Increased variability of the Arctic summer ice extent in a warmer climate

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[1] Simulations performed with general circulation models and a model of intermediate complexity show that the variability of the September sea ice extent in the Arctic of the 21st century increases first when the mean extent decreases from present-day values. A maximum of the variance is found when the mean September ice extent is around 3 million km^2. For lower extents, the variance declines with the mean extent. The behavior is clearly different in Antarctica where the variance always decreases as the mean ice extent decreases, following roughly a square-root law compatible with very simple geometric arguments. Several mechanisms are responsible for the non-linear behavior of the Arctic. However, the strong interhemispheric contrast suggests that the difference in geometrical setting, with an open ocean in the south and a semi-closed basin in the north, plays a significant role. **Citation:** Goosse, H., O. Arzel, C. M. Bitz, A. de Montety, and M. Vancoppenolle (2009), Increased variability of the Arctic summer ice extent in a warmer climate, *Geophys. Res. Lett.*, *36*, L23702, doi:10.1029/2009GL040546.

1. Introduction

[2] The perennial ice extent in the Northern hemisphere, which corresponds to the sea ice that remains during the summer minimum, has decreased over the years 1979–2007 by more than 10% per decade [*Stroeve et al.*, 2007; *Comiso et al.*, 2008]. The decline has been faster over the recent years, leading to very low ice concentration in the summers of 2007 and 2008. This abrupt reduction has led to the suggestion that the Arctic may have crossed a tipping point, inducing an irreversible shift in the system, but this speculation is still strongly debated [*Lindsay and Zhang*, 2005; *Eisenman and Wettlaufer*, 2009]. Models also simulate abrupt reductions of the ice cover when driven by a smooth increase in the greenhouse gas concentration in the atmosphere [*Holland et al.*, 2006]. However, it does not seem to be associated with a particular threshold in the system. The occurrence of such abrupt changes is thus highly unpredictable in the simulations [*Holland et al.*, 2009].

[3] The majority of the recent studies devoted to future evolution of the Arctic ice cover have been focused on estimates of the future evolution of the mean winter and summer ice extent and of the possible change in the rate of the decline of the ice cover [*Arzel et al.*, 2006; *Holland et al.*, 2006; *Parkinson et al.*, 2006]. However, it is also important to analyze possible modifications in the amplitude of the interannual variability of the system. First, it is deeply linked with our interpretation of the observed changes. An observed rapid decline can indeed be the sign of a long-term trend but could also be the sign of a large amplitude interannual fluctuation. Second, estimating the amount of interannual variability has clear practical applications. For instance, if the interannual variability increases in the future, the uncertainty in the prediction of the localization of the ice edge may be higher.

[4] In a recent study, *Holland et al.* [2009] have shown than in the CCSM3 model, the variability of the total September ice extent increases when sea ice extent declines. They relate this model response to the decrease in May ice thickness averaged over the Arctic. Our goal here is to show that such an increase in the variability in the summer ice extent is a common characteristic of the majority of the presently available climate models in the Arctic, but not in the Antarctic, and to get further insight into the mechanisms responsible for this behavior.

2. Methods

[5] In order to systematically study the influence of changes in the mean state on the interannual variability, an ensemble of simulations covering nearly continuously a wide range of mean summer ice extent would be required. This is not presently available from any single General Circulation Model (GCM). However, we can take the opportunity of the availability of projections for the 21st century using different models to obtain a sample of different states (Figure 1a). Here we will use the simulations from the "Climate of the 20th Century Experiment" (20C3M) and from the scenario SRES A1B, which corresponds to a continuous increase of CO_2 concentration over the 21st century until a level of 720 ppm by 2100. More specifically, 14 models are used to assess the future evolution of sea ice variability during summer. Those include the IPSL-CM4, CNRM-CM3, GISS-AOM, GISS-ER, CSIRO-Mk3.0, INM-CM3.0, UKMO-HadGEM1, UKMO-HadCM3, MRI-CGCM2.3.2, MIROC3.2 (hires), MPI-ECHAM5, CGCM3.1 (T47), CCSM3 and PCM models. Detailed information about these models can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. For all the simulations, non-overlapping 20 years periods are analyzed. The time series of the ice extent are first detrended over those 20 years and the mean and standard deviation of the ice extent are computed to obtain one point on Figure 1.

