GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08502, doi:10.1029/2008GL033244, 2008

Ensemble 1-Year predictions of Arctic sea ice for the spring and summer of 2008

Jinlun Zhang,[1] Mike Steele,[1] Ron Lindsay,[1] Axel Schweiger,[1] and James Morison[1]

Received 10 January 2008; revised 10 March 2008; accepted 21 March 2008; published 22 April 2008.

[1] Ensemble predictions of arctic sea ice in spring and summer 2008 have been carried out using an ice-ocean model. The ensemble is constructed by using atmospheric forcing from 2001 to 2007 and the September 2007 ice and ocean conditions estimated by the model. The prediction results show that the record low ice cover and the unusually warm ocean surface waters in summer 2007 lead to a substantial reduction in ice thickness in 2008. Up to 1.2 m ice thickness reduction is predicted in a large area of the Canada Basin in both spring and summer of 2008, leading to extraordinarily thin ice in summer 2008. There is a 50% chance that both the Northern Sea Route and the Northwest Passage will be nearly ice free in September 2008. It is not likely there will be another precipitous decline in arctic sea ice extent such as seen in 2007, unless a new atmospheric forcing regime, significantly different from the recent past, occurs. **Citation:** Zhang, J., M. Steele, R. Lindsay, A. Schweiger, and J. Morison (2008), Ensemble 1-Year predictions of Arctic sea ice for the spring and summer of 2008, *Geophys. Res. Lett.*, *35*, L08502, doi:10.1029/2008GL033244.

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 plummeted to the lowest level since the 1970s (Figure 1). Concurrently, there were observations of unusually warm surface waters in the Chukchi, East Siberian, and Beaufort seas, where amplified surface absorption of solar energy occurred because of the disappearance of ice cover [*Steele et al.*, 2008]. This is also reflected in the model-simulated increase in sea surface temperature (SST) by as much as up to 6°C in those areas in summer 2007 (Figures 1c and 1d).

[3] How would this unprecedented decline of summer sea ice, together with exceptionally warm surface waters in the Arctic Ocean, affect the ice conditions in the coming spring and summer? This is not only a climate issue but also a practical question. Intensive scientific field work is to take place during the spring and summer of 2008 as part of the International Polar Year activities and an outlook of sea ice conditions could be useful for field work planning. For example, will the ice near the North Pole be thick enough for successful ice camp operations with large airplanes in spring 2008 when hydrographic and other measurements are to be taken there? An outlook will also be useful for planning other activities such as marine transportation, fishing, and resource exploitation. For example, how will the record low ice cover in summer 2007 affect the ice conditions along the main Arctic shipping routes, the Northern Sea Route north of Russia and the Northwest Passage through northern Canada, in summer 2008? In attempt to answer these questions, we have conducted a set of ensemble predictions of 2008 arctic sea ice using a coupled ice-ocean model.

2. Model Description

[4] The model is the Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS). It consists of a thickness and enthalpy distribution sea-ice model coupled with the Parallel Ocean Program developed at the Los Alamos National Laboratory [*Zhang and Rothrock*, 2003]. The sea-ice model employs a teardrop viscous-plastic rheology [*Zhang and Rothrock*, 2005], a mechanical redistribution function for ice ridging [*Thorndike et al.*, 1975], and a LSR (line successive relaxation) dynamics solver [*Zhang and Hibler*, 1997]. The model covers the region north of 43°N and is capable of assimilating satellite ice concentration data following *Lindsay and Zhang* [2006]. Model forcing is based on the NCEP/NCAR reanalysis data, which consist of surface wind and air temperature, specific humidity, precipitation, evaporation, downwelling longwave radiation, and cloud fraction. Air temperature and cloud fraction are used to calculate downwelling shortwave radiation following *Parkinson and Washington* [1979].

3. Design of Ensemble Predictions

[5] We aim for an outlook of sea ice in the spring and summer 2008 after the record decline of sea ice in summer 2007 (Figures 1a and 1c). The ensemble predictions consist of seven numerical experiments with PIOMAS. Each of these seven individual ensemble members is associated with a unique set of forcing fields that are used to drive the model from 1 October 2007 to 30 September 2008. We use daily forcing fields from the NCEP/NCAR reanalysis such that ensemble member 1 uses the reanalysis forcing over the period 1 October 2000 through 30 September 2001, member 2 over the period 1 October 2001 through September 30, 2002, etc., and member 7 over the period 1 October 2006 through 30 September 2007. To our knowledge this is the first time ensemble prediction methods have been applied to forecasts of Arctic sea ice.

