Palmer LTER Mid-Term Review 2024
Boulder, Colorado

PAL LTER Mid-Term Review- Overview and Progress Report

A. Site-based Research

1. Publications and data

Please see the Site Review secure box drive (to which you were sent an invitation) for supporting documents for the 2024 mid-term review including a theses and PAL reference list in Appendix 1. The PALmer (PAL) LTER website https://pallter.marine.rutgers.edu includes a complete listing of PAL LTER Publications https://pallter.marine.rutgers.edu/catalog/papers/. Selected manuscripts currently in review are also available in the Site Review box drive published over the current award. The PAL-LTER database is also accessible at the main PAL website https://pallter.marine.rutgers.edu/data/.

2. Project Summary

The PAL LTER program seeks to understand how sea ice-influenced marine ecosystem productivity and structure is driven by local, regional, and remote physical forcing. Our current research builds on three decades of long-term research along the western side of the Antarctic Peninsula (WAP) and is focused on developing a predictive framework of the observed ecosystem changes in response to disturbances spanning long-term, sub-decadal, and higher frequency "pulses". PAL has been documenting how these disturbances are altering food-web composition and ecological interactions across time and space scales. Our program is contributing to fundamental understanding of how population dynamics and biogeochemical processes are responding to profound climate-driven changes. Our conceptual framework is that observed/future ecological trajectories are driven by interactions of multiple disturbances operating over a wide range of temporal and spatial scales. The ecological dynamics in the WAP differ from other marine pelagic systems given the importance of glacial/sea ice on marine food webs by modulating solar inputs to the ocean, inhibiting wind mixing, altering the freshwater balance and ocean stability, and providing a physical substrate for organisms. Current warming suggests the system may be undergoing a state change and transitioning from polar sea dominated to a warmer maritime pelagic system. We organize our research efforts under three focused themes: *A. Drivers of disturbance across time and space scales: ecological and latitudinal response, B. Vertical and alongshore connectivity as drivers of ecological change on local to regional scales, and C. Changing food webs and carbon cycling.*

Our sampling, analyses, and modeling cover multiple time scales–from diel, seasonal, interannual, to decadal intervals, and space scales–from hemispheric scale investigated by remote sensing, regional scale covered by a summer oceanographic cruise along the WAP, to local scale accessed by daily to biweekly small boat sampling at Palmer Station. Autonomous vehicles and moorings enable us to expand and bridge time and space scales not covered by vessel-based sampling, thus providing a seasonal to annual context. These observations are complemented with process studies that include manipulative experiments conducted during our research cruise and at Palmer Station. An extensive modeling effort with varying complexity allows us to improve mechanistic and dynamical understanding of the underlying processes driving change. These efforts are anchored by graduate and undergraduate students, and postdoctoral researchers. Our broader impact efforts are focused on climate change and ecological transformation with our education and outreach programs promoting the global significance of polar systems. We use the recently developed Polar Literacy Principles that we developed as a foundation for our virtual schoolyard program via virtual field trips and dissemination of new polar instructional materials for K-12 educators to facilitate their professional development and curricula.

3. Program History and Personnel

PAL LTER Start: Oct., 1990
Funding cycles: 90-96, 96-02, 02-08, 08-14, 14-20, 20-22 & 22-26

Lead Principal Investigators: Robin Ross & Langdon Quetin, UCSB (1990 – 1995)
Ray Smith, UCSB (1996 – 2001)
Hugh Ducklow, VIMS/MBL/Columbia (2002 – 2019)
Oscar Schofield (Rutgers) & Deborah Steinberg (VIMS) (2020 – pres.)

Palmer Field Seasons (~ late Oct/early Nov. to late Apr.): 32 to date (Nov., 1991 to Oct., 2024; only 1 season missed due to new Palmer pier build)

Summer Survey Cruises (~ late Dec. to early Feb.): 31 to date (Jan., 1993 to 2024; only 1 cruise missed due to COVID)

Current Investigators/coPIs:

Name	**Institution**	**Component**	**Joined**
Schofield, Oscar	Rutgers	Phytoplankton & Gliders	2008
Steinberg, Deborah	VIMS	Zooplankton ecology & Biogeochemistry	2008
Stammerjohn, Sharon	U Co	Climate & Sea ice	2008
Doney, Scott	UVA	Modeling & Biogeochemistry	2008
Friedlaender, Ari	UCSC	Cetaceans	2014
McDonnell, Janice	Rutgers	Education/Outreach	2015
Moffat, Carlos	UDel	Physical oceanography	2020
Van Mooy, Benjamin	WHOI	Microbes & Biogeochemistry	2020
Cimino, Megan	UCSC	Seabirds	2020
Lichtenwalner, Sage	Rutgers	Information Management	2021

Collaborator Affiliated Investigators (2020-2024):

Name	**Institution**	**Component**	**Joined**
Meredith, Mike	UK-BAS	Physical oceanography	2008
Bowman, Jeff	SIO	Microbes & Biogeochemistry	2014
Stukel, Mike	FSU	Particle Export	2014Dierson,
Heidi	UConn	Remote Sensing	2022
Turner, Jessie	ODU	Phytoplankton & Remote Sensing	2022
Dinniman, Mike	ODU	Physical oceanography	2022

Graduate Students (2020-24): *attending site visit; +graduated

Name	**Institution**	**Topic**	**Advisor**
Randolph, Kaylan	UConn	Ocean Optics	Dierssen
Rohr, Tyler+	WHOI	Biogeochemical modeling	Doney
Stack, Mary+	UVA	Storms & snow	Doney
Trinh, Rebecca+	Columbia	Microbial biogeochemistry	Ducklow
Pallin, Logan+	OSU/UCSC	Cetacean reproductive physiology	Friedlaender
Nichols, Ross+	UCSC	Cetacean foraging ecology	Friedlaender
Modest, Michelle+	UCSC	Cetacean migratory behavior	Friedlaender
Mastick, Natalie+	OSU	Cetacean behavioral ecology	Friedlaender
Torello, Arianna*	UCSC	Cetacean phenology	Friedlaender
Cole, Mason	UCSC	Cetacean foraging ecology	Friedlaender
Larsen, Greg	Duke	Cetacean remote sensing	Johnston/Friedlaender
Bierlich, KC	Duke	Life history dynamics	Johnston
Moreno, Carly+	UNC	Phytoplankton genomics	Marchetti
Benz, Frederike	UDel	Frontal dynamics on extended grid	Moffat
Cappola, Michael	UDel	Long-term trends of upper ocean	Moffat
Gessay, Jake	UDel	Seasonal variability of SBF	Moffat
Quinter, Evan+	UDel	Storminess trends/penguin impacts	Moffat
Wang, Xin+	UDel	Along-shore exchange dynamics	Moffat

Brown, Michael	Rutgers	Phytoplankton and CO2 chem	Schofield
Nardelli, Schuyler+*	Rutgers	Phytoplankton phenology	Schofield
Diou Cass, Quintin*	Rutgers	Photoacclimation in phytoplankton	Schofield
Sharp, Mya	Rutgers	Glacial melt impacts on plankton	Schofield
Thomas, Maya*	VIMS	Zooplankton carbon export	Steinberg
Nolan, Meredith	VIMS	Zooplankton physiology/heat shock	Steinberg
Mowatt-Larssen , Tor	VIMS	Larval mesopelagic fish	Steinberg
Conroy, John (Jack) +*	VIMS	Phenology coastal zooplankton	Steinberg
Corso, Andrew +	VIMS	Larval fish long-term change	Steinberg
Bent, Shavonna *	WHOI	Microbial stressors	Van Mooy
Girard, Zephyr	WHOI	Microbial carbon export	Van Mooy
Lowenstein, Daniel	WHOI	Microbial energy budgets	Van Mooy
Holm, Henry +	WHOI	Sea ice microbial lipidomics	Van Mooy
Hermanson, Victoria	UCSC	Seabird Distributions	Cimino
Voirol, Grant+	UDel	Penguin Foraging	Oliver/Fraser/Cimino
Fradet, Danielle	UNH	Penguin Acoustics	Kloepper/Cimino

Post-doctoral Fellows (2020-24):

Name	Institution	Topic	Advisor
Yajuan, Lin	Duke	Microbial drivers of NCP	Cassar
Conroy, Jack*	UCSC	Zooplankton modeling	Cimino
Turner, Jessie	UConn/Rutgers	Ocean Optics	Dierssen/Schofield
Kim, Hyewon	UVA	Biogeochemistry & models	Doney
Eveleth, Rachel	UVA	Biogeochemistry & models	Doney
Yang, Bo	UVA	Biogeochemistry & models	Doney
McKee, Darren	UVA	Biophysics & remote sensing	Doney
Ferenbaugh, Joy	UVA	Biogeochemistry & food webs	Doney
Hartman, Savannah	UVA	Biogeochemistry & food webs	Doney
Menendez, Alana	UVA	Remote Sensing	Doney
Weinstein, Ben	OSU	Cetacean movement ecology	Friedlaender
Pallin, Logan	UCSC	Cetacean reproductive physiology	Friedlaender
Botero-Acosta, Natalia	UCSC	Cetacean population dynamics	Friedlaender
Reisinger, Ryan	UCSC	Cetacean movement ecology	Friedlaender
Cade, David	UCSC	Cetacean foraging behavior	Friedlaender
Allen, Jennifer	UCSC	Cetacean behavioral ecology	Friedlaender
Gallagher, Kathryn	SBU	Penguins & Marine Debris	Lynch/Cimino
Saenz, Ben	U Co	Ocean modeling (sea ice)	Stammerjohn

4. PAL LTER Conceptual Model

A shifting climate (warming, ocean acidification, increasing storminess) is predicted to have a disproportionately large impact on polar marine ecosystems. Our conceptual framework is focused on how drivers of disturbance along the WAP will alter polar pelagic food webs based on the fundamental concept that sea ice plays a central role in structuring population dynamics and life history strategies of organisms across all trophic levels of the polar food-web, spanning bacteria, phytoplankton, zooplankton, penguins and other seabirds, and marine mammals (Fig. 1). Ongoing shifts in sea ice underlies system-wide ecological transitions from a polar to a subpolar marine pelagic food web in the WAP. Predicting ecological trajectories/change requires understanding ecological responses to, and variability resulting from, the interactions of multiple disturbances operating over a wide range of temporal and spatial scales. PAL has the unique opportunity to study the rate of transition between two marine states, one represented by a fully polar system characterized by a productive, short, linear food web with high carbon export to a subpolar system with a more complex food web and lower rates of carbon export. These shifts have global implications as the Southern Ocean are disproportionately important in planetary biogeochemistry.

