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Regions of rapid sea ice change: An inter-hemispheric seasonal comparison

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[1] This bi-polar analysis resolves ice edge changes on space/time scales relevant for investigating seasonal ice-ocean feedbacks and focuses on spatio-temporal changes in the timing of annual sea ice retreat and advance over 1979/80 to 2010/11. Where Arctic sea ice decrease is fastest, the sea ice retreat is now nearly 2 months earlier and subsequent advance more than 1 month later (compared to 1979/80), resulting in a 3-month longer summer ice-free season. In the Antarctic Peninsula and Bellingshausen Sea region, sea ice retreat is more than 1 month earlier and advance 2 months later, resulting in a more than 3-month longer summer ice-free season. In contrast, in the western Ross Sea (Antarctica) region, sea ice retreat and advance are more than 1 month later and earlier respectively, resulting in a more than 2 month shorter summer ice-free season. Regardless of trend magnitude or direction, and at latitudes mostly poleward of 70° (N/S), there is strong correspondence between anomalies in the timings of sea ice retreat and subsequent advance, but little correspondence between advance and subsequent retreat. These results support a strong ocean thermal feedback in autumn in response to changes in spring sea ice retreat. Further, model calculations suggest different net ocean heat changes in the Arctic versus Antarctic where autumn sea ice advance is 1 versus 2 months later. Ocean-atmosphere changes, particularly in boreal spring and austral autumn (i.e., during ~March-May), are discussed and compared, as well as possible inter-hemispheric climate connections. **Citation:** Stammerjohn, S., R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, *Geophys. Res. Lett.*, *39*, L06501, doi:10.1029/2012GL050874.

1. Introduction

[2] Major changes are apparent in the global distribution of sea ice, a critical ecological habitat, a key modulator of Earth's climate system, and a sensitive indicator of climate variability/change [e.g., *Thomas and Dieckmann*, 2010]. Previous assessments of space/time averages of polar sea ice extent show a statistically-significant circumpolar decrease in the Arctic (−3.8 ± 0.2% per decade over 1979–2008) and a small circumpolar increase in the Antarctic (+1.2 ± 0.2% per decade) [e.g., *Comiso*, 2010]. It has been suggested that the different hemispheric sea ice changes are largely resulting from different topographic factors and land/sea distribution [*Turner and Overland*, 2009]. However, the largest and fastest sea ice changes are on regional/seasonal scales and are resulting in significant alterations to the marine ecosystem [e.g., *Ducklow et al.*, 2007; *Grebmeier et al.*, 2010].

[3] Of major concern are regions of rapid sea ice decrease as observed in the East Siberian-Chukchi-Beaufort seas in the Arctic [e.g., *Comiso*, 2012] and in the southern Bellingshausen-eastern Amundsen seas in the Antarctic [e.g., *Pezza et al.*, 2012], as well as the rapid sea ice increases in the western Ross Sea (Antarctica) [*Turner et al.*, 2009]. The rapid sea ice changes point to strong seasonal feedbacks, e.g., an ice-albedo feedback accelerating/decelerating spring melt-back [e.g., *Perovich et al.*, 2007] and/or an ocean thermal feedback accelerating/decelerating autumn freeze onset [e.g., *Meredith and King*, 2005; *Steele et al.*, 2008; *Screen and Simmonds*, 2010a]. Here, we offer an analysis that resolves seasonal ice edge changes on space/time scales relevant for investigating seasonal feedbacks and phenological impacts on the marine ecosystem.

[4] Our approach consists of mapping the satellite-observed ice edge location in time (day of arrival and day of departure) at every pixel location to create yearly maps showing the spatio-temporal variability in the timing of sea ice advance and retreat, from which we can then compute the spatial climatology, anomaly and trend (Figure 1 and Figures S1 and S2 in the auxiliary material).[1] This approach allows direct quantification of seasonal change not obscured by regional or temporal averaging. This approach was first applied to analyses of Antarctic sea ice, which helped resolve how changes in the timing of sea ice advance and retreat related to seasonal atmospheric circulation changes [*Massom et al.*, 2008; *Stammerjohn et al.*, 2008; *Massom and Stammerjohn*, 2010] and surface ocean changes [*Stammerjohn et al.*, 2011].

[5] In this study, we apply this analysis to both polar regions to allow a focused investigation of when (seasonally) and where (regionally) the largest sea ice changes are occurring. This allows us to evaluate and compare potential seasonal feedbacks and sensitivities associated with regions of rapid sea ice change. It also provides an additional metric of sea ice variability that is particularly useful