[6] To incorporate the effect of the record low ice cover and the unusually warm surface waters in summer 2007 into the ensemble predictions, all of the seven ensemble members

[1]Polar Science Center, Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle, Washington, USA.

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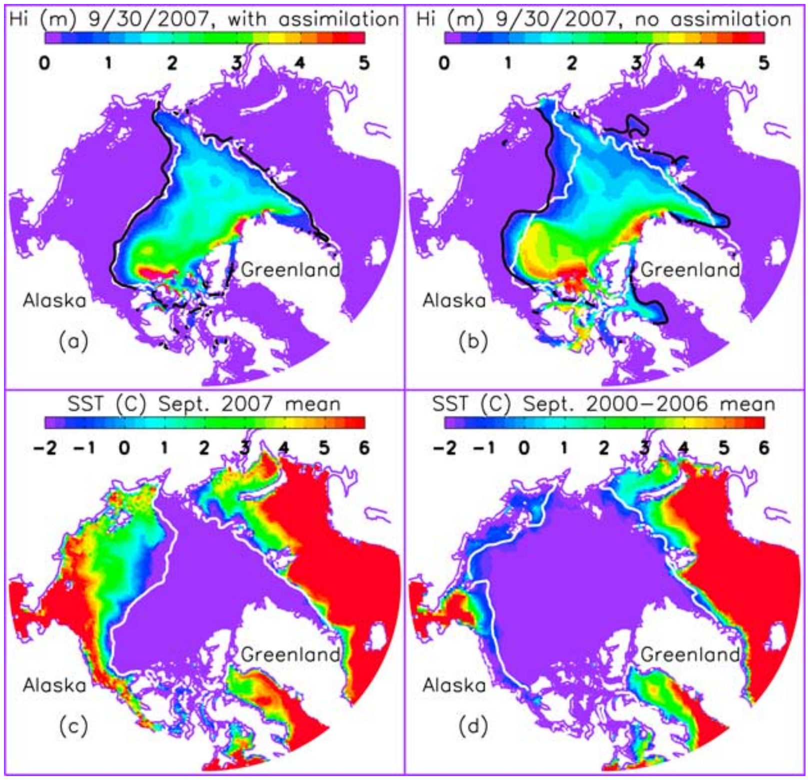

Figure 1. Sea ice thickness (H_i) on 30 September 2007 (9/30/2007) simulated by PIOMAS (a) with and (b) without assimilating satellite sea ice concentration data; (c) September 2007 mean and (d) September climatology (2000–2006 mean) sea surface temperature (SST) simulated by PIOMAS with assimilation of ice concentration data. The corresponding satellite-observed (simulated) ice extent is shown by a white (black) line.

start with the same initial sea ice and ocean conditions of 30 September 2007, as shown in Figures 1a and 1c. These initial conditions are obtained by a model spin-up followed by a retrospective integration. Model spin-up consists of an integration of 30 years, starting with 2 m thick ice in the areas with surface air temperature below freezing. The 30-year spin-up is forced by 1948 reanalysis data repeatedly. After this spin-up the ice thickness is close to steady state and the model proceeds to retrospectively simulate the period from 1 January 1948 to 30 September 2007. In order to obtain the "best possible" initial sea ice and upper ocean conditions for ensemble predictions, we assimilate satellite ice concentration data acquired from the National Centers for Environmental Prediction ftp://polar.ncep.noaa.gov/pub/cdas/). As a result, the simulated 30 September 2007 ice extent agrees well with the satellite observations (Figure 1a), and is used as sea ice initial conditions for ensemble predictions of 2008.

[7] In prediction mode, PIOMAS must be run without assimilating satellite ice concentration data; therefore its performance in simulating arctic sea ice without data assimilation must be assessed. For this purpose, PIOMAS is integrated from 1 January 1948 to 30 September 2007 without assimilating ice concentration data ("model-only simulations"). As shown in Figure 2a, even without data assimilation, PIOMAS-simulated April and September ice extents are still highly correlated with satellite observations over 1978–2007 (R = 0.92 and 0.91) with low RMS differences (RMS = 0.07 and 0.27 10^{12} m^2). The correlation between the simulated ice thickness and submarine observations available over 1987–1997 [*Rothrock et al.*, 2003] is 0.71, with a mean bias of 0.06 m (not shown). PIOMAS is able to capture the basic features of the reduced ice cover in 2007 (Figure 1b). However, it tends to overestimate ice extent somewhat in the Arctic Basin and mainly in the Canadian Archipelago region (Figures 1b and 2).

