Ocean and Climate Sciences

Cape Denison, eastern Antarctica: The windiest place on Earth

Gerd Wendler *and* Uwe Radok, *Geophysical Institute, University of Alaska, Fairbanks*

In 1911, the Australasian antarctic expedition led by Douglas Mawson sailed to Antarctica to explore the area close to the magnetic South Pole. Mawson established his main station at Cape Denison (67°1'12" S, 142° 40'48" E), in Commonwealth Bay (figure1). The ship encountered no sea ice in the coastal area and thus was able to reach the shore. The absence of sea ice might have been taken as an indication of strong winds from the continent, and indeed, the wind speeds observed from February 1912 to October 1914 were the highest found anywhere, close to sea level, on Earth (Madigan 1929, Kidson 1946). Mawson (1915) reported on this in his popular description of the expedition, properly entitled "The Home of the Blizzard". The wind speeds he recorded were doubted after returning from Antarctica; and a recalibration of his "puff-ball" anemometer in a wind tunnel reduced the calibration constant for strong winds as much as 20 percent. It was later speculated that the corrections were excessive, but even after this adjustment, the values, an annual mean wind speed of 19.1 meters per second (ms-1) was established. The speeds were less severe during the summer months and had a very broad maximum during the rest of year. Hence, the maximum did not necessarily occur in mid-winter. This might be expected because the katabatic wind is driven by thermal contrast, and the annual course of the temperature variations include a coreless winter (Wendler and Kodama 1993).

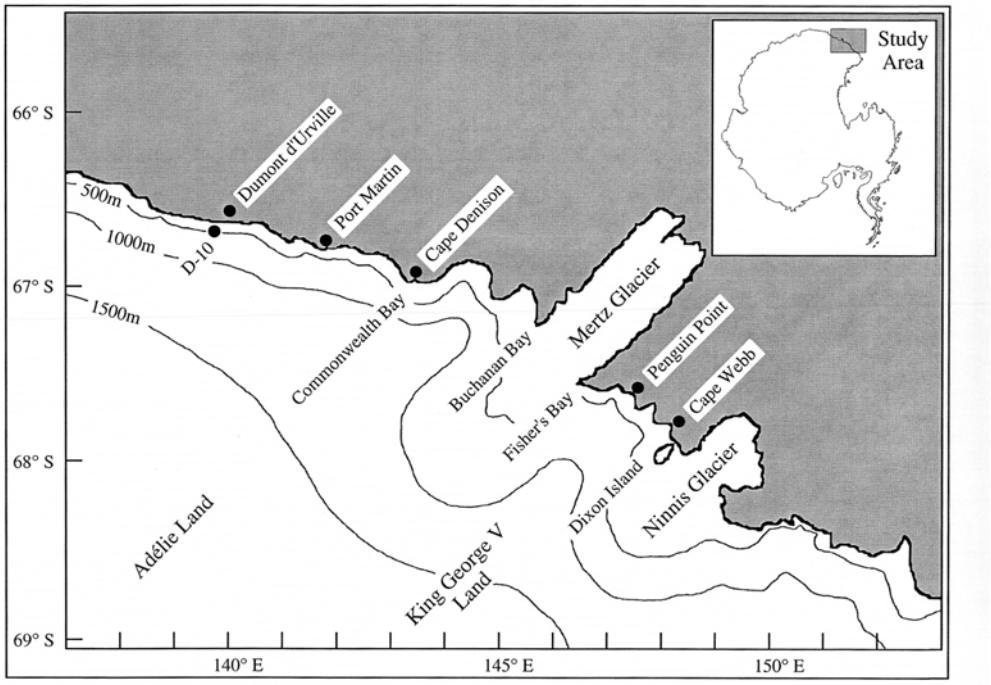


Figure 1. Area map of Adélie Land, East Antarctica.

Some 40 years later, the French established the station Port Martin, some 62 kilometers west of Cape Denison. The wind conditions there were also extreme, and a mean annual wind velocity of 17.9 ms-1 was calculated (Boujon 1954). Together, these results suggest that these extraordinarily strong katabatic winds were not limited to a specific site but rather dominate part of the coast, a conclusion reinforced by Parish's analysis (1981) of data from Mawson's sledding parties.

In 1952, Port Martin was destroyed by fire, and the French moved their base to a summer camp 64 km west to Ile des Petrelles, an island 2 km from the coast. Here, the mean annual wind speed was 10.5 ms-1, about half that measured at the other two stations. The French therefore chose this site for their International Geophysical Year station Dumont d'Urville, which became the only station along the coast to develop a long — and still continuing — climataological record (Periard and Pettré 1993). Cape Denison and Port Martin were never occupied again on a year-round basis, and it was only with the advance of remote data sensing techniques that new climate data could be collected at these sites.

By 1980, automatic weather stations (AWS) had become sufficiently advanced to be used in Antarctica (Stearns 1982). These stations, which transmit their data by satellite, measure temperature, humidity, atmospheric pressure, and wind speed and direction. An initial AWS array was established from close to Dumont d'Urville up to Dome C, at 3,280 meters altitude, and some 1,080 km inland. Some 10 years later, the coastal station array shown in figure1 was set up. At Cape Denison we were able to

locate and occupy the "Anemometer Hill" where Mawson's expeditions had carried out their wind observations. The wind speeds from the new data collected there and at Port Martin were indeed very high (Wendler et al. 1997), while the stations to the east and west reported much less extreme conditions. Often our wind sensors did not survive the extreme winds, however, and thus provided only a frequently broken record, which nonetheless indicated that the maximum speeds could occur in fall, accelerated by the thermal contrast between the already cold continent and the still ice-free ocean.

During the summer of 1994-1995, very rugged anemometer built by Hydrotech (Taylor) in Washington became available and was installed at our stations, for the first time allowing us to gather year-round data. Cape Denison was confirmed as the windiest place, close to sea level, on Earth (figure 2). In each of 4 consecutive months, we recorded a mean monthly wind speed in excess of 25 meters per second. The highest speed, 27.7 ms-1, was in June; the second highest wind speed, 27.2 meters per second, in March. Eight months of the year had mean monthly wind speeds above 24 meters per second. For 5 months the maximum wind speeds exceeded 50 meters per second. Directional constancy was high throughout the year. Even its minimum in December remained well above 90 percent. A secondary minimum occurred in mid-winter; this may have been a feature of the 1995 winter only. Hurricane wind speeds (>32 meters per second) were observed during 19.9 percent of the time, and during 29.2 percent of the time in the winter months.