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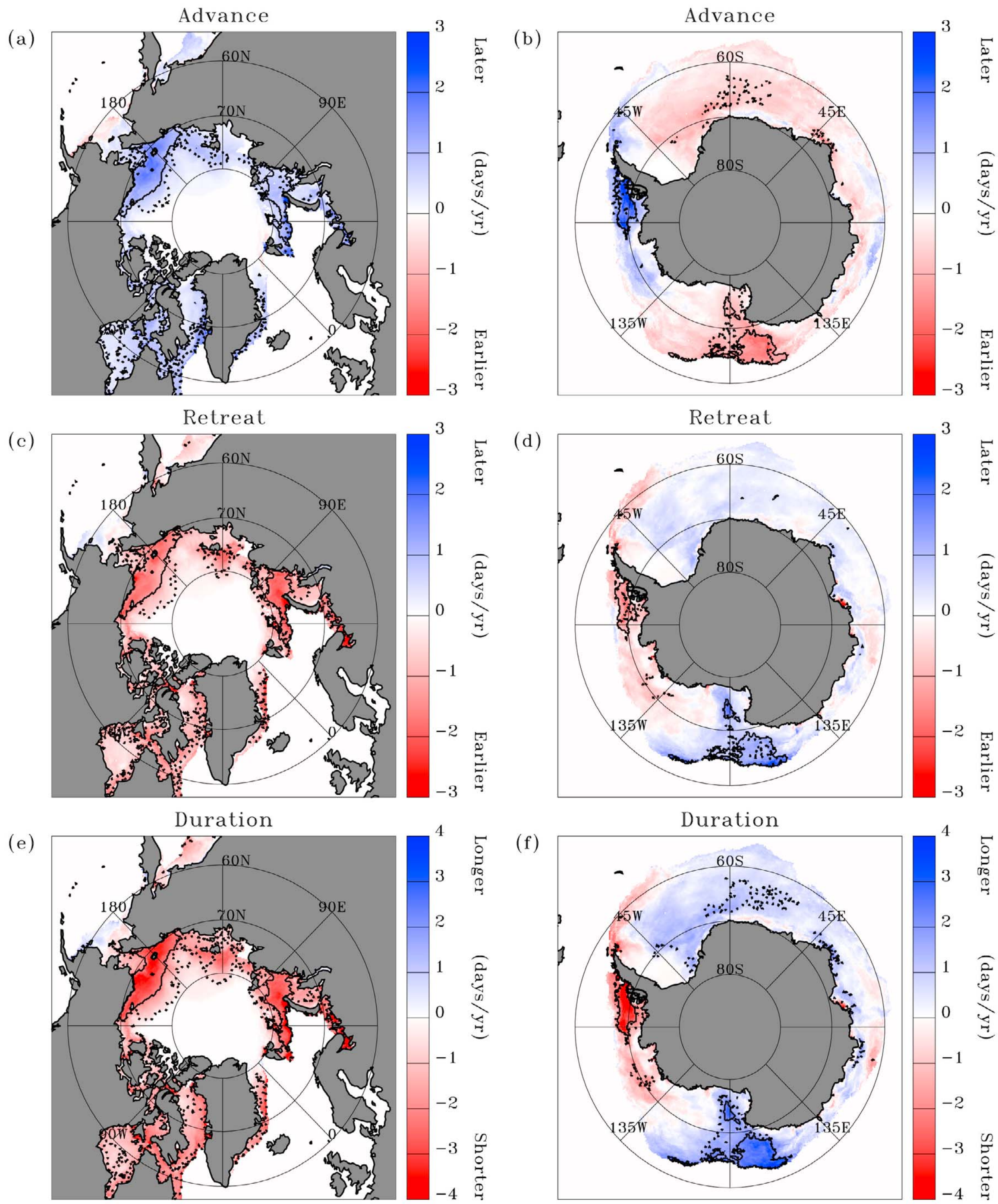

Figure 1. Trends (days/year) over 1979/80 to 2010/11 in (a, b) sea ice advance, (c, d) sea ice retreat, (e, f) ice season duration, for (left) the Arctic, and (right) the Antarctic. The black solid contour delineates the sub-regions reported in Table 1, while the black dotted contour delineates those trends with significance at the $p < 0.01$ level, with standard error determined using the effective degrees of freedom present in the regression residuals. The upper and lower ranges on the colorbars are designated as >= and <=, respectively.

for investigating phenological ice-ecosystem linkages [*Ducklow et al.*, 2007; *Massom and Stammerjohn*, 2010].

2. Methods

[6] This study uses the GSFC Bootstrap SMMR-SSM/I Version 2 quasi-daily time series (1979–2007) of sea ice concentration [*Comiso*, 2010] from the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC, University of Colorado at Boulder, http://nsidc.org), augmented with SSM/I and near real-time data (2008–2011), to produce a times series extending from 1979/80 to 2010/11. Our approach consists of identifying the day of annual sea ice advance and retreat for each gridded (25 × 25 km pixel) location and for each sea ice year that begins/ends during the mean summer sea ice minimum,

Table 1. Area-Averaged Trends in Sea Ice Advance, Retreat and Ice Season Duration Over 1979/80 to 2010/11 for the Highest Trending Polar Regions[a]

Region	Day of Advance (days/year)	Day of Retreat (days/year)	Ice Season Duration (days/year)	Correlation: Retreat Versus Subsequent Advance
eS/C/wB	+1.3 ± 0.2 (later)	−1.5 ± 0.2 (earlier)	−2.8 ± 0.5 (shorter)	−0.81
K/B	+1.0 ± 0.5 (later)	−1.8 ± 0.5 (earlier)	−2.8 ± 1.0 (shorter)	−0.78
AP/B	+1.9 ± 0.5 (later)	−1.2 ± 0.4 (earlier)	−3.1 ± 1.0 (shorter)	−0.70
wR	−1.3 ± 0.3 (earlier)	+1.2 ± 0.3 (later)	+2.5 ± 0.4 (longer)	−0.42

