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The seasonality of Antarctic sea ice trends

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Key Points:
- A study of seasonality of trends in Antarctic sea ice concentration and growth
- Largest concentration trends in autumn are caused by spring ice loss changes
- All sectors cause the increase; Weddell-Amundsen-Bellingshausen compensate

Supporting Information:
- Readme
- Figures S1–S7

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Abstract Antarctic sea ice is experiencing a weak overall increase in area that is the residual of opposing regional trends. This study considers their seasonal pattern. In addition to traditional ice concentration and total ice area, temporal derivatives of these quantities are investigated ("intensification" and "expansion," respectively). This is crucial to the attribution of trends, since changes in forcing directly affect ice areal change (rather than ice area). Diverse regional trends all contribute significantly to the overall increase. Trends in the Weddell and Amundsen-Bellingshausen regions compensate in magnitude and seasonality. The largest concentration trends, in autumn, are actually caused by intensification trends during spring. Autumn intensification trends directly oppose autumn concentration trends in most places, seemingly as a result of ice and ocean feedbacks. Springtime trends are reconcilable with wind trends, but further study of changes during the spring melting season is required to unravel the Antarctic sea ice increase.

1. Introduction

Continual satellite monitoring of sea ice concentration since late 1978 shows that the Antarctic ice cover is expanding slowly overall, with this weak signal made up of much larger opposing regional trends [*Comiso and Nishio*, 2008; *Parkinson and Cavalieri*, 2012; *Zwally et al.*, 2002]. These ice concentration trends can also be viewed as changes in the length of the ice season [*Parkinson*, 1994; *Simpkins et al.*, 2013; *Stammerjohn et al.*, 2008, 2012]. The changes in ice cover are closely related to observed trends in ice drift [*Holland and Kwok*, 2012], and model studies suggest that they are accompanied by changes in ice thickness [*Holland et al.*, 2014; *Massonnet et al.*, 2013], implying an increase in ice volume. The overall increases in ice concentration and volume are significantly smaller than the corresponding declines in Arctic sea ice, but the regional trends are of a similar magnitude [*Cavalieri and Parkinson*, 2012; *Parkinson and Cavalieri*, 2012; *Stammerjohn et al.*, 2012].

The origin of these trends is unclear. Several possibilities exist, though the chief candidate seems to be that multidecadal wind trends over the Southern Ocean have forced ice changes through a combination of dynamic and thermodynamic effects, perhaps amplified by atmosphere and ocean feedbacks [*Goosse and Zunz*, 2014; *Holland and Kwok*, 2012; *Holland et al.*, 2014; *Stammerjohn et al.*, 2012; *Zhang*, 2007, 2014]. Climate models produce an ice decline in response to ozone depletion and greenhouse gas increases, and this conflict with the observed trends suggests that in reality a forced decline may be overcome by natural variability [*Polvani and Smith*, 2013; *Swart and Fyfe*, 2013; *Zunz et al.*, 2013]. However, it is unclear that such conclusions can be drawn with confidence because the models cannot reproduce the observed Antarctic trends or variability [*Turner et al.*, 2012a; *Zunz et al.*, 2013]. Several studies have investigated the relationships between Antarctic sea ice and various climate modes [*Lefebvre and Goosse*, 2008; *Li et al.*, 2014; *Simpkins et al.*, 2012; *Stammerjohn et al.*, 2008; *Yuan*, 2004; *Yuan and Li*, 2008]; the results are seasonally dependent, and no comprehensive explanation has yet emerged.

The seasonal variation in these trends provides important clues toward their origin. However, previous studies of seasonal trends and their attribution neglect the fact that changes in climate forcing directly affect the rate of ice growth, not the amount of ice. For example, an interannual cooling in autumn may cause more ice area gain during autumn, but does not necessarily imply an increase in the autumn ice area, since that also depends upon changes in the ice area present at the start of autumn. Anomalous ice area in any given season is the time integral of anomalous area gain in previous seasons, so to attribute the Antarctic ice area trends we need to first determine trends in ice area gain. This principle is applied here by comparing trends in ice concentration to trends in a new quantity, "intensification," the temporal derivative

