1996-2002 Proposal for Palmer LTER PALMER LONG-TERM ECOLOGICAL RESEARCH PROJECT

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1. Summary and Results of Prior Support

1.1 Summary: "Long-Term Ecological Research on the Antarctic Marine Ecosystem: An Ice-Dominated Environment" (DEB -9011927; 10/1/90 to 9/31/96)

The present proposal requests funds to continue, for a second six year period, the Palmer Long-Term Ecological Research (PAL) program which focuses on the marine ecosystem in the western Antarctic Peninsula (WAP) region. The addition of the PAL to the LTER Network in October 1990 extended the geographical and ecological range significantly and provided the opportunity to link ecological processes between hemispheres as well as across terrestrial and marine biomes.

A central tenet of the PAL is that the annual advance and retreat of sea ice is a major physical determinant of spatial and temporal changes in the structure and function of the Antarctic marine ecosystem, from total annual primary production to breeding success in seabirds. We are currently evaluating a number of testable hypotheses linking sea ice to: the timing and magnitude of seasonal primary production, the dynamics of the microbial loop and particle sedimentation, krill abundance, distribution, and recruitment, and the breeding success and survival of apex predators. The overall objectives of the PAL are to:

(1) document the interannual variability of annual sea ice and the corresponding physics, chemistry, optics, primary production and the life-history parameters of secondary producers and apex predators within the PAL area,

(2) create a legacy of critical data for understanding ecological phenomena and processes within the Antarctic marine ecosystem,

(3) identify the processes that cause variation in physical forcing and the subsequent biological response among the representative trophic levels,

(4) construct models that link ecosystem processes to environmental variables, which simulate spatial/temporal ecosystem relationships, and employ such models to predict and validate ice ecosystem dynamics.

Since 1991 the PAL program has included spatial sampling during annual and seasonal cruises in portions of our regional grid in the WAP region (Fig. 1a) and temporal sampling from spring through fall (October to March) in the area adjacent to Palmer Station (Fig. 1b). Our program was designed to sample at multiple spatial scales within one regional scale grid, permitting repeated sampling on both seasonal and annual time scales, thus addressing both short and long-term ecological phenomena, as well as providing a basis for specific mechanistic studies. To date, there have been seven regional PAL cruises and two additional cruises emphasizing microbial dynamics (Tables 1 and 2). Core and other variables routinely sampled and /or occasionally monitored from shipboard during our annual cruises are listed in Tables 3 and 4, respectively. Tables 5 and 6 list those obtained from Palmer Station throughout each field season. Documentation and data storage are organized through an electronic hub at the Institute for Computational Earth System Science (ICESS) at the University of California at Santa Barbara which also serves as a data archive as needed. There are online definitions of core data, datasets and metadata, organized to facilitate rapid information exchange and online data documentation (Fig. 2). Core data currently available electronically to PAL investigators are listed in Tables 7 and 8.

The PAL program is multidisciplinary and currently involves ten Principle Investigators (PIs). PAL program milestones in the context of the LTER network as a whole are summarized in Table 9. In 1992 the component of microbial ecology, including measurements of carbon exchange between air-sea and water-sediment interfaces, was added to the program by the addition of D. Karl. Until this renewal, D. Karl was funded separately from the PAL grant, although his research was fully integrated and he has had full PI status with the PAL group. In this renewal his funding will be integrated with the PAL grant. In 1993 K. Baker was made a PI in recognition of the importance of data management to the program. In 1994 M. Vernet replaced B. Prezelin for the phytoplankton component.

Work to date, summarized below and described in detail in publications (Sect. 1.3), indicates that the PAL is ideally sited in a climatically sensitive region where ecosystem studies have the potential for detecting, against a background of natural variability, long-term trends and /or human disturbance to the Antarctic ecosystem. It is an area where "natural" experiments can be conducted to investigate mechanisms linking physical forcing and ecosystem response under vastly different year-to-year climatic conditions and where perturbations such as global warming, ozone related UV-B increases and associated anthropogenic impacts on ecological processes can be studied in an otherwise remote and relatively pristine environment. The PAL location makes an ideal natural laboratory in which to study long-term trends and cycles.

An overview and synthesis of various aspects and processes associated with the Antarctic marine ecosystem in the WAP and in the vicinity of Palmer Station, as well as analyses of historical data and early PAL results, will be published in early 1996 in a book entitled, Foundations for Ecological Research West of the Antarctic Peninsula. Ten chapters were authored or co-authored by PAL PIs. During the first several years of the PAL program, considerable effort was devoted to establishing a sampling and research routine for long-term research in this area. This early effort is now beginning to pay dividends in a significant number of results (Table 10 and Sect. 1.2) and publications (Sect. 1.3). The upward ramp in productivity by the PAL (shown in Table 10) is in agreement with the exponential intellectual growth expected for long term programs as described by Likens (1985).

1.2 Results of Prior Support

R. C . Smith (remote sensing and bio-optics component) and B.B. Prezelin and M. Vernet (primary production component)

The combined efforts of these two components have focused on (1) a sea ice and surface air temperature climatology, (2) the spatial and temporal variability of phytoplankton biomass and primary production, and (3) factors controlling phytoplankton biomass, production and community structure. The approach included analyzing (1) satellite data to derive ice coverage and phytoplankton biomass distributions, (2) surface air temperature data taken by research and automatic weather stations in the WAP region, and (3) bio-optical field measurements of photosynthetically available radiant energy (PAR), pigment biomass and plant pigments (HPLC) and C-3 14 measurements for phytoplankton growth and physiological parameters. There has been full participation to date in all field cruises and nearshore time series sampling by both of these components. Results from the sea ice and surface air temperature climatologies in the PAL region show (1) an annual sea ice cycle involving a relatively short period of ice retreat (about 5 months) followed by a longer period of ice advance (about 7 months), which contrasts with other regional annual cycles where ice retreat is longer than ice advance, (2) a confirmation that while the Southern Ocean as a whole shows relatively little interannual variability (< few %), deviations up to 66% and 130% from mean maximum and minimum ice coverage, respectively, have been observed for the PAL region, (3) a confirmation of a significant warming trend (+4-5(degrees C) in mid-winter surface air temperatures in the WAP region over the past half-century (1941-1991), (4) a significant anti-correlation between surface air temperature and sea ice extent, and increased variability in fall and winter observed in both variables, and (5) a long-term persistence in monthly sea ice and surface air temperature anomalies (Fig. 3), wherein two to four high ice /low temperature years are followed by one to three low ice /high temperature years, a pattern which is coherent with the Southern Oscillation Index (SOI), suggesting teleconnections between the WAP and lower latitudes. Significant findings from phytoplankton studies include: (1) a persistent on/offshore gradient modulated alongshore by latitudinal variability which follows the annual advance and retreat of sea ice, (2) a strong seasonal and interannual variability in timing and intensity of phytoplankton blooms, strength in on/offshore and alongshore gradients and overall annual biomass accumulation, (3) a consistency between the regional gradients in phytoplankton biomass and the temporal observations from Palmer Station, suggesting that the dynamics in Chl-a accumulation in the vicinity of Palmer Station are representative of those within the shelf waters and that the seasonal nearshore variability is related to the PAL regional variability in Chl-a biomass, (4) a tight coupling between productivity and daylength, with more than 90% of the biomass and primary production occurring between November and April (not including a possible and currently unknown contribution during winter), (5) a seasonal structure that, generally, includes two major pulses in primary production in late spring (Dec/Jan) and in summer (Feb/Mar), where the first pulse is generally larger, although in 'high' production years (i.e., 1994-95) three large pulses were observed between mid-Dec and late Feb.

D.M. Karl (microbial dynamics and carbon flux; OPP 9118439)

To date, the research supported by this component has focused on three related topics: (1) dissolved inorganic carbon (DIC) and organic carbon (DOC) pool dynamics, (2) controls on the distributions, abundances and growth rates of bacteria, and (3) particle sedimentation and export production. The approach involved making repeated measurements of carbon pools (total DIC and DOC, bacterial biomass) and carbon fluxes (bacterial production, dissolved organic matter turnover rates, particle sedimentation) in the PAL region during the annual cruises, and conducting field experiments to test various ecological predictions of the general PAL hypothesis regarding the role of ice in the control of ecosystem processes and carbon/energy flux. By the end of this current project period, we will have participated in six PAL cruises in addition to two special focus microbial dynamics cruises. Several significant results include: (1) documentation of carbon dioxide partial pressure (pCO2) by continuous underway measurement which reveals significant reductions in pCO2 associated with the spring phytoplankton bloom, with values as low as 260 ppm compared to atmospheric values of 340-350 ppm, suggesting that the entire PAL region may be a moderate sink for atmospheric CO2 during summer, (2) confirmation of our previous observations supporting a temporal decoupling between primary production by phytoplankton and secondary production by bacterioplankton (reasons for this enigmatic decoupling are not known but have important implications for parameterization of secondary production and nutrient regeneration in polar waters and in our modeling of PAL region primary production), (3) quantification of the downward flux of particulate matter which displays annual variations in excess of 1000-fold from values of 2 g m-2 d-2 in summer to <1 mg m-2 d-2 in winter and which displays interannual variability, with highest export in heavier than average ice years, and (4) in collaboration with Ed DeLong (UCSB), continued investigation of the relatively high abundances of Archaea in the water column near Palmer Station (up to 30% of the total rRNA), an observation that derived from B. Prezelin's PAL research.

L.B. Quetin and R.M. Ross (prey component)

Research by this component focused on three topics: (1) zooplankton abundance and community structure, with particular focus on Euphausia superba (Antarctic krill), (2) krill distribution, number and size of aggregations, and (3) krill/sea ice interactions. Our general approach involved sampling the water column with obliquely towed 1-m or 2-m nets while simultaneously obtaining acoustic backscatter signals from a transducer (BioSonics, 128 kHz). Specimens were analyzed immediately, preserved or used for physiological experiments. To date, the research for this component has resulted in several significant findings. (1) Estimates of short-term grazing pressure and flux of fecal pellet carbon to the sediments, calculated in conjunction with PAL data on phytoplankton biomass and production, vary with the temporal and spatial abundance and community composition of larger zooplankton (Table 11). (2) Krill aggregations, distribution, number, size and composition vary on several temporal scales. (3) Integrated krill biomass levels and length frequency distributions vary with season. During summer, there is a strong on/offshore gradient, with small krill abundant and dominant inshore, whereas the larger reproducing krill are primarily located offshore on the outer continental shelf and at the shelf break. This on/offshore gradient in krill size parallels that found for phytoplankton biomass for all cruises. During fall and winter all size classes shift towards inshore regions, and large aggregations (which contain a disproportionate amount of the biomass) become most abundant inshore. (4) There was a sharp decrease in the spatially averaged krill biomass during the transition from summer to fall in 1993, which suggests that large scale shifts in biomass distribution are possible in short time periods. This has implications for estimates of total krill biomass, as well as for local penguin populations, causing changes in foraging behavior, both within a season and interannually. (5) Quantitative diver censuses of the under-ice population (August 93) show that the majority of the krill which are closely coupled to the ice in winter are the young-of-the-year or AC0 (Age Class 0, krill in the first year of existence) population, whereas adults are rare. The differences in AC0 and adult krill distributions in winter are attributed to 'risk balancing'. (6) Interannual variability in recruitment success for Antarctic krill, as shown by patterns in length frequency distributions from the mesoscale grid for the four spring/summer cruises (Figure 4), is extremely high and follows the pattern predicted from initial PAL hypotheses concerning the effect of sea ice on winter-over survival of AC0s (i.e., strongest year classes are associated with years in which winter ice is both above average in extent and retreats late in spring).

W.R. Fraser and W.Z. Trivelpiece (seabird component)

Seabird research at Palmer Station, which has been supported both by the National Science Foundation and the National Oceanic and Atmospheric Administration through the National Marine Fisheries Service, encompassed basic and applied research, in which monitoring of key parameters related to seabird ecology played a critical role. An important assumption guiding our general research approach is that the persistence of any seabird population over time ultimately reflects the coincident availability of suitable nesting and foraging habitats. We concluded the first funding phase of the PAL program with the development of a conceptual model that addressed the role that sea ice has in affecting the availability of these habitats. Our approach embraced a step-wise series of analyses involving new and historical data on Pygoscelis adeliae (Adelie penguin) demography, foraging ecology, behavior and biogeography. Three key results were particularly influential in structuring model development. (1) Population changes of many Southern Ocean, upper-trophic level predators during the last five decades are better explained by changing winter sea ice conditions resulting from environmental warming than by the long accepted tenet that depletion of baleen whale stocks led to an increase in krill availability and competitive release. (2) Variability in the terrestrial breeding habitat of Adelie penguins, a result of changing precipitation patterns because of increasingly warmer winters with less sea ice, is an important, but only recently recognized factor affecting long-term reproductive performance and recruitment. Because the disappearance of breeding groups can be fairly rapid, it is suggested that very short term changes in the environment can result in rapid shifts of the populations in an area. (3) There is a direct causal relationship between variability in sea ice cover, krill recruitment, krill availability and predator foraging efficiency. Based on these results, the aforementioned model describes a "habitat optimum" for Adelie penguins that varies in space and time in accordance with changing atmospheric and oceanic processes and the consequent effects on sea ice formation, which ultimately mediates the availability of breeding and foraging habitats. The model and the analyses on which it is based have multiple implications for Southern Ocean ecosystem studies and illustrate how community structure and function may respond to climate change.

