Sea Ice in the Western Antarctic Peninsula Region: Spatio-Temporal Variability from Ecological and Climate Change Perspectives

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Abstract

The Antarctic Peninsula (AP) region is undergoing rapid change: a warming in winter of almost 6ºC since 1950, the loss of 7 ice shelves, the retreat of 87% of the marine glaciers, and decreases in winter sea ice duration. Concurrently there is evidence of profound ecosystem change along the western Antarctic Peninsula (wAP). Given that the life histories of most polar marine species have evolved to be synchronized with the seasonal cycle of sea ice, our objective is to identify seasonal patterns of sea ice variability and climate co-variability and assess how the seasonal cycle is changing in the wAP region. Four new metrics of seasonal sea ice variability relevant for understanding ice-climate and ice-ecosystem co-variability were extracted from spatial maps of satellite derived daily sea ice concentration: (a) day of advance, (b) day of retreat, (c) the total number of sea ice days (between day of advance and retreat), and (d) the percent time sea ice was present (or sea ice persistence). The spatio-temporal variability describes distinct on-to-offshore and alongshore differences in ice-ocean marine habitats, characterized overall by a longer sea ice season in coastal regions (6.8 to 7.9 months) versus a shorter sea ice season over the shelf (4.1 to 5.3 months), with on-to-offshore differences increasing south-to-north. Large perturbations in the seasonality of the marine habitat occur in association with ENSO- and SAM-related regional atmospheric circulation anomalies. The local response to these climate modes is largely manifested in the strength and direction of the meridional winds during spring-to-autumn, which in turn affect the timing of the sea ice retreat and subsequent advance. These perturbations are embedded in overall trends towards a later sea ice advance, earlier retreat and consequently shorter sea ice season, the impacts of which are expected to be generally unfavorable for the marine ecosystem. A suite of ocean-atmosphere-ice interactions are described that are consistent with the amplified warming in late autumn, early winter.

1. Introduction

The seasonal and interannual variability of sea ice affects many levels of the Antarctic marine ecosystem, from the timing and magnitude of seasonal primary production to the breeding success and survival of apex predators (Smith et al., 1995; Ross et al., 1996; Ducklow et al., 2007). This is consistent with the idea that the dominant influence causing variability in *marine* ecosystems is external physical forcing rather than internal biological mechanisms, which are the more dominant influences in *terrestrial* ecosystems (Steele, 1991). Therefore, understanding sea ice variability, and the possible mechanisms influencing it, are essential aspects toward understanding changes in the polar marine ecosystem. This study evaluates seasonal sea ice variability in the western Antarctic Peninsula (wAP) region, where there is strong evidence that both climate and ecosystem change has, and is, occurring. Particular attention will be given to the area studied by the Palmer Antarctic Long-Term Ecological Research (PAL LTER) project (Figure 1), which has conducted interdisciplinary research of the wAP marine ecosystem since its inception in 1990.

Passive microwave satellite remote sensing of polar oceans has provided continuous, full seasonal estimates of sea ice concentration since 1979. These data are invaluable not only for characterizing sea ice variability within the PAL LTER region, but also for providing a longer and larger (Figure 1) scale context for the PAL LTER. Previous studies of sea ice variability in the PAL LTER region were based mostly on regional monthly averages of sea ice coverage (Stammerjohn and Smith, 1996; Stammerjohn and Smith, 1997; Smith et al., 1998; Smith and Stammerjohn, 2001). Using these spatially averaged quantities, considerable variability in the annual cycle of seasonal sea ice coverage in the PAL LTER region was revealed (Figure 2). Over 1979-2004 the onset of the autumn sea ice advance was as early as March or as late as May. Similarly, the termination of the spring retreat was as early as October or as late as March. Consequently, the duration of the sea ice season was anywhere from 5 (1989) to 12 (1980) months.

In addition to the high seasonal variability observed in the PAL LTER region, there also has been a strong and rapid warming of *winter* air temperature (almost a 6ºC increase since 1950) (King, 1994; King and Comiso, 2003; Vaughan et al., 2003), coincident with a trend towards decreased winter sea ice *duration* in the greater Antarctic Peninsula region (Smith and Stammerjohn, 2001; Vaughan et al., 2003; Parkinson, 2004; Stammerjohn et al., 2007). This is in contrast to weaker sea ice trends observed elsewhere in the Southern Ocean except in the western Ross Sea, which shows strong positive trends in ice season duration (Yuan and Martinson, 2000; Parkinson, 2002; Liu et al., 2004; Stammerjohn et al., 2007). Stammerjohn et al. (2007) show that this decrease in the sea ice season is primarily due to a strong trend towards a later autumn advance and a somewhat weaker trend towards an earlier spring retreat (whereas in the western Ross Sea the increase in the ice season was due to trends towards an earlier advance and later retreat).

Coincident with the trend towards a shorter sea ice season, there has been an increase in intra-seasonal variability between the 1980s and 1990s in the PAL LTER region (Figure 2b). Sea ice anomalies in the 1980s persisted longer, resulting in one to several years of positive anomalies followed by one to several years of negative anomalies. This several year oscillation in the 1980s was consistent with observations of an Antarctic Circumpolar Wave (ACW), which appeared to operate on a 7-8 year periodicity (White and Peterson, 1996). This behavior also made it easy to refer to a given year as a high or low ice year. In contrast, sea ice anomalies in the 1990s often switched sign during a single sea ice season, thus precluding the simple definition of high or low ice year (Smith et al., 1998; Stammerjohn et al., 2003). In general, there was much less persistence in the monthly sea ice extent anomalies in the 1990s, and the 7-8 year oscillation was no longer readily apparent.

Throughout the South Pacific and western South Atlantic sectors of the Southern Ocean studies have shown strong co-variability between sea ice and El Niño Southern Oscillation (ENSO) (Simmonds and Jacka, 1995; Harangozo, 2000; Yuan and Martinson, 2000; Venegas et al., 2001; Yuan and Martinson, 2001; Kwok and Comiso, 2002; Meredith et al., 2004a; Turner, 2004; Yuan, 2004; Holland et al., 2005; Lefebvre and Goosse, 2007). In general, positive sea ice extent anomalies in the PAL LTER region co-occur with El Niño events, while negative sea ice extent anomalies co-occur with La Niña events (Figure 2b). There also is increasing evidence that the variability in the Southern Annular Mode (SAM), also known as the Antarctic Oscillation, is a strong influence on ocean-atmosphere-ice interactions in the wAP region (Hall and Visbeck, 2002; van den Broeke and Lipzig, 2003; Lefebvre et al., 2004; Liu et al., 2004; Meredith et al., 2004b; Lefebvre and Goosse, 2005; Marshall et al., 2006; Meredith and Hogg, 2006; Sen Gupta and England, 2006; Meredith et al., 2007), particularly in the 1990s which saw a relatively high occurrence of the strong positive phase of SAM (Thompson et al., 2000; Thompson and Solomon, 2002; Marshall, 2003). Both ENSO- and SAM-related sea ice variability in the wAP region will be further explored in this study.

Every austral summer since 1993 the PAL LTER has conducted research cruises in the wAP region (Figure 1). In most years the PAL LTER region is free of sea ice in summer, but it may have just retreated several weeks, or several months, before the ship's arrival. The question then is how does ecosystem variability, as measured over a suite of physical-biogeochemical variables every summer, relate to the previous winter's sea ice cover? To begin examining this question, we needed to distill the seasonal information provided by the daily satellite data into ecologically meaningful yearly variables. As noted above, several components of the annual cycle of sea ice are believed to be ecologically relevant, which directed us to extract the following four sea ice characteristics from the daily maps of sea ice concentration: (a) the day of sea ice advance, (b) the day of sea ice retreat, (c) the total number of days sea ice was present (or total sea ice days), and (d) the percent time sea ice was present (sea ice persistence) during the defined winter period. With these four sea ice characteristics the key components of the annual cycle of sea ice were mapped for the wAP region, showing geographically where sea ice arrived and departed earlier or later, where it persisted longer, or came and went throughout the winter period.

In this paper our primary focus is to examine sea ice variability from 1992-2004 so that it can be related to *in situ* data collected within the PAL LTER program. However, given the changes we noted in reference to Figure 2, we also will compare this time period to changes that occurred over the longer (1979-2004) satellite period and over the greater wAP region. There are four hydrographic and biogeochemical subdivisions in the wAP region based on the delineations of major frontal systems that control nutrient dynamics and hence phytoplankton production (Tréguer and Jacques, 1992): (1) a highly productive Coastal and Continental Shelf Zone (CCSZ), (2) a relatively productive Seasonal Ice Zone (SIZ, that area annually covered by sea ice), (3) a highly but intermittently productive zone within the SIZ that lies over the area of the Southern Antarctic Circumpolar Current Front (SACCF) just offshore of the shelf break, and (4) a less productive Permanently Open Ocean Zone (POOZ). For the sea ice analyses, we define a sea ice grid (Figure 1), which delineates the minimum area covered by sea ice every year of 1992-2004, thus it does not include the POOZ. However, Smith et al. (2007) discusses all four of these hydrographic and biogeochemical subdivisions in the wAP region within the context of satellite derived phytoplankton biomass, winds and sea ice.

The paper is organized as follows. The data and methods are presented next (Section 2), followed by the results which are sub-divided as follows: (3.1) mean and temporally varying seasonal sea ice patterns, (3.2) seasonal ice-ocean co-variability, (3.3) ENSO- and SAM-related ice-atmosphere anomalies, and (3.4) ice-climate co-variability and trends. A discussion is provided on (4.1) ocean-atmosphere-ice interactions within the context of AP warming, and (4.2) ice-ecosystem interactions and change. A summary (Section 5) concludes the paper.

2. Data and Methods

Satellite measurements of sea ice concentration are from NASA's Scanning Multichannel Microwave Radiometer (SMMR) and the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I). Sea ice concentrations were determined using the Bootstrap passive microwave algorithm (Comiso, 1995; Comiso, 2003), from which a SMMR-SSM/I time-series was created that minimizes the differences between the various SMMR and SSM/I sensors (Comiso et al., 1997). This study uses the every-other-day SMMR and the daily SSM/I time-series (1979-2004) as well as the monthly averaged data as provided by the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center, University of Colorado in Boulder, Colorado (http://nsidc.org). The sea ice concentration data are mapped to a 25 x 25 km grid on a polar stereographic projection and include a landmask and latitude/longitude pairs for geolocating pixels.

Four sea ice characteristics (day of advance, day of retreat, ice days, and ice persistence) were determined from the (quasi) daily images of SMMR-SSM/I sea ice data. The year days of advance and retreat were determined at each grid point for each sea ice year (defined here to begin and end at the mean summer sea ice extent minimum as observed in the PAL LTER region: March 15 of current year to March 14 of following year). When sea ice concentration increased past 15% (or for comparison, 50%) and remained above that threshold for at least 5 days, then the day of advance was identified as the first day of that 5-day sequence. Day of retreat was similarly defined as the last day when sea ice concentration decreased past the given threshold and remained below that threshold for at least 5 consecutive days until the end of the sea ice year. If sea ice concentration never decreased below the given threshold for the year in question (i.e., remained annually ice covered at that threshold), then day of advance and retreat were set to the lower (March 15) and upper limits (March 14 of following year), respectively. If sea ice concentration never exceeded the given threshold for at least 5 days, then all four sea ice variables were set to zero, the value for open ocean.

Ice days are the number of days between day of advance and day of retreat when sea ice concentration exceeded the given threshold. The number of sea ice days can be less than the interval between day of advance and retreat if (1) the ice-edge advanced then retreated in an oscillatory fashion usually during the autumn advance or spring retreat, or (2) openings occurred within the pack ice during periods of divergence (e.g. by winds, tides, currents). This difference is captured by the last sea ice characteristic, sea ice persistence, which is the percent time sea ice is present within the interval between day of advance and retreat.

The sea ice characteristics were processed on the original satellite polar stereographic gridded data (25 km by 25 km) then re-mapped into the PAL LTER grid to facilitate direct comparisons to other PAL LTER data. The PAL LTER grid has a cell size of 40 km (on-to-offshore) by 100 km (along-shore). Given the higher resolution and different projection of the satellite grid, 5-8 satellite observations per year were binned into each PAL LTER grid and averaged. Although the sea ice characteristics are derived from daily satellite data, the extracted information (e.g. day of advance) represents just one yearly value per PAL LTER grid cell for a total of 13 years of data (1992-2004). We present spatial maps of both the climatology and yearly anomalies, which show, for each grid cell, the 13-year mean and yearly departure from the 13-year mean, respectively.

Further quantification and insight into the interannual variability and its spatial structure is obtained via classical Principal Component Analysis (PCA), which decomposes the data into orthogonal modes. The spatial structure of these modes is contained in the empirical orthogonal function (EOF), which is calculated from the sample covariance matrix, where the lower order EOFs represent spatially-coherent structures whose shapes are preserved through time. The time-varying amplitudes of these shapes (the full modal structure of the EOFs) are then calculated; these are the principal components (PCs). Martinson et al (2007) give further details of the PCA analysis employed on the PAL LTER data. Here we show only the first (gravest) mode, which describes the largest amount of the data variance.

In this study we also compared sea ice variability to ENSO and SAM variability. The ENSO index shown in this study is the Niño 3.4 sea-surface temperature index consisting of averaged eastern equatorial Pacific sea surface temperature for 5ºN-5ºS, 170-120ºW (Cane et al., 1986) (available at http://iridl.ldeo.columbia.edu/docfind/databrief/cat-index.html). However, we also compared our results to the Southern Oscillation Index (SOI) that consist of the difference between the standardized sea level pressures at Tahiti and Darwin (available at the IRI website given above). In general, we obtain similar results when using either the Niño3.4 or SOI index. The SAM index used here is an observation-based index provided by Gareth Marshall (available at http://www.nerc-bas.ac.uk/icd/gjma/sam.html) (Marshall, 2003). We also use 10m wind and sea-level pressure data (1990-2004) of the wAP region extracted from numerically analyzed data of the National Center of Environmental Prediction and National Center for Atmospheric Research Reanalysis (NNR) Project (Kalnay et al., 1996).