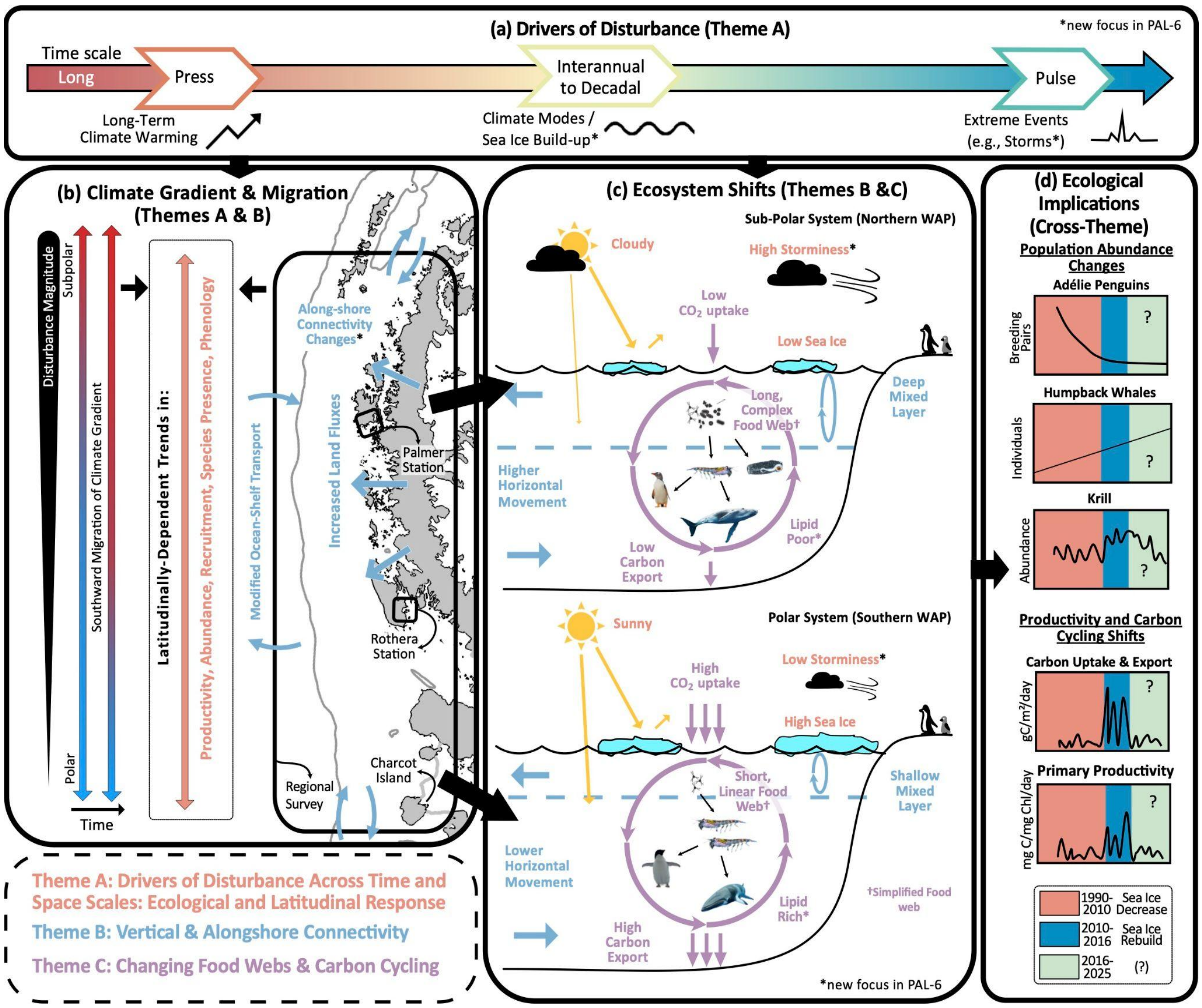


***Figure 1. PAL Conceptual model and research themes**: PAL spans a space and time climate-biogeographic gradient that has shifted due to local and atmospheric circulation changes affecting the ocean (1b). The shifting sea-ice structured polar system is affected by a range of disturbances spanning climate press (long term warming), interannual to decadal variability (e.g., from ENSO, SAM) and pulses (storms) that affect both land and seascapes (1a). A southern migration of the climate gradient and latitudinally varying disturbances is predicted to result in continued change in ecosystem properties, across all trophic levels, at regional scales which has implications for food web structure and the cycling of carbon (1c). Combined, these responses result in significant system-wide ecological consequences for population abundance of key species, productivity and carbon cycling (1d). Note color coding of our three major research themes (bottom left) is also depicted to show where they play a specific role in the conceptual model (1b and 1c).*

Within our conceptual framework, we take a system-wide approach to determine how long-term press (warming) and shorter-term pulse disturbances (e.g., storms) interact to drive ecosystem transitions. We exploit the near-continuum of "press-to-pulse" temporal drivers which is differentially expressed along the WAP, providing a climate gradient over our study domain. The northern regions are characterized by subpolar climate (shorter ice season, warmer moist atmosphere) and the southern regions by a polar climate (longer ice season, cooler dry atmosphere). The transition between the two appears to be shifting from north to south along the WAP and currently the "hinge point" of the transition is located at our long-term study site at Palmer Station. We predict this hinge point will continue to move southward, a process we term *climate migration*, reflecting the long-term press of planetary warming, providing us with an opportunity to study the ecosystem transition. Additionally, we use the variability associated with the relatively wide continental shelf (100-200 km) that has an on-to-offshore gradient– from the land-influenced nearshore region driven in part by melting glaciers and an along-shore coastal current–to open ocean conditions on the continental slope more influenced by the Antarctic Circumpolar Current and deep-water upwelling. On local scales (10's of km in the horizontal, 10-100s meters in the vertical), physical dynamics influence key ecosystem processes like rates of marine productivity and the breeding success of near-shore penguin colonies. These drivers appear to be interdependent: SAM is influenced by human-driven climate change, and the pulse-like forcing of individual storms shows a long-term southward migration along the WAP. The strong north-south climate and sea-ice gradients provide a biogeographic trend along the WAP. Polar ecosystems are typically characterized by relatively short, linear food webs, with diatoms, abundant krill and ice fish, and sea-ice obligate species such as Adélie penguins. Longer, more complex food webs with higher regenerated productivity with sea-ice avoiding species tend to define sub-polar ecosystems. On interannual timescales, years with high sea-ice extent are followed by higher primary productivity, krill recruitment, and penguin breeding success. Conversely, krill recruitment is poor following low sea-ice years with conditions favoring gelatinous salp blooms. The cumulative impacts of sea-ice decline and climate migration result in shifts in species composition, distributions, phenology, mismatches in trophic coupling, and carbon cycling and export.

5. Site Description

The main PAL site is located at Palmer Station (64º 46' S, 64º 04' W) on Anvers Island, west of the Antarctic Peninsula, and our regional study area encompasses the immediate coastal region and the offshore oceanic region covered annually by the advance and retreat of sea ice (Fig. 2). The regional sampling grid was expanded during the present funding cycle and now extends 1000 km along the Peninsula, from Cape Shirreff to Charcot Island, capturing the northern region near Palmer Station where sea ice duration has been reduced by ~80 days since the light 1970s, and a southern area near Charcot Island with persistent summer sea ice cover. The sampling grid extends 200 km across the continental shelf encompassing coastal, shelf, and oceanic slope waters. Our study area thus spans the latitudinal climate gradient of the WAP from northern more subpolar, maritime conditions (warmer, wetter) to southern more polar conditions (colder, drier), which is central to our conceptual model.

6. Science Strategy: Regional spatial and temporal observations with modeling

Our integrated sampling/modeling strategy is based on a multi-faceted program that incorporates the logistical realities of working in this remote polar environment. The sampling strategy is designed to resolve key ecological processes influenced by press-to-pulse disturbances that are expressed over a range of space/time scales. This is accomplished through a combination of multi-tiered and multi-platform sampling approaches, annual process-based high-resolution seasonal sampling, and field manipulative experiments. The results of the sampling activities inform modeling efforts that fill gaps through improved parameterization of key processes and provide data for assimilation modeling synthesis efforts. In turn, models guide the development of field process studies.

The PAL LTER sampling program (Fig. 2) has four complementary facets: The first is a regional-scale oceanographic cruise during January aboard the Antarctic Research and Supply Vessel (ARSV) *Laurence M. Gould* (LMG) (decommissioned in July 2024) or the Research Vessel *Nathaniel B. Palmer*

(NBP). The second includes continuous regional-scale autonomous instrumentation including physical oceanographic sensor moorings and Slocum gliders to provide seasonal-to-yearly temporal coverage, as well as airborne drones for habitat mapping and whale imagery. The third facet is manipulative experiments carried out aboard ship and at Palmer Station. The fourth is local-scale daily to weekly sampling during the October to April growing season near Palmer Station, measuring many of the same properties also sampled on the regional cruises and including observations and measurements at Adélie, gentoo, and chinstrap breeding colonies (the WAP is unique in that all three *Pygoscelid* penguins breed here), and of other seabirds and whales. At Palmer Station, penguin observations were initiated in 1975,

