

## **PALMER, ANTARCTICA LONG-TERM ECOLOGICAL RESEARCH PROJECT**

### **"Long-Term Ecological Research on the Antarctic Marine Ecosystem: Climate Change, Ecosystem Migration and Teleconnections in an Ice-Dominated Environment"**

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The Palmer, Antarctica, Long Term Ecological Research Project (PAL) seeks to understand the structure and function of the Antarctic marine and terrestrial ecosystem in the context of physical forcing by seasonal to interannual variability in atmospheric and sea ice dynamics as well as to dynamics driven by long-term climate change. The PAL LTER measurement system (or grid) is designed to study marine and terrestrial foodwebs consisting principally of diatom primary producers, the dominant herbivore Antarctic krill, *Euphausia superba*, and the apex predator Adélie penguin, *Pygoscelis adeliae*. An attenuated microbial foodweb, in which planktonic Archaea and bacterivorous protozoa is also focused on in this LTER. PAL studies Western Antarctic Peninsula ecosystems annually over a regional scale grid of oceanographic stations and seasonally at Palmer Station. Sea ice extent and variability affects ecosystem changes at all trophic levels. In recent years sea ice extent has diminished in response to a general warming in the region. Long-term population trends of ice-dependent Adélie penguins in the Palmer LTER study region provide a clear example of impact of the climate warming trend in the in the region. Adélie populations at the five major rookeries studied near Palmer Station for the past 30 years have all shown a gradual decrease in numbers. The site of PAL-LTER research, the Western Antarctic Peninsula, runs perpendicular to a strong climatic gradient between the cold, dry continental regime to the south, characteristic of the Antarctic interior, and the warm, moist, maritime regime to the north. North-South shifts in the gradient give rise to large environmental variability to climate change in the region. Currently more maritime conditions appear to be replacing the original polar ecosystem in the northern part of the peninsula as the climatic gradient shifts southward. To date, this shift in the climatic gradient appears to be matched by an ecosystem shift along the peninsula as evidenced by declines in Adélie penguin rookery populations that require longer snow-cover seasons for successful recruitment. We hypothesize that ecosystem migration is most clearly manifest by changes in upper level predators (penguins) and certain polar fishes in predator foraging environments because these longer lived species integrate recent climate trends (and because individual species are more sensitive indicators than aggregated functional groups). We hypothesize that analogous modifications will be manifest at lower trophic levels in the marine parts of the system in the years ahead. However, these lower level changes are likely to be observed only through long-term observations consistent with the concept of expansion and contraction of ecosystem boundaries along the Western Antarctic Peninsula. In this proposal we seek support to continue PAL LTER to investigate ecosystem changes along the at lower trophic levels Western Antarctic Peninsula, in response to the continued, dramatic climate warming and shifts in the poleward shifts climatic gradient along the Western Antarctic Peninsula. Through these studies we seek to understand the impacts of climate-gradient shifts through the spatio-temporal study of extant foodwebs in both the marine and terrestrial environments along the Western Antarctic Peninsula.

# 1 Summary and Results of Prior Support

## "Long-Term Ecological Research on the Antarctic Marine Ecosystem: An Ice-Dominated Environment" (OPP-9632763; 10/1/96 to 9/31/02)

This proposal seeks funds to continue, for a third six year period, the Palmer Long-Term Ecological Research (PAL) program which focuses on the marine ecosystem of the West Antarctic Peninsula (WAP). The central tenet of 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. Our observations, data analyses and synthesis activities over the past 6 years have led us to a new conceptual understanding of the WAP system. We now recognize the WAP as a premier example of a climate-sensitive region experiencing major changes in species abundance and composition due to changes in range and distribution (Smith et al., 1999, 2001a) that are occurring in response to regional climate change manifested here primarily as a southern migration of principal climate characteristics, hereafter referred to as climate migration. In effect, the maritime system of the northern WAP is replacing the continental, polar system of the southern WAP along the Peninsular climate gradient. This change is driven by regional warming, which is modulated by regional hydrography, sea ice processes and global teleconnections to lower latitude atmospheric variability. Consistent with our original objectives (Table 2.1), we seek to understand the full ecological implications of climate migration in the WAP, and uncover the mechanisms linking them through teleconnections to global climate variability.

PAL has 7 research components addressing the 5 LTER core areas (Table 2.2). Since 1991 the PAL program has included both regional spatial and local temporal sampling (Figs. 2.1ab). Our sampling program addresses multiple spatial scales within one regional scale 'grid' of ca 50 regularly occupied oceanographic stations at which core measurements are conducted (Fig. 2.1a), permitting repeated sampling on both seasonal and annual time scales, covering short and long-term ecological phenomena, and specific mechanistic studies (Section 2.5.1). The sampling grids add a unique strength to both the field and modeling programs as they unify measurements across all field components and facilitate data integration. To date, there have been ten (1993-2002) annual summer cruises and five additional cruises emphasizing fall, winter and spring processes (Table 2.3). Core and other variables are documented and available online at the PAL web home page [<http://pal.lternet.edu>]. Tables 1.1, 1.2 summarize our data history. (NB: for convenience, check \*-ed entries in regular Reference list for citations below.)

**I. Climate change, long-term trends and seasonal - decadal variability.** The focus of our research has been to identify and understand the mechanistic couplings by which the life histories of key species or functional groups (microbial foodwebs, phytoplankton, the Antarctic Krill, *Euphausia superba*, and Adélie penguins, *Pygoscelis adeliae*), and biogeochemical processes (1<sup>o</sup> and 2<sup>o</sup> production, sedimentation, CO<sub>2</sub> absorption) are affected by physical processes, particularly the annual cycle and interannual variability of sea ice (Fig. 2.2ab). Accumulating evidence continues to support our original hypothesis that all trophic levels respond to sea ice dominated forcing in this Antarctic marine ecosystem. We now have strong evidence linking the timing and magnitude of sea ice advance and retreat to the seasonal progression and life history patterns of phytoplankton, krill and sea birds (Quetin et al., 1996; Fraser and Trivelpiece, 1996; Smith et al., 1998c, 1999; Fraser & Hofmann, *submitted*; Hofmann & Fraser, *submitted*; Quetin and Ross, 2001; Vernet et al., *in revision*) as well as key biogeochemical processes (Karl et al., 1996; 2000). Sea ice indices provide a common,

quantitative context for linking sea ice dynamics to variability in climate and marine ecosystems (Smith et al., 1998a). We have documented statistically significant warming trends, and a significant negative correlation between air temperature and sea ice extent in the WAP, including a significant lengthening of the ice-free period during spring and summer (Figure 2.2b; Smith et al., 1996b; Stammerjohn & Smith, 1996, 1997; Smith & Stammerjohn, *accepted*). Climate warming is underway in the WAP study region, and the impacts can already be detected in the form of changes in the abundance and distribution of key ice-dependent species.

We have described the hydrography, circulation, heat and salt budgets of the WAP (Hofmann et al., 1998; Hofmann and Klinck, 1997; Klinck, 1998, Smith, DA et al., 1999). The large-scale circulation appears to consist of two intense small-scale sub-gyres contained in a weak, but larger-scale clockwise gyre that overlies much of the shelf in the PAL study grid (Smith, DA et al., 1999). The two gyres may exchange properties above 200 m but retain plankton in the region. High resolution satellite data revealing high frequency variability of sea-ice conditions & kinematics in response to meteorological forcing (Stammerjohn et al., *in review*) show how synoptic-scale systems influence sea ice coverage and drift. Long-term trends, such as those documented for air temperature and sea ice distribution, will be superimposed on higher frequency variability, as shown by cycles seen in krill and primary production (PP; Fig. 2.3). This variability is likely tied to statistical linkages between WAP sea ice extent & ENSO (Figs. 2.13, 2.14; Smith et al., 1996b; Smith & Stammerjohn, *accepted*; Yuan & Martinson, 2001). Two dominant modes of atmospheric forcing in the WAP region induce positive & negative sea ice anomalies, respectively. A shift in dominance from season-to-season and year-to-year between the cold, dry continental regime to the south and the warm moist maritime regime to the north creates a highly variable environment sensitive to climate change (Smith et al., 1999), and creates a strong north-south climate gradient.

One of the mechanisms by which climate change may induce changes in ecosystems is by disrupting the evolved life history strategies of component species (Rhodes & Odum 1996). By changing the physical and biological conditions associated with particular ecosystems, climate warming basically cripples the “adaptive function” of some life history strategies, and the species dependent on such strategies begin to decline and eventually disappear from the system. Long-term population trends of Adélie penguins provide a clear example of a postulated impact of the warming trend in the WAP. Adélie Penguin populations at the five major rookeries studied near Palmer Station for the past 30 years have all shown a gradual decrease in numbers (Fig. 2.4; Fraser & Patterson, 1997; Patterson, 2001; Smith et al., 2001). Regional scale population trends are forced by a gradual decrease in the availability of winter sea ice, while local scale population trends are forced by a gradual increase in spring snow accumulation (Fraser & Patterson, 1997; Patterson, 2001; Patterson et al., 2001). These processes can be linked directly to the effects of climate warming, and both operate by producing a spatial and/or temporal mismatch between critical aspects of penguin life history and prey availability.

Overwinter survival of adult penguins was earlier thought to be key to understanding the decline of populations over time, but we now recognize that adult overwinter survival is only part of the equation. The overwinter survival of fledglings, a major determinant of future recruitment and subsequent population trends, appears to be a more critical factor (Fraser et al., *submitted*). Three lines of evidence led us to this conclusion. First, a 15-year time series of Adélie penguin fledging weights suggests that chicks weighing less than 2850 g have a low probability of surviving the winter and returning as breeding adults. Second, an Adélie penguin chick growth model (Salihoglu et al., 2001) shows that low weights result when there is a

temporal mismatch between krill availability and critical stages in the early development of the chicks. Finally, Adélie penguin populations in rookeries decreasing at twice the average rate produced a much higher proportion of penguin chicks weighing less than 2850 g (Fraser et al., *submitted*). Due to unique, rookery-specific geomorphology, a larger proportion of the available penguin breeding habitat is found on landscapes where snow deposition is enhanced during late winter and early spring storms. As a result, chicks hatch later in the year, and their critical growth period takes place primarily in early February when local krill abundances are declining. This effect may be further exacerbated by variability in the timing of the seasonal horizontal migration of Antarctic krill through the foraging region (Ross et al., *submitted*; Fraser et al., *in prep*). The delayed hatch leads to lower food delivery rates, lighter chick fledging weights, and reduced probabilities of surviving winter to recruit back into the breeding population. We believe that Adélie penguin populations in the PAL region are operating at the very limits of their capacity to handle local environmental variability and will thus continue to decline.

Our decade-long time series over the PAL grid has yet to show a significant decline in krill abundance, intensity of reproduction (Fig. 2.3a; 2.5; Quetin and Ross, 2001) or recruitment success (Fig. 2.5, Quetin and Ross, *submitted*). Distribution and abundance of Antarctic krill in the gyre-enclosed region is a function of recruitment success and krill movement, passive and active (Ross et al., 1996, Lascara et al., 1999). Recruitment success is episodic in these long-lived animals, with two sequential successful year classes dominating 5-6 year cycles (Quetin and Ross, *submitted*). Reproductive output of the population, and overwinter survival of the larvae, are keyed to the 23-yr average sea ice conditions in spring and winter, respectively. Annual reproductive output is a function of the percentage of the population reproducing (Fig. 2.3a) (Shaw, 1997; Quetin and Ross, 2001), e.g., individual females may skip reproduction in any one season. Within the study period, average spring sea ice conditions, and high annual primary production resulted in the highest percentage of the population reproducing (Quetin and Ross, 2001). The maximum extent of sea ice in 1991-1999 was *not* strongly correlated with recruitment success; rather, an early onset and the duration of *at least average* sea ice extent were the critical variables (Fig 2.5). The implication of these results is that deviations from average conditions in the timing, duration and extent of sea ice will adversely impact krill recruitment and availability to predators.

There is substantial seasonal to interannual variability in phytoplankton abundance and composition (see also Section 2.2). The growth season starts in Oct/Nov and extends to Mar/Apr (Moline and Prézelin, 1996, 1997; Smith et al., 1998b). Seasonal primary production (PP) showed 7-fold interannual variation in inshore areas and 4-fold on the shelf. Production peaked in 1994-95 and 1995-96, defining a 7-year cycle from 1992-93 to 1998-99 (Fig. 2.3). Spatial variability in phytoplankton composition on time scales of weeks can be related to vertical mixing (Prézelin et al., 2000), mixed layer depth, krill grazing and micronutrient limitation (i.e. Fe) in offshore waters (Garibotti et al., 2001a,b). Nearly a decade (1991-2000) of observations (Smith et al., 2001), using both satellite (SeaWiFS, Dierssen et al., 2000) and *in situ* detection ( $^{14}\text{C}$ ), have established clear links between sea-ice variability and PP. As initially hypothesized, PP is positively correlated with sea ice extent as well as sea ice area but timing is also important. Late ice melting favors high PP, as exemplified by the 1995-96 PP maximum that occurred in a warm summer following a cold spring (Fig. 2.3b, Vernet et al., *submitted*). PP is highest when diatoms are most abundant, suggesting they are the major drivers of variations in PP.

**II. Trophic interactions and physical processes.** The linkage of seasonal sea ice distribution to PP is the principal route by which physical forcing enters the WAP ecosystem.

Diatoms concentrate near the coast in the center and southern sections of the sampling grid during years with mean PP (Fig. 2.6), and become abundant in the NE section in highly productive years. Thus the preferred food for krill is distributed throughout the area but concentrated in the south. If the warming trend continues, high-diatom years in the north might diminish in frequency to the extent of affecting krill and apex predator populations. Cryptomonads, less preferred by krill, could also become more prevalent if diatom blooms decrease, coinciding with increased glacier melt (Moline et al., 2000; Dierssen et al., *accepted*). These results lead us to hypothesize that the krill-dependent WAP ecosystem has become increasingly vulnerable to climate-induced perturbations (Fraser & Hofmann, *submitted*), and it is from this perspective that we are exploring interactions between climate migration and ecosystem response, including changes in the diatom-krill-higher predator classical food web.

About 70% of the variability in growth in young krill in spring can be explained by phytoplankton abundance and taxonomic composition, strong field evidence that Antarctic krill are food-limited herbivores (Ross et al., 2000). Growth reaches a maximum at relatively high standing stocks of phytoplankton characteristic of bloom conditions ( $\sim 3.5 \text{ mg Chl m}^{-3}$ , Ross et al., 2000). Haberman et al., (*submitted*) showed that adult krill are selective consumers, preferring diatoms over other phytoplankton; she also developed an antibody technique to detect grazing on *Phaeocystis* sp. (Haberman et al., *accepted*). In some years grazing pressure from krill populations can be a significant loss factor to the primary production (Ross et al., 1998). Thus the phytoplankton community composition affects production of krill, and krill can alter community composition and standing stock (Garibotti et al., 2001a).

The availability of Antarctic krill to their Adélie predators is mediated by interactions between sea ice and hydrography (Fraser & Hofmann, *submitted*; Hofmann & Fraser, *submitted*). A long-term study of diets in Adélie penguins near Palmer demonstrates that changes in the abundance and availability of krill to Adélies is cyclical, reflecting the periodicity in krill recruitment. Thus, following the emergence of a strong year-class or cohort, the duration of penguin foraging trips may decrease up to three-fold. The role of hydrography is more complicated, but it appears that a sub-gyre associated with the Palmer foraging area (Smith, DA et al. 1999) retains these cohorts within the foraging area during their life span. During the interim years between strong cohorts, penguin foraging trip durations increase due to a gradual decrease in krill abundance. These findings have led Fraser & Hofmann (*submitted*) to propose that these sub-gyres are focal points of krill life history and essential for successful feeding, reproduction and recruitment. One important implication of these findings is that predator-prey interactions are now thought to occur in more of a closed system than previously thought, and involve krill populations that may be quasi-independent of other regional populations.

Not only apex predators, but also biogeochemical properties integrate physical variability. We are just beginning to accumulate sufficient spatially extensive (Fig. 2.7) and temporally intensive data (Fig. 2.8) to identify seasonal and longer-term cycles and trends in biogeochemistry and relate them to ice and ecological processes. Sedimentation of carbon has a seasonal maximum each summer and varied by an order of magnitude interannually. Vertical fluxes at PAL are among the highest and lowest measured anywhere (Karl et al., 2000). The annual export is not related to the amplitude of the brief annual maximum, but rather to the duration of higher fluxes. The distribution of dissolved  $\text{O}_2$  and  $\text{CO}_2$  in the water column reflects the metabolic balance (photosynthesis minus respiration) of the surface waters as well as heating and cooling (Fig 2.9). There are substantial depletions in  $\text{pCO}_2$ , especially near Palmer Basin and in Marguerite Bay, that are associated with and indicative of hypereutrophic conditions and

extensive net production of particulate organic matter. The fate of the net production is unclear. Bacterial activity is uncoupled from seasonal PP (Bird and Karl, 1999), suggesting microbial oxidation may not be a key sink. One of our goals in the next few years is to determine how ice and PP variations are transmitted to microbes and biogeochemical property distributions and if they reflect changes in ecosystem properties along the peninsular gradient.

**III. Winter Trophic Interactions.** Sea-ice and meteorological data obtained during the June 1999 PAL ice formation cruise are being used to examine the details of sea-ice formation on the physical and biochemical characteristics of the ice (Ukita et al., *submitted*). The atmospheric influence is manifested in three different sea-ice processes, with distinct spatio-temporal patterns: (1) an early winter initial expansion of the ice field, leaving a relatively high concentration of granular ice; (2) subsequent fracturing, opening, and rafting/ridging processes, producing a mixture of granular and columnar ice; and (3) snow-ice formation after the initial storm-influenced period. Phytoplankton are entrained into the ice during formation. Chl concentrations during this early winter period support both a scavenging and pumping mechanism for the increase in biomass in the new ice over the background water column concentrations. Diatoms are preferentially concentrated when ice is formed under turbulent conditions. Flagellates dominate newly formed ice in non-turbulent conditions (i.e. nilas; Ferrario et al., 1999) while diatoms are preferentially concentrated when ice is formed under turbulent conditions. Flagellates, the dominant fraction in the underlying water column, are also entrained but their relative abundance is lower in newly formed ice suggesting lower entrainment into ice particles or cell breakage when in contact with the ice. Larval krill are obligate inhabitants of the ice habitat in winter (Frazer et al., 1997, 2002) where sea ice microbial communities are the major food source. If the ice habitat is present the larvae show positive, though variable growth (Quetin & Ross, 1991; Quetin et al., *submitted*). However, the growth increment of larvae in the austral fall and winter is directly proportional to the daylength, a correlation hypothesized to be related to the dynamics of ice formation and its effects on the sea ice microbial community (Quetin et al. *submitted*)

**IV. Ecosystem Synthesis.** Our research has established that the PAL study region encompasses an ecological gradient between a southern continental region and a northern maritime region, and that the boundary between these two regions is migrating north to south along the WAP. The response of the ecosystem to climate migration is best illustrated by changes in the populations and diets of some top predators. For example, apart from the data on Adélie population trends, the diets of northern Adélies no longer contain certain polar fishes that were common in these diets pre-1988 (Fraser & Patterson, 2001). However, the contemporary (post-1994) diets of southern Adélies match in fish species composition the pre-1988 diets of northern Adélies. This contrast suggests the northern WAP is experiencing a shift away from polar conditions that is encompassing a range of trophic levels in both marine and coastal habitats (Fraser & Patterson 2001). Changes in the frequency, timing and duration of sea ice in the northern WAP favor species with life histories that are either less dependent on sea ice or are ice intolerant. Relevant historical observations & paleoecological records on sea ice, diatom stratigraphy and penguin colonization place the current PAL data into a longer term perspective (Smith et al., 1999, 2001) showing that this century's rapid climate warming is occurring concurrently with a shift in the population size & distribution of penguin species. This remains one of the more statistically convincing illustrations of ecological response to climate change and provides strong evidence for the value of the Palmer LTER and its location in the WAP.

Results and progress in data management are discussed in detail in **Section 5**.

## 2 Project Description.

### 2.1 Working Hypotheses.

The PAL LTER was established in 1990 within the framing hypothesis that the annual advance and retreat of sea ice is the major physical determinant of spatial and temporal changes in the structure and function of the Antarctic marine ecosystem. As the program matured, the core of PAL remained focused on the ecological role of sea ice, the physical and climatic controls on interannual sea ice variability, and on the effects of this variability on trophic interactions and biogeochemical processes. During PAL I and II, we detected a progressive poleward shift in the dominant climatic gradient along the West Antarctic Peninsula, observed a contemporary ENSO signal in sea ice patterns and primary productivity, and established a temperature trend we believe to be associated with observed global warming. In short, the atmospheric and marine fluids that support and sustain the ecosystems of the Palmer area are dynamic in time and space. At the inception of PAL, we established a measurement system along the West Antarctic Peninsula and in the environs of Palmer Station that permits us to study ecological dynamics as they vary in time and space in response to climate variation and climate change.