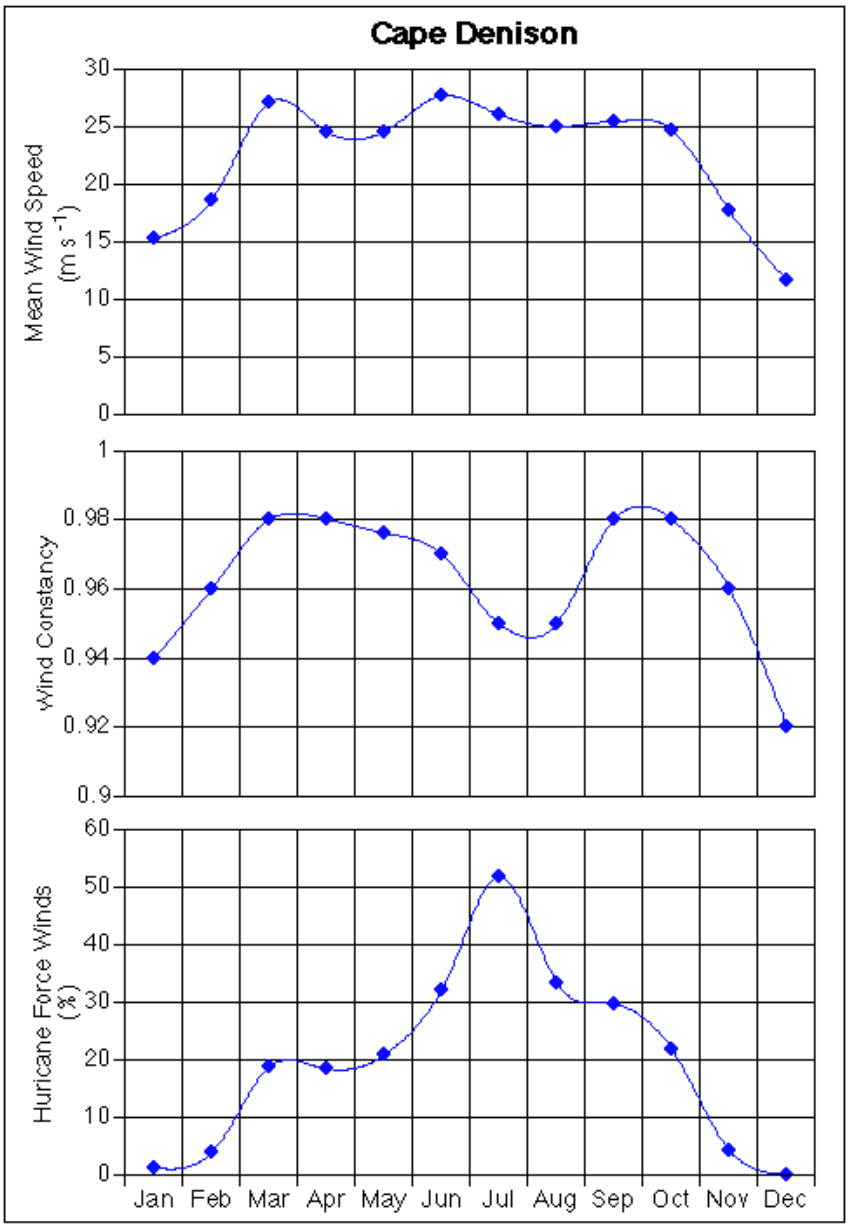


Figure 2. Annual course of wind speed, wind directional constancy, and frequency of hurricane-force winds (>32 ms^{-1}) at Cape Denison, Commonwealth Bay.

In addition to the gravitational force (Ball 1960, Radok 1973), these extraordinary winds reflect a funneling of the flow by terrain features. Model simulation of the antarctic surface winds identified the Adélie Land coast as one of the major confluence regions (Parish and Bromwich 1987). A detailed model of this coastal region (Parish and Wendler 1991) provides wind data, which we compared with our measurements in figure 3. While the model overestimates the annual mean wind speeds both to the west (D10) and to the east (Cape Webb) of Cape Denison, the general trends — and the maximum at Cape Denison — are in good agreement with the measurements.

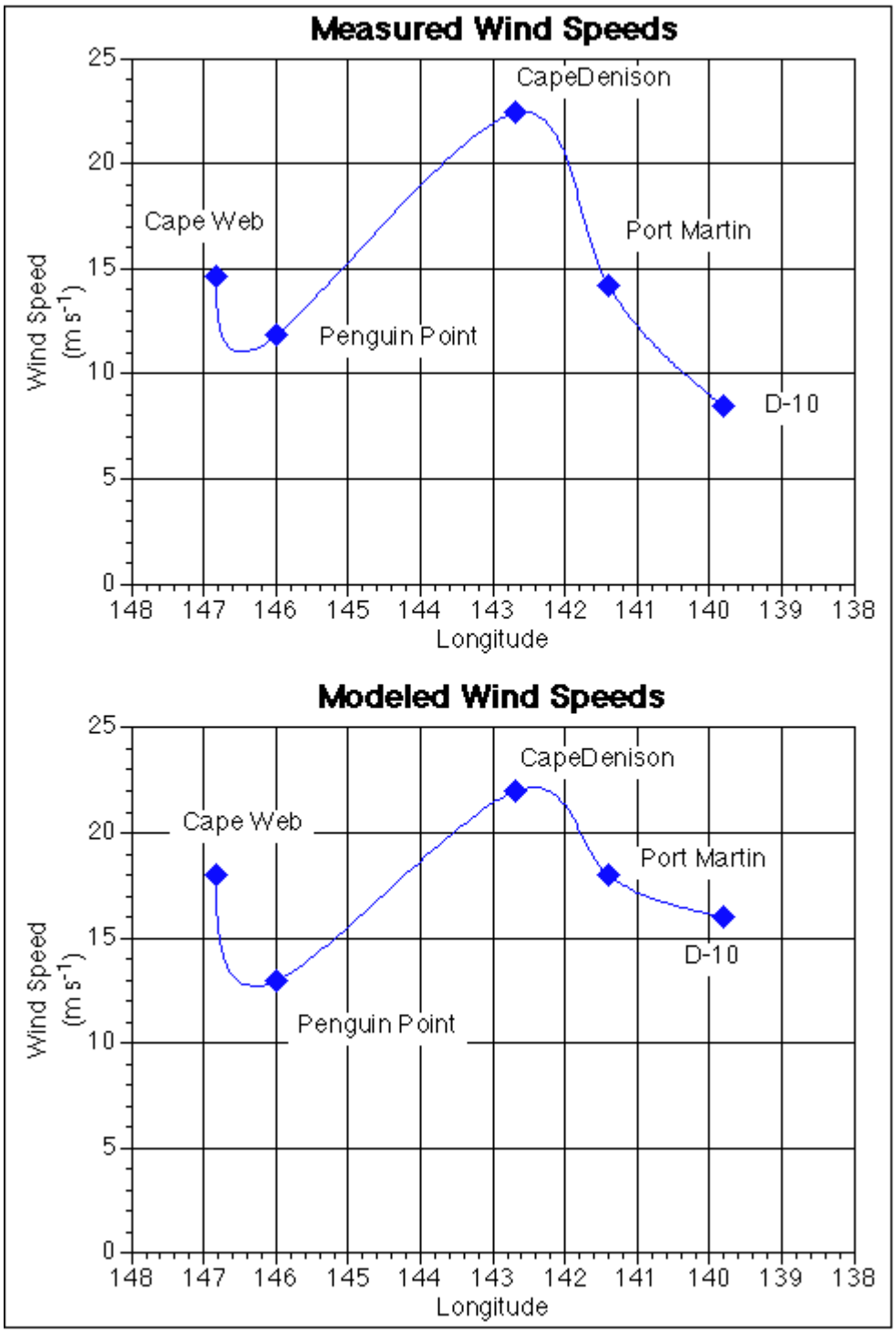


Figure 3. Measured and modeled annual mean wind speed for coastal stations in Adélie Land between 139ºE and 147ºE. The modeled values were deduced from figure 5c by Parish and Wendler (1991).

Finally, the mean annual wind speed we measured in 1995 was 22.4 meters per second. This is 17 percent higher than the "corrected" wind speeds of Mawson's

expedition, indicating that those corrections were overdone, as Loewe (1972) had demonstrated.

This study was supported by NFS Grant OPP 94-13879. Our thanks go to many people from the U.S. Coast Guard Cutter Polar Star, U.S. Antarctic Program and Expeditions Polaires Françaises, without whose help this study could not have been carried out. Blake Moore did the data reduction and Gunter Weller made valuable comments.

References

Ball, F.K. 1960. "Winds on the ice slopes of Antarctica" in *Antarctic Meteorology*, 9-16, New York: Pergamon Press.

Boujon, H. 1954. Meteorological observations at Port Martin in Adélie Land, 66º 49'04" S 141º23'39" E, altitude 14 meters, Section1. Surface and upper atmospheric conditions from February 14, 1950 to January 14, 1951, daily tables and commentaries. [Les observations météorologiques de Port-Martin en Terre Adélie,. Fasc. I, Conditions atmosphériques en surface et en altitude du 14 Février 1950 au 14 Janvier 1951: Relevés quotidiens et commentaires.] *Expeditions Polaires Francaise*, Series S, 5, 167 pp

Kidson, E. 1946. *Meteorology. Discussions of observations*, Australasian Antarctic Expedition 1911-1914, Scientific Report, Series B, VI, 120 pp

Loewe, F. 1972. The land of storms. *Weather*, 27 (3), 110-121.

Mawson, D. 1915. *The Home of the Blizzard*; being the story of the Australasian Antarctic Expedition 1911-1914, 438 pp., London: W. Heinemann.