3. Results

3.1 Mean and Temporally Varying Seasonal Sea Ice Patterns

The 1992-2004 climatologies of the four sea ice characteristics within the wAP region (with the PAL LTER area highlighted by the rectangle) show both strong on-to-offshore and alongshore differences (Figure 3). Sea ice advance is earlier and retreat later both inshore and south compared to offshore and north, and these differences in the timing of advance and retreat manifest as a longer sea ice season in coastal areas versus a shorter sea season over the shelf, again with on-to-offshore differences increasing northward. For example, in the northern part of the PAL LTER area the on-to-offshore difference in the timing of ice advance is about 2.6 months, retreat about 3.5 months, thus explaining the approximate 6.1 months difference in the number of ice days on-to-offshore. This is in contrast to an on-to-offshore difference in the number of ice days of only 2.5 months for the southern part of the grid.

The coastal regions within the PAL LTER area are further distinguished by varying sea ice persistence (Figure 3d) and overall year-to-year variability (not shown). Despite a relatively long sea ice season in the northern coastal region (i.e., the Palmer Basin area), there is lower sea ice persistence here, indicating frequent openings of the sea ice cover, as well as higher year-to-year variability. This is in contrast to high persistence and low variability observed elsewhere along the coast. We also examined the timing of sea ice advance and retreat for sea ice concentrations greater than 50% (not shown) that indicate the arrival of more consolidated ice conditions. We found the greatest temporal lags between when the ice edge first arrived versus when consolidated ice conditions appeared in both the northern and central coastal regions within the PAL LTER area. Thus, the longer sea ice season in the northern and central coastal regions was due to a longer duration of low (15-50%) sea ice concentration. In contrast, the southern coastal region within the PAL LTER area (i.e., the mouth of Marguerite Bay) shows the highest sea ice persistence and the longest sea ice season with concentrations greater than 50% (relative to the rest of the PAL LTER area).

The 13 yearly anomalies for day of advance, retreat and ice days illustrate spatially the year-to-year variability about the climatology (Figure 4). The most notable anomalies for day of advance (Figure 4a) are the two strong negative anomalies in 1992 and 2002 (indicating early autumn advances) and the 3 consecutive large positive anomalies from 1999 to 2001 (indicating late autumn advances). In general there seems to be a grid-wide temporal shift from mostly negative anomalies in 1992-1997 to mostly positive anomalies from 1998-2001 (i.e., a shift towards a later autumn advance). Martinson et al (2007) also report similar temporal shifts in upper ocean bulk properties. In contrast, the yearly anomalies for day of retreat (Figure 4b) show no indications of a temporal grid-wide shift and instead show for most years more on-to-offshore variability (i.e., sharp transitions from positive to negative anomalies, or vice-versa). The yearly anomalies for ice days (Figure 4c) integrate the anomalies in both advance and retreat, and like the yearly anomalies for day of advance, there is an indication of a temporal grid-wide shift, illustrated here as a shift to strong negative anomalies (fewer ice days) from 1998 to 2001. The timing of this shift appears to begin in the autumn of 1998 and ends, or is interrupted, in the summer of 2002. (Since our time series goes only to 2004, there is no way to assess whether this shift is long term or not). This grid-wide temporal shift, as well as the rapid shifts from high to low (1997-98) and low to high (2001-02) sea ice conditions, will be discussed further in Section 3.3 within the context of ENSO and SAM variability.

The dominant spatio-temporal anomaly patterns are revealed in the first PCA mode (Figure 5), thus are useful for distilling the observed variability in the anomaly maps into the most frequently occurring spatial patterns; depending on the sea ice characteristic, PCA mode 1 explains 47% to 70% of the temporal variance. Therefore, the spatial anomaly patterns in the EOF mode 1 maps are patterns that coherently vary from year-to-year, the magnitude of which is given by the PC. For example, year 1998, the highest negative PC for ice days, was characterized as having the highest negative anomalies offshore but only moderately negative anomalies inshore, while year 2002 had the highest positive anomalies offshore but only moderately positive anomalies inshore. In general, the PC time series indicates high variability during 1998-2002 and 2004 as compared to other years. Spatially, the EOF mode 1 patterns for sea ice retreat, ice days and ice persistence show similar on-to-offshore patterns, with highest variability over the shelf, little to none near the coast. In contrast, the EOF mode 1 pattern for advance is distinctly different showing highest variability mid-shelf in the northern part of the grid and in the south coastal region (i.e., mouth of Marguerite Bay).

For the PAL LTER region and for the Southern Ocean as a whole there is little temporal co-variability between the autumn sea ice advance and the spring sea ice retreat, indicating that anomalies are not coherently generated over the autumn-to-spring (i.e., over winter) period (Stammerjohn et al., 2007). In contrast, there is more co-variability between the spring sea ice retreat and subsequent autumn sea ice advance, particularly for the near coastal regions extending eastward from the western Ross Sea to the southern Bellingshausen Sea, indicating that more often than not, coherent anomalies are generated over the spring-to-autumn (i.e., over summer) period. Also there is more spatial coherency on-to-offshore in the autumn sea ice advance than there is in the spring sea ice retreat. This may in part be due to the fact that the equatorward expansion of sea ice during advance is unconstrained physically (no continental boundary to the immediate north), thus is able to respond coherently to cooling air temperatures from south to north as the autumn season progresses into winter. In addition, sea ice advance (more so than sea ice retreat) is sensitive to rapid changes in atmospheric conditions given the ability to rapidly vent ocean heat, especially during cold air outbursts. In contrast, the spring sea ice retreat is constrained both physically by the Antarctic continent, and by increasing sea ice thickness to the south. Finally, the temporal variability in sea ice advance, more so than sea ice retreat, is more strongly correlated to temporal variability in ice days (Stammerjohn et al., 2007). As will be shown in Section 3.3 and 3.4, the temporal variability in sea ice advance appears to more clearly capture climate signals given its sensitivity to ocean-atmospheric variability and its free-drift expansion.

3.2 Seasonal Ice-Ocean Co-variability

The melting of sea ice every spring constitutes a cold (–1.8 ºC), freshwater (6 ppt, average sea ice salinity) input into the ocean surface mixed layer. It therefore follows that the variability in sea ice has some influence on the salt and heat content of the upper ocean summer mixed layer. To test these relationships we use two ocean bulk properties defined and described by Martinson et al (2007): (1) the summer mixed layer seasonal salt deficit (SDS), whereby a positive SDS anomaly indicates a larger volume of freshwater content (i.e., larger salt deficit), and (2) the summer mixed layer thermal insulation (TI), whereby a positive TI anomaly indicates higher heat content (thus a stronger insulator of the cold, salty winter water that is isolated directly below the surface mixed layer). In general, there is higher salt (lower SDS, Figure 6a) and heat content (higher TI, Figure 6c) offshore versus inshore, together with deeper mixed layers (not shown, but the spatial pattern is very similar to the TI climatology). Along the coast, there are distinct relative differences: the northern coastal region shows higher salt but lower heat content and shallower mixed layers, while the southern coastal region shows lower salt (high SDS) but higher heat content and deeper mixed layers.

Throughout most of the PAL LTER area the temporal variability in SDS co-varied most strongly and widely with the previous winter's number of ice days (Figure 6b), whereby higher SDS (greater freshwater content) was associated with a longer sea ice season in the previous winter. The exceptions are the northern and central coastal regions and to a lesser degree the southern shelf break region (which becomes a more obvious exception when sea ice concentrations >50% are used). Additional observations indicate that the northern coastal region is strongly influenced by glacial meltwater input (Dierssen et al., 2002), while the southern shelf break region is susceptible to intrusions of (salty) upper Circumpolar Deep Water (Martinson et al., 2007). It also is noteworthy that SDS correlates well with ice days even for years when the sea ice retreat was early, thus exposing the ocean surface earlier (and therefore longer) to other potential influences (e.g. precipitation, cross-pycnal mixing, coastal inputs). This indicates that the melting of sea ice is the dominant contributor determining the salt content (barring the noted exceptions), and that other processes influencing summer mixed layer properties are not large enough in magnitude to significantly change the salt content of the summer mixed layer established by the ablation of the previous winter's sea ice cover. The strong relationship between SDS and ice days also infers that the number of ice days can serve as a proxy for ice volume: a longer (shorter) ice-covered period infers thicker (thinner) sea ice (via both thermodynamic and mechanical thickening processes).

In contrast, the temporal variability in TI co-varied most strongly (though not as widely) with the previous spring's timing of sea ice retreat, whereby lower TI (colder surface mixed layer) was associated with a later spring sea ice retreat (i.e., less time between when sea ice retreated and TI was measured). This relationship is strongest in the northern half of the grid (except inshore of the 600 line) as well as in the mouth of Marguerite Bay (inshore of the 200 and 300 lines). This relationship also was strongest for sea ice retreat at the 50% sea ice concentration threshold, versus the 15% threshold, indicating that heating by insolation already begins when the pack ice first starts to open. An examination of the data shows that the outliers of this relationship coincide with strong anomalies in surface air temperature. Though surface air temperature typically co-varies with sea ice extent in the wAP region (e.g. Weatherly et al., 1991), there were notable exceptions in the 1990s when this was not the case, particularly during spring-summer when sea ice was retreating (see also Section 3.4).

To summarize the above spatial patterns of the seasonal sea ice characteristics and of ice-ocean co-variability, the main on-to-offshore and alongshore differences are highlighted for the PAL LTER region (Table 1) and include two sub-regions over the shelf (north and south) and three along the coast (north, central and south). A sixth sub-region, lying offshore of the shelf break, is included as further contrast and is discussed by Smith et al (2007) who show this region to be influenced by the Southern Antarctic Circumpolar Current Front (SACCF). Mean statistics for each of the five PAL LTER sub-regions are provided as supplementary online material (Table S1 and S2).

In general, the north coast sub-region is distinguished by a long season of low sea ice concentration, as well as frequent openings and closings of the sea ice cover. In turn, this high variability in sea ice of low concentration is related to high variability in heat content (TI): the variable sea ice conditions create a highly variable upper ocean light environment and thus variable heating by insolation. Low sea ice concentration also indicates that freshwater input from sea ice melt is minimal here (relative to the other coastal regions). As mentioned above, this area is strongly influenced by glacial meltwater input (Dierssen et al., 2002), examples of which are the summers of 1997, 1998 and 2001 when the previous winter's ice days were low (Figure 4c), but freshwater content in the summer surface mixed layer was high (high SDS) (Martinson et al., 2007). The summers of 1997, 1998 and 2001 showed very warm air temperature, which would have contributed to significant amounts of glacial meltwater input, thus contributing to the high freshwater content. These inferences of a glacial meltwater influence are supported by analyses of water chemistry (Carrillo, pers. comm.) and water turbidity (Dierssen et al., 2002).

The central coast sub-region is distinguished by numerous archipelagos and by a long, persistent sea ice season. The islands appear to aid and abet the retention of both sea ice and freshwater ice (e.g. icebergs and brash ice). The characteristically high mixed layer freshwater content is therefore the result of large volumes of ice melting *in situ*, with potentially large, but varying, contributions from freshwater ice. Spatial variability in mixed layer heat and salt content also shows this region to be a transition zone between the high variability in heat content in the north coast sub-region and the high variability in salt content in the south coast sub-region.

The south coast sub-region is distinguished by being the entrance to Marguerite Bay. It also is distinguished by having the highest mixed layer freshwater content across the grid, indicating large volumes of sea ice melting *in situ*. Indeed, the mean number of ice days (greater than 50% sea ice concentration) and sea ice persistence are highest here. Glacial meltwater contributions, though likely present, especially during warm summers, appear to be minimal relative to the contribution from *in situ* ice melt.

The north and south shelf regions are generally characterized by high mixed layer heat and salt content, high correlations between summer salt content and previous winter's number of ice days, and low variability in summer surface mixed layer properties. The south shelf region is distinguished from the north by a longer sea ice season and evidence of frequent intrusions of upper Circumpolar Deep Water (Martinson et al, 2007). Finally, the region offshore of the shelf break shows the shortest ice season and lowest sea ice persistence (relative to the PAL LTER area), as well as evidence of an SACCF influence (Smith et al, 2007).

3.3 ENSO- and SAM-Related Ice-Atmosphere Anomalies

The wAP region is particularly sensitive to both ENSO and SAM variability (references given in Introduction). The high latitude ENSO response in the South Pacific sector of the Southern Ocean shows positive pressure anomalies roughly centered on 60-70°S and 90-130°W (i.e., just upstream of the wAP region) in response to El Niño and negative pressure anomalies in response to La Niña (e.g. Yuan, 2004; Lachlan-Cope and Connolley, 2006; Meredith et al., 2007). SAM variability is characterized by zonally symmetric atmospheric pressure anomalies of opposite sign between Antarctica and mid-latitudes (e.g. Thompson and Wallace, 2000), whereby positive atmospheric pressure anomalies at mid-latitudes together with negative anomalies at high latitudes indicate a +SAM phase and vice-versa for a -SAM phase. Although SAM is defined as an annular mode, there is a regionally strong non-annular spatial component (Hall and Visbeck, 2002; van den Broeke and Lipzig, 2003; Lefebvre et al., 2004; Liu et al., 2004; Lefebvre and Goosse, 2005; Meredith et al., 2007). The non-annular component shows pressure anomalies roughly in the same area as described for ENSO above, with positive anomalies in the vicinity of 60-70°S and 110-140°W during –SAM (similar to El Niño) and negative anomalies during +SAM (similar to La Niña).

Therefore, the *local* high latitude atmospheric response to either ENSO or SAM variability can be inferred by the variability in sea-level pressure (SLP) anomalies averaged over 60-70°S and 65-100°W (Figure 7). In general, negative SLP anomalies indicate stormy conditions in the wAP region, with regional cyclonic atmospheric circulation to the west and northerly winds over the wAP. Positive SLP anomalies indicate blocking (quiescent) conditions in the wAP region, with regional anticyclonic atmospheric circulation to the west and southerly winds over the wAP. Thus, during El Niño or –SAM there are generally cold, southerly winds over the wAP (favorable conditions for sea ice), while during La Niña or +SAM there are generally warm, northerly winds over the wAP (unfavorable conditions for sea ice).