[8] To assess the model's performance in ensemble predictions, we use the same scheme to predict September arctic sea ice for the period 2003–2007 beginning with initial conditions from the previous year. In each case the seven previous years are used for forcing data and each one constitutes a member of the ensemble for the predicted year. In general, the median of the ensemble is able to predict well the September Arctic Basin-mean and North Pole ice thicknesses for 2003–2007 in comparison with the retrospective simulation results (Figure 2b). Most of the retrospective thickness values are within the range of one standard deviation below or above the ensemble median. The value of the prediction skill defined by *Lindsay et al.* [2008] is close to 0.60 for the basin-mean and the North Pole ice thicknesses (a prediction has no skill with a value of zero or less and a perfect skill with a value of 1) (Figure 2c). Using less than seven ensemble members generally reduces prediction skill, while using more than seven ensemble members does not necessarily enhance it.

4. Ensemble Prediction Results

[9] We first examine the summer prediction results. The predicted ice thickness and extent vary considerably among

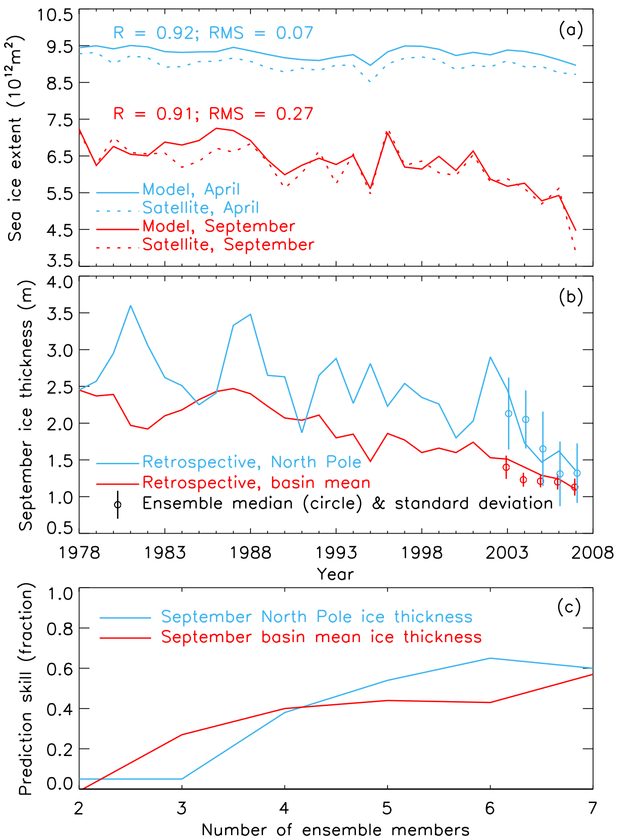

Figure 2. (a) Model simulated and satellite observed arctic sea ice extent, (b) retrospectively simulated and ensemble predicted Arctic Basin-mean and North Pole ice thicknesses, and (c) prediction skills for the period 2003–2007 with varying ensemble members. Model-data correlation (R) and root-mean-square (RMS) difference over 1978–2007 are indicated.

the seven ensemble members (Figures 3a–3g), reflecting the interannual variability of the atmospheric forcing from 2000 to 2007. The ensemble standard deviation (SD) is up to 0.6 m in most of the Beaufort Sea and Eurasian Basin, and along some of the coasts of Canada and Greenland (Figure 3i), even though the predicted ice thickness from any of the seven members is mostly less than 1.5 m (Figures 3a–3g). The predicted ice extent is the largest for member 1 forcing and the least for member 7 forcing (Figures 3a and 3g), reflecting the general trend in recent years with warming climate and shrinking ice cover in the Arctic. Ensemble member 7 is deemed as the worst case scenario for this set of forcing data.