Parish, T. R. 1981. The katabatic winds of Cape Denison and Port Martin. *Polar Record,* 20 (129), 525-532

Parish, T.R., and D.H. Bromwich. 1987. The surface windfield over the Antarctic ice sheets. *Nature,* 328 (6125), 51-54

Parish, T. and G. Wendler. 1991. The katabatic wind regime at Adélie Land, Antarctica. *International Journal of Climatology,* 11 (1), 97-107

Periard, C., and P. Pettré 1993. Some aspects of the climatology of Dumont d'Urville, Adélie Land, Antarctica. *International Journal of Climatology* ,13 (3), 313-327

Radok, U.1973. On the energetics of surface winds over the Antarctic Ice Cap. Energy fluxes over polar surfaces. In Proceedings of the IAMAP/IAPSO/SCAR/WMO Symposium, Moscow. *Tech.* Note 129, pp. 69-100, World Meteorological Organization, Geneva

Stearns, C. 1982. Automatic weather station technical manual. Department of Meteorology, University of Wisconsin, Madison.

Wendler, G., and Y. Kodama 1993. The kernlose winter on Adélie Coast. In D.H. Bromwich and C.R. Stearns (eds.) *Antarctic Meteorology and Climatology: studies based on automatic weather stations*, Antarctic Research Series, Vol.61, 130-147. Washington, D.C.: American Geophysical Union.

High levels of ultraviolet radiation observed in November 1998 at Amundsen-Scott South Pole Station

Germar Bernhard, Charles R. Booth, *and* James C. Ehramjian, *Biospherical Instruments Inc.*

A decrease in atmospheric ozone concentration leads to increased levels of biologically harmful solar ultraviolet (UV) radiation at the Earth's surface. Motivated by the discovery of substantial ozone depletion over Antarctica in the 1980s, the National Science Foundation (NSF) initiated the development of a high-latitude monitoring network for UV radiation. The network, established in 1988, currently consists of six monitoring sites: three in Antarctica; Ushuaia, Argentina; Barrow, Alaska; and San Diego, California. The antarctic sites are Amundsen-Scott South Pole Station (90° S), McMurdo Station (78° S, 167° E), and Palmer Station (65° S, 64° W). Network operation and data dissemination are managed by Biospherical Instruments Inc. (BSI).

The network is equipped with SUV-100 UV scanning spectroradiometers (Booth et al. 1994). The quantity measured is global spectral irradiance. This is the radiant power arriving per unit wavelength interval and per unit area on a horizontal surface from sun and sky. To derive biologically meaningful values, the measured spectra of global irradiance are multiplied with various biological weighting functions and integrated over wavelength. In this study we focus on the weighting function for DNA damage (Setlow 1974). If there were no uncertainties in both measured spectra and weighting function, the resulting "DNA-weighted irradiance" would be proportional to the ability of the solar UV radiation to damage unprotected DNA.

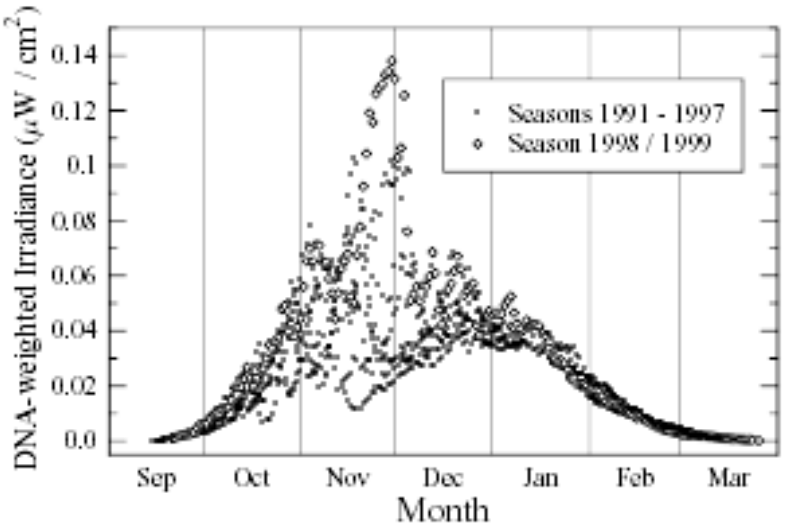


Figure 1. Daily mean DNA-weighted irradiance at Amundsen-Scott South Pole Station between 1991 and 1999.

Figure 1 shows a time-series of the daily mean DNA-weighted irradiance derived from the spectral measurements at South Pole Station between 1991 and 1998. The data for November 1998 clearly exceed November measurements of previous years and mark the highest UV levels to date observed over the South Pole by the NSF network radiometer. These significantly increased UV levels are caused by a combination of extraordinarily low total column ozone in mid- to late-November 1998 and already comparatively high solar elevations during this part of the year.

The "ozone hole" usually develops in mid-September and starts to recover in November, with the period of the greatest ozone depletion in October. The 1998 ozone hole was unusual in several respects. According to scientists from the National Oceanic and Atmospheric Administration (NOAA), the 1998 ozone hole was the largest observed since it first developed in the early 1980s (Viets et al. 1998). The minimum total column ozone over South Pole measured by the "Total Ozone Mapping Spectrometer" (TOMS) was 104.6 Dobson Units (DU) on October 6, which is close to the all-time low of 86 DU reached at October 12, 1993. One reason for the large ozone depletion in 1998 was unusually low temperatures in the lower stratosphere, for example measured at South Pole by NOAA's Climate Monitoring and Diagnostics Laboratory (CMDL) (see http://www.cmdl.noaa.gov/ozsondes/spo/). Low temperatures enhance the formation of polar stratospheric clouds (PSC). Ozone destruction leading to the austral ozone hole is primarily caused by heterogeneous chemistry at the surface of PSCs. Although the 1998 ozone hole started to fill up in mid-October (TOMS measured 212.9 DU on 17 November), ozone values dropped again after mid-November reaching 162.3 DU on 27 November. The final recovery started in early December (270.6 DU on 6 December). Consequently, the period between mid-November and December 6 is when high UV levels were observed.

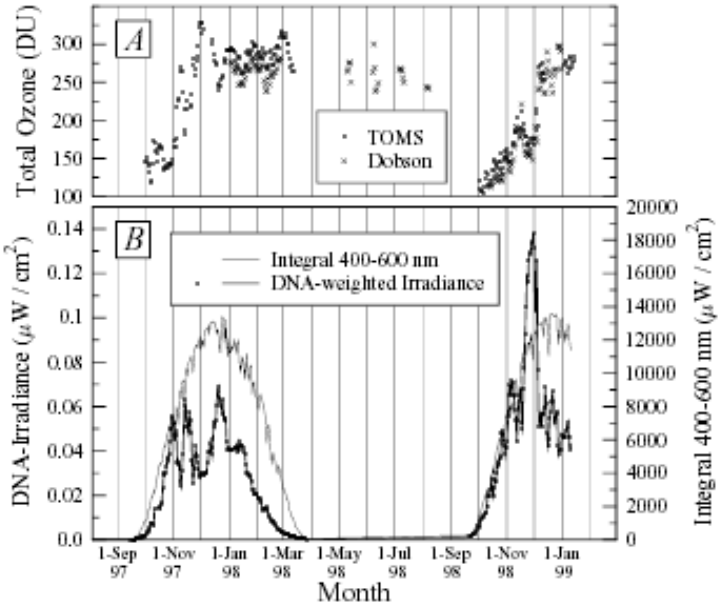


Figure 2. Total column ozone and global irradiance measured over Amundsen-Scott South Pole Station in the 1997-98 and 1998-99 seasons. A. Total column ozone. B. DNA-weighted irradiance (left axis) and spectral irradiance integrated between 400 and 600 nm (right axis).

To illustrate the anti-correlation between ozone and UV, figure 2 shows time-series of total column ozone and DNA-weighted irradiance at South Pole spanning the 1997-1998 and 1998-1999 austral summer seasons. In addition to TOMS ozone values, measurements of a Dobson spectrometer operated by CMDL/NOAA are also included in figure 2. The peak in DNA-weighted UV between mid- to late-November correlates well with the drop in ozone. Though total column ozone is lowest in October, UV levels are higher in November because of higher solar elevations later in the year. Irradiance measurements at wavelengths between 400 and 600 nm, which are not affected by ozone absorption, indicate that there was no significant difference in the visible region of the solar spectrum (thin line in figure 2) between both years.