[a]With a greater than 2 day/year change in ice season duration as delineated by the black solid line contours in Figures 1e and 1f. The two Arctic regions include: the eastern Siberian, Chukchi, and western Beaufort (eS/C/wB) region (870,121 km^2) and the Kara and Barents (K/B) region (604,820 km^2). The two Antarctic regions include: the Antarctic Peninsula and Bellingshausen (AP/B) region (332,460 km^2), and the western Ross (wR) region (727,073 km^2). Trends are reported in days per year and are significant at the $p < 0.01$ level, with standard error determined using the effective degrees of freedom present in the regression residuals. The last column lists the correlation between the spring sea ice retreat and subsequent autumn sea ice advance based on detrended time series (see Figures 2e–2h).

i.e., mid-September for the Arctic and mid-February for the Antarctic. We also present analyses of ice season duration, the time elapsed between day of sea ice advance and retreat. In our analysis, we reference the year in which sea ice advance occurred (e.g., 1979/80 refers to the Arctic 9/1979 to 9/1980 ice year and the Antarctic 2/1979 to 2/1980 ice year). This analysis is described in further detail by *Stammerjohn et al.* [2008] and follows, e.g., *Parkinson* [1994], who was first to report ‘length of sea ice season’ changes in both polar regions. However, here we focus on the timing of sea ice advance and retreat (analyses not presented by Parkinson or others).

3. Results

[7] Maps of the trends in sea ice advance, retreat and ice season duration over 1979/80 to 2010/11 are shown in Figure 1. Regions showing statistically-significant sea ice changes in the Arctic (as delineated by the dotted contour) indicate change towards a later advance, an earlier retreat, and thus shorter ice season duration. Those regions showing the largest changes (greater than 2 days/year change in ice season duration as delineated by the black solid line contour in Figure 1e) are featured in Table 1 and Figure 2 and include: the eastern Siberian/Chukchi/western Beaufort (eS/C/wB) sea region (between ∼70–76°N, ∼138°W–155°E) and the Kara/Barents (K/B) sea region (between ∼74–81°N, ∼25°E–95°E). Over the 32-year period analyzed (1979/80 to 2010/11), these two regions (Figure 2) experience a later sea ice advance by 1 to 1.4 months, an earlier sea ice retreat by 1.6 to 1.9 months, and a shorter ice season duration by 3 months. There are other smaller areas (e.g., Laptev Sea, east Greenland Sea) that show strong trends as well, but the two regions listed above show the largest contiguous areas of change.

[8] Consistent with previous analyses of sea ice extent [e.g., *Comiso*, 2010] and concentration changes [e.g., *Liu et al.*, 2004], the Antarctic shows regionally-opposing sea ice changes (Figure 1), particularly between the Antarctic Peninsula/Bellingshausen (AP/B) sea region (between ∼65°S–72°S, ∼64°W–100°W) and the western Ross (wR) sea region (between ∼62°S–76°S, ∼155°E–206°W). The sea ice changes in the AP/B region show a later sea ice advance by 2 months, an earlier sea ice retreat by 1.3 months, and a shorter ice season by 3.3 months (Table 1 and Figure 2). The wR region shows the opposite: an earlier sea ice advance by 1.4 months, a later sea ice retreat by 1.2 months and a longer ice season by 2.6 months. However, regardless of trend magnitude or direction, there is strong correspondence between anomalies in spring sea ice retreat and subsequent autumn sea ice advance, as detailed below.

[9] By definition, the timings of sea ice advance and retreat determine the winter ice season duration; conversely, sea ice retreat and subsequent advance determine the length of the summer open water season. When we compare the de-trended seasonal time series, we see weak correlations between the autumn sea ice advance and the subsequent spring sea ice retreat (i.e., over winter) (Figures 3a and 3b). In contrast, strong correlations occur between the spring sea ice retreat and subsequent autumn sea ice advance (i.e., over summer), indicating that an early (late) sea ice retreat is often followed by a late (early) autumn sea ice advance (Figures 2e–2h, 3c, and 3d). The correlations are strongest in the inner pack ice regions and mostly poleward of ∼70° (N/S) (except in the western Weddell Sea where correlations are high out to 60°S, likely due to the effect of the Weddell Gyre in retaining ice-ocean anomalies in this area).

[10] The strong relationship between spring sea ice retreat and subsequent autumn advance is consistent with the expected seasonal feedback, e.g., an earlier (later) spring retreat leads to increased (decreased) solar ocean warming, resulting in a later (earlier) sea ice advance in autumn. This feedback is likely obscured in the outer pack ice regions at lower latitude, where there is higher frequency wind variability. In comparing the largest sea ice changes, we also note that the eS/C/wB and AP/B regions show a 49-day versus 39-day earlier sea ice retreat over 1979/80 to 2010/11, and a 41-day versus 61-day later sea ice advance, respectively (Table 1). The seasonal trend asymmetry is likely due to different seasonal and regional ocean-atmosphere forcing (discussed in Section 4) or due to different seasonal sensitivities to surface forcing. For example, wind *direction* can influence ice edge advance and retreat differently and asymmetrically [*Watkins and Simmonds*, 1999; *Stammerjohn et al.*, 2008].