E.E. Hofmann and J.M. Klinck (modeling and physical oceanography component)

The ODU component of the PAL took responsibility for (1) processing and analysis of hydrographic data, (2) describing the hydrography and circulation in the WAP region and over Antarctic continental shelves in general, and (3) developing circulation and coupled physical-biological models. The approach consisted of participating in the collection of and all post-processing of hydrographic measurements from the first four PAL cruises. Results from historic and PAL hydrographic data show that the Antarctic shelf regions are greatly influenced by a warm, salty water mass, the Circumpolar Deep Water (CDW). The circulation pattern in the WAP region shows that the large-scale geostrophic flow may be composed of one or more clockwise gyres. This mesoscale variability is likely the result of the rugged bottom topography and has implications for the transport and retention of physical and biological properties. Surface drifters indicate that the circulation in Bransfield Strait is clockwise and may be continuous with the circulation in the WAP above 500 m. Also, the westward flowing Polar Slope Current, which has been observed north of the South Shetland Islands, does not appear to extend beyond Smith Island . The Princeton Ocean

General Circulation Model (POGCM) has been configured to use geography, bathymetry, and hydrographic climatology for the PAL region, and simulations are now being done with this model to investigate processes underlying the circulation in the WAP region. In support of ecosystem synthesis studies, we have also analyzed some of the multidisciplinary data sets collected during the first four PAL cruises in an effort to understand krill distributional patterns in relation to other habitat characteristics. This work showed the need for a mathematical model on the growth and development of krill larvae which has been developed and is now operational.

K.S. Baker (data management component)

Data management is discussed in detail in Section 5, which also provides a discussion of the PAL data policy and a guide to PAL online data.

2. Project Description

2.1 Antarctic Marine Ecosystem Introduction

The Antarctic marine ecosystem, the assemblage of plants, animals, microbes, ocean, sea ice and island components south of the Antarctic Convergence, is among the largest readily defined biomes on Earth (36 x 10^6 km2) (Hedgpeth 1977; Petit et al. 1991). This environment is composed of an interconnected system of functionally distinct hydrographic and biogeochemical subdivisions (Treguer and Jacques 1992) and includes open ocean, frontal regions, shelf-slope waters, sea ice and marginal ice zones. Oceanic, atmospheric, and biogeochemical processes within this system are thought to be globally significant, have been infrequently studied and are poorly understood relative to more accessible marine ecosystems (Harris and Stonehouse 1991; Johannessen et al. 1994). The PAL area west of the Antarctic Peninsula (Fig. 1a) is a complex combination of a coastal/continental shelf zone (CCSZ) and a seasonal sea ice zone (SIZ), as this area is swept by the yearly advance and retreat of sea ice.

Polar regions are unique in that sea ice, a dominant and distinguishing characteristic of Southern Ocean marine ecology, forms a range of habitats for animals as well as extensive and varied surfaces for algal and microbial populations. The influence of sea ice on nearshore marine ecosystems is pervasive and strongly affects the vertical zonation of sublittoral habitats (Clarke 1996). In the pelagic realm, sea ice not only provides a surface for algae but is also thought to provide a refuge and an important wintertime grazing area for juvenile krill at the ice/water interface (Smetacek et al. 1990; Ross and Quetin 1991). In addition, different springtime seabird habitats are associated with varying sea ice coverage, which therefore alter trophic level interactions, foraging efficiency and , ultimately, breeding success (Hunt 1991; Ainley et al. 1994). These habitats include: (1) open leads and polynyas, through which seabirds can gain access to the water column and underside of sea ice, (2) the ice edge, which is a major ecological boundary and can either be compact or diffuse, and (3) the outer marginal ice zone (MIZ), where meltwater contributes to stabilization of the water column and provides the potential for enhanced phytoplankton growth. The MIZ is an area bounded on the open ocean side by the stabilizing influence of meltwater and on the pack ice side by the penetration of ocean swell. The physical action of ocean swell imparts distinctive structure to Antarctic sea ice (Ackley et al. 1979) and creates a range of ice-related habitats which support the development of diverse biological sea ice communities (Legendre et al. 1992; Ackley and Sulllivan 1994). The MIZ can be up to 250 km in width and is often an area of high productivity (Smith and Nelson 1985) relative to the open ocean. It is therefore an ecosystem boundary where the flow of energy, the cycling of nutrients and the structure of biological communities change dramatically, both temporally and spatially. In addition, the areal extent of sea ice cover and the associated timing of the MIZ in relation to specific geographic areas (e.g., seabird rookeries) have high interannual variability. The range for variable ice cover is shown schematically in Fig. 1a. Sea ice extent for low (1989), average (1993) and high (1987) ice years are indicated (Stammerjohn and Smith 1996).

Mesoscale oceanic circulation patterns in the WAP region are not presently well-known (Hofmann et al. 1996). The barotrophic circulation is also not known, and there are no direct current measurements anywhere in the region. Even tidal characteristics are poorly known (Amos 1993). There are some suggestions of the direction of flow on the shelf from dynamic calculations and other indirect means. The Antarctic Circumpolar Current (ACC) clearly stands out in all calculations and flows northeasterly off the shelf. There are a number of indications of southward flow on the inner part of the shelf. This is shown schematically in Fig. 5. Some studies suggest the existence of two gyres (Stein 1992), but it is not certain whether permanent eddies are part of the coastal circulation, or if the coastal flow is merely convoluted and not sampled sufficiently to resolve the features. The most prominent water mass in the WAP is Circumpolar Deep Water (CDW) is characterized by temperatures above 1.5degC, salinities of 34.6 to 34.8 and oxygen values below 4.5 ml l^-1. It is found between 200 and 700 m and present in all seasons throughout the region examined. Below 200 m this water mass floods the WAP continental shelf. CDW is also found in Bransfield Strait, but with distribution limited to the northern side of the Strait near the South Shetland Island s (Hofmann et al. 1996). The CDW brings macronutrients and dissolved inorganic carbon, in addition to warm salty water, onto the shelf. The presence of this water mass near the bottom of the mixed layer has considerable implications for heat, salt and carbon budgets in this region. Also, the circulation patterns and the presence of CDW may impact the timing and coverage of sea ice, as well as the transport and /or retention of physical and biological properties in the PAL area.

Smith et al. (1996a) have recently reviewed historical phytoplankton biomass and productivity data for the PAL region and conclude that the average productivity of the region is on the order of 100 to 200 g C m-2 y-1 which is roughly about a factor of 5 lower than other productive coastal areas of the world's oceans (Chavez and Barber 1987). Factors that regulate primary productivity within this environment include those that control cell growth (light, temperature, and nutrients) and those that control the accumulation rate of cells and hence population growth (water column stability, grazing, sinking and advection). It is important to note that the process of primary production is a complex integration of these independent factors and may vary independently from total biomass. For example, the accumulation of Chl-a during a bloom may result either from a moderate rate of primary production in the absence of grazing or from a high rate of production in the presence of grazing. Sea ice mediates several of these factors and often, but not always, conditions the water column for an initial bloom which is characterized by a pulse of production restricted in both space and time. The relationship of the relative contribution of bloom versus non-bloom primary productivity to the timing and balance of the resulting food web dynamics is currently unknown. Also, we only roughly know the relative contribution of microalgal and bacterial production of biogenic carbon in the MIZ, under pack ice and within sea ice (Legendre et al. 1992; Smith et al. 1995b) and we identify this as a critical area for our further research. Finally, there appears to be a metabolic uncoupling, in time, between phytoplankton and bacterioplankton activities in Southern Ocean habitats contrary to studies conducted in temperate marine ecosystems (Karl 1993), and the timing and fate of biogeochemical fluxes of carbon associated with these various pelagic and sea ice-related communities is presently unknown.

Like most marine food webs, the trophic relationships in Antarctica are complex. However, the links between primary producers, grazers and apex predators (seabirds, seals and whales) are often short and may involve fewer than three or four key species (Fig. 6). Predators tend to concentrate on a core group of prey species, for example, the abundant euphausiids and fish close to the base of the food web. The general sampling approach in our study capitalizes on the close coupling between trophic levels, the limited number of species involved, and the fact that one of the dominant predators is seabirds that nest on land and are thus easily accessible during the spring and summer breeding season. An important apex predator is the Adelie penguin, which dominates the seabird assemblage near Palmer Station in terms of abundance and biomass. During the summer breeding season, these seabirds depend on resources found within their foraging range, which is thought to be within 100 km of the breeding sites (Fraser and Trivelpiece 1996a). Finding sufficient prey within these foraging ranges is critical to the reproductive success of these birds. Preferred prey for Adelie penguins are krill, a keystone species with a circumpolar distribution. However, the timing of prey availability and abundance is highly variable from year to year.

2.2 Conceptual Model of Physical and Biological Linkages

Solar radiation, atmospheric and oceanographic circulation as well as sea ice coverage are the physical forcing mechanisms driving variability in biological processes at all trophic levels in Antarctica. Extreme seasonality and the relatively large interannual variability (both in magnitude and timing) of physical forcing may be compared and contrasted with conditions for biological growth, development and survival of key species from each trophic level, providing a conceptual model for the discussion of trophic linkages (Fig. 7). As discussed below, some of the components in Fig. 7 are known with relative certainty, while others are suggested according to our current knowledge and related hypotheses. A key point is to first identify, then understand and ultimately model these temporal linkages. Long-term, systematic time-series data are essential for this effort.

Daylength, precipitation, air temperature, and sea ice cover have a strong seasonal cycle at high latitudes. Weather, while mild by comparison to the interior of Antarctica, is punctuated by episodic storm events, is modified by a changing seasonal balance between relatively warm and moist maritime and relatively cold and dry continental influences, and shows more year-to-year variability in winter (Smith et al. 1996b). In spite of this large interannual variability, statistically significant warming trends have been detected in the relatively short WAP station records (Smith et al. 1996b and references therein). However, until 1994 weather data for the WAP region were available only from stations located on the coast or on island s near the coast. At the request of the PAL, automatic weather station (AWS) units (Bromwich and Stearns 1993) have now been installed at the end of Bonaparte Point near Palmer Station and in the Hugo archipelago, a small group of low lying island s, approximately 90 km west southwest of Palmer Station (Fig. 1b). Data from coastal (AWS Bonaparte) and oceanic (AWS Hugo) stations help to characterize the different weather regimes and relative influences of a coastal versus a more oceanic environment. With the AWS on Racer Rock in the Gerlache Strait, there is now a suite of three AWS installations within the PAL study area, providing more continuous weather data, in addition to the weather records from Palmer, Faraday and Rothera Stations (Baker and Stammerjohn 1995).

There are also seasonal variations in the hydrography of the PAL. For example, in winter, temperature and salinity are uniform down to approximately 100 m (Hofmann et al. 1996). Beginning in spring and during summer, the ocean warms from the surface, creating one or more layers of warmer water that are a few tens of meters thick. Episodic storms mix these layers so that the vertical temperature structure near the surface can be quite variable. The freshening of the surface layer during summer due to sea ice and glacier melt also can play a key role in stabilizing the water column and hence increase rates of primary production. Although variations in salinity are small, the density and stability of the upper water column are more a function of salinity than temperature. It appears that the CDW floods the shelf throughout the year, characterizing the deep waters in the PAL study area. The annual heat flux associated with the CDW (12 W m-2) is sufficient to be an important factor in determining the extent and thickness of sea ice in the WAP region. It is therefore critical to understand the factors controlling the variability of the annual heat flux associated with the CDW.

The timing and extent of the annual advance and retreat of sea ice in the vicinity of Palmer Station (i.e., the Adelie penguin foraging area) are highly variable and have been discussed in detail (Stammerjohn 1993; Stammerjohn and Smith 1996). The satellite time series is still too short to statistically resolve any persistent low frequency periodicities, but there is evidence that high interannual variability in magnitude, timing of ice advance and retreat, duration of near maximum and minimum ice coverage, and apparent clumping of high or low ice years have significant impacts on the survival rates, distributions and /or life histories of key indicator species (Ross and Quetin 1991a; Quetin and Ross 1992; Quetin et al. 1994; Siegel and Loeb 1995; Fraser et al. 1992b; Fraser and Trivelpiece 1996a). Further, we are beginning to define the physical forcings (e.g., thermodynamics versus advective processes) controlling variability in sea ice coverage and the resulting ecological consequences.