For PAL III we advance the hypothesis that spatial displacement of the Palmer ecosystem will become manifest as a change in trophic (foodweb and elemental cycling) structure that is driven by climate migration, ENSO events and global scale warming of the planet. In advancing this hypothesis, we recognize there are two paradigms concerning the way ecosystems may respond to climate change, and that each paradigm carries inherent limitations as means of understanding and predicting how ecosystems will actually respond to climate change (McCarthy et al., 2001; Peterson et al., 2001). **Ecosystem movement** is a simplified paradigm that assumes the ecosystem will follow relatively intact the movement of a climate shift to a new location that better matches the original climate and environment. While idealized, this paradigm is useful for forecasting trends that may be associated with climate change and to formulate testable hypotheses. **Ecosystem modification** is an alternative paradigm that assumes there will be *in situ* changes in the abundance and distribution of key species in response to climate and environment change. This paradigm recognizes that species will have different climatic tolerances, different migration abilities and other traits that are likely to lead to different ecosystem types as climate changes. We will use these paradigms to frame our proposed research, but we introduce the concept of **climate migration and ecosystem response** to focus PAL III both theoretically and empirically. Our rationale for adopting this conceptual approach is described below. Although the processes of ecosystem change in response to climate modification are being studied at other LTER sites, they tend to be concerned with longer lived species (e.g., trees) and sometimes are limited to paleo record use such as pollen to establish changing patterns in time and space. PAL is an ideal site to complement other LTER studies because marine species are comparatively short-lived, and change – as we show – is evident on the scale of decades or less.

During the first grant periods, our research naturally focused on seasonal phenomena and interannual variability as we built sustainable data sets for the longer term. Now that PAL has passed the decade mark, our investigations are increasingly turning to longer-term processes. This expected evolution in our efforts is stimulated by detection of significant long-term trends in the climate and sea ice records, the discovery of important climatic teleconnections that appear to impart a quasi periodic variability to these longer-term trends, and the observation that

significant changes in the abundance and distribution of ice-dependent predators and polar fishes that were once prevalent in their diets have occurred during the last 30 years (Fraser et al., 1992; Fraser & Patterson, 1997, 2001; Smith et al., 1996b, Smith & Stammerjohn, *accepted*; Smith et al., 1999; 2001; Stammerjohn & Smith, 1996). These important findings are reflected in several new hypotheses focused on our observations that due to climate migration a maritime regime is gradually replacing the continental system within the Palmer Station region. In our view, the concept of climate migration and ecosystem response captures the empirical essence of what has already been measured during PAL I and II, which is to say the southward displacement of a continental regime with its associated colder, dryer atmosphere, sea ice that previously extended well to the north of Palmer Station, and robust populations of Adélie penguins and several polar fishes. The large scale design and repeated occupation of our sampling grid allows us to link the biosphere to climate migration by looking at concurrent spatial and temporal changes in ecosystem trophic structure in both the maritime and continental regimes that are associated, respectively, with the northern and southern sectors of our sampling grid. This presents a unique opportunity to place the concept of climate migration and ecosystem response within the framework of testable hypotheses implied by the ecosystem movement versus ecosystem modification paradigms. Below, we state a revised, 2-part central hypothesis and several related sub-hypotheses for PAL III that together comprise our integrated, interdisciplinary research prospectus.

**Ho(a): Climate migration associated with a warmer, more moist maritime regime that is becoming increasingly dominant along the north and central WAP region, is giving rise to ecosystem responses that take the form of changes in the abundance, distribution and community structure of all trophic levels.**

**Ho(b): Teleconnections to global scale atmospheric processes, with attendant quasi-periodic variability within this Antarctic marine ecosystem, modulates the observed longer term trends in climate and ecological processes.**

The dynamics and three-dimensional nature of sea ice are major factors in the marine ecology of the Southern Ocean in general and our coastal (WAP) area in particular. As hypothesized since the beginning of the program, the ecological influence of sea ice on the marine system is a function of interactions that occur over many spatial and temporal scales, and the shift southward of the influence of sea ice on some of these interactions is already being observed (Fraser & Patterson, 2001). A new conceptual framework for understanding the coupling between global climate and sea ice-ecosystem interactions over a hierarchy of scales is shown in Figure 2.10. The schematic illustrates how SST anomalies in the tropical central Pacific appear teleconnected to the sea ice - ecosystem linkages. Given the global influence of ENSO, we and others (e.g., Rind et al., 2001; Liu et al., *in press*) assume this is a causal link though the mechanism is yet to be definitively determined. Within this framework we are advancing the concept of climate migration and ecosystem response to describe how the combined influence of a long-term warming trend coupled with quasi-periodic variability driven by higher latitude teleconnections is significantly modifying the northern WAP region ecosystem. These modifications are most clearly manifested by changes in upper level predator populations (Fraser & Patterson, 1997; Patterson, 2001; Patterson et al., 2001; Smith et al., 1999, 2001; Fraser & Hofmann *submitted*) and the absence of certain polar fishes (e.g., *Pleuragramma*) in predator foraging environments (Fraser & Patterson, 2001). We hypothesize that analogous modifications will be manifest at lower trophic levels as well, but these changes are likely to be observed only after longer term observations consistent with the concept of climate migration. We anticipate

that as the boundary between maritime and continental climate regimes moves south, it will ultimately be evident at all trophic levels with significant changes in the marine ecosystem in the northern WAP region. A challenge now is to fully elucidate the ecological impacts of these changes. The following specific sub-hypotheses will guide proposed research that is conceptually linked to the effects of climate migration on ecosystem components.

- H1:** Interannual variations in ice dynamics, and ecological responses to this variability are a predictable manifestation (at some level of success) of teleconnections with large-scale, coupled ocean-atmospheric circulation processes, e.g. ENSO. For example, the population dynamics of krill is driven by the links of reproductive output and winter-over survival of larvae to the long-term, climatological means of spring and winter sea ice distribution (respectively), and their impact on food availability.
- H2:** The dominance of diatoms within the phytoplankton community is enhanced by high ice during the previous winter and spring, followed by late ice retreat and a warm summer, resulting in increased water column stability. Both interannual and longer term variations in sea ice duration and extent are transmitted via diatom primary producers to krill and penguins. A warming trend will decrease either average diatom distribution and/or the frequency of diatom blooms in the northern region replacing them with smaller flagellates and causing a shift from krill-dominated to other zooplankton community structure, presumably where the microbial loop has a more prominent role.
- H3:** The significant decrease in the duration of ice-covered waters in the summer in the LTER study region may be evidence of a decrease in the permanent pack ice habitat, with Antarctic silverfish (*Pleuragramma antarcticum*) and the ice krill (*Euphausia crystallorophias*) as indicator species. As the warm maritime climate replaces the cold continental climate, the habitat of these two indicator species will decrease in the Palmer station region and the locus of their distribution will be confined to the southern end of the grid.
- H4:** Adélie Penguin population trends ultimately reflect the coincident availability of suitable foraging and breeding habitats. Given the critical role that sea ice plays in Adélie Penguin life history, and taking into consideration the time lags over which the presence or absence of sea ice affects foraging and breeding habitats, we predict that Adélie penguins will become locally extinct in the northern LTER region as climate warming continues to alter the climatological mean sea ice conditions and local snow accumulation patterns.
- H5:** The relative extent of organic matter decomposition, export from the surface layer, preservation and burial are governed by sea ice distribution. The apparent uncoupling of bacterial from primary production in the region is a function of intense top-down control of standing stocks by bacteriovores. Interannual variability in bacterial dynamics in response to sea-ice driven variations in primary production is attenuated by foodweb interactions. As the local climate warms and the maritime regime shifts down the peninsula, terrestrial (bottom-up) inputs of organic matter may begin to impact the balance between bacterial production and removal. The exchange of CO<sub>2</sub> between the atmosphere and the surface ocean (limited to ice-free periods) is influenced primarily by intense primary production driven within the marginal ice zone and is thus also subject to forcing by global scale teleconnections and longer term climate change, as well as the shorter term variability in local sea ice dynamics.

## 2.2 The Antarctic Marine Ecosystem.

The Antarctic marine ecosystem, the assemblage of plants, animals, microbes, biogeochemical cycles, ocean, sea ice and island components south of the Antarctic Convergence, is among the largest readily defined biomes on Earth ( $36 \times 10^6 \text{ km}^2$ ; Hedgpeth 1977; Petit et al., 1991). Space and time scales of marine systems are tightly coupled to physical forcing so that lags between physical events and biological responses tend to be shorter than in terrestrial ecosystems (Steele, 1991). Oceanographic zones, which mark the boundaries of distinct water masses and changes in autotrophic biomass fields, are used to define biogeochemical provinces (Longhurst, 1998; Smith et al., 1998bc) that provide operational definitions of spatial structure in the marine ecosystem. These provinces are roughly analogous to terrestrial biomes imbedded within a fluid medium. The Antarctic marine environment is composed of an interconnected system of distinct hydrographic and biogeochemical subdivisions (Treguer and Jacques 1992) including the open ocean, frontal regions, shelf-slope waters, sea ice and marginal ice zones, and ice-free terrestrial environments occupied by birds and mammals. The PAL region (Fig. 2.1a) includes a complex combination of a coastal/continental shelf zone and a seasonal sea ice zone, swept by the yearly advance and retreat of sea ice. Circumpolar Deep Water (CDW), the most prominent water mass, is found between 200 and 700 m and is present in all seasons throughout the region. Below 200 m CDW floods the WAP continental shelf, bringing macronutrients and dissolved inorganic carbon, in addition to warm salty water, onto the shelf. Circulation patterns and the presence of CDW probably impact the timing and coverage of PAL sea ice, and the presence of gyres affects transport and /or retention of physical and biological properties, such as gelatinous grazers (Nicol et al., 2000). Weather in the WAP is modified by a temporally and spatially changing balance between relatively warm and moist maritime and relatively cold and dry continental influences (Smith et al., 1996b); the shift in dominance between these contrasting climatic conditions is hypothesized to shift biogeochemical provinces, and hence, give rise to climate-induced ecosystem responses.

South polar regions are unique in that sea ice, a dominant and distinguishing characteristic of Southern Ocean marine ecology, forms a range of habitats for juvenile krill as well as extensive and varied surfaces for algal and microbial populations (Smetacek et al., 1990; Ross and Quetin 1991). In addition, different springtime seabird habitats are associated with varying sea ice coverage, which therefore alters 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, a major ecological boundary, 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 of high productivity (Smith and Nelson 1985), up to 250 km in width 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 Sullivan 1994; Arrigo et al., 1997). 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.

The average primary productivity of the WAP region is  $162 \pm 114 \text{ g C m}^{-2} \text{ y}^{-1}$  which is about a factor of 5 lower than other productive coastal areas of the world's oceans (Smith et al., 1996a, 1998b, 2001; Dierssen et al., 2000; Vernet et al., *in prep*) and similar to other shelf areas

in Antarctica (Arrigo et al., 1998) but higher than the Polar Front (Moore et al., 2000). Phytoplankton biomass in the PAL area starts to accumulate near the end of November in an average ice year, triggered by the increase in daylength and the melting of sea ice, both of which contribute to water column stratification. In non-average ice years the subsequent timing shifts accordingly (cf. Fig. 2.12). Mean Chl in the top 30 m can increase from  $<0.5 \text{ mg m}^{-3}$  in a pre-bloom period, to higher than  $15 \text{ mg m}^{-3}$  during a spring bloom, with average values between 1 and 3 (Smith et al., 1996a). Blooms are mostly dominated by cells  $>20 \mu\text{m}$ , typically large-celled or chain-forming diatoms, although cells  $<20 \mu\text{m}$  also grow during a bloom (e.g., cryptomonads and prasinophytes; Vernet and Kozłowski, *in prep*). 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 water column stability and/or favorable meteorological conditions (Smith, WO and Nelson, 1986; Smith et al., 1987; Lancelot et al., 1993; Smith et al., 1998bc), ice ablation (Vernet et al., *submitted*) or glacier meltwater later in the season (Moline et al., 2000; Dierssen et al., *accepted*). Offshore, episodic blooms might be associated with intrusions of the southern boundary of the Polar Front (Boyd et al., 1995; Savidge et al., 1995). The timing of the blooms 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. 2.11, 2.12). These couplings are subject not only to the progression of the seasons, but also to intra-seasonal episodic events that disrupt and/or reset the cycle of water column stability, phytoplankton productivity and subsequent linkages (Moline and Prezelin, 1996). The balance of input and loss terms, affected by environmental factors that control intrinsic growth (i.e. light, micronutrient limitation, Smith WO et al., 2000) or population losses (e.g., krill grazing; Walsh et al., 2001), may shift in space and time in response to inter-annual variability and may change further with climate migration, so as to alter foodweb structure and subsequent function (e.g., export and burial).

Microorganisms, including unicellular algae, bacteria, viruses, protozoans and small metazoans, are vital components of Southern Ocean ecosystems (Karl 1993). We still have critical gaps in our knowledge of the seasonal cycles and especially the longer term variability of *Bacteria*, *Archaea* and other microbes in oceanic and Antarctic systems (Rivkin, 1991; Bird & Karl, 1999; Ducklow et al., 2001). In the WAP region, bacteria appear to be uncoupled from phytoplankton and have only a low amplitude seasonal cycle (Bird & Karl, 1999). In contrast, bacteria in the Ross Sea clearly respond to the annual *Phaeocystis* bloom by blooming about a month later (Ducklow et al., 2001). The flux of dissolved organic matter (DOM) from phytoplankton and zooplankton is the major source of bacterial nutrition, supplemented by particle solubilization (Anderson & Ducklow, 2001). DOM contributes a relatively small portion to the total carbon flux in the Ross Sea, at least in comparison to subtropical oceanic systems, where it tends to dominate the carbon budget (Carlson et al., 1998). A similar budget is planned for the nearshore or offshore zones in the WAP.

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. 2.11). 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. Prey/predator interactions (i.e., krill/Adélie penguins) are strongly mediated by critical periods during reproduction of both prey and predator. Antarctic krill live for 5 to 7 years, reproducing for up to four summers. Successful recruitment, however, is intermittent (Fig. 2.5) and appears to be dependent on seasonal sea ice

distribution (Ross and Quetin, 1991; Siegel and Loeb, 1995; Quetin et al., 1996). Ice-associated food (release of ice algae from melting ice and ice-edge blooms) is essential for ovarian development, and ultimately to high reproductive output in summer (Quetin et al., 1994; Quetin and Ross, 2001). Winter is a critical period, because unlike adults (Quetin and Ross, 1991), larvae lack energy stores, and may starve during the 6-mo fall and winter period of low food availability in the water column (Ross and Quetin 1991). The essential winter grazing ground for the young-of-the-year (AC0s) is the under-ice habitat, especially in layers between over-rafted ice floes, where they feed on ice algae (Frazer et al., 1997). Thus, AC0 survival, growth and recruitment are hypothesized to be enhanced by the presence and duration of over-rafted winter ice (Quetin et al., 1996; Frazer et al., *in revision*).

Gradients in distribution of zooplankton and fish larval populations along the Peninsula may reflect ecosystem responses in the region due to climate migration. The convergence at the northern edge of the permanent pack ice province (Smith and Schnack-Schiel, 1990) in this region may have moved south as climate has warmed, shifting populations of zooplankton and nekton dependent on summer ice-covered waters to the south. Typical biota in this province would include the Antarctic silverfish, a key prey item for seabirds, and the euphausiid *E. crystallophias* (Smith and Schnack-Schiel, 1990). Historical trawling data compared to PAL observations suggest that the fish population in the region near Anvers I. has changed over the past two to three decades, and this is confirmed by changes in seabird diets that span the last 30 years (Fraser & Patterson 2001). In the late 1970's and early 1980s, Kellerman (1986) collected large numbers of Antarctic silverfish in the Palmer LTER study region, and Daniels (1982) observed shoals of this species feeding under the ice in winter near Palmer Station. However, extensive trawling operations in 1993 and 1994 failed to yield significant numbers of Antarctic silverfish in the northern part of the grid (*unpub. obs.*). Populations were found in waters close to the continent (Crystal Sound and Marguerite Bay) in the southern part of the grid in areas close to regions of permanent summer pack ice (*unpub. obs.*).

Adélie penguins have a circumpolar distribution and a breeding season that passes through a series of stages. Egg-laying and a month long incubation period last from late November through December. After egg-laying the female goes to the ice edge in search of a predictable source of krill (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 (Salihoglu et al., 2001). 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 (Fraser & Trivelpiece, 1996). An important challenge is to understand the mechanisms by which oceanic biogeochemical provinces, broadly defined by large and regional scale physical forcing, influence the various trophic levels and their subsequent interactions.

### **2.3 Conceptual Models: Physical - Biological Linkages Between Climate Migration and Ecosystem Responses**

As our research has extended and matured, we have begun to refine our conceptual models to guide ongoing investigations (Ross et al., 1996; Smith et al., 1995; Fraser & Patterson, 1997; Fraser & Hofmann, *submitted*). Here we summarize the evolving conceptual foundation of PAL, pointing out continuity with our earlier, simpler models and identifying the significant advances in our thinking about the Antarctic marine ecosystem. Solar radiation, atmospheric and oceanographic circulation as well as sea ice coverage and snow deposition patterns 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 investigating trophic linkages (Fig. 2.11, 2.12). Some of the components in Fig. 2.11 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.

Interannual variability in sea ice extent is significantly and inversely related to air temperature (Stammerjohn 1993; Stammerjohn & Smith 1996; Smith et al., 2001). There is also 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 impact 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., 1992; Fraser and Trivelpiece 1996; Fraser & Hofmann, *submitted*). The shift in the northern WAP away from continental conditions likely encompasses a range of trophic levels. The common trend is that species whose life histories are ice-dependent (e.g., Adélie penguins) are slowly being extirpated from the northern WAP (Fraser et al., 1992; Fraser & Patterson, 1997; Smith et al., 2001). Concomitantly, food sources such as the silverfish *Pleurogramma* have disappeared from the Palmer area but remain in the South near Marguerite Bay (Fraser & Patterson 2001). At the lower trophic levels, we expect a shift from large diatoms to smaller flagellates, thus altering food sources for grazers as well.

The West Antarctic Peninsula itself is the basis of a conceptual model relating climate migration to ecosystem response (Smith et al., 2001). As the focus of PAL research, the WAP defines a strong climatic gradient between the cold, dry continental regime to the south, characteristic of the Antarctic interior, and the warm, moist, maritime regime to the north. This pattern gives rise to large environmental variability, sensitive to longer-term climate perturbations. Currently, in response to the warming trend in the WAP over the past 100 years, the northern part of the continental ecosystem in our grid is being replaced by more maritime conditions. The process may be driven by the warming trend we have already noted, but variability over several scales complicates process interpretation because the trend is overlain by various cycles. Our conceptual models now extend thinking about sea ice variability to global scales. This variability appears to reflect a teleconnection to variations in sea surface temperature in the tropical Pacific – the well known ENSO cycle (Fig. 2.10), but we do not know the mechanisms causing the teleconnection. Within the WAP, there are statistically significant couplings to global climate indices (e.g., ENSO; Smith et al., 1996b; Stammerjohn & Smith, 1996; Smith et al., 2001; Yuan and Martinson, 2001). Sea ice coverage and drift are influenced

by synoptic-scale systems (Stammerjohn et al., *submitted*), and show two dominant modes of atmospheric forcing that induce positive and negative sea ice anomalies. An understanding of the relative dominance of these two modes and their variability over time provides a mechanism for understanding the documented long term climate variability in this region (Smith et al., 1999).

