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The Larsen Ice Shelf System, Antarctica (LARISSA): Polar Systems Bound Together, Changing Fast

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ABSTRACT

Climatic, cryospheric, and biologic changes taking place in the northern Antarctic Peninsula provide examples for how ongoing systemic change may progress through the entire Antarctic system. A large, interdisciplinary research project focused on the Larsen Ice Shelf system, synthesized here, has documented dramatic ice cover, oceanographic, and ecosystem changes in the Antarctic Peninsula during the Holocene and the present period of rapid regional warming. The responsiveness of the region results from its position in the climate and ocean system, in which a narrow continental block extends across zonal atmospheric and ocean flow, creating high snow accumulation, strong gradients and gyres, dynamic oceanography, outlet glaciers feeding into many fjords and bays having steep topography, and a continental shelf that contains many glacially carved troughs separated by areas of glacial sediment accumulation. The microcosm of the northern Antarctic Peninsula has a tendency to change rapidly—rapid relative not just to Antarctica's mainland but compared to the rest of the planet as well—and it is generally warmer than the rest of Antarctica. Both its Holocene and modern glaciological retreats offer a picture of how larger areas of Antarctica farther south might change under future warming.

INTRODUCTION

Ice sheets cover most of the Antarctic continent and, in some places along the margin, connect to ice that has flowed from the land and now floats above liquid water. These areas of floating ice, called ice shelves, are dynamic in space and time and, while their loss does not directly contribute to sea-level change since the ice is already floating, they serve as a buttressing force to the glaciers behind them (Scambos et al., 2004). Among the most sensitive ice shelves are those in the northern Antarctic Peninsula. The major iceberg calving event on the Larsen C Ice Shelf in 2017 refocused attention on the ongoing ice loss from the Larsen Ice Shelf and the rapid changes in climate, ice, ocean, and life in this part of Antarctica. In January 1995 and again in March 2002, large areas of the more northerly sections of the Larsen Ice Shelf disintegrated. Covered with melt ponds and riven with wide cracks, these 200-m-thick ice shelves lost thousands of square kilometers of area in just days to weeks (~1500 km^2 and 3250 km^2, respectively, for the Larsen A and B ice shelves; for comparison, Rhode Island is ~3150 km^2). The lost areas of ice broke into myriad small ice blocks that toppled over, creating a rapidly expanding floating mass of ice rubble (MacAyeal et al., 2003). These breakup events stunned glaciologists and have become iconic examples of the effects of global climate change, rapid regional warming, and ice-shelf instability.

The Antarctic Peninsula has been among the fastest-warming areas on Earth. Data from weather stations and ice cores show a 2 to 3 °C increase in mean temperatures over the past 80 years (Zagorodnov et al., 2012; Barrand et al., 2013). The trend is attributed to the combined, and probably linked, effects of an increased northwesterly flow of warm, maritime air across the Antarctic Peninsula and a reduction in sea-ice extent in the northern Bellingshausen