The month-to-month co-variability between ENSO and SAM is weakly negative (Figure 7a), but became more strongly negative during spring (Sep-Nov) into the 1990s (e.g. R=-0.60 for 1992-2004) (see also Fogt and Bromwich, 2006; Stammerjohn et al., 2007). The co-variability between ENSO and local SLP, and SAM and local SLP, also increased during spring 1992-2004 (relative to the month-to-month co-variability shown in Figure 7b and 7c): R=+0.53 and R=-0.73, respectively (see Figure 16, Martinson et al, 2007).

Sea ice, particularly the ice edge and particularly in the wAP region, is sensitive to the strength and direction of the meridional wind (Stammerjohn et al., 2003; Turner et al., 2003; Harangozo, 2004; Harangozo, 2006; Harangozo and Connolley, 2006; Massom et al., 2006; Massom et al., 2007). For example, the ice edge can episodically advance then retreat in response to changes from southerly to northerly winds, respectively. The anomalies in the spring sea ice retreat and subsequent autumn sea ice advance are shown together with monthly wind anomalies for the period 1997-98 to 2002-03 (Figure 8). This period coincides with strong transitions from El Niño (and slightly –SAM) conditions in 1997-98 to La Niña and +SAM conditions from the autumn of 1998 through to the spring of 2001 (though somewhat weakened in spring 2000 when SAM went negative), then back to El Niño and –SAM conditions in 2002-03. From the autumn of 1998 through to the spring-summer of 2001 the spring sea ice retreat was often early, while the autumn advance was without a doubt late, consistent with the inferences from Figure 7 that persistent northerly winds occurred in response to the sustained La Niña and +SAM conditions during this period.

The spring-summer of 2001-2002 is particularly noteworthy in that some of the strongest northerly winds in the wAP region were experienced from September to February. These winds facilitated an early sea ice retreat offshore but a late sea ice retreat inshore due to the compaction of sea ice against the Antarctic Peninsula that dynamically thickened sea ice up to 20m in places (Massom et al., 2006). The northerly winds were particularly strong and persistent in 2001-2002, and the ocean-atmosphere-ice-ecosystem responses were varied and complex, all of which is described in detail by Massom et al (2006). In addition, Martinson et al (2007) show for 1998-2004 a positive trend in upper ocean heat content within the PAL LTER area due to increases in the presence of upper Circumpolar Deep Water (UCDW) on the shelf. However, January 2002 was a particularly large positive anomaly in ocean heat content, an outlier even with respect to the positive trend. The exceptionally strong northerly winds in the spring of 2001, as well as in the three preceding springs from 1998-2000, are implicated in causing the increased intrusions of UCDW on the shelf (and thus the increased upper ocean heat content) in the late 1990s (Martinson et al., 2007). These wind-driven intrusions, co-occurring with wind-driven anomalies in sea ice retreat and subsequent advance, are in turn associated with the high latitude atmospheric response to La Niña and +SAM as described above.

In considering the potential for strong ocean-atmosphere-ice interactions and climate co-variability in the wAP region, the following key points are emphasized: (1) changes in ice season duration are caused mostly by changes in autumn sea ice advance and to a lesser degree, the spring sea ice retreat, (2) changes in the spring sea ice retreat and subsequent autumn sea ice advance, and by inference the frequency and/or intensity of UCDW intrusions on the shelf, are mostly in response to changes in the meridional winds (that can induce both a mechanical, wind-driven ice drift response and a thermodynamic response caused by warm/cold air advection), and (3) the presence of strong meridional winds in the wAP region are mostly in association with the high latitude atmospheric response to ENSO and/or SAM variability.

3.4 Ice-Climate Co-Variability and Trends

The 1979-2004 monthly sea ice extent data for the PAL LTER region (Figure 2) showed indications of trends towards earlier retreats and later advances. To view these changes spatially, climatologies were calculated for the earlier, pre-PAL LTER, period (1979-1991) and were subtracted from 1992-2004 (Figure 9). The differences indicate tendencies towards (a) a later (positive difference) advance across the entire region, (b) an earlier (negative difference) retreat within the PAL LTER grid and south (versus a later retreat north of the grid), (c) fewer ice days (negative difference) across the entire region, and (d) higher persistence in the northern mid-grid vicinity, with near zero differences elsewhere. Within the PAL LTER grid area the magnitude of the difference is highest in the mid-shelf region (approximately between stations 50-100): mean day of advance occurred 20-30 days later, retreat 15-25 days earlier, and there were 30-40 fewer ice days during 1992-2004 versus 1979-1991. Over the full time series (1979-2004) trends were detected in most of the sea ice characteristics (persistence excluded) and across most of the sub-regions (Table S2 in the supplementary online material).

Ice-climate co-variability in the PAL LTER region (Figure 10) is summarized as follows: (a) PAL LTER sea ice extent negatively co-varies with Faraday/Vernadsky air temperature (1979-2004 monthly, R=-0.79, annual, R=-0.94); (b) 10-year running correlations show that co-variability decreased into the 1990s; (c) PAL LTER sea ice extent positively co-varies with the ENSO Niño3.4 index (1979-2004 monthly, R=0.28, annual, R=0.47); and (d) 10-year running correlations show that co-variability between PAL LTER sea ice extent and ENSO decreased into the 1990s (unless the time-series are first smoothed, blue lines) and that co-variability between Faraday/Vernadsky air temperature and ENSO was generally low both before and after the 1980s. (Similar results to (b) and (d) are obtained when the Southern Oscillation index is used.)

Concurrent with decreased climate co-variability in the 1990s is increased intra-seasonal variability in PAL LTER monthly sea ice extent (Smith et al., 1998; Smith and Stammerjohn, 2001; Stammerjohn et al., 2007). The increase in intra-seasonal variability between the 1980s and 1990s (Figure 2) is captured by the degree of persistence in monthly sea ice extent anomalies, which decreased from 12-13 months in the 1980s to 2 months in the 1990s (based on autocorrelation analysis). Increased intra-seasonal variability is largely a result of increased variability in the timing of sea ice advance and retreat in the 1990s.

In contrast, correlations between the timing of sea ice advance and retreat (as captured by PCA mode 1, Figure 5a) versus seasonal averages of the ENSO index shows stronger correlations with ENSO into the 1990s (Figure 10e). Given the increased intra-seasonal variability of sea ice in the wAP region, monthly sea ice extent may not be the best variable for examining an ENSO relationship. The results presented here on sea ice advance and retreat, in addition to results from Stammerjohn et al (2007), seem to indicate that we better capture sea ice sensitivity to ENSO variability by restricting our focus to the periods (seasons) of sea ice advance and retreat.

The sensitivity of the sea ice retreat and subsequent advance to ENSO and SAM variability is consistent with the fact that the high latitude atmospheric response to these climate modes is strongest during the austral spring-summer (ENSO) (e.g. Fogt and Bromwich, 2006) and summer-autumn (SAM) (Marshall, 2003; Stammerjohn et al., 2007). The key question however is how to explain the trends in sea ice, when sea ice variability is clearly related to the oscillations in these two climate modes. In other words, how do we go from an oscillation to a trend? The high latitude atmospheric response to ENSO in the South Pacific intensified between the 1980s and 1990s (Fogt and Bromwich, 2006; Stammerjohn et al., 2007). The strengthening of the high latitude atmospheric circulation in the 1990s during large ENSO events appears to be related to stronger and more *sustained* periods of co-variability between ENSO and SAM during spring-to-autumn (Figure 8a). Concurrently, there has been a positive trend in SAM (e.g. Thompson et al., 2000; Marshall, 2003), which is implicated in asymmetrically strengthening the high latitude response to La Niña over El Niño events. Stammerjohn et al (2007) show that the episodic loss of sea ice during spring-to-autumn in the southern Bellingshausen region coincided with La Niña and/or +SAM events. The negative impacts resulting from these events resulted in remarkably large 26-year changes in the AP and southern Bellingshausen Sea region: sea ice is retreating 31 ± 10 days earlier and advancing 54 ± 9 days later, resulting in a decrease of 85 ± 20 annual sea ice days over 1979-2004. The complete loss of perennial sea ice in the southern Bellingshausen in 1998-1999 and 1999-2000 quite dramatically reflects the severe impacts resulting from co-occurring La Niña and +SAM events.

4. Discussion

4.1 Ocean-Atmosphere-Ice Interactions within the Context of AP Warming

The strongest trends in surface air temperature in the AP region are during autumn and winter (e.g. King, 1994; King and Comiso, 2003; Vaughan et al., 2003), with July showing the strongest trend: a 6.5 °C increase over 1950-2005 (http://www.antarctica.ac.uk/met/gjma/temps.html). Concurrently, the strongest trend in sea ice in the greater wAP region is a later sea ice advance in autumn/early winter. Delayed sea ice advance in the wAP region has been associated with increased northerly winds (Figure 8). The increased northerly winds infer that the ice-edge advance is hampered by the constant advection of sea ice southeastward toward the coast. Without an insulating sea ice cover, the ocean heat flux to the atmosphere dramatically increases. Thus, the trend towards a later sea ice advance is (1) an indicator of increased northerly winds, which advect warm air into the region from lower latitudes, and (2) facilitates increased ocean heat flux, which vents ocean heat to the overlying atmosphere. Both processes, increased warm air advection and open ocean heat flux, would contribute to, and/or amplify, warming in the AP region in autumn/early winter as has been suggested by others (e.g. Vaughan et al., 2003; Meredith and King, 2005; Harangozo, 2006).

In addition, there is the potential for inter-seasonal feedbacks well into winter. The trend towards a later sea ice advance (and somewhat earlier sea ice retreat) results in decreased winter sea ice days. A shorter sea ice season implies less time for sea ice to thicken (both thermodynamically and mechanically). The strong co-variability between the summer mixed layer freshwater content and the previous winter's ice days (Figure 6) also infers that the number of ice days serves as a proxy for ice volume. Additionally, a trend towards decreased sea ice concentration (e.g. Liu et al., 2004) and a seasonally more variable sea ice cover (Figure 2b) imply thinner sea ice and/or increased lead fraction. Decreased winter sea ice duration, concentration, thickness and/or increased lead fraction are changes that would continue to drive an increased ocean heat flux to the overlying atmosphere throughout winter (Martinson et al., 2007).

Examples of ice-atmosphere co-variability in the PAL LTER region (Figure 11) lend further support to the working hypothesis described above. Beginning in spring (Sep-Nov), winds strongly co-vary with the spring-summer sea ice retreat in the PAL LTER coastal region (R = +0.87) such that strong winds are associated with a late coastal sea ice retreat, and vice-versa for weak winds (Figure 11a). In turn, the variability in the spring-summer coastal sea ice retreat strongly co-varies with coastal summer (Dec-Feb) air temperature (R = -0.72) such that a late spring-summer coastal sea ice retreat induced by strong spring winds is associated with cool summer coastal air temperature, and vice-versa for an early coastal sea ice retreat (Figure 11b). In autumn (Mar-May) winds strongly co-vary with sea ice advance over the shelf (R = +0.61) such that high winds are associated with a late autumn sea ice advance, and vice-versa for low winds (Figure 11c). In turn, the autumn sea ice advance over the shelf strongly co-varies with winter (Jun-Aug) coastal air temperature ($R = +0.79$) such that a late autumn sea ice advance induced by strong northerly winds is associated with warm winter air temperature (Figure 11d). Of particular relevance to AP warming is the strong correlation between sea ice advance and winter air temperature. The correlation between sea ice days and winter air temperature is less ($R = -0.50$) than that shown for sea ice advance and winter air temperature (Figure 11d), but may be suggestive of the continued influence of ice-ocean interactions on air temperature throughout the winter (e.g., less ice days, more ocean heat flux to the overlying atmosphere).

4.2 Ice-Ecosystem Interactions and Change

The central hypothesis of the PAL LTER states that the seasonal and interannual variability of sea ice affects all levels of the Antarctic marine ecosystem, from the timing and magnitude of seasonal primary production to the breeding success and survival of apex predators. In addressing the former (seasonal primary production), the timing of the spring sea ice retreat in the wAP region has some association with when and where the spring-summer phytoplankton blooms occur (Garibotti et al., 2005; Smith et al., 2007b), but these associations are not always consistent across the wAP region, particularly off-to-onshore. For example, sea ice retreat was late offshore of the shelf break during Oct-Nov in 1997 and 2002 (i.e., was still over the SACCF region in November), and consequently the offshore spring bloom did not occur. Subsequent to the late retreat offshore, the retreat over the inshore shelf area was relatively early, and chl-a biomass concentrations were low in Jan-Feb of 1998 and 2003 (Smith et al., 2007b), presumably due to a lack of a well-developed ice-edge bloom. Therefore, a late retreat offshore of the shelf break region and an early retreat over the shelf were associated with low pigment biomass in both of these locations.

In contrast, the retreat in 1995 and 2001 was early offshore and late inshore, and subsequently the chl-a concentration in Jan 1996 and 2002 were two of the highest grid averages measured within the PAL LTER during 1994-2004 (Vernet et al., 2007). The pigment biomass concentrations also were high offshore of the shelf break in 2001, and we presume in 1995 as well, but SeaWiFs data only became available starting in 1997. In further contrast, the lowest chl-a concentrations detected within the PAL LTER were in Jan 1999 and the previous spring retreat was early across the *entire* wAP region. But, despite the low concentrations detected within the PAL LTER region in Jan 1999, the SeaWiFs imagery shows a well developed offshore bloom that started as early as October, presumably in response to the earlier sea ice retreat for this location. Therefore, the associations between anomalies in the timing of the spring sea ice retreat and phytoplankton biomass concentration are spatially and seasonally mixed. In general, however, these various studies indicate that an early sea ice retreat offshore of the shelf break favors a spring bloom in this location, whereas a later sea ice retreat over the shelf and along the coast favors a summer bloom in that location. Massom et al. (2006) give further examples of complex ice-ecosystem interactions that resulted from anomalous ice-atmosphere interactions in 2001-02 that in turn resulted in strong off-to-onshore sea ice retreat anomalies that had both positive and negative impacts on the marine ecosystem.

