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What drove the dramatic retreat of arctic sea ice during summer 2007?

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[1] A model study has been conducted of the unprecedented retreat of arctic sea ice in the summer of 2007. It is found that preconditioning, anomalous winds, and ice-albedo feedback are mainly responsible for the retreat. Arctic sea ice in 2007 was preconditioned to radical changes after years of shrinking and thinning in a warm climate. During summer 2007 atmospheric changes strengthened the transpolar drift of sea ice, causing more ice to move out of the Pacific sector and the central Arctic Ocean where the reduction in ice thickness due to ice advection is up to 1.5 m more than usual. Some of the ice exited Fram Strait and some piled up in part of the Canada Basin and along the coast of northern Greenland, leaving behind an unusually large area of thin ice and open water. Thin ice and open water allow more surface solar heating because of a much reduced surface albedo, leading to amplified ice melting. The Arctic Ocean lost additional 10% of its total ice mass in which 70% is due directly to the amplified melting and 30% to the unusual ice advection, causing the unprecedented ice retreat. Arctic sea ice has entered a state of being particularly vulnerable to anomalous atmospheric forcing.

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1. Introduction

[2] Significant decline of arctic sea ice has been detected in recent years [e.g., *Comiso*, 2006; *Meier et al.*, 2007; *Nghiem et al.*, 2007]. The decline was particularly dramatic during summer 2007 when arctic sea ice extent plunged to the lowest level since satellite observations of sea ice began in the 1970s (Figures 1a and 2a) [also see *Stroeve et al.*, 2008; *Comiso et al.*, 2008]. This new record low in summer ice extent occurred at a time of significant arctic warming. Surface air temperature (SAT) over the Arctic Ocean has increased steadily [*Hassol*, 2004], especially in the most recent decade as reflected in the NCEP/NCAR reanalysis data (Figure 1b). During the first nine months of 2007, however, SAT was actually lower than in the previous two years. To understand the mechanisms of the arctic atmosphere-ice-ocean system that led to the unprecedented retreat of sea ice during summer 2007, we conducted a model retrospective study using the Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) driven by the NCEP/NCAR reanalysis atmospheric forcing.

[3] Changes in sea ice are determined by dynamic and thermodynamic processes. A change in ice thickness (Δh) at a given time can be described by a simple imbalance between the local net ice production (Δh_p), due to surface cooling or heating and ocean heat flux, and local ice advection ($\Delta h_a = -\nabla \cdot (\mathbf{u}h)$), due to ice motion ($\mathbf{u}$) and ice mass convergence, such that $\Delta h = \Delta h_p + \Delta h_a$. Integrating the imbalance between local ice advection and ice production over the whole Arctic Ocean yields $\Delta V = P + E$, a statement that a change in the arctic ice volume (ΔV) in a given time is due to an imbalance between the total ice production (P) inside the ocean domain and ice export (E) at its open boundaries, mainly at Fram Strait [*Kwok and Rothrock*, 1999]. Changes in ice production and export are closely linked to changes in the atmospheric forcing [e.g., *Rothrock and Zhang*, 2005]. Here we focus on how ice production and export respond to changes in the atmospheric forcing in summer 2007.

2. Model Evaluation

[4] PIOMAS consists of the thickness and enthalpy distribution sea-ice model [*Zhang and Rothrock*, 2003] coupled with the POP (Parallel Ocean Program) ocean model [*Smith et al.*, 1992]. The daily NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] forcing consists of 10-m surface winds, 2-m surface air temperature (SAT), specific humidity, precipitation, evaporation, downwelling longwave radiation (DLR), sea level pressure (SLP), and cloud fraction. SAT and cloud fraction are used to calculate downwelling shortwave radiation (DSR) following *Parkinson and Washington* [1979].

[5] PIOMAS is integrated from 1948 to September 30, 2007 using the reanalysis forcing without data assimilation. To make sure that the combination of PIOMAS and the atmospheric forcing is a useful tool for this study, its performance in simulating summer ice extent is examined (Figure 1a). The simulated September ice extents are highly correlated with satellite observations over 1978–2007 (R = 0.91), with a low RMS (root-mean-square) error of 4%. The model overestimates September ice extents in the 1980s, but is in a good agreement with observations since 1995. It captures the basic spatial pattern of the much reduced ice cover in summer 2007 (Figure 2a). However, it overestimates the 2007 September ice extent to some degree (Figures 1a and 2a).