[6] Additional simulations have been performed with the Earth Model of Intermediate Complexity LOVELIM

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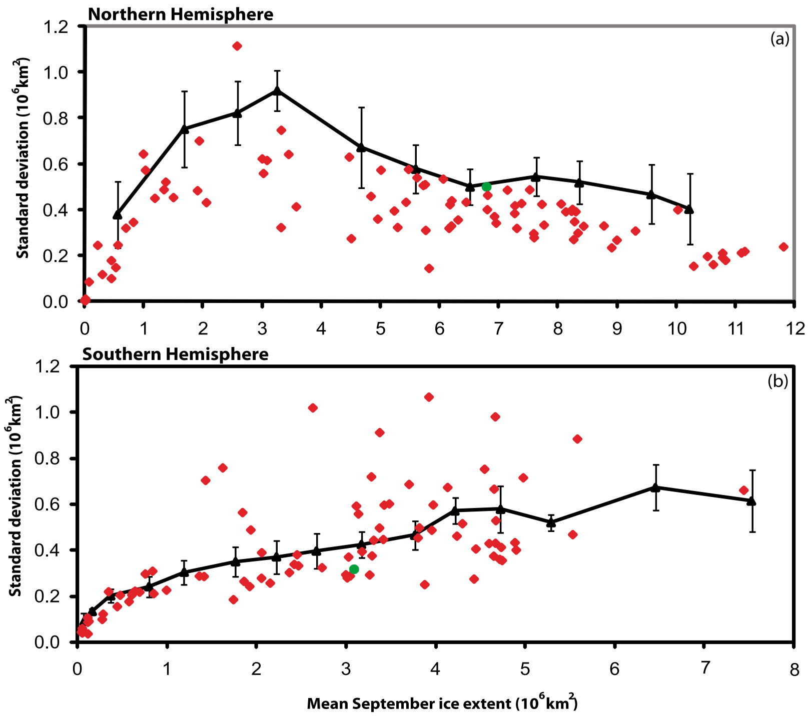

Figure 1. Standard deviation of the summer ice extent as a function of the mean ice extent for 20-year periods in various simulations performed with GCMs over the 21st century (red dots) and with the EMIC LOVECLIM using different values of the CO_2 concentration of the atmosphere (black). (a) Northern Hemisphere (September). (b) Southern Hemisphere (March). The green dots are derived from the observations over the period 1979–2007.

[*Driesschaert et al.*, 2007], using the same configuration as in experiment E3 of *Goosse et al.* [2007], which reproduces reasonably well the mean ice extent and its variability in both hemispheres. As LOVECLIM is much faster than GCMs, it is possible to make long simulations with different concentration of CO_2 in the atmosphere, leading to different mean summer ice extent and eventually different variance of the summer ice extent. A reasonable range of mean summer ice extent has been achieved here using CO_2 concentrations between 140 ppm and 600 ppm. LOVECLIM results have also allowed showing that the choice of the length of the period used to compute the standard deviations (20 years here) does not have a strong impact on the conclusions of our analyses.

[7] For present-day conditions, we will also analyze the results of a simulation performed with the sea-ice-ocean model NEMO-LIM3 driven by NCEP-NCAR reanalysis over the period 1979–2006 [*Vancoppenolle et al.*, 2009]. This model displays a more realistic representation of the ice cover than LOVECLIM and GCMs while, compared to observations, it provides a physically consistent description of all the variables representing the system over that period, in particular of the sea ice thickness.

3. Results

[8] As observed in CCSM by *Holland et al.* [2009], the majority of the models at first display an increase of the standard deviation of the total Arctic ice extent in September (henceforth referred to as just "extent") as the ice cover declined compared to present-day conditions (see Figure 1a). The standard deviations tends to peak when the extent is around 3 10^6 km^2. For smaller extents, the variance decreases and of course reaches 0 when the extent is 0. Among GCMs with extent between 2 and 4 10^6 km^2, the average standard deviation is 0.61 $10^6 \pm 0.23$ 10^6 km^2. It is more than the corresponding value for GCMs with more extensive ice (between 6 and 8 10^6 km^2), which equals 0.40 $10^6 \pm$ 0.07 10^6 km^2. This difference between the two values is highly significant ($p < 0.01$ using a Mann-Whitney test). In these computations, the uncertainty is measured from the standard deviation over all the model simulations available in the analyzed range of sea ice extent.