Though there appear to be clear associations between the timing of sea ice retreat and phytoplankton biomass, other associations with higher trophic levels (e.g. zooplankton, seabirds) are more complex. There are indications that fewer sea ice days, when coupled with an early sea ice retreat, may be unfavorable for krill reproduction (but favorable for other zooplankton species such as Salps) (Ross et al., 2007). Fewer sea ice days, if indicative of sea ice thickness, also may be unfavorable for juvenile krill, given that a thicker, rafted sea ice cover provides a better underwater refuge (Quetin et al., 1996; Frazer et al., 1997; Ross et al., 2004; Massom et al., 2006).

Consequently, any decreases in krill recruitment or availability will adversely affect predator populations (e.g. Adélie penguins) via changes in predator foraging and breeding performance (Fraser and Hofmann, 2003). Increased occurrences of earlier sea ice retreat are associated with increased storminess and precipitation, conditions unfavorable for Adélie penguin egg laying (Fraser and Patterson, 1997; Patterson et al., 2003; Massom et al., 2006). Deep snow at penguin nesting colonies has been associated with increased egg mortality caused by the formation of snowmelt pools at the nest. Other ice-mediated factors like foraging trip durations during spring breeding, food availability to fledging chicks in summer, ice-edge foraging in winter, affect Adélie penguin recruitment and mortality. The observation that Adélie penguins are rapidly declining in the Palmer Basin area (Fraser et al., 2007) is strong supporting evidence that ice-ecosystem changes have quite drastically occurred in the wAP region in response to the rapid regional climate change (Ross et al., 1996; Smith et al., 1999; Domack et al., 2003; Smetacek and Nicol, 2005; Ducklow et al., 2007; Smith et al., 2007a, and all other references in this special DSR issue).

5. Summary

The spatial and temporal (1992-2004) variability of sea ice has been described for the PAL LTER and greater wAP region using 4 sea ice characteristics that capture key components of the annual cycle of sea ice: (1) day of advance, (2) day of retreat, (3) number of sea ice days, and (4) sea ice persistence. We also examined the co-variability between upper ocean summer mixed layer properties and sea ice the previous winter. ENSO- and SAM-related ice-atmosphere anomalies in the wAP region were described and climate co-variability and trends were assessed. The following is a summary of key findings.

(1) The strongest geographical distinction across the PAL LTER grid is the longer sea ice season in the coastal regions (6.8 to 7.9 months) versus the shorter sea ice season over the shelf (4.1 to 5.3 months), these on-to-offshore differences increasing south-to-north. In general, coastal environments are more complex. For example, the northern coastal region is characterized as having a long ice season, but nearly half of this season is characterized by loose, open pack ice conditions (i.e., concentrations less than 50%), consistent with more frequent opening and closing of the pack ice throughout the winter and relatively high year-to-year variability. In contrast, the southern coastal region has a long sea ice season characterized by heavy sea ice conditions (i.e., concentrations greater than 50%), fewer opening and closing events throughout the season and relatively low year-to-year variability.

(2) The temporal and spatial variability of sea ice advance in the wAP region is distinctly different from that of sea ice retreat, thus differently affecting the duration of the sea ice season. Due to the unconstrained (free-drift) movement of sea ice during advance, the spatial variability of sea ice advance is more spatially coherent from year-to-year, its temporal variability co-varies more strongly with ice season duration (than does retreat), and overall the advance appears to be more sensitive to climate variability given that it can quickly and coherently respond to changes in atmospheric conditions. In contrast, the retreat is more variable both in space and time, and the movement of sea ice during retreat is heavily constrained by increasing thickness to the south and the geographic barrier of the peninsula.

(3) The freshwater content of the summer surface mixed layer strongly co-varies with the number of ice days the previous winter (e.g. high freshwater content co-occurs with high number of ice days) for all but the north coast sub-region (where glacial meltwater input appears to be a significant contributor of freshwater) and to a lesser degree the southern shelf-break region (where upper Circumpolar Deep Water may be influencing surface mixed layer freshwater content). In contrast to freshwater content, the heat content of the summer surface mixed layer primarily reflects surface air temperature variability but also coincides with the timing of the spring sea ice retreat (e.g. earlier retreat, greater heat content) except when sea ice co-variability with surface air temperature breaks down, a tendency that appeared in the mid-1990s.

(4) Anomalies in sea ice advance and total ice days show a grid wide shift between 1992-1997 and 1998-2001. The former period was characterized by earlier advances and higher numbers of ice days, while the latter period was characterized by later advances and lower numbers of ice days. Persistent northerly winds, particularly during the autumns of 1998-2001, appeared to contribute to the delayed sea ice advance over this period (Figure 9). In turn, these anomalous atmospheric circulation anomalies were associated with a period of sustained La Niña and +SAM conditions. The spring-summer 2001-2002 was particularly noteworthy given the severity and persistence of the northerly winds in the PAL LTER region from September to February. As detailed by Massom et al. (2006) the ocean-atmosphere-ice-ecosystem responses to this extreme atmospheric forcing event were varied and complex.

(5) Trend analyses of PAL LTER sea ice characteristics indicated that over the shelf the mean day of advance was occurring 20-30 days later, the retreat 15-25 days earlier, and there were 30-40 fewer ice days in 1992-2004 relative to 1979-1991. Changes in ice

season duration are caused mostly by changes in autumn sea ice advance and to a lesser degree the spring sea ice retreat. The largest anomalies towards a somewhat earlier retreat and a much later advance co-occur with strong northerly winds during La Niña and/or +SAM.

(6) Ocean-atmosphere-ice interactions and trends are consistent with the overall rapid regional warming of the Antarctic Peninsula region: (a) the trends towards a delayed autumn advance is an indication of increased northerly winds (which advect warm air into the region from lower latitudes), and facilitates increased ocean heat flux (which vents ocean heat to the overlying atmosphere), (b) the trend towards a shorter sea ice season is concurrent with a decrease in sea ice concentration and an increase in intra-seasonal variability, changes that infer relatively thinner sea ice and/or increased lead fraction and therefore increased ocean heat fluxes to the atmosphere throughout winter, and (c) together, these seasonal sea ice-mediated changes (i.e., increased warm air advection increased and increased ocean heat flux), would contribute to, and/or amplify, warming in the AP region in autumn/early winter as has been suggested by others (Vaughan et al., 2003; Meredith and King, 2005; Harangozo, 2006).

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Table 1: Summary of mean ice-ocean characteristics for five sub-regions within the PAL LTER area, as well as for the area just offshore of the PAL LTER. Relative qualifiers are meant to highlight sub-regional differences only. For sea ice advance/retreat, the mean (1992-2004) day is given (in month/day) and for ice season duration/consolidation, the monthly duration. Consolidated refers to portion of ice season with concentrations greater than 50%. Opening/closing refers to opening/closing of pack ice after initial ice-edge advance and before final retreat. Salt and heat content refer to integrative quantities of the summer surface mixed layer (see Martinson et al, 2007). SACCF: Southern Antarctic Circumpolar Current Front; UCDW: Upper Circumpolar Deep Water.

<table>
<tr><th>Line:</th><th>Offshore of Shelf</th><th>Shelf</th><th>Coast</th></tr>
<tr><td>600</td><td rowspan="5">North-South (200-600 lines)
1. Latest advance
2. Earliest retreat
3. Shortest ice season
4. Lowest ice persistence
5. SACCF influence</td><td rowspan="3">North (400-600 lines)
1. Late advance (6/28)
2. Early retreat (11/09)
3. Short ice season (4.1 mo.)
4. Short consolidated (3.3 mo.)
5. Frequent opening/closing
6. High salt and heat content</td><td rowspan="2">North (500-600 lines)
1. Early advance (5/20)
2. Late retreat (1/16)
3. Long ice season (7.3 mo.)
4. Moderate consolidated (4.1 mo.)
5. Frequent opening/closing
6. Moderate salt and heat content
7. Glacial meltwater influence</td></tr>
<tr><td>500</td></tr>
<tr><td>400</td><td>Central (400 line)
1. Early advance (5/19)
2. Late retreat (1/24)
3. Very long ice season (7.9 mo.)
4. Long consolidated (5.5 mo.)
5. Moderate opening/closing
6. Low salt, low heat content
7. Glacial meltwater influence</td></tr>
<tr><td>300</td><td rowspan="2">South (200-300 lines)
1. Moderate advance (6/05)
2. Early retreat (11/23)
3. Moderate ice season (5.3 mo.)
4. Moderate consolidated (4.7 mo.)
5. Moderate opening/closing
6. High salt and heat content
7. UCDW influence</td><td rowspan="2">South (200-300 lines)
1. Early advance (5/24)
2. Moderate retreat (12/25)
3. Long ice season (6.8 mo.)
4. Long consolidated (5.9 mo.)
5. Few opening/closing
6. Low salt, moderate heat content
7. Large in situ sea ice melt</td></tr>
<tr><td>200</td></tr>
<tr><td>Sta:</td><td>350-200</td><td>200-070</td><td>070-000</td></tr>
</table>

Figure Legends

Figure 1. Map showing the PAL LTER sampling area west of the Antarctic Peninsula with contoured bathymetry (gray lines at 500m intervals). There are 10 nominal sampling lines, 100 km apart (numbered 000, 100, up to 900), and 11 sampling stations along each line, 20 km apart (numbered 000, 020, 040, up to 200). The dashed line labeled SACCF is the approximate location of the Southern Antarctic Circumpolar Current Front. In this paper we focus our attention on the spatio-temporal variability within the rectangular box (dotted line) labeled ice grid, which demarcates the minimum area that is fully covered by sea ice every year and therefore does not include the permanently open ocean zone (POOZ). Additional analyses will be performed on data from the PAL LTER Grid (bold box, includes lines 200 to 600). The larger box (thin line) labeled the Extended Grid defines the area analyzed by *Smith et al* (2007b) in their study of SeaWiFS derived pigment biomass variability.

Figure 2: **(a)** PAL LTER monthly sea ice extent (km^2) and **(b)** monthly anomalies normalized by the standard deviation. In (a) the mean summer sea ice extent minimum (16,084 km^2) occurs in March, while the mean winter maximum (172,455 km^2) occurs in August. The trending lines schematically show that autumn sea ice advance is occurring later with time, spring sea ice retreat is occurring earlier with time, both are creating a shorter winter ice season duration with time. In (b) ENSO years are defined according to the Climate Prediction Center (available from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Figure 3: Spatial climatology maps of (a) day of advance (year day), (b) day of retreat (year day), (c) ice days (total days), and (d) ice persistence (%). The box outlines the PAL LTER grid shown in Figure 1, and the dashed line shows the approximate location of the Southern Antarctic Circumpolar Current Front (SACCF), just seaward of the shelf break.

Figure 4: Spatial anomaly maps for (a) day of advance, (b) day of retreat, and (c) ice days. The rectangle box is the PAL LTER grid shown in Figure 1 and detailed in Figure 5. The positive (red) anomaly in the 1998 map for day of retreat (left edge, middle) was caused by an iceberg track (indicating an isolated region of late retreat but in fact the actual *sea ice* retreat was early). The iceberg trace is still visible in the subsequent 1999 advance, seen as the negative (blue) anomaly upper left.

Figure 5: (a, top) The time expansion coefficients (1992-2004) of the first principal component (PC) shown for the four sea ice characteristics for the PAL LTER grid area, and (bottom) the individual spatial EOF maps for (b) day of advance, (c) day of retreat, (d) ice days, and (e) ice persistence. The percent variance explained by the first mode is given for (b-e).

Figure 6: (a) Spatial climatology map of summer salt deficit (SDS), (b) correlation map of SDS versus the number of ice days the previous winter (orange-reds indicate strong positive correlation), (c) spatial climatology map of summer thermal insulation (TI), and (d) correlation map of TI versus day of retreat the previous spring (blues indicate strong negative correlation).

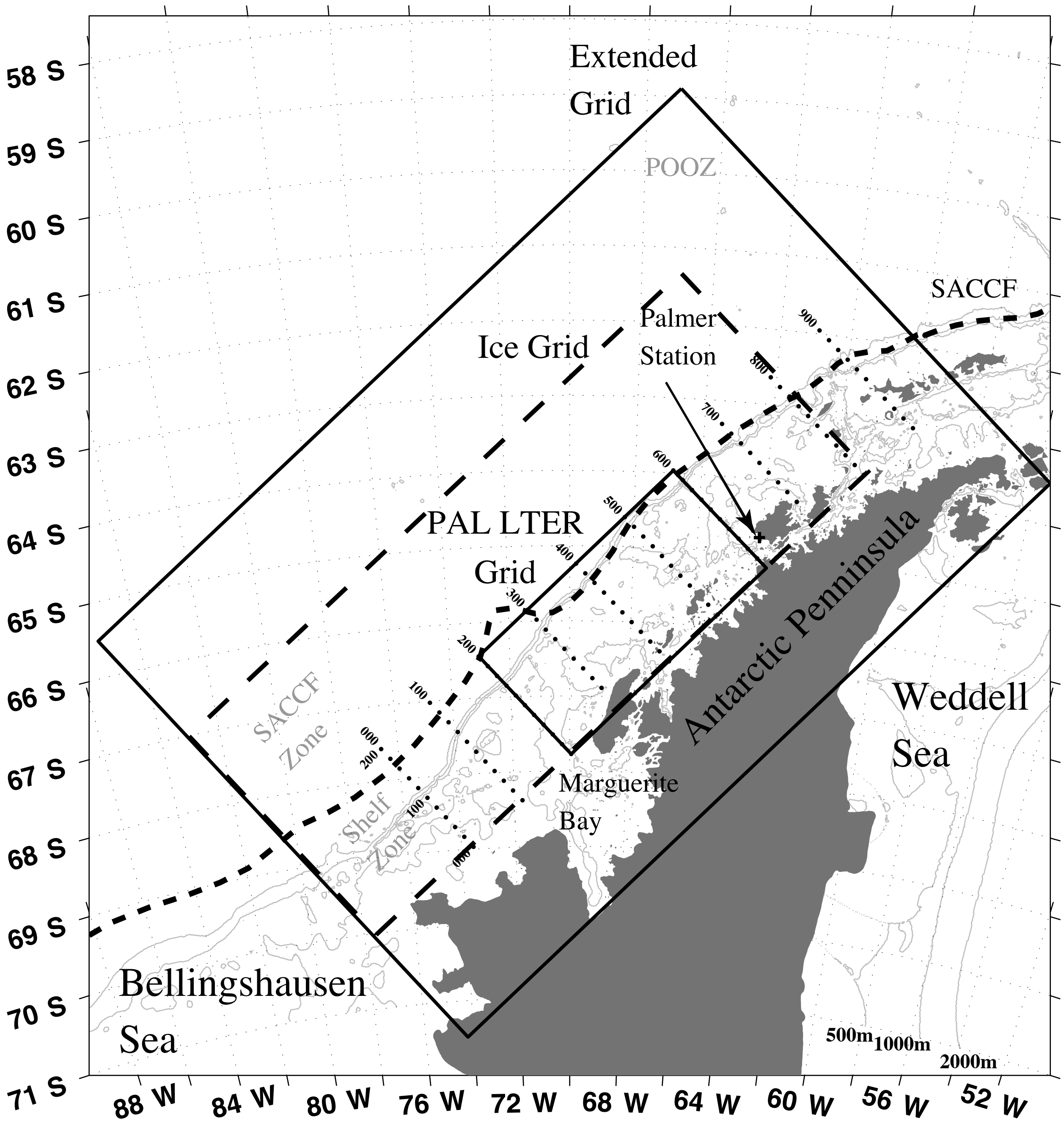
Figure 7: 1979-2004 monthly time series of (a) Niño 3.4 (black) and SAM (blue) indices, (b) Niño 3.4 index (black) and wAP SLP (blue), (c) SAM index (black) and wAP SLP (blue). The SAM index and wAP SLP were smoothed with a 7-month running mean. All time series are monthly anomalies normalized by the standard deviation. The wAP SLP data are from the region 60-70°S and 65-100°W.

