Arctic sea ice decline and ice export in the CMIP5 historical simulations

H.R. Langehaug a,b,⇑, F. Geyer a, L.H. Smedsrud c,b, Y. Gao a,b,d

a Nansen Environmental and Remote Sensing Center, Bergen, Norway
b Bjerknes Centre for Climate Research, Bergen, Norway
c Uni Research AS, Bergen, Norway
d Nansen-Zhu International Research Center, Institute of Atmospheric Physics, Beijing, China

Abstract

Arctic sea ice properties and Fram Strait ice export from six CMIP5 Global Climate and Earth System Models are evaluated and investigated for the period 1957–2005. Over the last decades most ensemble members simulate a decreasing September sea ice area and a slow, general thinning of the sea ice cover. While the different ensemble members both under- and overestimate the decline in observed September sea ice area, none of the members reproduce the observed thinning.

This study is a first attempt to evaluate the Fram Strait ice area export in the CMIP5 models, and the role it has played for Arctic sea ice area and thickness. Five of the six models evaluated reproduce the seasonal cycle and the inter-annual variance of the ice area export in the Fram Strait reasonably well. The simulated southward export of sea ice in the Fram Strait constitutes a major fraction of the Arctic sea ice in these five models; 10–18% of the sea ice covered Arctic Basin is annually exported. For the same models the year-to-year variability in Fram Strait ice volume export carries 35% of the year-to-year variability in the Arctic Basin sea ice volume.

We have found low but significant correlations on inter-annual timescales between the Fram Strait ice export, both in terms of area and volume, and the Arctic Basin sea ice thickness. All six models show that an increase in ice area export leads a decrease in the sea ice thickness. This inverse relationship also holds when considering the long-term trends; the larger the increase in Fram Strait ice area export, the larger the thinning of the Arctic Basin sea ice cover and the larger the loss in the September sea ice area. The different ensemble members show both negative and positive ice export trends. Focusing on the model with the largest number of ensemble members (10), we have been able to quantify the effect of the ice area export on the Arctic Basin sea ice for this particular model. For this model an increase of the ice area export similar to the estimated trend (from NCEP) can explain almost 20% of the total simulated decline in sea ice area and thickness.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Fifty years ago the Arctic Ocean was sea ice covered all through the year. Dramatic changes have become evident during the last decades, and over the last 30 years, satellite data document a loss of summer Arctic sea ice area of −13.5 % per decade (Comiso, 2012). The loss of sea ice area has increased with time, since it was around −3.0 % per decade up to the 1990s (Johannessen et al., 2004). The sea ice loss has been attributed both to human influence and natural variability (e.g., Lindsay and Zhang, 2005; Min et al., 2008; Overland et al., 2008), but the contributions from each are still under debate. Kay et al. (2011) estimated with use of a climate model the contribution from anthropogenic forcing and internal variability to the September Arctic sea ice loss, and found that the latter explains about half of the observed loss from 1979 to 2005.

The Arctic sea ice thickness is more difficult to observe, and changes in sea ice thickness thus remains less documented than for sea ice area. Submarine observations document a change from ~3.5 m in the 1960s to ~2.0 m in the 1990s in the central parts of the Arctic Ocean, suggesting a massive loss of sea ice mass before the sea ice area loss started to accelerate (Yu et al., 2004). Satellite data supports such a large loss of sea ice mass, as it shows that the trend for thick multiyear winter sea ice area is a loss of −17.2% per decade since 1979 (Comiso, 2012), and confirms that the mean thickness during the last decade was around 2 m (Kwok and Rothrock, 2009).

Various mechanisms have been suggested to explain parts of the sea ice loss. Observations of surface air temperature indicate a warming mainly consistent with the reduction in sea ice cover...
Other mechanisms that have been suggested are increased ocean heat transport from the Atlantic (e.g., Kinnard et al., 2011; Polyakov et al., 2010) or the Pacific Ocean (Woodgate et al., 2010), circulation and heat advection in the atmosphere (e.g., Maslanik et al., 2007; Serreze et al., 2007), local radiative processes (e.g., Francis et al., 2005), and an increasing ice area export in the Fram Strait (Smedsrud et al., 2011).