[9] The performance of the models is generally lower in the Southern Hemisphere than in the Northern Hemisphere [*Arzel et al.*, 2006; *Parkinson et al.*, 2006]. The scatter between the results of different models is thus larger. However, the standard deviation of the summer ice extent generally increases there as a function of the mean summer ice extent, in clear contrast to the behavior in simulated in the Arctic (Figure 1b).

[10] In order to understand the causes of this non-linear dependence of the variability on the mean state, it is required to analyze the simulated local changes in the ice cover. This has been done here by studying Pr{melt}, which is the probability that the ice melts in summer at a particular point. For a particular period, Pr{melt} is equal to one if ice always melts completely by end of summer or is equal to zero if ice always survives to the end of summer (then the corresponding grid box does not contribute to the variance of the ice extent). By contrast, if Pr{melt} is, for instance between 10% and 90%, the sea ice there has a reasonable probability of either possibility (to melt totally or to survive the summer), with a clear impact on the standard deviation

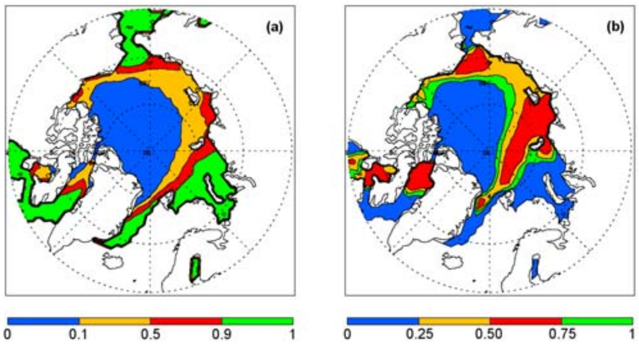

Figure 2. (a) Probability that sea ice totally melts in summer; (b) P (h1 < h < h2) for NEMO-LIM3, 1979–2006. h_1 = 1.24 m and h_2 = 2.33 m correspond to Pr{melt|h_i} equal to 90% and 10% respectively. The equivalent of Figure 2a based on observations is very similar to the one obtained for NEMO-LIM3.

of the ice extent. We will refer later to this zone where 10% < Pr{melt} < 90%, and thus where ice is present in summer some years but not in others, as the Interannually Variable Ice Zone (IVIZ). In a given year at a given model grid box, we assume that ice has melted completely if the September mean ice concentration at the location is lower than 15%.

[11] Many studies have shown that the winter ice thickness has a large influence of the summer melt [e.g., *Maslanik et al.*, 2007]. Consequently, the variable selected here to interpret Pr{melt} maps is the mean sea-ice thickness in April (h_i) in each grid box of the Northern Hemisphere. Assuming for simplicity that the geographical distribution of this mean ice thickness has been decomposed in N classes of thickness h_i for the period studied, Pr{melt} can be expressed as:

$$\Pr\{\text{melt}\} = \sum_{i=1}^{N} \Pr\{\text{melt}|h_i\}.\Pr\{h_i\} \quad (1)$$

where Pr{melt|h_i} is the probability that the ice melts in summer if its thickness in winter is equal to h_i and Pr{h_i} the probability that the thickness is equal to h_i.

[12] Pr{h_i} and Pr{melt|h_i} are dependent on time and location. For instance, a floe of thickness h_i equal to 2.5 m has a lower probability to melt if it is located in the center of the pack than if it is close to the ice edge, in a region where the ice velocity is high, and the ice can thus be transported easily to warmer waters. In the latter case, adding a dependence of Pr{melt} as a function of the velocity may appear a natural choice and would have helped taking into account more explicitly the influence of dynamical processes on the probability of ice melting. However, if we make the first-order approximation that Pr{melt|h_i} is spatially constant and do not include any other variable to explain Pr{melt}, we obtain in the simulations performed with NEMO-LIM3 over the period 1979–2006 that, in the Arctic, Pr{melt} is between 10 and 90% if the ice thickness is between 1.24 and 2.33m. Those two critical ice thicknesses between which ice has a reasonable chance to survive the summer seasons in some years and to melt totally in others will be referred later as h_1 and h_2.

[13] To test whether this approximation is realistic, we compare the areas where the ice thickness is between those bounds (Figure 2b) and the probability of total melt (Figure 2a). The relatively good correspondence in NEMO-LIM results confirms that winter ice thickness plays a dominant role in the probability of total melt at a particular location and that assuming the critical ice thicknesses as independent of the location provides useful information on the summer melt for the majority of regions. Applying equation (1) to analyze future changes appears thus reasonable.