Our current models of the trophic organization of Antarctic marine ecosystems have evolved considerably during the past decade. Prior to 1980, energy flow in Southern Ocean habitats was thought to be dominated by relatively short and therefore efficient transfers from large (>20 Mm) phytoplankton cells to krill and subsequently to apex predators. More recently, our concept of the marine food web expanded to reflect the potential roles of heterotrophic microorganisms including bacteria, protozoans and small (<150 Mm) non-krill crustaceans. Heterotrophic microorganism-based food webs, also referred to as microbial loops (Azam et al. 1983), are present in all aquatic environments including the Antarctic marine ecosystem. These detritus driven systems are fueled by non-respiratory community carbon losses, including dissolved and particulate organic matter released by excretion, predation and mortality. Because microbial loops require several trophic levels to transfer carbon and energy to apex predators, most detritus based food webs are inherently inefficient and sometimes constitute major energy sinks. It is important to emphasize that comprehensive, quantitative ecosystem studies of energy and carbon flow in Antarctic food webs do not exist. At best, there are order of magnitude estimates for a few selected regions. A major, unexpected result of the Antarctic field studies conducted to date is the apparent short-term uncoupling of algal and bacterial metabolic processes (Cota et al. 1990; Karl et al. 1991; Karl and Bird 1993). Reasons for this uncoupling are not well understood at present. Consequently, we must view the microbial loop models as hypotheses that deserve a thorough, quantitative field evaluation.

Sea ice provides one of the major habitats for microorganisms in Antarctic marine ecosystems, and it is possible that some microbial food webs may be entirely ice-associated (Palmisano and Garrison 1993). In the PAL program, we have just begun to systematically investigate these unique habitats. Preliminary results suggest that the bacterial community goes through several, as yet poorly defined, stages of succession as the annual pack ice recedes (Christian and Karl 1995a). The water is initially seeded with bacteria, as well as substantial inputs of organic matter that may be quite different in chemical composition than the organic matter in the water column. Phytoplankton blooms at the receding ice edge provide additional sources of organic matter, through excretion, lysis, and grazing, that are likely to be present only for a short time. Furthermore, photochemical alteration of dissolved organic matter may be accelerated in the sea ice habitat, because it is immobilized in a region of high UV and visible light flux. These processes are likely to play important roles in the adaptation of marine bacteria to this seasonally variable environment, and the biochemical characteristics of the bacteria may change rapidly with time. Future studies will focus on the quantitative role that variations in ice cover may have on the presence and intensity of microbial processes.

Associated with the increase in daylength and the melting of sea ice, both contributing to water column stratification, phytoplankton biomass (Chl-a) in the PAL area starts to accumulate near the end of November in an average ice year. In non-average ice years the subsequent timing shifts accordingly. Mean Chl-a in the top 30 m can increase from <0.5 mg m-3 in a pre-bloom period, to higher than 15 mg m-3 during a spring bloom, with average values between 1 and 3 mg m-3 (Smith et al. 1996a). Blooms are mostly dominated by cells >20 Mm, which are typically large or chain-forming diatoms, although cells <20 Mm also grow during a bloom (i.e. cryptomonads and prasinophytes). On occasion, the bloom is dominated by the colonial prymnesiophyte Phaeocystis pouchetii. Smaller diatoms and flagellates dominate during nonbloom and post-bloom periods (Holm-Hansen et al. 1989). The termination could be caused by cell advection, sinking and /or zooplankton grazing which leads to recycling of materials in the euphotic zone and reduces export particle flux. Large fluxes of organic matter (> 1-2 gC m-2 d-1) have been observed in sediment traps, sometimes after a period of intense erosion of the mixed layer, as might occur during a storm. In contrast, the development of a massive coastal bloom, even for a short period of time (days or weeks), can significantly decrease inorganic nutrients which can also lead to bloom termination. Surface nitrate concentrations in coastal waters of the WAP region can decrease from 25 MM, when non-bloom Chl-a concentrations are typically 0.5 mg m-3, to near depleted levels (<0.1 MM), when bloom Chl-a concentrations can be >35 mg m-3 (Kocmur et al. 1990). The coastal bloom, in terms of continued new/export production, crashes unless nutrients are then replenished by mixing and erosion of the mixed layer or by advection of richer offshore waters. However, primary production can continue without allochthonous nutrients, if nutrients are locally regenerated, but new production ceases. During summer, in both open ocean and coastal areas, Chl-a concentrations remain intermediate (1-2 mg m-3), although periodic blooms may still occur nearshore. Fall phytoplankton blooms may appear in late February and March.

The relative contribution of MIZ related production to overall production continues to be debated. Smith and Nelson (1986) and Smith et al. (1987b) show evidence that the MIZ, especially in spring, supports high phytoplankton biomass and /or high production rates. On the other h and , recent observations (Lancelot et al. 1993; Boyd et al. 1995) suggest that specific meteorological conditions influence whether blooms do or do not occur in the MIZ. Nonetheless, total annual productivity is thought to be dominated by the high production rates associated with spring blooms, whose development may be timed and paced by ice-driven water column stability and /or favorable meteorological conditions. The timing of this burst of productivity and consequent food availability for prey (krill) and subsequently, predators (penguins), as well as the habitat considerations associated with these environmental conditions, creates a complex trophic matrix and associated temporal linkages (Figs. 6 and 7). These couplings are subject not only to the progression of the seasons, but also to episodic events that disrupt and /or reset the cycle of water column stability, phytoplankton productivity and subsequent linkages.

Prey/predator trophic interactions (i.e., krill/Adelie penguins) are strongly mediated by critical periods during reproduction of both prey and predator. Our chosen prey/predator pair is composed of relatively long-lived species. Antarctic krill live for 5 to 7 years, reproducing as early as their third summer. Ovarian development begins in austral spring, and the rate of ovarian development is dependent on food availability. A prolonged spawning season runs from late December to early March. Both the proportion of the population reproducing and the length of the spawning season are dependent on food availability during spring and summer. Release of ice algae from melting ice and ice-edge blooms, occurring prior to open-water blooms, are thought to be one source of food essential to high reproductive output throughout the summer (Quetin et al. 1994). After spawning the embryos sink, hatch at depth, and the early non-feeding AC0s ascend through the water column. The first critical period occurs when early AC0s arrive at the surface, about three weeks after release and need food. Winter is the second critical period, because unlike adults, larvae lack energy stores. The six-month fall and winter period of low food availability in the water column can create starvation conditions for the AC0s (Ross and Quetin 1991a). The essential winter grazing ground for AC0s is the under-ice habitat where they feed on ice algae. Thus, recruitment and AC0 survival and growth are hypothesized to be enhanced by the presence and duration of winter ice.

Adelie penguins have a circumpolar distribution and a breeding season that passes through a series of stages. The season begins with a three week courtship period, during which time both members of the pair remain ashore fasting. This is followed by egg-laying and a month long incubation period from late November through December. The incubation duties begin with the male on the nest which requires him to fast for an additional two weeks, while the female goes to sea to feed. During this first critical period the female is believed to return to the ice edge in search of a predictable source of krill in order to restore her body condition (Trivelpiece and Fraser 1996). If the female fails to replenish her supply of fat and return to the nest within two weeks, the male abandons the nest to forage, and the eggs are lost. If the female is successful in finding food, she relieves her mate at the nest, and he spends the following two weeks at sea recovering from his five weeks of fasting. Upon the return of the male, the pair alternate between attending the eggs and foraging at sea on progressively shorter time intervals, until they are switching duties daily by the time the eggs (usually two) hatch. Following hatching, the pair continue alternating between guarding the chicks at the nest and foraging for food for their young until the chicks reach approximately three weeks of age. A second critical period affecting breeding success occurs in mid to late January, when the chicks are between three and seven weeks old. During this "creche stage", the food/energy demands of the chicks are at their highest. The parents must find adequate supplies of prey (typically krill) within a foraging area of about 100 km, or preferably much closer, otherwise breeding success may be significantly reduced.

2.3 Working Hypotheses

The PAL program remains focused on understanding the ecological role of sea ice with the primary object being to gain a general understanding of the physical and climatic controls on interannual sea ice variability, the effects of this variability on trophic interactions, and the biogeochemical consequences thereof (PAL Group 1996; Smith et al. 1995c). Our observational and experimental programs reflect this primary research goal. In the following, we restate the central null hypothesis and present several alternate hypotheses that together comprise our integrated, transdisciplinary research prospectus. We then discuss in both general and specific terms the various ecological predictions that derive from the alternate hypotheses through the use of conceptual models that illustrate the hypothesized coupling between sea ice and biological processes at various trophic levels.

H0: Neither the presence nor the extent of annual sea ice in the PAL study area influences ecosystem structure and dynamics.

HA1: Interannual variations in ice dynamics are a quasi-predictable manifestation of ocean and atmospheric circulation processes which influence the extent of CDW upwelling onto the continental shelf. The presence of this warm, salt water mass affects the heat and salt budgets of the region and hence controls ice dynamics.

HA2: Primary and secondary production are enhanced during high ice years, causing a general intensification of biogeochemical cycling rates and particle export processes.

HA3: Increased food production and under-ice refuge during sequential above normal sea ice years promotes optimal recruitment and growth of krill and , in subsequent years (1-2 yr lag), a greater breeding success and survival of apex predators (e.g., Adelie penguins).

HA4: The exchange of carbon dioxide between the atmosphere and the surface ocean is influenced by ice dynamics, CDW upwelling, primary and secondary production rates and organic particle sedimentation. The WAP region may be an important, albeit temporally-variable, source/sink term in global carbon budgets.

Ackley and Sullivan (1994) have described the seasonal cycle of pack ice development, formation, and the entrainment, accumulation and growth of microalgae within various pack ice micro-environments (Ackley and Sullivan, Fig. 1). Several other studies (Smetacek et al. 1990; Ross and Quetin 1991a; Quetin et al. 1996) have presented comprehensive summaries of the life cycle of Antarctic krill, including vertical distribution and timing of early life history stages in relation to seasonal cycles of daylight, ice cover and phytoplankton. Figures 8a and b present summary conceptual diagrams of these processes and the hypothesized linkages for the PAL region.

Key points of these figures are that the development of the sea ice community (1) is a dynamic process, (2) is a strong function of the distinct environmental conditions during sea ice formation, development, deformation and subsequent melt, and (3) has a varied history which leads to discrete physical, optical, chemical and biological features within distinct ice-related habitats. Consequently, the timing and extent of sea ice, from the formation to the subsequent deformation and eventual melting, plays a complex and not fully understood role in the ecology of sea ice biota. Interior sea ice communities were first described by Ackley et al. (1978), and the physical and biological controls of Antarctic sea ice communities have been addressed by Ackley and Sullivan (1994) and Garrison and Mathot (1996), while Maykut (1986) and Lange et al. (1989) have described the formation of sea ice in detail. Some of these processes are conceptualized in Figs. 8a and b which show (1) the incorporation of biological material during fall frazil ice formation, (2) the in situ growth of material within the ice during the lifetime of the ice cover and subsequent deformation, and (3) the ice melt and release of biological material to the water column in spring. Microalgal sea ice communities include those scavenged from the water column during the formation of frazil ice and those deposited by flooding and rafting (Ackley and Sullivan 1994). There are few quantitative surface sea ice observations in the WAP region but qualitative shipboard observations suggest a region with little, if any, multi-year ice and significant (but not yet quantified) deformation and ridging prior to melt.

A critical issue is the relative contribution of sea ice algae to the total overall primary production within this ecosystem. The estimates of Smith et al. (1995b) and Legendre et al. (1992) for the Southern Ocean are reasonably consistent (0.46 and 0.29 GtC y-1, respectively) when considering only the CCSZ and SIZ (Table 12), however other historical estimates vary by more than an order of magnitude. With caution, oceanic regional production estimates permit consideration of the relative contribution of distinct hydrographic/biogeochemical sub-divisions of the Antarctic marine ecosystem and facilitate comparison among geographic regions. These estimates suggest that the contribution of sea ice algae to the base of the food web is quantitatively important, in addition to any contribution via conditioning of water column production. Also, a high proportion of sea ice production may be new, rather than recycled, production so that the impact may be particularly significant with respect to export flux (see discussion below). Further, these estimates, and associated assumptions and errors, emphasize the need for better characterization of the areas comprising the distinct biogeochemical zones (CCSZ, MIZ, SIZ) and the periods over which sea ice and water column blooms take place within these zones (e.g., "Sampling Strategy", Sect. 2.5).