[11] Concerning ice-ocean feedback and the ocean heat storage associated with reduced sea ice coverage during spring-summer and its possible effect on sea ice advance in autumn, we note the following. With an earlier sea ice retreat, there is opportunity for increased solar ocean warming (in time and space), which also may be enhanced by less latent energy required to melt an overall thinner sea ice cover (as can happen with a shorter ice season), thus making available more sensible energy to warm the ocean [e.g., *Meredith and King*, 2005]. From observations,

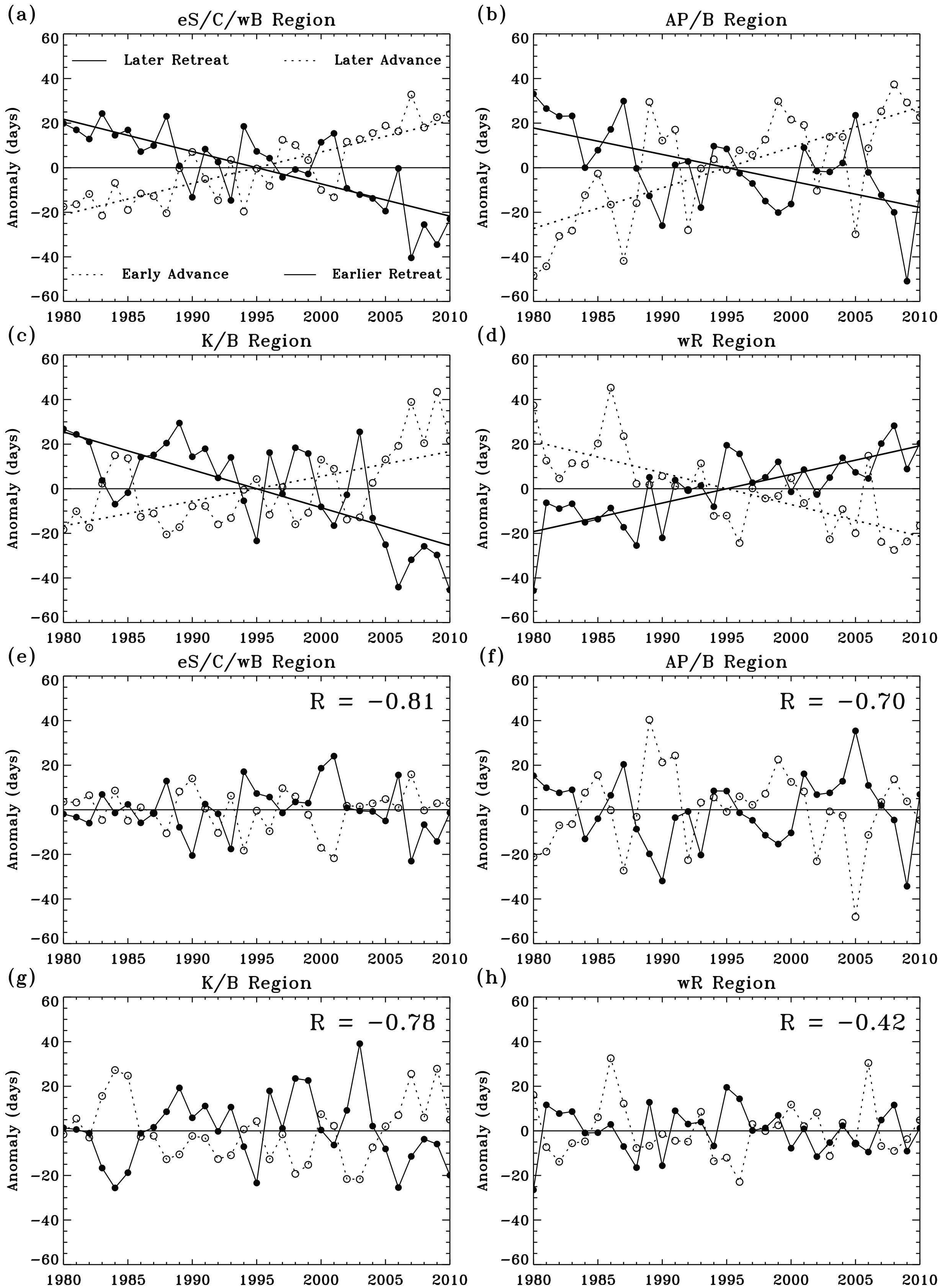
(a)
eS/C/wB Region
Later Retreat
Later Advance
Early Advance
Earlier Retreat
(b)
AP/B Region
(c)
K/B Region
(d)
wR Region
(e)
eS/C/wB Region
R = −0.81
(f)
AP/B Region
R = −0.70
(g)
K/B Region
R = −0.78
(h)
wR Region
R = −0.42
Anomaly (days)
60
40
20
0
−20
−40
−60
1980
1985
1990
1995
2000
2005
2010