The relationship between total column ozone and DNA-weighted irradiance was further investigated by correlating measurements conducted between September and December 1998 (period of ozone hole) with measurements at the same solar elevations but half a year earlier, namely between December 1997 and March 1998. In figure 3, the increase in DNA-weighted irradiance, $[(E^*-E)/E]\cdot 100\%$, is plotted versus the change in ozone derived from TOMS, $[(O^*_3-O_3)/O_3]\cdot 100\%$. E^* and E are the DNA-weighted irradiances for the Sep-Dec 1998 and Dec 1997 - Mar 1998 periods, respectively, and O^*_3 and O_3 are the matching ozone values. The irradiance data is based on daily averages. To avoid the influence of clouds, only data were used where the change in irradiance between consecutive scans was less than ± 5% and a daily average is based on at least 20 scans.

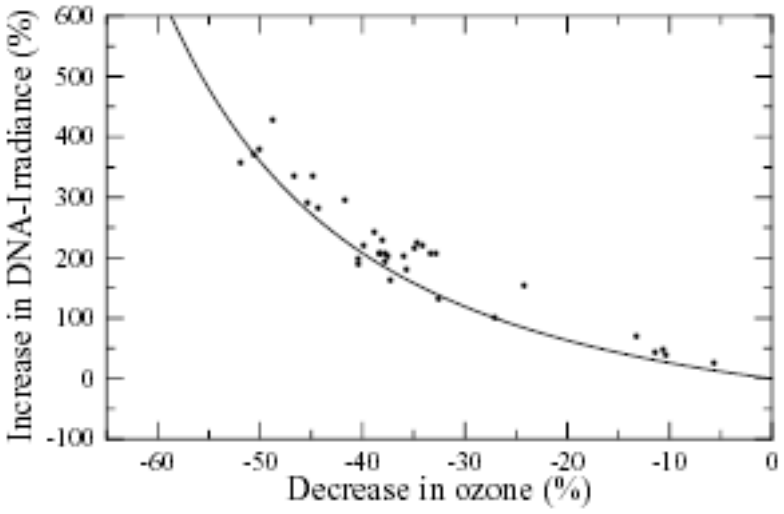


Figure 3. Increase in DNA-weighted irradiance versus change in total column ozone. The solid line shows a parameterization of this relationship as suggested by Booth and Madronich (1994). The experimental data (dots) are in close agreement with this theoretical approach.

Figure 3 demonstrates that total column ozone in the September-December 1998 period may be reduced by more than 50% compared to values in spring 1998, causing an increase in DNA-weighted UV by more than 400%.

One might argue that the high UV levels observed in 1998 have only minor

consequences because there is no life at South Pole except human beings. However, 1998 measurements at McMurdo have also shown the highest UV levels since monitoring began in 1988. Although the difference in measurements performed in previous years is not as prominent as for the South Pole site, this indicates that the phenomenon has a large spatial coverage and extends to regions with marine life. Further cooling of the stratosphere might lead to an extension of the ozone hole, with respect to both time and spatial coverage. This would also affect UV irradiance and in turn might have consequences for life in the Southern Oceans including phytoplankton at the start and fish, whales, and man at the end of the food chain. However, a quantification of the impacts of changing UV on biological matter is still the subject of significant uncertainties due to the complexity of the processes involved. Future measurements will demonstrate whether the high UV levels observed in November 1998 were an exception or a first indication of a more substantial change in the antarctic UV climate.

We wish to express our thanks to Lauriana Cabasug for preparing the data, James Robertson for his operational support, and John Booth and Curt Trimble, who were the site operators at South Pole station. This work was supported by the National Science Foundation, contract OPP 89-2832.

References

Booth, C.R., T.B. Lucas, J.H. Morrow, C.S. Weiler, and P.A. Penhale. 1994. The United States National Science Foundation's polar network for monitoring ultraviolet radiation. *Antarctic Research Series,* 62, 17-37.

Booth, C.R. and S. Madronich. 1994. Radiation amplification factors: Improved formulation accounts for large increases in ultraviolet radiation associated with Antarctic ozone depletion. *Antarctic Research Series,* 62, 39-42.

Setlow, R.B. 1974. The wavelength in sunlight effective in producing skin cancer: A theoretical analysis. *Proceeding of the National Academy of Science*, 71(9), 3363-3366.

Viets, P., S. Kenitzer, B. McGehan. 1998. Antarctic ozone hole sets new record. NOAA Press Release 98-064, 10/06/98, http://www.publicaffairs.noaa.gov/pr98/oct98/noaa98-064.html.

Temporal and spatial variability of particulate matter in the Ross Sea, Spring—Fall 1996-1997

Wilford D. Gardner *and* Mary Jo Richardson, *Department of Oceanography, Texas A&M University*

The abundance of particulate matter in the Ross Sea changes markedly during the year, as primary production varies from low winter values beneath the ice to spring/-summer bloom conditions. Primary productivity is part of the biological pump that converts the greenhouse gas carbon dioxide (CO_2) into particulate matter (PM) — particulate organic carbon (POC) and particulate inorganic carbon (carbonate) — that can settle out of the upper water column. Changes in the net particle load in the water are manifest in the optical transparency and the stimulated fluorescence of seawater.

As part of the JGOFS (Joint Global Ocean Flux Study) program in the Ross Sea, a SeaTech transmissometer and fluorometer were interfaced with a CTD during four cruises in 1996 and 1997. An east-west transect along 76.5º S from 169ºE to 178º W was occupied twice in October 1996 (early spring), twice in January/February 1997 (bloom period), once in April 1997 (fall), and twice in November 1997 (early bloom period). Water samples were filtered to measure total PM concentrations (during the January-February 1997 cruise) and concentrations of POC and chlorophyll-a (chl-a) during all cruises. Our ultimate goal is to quantify the changes in PM and POC during the year in the Ross Sea to compare the increases with primary production and the decreases with fluxes of particulate matter and carbon measured with moored sediment traps in the Ross Sea.

Transmissometers measure the percent of light transmitted across a path of known length. From the percent transmission, we calculate a beam attenuation coefficient (m-1), which is linearly related to total PM concentration (Gardner et al., Chung, Richardson and Walsh, 1995) and to POC concentrations (Gundersen et al. 1998). Fluorescence measurements are calibrated with the chlorophyll a bottle measurements. Using these calibrations, we can map the distribution of PM, POC and chlorophyll-a at the same spatial resolution as we record temperature and salinity. Here we discuss the distribution of PM in the Ross Sea.

In October 1996 the PM concentrations were 10-70 µg l-1, with the highest concentrations in the upper 60 meters (m) of the central stations and subsurface maxima down to 250 m (figure 1A). Note the order of magnitude difference in concentration scales between figure 1A and 1B). In January 1997 PM concentrations exceeded 2000 µg l-1 in the upper water column. The general trends of highs and lows in the January transects were similar for chlorophyll fluorescence, indicating that most of the particulate matter was composed of phytoplankton and associated material. We found significant variation along the transect in the vertical structure, with the particle (and chlorophyll) maximum occurring at 50-70 m at the western stations, but near the surface in the central and eastern regions (figure 1B). These features were well correlated with the temperature

structure, but not the density structure, which was dominated by the salinity distribution. In April particle and chlorophyll concentrations declined to the October pre-bloom values, suggesting that by April, primary production rates were low and most of the standing stock of particulate matter had settled out or been remineralized. These changes constitute an unusually large buildup and a rapid loss of PM.