Figures 8a and b also conceptualize hypothesized linkages between the seasonal cycle of sea ice and krill. Note that a distinction is made between these linkages for AC0 and adult krill. AC0s are hypothesized to be obligate inhabitants of the underside of sea ice during winter (Ross and Quetin 1991a). Biological material entrained during ice formation and the subsequent growth of microalgae within the fall/winter sea ice can be utilized by AC0s. Over-rafted sea ice provides refuge for AC0s as well as increased surface areas, often with light-trapping properties, for enhanced ice algae populations. During the spring ice melt, ice algae released into the water column not only provides a possible inoculum for a spring bloom, but a source of food for both AC0s and adult krill that are developing into reproductive condition. Figure 9 summarizes these hypothesized relationships between sea ice, microalgae and krill which will be discussed in greater detail below.

Sea ice and associated phyto and zooplankton also play a key role in both the timing and magnitude of carbon flux exported from the euphotic zone. In Figs. 10a and b, which show idealized examples of ecosystem structure and function, we hypothesize that there are two separate end-member biological controls on particle export: phytoplankton control and zooplankton (krill) control under both low and high ice conditions. When krill population densities and herbivore grazing pressures are low (i.e., phytoplankton control of export, Fig. 10a), we hypothesize that large accumulations of phytoplankton (i.e., "blooms") will occur with attendant decreases in nitrate and total inorganic carbon. In the PAL study area, these spring-summer blooms are common. In the absence of efficient grazing by macrozooplankton, the growth of photoautotrophs is eventually limited by nutrients (nitrate, or for diatoms, silicate) and /or by light. Under these environmental conditions, cell aggregation and sinking of whole, ungrazed phytoplankton cells dominates the total particulate matter export from the euphotic zone. However, the presence of ice may influence these processes by at least two independent mechanisms. (1) When the ice melts in early spring, the release of ice algae serves as both an agent for immediate particle export as well as for subsequent in situ growth and export processes. This seed population can influence both the timing of the bloom and the relative abundance of potential phytoplankton species. (2) AC0 and adult krill associated with sea ice in spring could impose a grazing pressure on the phytoplankton population, suppressing the accumulation of Chl-a and , therefore, the presence of a bloom in the early spring-early summer (Nov-Jan) period. However, another important consequence of grazing activity is that it could regenerate nutrients (especially the conversion of particulate organic nitrogen, PON, to NH_4^+) which in turn could sustain the growing season, thus triggering phytoplankton species succession and a secondary bloom in the late summer to early fall period. A coupled particle export pulse would accompany this fall bloom.

When zooplankton are relatively abundant (Fig. 10b), their efficient grazing activities prevent the accumulation of Chl-a and cause a fundamental shift in the nature of the exported materials from primarily intact phytoplankton cells to mostly fecal pellets (i.e., zooplankton control of export). An important biogeochemical consequence of this shift is that the C:N and C:P ratios of fecal pellets are generally much greater than those of the phytoplankton cells. This results in a stoichiometric uncoupling of export from production and favors a net removal of C, relative to N or P, from the surface layers of the ocean. This net sequestration of particulate carbon in the subeuphotic zone and depletion of dissolved inorganic carbon in the surface layers establishes conditions necessary for the transport of atmospheric carbon into the ocean. Our direct measurements of the air to sea gradient of partial pressure of CO_2 in the PAL study area (>100 ppm, with the sea water being lower) are consistent with this hypothesized role of the Antarctic coastal regions serving as a large but transient sink for atmospheric CO_2. The regeneration of N by krill, primarily in the form of NH_4^+, also has important implications for new vs. regenerated production and for phytoplankton species succession, as mentioned above. We hypothesize that an above average ice year increases the probability and intensity of the "zooplankton control" of exporting particulate matter. Therefore, we suggest that phytoplankton control dominates in below average ice years and that zooplankton control dominates in above average ice years, primarily as a result of the role of sea ice in the krill life cycle (Figs. 8 and 9).

2.4 Motivation and Future Direction

Phytoplankton Production and Export Processes Photoautotrophic microplankton provide the base of the food web (Fig. 6) and therefore influences the temporal and spatial variability of higher trophic levels, while a fraction of this production is transported to depth providing a potential sink for CO_2. Our observations show that the seasonal and interannual variability of phytoplankton biomass in the shelf-slope system of the WAP area has fundamentally different characteristics compared to pelagic areas of the Antarctic marine ecosystem (Smith et al. 1995a,1996a). Regional coverage from the annual PAL cruises shows that the on/offshore gradient in pigment biomass is an enduring characteristic (El Sayed 1968), with nearshore areas roughly four times higher than offshore areas. Further, there is some evidence for an alongshore gradient, perhaps associated with the timing of the seasonal alongshore retreat of sea ice and /or latitudinal atmospheric and oceanic influences.

Estimates of total primary production for the Southern Ocean and the PAL area have been computed using both a light-chlorophyll production (LCP) (Smith et al. 1987; Bidigare et al. 1992; Morel and Berthon 1989; Byers et al., submitted) and an ice edge production model (Smith and Nelson 1986; Wilson et al. 1986; Smith et al. 1988). Input parameters (chlorophyll concentrations, total photosynthetically available radiation (PAR) and sea ice concentrations) for these models were derived from satellite data. Chlorophyll concentrations and PAR, in addition to hydrodynamic conditions, have also been determined from shipboard and Palmer Station observations during the PAL field seasons. Comparisons of the spatial and temporal variability of model results with both historical shipboard and our field observations (Smith et al. 1995b,1996a) are consistent. A sensitivity analysis of the PAL area shows that the annual retreat of the MIZ is likely to contribute between 5 and 40% to the productivity of this CCSZ/SIZ area. However, comparison of field and model results, in addition to direct measurement of photosynthesis-irradiance parameters, suggests that considerable phytoplankton productivity within the Southern Ocean takes place under light-saturated conditions. Under these conditions LCP models for estimating productivity will need to be revised and /or replaced with models that more accurately reflect the physiological conditions of phytoplankton within Antarctic waters.

In order to document the temporal and spatial variability in phytoplankton abundance and distribution within the PAL area and to understand the underlying controlling processes, we will concentrate on (1) processes associated with ice edge and shelf-related blooms (phytoplankton accumulation) and their regulation, (2) on/offshore processes which are responsible for the observed patterns on the continental shelf, (3) the balance between phytoplankton growth vs loss rates (respiration, sedimentation and grazing) on the observed patterns of phytoplankton distribution, and (4) the relative contribution of sea ice algae production to overall production within the PAL area. Time series data of primary production are virtually nonexistent for the Southern Ocean, so we expect to use our field data, as well as laboratory experimental manipulation, to test our general hypotheses (Figs. 8, 9 and 10) linking sea ice, microalgae and krill.

The role of the ocean as a reservoir in the global carbon cycle is dependent largely upon the export flux of planktonic primary production from the euphotic zone (Eppley and Peterson 1979; Williams and von Bodungen 1989). This supply of reduced carbon and energy to intermediate ocean depths occurs by downward advection and diffusion of dissolved organic matter (Toggweiler 1989), gravitational settling of particulate matter (McCave 1975) and by the vertical migrations of pelagic animals (Longhurst and Harrison 1989) and phytoplankton (Villareal et al. 1993). Each of these individual processes, collectively termed the "biological pump" (Volk and Hoffert 1985) is controlled by a distinct set of environmental factors, and therefore, the relative contribution of each process may be expected to vary with changes in habitat, water depth and , in polar regions, sea ice (Figs. 8 and 10).

Results from broad-scale, cross-ecosystem analyses suggest that the export of living and non-living materials from the euphotic zone is a positive, non-linear function of total integrated primary production (Suess 1980; Pace et al. 1987; Martin et al. 1987; Wassman 1990), with values ranging from less than 10% in oligotrophic waters to greater than 50% in productive coastal regions. It should be emphasized, however, that the field data from which the existing export production models were derived are limited and that open ocean and Antarctic habitats are both underrepresented. A majority of the Southern Ocean is characterized by high surface nutrient concentrations but low rates of primary production and export production (Holm-Hansen et al. 1977; Honjo 1990). Broecker (1982) suggested that if all the surface nutrients in the Southern Ocean were efficiently used by the phytoplankton, the biological pump activity could transfer a significant amount of atmospheric CO2 to the ocean's interior. However, at the present time the biological pump appears to be functioning at less than full capacity in polar environments (Knox and McElroy 1984), and a resolution of this enigma is of great importance in the study of oceanic carbon cycles (e.g. Broecker 1991; Longhurst 1991).

The intensive austral spring/summer phytoplankton bloom in the Antarctic Peninsula region can result in phytoplankton standing stocks in excess of 20 mg Chl a m-3 and sustained production rates of 2-5 g C m-2 d-1 (Holm-Hansen and Mitchell 1991; Vernet et al. 1995). Though the phytoplankton bloom productivity is well documented, we know less about the fate of this seasonally accumulated organic matter. During the past decade, numerous field experiments using particle interceptor traps (i.e., sediment traps) were conducted to determine the amount and nature of the particulate matter exported from representative marine and freshwater ecosystems (Honjo 1990). A fairly extensive particle flux data base exists for the Antarctic Peninsula region (Karl et al. 1994b,1996), and sediment-trap derived particle flux estimates in the WAP region are among both the highest (>1 g C m-2 d-1 during and immediately following the spring bloom) and the lowest (<0.05 mg C m-2 d-1 during austral winter) values reported for the world ocean. Furthermore, during the initial stages of the spring/summer phytoplankton bloom, particle export may be decoupled from contemporaneous new production for periods of several weeks or more. In addition, the abrupt termination of the spring bloom may be controlled, at least in part, by storm events which have the net effect of dissipating the phytoplankton crop and reducing net photosynthesis and growth. If the water column is allowed to re-stratify, a second spring bloom is possible. In order to model carbon and energy flows in the Antarctic coastal ecosystem, we require specific additional information on the residence time of particulate organic matter in the euphotic zone and on the processes responsible for controlling the rates of export.

The low to undetectable fluxes of total mass and biogenic matter consistently observed during austral winter periods are enigmatic. Although the Antarctic winter is known for harsh environmental conditions of deep-mixed layers and low solar radiation, most oceanic regions in the Antarctic Peninsula area support measurable net primary production year round. Cochlan et al. (1993a) measured Chl-a concentrations of 4 mg m-2 (0-75 m) and photosynthetic rates of 35-50 mg C m-2 d-1 in Gerlache Strait during July 1992. Furthermore, the reported f-ratio of the wintertime phytoplankton assemblage (e.g., [NO3-] uptake rate divided by the sum of [NO3 and NH4+ and urea] uptake rates) was 0.87 suggesting that the majority of primary production was supported by "new" nitrogen (Cochlan et al. 1993b). In spite of these substantial new and total production rates, the measured wintertime export fluxes in Antarctic coastal waters are <0.5 mg C m-2 d-1. Obviously the time scale for integration and reliable comparison of new and export production rates in high latitude, seasonally-phased environments such as the PAL region must be longer than those used previously in temperate habitats that are sometimes assumed to be in steady-state biogeochemical balance. Given the large interannual variability of ice dynamics and the consequent well-documented effects on primary production and particle export processes, the proper time scale may need to be extended to several years, or perhaps longer, to achieve an acceptable balance.

Microbial Processes Microorganisms, including unicellular algae, bacteria, viruses, protozoans and small metazoans, are vital components of Southern Ocean ecosystems (Karl 1993a). They are largely responsible for the production and decomposition of organic matter, for the primary uptake and regeneration of inorganic nutrients and for export of carbon and energy to intermediate ocean depths. Furthermore, microbial growth and metabolism can have a profound effect on seawater pH and redox state and can influence the distribution, speciation and availability of certain elements and compounds. Consequently, field data on individual groups of microorganisms and on the complex interactions among them are necessary for complete assessment of the role of marine microorganisms in both local and global environments.

The microbial loop plays an important role in marine and freshwater plankton ecosystems in all climatic zones (Hobbie 1994). However, models of microbial ecosystem dynamics continue to elude a general scientific understanding. The marine bacterioplankton are a mixed community, both physiologically and taxonomically diverse, and substantially uncharacterized (DeLong et al. 1994). Yet there are characteristics that appear ubiquitous. Uptake of organic monomers like glucose or leucine, and the activities of enzymes such as leucine aminopeptidase and B-glucosidase, are common metabolic features. Abundance (biomass) and growth rate (production) are among the most widely measured parameters in aquatic microbial ecology and the collective data sets of measurements have provided the necessary guidance for the design of the next generation of field experiments. A major obstacle, however, is our inability to characterize much of the dissolved organic matter (DOM) pool in the ocean and to determine the rates at which its components are utilized by bacteria. This will be a major goal of our future field research effort.