Figure 8: (left column) Day of retreat anomalies with November wind anomalies overlaid; (right column) day of advance anomalies with May wind anomalies overlaid for (a-b) 1997-1998, (c-d) 1998-1999, (e-f) 1999-2000, (g-h) 2000-2001, (i-j) 2001-2002, and (k-l) 2002-2003.

Figure 9: Spatial maps of the difference between the1992-2004 climatology minus the 1979-1991 climatology for (a) day of advance, (b) day of retreat, (c) ice days, and (d) ice persistence (%).

Figure 10: (a) 1979-2004 time series of monthly anomalies (normalized by the standard deviation) of PAL LTER sea ice extent (SIE) and Faraday/Vernadsky surface air temperature (SAT), (b) 10-year running correlations between SIE and SAT, (c) 1979-2005 time series of normalized anomalies of SIE and the Niño 3.4 ENSO index, (d) 10-year running correlations between SIE and Niño 3.4 index, and between SAT and Niño 3.4 index, and (e) 10-year running correlations between the 1st principal components (PC1) of sea ice advance (adv) and Niño 3.4, and between PC1 of sea ice retreat (ret) and Niño 3.4. In (a) and (c) the SIE time series were smoothed with a 5-month running average, and in (b) and (d) the blue lines for the running correlations indicate that SIE and SAT were first smoothed with a 10-month running average.

Figure 11: 1990-2004 time series of normalized anomalies of (a) spring (Sep-Nov) winds averaged for the central wAP area and the spring sea ice retreat in the central coast region ($R = +0.87$), (b) the spring sea ice retreat in the central coast region and summer (Dec-Feb) surface air temperature at Faraday/Vernadsky ($R = -0.72$), (c) autumn (Mar-May) winds averaged for the northern wAP area and the autumn sea ice advance over the northern shelf ($R = +0.61$), and (d) the autumn sea ice advance and winter (Jun-Aug) surface air temperature at Faraday/Vernadsky ($R = +0.79$).



58 S
59 S
60 S
61 S
62 S
63 S
64 S
65 S
66 S
67 S
68 S
69 S
70 S
71 S
88 W
84 W
80 W
76 W
72 W
68 W
64 W
60 W
56 W
52 W
Extended
Grid
POOZ
SACCF
Palmer
Station
Ice Grid
PAL LTER
Grid
Antarctic Penninsula
Weddell
Sea
SACCF
Zone
Shelf
Zone
Marguerite
Bay
Bellingshausen
Sea
500m
1000m
2000m

Figure 1

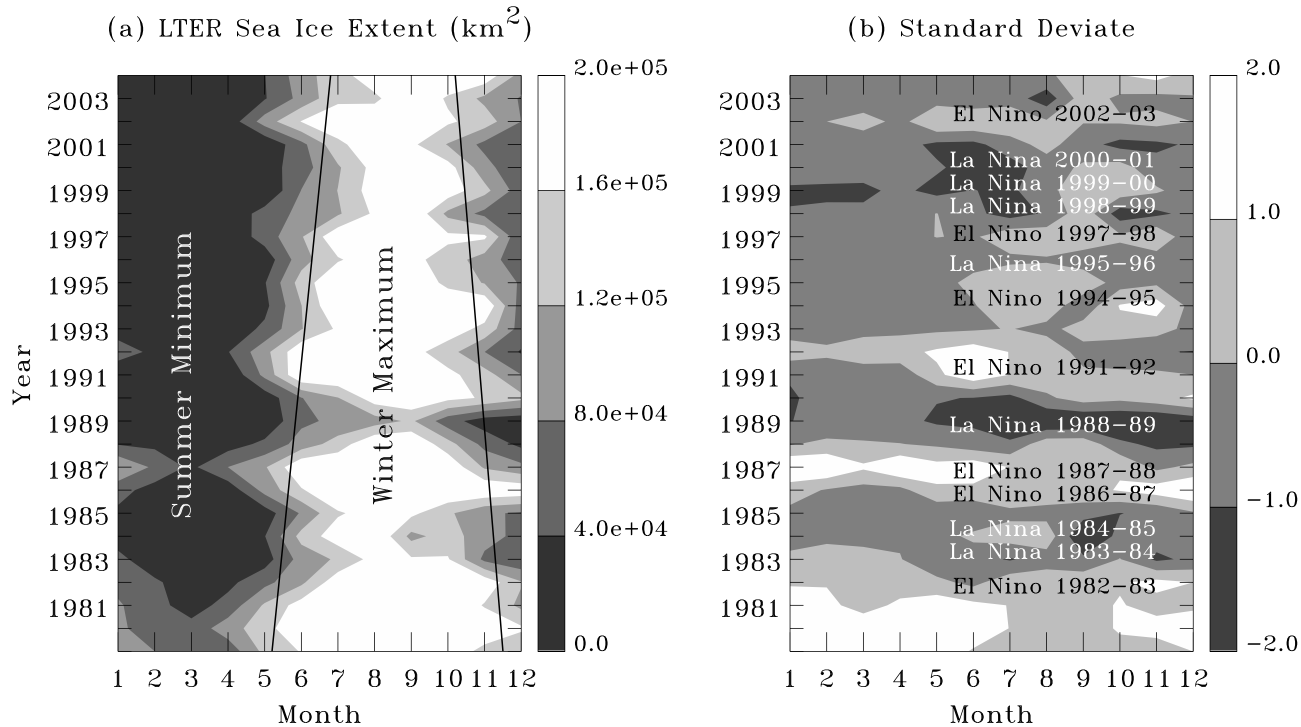

(a) LTER Sea Ice Extent (km2)
(b) Standard Deviate
Year
Month
Summer Minimum
Winter Maximum
2003
2001
1999
1997
1995
1993
1991
1989
1987
1985
1983
1981
1 2 3 4 5 6 7 8 9 10 11 12
2.0e+05
1.6e+05
1.2e+05
8.0e+04
4.0e+04
0.0
2.0
1.0
0.0
−1.0
−2.0
El Nino 2002-03
La Nina 2000-01
La Nina 1999-00
La Nina 1998-99
El Nino 1997-98
La Nina 1995-96
El Nino 1994-95
El Nino 1991-92
La Nina 1988-89
El Nino 1987-88
El Nino 1986-87
La Nina 1984-85
La Nina 1983-84
El Nino 1982-83

Figure 2

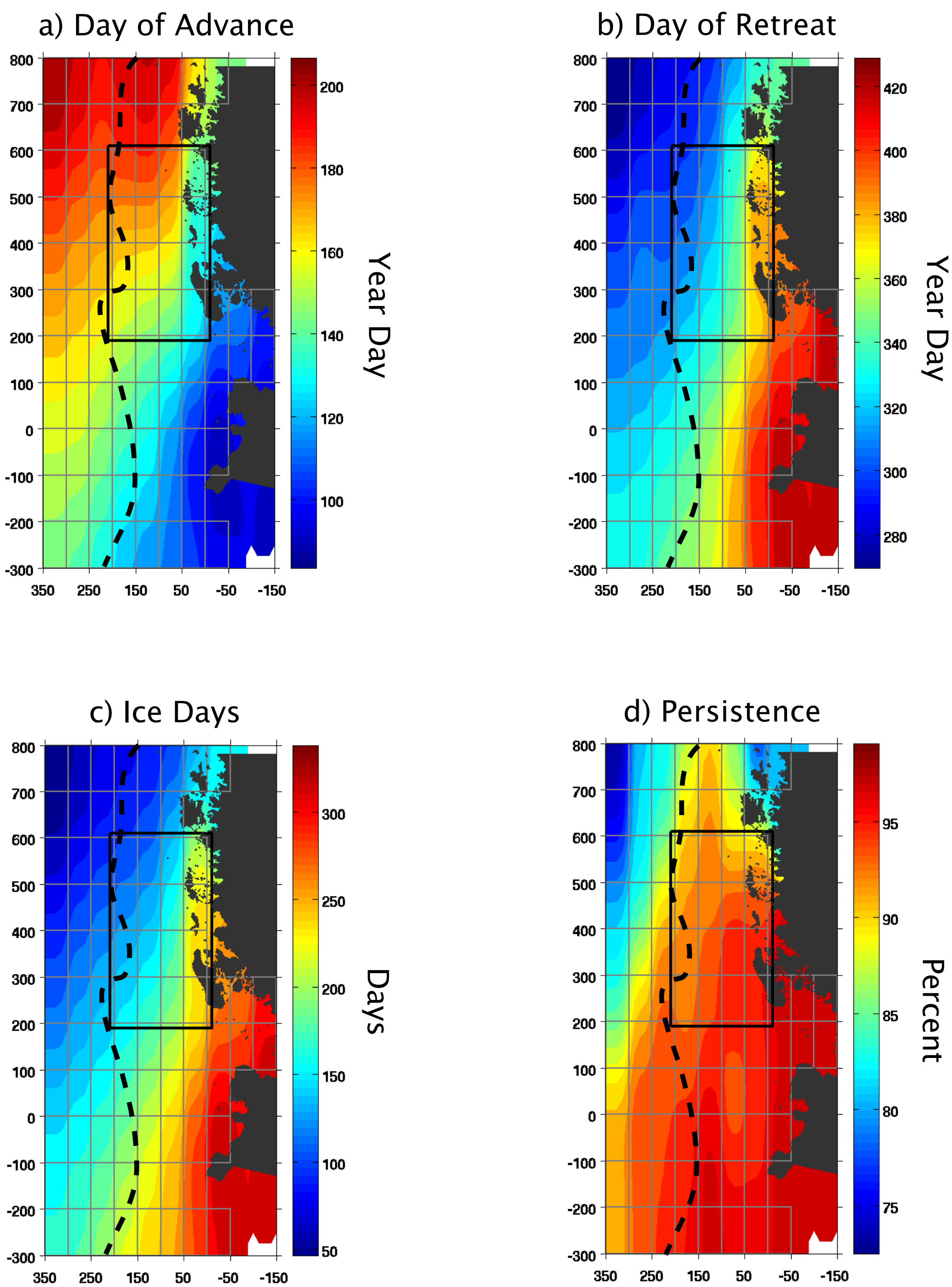

a) Day of Advance
b) Day of Retreat
c) Ice Days
d) Persistence
Year Day
Year Day
Days
Percent
800
700
600
500
400
300
200
100
0
-100
-200
-300
350
250
150
50
-50
-150
200
180
160
140
120
100
420
400
380
360
340
320
300
280
300
250
200
150
100
50
95
90
85
80
75