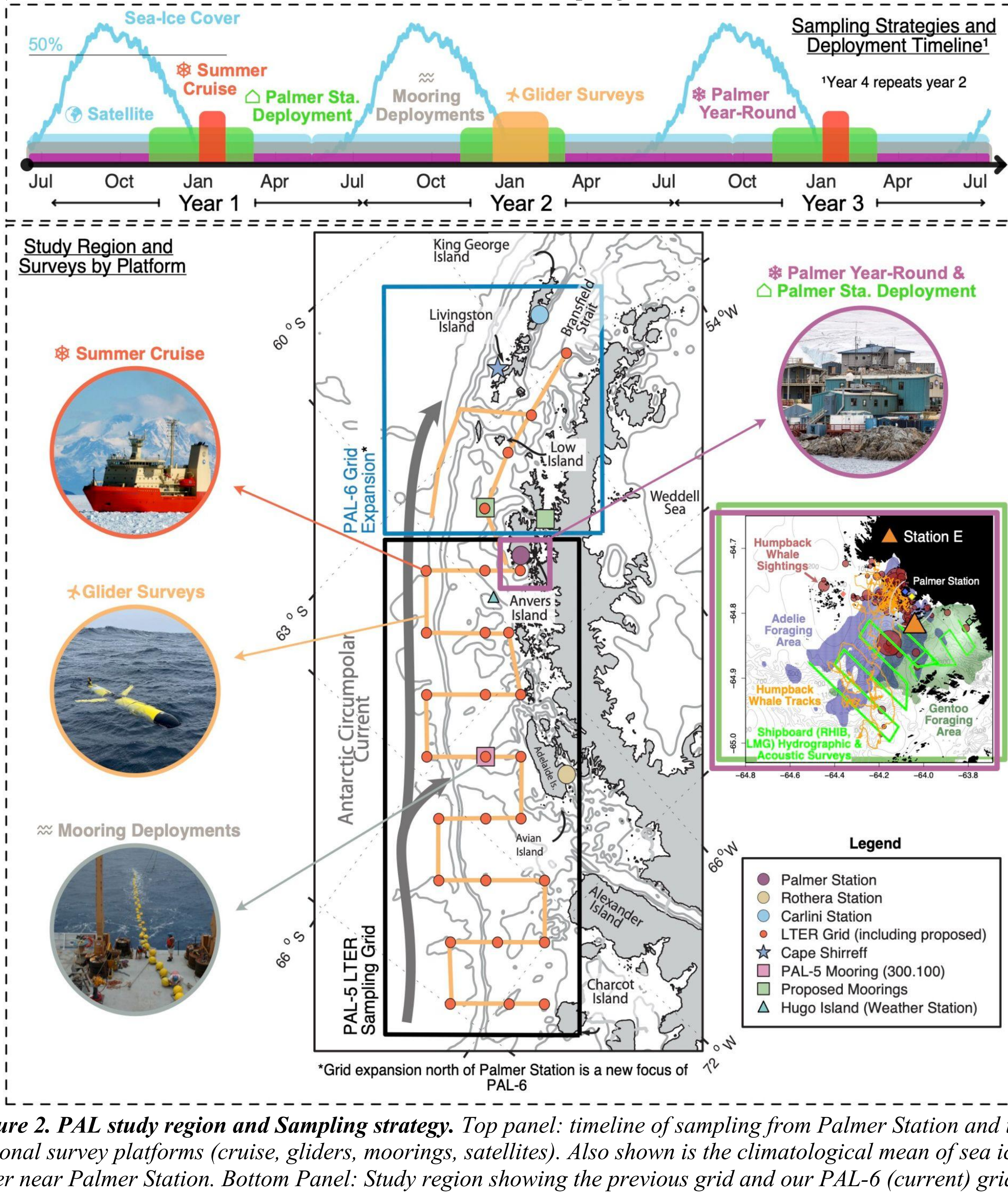


Figure 2. PAL study region and Sampling strategy. *Top panel: timeline of sampling from Palmer Station and the regional survey platforms (cruise, gliders, moorings, satellites). Also shown is the climatological mean of sea ice cover near Palmer Station. Bottom Panel: Study region showing the previous grid and our PAL-6 (current) grid expansion, cruise and gliders, moorings, sampling sites and key partner research stations. Map inset on right shows typical local-scale presence/foraging of whales, penguin colonies, acoustic surveys and sampling at Palmer Station.*

and annual hydrographic sampling began in 1991. Our instrument deployment strategy is closely Coordinated with the NOAA AMLR program, which also deploys moorings and gliders off Cape Shirreff and Bransfield Strait. The partner time series by NOAA is over 20 years in length. The British Antarctic Survey also has a complimentary 27-year hydrographic, weather, and benthic time series collected at Rothera Station approximately 500 km south of Palmer Station (Fig. 2).

During this award period, the pandemic prevented the annual January cruise in 2020-21 and we were limited to only a four-person field team at Palmer Station (versus our allotted ten). The Palmer Station pier rebuild in 2021-22 precluded any station science and we were limited to a research cruise in November 2021 (~2 months earlier than is typical). Our fieldwork got back on schedule in 2023-24, with a cruise in January 2024 aboard the LMG, but our allotted science team at Palmer Station during the 2023-24 season was ~half of what was in the funded proposal due to a station construction project. This year marked the last cruise on the LMG (NSF did not renew the contract) after sailing for over three decades as part of the PAL program; future cruises will be on the NBP, but every other year. This is a significant change for PAL and we intend to make optimal use of autonomous and remote sensing and modeling at a range of time and space scales to fill in the gaps, but we acknowledge this cannot fully replace shipboard grid sampling.

We were able to fill some critical data gaps by collaborating closely with colleagues from the British Antarctic Survey, which had deployed an autonomous coastal ARGO float near the middle of the PAL sampling grid that provided weekly data from 2020-23. This technology is proving critical to obtain full-depth, year-round observations on the Antarctic shelves where sea ice and deep icebergs prevent traditional mooring deployments with upper ocean instrumentation. The successful deployment of ARGO floats on the shelf demonstrates a new approach to both fill the gaps from summers when we will not have a cruise and augment our datasets with year-round observations. A new weather station on Hugo Island (70 km offshore) successfully deployed in January 2024 is providing new weather forcing data from the open shelf to complement both the existing, subsurface mooring deployments and planned ARGO float deployments.

Data synthesis and numerical modeling are integral to the PAL research effort, and during the current award period we continued to pursue an integrated approach for linking ocean bio-physical models across time-space scales and levels of complexity. We completed development on a 1-D column food-web model, with model physics forced from hydrographic observations and key biological parameters tuned to observed seasonal cycles via variational data assimilation (Kim et al., 2021, 2022). We also published results from a new, fully dynamic 1-D sea-ice ocean physics model for the WAP shelf with/without assimilation of mooring and satellite sea-ice observations (Saenz et al., 2023); pilot studies are underway incorporating a phytoplankton, zooplankton, nutrient, detritus module to explore synoptic to seasonal responses to environmental drivers of vertical mixing, freshwater, winds, and sea-ice cover.

On the regional scale, we conducted model simulations with a new coupled 3-D bio-physical ocean-sea ice model for the WAP and adjacent Southern Ocean (Schultz et al. 2020, 2021). The 3-D model, built on the MIT-GCM, leverages collaboration with colleagues at the British Antarctic Survey. The multi-decade long simulations at eddy resolution (6-9 km on the WAP shelf) examine climatic controls on interannual and geographic variations across the WAP shelf/slope domain (north-south and onshore-offshore) in physics (ocean temperature and salinity, sea-ice extent, mixed layer depth, and freshwater inputs from the atmosphere and glaciers) and biogeochemistry (e.g., phytoplankton blooms and air-sea CO_2 flux). Linking to basin-scale and global scales, PAL team members contributed to a Southern Ocean paper from REgional Carbon Cycle Assessment and Processes (RECCAP2) project (Hauck et al., 2023). We also continued modeling collaborations with the Northern Gulf of Alaska (NGA) LTER, who are advancing similar regional ocean biogeochemical variability simulations (Hauri et al. 2020; Hauri et al., 2021), with a specific recent focus on heat, acidity, and low oxygen compound extreme events in the Gulf of Alaska (Hauri et al., 2024).

7. Science Results Summary (by theme)

A. Drivers of disturbance across time/space scales Theme A focuses on disturbance to determine how long-term “press” and short-term “pulse” disturbances interact to drive observed changes in the WAP food web, the response of individuals and populations over time (reflecting resilience), and if there is evidence of legacy (long-lasting) effects. The sub-themes include long- and short-term spatial shifts in ecosystem productivity, trophic responses to temporal shifts in seasonal phenology, and the role of storm forcing in structuring land-based elements.

Compared to temperate and tropical ecosystems, polar systems experience high levels of natural climate variability intrinsic to polar seasonality, and the impact of both regional and remote climate modes make distinguishing long-term trends in these systems (Fig. 3) a challenge. Despite these complexities PAL uses the intrinsic interannual variability in sea ice to assess food web responses, which are superimposed on long-term warming trends. While the WAP long-term trend shows the number of sea-ice days per year has rapidly declined since the late 1970s, there was a significant reversal that started around 2010 and ended in 2019. This period of increased sea-ice provided a natural experiment for assessing potential for this polar system to reset to its prior state during a several-year sea-ice recovery. Our sustained sampling allowed us to show short-term responses at lower trophic levels (e.g., enhanced phytoplankton productivity, increased krill recruitment) but limited response in upper trophic levels (e.g., no evidence of increased survival in Adelie penguins), suggesting that the long-term regional warming and sea-ice decline, combined with increasing storminess, may be offsetting predicted recoveries during a relatively short period of sea-ice recovery (Schofield et al, 2024). Because storms are new focus for PAL, our recent efforts include different approaches, including storm tracks (Stack, 2023) and synoptic-scale wind fields (“storminess”, Quinter 2023, Schofield et al. 2024) and developing metrics that are relevant for evaluating ecosystem impacts (e.g., Quinter 2023 for penguin behavior).

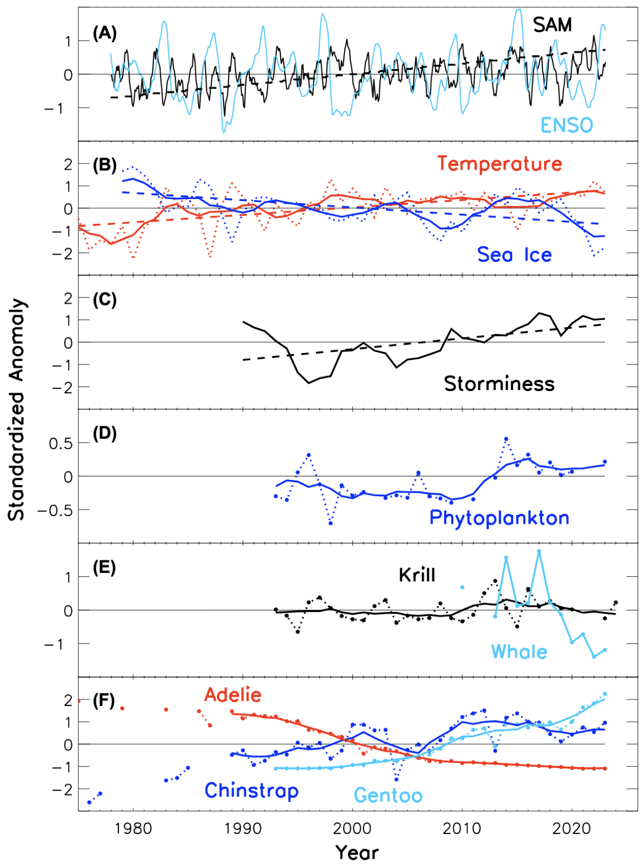


Figure 3: Decadal variability along the West Antarctic Peninsula. *Long-term trends observed in (A) climate cycles, (B) physical drivers (winter air temperature and sea ice duration), (C) summer storminess derived from ERA5 reanalysis from the European Centre for Medium-Range Weather Forecast weather reanalysis, (D) January depth-integrated phytoplankton, (E) January Antarctic krill (Euphausia superba) abundance and whale pregnancies, and (F) penguin (Adélie, Pygoscelis adeliae; gentoo, Pygoscelis papua; and chinstrap, Pygoscelis antarcticus) breeding pairs at Palmer Station. Shown are standardized anomalies (dotted), smoothed multi-yearly variability (unbroken), and long-term trends (broken) for those series with trends at P <0.05 significance. (Schofield et al. 2024)*

From a circumpolar perspective, teleconnections have contributed to observed Antarctic and Southern Ocean changes (Li et al. 2021; Xin et al. 2023), including regions of rapid surface warming and sea-ice decline (e.g., the WAP and West Antarctic Ice Sheet) versus regions of moderate cooling and sea-ice expansion (e.g., the western Ross Sea) (Stammerjohn and Scambos, 2000; 2021), along with a sudden post-2016 circumpolar sea-ice reduction (Himmich et al., 2024). These dynamics play a major role in the transport of heat via ocean circulation onto continental shelves, especially along the WAP, with its proximity to the Antarctic Circumpolar Current (Moffat and Meredith 2018; See Theme B), with consequent impacts on sea-ice thickness and seasonality (Saenz et al. 2023).