[10] The predicted September 2008 ensemble median thickness shows that the ice is extraordinarily thin in most of the Arctic (Figure 3h). This is because the predicted ice is mostly thin among the individual ensemble members (Figures 3a–3g). There is little ice along the Northern Sea Route as shown in the ensemble median thickness field (Figure 3h). Given that there is a 50% probability at which the predicted ice thickness is either below or above the median, this means that there is a 50% chance that the shipping route along the Russian coast will be mostly ice free in September 2008. In contrast, the ensemble median field shows some ice in the Canadian Archipelago region (Figure 3h). However, as mentioned earlier, the model tends to overestimate ice in that region when ice concentration data are not assimilated. To avoid this model bias, the ensemble median thickness field, predicted without data assimilation, is compared with the September 2007 ice thickness field also simulated without data assimilation. The comparison indicates that the ensemble median thickness is considerably lower than the September 2007 thickness in most of the Canadian Archipelago region (Figure 3k). Given that in reality the Northwest Passage was almost entirely ice free in September 2007, as illustrated by satellite images http://nsidc.org/data/seaice_index), we conclude that there is at least a 50% likelihood that this would happen again in September 2008.

[11] What is the effect of the record low ice cover and the unusually warm surface waters in Fall 2007 on the predictions of summer 2008 ice conditions? The effect is illustrated by the difference between the predicted September 2008 ensemble mean ice thickness and the retrospectively simulated September mean ice thickness over 2001–2007 (Figure 3j). Note that the retrospective simulations over 2001–2007 and the ensemble predictions are based on the same forcing fields. They differ only in the initial conditions each October. Figure 3j shows that the ice thickness in summer 2008 is likely to be reduced by up to 1.2 m in a large area of the Canada Basin and Archipelago.

[12] Also of interest are the ice conditions predicted by ensemble member 7, the worst case scenario. Illustrated in Figure 3l is the difference between the September 2008 member 7 ice thickness and the retrospectively simulated September 2007 ice thickness, both of which are based on the same forcing fields but different initial conditions. Because of the formation of a large ice free area in the Pacific sector of the Arctic Ocean, the effect only manifests itself in the central Arctic Basin and the Canadian Archipelago region where the predicted ice thickness is reduced by up to 1.2 m. This is a substantial reduction considering that the 2007 summer ice is already very thin (Figures 1a and 1b). Also note that, even with the September 2007 sea ice and ocean conditions as initial conditions and even with the October 2006 through September 2007 forcing that is able to create the summer 2007 conditions, ensemble member 7 would predict only a slight reduction in ice extent for September 2008 compared to that in September 2007 (Figures 3g and 3l).

[13] The ensemble predictions of spring 2008 ice conditions are shown in Figure 4. The ensemble median (minimum) ice thickness in April 2008 is often above 2 (1.5) m in the Arctic Ocean (Figures 4a and 4b). The ensemble SD of spring ice thickness (mostly below 0.3 m, Figure 4c) is significantly lower than that of summer ice thickness (Figure 3i). This means that the ice cover in spring is less variable or less sensitive to dynamic thermodynamic forcing than in summer. The lower SD also indicates a higher prediction skill in predicting the spring ice conditions. Again the effect of the record low ice cover and the unusually warm surface waters in summer 2007 is to reduce ice thickness by up to 1.2 m in the Canada Basin (Figure 4d). Nevertheless, because of the ensemble minimum ice thickness is often above 1.5 m, we believe that the ice cover will be adequate for maintenance of springtime ice camps and other

