SECTION 1. RESULTS FROM PRIOR NSF SUPPORT

"Long-Term Ecological Research on the Antarctic marine ecosystem: Climate migration, ecosystem response and teleconnections in an ice-dominated environment" (OPP0217282; 10/02-9/08). The Palmer Long Term Ecological Research (PAL) program seeks to obtain a comprehensive understanding of the Antarctic marine ecosystem – the climate, plants, microbes, animals, ocean, and sea ice south of the Antarctic Polar Front (northernmost extent of ice-influenced water). A central hypothesis of PAL is that the seasonal and interannual variability of sea ice affects all levels of the Antarctic marine ecosystem, from the timing and magnitude of seasonal primary production to the breeding success and survival of apex predators. PAL has had seven research components (Table 2.1) and is now adding a numerical modeling component. Our sampling program addresses multiple spatial scales from hemispheric, climate-relevant scales to regional and local, process-relevant scales.

Our long-term regional observations are embedded in a hydrographic station grid of ca 50 regularly occupied oceanographic stations (**Figs. 2.1, 3.1**) at which core measurements are conducted, permitting repeated sampling on both seasonal and annual time scales, covering short and long-term ecological phenomena, and specific mechanistic studies. The sampling grid adds a unique strength to both the field and modeling programs as they unify measurements across all field components and facilitate data integration and analyses. To date, there have been 16 annual summer cruises (1993-2008). Additionally, our hemispheric-scale analyses (using satellite and numerically analyzed data) place the PAL regional observations within a global, climate-relevant context (Smith *et al.*, 2008; Stammerjohn *et al.*, 2008a). Core and other variables are documented and available online at the PAL home page (http://pal.lternet.edu/publications/documents/protocols/). **Tables 1.1 and 1.2** summarize our publications and online data holdings and usage, respectively. Other articles cited are listed in Biographical sketches.

Our recent results emphasize detailed analyses of long-term spatial and temporal patterns, and understanding the variability and trends about those patterns. We have developed long-term climatologies (average spatial distributions) of properties and have begun to determine the relationships among their space and time variations using empirical orthogonal function (EOF) analysis. A group of papers describing this work are in review or revision for a dedicated volume of Deep Sea Research (Ducklow 2008). Manuscripts are available at http://oceaninformatics.ucsd.edu/workingpal/DSRCollection/. The following narrative highlights these results.

The life histories of most polar marine species have evolved to be phenologically synchronized with the seasonal cycle of sea ice. We have identified seasonal patterns of sea ice variability and climate co-variability to assess how the seasonal cycle is changing in the west Antarctic Peninsula (WAP) region (Stammerjohn *et al.*, 2008a). Four new metrics of seasonal sea ice variability relevant for understanding ice-climate and ice-ecosystem co-variability were extracted from spatial maps of satellite derived daily sea ice concentration: (a) day of advance, (b) day of retreat, (c) the total number of sea ice days (between day of advance and retreat), and (d) the percent time sea ice was present (or sea ice persistence). The spatio-temporal variability describes distinct on-to-offshore and alongshore differences in ice-ocean marine habitats, characterized overall by a longer sea ice season in coastal regions (6.8 to 7.9 months) versus a shorter sea ice season over the shelf (4.1 to 5.3 months), with on-to-offshore differences increasing south-to-north (**Fig. 2.3**). Large perturbations in the seasonality of the marine habitat are associated with ENSO- and Southern Annular Mode (SAM)-related regional atmospheric circulation anomalies. The local response to these climate modes is largely manifested in the strength and direction of the meridional winds during spring-to-autumn, which in turn affect the timing of the sea ice retreat and subsequent advance. These perturbations are embedded in overall trends towards a later sea ice advance, earlier retreat and consequently shorter sea ice season (**Fig. 2.5**). These sea ice changes impact *seasonal* ice-ecosystem interactions, are contributing to climate migration along the WAP, and are profoundly changing the WAP marine ecosystem (e.g., **Figs. 2.6-2.8**; Massom *et al.*, 2006).

Our CTD dataset offers the most long-lived, consistent gridded observations of Antarctic waters (Martinson *et al.*, 2008). The physical characteristics, water column structure and spatio-temporal modes of variability are related to clearly defined variations in plankton distributions and processes. The water masses in the study region are well separated according to classic T-S defined water mass characteristics and bathymetrically controlled features, dividing the sample domain into three sub-regions: slope, shelf and coastal waters (**Figs. 2.1, 2.9, 2.14**). In collaboration with R. Beardsley (WHOI, http://www.whoi.edu/science/PO/LTER_Drifter/), we deployed Lagrangian surface current drifters in January 2005, 06, 07 (**Fig 2.21**). The drifter tracks reveal complex circulation patterns, but show: 1) retention of properties over the shelf on cruise timescales (approx. 5 weeks), 2) beyond the shelfbreak, rapid transport in the Antarctic Circumpolar Current (ACC) to the northeast, and reveal 3) the southward-flowing coastal current along Adelaide Island and in Marguerite Bay. Consistent with isolated observations reported previously, the ACC is always present along the shelf-break where the Upper Circumpolar Deep Water (UCDW) marks its farthest southern extent in the WAP. Flooding of UCDW onto the continental shelf provides the heat responsible for providing ~28 Wm^{-2} on annual average to the WAP (**Fig. 2.4**), which is presently undergoing the most rapid recent regional winter warming on Earth. The spatio-temporal variability of the delivery and distribution of ocean heat is consistent with changes in the state of ENSO and in the strength of the SAM. La Niña and positive SAM drive enhanced upwelling in this region. The large 1997-1998 El Niño, followed by the transition to the strong La Niña of 1998-1999 (amplified by a large +SAM) introduced a regime shift on the shelf, resulting in the elimination of ~0.5 m of sea ice melt. The anomalous year 2001-02 coincided with extraordinary storm forcing (Massom *et al*., 2006), driving a 4.5° increase in the heat content on the shelf. These jumps coincide with considerable changes in sea ice distribution as well.

We used satellite imagery to examine physical forcing and possible mechanisms influencing the distribution of phytoplankton biomass in the WAP (Smith *et al.*, 2008). SeaWiFS observations (**Figs. 2.12, 2.13, 2.16**) of chlorophyll-a (Chl-a) responses to the spatial and temporal variability of sea ice extent (derived from passive microwave satellite data) has provided the most complete synoptic space/time views of phytoplankton biomass within this region to date. The 7 years of ocean color data exhibit high interannual variability, but persistent spatial patterns of phytoplankton biomass indicate important regional-scale physical controls on phytoplankton blooms. These include the position of the marginal ice zone and its impact on the mixed layer depth, the timing of spring sea ice retreat, the presence of the Southern Antarctic Circumpolar Front (SACCF, or southern edge of the Antarctic Circumpolar Current, ACC) and teleconnections with sub-polar regions (see above). The satellite observations suggest that the SACCF may be as important as sea ice retreat in facilitating spring phytoplankton blooms, depending on if and when (e.g., Nov) the frontal region is ice free.

In shelf waters of the WAP, with abundant macro- and micronutrients, water column stability is the main factor controlling primary production. Freshwater input from melting sea ice forming a shallow summer mixed layer is the principal factor in stabilizing the upper water column. Retreating sea ice in the spring and summer define the area of influence. A 12-year time series (1995-2006) confirms that the spatial and temporal patterns in primary production are related to sea ice dynamics and mixed layer depth (Vernet *et al.*, 2008). Average primary production rates vary by an order of magnitude, from <20 to >100 mmol C m^{-2} d^{-1} in midsummer (January, **Fig. 2.14**). A strong onshore-offshore gradient is evident with higher production observed in inshore waters. High primary production in January is associated with enhanced shelf production to the south. Positive annual primary production anomalies are related to positive anomalies in the timing of sea ice retreat in the spring and summer (i.e., late retreat, **Fig. 2.15A**) supporting the hypothesis that production in the WAP shelf is related to ice-mediated ocean dynamics. To first order, shallower summer mixed layer depths on the shelf correlate with late sea retreat (**Fig. 2.15C**), in support of the hypothesis that water column stability promotes higher primary production. Mean Chl-a has increased in the south and decreased in the north since 1986 (**Fig 2.16**).

The temporal and spatial variability of phytoplankton size structure was also investigated using the satellite record (Montes-Hugo *et al.*, 2008). It is hypothesized that 'small' phytoplankton (<20 µm) have increased in the last decade in WAP waters due to ongoing regional climate change. Time series of an optical satellite-derived phytoplankton size structure index (γ_{bp}; the spectral slope of particle backscattering; Montes-Hugo *et al.*, 2007) as well as of Chl-a, sea ice extent, temperature, salinity, nutrients, and mixed layer depth were analyzed in relation to ENSO and SAM. Temporal transitions in cell size coincided with a switch in ENSO and SAM anomalies as well as an increase in heat content of shelf waters over the WAP region. A greater frequency of southerly winds during spring and autumn (as can occur during El Nino and/or –SAM) is expected to favor the dominance of 'small' (<20 µm) phytoplankton cells in WAP waters. Conversely, the greater intensification of the Antarctic Circumpolar Current interaction with the WAP shelf-break during +SAM is expected to intensify topographically-induced upwelling and favor the dominance of 'large' (>20 µm) phytoplankton cells (mainly diatoms) that are known to flourish in upwelling systems and well-mixed waters.

Analyses of the 12-yr time-series (1993-2004) of oblique net hauls (Ross *et al.*, 2008) showed that the numerically dominant macro- and mesozooplanktonic species >2 mm included three species of euphausiids (*Euphausia superba*, Antarctic krill*; Thysanoëssa macrura*; *Euphausia crystallorophias*, ice krill), a shelled pteropod (*Limacina helicina*), and a salp (*Salpa thompsoni*). Life cycles, life spans, and habitat varied among these species. Patterns in the climatological distributions of these five species were distinct (**Fig. 2.9**), and correlated with sea ice parameters. Common features included higher abundance in the north compared to the south, independent of the cross-shelf gradients, and cross-shelf gradients with highs in abundance either inshore (*E. crystallorophias*) or offshore (*S. thompsoni*). Anomalies revealed cycles in the population, such as episodic recruitment in Antarctic krill. The episodic pattern in krill recruitment was two strong year classes in succession followed by three or four moderate or poor year classes. The krill recruitment index was positively correlated with the absolute value of a seasonal ENSO index, with strongest recruitment during the neutral or moderate periods of ENSO (Fraser and Hofmann, 2003; Quetin and Ross, 2003). The 1998 year, which coincided with a rapid change from El Nino to La Nina, emerged as a year of significant anomalies for several species, and marked a change in anomaly patterns for others. The mechanism underlying the strong link between the krill recruitment index and ENSO is most likely the effects of seasonal sea-ice dynamics on both reproduction and winter-over survival of the resulting larvae (Quetin and Ross, 2003). Focused fall- and winter-time studies of krill larvae development (Frazer *et al.*, 2002; Quetin *et al.*, 2003) indicated that highest growth rates in late winter were likely a combination of factors such as day length, water column and sea ice primary production, and food concentration. The mechanisms driving variability in the temporal/spatial distribution of the shorter-lived, more oceanic species were less complex and more direct than those for the longer-lived euphausiids (Ross *et al.*, 2008). Salps have been more consistently present across the shelf post-1999 and the range of the pteropod *L. helicina* has been expanding. With shorter life spans, these two species can respond more quickly to the increasing heat content on the shelf in this region. Correlations show, for example, more salps on the shelf but fewer ice krill inshore when the previous ice season was short and/or sea ice retreat was early. These results suggest that several environmental controls on distribution and abundance of these species were linked to seasonal sea-ice dynamics (Ross *et al.*, 2008).

Capitalizing on observations (Fraser and Hofmann, 2003; Patterson *et al.*, 2003; Fraser *et al.*, 2008), natural and planned field experiments (Massom *et al*., 2006) and integration through modeling (Chapman *et al.*, 2008), the consequences of changes in the phenology of sea ice advance and retreat continue to emerge as key deterministic processes regulating Adélie penguin (*Pygoscelis adelaie*) population dynamics. While this observation is not new to PAL, recent results combined with model-based studies suggest that the processes in question operate over scales that are much smaller than previously thought, and affect Adélie penguin population dynamics by imposing greater or smaller energetic costs on key life history parameters. The foraging movements of Adélie penguins were tracked during April 2001 to April 2003 by satellite telemetry. Data indicate that during all seasons penguins more consistently foraged over deep cross-shelf canyons (**Fig 2.17**) that may offer more predictable prey concentrations due to a combination of upwelling, bathymetry and circulation. Foraging success, however, was strongly mediated by the length of the sea ice season through its effects on krill recruitment (Fraser and Hofmann, 2003) and changes in the spatial and temporal patterns of access to these key foraging areas, especially during the critical winter period (Fraser *et al*., 2008). In contrast to effects linked primarily to marine dynamics, a terrestrial or “landscape” effect with the potential to negatively impact Adélie penguin recruitment is described in Massom *et al*. (2006), who observe that specific anomalies in sea ice and atmospheric conditions result in equally anomalous high snowfall during the breeding season. The most obvious result is a decrease in breeding success due to egg and chick mortality induced by nest flooding. A more subtle and previously unrecognized effect is a reduction in chick fledging weight as late-breeding parents are decoupled from the peak in prey abundance. Artificial landscape manipulations using snow fences that enhance snow deposition (experiments ended in March 2007; data analysis and writing are in progress) have confirmed this effect and suggest a new mechanism operating over smaller scales that has negative consequences to winter survival and recruitment. Modeling of these and other dynamics (Chapman *et al*., 2008) suggests that changes in sea ice phenology can fundamentally alter the energetic costs that determine physiological condition, and, ultimately the survival of adults, nestlings and/or fledged offspring.

Vertical export of particles from the upper 160 m into as estimated by sediment trap collections (1993 – 2007) (Ducklow *et* al., 2006, 2008) exhibited strong seasonality with high fluxes (1-10 mmol C m^{-2} d^{-1}) in November-March following ice retreat and very low fluxes (<0.001 mmol C m^{-2} d^{-1}) during the Austral winter and under sea ice cover (**Fig. 2.10**). An average of 75% of the annual export of 196 mmol C m^{-2} occurred during the seasonal flux pulse. Over the trap record, the peak flux has shifted to occur later in the Austral summer by about 40 days since 1993 (**Fig. 2.11**). This is about the same as the increase in duration of the ice-free period in this region, believed to be a response to rapid climate warming. The annual export ratio averaged 1% of the annual primary production of 15 mol C m^{-2}. This low value (in contrast to 6% at Bermuda) suggests a foodweb structure efficient at retention and recycling of the net community production. This conclusion is consistent with the elemental composition of material captured in the traps, with average C:N:P of 225:28:1, greater than the canonical Redfield values. High C:P ratios (400-600) corresponded closely to the annual flux peak, indicating intensive reworking of the sinking particles in the upper 160 m during the ice-free period. The composition of the exported material more closely approximated the Redfield composition during the low-flux, winter period.

The first eight years of oceanographic monitoring in northern Marguerite Bay (**Fig. 3.1**), through our collaboration with the British Antarctic survey (via PAL co-PI A. Clarke and the *Rothera Oceanographic and Biological Time-Series* (RaTS) project) (Clarke *et al*., 2007, 2008), provide complementary, year-round information on ocean and plankton dynamics 400 km south of Palmer Station. Strong seasonality in the topmost Antarctic Surface Water (AASW) is driven by summer solar heating and winter cooling with brine rejection during ice formation. The depth of the winter mixed layer reaches >140 m in August. CTD profiles at depth indicate the presence of modified UCDW far inshore of the shelf break. Summer Chl-a typically exceeds 20 mg m^{-3}, with the peak in January. Vertical flux of phytodetritus is also predominantly in January. The summer bloom is dominated by large diatoms and colonial forms, whereas in winter most of the Chl-a is in the nanophytoplankton (20-5 µm) fraction. Macronutrients show marked seasonality with N:P close to Redfield (~15.3) and Si:N stoichiometry ~1.67. Summer dissolved organic carbon (DOC) values show little seasonality and relatively high winter levels (>50 µM). Surface waters also exhibit a marked interannual variability, with ENSO as an important driver at subdecadal scales.

Taken together all of our results of over a decade of observations and process studies (rate measurements and coordinated observations over diel to seasonal timescales) indicate several key findings: the rapid warming and loss of sea ice, dependence on sea ice variability at all trophic levels, the input of UCDW and associated heat onto the shelf, distribution patterns of biota dominated by strong gradients in the north-south (reflecting the polar-maritime climate gradient) and inshore-offshore (reflecting gradients in sea ice duration, oceanic influences and possibly glacial freshwater inputs) distribution patterns. Questions and issues arising from the synthesis of these and other findings form the basis of this proposal.

There are 3 new co-PI’s in our proposal. They have not received prior support from LTER:

Scott Doney (Role of Ecosystem Dynamics on the Global Ocean Carbon Cycle: A JGOFS Model–Data Synthesis, OCE0222033, 7/02-6/06): A newly developed, advanced marine ecosystem model (Moore *et al.*, 2002a, b) coupled with 3-D ocean biogeochemical simulations (Doney *et al.*, 2001; Doney *et al.*, 2003), quantifies the impact of multi-nutrient limitation, iron dynamics, and community structure on marine ecology and biogeochemistry. In a North Atlantic 3-D simulation (Lima and Doney, 2004), spatial and temporal variations in light and nutrient limitation lead to the dominance of pico/nano-plankton and episodic diatom blooms in the subtropics, nutrient-controlled seasonal plankton succession at higher latitudes, and associated seasonal/depth changes in new and regenerated production and particle export. In a global simulation (Moore *et al.*, 2004), iron limitation generates the observed High Nitrate, Low Chlorophyll (HNLC) conditions in the Southern Ocean, subarctic and equatorial Pacific. Nitrogen fixing diazotrophs directly account for a small fraction of primary production (0.54%) but indirectly support ~10% of primary production and particulate organic carbon (POC) export. Diatoms disproportionately contribute to export of POC out of surface waters, but $CaCO_3$ from the coccolithophores is the key driver of POC flux to the deep ocean in the model. In Moore *et al.* (2006), higher (lower) dust deposition increases (decreases) diatom and export production, nitrogen fixation, and oceanic net CO_2 uptake from the atmosphere. The response is modulated on decadal time-scales by direct effects in HNLC regions; on longer timescales, an indirect nitrogen fixation pathway grows in importance, significantly amplifying the ocean biogeochemical response. (Moore and Doney, 2007) argue that iron limitation partially decouples oceanic feedbacks between nitrogen fixation and denitrification.

Oscar Schofield (Evolution and Radiation of Eukaryotic Phytoplankton Taxa-“EREuPT”, OC0084032, 09/00-08/05; Falkowski, Miller, Schofield, co-PIs): The goal of this multidisciplinary study was to understand when, why, and how a diverse group of eukaryotic phytoplankton rose to ecological prominence in the Mesozoic and continue to dominate the contemporary oceans. Our project clarified the fossil record of thecate dinoflagellates, coccolithophores, and diatoms; biochemical composition of extant taxa and their phylogenetic relationships; constructed physiological and molecular biological “portraits” of extant taxa; reconstructed ocean paleochemistry and changes in sea level; and developed adaptive evolutionary simulation models that demonstrate the influence on long-term ecosystem structure (Falkowski *et al.*, 2004). This project documented that the physical regulation of the global succession between major bloom forming phytoplankton taxa could be explained by the basic physiological innovations such as a vacuolated cell (Tozzi *et al.*, 2004). Additionally the sea level dynamics, which modulated the spatial extent of the continental shelf, were correlated with a shift in the size spectrum within the phytoplankton taxa (Finkel *et al.*, 2005, 2007), and these shifts directly impact dynamics in the grazer communities (Jiang *et al.*, 2005). A partial list of >80 articles resulting from this award can be found at http://www.marine.rutgers.edu/~yana/.

Deborah Steinberg: (**Collaborative Research: VERtical Transport In the Global Ocean (VERTIGO) (PI's K. Buesseler, D. Steinberg, M. Silver, D. Siegel, P. Boyd, T. Trull, J. Bishop, OCE0324402, 8/03-7/06).** The central question in VERTIGO was: What controls the efficiency of particle export to the deep ocean? The study took place at two contrasting sites in the subtropical (HOT) and the subarctic (K2) North Pacific Ocean (Buesseler *et al.*, 2007b). We characterized the mesopelagic zooplankton and microbial community, and sinking particle flux, to determine the potential contribution of the biota to processing of sinking particulate organic carbon (POC). Steinberg *et al*. (2008b) estimated the contribution of mesopelagic zooplankton and bacteria to remineralization of sinking particles by comparing losses of sinking C in sediment traps with metabolic requirements. Bacteria carbon demand exceeded that of zooplankton at HOT, while bacteria and zooplankton required relatively equal amounts of POC at K2. We suggest diel vertical migration plus carnivory supports a greater fraction of mesopelagic carbon demand than does sinking POC. Significant changes in types of zooplankton (Steinberg *et al.*, 2008a) and their fecal pellets with depth occurred at both sites (Wilson *et al.*, 2008), indicative of midwater consumption and repackaging of sinking particles. These include changes in flux of larvacean, large copepod, and carnivore fecal pellets with depth (S Wilson, PhD Thesis in progress.

SECTION 2. PROJECT DESCRIPTION

Conceptual framework/unifying ecological theme. As the world warms, ecosystems are responding and the world is changing literally before our eyes (Kerr, 2007). Ford (1945) may have been the first to implicate the 20th century warming trend as a cause of unprecedented changes in species distributions. The magnitude and pace of the 20th-21st-century warming is expected to produce novel climate conditions (no-analog climates) with combinations of temperature, precipitation and seasonal variations that do not exist in the contemporary world (Fox, 2007). The no-analog climates in turn are shuffling populations and communities, possibly producing no-analog ecosystems. The scientific literature is now rich with examples of organisms across the phylogenetic spectrum and at all trophic levels that have responded to climate change (McCarthy *et al.*, 2001; Parry *et al.*, 2007). For example, mid-range warming scenarios for 2050 suggest extinctions of 18-35% of species in selected terrestrial habitats (Thomas *et al.*, 2004). Though terrestrial examples, especially studies of changing ranges for birds and plants, are most common, there are also clear examples of changes in marine pelagic communities. Best documented are changes off southern California: a 1400-year time series of planktonic foraminifera collected from sediments shows species shifts coincident with the 20th century warming (Field *et al.*, 2006). Contemporary sampling in the CalCoFI time series (1950-present) shows a long-term decline in the abundance of pelagic tunicates (primarily salps) in the same region as the California Current Ecosystem LTER (CCE), coincident with a long-term increase in water column stratification (Lavaniegos and Ohman, 2007). Fish, squid, kelp, seals, sea lions and seabirds have also been affected by increasing frequency of warm anomalies along the California coast (McGowan *et al.*, 1998). While globally coherent responses across many groups have been documented (Parmesan, 2006), studies at the ecosystem level are less common. The British Continuous Planktonic Recorder (CPR) Survey (1931-present) shows changes in the North Atlantic at all trophic levels (Richardson and Schoeman, 2004), suggesting a regime change across the basin. In the North Pacific subtropical gyre, regime change included increases in Chl-a and primary production, as well as shifting microbial community composition and biogeochemical processes (Venrick *et al.*, 1987; Karl, 1999). Increases in ocean temperatures extending throughout the water column as well as air temperatures and reductions in sea ice have triggered extensive changes across trophic levels in the Bering Sea (Grebmeier *et al.*, 2006). Declining benthic prey and their mammalian predators have been accompanied by a shift toward a pelagic-dominated foodweb with increased fish populations in the rich Bering system, site of several valuable commercial fisheries.