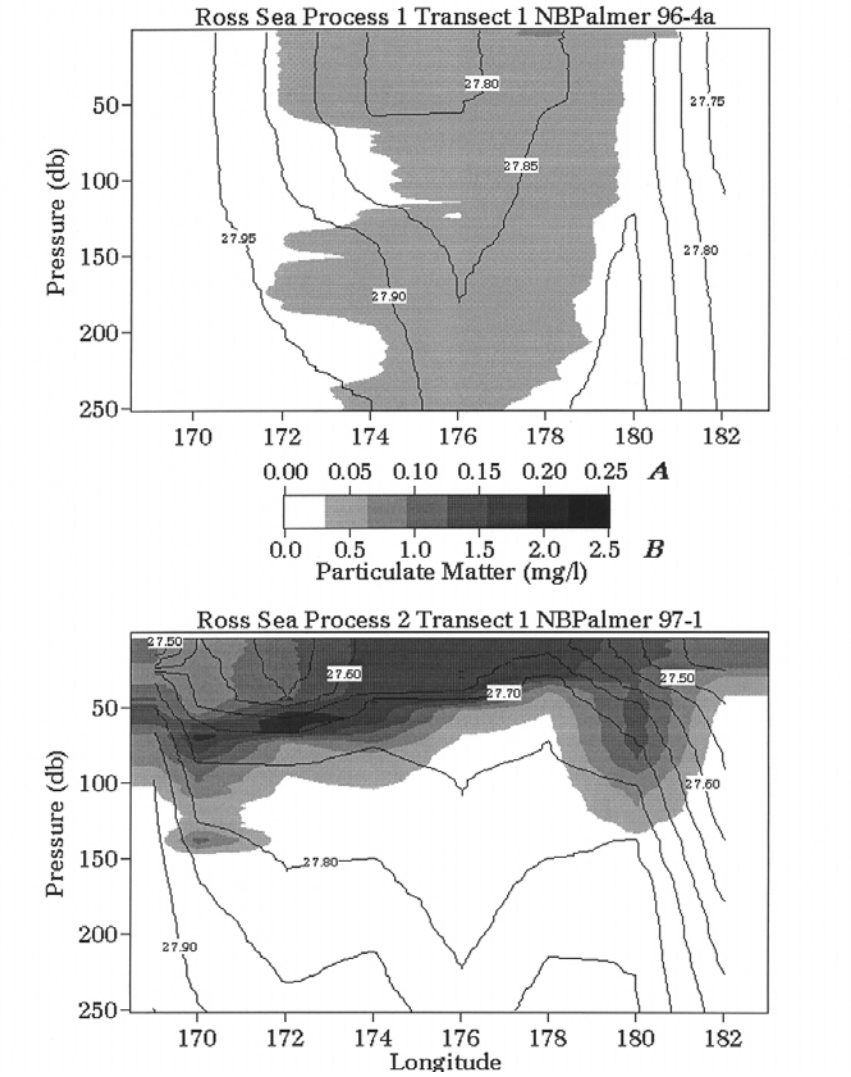


Figure 1 A) Distribution of particulate matter (PM) concentration (mg l^{-1}) along an east-west transect in the Ross Sea, during: (A) October 1996. Contours are density in both sections; and. (B) Distribution of PM concentration (mg l^{-1}) in January 1997. (Note the PM concentration scale is an order of magnitude larger for PM data from the later cruise (B).

Standing crops of particulate matter that were integrated through the upper 100 m during this period of the bloom (January) ranged from 40 to 135 g m-2 along the transect, compared with 1-5 g m-2 before and after the bloom (October and April). We can grossly estimate the rate of production and loss of particulate matter by calculating the change in the standing stock for the three periods. At 76.5ºS and 178ºW, the site of the

Honjo/Dymond/Collier sediment trap Mooring 7 (76.5ºS 178ºW), the standing stock of PM increased by approximately 130 g m-2 in 90 days and decreased by the same amount over the same length of time. This yields a minimum rate — of growth and loss — of 1.44 g m-2 day-1, but obviously this simple calculation ignores daily losses between the first two periods as well as continued production between the last two periods. Thus, the growth and loss rates are likely to be much higher. Total mass flux measured in the sediment trap at 465 m was on the order of 0.3 g m-2 day-1 after the January section was made (S. Honjo, personal communication), which is about 20 percent of the minimum loss rate from the upper 100 m at that time. This suggests substantial remineralization of particulate matter in the upper 400 m.

During January, we monitored temporal variations were monitored during January at two stations that were occupied for 36-48 hours and sampled every 3-4 hours. Over that time, PM, POC, and chlorophyll-a changes of about 20 percent were recorded in optical properties, but physical parameters (temperature and salinity) also varied. Consequently, it was difficult to differentiate ecosystem changes (growth, grazing, and community composition) from advection of different water past the site.

Our next step is to relate beam attenuation to concentrations of particulate organic carbon in order to map its distributions and standing stocks (Richardson, Gardner, and Smith 1999). We will then compare POC and PM concentrations and standing stocks with primary production and fluxes in the sediment traps.

We thank Dr. John Morrison and members of the hydro team and other scientists and personnel, as well as Antarctic Support Associates personnel who helped collect these data on the research ship *Nathaniel B. Palmer* cruises, and Christopher Nugent and Sarah Searson for data processing. This work was supported by the National Science Foundation grant OCE 95-30837.

References

Gardner, W.D., S.P. Chung, M.J. Richardson and I. D. Walsh. 1995. The oceanic mixed-layer pump. *Deep-Sea Research II*, 42 (2/3), 757-775.

Gundersen, J.S., W.D. Gardner, M.J. Richardson and I.D. Walsh. 1998. Effects of monsoons on the seasonal and spatial distributions of POC and chlorophyll in the Arabian Sea. *Deep-Sea Research II,* 45 (10-11).

Honjo, S. Personal communication.

Richardson, M. J., W. D. Gardner and W. O. Smith., 2000. Seasonal patterns of water column particulate organic carbon and fluxes in the Ross Sea, Antarctica. In W.O. Smith and R.F. Anderson (eds.) U.S. Southern Ocean JGOFS Program (AESOPS), *Part II: Topical Studies in Oceanography*, 47 (15-16). Oxford, United Kingdom: Peragmon, Oxford, International.

Thorium fluxes and carbon export from the Ross Sea: A preliminary report

Lary A. Ball, John E. Andrews, *and* Ken O. Buesseler, *Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution*

Export of organic carbon from the euphotic zone is an important parameter in modeling the global carbon cycle (Buesseler 1998a). Using ^{234}Th, the 24-day, half life daughter of ^{238}U, a consortium of oceanographic radiochemical groups (see acknowledgments) measured the removal of particles from the upper water column in the Ross Sea during 3 US JGOFS (US Joint Global Ocean Flux Study) sponsored cruises (October-November, 1996; Jan-Feb, 1997; and April-May, 1997) on the U.S. research icebreaker *Nathaniel B. Palmer*. The Ross Sea is an oceanic basin known to be a site of intense episodic plankton blooms following the spring ice breakup. The cruises were timed to bracket the bloom and capture in time the post bloom sinking particles. JGOFS participants were charged with characterizing the natural history, primary productivity and carbon removal rate of this bloom. We report here the sample sites and sample log of these three cruises during the 1996-1997 Austral spring-summer period. Data processing for these cruises is ongoing. Preliminary results can be found at the JGOFS website (http://www1.whoi.edu/) as well as maps, cruise reports and ancillary data.

The method of relating ^{234}Th deficit to carbon export has been widely used and most recently overviewed by Buesseler et al.1998a. ^{234}Th is supplied at a concentration or activity equal to its radiogenic parent ^{238}U which is conservative with salinity in aerobic oceanic environments. This activity is approximately 2.5 disintegrations per minute per liter (dpm/l) of seawater at a salinity of 35 per mil. The ^{234}Th, in contrast to the ^{238}U is particle reactive. The fraction of ^{234}Th removed from the dissolved phase depends on the population and properties of the particles. Vertical removal of ^{234}Th occurs as particles sink through the water column. ^{234}Th will return to equilibrium with its uranium parent if no losses occur over a period of several half-lives (half-life = 24.2 days). Hence, ^{234}Th is a self-replenishing tracer of particle export. At sea, collection of samples was done at discrete depths over the mixed layer using computer-controlled pumps (Challenger Oceanic and McLane Industries). Where wire time was not sufficient to permit deployment of multiple pumps, integrated samples were obtained using a depth averaging computer-controlled pump, the "Slurper" (Buesseler et. al. 1998b). The Slurper was slowly pulled through the desired depth range. Feedback between the depth sensor, computer and pump allowed discrete volumes to be sampled over small increments of the depth range. For example, 20-liter volumes at 5-meter intervals over a 100-depth interval would result in a 400 liter integrated sample.