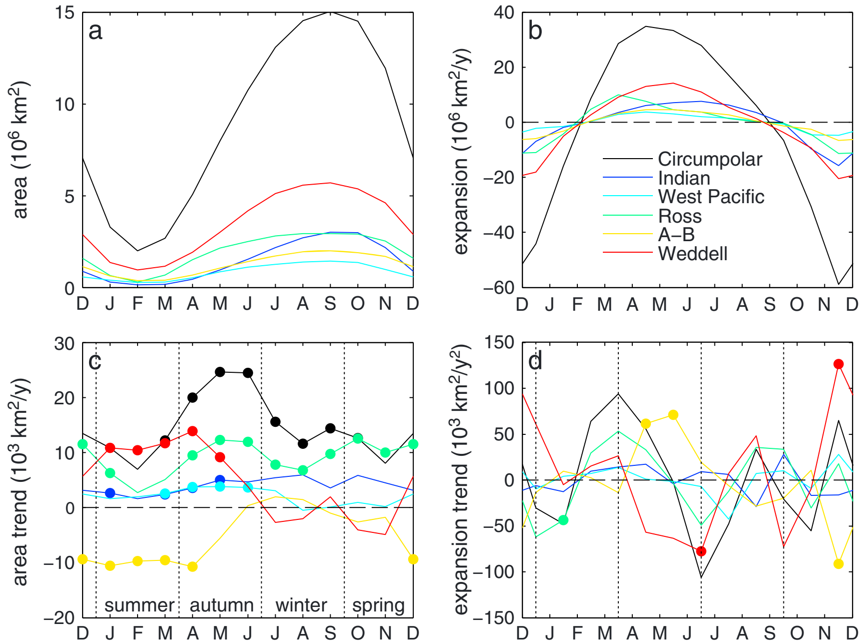

Figure 1. Seasonal variation of various ice quantities for each region and the whole Southern Ocean. (a) Mean monthly total ice area. (b) Mean monthly total ice expansion (the temporal derivative of monthly total ice area). (c) Interannual trends in monthly total ice area. (d) Interannual trends in monthly total ice expansion. Ice expansion in Figure 1b causes seasonal variation in ice area in Figure 1a, and ice expansion trends in Figure 1d cause seasonal variation of ice area trends in Figure 1c. In trend plots, circle markers show trends significant at 90% or above, and vertical lines show the seasonal boundaries used to average the data in other figures. A-B denotes the Amundsen-Bellingshausen region.

of ice concentration. It is important to note that this study only examines ice area, not ice volume, and that area changes occur through both thermodynamic and dynamic mechanisms.

2. Method

The study employs gridded quasi-daily sea ice concentration data from 1979 to 2012 derived from passive microwave satellite measurements processed using the "NASA Team" algorithm [*Parkinson and Cavalieri*, 2012; *Zwally et al.*, 2002]. Ice concentration and total ice area are defined conventionally, as the ice-covered fraction of grid cells and, respectively, the spatial summation of the product of concentration and cell area wherever concentration exceeds 15% in a region of interest. Ice intensification is newly defined as the temporal derivative of ice concentration, and ice "expansion" as the temporal derivative of ice area. Concentration (%) and intensification (%/yr) are time-varying spatial fields, while area (km^2) and expansion (km^2/yr) are scalar time series.

Intensification fields are calculated by simple forward differencing of successive quasi-daily concentration fields. Spatial fields of seasonal mean trends in concentration and intensification are calculated by temporally binning the data into seasons and then calculating the interannual trend for each season at each grid point. After some experimentation, scalar time series are presented using monthly means, revealing the seasonal variability while minimizing noise in the temporal derivatives. Expansion is calculated by forward differencing successive monthly mean areas, so each expansion value is centered on the transition between months. This approach has the conceptual advantage that the seasonal variation of expansion trends is the temporal derivative of the seasonal variation of area trends. All fields are masked wherever the mean ice concentration is below 15%. Assuming a typical ice concentration error of 10% [*Comiso et al.*, 1997], intensification error can be simply estimated at 20%/yr and intensification trend error at 0.66%/yr^2 for a 30 year trend. The signals found here are much larger than these simple error estimates.

Many studies have shown that ice trends can be related to wind trends [*Holland and Kwok*, 2012; *Lefebvre and Goosse*, 2008; *Li et al.*, 2014; *Stammerjohn et al.*, 2008], so supporting analyses use fields from the