In all these cases, climate change has been implicated but the mechanisms of ecosystem response are less clear (Greenland *et al.*, 2003). What is clear is that climate change causes ocean warming or changes in winds, circulation and sea ice cover; these physical changes may directly influence regional species distributions. Even direct effects on individual species ranges may lead to complex changes at the community level. For example, as the tropic belt widens (Seidel *et al.*, 2008), new species invasions may precede local extinctions, causing transient increases in species diversity (Walther *et al.*, 2002). We are seeing such a species invasion along the Antarctic Peninsula, where Chinstrap (*P. antarctica*) and Gentoo penguins (*P. papua*) have successfully invaded the region, coexisting with long-resident Adélie penguins (*P. adeliae*) (Ducklow *et al.*, 2007). In addition the physical changes also affect rates and composition of the primary producers and corresponding prey abundance, thus indirectly affecting upper trophic level predators (Walther *et al.*, 2002). The principal mechanism of ecological response to climate change appears to be trophic mismatch driven by differential changes in species phenologies, disrupting the synchrony between species and their food or habitat resources (Parmesan, 2006). This effect is overlain on differential expansion/shift in ranges of predator-prey groups as suggested above.

Climate-driven changes in trophic interactions causes disruption in both time and space (Harrington *et al.*, 1999). Flycatchers in the Netherlands have advanced their breeding dates in the spring, but the hatching date of their caterpillar prey has advanced even more (Both *et al.*, 2006). The predator populations with the largest mismatches have declined most, and there is selection for earlier breeding dates. Phenology change and trophic mismatch may be particularly important in temperate and polar marine habitats where consumers depend on episodic pulses of primary and secondary production. The

CPR Survey (1958-2002) found evidence for shifts in seasonal peaks of abundance in 34 of 37 planktonic consumer taxa that peaked under stratified (summer) conditions. In contrast, there was no change in the timing of the spring phytoplankton bloom, driven by large diatoms that flourish in well-mixed, turbulent conditions. The result, overall, is a growing mismatch between diatoms and their consumers (Edwards and Richardson, 2004). These changes and other climate-driven shifts in copepod biogeography, including the expansion of warm-water species poleward and the shrinkage in subarctic and arctic species ranges have been implicated in the decline of North Sea cod stocks (Beaugrand *et al.*, 2003).

One general model for understanding how climate change affects marine ecosystems is that changes in physical oceanographic processes (mixing, stratification, circulation, sea ice) mediate top-down effects of climate warming on foodwebs via trophic mismatches initiated at the upper trophic levels. The changes at higher trophic levels in turn lead to top-down trophic cascades resulting in reorganization of entire foodwebs. An alternative model is that climate change induces bottom-up responses in lower trophic level populations. Examples include changes in phytoplankton size classes and krill reductions in response to declining sea ice. The reality is most likely a combination of both top-down and bottom-up interactions, varying in strength for different ecosystems and ecological measures. In either case, it is now apparent that the structure and function of the marine ecosystem of the WAP (**Fig. 2.1**) cannot be understood except in the context of the rapid climate and ecological change taking place there. The WAP atmosphere has warmed in winter by almost 6°C since 1950 (**Fig. 2.2**), over five times the global average (Vaughan *et al.*, 2003; Anisimov *et al.*, 2007; Ducklow *et al.*, 2007). The paleorecord of species-specific penguin occupation suggests the recent warming is unique over at least the last few millennia and possibly longer (Smith *et al.*, 1999b; Domack *et al.*, 2003).

PAL set out originally to test the hypothesis that changes in the marine polar ecosystem were forced by changes in the ocean and sea ice system -- a physical change forcing a cascade of food web changes (Ross *et al.*, 1996). This hypothesis was confirmed (Smith *et al.*, 1998; 1999b). In our last proposal we hypothesized 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."* We hypothesized that the principal link between climate change and ecosystem response is declining sea ice (Stammerjohn *et al.*, 2008a, 2008b). The results described in more detail below (Scientific Background) strongly confirm that climate migration is: 1) occurring along the WAP, 2) most evident in the region between Palmer and Rothera Stations, 3) largely absent south of Marguerite Bay, 4) affecting all trophic levels and element cycling, and 5) doing so via trophic mismatches occurring throughout the system. In this proposal, we place increasing emphasis on elucidating the dynamics governing climate-driven top-down and bottom-up responses and in developing improved predictive capabilities for ecological forecasting.

Our analysis of the long-term datasets now leads us to the conviction that we need to extend our routine shipboard sampling activities farther south in order to better document ecosystem structures and processes where the effects of climate change are less advanced than over the more northerly part of our study region. The northern area appears to be well on its way toward transitioning into a subpolar ecosystem. Our long-term observational program also will be extended in space and its temporal resolution will be enhanced by addition of moored instrumentation and autonomous gliders. We further propose to improve to improve our quantitative understanding of the physical, ecological and biogeochemical processes of climate change and ecosystem response through new process, modeling and other mechanistic studies (**Table 2.1**). With a few notable exceptions (e.g., using snow fences near penguin colonies to enhance snow deposition; see below), plot to ecosystem-scale manipulations are not technically, economically or even legally feasible in the Antarctic sea ice zone, due to restrictions of the Antarctic Treaty. We will rely on shipboard process studies and numerical modeling approaches to test hypotheses about mechanisms of ecosystem change in the WAP region (e.g., (Chapman *et al.*, 2008). Where appropriate, these studies will be complemented by smaller-scale (mesocosm) perturbation experiments. Finally, our ultimate goal is improving our system-level understanding sufficiently to be able to project, through models and scenario-building exercises, the future course of ecosystem change across our study region, from the already significantly altered system in the north to the less perturbed regimes to the south of our traditional study region. Our approaches and the rationales supporting them are described below.

Objectives and Hypotheses. The overall objectives of the Palmer, Antarctica LTER are:

1. To document and quantify the processes of climate and ecosystem change in the west Antarctic Peninsula continental shelf via nearshore land-based, offshore shipboard, unattended mooring, autonomous glider and satellite remote sensing observations;
2. To understand, through process measurements, manipulative experiments, comparative analysis against other marine ecosystems, data synthesis and modeling, the physical and ecological mechanisms of climate and ecosystem change; and
3. To predict/project the future course of ecosystem change in the west Antarctic Peninsula region.

In order to investigate the mechanistic linkages between climate change and ecosystem response, we have broken the problem down into three inter-related components. Each of these forms the basis for a hypothesis and a group of coordinated observations, experimental process studies and modeling studies:

Hypothesis 1: Regional warming, increased glacial meltwater inputs and sea ice decline associated with historical and on-going climate migration in the northern part of our study area have altered key trophic relationships, leading to changes in species distributions, increasing trophic mismatches and changes in habitat, food availability, ecosystem dynamics and biogeochemical cycling.

The observations to address Hypothesis 1 include continuing the long-term historical PAL time-series near Palmer Station (nearshore ocean time-series and penguin ecology studies), offshore observations along the northern WAP (annual ship-based survey, sediment trap and expanded mooring network), and satellite remote sensing observations. New glider (small autonomous submarines equipped with sensors, **Fig. 2.19**) transects prior to, during, and after the ship-based survey will extend the seasonal observational coverage, and new bio-optical and trace metal measurements will probe in more detail aspects of phytoplankton physiology. In order to better characterize climate-trophic interactions, we will quantify the temporal and spatial correlations between observed physical variations and biogeochemical and ecological responses. Targeted process studies and local 1-D numerical simulations will be conducted to elucidate the mechanisms behind observed relationships.

Hypothesis 2: Ecosystem conditions that prevailed prior to climate migration in the north will be found farther south along the Peninsula, forming a disturbance continuum along the WAP. We anticipate the climate migration trend will continue and reach the southern extreme of our study area within the next one to two decades, with our proposed studies providing a baseline for assessing future change.

The ship-based annual regional survey and glider transects will be extended 200 km farther south to ocean areas ahead of the WAP climate migration, areas already covered by our on-going satellite data analysis. Comparative data analysis will be carried out on the northern and southern parts of the PAL survey grid, and process studies in both regions and the Palmer and Rothera time series will assess how climate gradients along WAP alter physical-ecological relationships. The field-based findings will be compared with 3-D regional ocean simulations along the Peninsula.

Hypothesis 3: Deep cross-shelf troughs are focal regions with predictable elevated food resources for top-predators such as penguins, influencing their foraging ecology and the geographic distributions of breeding and wintering populations on timescales that are long relative to recent climate change. These relationships may already be disrupted in the northern part of our sampling grid.

Mesoscale ship- and glider-based surveys and intensive process investigations will be used to identify better the physical and lower trophic level properties supporting the concentration of top predators above the troughs. Below we describe and further summarize our long-term observations, and follow with the proposed research for 2008-14. The proposed research has three major components: long-term observations, including manned shipboard and remote, autonomous mooring and glider instrumentation; land- and ship-based process studies; and a new modeling component.

Scientific Background: Long-term observations and sampling design (current and past).

PAL initiated a program of long-term oceanographic observations (Waters and Smith, 1992) (**Table 2.2**) to test the hypothesis that interannual variations in regional-scale distributions of sea ice were a major determinant of foodweb structure and dynamics in the Antarctic marine ecosystem. The PAL hydrographic grid extending 1000 km from north to south along the west Antarctic Peninsula encompasses the 200 km wide continental shelf and its three bathymetrically, hydrographically and ecologically-defined domains: the coastal, shelf and slope regions (**Figs. 2.1, 3.1**) (Martinson *et al.*, 2008b; Stammerjohn *et al.*, 2008b). Observations are carried out annually during the Austral summer (January-February) with a wide suite of climate, meteorology, physical, chemical and biological oceanographic measurements made in the core study region of ~55 stations on the 200-600 lines (**Figs. 2.1, 3.1**). Intensive observations of penguin breeding biology, foraging ecology and demography along with related water column measurements are made throughout the October to April breeding season at Palmer Station. The following results of the long-term observations and process investigations represent a synthesis of 16 years of research using this observing system.

Climate Change and Ecosystem Response in the WAP. At the core of our research is the role of the ocean in driving the dramatic climate change (including glacial melt) now occurring in the WAP. Air temperatures have increased throughout the year, particularly in winter at Palmer and Faraday (now Vernadsky) Stations. There has been less of an increase at Bellingshausen Station to the north (which is subject to the colder Weddell influence) and to the south at the Rothera station (**Fig. 2.3**). 87% of WAP glaciers are in retreat (Cook *et al.*, 2005), new reports indicate accelerating losses of ice mass, particularly on the WAP and in West Antarctica (Rignot *et al.*, 2008) and WAP perennial sea ice has disappeared (Stammerjohn *et al.*, 2008b). Vaughan *et al.* (2003) note that the timing of the glacial melt is inconsistent with that of the atmospheric warming, suggesting a role for the ocean, the only substantial source of heat in winter. (Martinson *et al.*, 2008b) show that the ocean heat content supplied to the WAP shelf has increased dramatically since the 1980s, with hints from historical observations of a steady increase since the 1960s (**Fig 2.4**). The largest source of heat in the region is the Antarctic Circumpolar Current (ACC). The flow of the ACC adjacent to the WAP shelf and slope can impact on shelf water properties via the upwelling of Upper Circumpolar Deep Water (UCDW), a watermass underlying surface waters off the Antarctic shelf. This has raised the heat content of the shelf waters by nearly $1x10^9$ J m^{-2} since the 1970s, equivalent to a ~0.7°C temperature increase throughout the 300 m water column below the winter mixed layer (Martinson *et al.*, 2008a). The recent regional warming appears to be due to increased upwelling-favorable winds associated with stratospheric ozone depletion (Thompson and Solomon, 2002) and a global warming-induced change toward more positive phases of the SAM (Shindell and Schmidt, 2004), driving more UCDW onto the shelf where it can make contact with the marine termini of retreating glaciers.

In addition to the atmosphere and deeper (ACC) waters in the region, the surface ocean has also undergone a profound warming in the WAP region. Meredith and King (2005) report that summer surface ocean temperature has risen by over 1°C since 1950, substantially higher than the warming of UCDW. The warming trend is surface-intensified, indicating that this upper-layer ocean warming is forced predominantly via interactions with the atmosphere and cryosphere rather than the deeper ocean (Meredith and King, 2005). A concurrent summer salinity increase of the upper waters adjacent to the WAP was also found. These trends are driven predominantly by the strong reductions in sea ice cover along the WAP in recent decades (Parkinson, 2002; Stammerjohn *et al.*, 2008a; 2008b). These surface ocean trends constitute positive feedbacks, and will act to sustain and amplify the atmospheric warming. Changes in the sea ice field are shown clearly in **Fig. 2.5**, which illustrates the dramatic 85 day reduction in sea ice duration since 1978 and the strengthened response of the sea ice advance to La Nina and +SAM anomalies in the 1990s. The sea ice duration in the area north of Rothera has declined from 250-350 days to 150-200 days, but remains near 300 days in southern Marguerite Bay and farther south along the coast. These patterns suggest a climate shift is occurring along the WAP, with greater warming and sea ice reduction in the mid-Peninsular region, and less change farther south.

To better understand the causes and mechanisms of sea ice change in the WAP region, we have taken a global perspective by assessing ice-climate changes throughout the Southern Ocean, which has revealed the following: the WAP and adjacent ocean regions (northwestern Weddell Sea, southern Bellingshausen Sea) are experiencing shorter winter sea ice seasons due to later autumn sea ice advances and earlier spring sea ice retreats, while the western Ross Sea region is experiencing longer winter sea ice seasons due to earlier autumn sea ice advances and later spring sea ice retreats (Stammerjohn *et al.*, 2008b). The changes in the timing of sea ice advance and retreat are primarily wind-driven and in response to changes in regional atmospheric circulation (Stammerjohn *et al.*, 2003, 2008a; Massom *et al.*, 2006). These changes in turn appear to be related to changes in the high latitude atmospheric response to the El Niño-Southern Oscillation (ENSO) during austral spring and summer and to the strong positive trend in Southern Annular Mode (SAM) during austral summer and autumn. More specifically, there is some suggestion that the high latitude response to ENSO has changed from the 1980s to the 1990s in response to both tropical ENSO variability and a more positive SAM, ideas we are pursuing further using global model simulations (Rind *et al.*, *in prep.*). The implications of research with regard to rapid warming in winter in the WAP region is that the delayed sea ice advance well into June (austral winter) is primarily a dynamical response to the increase in northerly winds (i.e., any newly formed sea ice is advected southwards by the winds) during autumn/early winter. Consequently, the delayed sea ice advance is allowing for large amounts of ocean heat ventilation and release to the atmosphere during late autumn and early winter, thus feeding back on, and amplifying, regional warming.

We have observed profound changes in the ecosystem in response to the warming climate and sea ice reduction, exemplified by several aspects of the ecology of the Adélie penguin and other ice-dependent species. Fish such as Antarctic silverfish (*Pleuragramma antarcticum*) have disappeared from Adélie penguin diets in the Anvers Island region since the late 1970s (**Fig. 2.6**). This loss is most likely explained by the coincident loss of regional sea ice because silverfish depend on sea ice for spawning and larval growth (Vacchi *et al.*, 2004). Thus, we suspect that the observed extirpation of this species from the region is forced primarily, if not exclusively, by a lack of reproductive success and diminished recruitment as sea ice continues to decrease (Stammerjohn *et al.*, 2008b). In contrast, lanternfish (*Electrona antarctica*) populations are expanding in the Palmer region. This is a species that for a variety of physiological reasons, including a lack of appropriate antifreezes, cannot tolerate waters colder than –1 ºC, and as a result is generally found below the cold Winter Water (WW) layer in the deeper, warmer waters that characterize UCDW (Lancraft *et al.*, 2004; Donnelly and Torres, 2008; Moline *et al.*, 2008). Silverfish still contribute ~50% to the diets of Adélie penguins at Avian Island in Marguerite Bay, as they did before 1985 at Palmer Station, suggesting lower impact of climate change and less trophic mismatch to the south. Over the same time period ice-dependent Adélie penguins in the Anvers Island colonies have undergone drastic population reduction (**Fig 2.7**), a decline mirrored by the equally ice-dependent Weddell seals (*Leptonychotes weddellii;* **Fig. 2.8**). At the same time, ice-avoiding species of penguins (Gentoo and Chinstrap; **Fig. 2.7**) and seals (Fur and Elephant; **Fig. 2.8**) have been rapidly increasing in the northern part of the PAL study area near Palmer Station (Ducklow *et al.*, 2007; Siniff *et al.*, 2008). New, large breeding colonies of Gentoo and Chinstrap penguins now exist within 10-20 km of Palmer Station, thus providing a clear marker for the current extent of climate migration along the Peninsula.

There is evidence of changes at other trophic levels as well. Antarctic krill and salps are major grazers in the WAP (**Fig 2.9a,b**) and comprise respectively ~70% and 10% of the zooplankton abundance in this region (Ross *et al.*, 2008). The PAL record of zooplankton distributions over the 1993-2004 period suggests salps are increasing their range and frequency of occurrence in the northern region (Ross *et al.*, 2008), although in the last several years this trend has not persisted. While the longer-term trend remains to be elucidated, an increase in salps is likely a direct effect of the ice-free oceanic waters, which are increasingly occurring on the shelf and the preference of salps for ice-free waters. Krill appear to be declining over a larger region in the Atlantic sector (Atkinson *et al.*, 2004), coincident with the sea ice decline. To date, however, krill abundance does not show a trend in the smaller PAL region (Ross *et al.*, 2008).

Community structure, foodweb dynamics and change. As stated above, climate change acts through the physical system of watermass characteristics, circulation and sea ice extent and duration to influence foodweb dynamics by a) bottom-up changes in phytoplankton and zooplankton for predators and b) disrupting phenological connections between predators and their prey. Our observations suggest both processes are occurring along the WAP.

Phytoplankton and zooplankton. It has been suggested that cryptophytes (small naked flagellate phytoplankton) are replacing diatoms in nearshore regions in response to increased glacial melt inputs (Moline *et al.*, 2004), but no long-term trend is evident. Phytoplankton play a major role in elemental cycling especially in the Southern Ocean where past changes in primary productivity have been hypothesized to be a significant factor in past climate oscillations (Martin, 1990; Sigman and Boyle, 2000). Numerical studies suggest that climate change will have a major impact on polar biogeochemistry (Lovenduski *et al.*, 2007) by altering upper ocean stratification (Sarmiento *et al.*, 1998, 2004b) which underlies changes in phytoplankton productivity and community composition (Arrigo, 1999; Boyd and Doney, 2002). These changes will impact on the rest of the ecosystem and regional biogeochemistry by altering particle export and deep-sea sequestration of carbon and other elements (Michaels and Silver, 1988; Legendre and Fèvre, 1995; Ducklow *et al.*, 2001).

Within the WAP, phytoplankton productivity and community dynamics are spatially and temporally complex with distinct phasing according to latitude and regime (**Fig. 2.12).** The bloom typically starts offshore and migrates shoreward following the retreating ice edge, culminating in a large summer bloom in Marguerite Bay (**Fig. 2.13**). In the early years of PAL this large bloom also occurred near Palmer, but it has disappeared from the north in recent years (**Fig. 2.16**; Smith *et al*. 2008). Rates of primary production are strongly enhanced near the coast (**Fig. 2.14**) (Vernet *et al.*, 2008). In the most nearshore waters, the highly productive coastal phytoplankton communities (Moline *et al.*, 2004) appear to be sensitive to the expanding hydrographic fingerprint associated with melting glacial ice (Dierssen *et al.*, 2002). For example, in many Antarctic regions low salinity waters from increased ice melting have resulted in a decrease in the algal size distribution, directly impacting higher trophic levels (McClatchie and Boyd, 1983; Boyd *et al.*, 1984; Quetin and Ross, 1985; Moline *et al.*, 2004). Spatial variability embedded within the nearshore/offshore gradients reflect topographically steered circulation that delivers nutrient-rich UCDW to specific locations, fostering diatom blooms (Prézelin *et al.*, 2000, 2004; Martinson *et al.*, 2008b). Areas of UCDW upwelling near the land margin appear to be biological hot spots associated with deep, cross shelf troughs that are disproportionately important to higher trophic levels (Fraser and Trivelpiece, 1996; Burns *et al.*, 2004; Chapman *et al.*, 2004b; Fraser *et al.,* 2008; Ribic *et al.*, 2008). Large interannual variability in the WAP region is related to the relative position and strength of the climate gradient between the warm moist maritime climate to the north and the cold continental climate regime to the south (Smith *et al.*, 1999). This atmospheric front regulates the intensity and location of storms which then modulates the depth of the upper mixed layer (Smith *et al.*, 2008). Variations in mixed-layer depth driven by changes in sea ice retreat (**Fig 2.15c**) are the principal factors explaining variability in annual production rates (**Fig. 2.15a,b**) (Garibotti *et al.*, 2005; Vernet *et al.*, 2008). On shorter time-scales, the regular year-round observations undertaken by the British Antarctic Survey (BAS) in Ryder Bay, northern Marguerite Bay, and at Palmer Station (both described more fully below) will allow the within-season influence of mixed layer dynamics and glacial meltwater input on primary production to be determined.

A switch from a krill- to a salp-dominated system could significantly alter carbon (C) flux. Salps are non-selective filter feeders that efficiently re-package microplankton into large, rapidly sinking fecal pellets, greatly enhancing the efficiency of C transport to depth (Michaels and Silver, 1988; Pakhomov *et al.*, 2006). Diel vertically migrating zooplankton transport C and nutrients to depth by feeding in surface waters during the day, and descending to daytime mesopelagic residence depths where they metabolize their food. This "active flux" can take the form of defecation at depth (Atkinson *et al.*, 1996; Morales *et al.*, 1999; Schnetzer and Steinberg, 2002) or by respiring and excreting this C in a dissolved form at depth (Longhurst *et al.*, 1990; Zhang and Dam, 1997; Steinberg *et al.*, 2000). Changes in zooplankton community composition, biomass, and distribution in the WAP (as tied to climate change, sea ice dynamics, food availability and other factors) affect penguin populations and other top predators in complex ways. Changes in timing of krill reproduction and recruitment (Fraser and Hofmann, 2003; Quetin and Ross, 2003), krill lipid content, or oscillations between salp or krill as the dominant macrozooplankton prey will affect penguin fledging weight and success (Chapman *et al.*, 2008). A shift from a krill-dominated to salp-dominated ecosystem would have a dramatic effect on ecosystem structure and biogeochemical cycling. As a prey item for higher trophic levels, the chemical energy content of krill (e.g., proteins 65% and lipids 14% of dry weight) far exceeds that of salps (e.g., proteins 5% and lipids 6% of dry weight; Dubischar *et al.*, 2006). Thus, under a low krill, salp-dominated scenario, predators (fish, penguins and other sea birds, seals, and whales) may be unable to meet their energetic requirements, leading to a decrease in some predator populations, as we have observed (**Figs. 2.7, 2.8**).

Top-down disruption of phenologies. From an ecological (as opposed to biogeochemical) perspective, the mechanistic core that holistically underpins the biological responses to climate migration is trophic mismatch theory (Cushing, 1990). The idea that life history strategies remain successful in a changing environment depends on the extent that the evolving spatial and temporal range of variability in the critical resources they require remain viable and do not exceed the thresholds under which they evolved (Fraser and Trivelpiece, 1996; Rhodes and Odum, 1996; Forcada *et al.*, 2006). Within the suite of organisms under study in the PAL region, the trophic level that most clearly exemplifies the conceptual and empirical foundation for climate migration and match-mismatch is composed of top predators, the Adélie, Gentoo and Chinstrap penguins that have been the focal point of our research for more than 30 years (Parmelee, 1992; Fraser and Trivelpiece, 1996; Smith *et al.*, 1999b; Fraser and Patterson, 1997; Patterson *et al.*, 2003). Adélie penguins are a true polar species, with a core range centered in the high latitudes of the Ross Sea and a life history that is critically dependent on the availability of sea ice, especially during winter (Fraser *et al.*, 1992a; Ainley, 2002). Although episodic glacial scour of terrestrial breeding sites has probably biased the record, paleoecological data indicate that in the WAP the longest, continuously occupied colonies (~ 6,000 years) occur in the Marguerite Bay region (Emslie and McDaniel, 2002). The core ranges of the other two species encompass sub-Antarctic latitudes, which in the case of Gentoo penguins actually reach the quasi-temperate regions of the Falkland Islands (~ 51^{o} S, Williams 1995). Chinstrap and Gentoo penguins have life histories that are ice-avoiding (Fraser *et al.*, 1992a; Forcada *et al.*, 2006; Hinke *et al.*, 2007). Indeed, the population trends evident in **Fig. 2.7** for these two species are the product of founder populations only recently established (1976 and 1994, respectively), thus possibly signaling a unique event in the Palmer Station area given paleoecological evidence suggesting that these two sub-Antarctic species have not been present locally for at least the past 700 years (Emslie *et al.*, 1998). The environmental conditions promoting these population increases are unprecedented within the temporal limits of this record.