Projections from global climate models suggest that the Arctic could be sea ice free during summer sometime between 2040 and 2100 depending on the future release of greenhouse gases, the choice of a model, and natural variability within the model (Eisenman et al., 2007; Stroeve et al., 2007; Wang and Overland, 2009; Stroeve et al., 2012). A recent study of CMIP5 models (also used herein) shows that the timing of an ice free summer Arctic can be constrained. By applying simulated sea ice properties from the period 1979–2010, the timing is reduced to the period 2041–2060 in a high forcing scenario (Massonnet et al., 2012).

The Fram Strait, between Greenland and Svalbard, is the widest and deepest passage between the Arctic Ocean and the rest of the world oceans (Fig. 1). Annually, about 10% of the sea ice area within the Arctic Basin is exported here, and the ice export through the other Arctic gateways is an order of magnitude smaller (Kwok, 2009). The ice export is largely driven by the local wind (Vinje, 2001). An increase of the ice export during the 1990s likely drove some of the thinning during that decade (Vinje, 2001), but generally, no long-term trend in ice export has been found (Vinje, 2001; Kwok, 2009). However, a recent study found a higher export of ice in the 2000s than in any decade since the 1950s (Smedsrud et al., 2011). Such an increase would have a significant influence on the Arctic mean sea ice thickness (Vinje, 2001; Björk, 1997; Smedsrud et al., 2008; Stranne and Björk, 2011).

In this paper, we explore connections between the southward ice export in the Fram Strait and the reduction of Arctic sea ice in a set of CMIP5 models. To achieve this, we first assess the simulated historical Arctic sea ice area and thickness and then the simulated Fram Strait ice export. Afterwards we test the hypothesis that the ice area or volume export through the Fram Strait could be a potential driver for the decline of sea ice area or thickness within the Arctic Basin. The paper is organized as follows. The CMIP5 historical simulations and the observational and reanalysis data are presented in Section 2, followed by a description of the statistical methods used. In Section 3, we discuss and evaluate mean properties, seasonal cycles and long-term trends of the different variables separately. In Section 4, relationships between the Fram Strait ice area or volume export, and Arctic Basin sea ice area or thickness, are discussed. Finally, the main conclusions from this study are drawn in Section 5.

2. Model simulations, observations and methods

2.1. CMIP5 historical simulations

This study is based on Global Climate and Earth System Models simulations from the fifth phase of the Coupled Model Intercomparison Project CMIP5 (Taylor et al., 2012). The CMIP5 multi-model ensemble provide a range of different experiments. Herein we have used the historical experiment, which is a simulation of the recent past (1850–2005). Not all models have available output data to calculate the ice export through the Fram Strait. In this study we have examined six models, including 24 ensemble members, with Fram Strait ice export. The analysis is confined to the period 1957–2005, which overlaps the time period with available estimates of the Fram Strait ice area export. However, when comparing simulated and observed sea ice area we have used the period 1979–2005, since satellite data of sea ice concentration is available from 1979. Most models provide at least three ensemble members for this experiment, while some only provide one. Table 1 gives an overview of the models used, and the number of ensemble members for each model.

In this study we have focused on the following properties of the CMIP5 Northern Hemisphere sea ice: geographical distribution of sea ice, integrated area and volume, and area weighted thickness (i.e., thickness is multiplied by the area of the corresponding grid cell and divided by the total sea ice area). The sea ice volume and thickness is only given for the Arctic Basin. The Arctic Basin is defined here as the region north of 70°N, where the Canadian Arctic Archipelago, the Nordic Seas, and the Barents Sea have been excluded (see blue shaded area in Fig. 1). The sea ice thickness is obtained by dividing the Arctic Basin sea ice volume by the area where sea ice is present (thickness larger than 0 m). The sea ice area fraction is either integrated over the Arctic Basin or north of 40°N. Regarding the latter, sea ice area fraction in grid cells with sea ice concentration less than 15% have been excluded, and is in the following referred to as the ‘Northern Hemisphere sea ice area’.