Figure 2

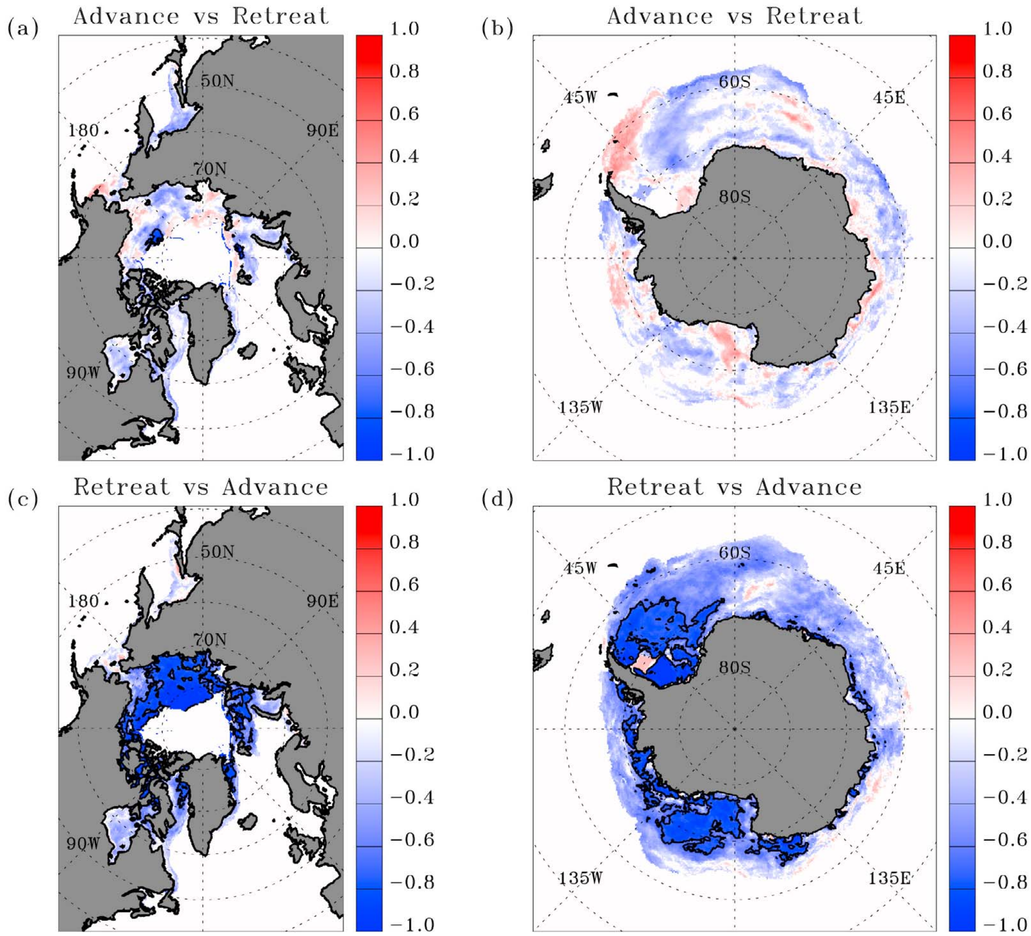

Figure 3. Correlation maps of (a, b) sea ice advance versus subsequent sea ice retreat, (c, d) sea ice retreat versus subsequent sea ice advance, for (left) the Arctic and (right) the Antarctic based on the 1979/80 to 2010/11 time series. The black contour in Figures 3c and 3d delineates the −0.7 correlation for reference. (Time series were de-trended before determining correlations.)

we know for the eS/C/wB and AP/B regions in particular that there have been significant ocean heat increases (detailed below). We compare these observed increases to calculated estimates of ocean heat (OH) using the observed time delay in sea ice advance, i.e., we calculate the amount of OH that must be removed before sea ice production can commence.

[12] Previous estimates of OH increases based on solar ocean warming in the eS/C/wB region are on the order of 200 MJ m^{-2} over 1979–2005 [*Perovich et al.*, 2007]. Using reasonable ranges of air-water temperature differences and wind speeds [from *Steele et al.*, 2008] and based on the OH needed to delay autumn sea ice advance for 35 days (at 1.3 days yr^{-1} over 1979–2005), our calculations suggest OH increases ranging from 100 to 400 MJ m^{-2} in that region (see auxiliary material for details). These results, though poorly constrained, bracket the observed additional solar warming estimate, and imply that it would be sufficient (or nearly so) to force the observed delay in sea ice advance. These results are also consistent with recent interpretations of autumn-winter ocean heat loss [*Screen and Simmonds*, 2010b].

[13] For the AP/B region with a 51-day delay (at 1.9 days yr^{-1}), requisite OH increases range from ∼150 to 600 MJ m^{-2}. Previous observations indicate a summer warming rate of ∼0.04°C yr^{-1} [*Meredith and King*, 2005], or an increase of 1.1°C over 1979–2005 (to make it comparable to the Arctic period analyzed above). If this warming were distributed over a summer mixed layer depth of 25 m [e.g., *Martinson et al.*, 2008], then the observed

Figure 2. Time series of area-averaged anomalies (based on the 1979/80 to 2010/11 mean) of sea ice retreat (filled circles) and subsequent sea ice advance (open circles), such that the sea ice advance time series is lagged one year (e.g., the first data point shows the 1979/80 sea ice retreat against the subsequent 1980/81 sea ice advance) for (left) the Arctic regions (eS/C/wB and K/B regions) and (right) the Antarctic regions (AP/B and wR regions) (see Table 1 for regional definitions). (a–d) Trend lines are based on a linear least squares fit; (e–h) these trends are removed and correlations between sea ice retreat and subsequent advance are given in upper right corner of each subplot.

increase in OH would be $\sim$113 MJ m^{-2}. This is too low to produce the observed sea ice delay, but there are numerous possible reasons for this, including that this region is experiencing a much greater OH loss, perhaps due to additional heat provided by wind-induced upwelling of warm Circumpolar Deep Water [e.g., *Martinson*, 2011].