DOM concentrations in the Antarctic Peninsula region include some of the lowest as well as the highest concentrations ever measured (Karl et al. 1996). There has been a tendency to focus on biomass and production so there is much less information on the kinds of substrates that sustain natural populations in the ocean. Our inability to characterize much of the DOM in the ocean has encouraged a "stoichiometric" as opposed to a "biochemical" approach. Organisms are viewed in terms of C, N, and P rather than protein, carbohydrate, etc., although different compounds containing similar amounts of each element are unlikely to be equivalent to the organism. The biochemical compounds utilized by the bacterioplankton may differ substantially among ocean basins and regions. Identifying oceanographic biogeochemical provinces within which consistent patterns of substrate utilization occur is an important step towards incorporating the bacteria into ecological models and defining appropriate experimental protocols for routine use in the field.

Growth of the heterotrophic bacterioplankton community is far more difficult to parameterize in ecological models than that of phytoplankton or microzooplankton. A functional response based on the Monod (1942) equation has been widely used to simulate nutrient limitation in plankton populations. Although there is uncertainty about the exact form of the equation and the values of the coefficients, the independent variable is far more easily identified for phytoplankton (nitrate and /or ammonium) or protozooplankton (prey abundance) than for bacteria (Fasham et al. 1990; Fasham 1993). A more comprehensive description of DOM, including identification of sources and sinks as well as chemical composition, will provide critical data for understanding the role of microbial food webs in the PAL region.

Macrozooplankton Ecology Antarctic krill is a keystone species within the Antarctic marine ecosystem and a critical link between primary producers and many top predators. While widely studied, the hypothesized linkages (Fig. 8) have yet to be verified. Processes that control recruitment and distribution as well as interactions with food (phytoplankton) and predators (Adelie penguins) need to be better understood. Our conceptual view of these processes has improved significantly but has become more complex in light of the results from the last several years (Quetin et al. 1994, 1996).

Adult krill survive winter by a combined strategy of lowered metabolic rates and stored food reserves (Quetin and Ross 1989), but AC0s spawned in summer have not yet accumulated the lipid reserves necessary to survive the austral winter without eating. Winter-over survival of AC0s depends on finding a food source other than open water phytoplankton. Ice algae, either in the sea ice or in the water column after winter storms have broken up the ice and released the cells, is a logical source (Figs. 8a and b). The presence of fall water column blooms will also impact survival by delaying the onset and thus the duration of near starvation conditions in the water column. Physiological condition in AC0s decreases progressively with starvation (i.e., lower condition factor, lower lipid and zero or negative growth rates) and has been documented to be lower during winters of low versus high ice extent (Ross and Quetin 1991c), supporting the premise that AC0s benefit from ice biota. Condition factor for AC0s emerging from winter will reflect the sum of nutritional conditions throughout the winter and early spring. Poor condition factor and poor recruitment are probably correlated, as has been shown for fish, thus condition factor can be an index of recruitment, which in turn can be related to seasonal sea ice dynamics.

However, recruitment success is a function of both AC0 survival and reproductive output of adult krill, combined with estimates of spawning stock to estimate population fecundity. Results of several indices (total egg number and volume, average egg size, and timing and frequency of spawning) show that reproductive output of individual Antarctic krill is high after an above mean spring ice season (Stammerjohn, pers. comm.) combined with high phytoplankton biomass and production in the subsequent January (Smith et al. 1995a,b), and is low after a below mean spring ice season, which also had low phytoplankton biomass and production in the subsequent January. These preliminary results support the original hypothesis that reproductive output in krill depends on food availability, with ice edge blooms postulated as an important food source in spring, which emphasizes the importance of the timing of ice retreat, but also suggests that the role of summer food availability cannot be ignored.

Another factor in reproductive output is spawning stock. Siegel and Loeb (1995) suggest that recruitment success is not correlated to previous summer krill stocks. This lack of correlation may be because either (1) variation in stock size of larger reproducing krill is lower than for individual year classes, (2) the relevant parameter is the proportion reproducing not the absolute abundance (Fig. 11), or (3) interannual variability exists in the alongshore distribution of spawning populations within the PAL grid. Spawning aggregations are consistently found in the southern region off Adelaide I. but not near Anvers I., suggesting that the predictable supply of larvae is from females in those regions that are always covered with sea ice in the early spring (Stammerjohn 1993; Stammerjohn and Smith 1996).

Interannual variability in the composition and abundance of the zooplankton community inhabiting the PAL study area, which includes the foraging range of the Adelie penguins nesting near Palmer Station, is driven primarily by variations in oceanic circulation and seasonal sea ice dynamics that alter distribution of the zooplanktonic assemblages with respect to fixed geographical locations. Diets of Adelie penguins from Palmer Station are generally dominated by krill > 35 mm in total length (Fraser and others in 1992-94 AMLR Field Season Reports), which are age class 3 or older, although other prey items are also taken in times of low krill abundance. For example, Thysanoessa sp., a small euphausiid, was found in diets (Fraser et al. in Rosenberg 1995 AMLR Field Season Reports) when krill were scarce (Quetin et al. 1995a). In addition, the size distribution of krill within the foraging range of Adelie penguins is a function of both recruitment variability, which affects the length frequency pattern for the entire krill population, and the on/offshore gradient, where smaller krill are onshore and larger krill are offshore. This gradient is an annual summer phenomenon, but may shift on/offshore with respect to specific geographical features, altering whether the size distribution of krill within the presumed foraging area matches that of the entire population (Fig. 12).

The grazing impact of krill is proportional to phytoplankton production and grazer abundance and composition (Ross et al. 1995c). However, high grazing rates also mean an increase in ammonium excretion rates (Ikeda and Dixon 1984) which may affect nutrient uptake and the coupling between the grazer and primary production communities. In a detailed study on the interaction between phytoplankton community composition and grazing, Haberman (Haberman et al. 1993; Haberman pers. comm.) found that grazing rates of krill depend on the physiological state and morphology of the phytoplankter. These differences will affect both the impact of the grazers on the phytoplankton community, and also the usefulness of that community as a food source to secondary producers. However, analysis of a seasonal series of instantaneous growth rate (IGR) experiments with AC0s collected from the water column in 1991-92 suggests that growth rates increase with total phytoplankton biomass (integrated over the top 30 m) up to about 55 mg Chl-a m-2 (Fig. 13). Growth rates inshore will be higher than those offshore because of the higher phytoplankton biomass inshore.

Seabird Ecology A key assumption guiding the PAL seabird research is that the persistence of any seabird population over time reflects the coincident availability of suitable nesting and foraging habitats (Fraser and Trivelpiece 1996a). Implied, is that interactions between physical and biological processes ultimately drive both the magnitude and direction of change in seabird populations. Although considerable progress has been made during the last decade towards identifying some of the physical and biological variables that may be important determinants of change in Southern Ocean seabird populations (Croxall et al. 1988; Fraser et al. 1992; Fraser and Patterson 1996), interactions between these variables are just becoming apparent (Trivelpiece and Trivelpiece, submitted; Trivelpiece et al., submitted).

A particularly crucial area of research is understanding how the physical environment influences the abundance and distribution of prey on which these predators depend (Croxall 1992). Understanding these processes may be viewed as one of the fundamental objectives of the PAL because it requires an integrated link between components and the basis for designing and testing related hypotheses. Seabirds are long-lived upper-trophic level predators which can integrate the effects of variability of the physical and biological environment over large spatial and temporal scales. The expression of this variability can, for example, be measured annually as changes in breeding success (Croxall et al. 1988; Trivelpiece et al. 1990), or over the course of decades and centuries as changes in populations and biogeography (Fraser et al. 1992; Emslie 1995; Fraser and Patterson 1996; Fraser and Trivelpiece 1996a; Trivelpiece and Fraser, 1996). The factors that affect seabird populations at smaller scales can thus provide the basis for understanding ecological processes in the marine environment at larger scales.

Adelie penguins, the predator selected as representative species of the PAL (Smith et al. 1995), exhibit high, sometimes extraordinary interannual variability in breeding success, overwinter survival and other aspects of biology (Fraser et al. AMLR Reports 1988-1994; Trivelpiece et al. 1990a,b; Fraser et al. 1992a). Although some of this variability is due to factors that are independent of the marine environment (Fraser and Patterson 1996), it is clear that the dominant signal is mediated by the marine system, with sea ice playing a pivotal role because of its significance in the life history strategies of prey and /or their predators (Daly, 1990; Ross and Quetin 1991a; Fraser et al. 1992a; Fraser and Trivelpiece 1995b,1996a; Trivelpiece and Fraser 1996). Our research during the last six years has thus focused on understanding how variability in annual seal ice conditions (extent and duration) affects the prey field, and is in turn manifested by apex predators.

To address this focus, recent and long-term data (20 years) on the diets of Adelie penguins were combined to test whether (1) krill recruitment is linked to variability in sea ice cover (Table 13), (2) the recruitment signal is apparent as a change in the size frequency distributions of krill obtained annually by Adelie penguins and , (3) foraging trip durations, a sensitive indicator of krill availability (CCAMLR 1992), increase or decrease in accordance with successive years of low and high krill recruitment, respectively. This synthesis was motivated by a recent model (Priddle et al. 1988) which suggests that low recruitment years skew krill size-frequency distributions towards the larger size classes while high recruitment years have the opposite effect. In the PAL study region, maxima in sea ice cover (i.e. the overwintering habitat of larval krill, Ross and Quetin 1991a) occur every 5-7 years (Fig. 3; Fraser et al. 1992a; Stammerjohn 1993; Stammerjohn and Smith 1996). This periodicity could determine the structure and abundance of krill populations on a regional scale. This would suggest that the parameters that ultimately determine predator population responses, such as the combined effects of breeding success and survival on recruitment, may be similarly punctuated by quasi-predictable highs and lows that follow, after an appropriate time lag, the ice-induced krill recruitment signal (Fraser and Patterson 1996c; Fraser and Trivelpiece 1995d; Trivelpiece and Trivelpiece, submitted; Trivelpiece et al., submitted).

As shown in Table 13, ice cycles start and end with populations of large krill, the spawning stock (Ice Events 1 and 5); recruitment follows winters of ice maxima, creating a super cohort (Ice Event 2); this cohort maintains its identity because of missing age classes that result from sea ice minima and failed or poor recruitment (Ice Events 3,4,5). This pattern also implies that within a cycle, the krill abundance minimum and maximum should occur during Ice Events 1 and 2, respectively (i.e. minimum and maximum representation of age classes), as suggested by the Priddle et al. (1988) model. A 17-year record of krill stock estimates (cf. Siegel and Loeb 1995) agrees with this prediction, showing that krill abundance extremes within a cycle are specifically linked to Ice Events 1 and 2 (Fig. 14). Equally important in terms of understanding some of the mechanisms by which signal transfer occurs between variability in ice cover and the response of upper-trophic level predators, Adelie penguin foraging trip durations exhibit an inverse relationship with krill abundance (Fig. 14, the 19891993 series of ice events).

These results provide the first evidence of a direct, causal relationship between variability in sea ice cover, krill recruitment, prey availability and predator foraging behavior in Southern Ocean ecosystem studies. Given the potential consequences that interannual variability in foraging success may have on predator breeding success and survival (cf. Croxall et al. 1988), they also support the earlier expressed idea that predator recruitment patterns may indeed be punctuated by highs and lows that are ultimately mediated by the periodicity, duration and extent of sea ice cover. This hypothesis underpins the conceptual framework of a recently proposed model that describes how climate change may affect apex predator populations over multiple time and space scales, thus ultimately affecting biogeography and community structure (Fraser and Trivelpiece 1996a). To better address the implications of this model, the focus of future research includes: (1) the effects of local nearshore processes such as the timing and duration of phytoplankton blooms on the foraging ecology of Adelie penguins (foraging trip durations and the species composition and characteristics of the diet), (2) the effects of regional characteristics in the duration, extent and periodicity of sea ice cover on Adelie penguin survival and breeding success (recruitment), and (3) the effects of within and between-year differences in precipitation on the availability of Adelie penguin nesting habitat.

Hydrography/Circulation and Biological Modeling Studies To understand the processes responsible for the observed water mass and circulation distributions in the WAP region, Princeton Ocean General Circulation Model (POGCM) was adapted. The POGCM is a publicly available, three-dimensional, time dependent, stratified fluid, hydrostatic, finite difference, primitive equation ocean circulation model (Blumberg and Mellor 1987). The model dependent variables are three components of fluid velocity, temperature and salinity which are known on a vertically and horizontally staggered three dimensional grid. The density and pressure are calculated from depth, and temperature and salinity are determined using a nonlinear equation of state (Mellor 1991) and the hydrostatic assumption. The vertical dimension is scaled by the local water depth (sigma transformation) which allows bottom topography to be correctly represented, and grid points are distributed in the vertical to resolve surface and bottom boundary layers. The horizontal grid is specified as a general curvilinear coordinate system (e.g., spherical coordinates), and variables are distributed according to the Arakawa C scheme (Mesinger and Arakawa 1976). A second moment turbulence closure submodel is used to estimate vertical mixing coefficients (Mellor and Yamada 1982) and can thereby represent time variable surface mixed layers. Surface forcing is specified as fluxes of heat, salt and momentum. Heat flux can be directly specified or calculated as part of a complete surface radiation budget. Both bottom drag and lateral diffusion provide dissipation in the model. For efficiency, time integration is accomplished by a splitting scheme where the vertically integrated (shallow water) dynamics proceed with a shorter time step while internal dynamics and mass redistribution occur with a longer step. Means are taken to avoid time step constraints associated with small vertical grid spacing and large diffusion coefficients.