The variance is reduced when calculating the ensemble mean, i.e., internal variability is averaged out and if enough ensemble members are included the ensemble mean constitutes the externally forced response to a signal. In order to preserve the variance in time series, figures usually show each ensemble member. Exceptions are made in Figs. 1–4 and 8–9 when evaluating the mean sea ice cover and the mean seasonal cycles over longer time periods. Note that lagged correlations are calculated for each individual ensemble member (Fig. 13), but the plotted correlation coefficients are averaged over the ensemble members as described in Section 2.5.

The CMIP5 models are constrained by external forcing (e.g., solar forcing and CO₂), but from the starting point they are free to follow their own simulated climate (i.e., their own dynamics). The
Table 1
List of models included in this study.

<table>
<thead>
<tr>
<th>Model name</th>
<th>N*</th>
<th>Modeling group</th>
</tr>
</thead>
<tbody>
<tr>
<td>NorESM1-M</td>
<td>3</td>
<td>Norwegian Climate Centre</td>
</tr>
<tr>
<td>CNRM-CMS</td>
<td>10</td>
<td>Centre National de Recherches Meteorologiques/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Centre Europeen de Recherche et Formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avances en Calcul Scientifique</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>3</td>
<td>Max Planck Institute for Meteorology</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>5</td>
<td>Meteorological Research Institute</td>
</tr>
<tr>
<td>ACCESS1–3</td>
<td>1</td>
<td>The Centre for Australian Weather and Climate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Research</td>
</tr>
<tr>
<td>MPI-ESM-P</td>
<td>2</td>
<td>Max Planck Institute for Meteorology</td>
</tr>
</tbody>
</table>

N* = number of ensemble members in the historical simulations (1957–2005).

models’ temporal evolution is thus not expected to follow that of the actual natural climate. Despite this, a comparison of the simulations and the observations can provide valuable information on three different aspects; how well (1) the absolute value, (2) the variance, and (3) the trends, are reproduced by the models.

2.2. Calculation of Fram Strait ice export in CMIP5 models

The Fram Strait ice area and volume export at 79°N are not explicit output variables in the CMIP5 data base, and therefore need to be calculated for each ensemble member. The ice area export $F_A$ (m²/s) and the ice volume export $F_V$ (m³/s) at 79°N are obtained using monthly fields of sea ice and snow mass flux per boundary length $M$ (kg/s), sea ice and snow mass per unit area $m$ (kg/m²), sea ice concentration $c$, and sea ice thickness $h$ (m) and the length of the section at 79°N $l$ (m):

$$
F_A = \int_0^l c M_{north} \frac{dl}{m}
$$

$$
F_V = \int_0^l c M_{north} \frac{h dl}{m}
$$

To handle the differently stacked, stretched and rotated grids of the CMIP5 models the following procedure was followed. First mass transport vector fields were normalized by the grid cell boundary lengths, then rotated to longitude-latitude grid, and at the end each variable was separately interpolated to a line between Greenland and Svalbard along 79°N. Some of the models (MPI-ESM-LR, MRI-CGCM3, NorESM1-M) also provided sea ice velocity fields as daily data. The low-resolution MPI-ESM-LR model was chosen as a worst case test for possible interpolation errors by comparing monthly fluxes calculated from daily sea ice velocity fields with monthly fluxes calculated as described above. In both cases data were interpolated from the respective stacked grid points of each variable to 79°N, where the fluxes were calculated. Due to the different grid locations of the variables this tested both the effects of interpolation and for the effects of using monthly versus daily data. The comparison showed essentially identical results. Differences between the two calculation methods are noise-like and account for less than 5% of the calculated monthly fluxes. Note that this applies for climate model simulations and that there might be larger differences when using observations, which have more temporal variability on a daily time scale.
2.3. Observations