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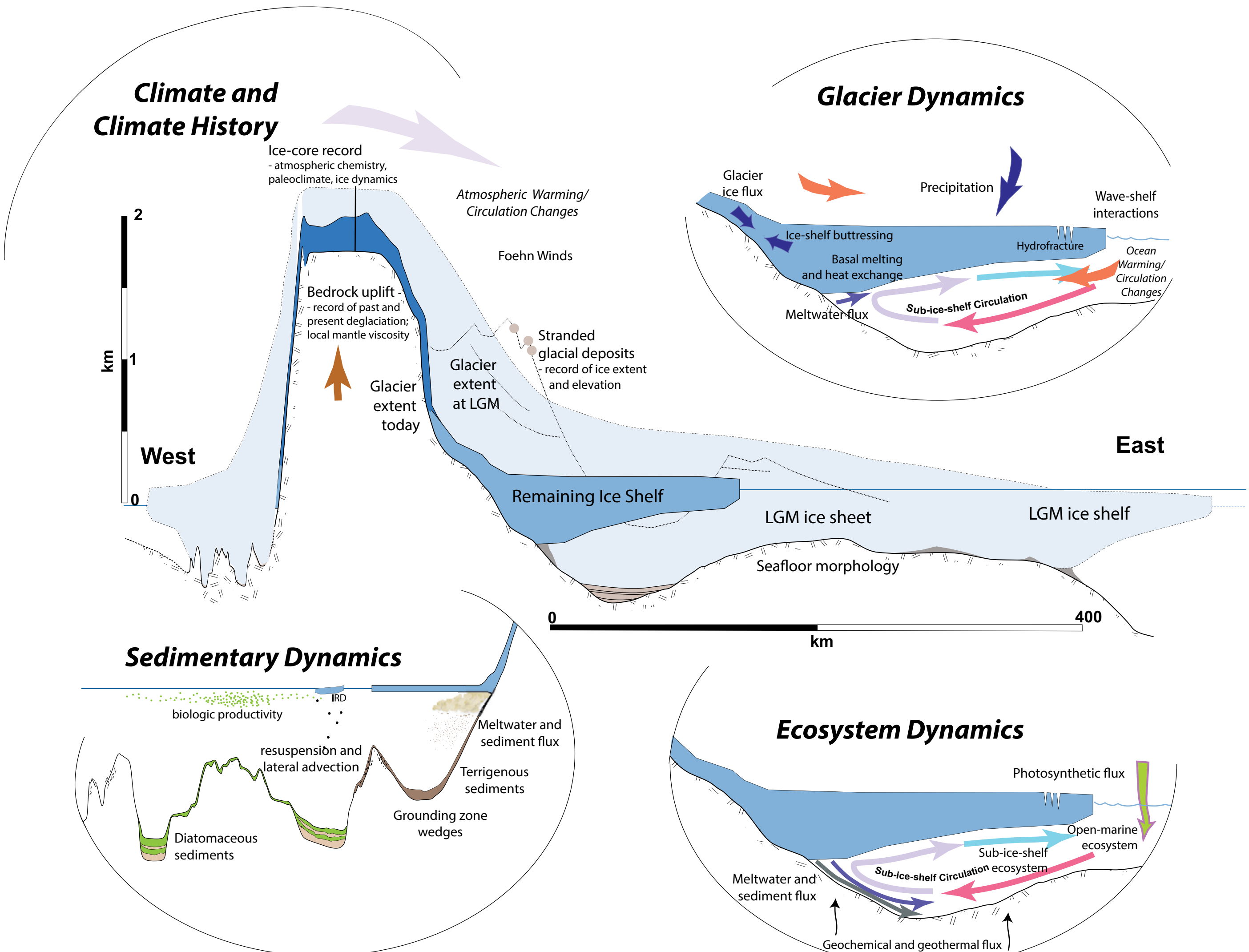

Figure 1. Schematic cross section through the Antarctic Peninsula showing the linked sedimentary, oceanographic, cryospheric, and biological systems from the western fjords to the Larsen embayment that were studied as part of the interdisciplinary LARISSA program. IRD—ice-rafted debris; LGM—Last Glacial Maximum.

and northwestern Weddell Seas. However, since ca. 2000, the warming trend has moderated (Turner et al., 2016), and a slight cooling has been observed since 2006 (Blunden and Arndt, 2012). During this period, sea-ice conditions in the northwestern Weddell Sea have been generally heavier, and landfast sea ice has persisted in the Larsen A and Larsen B embayments through several austral summers since 2012.

Disintegration of the ice shelves had large subsequent impacts on the region. Tributary glaciers of the ice shelves showed significant acceleration and drawdown following the event (Scambos et al., 2004). Regionally, increased ice flow from the Larsen A and Larsen B tributary glaciers now contributes a net ~10 Gt/yr of ice mass to the oceans (Berthier et al., 2012; Scambos et al., 2014). The rapid changes in the Larsen Ice Shelf and northern Antarctic Peninsula region impacted an interconnected set of polar systems, presenting a natural laboratory for investigating an area of the Antarctic undergoing the kinds of effects anticipated in other areas under continued warming. The component systems have interrelated physical and ecological responses spanning annual to multi-millennial temporal scales (Fig. 1).