The common and fundamental element that links these population trends (**Fig. 2.7)**, is the extent to which the life histories of these three penguin species are ice dependent or ice avoiding.. As the timing of sea ice advance and retreat has migrated away from more persistent sea ice conditions, ice-avoiding life history strategies have been favored and the structure of this top predator community has changed accordingly. Explaining these population trends mechanistically, however, lags the empirical evidence, at least at the community level. Analyses focused especially on the longer-term Adélie penguin data, though, have identified 2 critical processes that are operating quasi-independently over local to regional scales and can be linked directly to the effects of rapid climate warming.

Adélie penguin populations in the mid- to northern WAP are all decreasing (Woehler *et al.*, 2001), and there is wide concurrence that these regional-scale trends are coherent with a gradual decrease in the availability of winter sea ice, i.e., a decrease in ice season duration (Fraser *et al.*, 1992a; Fraser and Trivelpiece, 1996; Ainley, 2002; Croxall *et al.*, 2002; Forcada *et al.*, 2006). The exact role played by sea ice in the ecology of this species, however, remains equivocal primarily because few winter studies have been conducted and these have been limited in scope (Fraser and Trivelpiece, 1996; Ainley, 2002; Hinke *et al.*, 2007). In an unprecedented effort to address this gap in our understanding of this species, their movements, distribution and foraging ecology were studied continuously for 24 months using satellite telemetry, at-sea censuses and extensive field collections of diet information (Chapman *et al.*, 2004a; Fraser *et al.*, 2008; Ribic *et al.*, 2008). Two key findings have emerged. The first is that the winter distributions of Adélie penguins and their prey are extremely heterogeneous (**Fig. 2.17**), co-occurring only in regions characterized by a unique combination of deep bathymetry, circulation and upwelling. The second is that access to these "hotspots" is mediated by winter sea ice. This ensues from the fact that Adélie penguins are flightless and do not forage at night, and as a result are extremely constrained in their abilities to search the marine environment for prey during the short day lengths associated with polar winter (Fraser and Trivelpiece, 1996). The absence of winter sea ice close to these hotspots in effect denies this species a platform for access to predictable prey concentrations, implying that as sea ice continues its long-term decline in the WAP, it is spatially and temporally decoupling Adélie penguins from productive winter foraging regions.

A second process clearly implicated in the decrease of Adélie penguin populations, but discovered based on work at Palmer Station specifically, appears to be causally related to increasing snow precipitation in the WAP (Thompson *et al.*, 1994). Snow affects Adélie penguin colonies breeding on landscapes where accumulations are enhanced by landscape aspect and prevailing winds during spring storms. These colonies have, over the last 30 years, decreased significantly faster than colonies where wind-scour abates snow accumulations (Fraser and Patterson, 1997; Patterson *et al.*, 2003). Moreover, using snow fences to artificially enhance snow deposition in experimental colonies (experiments ended in March 2007; data analysis and writing are in progress), we have determined that increasing snow deposition delays breeding chronology and results in chicks whose fledging weights are significantly lighter relative to non-manipulated control colonies. In seabirds, fledging weight has long been recognized as a strong determinant of survival during the first winter of life (Perrins *et al.*, 1973; Jarvis, 1974; Hunt *et al.*, 1986), suggesting this landscape effect compromises future recruitment by affecting the timing and duration of parental food delivery to nestlings. Interestingly, Palmer populations of the ice-avoiding Chinstrap and Gentoo penguins have maintained their sub-Antarctic breeding chronologies (Williams, 1995); hence by breeding approximately three weeks later than Adélie penguins, these two species in effect permit spring melt to circumvent the negative effects of snow accumulation. Likewise, in winter, both species have obviously retained their need to avoid ice-covered waters to forage successfully (Fraser *et al.*, 1992b; Williams, 1995; Forcada *et al.*, 2006; Hinke *et al.*, 2007; Trivelpiece *et al.*, 2007), but the specific foraging and other life history advantages these species have over Adélie penguins within the context of a rapidly changing WAP marine system will require considerable further research.

Thus, since our last renewal proposal, our thinking regarding the demographic responses of these three penguin species (**Fig. 2.7**) to WAP climate change has been revised in 2 fundamental ways. The first is that while variability in sea ice seasonality still emerges as a key, large-scale deterministic factor, the mechanistic processes responsible for regulating populations (e.g., landscape changes) appear to operate over much smaller scales. The second, not unrelated to the first, is that without integrating a more comprehensive food web perspective into our research, these processes are not likely to be elucidated. Although this may seem intuitively obvious, we now have empirical evidence that the food web at mid-latitudes of the WAP (Palmer Station) is compromised relative to past decades, having experienced both a loss of critical prey species (e.g., Antarctic Silverfish, **Fig. 2.6a**) and possibly significant decreases over a large geographic region in the abundance of remaining important prey (e.g., krill; Atkinson *et al.* 2004). Indeed, model simulations parameterized with these data clearly show that even subtle changes in food web structure and/or prey quality and availability can have significant negative consequences to key demographic parameters such as penguin fledging weights (Salihoglu *et al.*, 2001; Chapman *et al.*, 2008).

Biogeochemistry and microbial processes. As suggested above, climate-driven changes in lower trophic levels (phytoplankton and zooplankton) have the potential to force changes in biogeochemical cycling. Sedimentation has been monitored year-round at a single site in the northern study region since 1993 and dissolved inorganic carbon has been monitored along the core grid since routine cruise-based sampling started in the same year. However no systematic microbial data were produced before 2002, when bacterial production and dissolved organic carbon measurements were initiated to provide a reference from which potential change could be evaluated. In general it appears from our observations that changes are appearing earlier and more conspicuously at higher trophic levels (predators) than at lower levels and in biogeochemical cycling.

As a result of intense net primary production (NPP), the PAL region is a net sink for atmospheric CO_2 in summer (Carrillo and Karl, 1999; Carrillo *et al.*, 2004), with the region averaging $\Delta p CO_2$ (sea minus air difference) of -50 to -100 μatm (1993-2006). Biological activity is the main control of air-sea CO_2 gradients explaining >80% of the ΔCO_2 variability (Montes-Hugo *et al.*, 2008a). The NPP averages 170 gC m^{-2} over the 180-day, October to April growing season at Palmer Station (1993-2006; Ducklow *et al.*, 2007), and ~800 mgC m^{-2} d^{-1} over the PAL grid in midsummer (200-600 lines, January-February 2003-07). The atmospheric CO_2 sink was more intense closer to the coast and in the southern part of the study area where phytoplankton biomass, as estimated from Chl-a concentration and primary production were generally higher. $\Delta p CO_2$ is near zero offshore of the shelfbreak where high-$p CO_2$ UCDW water upwells onto the shelf, especially in the north. Diatoms are the major contributor to observed $\Delta p CO_2$ variability. In general, larger $\Delta p CO_2$ gradients were associated with large (>20 μm) phytoplankton, again indicating the importance of plankton community structure on system processes. Measurements between 1997 and 2006 suggest a positive relationship between sea ice extent (previous winter), Chl-a, average cell size of phytoplankton assemblages, and the relative proportion of diatoms with respect to cryptophytes (fucoxanthin/alloxanthin) (Montes-Hugo *et al.*, 2008a). These relationships suggest the potential for climate-driven changes in community structure to influence biogeochemical cycling in the Southern Ocean

Less than 5% of the annual production is exported from the surface layer (the e-ratio) on the midshelf in the northern study region (Ducklow *et al.*, 2008). The fraction of the NPP grazed by mesozooplankton is uncertain. (Daniels, 2003) estimated from an inverse foodweb reconstruction that krill removed about 40% of the PP, but the figure is poorly constrained by experimental measurements of ingestion. This leaves at least 50% of the PP unaccounted for. Other potential sinks include microzooplankton grazing, microbial breakdown and horizontal advection. It is also possible that the moored sediment trap underestimates the export (Buesseler *et al.*, 2007a) but even a very liberal 2 to 4-fold undercollection rate would leave a low e-ratio and a large gap in the carbon budget. The annual export is dominated by a seasonal pulse with >75% of the total flux occurring in the ice-free season (**Fig. 2.10**). The export term is not known in the southern region, where we believe climate change has not influenced the ecosystem as much as in the north and where the phytoplankton assemblage is more diatom-dominated. We believe that the low export efficiency is due to a combination of zooplankton and microbial turnover of particulate detritus. There was no relationship between the annual flux and krill abundance, but 1997, the lowest flux year except 2005 (**Fig. 2.11**), coincided with the highest krill abundance in our records. Conversely, the high flux years of 1995, 98, 99 were all low krill years. Intense particle removal by zooplankton (Lam and Bishop, 2007) both directly reduce the export flux by consumption and particle size reduction (Goldthwait *et al.*, 2004), and indirectly reduce it by stimulating the exoenzymatic activities of particle- and aggregate-associated bacteria. These in turn degrade both particles and the exopolymeric material that binds particles into large, rapidly-sinking aggregates (Hoppe *et al.*, 1993; Murray *et al.*, 2007).

Bacterial production rates (principally free bacteria measured in small-volume incubations) average <5% of the concurrent NPP (from $DI^{14}C$) rates, much less than in most oceanic systems (Ducklow, 1999, 2001). Using a conversion efficiency of 30% for freshly-released dissolved organic matter (DOM) (Carlson *et al.*, 1999), the bacterial carbon demand (gross production or total utilization) is <25% of NPP. There is little seasonal accumulation of semilabile DOM and together these observations indicate that the majority of NPP in the system is routed through the particulate carbon pool (Carlson *et al.*, 1998; Ducklow and Yager, 2007). Our routine bacterial production assays may neglect the bacterial activity associated with particles, principally because small-volume collections undersample large particles that could harbor higher bacterial activity. Intense particle-associated bacterial activity was deduced from carbon budgets in the subarctic north Pacific (Boyd *et al.*, 2004). The bacterial production rate is highest near Anvers Island (**Fig. 2.9c**) where the effects of regional warming have been most apparent (e.g., **Fig. 2.18**). Future research will emphasize continued monitoring of total bacterial production across the grid, experimental investigation of factors limiting bacterial growth (e.g., carbon limitation, (Church *et al.*, 2000), and bacterial turnover of suspended and sinking particles. In a separate but closely related project, we are investigating the factors influencing bacterial community composition, in particular how and why it changes from a high-diversity, low-abundance community in winter to one dominated by a few higher abundance phylotypes in the summer.

Proposed Research

To capture the great temporal and spatial variability in ice-ocean properties, we will continue the regional-scale, multi-platform approach long employed by PAL (**Table, 2.2**; Smith *et al.*, 2001). The long-term satellite data and shipboard observations made on the midsummer cruises form the foundation of our conceptual and empirical approach to understanding the dynamics of the marine ecosystem of the WAP, as described above. We now propose to extend and augment our existing observational program combining our traditional research vessel, land-based (terrestrial and small boat) and satellite observations with new autonomous moorings and Slocum Webb gliders (Schofield *et al.*, 2007); and complement all these with experimental process studies and a new modeling component.

To quantify the impact of regional warming on the WAP ecosystem, data will be collected across the full climate gradient along the WAP in both space and time. Additionally, processes studies will sample localized “hot-spots” and “cold-spots” of biological activity to place the importance of "hot-spots" in context within the wider PAL sampling grid. Spatial data will be collected from Anvers Island to south of Marguerite Bay and the temporal sampling footprint will span the productive summer ice-free season. Seasonal dynamics in the northern and southern regions will be provided by comparative studies conducted in the Palmer and Rothera time series programs, which will also be compared to the high frequency seasonal data collected by the moorings deployed across the WAP. Detailed year-round observations of ecological process are made by the RaTS project at Rothera. We will combine all available international satellite data (see below) with at least four months of regional subsurface glider data, moorings and the annual January ship-based hydrographic grid. In concert this multi-platform sampling regime will provide an extended spatial and temporal data base spanning the WAP climate regimes, complement the historical time series and enable the proposed modeling studies. Specifics of the sampling strategies are outlined below.

Long-term Observations.

Shipboard sampling strategy. Our core and other measurements are detailed online (http://pal.lternet.edu/publications/documents/protocols/). We will expand the existing suite of measurements to include micronutrients (Fe), ocean δ^{18}O, and stable isotopes in penguin tissues and their food sources. Also we will alter the sampling grid, as suggested above, to address all 3 of our motivating hypotheses. In particular, we will extend our shipboard sampling farther south to encompass less-altered conditions while maintaining critical long term core observations to the north. Even so, we will devote more of our fixed shiptime allocation (28 science days per year aboard LM GOULD accommodating 22 scientists[*]) to mechanistic process studies during each year’s cruise, and less time to traditional hydrographic operations. Due to shiptime constraints, sampling over a larger region will require redesigning the traditional PAL sampling grid. Shiptime and transit allowances show that we can extend our sampling to the PAL 000 line west of Charcot Island (**Figs. 2.1, 3.1;** 69S, 73.5W to 68.3S, 75.1W, 200 km south of the limit of current routine sampling at the 200 line). Design of the new grid will be a group process

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[*] 10 additional days are reserved for transit, setup and packing. Two of 22 berths in any year are for non-LTER scientists with NSF-funded programs, or to observers from Chile or Argentina (US State Dept requirement).

aimed at best capturing the climate and ecosystem processes across the expanded study region and will build on knowledge gained with our previous 16-year record of observations. Optimal sparse sampling of the present grid will follow the work of (Evans, 1999), employing the reduced space optimal analysis of (Kaplan *et al.*, 1997, 1998) who shows that subsampling captures most of the full grid variance if positioned at the locations of maximum variance in the lowest order modes (i.e., highs/lows in EOF maps of the variable of interest; though we have the added advantage of grid-wide autonomous sampling of physical properties and Chl-a fluorescence through our proposed glider fleet).

The grid optimization is somewhat complicated by the fact that the different variables of interest do not necessarily display the same empirical orthogonal function structures (Martinson *et al.*, 2008b), as shown in our collected papers for the first 12 years of data (see Results/Prior section). To develop a subsampling scheme that best captures the most covariance of this multivariate system with the fewest stations sampled, Kaplan will develop the spare grid optimal solution, modifying his approach to include a global optimization involving simulated annealing, as he did when he developed the optimal number and location of sensors for our recently deployed moorings. The analysis will be completed before the January, 2009 cruise. Climate change is plagued with uncertainty, not the least of which, is if the change will project itself onto existing climate patterns, or manifest in new ones (NAS, 2008). This is a question regarding the stability of the covariance structure during change. To date, it appears that on a global scale, the change is being projected on existing patterns (e.g., ENSO still exists, though perhaps its frequency and intensity is changing). We assume that an ability to preserve a stable covariance structure on our smaller scale grid holds even stronger than on the global scale. We propose to check this assumption (for as long as we need good representation of variables across our existing northern grid) in a standard manner. Specifically, we intend to continually optimally fit our lowest order EOF structure onto the subsampled grid in the north, and examine the residual mean squared (rms) of the fit (following Kaplan *et al.* 1997, for testing construction of a >100 yr SST reconstruction). If the rms exceeds our required precision, we will plan to resample the existing grid completely for refining the covariance matrix at the heart of the optimization (maintaining our southern presence with our fleet of gliders).

The southern extension of the grid will allow sampling in regions not yet experiencing climate change to the extent it has been observed in the north, thus possibly reflecting the conditions that influenced the northern region when the PAL project began in 1990. We will then be in a better position to capture the early changes in physical forcing (ideally, tracking its path through the physical system: ocean, sea ice and atmosphere). Some changes may already be underway, which we will not know until we move to the south. If we find that to be the case, we will continue to expand southward in search of representative pre-change conditions within the limit of viable summer sampling (i.e., shipboard time). This southern extension of the grid will allow us to directly address all 3 of our motivating hypotheses. In particular, hypotheses 1 and 2 demand sampling in a region that has not yet undergone the change experienced in the north. Hypothesis 3 will allow us to test our understanding of trough processes by evaluating previously unsampled troughs in the south, especially near the penguin colony on Charcot Island (**Fig. 3.1**). Our current understanding suggests that over the next funding period we will demonstrate that there are spatially and temporally predictable food resources for top-predators such as penguins near the head of such troughs.

Satellite observations. Data from the international constellation of satellites will be collected and used to generate the traditional satellite proxies (sea surface temperature, sea ice, Chl-a, phytoplankton productivity, spectral backscatter and absorption), novel new satellite proxies (particle size distribution; e.g., (Montes-Hugo *et al.*, 2007, 2008a, 2008b), and bio-informatic derived water mass maps (Oliver *et al.*, 2004). Although there are limitations to remote sensing in these waters, the annual cycle of primary production and water mass distribution can be elucidated when analyzed alongside ship and glider data. See the Modeling and Synthesis section below for additional discussion of remotely sensed data.

Glider Program. Gliders are autonomous vehicles programmed to swim along prescribed tracks in the upper ~100 meters, making ~60 vertical profiles over ~30 km each day. Buoyancy-driven propulsion affords high efficiency battery use and low energy consumption. The satellite surface and shipboard observations will be augmented with subsurface seasonal data to be collected by long duration Webb gliders, capable of traveling 600-800 km/battery (**Fig 2.19**), which have been demonstrated to be robust vehicles in these waters (Dubinsky and Schofield, 2008; Martinson *et al.*, 2008a). Rutgers personnel will provide a minimum of two gliders to the program during the field season; and efforts are underway to accumulate a dedicated fleet of gliders for the WAP science community. Prior to the annual January cruise, two gliders will be deployed from Palmer Station for a pre-cruise phase. These gliders will be outfitted to measure temperature, salinity, depth-averaged and surface currents, spectral backscatter, spectral irradiance, Chl-a and Colored Dissolved Organic Matter fluorescence (CDOM). One pre-cruise glider will conduct a ~45-day survey on a southerly transect along the WAP once the annual ice field opens (determined by satellite), then will survey the northern lines of the historical PAL ship sampling grid. A second glider will map the dynamics over the Palmer Deep canyon south of Anvers Island (**Fig 3.1**). The subsurface data will enable sample planning prior to the beginning of the cruise. Data will be transmitted, analyzed, and then delivered to all PAL personnel. Both gliders will be recovered and then redeployed to complement cruise-based observations. During the ship surveys, one glider will be outfitted to measure fluorescence kinetics (Fv/Fm), using a recently developed system by Satlantic and Rutgers. The two gliders will survey southern regions of the ship sampling grid by transecting to and collecting data over the southern deep troughs prior to each process study. After the cruise a second glider survey will be conducted from Palmer station to expand the spatial sampling season into early March. As technology matures, through separate funding, efforts will be made to develop a year-round presence which will require a capacity to operate within and under ice. The gliders will be outfitted to make measurements to 500 meters depth. We will use the new stretch-body glider developed by Webb Research and Rutgers to extend battery life in cold water.

Moorings. The PAL observing system now includes five ocean moorings deployed in 2007-08 (**Fig. 3.1**). The moorings, which will sample at 10 minute intervals for the entire year, are situated to help us carefully monitor the change in ocean heat content (**Q**) on the continental shelf. Ocean heat is available via the shelf to melt the marine terminus of the glaciers and to vent to the atmosphere, thus potentially contributing to the observed retreat of marine glaciers and the unprecedented winter warming, respectively. The mooring strings are fitted with SeaBird temperature sensors, some including pressure. Sensor location on the strings was driven by our desire to most accurately document the temporal change in sub-pycnocline ocean heat content ($\mathbf{Q} = \int_{z_p}^{z_b} \rho c_p T(z)dz$; where z_p is depth of permanent pycnocline, and z_b is shelf bottom). This is where the main body of modified UCDW— the T_{max} water and source of ocean heat — resides. The moorings (except for mooring #5, at the southern end of Adelaide Island) are situated in water approximately 450 m deep. Each mooring has 17 T sensors that have been vertically positioned using the Kaplan *et al.*, (1997) optimal analysis. In particular, we desire the most accurate estimate of Q using fixed-depth sensor locations. Based on analysis of the previous 14 years of CTD profiles at the mooring locations, the optimal analysis provides the global optimum (through simulated annealing) placement of the 17 sensors to most accurately capture Q (results of this methodology are being prepared for publication showing a general method for optimal fixed–depth sensor placement on lined–sampling platforms; Kaplan, Martinson, Iannuzzi, in prep).

Mooring locations were dictated by our previous data analyses suggesting where the UCDW enters the continental shelf, predominantly through the troughs (especially, Marguerite Trough, also documented by (Klinck *et al.*, 2004). Moorings #1&2 are designed to capture UCDW after it fills the trough and begins to flood onto the nominal shelf bottom. Moorings #3&4 serve a similar purpose, with #4 also being near the head of a northern fork of Marguerite Trough as it merges onto the shelf floor in the vicinity of one of the penguin colonies. Mooring #5 is located on a branch off of the southern fork of Marguerite Trough, again situated near a penguin colony.

We propose to add a second sediment trap mooring in the southern study region, likely near Charcot Island (see Process Studies, below). The new trap will be deployed about 2-3 weeks following the northern trap each year, but the collection intervals will be synchronized between the two traps.

Palmer and Rothera Station Oceanographic and Biological Time-Series (RaTS). At Palmer Station, PAL carries out detailed, intensive studies of penguin breeding biology, foraging ecology and demography in the Anvers Island colony (**Fig. 3.1**). In support of this research we also carry out semiweekly sampling of phytoplankton and bacterial production rates and water column properties at nearshore stations accessed by Zodiac. This research extends from mid-October until the end of March each year (**Table 2.2**). In the winter weekly samples are taken at a near shore intake for Chl and $\delta^{18}O$. This work is necessarily limited to one geographic location, but it will now be enhanced and supplemented by regional-scale glider-based sensing of selected physical and optical properties to help define the surrounding environment. Complementary research is carried out in the south, in the Rothera Oceanographic and Biological Time-Series (RaTS) project run by the British Antarctic Survey at Rothera research station. The RaTS project involves year-round, quasi-weekly observations at a fixed oceanographic station in Ryder Bay, northern Marguerite Bay. Each event consists of a CTD cast with associated fluorometer and PAR sensor, and a Niskin water bottle sample from 15m (which is the climatological depth of the Chl-a peak). The water sample provides data on size-fractionated Chl-a (with cuts at 20, 5, 2 and 0.2 microns), macronutrients and DOC. It is also used for determination of $\delta^{18}O$, which is a powerful tracer of freshwater origins in polar regions (Meredith *et al*., 2008a). In addition there are associated biological observations, including feeding activity in a range of suspension feeders, and reproductive output in selected benthic invertebrates. Comparative studies have shown that the water column in Ryder Bay receives modified UCDW, and both the thermal behavior and primary production at the RaTS station are broadly representative of those in northern Marguerite bay. In contrast the ice dynamics are controlled predominantly by local topography and weather.

Numerous linked projects (of finite duration) have been created and executed alongside RaTS, and using RaTS infrastructure. These include studies of particle fluxes, bromocarbon gas production, carbon fluxes, and ocean internal waves and mixing. As part of these studies, sediment traps and marine physics moorings will be *in situ* at the RaTS site and farther offshore on the WAP over the next few years, and will provide further connection between RaTS and comparable PAL activities.

The overarching aims of the RaTS project are twofold, to provide environmental data as context for the range of marine ecological projects undertaken at Rothera, and to document the variability in the dynamics of water column physics and Chl-a on seasonal, interannual and longer timescales. Analysis of the first decade of data (Meredith *et al*., 2004; Clarke *et al*., 2008) have shown that the influence of ENSO variability, which is seen clearly across the WAP area, is also evident on a small scale in Ryder Bay. Corresponding analyses using remotely-sensed data have elucidated the oceanic, atmospheric and cryospheric processes whereby ENSO variability, and also variability associated with the Southern Annular Mode, impacts on the WAP around the RaTS site, and the broader Pacific-Atlantic sector of the Southern Ocean (Meredith *et al*., 2008).