In turn, climate change is leading to phenological shifts across a wide range of species. PAL reviewed the phenology of year-round residents and seasonal visitors from bacteria to whales to demonstrate how years with early vs. late sea ice retreat led to opposing ecosystem and species responses (Cimino et al. 2023). We characterized both the seasonal succession patterns of coastal phytoplankton species near Palmer Station (Nardelli et al. 2023), and across the WAP, we show blooms are shifting later in the season over time in ice-associated waters (Turner et al. 2024). Consequences of these shifts include changes in surface ocean carbon uptake, food web dynamics, and trophic cascades. For zooplankton, seasonal succession was apparent, typically in decreasing zooplankton size and a shift to species that are less dependent upon phytoplankton, with various taxa shifting their phenology between years (Conroy et al. 2023). From an Adélie penguin perspective, earlier sea-ice retreat and shifts in the timing of suitable conditions or prey characteristics often lead to mismatches, or asynchronies, that influence chick mass at fledging, and ultimately their survival (Cimino et al. 2023). We recently employed continuous passive acoustic recorders around Palmer Station to test hypotheses regarding how these shifts in ecosystem processes impact the presence and phenology of baleen whale arrival/departure.

Near Palmer Station, since 1990, there has been high variability in local weather parameters, including decadal variability in windy/snowy years. Linear trends include the snow-free period starting later in the spring over time (meaning that snow is more frequently present in the early seabird breeding season) and more snow events during the Adélie penguin breeding season (Cimino et al., in review). On the small islands near Palmer, topography and wind influences snow cover patterns, which impacts seabird nest sites and colony locations (e.g., Larsen et al. 2023). For example, snow accumulates on lower elevations and south-facing slopes driven by the north-northeasterly winds while Adélie penguin colonies occur on higher elevations and more north-facing slopes (Cimino et al., in review). On Torgersen Island, a focal study site containing ~50% of the local Adélie penguin breeding population, all sub-colonies on south aspects have gone extinct, and only five of the 23 historic sub-colonies remain active, containing 7% of the 1975 population. We estimate Adélie penguins on this island and in the Palmer Station area will be extinct in <25 years, likely due to a combination of long-term "presses" and short-term "pulses".

B. Vertical and alongshore connectivity as drivers of ecological change on local to regional scales. Theme B addresses how upper-ocean ecosystem function/structure is shaped by wind forcing and along-shore exchange. A first subtheme aims to understand the role of storminess as a driver of disturbance for the WAP ecosystem, in conjunction or in competition with other critical environmental forcings like warming, changes in sea ice cover, and interactions with land via melting of continental ice. A second subtheme focuses on the significant along-shore physical and ecological gradients along the WAP, and the role that along-shore exchange across these fronts has on the WAP ecosystem. A third subtheme aims to shed light on how storminess impacts both krill aggregations and their predators.

The potential role of storminess (Schofield et al. 2024) and other environmental forcings (e.g., continental melt and sea ice changes) in modulating the upper ocean structure and marine productivity is ongoing. The winter/spring of 2022 had record low sea ice extent in the PAL study region (Fig. 4). The PAL dataset shows that this extreme event was followed by a 30-year-record high in upper ocean heat content and record deep mixed layer depths and a significant breakdown of upper ocean stratification in summer 2023. Our analyses show that these summer conditions developed over several years starting in 2020, as the Amundsen Sea Low entered a persistent negative phase, which led to both extreme ice-free and stormy conditions in spring, 2022 (windiest Nov. on PAL record) and summer, 2023 (windiest Jan. on PAL record). This in turn promoted ventilation of deep heat and the formation of deep mixed layers (Moffat et al. *in prep*). The latter constitutes a rapid reversal of the mixed layer depth trending toward shallower values, which is likely driven by enhanced melting of continental glacial ice that freshens the upper ocean along the WAP (Cappola et al. in prep). These glaciological changes are driven in turn by sustained ocean warming, as illustrated by two recent studies in collaboration with glaciologists from the University of Leeds (Wallis et al. 2023, Davidson et al. 2024).

Ongoing analysis of the impact of the above events on the marine ecosystembut shows both PAL *in situ* and satellite chlorophyll data (in collaboration with J. Turner, ODU) were low-to-record-low in summer 2023. This indicates that the deepening mixed layers—a result of the development of the sea ice minimum and increase in storminess—led to a significant drop in marine productivity. This suggests strong competition between long-term "press"-like processes like continental ice loss leading to shallower mixed layers and enhanced productivity and "pulse"-like sudden changes in sea ice and storminess that led to deep mixed layers and low productivity in 2023. Whether the recent low-ice conditions and storminess are short lived or persist in the future is an open and critical question.

Undertsnading the impact of storms on krill and krill predators is an important focus of current project. PAL designed krill acoustic surveys within foraging regions of breeding penguins that have been surveyed weekly (when possible) from Dec to March since 2018. All data have been processed this year (in collaboration with K. Benoit-Bird, MBARI) and are being analyzed alongside environmental and penguin foraging data. Preliminary results show the seasonal phenology and maximum dive depth of penguins are correlated with the seasonal phenology and depth of high-density prey. They also show Adélie and gentoo foraging depths align with peaks in prey abundance within each species foraging range and foraging depths increase over the season. During strong wind stress events in 2020, Adélie and gentoo penguin maximum dive depths increased by ~13 and 36 m, and dive depths returned to pre-wind event depths within 6 to 12 hours (Quinter et al. 2023). Work is also underway to compare the number of humpback whale sightings in relation to storm events to understand if whales leave the Palmer area after storms in search of high-quality prey patches (Gonzalez et al. in prep.).

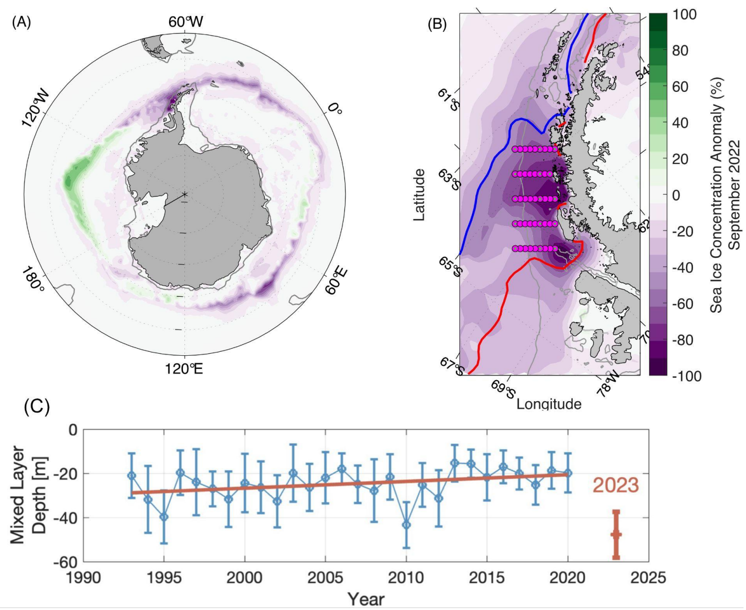


Figure 4: Extreme events along the WAP. *Anomalously sea ice developed around Antarctica in September 2022 (Panel A), with a record along the WAP (Panel B). Sea ice and wind anomalies (not shown) lead to the deep average mixed layer depth in the subsequent summer of 2023 (Panel C).*

PAL modeling of along-shore exchange processes highlights that while circumpolar water was critical in transporting heat onto the shelf, it was countered by along-shore flooding by cold Weddell Sea water. The transport of the Weddell water via the Bransfield Strait plays a key role in determining the overall heat budget around Palmer Station (Wang et al. 2022). PAL has expanded sampling in the northern extended grid (Fig. 2) to understand along-shore exchange and its impact on the WAP ecosystem, a second subtheme. We have collected two years of mooring data off northern Anvers Island, which shows frequent, synoptic-scale intrusions of cold Weddell-sourced water into the PAL study region. Confirming modeling results (Wang et al. 2022), these intrusions are prevalent in fall and winter, emphasizing the need for year-round observations. The Southern Bransfield Front (SBF), which separates the cold northern WAP from the warm southern WAP, is being characterized using data from a glider deployed in 2021-22 (Benz et al. in prep). Data from a newly recovered mooring array deployed in 2023-

24 on the extended grid in collaboration with NOAA will provide unique insights into variability and spatial structure of the SBF.

C. Changing food webs and carbon cycling. Theme C addresses a central component of our conceptual model, that the structure of the pelagic food web plays a fundamental role in regulating net community production, air-sea exchange of carbon dioxide (CO_2), and the export of organic carbon to the deep ocean. Interactions between food web components furthermore affect assimilation and trophic transfer efficiency of energy and carbon throughout the food web. Subthemes include: phytoplankton primary productivity, diversity, and carbon dynamics; energy storage and food web interactions; and food webs, carbon cycling, and export processes.

The WAP exhibits strong seasonal biological drawdown of inorganic nutrients and dissolved inorganic carbon (DIC) modulated by sea ice, glacial freshwater input, and air-sea exchange. Using a new sea-ice and biogeochemistry model (Schultz et al. 2021) we examined the effect of sea ice on phytoplankton blooms and surface seasonal DIC drawdown; in years of early sea-ice retreat, a longer growth season leads to larger seasonally integrated net primary production (NPP) but some of the biological uptake of DIC by phytoplankton is counteracted by increased oceanic uptake of atmospheric CO_2. In years of late sea-ice retreat, despite lower seasonal NPP, we find larger DIC drawdown due to lower air-sea CO_2 fluxes and increased dilution by sea-ice melt. These modeling studies were complemented by the first year-round carbon budget assessment on the WAP continental shelf with mooring observations (Yang et al. 2021), showing significant mixed layer biological DIC drawdown in spring/summer was replenished by physical processes.