The LARsen Ice Shelf System Antarctica (LARISSA) project was designed to study the evolution of the northern Larsen from a holistic perspective. As part of the 4th International Polar Year (2007–2009), a set of multi-institution grants were awarded under the newly created U.S. National Science Foundation Antarctic Integrated System Science (AISS) program. The collaboration of investigators spanned several universities across the United States, and included research partners in seven countries. Three major research cruises and six field visits were conducted over six years, beginning in 2009. Major cruises were conducted on the U.S. RV/IB *NB Palmer* and were supported by shorter cruises on the R/V *LM Gould*. International logistical and field support included a cruise on the RV/IB *Araon* with the Korea Polar Research Institute, Twin Otter air support out of Rothera Station from the British Antarctic Survey, logistical and collaborative support from Instituto Antártico Argentino, and, finally, remotely operated vehicle operations from the University of Ghent, Belgium. While the research has produced numerous discipline-specific results and publications, we focus here on the cross-disciplinary results of the project. These studies focus on past climate variability from ice core records, current climate changes, seabed landforms (a window on past ice-flow patterns), and marine geologic core analysis (combining climatic, glacial, biological, and oceanographic histories preserved in sedimentary strata). Extensive sea ice and landfast-ice cover in the area of the Larsen Ice Shelf forced parts of each major cruise to include work on the western side of the Antarctic Peninsula. These western Antarctic Peninsula data have supported a comparison across the drainage divide between the warmer, wetter western Antarctic Peninsula and the colder, dryer Larsen side of the Antarctic Peninsula.

SEAFLOOR RECORDS OF CHANGES SINCE THE LAST GLACIAL MAXIMUM (LGM)

Multibeam sonar mapping was conducted on both sides of the Antarctic Peninsula and merged with existing multibeam mapping data of the area (Lavoie et al., 2015). This work shows that an extensive system of outlet glaciers and lateral ice domes extended from the present coastline during the LGM, reaching the shelf break in at least some areas on each side of the Antarctic Peninsula. Evidence for flowing grounded ice in the Larsen B embayment was found as deep as 1100 m below modern sea level. However, some areas that are inland of the maximum grounding line, and thus were overridden by glacial ice, show no evidence of having had grounded ice on the seafloor. Rather, these areas show flat-lying sedimentary layering interpreted as subglacial lake deposits formed when ice was grounded farther offshore but not in the deepest parts of the inland basin (Rebesco et al., 2014). A sudden drop in elevation in one area of Crane Glacier just inland of a set of exposed lake deposits within the fjord seabed was interpreted as a subglacial lake drainage event induced by recent (post-ice-shelf disintegration) surface slope changes (Scambos et al., 2011).

When expanded during the LGM, ice was grounded on the eastern continental shelf for several hundred kilometers beyond the current glacier grounding lines (Lavoie et al., 2015; Campo et al., 2017). Glacial geomorphic features on the seafloor record shifting ice-flow patterns as deglaciation and flotation of the ice sheet progressed (Fig. 2). Flow reorientation during retreat, generally from flow that included a component of alongshore flow toward flow more directly offshore, reflected the changing ice sheet geometry as the grounding line of the ice sheet neared the modern coastline (Fig. 2). Strong elongation of the seabed features indicates rapid ice flow during the glacial maximum period. Several possible LGM-era ice-shelf collapses are noted near the continental shelf break in the form of iceberg furrows oriented sub-parallel to the seabed lineations. The arrangement of seabed features indicates a sudden discharge of many icebergs whose drift is still partially controlled by surrounding grounded ice. Ongoing ice retreat is governed in part by reorganization of flow patterns accompanying grounding line movement.