We have begun to conceptualize the physical forcings (e.g., thermodynamic versus dynamic processes) controlling variability in sea ice. Atmospheric influence is manifested in three different sea-ice processes, which result in distinct spatio-temporal distributions of the physical and biochemical characteristics of sea ice (see Results of Prior Support). Rafting and ridging processes, directly related to the passage of storms, lead to considerable expansion of habitat volume for larval krill. The importance of atmospheric forcing in this process was dramatically displayed during our recent late-winter cruise (Sep-Oct 2001). A wind-driven ice edge recession toward the peninsula was accompanied by rafting and ridging to depths greater than 15 m such that the decreased ice extent was likely accompanied by a large increase in the ice volume. The overwhelming rafting/ridging in this area is probably unique to a coastal environment, in the manner that it will exaggerate open ocean processes so we can document and understand other Antarctic maritime conditions on a shorter time scale, due to the exaggeration. The formation of ice from snow (in contrast to seawater) is detected by changes in the vertical distributions of  $\delta^{18}\text{O}$  in the ice column. The biological consequences of snow-ice are currently under study, but this mechanism appears to be important in the creation of a suitable ice-related habitats for algae and krill. Thus, the range of events associated with the annual cycle of sea ice formation, consolidation, retreat and associated ecological and biochemical consequences (Ackley and Sullivan, 1994) continues to be an important focus for our analysis and modeling.

We are now testing many of these linkages at seasonal to interannual scales using eigenvector methods, or Empirical Orthogonal Function (EOF) analysis, focusing on that subset, Principal Components Analysis, PCA initially. These multivariate statistical methods are used to characterize the dominant modes of spatial variation in geophysical and biological data and to track the temporal variations in the importance of the spatial modes in the time domain. Thus far, three levels of analysis have been employed which provide a coherent method of study across disciplines. First we calculate the long term mean (climatology) and standard deviations across the grid. Next we obtain the EOFs or PCs which are used to optimally interpolate the data set (Kaplan, et al., 1996) and then calculate the yearly anomalies as the difference in the interpolated yearly value with respect to the climatological mean. simple correlations between variables necessary for exploratory analysis of covariability as well as hypothesis testing (Martinson and Iannuzzi, accepted: preprint available at [http://www.ldeo.columbia.edu/polar/Publications\\_Page.html](http://www.ldeo.columbia.edu/polar/Publications_Page.html)). We are using EOF analysis to describe the spatial and temporal covariability among variables, that is, to look at physical-biological linkages and trophic dynamics. For example, Fig. 2.13 shows climatologies for both the rate of phytoplankton primary production (prey) and adult krill abundance (grazer) and the temporal correlation of the interpolated variables (Fig. 2.14). The rate of daily carbon incorporation, integrated over the euphotic zone, has both onshore-offshore and North-South gradients. Values are highest over Palmer Basin, inside of the 600 cruise track line. The gradient between coastal and offshore areas is about one order of magnitude. Highest variability is observed in the areas of highest production, mainly along the coast but also offshore in the south, at the 200.200 and 300.200 stations. The year with highest production was 1996 while 1999 shows the lowest production. On the other hand, adult krill have an average distribution in January that increases from SW to NE, towards Palmer Basin.

The covariability of krill abundance and primary production is highest in the center and northern half of the grid.

One hypothesis on the control of phytoplankton production relates to the presence of shallow mixed layers in response to reduced turbulence (Holm-Hansen and Mitchell, 1991). Summer mixed layer depth is minimum (<15 m) inshore in the north and center of the grid. The source of the shallow summer mixed layer inshore could be due to freshwater input into the system, from sea ice melt, providing a fresh lens at the surface. Thus, we would expect to see a shallower mixed layer correlating with spring ice melt, a prediction that can be tested with canonical correlation analysis (CCA). The first EOFs of both primary production and the ice melt timing index both explain over 60% of the variance, and is related to the on/offshore gradient. The first mode of canonical correlation between the timing of spring ice melt and primary production explains 99% of the covariability. Spatially, the primary production shows high values inshore when springtime ice melt is late inshore, in particular at the center of the grid. The time series shows a positive pattern of variability in productive years such as 1995 and 1996 and a negative pattern (or early ice melt in coastal waters) in 1998, the winter before the lowest productive summer (January, 1999). These results support our hypothesis that water-column stability causes the onshore-offshore gradient in phytoplankton abundance and production, and provides a mechanism for explaining the enhanced variability observed in inshore primary production. This example illustrates our use of refined conceptual models of climate and sea ice variability, and of physical-biological couplings as well as a basic ecological understanding of the WAP system to generate hypotheses we test with EOF and related analyses of our long term, spatially-extensive, 3-dimensional data sets. Our sampling grid and integrated component measurements provide a database that is uniquely suited (and rarely found) for EOF analysis.

## **2.4 Proposed Research**

Proposed research is organized under three thematic sections: Core Measurements, Synthesis & Modeling (including Information Mgt.) and Experimental Work & New Initiatives. In the latter two sections, our research is increasingly collaborative and integrated with individual components pursuing both individual goals as well as cooperative efforts.

### **Core measurements & continuing work.**

Reliance on an integrated and mutually supporting suite of ongoing core measurements forms the intellectual and logistic core of PAL research. Core data sets are listed online at <http://www.crseo.ucsb.edu/lter/forms/> and are measured using protocols defined and documented at the same site. Data availability is summarized in Tables 1.1, 1.2.

### **Synthesis & Modeling.**

Synthesis and modeling are an increasingly collaborative component of the PAL. This element of PAL should also be considered ‘core’ work, carried out at the level of individual components and collaboratively across the entire program as described below. We describe first several integrating activities which involve most or all PI’s, then highlight several efforts aimed at more limited objectives – which nonetheless enrich the whole program.

**Information management (IM)** is a critical element of our data synthesis and modeling effort and we propose several enhancements to our data system and web pages to facilitate the proposed synthetic work. IM will focus on services designed to facilitate synthesis and modeling within and beyond PAL: web redesign, metadata migration, and database services with a dynamic web interface. Plans are underway to redesign the web site to transform to a contemporary approach compliant with new design standards. The Palmer LTER IM component

has initiated a variety of partnerships that enable investigation into new information management techniques through collaboration with computer scientists, information scientists, digital librarians and social scientists. Work with the San Diego Supercomputer Center focuses recently on establishing bibliographic databases, best practices, and exchange as well as more general document handling systems. A mapping of current metadata to the Ecological Metadata Language (EML) (Gross et al., 1995; Michener et al., 1997) will stage Palmer LTER data for transformation into eXtensible metadata language (XML) directly or for import into existing applications such as Morpho, a tool developed by the National Center for Ecological Synthesis and Analysis (NCEAS) for managing both an individual's and a site's metadata. Metadata will be transformed to fully parsable ASCII and into a queryable format which provides for improved access control, data discovery, and export for data exchange. Approaches that enhance both site and data identity will continue to be investigated. These include development of a site description directory in collaboration with the LTER Network Office and exploration of ways to ground environmental data through metadata.

**Grid/EOF Analysis of climatologies.** This effort is in progress, synthesizing data from all PAL components to test the climate migration/ecological response hypotheses. Analysis through application of EOF methodology to the data from the summer cruises has proven to be one of our most valuable tools for exploring the longer term patterns, trends and covariability in our data. Several key data sets have been analyzed and several remain to be added to the EOF analyses (microbes, biogeochemical variables, bird observations) in order to complete the EOF data matrix as well as adding the 2001 and 2002 cruises. We are currently preparing several manuscripts on the EOF analysis of core data sets. We will also begin a more concentrated focus on eigen-techniques designed to more specifically identify covariability among our various physical and biological variables. These include canonical correlation analysis (CCA, and its subtle variant, often referred to as SVD analysis), redundancy analysis and other such techniques which should help us more directly test some of our hypotheses. In addition, high density small scale grid observations that have been collected within the immediate foraging area of the Palmer penguin rookeries will be analyzed in an analogous way.

Continued EOF analysis of bio-optical data from both large scale and high density grid observations. The latter will be used to directly test our hypotheses that specific environmental characteristics (sea ice, bottom topography, proximity to islands, etc.) would be tightly coupled to phytoplankton, krill & seabirds within the foraging area of the Palmer penguins. In testing this hypothesis we expect that the observed interannual variability in these linkages will provide particular insight with respect to trophodynamic mechanisms within our ecosystem.

**Network modeling and plankton simulation.** This will be a new effort which seeks to maximize our knowledge of foodweb structure to test hypotheses about ecosystem modification. Various approaches to network analysis (Ulanowicz, 1986; Moloney et al., 1991; Huntley et al., 1991; Fath & Patten, 1999; Ducklow et al., 1989) will be applied to build a more detailed understanding of the structure of the WAP foodweb. Limitations in methodology and sampling (e.g., aliasing) prevent us from observing all the trophodynamic interactions we want to understand and model. Thus our observations alone cannot provide an objective description of the ecosystem, no matter how long we sample it. It follows that observations alone are limited in supporting assessment of long-term changes in response to climate change. Inverse methodology and data-model assimilation techniques can be applied to incomplete observational data to provide objective estimates of missing intercompartmental flows (Vezina & Platt, 1987; Jackson & Eldridge, 1992) while application of flow analysis can suggest if existing rate measurements

are correct within specified tolerances (Anderson and Ducklow, 2001). We will use estimates of long-term, climatological mean and extreme states of the foodweb (standing stocks and production data) for the 1993 – 2001 period, as input to these models to construct foodweb scenarios for high, mean and low ice conditions. These synthetic foodwebs will provide baseline data for creation of more complex plankton dynamics simulations (see above) and for assessing the ecosystem responses over the next few years.

**Physical circulation modeling and coupled models.** Coupled physical – biological modeling will use insights gained from the first two activities to provide dynamic simulations which could ultimately address climate migration in their forcing functions and ecosystem response in the outputs. We intend to test elements of our hypotheses and the causality of relationships suggested by our covariability grid analysis using a one-dimensional (in the vertical) physical-biogeochemical (PBC) model of the upper ocean, sea ice and biogeochemical system. The model has been developed through another funded program by Martinson, Kiefer and Takahashi (unpublished). This model has proven successful in predicting the seasonal and shorter time scale evolution of the PBC system in the Weddell gyre region. We have recently improved the sea ice model component (Ukita and Martinson, *accepted*) to more accurately reflect the effects of short-term climate variability on the sea ice growth and internal structure, which may prove useful in better treating short-term influences that may have an effect on the ecology as discussed previously. In an effort to determine the sensitivity of our simulations to the PBC representations, we will also consider inserting other models (e.g., Fasham et al., 1990) in place of the Kiefer model (ref needed), and including the bio-optical model described in the following section. We intend to apply this model to the PAL study region, using our extensive data to initialize, force and diagnose the model. We will attempt to understand key PBC relationships in the WAP region and make modifications to the model according to the simulation-data comparisons and input from the other PIs based on their understanding of the PBC system. We also intend to couple this model into the high resolution (5 km grid) ROMS primitive equation model (Regional Ocean Model, Haidvogel and Beckmann, 1999) of the WAP region currently being used by Enrique Curchitser (LDEO; the modifications will be performed under a separate complementary proposal).

In addition to the numerical modeling effort, work will continue on the synthesis focusing more now on coupled analyses such as Canonical Correlation Analysis and Redundancy Analysis, and on continued collection of the core physical hydrographic data. Model results will also be used to guide further data analysis, particularly for expected coupled relationships, including lagged relationships. We have had success in such analyses using GCMs and larger scale polar-global teleconnections (Liu et al., in press).

**Population modeling.** Modeling of individual species population dynamics informs the holistic, cross-program efforts just described. We are continuing to develop new approaches to understanding the growth and predator-prey dynamics of our key species pair, *E. superba* (krill) and *Pygoscelis adeliae* (Adélie penguins). We will develop a krill population cohort model with birth and death rates derived from data collected previously. Stella II and its population cohort and fisheries reserve models will serve as the starting points. The MLMIX program for fitting a mixture distribution to length-density distributions derived from net-survey data (de la Mare, 1994) will be used to identify cohorts from length-frequency data. Experimental growth rate and acoustic biomass data will be used to constrain increases in cohort mean size, and adjust the numbers in each cohort at each station. Birth rates will be derived from estimates of individual reproductive output and the reproducing female population to yield a population fecundity, i.e.

number of potential recruits. Age-specific survival rates will be derived from the length frequency data and from the literature (Siegel, 1992, 2000; Pakhomov 1995 a, b) that show variation in mortality rates with age. Birth and survival rates will vary as a function of environmental variables such as sea ice duration. The model will provide predictions of population size, numbers and biomass of *E. superba* for carbon flow estimates, and for trophic interactions (grazers, prey items). Another approach to understanding krill growth involves calculation of turnover rates or production:biomass (P:B) ratios for *E. superba*. To date estimates of P:B ratios for Antarctic krill vary from 0.53 to 2.77 (Siegel, 1986, 1992, 2000; Miller et al., 1985), but the data have not been available to estimate variance in space and time. With size-specific production rates from growth experiments and size-specific biomass from length frequency and acoustic estimates, we can estimate interannual and spatial variability in P:B ratios which in turn can be related to turnover rates in the phytoplankton community.

The observation that both marine and landscape effects potentially influence the demography of Adélie penguins has focused our modeling and synthesis efforts on understanding the causal elements forcing the implied dynamics. Two of these models have either been published or submitted; with another still under development. A model describing the responses of Adélie Penguin chick growth on the breeding colonies (Salihoglu et al., 2001) to variability in krill availability now provides the basis for understanding the periods in the growth cycle that may be especially sensitive to perturbations in the timing and delivery of food. This work is extended further in a related synthesis and model (Fraser & Hofmann *submitted*, Hofmann & Fraser *submitted*) that explores the marine sources of variability in the abundance and availability of krill to Adélie penguins. This work suggests a direct, causal relationship between variability in ice cover, krill recruitment, changes in krill abundance and availability, and the foraging responses of Adélie penguins. A final model under development (with Dr. Christine Ribic, UW Madison) addresses Adélie Penguin population processes, and specifically the possibility that habitat-specific demography and source-sink dynamics (cf. Pulliam, 1988, 1996) are directly applicable, with some modifications, to understanding the long-term population trends exhibited by Adélie Penguins at Palmer Station.

**Remote Sensing & Bio-Optics.** Remote sensing provides the main bridge allowing extrapolation from the local scales at which most measurements are made to the regional and global scales. Previously obtained spectral absorption (AC-9) & spectral backscattering (HydroScat-6) data will be applied to test hypotheses concerning the unique bio-optical characteristics of Southern Ocean (SO) waters. To the best of our knowledge these are the first inherent optical property (IOP) data to be obtained in the SO and we anticipate that these data (LTER and GLOBEC *in situ* pigment, CDOM & phytoplankton absorption data collected by PAL LTER and GLOBEC PI Ray Smith in both programs) will permit a quantitative assessment of hypotheses related to the optical properties of the SO. Our empirical SeaWiFS algorithm for the SO (Dierssen & Smith, 2000; Dierssen et al., 2000; Smith et al., 2001) can be placed on a more analytical basis by making use of Local Area Coverage (LAC) data from Palmer station along with contemporaneous surface bio-optical observations (including upwelling spectral radiance) made throughout the past several seasons. Our intent is to analyze these data with the aim of understanding the unique characteristics of ocean color algorithms for the SO. Our ability to detect a possible shift in phytoplankton functional groups that may be associated with climate variability would not likely be detected by empirical algorithms alone. Our analysis also will test if the bio-optics of the WAP are representative of the rest of the SO.

Further synthesis and modeling initiatives will include bio-optical characterization and modeling the waters of the WAP area making use of “Hydrolight” (Mobley and Sundman, 2000); incorporation of optical results into physical models developed by Martinson; a fresh analysis of sea ice data and dynamics making use of satellite observations and data from our two sea ice cruises.

#### **New initiatives & experimental work.**

Core measurements of distribution and production of phytoplankton, krill, apex predators, and microbes continue the long-term studies of their dynamics in the context of environmental variability. Thus, the environment defines natural, uncontrolled, experiments conducted over seasonal to interannual scales. Although some of our hypotheses can only be tested through strategically-designed observations of the natural environment, others require controlled experiments. Therefore we propose a series of experiments and other initiatives to evaluate new approaches to observing and understanding the WAP ecosystem as it experiences changes due to climate migration. These are described in the context of our program components.

**Remote Sensing & Bio-Optics.** Smith and Vernet will collaborate to get a suite of Autonomous Profiling Vehicles (APV’s) operational within the Palmer area. These are profiling instruments that use a small winch attached to the seafloor and which periodically profile the water column from the bottom up. The first such instrument was deployed this season and the intent is to gradually increase our seasonal coverage in the Palmer Station region along the 500 and 600 lines. Several properly instrumented APV’s will provide valuable core physical and bio-optical data to the program. In particular, we seek to extend our seasonal coverage, provide a wider set of surface observations to complement satellite observations and, possibly, reduce field personnel.

**Phytoplankton dynamics.** Phytoplankton population growth is a function of photosynthesis minus respiration, grazing, sedimentation, advection, excretion and lysis. We propose to focus first on three loss terms that have ties to other components within the project: grazing (both by micro- and macrozooplankton), sedimentation and DOC excretion. Carbon excretion will be measured as part of our daily primary production experiments (Vernet et al., 1998). Sedimentation of phytoplankton cells and fecal pellets will be measured in chambers (Heiskanen and Keck, 1996) in collaboration with Ross and Quetin, both at Palmer Station and on the cruises, by collecting fresh fecal pellets from recently caught krill, salps and copepods and measuring their sinking rates. Sediment trap data suggest that between 0.3 and 7% of the annual primary production on the grid sinks to 300 m depth. Assuming an 85% assimilation efficiency by macrozooplankton, and assuming that all carbon in the traps is the result of fecal pellets, between 2% and 47% of the annual primary production is grazed. The rest of the carbon must be recycled in the upper water column (Carrillo 2001). Uneaten phytoplankton cells can also sink, in particular when under stress (Waite et al., 1992) transporting vegetative cells and resting spores to depth (Ferrario et al., 1998). We will measure sedimentation rates of phytoplankton during the austral summer and fall when the sediment traps indicate maximum sedimentation. Microzooplankton grazing will be carried out by the dilution method both in the light and in the dark (Caron et al., 2000).

**Zooplankton and micronekton.** We propose to extend our sampling to include three consistent groups of stations along a meridional gradient on the inner shelf (Grandidier Channel, Crystal Sound and Marguerite Bay) of our study area to identify the hydrographic characteristics and zooplankton and fish larval composition of the biogeographical provinces (Smith and Schnack-Schiel, 1990) of the shelf region. Differences in these characteristics between the early

1990s and the next 6 year period may reflect ecosystem responses due to climate migration.. We will continue to monitor any trends and/or periodicities in the reproductive cycle and recruitment success of Antarctic krill. We will use the data to test whether the populations within the two subgyres are separate (experiencing the marine and continental climates respectively), or if they may reflect differences in seasonal sea ice extent and duration within the one gyre. The two alternatives will be investigated both with data analysis and with the population cohort model (see Modeling and Synthesis).

During the January cruises, one team will remain on station to conduct frequent acoustic surveys during the period of chick growth. The increased surveys will allow us to better identify interannual variability in the peaks and lows of prey abundance to relate to chick fledgling weight. During the initial two austral springs of the funding period, as continuation of a Ph.D. Thesis, we will continue to compare ingestion rates of AC0 krill feeding on the undersurface of the ice and in the water column. Preliminary results indicate there is a difference in the functional response curve between the two feeding behaviors, type II versus type III (Holling, 1959).

**Penguins.** Data on the demography and foraging ecology of Adélie penguins currently provide some of the best examples of the effects of climate migration on WAP ecosystems, and we have identified two areas of research that are key to filling existing gaps in our understanding of the mechanistic processes involved. The recent finding that northern and southern WAP subgyres may be the focal points of quasi-independent, gyre-specific interactions between sea ice, krill recruitment, krill abundance and Adélie foraging responses (Fraser and Hofmann, *submitted*; Hofmann & Fraser *submitted*), suggests we need to learn more about the local movements and locations of foraging Adélies and the habitats used in their annual migrations. This we intend to investigate with the use of satellite tags deployed during the breeding season that provide data on foraging location, dive depth and water temperature. Likewise, the observation that interactions between breeding habitat geomorphology and changing patterns of snow deposition due to climate warming may produce penguin fledglings whose weights are not conducive to winter survival (Fraser et al., 2001a), suggests that it may be useful to use small-scale investigations to examine if the suspected causal mechanisms are generating the larger-scale patterns (cf. Root & Schneider, 1995). By altering snow deposition patterns at selected colonies with the use of snow barricades and fences, we intend to use a habitat manipulation experiment to investigate relationships between the timing of breeding and the fledging weight of Adélie Penguin chicks.

**Microbes and organic biogeochemistry.** We will initiate weekly to biweekly seasonal sampling (Oct. – April) for *Bacteria*, *Archaea* and selected biogeochemical properties within the Palmer Station nearshore study area, in close collaboration with other PAL scientists. This area has not previously been a focus of microbial research in PAL. The main aim is to test Karl's hypothesis that bacteria are uncoupled from phytoplankton in Southern Ocean systems (Karl, 1993). Our sampling program will determine bacterial community structure using DGGE and TRFLP (Muyzer et al., 1993; Liu et al., 1997), to monitor potential changes in response to climate change. Drs. Craig Carlson (UCSB and SBC LTER) will collaborate in the molecular community structure work.

