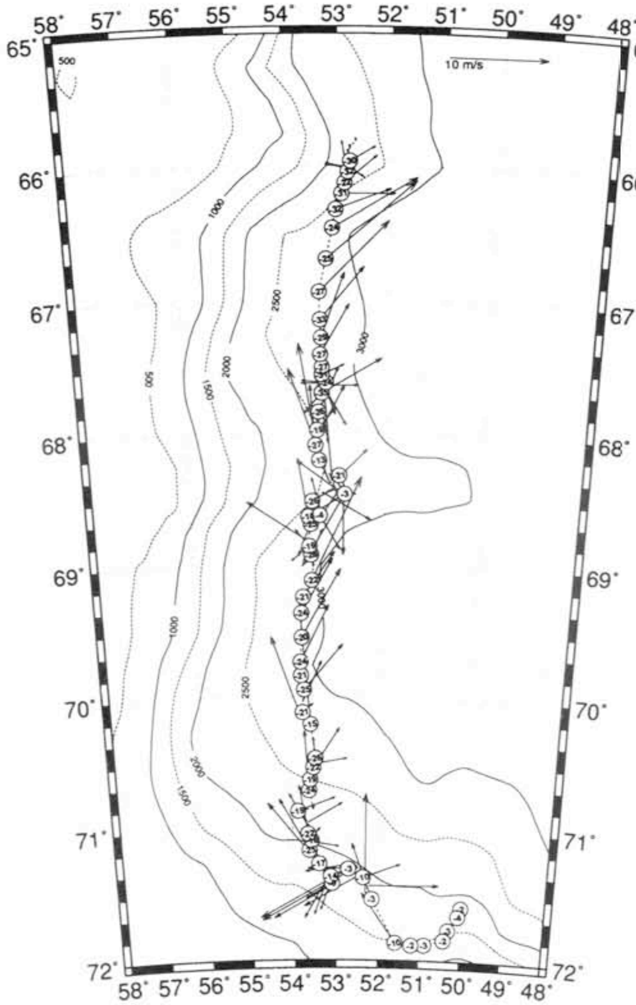


Fig. 2. Ice Station Weddell-1 drift track, with noon wind and air temperature values. Wind vectors point toward the direction in which the wind is blowing.

Atmospheric Measurements

The American-Russian meteorology program on ISW-1 [*Andreas et al.*, 1992; *Makshtas et al.*, 1992] measured wind speed, direction, air temperature, humidity, and barometric pressure almost continuously with several different instruments. Vertical profiles of wind speed and temperature were recorded, as were a complete suite of radiation and sea-ice surface temperature data, with both a precision infrared radiation thermometer and a hygrometric technique. Finally, direct measurements of the Reynolds fluxes of momentum, heat, and moisture were made with fast-responding instruments. An early result of these data suggests that the air-ice drag coefficient ranges from 1.3 to 2.5×10^{-3} and varies with the orientation of the wind over the ice floe, changing by as much as 50% with only a 10° shift in wind direction [*Andreas and Claffey*, 1992].

Upper-air soundings were made nominally at 12 P.M. and 12 A.M. GMT during the entire drift with either tethered or free-flying radiosondes [*Claffey et al.*, 1992]. The tethered radiosondes recorded pressure, air temperature, dew point, wind speed, and direction. The free-flying radiosondes recorded only pressure, air temperature, and dew point. The height parameter for both types was determined from the pressure sensor on the sonde by integrating the hydrostatic equation. The radiosounding program gave early insight into the structure and physics of the atmospheric boundary layer (ABL) (Figure 3). The ABL was shallow (100- to 300-m thick) with stable stratification. It had weak surface winds, typically 2–3 m/s topped with an atmospheric jet in which speeds were 14–15 m/s. On April 20, 1992, for example, the air temperature was −16.9°C at the surface and 0°C at 240 m. Surface wind was 3 m/s but values of over 11 m/s were measured in the jet core at 100 m. At times, the stable ABL broke down, and the high-energy jet mixed down to the surface and produced rapid northerly drift.