Marine sediment core data document a major difference in the long-term histories of the Larsen A and Larsen B embayments (Fig. 3). The former Larsen A experienced periods of shelf removal during the mid- to late Holocene (Brachfeld et al., 2003). Cosmogenic-nuclide exposure ages from coastal sites support a Larsen A ice-shelf collapse during the mid-Holocene (Balco et al., 2013).

In contrast, the Larsen B embayment was continuously occupied by an ice shelf for at least 12,000 years prior to its 2002 disintegration (Domack et al., 2005a; Rebesco et al., 2014). Absolute diatom abundance in Larsen B sediment cores increased sharply upon ice-shelf breakout; however, pre-breakup Holocene sediments are almost completely depauperate (Domack et al., 2005a; Rebesco et al., 2014). This suggests either limited contribution from Weddell Sea waters to the sub-ice cavity or that these waters were diatom poor, which could be attributable to heavy sea-ice cover in the Weddell Sea limiting primary productivity.

Even during times of extended Holocene ice-shelf cover, styles of sediment accumulation differ between the two Larsen embayments. Though ice-shelf–free conditions are recorded only in mid-Holocene sediments from the Larsen A embayment, the consistent presence of diatom valves in sediment cores indicates their advection into the sub-ice cavity throughout the Holocene (Brachfeld et al., 2003). The Larsen A area is connected to the Bransfield

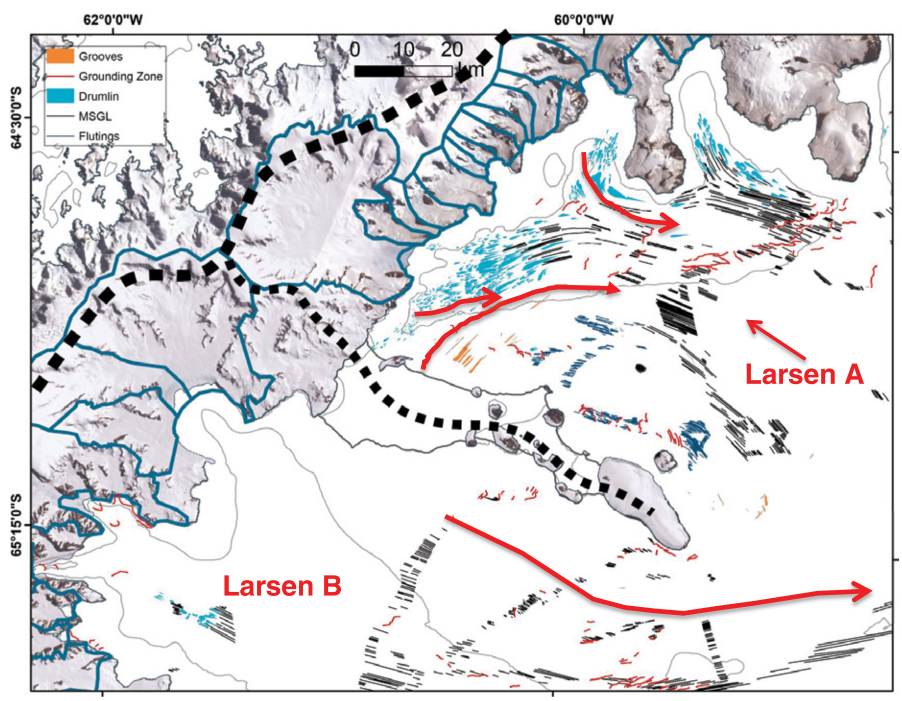

Figure 2. Geomorphic features mapped on the seafloor of the Larsen A and Larsen B embayments, which were used for reconstructing paleo-ice flow patterns on the shelf. Features are mapped across the area where multibeam data were collected. Gaps in the feature mapping largely represent areas where no geophysical data could be collected due to extensive ice cover. Thin solid lines are 500 m bathymetry contour. Blue lines represent modern ice divides. Dashed lines represent paleo-ice divides (Lavoie et al., 2015). Based on mapping from Campo et al. (2017). MSGL—mega-scale glacial lineations.