3. Results

[6] To understand the events leading to the summer (July–September) of 2007, we focus on the results for the first nine months of 2007 in comparison with those averaged over 2000–2006, a period of relatively low summer sea ice extent. Here, the 2000–2006 average is also referred

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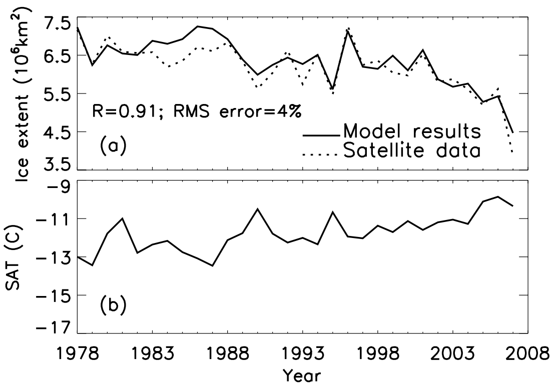

Figure 1. (a) Simulated and observed September arctic sea ice extent and (b) NCEP/NCAR reanalysis surface air temperature (SAT) over the Arctic Ocean for January through September; model-data correlation (R) and root-mean-square (RMS) error indicated.

to as "recent average" and the difference between the 2007 result and the recent average value is referred to as an "anomaly." As shown in Figures 3a and 3b, the simulated arctic sea ice extent and volume in 2007 are significantly lower than the recent average, reflecting the fact that the ice cover has been shrinking and thinning in a warming climate (also see Figure 1a). SAT and DLR (similar to SAT in temporal and spatial patterns, not shown) are anomalously high in April (Figure 3c), causing a slight drop in ice volume anomaly (Figure 3b). Both extent and volume anomalies fluctuate little from January to July and then decrease steeply in August and September.

[7] Why would the 2007 ice extent and volume appear to be "normal" leading to summer and then "abnormal" suddenly in August and September? This is because there is a significant increase over the recent average in ice export at Fram Strait in these two months (Figure 3d). The increase is 0.10×10^3 km^3 in August and 0.13×10^3 km^3 in September or 0.23×10^3 km^3 in total (standard deviation of the combined August–September ice export over 2000–2006 is 0.076×10^3 km^3). At the same time, the total ice production over the Arctic Ocean is reduced (Figure 3e). In summer, a decrease in ice production is equivalent to an increase in ice melting. The increase in ice melting is 0.30×10^3 km^3 in August and 0.27×10^3 km^3 in September or 0.57×10^3 km^3 in total (standard deviation of the combined August–September ice melt over 2000–2006 is 0.19×10^3 km^3). Overall, the Artic Ocean lost 0.80×10^3 km^3 more ice than the recent average in August and September – about 30% of the loss is due directly to the strengthened ice export and 70% due to the enhanced ice melt. This corresponds to an anomalous loss of ice extent by 1.1×10^6 km^2 in August and September (Figure 3a), which is about 12% of the Arctic Ocean area. This model simulated decrease in ice extent is, however, an underestimation when compared to satellite observations (Figures 1a and 2a).

[8] What causes an increase in ice export in August and September? Changes in the atmospheric circulation play a prominent role. Beginning in July, SLP strengthens considerably in much of the Arctic Basin and weakens over a large area in Russia in association with strong southerly winds in part of the Arctic Basin and easterly winds along the East Siberia coast (Figure 4a). The winds increase the transpolar sea ice drift (up to 0.1 m s^{-1} increase in ice velocity), producing considerable changes in ice thickness due to ice advection almost everywhere (Figure 4c). Ice thickness is reduced in a large area of the Pacific sector (Chukchi, East Siberian, and Beaufort seas, Arlis Plateau, and part of the central Arctic Ocean), and increased in the Eurasian Basin, part of the Canada Basin, and the Laptev Sea. The reduction in ice thickness due to ice advection is up to 0.5 m/month more than the recent average in some areas of the central Arctic, while the northern Greenland Sea gains ice mass due to ice advection (Figure 4c), which is also reflected in an increase in ice export at Fram Strait (Figure 3d). However, there is no significant drop in ice extent in July compared to recent years. This is because the enhanced reduction of up to 0.5 m/month in ice thickness due to advection in some areas is not enough to reduce ice extent in July when most of the ice cover is thicker than 0.5 m. Nevertheless, the reduction in ice thickness due to ice advection in July leaves a large area in the central Arctic with a much thinner and less compacted ice cover, which prepares the ice cover for a precipitous retreat in the rest of the summer.