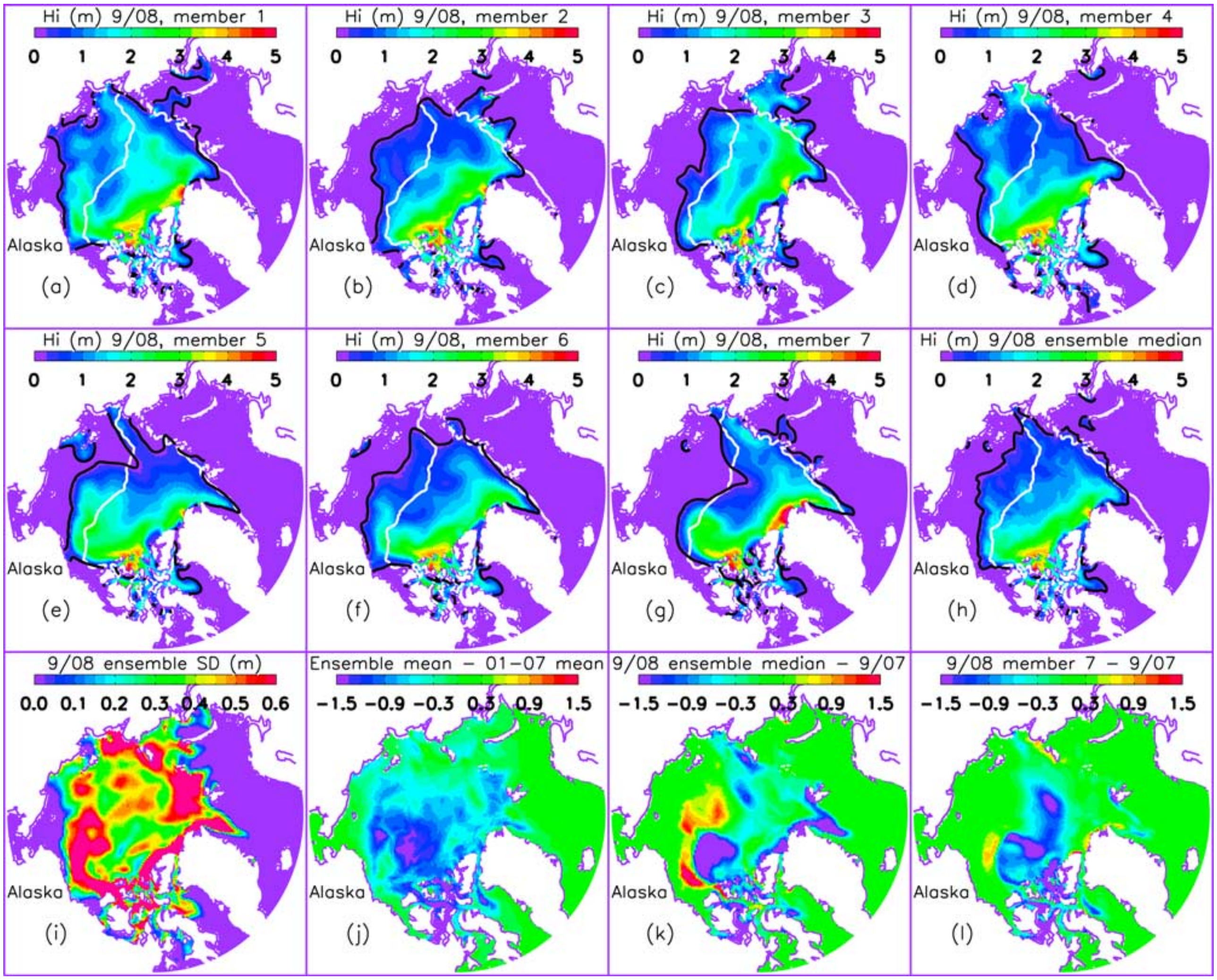

Figure 3. (a–g) Predicted September 2008 (9/08) mean sea ice thickness from individual ensemble members; (h) ensemble median ice thickness; (i) ensemble standard deviation (SD) of ice thickness; (j) predicted September 2008 ensemble mean minus the retrospective September 2001 to September 2007 mean ice thickness; (k) predicted September 2008 ensemble median ice thickness minus simulated September 2007 mean ice thickness; (l) predicted September 2008 ice thickness with ensemble member 7 minus simulated September 2007 ice thickness. The observed (simulated) 2007 extent is shown in white (black).

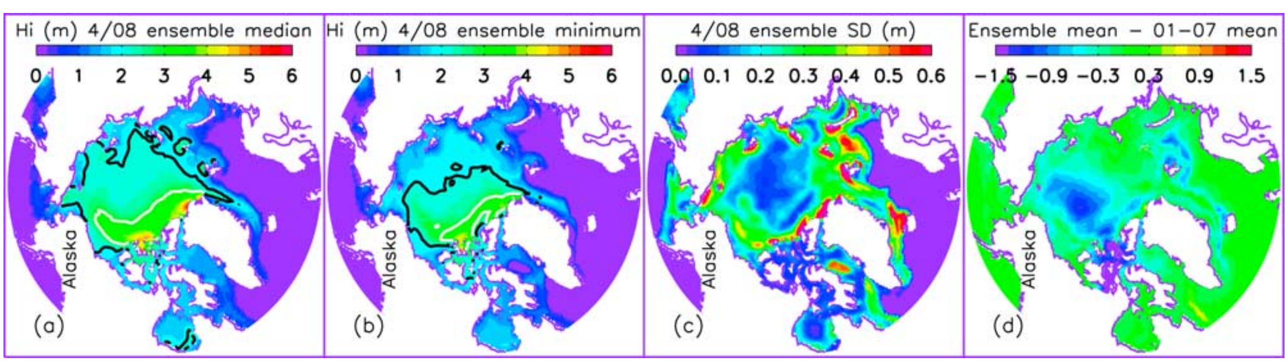

Figure 4. (a–b) Predicted April 2008 (4/08) ensemble median and minimum ice thicknesses; (c) ensemble SD of April 2008 ice thickness; (d) predicted April 2008 ensemble mean ice thickness minus the retrospective April 2001 through April 2007 mean ice thickness. The black line in Figures 4a and 4b is the 2 m contour, and the white line is the 3 m contour.

activities supported by aircraft operations. The extremely thin summer ice in most of the Arctic (Figure 3h) will enhance the distances that may be covered by summer icebreaker surveys.