Phytoplankton diversity, taxonomic structure, and physiology change with warming and declining sea ice, ultimately driving changes in CO_2 uptake and carbon export. Recent results on WAP phytoplankton communities indicate while WAP diatoms exhibit high diversity (Lin et al. 2021), cryptophytes surprisingly show remarkably low genetic diversity (Brown et al. 2021). Diatom diversity was lower in warmer waters, suggesting diatom diversity will be impacted by continued ocean warming (Lin et al. 2021). Models assessing warming impacts were not able to resolve these dynamics reflecting the difficulty of parameterizing different species (Zaiss et al. 2021). Phytoplankton taxa have unique biochemical profiles reflecting cellular compositions (pigments, proteins, lipids, carbohydrates) and their light-chemical environment. Using metatranscriptomes, paired with lipidomics, we have new insights on how phytoplankton lipid production and utilization is influenced by light (Bowman et al. 2021), with different phytoplankton taxa showing distinct transcriptional profiles suggesting diverse ecological strategies during the polar winter–spring transition. Ongoing work is examining how changes in phytoplankton energy storage lipids could influence the energy density of krill that consume them, including in seasonal sea-ice phytoplankton (Holm et al., 2024). As the maximum photoperiod is in summer, we hypothesize this could facilitate high food-quality krill during the penguin chick rearing period (Cimino et al. 2023); processing of krill and of penguin diet samples for lipids are underway to quantify prey energy content to test this hypothesis. A global meta-analysis of lipidomes shows microbes living in cold (−2°C) regions have threefold more unsaturated fatty acids than those in warm waters, thus declines in unsaturation of planktonic essential fatty acids under different scenarios of climate change could have negative consequences for food webs (Holm et al. 2022). Model simulations also documented a shift from low to high nucleic acid bacteria with a warming climate (Kim et al. 2022).

New results from our food web studies indicate omnivorous summer feeding by juvenile Antarctic krill in coastal waters (Conroy et al. 2024), indicating these young stages can also significantly supplement their phytoplankton diet with metazoans, such as copepods, and with heterotrophic protists. While these results challenge the paradigm of a short polar food web reflecting efficient krill grazing of large diatom cells, they do explain our prior study results indicating krill could not meet their daily ration requirements consuming phytoplankton alone. Moving up the food web, we find annual pregnancy rates in humpback whales were strongly correlated with winter sea-ice extent from the previous year due to its impact on krill availability (Pallin et al. 2023). When baleen whales arrive near Palmer Station after fasting during their breeding season in tropical waters, their foraging behavior is directly linked to krill availability in the upper water column and they take advantage of this continuous availability by foraging during all hours of the day at high rates (Nichols et al. 2022). This pattern changes as photoperiod and diel vertical migration of krill becomes more evident later in the season and whale foraging activity decreases commensurately. Interestingly, we showed the recent adaptation of humpback whales employing/creating bubble nets during the early periods of the summer to enhance foraging efficiency via prey aggregation (Allen et al. 2024).

Carbon export to the deep sea was investigated using surface ocean thorium dynamics in the surface ocean over a full ice-free season at Palmer Station (Stukel et al. 2022). The low C:^{234}Th ratios of sinking particles was indicative of fecal pellets, while C:^{234}Th ratios of suspended particles were correlated with chlorophyll and particulate organic carbon, likely reflecting high diatom abundance during the spring bloom. Our prior research found Antarctic krill (*Euphausia superba*) fecal pellets contribute a disproportionately large fraction of the carbon export in the WAP, but recently we also show that krill body size and life-history cycle, as opposed to overall krill biomass or regional environmental factors, exert the dominant control on POC flux (Trinh et al. 2023) (Fig. 5). Warming is causing shifts in the krill population (Atkinson et al 2019), which may alter these export patterns of fecal pellets, leading to changes in ocean carbon storage.

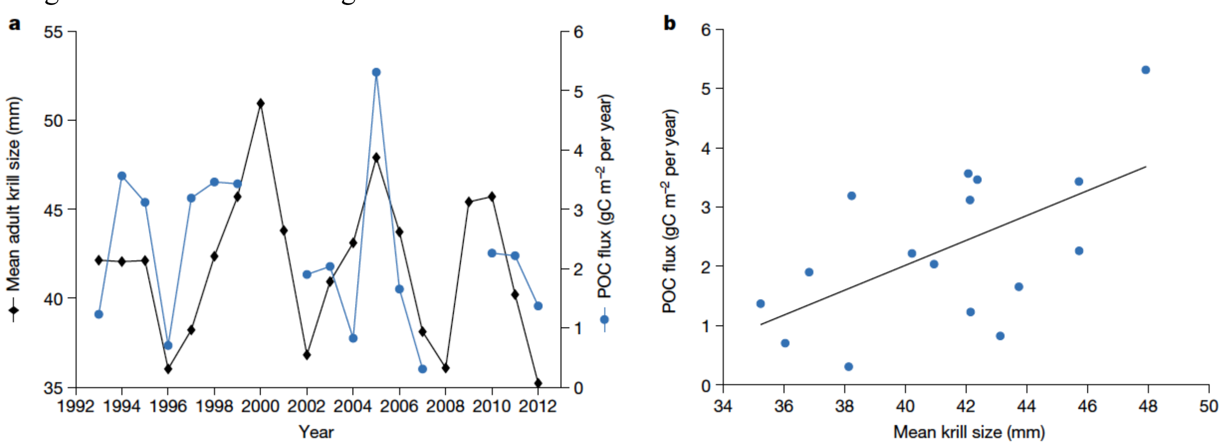


Fig. 5. Summer Antarctic krill body size drives annual POC flux*. a. Annual POC flux and annual mean adult E. superba body size from 1993 to 2012. b. Annual POC flux as a function of annual mean adult krill body size (R2 = 0.34, P = 0.018). From Trinh et al. (2023), Nature.*

B. Information Management

The lead Information Manager (IM) is Sage Lichtenwalner at Rutgers University works with the research technicians, students, and Co-PIs within each research group to ensure the project adheres to the data and information management guidelines, best-practices, and policies set forth by NSF and the LTER community. In 2021, at the conclusion of the previous award, the PAL IM component moved from SIO to Rutgers, following a 1-year transition. At the same time, several new Co-PIs joined the project, resulting in a shift in personnel and institutions that required reviewing and updating all IM tools and processes, including the redesign of our data management workflow to account for the deprecation of the SIO Data Zoo. This, coupled with the pandemic, resulted in a delay of release of several datasets. During the transition, the PAL IM team relied on the LTER IM network, EDI staff, and the broader scientific data management community to identify tools, opportunities, and best practices. In keeping with LTER recommendations, we generally release all datasets as Creative Commons Attribution (CC-BY), to facilitate collaboration with and usage by other researchers and educators.

Accomplishments to date with the current award include: A) The PAL website, originally hosted in Drupal at SIO, was redesigned, and migrated to a WordPress installation hosted by Rutgers. The new site features a full team roster, research group descriptions, searchable publications and dataset lists, information on educational efforts, and regular project news/updates (i.e., blog posts) as needed. B) PAL citations were migrated to a shared Zotero group library. The database currently includes 729 entries and is directly searchable on the PAL website using an adapted version of the BLE's *Zotero-JavaScript-Search-Client* tool. Zotero's native tagging feature is used to facilitate the filtering of recent articles by research group. C) PAL datasets in EDI are now easily searchable on the PAL website using a new interface adapted from BLE's *PASTA-JavaScript-Search-Client* tool. D) A custom CakePHP web application was built to track PAL personnel changes, dataset status, and the workflow of dataset updates. D) Team communications are now facilitated by 4 mailman mailing lists and a team Slack channel, which are both regularly synchronized with the PAL personnel database. E) Due to the sunset of the Data Zoo application, new IM workflows were developed to facilitate dataset and metadata updates. This includes a new Git-based workflow for compiling, documenting, and reviewing long-term datasets and relying on ezEML to facilitate collaborative data package version updates between the research team and IM.

Data Management Overview. Core Palmer LTER datasets now include over 30 years of measurements, highlighting the crucial need for maintaining robust sampling and data processing procedures. The PAL information management systems have evolved to make datasets compliant with the FAIR principles, utilizing the EML standard, as recommended by the LTER Network.

In 2021, we began a concerted effort to improve the PAL data management and delivery pipeline to better support researcher and end-user needs. Our goal was to rely more on LTER and EDI provided tools, like ezEML, which enable scientists to be directly involved in the dataset and metadata creation process, rather than relying on the IM to integrate datasets into custom software tools. This transition was necessitated by the deprecation of the SIO Data Zoo, but it also allowed us to take advantage of newer tools and features provided by the Environmental Data Initiative. Our core data management workflow currently relies on EDI's data portal for archiving data, and their relatively new ezEML interface to streamline metadata management, review, and collaboration. In addition, the PAL IM utilizes a custom database for tracking dataset update tasks, and several new scripts and workflows have been developed this year to better manage individual datasets. We are undergoing a thorough review and update of our core and historic datasets (several of which were impacted by pandemic disruptions). During the last year we published 18 updates to 16 datasets (2 weather datasets received 2 updates each). Another 35 dataset updates are currently in process, which we hope to make in the next year (many await sample processing or QC review), and several new datasets are in development. As of August 2024, our archive includes 51 active datasets and 94 total datasets; 37 are long-term datasets with over 30 years of measurements.

The general workflow supporting the full data lifecycle, from collection through archiving, consists of the following steps: 1) New observations or samples are collected during the annual field season and cruise following documented procedures, 2) Raw data files and processed sample information are stored locally by each research group, 3) Required dataset updates are logged in a tracking database and new datasets are given a unique identifier, 4) Processed data is formatted, reviewed, cleaned, and merged into an existing time series (if applicable), typically in CSV format, 5) Data and metadata are updated and reviewed in ezEML by both the research group and IM, 6) EML data packages are exported from ezEML (and manually edited if needed) and published to the EDI archive as a new data package or a revision of an existing one, 7) Users can access the archived datasets directly from the EDI data portal, or via the searchable list on the PAL website, and 8) Selected datasets will also be published to our local ERDAPP server for direct access by researchers and educational audiences.

Data & Sample Collection. The PAL project collects long-term core datasets (e.g., phytoplankton, zooplankton distributions, and penguin population studies), and shorter-term research project datasets during both field seasons at the Palmer Station and aboard annual LTER cruises. Sampling aboard the ship and on station has been standardized over the years, and each research group's sampling and analysis standards/protocols have been tuned to follow PAL, LTER, and community accepted best practices. Each research group (Physical Oc., Sea Ice, Phyto- and Zooplankton, Microbes, Sea Birds, Whales, Modelling) is responsible for storing and maintaining their own archive of raw digital data and physical samples (if needed), relying on their local university IT and physical storage facilities. Rutgers maintains a digital archive of all core ship and station raw data files in a robust, secure, and well backed-up file system.