Figure 3

(a) Day of Advance Anomalies

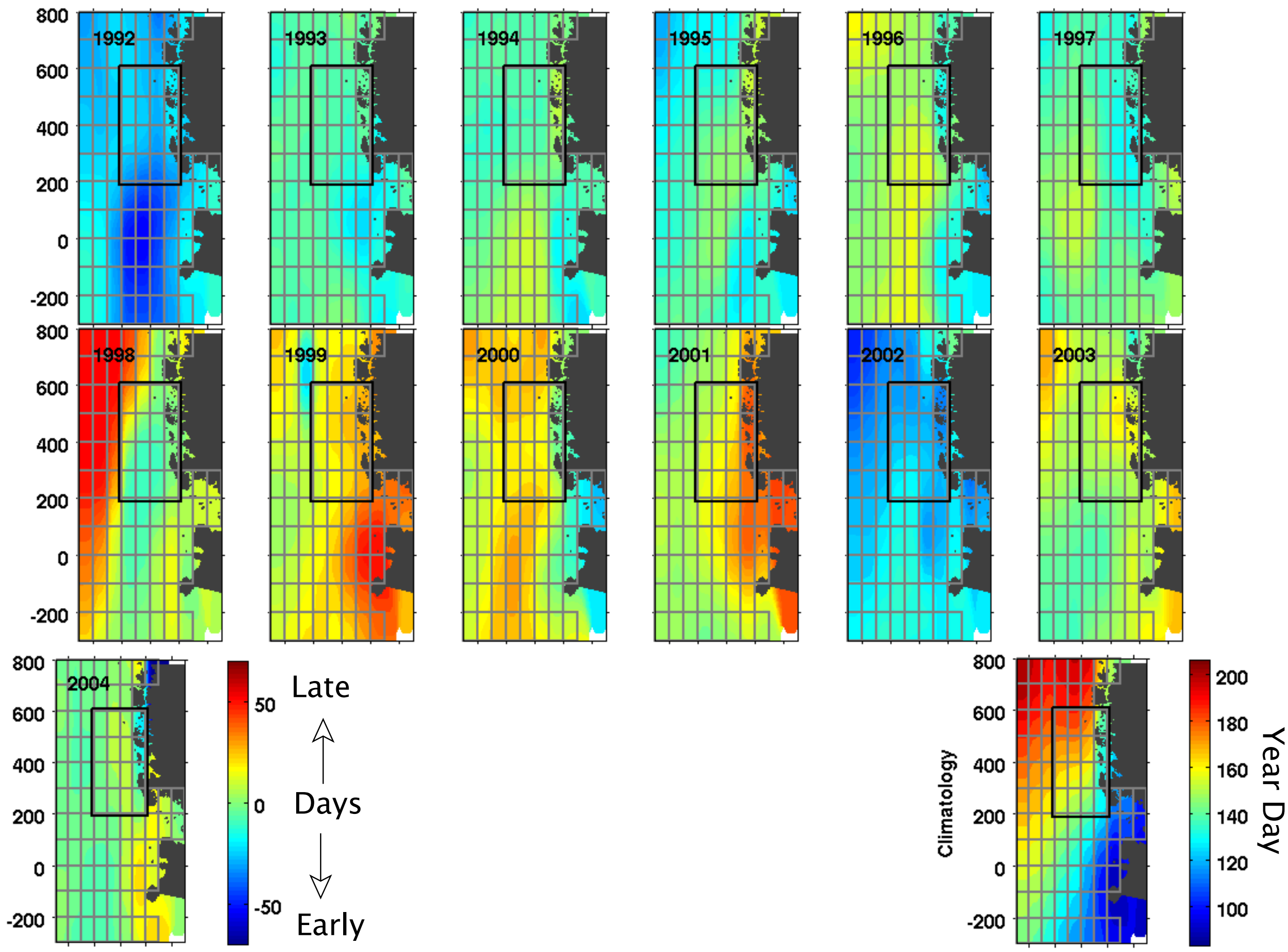


Figure 4a

(b) Day of Retreat Anomalies

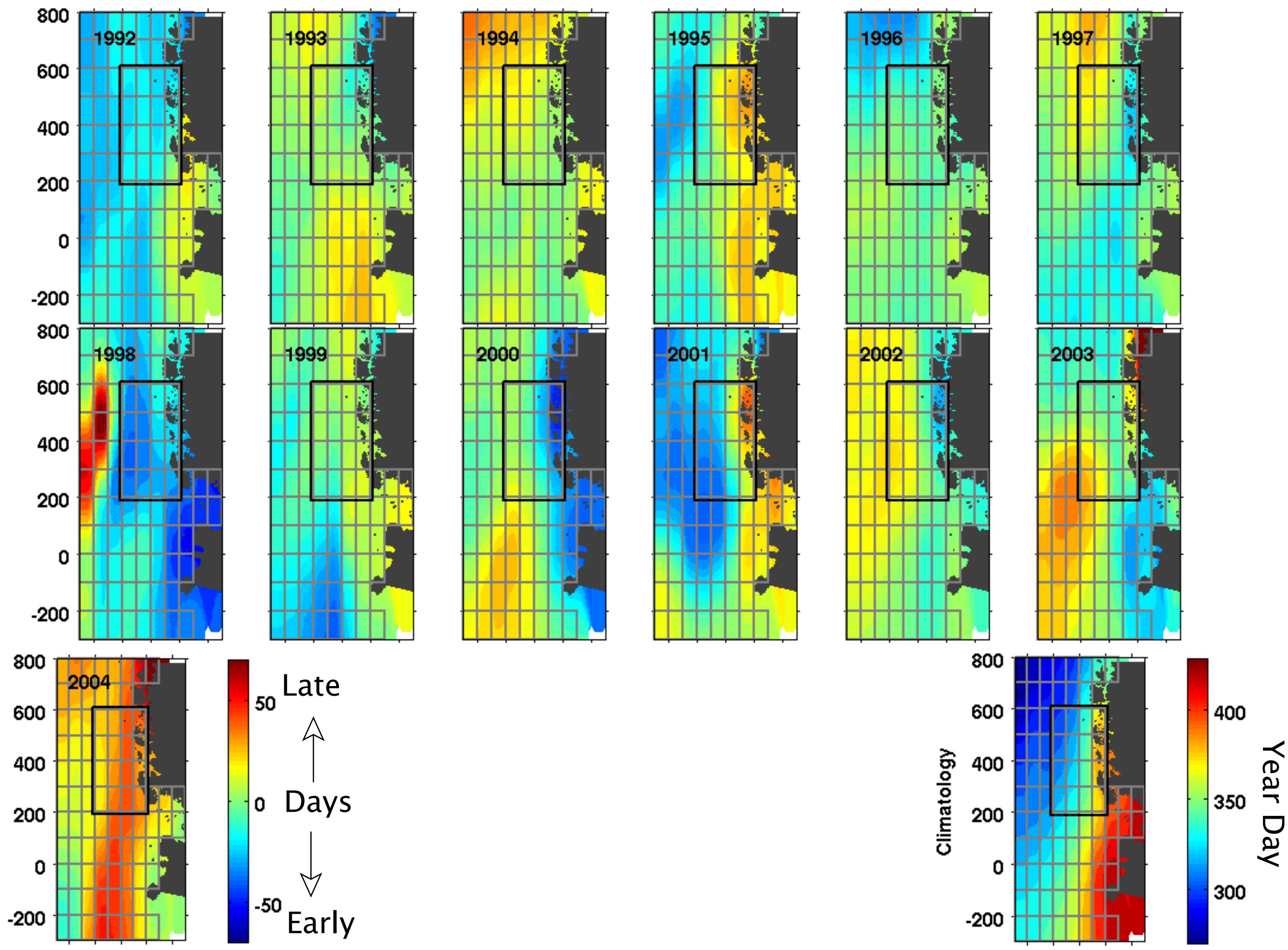


Figure 4b

(c) Ice Days Anomalies

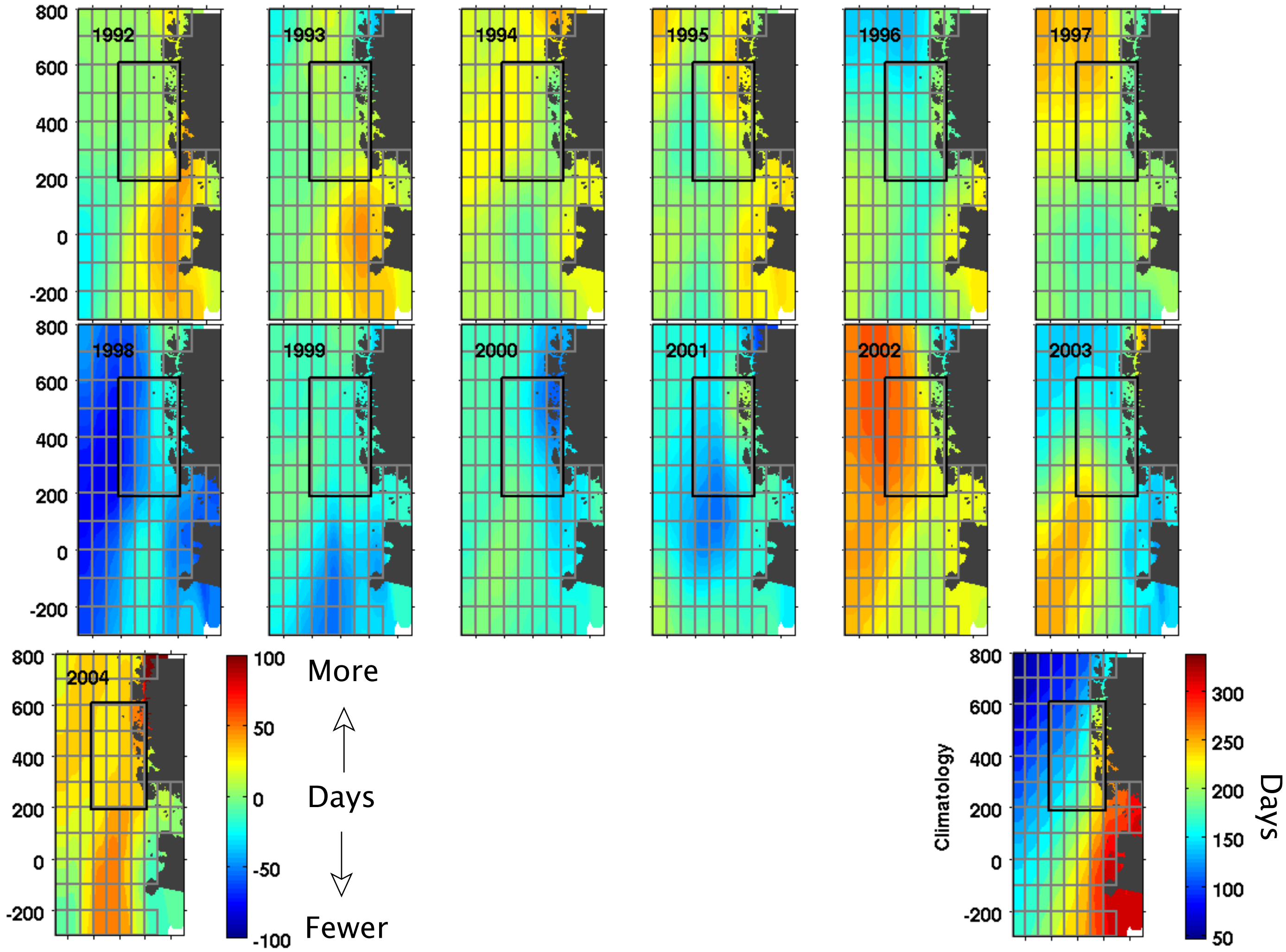


Figure 4c

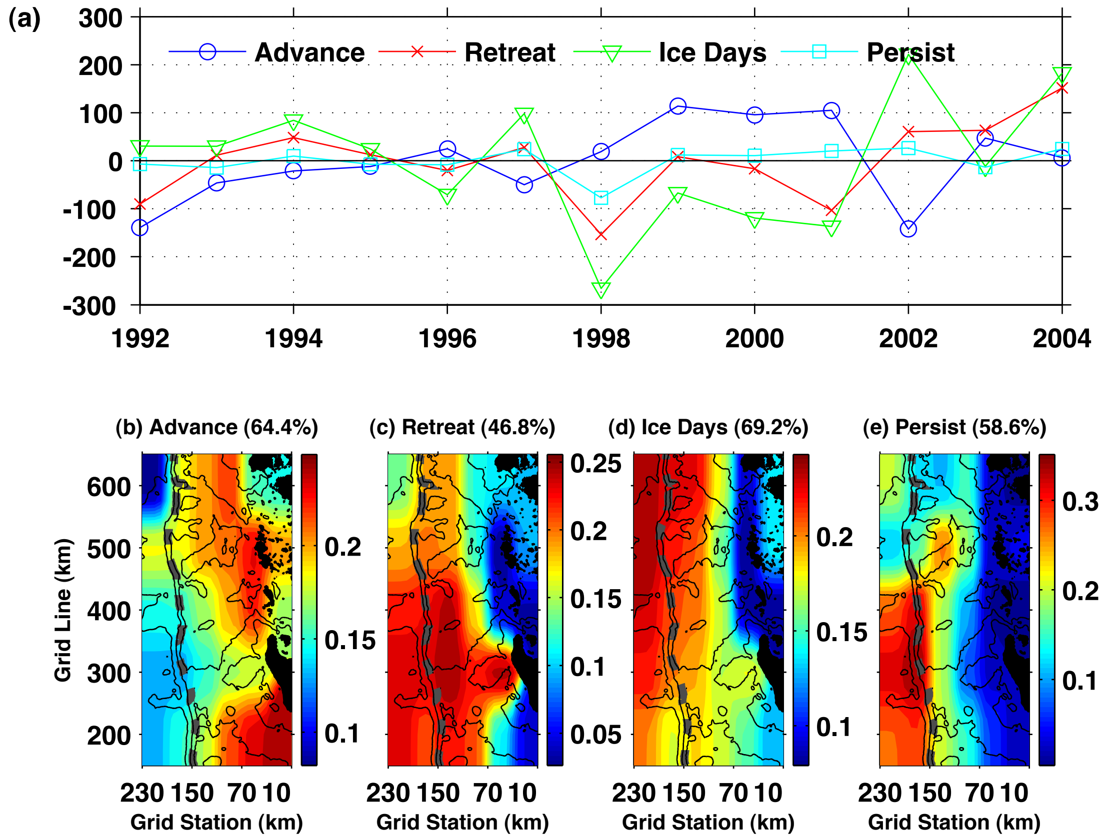


Figure 5: (a, top) The time expansion coefficients (1992-2004) of the first principal component (PC) shown for the four sea ice characteristics for the PAL LTER grid area, and (bottom) the individual spatial EOF maps for (b) day of advance, (c) day of retreat, (d) ice days, and (e) ice persistence. The percent variance explained by the first mode is given for (b-e).