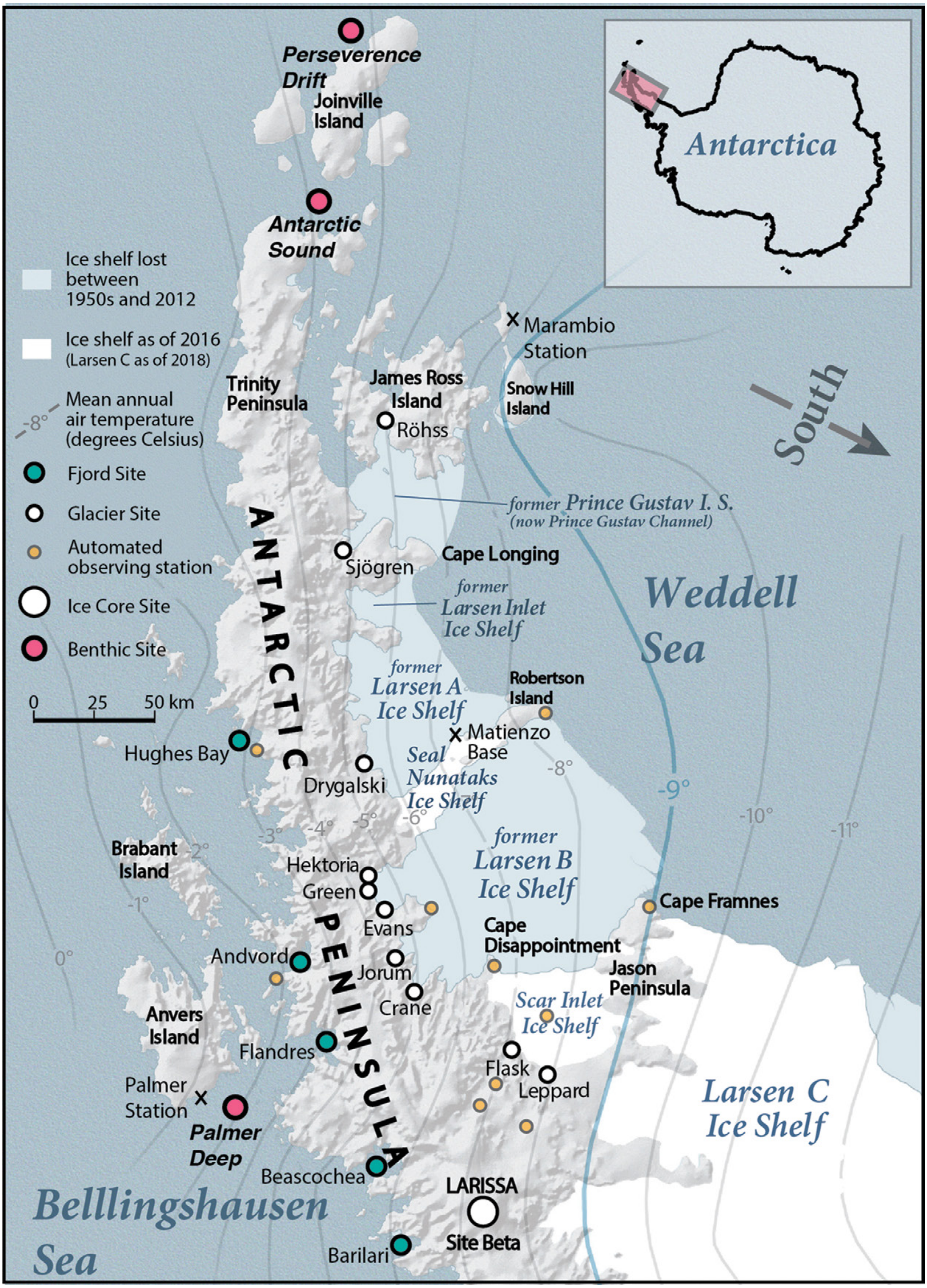

Figure 3. LARISSA study region and sites of research focus. Geographic features highlighted by circles were areas of detailed investigations or instrumentation in support of regional characteristics. Contours are isotherms of mean annual temperature at sea level; –9 °C has been suggested as the limit of long-term ice-shelf stability in previous studies. Base map provided with permission from XNR/Terra Carta (www.terracarta.com).

