Recent changes in the dynamic properties of declining Arctic sea ice: A model study

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1 Introduction

Since the dramatic retreat of Arctic sea ice in summer 2007 [e.g., Stroeve et al., 2008], the summer extent of the Arctic sea ice cover has been at the lowest levels on record [Comiso, 2012], with a new record minimum seen in 2012. The steep decline occurred after years of shrinking and thinning of the ice cover in a warming Arctic [e.g., Meier et al., 2007; Lindsay et al., 2009; Kwok and Rothrock, 2009], leading to a significant reduction in Arctic sea ice volume [Kwok et al., 2009; Schweiger et al., 2011]. Meanwhile, ice drift speed increased [e.g., Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011]. This increase is linked to the thinning of the ice cover, which tends to reduce ice mechanical strength and increase ice deformation and hence fracturing and lead opening [Rampal et al., 2009]. These changes in sea ice dynamics may have a significant impact on the ice mass balance of the Arctic Ocean.

3 This model study aims to examine the recent changes in the dynamic properties of the thinning ice cover. We focus on the period 2007–2011 because of the record low sea ice extent and volume. Results from the period 2007–2011 are compared with those from the period 1979–2006. We try to quantify the link between changes in ice volume or thickness, mechanics, and dynamics. It is hoped that the results of this model study may assist the design of observational studies to further improve our understanding of the impact of the declining sea ice cover. To this end, we conducted a model hindcast using the coupled Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) [Zhang and Rothrock, 2003].

2 Model Description and Evaluation

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 ice model simulates the evolution of a 12-category ice thickness distribution and ice ridging processes explicitly following Hibler [1980]. Ice motion is solved following Zhang and Hibler [1997] based on a momentum equation that consists of a teardrop plastic rheology describing a relationship among ice internal stress, strain rate, and mechanical strength [Zhang and Rothrock, 2005]. The model is driven by daily NCEP/NCAR reanalysis atmospheric forcing including 10-m surface winds and 2-m surface air temperature (SAT) [Zhang and Rothrock, 2003]. Model spin-up consists of an integration of 30 years using 1948 reanalysis forcing repeatedly, initialized with a constant 2 m ice thickness in the areas of freezing surface air temperature, ocean temperature and salinity climatology [Levitus, 1982], and zero ice and ocean velocity. After this spin-up the model proceeds to simulate the period 1948–2011 without data assimilation. Model results over 1979–2011 are examined here.

Model results of ice volume and thickness have been evaluated against a range of observations [Schweiger et al., 2011]. The simulated ice thicknesses agree well with ICESat ice thickness retrievals over 2003–2008 (~0.1 m mean model bias) for the area in the central Arctic where submarine data are available. They are also in good agreement with in-situ observations from submarines, moorings, and aircraft-based measurements over 1975–2008 (0.18 m mean bias, R = 0.73)

1 Results from a numerical model simulation show significant changes in the dynamic properties of Arctic sea ice during 2007–2011 compared to the 1979–2006 mean. These changes are linked to a 33% reduction in sea ice volume, with decreasing ice concentration, mostly in the marginal seas, and decreasing ice thickness over the entire Arctic, particularly in the western Arctic. The decline in ice volume results in a 37% decrease in ice mechanical strength and 31% in internal ice interaction force, which in turn leads to an increase in ice speed (13%) and deformation rates (17%). The increasing ice speed has the tendency to drive more ice out of the Arctic. However, ice volume export is reduced because the rate of decrease in ice thickness is greater than the rate of increase in ice speed, thus retarding the decline of Arctic sea ice volume. Ice deformation increases the most in fall and least in summer. Thus the effect of changes in ice deformation on the ice cover is likely strong in fall and weak in summer. The increase in ice deformation boosts ridged ice production in parts of the central Arctic near the Canadian Archipelago and Greenland in winter and early spring, but the average ridged ice production is reduced because less ice is available for ridging in most of the marginal seas in fall. The overall decrease in ridged ice production contributes to the demise of thicker, older ice. As the ice cover becomes thinner and weaker, ice motion approaches a state of free drift in summer and beyond and is therefore more susceptible to changes in wind forcing. This is likely to make seasonal or shorter-term forecasts of sea ice edge locations more challenging. Citation: Zhang, J., R. Lindsay, A. Schweiger, and I. Rigor (2012), Recent changes in the dynamic properties of declining Arctic sea ice: A model study, Geophys. Res. Lett., 39, L20503, doi:10.1029/2012GL053545.
and capture observed long-term variability. Here we focus on evaluation of model ice speed, comparing model results to daily buoy drift speeds [Ortmeyer and Rigor, 2004] over 1979–2010 (with 241127 data points). The simulated daily ice speed is highly correlated (R1 = 0.80) with all the available daily buoy data over that period, with a low overall bias of $-1\%$ (Figure 1a). Annual mean model ice speed is also significantly correlated with annual mean buoy speed (R2 = 0.76). Thus the model captures 58% of the interannual variance of the buoy observations.