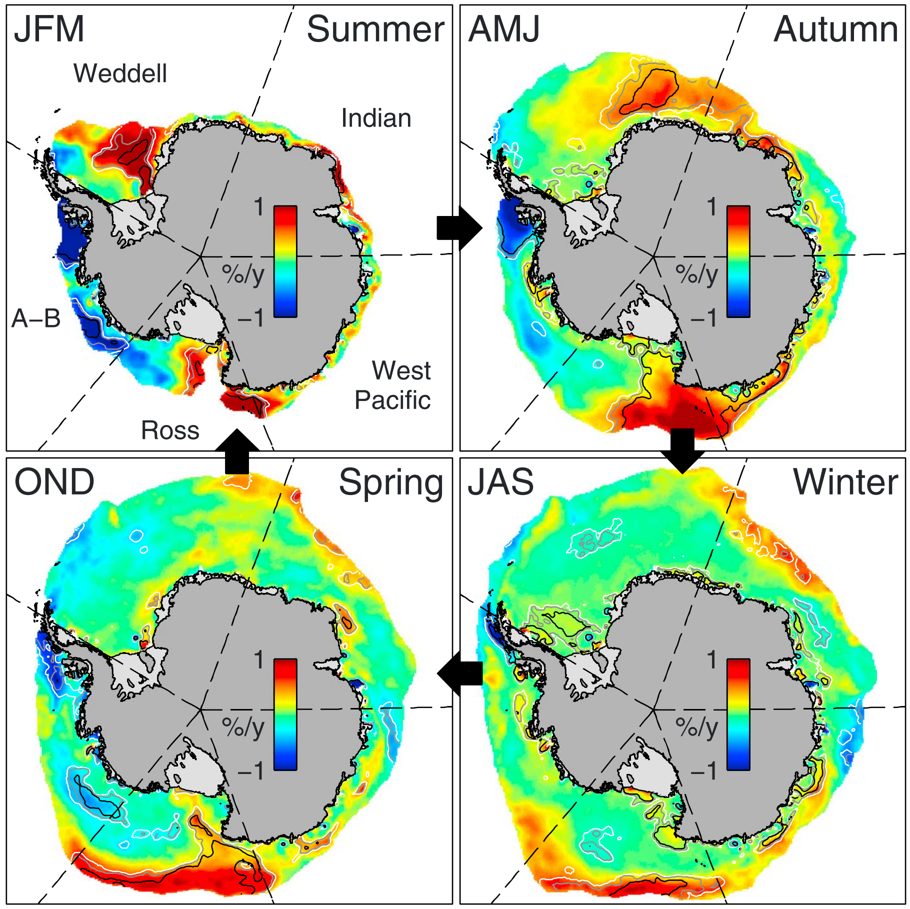

Figure 2. Maps of seasonal trend in ice concentration, showing large increases in the Ross and Weddell seas and decreases in the Amundsen-Bellingshausen (A-B) region. White, grey, and black contours show 90%, 95%, and 99% significance, respectively, and the regions for which time series are plotted in Figure 1 are indicated.

European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (ERAI) reanalysis, obtained as daily means on the full N80 Gaussian grid (approximately 0.7° resolution).

3. Results

Supplementary Figures S1 and S2 show the seasonal mean fields of ice concentration and intensification to illustrate the linkage between the two and provide background for the study of trends. Most ice concentration gain (positive intensification) is accomplished during autumn, with additional gain around the ice edge in winter. Almost all ice concentration loss (negative intensification) occurs during spring. Previous studies have investigated intensification fields in detail, revealing spatial and seasonal patterns in their dynamic and thermodynamic contributions [*Holland and Kwok*, 2012; *Kimura and Wakatsuchi*, 2011].

Figure 1 shows the seasonal cycle of the interannual mean and trends of total ice area and expansion. As well as the circumpolar total, five standard subregions of the Southern Ocean are shown, as marked on Figure 2 [e.g., *Zwally et al.*, 2002]. The seasonal cycle of ice area (Figure 1a) shows asymmetry in advance and retreat, and the cycle of expansion (Figure 1b) shows the rapid and short-lived spring area loss (September–February) compared to the slower autumn and winter area gain. Figure 1c shows ice area trends by month [e.g., *Parkinson and Cavalieri*, 2012]. The circumpolar increase in area is only statistically significant during autumn and winter, peaking in autumn, but this circumpolar trend seasonality is a complicated sum of regional trends. The Indian sector shows a seasonally uniform increase, significant in summer and autumn, while the Ross sector shows a larger and variable increase that is significant all year except late summer. Weddell and West Pacific sectors show significant increases in summer and autumn but not winter and spring, mirrored by the