[14] These model calculations suggest potentially different net ocean heat changes in the Arctic versus Antarctic, where autumn sea ice advance is 1 versus 2 months later. However, to better constrain the problem, we require difficult-to-obtain *in situ* time series observations during the transitional seasons, such as from a suite of bottom ocean moorings, ice-tethered profilers and ice mass balance buoys, if we wish to improve our understanding of how the upper ocean is changing in response to the regional delays in sea ice advance.

4. Discussion

[15] We now place our results within the context of previously reported ocean-atmosphere-ice changes to highlight potential causes for the observed seasonal trend asymmetry, addressing first the Arctic. *Perovich et al.* [2007], in analyzing increased solar ocean warming in the eS/C/wB region in particular, showed that increases in open water fraction within the Arctic pack ice appear to initiate the ice-albedo feedback. The increase in open water fraction, and hence earlier sea ice retreat, have been attributed to an initial increase in divergent (cyclonic) winds, activating the ice-albedo feedback, followed by convergent (anticyclonic) winds in early summer, driving ice edge retreat poleward [*Screen et al.*, 2011]. *Belchansky et al.* [2004] also noted that synoptic activity increases after the Arctic winter, thus strongly but variably impacting local-scale melt conditions, whereas an observed *decrease* in synoptic activity in autumn favours more stable and consistent local-scale freezing conditions. Thus, the subsequent delay in sea ice advance has been attributed to solar ocean warming [e.g., *Perovich et al.*, 2011], with no large changes in wind forcing to modulate the ice-ocean feedback.

[16] Further, an earlier break-up and retreat of Arctic sea ice would be more easily facilitated by an overall thinner sea ice cover caused by long-term warming and/or a residual effect from a more positive Northern Annular Mode (NAM) in the 1990s that flushed thicker/older sea ice out of the central Arctic [e.g., *Serreze et al.*, 2007]. The observation that sea ice continued to decline, particularly in the eS/C/wB and K/B regions, after the NAM became more neutral (since the mid-1990s) may indicate that, relative to the 1980s, more regional-scale atmospheric and/or oceanic forcing would be sufficient [*Shimada et al.*, 2006; *Maslanik et al.*, 2007; *Simmonds and Keay*, 2009] to break-up what appears to be a thinner sea ice cover [e.g., *Kwok*, 2009]. Finally, we also note that the eS/C/wB and K/B regions are at higher latitudes (70–76°N) and thus experience longer days during the retreat season compared to the AP/B region (65–72°S), which may also partly explain the stronger trends in sea ice retreat in the eS/C/wB and K/B regions versus the AP/B region.

[17] Concerning previously reported changes in the Antarctic, the AP/B region in particular is an area where ice edge anomalies are strongly associated with changes in meridional winds [e.g., *Van Den Broeke*, 2000]. This is illustrated for example by enhanced poleward winds accelerating spring sea ice retreat [e.g., *Massom et al.*, 2008] and delaying autumn sea ice advance [*Stammerjohn et al.*, 2008]. Similarly, ice edge anomalies in the southwestern Ross Sea region also respond to changes in the meridional winds, while ice edge anomalies in the northwestern Ross Sea region appear to respond more to changes in the zonal winds [e.g., *Turner et al.*, 2009].

[18] Wind-driven ice-atmosphere interactions, particularly in the AP/B and wR regions, are strongly influenced by El Niño-Southern Oscillation (ENSO) and Southern Annular Mode (SAM) variability [e.g., *Liu et al.*, 2004; *Fogt and Bromwich*, 2006; *Stammerjohn et al.*, 2008; *Yuan and Li*, 2008; *Turner et al.*, 2009]. Up until the late 1980s, the pattern of earlier (later) sea ice advance and later (earlier) retreat in the AP/B (wR) region corresponded to a period when negative SAM and/or El Niño conditions predominated [*Stammerjohn et al.*, 2008]. This was characterized by the prevalence of a positive sea level pressure anomaly centered over the high latitude Southeast Pacific [see also *Fogt and Bromwich*, 2006]. In contrast, the subsequent switch to a pattern of predominantly later (earlier) advance and earlier (later) retreat in the AP/B (wR) regions coincided (from about 1987–88 onwards) with a dominance of positive SAM and/or La Niña conditions, characterized by a negative sea level pressure anomaly in the high latitude Southeast Pacific. Also, the high latitude atmospheric response to ENSO intensified in the 1990s, perhaps due to a more positive SAM [*Fogt and Bromwich*, 2006]. It may be too that the inferred increases in ocean heat flux during autumn-winter in the AP/B region help to fuel increases in regional storminess [e.g., *Yuan et al.*, 1999; *Pezza et al.*, 2012], and to explain the enhanced wind-driven delay in AP/B sea ice advance in particular. Finally, the physical blocking effect of the Antarctic Peninsula appears to be a key factor contributing to persistent ice-atmosphere circulation anomalies in the AP/B region [*Van Den Broeke*, 2000] that again may help explain the somewhat stronger sea ice changes in the AP/B region (as compared to the other regions highlighted in Table 1).