Sea Ice

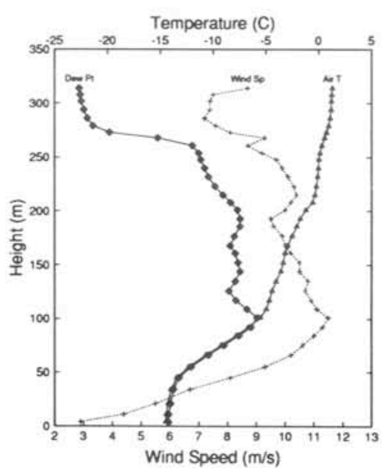
Churun et al. [1992] find the ISW-1 floe was composed of a matrix of first-year ice interspersed with cakes of multiyear and first-year ice (ice breccia). The multiyear ice cake pieces had horizontal dimensions of 8–10 m and average salinities and thicknesses of 3 ppt and 1.8 m, respectively. Many small-scale surface and bottom features contributed to a high point-to-point variability in the relief and consequently in the ice thickness. The first-year ice had salinities of up to 15 ppt and pieces varying from 90- to 150-cm thick, each with a relatively flat bottom. The variation in first-year ice thickness reflects distinct events in the formation history of the floe. Sea-ice dynamics and thermodynamics were measured to identify contributions to net ice production during the period of the station drift. Using eight imbedded thermister strings placed in a sampling of the various ice thicknesses found on the ISW-1 floe (0.5- to 4-m thick), along with core sampling and snow pits at these same sites, concurrent measurements of the thermodynamics and evolving physical structure of the ice were made [*Ackley et al.*, 1992]. Ice dynamics processes were measured from imbedded stress sensors at several local sites on the station floe and from Global Positioning System (GPS) and Argos positioning of the station drift and several remote sites, placed as shown in Figure 1. From these measurements, we estimate new ice growth of the order of 0.5 m from a combination of three processes: lead formation and ridge building, freeze-back of flooded surface snow, and freezing of internal void layers within the thicker ice. This production is of the same order as the annual mean thickness of sea ice formed to the east of this region by in-situ freezing as the ice edge advances. The new ice production in the western edge of the Weddell Gyre is, therefore, similar to that of the central and eastern portions although the formation processes are quite different in the two regions.

Thermohaline Stratification

CTD measurements at ISW-1 [*Gordon and Huber*, 1992] (Figure 1) consisted of conductivity, temperature, and depth (CTD)/hydrographic casts to the seafloor at the ISW-1 site with a nominal spacing of 10 km along the drift track (the Russian CTD program obtained daily stations to 1000 m) and CTD casts using lightweight equipment flown by helicopter to remote sites (hCTD). Seventy CTD/hydrocasts were obtained at the ISW-1 site using nonconducting wire with up to fifteen 5-L bottles per station with an internally recording CTD profiler. Water samples were drawn and analyzed for salinity and dissolved oxygen. Additional samples were drawn for later analysis of tritium, helium, oxygen-18, and chlorofluorocarbons. There were thirty-seven hCTDs, mostly bottom-reaching stations forming four sections perpendicular to the drift track reaching onto the continental shelf. CTD/rosette casts were also obtained from the *Akademik Fedorov* and the *Nathaniel B. Palmer* during deployment, rotation, and recovery of the ice station. The array of 137 CTD measurements from a variety of sources opens up the western edge of the Weddell Sea to a thorough water mass analysis.