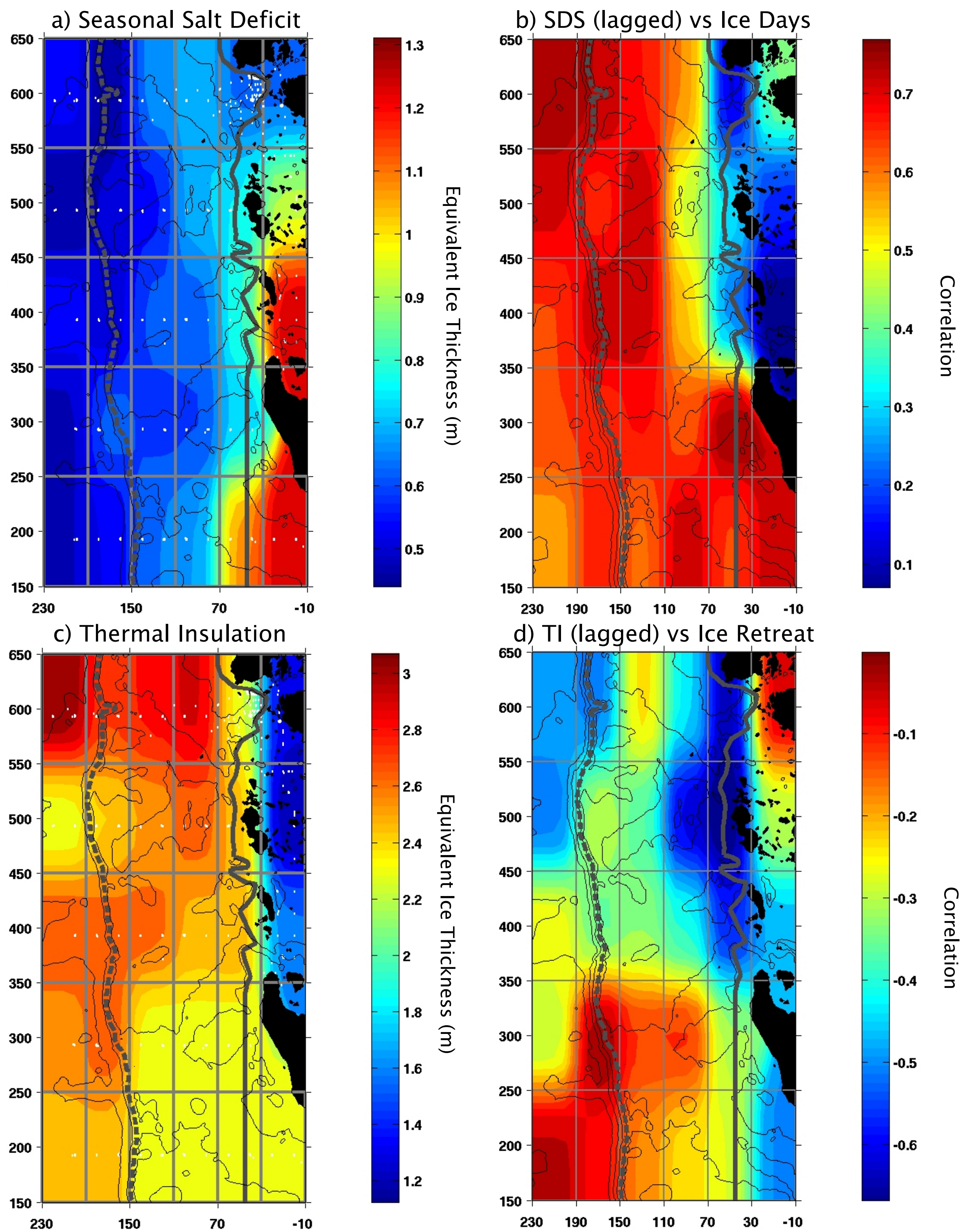

a) Seasonal Salt Deficit
Equivalent Ice Thickness (m)
b) SDS (lagged) vs Ice Days
Correlation
c) Thermal Insulation
Equivalent Ice Thickness (m)
d) TI (lagged) vs Ice Retreat
Correlation

Figure 6

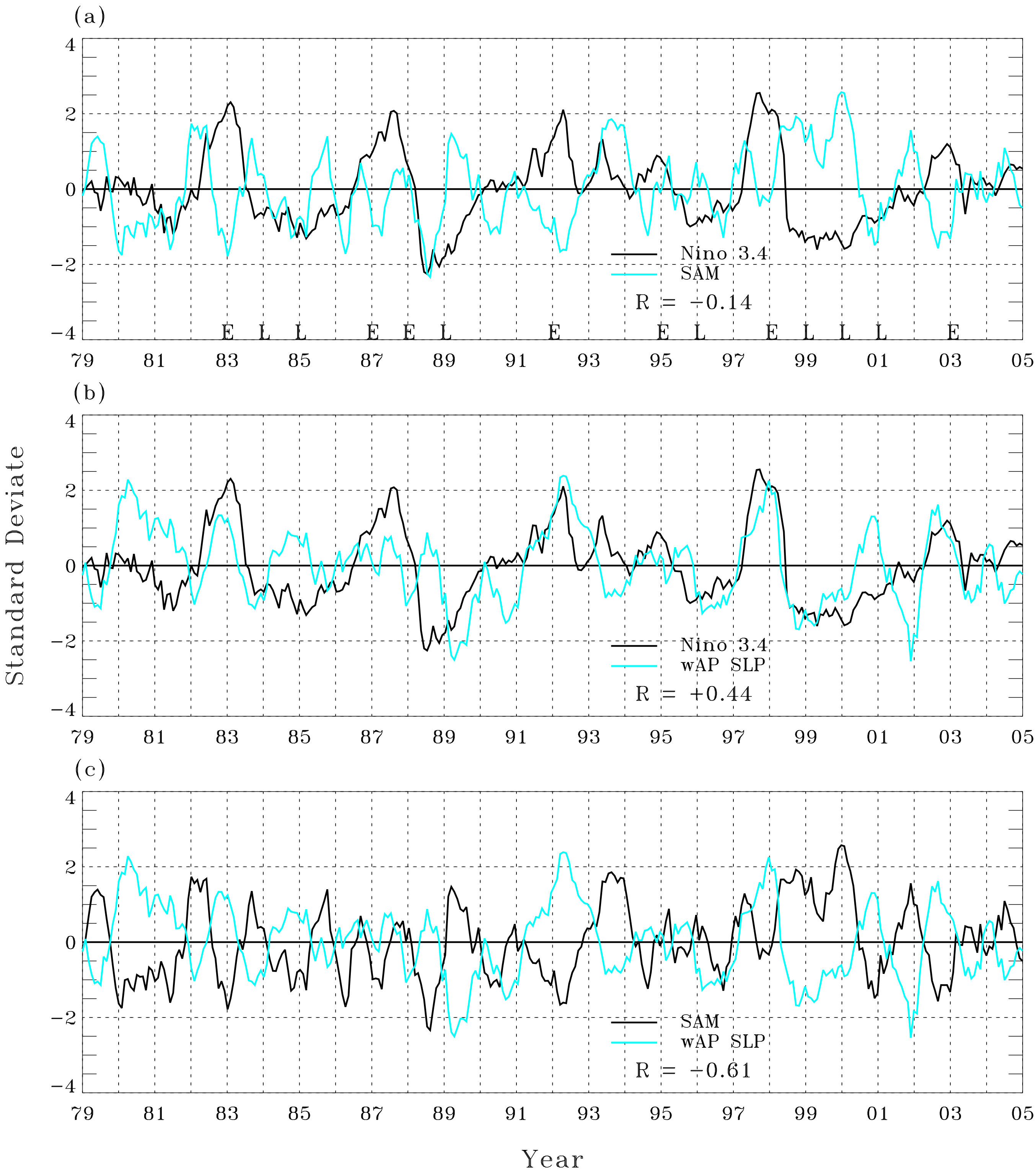
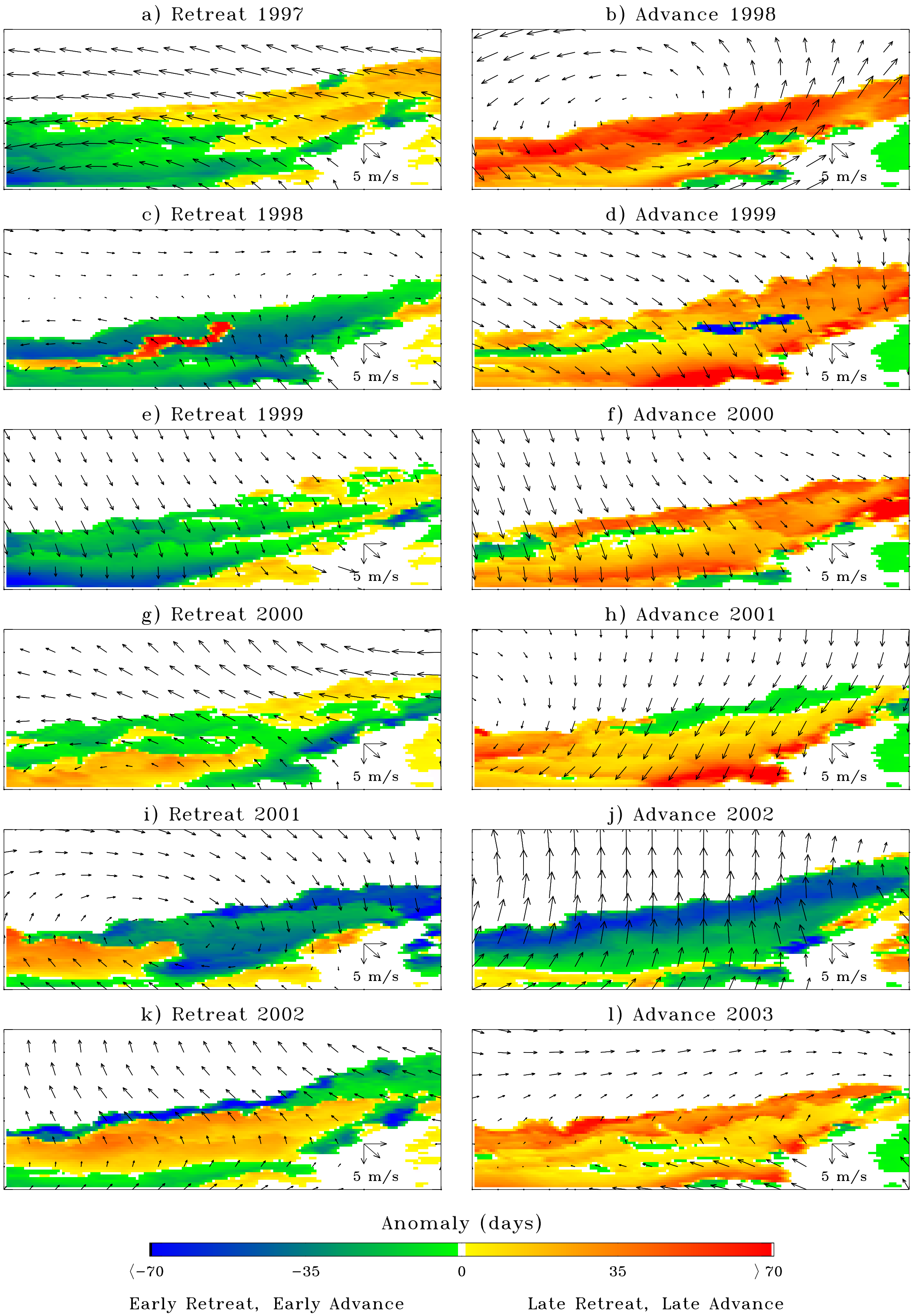

(a)
Nino 3.4
SAM
R = −0.14
E L L E E L E E L E L L L E
(b)
Standard Deviate
Nino 3.4
wAP SLP
R = +0.44
(c)
SAM
wAP SLP
R = −0.61
Year
4
2
0
−2
−4
79 81 83 85 87 89 91 93 95 97 99 01 03 05

Figure 7



a) Retreat 1997
b) Advance 1998
c) Retreat 1998
d) Advance 1999
e) Retreat 1999
f) Advance 2000
g) Retreat 2000
h) Advance 2001
i) Retreat 2001
j) Advance 2002
k) Retreat 2002
l) Advance 2003
5 m/s
Anomaly (days)
⟨-70
-35
0
35
⟩ 70
Early Retreat, Early Advance
Late Retreat, Late Advance

Figure 8

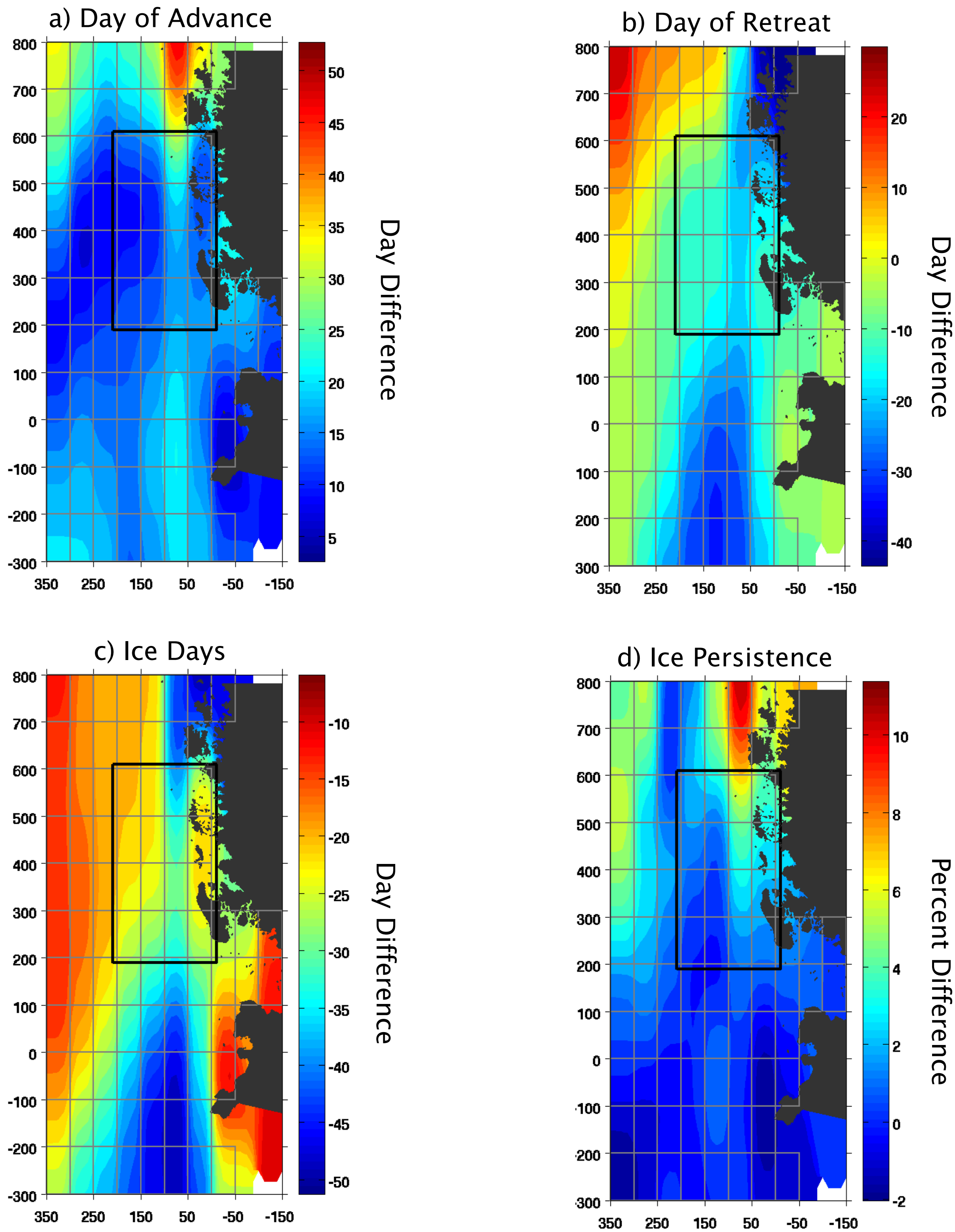

a) Day of Advance
Day Difference
b) Day of Retreat
Day Difference
c) Ice Days
Day Difference
d) Ice Persistence
Percent Difference