The value of the Palmer Station and RaTS observations is that they provide 1) comparative data on processes in the north and south of our study region and 2) data at high temporal resolution to supplement the wide spatial coverage of the PAL grid. In particular, RaTS directly monitors winter processes that can only be inferred from PAL grid data. In terms of the three PAL hypotheses, the RaTS data from Ryder Bay will provide detail of the functional links and phenological relationships between ice dynamics, the timing of the phytoplankton bloom, and grazing by zooplankton (Hypothesis 1). The data series since 1997 should also provide a valuable baseline in terms of a quantitative assessment of natural variability in the northern Marguerite Bay system before climate migration has had a strong effect (Hypothesis 2).

Experiments and Process studies.

Overview. As previously discussed, manipulative experiments in the marine ecosystem of the Antarctic sea ice zone are not generally feasible for a variety of logistical and other reasons and are well beyond the scope that can be supported by this proposal. Fraser however conducted a manipulative study on land near Palmer Station by dividing two penguin colonies with snow fences to test the impact of increased and reduced snow accumulation on penguin breeding success and fledging weights. As an alternative to manipulative studies in the ocean itself, we propose an ongoing series of *process studies* to address hypotheses about ecosystem responses to climate change in our study region. A shipboard process study involves occupation of a station or region with intensive repeated sampling and measurements of temporal changes in scalar properties and rate processes. Examples of process studies include the JGOFS North Atlantic Bloom Experiment (Ducklow, 1989; Ducklow and Harris, 1993) and the recent VERTIGO experiment in the North Pacific (Buesseler *et al.*, 2007b; Steinberg *et al.*, 2008a, 2008b). Over the next six years of fieldwork proposed here, and in addition to our continued long-term research at Palmer Station, we will address each of our three primary hypotheses by devoting about half of each midsummer cruise to intensive process studies in selected areas, including 3-5 day field camps at nearby penguin colonies. Figures **2.6b** and **2.20** are examples of changing north to south trends in food web patterns based on data from past field camps. Each study will be repeated over several years to gain an understanding of the scale of interannual variability of foodweb processes and to gain multiple realizations of each type of study. Supporting parameter determinations and manipulative studies will also be carried out using experimental mesocosms at Palmer Station (e.g., (Carlson *et al.*, 1999; Ducklow *et al.*, 1999). Our process studies will focus on the deep, cross-shelf troughs arrayed north to south in the PAL study region (**Fig 3.1**). The rationale and plans for these process studies are explained below.

Trough system physical and biological properties. The WAP continental shelf is about 500 m deep at the outer edge and remains near this depth until the inner shelf where it shallows to about 200-300 m (**Fig. 3.1)**. The area is characterized by complex circulation (**Fig. 2.21**) and deep cross-shelf troughs or canyons that extend from the land margin to the shelf break. These troughs form ecological domains with unique physical and biological properties that appear to be disproportionately important, in terms of their relative areal extent, to the WAP ecosystem. A shallow (250-350 m) plateau near Renaud Island that separates the shelf into northern and southern regions is noteworthy because of its effects on circulation. Bathymetry and circulation separate the oceanic environments associated with the trough systems in the northern and southern regions of the PAL grid. Although the regional surface circulation consists of a large-scale, clockwise gyre that is continuous above 200 m, below this depth the circulation is bathymetrically steered by the Renaud Island plateau and forms two clockwise flowing sub-gyres. The northern sub-gyre is superimposed over the Palmer Deep near Anvers Island, while the southern sub-gyre is superimposed over the remaining trough systems to the south (Smith *et al.*, 1999a; Beardsley *et al.*, 2004; Klinck *et al.*, 2004; Martinson *et al.*, 2008b). Evidence suggests that the relative composition of the prey field in the two areas is different (**Fig. 2.6**), and in the case of krill in particular, may encompass populations that are quasi-independent as a result of retention by shelf circulation (cf. Fraser and Hofmann, 2003), a pattern that has also been observed near the northern tip of the Antarctic Peninsula (Siegel *et al*. 2004).

Process Study Sites. Because all three of our hypotheses share climate migration and its effects on ecosystem response as a common theme, we will site our process studies in the vicinity of three of these troughs along the north-south gradient of our sampling grid (**Fig. 3.1**). The first, northernmost site, and the best studied among the three, encompasses the Palmer Deep off Anvers Island (Leventer *et al.*, 2002) on which Palmer Station is located. Food web dynamics are dependent upon the distribution of water masses in this region. The waters in the vicinity of Palmer Station appear consistently anomalous reflecting a nearly complete loss, or non–development, of cold Winter Water (WW; **Fig 2.18**). In the absence of WW, the coldest waters present in the January water column are significantly warmer than -1ºC. Loss of WW in this region has likely benefited one prey species (lanternfish) at the expense of another (silverfish), leading to the disappearance of silverfish from Adélie penguin diets (**Fig. 2.6**). The reason for the lack of WW near Anvers Island is unknown, with suspicions leaning toward reduced sea ice cover in the winter (producing a smaller volume of WW), or import of waters from an area where WW is not fully formed. Results from our 2007 SLOCUM glider flight shows that the anomalous water originates from east of Anvers Island (Martinson *et al.*, 2008a); though it is not clear if the water is flowing out from coastal (glacier) embayments, or flowing through Gerlache Strait from north of Anvers Island into the southern location. We intend to locate and document the source of this anomalous water in an attempt to understand the mechanisms responsible for the lack of the ubiquitous (in fact, defining) WW, so that we might anticipate future changes to the food web elsewhere given similar conditions leading to the lack of WW. This will be accomplished by CTD and glider surveys in the Palmer-Gerlache Strait region.

The second site is 400 km south and includes the less well known Marguerite Trough, a trough system off Adelaide Island where field camps have been in operation (on nearby Avian Island) annually since 1995. Adélie penguins from the large colony on Avian Island forage at the head of Marguerite Trough (**Fig. 2.17**). The third site is at the southern boundary of our new proposed sampling grid south of Marguerite Bay. Located off Charcot Island, this trough system was briefly investigated in winter 2001 during Southern Ocean GLOBEC program investigations (Hofmann *et al*., 2001). Adélie penguins breed on nearby islands at the head of this trough (Woehler, 1993), but otherwise few data exist for this remote and still ice dominated region.

Our choice of these sites is motivated primarily by Hypothesis 3 and by the location of penguin foraging areas near the heads of the troughs. This association cannot be explained by a shortage of potential breeding habitat. As flightless predators, Adélie penguins are highly constrained in their abilities to broadly search the marine environment for prey. The extreme heterogeneity evident in the distribution of their breeding populations, winter aggregations and foraging ranges in the PAL grid (**Fig. 2.17)** may reflect the equally heterogeneous distributions of the key biophysical features and processes that structure the food webs on which they depend (Fraser *et al*., 2008). The north to south distribution of these troughs provides an ideal natural laboratory to investigate causal mechanisms associated with the further effects of climate migration on foodweb processes and Adélie penguin population ecology. We postulate that the causal factors fostering this association are likely related to biophysical processes that are unique to the marine environment associated with these trough systems. For example, we know that diatom blooms occur over the troughs (Prézelin *et al*., 2004), and we will investigate processes such as upwelling of iron-rich UCDW as one of the factors contributing to the diatom blooms.

Process study activities. To address these dynamics and their implications for the 3 hypotheses being tested, process studies will incorporate complementary marine and terrestrial components. The marine component will sample during each January cruise for approximately four days at each of the three process study sites. The terrestrial component will concentrate on the two southern sites, with work at the northern site (Palmer Station) on-going between October and April. Activities associated with the terrestrial component will focus on Adélie penguin demography and foraging ecology, using established protocols. The protocols and instruments will provide comparable metrics (e.g., **Fig. 2.6, 2.17**) between sites on population status and breeding chronology; chick population age structure, body condition and diet composition; and foraging trip duration, depth, location and basic water column properties (temperature, salinity and turbidity). Penguin studies will include stable isotopic composition of tissues and diet, as described further below.

Turning to the marine component of the process studies, we will perform a suite of shipboard measurements and experiments at each of the study sites that will address each of our three primary hypotheses. The 4 days dedicated at each of these three sites will allow time for multi-day experiments and a number of measurements in addition to those performed during our regular grid sampling, such as detailed grazing rate determinations, zooplankton protein and lipid content and phytoplankton-bacteria coupling via DOC excretion and uptake. The multiday process studies will also enable more detailed, higher-resolution hydrographic surveys to define watermass properties and circulation in each region. For example, in the Palmer Station area a key focus will be to investigate the source areas of warm water and explain the loss of WW from this region. An important element in this effort insofar as testing Hypothesis 3, will be to sample both within and outside the primary summer foraging ranges of Adélie penguins, and to compare findings with those of the land-based studies. These studies will be complemented with spatial data from gliders collected prior to and after the PAL cruise.

To support our regular grid measurements and address our hypothesis concerning climate-induced shifts in species distributions, trophic relationships, and biogeochemical cycling along the north to south gradient (Hypothesis 1), one focus of our process studies will be on plankton and higher trophic level community structure and resulting changes in flows of C and N along the climate gradient of the WAP, and on comparing the controlling mechanisms and strength of the biological pump in the three study regions. At each site we will measure key rate processes for various components of the food web (from bacteria to key penguin prey species) and the biological pump (i.e., sinking particle flux, active transport by zooplankton diel migrators, vertical advection of DOM; Ducklow *et al.*, 2001). Our results will allow us to compare the contribution of these processes to overall pump strength and efficiency along the climate gradient, and to predict future effects of climate change on the WAP as an atmospheric C sink.

At each of the three sites, this will involve measurements of primary production, bacterial production and respiration, zooplankton grazing, photosynthetic competence (Fv/Fm), seawater oxygen, pCO_2, dissolved inorganic carbon, and alkalinity, inorganic nutrients including dissolved iron, DOM, stratification, and phytoplankton and zooplankton community structure. Nitrogen and iron uptake, and the corresponding photosynthetic productivity and growth rates will be experimentally measured on natural communities in order to improve parameterizations of resource limitation-based productivity models for the major bloom forming taxa within the PAL study zone (Tozzi *et al.*, 2004; Litchman *et al.*, 2007). These incubations will be complemented with measurements of dissolved radiolabeled organic carbon exudation rates (Moran *et al.*, 2001).

Zooplankton feeding and fecal pellet production rate experiments will be performed in order to measure the contribution of zooplankton to particle consumption and transport to depth. Active transport of C and nutrients by zooplankton diel vertical migration will be estimated by day/night tows with a MOCNESS zooplankton net system (Steinberg *et al.*, 2000; Steinberg *et al.*, 2008a). A new sediment trap mooring in the southernmost site (**Fig. 3.1**) is an important part of our overall strategy to compare the N vs S regions of the study area. The moored trap collections will be complemented by short-term floating sediment trap deployments (Buesseler *et al.*, 2007b) at each process study site. The floating trap arrays allow cost-effective sampling of the flux at several depths to evaluate the export efficiency (flux at depth/surface export flux) within and outside trough areas. We also plan to examine the biological processes controlling particle transport efficiency at the two sites (e.g., bacterial vs. zooplankton metabolism of sinking particles; Steinberg *et al.*, (2008b). Over time, we expect to build up a much more detailed picture of foodweb structure and dynamics, carbon transport and transformation than we can achieve by fragmentary snapshots obtained at the routine hydrographic stations.

New measurements. Our traditional list of core measurements (http://pal.lternet.edu/publications/documents/protocols/) conducted at each grid station will be augmented with new analyses of several additional properties. We will complement the existing hydrographic profile data by incorporating a wider suite of bio-optical measurements made with a spectral Wetlabs absorption-attenuation meter (9 wavelengths), two Wetlabs backscatter sensors (6 wavelengths), and a Satlantic hyperspectral radiometer (downwelling irradiance and upward radiance). These data will be used to calibrate remote sensing and glider data allowing enhanced extrapolation of the data in both space and time. The data will be inverted to provide optical proxies which have proven to be a powerful tool to augment the limited number of discrete samples that are collected during the standard ship surveys (Schofield *et al.*, 2004, 2006). The ship-board data will also be complemented with a surface mapping spectrometer system that will be incorporated into the ship's seawater sampling system.

We will add measurements of dissolved trace metals using ICP-MS (Field *et al.*, 1999), to evaluate the importance of trace metal limitation on rates of primary production. It has been hypothesized that coastal Antarctic phytoplankton are iron-limited, particularly later in the season (Sedwick and DiTullio, 1997; Vernet *et al.*, 2008). Iron-containing dust accumulates on the sea ice during the winter and is released into the water when the ice melts, triggering blooms. When blooms sink, they deplete surface waters of iron, hypothetically rendering late-season phytoplankton iron-limited. Systematic sampling across our sampling grid in midsummer (January-February period) will help us evaluate this idea. We propose to measure lipid content of krill and other dominant macrozooplankton (Hagan *et al*. 2001, Dubischar *et al*. 2006) to investigate how hypothesized changes in chemical energetic content of prey, and oscillations in relative prey abundance (e.g., krill vs. salps), affects penguin fledging weight and success (Chapman *et al*. 2008).We also propose new analyses of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope signatures in Adélie penguin chick tissues (toenails) and the prey they consume. As shown by preliminary data (**Fig. 2.20**), there may be fundamental, climate-induced differences already evident in nutrient sources, biogeochemical cycling and food web structure between the northern and southern regions of the PAL grid.

Modeling and Synthesis.

The PAL data set offers a unique context for building, testing and applying numerical models of marine ecosystem dynamics spanning a wide range of trophic interactions and in a region of substantial natural and anthropogenic climate change. It also provides an important end-member for comparison with other marine ecosystems. A new synthesis and modeling component will be added to the program to help integrate the individual field and remote sensing observational efforts, quantify mechanisms, and develop future projections for the response of the WAP ecosystem to climate change. The biological-chemical-physical modeling component will involve a combination of three complementary research tools, pursued in parallel: forward and inverse box models, a generalized vertical 1-D modeling framework and a 3-D regional ocean general circulation model. The box models and 1-D model will be used for data analysis, development of new model components and exploration of specific hypotheses. The 3-D work will build from lessons learned in 0-D and 1-D and will be used to interpret and provide a spatial-temporal context for the field observations and to examine biological-physical signals arising from natural climate variability and climate change.

A 1-D ocean-ice physical model has already been constructed for the WAP region using the K-Profile Parameterization (KPP) upper-ocean mixing model (Large *et al.*, 1994) linked to the thermodynamic component of the Community Climate System Model (CCSM) sea-ice model (Breigleb *et al.*, 2004). Preliminary work is underway using the vertically coupled 1-D ice-ocean model to assess the seasonal sensitivities of the ocean-atmosphere-ice system, in particular the predicted consequences of changing atmospheric surface forcing for ice mass balance and ocean heat ventilation (Stammerjohn *et al.,* in prep). A regional 3-D ocean-ice model will be developed from pilot simulations for the WAP using the Regional Ocean Modeling Systems (Shchepetkin and McWilliams, 2005). The physical simulations will be driven with time-varying atmospheric forcing based on the NCEP/NCAR atmosphere reanalysis and satellite data products (Large and Yeager, 2004). We will leverage existing and future planned global ocean and coupled ocean-atmosphere-sea-ice simulations from the CCSM as initial and lateral boundary conditions and atmospheric forcing for the WAP simulations. Within CCSM, we have available currently ocean-only historical hindcast simulations (1958-present) (Doney *et al.*, 2007) and fully coupled ocean-atmosphere simulations projecting past and future climate change (1820-2100) in response to different anthropogenic CO_2 emission scenarios (Fung *et al.*, 2005; Doney, 2006).

The historical hindcast exhibits substantial skill in replicating Southern Ocean physical variability associated with interannual variations and secular trends. Using CCSM coupled ocean-atmosphere simulations, Boyd *et al.* (submitted) compare interannual climate variability and projected 21st century climate change trends in Southern Ocean surface waters for a suite of physical/chemical variables relevant to phytoplankton growth (temperature, mixed layer depth, sea-ice fraction, upwelling, pCO_2). Similar to other models, the CCSM predicts significant warming, freshening and acidification of Southern Ocean surface waters over the 21st century due to the rise in atmospheric carbon dioxide (Sarmiento *et al.*, 2004a; Doney, 2006). Other predicted trends include a poleward shift and strengthening of the westerly winds and more positive values for the Southern Annular Mode, a measure of the atmospheric surface pressure difference between the subtropical high pressure and Antarctic low (Le Quere *et al.*, 2007; Lovenduski *et al.*, 2007).

Questions posed by our recent findings are whether the regional climate contrast in the Southern Ocean (and Antarctica) is a response that is (1) geographically imposed and/or tropically forced, and (2) transient or seasonally stationary. The causes of the regional ice-climate changes are implicated in the role of the Southern Ocean with regards to the meridional overturning circulation and the consequent effects on global climate. Further, the regional climate contrast in the Southern Ocean is unlike the widespread warming in the Arctic and poses the question as to whether the WAP warming is a harbinger of polar amplification in the south (that has not yet been fully realized), or whether the WAP region is geographically and physically unique due to local, isolated feedbacks that are amplifying transient (natural variability) trends. To begin addressing these questions, we will, in collaboration with David Rind at NASA GISS, examine global modeled simulations under various climate scenarios. We are focusing in particular on how certain combinations of positive or negative Southern Annular Mode states, together with El Niño or La Niña temperature patterns, might produce the observed ice-atmosphere anomaly patterns that are contributing to the regional sea ice trends. We hope to identify, for example, the planetary wave generation and propagation changes associated with these modes of climate variability, as well as possible local atmosphere-ocean feedbacks that might be affecting the sea ice response.

As a starting point for the ocean biology, we will initially couple the 1-D and 3-D physics codes to a well-tested, global ocean ecosystem-biogeochemistry model (Moore *et al.*, 2004; Doney *et al.*, 2008). This model is primarily focused on bottom-up inorganic carbon-nutrient-phytoplankton interactions and includes multiple phytoplankton functional groups (e.g., diatoms, pico/nano-plankton, coccolithophores, tropical diazotrophs), multiple limiting nutrients (N, P, Si, Fe), and a full carbon biogeochemistry system including air-sea exchange and ocean acidification. For this project, a model variant will be tailored to the WAP ecosystem. One planned model development step is to modify the globally tuned model parameters (e.g., phytoplankton Chl-a/carbon ratios; photosynthesis-irradiance initial slope, etc.) to match better the organisms in the WAP ecosystem, which are known, particularly for biooptical properties, to differ from organisms from outside the Southern Ocean. Preliminary efforts along these lines have already been completed for seasonal ice zone and subpolar sites in the Southern Ocean Pacific Sector (Krishnamurthy *et al.*, 2007), and further refinement will be done using parameter optimization methods (Friedrichs *et al.*, 2007).

The coupled ocean-ice-ecosystem 1-D model will be used to characterize bottom-up ecosystem changes driven by climate migration along the WAP. For instance, we will examine predicted shifts in the phytoplankton phenology, primary production and vertical distribution of nutrients and biomass in response to the shorter sea-ice season. The changes in the timing of sea ice advance and retreat also have strong implications for seasonal air-sea CO_2 fluxes. Sea ice acts to rectify air-sea gas exchange of CO_2 by slowing out-gassing of CO_2 enriched waters in winter and encouraging in-gassing of CO_2 during spring-summer when surface waters are stratified and large phyto- and zooplankton blooms can exist. Our data synthesis and modelling efforts will allow us to test the hypothesis that the seasonal rectification of air-sea CO_2 flux by sea ice has and will continue to decrease in the WAP region due to changes in the timing of sea ice advance and retreat. Our goal is to provide an improved predictive model for ice-ocean-ecosystem interactions, which can be scaled regionally/globally for comparison to other model estimates of global climate change and air-sea CO_2 flux, thereby informing the coarser resolution models with regard to subgrid-scale ice-ocean physics, a more detailed resolution of the seasonal cycle, more complete treatments of ecosystem interactions, and potential climate-carbon cycle feedbacks.

The second model development task will be to expand the functionality of the (Moore *et al.*, 2004) model to better address issues of trophic mismatch driven by climate migration along the WAP. Planned tasks include adding *Phaeocystis* as a phytoplankton functional group, subdividing the present single adaptive zooplankton pool into group-specific zooplankton compartments (i.e., krill, salps, pteropods, copepods), directly treating ocean acidification effects on calcifying organisms such as pteropods (Orr *et al.*, 2005), and incorporating two-way interactions of higher trophic levels and zooplankton to better explore the mechanistic processes associated with observed changes in penguin populations. Here, we will take advantage of relatively advanced modeling approaches for Southern Ocean krill developed under SO-GLOBEC and other programs that incorporate prey age-structure, vertical migration and the timing and frequency of spawning (Fach *et al.*, 2002; Hofmann and Husrevoglu, 2003; Chapman *et al.*, 2008). As indicated by other research (Salihoglu *et al.*, 2001; Fraser and Hofmann, 2003; Chapman *et al.*, 2008), these parameters have the potential to strongly influence penguin population dynamics through interactions between foraging efficiency, adult survival and fledgling mortality and recruitment. Indeed, much in line with one of the themes in this proposal, current model simulations suggest (Chapman *et al.*, 2008) that changes in the phenology of sea ice development and phytoplankton blooms are mechanistically important processes affecting penguin population dynamics because of the effects these changes can have on the quality of the prey field (abundance, availability and energy density). By informing our proposed models with better empirical data on sea ice/phytoplankton bloom phenologies and prey field quality, we see great potential for exploring these implied causal ecological relationships.

The modeling studies will be integrated with the PAL field observations in several ways. Standard model-data skill metrics (Doney *et al.*, 2008) will be used to evaluate model performance against satellite observations and the historical PAL data sets, guiding model development and establishing confidence in model behavior. In particular, we want to assess whether the models can capture the major patterns exhibited in the field data over space (on-shore/off-shore, north-south) and time (ENSO and SAM modes; secular warming trends). The process studies to be conducted in the PAL region will inform the choices for model functional forms and parameter values and test aspects of the underlying model dynamics. For the large number of processes for which data-based constraints are limited, we will use the model simulations to characterize the mechanisms driving observed ecosystem patterns. In particular, we will explore the balance between bottom-up driven forcing (e.g., the links between surface fresh water supply, sea-ice melt, mixed layer depth and phytoplankton blooms) versus more top-down effects, such as shifts between krill and salps or variations in higher level predation.

Future projections for the WAP ecosystem will be conducted using climate anomalies generated from the global CCSM model. We will focus on several specific questions: For different ecosystem indices, when will the anthropogenic climate change driven signal be detectable above the background of substantial natural climate variability (Boyd *et al.*, 2007)? At what rate will the climate-driven ecosystem signals propagate southward along the WAP? Will climate change be expressed as a poleward migration of the intact ecosystem or to what extent will climate change differentially impact different ecosystem components? Are there non-linearities or tipping points in the system which could lead to whole-scale ecological regime shifts and if so what are the implications for ecosystem function? How will ocean acidification impacts interact with those from climate change?

Regionalization, cross-site, LTER Network and other collaborative efforts. PAL has been inherently regional since its inception (Waters and Smith, 1992; Smith *et al.*, 2008; Stammerjohn *et al.* 2008a, 2008b; **Fig. 2.1**). To further enhance our regional understanding we collaborate closely with the British Antarctic Survey program located in the south part of our study region at Rothera Station on Adelaide Island. This relationship is formalized through a Memorandum of Understanding between the NSF and BAS and by including a British Antarctic Survey Senior Scientist as a co-PI in our project (formerly Andrew Clarke, now transitioning to Mike Meredith with Clarke's retirement).

PAL contributed scientific, local geographic and other expertise to the recent initiative to classify the Palmer region as an Antarctic Specially Managed Area (pending) under the Antarctic treaty. PAL scientists participated fully in the two international workshops on WAP Climate Variability (Cambridge, UK, 2004; Boulder CO, 2006). PAL members have been active in the LTER scientific community through serving on standing committees, participation in All-Scientist's meetings and several synthesis workshops including most recently, the creation of the LTER Decadal Plan, including the Integrated Science for Society and the Environment initiative. Ducklow co-organized a workshop at the 2006 ASM on comparative microbial genomics, which later resulted in 2-day workshop at Michigan State (Nov 2007, T. Schmidt, KBS). Two activities form the core of our cross-site effort. We have a close ongoing relationship with the McMurdo Dry Valleys (MCM) LTER and held a 2-day workshop in Estes Park in 2006, outlining a new research plan to investigate simultaneous ecosystem responses to short-term climate variability linked by ENSO. Currently we are planning a new joint workshop to identify themes and explore opportunities for social sciences research involving the public's fascination with Antarctica and concerns about climate change. Our other main cross-site link is CCE, with whom we share our IM PI and Education/Outreach coordinator. Our first collaboration is in the form of a book, "A Tale of Two Krill," for the LTER Children's book series. We are discussing joint comparative and synthesis studies with CCE – a natural project as we are the only two marine pelagic sites in the network. Ducklow co-organized the NSF-LTER Mini-symposium on marine LTERs in 2006, and is an invited speaker for the 2008 symposium.