The circulation simulations done with POGCM have focused on the time-dependence and thermodynamics of the mixed layer and the larger scale flow over the continental shelf. These latter simulations have considered the role of surface forcing versus offshore forcing due to the Antarctic Circumpolar Current (ACC) in structuring the flow over the shelf. The mixed layer simulations have indicated that double diffusive processes are likely important in determining the amount of exchange between CDW and the upper water column.

The biological modeling aspect of the PAL program has focused on developing a time-dependent size-structured model of the growth and dynamics of Antarctic krill. This model represents the life history of krill, between 10 and 60 mm in length, in terms of 300 energy-based (i.e., calories) size classes. Growth (or shrinkage) processes, which result from positive (negative) net production, result in the transfer of individuals between size classes. Net production is determined from the difference between assimilation and respiration. Environmental conditions (e.g., temperature) and food availability (phytoplankton composition) are input to the model as prescribed idealized time series or as time series constructed from measurements. Preliminary results with the size-based krill model indicate that the size composition of the available food (i.e., the phytoplankton population structure) is important in the survival of krill larvae, especially in the winter. Moreover, seasonal variations appear to exist in the physiological processes that contribute to krill growth.

Our efforts in the next phase of this project will consist of data analysis and modeling components. We will continue analysis of hydrographic data collected on PAL annual and process cruises. In particular, we will investigate interannual variations in the distribution of CDW. Mixing of CDW results in reduction of the oxygen content of the overlying waters by 25 to 45%, which suggests an average annual entrainment rate for the WAP of 0.7 to 1.43 x 10-6 m s-1. The freshwater input needed to balance the salinity input from CDW is on the order of 0.63 m y-1, which can be supplied by local precipitation and advection of ice into the region from the Bellingshausen Sea, which then melts. The annual heat flux associated with CDW is 12 W m-2, which is sufficient to melt this amount of ice. Hence, CDW is an important factor in determining the amount and extent of sea ice in the WAP region, and understanding of how this water mass varies is critical to understanding variations in ice cover. We will also continue our analysis of hydrographic data in terms of attempting to determine interactions/correlations between the physical environment and biological structures.

Our modeling efforts will be directed towards continued development of the circulation model and in particular we will develop sea ice and mixed layer dynamics models that can be interfaced with the circulation model. We currently have several different mixed layer models operational and are evaluating these for use with the POGCM and for application to the WAP continental shelf region. Similar preliminary calculations are underway with sea ice models. Simulations with this combined sea ice-mixed layer circulation model will be done to investigate processes controlling circulation and sea ice distributions in the WAP region.

In terms of interdisciplinary modeling, the size-structured krill model will be embedded in the circulation model. This combined model will be used to investigate residence times, exchanges and general transport pathways for krill in the WAP region. The results of these simulations will be used to interpret/explain variations in penguin recruitment and abundance, as well as the large-scale krill distributions. Our final modeling effort will be to embed a primary production model in the mixed layer and circulation model. This combined model will be used to address questions related to the role of physical and biological processes in controlling the observed distribution of phytoplankton in the WAP continental shelf area. We have already made some progress in determining the correspondence between physical variables, such as mixed layer depth and water column stability, and phytoplankton biomass.

2.5 Science Plan and Methods

Sampling Strategy

The harsh and logistically difficult working environment of the Southern Ocean, in addition to the extreme variability of physical, chemical, optical and biological processes, dictates a varied and flexible sampling strategy (Smith et al. 1987a and Fig. 15). Ships, the classical oceanographic sampling platform, can provide relatively accurate point surface measurements of a wide variety of desired variables, in addition to vertical measurements of the water column. Ships can also be used to obtain 'along-track' samples and observations. The disadvantage of ships is their limited spatial coverage and working constraints during foul weather. Moored buoys are even more limited in spatial coverage but are extremely valuable in providing long time series at selected locations. Satellite remote sensing is often the most effective way (and in some cases, the only way) to study large-scale surface physical and biological processes in polar regions (Comiso 1995). >From the perspective of long-term observations, satellite sampling is spatially and temporally comprehensive, and the measurements operationally consistent. Remote sensing by aircraft fills a gap between conventional surface measurements and those made by satellite sensors. In the PAL region, with high level clouds typically 90% of the time, aircraft also provide a unique opportunity (by flying under the generally high cloud cover) to utilize ocean color methods (visible portion of the spectrum) for estimating near surface pigment biomass under conditions which would limit satellite ocean color observations. To date, the PAL have used data from satellites, ships, small boats (zodiacs), moorings both at sea and on l and (AWS units), and l and -based observations at the seabird nesting sites. The proposed collaboration with the British Antarctic Survey (see Sect. 2.7) is expected to add remote sensing using aircraft during our next funding period. We are also following the technological progress of autonomous vehicles, both airborne and underwater, and small seabird transmitters so as to incorporate these advances in our sampling strategy when this technology becomes economically cost effective.

Our science plan addresses both long-term and short-term processes and encompasses sampling flexibility while maintaining long-term consistency with our first funding period. The general plan maintains our regional scale summer sampling program of hydrographic, optical and biological sampling within the 200 to 600 line region of the PAL grid (Fig. 1a) and the high density sampling of phytoplankton, krill, seabird observations within the Adelie foraging area (Fig. 1b). While maintaining this unique and important long-term data set, we anticipate increased flexibility by less intensive sampling within some areas and periods, in order to increase attention to sea ice related linkages. Table 14 presents our proposed ship schedule. Austral summer cruises are timed to match the critical period of Adelie penguin breeding (Fig. 7) in order to investigate trophic level linkages. PAL January cruises typically have two sampling modes: (1) large scale cardinal grid sampling including stations "inside" the islands, and (2) finer scale sampling within the Adelie foraging area. The first mode determines key environmental variables sampled on a fixed grid which facilitates separating long-term systematic trends from interannual variability. The second mode is aimed at observations linking water column variables with fine scale (few km) krill and seabird observations. Tables 1 and 2 list annual cruises to date, and brief cruise reports are summarized in Antarctic Journal of United States (JUS) articles (references in Sect. 1.3.2). Samples and experiments conducted during the mesoscale cruises help to address several of our general hypotheses, including variations in: (1) oceanic and atmospheric processes which influence the extent of CDW upwelling onto the continental shelf (HA1), (2) primary production and physical processes influencing the abundance and distribution of phytoplankton (HA2,3,4), (3) recruitment, growth rates, and reproductive output of krill, in addition to other zooplankton assemblages present, as well as the distribution, size, density, and depth of krill aggregations and length frequency distributions (HA3,4). The finer scale grid during these cruises allows us to investigate these same hypotheses with greater resolution within the penguin foraging area during the critical period of chick rearing, and provides prey population information which can be compared to data collected from the rookeries on foraging duration, diet samples, and reproductive success of penguins.

Table 14 also shows that in two of the next six field seasons, sea ice process cruises are planned (dependent upon predicted sea ice conditions) during spring retreat (Sep/Oct/Nov97) and fall/winter growth (Apr/May/June00) periods. In addition, it is anticipated that increased flexibility during summer cruises will allow some time to sample in the southern end of the PAL grid at the ice edge. The ship time at the ice edge and in the ice will be designed to address short-term mechanistic processes and hypotheses linking sea ice, microalgae, krill, penguin and export processes (Figs. 8,9 and 10) within and outside of areas occupied by populations of juvenile Adelie penguins dwelling on the pack ice. For example, Figs. 8 are conceptualized diagrams showing the annual cycle of hypothesized linkages between sea ice, ice algae, water column phytoplankton, krill and the export of carbon from surface layers, which we hope to elucidate from the two ice process cruises planned in fall/winter and spring (Table 14). Fall and early winter are the periods when pancake ice forms and aggregates into a continuous, consolidated ice cover (Lange et al. 1989). Biological material is incorporated into pancake ice when wind, wave action and frazil ice formation give rise to the accumulation of suspended biological material into circular discs of ice. This is also a transition time for AC0s as they move from a strong diel vertical migration through the water column to a close association with under ice surfaces as found later in the winter. The timing of fall blooms, early ice advance and the linkage with AC0s has been little studied in the WAP area and , as hypothesized, this period may be of vital significance in AC0 survival under certain conditions. Key objectives of this fall ice process cruise will be the investigation and understanding of sea ice growth processes and its related biota during that period. In addition, an effort will be made to determine where Adelie penguins are located during this time.

Sea ice conditions in spring and early summer are hypothesized to be characterized by the melting cycle where there is a return of particulate organic material (POM) back into the water column either as a seed for phytoplankton bloom or enhanced sedimentation (Figs. 8). The retreating pack ice is expected to have primarily AC0s under the ice, with progressively older stages of krill associated with the MIZ and /or ice edge bloom (Quetin et al. 1992). Investigations during this spring cruise would include: (1) the degree of coupling of AC0 and adult krill with ice and the associated physical characteristics, (2) linkages between processes associated with krill, ice algae, nutrients, gases, bacteria and particle flux, (3) quantification of the relative contribution of ice-related production compared with production driven by non-ice processes, and (4) relationship to MIZ and the first critical period for breeding Adelies (Fig. 7). These ice process cruises would work from the open sea, to within the MIZ and then penetrate into the pack ice to a distance sufficient to be beyond significant surface wave influence (or as far as the ship can safely and usefully operate).

Another significant element of our sampling strategy is directed toward time series data taken in the vicinity of the Adelie nesting sites near Palmer Station. These data document seasonal progression and allow both the regional cruise and shore-based seabird data to be placed into a more comprehensive seasonal and interannual perspective. The field season at Palmer Station also permits longer time scale mechanistic studies, which are impractical and costly to conduct on ship.

Finally, the Palmer Station data provide surface validation for both satellite and aircraft remotely sensed observations. Continued Palmer field work will be consistent with our previous time series observations but with increased emphasis on process oriented studies in the local area. We anticipate, among all PAL components, 10 personnel on station throughout each field season (Oct-Mar).

An important contribution to our time series is the data from the sediment traps. One trap will be maintained at the Hugo I. site which already has 3 years of continuous data. A second mooring is located near a recently moored site (Domack, personal communication and see Sect. 2.7) in Palmer Basin (64 degrees 50.11'S 64 degrees 08.36'W), and one or two more sites will be added in this Basin along the "hypothesized" penguin foraging axis. It is also planned to add both temperature sensors and current meters on these deep mooring so as to better understand the seasonal changes in local water masses and current movements in this area. Thus, the entire suite of data from cruise, mooring and Palmer Station field observations helps elucidate some of the mechanisms underlying the space and time variability of trophic interactions.

Methods

Space limitations do not permit a detailed discussion of methods which are outlined within the tables listing PAL data (Tables 3,4,5,6) under the heading "Analytic Standard and QA/QC". Quality Assurance / Quality Control is discussed in detail in the following section (2.6). Typically our methods follow recognized standard procedures often using state-of-the-art equipment. For example, the Bio-Optical Profiling System (BOPS-II) is a recently modified instrument that allows real time readout of water column properties (listed bio-optics, 'BO', in Table 3) as well as providing a 12-bottle rosette for discrete water sampling of the water column based upon real time readout. This is a robust seagoing instrument that over the first six years of the program has been used for nearly 2000 successful casts. Krill methods include both acoustical techniques and nets of several sizes to document temporal and spatial variability in secondary producer abundance and distribution. Each have their intrinsic errors, but are equally valid (Everson 1988) and yield different information. On cruises, oblique net tows with simultaneous acoustic transects about 2 km in length are centered at each station. This approach allows local and regional variability in acoustic biomass and krill aggregation characteristics and distribution to be correlated with other habitat characteristics. Identical or very similar methods are used for sampling and analysis of seasonal data which is collected from zodiacs, and for the fine scale grids to study the relationships between krill and Adelie penguins within the foraging area. Penguin observations follow the CEMP standard methods (the 'CEMP protocols', CCAMLR 1992; CCAMLR Commission for the Conservation of Antarctic Marine Living Resources, CEMP CCAMLR Ecosystem Monitoring Program). Seabird data collection at sea follows methods summarized in Spear et al. 1992).