5. Concluding Remarks

[19] The two processes indicated in Sections 3 and 4 as being responsible for the rapid sea ice changes are seasonal feedbacks (the ice-albedo and ocean heat feedbacks) and wind-driven changes. We now ask the question of whether the polar sea ice changes are responding to a common cause that might explain the significant ‘shifts’ in atmospheric circulation around the late 1980s (as described in Section 4), with a preferential focus, or initiation, in boreal spring and austral autumn.

[20] While there is significant variability in high latitude atmospheric pressure distributions that influence wind patterns, one common denominator discussed above for both polar regions is the forcing by the atmospheric annular modes [*Turner and Overland*, 2009] and the appearance of more positive phases, i.e., positive NAM up through the mid-1990s, and positive SAM from the late 1980s onward. Tropical warming leads to a tendency for a more positive annular mode in polar regions [*Rind et al.*, 2005].

Significant overall tropical warming has been evident over this time period (on the order of 0.5°C in the GISS analysis, shown at http://data.giss.nasa.gov/gistemp/tabledata/ZonAnn.Ts+dSST.txt). This is expected to continue and intensify, and hence potentially force a continuation of the regional sea ice trends highlighted here, in particular the wind-driven component of the trends described in Section 4.

[21] In addition, decreased Southern Hemisphere spring ozone produces a more positive SAM in austral summer-autumn [e.g., *Thompson and Solomon*, 2002; *Turner et al.*, 2009]. Along these lines, there is some evidence for a possible stratospheric inter-hemispheric connection [*Rind et al.*, 2009], where change is first initiated in the Southern Hemisphere during the austral spring (September-November) and then expressed at the surface in the boreal winter-spring and the austral summer-autumn (~December-May) with positive NAM and SAM modes, respectively. The effectiveness of these potential stratospheric mechanisms would be expected to decrease as the ozone hole diminishes during the rest of this century, which then might favor a reduction in this particular component. However, assessing the effect of both climate and ozone changes together in models, *Intergovernmental Panel on Climate Change* [2007] concluded that a more positive SAM is likely to continue. Meanwhile, Arctic sea ice is now substantially thinner and more susceptible to regional scale forcing and wind-driven sea ice export. Hence, trends towards later austral autumn sea ice advance and earlier boreal spring sea ice retreat may well continue in both hemispheres.

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References

Belchansky, G. I., et al. (2004), Duration of the Arctic sea ice melt season: Regional and interannual variability, 1979–2001, *J. Clim.*, *17*, 67–80, doi:10.1175/1520-0442(2004)017<0067:DOTASI>2.0.CO;2.

Comiso, J. C. (2010), *Polar Oceans From Space*, Springer, New York.

Comiso, J. C. (2012), Large decadal decline of the Arctic multi-year ice cover, *J. Clim.*, *25*, 1176–1193, doi:10.1175/JCLI-D-11-00113.1.

Ducklow, H. W., et al. (2007), Marine pelagic ecosystems: The West Antarctic Peninsula, *Philos. Trans. R. Soc. B*, *362*, 67–94, doi:10.1098/rstb.2006.1955.

Fogt, R. L., and D. H. Bromwich (2006), Decadal variability of the ENSO teleconnection to the high latitude South Pacific governed by coupling with the Southern Annular Mode, *J. Clim.*, *19*, 979–997, doi:10.1175/JCLI3671.1.

Grebmeier, J. M., S. E. Moore, J. E. Overland, K. E. Frey, and R. Gradinger (2010), Biological response to recent Pacific Arctic sea ice retreats, *Eos Trans. AGU*, *91*(18), 161, doi:10.1029/2010EO180001.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Kwok, R. (2009), Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res.*, *114*, C07005, doi:10.1029/2009JC005312.

Liu, J., J. A. Curry, and D. G. Martinson (2004), Interpretation of recent Antarctic sea ice variability, *Geophys. Res. Lett.*, *31*, L02205, doi:10.1029/2003GL018732.

Martinson, D. G. (2011), Antarctic circumpolar current's role in the Antarctic ice system: An overview, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, doi:10.1016/j.palaeo.2011.04.007, in press.

Martinson, D. G., et al. (2008), Western Antarctic Peninsula physical oceanography and spatio-temporal variability, *Deep Sea Res., Part II*, *55*, 1964–1987, doi:10.1016/j.dsr2.2008.04.038.

Maslanik, J., S. Drobot, C. Fowler, W. Emery, and R. Barry (2007), On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions, *Geophys. Res. Lett.*, *34*, L03711, doi:10.1029/2006GL028269.

Massom, R. A., and S. E. Stammerjohn (2010), Antarctic sea ice change and variability—Physical and ecological implications, *Polar Sci.*, *4*, 149–186, doi:10.1016/j.polar.2010.05.001.

Massom, R. A., S. E. Stammerjohn, W. Lefebvre, S. A. Harangozo, N. Adams, T. A. Scambos, M. J. Pook, and C. Fowler (2008), West Antarctic Peninsula sea ice in 2005: Extreme compaction and ice edge retreat due to strong anomaly with respect to climate, *J. Geophys. Res.*, *113*, C02S20, doi:10.1029/2007JC004239.