Strait to the north and west, and source waters circulate between them, potentially allowing the influx of diatom valves. The Larsen B, on the other hand, is an embayment connected only to the continental shelf of the Weddell Sea, where gyre circulation brings water from the south, which has heavy perennial sea-ice cover and low productivity. The limited ocean circulation to the Larsen B cavity, now embayment, is also apparent from benthic foraminiferal faunal and stable isotope data (Domack et al., 2005a), indicating an absence of upper Circumpolar Deep Water or other warm, deep-water masses in the area.

Large increases in sediment flux occurred in all the ice-shelf–covered areas after shelf breakup. These included organic particulates and ice rafted and hemipelagic siliciclastic materials. Some sites received >3 m of sediment per year following ice-shelf breakup in the immediate vicinity of the glacier fronts (Rebesco et al., 2014), in contrast to <1 mm per year in the shelf-covered cavities during the Holocene (Domack et al., 2005a).

Similar to the Larsen A embayment, reduced glacier-ice extent and seasonally open water during the early to mid-Holocene is observed on the western Antarctic Peninsula in Barilari Bay, followed by late Holocene expansion of sea-ice cover that reached a maximum during the Little Ice Age (Christ et al., 2015). Outer bay glaciers in their advanced late Holocene positions were also sensitive to conditions akin to positive mean Southern Annular Mode (SAM) states (Reilly et al., 2016). Late Holocene cooling is also recorded in sediments from the tip of the Antarctic Peninsula, where the western and eastern Antarctic Peninsula systems meet (Kyrmanidou et al., 2018).

CLIMATE AND CRYOSPHERE EVOLUTION

At the ridge summit above the southernmost Larsen B, a 448.12 m ice core was collected to bedrock (LARISSA Site Beta ice core; Fig. 3). The time period from AD 1900 to 2009 is recorded in approximately the top 195 m of the ice core (Goodwin et al., 2016). The core records an increase in annual net accumulation over the twentieth century, with the greatest increase beginning in the 1970s contemporaneously with the increasing positive trend in the SAM. However, the relationship between SAM and accumulation greatly depends on the phase of Pacific multi-decadal oscillation, underscoring the importance of tropical–polar teleconnections (Goodwin et al., 2016). The ice core–derived accumulation record also correlates with Bellingshausen Sea sea-ice extent, and both records exhibit a common response to short-term variations in the SAM and El Niño Southern Oscillation (Porter et al., 2016). Interestingly, mean air-temperature trends derived from an inversion of borehole temperature profiles (Zagorodnov et al., 2012) show differences from those estimated from the ice core–derived $\delta^{18}O$ record. Core sample $\delta^{18}O$ enrichment, which indicates warming, is modest during the twentieth century. This suggests that in addition to increased local near-surface temperatures, which are well documented from station data, other processes may have influenced the isotopic signature of the water vapor arriving over the Bruce Plateau (Goodwin et al., 2016). Moreover, in addition to conditions in the moisture source area such as reduced sea-ice extent in the Bellingshausen Sea, the increased annual net accumulation likely reflects other processes that affect the rate at which precipitation is delivered to the site.