PAL personnel contributed to several NSF-hosted workshops including the Antarctic Integrated Systems Science (AISS, May, 2007), joint US-Sweden planning workshop for Icebreaker Oden-based research (Feb., 2008), and the Polar Research Roundtable at the George Bush (Senior) US-China Relations Conference (Nov., 2007). Scott Doney, the new PAL PI on modeling and synthesis, will participate in the upcoming international IMBER/GLOBEC Southern Ocean Modeling Workshop (April, 2008). Ducklow will attend the SCAR-BAS Antarctic Gradients workshop in Cambridge UK in May, 2008.

We have had several individual collaborations with other Antarctic researchers who specifically designed programs to interface closely with PAL field operations and use our data. Collaboration with R. Beardsley (WHOI) resulted in new understanding of circulation (**Fig. 2.21**). J. Hollibaugh (UGA) participated in two of our cruises and worked at Palmer Station, investigating nitrifying bacterial ecology (2005-06). We worked closely with the multi-investigator project on DMS sources and sinks (P. Matrai, PI, 2005-06), contributing personnel, measurements, data and local support. Alison Murray (DRI) and Ducklow have a new IPY project at Palmer to compare bacterial genomic adaptations to Austral winter and summer. The summer portion is accommodated within our LTER research. We continue to make space available on our cruises for colleagues who want to collaborate or initiate new joint projects.

Synthesis. PAL research documents whole-scale shifts in the physical climate and higher trophic level dynamics within the west Antarctic Peninsula ecosystem and outlines hypotheses linking observed changes in response to interannual climate variability (ENSO, SAM) and anthropogenic climate change. While maintaining the historical core PAL measurements, we propose to explore and test in more detail the mechanisms governing climate-biological interactions using an integrated research program of spatially and temporally enhanced long-term observations, targeted process studies, and synthesis and numerical modeling. A major focus will be to unravel some of the unique aspects of the WAP ecosystem, including the strong dependence of many species on the distribution and timing of seasonal sea-ice cover and the geographic concentration of biological activity over canyon systems associated with the underlying topographically controlled upwelling field. The underlying ecological themes of bottom-up response to perturbations in nutrient supply and ocean circulation and trophic mismatch of predator-prey interactions at the zooplankton-fish-apex predator level are general across marine biomes. As part of the PAL synthesis component, we will interpret our results in the context of other marine time series in contrasting ecological settings. The PAL PIs have extensive experience with and links to other regional data sets including, for example, the seasonal coastal upwelling system captured by CalCOFI and the California Current Ecosystem LTER, the seasonally oligotrophic North Atlantic subtropical gyre studied by the Bermuda Atlantic Time-series Study (BATS), the permanently stratified North Pacific subtropical gyre through the Hawaii Ocean Time-Series (HOT), and other Southern Ocean and high-latitude northern hemisphere datasets from the U.S. and international JGOFS and GLOBEC programs.

Table 2.1. PAL research components and linkage to LTER core research areas[1].

Component (co-PI)	**Primary Core areas** (secondary areas)
Physical oceanography (**D. Martinson**)	**A,D** (B,C,E)
Climate & sea ice (**S. Stammerjohn**)	**A,E** (B,C,D)
Phytoplankton ecology (**O. Schofield**)	**A,C,D** (B,E)
Zooplankton ecology (**D. Steinberg**, V. Fabry[2])	**A,B,C** (D,E)
Apex predators (**B. Fraser**, C. Ribic[2])	**B,E**
Microbes & biogeochemistry (**H. Ducklow**, R. Sherrell[2])	**C,D** (A,B,E)
Modeling (**S. Doney**, D. Martinson)	**A-E**
Rothera Time Series (A. Clarke & **M. Meredith**, BAS)	**A-E**
Information management (**K. Baker**)	(A-E)
Outreach & education (**B. Simmons**)	(A-E)

[1] **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.

[2] Associated Investigators (see Section 3) and Biographical Sketches.

Table 2.2. 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 form the ongoing core of long-term observations. Studies at Palmer Station focus on seabird breeding season phenologies and ecology. Nov91, Nov92, Mar93, Aug93 were special process cruises to study ecosystem seasonality. Jun99 and Sep01 special process cruises focused on sea ice studies. Cruises extending several weeks beyond one month are indicated by '•'. The ' T ' were short December cruises to replace/turn around sediment traps. The 'I' and 'G' were related cruises in other programs (Icecolors and GLOBEC).

Field Season	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
LTER CYCLE 1												
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	-	-	-
LTER CYCLE 2												
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	•	-
LTER CYCLE 3												
02/03	G4	•	•	x	x	x	Jan-03	•x	x	-	-	-
03/04	-	-	-	x	x	x	Jan-04	•x	x	-	-	-
04/05	-	-	-	x	x	x	Jan-05	•x	x	-	-	-
05/06	-	-	-	x	x	x	Jan-06	•x	x	-	-	-
06/07	-	-	-	x	x	x	Jan-07	•x	x	-	-	-
07/08	-	-	-	x	x	x	Jan-08	•x	x	-	-	-
LTER CYCLE 4												
08/09	-	-	-	x	x	x	Jan-09	•x	x	-	-	-
09/10	-	-	-	x	x	x	Jan-10	•x	x	-	-	-
10/11	-	-	-	x	x	x	Jan-11	•x	x	-	-	-
11/12	-	-	-	x	x	x	Jan-12	•x	x	-	-	-
12/13	-	-	-	x	x	x	Jan-13	•x	x	-	-	-
13/14	-	-	-	x	x	x	Jan-14	•x	x	-	-	-

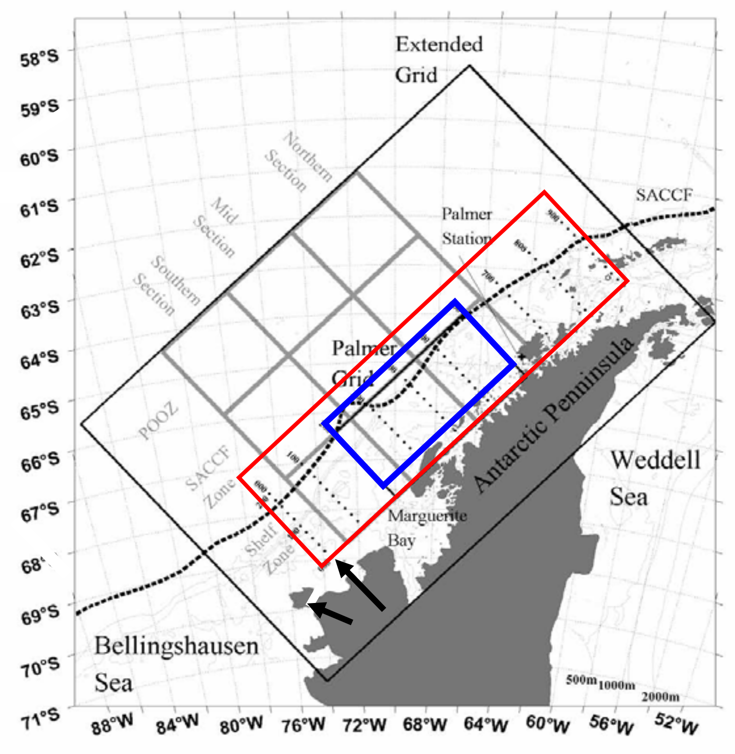


Figure 2.1: Map of the Antarctic Peninsula showing the core study region (blue box), the entire PAL survey region (red box; southern 000 to northern 900 lines) and extended regional grid based on satellite studies. Arrows highlight the 000 line, which we propose to commence sampling regularly to observe conditions less-influenced by climate change, and Charcot Island, proposed site of new detailed process studies. Lines are spaced 100 km apart and station spacing is 20 km. POOZ: Permanent Open Ocean Zone (no sea ice). SACCF: Southern Antarctic Circumpolar Front (dashed line). Maps after Ducklow et al (2007) and Smith et al (2008). See Fig. 3.1 for detail of red box.

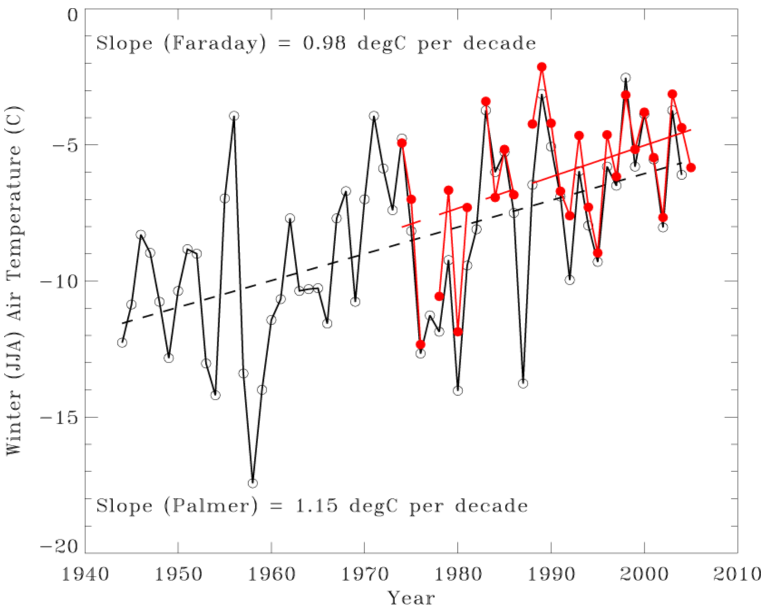


Figure 2.2: Rapid regional warming of the west Antarctic Peninsula Region. Long-term temperature record (black line,1944-2005) at the former British Faraday Station (65°12'S, 64°16'W; became the Ukraine Vernadsky Base in 1997) and at Palmer Station (red) indicates a mean winter (June-July-August) warming rate of ~1°C per decade. The temperature record from Faraday/Vernadsky is available from ttp://www.antartica.ad.uk/met/data.html.

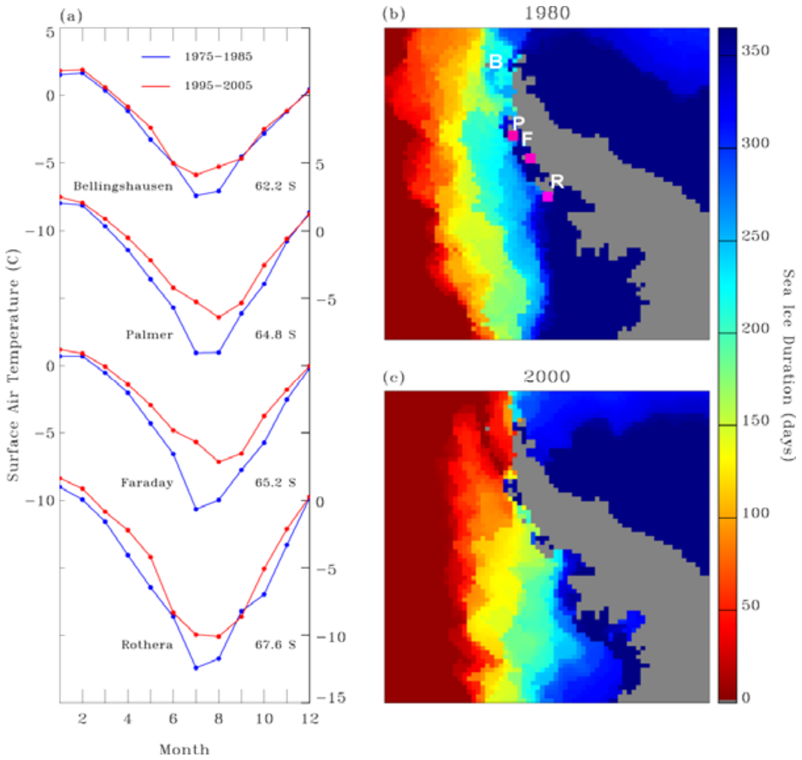


Figure 2.3: **A** Monthly mean surface air temperature from four research stations along the west Antarctic Peninsula: Bellingshausen (B, 62S), Palmer (P, 65S), Faraday/Vernadsky (F, 65S) and Rothera (R, 67S). Two 10-year averages are shown, 1975-1985 (except Rothera, 1978-1985), and 1995-2005 to highlight the warmer winter temperatures for the latter period and to show the approximate 1-month delay (July to August) in reaching the winter monthly minimum at all stations except Bellingshausen. Maps of sea ice duration (total days per year) for years **B** 1980 and **C** 2000 are shown on the right and serve to illustrate the strong decreasing trend in sea ice duration (~31 day decrease per decade) that has occurred over 1979-2005. The locations of stations, whose air temperature records are shown in **A**, are marked by station letter in (b). The pink squares show the locations of penguin rockeries on Anvers (where Palmer is located), Renaud (just south of Faraday/Vernadsky) and Adelaide (where Rothera is located) Islands. Note the smaller winter increase at Rothera and the longer sea ice duration in southern Marguerite Bay, suggesting less warming to the south.

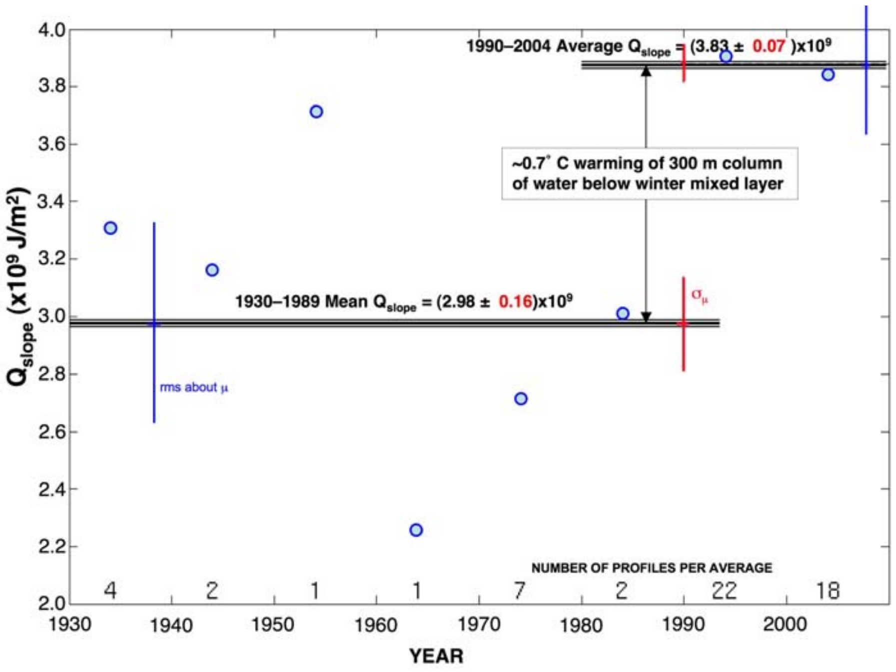
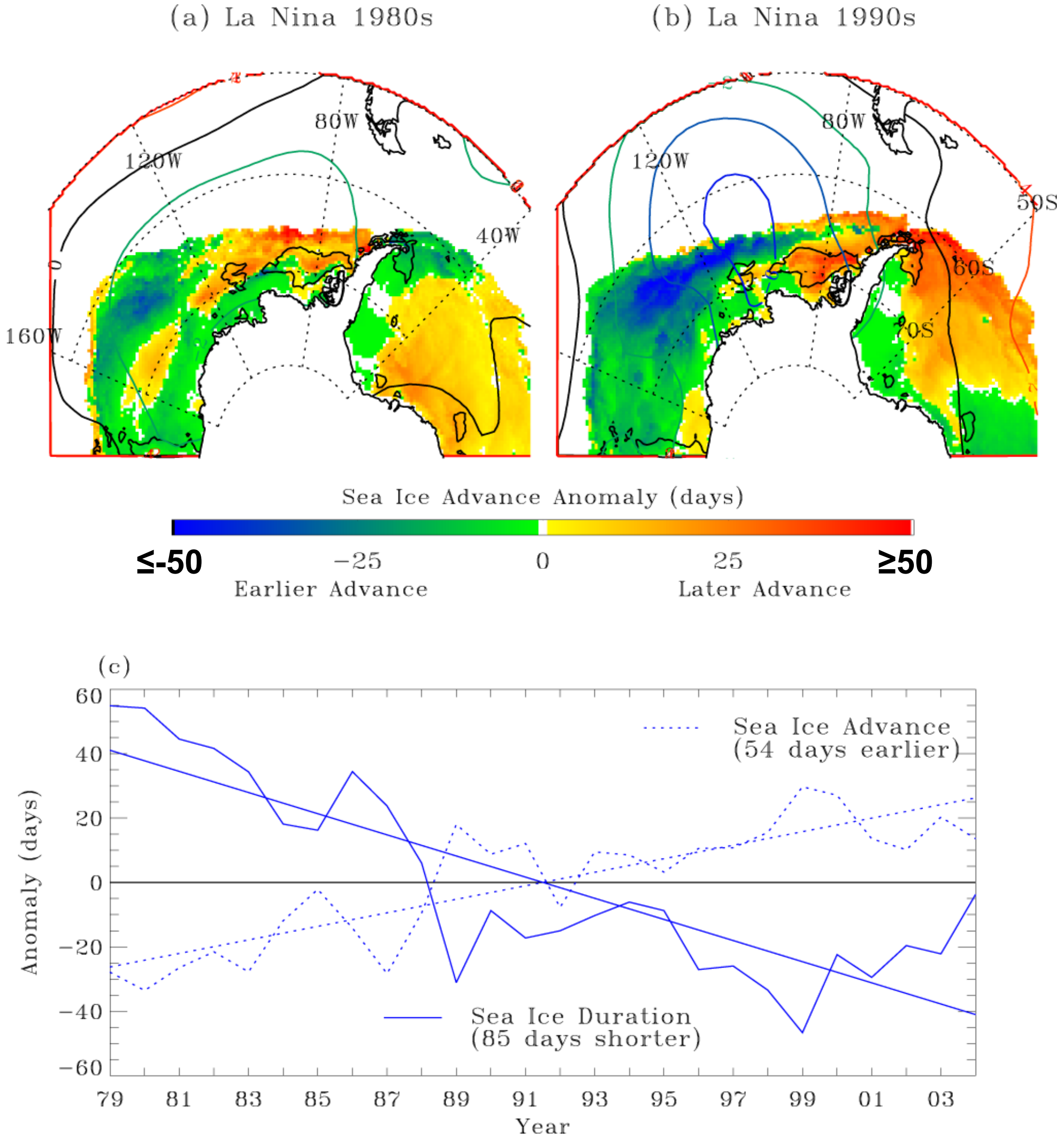


Figure 2.4. Decadal averages of Q_{slope} (heat content of water being delivered to LTER grid) as function of time, with decadal average Q_{slope} values for period before LTER and during LTER showing tremendous jump in slope heat content. Average values indicate rms scatter (blue) about the mean and uncertainty in the mean value as one standard error (red; Martinson et al. 2008)

Figure 2.5: Composites of Mar-Apr-May (MAM) sea-level pressure (color contours) and sea ice advance (color shading) anomalies for (a) 3 La Nina events in the 1980s (1983-84, 1984-85, 1988-89) and (b) for 3 La Nina events in the 1990s (1995-96, 1998-99, 1999-00). The black contoured region highlights those trends that had significance at p<0.01 (after computing effective degrees of freedom). The MAM sea-level pressure anomalies are shown, since this is the time when sea ice is advancing across the contoured region (i.e., in the southern Bellingshausen Sea). (c) Time series of sea ice advance and duration anomalies averaged for the region contoured in black are shown at the bottom. Not shown are the trends in sea ice retreat (which is occurring 31 days earlier over 1979-2004). There has been an intensification in the 1990s of the high latitude response to La Niña in particular, as well as a more positive Southern Annular Mode (SAM), and the atmospheric circulation anomalies associated with these climate modes led to anomalously strong and persistent north-westerly winds west of the Antarctic Peninsula during the spring-to-autumn period. In turn, those winds were associated with anomalously early sea ice retreats and late sea ice advances, particularly during the La Niña years of 1988-89, 1998-2000 which co-occurred with strong positive phases of SAM (Stammerjohn et al. 2008b).



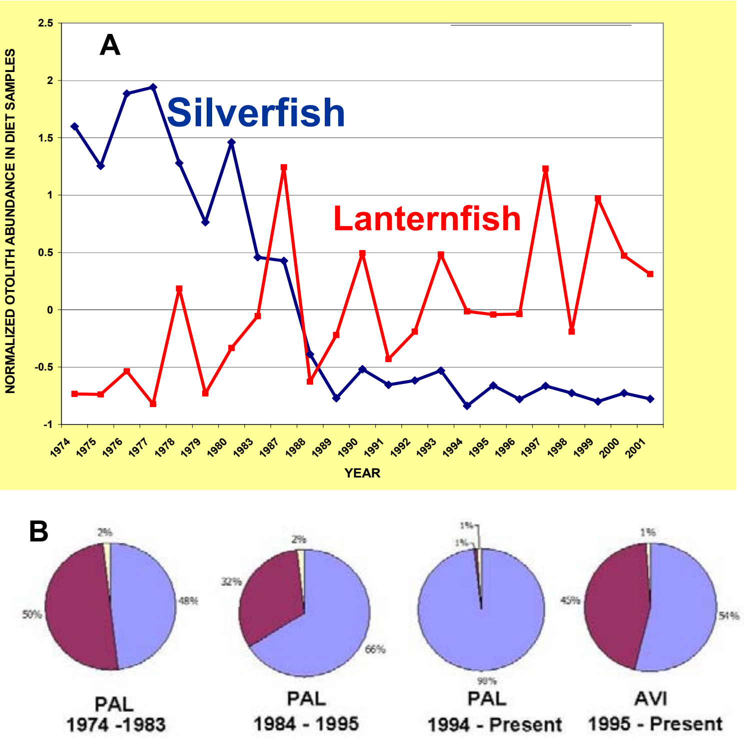


Figure 2.6. A: Incidence of otoliths of the Antarctic silverfish, *Pleuragramma antarcticum* and the Lanternfish, *Electrona antarctica* in Adelie penguin and South Polar Skua diets sampled at Anvers Island, 1974 -2001. **B:** Proportions of krill (blue) and silverfish (red) in Adelie penguin diet samples at Anvers Island (PAL) and Avian Island (AVI) in Marguerite Bay. *Pleuragramma* is an ice-dependent species (Vacchi et al. 2004), possibly accounting for its disappearance from the diet of the Adélie penguins near Palmer Station. *Electrona* prefers warmer (> 1° C) waters, which may account for their increase in the PAL region (Moline et al. 2008; also see **Fig. 2.17**).

Figure 2.7. Breeding pairs of the 3 pygoscelid penguins at Anvers Island near Palmer Station, 1975 -2007 (Ducklow et al. 2007). Note the decrease in the Adélie penguin population (red line) and the increase of Chinstrap (blue line) and Gentoo penguin (black line) populations.