[9] In August and September 2007, the area of high SLP anomaly is confined in the Canada Basin in conjunction with even stronger southerlies (Figure 4b) [*Comiso et al.*, 2008], which further strengthens the ice motion and transpolar drift (Figure 4d). This is also reported by *Kwok* [2008] based on satellite observations. Thus, the central Arctic continues to lose ice. Again, the enhanced reduction in ice thickness due to ice advection is up to 0.5 m/month. From

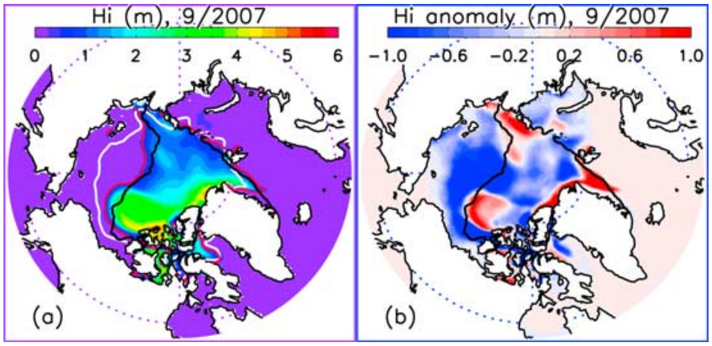

Figure 2. Simulated sea ice thickness (H_i) and anomaly. The red (black) line represents simulated (observed) September 2007 ice extent and white line simulated September 2000–2006 average.

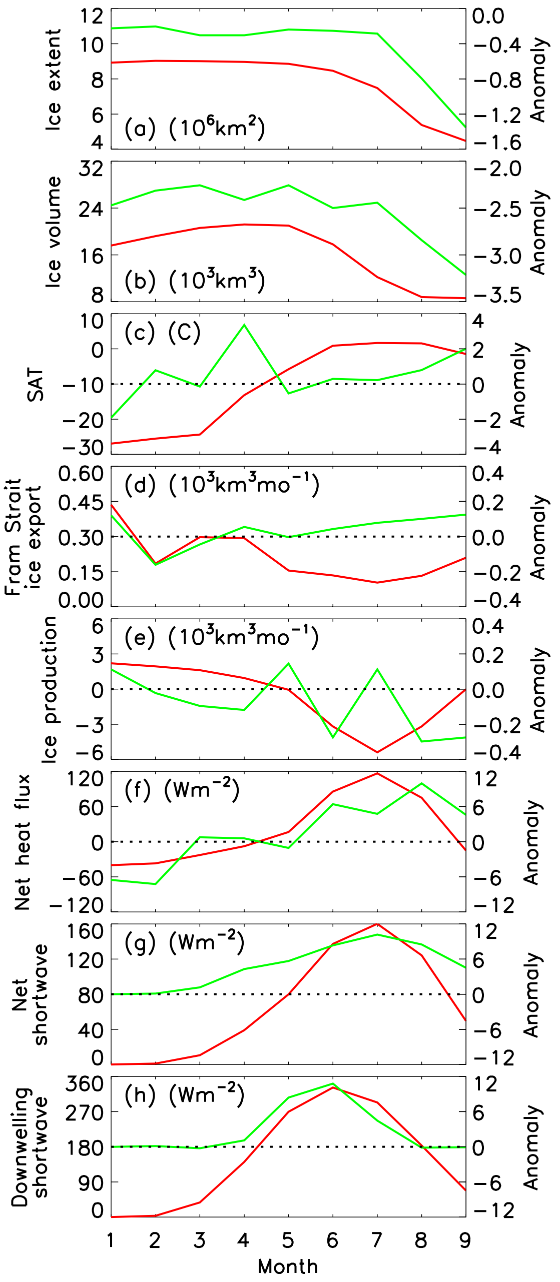

Figure 3. Monthly mean simulated arctic sea (a) ice extent and (b) volume, (c) surface air temperature, (d) simulated ice export at Fram Strait, (e) arctic total ice production, (f) surface net heat flux, and (g) surface net shortwave radiation, and (h) downwelling shortwave radiation derived from the NCEP/NCAR reanalysis data; the red line represents 2007 results and green line the difference (anomaly) between the 2007 result and the 2000–2006 average value.

July to September 2007 the advection-induced total loss of ice thickness in a large area of the central Arctic Ocean is up to 1.5 m more than the recent average. Some of the ice from the central Arctic moves out of Fram Strait and some to other areas of the Arctic, such as an area in the Canada Basin and along the coast of northern Greenland [also see *Kwok*, 2008] where ice becomes thicker (Figures 4c, 4d, and 2b), leaving behind an unusually large area of thin ice and open water in the Pacific sector and in the central Arctic Ocean (Figure 2a).