3. Results

[6] The model simulates a substantial decrease in sea ice volume in the Arctic Ocean (including the Arctic Basin and
Chukchi, Beaufort, East Siberian, Laptev, Kara, and Barents marginal seas) during 1979–2011, which is closely correlated (R = −0.89) with increasing SAT (Figure 1b and Table 1). To highlight changes in the dynamic properties of sea ice during 2007–2011, we define “recent change” hereinafter as the difference between the five-year 2007–2011 mean and the 27-year 1979–2006 mean, which may be termed “climatology.” According to the model, there is a 33% decrease in ice volume during 2007–2011 compared to the 1979–2006 mean (Table 1). This decrease is a result of the steady decline in the past decades (Figure 1b). During 2007–2011 ice volume decreases in all seasons, particularly in July–October (Figure 2a). It rebounds to some extent from November to April, but remains well below the climatology. In addition, the model simulates a decrease of 10% in ice area in the Arctic (Figures 1c and 2b and Table 1). The decrease in ice concentration occurs mostly in the marginal seas (Figure 3d), though the decrease in ice thickness occurs over the entire Arctic, most severely in the western Arctic (Figure 3b). This is why the decline in ice volume is greater than the decline in ice area (Table 1).

The simulated reduction in ice thickness and concentration during 2007–2011 leads to a 37% reduction in ice mechanical strength, since the model represents ice strength as function of ice thickness and concentration [Hibler, 1979] (Table 1 and Figure 1d). The ice strength field (Figure 3e) resembles the ice thickness field (Figure 3a), with the largest ice strength reduction in the western Arctic (Figure 3f) where ice thickness decline is the greatest (Figure 3b). Ice strength decreases the least in summer (July–September) (Figure 2c), but ice volume decreases the most in summer (Table 1). This is because in summer ice strength is already low (Figure 2c).

The reduction in the simulated ice strength during 2007–2011 has a key role in the 13% increase in model ice speed (Table 1 and Figure 1e). Decreasing ice strength tends to reduce ice internal stress and hence weaken the internal ice interaction force (∇ · σ where σ is ice internal stress tensor) (Table 1). Ice interaction force, like water drag, tends to oppose wind stress and thus a decrease in the interaction force allows greater ice acceleration under wind stress [Hibler, 1979]. The increase in ice speed occurs in all seasons except summer (Figure 2d) because in summer the magnitude and decrease of ice strength, and hence those of ice interaction force (not shown) are all much less (Figure 2c). The increase in ice speed is greatest in fall (October–

Table 1. The 1979–2006 and 2007–2011 Mean and Change in the 2007–2011 Mean Over the 1979–2006 Mean for Some Variables of NCEP/NCAR Reanalysis Data and Model Results Averaged Over the Arctic Ocean

<table>
<thead>
<tr>
<th></th>
<th>1979–2006 Mean</th>
<th>2007–2011 Mean</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reanalysis surface wind speed (m s⁻¹)</td>
<td>4.78</td>
<td>4.85</td>
<td>1</td>
</tr>
<tr>
<td>Reanalysis surface air temperature (°C)</td>
<td>−14.0</td>
<td>−12.3</td>
<td>12</td>
</tr>
<tr>
<td>Ice volume (10¹² m³)</td>
<td>20.5</td>
<td>13.7</td>
<td>−33</td>
</tr>
<tr>
<td>Ice area (10¹² m²)</td>
<td>7.74</td>
<td>6.97</td>
<td>−10</td>
</tr>
<tr>
<td>Ice strength (N m⁻¹)</td>
<td>36722</td>
<td>23148</td>
<td>−37</td>
</tr>
<tr>
<td>Magnitude of ice interaction force (N m⁻²)</td>
<td>0.062</td>
<td>0.043</td>
<td>−31</td>
</tr>
<tr>
<td>Ice speed (cm s⁻¹)</td>
<td>7.7</td>
<td>8.7</td>
<td>13</td>
</tr>
<tr>
<td>Ice deformation rate (yr⁻¹)</td>
<td>16.0</td>
<td>18.7</td>
<td>17</td>
</tr>
<tr>
<td>Rridged ice production (10¹² m³ yr⁻¹)</td>
<td>4.82</td>
<td>4.68</td>
<td>0</td>
</tr>
<tr>
<td>Ice volume export (10¹² m³ yr⁻¹)</td>
<td>2.76</td>
<td>2.34</td>
<td>−15</td>
</tr>
</tbody>
</table>