2.6 Core Measurements and Quality Assurance / Quality Control Procedures

There are both scientific and logistical considerations involved with the establishment of any long-term, time-series measurement program. Foremost among these are site selection, choice of variables to be measured and general sampling design, including sampling frequency. Equally important design considerations are those dealing with the choice of analytical methods for a given candidate variable, especially an assessment of the desired accuracy and precision, availability of suitable reference materials, and the hierarchy of sampling replication and mesoscale horizontal variability. All LTER programs include a core suite of environmental variables to track both physical and biological processes in the habitat of interest. For the PAL program we selected parameters that might be expected to display detectable change on time scales of days to a few decades.

The PAL sampling design includes (1) continuous and discrete measurement of key environmental parameters, (2) collection of zooplankton and fish using nets/trawls, (3) measurements/observations of seabird distribution, abundance and biomass, and (4) satellite-based remote sensing observations (Tables 3,4,5,6). During each annual cruise water samples are routinely collected generally from the surface to ~200 m for the measurement of a variety of chemical and biological variables. At selected stations, samples are collected over the full depth of the water column. To the extent possible, we collect samples for complementary biogeochemical measurements from the same or from contiguous casts to minimize aliasing caused by time-dependent changes in the density field. This is especially important for samples collected in the upper 200 m of the water column. Water samples for salinity determinations are collected from selected water bottles to identify sampling (bottle trip) errors. Approximately 10-20% of the water samples are collected and analyzed in triplicate to assess and track our analytical precision in sample analysis.

Our primary study area is characterized by cold (<1degC) surface waters with high nitrate concentrations (>30 MM), seasonally variable surface mixed-layers (10-200 m), and variable standing stocks of living organisms (1-1000 Mg C l-1). Ideally, the suite of measurement parameters should provide a data base to validate existing biogeochemical models and to develop improved ones. Our list of core measurements has evolved since the inception of the program in 1990, and now includes both continuous and discrete physical, biological and chemical ship-based measurements, in situ biological rate experiments, and observations and sample collections from bottom-moored instruments (Tables 3 and 5). Continuity in the measurement parameters and maintenance of quality, rather than the methods employed, are of greatest interest. Detailed analytical methods are expected to change over time through technical improvements. The precision and accuracy of each determination is of utmost importance, especially if the program objectives are to assess environmental change. For the PAL program, the precision of most measurements is determined by the collection and analysis of replicate samples on a routine basis. This information is then used as a measure of analytical information which in turn is used as a measure of analytical reproducibility for each of the candidate variables. The question of measurement precision is more problematic because some of the parameters that we measure on a routine basis (e.g., primary production, bacterial production, bacterial cell number) have no commercially-available reference standards. However the measurement accuracy for most of the ecosystem variables (e.g., oxygen, salinity, nutrients, carbon dioxide, alkalinity, particulate carbon, nitrogen, phosphorus and mass) can be determined using certified (e.g., NBS or NIST) reference materials. The environmental sensors used for the continuous measurement of pressure, temperature and conductivity are routinely calibrated at the Northwest Regional Calibration Facility in Seattle. Our optical sensors are periodically calibrated using both recalibration by the original manufacturer and more frequently (pre and post-cruise) at our own optical calibration facility at UCSB using optical standards traceable to NIST. In addition, SeaWiFS related optical instruments have and are cross calibrated against SeaWiFS instruments of other investigators. Finally, we have recently initiated an interlaboratory exchange program for the measurement of selected variables, and we anticipate an expansion of these activities during the next phase of our field work.

2.7 Regionalization and Cross-site Efforts

British Antarctic Survey (BAS)

Research on the nearshore marine ecosystem will be undertaken by the BAS at Rothera Station on Adelaide I. (Fig. 1a) in the 1996/97 season. This will comprise a long-term program (at least ten years) of year-round oceanographic monitoring, together with a series of individual autecological or process studies. It is also intended to fly ocean color sensors from BAS DHC-6 (twin otter) aircraft fitted for remote sensing to provide detailed spatial coverage of Marguerite Bay and the adjacent PAL grid area. This work will be in collaboration with the bio-optics component of the PAL who will be collecting periodic surface bio-optical data in the vicinity of Palmer for validation and algorithm development studies. It is anticipated that aircraft coverage of the PAL grid will provide complementary spatial and temporal coverage not otherwise available to the PAL. Emphasis on the nearshore (benthic) marine ecosystem will complement the PAL, permit a latitudinal (along the peninsula) comparison with the PAL work, and complement (with aircraft) the PAL ship and station sampling strategies.

Antarctic Marine Living Resources (AMLR)

The U.S. AMLR program, supported by NOAA, is based at the northern tip of the Antarctic Peninsula several hundred kilometers north of the PAL grid in the vicinity of Elephant I. (Fig. 1a). The objective of this long-term study, initiated in the mid 1980's, is to describe the functional relationships between krill, their predators, and key environmental variables. Emphasis is on an ecosystem approach to resource management within the Antarctic, with particular focus on fisheries impacts on krill and their dependent predator populations. The program includes monitoring the impacts of the krill fishery in the area of King George and Elephant Islands and has also included collaborative krill-penguin research at Admiralty Bay with W. Trivelpiece. AMLR also funds research of Adelie penguins at Palmer (B. Fraser), which serves as a nonfished control site. The AMLR study provides complementary information for comparison with PAL data in an area with different oceanographic and sea ice regimes.

Canadian Space Agency (CSA) Radarsat program

Based on results of our PAL sea ice work, R. Smith is now funded under the sponsorship of NASA, to participate in the international research of the CSA Radarsat program and will be obtaining high resolution (100 m) Synthetic Aperture Radar (SAR) data for the WAP area. Our objectives for the SAR data, within the context of the PAL are to: (1) more accurately demarcate sea ice-related habitats of the marine ecosystem of the Southern Ocean, (2) determine the seasonal and interannual space/time variability of these habitats in relationship to atmospheric and oceanographic forcing, (3) relate sea ice variability to subsequent impacts on keystone species within this marine ecosystem, and (4) evaluate parameters derived from SAR data with parameters derived from other satellite data (e.g, SSM/I, AVHRR, SeaWiFS) and surface data so as to validate and improve satellite-derived products from the Radarsat data.

LTER Cross-site comparison

In Jan 1996, D. Karl received funding from the NSF-DEB to conduct an LTER cross site comparison. This project, "Microbial loop dynamics and regulation of bacterial physiology in subtropical and polar marine habitats" will evaluate the structure and function of the microbial food web in two contrasting habitats: the Antarctic coastal/shelf/oceanic ecosystem and a subtropical oceanic ecosystem in the central North Pacific Ocean. Both habitats are isolated from significant inputs of terrestrially-derived organic matter thereby providing the basis for a comprehensive, comparative study of bacterial metabolism of autochthonous organics of marine phytoplankton origin. Strong contrasts in plankton community parameters (high vs. low inorganic nutrients, large vs. small phytoplankton, metazoan vs. protozoan grazers) make these two sites ideal for this cross-site investigation. The project will be embedded within ongoing programs at the two sites, the U.S. JGOFS Hawaii Ocean Time-series (HOT) in the North Pacific and the PAL in Antarctica, and will build upon the core datasets that are collected.

Southern Ocean Ocean Color

R. Smith is funded by NASA, "Bio-Optics, Photoecology and Remote Sensing Using SeaWiFS", to develop bio-optical models specifically for the Southern Ocean. These models provide a quantitative representation of the link between in-water biogenic material and ocean optical properties, thus allowing data from optical sensors to be used for remote and /or proxy estimates of important biological parameters in the ocean, and permitting sampling over a range of space/time scales that otherwise would not be possible (Fig. 15). We anticipate use of optical sensors on moorings, the BAS aircraft and satellite (SeaWiFS, MODIS) which will significantly complement our research objectives throughout the duration of the PAL program.

Sediment Core Study

In 1995, scientists in the PAL initiated a collaborative program with E. Domack (Hamilton College) and A. Leventer (Univ. Minnesota) to investigate the 200-300 year productivity cycles in the PAL region that have been revealed through a comprehensive analysis of sediment cores collected in the Palmer Basin. Regional trends in climate, including but not limited to warming, ice shelf melting, sea ice dynamics and predator-prey cycles all affect particle composition and fluxes, as well as the long term sediment accumulation rates. Since 1992 several gravity cores have been recovered and analyzed by Leventer, Domack and colleagues. Measurements include 14C-chronology, sedimentology and geochemistry, magnetic susceptibility and a quantitative description of diatom and foraminifera assemblages. In Dec 1995, on a PAL cruise, three additional cores were collected, and a permanent sediment trap site was established. We expect the PAL data sets on contemporaneous ecosystem processes to be a great help in resolving the paleoclimate history of this region.

3. Literature Cited

(Note: PAL citations are given in Section 1.3)

4. Site Management

The Protocol on Environmental Protection to the Antarctic Treaty, signed in 1991, designates Antarctica as a natural reserve and sets forth requirements for all activities in Antarctica. Subsequently, the Antarctic Treaty Consultative Meeting approved a protected area management plan for "Multiple Use Planning Area: SW Anvers Island and Vicinity" which includes much of the PAL study area. Treaty nations are to voluntarily follow the guideline for the protection of fauna and flora, while the plan is being rewritten to conform with the new format and guidelines established by the 1991 Madrid Protocols, which increased protection of the Antarctic environment. An overview of the Antarctic Treaty System is provided in workshop proceedings (Polar Research Board 1985), and Naveen (1996) has provided a recent review with emphasis on the potential adverse effects of human disturbance on the Antarctic environment within the context of the Antarctic Treaty.

Of immediate concern to PAL is the ability to guarantee that the site will remain undisturbed by uncontrolled human influences. Naveen (1996) also discusses the Antarctic Site Inventory project, initiated as a pilot study in 1994 by the U.S. NSF, to determine if periodic site inventories of biological and physical features in areas commonly visited by tourists would provide a way to monitor potential environmental impacts. Within the PAL area, visitors are not permitted to l and on most islands with nesting seabirds during the breeding season, and the few sites where visitors are permitted are under study for possible adverse impacts.

Also of concern is how far from pristine the environment of the WAP area has become (Palmer LTER Group 1996). In connection with shore-based scientific research stations and the growing tourist industry, Kennicutt and McDonald (1996) summarize and discuss inventories of contaminants, contaminant sources, transport and depositional processes, and potential biological impacts in the WAP area. Although there is evidence that organisms have been exposed to contaminants, most events are local (100s of meters) and are confined to regions of human activity. Fossil fuel spills from ship traffic pose the greatest risk of future contamination, although the nature and volume of the potential spills would indicate that long-term damage would be minimized (Kennicutt and McDonald 1996). Overall, these authors conclude that the WAP is still relatively pristine. Site management of Palmer Station is carried out by the Antarctic Support Associates (ASA), under contract to the NSF.

The Executive Committee consisting of the ten PIs is the primary governing body of the PAL. The committee provides general scientific direction and budget guidelines. Issues are decided in the Executive Committee by majority vote. Formal communication is maintained between PIs with a periodic agenda sent by email and two annual meetings. The lead PI (Ray Smith) is the direct administrative contact of the PAL to the LTER Network and the NSF. Karen Baker has been assigned responsibility for data management issues with respect to the LTER Network. Charleen Johnson has been assigned the responsibility of Single Point of Contact (POC) for PI interaction in coordinating logistic matters with the ASA. The Marine Science Institute at UCSB handles and coordinates contract issues for the PAL. The Institute for Computational Earth System Science at UCSB is the data hub for the PAL. The lead PI coordinates the monthly agenda, Executive and Steering Committee meetings and the overall field season, and performs other general administrative functions. The research, modeling and data management activities of the PAL are divided into several components with each administered by one to two PIs. The PIs of each component plan the detailed logistics for field season research and are responsible for collection and publication of specific data sets and entry of data and results into the PAL data base. Field work at Palmer Station is often the responsibility of technicians or graduate students in the absence of the PI. Undergraduate student volunteers comprise an important element of the field teams and are of great importance to our success.

5. Data Management

PAL data management is based on several distinct concepts: (1) acceptance of a diversity of computer platforms and tools among the various PIs, (2) establishment of a distributed system of communication with effective connectivity among PIs, and (3) development of an electronically available central database which offers continuity, accessibility and extensibility for evolving long-term core data. We follow a decentralized model of data management, where each PI is responsible for a subset of core and non-core data. Documentation and data storage are organized through an electronic hub at the Institute for Computational Earth System Science (ICESS) at the University of California at Santa Barbara which also serves as a data archive as needed (http://www.icess.ucsb.edu/lter). The data archive structure has been organized to facilitate rapid information exchange and online data documentation while supporting platform independence and low maintenance overhead. As the eighteenth LTER site, we benefit from the collective experience of the other LTER sites (Michener et al. 1994).