Figure 9

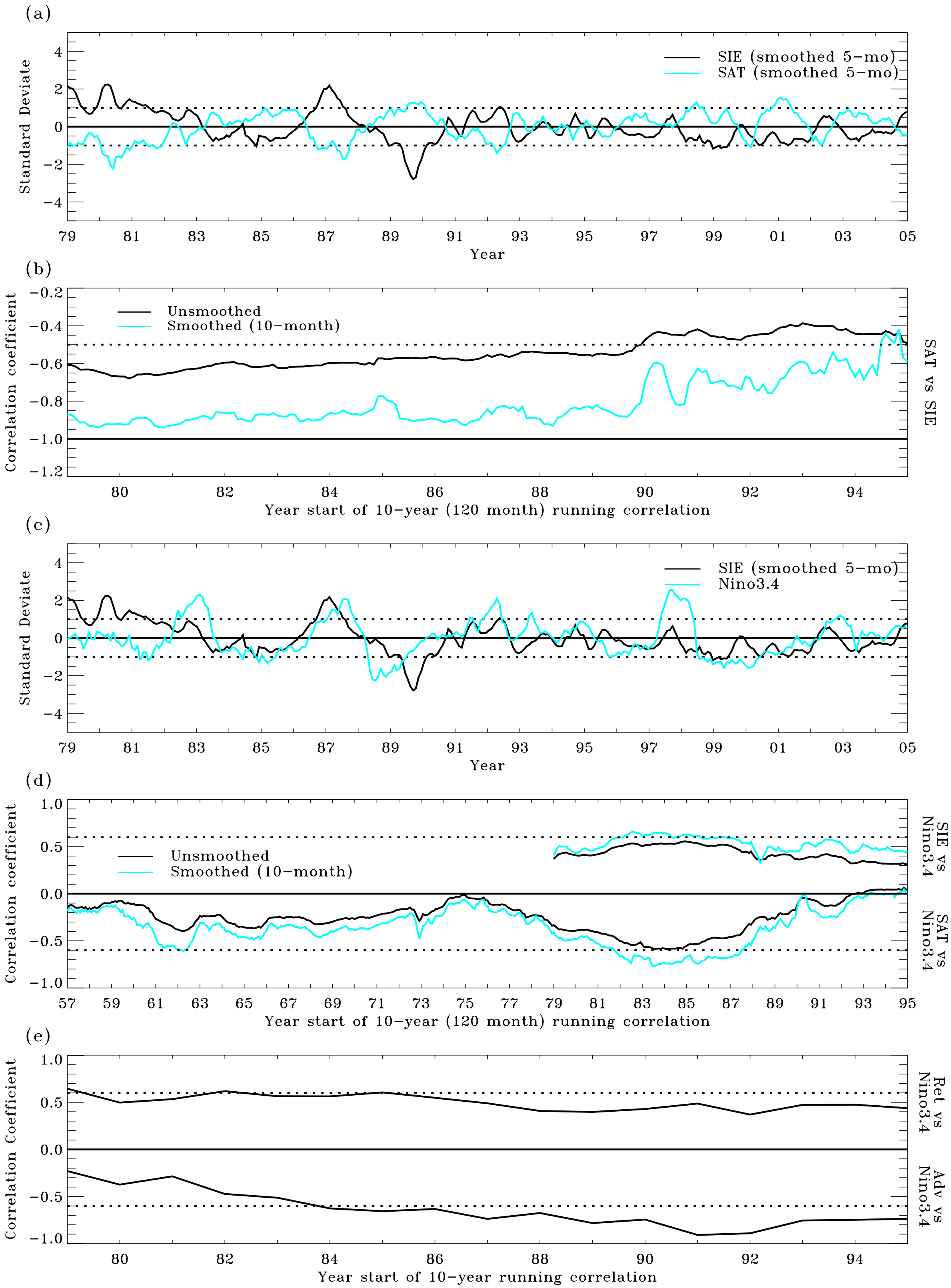

(a)
SIE (smoothed 5-mo)
SAT (smoothed 5-mo)
Standard Deviate
Year
(b)
Unsmoothed
Smoothed (10-month)
Correlation coefficient
SAT vs SIE
Year start of 10-year (120 month) running correlation
(c)
SIE (smoothed 5-mo)
Nino3.4
Standard Deviate
Year
(d)
Unsmoothed
Smoothed (10-month)
Correlation coefficient
SIE vs Nino3.4
SAT vs Nino3.4
Year start of 10-year (120 month) running correlation
(e)
Correlation Coefficient
Ret vs Nino3.4
Adv vs Nino3.4
Year start of 10-year running correlation

Figure 10

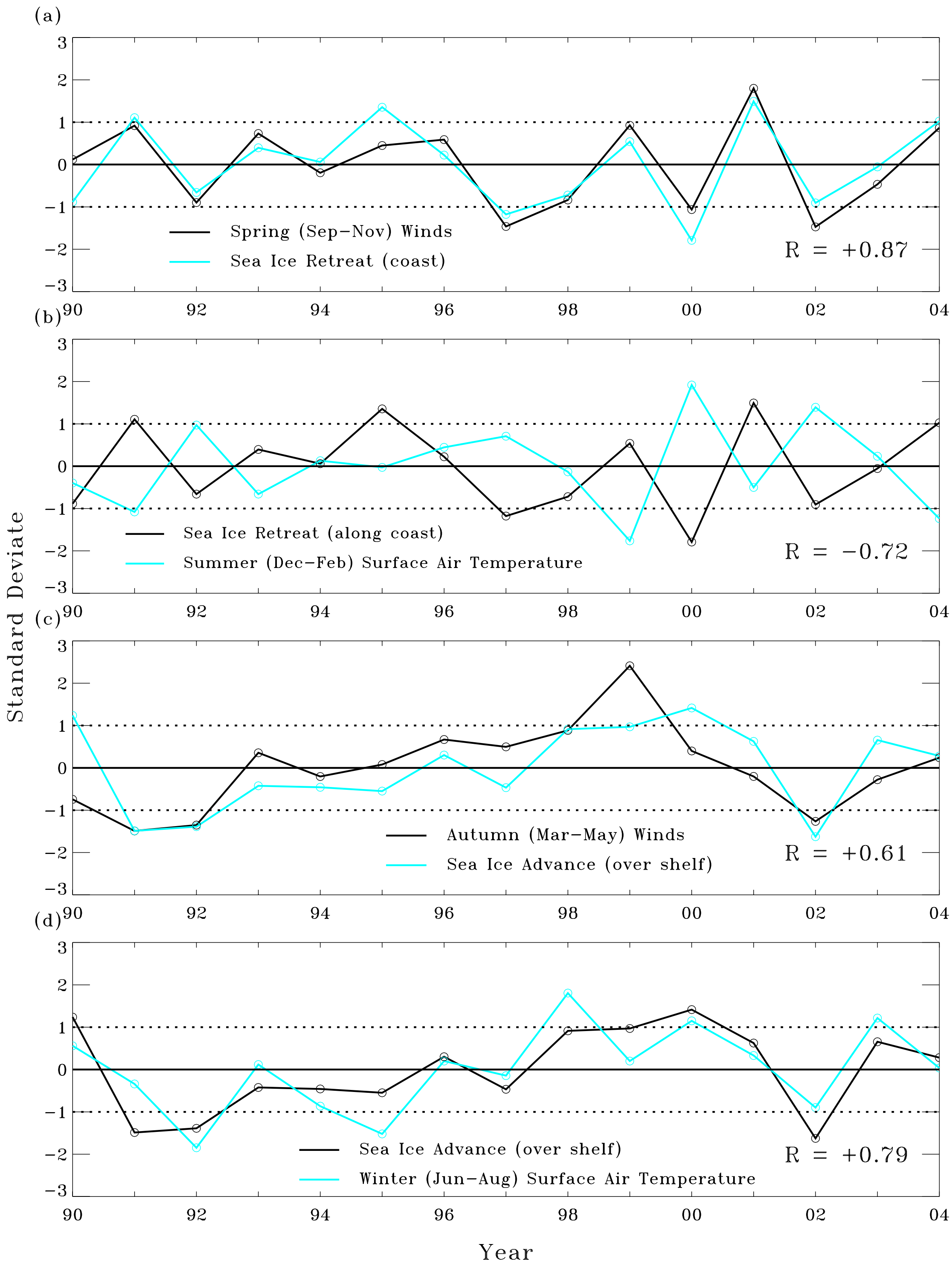

(a)
Spring (Sep–Nov) Winds
Sea Ice Retreat (coast)
R = +0.87
(b)
Sea Ice Retreat (along coast)
Summer (Dec–Feb) Surface Air Temperature
R = −0.72
(c)
Autumn (Mar–May) Winds
Sea Ice Advance (over shelf)
R = +0.61
(d)
Sea Ice Advance (over shelf)
Winter (Jun–Aug) Surface Air Temperature
R = +0.79
Standard Deviate
Year
90 92 94 96 98 00 02 04

Figure 11

Supplementary Online Material

Contents:
Table S1a and S1b
Table S2

SOM Table S1a. Mean values (± std) for each of the 5 sub-regions for each of the 4 sea ice characteristics. Values are reported for 3 different time-series: (1) 1992-2004 based on the 15% threshold, (2) 1979-2004 based on the 15% threshold, and (3) 1992-2004 based on the 50% threshold. In parentheses mean day of advance and retreat are reported as calendar days, and ice days as months.

Sub-Region		Advance (Year day)	Retreat (Year day)	Ice Days (Days)	Persistence (%)
N Coast	15%	140 ± 22 (5/20)	381 ± 28 (01/16)	224 ± 29 (7.3)	93 ± 4
	26yr	134 ± 29 (5/14)	391 ± 32 (01/26)	235 ± 52 (7.7)	92 ± 7
	50%	187 ± 27 (6/06)	333 ± 41 (11/29)	125 ± 39 (4.1)	81 ± 16
C Coast	15%	139 ± 22 (5/19)	389 ± 25 (01/24)	240 ± 24 (7.9)	95 ± 2
	26yr	128 ± 33 (5/08)	399 ± 30 (02/03)	254 ± 51 (8.3)	94 ± 4
	50%	176 ± 22 (6/25)	354 ± 27 (12/20)	168 ± 33 (5.5)	93 ± 6
S Coast	15%	144 ± 20 (5/24)	359 ± 20 (12/25)	208 ± 27 (6.8)	97 ± 2
	26yr	135 ± 26 (5/15)	366 ± 30 (01/01)	222 ± 48 (7.3)	96 ± 4
	50%	155 ± 18 (6/04)	344 ± 19 (12/10)	180 ± 28 (5.9)	95 ± 5
N Shelf	15%	179 ± 19 (6/28)	313 ± 19 (11/09)	125 ± 31 (4.1)	92 ± 8
	26yr	173 ± 26 (6/22)	319 ± 33 (11/15)	136 ± 51 (4.5)	91 ± 11
	50%	189 ± 21 (7/08)	301 ± 21 (10/28)	99 ± 34 (3.2)	87 ± 12
S Shelf	15%	156 ± 15 (6/05)	327 ± 22 (11/23)	162 ± 30 (5.3)	94 ± 7
	26yr	149 ± 22 (5/29)	333 ± 28 (11/29)	175 ± 45 (5.7)	94 ± 7
	50%	162 ± 16 (6/11)	316 ± 22 (11/12)	143 ± 33 (4.7)	92 ± 10

SOM Table S1b. The number of days (or percent difference) between the sub-regional means reported in Table 1 for the 15% threshold versus the 50% threshold for the 1992-2004 time-series.

Sub-Region	Advance (Days)	Retreat (Days)	Ice Days (Days)	Persistence (%)
N Coast	47	48	99	12
M Coast	37	35	72	2
S Coast	11	15	28	3
N Shelf	10	12	26	5
S Shelf	8	11	19	2

SOM Table S2. Trends in the 5 sub-regions for three different time-series: (1) 1992-2004 w/ 15% threshold, (2) 1992-2004 w/ 50% threshold, and (3) 1979-2004 w/ 15% threshold. Trends are reported as day/year for advance, retreat and ice days, and as %/year for persistence. Only trends greater than 0.20 significance are reported.

		Advance	Retreat	Ice Days	Persistence
NCoast	15%	---	---	---	---
	50%	2.4 (>0.15)	---	---	---
	26yr	1.1 (>0.10)	-1.2 (>0.10)	-2.0 (>0.15)	---
CCoast	15%	---	---	---	---
	50%	3.1 (>0.05)	---	---	---
	26yr	1.4 (>0.10)	-1.2 (>0.10)	-2.3 (>0.10)	---
SCoast	15%	---	---	---	0.16 (>0.20)
	50%	2.1 (>0.15)	---	---	---
	26yr	1.1 (>0.05)	-1.0 (>0.15)	-2.0 (>0.10)	---
NShelf	15%	1.7 (>0.20)	---	---	---
	50%	2.1 (>0.20)	---	---	---
	26yr	0.8 (>0.15)	---	-1.6 (>0.20)	---
SShelf	15%	1.4 (>0.20)	---	---	---
	50%	1.4 (>0.20)	---	---	---
	26yr	0.8 (>0.10)	---	-1.5 (>0.15)	---