[14] However, before considering how well the thickness-melt probability relation holds for future changes in the Arctic, let's study a very simple and idealized example of a pack characterized by a circular shape of radius R with thickness $h_i = \alpha\,(R - r)$, where α is a constant and r the distance from the center of the pack. These assumptions give IVIZ a constant width ΔR, independent of R (see Figure S1 of the auxiliary material).[1] If we make the additional approximation that $\Delta R \ll R$, the IVIZ occupies a surface with area S_{IVIZ} located between two circles of radii $R + \Delta R/2$ and $R - \Delta R/2$:

$$\begin{aligned} S_{IVIZ} &\sim 2\pi R\,\Delta R \\ S_{IVIZ} &\sim 2\,\Delta R\,\pi^{1/2}\,A^{1/2} \end{aligned} \quad (2)$$

where A is the surface of the pack ($A = \pi R^2$).

[15] If we assume Pr{melt|h_i} is spatially constant, then the variance of ice extent is proportional to S_{IVIZ}. Thus in this simple case, the variance of the ice extent increases as the square root of the ice extent. If we again consider that $h_i = \alpha\,(R - r)$, the variance is also higher as the mean thickness of the pack increases. These relations arise from simple geometrical considerations and do not require any deep investigation of the mechanisms ruling the system dynamics or the strength of various feedbacks in the Polar Regions. They appears to correspond relatively well to the response of the GCMs in the Southern Ocean (Figure 1b) where the pack has a relatively annular distribution, which loosely resembles the simple model if in the computation of S_{IVIZ} (equation (2)) we take into account the presence of Antarctica. For LOVECLIM, the best fit of the variability of the extent has a function of the mean state provides a power law with an exponent 0.43, i.e., quite close to the simple interpretation provided above (equation (2)).

[16] The simple model may also explain the relationship between extent variability and mean in the Arctic for ice extent lower than about 3 10^6 km^2 but clearly does not hold for larger ice extent. For instance, for late 20th century conditions (Figure 2a), the IVIZ does not have a relatively constant width: the zone where 10% < Pr{melt} < 90% occupies a narrow band close to ocean thermal fronts, such as near Spitzbergen; the corresponding area is larger on the continental shelves of Siberia, small again north of Alaska and equal to zero north of the Canadian Archipelago since sea ice there is too thick to melt in summer.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040546.

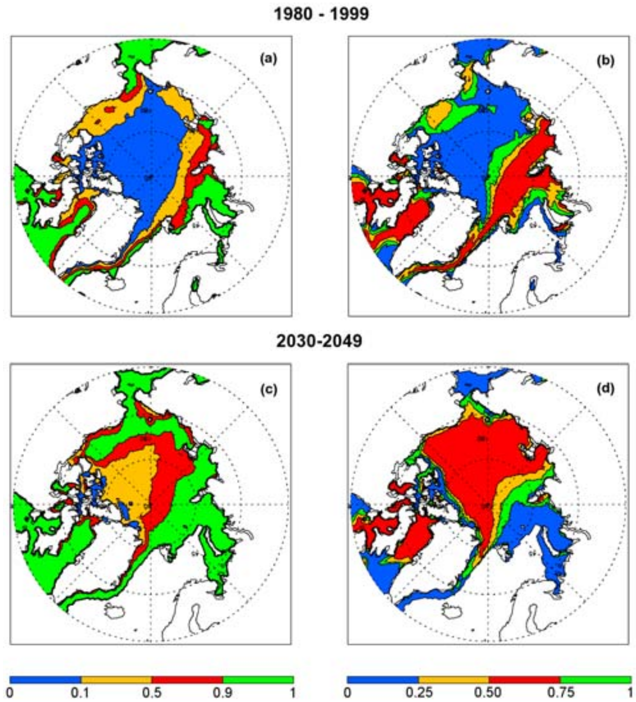

Figure 3. (left) Probability that sea ice totally melts in summer, (right) P ($h_1 < h < h_2$) computed for a simulation performed with CCSM3, for the periods (a and b) 1980–1999 and (c and d) 2030–2049. h_1 = 1.14 m and h_2 = 2.62 m were computed based on the period 1980–1999.