The water column at the ice station (Figure 3) is characterized by a relatively thin (mostly 50- to 125-m thick) surface mixed layer that became more homogeneous as the winter progressed (or as the floe carried ISW-1 to the interior of the perennial ice regime). In the mid-pycnocline there is a layer of greater stability than that found within the seasonal sea ice zone; this stability may account for reduced oceanic heat flux in the western Weddell [*McPhee et al.*, 1992] relative to heat flux in the east [*Gordon and Huber*, 1990]. A stable layer would suppress vertical exchange in the southern extent of the perennial ice regime during the critical spring season, thus allowing the sea ice to survive through the summer and following winter, splaying out the perennial ice cover as the ice drifts north. Stations seaward of about the 2500-m isobath reveal the frequent occurrence of thermohaline steps within the pycnocline, extending a pattern of such features observed elsewhere in the Weddell Gyre.

Perhaps the most unexpected observation is the persistent, thin (200- to 300-m thick), very cold, highly oxygenated bottom boundary layer over the seafloor seaward of the shelf break (Figure 3). The bottom layer often displays increased salinity at the seafloor, while the lower-salinity bottom water lifted slightly off the seafloor bears a greater concentration of glacial melt. The complex of benthic layer water can be traced to slope plumes forced by export of various layers of shelf water, with a likely role for cabballing and thermobaric "equation of state" processes. The saltiest bottom water involves outflow from the salty shelf water off the Ronne Ice Shelf. Clearly, the western edge of the Weddell injects additional bottom water into the western boundary current. Near 66°S, the thin benthic layer suddenly mixes up into the water column by at least 800 m. The *Nathaniel B. Palmer* CTD data extend to the north and northeast of the ISW-1 stations. Bottom water emerging from the western Weddell gives no hint of the complex layering of water types in the thin benthic layer along the western edge of the Weddell revealed for the first time by these ISW-1 data.



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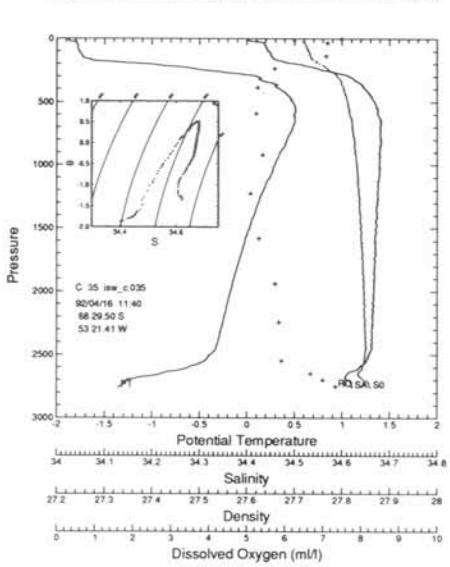

Fig. 3. Vertical profile of various parameters above and below the ice cover. The ocean profiles show potential temperature (PT), salinity (SA), oxygen (+), and sigma-0 (SO) at ISW-1 CTD station #35 (68° 29.50'S and 53° 21.41'W). The minimum in sigma-0 near 2670 m does not appear if density is reported with reference to higher pressure, for example sigma-2. The insert shows the full ISW temperature/salinity relationship in gray and that of station 35 in black. The atmospheric profiles show wind speed, air temperature, and dew point with distance above the snow surface.

Seafloor depth measurements were obtained at each CTD and hCTD station by precision depth recorder and acoustic pinger mounted on the wire. These data indicate that the continental margin is nearly 100 km west of the position indicated on the *General Bathymetric Chart of the Oceans*, confirming similar conclusions based on remote measurements of gravity and magnetic anomalies [*LaBrecque and Ghidella*, 1992].