[10] The total anomalous loss of ice due to an enhanced ice advection or export in August and September 2007 is considerably larger than the recent average at 0.23×10^3 km^3, but the total anomalous loss of ice due to a reduced ice production or an enhanced melting is 2.5 times that amount at 0.57×10^3 km^3. Thus changes in ice melt play a greater role in the summer ice retreat. Local ice melting, controlled by local atmospheric and oceanic heating in summer, often increases in the areas of ice depletion due to ice advection (Figure 4e). What causes the increase in ice melt? The reason lies in the increase in the net heat flux (NHF) at the surface (Figure 3f). The simulated summer 2007 NHF is greater than the recent average by up to 40 Wm^{-2} in most of the Pacific sector (Figure 4f). This tends to not only enhance surface melting but also increase heat deposit in the ocean through leads or open water, resulting in more lateral and bottom melting, as found also by D. Perovich (personal communication, 2008) based on in situ observations. The enhanced melting, together with the anomalous ice advection, plays a key role in making most of the Pacific sector ice free in September (Figure 2a).

[11] The summer increase in the surface NHF is closely linked to an increase in the surface net shortwave radiation (NSR). The amount of increase in NHF is close to that in NSR (Figures 3f and 3g). The spatial distribution of the NHF anomaly is also similar to that of the NSR anomaly (Figures 4f and 4g). There is also an increase in the simulated surface net longwave radiation (NLR) and turbulent heat flux (THF, summation of sensible and latent heat fluxes) in part of the Pacific sector (Figures 4h and 4i), though the increases are less than for NSR. This indicates that the increase in surface solar heating plays a dominant role in the summer increase in ice melt and therefore in the dramatic ice retreat.

NSR

[12] Not only does the simulated 2007 NSR remain above the recent average in summer but also in spring (Figure 3g). The spring increase is attributed to a significant increase in May and June [*Kay et al.*, 2008] in the surface downwelling shortwave radiation (DSR) based on the NCEP/NCAR data (Figure 3h). In these two months there were fewer clouds in the Arctic than the 2000–2006 average [*Schweiger et al.*, 2008]. The anomalously high DSR in May does not offset the effects of a decrease in both SAT (Figure 3c) and DLR (not shown), so ice production is above the recent average (Figure 3e). In June, with both SAT and DLR close to the recent average, the increase in DSR causes a drop in ice production, which thins the ice cover somewhat so that the ice volume is reduced while the ice extent is not (Figures 3a and 3b).

DSR

[13] In August and September 2007 DSR is close to the recent average (Figure 3h), but NSR remains much higher. This is because of a decrease in surface albedo. Surface albedo is strongly influenced by ice advection, which redistributes ice mass and creates areas of thin ice and open water [*Zhang et al.*, 2000]. The simulated surface albedo decreases mostly in the areas of large ice depletion due to ice advection (Figure 4j). This is why the surface NSR and hence NHF are increased and the local ice production is reduced in those areas (Figures 4g, 4f, and 4e). This means that the effects of ice-albedo feedback are mainly responsi-