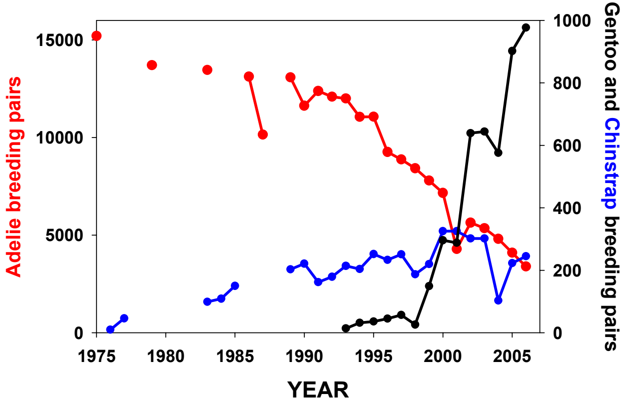
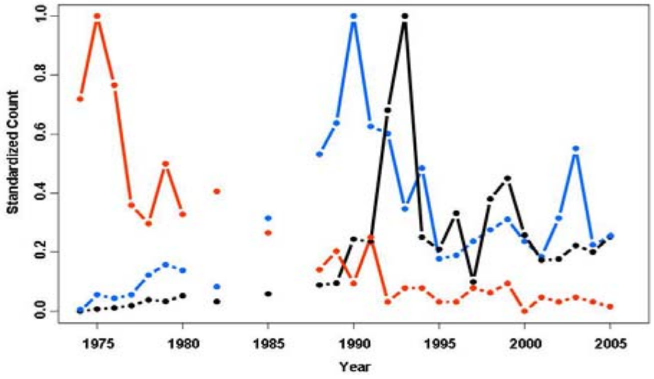


Figure 2.8. Standardized counts of Weddell (red line), Elephant (*Mirounga leonina;* blue line), and Fur (*Arctocephalus gazella;* black line) seals at study plots near Palmer Station 1974-2005, based on Oct to April data. The data were standardized using (count-minimum)/range so all species could be plotted on the same axis. Weddell seals are an ice-dependent species and ranged between 2 and 66. Fur and elephant seals are ice-avoiding species and ranged, respectively, between 0 and 874, and 22 and 276. The high population variability evident in the latter has been attributed to a possible regime shift (cf. Ainley *et al.*, 2005).



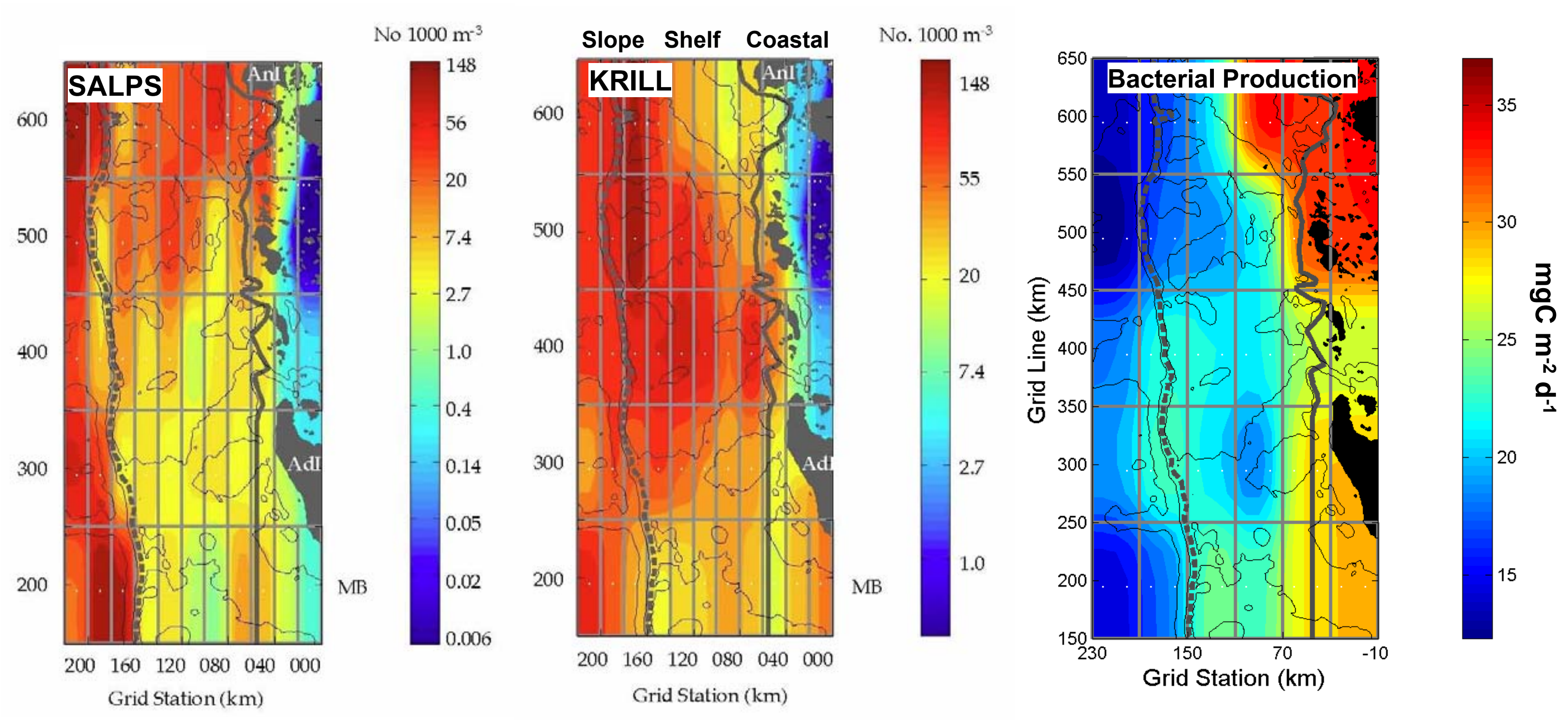


Figure 2.9. Contour plots showing averages of time series at each grid point (climatologies) of consumers. **A.** *Salpa thompsoni* and **B.** *Euphausia superba* abundances (ind 1000 m^{-3}; 0-120 m; 1993-2004) and **C.** bacterial production rate (BP, mgC m^{-2} d^{-1}; 0-50 m; 2003-2007); shown on the PAL long-term grid (200-600 lines as in Fig. 3.1). Gridding and interpolation details are given in Martinson et al. (2008). Islands are in black or grey. Color scales to right of panel. Heavy black line divides the coastal and shelf regions, dotted black line the slope and shelf regions. AnI, Anvers Island; AdI, Adelaide Island. A, B: Ross et al. (2008), C: Ducklow, unpublished data. Note offshore maxima for salps, presence of krill over shelf and offshore decline in BP.

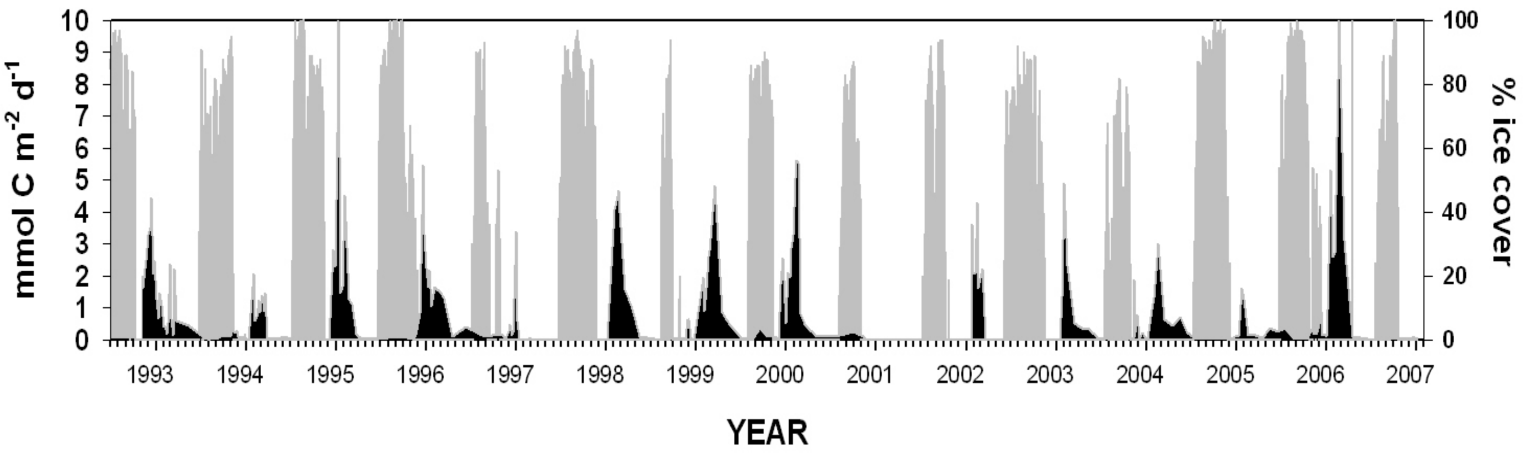
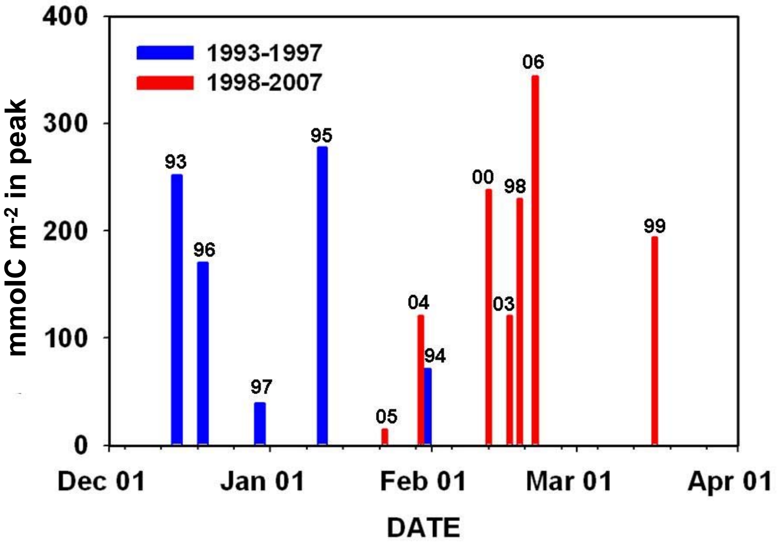


Figure 2.10. Sedimentation flux (black) of particulate organic carbon through 150 meters depth and sea ice cover (gray) at the PAL trap mooring (64º30' south latitude, 66º00' west longitude; see Fig 3.1), 1993-2007. From Ducklow et al. (2008). There were no data for Jan. 2001 to Jan. 2002 due to trap failure.

Figure 2.11. Sedimentation flux of particulate organic carbon through 150 meters depth: date and time-integrated flux during the annual peaks shown in Fig. 2.10. Peak date is date of annual maximum in sedimentation flux. Note shift in dates of peak occurrence after 1997. The trap failure for Jan 2001 to Jan 2002 prevented calculation of the full peak in early 2002 as well as the 2001 peak (Ducklow et al. 2008).



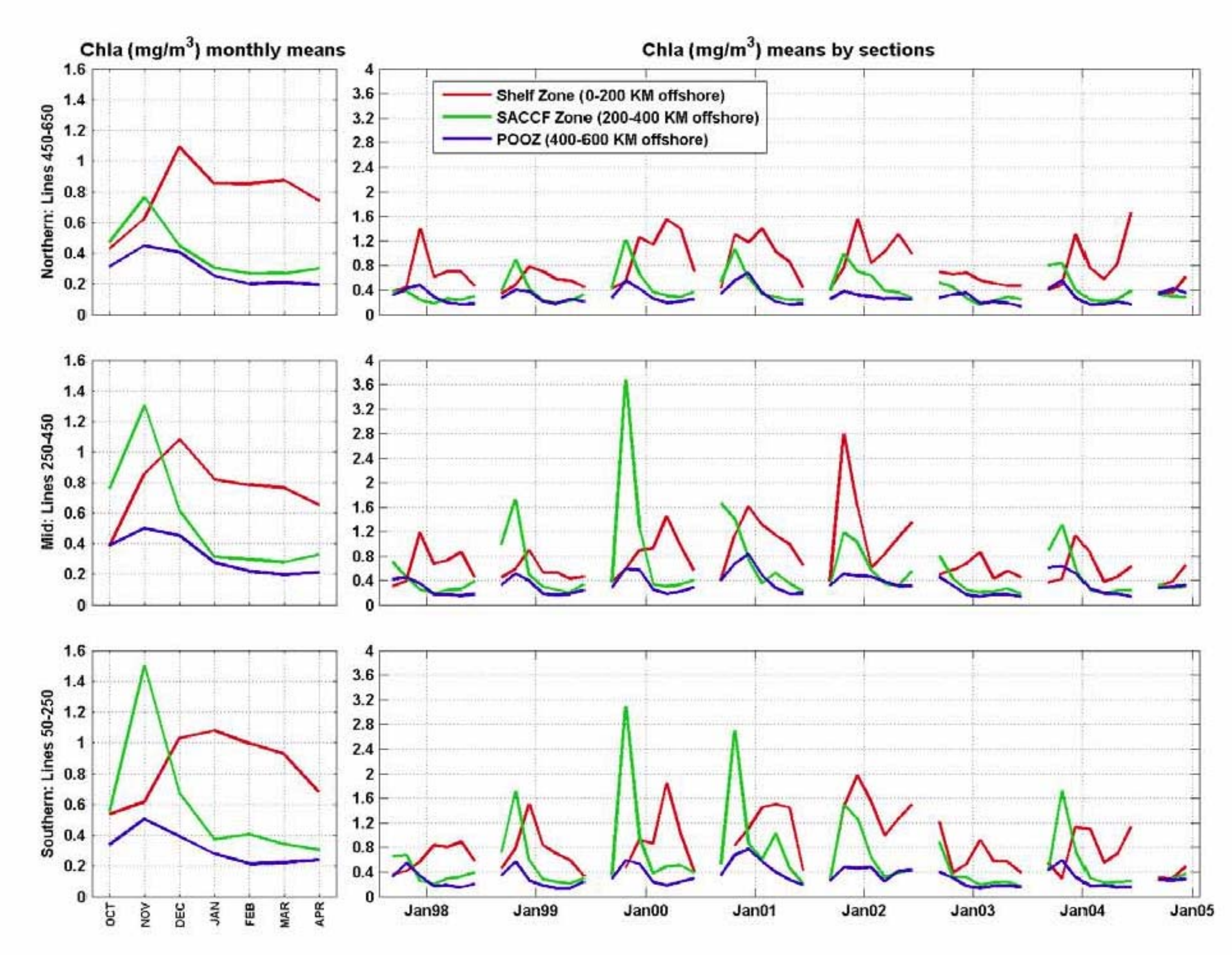
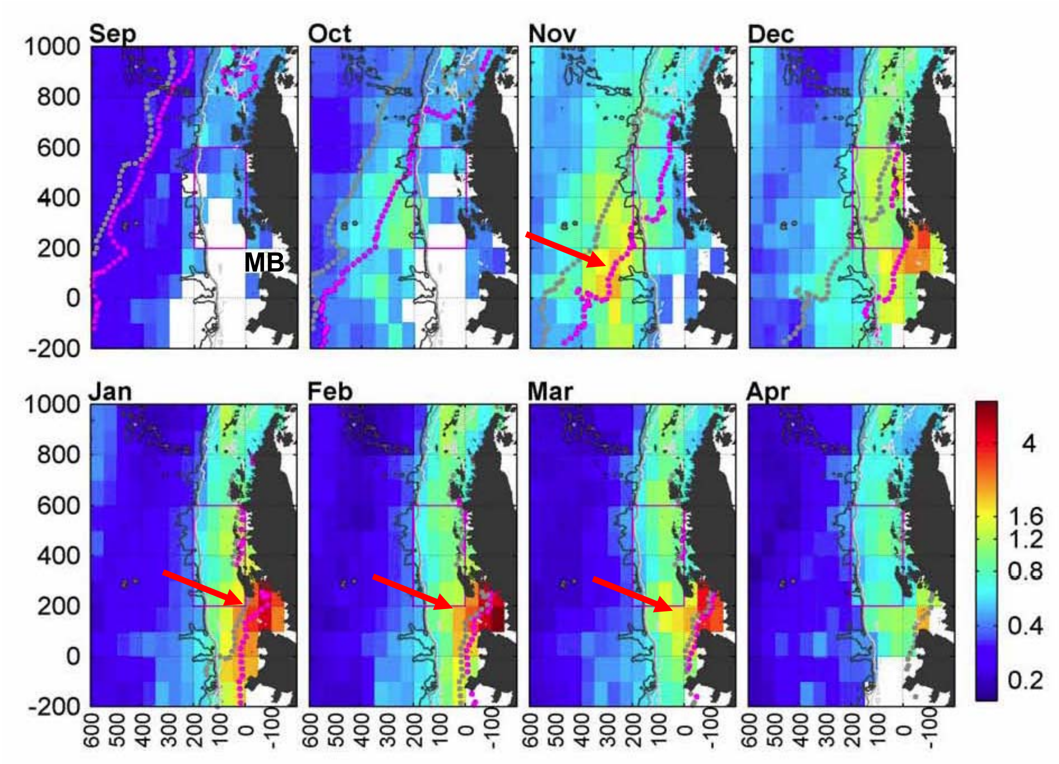


Figure 2.12: Time series SeaWiFS plots of (right hand side) chl-a concentrations [mg m^{-3}] presented for southern (50-250 lines), mid-grid (250-450 lines) and northern (450-650 lines) sectors and for shelf (0-200 km, red curves), Frontal (SACCF, 200-400 km, green curves) and open ocean (400-600 km, blue curves) zones within the Palmer LTER extended grid. The same sectors and zones (left hand side) but presenting mean curves averaged over seven year time period. (Smith et al. 2008). See Fig 2.1 for regional designations. Note interannual variability and lower bloom amplitude in north and offshore. Blooms occur first in SACCF and migrate into shelf zone. See Figs. 2.1, 3.1 for survey line descriptions.



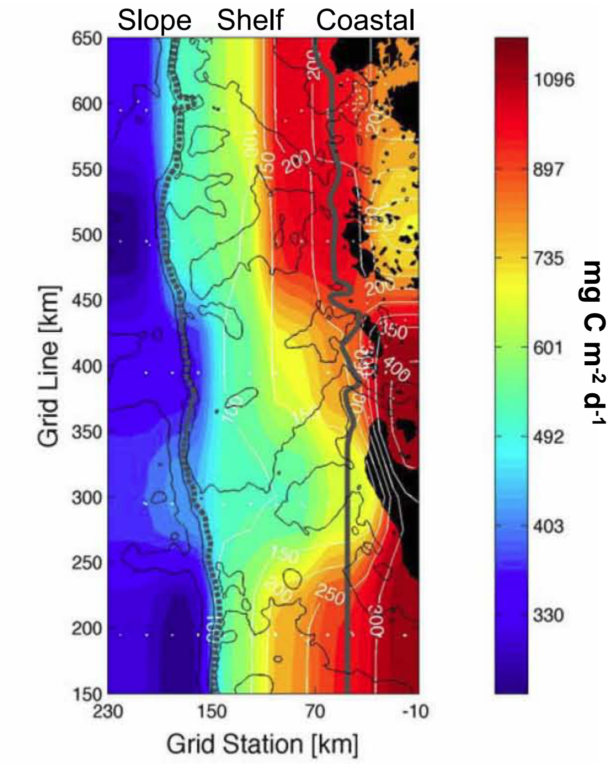


Figure 2.13. Average monthly chlorophyll-a distributions (based on LTER SO algorithm and seven years of SeaWiFS data) for the extended grid area (Fig 2.1) off the west coast of the Antarctic Peninsula [mg Chl-a m^{-3}]. Bathymetry lines are shown for 500m, 1000m and 2000m depth contours (grey to black). Magenta box outlines the PAL grid (between the 200 and 600 lines). Grey dotted line represents the mean (7 year) sea ice extent at the beginning of the month and the purple dotted line the mean extent at the end of the month. White areas indicate limited data due to sea ice coverage. (Smith et al. 2008). Note higher chl over shelf, start of bloom offshore in Nov and large Jan-March bloom in Marguerite Bay (arrows). Marguerite Bay labeled MB in Sep plot.

Fig. 2.14. Average distribution of daily integrated primary production (mg C m^{-2} d^{-1}; 1995-2006). (White lines: standard deviation of average at each grid point). Bottom topography (thin black lines) and water masses as in Fig 3.1. Note enhanced production rates inshore (inner shelf and coastal domains). The area of this figure is the magenta rectangle in Fig. 2.13 (and see Figs. 2.1, 2.9, 3.1; Vernet et al. 2008).

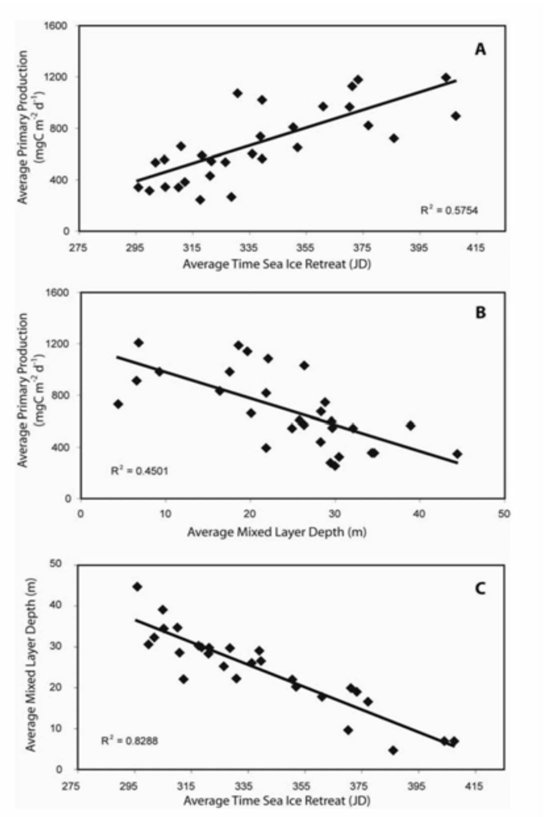
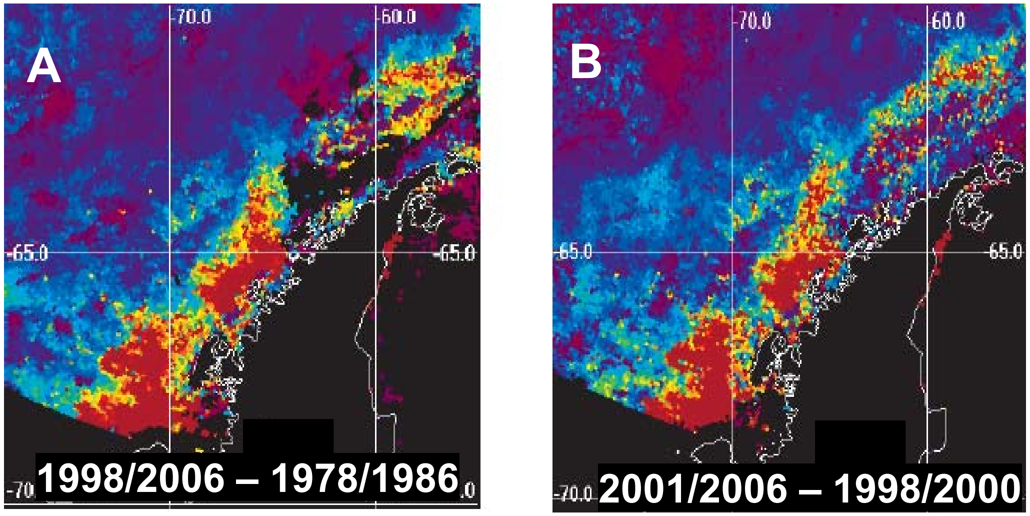


Figure 2.15 Correlations between the average primary production (as contoured in Fig. 2.14) and average values of environmental variables based on each grid cell **A:** Primary production vs. timing of sea ice retreat (r^2 = 0.57, n = 29); **B:** primary production vs. summer mixed layer depth (r^2 = 0.45, n = 29); **C:** summer mixed layer depth vs. timing of sea ice retreat (r^2 = 0.83, n = 29). After Vernet et al (2008).