The Antarctic represents a relatively simplified system relative to other continental shelf seas in terms of elucidating potential organic matter sources and sinks. However, an inherent complexity underlies the conceptually basic framework. Important questions about the dynamics of OM composition have yet to be addressed: What is the role of biologically active sea ice

communities in supplying and transforming DOM and POM? How do chemical and biological pathways transform recognizable compounds to substances that are unidentifiable in our widening analytical window? Antarctic coastal seas generally lack terrestrial inputs of organic matter. But if the maritime regime continues to migrate down the peninsula, terrestrial plants (mosses and grasses) may colonize more area in the WAP region, and provide a source of terrestrial organic matter to the coastal ocean and our study grid. We will initiate a study of lipid biomarker compounds to provide baseline information of current sources of organic matter (phytoplankton, zooplankton, bacteria, terrestrial) in this region. This foundation will also provide us with a benchmark against which we can compare future changes in organic matter inputs to this vulnerable ecosystem.

Biomarkers are organic molecules that carry embedded information as to the origin of OM (Killops and Killops, 1993). Because the basic skeletons of these compounds are often preserved in recognizable form throughout diagenesis, biomarkers have been widely used to assess both present (Wakeham and Lee, 1989) and past sources of OM (Meyers, 1999). Select biomarkers can also provide information about environmental conditions at the time of their formation or burial (e.g., temperature, sediment redox; Killops and Killops, 1993). We will determine the distribution of lipid biomarkers in both POM and ultrafiltered DOM (UDOM) in the nearshore sampling region at Palmer Station. In temperate regimes, the lipid composition of UDOM and POM are very distinct, reflecting both the predominant sources as well as differential lability of source-specific substances (Mannino and Harvey, 1999). Previous studies have isolated and identified specific biomarkers for Antarctic bacteria (Nichols et al., 1993) as well as phytoplankton/zooplankton (Nichols et al., 1990; Nichols et al., 1989). Biomarker work at Palmer Station has focused previously on the lipid composition of krill and zooplankton (Kattner et al., 1996; Kattner et al., 1998) and *Archaea* (DeLong et al., 1998). Our study will expand upon this body of work and represents the first comprehensive efforts to characterize the lipid biomarker composition of both POM and UDOM in this system. The proposed work will complement pigment analyses to be conducted by M. Vernet by providing information about bacterial, phytoplankton/zooplankton and terrestrial sources. A long-term data set has clear value for paleoecological studies and for monitoring global change.

## **2.5 Science Plan, cruises, sampling and methods.**

Our science plan addresses both long-term and short-term processes and encompasses sampling flexibility while maintaining critical (as dictated by our analyses to date) long-term consistency with our past observations. 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. 2.1a and Section 2.2) and the high density sampling of microbes, phytoplankton, krill, and seabirds within the Adélie foraging area near Palmer Station (Fig. 2.1b). As our project and understanding mature, we are progressively adopting an increasingly varied suite of systems to observe and sample the WAP ecosystem. 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 multiplatform, multiscale sampling strategy (Smith et al., 1987, 2001). Ships, the classical oceanographic sampling platform, are still the only means to conduct sophisticated experimental and process studies offshore, and they will still form the basis for much of our research. The disadvantage of ships is their limited spatial coverage and working constraints during foul weather and heavy ice conditions. Moored buoys and autonomous profiling vehicles (Smith et al., 1987) are even more limited in spatial coverage but are extremely valuable in providing long time series at selected

locations (though recent improvements in the latter are allowing for sampling over broader sampling domains, which we are investigating). Position-reporting transmitters affixed to penguins provide spatially extended information during brief but critical periods of the birds' reproductive cycle (Davis et al., 1996). 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. Finally, extended stays at Palmer Station provide the only means for obtaining high resolution time series (e.g., the seasonal cycle) for properties requiring complex experimental approaches and nonroutine analyses. These elements of our ongoing program are addressed below.

**The PAL Grid.** The sampling grid (Fig. 2.1a) lies at the heart of PAL. A three-dimensional georeferenced measurement system, our grid of oceanographic stations is an ecosystem observatory, which allows a scaling up to and statistical linkages with the 3-D global climate grids. Sampling is conducted annually along vertical profiles through the water column at each hydrographic station (grid point). Our observatory is now stocked with a decade of archived data. Each year the observatory becomes more powerful as new data are added. Our strategy for exploiting the grid data was described in Section 2.2 above.

Table 2.4 provides a detailed breakdown of the elements of a summer 'grid' cruise. Austral summer cruises are timed to match the critical period of Adélie penguin breeding (Fig. 2.12) in order to investigate trophic level linkages. PAL January cruises typically have two sampling modes: (1) large scale grid sampling including stations 'inside' the islands, and (2) finer scale sampling within the Adélie foraging area (Fig. 2.1). The first mode determines key environmental variables sampled on a fixed grid which facilitates separating long-term systematic trends from interannual variability (see Section 2.2). The second mode is aimed at observations linking water column variables with fine scale (few km) krill and seabird observations. The PAL sampling design includes (1) continuous and discrete measurement of key environmental and biogeochemical parameters, (2) determination of abundance of zooplankton and fish using nets/trawls and bioacoustic transects, (3) observations of seabird distribution, abundance and biomass, and (4) satellite-based remote sensing observations, and (5) experiments to determine  $1^{\circ}$  and  $2^{\text{nd}}$  production at selected stations. 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. Table 2.3 lists annual cruises to date, and brief cruise reports are summarized in Antarctic Journal of United States (*AJUS*) articles (references in Sect. 1).

The summer grid cruises form the central core of PAL research, encompassing a regional scale sampling strategy we have followed from the inception of our program. Full coverage of the entire grid region becomes increasingly critical with our new core scientific objective of understanding the causal mechanisms that link climate migration to ecosystem responses. Without sampling the extremes of the peninsular gradient, we cannot fully characterize the invading species, nor the core populations of those being extirpated from the PAL region.

**Process Cruise.** In the last funding period we performed two special process study cruises in addition to the annual summer cruises. These were undertaken without additional support, but they were critical for guiding our grid analysis and model testing of local interactions and covariability of the physical-biological system. To pursue our new program objective of detecting and understanding how climate migration impacts WAP ecosystems, we need to document the full range of penguin populations in the WAP region. Thus we will separately propose a single process cruise to determine the status of penguin populations and their potential prey items in the LTER grid between Anvers and Avian islands, and to link these populations through diet studies to aspects of their respective marine environments. With increasing base costs and level funding, we cannot achieve this important goal without additional support. This process study will also extend observations of other PAL core datasets into the spring – early summer period.

Penguin populations along the 400 km coastline that separates the northern and southern parts of the LTER grid have not been surveyed in more than 30 years (cf. Woehler 1993). The climate migration ecosystem response scenarios described in this proposal suggest several testable hypotheses regarding the status of these populations and the prey on which they depend. The hydrographic characteristics and zooplankton communities within the foraging habitats of the populations need to be detailed. North to south, we predict that the composition of Adélie Penguin diets will shift, with several polar fishes becoming a dominant component of the diet in the southern regions. We also predict that southern Adélie Penguin populations have remained more stable during the last three decades, and that Gentoo (*P. papua*) and Chinstrap (*P. antarctica*) penguins, two maritime species, will show both range expansions and population increases along this coastline. The cruise is planned for the mid-November to mid-December period, thus encompassing the key egg-laying stage for census purposes (CCAMLR 1992) and the early chick feeding periods to obtain diet data. All population censuses, diets studies and biophysical surveys of the marine environment will be focused on the three known Adélie Penguin population centers in the LTER grid (Fig.2.1a).

**Palmer Station.** Another significant element of our sampling strategy is directed toward time series data taken in the vicinity of the Adélie nesting sites near Palmer Station and the corresponding Adélie foraging area. 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 (Smith et al., 1998bc, 2001; Ross et al., 2000; Fraser & Hofmann *submitted*; Ross et al., *submitted*). The field season at Palmer Station also permits longer time scale mechanistic studies, which are impractical and/or more costly to conduct on ship (Haberman, 1998; Haberman et al., *submitted*; Haberman et al., *accepted*; Dierssen et al., 2000). Also, the Palmer Station data provide surface validation for both satellite and aircraft remotely sensed observations (Dierssen and Smith, 1996, 2000; Sanchez, 1999). Due to budget limitations, continued Palmer Station field work will have increased emphasis on deployment of Automated Profiling Vehicles (APV) and selected process oriented experiments. Our objective in deploying the moored APV's is to provide more complete seasonal physical and bio-optical data as well as to extend the spatial coverage of these seasonal data to include areas outside the Station boating limits so as to be more inclusive of the full foraging range of the Adélies during their breeding season. Specifically, we propose to place several APV's at selected sites within 100 km radius of the Adélie breeding sites. This will permit a more definitive evaluation of temporal variability within the foraging region. The APV's will be deployed and serviced from Palmer Station. New microbial studies will be initiated at Palmer Station to investigate the

seasonal cycle of bacteria and organic matter. We anticipate, among all PAL components, 8 - 12 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 8 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 moorings 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.

## **2.6 Core Measurement Methods and QA / QC Procedures.**

Our core methods which are outlined on the PAL website (<http://pal.lternet.edu/biblio/protocols>). Typically our methods follow recognized standard procedures (Knap et al., 1996; Everson 1988; CCAMLR, 1992; Spear et al., 1992). 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. Ideally, the suite of measurement parameters should provide a data base to diagnose, improve and 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. 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. Approximately 10-20% of the samples are collected and analyzed in triplicate to assess and track our analytical precision in sample analysis. The question of measurement accuracy 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, conductivity and acoustics are routinely calibrated. 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.

## **2.7 Regionalization and Cross-site Efforts**

### **2.7.1 British Antarctic Survey (BAS)**

Research on the nearshore marine ecosystem is supervised by PAL co-PI Andrew Clarke of the BAS at Rothera Station on Adelaide I. (Fig. 2.1a). This is a long-term program (at least ten years) of year-round oceanographic monitoring, together with a series of individual autecological

or process studies, focusing on benthic communities. As such it provides valuable complementary work in the southern, continental regime of the WAP.

### 2.7.2 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 region between Livingston and Elephant islands. (Fig. 2.1a). 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 Livingston, King George and Elephant islands. AMLR has also funded research on Adélie penguins at Palmer Station (W. 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. A developing collaboration with V. Siegel is part of the regionalization effort. Several indices of the population dynamics of Antarctic krill from the PAL study area and from the area around Elephant I. will be compared for the years of overlap (1993 to 2001).

### 2.7.3 LTER Cross-site comparison

In Jan 1996, D. Karl received funding from the NSF-DEB to conduct an LTER cross site comparison, "Microbial loop dynamics and regulation of bacterial physiology in subtropical and polar marine habitats." The project is 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. Although Karl has retired from PAL and has been replaced by Ducklow, we seek to continue and build on this effort. Ducklow's graduate student Matthew Church has been comparing *Bacterial* and *Archaeal* ecology at both sites. We also seek to extend our comparisons to the other US JGOFS site at Bermuda, where Ducklow has had long-term collaborations, to the Arctic LTER sites, through collaboration with microbial PI's at Toolik Lake and the temperate coastal regime by working with PI's at the Georgia Coastal sites. By combining studies of microbial carbon utilization and lipid biomarkers we propose to compare the relative reliance of both *Bacteria* and *Archaea* on labile, semilabile and refractory marine and terrestrial DOC. In another comparison study, Vernet will study *in situ* algal mixing rates by measuring physical microstructure in collaboration with S. McIntyre, UCSB. An independent proposal, including cross-site comparison with Toolik Lake, will be submitted in 2002.

### 2.7.4 Southern Ocean GLOBEC

The principal aim of the Global Ocean Ecosystem Dynamics (GLOBEC) Program is understanding the key intermediate links between physical circulation processes and fisheries recruitment, by concentrating primarily on zooplankton population dynamics. The Southern Ocean component of GLOBEC addresses the year-round population dynamics of Antarctic krill and their relations with ice dynamics and other factors. SO-GLOBEC profits from the long-term regional context and rich data sets provided by PAL. Several PAL PI's are involved. Martinson and Smith are studying the physical and optical properties of the sea ice and their relationship to the ecosystem to define the over winter environment of krill. They are also funded to incorporate the radiative transfer model of Perovich (1990, 1993) and optical model of Mobley into Martinson's physical – biogeochemical model. Buoys developed and deployed by this program will provide time series measurements through snow, ice and upper water column, providing a broader continuum to our LTER station data, and providing diagnostics, initial

conditions and a time series test case for evaluating, modifying and improving the model. Vernet will provide water column primary production during fall and winter and study its relationship to sea ice distribution. Ross, Quetin and Garrison (UC Santa Cruz) are investigating larval krill / sea ice interactions, to quantify the role of sea ice microbial communities (SIMCO) in the energetics of larval and juvenile krill, to identify the characteristics of the pack ice habitat influencing growth and ingestion rates, and distribution patterns in krill larvae. Participation in SO-GLOBEC includes an extensive cruise program, which is coordinated with PAL process and annual summer cruises and mooring deployments.

#### 2.7.5 Palmer Landscape Mapping Project

Initiated in 1998 and coordinated by William R. Fraser in collaboration with British Antarctic Survey, the US Geological Survey and the NSF (see Sanchez, 1999), this project used aerial stereo photography and GPS ground-truthing to georeference (1 meter resolution) the islands near Palmer Station where long term seabird research has been undertaken for the past 30 years. The resulting maps and data, which are currently in use to investigate the effects of landscape processes on Adélie penguins, will be made available to the public through an LTER web site link during summer 2002.

#### 2.7.6 Ultraviolet Radiation Effects.

Vernet (SIO) is also funded through the InterAmerican Institute of Global Change Research (IAI) to participate in an interdisciplinary project on the effects of ultraviolet radiation on marine and freshwater communities, with emphasis on regional-scale processes. This project seeks to understand the dynamics of UV stress along a latitudinal gradient and is carrying out experiments from 64S (Jubany and Palmer Stations) to 58 N (Rimouski, Canada).

#### 2.7.7 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 distribution 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 <sup>14</sup>C-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.

#### 2.7.8 Palmer Climate Studies and other LTER workshops.

Palmer has been active in LTER Network climate activities, contributing to the cross-site CLIMDES (<http://www.lternet.edu/documents/Publications/climdes/climdes.html>) and ongoing database (<http://sql.lternet.edu/climdb/climdb.html>) projects. An all-scientists' meeting workshop co-chaired by Greenland and Smith set the stage for a book 'Climate Variability and Ecosystem Response at LTER Sites' with a chapter contributed by PAL (Smith et al., *submitted*). PIs from the PAL LTER co-chaired several workshops at the All Scientists Meeting in Snowbird in August 2000. Robin Ross (PAL), Joel Trexler (Florida Everglades) and others led a workshop on a species interactions. Also our (Ross, Quetin, Vernet) participation in the Network Analysis workshop led to the participation of Quetin, Vernet and Smith in a Network Analysis Workshop in March 2001 that was sponsored by the LTER Network Office.

### 3 Site Management

The PAL LTER site is located on the west side of the Antarctic (Palmer) Peninsula, and encompasses both the immediate coastal region, centered at Palmer Station (64°46 S, 64°04 W) on Anvers Island (Figure 3.1a), and the offshore oceanic region swept annually by the advance and retreat of sea ice (Figure 2.1a, 3.1c). It is subject to intense meteorological forcing (Fig. 3.1b), and sea ice and atmospheric forcing give rise to large interannual variations in primary production (Fig. 3.1d). This variability cascades to all trophic levels. Extreme environmental forcing also creates extreme logistic challenges for conducting research and 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 remain undisturbed by uncontrolled human influences such as tourism. Within the PAL area, visitors are not permitted to land on most islands with nesting seabirds during the breeding season, and the few sites where visitors are permitted (Torgersen Island) are under study for possible adverse impacts. The most current data suggest tourism is having no detectable impacts on seabirds (Fraser & Patterson, 1997; Patterson, 2001; Patterson et al., 2001).

Also of concern is how far from pristine the environment of the WAP area has become. 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 indicate that long-term damage would be minimized (Kennicutt and McDonald 1996). Overall, these authors conclude that the WAP is still relatively pristine. NSF-OPP and PAL are currently supporting a research project assessing the global-scale atmospheric transport and deposition of persistent organic pollutants onto sea ice in the WAP (H. Ducklow and R. Dickhut, VIMS, PI's).

Site management of Palmer Station is carried out by the Raytheon Polar Services Company (RPSC), under contract to the NSF. RPSC controls access by all researchers to the site, and supports all logistic needs including transportation, housing and subsistence, research support, communications and data transmission, safety and security. All researchers are bound by the rigorous regulations of the Antarctic Treaty regarding environmental contamination and sample collection.

The eight PAL PIs (Table 2.2) are the primary governing body of the Project. Issues are decided in the group by majority vote. An Executive Committee (currently Ducklow, Ross, Smith, Vernet) serve as an interface between PAL PI's, NSF and the LTER Network.

Membership will rotate through the whole group on a staggered 3-year cycle, so every PI can serve in the 6-year funding cycle. Formal communication is maintained among PIs by frequent email, biweekly conference calls and two annual meetings. A change in site leadership has been subject of discussion the last two years; new lead PI Hugh Ducklow (VIMS) will be 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. The Virginia Institute of Marine Science (VIMS) will provide a new Single Point of Contact (POC) for PI interaction in coordinating logistic matters with Raytheon. VIMS 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 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 or 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. PAL co-PI's select an advisory Steering Committee whose members who serve for fixed terms (<http://pal.lternet.edu/notes/steering.html>).

Field work at Palmer Station is often the responsibility of experienced 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. Due to the logistic difficulties of travel to the site, limited funding sources and constraints on residence in the Antarctic, it is a great challenge to promote participation by a diversity of students and non-LTER colleagues at our site. PAL has accomplished this aim through participation in programs such as the NSF Teachers Experiencing the Arctic and Antarctica Program and with undergraduate and volunteer opportunities. We are striving to broaden the program through recognition of associates (see included vitae) and through affiliate PI's who write companion proposals for support from NSF-OPP to work at our site.

## 4 Information Management.

Information management (IM) for PAL provides for the long-term storage of Antarctic data and facilitates ecosystem research by supporting data organization and synthesis, data documentation and access, organizational infrastructure and communications in addition to participating in LTER network, national and education partnerships. Information system design follows a decentralized model, with each principal investigator responsible for a subset of core and non-core data. The data and document repository, which facilitates information exchange while maintaining platform independence and low maintenance costs, has been described as effective (site review 1999): "The review team was favorably impressed with the progress made in the area of information management."

Information Management is well integrated at the site (Ross et al., 2000; Smith et al., 1998a, 1998b, 2000, 2001). The Palmer LTER Information Manager coordinates with other principal investigators to manage project data while creating a broad base of partnership and support. The information manager, Karen Baker, a member of the marine bio-optics research team of Raymond C. Smith for twenty years, participates in PI meetings, workshops, and field planning. In recognition of the significant role that IM plays, the information manager has been a member of the site's primary governing body since 1993. The IM position is funded half-time to develop and maintain the central data structure in co-ordination with each of the individual investigators' data analysts who reside at separate institutions. Each research group has a unique computational environment optimized for research within local institutional infrastructure so groups coordinate through development of a robust connectivity. IM supports individual group efforts with specific data manipulation languages (e.g., idl, matlab) recognizing the strengths provided by an enriched set of options for analysis and display.

### 4.1 Information System Overview

Data management has been an integral part of planning for the Palmer LTER since its inception. We benefit from the collective experience of the other LTER sites (Michener and Brunt, 2000; Michener et al., 1998). The Palmer LTER information structure (Baker, 1996; Baker, 1998a), including data, metadata, bibliographic and personnel directories (see figure), is organized within the following conceptual framework:

- acceptance of a diversity of computer platforms and tools
- facilitation of distributed communications
- availability online of data and supplementary information
- extensibility to ensure flexibility to adopt technology changes

The PAL LTER database contains project overview documents as well as metadata in the form of standardized documentation describing the data taken for each field study. Information is maintained in ascii files readily available to all investigators. Quality control for metadata and the data itself is the responsibility of the individual investigator. The central data archive is a backup of each individual investigator's datasets and is itself backed up on a regular schedule.

