

35. THE 2014 HIGH RECORD OF ANTARCTIC SEA ICE EXTENT

F. MASSONNET, V. GUEMAS, N. S. FUČKAR, AND F. J. DOBLAS-REYES

The record maximum of Antarctic sea ice resulted chiefly from anomalous winds that transported cold air masses away from the Antarctic continent, enhancing thermodynamic sea ice production far offshore.

Introduction. Antarctic sea ice extent exceeded the symbolic level of 20 million km² for the first time since 1978, when reliable satellite measurements became available. After the successive records of 2012 and 2013, sea ice extent in 2014 once again reinforced the positive trend observed since the late 1970s. Previous studies have interpreted this trend as the result of powerful atmosphere– and ocean–sea ice feedbacks (Zhang 2007; Goosse and Zunz 2014), freshwater forcing from continental ice-sheet melting (Bintanja et al. 2013), or changes in wind regimes (Holland and Kwok 2012), although this trend was found to be compatible with internal variability (Polvani and Smith 2013). We conduct here a dedicated study to elucidate the origins of a major, and perhaps the most intriguing, climatic event of 2014.

Winter 2014 Antarctic conditions in context. The average September 2014 Antarctic sea ice extent reached 20.10 million km² according to the National Snow and Ice Data Center Sea Ice Index (Fetterer et al. 2015). This value represented a significant upward departure from the observed positive trend in total sea ice extent (Fig. 35.1a). The 2014 sea ice extent anomaly was the result of a circumpolar increase in sea ice concentration near the ice edge, except in the

Amundsen–Bellingshausen Seas (Fig. 35.1b). The spatial patterns of 2014 anomalies thus matched well the spatial trends in observed sea ice concentration over the past decades (Parkinson and Cavalieri 2012).

Wind is a primary driver of autumn and winter Antarctic sea ice variability at decadal time scales (Holland and Kwok 2012; Holland et al. 2014) through enhanced transport and divergence of sea ice (dynamic contribution), or near-surface air temperature advection, i.e., transport of near-surface air across a temperature gradient (thermodynamic contribution). In 2014, positive sea ice concentration anomalies in September were associated with anomalous southerly winds in the preceding austral winter in the Indian and Ross Sea sectors (Fig. 35.1b). Meanwhile, anomalous northerly winds blew in the Amundsen–Bellingshausen Seas where ice concentration anomalies were negative. Elsewhere around the hemisphere, the link between sea ice anomalies and the meridional component of the wind was less obvious.

While the link between 2014 winds and sea ice concentration seems solid in several regions of the Southern Ocean, three questions remain: 1) Is this link causal? 2) Are sea ice anomalies the result of anomalous dynamic or thermodynamic forcing? 3) Have other factors contributed to the record, namely preconditioning from the ocean in summer, anomalies in precipitation, or freshwater discharge from the Antarctic ice-shelves? To answer these questions, we implement a sensitivity analysis with a state-of-the-art ocean–sea ice general circulation model.

Attribution of the 2014 maximum through model experiments. We perform 10 (2005–14) 8-month-long simulations, labeled “CTRL” in Fig. 35.2, with the Louvain-la-Neuve sea ice model (LIM3; Vancoppenolle et al. 2009) embedded in the Nucleus for European Modelling of the Ocean (NEMO3.3; Madec 2008) ocean model forced by the ERA-Interim atmospheric reanalyses (Dee et al. 2011) following

AFFILIATIONS: MASSONNET—Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium, and Climate Forecasting Unit, Catalan Institute of Climate Sciences, Barcelona, Spain; GUEMAS—Climate Forecasting Unit, Catalan Institute of Climate Sciences, Barcelona, Spain, and Centre National de Recherches Météorologiques, Toulouse, France; FUČKAR—Climate Forecasting Unit, Catalan Institute of Climate Sciences, Barcelona, Spain; DOBLAS-REYES—Climate Forecasting Unit, Catalan Institute of Climate Sciences, and Catalan Institution for Research and Advanced Studies, and Barcelona Supercomputing Center-Centro Nacional de Supercomputación, Barcelona, Spain