Deployment of weather stations along the margins of the Larsen B, in conjunction with the analysis of a long-term weather time series recorded at the Argentine base Matienzo (situated between the Larsen A and Larsen B embayments; Fig. 3), provided further insight into the evolution of the regional climate since the 1960s. The observational record indicates a strong surface-warming trend over the Larsen embayments between 1962 and the early twenty-first century. This is linked to a higher frequency of foehn winds, warm, dry winds that flow down the lee side of a mountain range. In the Antarctic Peninsula, foehn winds result from the vertical deflection of the polar westerlies by the Antarctic Peninsula orography and dry adiabatic heating of the air mass as it descends the lee side (Cape et al., 2015). While their seasonal occurrence is tied to climatological storm tracks, their frequency is also tightly correlated to the SAM and the ongoing strengthening of the polar westerlies (Turner et al., 2014). Foehn events are responsible for almost all temperature excursions above the freezing point in the Larsen B region, linking melt intensity to seasonal foehn frequency. The combination of strong winds and low humidity during the foehn conditions contributes to strong snow ablation, so that relatively little surface melting is needed to consume the winter snowpack and initiate surface-melt ponding. This relationship is perhaps best illustrated by the foehn-induced proliferation of melt ponds prior to the 2002 disintegration event. Similar melt seasons and melt ponding occurred in 1995 (the year of the Larsen A disintegration) and 2006, but surface-melt ponding was moderated during the period of the LARISSA project due to cooler climate conditions (Turner et al., 2016). Moreover, the downslope wind regime creates an extreme precipitation shadow effect on the eastern Peninsula glaciers and shelf areas. Measurements from automated multi-sensor stations (automated meteorology-ice-geophysics observing systems, or AMIGOS) show that during 2010–2012, accumulation ranged from ~3 m water equivalent per year at the LARISSA Site Beta site, to ~0.5 m per year on lower Flask Glacier, and near zero on the Scar Inlet Ice Shelf surface (Fig. 3).

A series of bedrock-sited continuous GPS (cGPS) recording stations were installed to determine current uplift rates, arranged to surround the inferred Bruce Plateau ice dome and augment the longer-term record from Palmer Station. The cGPS records show exceptionally high uplift rates, up to 14.9 ± 2.7 mm yr^{-1} (Nield et al., 2014). The present-day rates of rapid uplift represent acceleration from the longer-term rates of uplift in the Antarctic Peninsula, which is tied to the accelerated loss of ice from the region (Nield et al., 2014). Further, the cGPS data were used to estimate a local mantle viscosity of (2×10^{18} Pa s) and infer the local crustal thickness. The very low upper mantle viscosity results in a lithosphere system that responds very rapidly to changes in mass loading. Almost none of the current uplift can be attributed to residual rebound from the LGM ice retreat (Nield et al., 2014).

ONGOING ECOSYSTEM CHANGES

A profound transformation in ecosystem structure and function has occurred in the region as a result of the ice-shelf collapse. The previously dark, oligotrophic waters beneath the Larsen B ice shelf now support a thriving light-based phytoplankton community, with productivity rates and phytoplankton composition similar to other productive areas of the Weddell Sea and Antarctic continental shelf (Cape et al., 2014). The Larsen B embayment is now intermittently a new coastal polynya, whose seasonal opening is triggered and maintained by the action of warm foehn winds. In this new state, the region has become an important component of the overall western Weddell Sea marine ecosystem. Its seasonal primary production will enable both pelagic and benthic habitat expansion.

Redistribution of chemical-based and light-based biological production following the ice-shelf breakup may have caused the demise of the extraordinary cold-seep ecosystem discovered in the newly exposed sub-ice-shelf area in 2005 (Domack et al., 2005b; Niemann et al., 2009). Extensive changes in the structure of benthic communities have occurred in the years following the shelf event, as previously absent phytodetritus materials accumulate on the seafloor (Gutt et al., 2011). Lipid biomarkers in surface sediments suggest that seasonal sea-ice diatoms are important contributors to this flux of organic matter (Shimizu, 2016). The development of a new paleoproductivity index in marine sediments links ocean productivity measured as DMSP (dimethyl sulfonopropionate) and MSA (methanesulfonic acid) measured in ice cores, within time scales of thousands of years. The DMSP data are supported by complementary data on absolute diatom abundances, which document the very recent influx of a sea-ice–associated diatom community (Rebesco et al., 2014).