Current Measurement

Time-series observations of currents were obtained from the western Weddell Sea from February to June 1992 using current meters suspended beneath the drifting ice [*Muench et al.*, 1992]. These measurements were obtained from 25-, 50-, and 200-m depths at a primary ISW-1 site and from 50- and 200-m depths at secondary sites 50-km east, 50-km west, and 100-km west of ISW-1. All four sites drifted northward during the approximately 4-month deployment, yielding records of upper-layer currents along the ISW-1 drift and zonally from the deep basin well to the continental slope of the Antarctic peninsula. Record-long mean ice-drift speeds were about 7 cm/s northward at each of the current meter sites. Record-long mean currents were primarily northward at each site. Mean 50-m northward current speed was greatest (about 5 cm/s) at the westernmost site and least (about 1 cm/s) about 50 km to the east of ISW-1. Mean upper-layer vertical shear was less than 0.5 cm/s between 50 m and 200 m. The dominant northward mean flow, westward increase in northward speeds, and very weak vertical shear are consistent with a predominantly barotropic, western intensified boundary current. Fluctuations with typical amplitudes of 10–20 cm/s were superposed on the mean flow and consisted of semidiurnal tidal, inertial, and lower-frequency "mesoscale" signals, some of which were associated with sharply elevated temperature at 200 m and may have been eddies.

Ocean Fine- and Microscale Structure

A special effort was made to measure the smaller-scale thermohaline and turbulent processes in the upper ocean for estimation of the vertical fluxes of heat, salt, and momentum from the pycnocline to the ice base. Temperature was measured at a 2-minute sampling rate at fifteen depths from the surface to 300 m. Over 600 microstructure profiles of temperature, salinity, and turbulent mixing rates were obtained from the surface to 340 m [*Padman and Levine*, 1992]. The temperature data recorded the destruction of the seasonal mixed layer during the austral autumn as well as mesoscale variability in the permanent pycnocline. The microstructure profiles revealed that no appreciable turbulent mixing occurred below the surface layer, which was mixed by the stress at the ice/water interface. Diapycnal fluxes in the permanent pycnocline are apparently limited to double-diffusive processes associated with diffusive-convective steps and large-scale intrusive activity. Preliminary estimates of heat fluxes through the larger thermohaline steps are of the order of 1–10 W/m^2. The microstructure profiles are also useful for investigating the mechanisms of decay of the seasonal pycnocline. Within the seasonal thermocline, mixing is a combination of episodic entrainment driven by surface stress and buoyancy flux and intermittent shear-driven instabilities that can occur in the absence of surface forcing.

McPhee et al. [1992] reported direct measurement of upper-ocean turbulent fluxes of momentum and heat at the ISW-1 site and inferred surface fluxes from buoy measurements at site Chris, about 50 km west. At ISW-1, turbulence clusters measuring velocity, temperature, and conductivity six times per second were mounted at 4-m intervals from the surface to 24 m below the ice/ocean interface. The unmanned data buoy cluster includes a basic meteorological package, temperature and conductivity pairs at six levels to 300 m, a high-resolution thermistor chain, and a travel-time acoustic current meter at 10 m. ISW-1 turbulence data from a storm in late March show an Ekman boundary layer with marked leftward turning of the relative velocity with depth, including an Ekman spiral in the horizontal Reynolds stress. A similarity model fitted to the stress observations implies an effective eddy viscosity of about 150 cm^2/s. Over 12 hours of the storm, heat flux varied from a maximum near 4 W/m^2 (upward) to slightly negative and was relatively uniform over the upper 24 m of the water column.

Preliminary analysis has been conducted using a one-dimensional, upper-ocean/sea-ice model [*Martinson et al.*, 1992]. This model has proven successful in simulating observations collected in seasonal sea ice further east. The initial model testing should determine if the vertical processes responsible for the seasonal sea-ice zone to the east can account for the thicker ($\sim$2 m) perennial ice in the west or if additional processes must be invoked (for example, lateral fluxes or enhanced freshwater influx). Initial results using idealistic monthly average winds and buoyancy forcing produce about 64 cm of ice growth over the 4 months of the drift. Growth was limited to a 5% lead area (equivalent to an average growth of about 10 cm/day in the leads). This area is elevated slightly above the observed in an attempt to account for the salinity influence of the growth associated with ice flooded by seawater. The mixed layer steadily deepens throughout the drift as a result of ice growth. The actual erosion of the seasonal pycnocline was more erratic, but since the overall deepening reflects densification due to growth, the agreement between the model and observations is good (both give a mixed layer depth of $\sim$100 m on day 123). The mixed layer is maintained predominantly by turbulent mixing. Vertical heat fluxes into the surface mixed layer were $<$5 W/m^2 (compared to $\sim$25–40 W/m^2 to the east), in good agreement with the actual measured fluxes analyzed to date.