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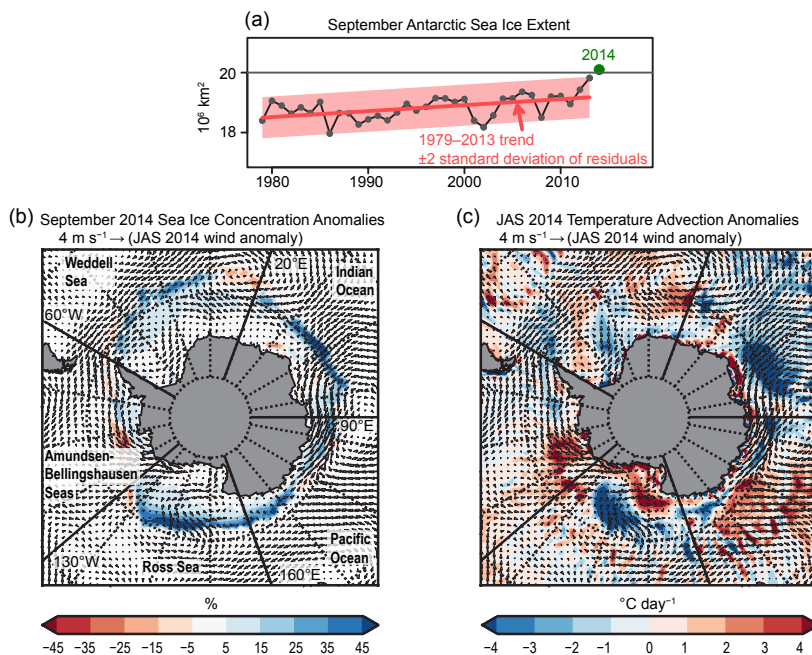


FIG. 35.1. Winter 2014 Antarctic conditions in context. (a) Sep Antarctic sea ice extent as retrieved from satellite imagery (Fetterer et al. 2015). Sea ice extent is defined throughout the text as the cumulative area of oceanic grid cells containing at least 15% of ice. The trend line (least-squares regression) across the period is shown as the red line, and the red shadow is the interval corresponding to two standard deviations of the residuals of the fit. (b) Anomalies of Sep 2014 sea ice concentration relative to 1979–2013 (Eastwood 2014) overlaid by 2014 austral winter [Jul–Aug–Sep (JAS) mean] wind anomalies from the ERA-Interim reanalysis (Dee et al. 2011) relative to the 1979–2013 average. (c) Anomaly of winter 2014 advection of near-surface temperatures relative to 1979–2013. Advection for 1979–2013 and 2014 is estimated as $-\bar{u} \cdot \nabla T$, i.e., the scalar product between the 10-m JAS ERA-Interim winds and the 2-m JAS mean temperature gradient. The gradient operator is itself estimated using a 6-point centered difference scheme along the meridional and zonal directions, respectively.

the bulk formulae of Large and Yeager (2004). The simulations are initialized on 1 March of each year from the Nucleus for European Modelling of the Ocean Variational data assimilation system–Ocean Reanalysis System 4 (NEMOVAR–ORAS4) oceanic reanalysis (Balmaseda et al. 2013) and from a sea ice reconstruction described in the online supplemental material. To account for uncertainty in the atmospheric forcing and initial conditions (ICs), we run ensembles of five members for each year (see online supplemental material). Since the skill of CTRL simulations depends in part on the realism of the atmospheric forcing, it is desirable to know that the ocean–sea ice model responds in a reasonable way to the forcing used in this study. This aspect is also discussed in the online supplemental material.

The CTRL experiment performs well in all sectors of the Southern Ocean except the Pacific Ocean sector

2012 Arctic sea ice minimum (Guemas et al. 2013), has the advantage of systematically isolating the role of individual factors that could have explained the 2014 record.

We run a first sensitivity experiment called “WND LOW,” in which we substitute surface winds of 2014 for those from earlier years corresponding to the lowest total Antarctic sea ice extents in the model (2007, 2008, 2011, 2012, and 2013, referred to as “low” years hereafter). All other parameters (ICs, near-surface air temperatures, precipitation) are left to their default values for 2014. As shown in Fig. 35.2, the replacement of winds has no significant effect on sea ice extent (that is, the new interval includes the CTRL value) except in the Pacific Sector, which we discard due to suspicious model performance. Because winds in the model only impact the sea ice mass budget through transport and divergence, we exclude the possibil-

(Fig. 35.2), for reasons that are still to be investigated. Therefore, we exclude this sector from subsequent analyses. Spurious sea ice variability over 2007–10 in the Pacific Ocean sector contaminates the skill of simulated total Antarctic sea ice extent and partly explains why September 2014 is not a maximum in the model. Figure 35.2 also illustrates why the correlation of total Antarctic sea ice extent can be a misleading metric of performance. Maps of gridpoint correlations over the period of interest reveal that more than 50% of the observed variance in sea ice concentration near the ice edge is explained by the model (Supplemental Fig. S35.2). We therefore argue that the model is adequate to conduct our attribution study given the spatial patterns of sea ice concentration anomalies in September 2014 (Fig. 35.1b). In addition to the CTRL experiment, we run four sensitivity experiments initialized on 1 March 2014. Each sensitivity experiment differs from CTRL by one aspect only. This approach, already implemented in an attribution study of the

ity that they have contributed dynamically to the 2014 record high.