Data Processing. Data for the PAL project is archived according to policies and requirements set forth by NSF and the LTER Network. Following the field season, the IM works with the research team to properly update, describe, and archive each dataset. Long-term datasets are incorporated into existing time series through a documented and structured workflow that enables process consistency and tracking. We are in the process of moving several datasets to a GitHub-based workflow that documents changes to the raw, processed, and merged datafiles, along with any code necessary to create combined datasets.

Data and Metadata Formats. Archived core measurements from PAL annual cruises and station seasons are generally made available as CSV files, to support wide adoption and easy usage. When appropriate, larger, or more complex dataset formats are utilized following community practices. For example, a new historical timeseries of Glacier terminus lines was provided as an open-source GeoPackage file, and we are currently working on a new CTD dataset that will be based on the NCEI NetCDF Profile Templates. As we look to share more advanced datasets in the future (e.g. IFCB imagery, acoustic moorings, drone survey data), we anticipate creating more hybrid datasets consisting of CSV index files along with other data file formats. Metadata for new and existing datasets is formatted as EML (Ecological Metadata Language), using EDI's new ezEML tool. ezEML includes the LTER controlled vocabulary for keywords and the LTER unit directory for standardizing metadata values. Recent upgrades to the data processing workflow have sought to align PAL IM with the "Best Practices for Dataset Management in EML" (currently version 3), which includes adding metadata tags for geographic coverage, taxonomy, project and funding sources, ORCID/ROR identifiers, and provenance.

Data QC, Archiving, and Storage. PAL datasets are primarily archived on the Environmental Data Initiative (EDI) data portal, as required by the LTER program. Most PAL data packages are updated once per year, following the field season and any necessary post-processing and review. Datasets are typically staged in ezEML by the IM or (more recently thanks to one-on-one training) the responsible science lead. They are then uploaded into EDI after the IM and science lead have both reviewed the data and metadata for any issues. ezEML's new metadata check, data QC check, and data explorer features have greatly aided this process, ensuring the data packages are complete and free from major errors. Several datasets are archived outside of the EDI workflow. Standard shipboard measurements from PAL annual cruises (e.g., CTD, ADCP) are collected by the ship techs and made available by the Rolling Deck to Repository (R2R) project and archived with the Marine Geoscience Data System (MGDS). Standard station measurements (weather, waterwall, snow stakes), which fall under the responsibility of station staff, are available in the AMRDC data repository. Glider datasets are available on the Rutgers glider data portal and archived in the IOOS Glider DAC. One genomic dataset is currently archived with NDBI. Research model datasets and code that are created for specific papers are generally archived on Zenodo. In compliance with NSF's specific requirements for Antarctic sites, the PAL project and its data are also listed with the U.S. Antarctic Program Data Center (USAP-DC).

Data Availability. Annual cruise and station datasets are typically processed and made available in the EDI archive within 6-12 months following each field season. Physical samples (e.g., chlorophyll, biopsies, oxygen isotopes, zooplankton) generally require additional time for processing as they depend on shipping and processing lab availability, though our goal is to make them available within 24 months. While dataset downloads are an imperfect metric of usage, the following figure shows the number of dataset downloads from the EDI data portal since 2018. The high traffic peaks are primarily due to the popularity of the palmerpenguins library, or other projects it has inspired, but a general trend upwards is also discernible (Fig. 6).

Future Challenges & Opportunities. Over the next 3 years, we hope to increase the timeliness, quality, and number of datasets we provide to the community, taking advantage of new community tools and best practices. Challenges include, 1) Adding new optical datasets (e.g., Imaging Flow CytoBot, IFCB) and developing a strategy for automated microscopy that provides millions of digital images each field season. Our approach will follow the lead of the NES LTER, who has pioneered robust strategies for managing these unique datasets. 2) Identifying effective strategies for storing and archiving large

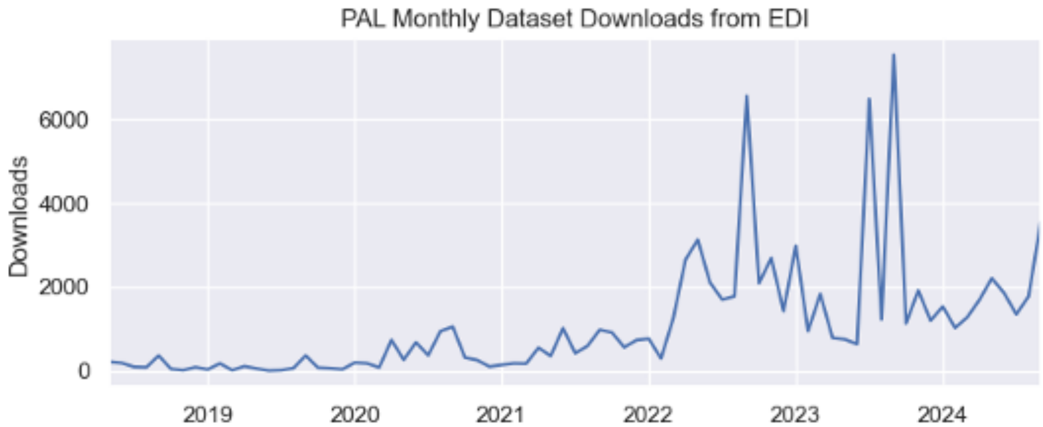


Figure 6. *PAL monthly datasets downloads from EDI*

datasets, including raw CTD, flow cytometer, hydrophones, drone footage, and whale tracks. 3) Continuing to improve the data quality, formats, and review processes of existing datasets, while considering the addition of new datasets that might be valuable for others in the wider scientific community. Opportunities include, 1) Developing trainings and guidance for graduate student to learn about data/information management, so they can build their own dataset packages without direct IM involvement. 2) Relaunching the PAL ERDDAP server, to provide more advanced tools for data access and visualization, enhancing public access of our core datasets for research and educational uses. ERDDAP provides a widely used data interface, facilitating easier access and visualization, but EDI will still serve as the primary long-term archive for PAL datasets, as required by the NSF Office of Polar Programs and LTER. 3) Developing code notebooks to showcase available PAL datasets and relevant ecological/oceanographic data analysis techniques to increase the usage of PAL datasets hosted by EDI. As PAL IM, Sage Lichtenwalner regularly participates in the monthly LTER IM team calls, and was a member of the LTER EML Best Practices review working group.

C. Network-Level Participation and Synthesis

Cross-site research and synthesis PAL is currently a partner in a cross-site LTER network synthesis grant entitled, "Interannual variability and long-term change in pelagic community structure across a latitudinal gradient". The effort amongst our four pelagic marine LTER sites (Northern Gulf of Alaska, NGA-lead; California Current Ecosystem, CCE; North East Shelf, NES; and PAL) is using our comparable, multi-decadal time-series data to investigate how species and communities are structured and how this varies both seasonally and inter-annually due to various types of environmental forcing. We are assessing commonalities across these latitudinally and ecologically diverse pelagic ecosystems, with three major directions having emerged as likely to inform ecological theory. First, we are examining whether two specific hypothesized mechanisms explaining long-term variability in plankton populations apply to all four sites: (1) The Linear Tracking Window hypothesis proposed that populations are most likely to track stochastic environmental forcing when their generation time matches the characteristic time scale of the environmental signal, and less likely when they are mismatched. (2) The Double-Integration hypothesis proposed that cumulative integrations of white-noise atmospheric forcing can generate marine population responses that are characterized by strong transitions and prolonged apparent state changes. Second, we are testing the Trophic Amplification hypothesis that proposes that global ocean animal biomass declines with climate warming, and that these impacts are amplified at higher trophic levels and at lower latitudes. This hypothesis has been found to be robust across several coupled marine ecosystem models; however, its predictions have not been tested with field data. The third focus of our efforts examine whether recently proposed patterns of planktonic community organization (based on size structure) hold up when exploring more taxonomically resolved data, and how/if these patterns have responded to stochastic or long-term environmental change. We are 1-year into the 2- year project and have completed preliminary cross-site data analyses for all three foci. A session proposal based on the initial results of this effort, and including other pelagic time series, has been submitted for the 2025 Association for the Sciences of Limnology and Oceanography (ASLO) Aquatic Sciences Meeting. Our goal is for these activities to produce a series of peer-reviewed manuscripts and position us for an even greater synthesis effort (for submission to NSF) that incorporates an even larger number of pelagic time-series beyond the LTER network.

PAL researchers also co-authored the LTER synthesis proposal "Quantifying ecological pulse dynamics using network-scale syntheses of long-term data" that was submitted in 2022 to the LTER office. While not funded that round, we plan to pursue some of the ideas stimulated by the effort. Other cross-site activities include participation by Co-PI Steinberg and her team on a cruise on the Northeast Shelf (NES) LTER sampling line with NES colleagues in summer 2022 to quantify micro- and macrozooplankton grazing rates (Menden-Deuer, Steinberg, et al. in prep).

International collaborations. We have had great success collaborating with our colleagues in the British Antarctic Survey, with whom we have had a formal Memorandum of Understanding since the early 2000s. Co-PI Moffat also just returned from a year's sabbatical where he was resident at BAS. We call at the BAS Rothera Base (Fig. 2) each year on our summer cruise along the Peninsula to cross-calibrate instruments and discuss comparative research between PAL and Rothera. BAS has operated a time series in coordination with PAL since 1998. We collect water samples at every discrete depth on our annual cruise and at surface samples at Palmer Station throughout the season for determination of ^{18}O of seawater by our BAS colleague Mike Meredith. These data, with temperature and salinity allow us to construct freshwater budgets and distinguish meteoric (glacial) and sea ice sources of water in the study region and over time. Two recent papers (Wallis et al. 2023, Davison et al. 2023) have expanded the above collaboration to a team of glaciologists in the UK (lead by Dr. Anna Hogg) to understand the interactions between the warming WAP and marine-terminating glaciers.

Another recent, productive international collaboration is with the National Antarctic Science Center of Ukraine. Oksana Savenko and Vadym Tchachenko joined Co-PI Friedlaender's lab at UCSC and are collaborating on collecting biopsy samples, UAS photogrammetry, and passive acoustic data from baleen whales around Vernadsky Station during both summer and winter months. These novel data are being used to determine the seasonal presence of whales during periods when the PAL LTER is not active locally as well as the population structure of whales that remain in Antarctic waters outside of our regular field season. Manuscripts are in prep. and results presented at numerous SCAR, IWC, and SMM international conferences.