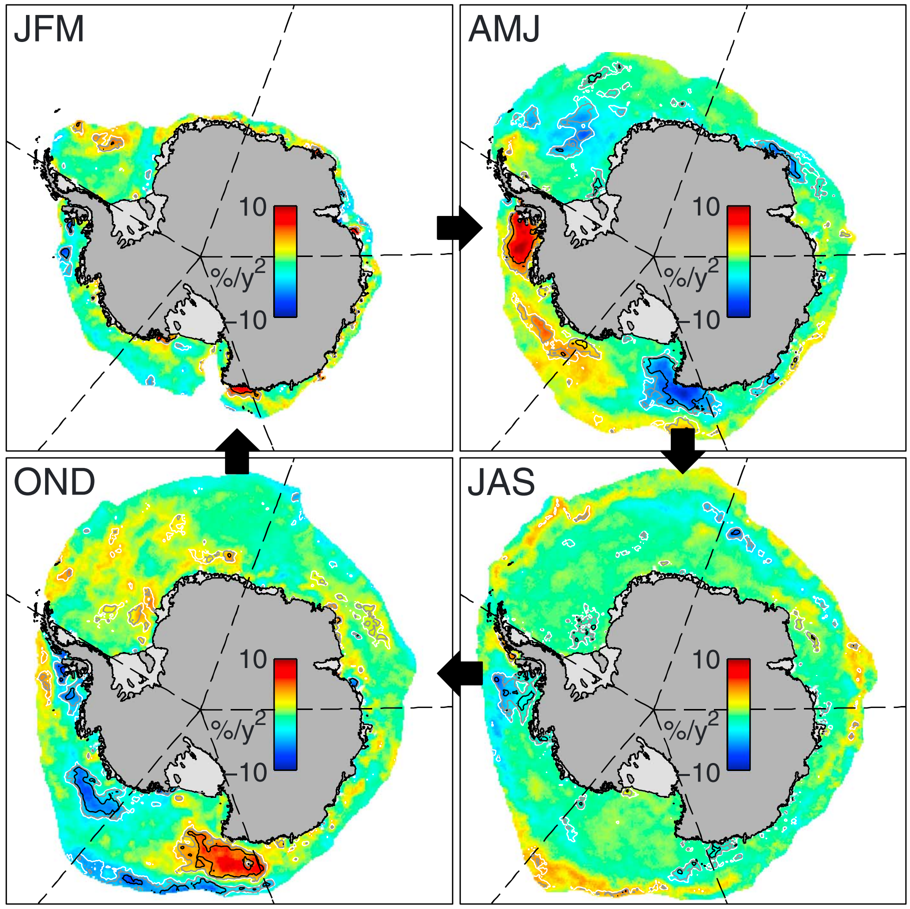

Figure 3. Maps of seasonal trend in ice intensification (the temporal derivative of ice concentration), broadly showing autumn trends that oppose those of ice concentration and spring trends that enhance them (compare to Figure 2). White, grey, and black contours show 90%, 95%, and 99% significance, respectively.

Amundsen-Bellingshausen sector, which shows a strong decrease in warm months but no change in cold months. The seasonality of the circumpolar trend is similar to the Ross sector, enhanced in autumn by the sum of the other sectors.

Figure 1d shows the monthly trends in ice expansion, providing insight into the seasonal structure of area trends because it is their temporal derivative. Expansion is noisier than ice area because the derivative amplifies variability at the monthly time scale, so interannual expansion trends are rarely statistically significant. There are no significant expansion trends in any month for the Circumpolar, Indian, or West Pacific regions. The Weddell Sea has a positive expansion trend in November–December (i.e., decreased spring ice area loss), and this is responsible for the positive area trend throughout the following summer. This area trend is only overturned in autumn (April–July), when a negative expansion trend (decreased ice gain) returns the area trend to an insignificant value. The Amundsen-Bellingshausen region has the opposite signal, with increased area loss in November–December causing a negative area trend that persists until increased area gain in April–June. Ross sector expansion trends are highly variable, with the only significant signal being an increase in January-February area loss that reduces the positive area trend to its lowest value in February.

We now turn to spatial maps of seasonal-average trends in ice concentration and intensification. Concentration trends (Figure 2) have a broadly periodic regional pattern, with increased concentration in the Ross Sea and western Weddell Sea, and decreases or no change around East Antarctica and the Amundsen-Bellingshausen seas [e.g., *Zwally et al.*, 2002]. The strongest trends in each single location are found in summer. Intensification trends (Figure 3) reveal the changes underlying these concentration trends and comparing them to Figure 2 is illuminating. For example, the Weddell sector shows diffuse positive trends in intensification in spring (decreased ice concentration loss), and this leads to a large positive trend in summer ice concentration. This concentration trend persists until autumn, when it is offset by a negative intensification trend (decreased ice gain), so that the region has virtually no concentration trend in winter. Intensification trends are highly variable, so monthly fields of all variables are shown in Supplementary Figures S3–S6 to support their interpretation.