Figure 2. Monthly mean model results and reanalysis SAT averaged over the Arctic. The solid line represents the 1979–2006 mean and dotted line represents the “recent change” defined as the difference between the 2007–2011 mean and the 1979–2006 mean. (a) Ice volume, (b) ice area, (c) ice strength, (d) ice speed, (e) ice deformation rate, and (f) rridged ice production.
On average, the speed increase is nearly Arctic-wide (Figure 3h), reflecting the spatial pattern of decline in ice thickness and ice strength.\[9\] Rampal et al. [2009] and Spreen et al. [2011] report that the increase in ice speed is unlikely due to an increase in wind forcing. Our model results also show insignificant changes in surface wind speed (SWS) during 2007–2011 (Table 1 and Figure 1e). Thus in the ice momentum balance, changes in the interaction force, controlled by ice strength, dominate over changes in wind-induced stress on decadal time scales. Although wind forcing does not contribute significantly to the positive ice speed trend, its influence on the interannual variability of ice motion is somewhat stronger. There is an increase in the annual correlation between daily SWS and model ice speed during 2007–2011 (Figure 1f). As the internal ice interaction force decreases (Table 1), its resistance to wind stress or its ability to modify the wind induced ice motion diminishes.

The increase in the annual correlation between SWS and model ice speed during 2007–2011 is due to a general increase throughout the seasons (Figure 4). Thus the internal ice interaction force decreases (Table 1), its resistance to wind stress or its ability to modify the wind induced ice motion diminishes.

December). On average, the speed increase is nearly Arctic-wide (Figure 3h), reflecting the spatial pattern of decline in ice thickness and ice strength.

Figure 3. Simulated 1979–2006 mean and the difference between the 2007–2011 mean and the 1979–2006 mean for (a, b) ice thickness, (c, d) ice concentration, (e, f) ice strength, (g, h) ice speed, (i, j) ice deformation rate, and (k, l) ice ridging. The Chukchi, Beaufort, East Siberian, Laptev, Kara, and Barents seas are marked by C, B, E, L, K, and Ba, respectively in Figure 3a.

Figure 4. Five-day running mean of daily correlation between ice speed and wind speed over the Arctic Ocean during 1979–2006 and 2007–2011. The straight black line represents a constant correlation value of 0.85.
influence of ice interaction. Summer ice motion may be considered free drift. If ice motion in free drift is defined as correlation above 0.85, then the duration of the ice in free drift during 2007–2011 would be expanded from summer to include part of spring and almost the entire fall (Figure 4). Though this definition is arbitrary, it shows that with decreasing ice strength and internal stress, ice motion is more in free drift and therefore may be more susceptible to changes in winds.

The increase in ice speed during 2007–2011 leads to an increase of 17% in ice deformation rate

\[
\left(\sqrt{\left(\dot{\epsilon}_{11} + \dot{\epsilon}_{22}\right)^2 + \left(\dot{\epsilon}_{12} - 4\dot{\epsilon}_{12}\right)^2}\right)\]

where \(\dot{\epsilon}_{ij}\) is strain rate tensor; including divergence and shear (Table 1 and Figure 1g). Ice deformation is much smaller in winter and spring than in summer and fall (Figure 2c). Like ice speed, the increase in deformation during 2007–2011 is strong in all seasons except summer, with the largest increase in fall. The spatial pattern of the deformation increase is also similar to that of the speed increase (Figure 3).

Increasing deformation tends to transfer more thin ice into thick ice mechanically through the ridging processes [Hibler, 1980]. This is reflected by generally greater ridged ice production in most of the marginal seas (Figure 3k) where there is more thin ice (Figure 3a) and deformation is larger (Figure 3i). However, the increasing deformation does not increase the area-average ridged ice production during 2007–2011; ridged ice production is 3% less (Table 1 and Figure 1g). This is because ridged ice production decreases strongly in most of the marginal seas (Figure 3i) where there is less ice to participate in ridging (Figure 3b). The decrease occurs mainly in fall when ice just starts to grow back in the marginal seas (Figure 2f). In parts of the central Arctic with sufficient ice, particularly in the areas near the Canadian Archipelago and North Greenland, ice ridging increases, owing to the increase in ice deformation. However, the increase in ridging in these areas does not compensate for the reduction in the marginal seas.