Stations and sample type for ^{234}Th, POC, and PON measurements.

Cruise NBP96-4B

Station	Latitude S	Longitude (E=+; W=-)	Date	Sample Type
Orca	-76.50	-177.97	10/08/96	10M-300M; 7 point profile
"S"	-76.50	179.96	10/19/96	5-105M integrated
"O"	-76.46	175.92	10/20/96	5-105M integrated
Pseudo-Minke	-76.56	169.07	10/23/96	10M-720M; 7 pt. profile
Orca	-76.49	-177.80	11/02/96	10M-300M; 7 point profile
"O"	-76.50	175.99	11/04/96	5-105M integrated
"O"	-76.50	175.99	11/04/96	110M
122	-76.49	172.01	11/05/96	5-105M integrated

Cruise NBP97-1

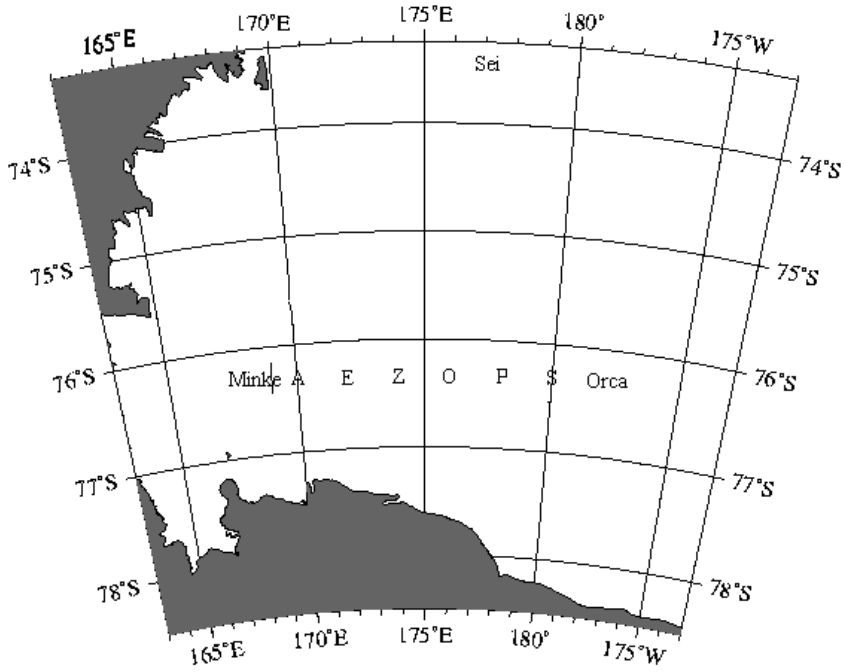
Station	Latitude S	Longitude (E=+; W=-)	Date	Sample Type
Minke	-76.50	169.00	01/13/97	10M-105M 4 pt. profile
Minke	-76.50	169.01	01/14/97	10M-110M integrated
"A"	-76.49	169.96	01/15/97	10M-110M integrated
"O"	-76.49	176.05	01/16/97	100M
"O"	-76.49	176.05	01/16/97	10M-110M; integrated
Orca	-76.50	-178.05	01/19/97	5M-105M; 4 pt. profile
Sei	-74.04	177.00	01/24/97	10M-305M; 5 pt. profile
Sei	-74.01	176.95	01/24/97	10M-110M integrated
Blue	-74.33	-175.99	01/26/97	5 pt. 1000M-1100M calibration
213	-76.59	168.91	01/28/97	10M-110M integrated
214	-76.56	170.26	01/29/97	10M-110M integrated
"O"	-76.40	176.31	01/31/97	100M
"O"	-76.40	176.31	01/31/97	10M-110M integrated
"S"	-76.51	179.99	01/31/97	10M-110M integrated
Orca	-76.50	-177.99	02/01/97	10M-500M; 6 pt. profile
224	-77.39	175.95	02/04/97	10M-110M integrated
225	-76.50	176.04	02/04/97	100M
225	-76.50	176.14	02/05/97	10M-110M integrated
Minke	-76.50	168.99	02/08/97	30M-600M; 5 pt. profile

Cruise NBP97-3

Station	Latitude S	Longitude (E=+; W=-)	Date	Sample Type
301	-67.63	175.16	04/10/97	4 pt. 1900M-2000M calibration
Sei	-74.35	175.97	04/13/97	5M-105M; 5 pt. profile
Orca	-76.44	-177.99	04/14/97	5M-105M; 6 pt. profile
Pseudo-Minke	-76.47	169.06	04/18/97	5M-105M; 6 pt. profile
RIS2	-77.99	-176.11	04/20/97	10M-75M; 4 pt. profile
Orca	-76.48	-177.96	04/23/97	5M-200M 7 pt. profile
"O"	-76.50	176.02	04/24/97	10M-125M; 5 pt. profile
Minke	-76.50	168.97	04/27/97	5M-200M; 10 pt. profile
Sei	-73.97	176.11	04/30/97	5M-200M; 8 pt. profile
Deep	-67.98	175.99	05/04/97	4 pt.1500M calibration

Measurement of ^{234}Th was made on two particle size fractions (>70μ and 1-70μ) and the dissolved phase (Hartman and Buesseler 1994) using at-sea beta and gamma counting instruments. Samples were returned to shore-based labs for POC/PON analysis of particulate phases and chemical yield measurements for the calibration of the at-sea counters. A flux or removal rate of ^{234}Th is calculated from the difference between the measured and equilibrium activities and is integrated over the depth sampled. The ratio of carbon or nitrogen to thorium concentration on the filters is multiplied by the integrated thorium flux to give integrated carbon flux.

The majority of the station locations sampled in the Ross Sea during the three cruises fall on the 76°30' S. latitude or "AESOPS" line (figure). Major stations Minke and Orca define the eastern and western boundaries of the line while an additional northern station "Sei" was visited less frequently. Station "Blue" or "Deep" (not shown) were sampled off shelf for deep ^{238}U/^{234}Th equilibrium deep water for method calibration. Additional stations were sometimes added as cruise time and conditions permitted and are referred to by a 3-digit number, the first digit referring to cruise 1, 2, or 3.



Station locations for Ross Sea JGOFS stations.

The first cruise, NBP96-4B (cruise participants: John Andrews and Dave Hirschberg), found high ice coverage of the sampling area. The phytoplankton bloom was only beginning to happen in the later days of the cruise when ice breakup was occurring. In fact, the ship was not able to occupy many stations sampled during later cruises due to

ice thickness. ^{234}Th values were uniformly near equilibrium, implying no particle scavenging or export. Cruise 2, NBP97-1 (cruise participants: Lary Ball and Alan Fleer), did not schedule wire time for as many multipoint profiles, hence the large proportion of integrated samples. This cruise experienced an intense phytoplankton bloom primarily of genus phaeocystis. The ^{234}Th shows deficits of up to 1.5 dpm/l in the region of station 214 (near station "A" on the map) signifying rapid particle removal. Cruise 3, NBP 97-3 (cruise participants: David Hirschberg and Ellen Rosen), was coincident with the end of the particle export period of cruise 2. ^{234}Th during this period was beginning to return to equilibrium values with deficits on the order of 0.5-0.8 dpm/l typically. The station "Pseudominke," is exceptional in showing deficits on the order of the 1.5 dpm/l as for NBP97-1.

The studies discussed here represent the activities of three separate research teams. The thorium consortium during these Ross Sea cruises consisted of the groups of Ken O. Buesseler (Cafe Thorium: John Andrews and Lary Ball), Michael Bacon (Alan Fleer and Ellen Rosen) and J. Kirk Cochran (David Hirschberg). We thank the captain and crew of the *Nathaniel B. Palmer* and the members of the Antarctic Support Associates for their professional assistance in this field effort.

This work was funded by the National Science Foundation grant OPP 95-30861 to KOB.