The Bellingshausen Sea shows a negative intensification trend that starts in winter (reduced ice gain) and persists inshore in spring and summer (increased ice loss), accumulating a negative concentration trend, before being dramatically offset in autumn (increased ice gain), leading to little concentration trend in winter [*Turner et al.*, 2012b]. The Amundsen Sea undergoes a large increase in spring ice loss which is offset by increased autumn ice gain, causing a negative summer concentration trend that disappears in winter.

Indian and West Pacific sectors have significant trends in concentration but few clear trends in intensification, and are therefore neglected in the remainder of this study.

In the Ross Sea, a large positive intensification trend in spring (decreased ice loss) causes a positive concentration trend in summer. This concentration trend is removed during autumn by a negative intensification trend (decreased ice gain) and is therefore absent from the inner pack in winter. At the Ross Sea ice edge, positive intensification trends during autumn and winter (increased ice gain) cause a concentration trend to persist in winter and spring. This signal is removed by a negative intensification trend (increased ice loss) during spring. Opposing trends compensate within the Ross region, accounting for the lack of clear expansion seasonality overall (Figure 1). However, the inner pack replicates the dominant pattern observed elsewhere of concentration trends created in spring, persistent through summer, and reversed in autumn.

4. Attribution of the Trends

It is possible to speculate upon the origin of the intensification trends by comparing them to ERAI reanalysis wind trends (Figure 4). For example, increased northward winds in autumn cause increased intensification through both enhanced northward ice drift and additional freezing from the advection of cold, dry polar air over the ocean. Conversely, southward autumn wind trends cause decreased intensification through slower northward drift and a reduction in freezing from the advection of warm, moist air. Ice-drift trend data can separate the dynamic and thermodynamic contributions but are unavailable for spring and summer [*Holland and Kwok*, 2012]. Both dynamic and thermodynamic processes are complex functions of wind trends, as the ice rheology modulates dynamic trends and thermodynamic trends are caused by changes in longwave and shortwave radiation and sensible and latent heat fluxes. For reference, seasonal mean pressure and wind fields are shown in Supplementary Figure S7. ERAI winds are known to be reliable and relevant, as they are highly correlated to observed ice drift [*Holland and Kwok*, 2012]. Other reanalysis variables, such as air temperature, are strongly constrained to follow the ice data used as the surface boundary condition in the reanalysis model and so cannot provide independent evidence of changes in forcing.

The increase in Weddell Sea winter ice gain at the ice edge seems to be a response to northwestward wind trends. The simplest way to reconcile the widespread springtime decrease in ice loss with southward wind trends is though the decreased southerlies causing less ice divergence. That would imply ice loss at the ice edge, which is not observed, but that may be because the circulating wind trends cause more cold, dry air from the ice sheet to be carried northward and then eastward over the ice edge. Reduced autumn ice gain could be a response to decreased southerlies or might simply occur because more ice has survived the summer. The concentration trends in Figure 2 show a large ice increase in the eastern Weddell Sea in autumn that is not explained by the intensification trend in this season. Examination of monthly intensification trends (Figure S6) shows that this anomaly is caused by an acceleration of the autumn ice edge advance, consistent with the eastward wind trend, which causes a moving pattern of opposing intensification trends that cancel out on the seasonal average.

The Amundsen Sea features an increase in spring ice loss colocated with weak southward wind trends, subsequently offset by an increase in autumn ice gain supported by strong northward wind trends. The linkage between wind and ice trends in the Bellingshausen Sea is less clear. Reduced winter ice gain might be attributable to the westward wind trends, which suggest a reduction in the climatological eastward