A new collaboration was started recently with the OCEAN:ICE program (https://ocean-ice.eu) on a project involving PIs from BAS (A. Meijers and P. Dutrieux), AWI in Germany (M. Janout) and the National Antarctic Scientific Center of Ukraine (E. Dykyi and collaborators). The project is focused on studying the Southern Bransfield Front (a new focus for PAL) and Co-PI Carlos Moffat recently provided scientific training for the Ukrainian scientists involved in the project. This will be a collaborative effort to collect new hydrographic data to share across groups for analysis. Moffat is also contributing to the COUPLING-II project led by researchers from the University of Las Palmas de Gran Canarias in Spain. The project is focused on physical-biological interactions on a region spanning the Weddell Sea and the northern WAP, providing an excellent opportunity for collaboration with Spanish colleagues. Another new collaboration is with Mario La Mesa at Istituto di Scienze Polari in Italy who has helped identify fish species/age from otoliths in bird diet samples. Analyzing otoliths requires specialized expertise. A master's student was also involved in the processing of these samples. Understanding fish species important to different seabird species will aid in understanding species responses to climate change.

Other synthetic activities. PAL PIs contributed to several international, peer-reviewed status reports and manuscripts, such as the BAMS State of the Climate Antarctica (BAMS is the authoritative annual summary of the global climate), the Southern Ocean report, and 'Status, Change, and Futures of

Zooplankton in the Southern Ocean' (Johnston et al. 2022). We participated and presented at a NSF funded workshop on 'Future Directions for Southern Ocean Antarctic Nearshore and Coastal Research' and at a Wilson Center workshop on 'The Rules-Based Order in Antarctica and Global Challenges'. We provided information for updating the Management Plan for Antarctic Specially Protected Area (ASPA) No. 139 Biscoe Point, Anvers Island, Palmer Archipelago. Using PAL data and observations, we helped on the proposal to expand the ASPA boundary to protect seabirds against increased tourism. The team also published the first record of marine debris in the Palmer region (Gallagher et al 2024a) and quantified potential sources in a regional context (Gallagher et al 2024b). The Palmer debris report was used by the ACA office as evidence of what countries (e.g., numerous Chinese water bottles) and types of activities (fishing) contributing to pollution. Marine debris observations are reported to CCAMLR.

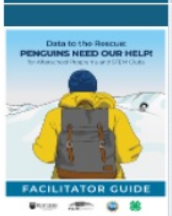
D. Education, Outreach and Training

Since its inception in 1990, the PAL LTER education and outreach program focuses on increasing knowledge and excitement for science conducted along the WAP through partnerships with a wide variety of informal science centers, universities, science museums, aquariums, nonprofit organizations, corporations, broadcast media, community and government leaders. Our objectives are to: Promote understanding of the environment along the WAP; support the next generation of young scientists through rich and innovative field and classroom experiences for K-12 students; and provide opportunities to pursue lifelong learning through public outreach initiatives, events, and meetings.

From 2016, the education and outreach efforts for PAL are facilitated by Janice McDonnell and a small education team who work closely with PAL researchers, school districts, community groups, and other educational and non-profit partners to promote STEM literacy through quality science education programs that focus on LTER-PAL science. McDonnell is the STEM Agent in the Department of 4-H Youth Development-Cooperative Extension, and a marine educator in the Department of Marine & Coastal Sciences (Rutgers). Our education and outreach initiatives focus on the Polar Literacy Principles, developed by McDonnell, Hotaling, and Schofield in 2018. For polar scientists, these principles define the important concepts to convey when communicating the broader impacts of their research. For educators, these principles provide guidance on significant concepts to teach about the Polar Regions. Our work also is consistent with the principles of the Next Generation Science Standards (NGSS), NJ Student Learning Standards (NJSLS), effective practices for community engagement of underserved/ underrepresented learners, and for onboarding students to STEAM workforce(s). We also follow effective practices for culturally responsive programming, in response to our Diversity, Equity, and Inclusion guidelines.

We collaborate with a broad range of partners and engage with various audiences including but not limited to graduate, undergraduate, and K-12 students, as well as informal learning environments such as 4-H, Boys and Girls Clubs, YMCA, and other community level non-profit groups. We provide support and training and mentorship for LTER researchers and graduate students on how to effectively communicate science. We also engage educators in compelling professional development programs that provide them with new content knowledge in the context of real-world scientific practices.

Undergraduate and graduate students, and post-doctoral scholars. PAL PIs pursue several strategies to recruit a diverse body of students and post-docs and integrate them into the different research themes. This includes advertising graduate opportunities across a broad network of potential prospective students, including a database maintained by one of our Co-PIs (See "Advisor Opportunities" a The Oceanography Society). At UDel, for example, Co-PI Moffat uses a consistent set of questions in prospective interviews (modeled after the fisk-vanderbilt Masters-to-PhD programs) to reduce bias and identify strong candidates for graduate school. Onboarding of new students include detailed discussions of PAL goals and how new projects contribute to achieve them. Across PAL, students and postdocs are exposed to frequent discussions about the site's themes and goals through monthly project meetings which include 1-2 talks by PAL team members or invited speakers. Research collaborations led by students are strongly encouraged, and time is set aside in our field efforts at Palmer station and the summer cruise to work in cross-disciplinary topics. Several PAL PI's institutions are REU sites, and we regularly engage these students in PAL research.

	K-12 Students	Audience Reach	Evaluation / Impact
	Explorers of the Deep 4-H commercially available curriculum that features LTER research and understanding climate change. Rutgers received a $50,000 grant to support the development of this resource. Done in collaboration with Oscar Schofield.	National curriculum reaching > 10,000 young people (3-6th grade) as part of the 2022-23 4-H STEM Challenge. Youth investigate challenges that ocean scientists, and engineers are currently exploring. Each challenge requires innovations and technical solutions that inspire public action.	4-H is part of university land grant programs reaching every county in all 50 states. Estimated 5 million youth are in 4-H nationally. The 4-H STEM Challenge is an annual event, celebrated and offered in every 4-H program, providing significant outreach for the LTER-PAL program nationally.
	Data to the Rescue: Penguins Need Our Help! Curriculum that features LTER seabird research and understanding the value of time series data. Rutgers led a 1.1-million-dollar NSF AISL project to support the development of this resource in collaboration with Megan Cimino, Sharon Stammerjohn, and Oscar Schofield	Eight-week afterschool program that encourages youth to explore the decline of Adelie penguin populations as monitored by the LTER-PAL program through data explorations. This program leverages the real-world scientific data to strengthen the practices of science, such as visualizing, analyzing, and interpreting data while engaging youth in discussing the impacts of climate change.	It was taught in 22 states reaching ~1,500 young people in grades 5-8 in both in and out of school learning environments. The program expands/supports the Data Jam concept envisioned by the LTER program, into informal learning environments. The program is offered commercially through STEMfinity and through other low cost 4-H initiatives.
	Video Teleconference (VTC) Programs From 2016-2019, PAL offered 6-8 video teleconference calls to approximately 3-5, 6-8, and 9-12th grade classrooms annually. Because of the pandemic, in 2020, we offered Ask a Palmer Station Scientist.	Educators partner with LTER educators and researchers to create a comprehensive experience for their students. Educators use LTER curriculum before the call and use the VTC as an opportunity to expand learning.	VTC program (2016-2019) reach 22 classrooms (~660 students live and 1,980 with re-broadcasts. Ask a Polar Scientist program as part of our 4-H from Home series where PIs Stammerjohn, Doney, and graduate student Andrew Corso engaged 65 youth in learning. Other collaborators include Ari Friedlaender, Carlos Moffett, and Megan Cimino.
	ID Antarctica with Andrew Corso During the winter of 2020 and 2023, this program was offered real-time via weekly blog posts. Andrew also facilitated a similar virtual program in conjunction with NJ 4-H from Home.	ID Antarctica is a collection of resources to help students and families explore life in the Southern Ocean. Youth are challenged to identify mystery organisms using a dichotomous key. Andrew Corso, a PAL PhD student, provides explanation and discussion in follow up video teleconferences.	The recorded version of this program supports ~1,480 students annually in classrooms across the U.S. including CA, MN, NJ, NY, VA, OH, AK, and FL.
	Professional development programs are offered annually in NJ and DE using LTER resources. Supported by Carlos Moffet, Oscar Schofield, and Megan Cimino.	In 2020-2024, PAL supported approximately 80 educators, in multi-day professional development programming. In 2024, NJ hosted a four-day professional development for 19 educators (5 NJ school districts). Delaware hosted 10 educators in a 4-day program.	Working with educators provides long-term and sustained impact. We also consider our educators partners in LTER education and outreach efforts as they support the co-development of resources and other LTER programs reaching ~5,000 students in 22 schools in NJ and DE.

E. Site Management

Site management of PAL is carried out by the civilian logistics contractor, currently Antarctic Support Contractor (ASC), a consortium of service providers under contract to the NSF. The NSF controls access of all researchers to the site, and supports most logistic needs including transportation, housing and sustenance, field research support, communications and data transmission, waste management, safety and security. Final research decisions are made in close consultation with NSF/ASC at the proposal stage and prior to each field season. There are strict limits to the numbers and roles of personnel we can deploy in the field, and the exact dates of stay. Deploying personnel must go through a comprehensive physical qualification process. Berthing for our project is limited to 10 at Palmer Station and 20 on the research vessel. Year to year changes in the available infrastructure has limited science personnel below what was requested in the proposal; thus, we consider our berthing request in the funded proposal as an upper limit. The Protocol on Environmental Protection to the Antarctic Treaty designates Antarctica as a natural reserve and sets forth requirements for all activities in Antarctica. All US Antarctic researchers are bound by the rigorous regulations of the Antarctic Conservation Act, the US legal instrument governing the provisions of the Antarctic Treaty regarding site occupation, environmental stewardship and sample collection. Of immediate concern to PAL is ensuring that the site remains undisturbed by uncontrolled human influences such as tourism or unsupervised research. The PAL research area is now designated as the Southwest

Anvers Antarctic Specially Managed Area (ASMA), conferring additional protection and additional obligations for researchers to define site management protocols, obtain field permits, and limit impacts. The SW Anvers ASMA facilitates site protection and defines how our site is managed.