References

Buesseler, K.O. 1998a. The de-coupling of production and particulate export in the surface ocean. *Global Biogoechemical Cycles*, 12 (2), 297-310.

Buesseler, K.O., J.K. Cochran, M.P. Bacon, H.D. Livingston, S.A. Casso, D. Hirschberg, M.C. Hartman and A.P. Fleer. 1992. Determination of thorium isotopes in seawater by non-destructive and radiochemical procedures. *Deep-Sea Research*, **39(7/8)**, 1103–1114.

Buesseler, K. O., L. Ball, J. Andrews, C. Benitez-Nelson, R. Belastock, F. Chai and Y. Chao. 1998b. Upper Ocean Export of Particulate Organic Carbon in the Arabian Sea derived from Thorium-234. *Deep-Sea Res. II, Arabian Sea Volume*, Vol. 12, No. 2, 297-310.

Hartman, M. C. and K. O. Buesseler. 1994. Adsorbers for In-Situ Collection and At-Sea Gamma Analysis of Dissolved Thorium-234 in Seawater. WHOI Technical Report, WHOI-94-15.

U.S.-China collaborative research program on particulate organic matter export in the southern Indian Ocean, East Antarctica

Cynthia H. Pilskaln, *Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor*

Vernon L. Asper, *University of Southern Mississippi, Stennis Space Center*

Steven. J. Manganini, *Woods Hole Oceanographic Institute, Woods Hole*

During the 1998-99 austral summer, a field-based research program was initiated through a collaborative agreement between the U.S. and Chinese government agencies—the U.S. National Oceanic and Atmospheric Administration and National Science Foundation and the Chinese Arctic and Antarctic Administration (Beijing), the State Oceanic Administration (SOA) of China, and the Chinese Polar Research Institute (Shanghai). The primary scientific objectives of the collaboration were to measure the production and export (or flux) of particulate organic matter in the Indian Ocean sector of the Southern Ocean, specifically within the region of Prydz Bay (figure 1). Such measurements are necessary to quantify the amount of atmospheric carbon that is removed to the deep ocean via biological processes, thus representing a potentially significant factor in global carbon cycling budgets. The project represented the first-time field collaboration between the United States and China to study carbon production and export dynamics in the Southern Ocean (Pilskaln et al. 2002).

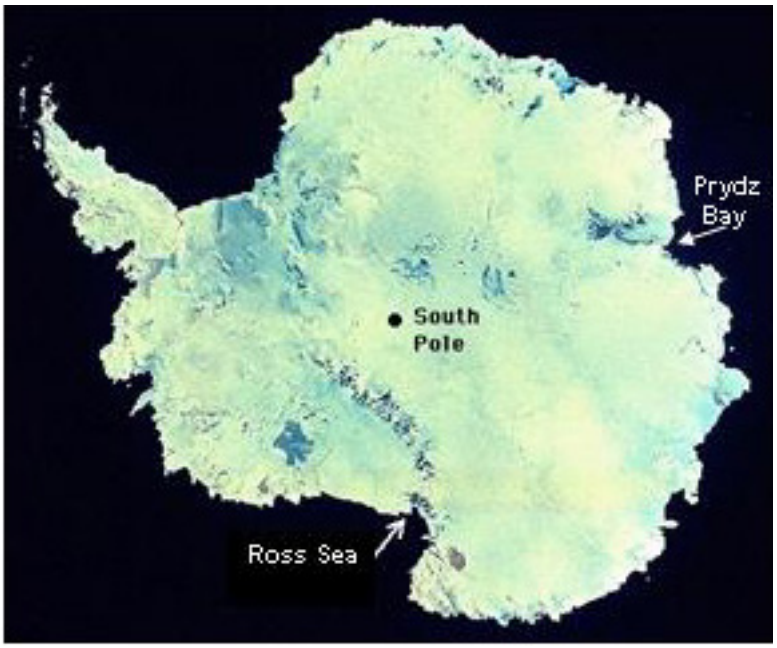


Figure 1. Polar satellite image of Antarctic continent showing Prydz Bay in the southern Indian Ocean sector off East Antarctica relative to the Ross Sea in the western Pacific Antarctic sector.

Since 1989, the Chinese polar research vessel the *Xue Long* ("Snow Dragon") annually transits from Shanghai to the Chinese Zhongshan Station in Prydz Bay, East Antarctica to bring supplies to the station (figures 1 and 2). An important component of the annual CHINARE (Chinese Antarctic Research Expedition) cruises is a series of hydrographic and water sampling stations in the Prydz Bay region. Up to 37 stations are completed annually between approximately 62°-69° S and 68°-108° E, encompassing Prydz Bay and areas offshore. The suite of scientific activities conducted by individuals from several Chinese universities and oceanographic research institutes, include conductivity-temperature-depth (CTD) and acoustic Doppler profiling, and measurements of primary productivity, dissolved nutrient concentrations, suspended mass of particulate organic carbon (POC), and zooplankton and phytoplankton biomass. From November 1998 to January 1999 (CHINARE-15) and from January to March 2000 (CHINARE-16), we joined the *Xue Long* to participate in the Prydz Bay station activities and to deploy, recover, and redeploy a time-series, sediment-trap mooring south of the polar front in the abyssal waters approximately 800 km north of Prydz Bay.

Figure 2. Photograph of the 167 meter-long, Russian-built Chinese polar research vessel* Xue Long *in heavy seasonal pack ice, Prydz Bay, 25 kilometers from the Chinese Zhongshan Station.

We deployed a subsurface, bottom-tethered mooring in 3,800-4,000 meters (m) of water at 62° 29' S, 72° 59' E for the year 1 particle flux time-series (collected between December 1998 and December1999), and at 63° 28'S, 76° 08'E for the year 2 flux time-series data set obtained from March 2000 to Feb 2001. The year-1 mooring consisted of three, high-resolution, time-sequencing sediment traps placed at depths of approximately 1,400, 2,400, and 3,400 m and an acoustic current meter at about 1,380 m to record current speed and direction above the shallowest traps. The year-2 mooring had one trap at approximately 1,300 m and 3,300 m and a current meter placed at 1,280 m.

Results from the current meter measurements revealed low average flows of ≤5 cm/sec at the trap sites. The sediment traps used in the present study were of the same design as those deployed in the 1996-1998 U.S. Southern Ocean Global Ocean Flux Program conducted in the Ross Sea and adjacent western Pacific sector waters (Honjo et al. 2001). These traps consist of a large aperture cone (0.5 m^2 opening) and a microprocessor-controlled, rotating carousel of sample cups (figure 3; Honjo and Doherty 1988). In the present study, sinking particulate samples were collected simultaneously by the time-sequencing traps on a 17-day frequency during the austral spring and summer (November to mid-March) when organic export fluxes were expected to be high and on a 40- or 41-day frequency throughout the austral fall and winter when POC production and export levels are low, coincident with extensive sea-ice cover. Sediment trap sample cups were filled with a 4% buffered (pH of 7.9-8.0) formalin/seawater solution before deployment to prevent bacterial oxidation of the particulate material and all trap samples were processed according to the standard protocols detailed in Pilskaln et al. (1998) and (Honjo et al. 2000).