The simulated reduction in ice volume export from the Arctic Ocean (calculated by integrating \(\nabla \cdot \mathbf{u}\) over the Arctic Ocean, where \(\mathbf{u}\) are ice thickness and velocity, respectively; equivalent to export from all gates including Fram Strait) during 2007–2011 is 15% (Table 1 and Figure 1h). This is expected given the 33% decline in ice volume. This means that the reduction of ice volume export from the Arctic tends to slow down the decline of ice volume in the Arctic. However, the 2007–2011 mean volume export normalized by ice volume is higher than climatology (Figure 1h). This suggests that without the decrease in ice thickness in recent years the increase in ice speed would have increased the ice volume export out of the Arctic.

4. Concluding Remarks

This model study compares the dynamic properties of declining Arctic sea ice in the period 2007–2011 to those in the period 1979–2006. There are substantial changes in the simulated sea ice dynamic properties during 2007–2011 that are closely linked to an apparent shift towards a new sea ice regime with a drastic decline in ice thickness and concentration and an increase in mean ice drift speeds. The primary reason for the decline of the ice cover is likely the steady Arctic warming over the past decades. The percentage decline of ice volume is much greater than that of ice area. This is because the ice cover is not only shrinking in mostly the marginal seas, but also thinning over the entire Arctic Ocean, particularly in the western Arctic. There has been a rapid depletion of thicker, older ice [e.g., Lindsay et al., 2009; Maslanik et al., 2011; Comiso, 2012] such that the Arctic sea ice system is approaching one dominated by thin, first-year ice.

The decline of ice thickness is at the center of the simulated changes in sea ice dynamic properties. It is linked to a decrease in ice strength and hence internal stress and interaction force, which boosts ice speed and hence deformation. The increase in mean ice speed has the tendency to cause a positive feedback because it has the potential to increase ice export, as suggested by Rampal et al. [2009]. However, ice volume export is reduced because of the steep decline of ice volume. That is, the rate of increase in ice speed does not match the rate of decrease in ice thickness. The effect of the reduction in ice volume export is to slow down the decline of Arctic sea ice.

The increasing ice deformation means increasing ridging. However, the simulated ridged ice production is increased mainly in parts of the central Arctic where there is plenty of ice to participate in the ridging processes. In most of the marginal seas with reduced availability of ice, ridged ice production decreases significantly. The marginal seas may be considered to be a “factory” of ridged ice because the simulated ridged ice production is generally higher there than in most of the central Arctic. However, the decrease in ridged ice production in most of the marginal seas is severe enough to cause an overall decrease in the Arctic average ridged ice production. Also, ridged ice production decreases mainly in fall, suggesting that the recent summer ice retreats are severe enough to suppress ridged ice production even with increasing ice deformation. The overall decrease in ridged ice production contributes to the demise of thick, multiyear ice as less ridged ice may be advected to the central Arctic from the marginal seas.

As the ice cover becomes thinner and weaker, ice motion may approach a state of free drift not only in summer but also in parts of spring and fall. Thus the ice cover will be more sensitive to changes in wind forcing. While there is little trend in wind forcing on interannual and decadal time scales during 1979–2011, the ice cover may be more susceptible to short-term atmospheric changes such as storms or strong southerly wind anomalies that contributed to the drastic ice retreat in 2007 [Overland et al., 2008; Zhang et al., 2008]. This may pose more challenges in forecasts of Arctic sea ice, particularly ice edge locations, on weekly to seasonal time scales.

While model studies can shed light on the changes in the dynamic properties of Arctic sea ice, it is important to monitor the changes through satellite and in situ observations. Our knowledge about Arctic sea ice is largely based on a system dominated by thick, multi-year ice. It is necessary to learn more about the dynamic processes of a thinner and younger sea ice cover. This can be achieved by measuring changes in some of the key dynamic properties, such as the ice mechanical strength as a function of thickness and concentration for first-year ice and the redistribution of ridged ice in first-year and multi-year ice packs. These observations will enhance our understanding of the dynamic
behavior of the declining sea ice cover and may improve model physics for a new sea ice regime.

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