Information System

This section of the database provides general information on the PAL project as well as documentation describing the data taken for each field study (metadata). Information is maintained in flat ascii files which are easily available to all investigators. Quality control for both metadata and field data is the responsibility of the individual investigators at their respective institutions. The central data archive is a backup of each individual investigator's dataset and , in addition, is backed up on a regular schedule.

In order to organize the metadata, a common vocabulary was developed and documented. For example, 'study' consists of either a field cruise or a season at Palmer Station. Within each study, data sets exist either as part of the pre-defined core data sets or as part of the non-core opportunistic and mechanistic study data sets. The study types and data set definition list is maintained online (Coreform Definition Table). Several documents for each study are standard: (1) an overview of the study, (2) site maps, (3) a participant list describing who was on site for the study, and (4) an event log listing chronologically the type and location of measurements made during the study. The event log provides an initial cross index of all component participation for the duration of each study. Efforts to streamline documentation are continually under development (e.g., recent provision of consistently prepared data forms for at sea operations and the encouragement of online procedure manual development for all components).

A group calendar, meeting schedule, field documents and the PAL annotated bibliography are maintained online in addition to all pertinent documents such as articles, abstracts, proposals, and meeting notes. Background material and several summary talks were installed on the web in order to make information more readily available. Communication links with outside groups are also available at our web site, such as information on weather station locations. Several of the cross-site activities including the all-site bibliography, the climate committee reports and the biodiversity committee efforts are coordinated by the PAL data manager. For example, a site species list was developed by building upon the National Oceanic Data Center's comprehensive taxonomic list. The list was acquired on CDROM, the PIs were provided with pertinent lists which they updated for the PAL region, and the results were posted at our web site (http://www.icess.ucsb.edu/lter/biodiversity). Investigation of Linnaeus Protist Taxonomic Software is ongoing.

Historical and long-term weather data have been compiled by the data manager and are available publicly. Data sets from past Antarctic projects within the PAL area, such as BIOMASS and RACER, have been made available or referenced through the data base. Data sets such as coastline and bottom topography for the WAP area have been acquired and maintained. In addition, the data manager is an active participant in obtaining and archiving weather data, as well as attending yearly Automatic Weather Station (AWS) meetings. Last year the AWS meeting was hosted at a PAL home institution. Data from two AWS units, which were installed for the PAL in cooperation with the University of Wisconsin, are monitored daily so that station failures can be rapidly corrected, as was the case in March of 1995 when a battery failure was corrected. Further, the historical Palmer Station weather record has been obtained, quality control of current Palmer station weather data initiated, and historic data validated in part by comparison with other historical records (Baker and Stammerjohn 1995; Smith et al. 1995).

Personnel Structure and Relationship to Projects

The PAL data manager works with the PIs to create on-line documentation and to manage and archive project data. The data manager participates in PAL PI meetings and attends workshops and field planning exercises. In recognition of the significant role data management must play in the development of an LTER project, the PAL data manager was made a member of the PAL Executive Committee (composed of all PAL PIs) in 1993 and has a separate component budget in this proposal. Currently, the data management position is funded to develop and maintain the central data structure in coordination with each of the individual PIs at their respective institutions. PAL data management is designed to take advantage of the existing strengths of each team member's home group expertise and foster an integration of component data and manage core data. Since each component has unique, independent hardware, a software organization specifically optimized for their own research agenda and each with an independent history of development, local computer development remains the responsibility of individual components. However, our data manager provides as powerful a connectivity as possible within this diversified computer environment. Thus, there is a standardization of vocabulary and information structure, while the variety of platforms creates an enrichment of options in terms of data analysis and display.

Computer system analysts at ICESS have provided input on networking, software, hardware and database planning, while making available state-of-the-art computer technology and ideas to address our scientific pursuits. Routine system functions such as data backups, gopher and web servers, color products and peripheral interfacing are in place. Storage of large datasets such as satellite data is available at ICESS in addition to the disks serving as the initial local data hub.

Because the PAL participants reside at different home institutions across the country or are conducting research in the Antarctic either on station or aboard ship, the development of the internet and the recent increase in reliable network software has played a critical role in the flow of data between individuals. Net tools have been adopted quickly and used effectively to make information readily available across all platforms. Internet connections for each component and location have been accomplished in a variety of ways, including campus broadband connections, gatorbox tunneling across the internet, and dial-up modems. Browsing tools, such as www and gopher, and file transfer tools, such as ftp, are being used effectively. Project discussions are carried on using the internet. Networking all the project participants also facilitates the transfer of both computer knowledge and computer resources which makes a significant contribution toward integrating group ideas and data.

The PAL data manager has played an active role in the LTER data management community, attending the annual data manager meetings since 1990, as well as other LTER organized meetings such as the all scientist meetings. Recognizing the value of cross-site coordination among LTER data managers, the PAL data manager helped plan and coordinate the first extended data manager meeting in 1994 when speakers and data managers from other projects were invited to share information and techniques and also coordinated cross-site information such as the "Site Capabilities' lists (http://lternet.edu:70/00/doc/SiteCapabilities), which facilitate sharing hardware and software information across all sites. Subsequently, the PAL data manager became a member of the LTER Data Task Committee, whose function is to co-ordinate meetings and data manager communications. The PAL data manager is also a member of the McMurdo Users Advisory Group and the Antarctic Communications and Computers Working Group which provides input on field needs and logistics. Further, consistent co-ordination with ASA for both ship and station equipment and computers is ongoing.

Data Availability and Data Policy

The intent is to have all data online as rapidly as possible so that investigators can have other component data available while evaluating their own. All PAL investigators have accounts on the ICESS server and are therefore networked to all data and documentation in the PAL central archive. The PAL group developed a data policy in order to define the rules of data sharing and to assure that each contributing scientist has first priority in the use and publication of their own data, while making the data available as rapidly as possible in order to promote rapid data assimilation between groups. Data policies at other data sites were considered (Porter 1993; Porter and Callahan 1993) in developing the PAL data policy (gopher://gopher.icess.ucsb.edu:70/11/datainfo/datamanagement/datapolicy). The PAL data policy states that data be put online by 1.5 years after collection, be available for the next 2 years for internal use with the data collector as sole proprietor if desired, then be available for the 2 years following for collaborative research within the PAL, and then after this period be publicly available.

All documentation is public and can be requested through the responsible PI, upon being entered in the database either through gopher or the web:

gopher://gopher.icess.ucsb.edu http://www.icess.ucsb.edu/lter

The data is first available online to the PAL group through their ICESS accounts and then as it is released, the data appear with the documentation on the public web. It is the responsibility of the individual investigator to provide their data and standard dataset documentation in digital ascii format in the central database as soon as it is processed. The database is structured so that these files are immediately visible online but do not have to be overseen by a librarian fluent in html so that the PAL archive is automatically updated whenever an investigator adds to or updates their metadata and /or data files.

Future

Future work will include continued efforts in facilitating connectivity and the submission of dataset forms and datasets. The gopher connection has proven useful but will be converted to a more transparent web structure. We have been primarily concerned during our first funding increment with the establishment of data taking, organization, storage, and availability, but it is recognized that as the amount of data increases, we need to consider the possibility of a relational database as well as the current cross site analysis tools. The database now is organized in such a way as to facilitate conversion to other structures. The priority will remain to produce a robust and powerful system while requiring as little maintenance and support as possible. An emphasis on publicly available software will also continue with an eye toward maintaining data convertibility.

6. Outreach

Human Resources.

Volunteers, undergraduates and graduate students have played an important role in our field and laboratory work throughout our first six years. The quality of our volunteers has been exceptionally high. Because we provide a unique opportunity to participate in Antarctic research, a significant number of our volunteers are mid-career adults who have enriched our program with their own scientific and technical abilities while helping in our field research. This mix of mid-career adults with students has been especially valuable in providing our younger volunteers with a broad spectrum of both research and 'real life' interactions. All volunteers return with a deep appreciation for the importance of scientific research and for Antarctica as a unique environment. Typically each field season includes 6 to 8 volunteers, whose only cost to the program is travel to and from the Antarctic.

Undergraduates have been involved both as volunteers and as participants in NSF's Research Experiences for Undergraduates (REU) program. During three of the five field seasons, PAL PIs served as advisors for REU students who joined research teams in Antarctica both onboard ship and at Palmer Station and stateside in laboratories. In 1991-92 7 REU students joined 3 research teams, in 1992-93 11 REU students joined 4 research teams, and in 1994-95 1 REU student joined the PAL field team. The research areas for these REUs included hydrography, ocean optics and remote sensing, primary production and phytoplankton physiology, and secondary production (pelagic zooplankton and fish). The overall objective of the REU program is to provide an educational experience to acquaint students with all aspects of the research process and to encourage them to continue their education in science. These experiences for PAL REU students include: (1) a seminar series, (2) pre-season training in the advisor's laboratory, (3) 10 weeks in Antarctica as an essential member of a research team, and (4) independent research projects involving data analysis and preparation of publications in the home laboratory. PAL REUs at UCSB receive academic credit for independent studies and /or field work in oceanography for their participation. One of the benefits to the student participants is the integrative aspects of the PAL as an interdisciplinary research program. Students evaluate the program at the end of their award, and the majority believe that their experience was beneficial in helping them to find a focus within aquatic science or to decide whether to continue in science as either technicians or graduate students.

Graduate students.

The following graduate students have received or are receiving full or partial funding from the PAL program.

UCSB:

Sharon Stammerjohn, Jan92-Dec93, M.A.: "Spatial and temporal variability in Southern Ocean sea ice coverage" Tom Frazer, Sep90-Nov95, Ph.D.: "On the ecology of larval krill, Euphausia superba, during winter: krill sea ice interactions" Karen Haberman, Sep91-present, Ph.D.: "Grazing by the Antarctic krill, Euphausia superba: Effects of phytoplankton type and food quality on ingestion, assimilation and growth of krill" Caroline Shaw, Sep95-present, M.A.: "Interannual variations in the ovarian cycle of Euphausia superba west of the Antarctic Peninsula" Mark Moline, Sep91-present, Ph.D.: "Variability and regulation of coastal Antarctic phytoplankton dynamics on interannual, seasonal and subseasonal time scales (1991-1994)" Heidi Dierssen, Sep93-present, Ph.D.: "Remote sensing of pigment concentrations and primary productivity in the West Antarctic Peninsula region" Phil Handley, Sep94-present, M.S.: "Annual and seasonal variability in hydrography near Palmer Station, Antarctica"

U of Hawaii:

James Christian,Sep90-Dec95, Ph.D.: "Biochemical mechanisms of bacterial utilization of dissolved and particulate organic matter in the upper ocean" John Dore, Sep89-May95, Ph.D. Ricardo Letelier,Sep88-May94, Ph.D.

ODU:

Cathy Lascara, Sep91-present, Ph.D.: "Seasonal and mesoscale distribution of Antarctic krill, Euphausia superba, in relation to environmental variability" David Smith, Sep92-present, Ph.D.: "Hydrography and circulation in the West Antarctic Peninsula region"

MSU:

John Carlson, Jun95-present, Ph.D.: "Long-term trends in Adelie Penguin populations in the vicinity of Palmer Station, Antarctic Peninsula: The effects of variability in the breeding habitat" Donna Patterson, Jan94-present, M.S.: "The effects of human activity on the biology of the Adelie penguin on Torgersen Island , Antarctic Peninsula " Nina Karnovsky, Jun94-present, Ph.D.: "The fish component of Pygoscelid penguin diets: Implications for Resource Partitioning and ecosystem monitoring" Tracey Mader, Jun95-present, M.S.: "The impacts of Leopard Seal predation on Pygoscelid penguins"

Public Education There have been a number of magazine articles and a video made about the PAL program including: "Life on a melting continent" and "The secret lives of krill" (Stevens 1995a and b, Newton 1992). Also, all PIs have been involved in presenting lectures and slide shows in local schools and community groups. Currently, Bill Fraser, a PAL PI, is teaching a class on "The Ecology of Antarctica" to several hundred high school students world-wide via internet from Palmer as part of a project called "Blue Ice".

International Interactions

The Scientific Committee on Antarctic Research (SCAR) and the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) are international governing bodies that receive recommendations on a host of issues related to the Southern Ocean through a diverse network of specialists and working groups. Two PAL PIs, William R. Fraser and Wayne Z. Trivelpiece, are, respectively, United States representatives to SCAR and CCAMLR, and address these bodies through participation in the Bird Biology Subcommittee of the Scientific Committee on Antarctic Research (WRF) and the CCAMLR Ecosystem Monitoring program (WRF and WZT). The most direct interactions with the PAL occur primarily through the CCAMLR Ecosystem Monitoring Program (CEMP), which seeks annual data on the ecology of Adelie penguins as part of its efforts to develop long-term monitoring programs. These data are delivered to CEMP through the Antarctic Marine Living Resources Program (AMLR), which provides U.S. funding for collection, analysis and preparation of annual reports (see reports by Fraser et al., 1988-1993).