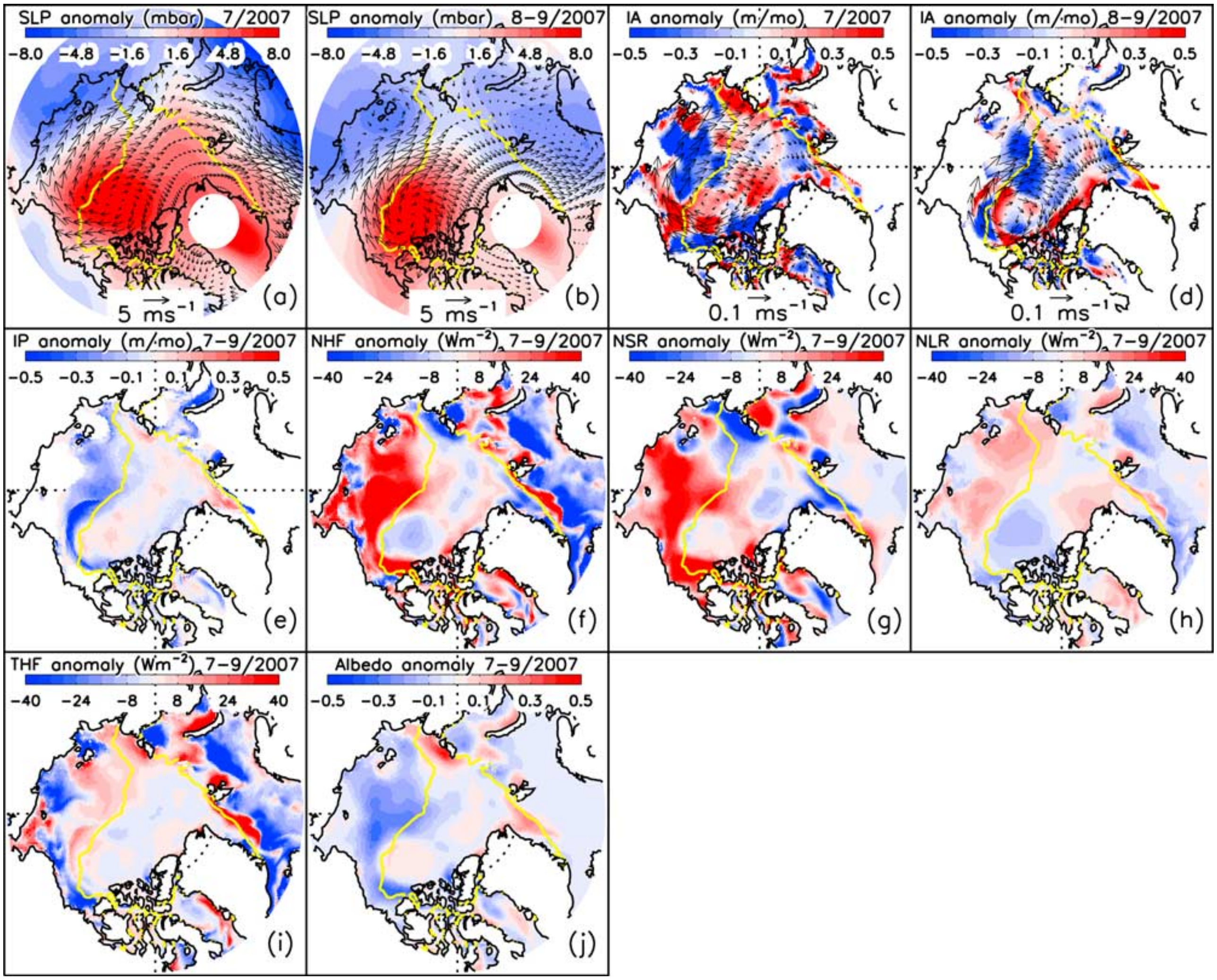

Figure 4. (a)–(b)Sea level pressure (SLP) and surface wind anomalies, (c)–(d) simulated anomalies of ice velocity and ice advection (IA), (e) local ice production (IP), (f) net heat flux (NHF), (g) net shortwave radiation (NSR), (h) net longwave radiation (NLR), (i) turbulent heat flux (THF), and (j) and surface albedo, averaged over various months of 2007. The yellow line represents satellite observed September 2007 ice extent. One of every 36 vectors is plotted in Figures 4a–4d.

ble for the enhanced melting in August and September (Figure 3e).

[14] Note that Pacific water may play a role in the enhanced melting. The anomalously strong southerly winds during summer 2007 likely drove more warm Pacific water into the Arctic, which may contribute to ice melting in the Chukchi and Beaufort seas. However, because it takes time for Pacific water, coming through Bering Strait, to penetrate deep into the Pacific sector, the enhanced melting in most of the Pacific sector is dominated by the effects of ice-albedo feedback.

4. Conclusions

[15] The dramatic decline of the arctic ice cover in summer 2007 occurred after years of shrinking and thinning (Figures 1a, 3a, and 3b) in a warming environment [*Hassol*, 2004]. The thinning of the ice began in 1988 with the epoch of strong positive Arctic Oscillation index (1989–1993) [*Lindsay and Zhang*, 2005]. The shrinking and thinning of sea ice has increased the surface absorption of solar radiation [*Perovich et al.*, 2007]. Perennial ice, particularly the oldest and thickest ice within the multiyear ice pack [*Maslanik et al.*, 2007], has been rapidly replaced in recent years by thinner first-year ice [*Nghiem et al.*, 2007; *Kwok*, 2007] that is more sensitive to changes in atmospheric and oceanic forcing. Thus, the arctic sea ice in the beginning of 2007 was preconditioned for radical changes [*Zhang et al.*, 2000; *Lindsay and Zhang*, 2005].