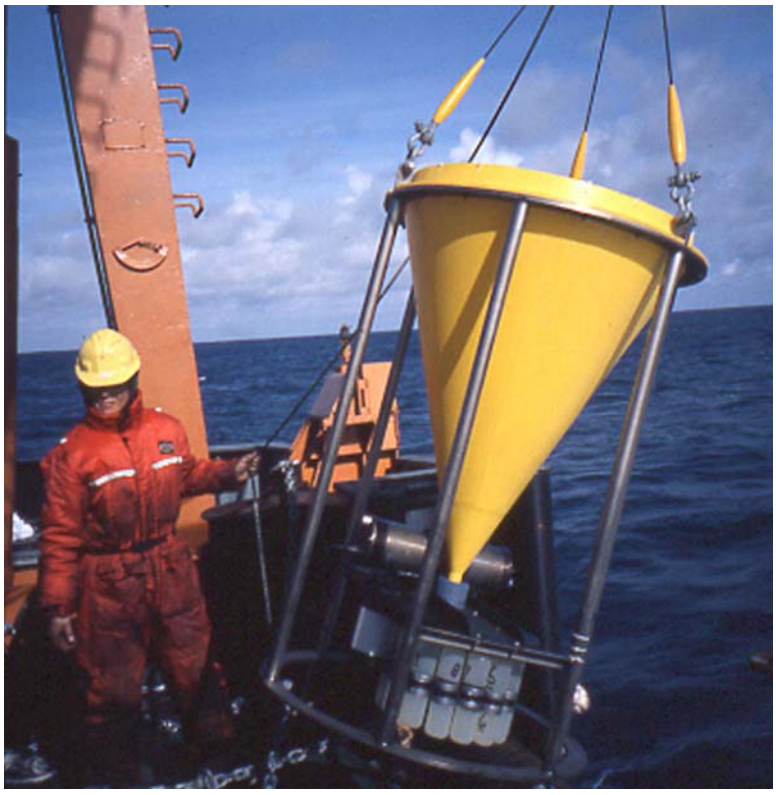


Figure 3. Deployment of a time-series sediment trap from the* Xue Long. *Settling particulate samples were collected in 500 ml cups that rotated beneath the yellow collection cone on a time-varying seasonal schedule.

CTD, beam attenuation, and suspended particle mass (SPM) profiles completed at a number of the CHINARE-15 and 16 hydrographic stations near the trap sites documented the presence of a well-defined, seasonal temperature minimum (Tmin)/pycnocline layer between about 50-150 m associated with a strong, sub-surface, particle maximum (Pilskaln et al. 2002). This feature, predominant during the austral

spring and summer and extending across the Antarctic Zone to the Polar Frontal Zone, represents a remnant of the cool, deeper winter-mixed layer overlain by a seasonally warmed and fresher surface layer (Toole 1981). In several other Southern Ocean studies, the Tmin/particle maximum layer was found to be coincident with a subsurface chlorophyll maximum produced by a mid-water accumulation of diatoms (Honjo et al. 2000; Parslow et al. 2001). Retention and accumulation of sinking diatoms along the seasonal Tmin/pycnocline density discontinuity surface may represent an important site of enhanced POC remineralization within the mid-water zone, possibly limiting the efficacy of carbon export below about 200 m by diatoms (Pilskaln et al. 2002).

The final recovery of the year-2 sediment trap mooring was completed in early 2001 from the U.S. research ship *Nathaniel B. Palmer*. A preliminary summary of the mooring project results is presented in Pilskaln et al. (2002). The time-series of total mass particle flux and the export fluxes of all major biogenic components (POC, biogenic silica and $CaCO_3$) displayed peaks at all depths in the austral summer months of January to February following the retreat of the sea ice, with secondary peaks in the winter (July) and early spring (October) recorded by the shallowest trap (figure 4, year-1 data shown). The seasonal mass flux pattern and the annual total export flux of 25 g/m^2/yr at the offshore Prydz Bay site compare well to that measured at 1,000 m in the Ross Sea Gyre (66^{o}S, 170^{o}W) of 27 g/m^2/yr (Honjo et al. 2000). Biogenic opal was the dominant particle flux component representing over 70% of the mass flux at the offshore Prydz Bay, similar to the results from the Ross Sea Gyre (Honjo et al. 2000).

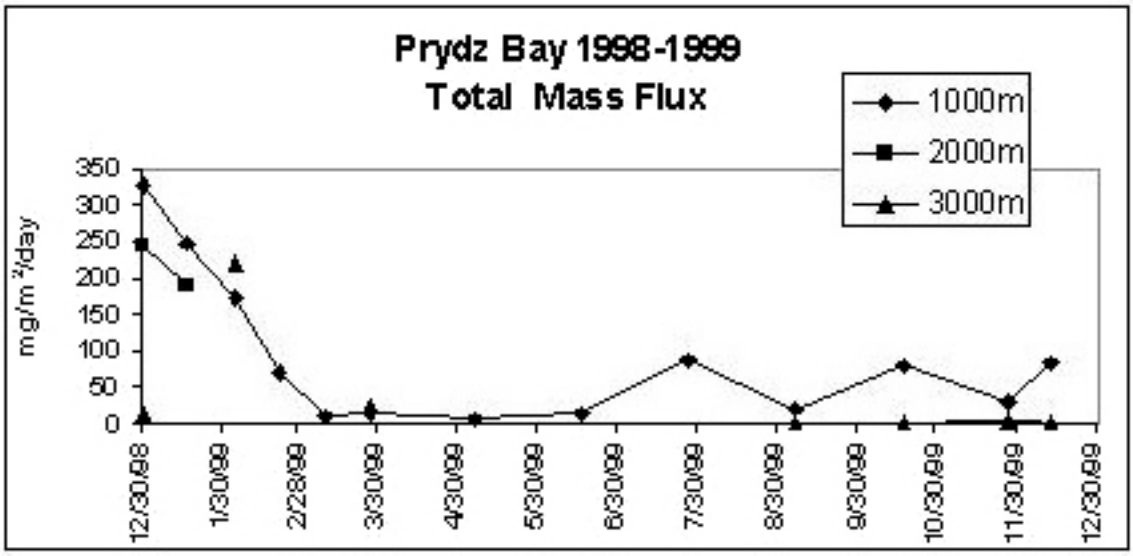


Figure 4. Time-series of total mass particulate flux (in mg/m^2/day) measured by the 1998-99 sediment traps (from Pilskaln et al., 2002). The ~2000 m trap was subject to a timer failure in January 1999 and the ~3000 m trap was retrieved with only 7 of the 13 sample cups due to mooring recovery problems experienced on the* Xue Long*. POC and biogenic silica fluxes displayed the same seasonal flux pattern as above.

Geochemical (stable isotopes, trace elements) and microfossil (diatoms, planktonic foraminifera) studies of the Prydz Bay trap samples are continuing through a research collaboration with the Australians (Pilskaln et al. 2002). A recently initiated

Japanese field program in the Prydz Bay region offers additional potential for a larger-scale, international collaborative research effort in this sector of the Southern Ocean.

We thank F. Chai (Co-principal investigator on OPP grant), Z. Dong (Director, Polar Research Institute of China), and B. Lettau (Program Manager, NSF/OPP) for their organization of and participation in the project planning meetings in China. We also thank the captains and crew of *Xue Long* and *N. B. Palmer* for their assistance at sea with the mooring work. The sediment trap project was supported by the National Science Foundation, Office of Polar Programs, grant OPP 97-26186 (Pilskaln, PI).

References

Honjo, S. and K.W. Doherty. 1988. Large aperture time-series sediment traps; design objectives, construction and application. *Deep-Sea Research I*, 35(1), 133-149.

Honjo. H., R. Francois, S. Manganini, J. Dymond and R. Collier. 2000. Particle fluxes to the interior of the Southern Ocean in the Western Pacific sector along 170°W. *Deep-Sea Research II*, 47 (15-16), 3521-3548.

Parslow, J. S., P. W. Boyd, S. R. Rintoul and F. B. Griffiths. 2001. A persistent subsurface chlorophyll maximum in the Interpolar Frontal Zone south of Australia: Seasonal progression and implications for phytoplankton-light-nutrient interactions. *Journal of Geophysical Research*, 106 (12), 31543-31558.

Pilskaln, C.H., J.B. Paduan, F.P. Chavez, R.Y. Anderson and W.M. Berelson. 1996. Carbon export and regeneration in the coastal upwelling system of Monterey Bay, central California. *Journal of Marine Research*, 54, 1149-1178.

Pilskaln, C., S. Manganini, V. Asper, T. Trull, W. Howard and L. Armand. 2002. Seasonal particulate export below the Polar Front in the Southern Indian Ocean sector of Prydz Bay, East Antarctica. *EOS Transactions*, 83, (4), 2002 Ocean Sciences Abs. Volume, Honolulu, HI, p. 101.

Toole, J. M. 1981. Sea ice, winter convection, and the temperature minimum layer in the Southern Ocean. *Journal of Geophysical Research*, 86 (9), 8037-8047.