Project Governance and Management. PAL consists of two co-lead PIs (Schofield and Steinberg; working together in PAL since 2008) and eight co-PIs (4 women, 6 men). All hold academic or research positions. Rutgers is the administrative lead institution. PAL is divided into 8 scientific components addressing the physical environment and ecosystem dynamics in the region: Climate and Sea Ice (Sharon Stammerjohn), Physical Oceanography (Carlos Moffat), Microbial Biogeochemistry (Benjamin Van Mooy), Phytoplankton, Optics and Gliders (Oscar Schofield), Zooplankton (Deborah Steinberg), Seabirds (Megan Cimino), Cetaceans (Ari Friedlaender), and Modeling (Scott Doney); plus Information Management and representative to the LTER Network (Sage Lichtenwalner) and Education/Outreach (Janice McDonnell). The Rutgers Center of Ocean Observing Leadership (RU COOL) is the data hub for PAL (see IM Section). The Palmer IM leverages a team of 4 software specialists in the COOL group. One co-PI is responsible for each component. The component co-PIs jointly plan the detailed logistics for field season research. Except for Schofield, McDonnell, and Lichtenwalner who are at Rutgers, the co-PIs are based at institutions around the US and are supported through subawards from Rutgers as per NSF guidance for the LTER submittal. All ten PAL co-PIs constitute the governing body of the project. Funding decisions and research issues are decided by full group consensus through monthly consultation. In the event of failure to resolve conflicting views (very rare), the lead PIs make decisions, following consultation with the NSF Program Managers or Contractor (if necessary). Formal communication is maintained among PIs by frequent email, monthly conference calls and an annual face to face meeting. The team's monthly call is split into two focus areas with one part of the call open to all collaborators, graduate students and technicians. The second part of the call is dedicated for PAL PIs.

Project turnover and succession. PAL has been fortunate to have strong continuity in the PI team; however, the team is currently planning for significant succession during the next renewal proposal in 2027. Drs. Steinberg, Stammerjohn, and Van Mooy will be retiring from the program at that time. This decision reflects readiness to 'pass the baton' after nearly two and three decades in the program for Steinberg and Stammerjohn, respectively, and the considerable effort and high costs associated with long annual field deployments for Van Mooy who is at a soft money institution. The PAL team is working on replacements for the future PAL renewal to bring in a zooplankton ecologist, microbial ecologist/ biogeochemist, and sea ice and climate expert. We are developing a short list and will recruit and involve new PIs prior to the renewal to ensure the new team is integrated before the proposal renewal.

Recruitment and Diversity Logistical constraints profoundly affect our opportunities for formal and informal collaboration, cross-site activities and other research, education and outreach in the Antarctic. Nonetheless we try to reserve some of our designated space at Palmer Station and on the research vessel each year for collaborating investigators. We also encourage outside investigators and postdocs to submit proposals to work at Palmer Station and aboard the research vessel and offer them sampling and data support from our ongoing observational program. This strategy has resulted in over a dozen new projects over the past 10 years and has significantly broadened our overall scientific productivity. PAL Investigators invite colleagues to join our program as Affiliated Investigators. 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 Affiliated Investigator status does not guarantee 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 (see below). Undergraduate student research assistants comprise an important element of the field teams at Palmer Station and on our cruises and are critical to our success. We use the unique opportunity to work in Antarctica to help promote participation by a diversity of students and underrepresented groups at our site (e.g., two black female Ph.D. students currently in PAL). PAL has accomplished this aim through participation in programs such as the NSF-sponsored Polar Interdisciplinary Coordinated Education ICE and Polar Literacy: A model for youth engagement and learning programs. Similar connections are being sought at the other co-PI institutions. Two of our newest co-PIs increased ethnic, gender and age diversity of PAL leadership (Cimino–early career female, Moffat–Hispanic, mid-career male). This will also be a focus for upcoming succession of project PIs.

Palmer Station Logistics. The PAL proposal was funded to provide long-term observations, process studies and field-based experimental work conducted both at Palmer Station during each October to April (Austral) growing season, and in January every other year at sea across the PAL sampling grid (Fig. 2) using US Antarctic Research Vessels. During non-regional cruise years, we have requested three days of ship time excluding transit (see below); however, this is revisited each year given the considerable constraints for access to the Antarctic. At Palmer Station, our proposed research requires 10 berths for five research components allocated as follows: seabirds and whales (Cimino-Friedlaender, 4 berths), phytoplankton (Schofield/Moffat, 2 berths), zooplankton (Steinberg, 2 berths), and microbial biogeochemistry (Van Mooy, 2 berths). During the season, team members are exchanged depending on their professional and personal obligations as well as the ship schedule; thus, although the maximum number of personnel on Station at any one time is limited to 10, a greater number of people will be traveling to and from the Station. We require dedicated use of rigid-hulled inflatable boats (RHIBs) and a zodiac boat for the seabird, zooplankton, microbial + phytoplankton and whale groups. A RHIB is required for zooplankton tows and acoustic mapping and two Solas RHIBs for daily seabird and whale surveys, as well as for deploying satellite tags and small mooring deployment/recovery. The two RHIBs have been plagued with mechanical issues, affecting our ability to sample over the last couple years.

Research & Mooring-turnaround Cruises. The oceanographic survey every other year of our regional-scale sampling grid is a key component of our long-term observations and mechanistic process studies. It is critical given the strong connectivity in the WAP system given the strong ocean circulation patterns in this region. During cruise years we can accommodate our full science group with an allocation of 20 science berths. Over the past eight years (excepting the pandemic), we had 28 days of LMG ship time dedicated to our research each year. Currently, we cover a 50% larger region due to our southern extension of the sampling grid, with more PIs and more activities, with essentially the same amount of ship time as in the project's original allowance in 1993. We requested 30 days of science ship time per cruise year in the last proposal. The additional days enable the team to collect samples and deploy satellite tags from the specialized RHIB. It also allows us to better support other non-LTER funded projects. For example, during the 2020 field season we provided significant support of the NSF sponsored SWARM (Kohut, Rutgers & Oliver, U. Delaware), E. Shadwick's NSF-sponsored mooring projects, C. Moffat's CAREER grant, H. Dierssen's radiation measurements, and J. Bowman's research on bacterial metabolomic diversity. We also routinely provided support to AMLR (e.g., setting up field stations and deploying/recovering gliders). It is critical that our cruise period be scheduled at the same dates as in the past (03 January-03 February, ± a few days) to maintain the scientific and statistical integrity of our 30-year long time series and provide a consistent viewing window to evaluate seasonal and interannual variability. However, in recent years, cruises started/ended approximately 1 week earlier due to unknown reasons, which is significant considering shifts in species phenology and distribution/abundance (Conroy et al., in prep). To accommodate the need to recover and re-deploy moorings designed for year-long deployments as well as gliders for summer surveys during years when no PAL regional cruise occurs, we requested three ship days in the PAL study area (i.e., excluding transit).

Related projects. The rapid pace of change in the WAP region, enhanced scientific infrastructure and the growing prominence of our project have resulted in increased numbers of related proposals to conduct cooperative research at Palmer Station, and requests to participate on our annual cruise. We actively encourage new PIs and new scientific research in the PAL region. The LMG has 22 science berths and 6 berths for the contractor science support personnel. We use 20 berths. The two additional science berths are reserved for other projects funded by NSF and requiring coordination or collaboration with PAL. We have accommodated partners in multiple projects over the last 4 years.

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Appendix 2 Graduate Degrees Directly Affiliated with PAL LTER Labs 2020-2024

Bent, S. M. (In progress) *Environmental variations in marine microbial populations via lipidomics*. (Ph.D. Thesis) Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Brown, M. (2020). *Drivers of phytoplankton dynamics, and corresponding impacts on the biogeochemistry, along the West Antarctic Peninsula* (Ph.D. Thesis). Rutgers University

Chen, M. (2024). *Seasonality of the Eddy Subduction Pump in the Southern Ocean* Rutgers University

Conroy, Jack (2022) *Diel, seasonal, and interannual changes in coastal Antarctic zooplankton community composition and trophic ecology*. (Ph.D. Thesis).Virginia Institute of Marine Science

Corso, Andrew (2023) *Ecology of larval fishes along the western Antarctic Peninsula: climate-change impact, taxonomy, phenology, and thermal tolerance*. (Ph.D. Thesis).Virginia Institute of Marine Science

Diou-Cass, Q. (In Progress). *Phytoplankton photoacclimation and diversity dynamics along a changing West Antarctic Peninsula*. Rutgers University

Dorbu, A. (2022). *An Analysis of the Effects of Temperature and other Environmental Factors on Microorganismal Productivity within Aquatic Ecosystems using Long-term Data from Various LTER and ILTER Sites*. Columbia State University.

Girard, Z. (In progress) *Lipidomic indicators of controls on ocean carbon export across latitudes.* (Ph.D. Thesis) Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Holm, H. C. (2024) *Microbial glycerolipids in the global carbon cycle: environmental controls and sinking flux dynamics.* (Ph.D. Thesis) Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Quinter, E. (2023). *Spatiotemporal Trends of Extreme Weather Events in the West Antarctic Peninsula and Their Impact on Penguin Foraging Behavior* (M.S. Thesis). University of Delaware.

Lowenstein, D. P. (In progress) *Lipid and carbohydrate dynamics in marine microbes and marine organic matter.* (Ph.D. Thesis) Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Mowatt-Larssen, Tor (In progress) *Long-term change and vertical migration in deep-sea fish larvae*. Virginia Institute of Marine Science

Nardelli, Schuyler (2021). Bio-optical and acoustic correlation scales along the West Antarctica Peninsula. Rutgers University

Nolan, Meredith (In progress). *Physiological mechanisms influencing Antarctic krill (Euphausia superba) distribution and abundance along the western Antarctic Peninsula*. Virginia Institute of Marine Science

Sharpe, M. (In progress). *Glacial melt and phytoplankton dynamics along the West Antarctic Peninsula*. Department of Marine and Coastal Sciences (Ph.D. 2023-present)

Stack, M. (2023). *Assessing the Influence of Storms on Sea Ice, Snow, and Adélie Penguins along the West Antarctic Peninsula*. University of Virginia. https://doi.org/10.18130/H7NS-2Q98

Thomas, Maya (in progress) *Role of krill and salps in the biological carbon pump along the Western Antarctic Peninsula*. Virginia Institute of Marine Science

Wang, X. (2024). *Variability and Dynamics of the Coastal Circulation Along the West Antarctic Peninsula* (WAP). (Ph.D. Thesis). University of Delaware.

Appendix 3: Recent PAL Publications

<u>Disturbance and Ecological Dynamics in Polar Systems</u>

Cimino, M. A., Conroy, J. A., Connors, E., Bowman, J., Corso, A., Ducklow, H., et al. (2023). Long-term patterns in ecosystem phenology near Palmer Station, Antarctica, from the perspective of the Adélie penguin. *Ecosphere*, *14*(2). https://doi.org/10.1002/ecs2.4417

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Enderlin, E. M., Moffat, C., Miller, E., Dickson, A., Oliver, C., Dryák-Vallies, M. C., & Aberle, R. (2023). Antarctic iceberg melt rate variability and sensitivity to ocean thermal forcing. *Journal of Glaciology*, 1–11. https://doi.org/10.1017/jog.2023.54

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