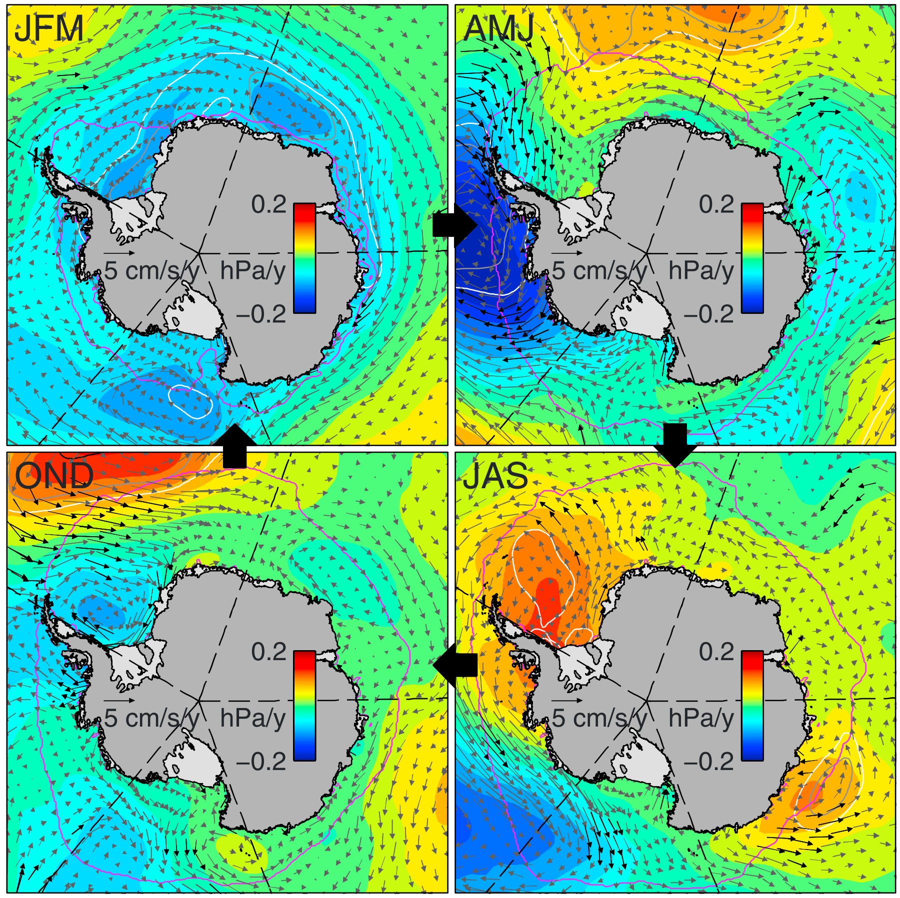

Figure 4. Maps of seasonal trend in sea level pressure and 10 m winds from the ERA-Interim reanalysis. White, grey, and black contours show 90%, 95%, and 99% significance of pressure trends, respectively, while black and grey vectors show wind trends with a meridional trend that is significant at the 90% level and insignificant, respectively. The magenta contour shows the mean 15% ice concentration for each season. Vectors are shown every third grid cell in the meridional direction and every sixth cell in the zonal direction.

importation of ice. The springtime increase in ice loss in the inner pack and decrease at the ice edge could be caused by the northward wind trends (decreased northerlies) driving less ice convergence. An increased ice area gain is present throughout autumn, strengthening in June and July (Figure S6). This acts in direct opposition to very strong southward wind trends, which should imply a considerable increase in southward ice drift and warm, moist air advection, all of which would reduce ice area gain. This suggests very strongly that the increase in autumn ice gain is a compensating climate response to the reduction in summer ice cover.

In the Ross Sea in winter, northward trending winds cause increased ice gain at the ice edge. However, in spring greater ice loss occurs at the ice edge, perhaps because the additional ice is thermodynamically unsustainable. The large spring reduction in ice loss in the inner Ross pack occurs in conjunction with increased northward winds. The significant decrease in autumn ice gain in this region is consistent with southward autumn wind trends (reduced southerlies) in the far southwestern Ross Sea but could also occur simply because more ice has survived the summer.

5. Discussion

Studies of Antarctic sea ice trends commonly focus on autumn and winter, the seasons with the largest circum-Antarctic ice concentration trends. However, the present study of ice intensification shows that ice area trends generally originate in spring, persist through summer, and are reversed in autumn (Weddell, Bellingshausen, and Amundsen Seas, and the inner Ross Sea). Trends in autumn ice gain oppose autumn ice concentration trends almost everywhere. It is unsurprising that the largest intensification trends are found in spring and autumn, since these seasons have the largest mean intensification. Further study of regional trends in spring ice melting is clearly needed to unravel the Antarctic sea ice increase.