In order to organize the metadata, a common vocabulary is documented. A study consists of a ship cruise or a season at Palmer Station. Within each study, data sets exist either as part of the predefined core data sets or as part of the non-core-opportunity data sets. The study types and dataset definition list are maintained online (<http://pal.lternet.edu/forms>). Overview information is made available by the information manager for each study: a corelist of measurements, site maps, a participant list, and an eventlog listing chronologically the type and location of measurements made during the study.

Data available online include more than 6000 datasets organized under 250 entries (see table) representing 2 gigabytes of data. The database is updated annually at the end of each field season. Considerable time is dedicated to data review and preparation for database entry thus maintaining compliance with the NSF data policy. Palmer LTER investigators have accounts on a central server giving them direct access to LTER data and documentation in the Palmer LTER central archive. The Palmer LTER group recently updated its data submission and availability policy to be more consistent with strict SOGLOBEC data policies.

#### **4.2 Communication and Information Flow**

Given the geographic distribution of PIs, the development of the internet and the recent increase in reliable network software has played a key role PI communication and interaction. The Palmer LTER recently created a virtual host (Baker, 2001) establishing a network identity independent of geography. Further, technological advances have enabled use of at-a-distance communications such as Microsoft Netmeeting, VNC and Dameware. Connectivity results in a transfer of both computer knowledge and computer resources which contributes to integrating the group as well as the data. Recently, web based document sharing has contributed to the success of workshops and multi-author publications (i.e. Smith et al., 1999). The personnel directory, group calendar, meeting schedule, and field documents are maintained online in addition to documents such as proposals, abstracts, meeting notes, background materials and species lists developed from the National Oceanic Data Center's comprehensive taxonomic list (<http://pal.lternet.edu/projects/biodiversity>). The information manager contributes to information synthesis and presentation (Smith et al., 1995, 1998, 2000; Stammerjohn et al., 1998; Baker et al., 1996a) and serves as historian through creation and maintenance of the bibliography, a visions timeline and milestones. To track file input to the site database, overview tables are created routinely summarizing data policy compliance.

#### **4.3 Field Support and Data**

Year round weather data collection, biomass monitoring and field updates continue along with evaluation of new methods or instrumentation. Beta testing of Turner Design fluorometric solid standards resulted in an improved biomass analysis procedure. Field support for the annual cruises, special cruises (i.e. Sea ice Jun99 and Sep01) and station work includes involvement with logistics, field procedures and summary (Baker et al., 1996b, 1997, 1998; Ross and Baker 1997; Vernet and Baker 1996; Smith et al., 1996a). Improved satellite communication with Palmer station has provided field internet connectivity permitting improved logistic support, data analysis and data exchange using real-time FTP for data screening and archive.

There are periodic reviews of selected datasets such as weather, biomass and satellite sea ice with past season efforts synthesized for publication (Smith et al., 1998a; Baker 1996; Baker 1998; Stammerjohn et al., 1997). Historical and long-term weather data have been coordinated by the information manager and are available publicly. The air temperature records have been put into context by comparison with other historical records (Smith et al., 1996a; Baker and Stammerjohn, 1995; Smith et al., 1995). Data sets from past Antarctic projects in the area such as BIOMASS and RACER and framework data such as coastline and bottom topography have been investigated and made available.

Site support includes membership on committees such as the McMurdo Users Advisory Group, the Palmer Area Users Group, and the Antarctic Communications and Computers Working Group. Co-ordination is ongoing with Raytheon for both ship and station equipment and computer needs. Attendance at the Automatic Weather Station, Digital Library and San Diego Supercomputer Center meetings provides important background information.

#### **4.4 Computational Infrastructure**

Computational infrastructure for the Palmer LTER is provided by the Institute for Computational Earth System Science (ICESS). PAL LTER documentation and data storage are organized through an electronic hub at ICESS (<http://www.icess.ucsb.edu/lter>). There have been significant recent upgrades: Windows NT PC networked workstations with supported transition upgrades (i.e. Windows XP); installation of an LTER NT database platform within ICESS infrastructure; file server upgrades addressing both fiber optic channel and scusi disk storage as part of a three-generational plan supporting both legacy and alternate systems; purchase of large format plotter; apache webserver reconfiguration and upgrades for FTP and color printer services. Palmer LTER available storage has increased from 1 Gigabyte in 1996 to 50 Gigabytes today. Storage of large datasets such as satellite data is available within the 2.5TB ICESS system. The ICESS system analysts, available on an as-needed basis, provide networking, software, hardware and database planning expertise on state-of-the-art computer technology.

#### **4.5 LTER Network Participation**

The LTER Palmer information manager has been an active part of the LTER community of information managers attending annual information manager meetings since 1992 as well as active in meetings such as the recent LTER All-Scientist Meeting and research projects (Baker et al., 1998, Henshaw et al., 1998, Porter et al., 1996; Wasser and Baker, 1998). Recognizing the value of LTER network IM participation, the LTER Palmer IM has been a member of the LTER Network IM Executive Committee since 1995 taking part in cross-site activities including coordinating meetings and conducting surveys. Baker led a multi-site team to describe the LTER Network Information System in a manuscript (Baker et al., 2000a) and poster "LTER IM: Paradigm Shift or Paradigm Stretch?" (Baker et al., 2000b). A 'Site System' survey, developed by the Palmer IM at the 1999 LTER IM meeting is implemented in support of the ongoing LTER Network Knowledge and Distributed Intelligence activities. A network 'Site Capabilities' survey gathers hardware and software information across LTER sites. Ongoing LTER activities include the all-site bibliography, the climate committee and the site description directory. Work to coordinate IM within the international arena began this year (Baker, 2001).

Development of synergistic projects is one element of the site IM strategy to insure experience with contemporary tools. Three small LTER Network Office internships in the past funding cycle provided valuable training for K. Baker as well as the opportunity to interface with the network office on projects such as the site description directory, network forms, web design, and proposal discussions. As a result of this collaboration, the LTER IM Newsletter DataBits, was re-designed and re-initiated in Spring 1999. A rotating editorship was established to provide a mechanism to engage information managers in network participation (Baker and Brunt, 1999). An ongoing grant with the LTER Network Office focuses on further development of a site description directory, a grant with the San Diego supercomputer center explores organizational informatics with a focus on bibliographic systems such as the CERN Document Management system and a grant with the UCSD communications department supports a post doctoral researcher exploring effective approaches to metadata for an LTER site.

## **5 Outreach**

### **5.1 Human Resources.**

Volunteers, undergraduates and graduate students play an important role in our field and laboratory work. 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 expertise. This mix of mid-career adults with students provides 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 a half dozen volunteers, whose only cost to the program are travel, plus physical and dental exams required of all Antarctic workers.

More than 60 undergraduates have been involved in the Palmer LTER projects since the program's inception. Half are supported through NSF's Research Experiences for Undergraduates (REU). PAL PIs serve as advisors for REU students who join research teams in Antarctica both onboard ship and at Palmer Station and stateside in laboratories. The PAL LTER REU student experiences have included (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.

Graduate students are an integral part of our program. In the first funding period (1990-1996) there were 3 Masters and 5 PhD awards for work related to the Palmer LTER; in the second (1996-2002) there have been 4 Masters and 7 PhD awards with eight ongoing students (see Table 5.1).

### **5.2 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. William R. Fraser is the United States representative to SCAR through participation in the Bird Biology Subcommittee. Participation in CCAMLR occurs primarily through the CCAMLR Ecosystem Monitoring Program (CEMP) which seeks annual data on fisheries-related entanglement, marine debris and the ecology of Adélie 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 has provided U.S. funding and other support for collection, analysis and preparation of annual reports (Fraser et al., 1988-1999 at <http://pal.lternet.edu/biblio>).

### **5.3 Education**

Outreach to the public takes place regularly through principal investigator communications (Vernet, 2000; Fraser, 1998; Ross, 1999; Smith et al., 1998a; Stammerjohn et al., 1997), teacher interactions (Dawson, 1999, 2000; Dawson and Baker 1999; Wallace 1999), reporter collaborations (Woodard, 1998, 2000; Kaiser, 1997; Petit, 2000; Culver, 1999) as well as through cooperation with sponsored Antarctic projects (Haines-Stiles et al., 1996; Live from Antarctica2, 1997) and national programs such as "Blue Ice" where W. Fraser teaches a class on

“The Ecology of Antarctica” to several hundred K-12 students worldwide via Internet from Palmer Station. All PIs have been involved in presenting lectures and slide shows in local schools and community groups.

Outreach and education efforts in partnership with information management have proven successful (site review, 1999): "The K-12 and public outreach activities are excellent and should be continued and expanded". Education products to date include publication of a Palmer LTER site brochure, a site CD (Smith et al., 2000), an education forum proceedings (Baker et al., 1999) and an outreach trunk. Development of further outreach products in a variety of multimedia formats is ongoing.

Attendance at two LTER Education Committee workshops and successful application for NSF/DEB Schoolyard LTER funds since 1999 set the stage for education efforts at the Palmer LTER research site. A subsequent Palmer LTER Education Outreach Forum (Baker et al., 1999) in conjunction with the National Center for Ecosystem Analysis and Synthesis (NCEAS) brought together national and local representatives (scientists, educators, teachers and information manager/technologists) to explore options for a sustainable long-term educational program. This forum developed prototypes for Education Outreach Goals and Guidelines on Creating a Long-Term Perspective in Classroom Science. Cooperation with NCEAS continues with focus on education metadata module evaluation.

Partnerships play an important role in creating a sustainable program. Palmer is building on previous years' coordination with the LTER Network Schoolyard program and participation in the national Teacher's Experiencing the Arctic and Antarctica (TEA) program. Palmer LTER is active both in facilitating schoolyard education efforts in partnership with the information management community (Baker, 1999) as well as the LTER network community (Boone et al., 2001). Palmer LTER contributed at the LTER All-Scientist Meeting (Baker et al., 2000c) and co-chaired a workshop "Learning from LTER Data in K-12 Classrooms". Schoolyard LTER (SLTER) education workshops culminated in an SLTER meeting (Dec00) in San Diego with logistics by Karen Baker in collaboration with the San Diego Supercomputer Center (SDSC). A poster "Long-Term Ecological Research Schoolyard Education Partners" was presented at a subsequent SDSC National Partnership for Advanced Computational Infrastructure (NPACI) meeting (Baker et al., 2001) and the Ecological Society of America (Sprott et al., 2001).

Active participation in the national TEA program continues. Teachers have been recruited and sponsored over the last years (summer 1998, 2000, 2002 and fall 2001) as part of our Antarctic field team. Palmer LTER TEA internships have been conducted with TEA participants in order to expand the opportunity for researcher-teacher interface beyond that funded by the TEA program itself. Note, Karen Baker continues as a TEA Advisory Board Member.

Developing efforts exist in several arenas: interface with the national program to place a Scout in the Antarctic each year began this year with the internship of eagle scout Tim Brox and web site hosting (<http://pal.lternet.edu/scoutonice>); collaborations with UCSD Academic Connections providing summer science classes for high school students; interface with the Digital Library for Earth System Education (DLESE) program building a community based dataset catalog with appropriate metadata.

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**Table 1.1. LTER Annual Cruise Core Data Online (Dec01)**

	93jan	94jan	95jan	96jan	97jan	98jan	99jan
<b>OVERVIEW</b>							
report	x	x	x	x	x	x	x
participants	x	x	x	x	x	x	x
eventlog	x	x	x	x	x	x	x
cruisemap	x	x	x	x	x	x	x
<b>ZOOPLANKTON</b>							
bioacoustics	x	x	x	x	x	x	x
trawl2m	x	x	-*	-	x	na	x
trawlgen	x	x	x	x	x	x	x
krillgrowth	x	x	x	x	x	x	x
spf	x	x	x	x	x	x	x
<b>PHYTOPLANKTON</b>							
chn	x	x	x	x	x	x	x
nutrientsdi	x	x	x	x	x	x	x
pigmhplc	x	x	x	x	x	x	x
prprodpi	x	x	na	x	na	na	na
prprodsis	na	na	x	x	x	x	x
<b>MICROBIAL</b>							
nutsdo	na	d	d	d	d	x	d
carbon	x	x	x	x	x	x	x
leucine	x	x	x	x	x	x	x
oxygen	x	x	x	x	x	x	x
h2o2	x	x	x	x	x	x	x
enzyme	-	x	x	-	x	x	x
sedelements	-	x	x	x	x	x	x
lps	x	x	x	x	x	x	x
<b>BIO-OPTICS</b>							
bopsts	x	x	x	x	x	na	na
bopsopthoon	x	x	x	x	x	na	na
bopsoxy	x	x	x	x	x	na	na
chl	x	x	x	x	x	x	x
<b>MODELING</b>							
ctd	na	na	na	x	x	x	x
<b>BIRDS</b>							
brcensus	x	x	x	x	x	x	x
<b>WHERE</b>							
na=not applicable							
d=derived data, in progress, depends upon synthesis of multiple datasets (ie inorg nuts)							
nutsdo will occasionally be posted but depend on qa/qc and inorganic nuts							
x=data available							
93mar-chn-analysis transferred from phyto to management (to be completed but priority low)							
95jan-trawl2m wet weight/total length relationship continues but length frequency dropped							
<b>NOTES</b>							
All measurements are discrete unless preceeded by 'bops' or 'ctd'							
carbon=dic/alk							
nutrientsdi-inorganic nutrients, ie nitrate,silicate							
nutrientsdo-dissolved organic nutrients carbon DOC, nitrogen DON,phosphorus DOP							
chn-particulate organic nutrients carbon POC and nitrogen PON							

**Table 1.2. LTER Season Core Data Online (Dec01)**

	9192	9293	9394	9495	9596	9697	9798	9899
<b>OVERVIEW</b>								
report	x	x	x	x	x	x	x	d
participants	x	x	x	x	x	x	x	x
eventlog	x	x	x	x	x	x	x	x
weather	x	x	x	x	x	x	x	x
<b>BIRDS</b>								
adforage	x	x	x	x	x	x	x	x
adtelem	x	x	x	x	x	x	x	x
adbreed	x	x	x	x	x	x	x	x
addemog	x	x	x	x	x	x	x	x
<b>ZOOPLANKTON</b>								
bioacoustics	x	x	x	x	x	x	x	x
krillgrowth	x	x	x	x	x	x	x	x
zodtrawl	x	x	x	x	x	x	x	x
<b>PHYTOPLANKTON</b>								
chn	x	x	x	x	x	x	x	x
nutrientsdi	x	x	x	x	x	x	x	x
pigmhplc	x	x	x	x	x	x	x	x
prprodpi	x	x	x	-	x	na	na	na
prprodsis	na	na	na	x	x	x	x	x
<b>BIO OPTICS</b>								
chl	x	x	x	x	x	x	x	x
ctdts	na	x	x	x	x	x	x	d
<b>SEDIMENT TRAPS</b>								
nutrientspo	na	-	-	-	-	-	-	-
sedbiomass	na	x	x	x	x	-	-	-
	9192	9293	9394	9495	9596	9697	9798	9899
<b>WHERE</b>								
na = not applicable								
x = data available								
d = derived, in progress								
<b>NOTE</b>								
adforage=krill,diet,prey,fish,time								
krillgrowth=igr								
nutrientsdi-dissolved inorganic nutrients, ie nitrate,silicate								
nutrientspo-particulate organic carbon, nitrogen, phosphorus, silica								
chn-particulate organic nutrients carbon POC and nitrogen PON								
sedbiomass-total dry weight								
bopsts-temperature,salinity from profiling CTD								

**Table 2.1.** Palmer LTER Objectives.

- 
- (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.
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**Table 2.2.** PAL components and linkage to LTER core research areas<sup>1</sup>.

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<b>Component (PI)</b>	<b>Primary Core areas (secondary areas)</b>
Physical oceanography, modeling (Martinson)	C, D (A, B)
Bio-Optics, remote sensing and sea ice (Smith)	A, B, E (D)
Phytoplankton ecology (Vernet)	A, B (C, D)
Zooplankton & micronekton ecology (Ross & Quetin)	B (A, C, E)
Apex predators (Fraser)	B, E
Microbes & biogeochemistry (Ducklow)	B, C (D, E)
Benthos and Rothera Station (A. Clarke, BAS)	B (D, E)
Data management (Baker)	(A-E)

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<sup>1</sup> **Core areas:** A, Pattern and control of primary production; B, Spatial and temporal distribution of populations selected to represent trophic structures; C, Pattern and control of organic matter accumulation and decomposition in surface layers and sediments; D, Patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters; E, Patterns and frequency of disturbances

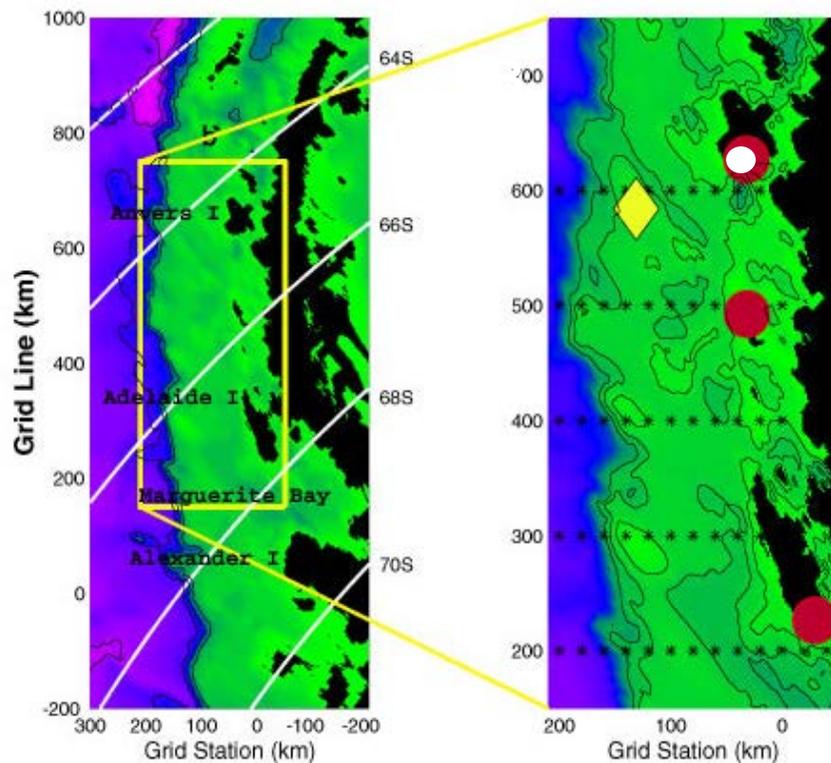
**Table 2.3. Timeline of field studies.** Past and proposed LTER cruise schedule (indicated by month and year) and field seasons at Palmer Station (indicated by x's). January cruises are to study physical and biological parameters associated with seabird breeding season. Nov91, Nov92, Mar93, Aug93 are special process cruises to study ecosystem seasonality. Jun99 and Sep01 are special process cruises focused on sea ice studies. Cruises extending several weeks beyond one month are indicated by '•'. The 'T' are short December cruises to replace/turn around sediment traps. The 'I' and 'G' are related cruises (Icecolors and GLOBEC).