This, however, does not exclude an indirect *thermodynamic* contribution of winds to the record by anomalous atmospheric heat advection. To explain the observed close association between winds and sea ice concentration in winter 2014 (Fig. 35.1b), we diagnose the rate of observed near-surface temperature change by advection. This diagnostic suggests that, in 2014, winds have played a role in bringing relatively cold air masses in the Indian Ocean and Ross Sea sectors far offshore, where ice eventually grew more than usual (Fig. 35.1c).

To confirm this hypothesis, we run a second sensitivity experiment, labeled “T2M LOW” in Fig. 35.2, in which we substitute only near-surface air temperatures of 2014 for those from “low” years. This single change in air temperatures results in a significant decrease of 0.41 million km² in total sea ice extent. More than the half of this decrease is due to a significant response of simulated sea ice in the Indian Ocean sector (where ice concentration reached anomalously high levels, Fig. 35.1b). Whether the same process was at play in the Ross Sea sector is less clear, given the lack of model response to surface temperature change in this sector. We conclude that the 2014 anomalous near-surface thermal conditions, resulting themselves from anomalous winds, favored the record high in 2014, since sea ice extent could have been lower than 2012 and 2013 otherwise.

We are aware that the experimental setup proposed has limitations. The atmospheric state forcing the model is no longer in dynamical balance when either temperatures or winds are replaced. We find, however, the two effects to be additive: a simulation