The study of *Holland and Kwok* [2012] failed to recognize that the autumn trends were a response to spring trends, leading to the erroneous conclusion that autumn concentration trends were driven only by autumn wind trends. The present study finds both the spring and autumn trends consistent with wind trends, but in some places less clearly than *Holland and Kwok* [2012] suggest. Autumn ice gain trends in the Bellingshausen Sea directly oppose wind trends, suggesting strongly that at least in this area, and perhaps everywhere, the autumn compensation of spring trends results from ocean-ice-atmosphere feedbacks. *Stammerjohn et al.* [2012] find that anomalies in autumn ice advance are better correlated to the preceding spring than the subsequent spring, and the negative correlation (earlier spring retreat corresponds to later autumn advance) suggests ice-albedo and ocean heat uptake feedbacks. In general, the ice-albedo feedback causes instability during spring and summer, whereby ice cover perturbations grow, while autumn and winter are dominated by a stabilizing longwave radiation feedback that mitigates perturbations (less ice causes greater heat loss and ice growth) [*Moon and Wettlaufer*, 2011]. The importance of these feedbacks is supported by studies of Antarctic sea ice predictability, which show that anomalies persist during summer but are lost in winter [*Holland et al.*, 2013]. However, the feedbacks do not necessarily explain why spring ice loss trends are equalled by autumn ice gain trends, giving no winter concentration trend. Winter ice losses are commonplace in the Arctic, and autumn wind trends might be expected to modify or offset the feedbacks, particularly in the Bellingshausen Sea.

The spatial and seasonal complexity of trends in ice intensification suggests that they cannot be simply characterized by a single climate forcing or physical process. The Antarctic ice increase is commonly cast as being the net result of a Pacific dipole of opposing changes in the Amundsen-Bellingshausen and Ross seas, but in fact, all regions contribute significantly to the overall trend at different times of the year. Moreover, the Ross and Amundsen-Bellingshausen trends do not offset each other seasonally and have different decadal structure within their multidecadal trends [*Simpkins et al.*, 2013]. In fact, the Amundsen-Bellingshausen and Weddell sectors are a better trend dipole, with strong opposing trends in summer and no change in winter. The total Amundsen-Bellingshausen-Weddell ice area has no significant trend in any month (not shown). The Amundsen-Bellinghausen winter ice extent anticorrelates with Weddell extent but not Ross extent [*Lefebvre and Goosse*, 2008; *Simpkins et al.*, 2012]. This multidecadal trend dipole resembles the Antarctic Dipole pattern of interannual variability associated with El Niño–Southern Oscillation (ENSO) [*Yuan and Martinson*, 2001], but linkages between ENSO and ice trends are far from straightforward [*Lefebvre and Goosse*, 2008; *Simpkins et al.*, 2012; *Stammerjohn et al.*, 2008; *Yuan*, 2004; *Yuan and Li*, 2008].

The central argument of this analysis is that trends in ice cover are caused by trends in ice growth, and to explain the former, we must understand the latter. Many studies attempt to relate trends in climate modes to Antarctic ice concentration trends, but this study suggests that, if anything, such modes should instead be linked to ice intensification. Correlations to intensification are not the same as lagged correlations to concentration. The seasonal and spatial differences between concentration and intensification are one possible explanation of why many studies have failed to find conclusive linkages between concentration trends and climate modes [*Lefebvre and Goosse*, 2008; *Simpkins et al.*, 2012; *Yuan*, 2004; *Yuan and Li*, 2008]. *Li et al.* [2014] are an exception, arguing that winter ice concentration trends are caused by the Atlantic Multidecadal Oscillation (AMO). The winter intensification trends found here contain some features of the AMO-predicted trends from *Li et al.* [2014], notably in the Pacific sector, but it is not clear that the AMO explains ice intensification trends around all of Antarctica. A comprehensive study of linkages between ice intensification and wider climate modes seems an obvious extension to the present study.

Acknowledgments
The NASA Team ice concentration data are available at the National Snow and Ice Data Center at http://nsidc.org/data/nsidc-0051. ERAI reanalysis data are available from ECMWF at http://apps.ecmwf.int/datasets/data/interim_full_daily.

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References

Cavalieri, D. J., and C. L. Parkinson (2012), Arctic sea ice variability and trends, 1979–2010, *Cryosphere*, *6*(4), 881–889.

Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, *113*, C02S07, doi:10.1029/2007JC004257.

Comiso, J. C., D. J. Cavalieri, C. L. Parkinson, and P. Gloersen (1997), Passive microwave algorithms for sea ice concentration: A comparison of two techniques, *Remote Sens. Environ.*, *60*(3), 357–384.

Goosse, H., and V. Zunz (2014), Decadal trends in the Antarctic sea ice extent ultimately controlled by ice-ocean feedback, *Cryosphere*, *8*, 453–470.

Holland, M. M., E. Blanchard-Wrigglesworth, J. Kay, and S. Vavrus (2013), Initial-value predictability of Antarctic sea ice in the Community Climate System Model 3, *Geophys. Res. Lett.*, *40*, 2121–2124, doi:10.1002/grl.50410.