Field Season	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
<b>LTER CYCLE 1</b>												
90/91	-	-	I	•	•	-	-	-	-	-	-	-
91/92	-	-	-	x	Nov-91	x	x	x	-	-	-	-
92/93	-	-	-	x	Nov-92	x	Jan-93	x	Mar-93/T	•	•	-
93/94	-	Aug-93	•	I	•	T	Jan-94/T	x	x	-	-	-
94/95	-	-	-	x	x	Dec-95	Jan-95	x	-	-	-	-
95/96	-	-	-	x	x	x	Jan-96/T	x	x	-	-	-
<b>LTER CYCLE 2</b>												
96/97	-	-	-	-	x	T	Jan-97	x	x	-	-	-
97/98	-	-	-	-	x	x	Jan-98/T	x	x	-	-	-
98/99	-	-	-	x	x	x	Jan-99/T	x	x	-	-	Jun-99
99/00	•	-	-	-	x	x	Jan-00	x	x	-	-	-
00/01	-	-	-	-	x	x	Jan-01/T	x	x	G1	•	•
01/02	G2	•	Sep-01/T	•	x	x	Jan-02	x	x	G3	•	-
<b>LTER CYCLE 3</b>												
02/03	G4	•	•	-	x	x	Jan-03	x	x	-	-	-
03/04	-	-	-	-	Nov-93	•	Jan-04	x	x	-	-	-
04/05	-	-	-	-	x	x	Jan-05	x	x	-	-	-
05/06	-	-	-	-	x	x	Jan-06	x	x	-	-	-
06/07	-	-	-	-	x	x	Jan-07	x	x	-	-	-
07/08	-	-	-	-	x	x	Jan-08	x	x	-	-	-

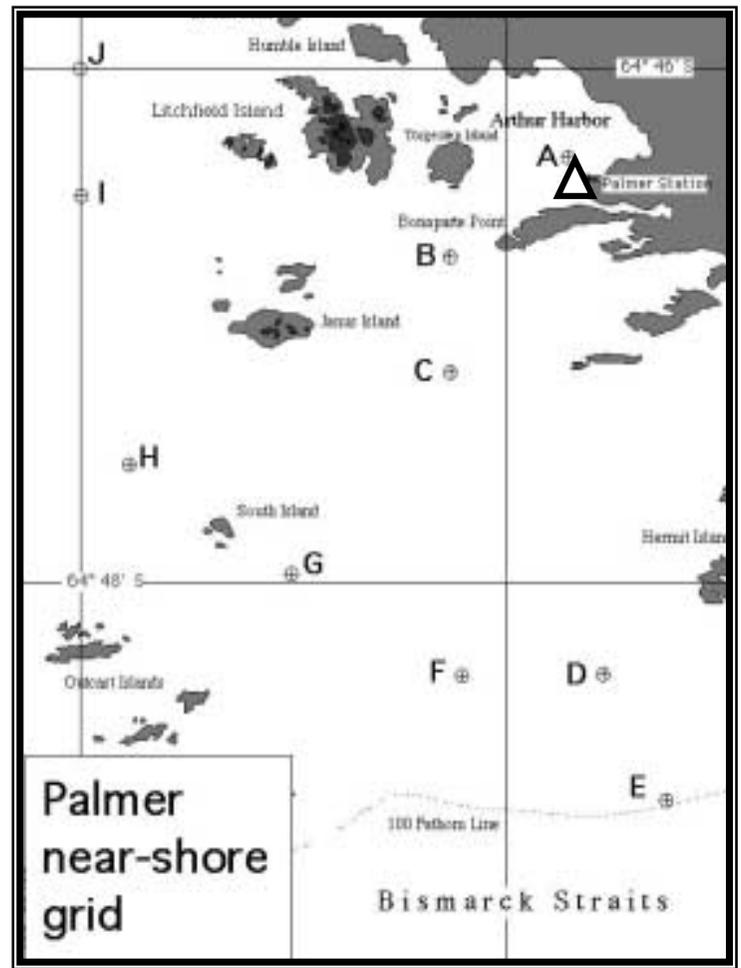
<b>Table 2.4.</b> Time budget for summer grid cruises.		
<b>Science Operations</b>	<b>Explanation</b>	<b>Time (30 d cruise)<sup>1</sup></b>
		<b>----- days -----</b>
On- and offloading at Palmer Station	1 day ea before and after cruise	2
Core Grid (200.000-600.200 lines <sup>2</sup> )	47 stations @ 4 stations/day @ 4 hr/station and transit time	12
Sediment trap re-deploy		1
Outer Grid Stations with transit (500.220, 500.240, 600.220, 600.240)	4 stations @ 6 hr/station and transit time	1.5
Inner Marguerite Bay Stations (200.-20 to 200.-80)	4 stations @ 4 h/station and transit time	1
Inshore Stations (Lemaire and Grandidier Channels, Crystal Sound)	2 d each at N and S inside	4
Picket lines (bird obs)		2
High density prey-predator survey	2 grids @ 1 day/grid	2
Avian Island bird census, prey sampling, Rothera collaboration		2
A-E stations at Palmer	As above	2
Contingency		0.5
<b>Total science</b>		<b>30</b>

<sup>1</sup>30 days of “science time” not including transits between Punta Arenas, Chile and Palmer Station. The transits add about 8 days to the total cruise time.

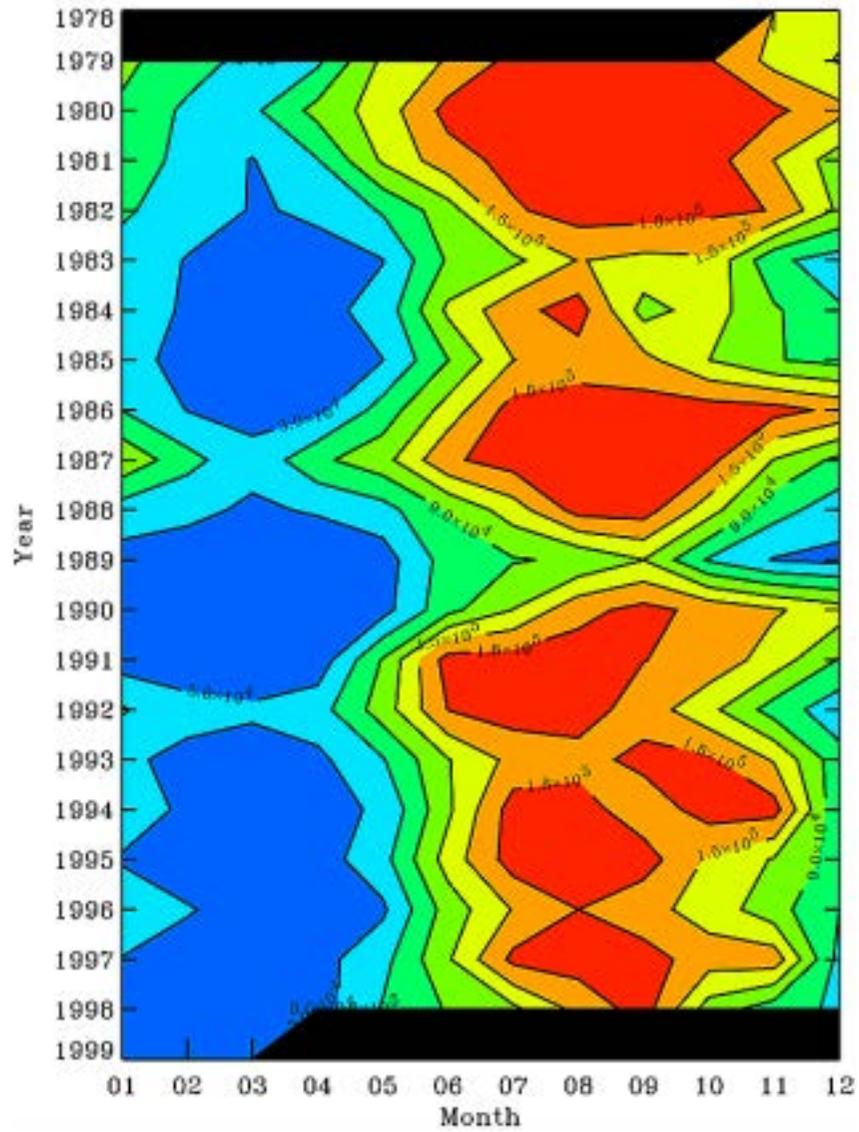
<sup>2</sup> See Figure 2.1a.



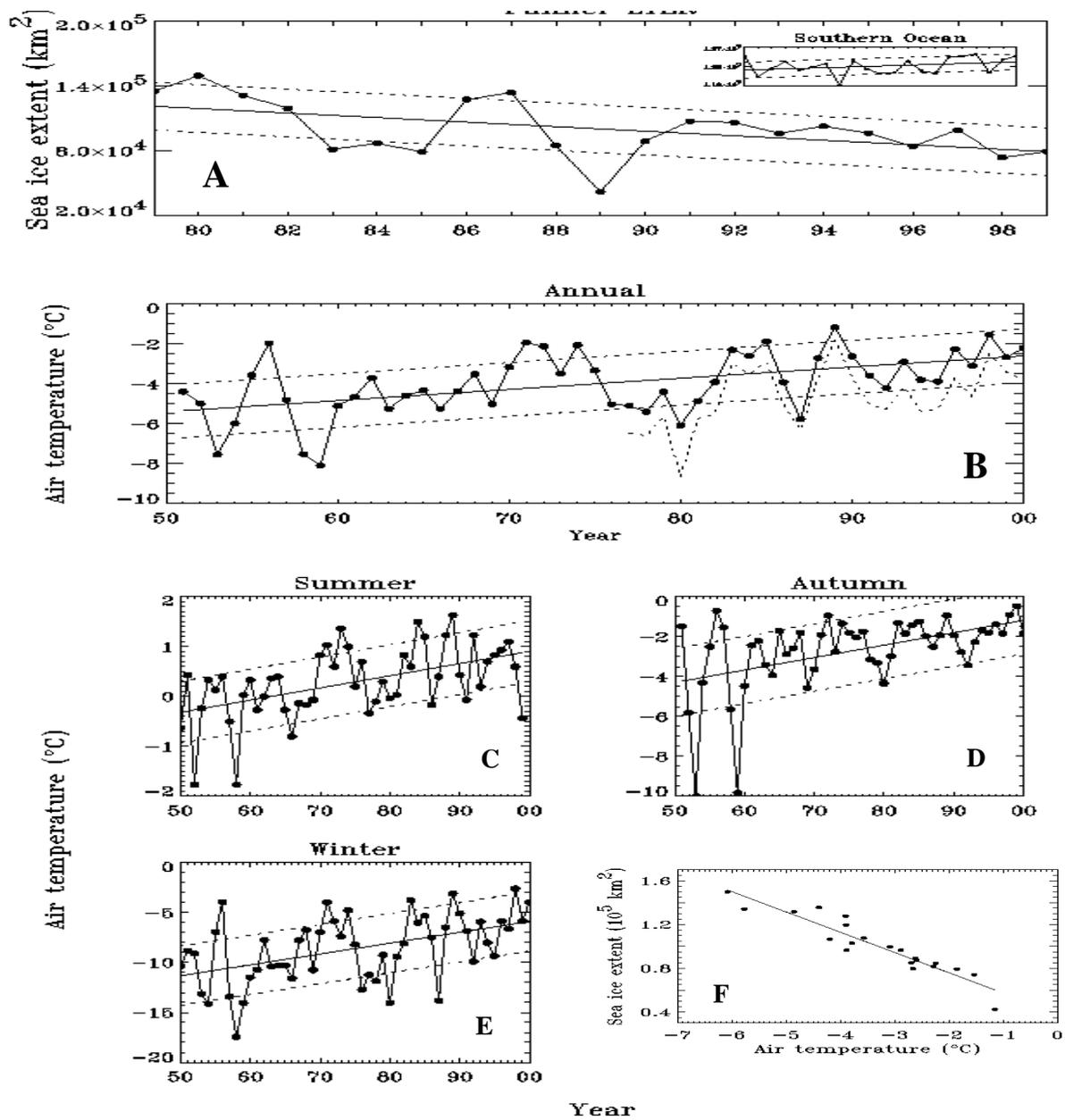
**Figure 2.1a.** A: Topographic map of WAP region with 1000 m depth contours (black lines) and latitude (white). B: detailed map with 250, 500, 750 m contours (black) and Adélie penguin colonies (red circles). The diamond is the sediment trap mooring. The small white circle in the red circle is Palmer Station on Anvers Island.



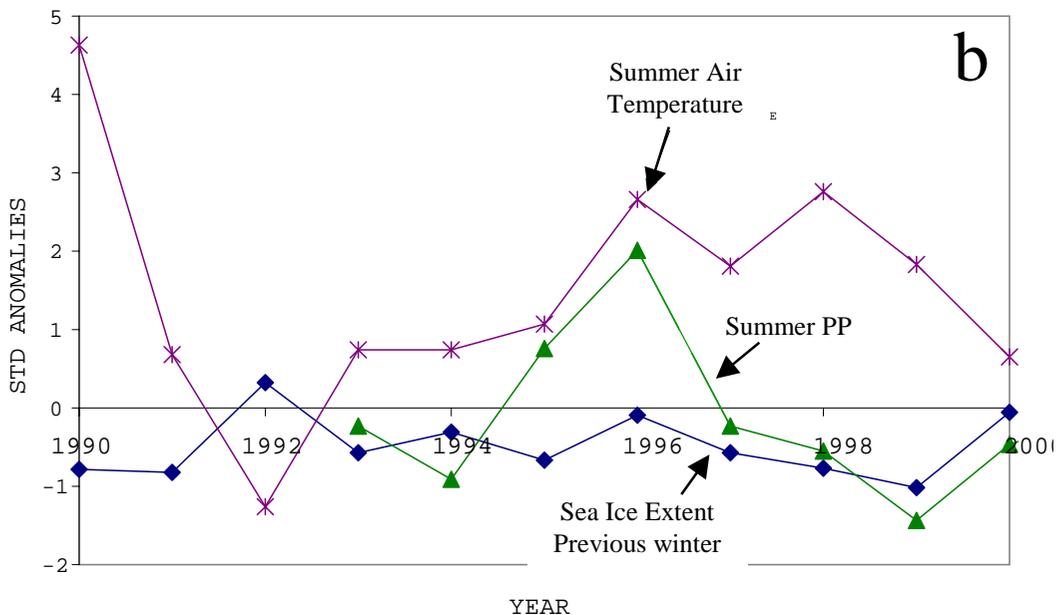
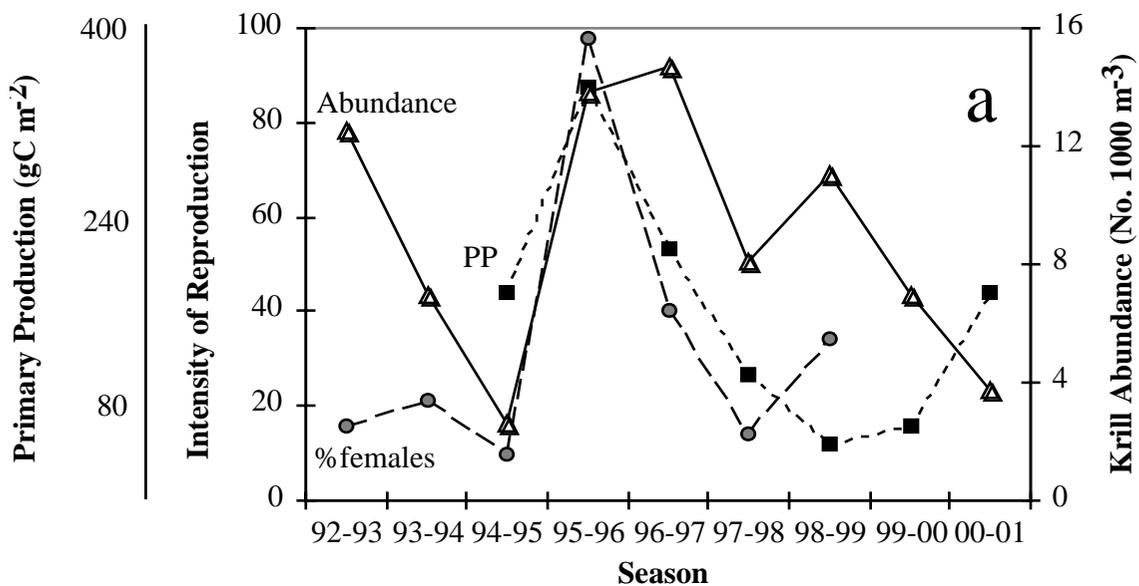
**Fig. 2.1b.** Palmer Station on Anvers I, Antarctica, (white triangle) showing the local, fine-scale sampling stations employed for biweekly seasonal sampling. See also Fig. 4.1



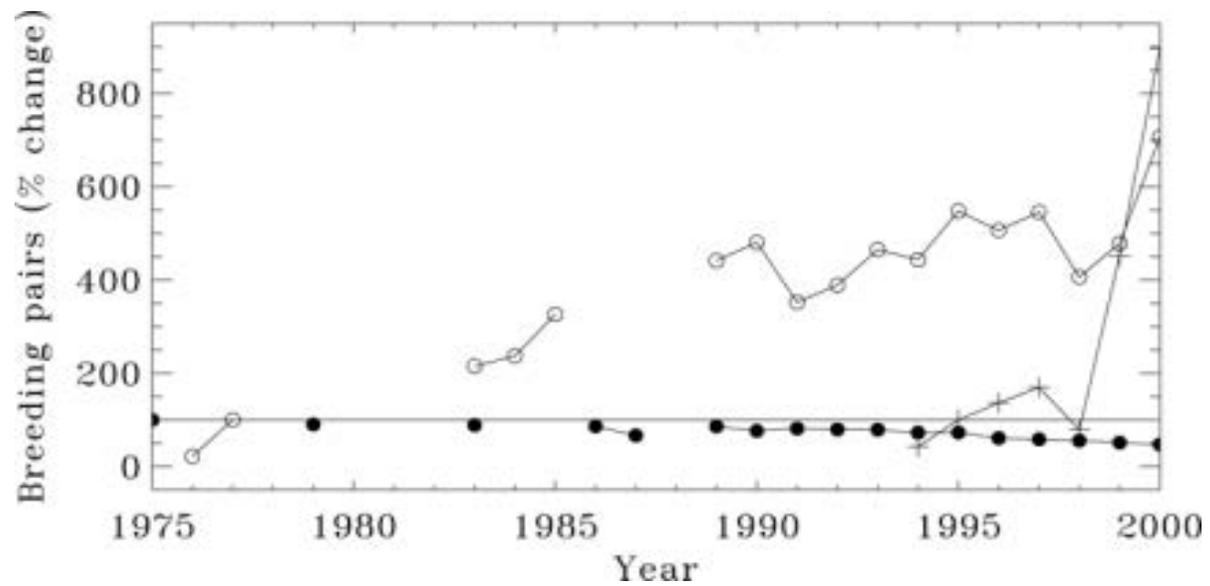
**Figure 2.2a.** Interannual variations in monthly sea ice extent in the PAL region. Note the difference in winter ice extent between the 70's-80's and 90's (decade of PAL observations).



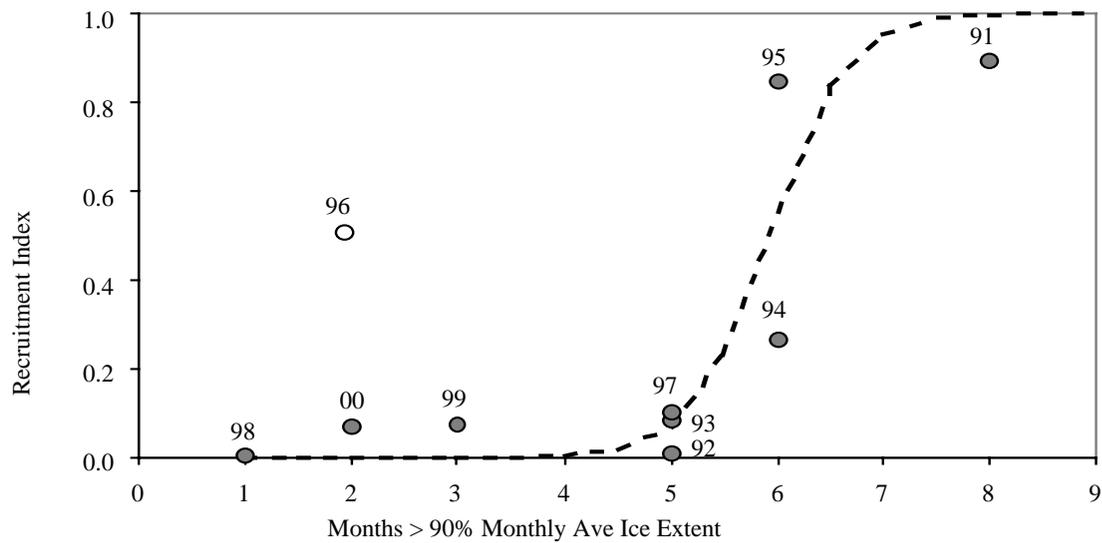
**Figure 2.2b.** **A:** Sea ice extent, **B:** annual and **C-E,** seasonal air temperature trends in the West Antarctic Peninsula. **F:** negative correlation between temperature and sea ice extent (Smith & Stammerjohn, 2000).