[17] In order to explain the maximum in the standard deviation of the ice extent that is seen in the Arctic when the mean extent is about 3 10^6 km^2, the width of the IVIZ must increase in some regions. Following equation (1), this can be due to two different processes. First, the shape of $Pr\{melt|h_i\}$, and in particular the critical thicknesses h_1 and h_2 corresponding to a probability of melting of 10% and 90% respectively, can change for a different climate. Estimating the thickness h_2 is often problematic because not enough thick ice is available for the warmest climate. For h_1, it is located between 1m and 1.5m in the majority of models (Figure S2), as computed for NEMO-LIM. As expected, its value tends to increase when the mean ice extent is lower and thus the pack is more fragile and vulnerable, for instance, to advection of warm air and warm water towards the ice covered zone. However, the changes are relatively small when mean ice extent decreases from 8 to 3 10^6 km^2, which corresponds to the large increase in the standard deviation of the summer ice extent (Figure 1a). As a consequence, the changes in h_1 do not appear to play a dominant role in the simulated increase in variance.

[18] Second, the surface where winter ice thickness is between the critical thickness h_1 and h_2 can increase when the mean ice extent is decreasing. This is clearly the case in all the models (one particular example is given in Figure 3). A first reason for this modification can be derived from purely thermodynamic considerations showing that thick ice display generally a faster melting rate than thin ice [e.g., *Bitz and Roe*, 2004]. This reduces the proportion of ice that is thicker than h_2 compared to the zone where the mean ice thickness is between h_1 and h_2. For instance, thick and thin ice are both found in many regions in CCSM during the period 1980–1999, leading to a relatively narrow IVIZ (Figures 3a and 3b). In 2030–2049, the thick ice has preferentially melted, inducing a wider IVIZ. Such a reduction of the surface covered by thick ice has also been observed recently [e.g., *Kwok et al.*, 2009]. A second cause is related to the geographical setting of the Arctic. For late 20th century conditions, only a few regions are characterized by winter thicknesses between h_1 and h_2 (Figure 3). Off the coast of eastern Siberia and Alaska, the winter thickness is in the upper part of this range. In the absence of continental barriers, one could imagine that the ice thickness on what is now Northern Siberia or Northern Alaska would be in the lower part of this range. All the longitudes would then fully contribute to the variability of the summer ice extent in the Arctic, as it is observed now for the Southern Ocean. By contrast, when the ice extent decreases, the mean ice thickness also decreases and nearly the whole Arctic becomes thin enough that it has a reasonable chance to melt in summer. All the regions can thus have strong variability of the summer ice cover, leading then to a higher standard deviation of the summer ice extent.

4. Discussion and Conclusions

[19] We have confirmed earlier findings that the variability of the summer ice extent in the Arctic will at first be higher in a warmer climate compared to present-day conditions. According to various models, the maximum of the variability is found when the mean ice extent is of about 3 10^6 km^2. This contrasts with the Southern Ocean where the standard deviation of the summer ice extent increases with the mean ice extent (and with the mean ice thickness). Several processes play a role in this behavior such as the faster melting of thick ice compared to thinner ice or the higher probability to melt relatively thick ice in a warmer climate. However, the clear contrast with the Southern Ocean suggests a strong role of shape of the Arctic basin. For late 20th century conditions, the pack is relatively thick and the thickness class corresponding to ice that can melt or survive in summer covers only a small fraction of the area (the location where we should find it for present-day climate conditions is mainly occupied by continents). When sea ice melts, the pack thins and this class of thickness covers a much wider area, leading to a higher variance of the summer ice extent. Similar geographic arguments were recently used to interpret the faster melting of the sea ice in summer compared to winter observed recently. I. Eisenman (Geometric muting of changes in the Arctic sea ice cover, manuscript in preparation, 2009) suggests that the distribution of the continents blocks the southward extension of the sea ice in winter, and thus reduce the amplitude of changes, while the summer ice edge is more free to evolve in response to the forcing.

[20] This general behavior of the models is clear and our results imply a significant increase of the variance of the summer ice extent in the decades to come, leading to a less predictive summer ice cover. However, the sea ice may be quickly melting. Over the 21st century, we might have only one single 20-year period during which the mean summer ice extent is between 2 and 4 10^6 km^2. From such a small

sample, the shift in variability might not clearly appear. Nevertheless, recognizing that the variability might increase is very important when interpreting the observed changes. Furthermore, our results can be applied to past periods where the summer ice extent was reduced compared to present-day conditions such as the early Holocene [e.g., *Goosse et al.*, 2007]. In particular, in addition to the potential changes in the mean state, a higher variability of the ice extent should be taken into account when analyzing the proxy records during those periods.

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