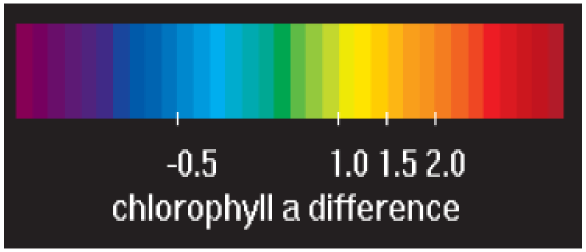


Fig.2.16. Observed changes in monthly mean chlorophyll (mg chl a m^{-2}). A) Changes in the January chlorophylls between 1978-1986 (as measured by CZCS) and 1998-2006 (as measured by SeaWiFS). B) Changes in the January chlorophylls between 1998-2000 and 2001-2006 (SeaWiFS). Enhanced ocean chlorophyll is visible as green-through red colors and the increase in the productivity in the southern WAP is readily evident (Panels A & B) as well as declines in the northern WAP in the last decade (Panel B). (Montes-Hugo et al. *in prep).*

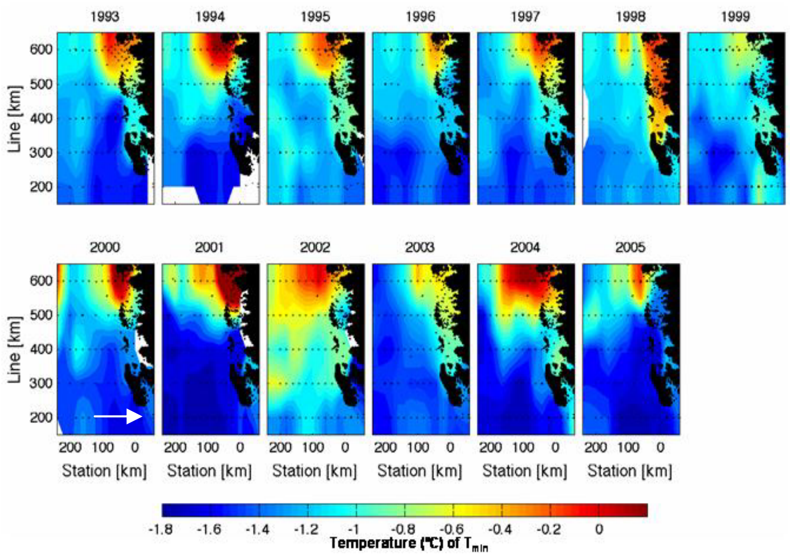


Fig. 2.18. Contour plots of Winter Water (the coldest water in the water column as observed in summer) in the PAL study region. There is little water <0°C in the water column in the vicinity of the Adélie penguin foraging range near Palmer Station (red). The temperature is more variable but generally <-1.2°C to the south of Marguerite Bay (arrow).

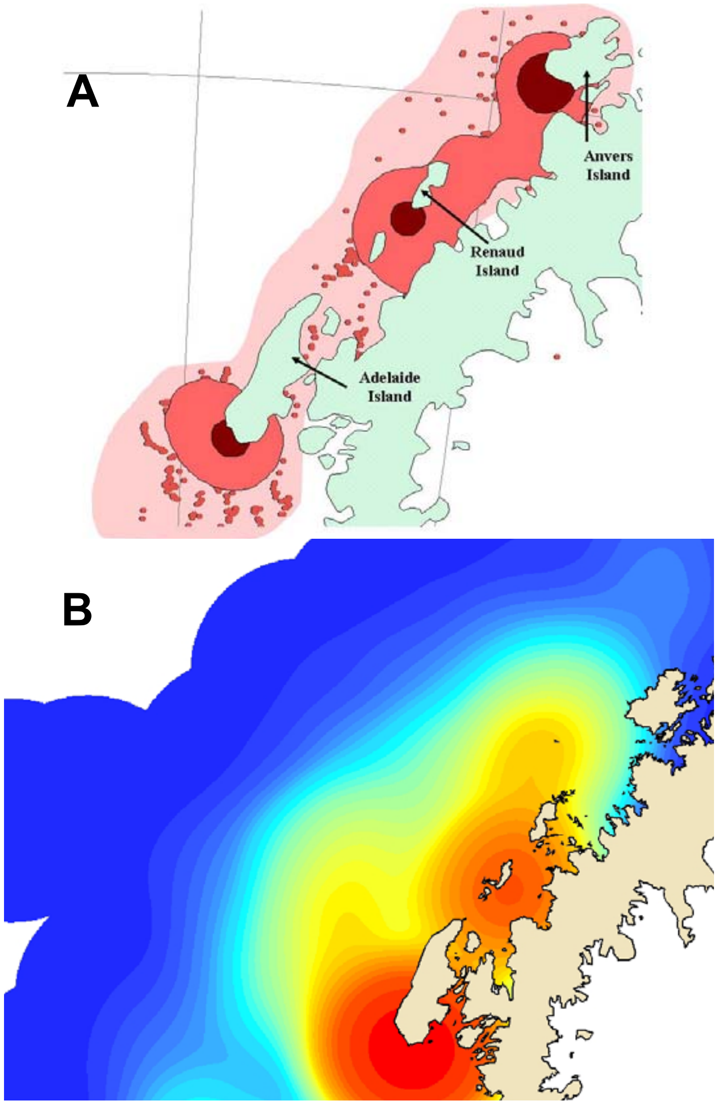


Figure 2.17 Summer (panel A) and Winter (panel B) foraging distributions of Adélie penguins in the LTER grid during 24 months beginning on 1 April 2001. The data are based on birds (N= 186) tagged with satellite-linked transmitters at summer breeding colonies and on winter pack ice. Patterns were developed using kernel analysis, and in each panel the darkest red colors represent the 50% contour, meaning that 50% of all detected locations fell within the contour's area. These areas correspond precisely with deep, cross-shelf canyons that offer predictable prey concentrations due to a combination of upwelling, bathymetry and circulation (Fraser et al. 2008).

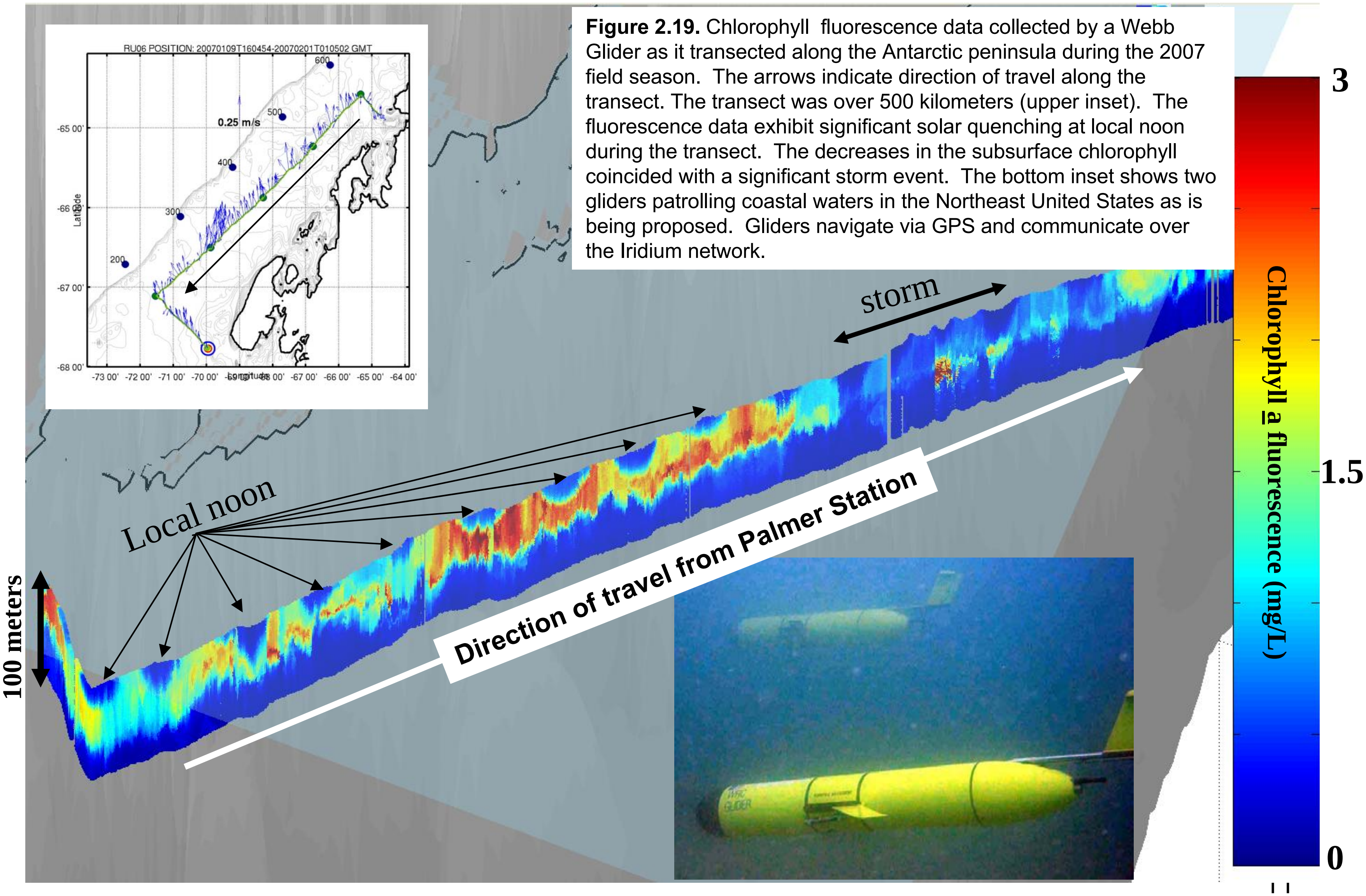


Figure 2.19. Chlorophyll fluorescence data collected by a Webb Glider as it transected along the Antarctic peninsula during the 2007 field season. The arrows indicate direction of travel along the transect. The transect was over 500 kilometers (upper inset). The fluorescence data exhibit significant solar quenching at local noon during the transect. The decreases in the subsurface chlorophyll coincided with a significant storm event. The bottom inset shows two gliders patrolling coastal waters in the Northeast United States as is being proposed. Gliders navigate via GPS and communicate over the Iridium network.

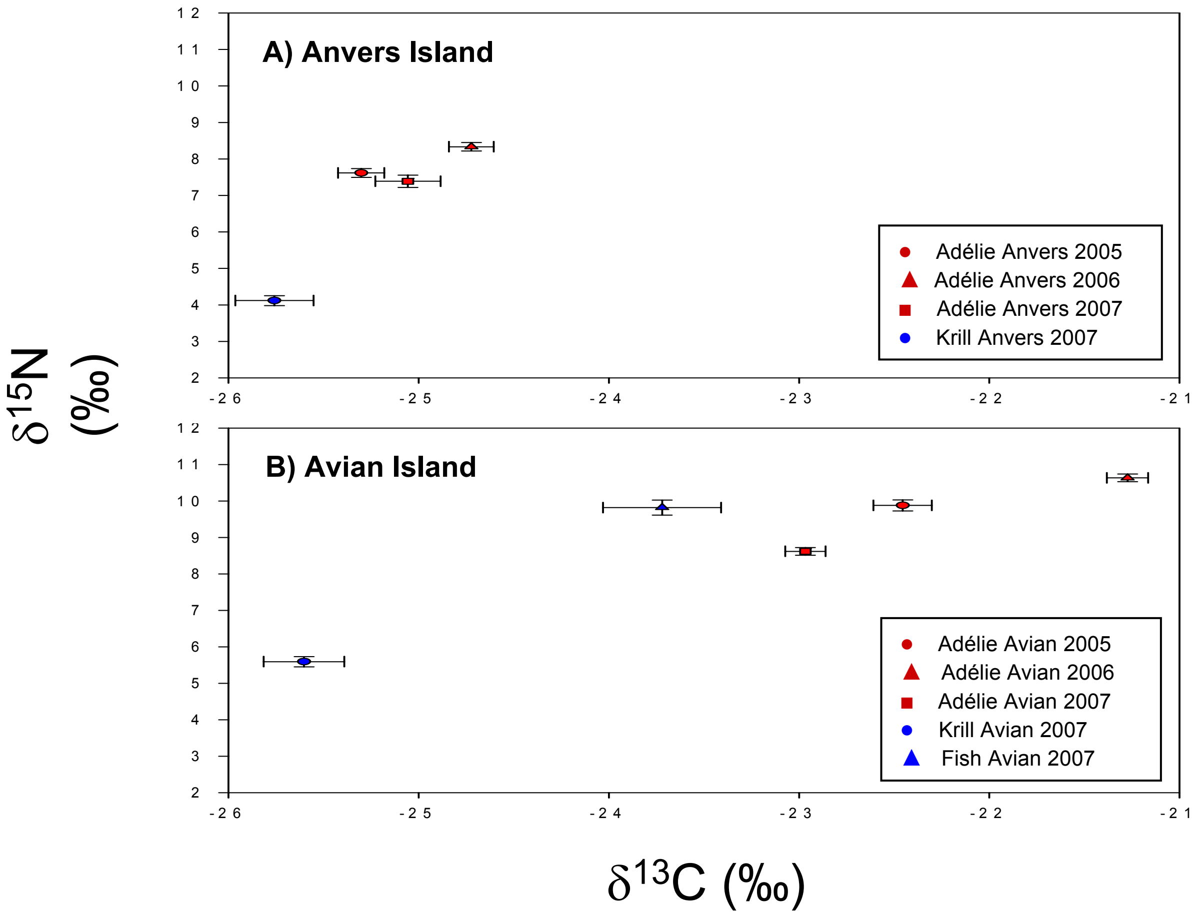


Fig. 2.20. Stable carbon and nitrogen isotope signatures of Adélie penguin toenail tissue (red symbols) from chicks reared at northern (A; Anvers Island) and southern (B; Avian Island) colonies, respectively. Parentally-derived diet items are shown as blue symbols. General linear models were used to examine variation in δ13C and δ15N signatures using LOCATION, YEAR, and SPECIES as explanatory/interacting variables and information-theoretic methods used to direct model selection. Values presented are group means (± 1 SE) as determined by most parsimonious models for δ13C and δ15N. Results suggest that chicks reared on southern colonies are enriched in δ13C and δ15N relative to congeners reared at northern colonies, and krill (*Euphausia superba*) from southern foraging regions are enriched in δ15N relative to conspecifics in northern regions. These results provide preliminary biogeochemical evidence for climate driven variation in the structure of marine food-webs along the west Antarctic peninsula due to rapid regional warming. Overall, the evidence suggests penguins feed at higher trophic levels in the south than the north, i.e., fish form a larger proportion of their diet at Avian compared to Anvers Island.

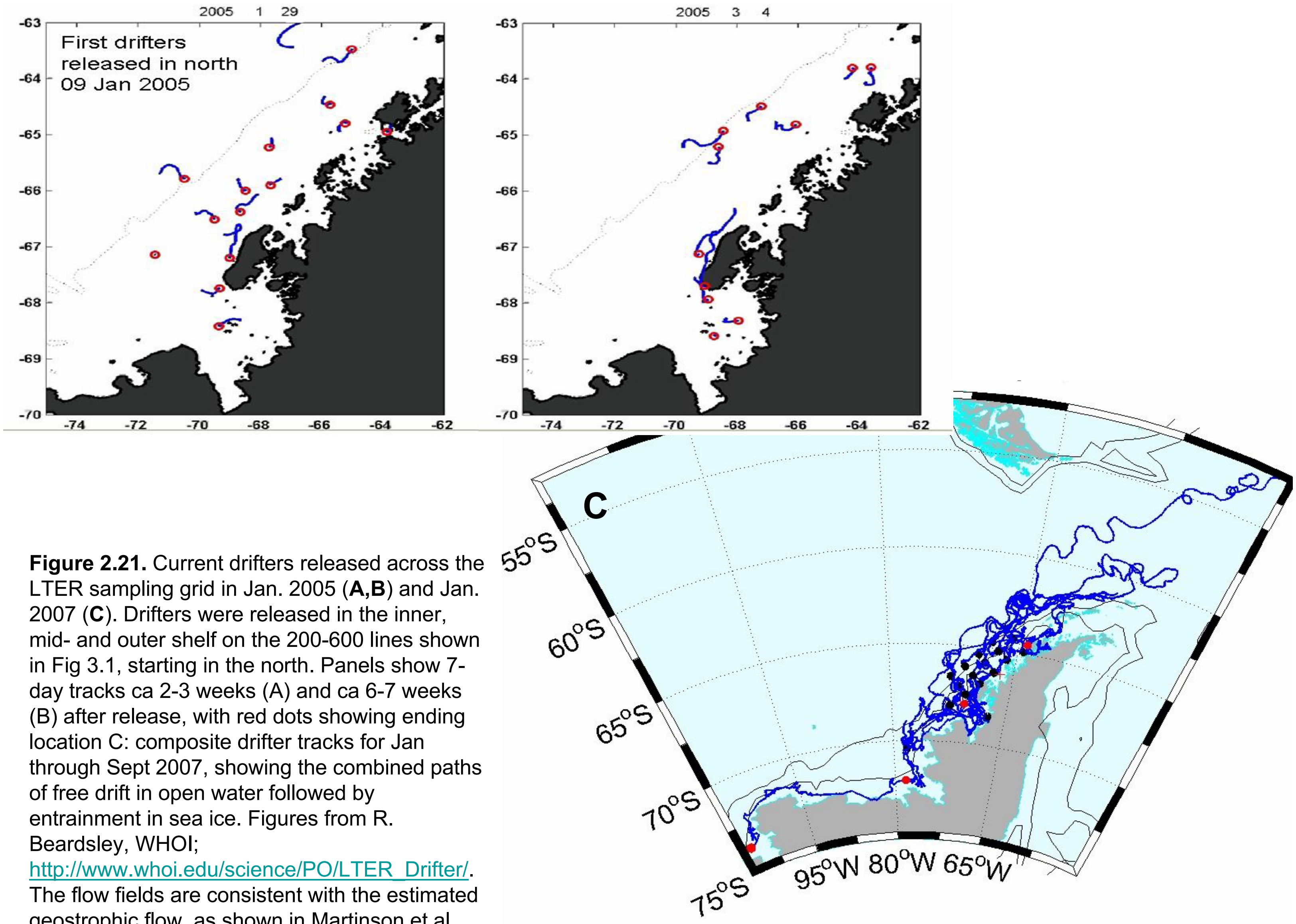


Figure 2.21. Current drifters released across the LTER sampling grid in Jan. 2005 (**A,B**) and Jan. 2007 (**C**). Drifters were released in the inner, mid- and outer shelf on the 200-600 lines shown in Fig 3.1, starting in the north. Panels show 7-day tracks ca 2-3 weeks (A) and ca 6-7 weeks (B) after release, with red dots showing ending location C: composite drifter tracks for Jan through Sept 2007, showing the combined paths of free drift in open water followed by entrainment in sea ice. Figures from R. Beardsley, WHOI; http://www.whoi.edu/science/PO/LTER_Drifter/. The flow fields are consistent with the estimated geostrophic flow, as shown in Martinson et al., 2008).

SECTION 3. Site Management.

The PAL site is located at Palmer Station (64º46 S, 64º04 W) on Anvers Island, west of the Antarctic Peninsula, and encompasses both the immediate coastal region and the offshore oceanic region swept annually by the advance and retreat of sea ice (**Figs. 2.1, 3.1**). It is subject to intense meteorological forcing that creates extreme logistic challenges for conducting research and site management. In spite of logistic challenges and the remote location our site is increasingly well-equipped. With the addition over the past year of 5 oceanographic sensor moorings and the proposed additions of a new sediment trap and the glider reconnaissance our site will become one of the most intensely studied sites in the Southern Ocean.

All US Antarctic researchers are bound by the rigorous regulations of the Antarctic Conservation Act (http://www.nsf.gov/od/opp/antarct/aca/aca.jsp), the US legal instrument governing the provisions of the Antarctic Treaty, regarding site occupation, environmental contamination and sample collection. 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. Treaty nations voluntarily follow the guidelines for the protection of fauna and flora. Of immediate concern to PAL is the ability to guarantee that the site remains undisturbed by uncontrolled human influences such as tourism or unsupervised research activities (e.g., http://www.mcmurdodryvalleys.aq/). Currently the PAL research area is in the process of designation as an Antarctic Specially Managed Area (ASMA), conferring additional protection and additional obligations for researchers to define their site management protocols, obtain field permits and limit human impacts. The expected adoption of the SW Anvers ASMA will greatly aid in site protection and largely defines how our site is managed.

Also of concern is how far from pristine the environment of the WAP area has become. In connection with long-range atmospheric transport, shore-based scientific research stations and the growing tourist industry, site biota are exposed to persistent organic pollutants (POPs). Research carried out with PAL support has recently documented the extent of pollutant contamination and the processes of pollutant entry into the region (Chiuchiolo *et al.*, 2004; Dickhut *et al.*, 2005). Contamination in local seabirds is being studied by current PAL gradate student Heidi Geisz under the supervision of Ducklow and Fraser.

The eight PAL PIs (**Table 2.1**) are the governing body of the Project. Funding decisions and research issues are decided in the group through consultation and consensus. In the event of failure to resolve conflicting views, the lead PI makes decisions, following consultation with the NSF Program Managers (if necessary). Formal communication is maintained among PIs by frequent email, monthly conference calls and an annual meeting. With Ducklow's recent (May 2007) move to the MBL, responsibility for project administration and logistics shifts to the Ecosystems Center at the MBL in Woods Hole. Karen Baker has responsibility for information management with respect to the LTER Network. The Integrative Oceanography Division (IOD) at Scripps Institution of Oceanography is the data hub for PAL. The research, modeling and data management activities of the PAL are divided into several components administered by the respective co-investigators. The co-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/aboutus/steering-committee/).

PAL Investigators have invited several colleagues to join our program as Associated Investigators (**Table 2.1**). They are selected through consensus among the PIs because they fill a gap in our expertise or have specific ongoing and closely related research in the PAL Study region. PAL Associated Investigator status does not necessarily provide financial support, but we do encourage full participation in the scientific activity of PAL including attendance at our annual meetings, access to all data, sample sharing and consideration for berths on the cruises or at Palmer Station, as part of our field teams.

Site management of PAL is carried out by the by the civilian contractor, currently Raytheon Polar Services Company (RPSC), under contract to the NSF. The NSF 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. The NSF requirement to define our logistics needs at the outset of each proposal further constrains our ability to respond to new discoveries or test emerging hypotheses within the grant cycle. The demands of the Antarctic treaty and NSF/RPSC oversight place strict constraints on the research we can perform. For example, there are strict limits to the numbers of personnel we can deploy in the field, and the exact dates of stay. Research decisions are thus made in close consultation with RPSC, often at the proposal stage. These considerations profoundly affect, for example, our opportunities for formal and informal collaboration, cross-site activities and other research, education and outreach. Nonetheless we try to reserve some of our designated space at Palmer Station and on the research vessel each year for collaborating and independent investigators who want to work with us.

Field work at Palmer Station is often the responsibility of experienced technicians or graduate students in the absence of the senior scientists. Undergraduate student volunteers comprise an important element of the field teams and are of great importance to our success. Due to the logistical 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 REU and volunteer opportunities. We strive to broaden the program through recognition of associates (see included vitae) and through affiliate PIs who write companion proposals for support from NSF-OPP to work at our site.