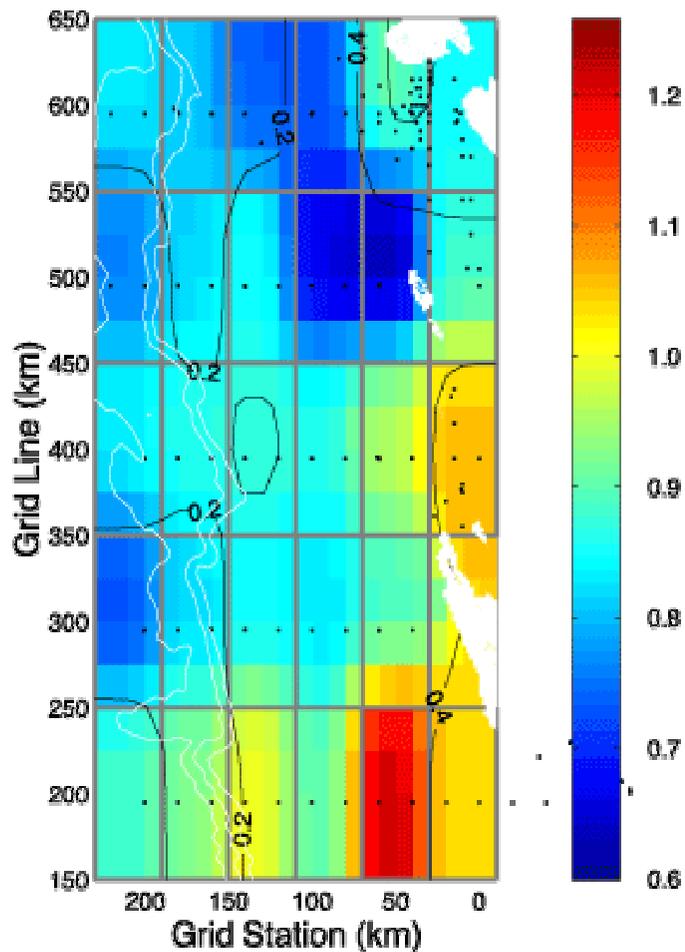
**Figure 2.3a.** Interannual variations in mean annual primary production, intensity of krill reproduction (% of females reproducing based on ovarian analysis) and abundance in Antarctic krill over the last decade. **b.** Interannual variations in mean annual primary production, sea ice extent and air temperature (as standard anomalies to long term mean).



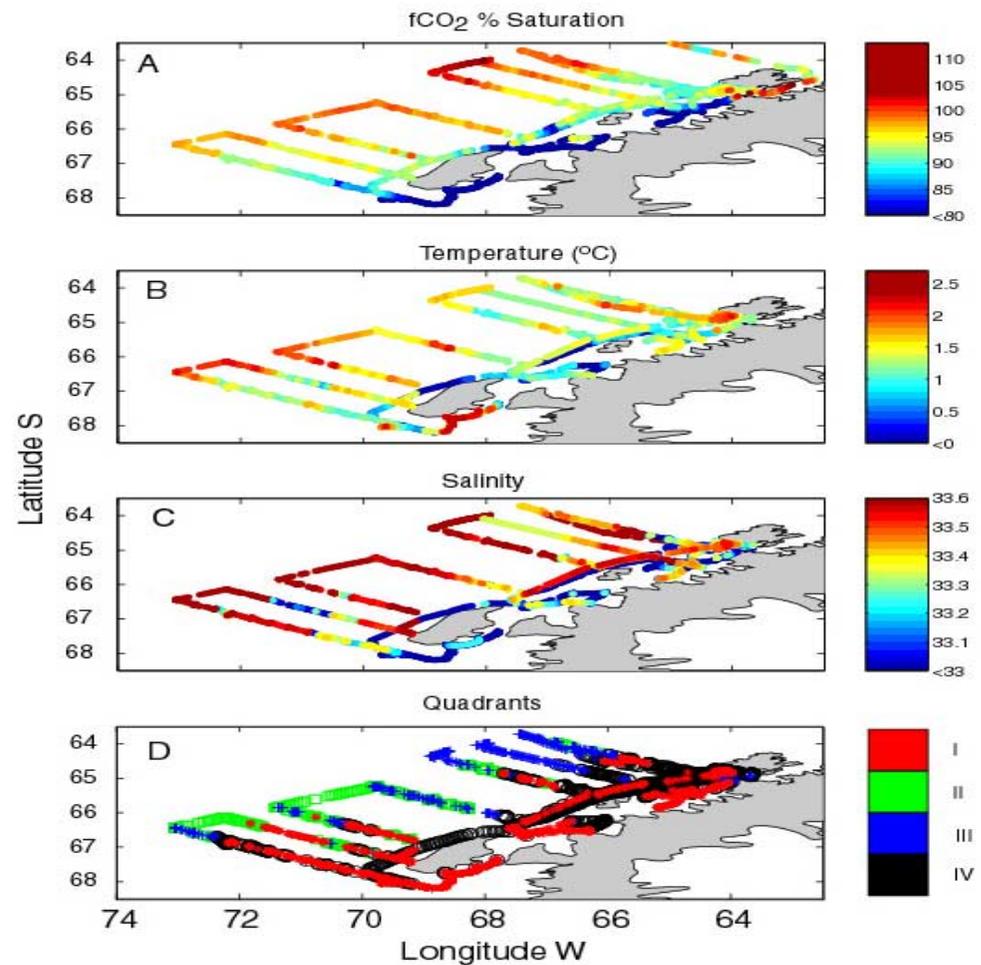
**Figure 2.4.** Changes in penguin breeding pairs in WAP region. Closed circles: Adélie. Open circles, Chinstrap penguins; crosses, Gentoo.



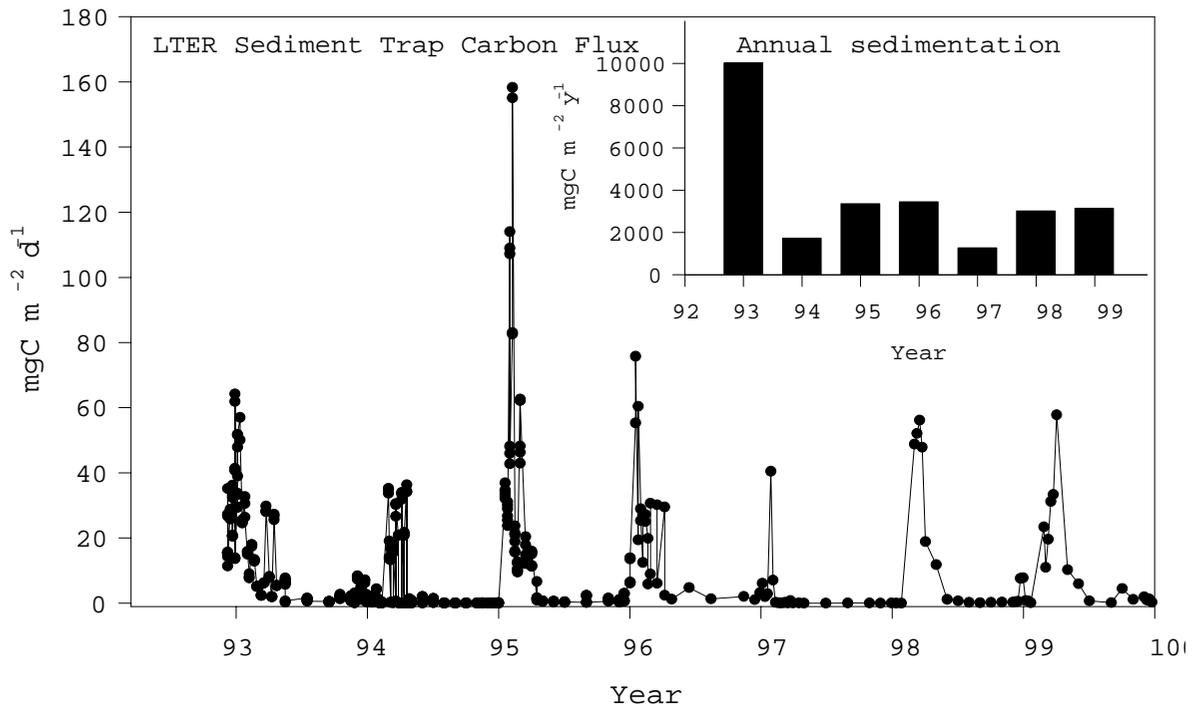
**Figure 2.5.** The krill recruitment index, plotted against the number of months between Apr and Dec when the sea ice extent for each month is +/- 10% of the 22-yr mean for that month. Symbols show year classes. The line is a sigmoidal response curve,  $r^2 = 0.88$ . The strong '96 year class was a consequence of a high % females reproducing.



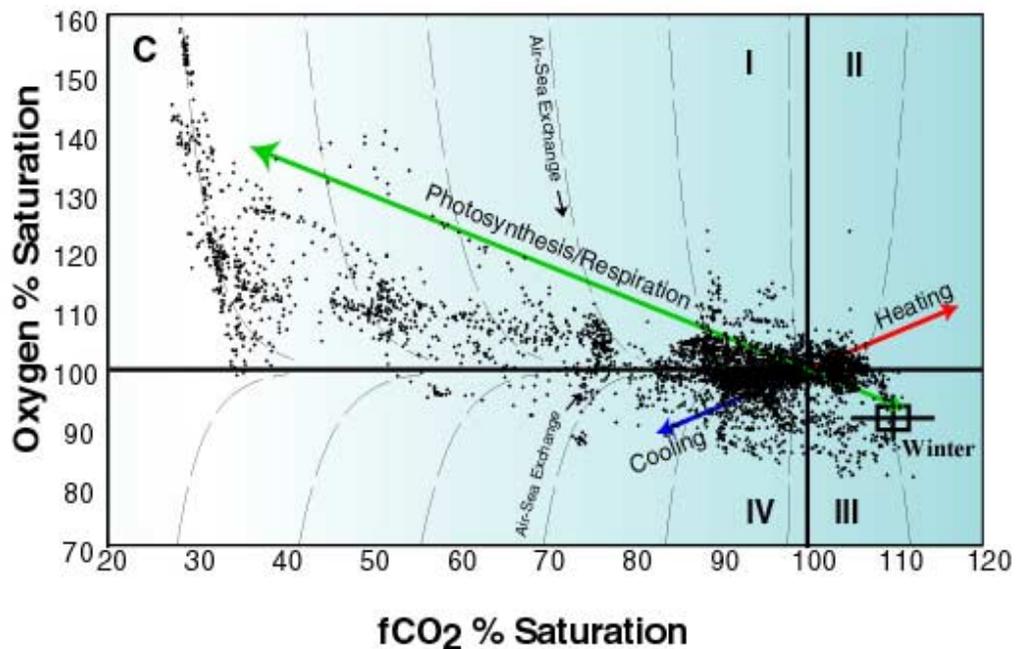
**Figure 2.6** Average distribution (climatology, color) and st. dev. (black contour lines) of diatom abundance, from fucoxanthin, a characteristic carotenoid pigment used as a biomarker, within the PAL grid.



**Fig 2.7** – Alongtrack, underway measurements of A: fCO<sub>2</sub> saturation, B: temperature, C: salinity and D: locations in each phase quadrant of gas solubility diagram (see Fig. 2.9), within PAL grid.

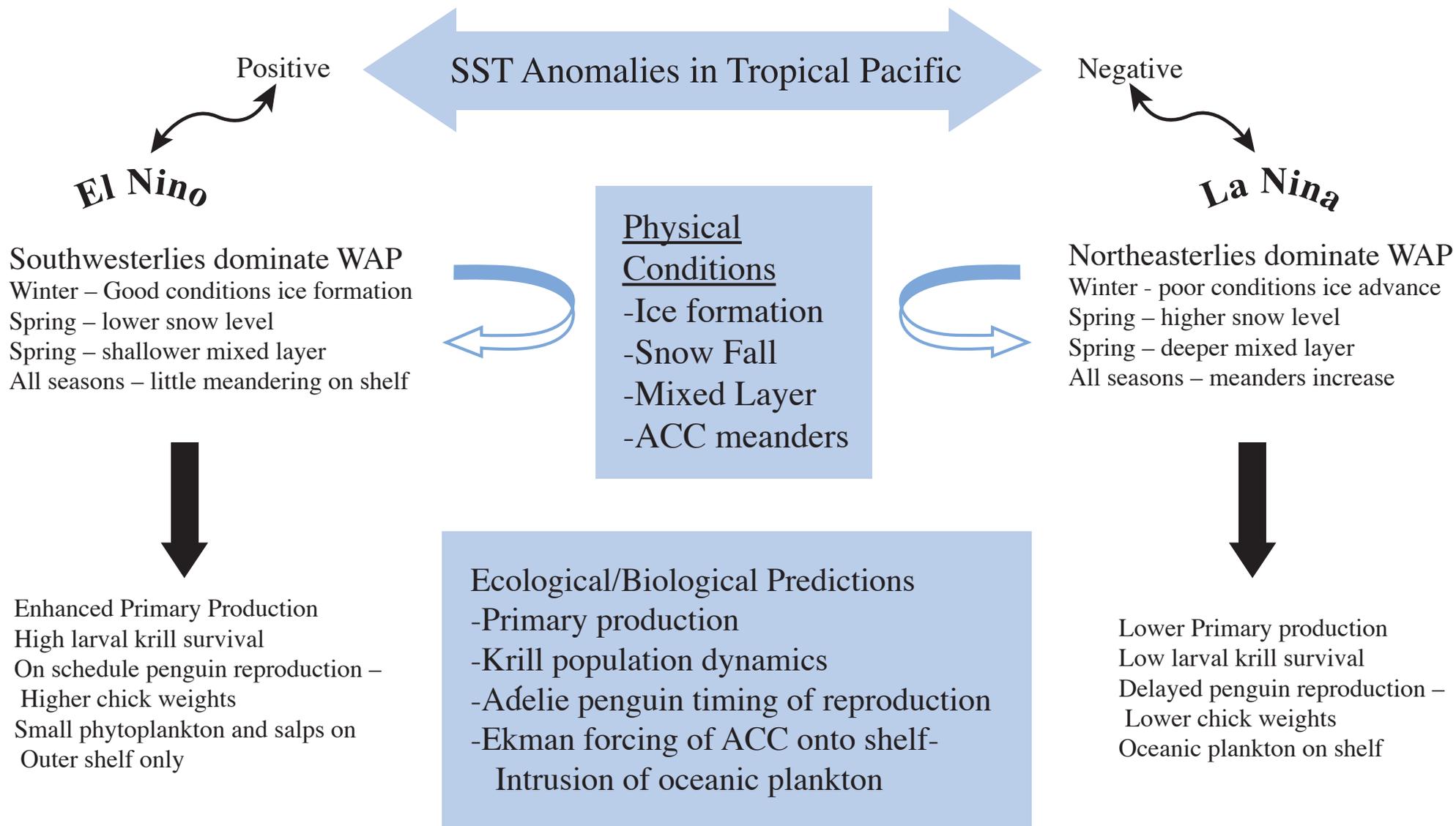


**Fig 2.8** – Annual cycle and interannual variability of particle flux determined by PAL moored sediment trap (see Fig. 2.1a).

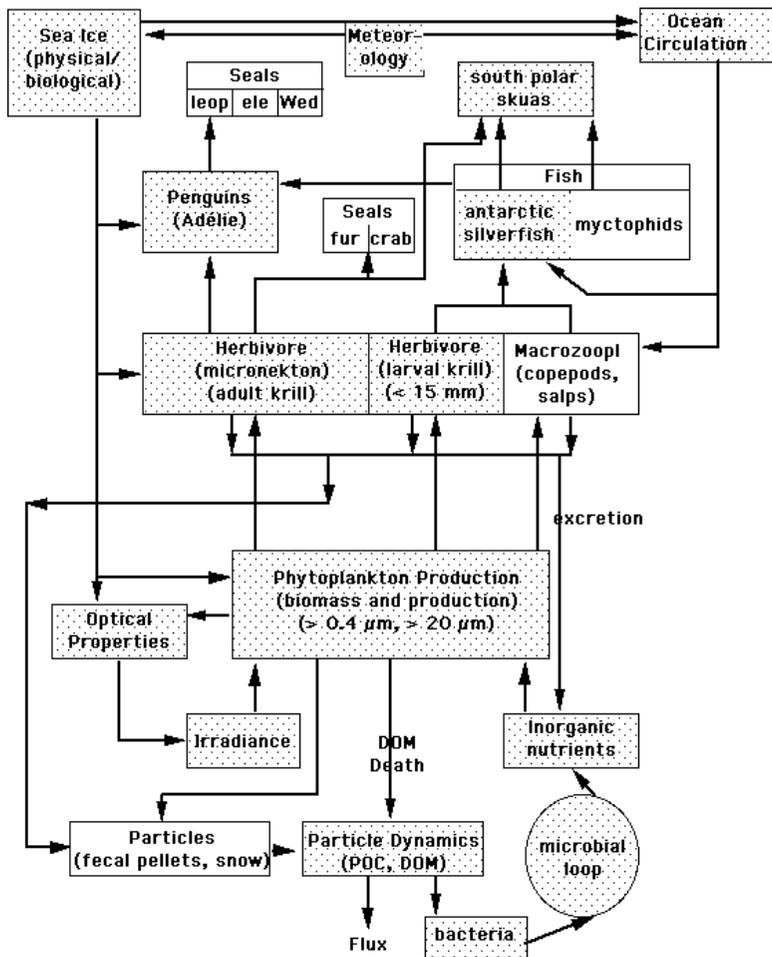


**Fig 2.9** – Dissolved oxygen and CO<sub>2</sub> saturation in PAL region, and physical and biological processes producing patterns of differential saturation. Quadrants are mapped in space in Fig. 2.7d.

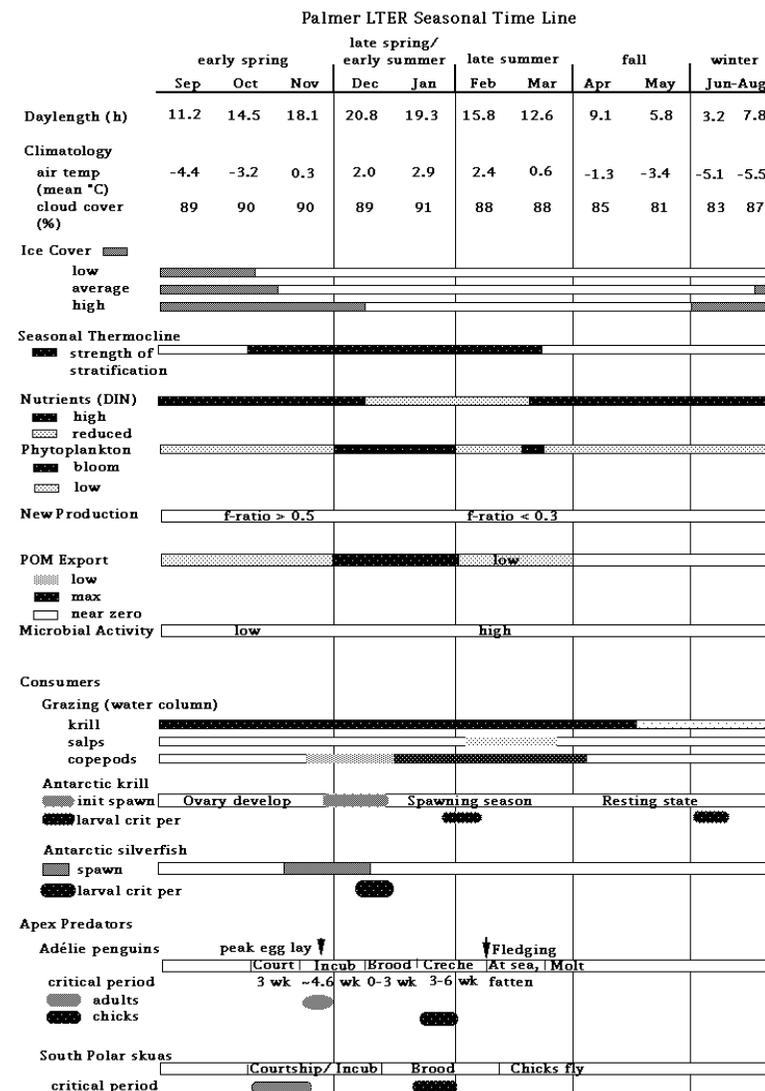
# Teleconnections to LTER study region



**Fig 2.10** – Conceptual model linking ENSO-frequency variability in the tropical Pacific with Sea Ice and related ecological cycles in the Antarctic marine ecosystem.