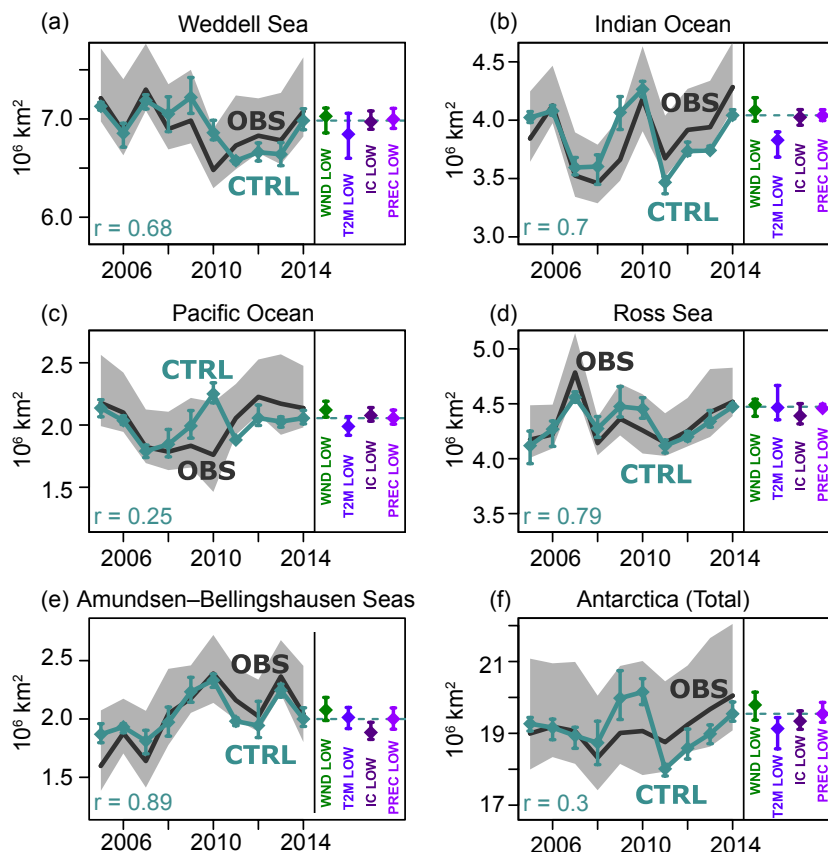


FIG. 35.2. Model sensitivity analyses. Sea ice extent as observed (black line; Eastwood 2014) and simulated (colors) by the NEMO–LIM3 ocean–sea ice model in various sectors of the Southern Ocean, corresponding to those identified in Fig. 35.1b. The CTRL simulation runs from 2005 to 2014 with initial conditions and atmospheric forcings from these years. The CTRL time series have been recentered on the time-mean of observed time series to account for systematic biases due to differences in land–sea masks. The correlations between the CTRL and observed time series are reported in the lower left corner of each panel. Gray shading corresponds to the estimated uncertainty in sea ice extent, based on a 14% nominal error in sea ice concentration typical of winter conditions (see the reprocessed products of Eastwood et al. 2014). In the right part of each panel, box plots refer to the four sensitivity experiments for 2014 described in the text: disabling the 2014 winds (WND LOW), near-surface air temperatures (T2M LOW), initial conditions (IC LOW), and precipitation (PREC LOW). The horizontal dashed line is the 2014 level for comparison. All error bars represent the range (minimum to maximum value) of the five-member ensembles, and diamonds represent the mean.

where both wind *and* temperatures were replaced would give a total sea ice extent response consistent with the cumulated responses of the individual simulations (not shown here).

In a third experiment (“IC LOW”), we substitute the 1 March 2014 oceanic and sea ice ICs with those from “low” years. No significant reduction is found except in the Amundsen–Bellingshausen Seas sector. In this sector, modeled sea surface temperatures were in fact colder by up to 1.5°C than for “low” years in

March 2014. We conclude that oceanic preconditioning did not play a fundamental role in explaining the sea ice record of September 2014.

We finally test whether anomalous hydrological conditions could have explained the 2014 anomaly. We first investigate the role of the *atmospheric* hydrological cycle: we replace the 2014 solid and liquid precipitations by those of “low” years. Increased precipitation could reduce upper-ocean density and convective overturning, thereby decreasing sea ice melt (Zhang 2007). However, we find no evidence that this factor has played a significant role in driving sea ice extent to a record in 2014 (Fig. 35.2). Regarding the role of the *continental* hydrological cycle, we have to acknowledge that the model is forced with climatological runoff data. That is, proper ocean-ice-sheet interactions are absent, making a clean sensitivity experiment impossible. Applying a 0.1 PSU decrease in the 1 March 2014 ocean salinity IC in the top 50 m and south of 55°S increased the total Antarctic sea ice extent of September 2014 by 0.20 million km² (not shown here). However, we cannot conclude that this mechanism was responsible for the 2014 record since, to our knowledge, no robust estimates of the freshening distribution of the upper-ocean due to Antarctic melt are available for 2014.

Conclusion: What drove the 2014 record of Antarctic sea ice extent? Following the results of both observational (Fig. 35.1) and model sensitivity (Fig. 35.2) analyses, we find that the primary cause for the 2014 record is anomalous thermodynamic sea ice growth near the ice edge in the Indian Ocean due to anomalous southerly advection of cold air there (Fig. 35.1c). Anomalous winds over winter 2014 are themselves the consequence of a strong dipole of mean sea level pressure anomaly at the boundaries of this sector (Supplemental Fig. S35.3). Oceanic preconditioning appears to have a secondary, but not negligible, influence on the total 2014 sea ice anomaly.

The 2014 Antarctic sea ice extent record can be explained as the superposition of a long-term, positive trend with a large positive anomaly for that particular year (Fig. 35.1a). Unlike the Arctic where the imprint of anthropogenic climate change can be detected in the multidecadal sea ice loss (Min et al. 2008), a rigorous attribution statement is not as straightforward for the long-term observed increase in Antarctic sea ice extent. Recent studies using coupled models of different complexity and at various resolutions (Sigmond and Fyfe 2012, 2014; Bitz and Polvani 2012; Ferreira et al. 2014) found evidence of a *negative* response of

total Antarctic sea ice extent to stratospheric ozone depletion at multidecadal time scales. Shorter time-scale variability of sea ice extent and concentration has been linked to large-scale atmospheric variability, such as the Southern Annular Mode (SAM; Lefebvre et al. 2004; Stammerjohn et al. 2008; Simpkins et al. 2012). However, in 2014, the winter (JAS) index of the SAM did not display a particular polarity (not shown here). Furthermore, anomalies in mean sea level pressure for winter 2014 (Supplemental Fig. S35.3) did not display a SAM-like signature. In light of our results and those from earlier studies, it is therefore difficult to formulate a robust attribution statement for explaining the 2014 record of Antarctic sea ice extent.

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