Biology

ISW-1 provided a unique opportunity to perform time series investigations of sea-ice microbial communities (SIMCO) to assess primary and secondary microbial production in the Antarctic pack-ice ecosystem. *Sullivan et al.* [1992] report on the ISW-1 biological program. The distribution of microalgal and bacterial biomass activity, as well as physico-chemical factors that influence the growth and accumulation of the microbial communities within first- and second-year pack ice were investigated at three sites. Each site revealed different habitat features along vertical profiles through the 0.3- to 2.05-m thick ice. Estimates of total algal pigments (chlorophyll and phaeopigments) from 10-cm sections of ice cores and vertically integrated pigments at each site reveal high vertical and horizontal variability of the SIMCO biomass distribution. Changes in concentration of key inorganic nutrients essential for algal growth were examined at all sites. Differences in physiological and chemical composition of SIMCOs along steep physico-chemical gradients within the ice suggest possible in-situ metabolism. During the course of the investigation, vertically integrated pigments increased substantially at two sites but only slightly at a third site. This indicates that net growth and accumulation may have taken place in situ, but similar patterns of particulate organic carbon and particulate organic nitrogen net accumulation, not yet analyzed, are necessary to confirm this. However, photosynthetic rate experiments with ice algal communities, incubated in situ for 24 hours, showed net fixation of ^{14}C-bicarbonate in support of the observed in-situ growth based on biomass change. These results indicated that pack-ice microbial communities grow in the extensive Antarctic sea-ice zone and should be considered in future models of Southern Ocean production.

Summary

Ice Station Weddell-1 may best be summarized by quoting a section of the closing statement prepared on June 9, 1992, at 65.63°S and 52.41°W aboard R/V *Akademik Fedorov* and R/V *Nathaniel B. Palmer* (see *Gordon and Lukin* [1992], for the complete closing statement): "The difficult environmental conditions of the western Weddell Sea have previously prohibited data collection in this segment of the Southern Ocean. Only now in the closing decade of the 20th century has this region been thoroughly observed through this joint effort. Ice Station Weddell-1, the first drift station of the Southern Ocean, becomes an important part of the history of Antarctic exploration, filling a large gap in our view of this remote part of the global ocean."—*Chairman of the Soviet Antarctic Expedition V. V. Lukin, and Chief Scientist for Ice Station Weddell-1, Arnold L. Gordon*

ISW-1 Group of Principal Investigators and Chief Scientists

Arnold L. Gordon, Jay Ardai, Hartmut Hellmer, Bruce Huber, Douglas Martinson, and Peter Schlosser, Lamont-Doherty Earth Observatory of Columbia University, Palisades, N.Y.; Valery Lukin, N. Kornilov, A. Danilov, A. Makshtas, V. Churun, N. Bagrantisev, and I. Melnikov, Arctic Antarctic Research Institute, St. Petersburg, Russia; Laurence Padman, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis; Robin Muench, Science Applications Inc., Bellevue, Wash.; Steve Ackley and Edgar Andreas, U.S. Army Cold Regions Research & Engineering Lab., Corps of Engineers, Hanover, N.H.; Jamie Morison, University of Washington, Polar Science Center, Seattle; Miles McPhee, McPhee Research Company, Naches, Wash.; Cornelius Sullivan, Hancock Institute of Marine Studies, Graduate Program in Ocean Science, Los Angeles, Calif.

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