Holland, P. R., and R. Kwok (2012), Wind-driven trends in Antarctic sea-ice drift, *Nat. Geosci.*, *5*(12), 872–875.

Holland, P. R., N. Bruneau, C. Enright, N. T. Kurtz, M. Losch, and R. Kwok (2014), Modeled trends in Antarctic sea ice thickness, *J. Clim.*, *27*, 3784–3801.

Kimura, N., and M. Wakatsuchi (2011), Large-scale processes governing the seasonal variability of the Antarctic sea ice, *Tellus, Ser. A*, *63*(4), 828–840.

Lefebvre, W., and H. Goosse (2008), An analysis of the atmospheric processes driving the large-scale winter sea ice variability in the Southern Ocean, *J. Geophys. Res.*, *113*, C02004, doi:10.1029/2006JC004032.

Li, X. C., D. M. Holland, E. P. Gerber, and C. Yoo (2014), Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice, *Nature*, *505*(7484), 538–542.

Massonnet, F., P. Mathiot, T. Fichefet, H. Goosse, C. K. Beatty, M. Vancoppenolle, and T. Lavergne (2013), A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980–2008 using data assimilation, *Ocean Modell.*, *64*, 67–75.

Moon, W., and J. S. Wettlaufer (2011), A low-order theory of Arctic sea ice stability, *Europhys. Lett.*, *96*(3), Article 39001.

Parkinson, C. L. (1994), Spatial patterns in the length of the sea-ice season in the Southern-Ocean, 1979–1986, *J. Geophys. Res.*, *99*(C8), 16,327–16,339, doi:10.1029/94JC01146.

Parkinson, C. L., and D. J. Cavalieri (2012), Antarctic sea ice variability and trends, 1979–2010, *Cryosphere*, *6*(4), 871–880.

Polvani, L. M., and K. L. Smith (2013), Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5, *Geophys. Res. Lett.*, *40*, 3195–3199, doi:10.1002/grl.50578.

Simpkins, G. R., L. M. Ciasto, D. W. J. Thompson, and M. H. England (2012), Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration, *J. Clim.*, *25*(16), 5451–5469.

Simpkins, G. R., L. M. Ciasto, and M. H. England (2013), Observed variations in multidecadal Antarctic sea ice trends during 1979–2012, *Geophys. Res. Lett.*, *40*, 3643–3648, doi:10.1002/grl.50715.

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 El Niño-Southern Oscillation and Southern Annular Mode variability, *J. Geophys. Res.*, *113*, C03S90, doi:10.1029/2007JC004269.

Stammerjohn, S. E., R. Massom, D. Rind, and D. G. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, *Geophys. Res. Lett.*, *39*, L06501, doi:10.1029/2012GL050874.

Swart, N. C., and J. C. Fyfe (2013), The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends, *Geophys. Res. Lett.*, *40*, 4328–4332, doi:10.1002/grl.50820.

Turner, J., T. Bracegirdle, T. Phillips, G. J. Marshall, and J. S. Hosking (2012a), An initial assessment of Antarctic sea ice extent in the CMIP5 models, *J. Clim.*, *26*, 1473–1484.

Turner, J., T. Maksym, T. Phillips, G. J. Marshall, and M. P. Meredith (2012b), The impact of changes in sea ice advance on the large winter warming on the western Antarctic Peninsula, *Int. J. Climatol.*, *33*, 852–861, doi:10.1002/joc.3474.

Yuan, X. J. (2004), ENSO-related impacts on Antarctic sea ice: A synthesis of phenomenon and mechanisms, *Antarct. Sci.*, *16*(4), 415–425.

Yuan, X. J., and C. H. 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. J., and D. G. Martinson (2001), The Antarctic dipole and its predictability, *Geophys. Res. Lett.*, *28*(18), 3609–3612, doi:10.1029/2001GL012969.

Zhang, J. L. (2007), Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, *J. Clim.*, *20*(11), 2515–2529.

Zhang, J. L. (2014), Modeling the impact of wind intensification on Antarctic sea ice volume, *J. Clim.*, *27*(1), 202–214.

Zunz, V., H. Goosse, and F. Massonnet (2013), How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent?, *Cryosphere*, *7*(2), 451–468.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, D. J. Cavalieri, and P. Gloersen (2002), Variability of Antarctic sea ice 1979–1998, *J. Geophys. Res.*, *107*(C5), 3041, doi:10.1029/2000JC000733.