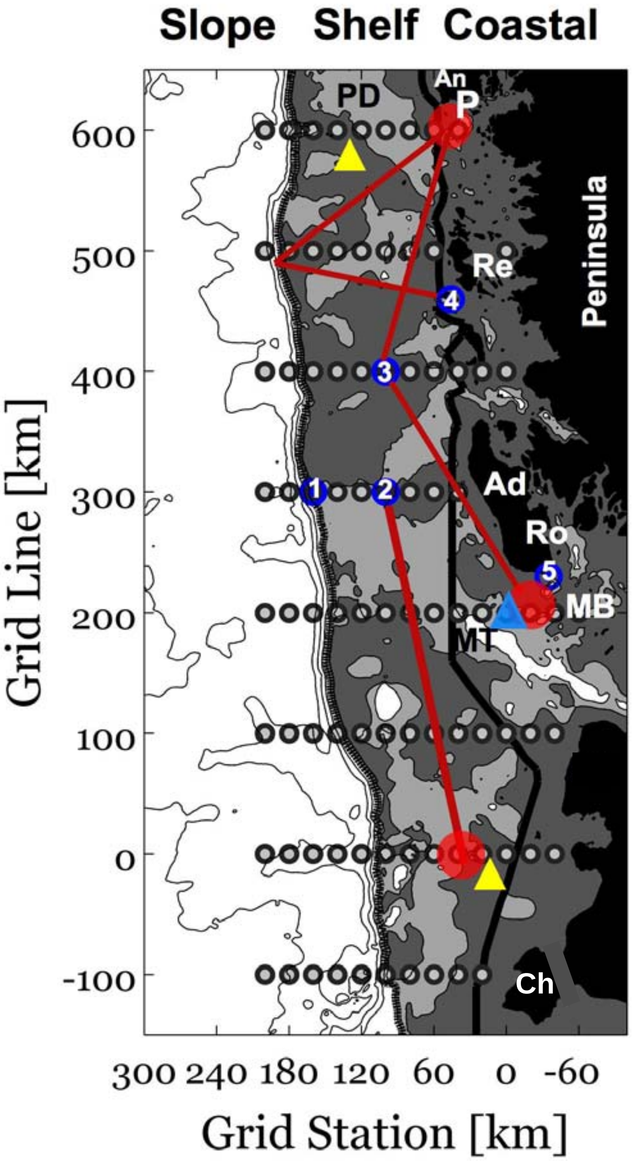


Fig 3.1. Map of PAL-LTER Site: the core study region encompassing the 200-600 grid lines occupied each January1993-2008 and the southern -100 and 000 lines proposed herein. Dotted and solid black lines identify the three bathymetrically-defined watermass regions (left to right, Slope-Shelf-Coastal). P: Palmer Station on Anvers Island (An); R: Renaud Is.; Ro: Rothera Station on Adelaide Is (Ad); MB, Marguerite Bay; Ch, Charcot Is. Yellow triangles: existing (northern) and proposed (southern) sediment trap moorings. The open triangle is the BAS-RaTS trap outside Marguerite Bay. Gray circles: hydrostations (20 x 100 km spacing). The shaded bathymetry (white<750 m, 750 <light-grey<450 m, dark-grey<450 m) identifies the locations of cross-shelf canyons (PD, Palmer Deep; MT, Marguerite Trough). Contours at the shelf break are greater than or equal to 1500 m at 750 m intervals. Numbered blue circles are physical oceanography moorings. Mooring 5 is at Avian Island in Marguerite Bay, site of an existing field camp and large penguin colony. The red lines represent the proposed Glider tracks. The 2 northern tracks will be surveyed prior to the LTER cruise from Palmer station and the 2 southern tracks during the cruise. Red circles indicate process study locations where gliders will focus on collecting intensive spatial data.

SECTION 4. Information Management

Background and History. Information management (IM) for PAL provides support for site data and metadata collection as well as for use and update of informatics techniques and technological methodologies. Design and use of a multi-project information system, DataZoo, together with a local information environment, Ocean Informatics, are core elements that support information management. These elements enable development of contemporary data practices, collaborative techniques, and communication among diverse program components. A local information management team facilitates PAL research by providing support for data organization and integration, data documentation and access, infrastructure building and collaborative technology use in addition to support for training in use of the information infrastructure. The PAL IM approach has been described in site reviews as effective; "The review team was favorably impressed with the progress made in the area of information management."(1999) and as impressive “The committee was impressed by the upgrades being made to the PAL Information Management System.”(2006).

IM specific aims are summarized by the following three objectives:

- Objective 1: Provide data management services needed to capture, preserve, and provide access to data as well as to develop of procedures for data presentation, quality control and workflow.
- Objective 2: Design, develop, and enact information management strategies that support development of 1) an information architecture that provides data organization and supports information systems as well as 2) a local information management environment for understanding and improving data practices, systems, and workflows that is informed by informatics and synergistic disciplines as well as by experience-based learning.
- Objective 3: Determine and carry out essential elements of data stewardship that enable the immediate local use of data as well as facilitating long-term sustainability and re-use through traditional data and information management methods in conjunction with sociotechnical design and comparative analysis in order to open up our understanding of the multiple dimensions of data practices and the digital record.

Data management has been part of PAL planning since its inception and is integral to site science (Smith *et al.*, 1995, 1999b; Ducklow *et al.*, 2007). In recognition of the significance of IM, the information manager has led one of the PAL site components with a designated budget since 2002. The IM position is funded as a part-time position to develop and carry out a project information management strategy and to coordinate with individual participants at geographically separate institutions. IM supports distributed data practices through focus on co-design and joint activities that engage participants with the local information environment. Communication among participants is enhanced through web services as well as the use of shared disks that provide a data commons to facilitate data exchange (Kortz, 2006).

The PAL IM team is responsible for design and support of the project website (http://pal.lternet.edu). The website was redesigned during the last project cycle to include a three tier modular template structure and dynamic delivery of materials that makes use of relational database technology. The delivery of information about participants has been coordinated through development of a personnel directory, PeopleZoo, that generates participant lists for the web site from a database that also produces the participant lists for the ship cruises in the DataZoo information system. The bibliography module is another dynamic element, providing both a search interface for the general user as well as a web management interface for citation entry over the web. A third active element is a media gallery used to make collections of photographs and videos along with their metadata available on the web.

Data and Information Architecture Overview. The PAL information system (Baker and Chandler, 2008); (http://oceaninformatics.ucsd.edu/datazoo/pallter) has developed over time with several major transitions. The data collection initially was developed as a pre-internet collection of datasets in the first funding cycle (1990-1996). A data system was developed in the second funding cycle (1996-2002) consisting of a web accessible collection of static files (http://pal.lternet.edu/data/study_catalog.php; (Baker, 1996, 1998). In the recent cycle (2002-2008), a relational database backend supporting queriable datasets staged for data integration was developed in partnership with the CCE LTER site that began in 2004. Launch of the DataZoo information system occurred at the PAL 2007 August annual meeting.

Management of data collections follows a decentralized model with data contributors responsible for submission and quality control of data. Initially, a data system provided access to data and metadata on the web using a hierarchical file structure organized by cruise and season. In 2002, plans to migrate the computational infrastructure to UCSD were initiated in conjunction with the decision to undertake implementation of a new information system capable of supporting data query as well as data access. Data are being merged into time-series datasets. The elements of the new system shown in **Fig. 4.1** include

- a relational database architecture
- a set of integrated applications
- a set of web management interfaces
- web interfaces for data access, query, visualization and integration
- a design that supports data exchange (e.g., EML delivery)

Our design approach includes: acceptance of a diversity of computer platforms and tools; emphasis on open source and open architecture elements; development of data services, re-design capacity, and system federation techniques; implementation of web services supporting data access, query, integration, and exchange; and design centering on user engagement, modularity and ongoing refactoring and redesign. In addition, we benefit from the collective experience of other LTER sites (Michener and Brunt, 2000; Benson *et al.*, 2006; Ingersoll *et al*, 1997). Metadata are stored in a relational database system so that metadata can be delivered dynamically in standard formats such as EML.

PAL research and infrastructure database types are summarized in **Table 4.1**. The research databases include data and metadata associated with a cruise, with a seasonal study, with external cross-study datasets such as the weather and bottom topography as well as with derived datasets such as those created for work with the LTER Network Trends project. The infrastructure databases contain administrative directories such as personnel and bibliographic citations that are central to work in a collaborative setting. The site made a design decision to qualify each dataset to the column level through development of unit, attribute, and attribute qualifier dictionaries. These dictionaries augment the EML metadata approach in order to enable site-specific data integration. We have worked on the unit dictionary and a unit registry together with other LTER sites and have summarized this work in several articles for the LTER IM Newsletter DataBits. Controlled vocabulary lists including terms sets and code sets are being developed and integrated into the DataZoo architecture.

Data available online are currently maintained in the original PAL data system as datasets go through quality control and then are migrated to the new DataZoo system (**Table 4.1**). PAL investigators have accounts on a central server providing access to shared data spaces and to community web management forms. Data policies are posted online and are consistent with those of NSF, LTER, and SOGLOBEC.

Information and Computational Infrastructure. Ocean Informatics (Baker *et al.*, 2005b) is a conceptual framework developed to provide a broad-based, integrative approach to designing an information environment able to address the growing array of technical, organizational, network and international information needs. A shared environment and a multi-project information system yield significant benefits in terms of base funding as well as critical mass of personnel to create a lively and sustainable design and learning environment. The information management team - consisting of a lead information manager, two database/web programmers, a data analyst, two systems administrators, and several part-time programmers – is made possible through a sharing of resources with co-located, long-term partners and partner programs such as the California Current Ecosystem LTER (CCE) and the California Cooperative Ocean Fisheries Investigations (CalCOFI). With this arrangement, tools and modules developed for one investigator or one site frequently migrate to subsequent use by others. For instance, CCE was able to launch its web site quickly with a contemporary web structure and bibliographic system drawing on previous PAL work while PAL benefited from media gallery and grid calculator web redesign projects done for CCE.

PAL computational infrastructure exists within the Integrative Oceanography Division (IOD) at Scripps Institution of Oceanography. The PAL structure includes three independent, networked servers: a computational platform (iOcean), a collaboration and web services platform (iSurf), and disk storage services in a RAID configuration. There have been significant recent upgrades with Open Directory LDAP services (Baker *et al.*, 2007). PAL available storage has increased from 1 Gigabyte in 1996 to 50 Gigabytes in 2002 to 1 Terabyte in 2008. IOD system administrators, available on an as-needed basis, provide networking, software, hardware and database planning expertise on state-of-the-art computer technology. Backups are conducted regularly and maintained offsite. We are investigating use of storage arrays for backup by the San Diego Supercomputer Center.

Oceanographic Community Collaboration. The PAL information manager is an active partner in the LTER community and the UCSD Science Studies Program as well as the oceanographic and international communities. Development of synergistic activities and comparative opportunities is an element of the site IM strategy that provides professional development and stimulates innovation through exposure to and experience with contemporary techniques. Initially, LTER Network Office internships supported PAL participation in community projects such as the site description directory, DataBits Newsletter re-launch, and the Network Information System (Baker *et al.*, 2000, 2002). Subsequently, PAL IM has provided leadership in cross-site activities such as the social science initiative that focuses on social informatics and ethnographic case studies in collaboration with Science Studies (Baker *et al.*, 2005a; Baker and Bowker, 2007). Current LTER IM community activities include the dictionaries initiative, the training committee, and continuing guidance for the LTER IM Newsletter DataBits.

IM activities are enriched through collaboration with oceanographic and library community efforts such as the JGOFS/BCO-DMO data management (Baker and Chandler, 2008) and digital library community interactions (Gold *et al.*, 2002; Karasti *et al.*, 2007). International collaboration continues in information infrastructure studies with Nordic ILTER and European participants (Karasti and Baker, 2004; Karasti *et al.*, 2007), with Canadian colleagues exploring data systems and cultures (Millerand and Baker, in press), and with science studies collaboration in considering how and why we do our science the way we do (http://interoperability.ucsd.edu).

Future Plans. Of primary importance is the completion of data migration from the original PAL data system and the augmented metadata population. Continuing work includes design, development, and population of an information system user help system and an expanded data visualization capability. Plans are underway to redesign the bibliography and media gallery modules in order to expand their capabilities and to further develop an API approach to coding found effective for longer term collaborative environments. We are continuing to develop web management interfaces in order to avoid the bottleneck of a few technical individuals being the gateway to data ingestion and data update.

Expansion of the Ocean Informatics toolkit (e.g., grid calculator, time format and log tools) is planned. New data types will be explored including streamed and model data. Though PAL datasets have been used extensively for site data exchange (informal communication) and for outside community use (e.g., Constible *et al*. 2007), electronic logging of data access was implemented only recently (January 2008). Electronic record keeping will generate a summary of data access. This summary will become meaningful when data migration is complete and access to the old system closed. Finally, the IM concept of a design studio for collaborative design will continue to focus on information infrastructure building and articulation work as well as on experience-based learning within an information environment.

Table 4.1: Research and Infrastructure Databases
Research Databases: Field Data
Cruise Study (C)
Seasonal Study (S)
External Cross-Study (E)
Trends Derived (T)
Infrastructure Databases: Administrative & Metadata
Personnel Directory
Bibliography
Unit Dictionary
Attribute Dictionary
Qualifier Dictionary
Term Sets
Code Sets
Geographic Dictionary

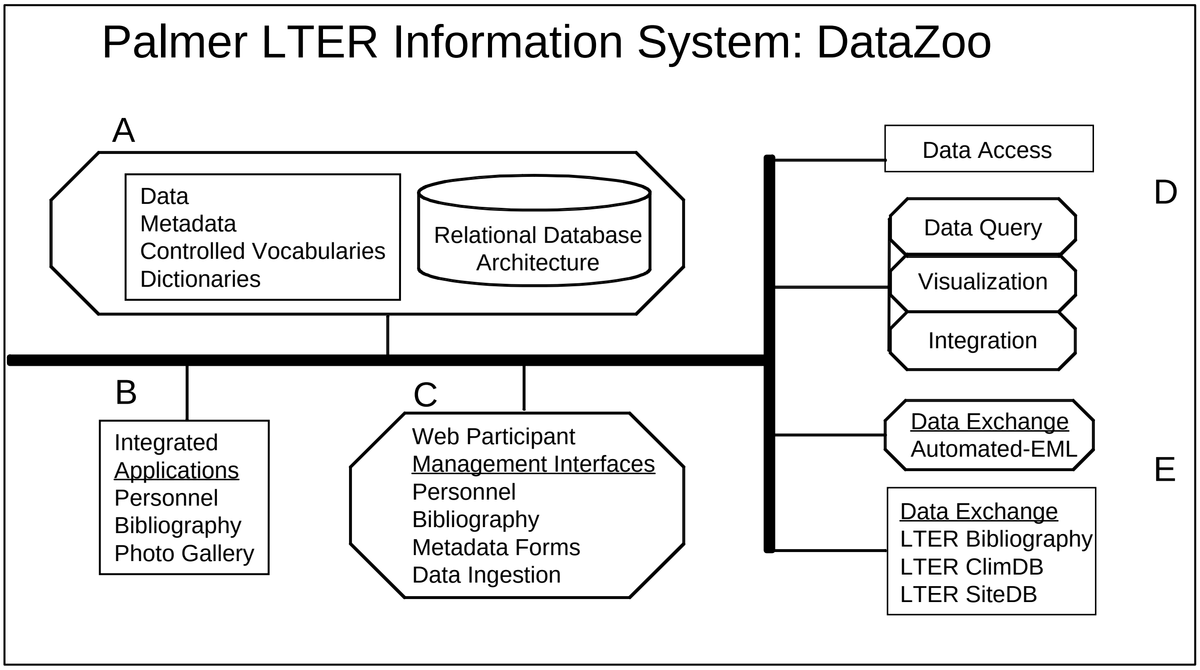


Figure 4.1: An Information System schematic showing a service bus (thick lines) connecting multiple system elements: a) databases for controlled vocabularies, dictionaries, data and metadata, b) independent applications that support or integrate with DataZoo, c) web enabled participant management interfaces that enable contributor participation in data work with the DataZoo community system, d) ‘data use’ functionality including data access, query, visualization, and integration; and e) ‘data re-use’ supporting delivery of data to outside repositories. In order to illustrate the recent transition from a dynamic data system providing access to an information system with a relational database architecture and web services, the earlier functionality is indicated by rectangular boxes and new functionality by octagons. New system features include storage of data as time-series datasets rather than by cruise, a multi-project architecture, and cross dataset functionality.

SECTION 5. Education and Outreach.

Education and Outreach (E&O) for the Palmer LTER program is under continuing development; it provides substantive inquiry science education in both formal and informal settings. From 1989 – 2001, prior to the hiring of a part-time outreach coordinator, extensive research took place to investigate possible synergistic partnerships. In 2001, the education outreach coordinator (who holds a Masters degree in curriculum design), took the lead in developing educational materials, forging new partnerships both locally and across the LTER network, and broadening outreach to include an online community via the world wide web. E&O participants understand the need to facilitate interactions between educators, researchers, graduate and undergraduate students and the general public. Our program utilizes the uniqueness of the LTER network to promote training, teaching and learning about long-term ecological research and Earth's ecosystems across interdisciplinary boundaries.

In the current grant period (2003-08) PAL trained or helped to train 4 postdoctoral scientists and PAL PIs supervised MSc or PhD theses for 5 graduate students (**Table 5.1**). 5 additional grad students are currently pursuing PAL-related theses. In addition we provided field or lab research opportunities for over 20 other grad and undergrad college students, and supported 12 REUs.

Creating a Dynamic Learning Environment. Palmer's Education and Outreach program is centered on learning. The outreach coordinator acts as a liaison to coordinate the translation of scientific perspectives, methods, data and knowledge among the researchers, the surrounding community and the broader public. Building this leaning environment is a cooperative task- one which draws upon the broad community of research scientists, graduate students, information managers, programmer analysts, educators, students and volunteers. The value of sustaining these collaborations fosters a culture that supports community learning (Hodson, 2003). This approach allows us to interface effectively with local and national organizations like the University of San Diego Preuss School, the Digital Library for Earth Systems Education (DLESE), National Marine Educators Association (NMEA), and the National Science Teachers Association (NSTA). An education framework has been designed for PAL's Education and Outreach program over the past few years. The aim of this framework is to create a dynamic learning environment that cultivates a context for building educational partnerships. The articulation of the framework allows principal investigators to become more involved in reviewing and making a viable platform from which to strengthen the infrastructure of future endeavors. The goal is to create a framework that seamlessly integrates ongoing long-term scientific research with pedagogical theories. PAL Education and Outreach draws upon the inherent fascination of the general public with the Antarctic environment and aims to broaden our outreach to increase awareness of ground-breaking science on the Western Antarctic peninsula and the surrounding Southern Pacific Ocean.

Educational Activities and Public Awareness on Broad Scales. To build a formal educational infrastructure and continue growing an innovative educational program, we are developing materials and products that align with state and national educational standards for primary and secondary level classrooms. Since many ocean-learning principles do not fall neatly into the science standards (Cava *et al.*, 2005), we have more recently turned to using "The Essential Principles of Ocean Science" (Ocean Literacy Standards, 2006) to demonstrate the interdisciplinary nature of learning science. Our participation and support in the Ocean Literacy Network, a 501(c)(3) not-for-profit global network managed by the College of Exploration in Virginia, USA, helps us maximize our partnerships with more comprehensive science organizations in compliance with one of the recommendations of the site review team.

We have developed opportunities to enhance the professional development of K-12 science educators through participation in Research Experience for Teachers funding opportunities by the Directorate for Biological Science at the National Science Foundation. This aspect of our program will continue to be enhanced as we begin to broaden our pool of teachers beyond the initial two schools: Rancho Bernardo High School in San Diego California and the University of California's Preuss School.

Additionally, we foresee continuing to apply for Research Experiences for Undergraduates (REU) funding. PAL's success with recruitment in this area is evident in the caliber of current graduate students. The REU extension of funding demonstrates PAL's dedication to education, program development and recruitment. It also serves to expand the educational learning environment and encourage careers in science.

Since more than 1200 tourists per year typically visit Palmer Station and the seabird colony on Torgersen Island, this next six-year proposal cycle will include new ways to effectively educate the tourists as a means of enhancing their experience while simultaneously encouraging them to consider the role of Antarctic science in their world. While scientists board many cruise vessels, give lectures and distribute literature, it appears that there is a need to create educational products to share in these venues. Reaching out to visitors potentially broadens our social impact and increases public awareness of science and environmental issues involving the west Antarctic Peninsula. One way in which this might be maximized is through the development of more web-based materials. Video pod-casting materials and the extensive re-design of PAL's educational outreach website are both effective means to increase public awareness on broader scales and to extend the access to Antarctic science beyond the station.

Collaborative Process/Partnerships. Collaboration links learning, scientific research, and ocean science literacy by building partnerships that enhance the development, implementation, and access to resources for educational purposes (Simmons, 2005b). Coordination with the LTER Schoolyard project has included contribution to the LTER education community handbook (Simmons, 2005a). A mutually beneficial relationship between CCE and PAL is just one example of added value in joining efforts to enhance learning. Together, PAL and CCE have participated in the LTER Network children's book series project creating a unique children's book that links two pelagic ecosystems; a coastal upwelling biome in the southern sector of the California current and one of the world's most extreme environments, the polar waters west of the Antarctic peninsula. The collaborative nature of this particular project in addition to its cross-site synthesis gathers participation from a suite of individuals including scientists, educators, authors, illustrators and photographers. It not only adds to the value of our dynamic learning environment but also exemplifies the meaning of collaboration. In addition to the development of both online education modules and a supplemental instructional guide that will accompany the book, the book series project will involve several phases of development and implementation over the course of the next few years and will be carried out in conjunction with existing and new partners.

Table 5.1. Student training and participation in Palmer LTER, 2003-08

Category / Name (Advisor)			
Post-doctoral researchers	**Institution**	**Field**	**Years of participation**
Carillo, Christopher (R Smith)	UCSB	Marine chemistry	2003-06
McCallister, Shannon (Ducklow)	VIMS	Organic geochem	2003
Montes-Hugo, Martin (Vernet)	UCSD	Ocean optics	2006-08
Stammerjohn, Sharon (Martinson)	NASA-GISS/LDEO	Sea ice & climate	2007-08
Graduate students (PAL-related thesis)	**Institution**	**Status / year in school**	**Year of degree or participation**
Chiuchiolo, Amy (Ducklow)	W&M/VIMS	MSc	2003 (graduated)
Daniels, Bob (Ducklow)	W&M/VIMS	MSc	2003 (graduated)
Carrillo, Christopher (Karl)	Hawaii	PhD	2003 (graduated)
Kozlowski, Wendy	San Diego State	MSc in progres	2003-08
Chapman, Erik (Fraser)	ODU	PhD in progress	2005
Oakes, Stephanie (Ross)	UCSB	PhD	2007 (graduated)
Stammerjohn, Sharon (Martinson)	Columbia	PhD	2007 (graduated)
Geisz, Heidi (Ducklow)	W&M/VIMS	PhD in progress	2003-08
Myers, Kristen (Ducklow)	Brown	PhD in progress	2007-08
Garibotti, Irene (Vernet)	Buenos Aires	PhD	
Becker, Elizabeth (Smith)	UCSD	PhD in progress	
Gorman, Kristen (Fraser)	Simon Fraser	PhD in progress	2006-08
Graduate Students (participated in program)	**Institution**	**Degree program**	**Year in program**
Veloza, Adriana	W&M	MSc	2003
Turnipseed, Mary	W&M	MSc	2003-04
France, Kristen	W&M/VIMS	PhD	2005
Waterson, Elizabeth	W&M/VIMS	MSc	2005
Heyl, Taylor	W&M	MSc	2005
Luo, Yawei	W&M/VIMS	PhD	2006
Erdmann, Eric	Wisconsin	MSc	2007-08

Schwager, Katherine

Undergraduates (REU)	College / University	College Class when in program	Year in program
Tutrow, Jonathan	Loyola Marymt	Jr	2002
Rogers, Lauren	Stanford	Sr	2003
Raulfs, Estella	Wm & Mary	Soph	2003
Middaugh, Nicole	Oberlin	Jr	2004
Tsui, Tracee	Wm & Mary	Sr	2004
Mills, Anne	Wm & Mary	Sr	2004
Haber, Shaun	UCSD	Sr	2005
Kelly, Joann	Virginia	Jr	2004, 06
Hoffman, Cliff	UCSB	Jr	2005
Moore, Kelly	UCSB	Jr-Sr	2006-07
Ma, Julian	Wm & Mary	Sr	2007
Pistone, Kristine	UCSD	Sr	2007-08

Undergraduates (participated in program)	College / University	College Class when in program	Year in program
Fuller, Michele	UCSC	Sr	2003
Wright, Matthew	UCSB	Soph	2003
Valicenti, Lyndon	UCSB	Jr	2003
Holmes, Michael	Cal Poly Obispo		2003
Ducklow, William	Virginia	Jr	2005
Quetin, Gregory	Washington	Jr	2005
Lum, Kimberly			2006
Powers, Meghan			2006
Conners, James	UCSD	Sr	2006
Koffman, Bess	Carleton	Sr	2006
Rich, Shannon	UCSB		2007
Nakase, Dana	UCSB		2007
Morgan, Erin	Wm & Mary	Sr	2008
Baker, Scott	UC-Berkeley	Sr	2008