**Fig 2.11** – The marine foodweb studied in PAL. Shaded boxes highlight the compartments studied currently.



**Fig 2.12** – Seasonal timeline of key processes and sampling activity in PAL.

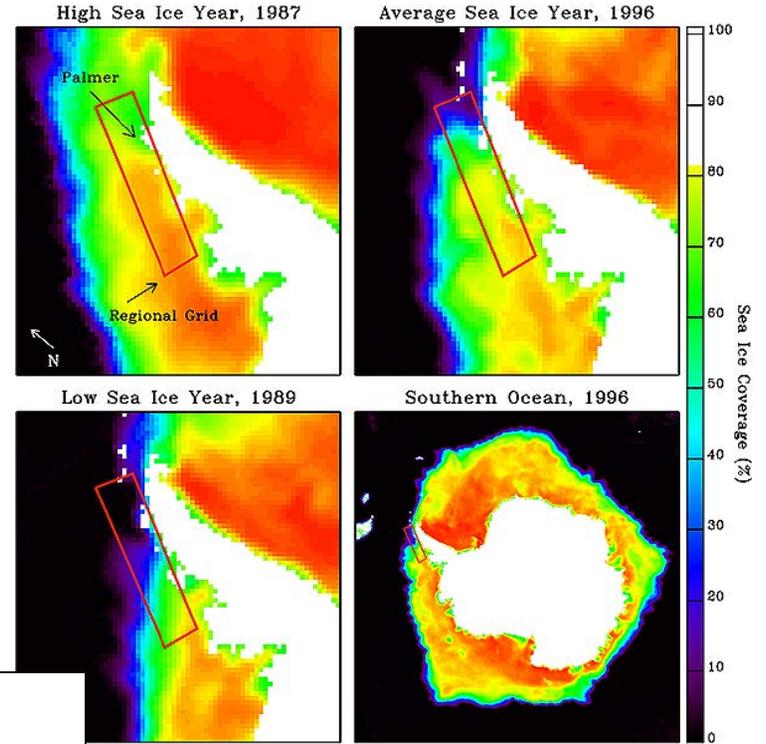
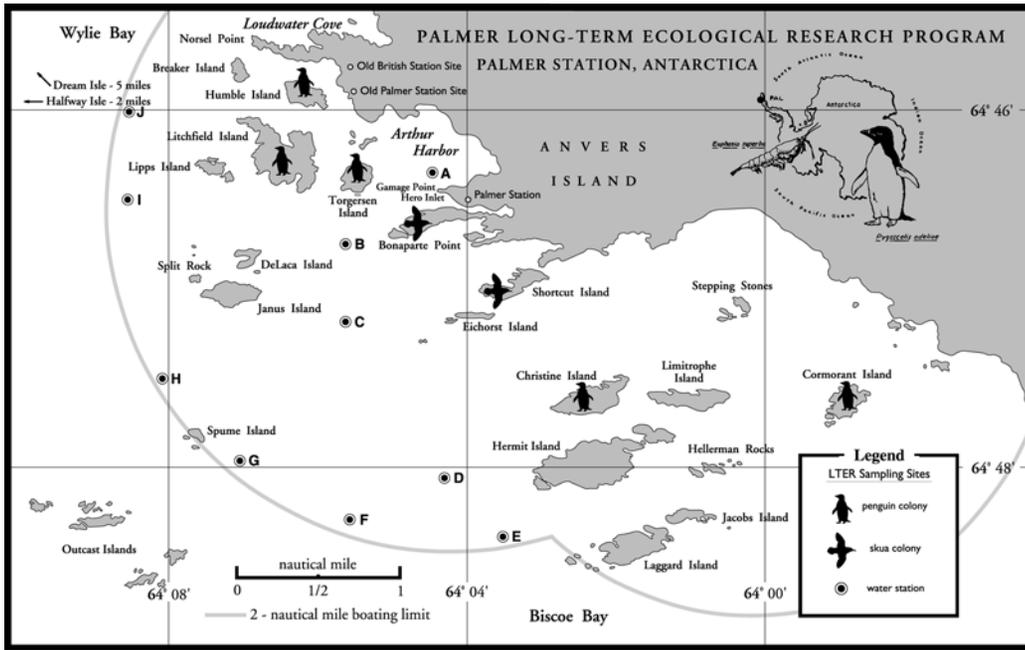
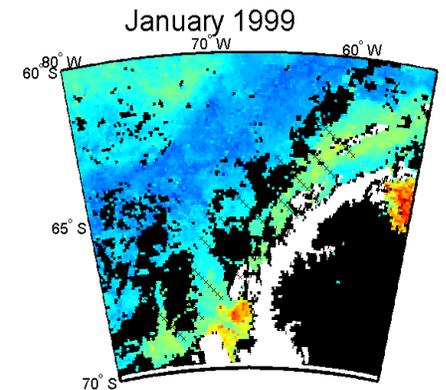
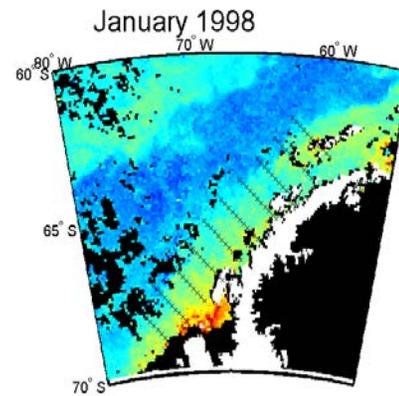
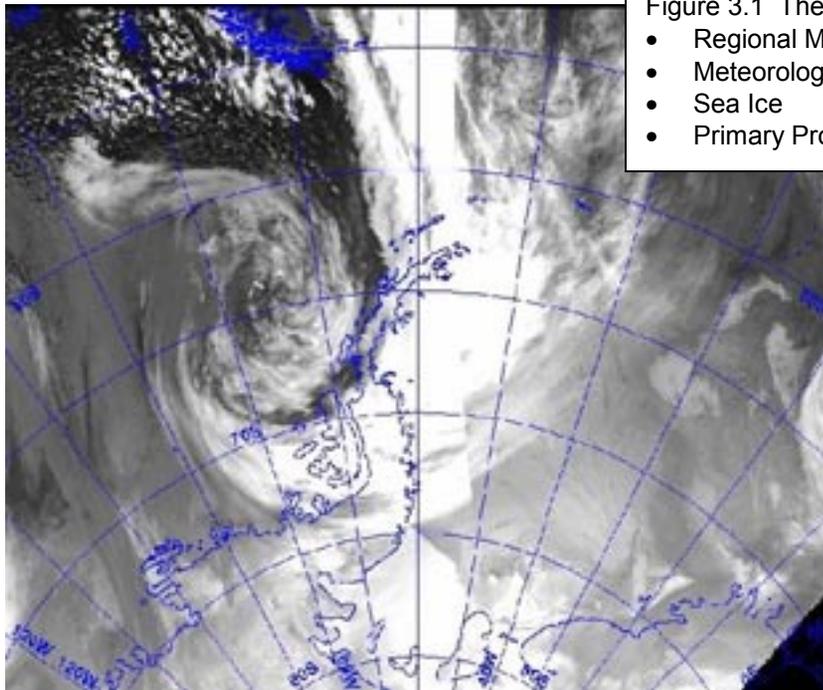


Figure 3.1 The Palmer LTER Site.

- Regional Map
- Meteorology
- Sea Ice
- Primary Productivity



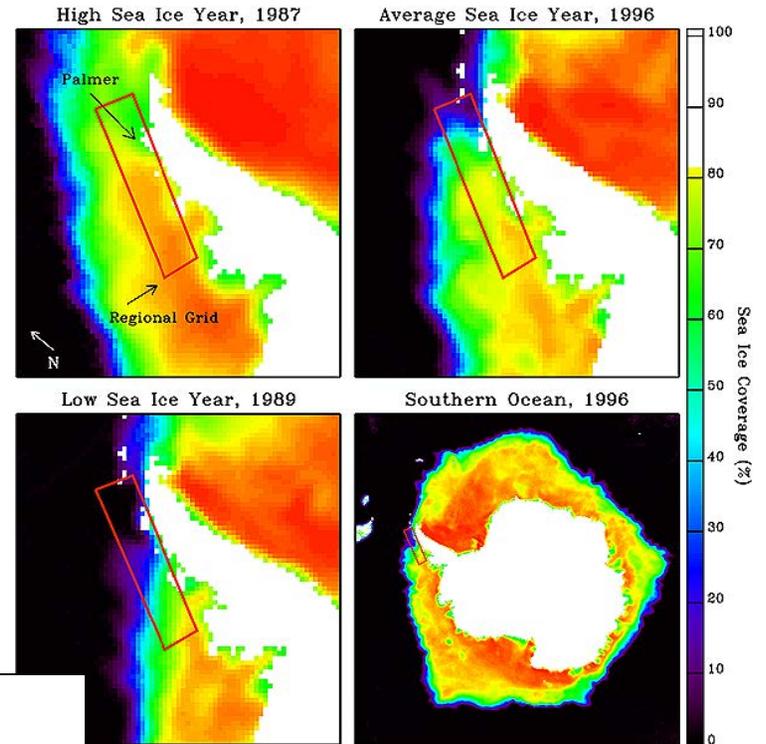
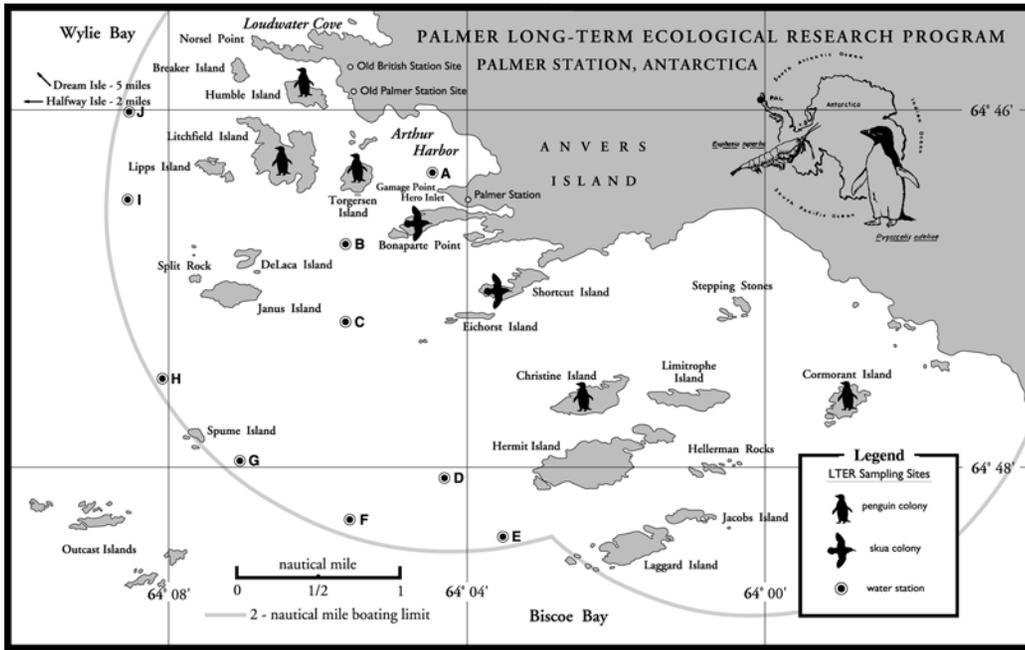
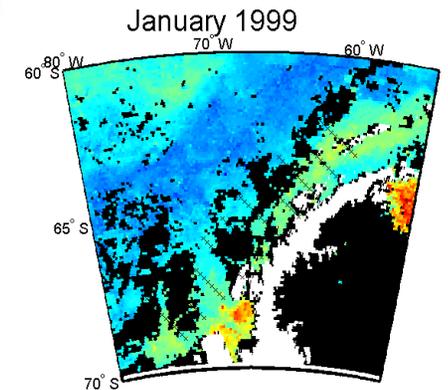
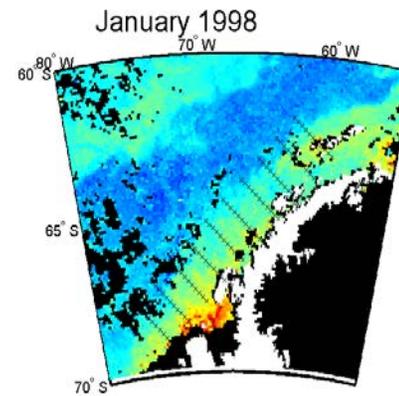
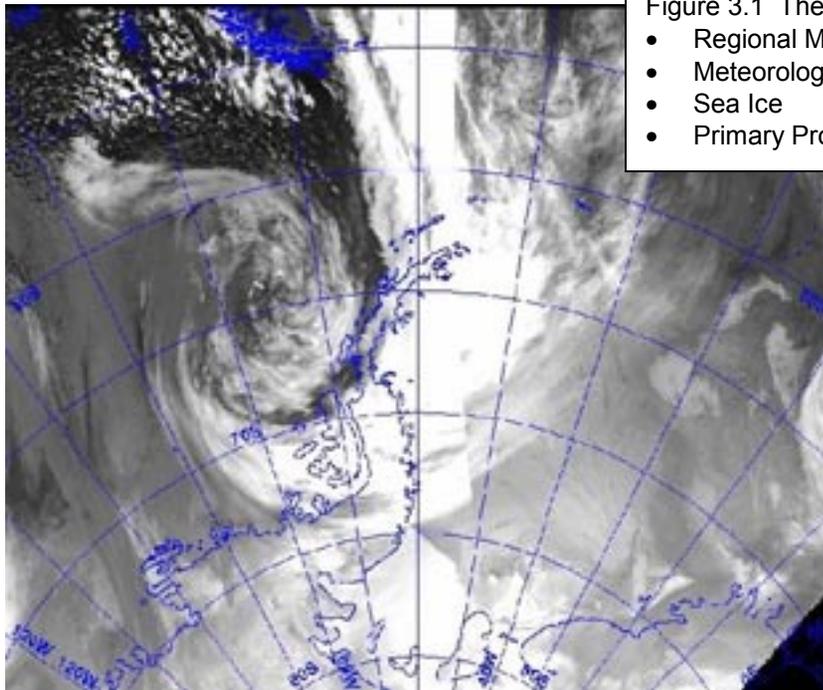
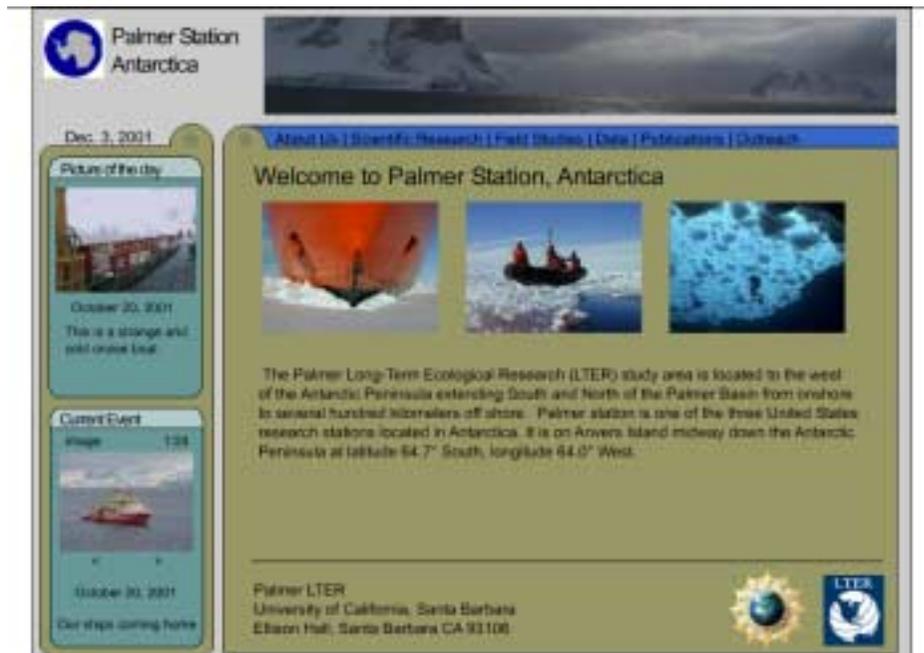


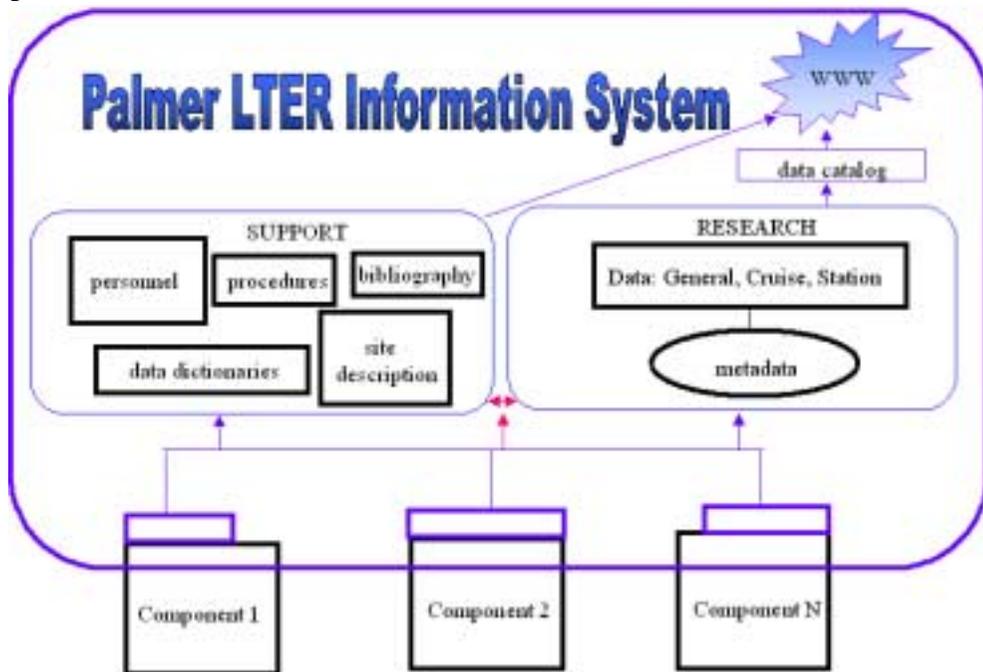
Figure 3.1 The Palmer LTER Site.

- Regional Map
- Meteorology
- Sea Ice
- Primary Productivity





**Figure 4.1.** The new PAL website housing interfaces to data management and archiving infrastructure at ICESS, UCSB, as well as a user-friendly portal for the public, K-12 students, etc to enter the world of PAL.



**Figure 4.2.** The Palmer LTER information structure (Baker, 1996; Baker, 1998)

Table 5.1. Palmer LTER Graduate Students: 1996-2002				
Name	Degree	Year	Institution	Title
C.Carrillo	PhD	Ongoing	U.Hawaii	Dissolved Inorganic Carbon Dynamics in Seawaters: Cross site Comparison Between the Western Antarctic Peninsula and the North Pacific Sub-tropical Gyre
I.Garibotti	PhD	Ongoing	Scripps	Phytoplankton Community Structure in the LTER Study Region Based on Microscopy Analysis
S.Oakes	PhD	Ongoing	UCSB	Modeling of Physiological Processes in Larval Antarctic Krill
S.Stammerjohn	PhD	Ongoing	LDEO	Southern Ocean Ice
M.Church	PhD	Ongoing	VIMS	Bacterial-Dissolved Organic Matter Dynamics in a Variety of Marine Ecosystems
R.Daniels	MSc	Ongoing	VIMS	Network Analysis and Inverse Solutions to Plankton Food webs
S.White	MSc	Ongoing	UCSB	Community Composition of Hard Bottom Benthos in Maritime Antarctic
H.Dierssen	PhD	2000	UCSB	Remote Sensing of Chlorophyll and Primary Production West of the Antarctic Peninsula
K.Patterson	PhD	2000	UCSB	Contribution of Chromophoric Dissolved Organic Matter to Attenuation of Ultraviolet Radiation in Three Contrasting Coastal Areas
D. Patterson	MSc	2000	MSU	The Effects of Human Activity and Environmental Variability on Long-Term Changes in Adelie Penguin Populations at Palmer Station, Antarctica
D.Smith	PhD	1999	ODU	Modeling and Observational Studies of Sea Ice-Mixed Layer Interactions on the West Antarctic Peninsula Shelf
K.Bjorkman	PhD	1999	UHawaii	Phosphorus Fluxes in the Upper Oligotrophic Ocean
E.Chapman	MSc	1999	MSU	Small Mammal and Vegetation Sampling
M.Rosenshield	MSc	1999	MSU	Ecotoxicology of Amphibians in the Green Bay Watershed
K.Haberman	PhD	1998	UCSB	Grazing by the Antarctic Krill, <i>Euphausia superba</i>
N.Karnovsky	PhD	1997	MSU	The Fish Component of Pygoscelid Penguin Diets
T.Mader	Msc	1997	MSU	Temporal Variation in Leopard Seal Presence and Predation Near an Antarctic Penguin Rookery
C.Shaw	MSc	1997	UCSB	Effect of Sea Ice Conditions on Physiological Maturity of Female Antarctic Krill
C.Lascara	PhD	1996	ODU	Seasonal and Mesoscale Distribution of Antarctic Krill, <i>Euphausia superba</i> , in Relation to Environmental Variability
M.Moline	PhD	1996	UCSB	Variability and Regulation of Coastal Antarctic Phytoplankton Dynamics on Interannual, Seasonal and Sub seasonal Time Scales (1991-1994)