Meredith, M. P., and J. C. King (2005), Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century, *Geophys. Res. Lett.*, *32*, L19604, doi:10.1029/2005GL024042.

Parkinson, C. L. (1994), Spatial patterns in the length of the sea ice season in the Southern Ocean, *J. Geophys. Res.*, *99*, 16,327–16,339, doi:10.1029/94JC01146.

Perovich, D. K., B. Light, H. Eicken, K. F. Jones, K. Runciman, and S. V. Nghiem (2007), Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback, *Geophys. Res. Lett.*, *34*, L19505, doi:10.1029/2007GL031480.

Perovich, D. K., et al. (2011), Solar partitioning in a changing Arctic sea-ice cover, *Ann. Glaciol.*, *52*(57), 192–196, doi:10.3189/172756411795931543.

Pezza, A. B., et al. (2012), Climate links and recent extremes in Antarctic sea ice, high-latitude cyclones, Southern Annular Mode and ENSO, *Clim. Dyn.*, *38*, 57–73, doi:10.1007/s00382-011-1044-y.

Rind, D., J. Perlwitz, P. Lonergan, and J. Lerner (2005), AO/NAO response to climate change: 2. Relative importance of low and high latitude temperature changes, *J. Geophys. Res.*, *110*, D12108, doi:10.1029/2004JD005686.

Rind, D., J. Jonas, S. Stammerjohn, and P. Lonergan (2009), The Antarctic ozone hole and the Northern Annular Mode: A stratospheric interhemispheric connection, *Geophys. Res. Lett.*, *36*, L09818, doi:10.1029/2009GL037866.

Screen, J., and I. Simmonds (2010a), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*, *464*, 1334–1337, doi:10.1038/nature09051.

Screen, J., and I. Simmonds (2010b), Increasing fall-winter energy loss from the Arctic Ocean and its role in Arctic temperature amplification, *Geophys. Res. Lett.*, *37*, L16707, doi:10.1029/2010GL044136.

Screen, J. A., I. Simmonds, and K. Keay (2011), Dramatic inter-annual changes of perennial Arctic sea ice linked to abnormal summer storm activity, *J. Geophys. Res.*, *116*, D15105, doi:10.1029/2011JD015847.

Serreze, M. C., et al. (2007), Perspectives on the Arctic shrinking sea-ice cover, *Science*, *315*, 1533–1536, doi:10.1126/science.1139426.

Shimada, K., T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. McLaughlin, S. Zimmermann, and A. Proshutinsky (2006), Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophys. Res. Lett.*, *33*, L08605, doi:10.1029/2005GL025624.

Simmonds, I., and K. Keay (2009), Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008, *Geophys. Res. Lett.*, *36*, L19715, doi:10.1029/2009GL039810.

Stammerjohn, S. E., D. G. Martinson, R. C. Smith, X. Yuan, and D. Rind (2008), Trends in Antarctic annual sea ice retreat and advance and their relation to ENSO and Southern Annular Mode variability, *J. Geophys. Res.*, *113*, C03S90, doi:10.1029/2007JC004269.

Stammerjohn, S. E., et al. (2011), The influence of winds, sea-surface temperature and precipitation anomalies on Antarctic regional sea-ice conditions during IPY 2007, *Deep Sea Res., Part II*, *58*, 999–1018, doi:10.1016/j.dsr2.2010.10.026.

Steele, M., W. Ermold, and J. Zhang (2008), Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, *35*, L02614, doi:10.1029/2007GL031651.

Thomas, D. N., and G. S. Dieckmann (2010), *Sea Ice*, 2nd ed., 621 pp., Wiley-Blackwell, Oxford, U. K.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*, 895–899, doi:10.1126/science.1069270.

Turner, J., and J. Overland (2009), Contrasting climate change in the two polar regions, *Polar Res.*, *28*, 146–164, doi:10.1111/j.1751-8369.2009.00128.x.

Turner, J., J. C. Comiso, G. J. Marshall, T. A. Lachlan-Cope, T. Bracegirdle, T. Maksym, M. P. Meredith, Z. Wang, and A. Orr (2009), Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, *36*, L08502, doi:10.1029/2009GL037524.

Van Den Broeke, M. R. (2000), The semi-annual oscillation and Antarctic climate. Part 4: A note on sea ice cover in the Amundsen and Bellingshausen Seas, *Int. J. Climatol.*, *20*(4), 455–462, doi:10.1002/(SICI)1097-0088(20000330)20:4<455::AID-JOC482>3.0.CO;2-M.

Watkins, A. B., and I. Simmonds (1999), A late spring surge in the open water of the Antarctic sea ice pack, *Geophys. Res. Lett.*, *26*(10), 1481–1484, doi:10.1029/1999GL900292.

Yuan, X., and C. Li (2008), Climate modes in southern high latitudes and their impacts on Antarctic sea ice, *J. Geophys. Res.*, *113*, C06S91, doi:10.1029/2006JC004067.

Yuan, X., D. G. Martinson, and W. T. Liu (1999), Effect of air-sea-ice interaction on winter 1996 Southern Ocean subpolar storm distribution, *J. Geophys. Res.*, *104*(D2), 1991–2007, doi:10.1029/98JD02719.

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