5. Discussion and Conclusions

[14] In an effort to investigate how the record low arctic sea ice concomitant with unusually warm surface waters in summer 2007 would affect sea ice in the spring and summer 2008, ensemble predictions have been conducted using PIOMAS. Some of the previous seasonal predictions are based on statistical analyses of the ice and ocean system [*Drobot and Maslanik*, 2002; *Lindsay et al.*, 2008]. The U.S. National Ice Center and the Canadian Ice Service jointly provide seasonal outlooks based on satellite and meteorological data and interpretation by their expert analysts http://www.natice.noaa.gov/pub/outlooks/). In contrast, these ensemble predictions are based on numerical simulations using the same initial sea ice and ocean conditions for the summer of 2007 and an ensemble of different atmospheric forcing fields.

[15] A difficulty in the ensemble predictions is the lack of prediction forcing since PIOMAS does not include an atmospheric component. Here we use the NCEP/NCAR reanalysis forcing fields from 2000 to 2007 for various individual ensemble predictions. This is based on the assumption that the climate of 2008 would not be fundamentally different from that in recent years. Given the fact that the retrospectively simulated ice extents over 1978–2007 have small RMS errors (Figure 2a), if 2008 had climate forcing conditions similar to those in the past years, the prediction errors would likely be small as well. The agreement of ensemble predictions of conditions in 2003–2007 with the retrospective simulations (Figure 2b), gives us confidence in the ensemble approach. However, the arctic system is a rapidly changing system as witnessed in recent years. Use of the climate forcing conditions from even the recent past (2000–2007) may add uncertainties to the predictions because they may be significantly different from the reality in 2008. In addition, because PIOMAS is not coupled to an atmospheric model, the predictions would miss the mechanism of the unusual warm surface waters of summer 2007 feeding back to and thus warming the atmosphere. The absence of this air-sea feedback tends to underestimate the delay of freeze-up in the fall and therefore the severity of ice decline in 2008. Furthermore, the model's performance in simulating ice thickness outside the areas of submarine observations is unknown. There are many other uncertainties with the model as well as the forcing [*Makshtas et al.*, 2007]. Therefore, the prediction results must be viewed with caution.

[16] The prediction results indicate that the exceptional summer 2007 sea ice and ocean conditions cause a substantial reduction in ice thickness in 2008. Up to 1.2 m ice thickness reduction is predicted in a large portion of the Canada Basin and Archipelago in both spring and summer 2008. This is because sea ice is unlikely to recover quickly from the record low of 2007 in a generally warming arctic environment as seen in recent years. Also, the large pool of warm waters in the Pacific sector at the end of summer 2007 tends to modify the timing of the fall freeze-up. Furthermore, the declining ice cover is likely to allow more surface absorption of solar energy in the summer of 2008 because of the ice-albedo feedback. All of these would contribute to a thinner ice cover.

[17] However, even with a much thinner ice cover, summer 2008 is not expected to have an additional steep ice-extent retreat such as seen in 2007, according to the ensemble results. If 2008 has the same forcing conditions as 2007, as represented by ensemble member 7, its summer ice extent would be reduced only slightly against September 2007 (Figure 3g). Of course that would be another record low, but it would be nothing like summer 2007 when the ice extent plummeted dramatically. The reason for a slight reduction in ice extent is that the ice cover is responding to the 2007 forcing fields and the atmosphere is not allowed to change if the ice conditions change. The regional pattern of ice extent is sensitive to winds and air temperatures, so with similar forcing we expect similar ice extents.

[18] **Acknowledgments.** This work is supported by NSF (grants ARC0229429, ARC0629326, ARC0629312, ARC0611967, and OPP0352754) and NASA (grants NNG04GB03G, NNG06GA84G, and NNG04GH52G). We thank H. Stern and four anonymous reviewers for constructive comments.

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R. Lindsay, J. Morison, A. Schweiger, M. Steele, and J. Zhang, Polar Science Center, Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA. (zhang@apl.washington.edu)