Studies conducted as part of LARISSA have also highlighted the dramatic differences between the rich benthic assemblages in fjords along the western Antarctic Peninsula and those on the open western Antarctic Peninsula shelf and in the Weddell Sea (Grange and Smith, 2013). Dropstone habitats add significantly to the diversity of benthic megafauna (Ziegler et al., 2017), indicating that ice-shelf collapse and massive dropstone production substantially alters formerly sub-ice-shelf ecosystems. Furthermore, LARISSA studies revealed that, in recent decades, a large population of king crabs crossed onto the western Antarctic Peninsula continental shelf. Warming trends along the western Antarctic Peninsula suggest that these relatively cold-intolerant crabs may extend their range farther onto the western Antarctic Peninsula shelf, with major invasive impacts in the next few decades (Smith et al., 2012).

RECENT EVOLUTION OF THE LARSEN CRYOSPHERE

Remote sensing, in conjunction with the automated multi-sensor stations, shows a dramatic evolution of the remaining section of the Larsen B Ice Shelf that suggests it is nearing an unstable state prone to disintegration (Khazendar et al., 2015). MODIS image series show increased bottom crevassing, and aerial photos as well as Landsat 8 images indicate both fine-scale surface fracturing and major new rifts in the Scar Inlet ice. Loss of the A-54 iceberg in February 2006 has led to instability in the Starbuck Glacier floating shelf front; however, cooling climate conditions have led to the formation of multi-year fast ice in the Larsen B embayment, which has been present continuously since early 2012. This fast ice appears to be inhibiting further calving of the Scar Inlet ice front. GPS systems installed on the ice as part of the AMIGOS stations indicate that while the ice shelf accelerated at a rate of ~5% yr^{-1} between 2010 and 2012, since the formation of the persistent fast ice in 2012, the shelf has ceased to accelerate and instead exhibits an ~3% seasonal oscillation in flow speed, lagging the annual peak and trough in air temperature by ~30 days. Given that the Scar Inlet ice is already structurally weak, it is likely that this stabilization is temporary and that the next warm year will lead to the loss of the fast ice and rapid breakup of the Scar Inlet Ice Shelf.

INTEGRATED APPROACH TO UNDERSTANDING ONGOING CHANGES

The interdisciplinary and international field-based LARISSA program addressed the rapid, system-level changes taking place in the Larsen Embayment, Weddell Sea region of the Antarctic Peninsula, where the Larsen B ice shelf underwent a spectacular collapse in 2002. The research team, composed of ice core scientists, glaciologists, oceanographers, marine geologists, and biologists, including dozens of students and early career scholars, collaborated to characterize the effects of the collapse on the marine ecosystem as well as on glacier dynamics and interactions among the ocean, ice, geology, and biology, and to place these changes in the context of past changes in the region. Individual disciplinary projects each documented system change both during the Holocene and under modern conditions. The startling outcome of synthesizing individual disciplinary studies is that the rapidity at which the area is changing now is not documented in data from the Holocene, yet is virtually universal in the recent changes observed in precipitation records, sediment accumulation rates, ecosystem changes, isostatic uplift, and, of course, ice cover. As dramatic change continues to characterize the Larsen region, potentially with additional breakup in the next warm year, additional study will provide insight into the complex evolution of one of the most interesting regions on Earth in a fundamentally integrated way. Knowledge of how changes unfolded in the Larsen B and adjacent areas will serve as a basis for understanding what may occur in larger drainage basins that will warm in the coming years and whose changes may have a greater effect far afield.

POSTSCRIPT

The LARISSA project was in many ways guided by the scientific vision of Eugene Domack, who dedicated much of his life to studying Antarctica and its connections to the rest of the world. Gene passed away suddenly during the preparation of this manuscript. The remaining authors, like colleagues around the world, mourn his passing.

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