[16] During summer 2007 the atmospheric changes considerably strengthened the ice motion and transpolar drift, causing more ice to move out of the Pacific sector and the central Arctic Ocean, to exit Fram Strait, and to pile up in part of the Canada Basin and along the coast of northern Greenland. The unusual ice advection is responsible for a large area of thin ice and open water in the Pacific sector as well as the central Arctic Ocean where surface albedo is lowered considerably, leading to intensified surface solar heating and enhanced ice melting. The Artic Ocean lost 0.80×10^3 km^3 more ice than the recent average in the

summer, which is about 10% of its total ice mass in September 2007 (Figure 3b) and corresponds to an additional loss of ice extent by 1.1×10^6 km^2 or 12% of the area of the Arctic Ocean. About 70% of the loss is due directly to the enhanced melting, while 30% the unusual ice advection. The amplified ice melting shows the dominant effects of the positive ice-albedo feedback that is significantly enhanced by the changes in the ice circulation. So if the changes in the atmospheric circulation are considered a trigger of the unprecedented ice retreat in summer 2007, then the ice-albedo feedback accelerated the retreat. The large loss of ice mass and ice extent may suggest that arctic sea ice has entered a state of being particularly vulnerable to anomalous atmospheric forcing.

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References

Comiso, J. C. (2006), Abrupt decline in the Arctic winter sea ice cover, *Geophys. Res. Lett.*, *33*, L18504, doi:10.1029/2006GL027341.

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Sock (2008), Accelerated decline in the arctic sea ice cover, *Geophys. Res. Lett.*, *35*, L01703, doi:10.1029/2007GL031972.

Hassol, S. J. (2004), *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*, 139 pp., Cambridge Univ. Press, New York.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kay, J. E., T. L'Ecuyer, A. Gettelman, G. Stephens, and C. O'Dell (2008), The contribution of cloud and radiation anomalies to the 2007 arctic sea ice extent minimum, *Geophys. Res. Lett.*, *35*, L08503, doi:10.1029/2008GL033451.

Kwok, R. (2007), Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005 summer, *Geophys. Res. Lett.*, *34*, L05501, doi:10.1029/2006GL028737.

Kwok, R. (2008), Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic sectors, *Geophys. Res. Lett.*, *35*, L03504, doi:10.1029/2007GL032692.

Kwok, R., and D. A. Rothrock (1999), Variability of Fram Strait flux and North Atlantic Oscillation, *J. Geophys. Res.*, *104*, 5177–5189.

Lindsay, R. W., and J. Zhang (2005), The thinning of arctic sea ice, 1988–2003: Have we passed a tipping point?, *J. Clim.*, *18*, 4879–4894.

Maslanik, J. A., C. Fowler, J. Stroeve, S. D. Robot, J. Zwally, D. Yi, and W. Emery (2007), A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, *Geophys. Res. Lett.*, *34*, L24501, doi:10.1029/2007GL032043.

Meier, W. N., J. Stroeve, and F. Fetterer (2007), Whither arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record, *Ann. Glaciol.*, *46*, 428–434.

Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colon, and J. W. Weatherly (2007), Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.*, *34*, L19504, doi:10.1029/2007GL031138.

Parkinson, C. L., and W. M. Washington (1979), A large-scale numerical model of sea ice, *J. Geophys. Res.*, *84*, 311–337.

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.

Rothrock, D. A., and J. Zhang (2005), Arctic Ocean sea ice volume: What explains its recent depletion?, *J. Geophys. Res.*, *110*, C01002, doi:10.1029/2004JC002282.

Schweiger, A. J., J. Zhang, R. W. Lindsay, and M. Steele (2008), Did unusually sunny skies help drive the record sea ice minimum of 2007?, *Geophys. Res. Lett.*, *35*, L10503, doi:10.1029/2008GL033463.

Smith, R. D., J. K. Dukowicz, and R. C. Malone (1992), Parallel ocean general circulation modeling, *Physica D*, *60*, 38–61.

Stroeve, J., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos (2008), Arctic sea ice extent plummets in 2007, *Eos Trans. AGU*, *89*, 13–14.

Zhang, J., and D. A. Rothrock (2003), Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates, *Mon. Weather Rev.*, *131*, 681–697.

Zhang, J., D. A. Rothrock, and M. Steele (2000), Recent changes in arctic sea ice: The interplay between ice dynamics and thermodynamics, *J. Clim.*, *13*, 3099–3114.

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