











**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  $200 \text{ MJ m}^{-2}$  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  $1.3 \text{ days yr}^{-1}$  over 1979–2005), our calculations suggest OH increases ranging from 100 to  $400 \text{ MJ m}^{-2}$  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  $1.9 \text{ days yr}^{-1}$ ), requisite OH increases range from  $\sim 150$  to  $600 \text{ MJ m}^{-2}$ . Previous observations indicate a summer warming rate of  $\sim 0.04^\circ\text{C yr}^{-1}$  [Meredith and King, 2005], or an increase of  $1.1^\circ\text{C}$  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  $\sim 113 \text{ MJ m}^{-2}$ . 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 ( $70\text{--}76^\circ\text{N}$ ) and thus experience longer days during the retreat season compared to the AP/B region ( $65\text{--}72^\circ\text{S}$ ), 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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