2.3.1. Arctic sea ice area

Monthly sea ice cover from 1979 to 2005 is estimated from passive microwave satellite data on a 25 km x 25 km grid from the National Snow and Ice Data Center NSIDC (Cavalieri et al., 1996). We have chosen to use the NASA Team algorithm estimates of sea ice concentration, which is one of the most developed algorithms. There are, however, a number of different algorithms available, and the difference among the algorithms is quite large. For example, in September the difference regionally can reach up to 40% in daily sea ice concentration. However, the trends over a 30 years period are quite similar among the algorithms (Ivanova et al., 2013, in progress). The raw data are derived from two multichannel microwave sensors, SMMR and SSMI, and the NASA Team algorithm is described in Cavalieri et al. (1999).

2.3.2. Fram Strait ice area export

High resolution Fram Strait ice area export observations are based on a Synthetic Aperture Radar (SAR) time series covering the period 2004–2010 (Smedsrud et al., 2011). The SAR images were used to track individual floes every three days manually. A high correlation between ice drift speed and geostrophic wind allowed for estimates of the ice area export for an extended period. Using re-analysis geostrophic wind from NCEP, the overall trend in ice area export between 1957 and 2010 was estimated to 4.9% per decade (Smedsrud et al., 2011). This trend was driven by an increase in the ice drift speed from 10 cm/s to 12 cm/s. The increase in ice drift is large enough to counteract the effect of a decrease in the sea ice concentration for the exported sea ice. The trend in ice area export is largely caused by low values during the 1960s, when no satellite observations exist, and the high values since 2004 when SAR images were used. As will be shown later, there is also a trend when only using data up to 2005. Annual values of the ice area export for the period 1980–2000 are similar to the estimates of Kwok (2009).

2.4. Taylor diagram

The Taylor diagram is a useful tool to quantify a comparison between observed and simulated variables (Taylor, 2001). The diagrams presented here concentrate on the seasonal cycle and show three aspects of the comparison: the skill of the model to reproduce (1) the timing of the observed variable (i.e., correlation coefficient), (2) the variance of the observed variable (i.e., standard deviation), and (3) the root mean square (rms) difference between the simulated and observed variable. The less distance between model data and observational data in the diagram, the better the model performance.

2.5. Statistical methods

The time series were linearly detrended prior to calculating correlations. The significance level is calculated by the standard Student’s t-test (e.g., O’Mahony, 1986) and shows whether or not the correlations are significantly above the 95% confidence level. We are using several ensemble members from each model, and the differences between them are the initial conditions, except for MRI-CGCM3. Two of the ensemble members from this model are different, both due to the initial conditions and to the perturbed sulfate aerosols physics (Seiji Yukimoto, personal communication). To calculate an average of the correlation coefficients from different ensemble members, the coefficients have been converted into additive measures, in this case z values using the Fisher transformation (Fisher, 1915, 1921). The 95% significance level is calculated in the same manner as for the single ensemble members, except that the number of degrees of freedom (N) is changed to N−1 (number of ensemble members).

Fig. 4. Taylor diagram of seasonal cycle of Northern Hemisphere sea ice area for the period 1979–2005 for CMIP5 models (D-I, ensemble means). Number in parentheses indicate number of ensemble members included. The x-axis is the same as the y-axis, showing the standard deviation. The root mean square (rms) difference between the simulated (D-I) and observed variable (A) is proportional to their distance apart.
Error estimates of all long-term trends are calculated according to the method presented in Santer et al. (2008). Here the effective degrees of freedom is a function of the auto-correlation at one year time lag. The time series are detrended before calculating the auto-correlation. Following Santer et al. (2008), pairwise p-tests were used to evaluate the trends.

The least square linear fits of the trends in Section 4.3 are based on 5000 Monte Carlo runs to account for the uncertainty of both X and Y values in the linear regression. The uncertainty in the least square linear fit (see equation in Figs. 11 and 14) comes from the standard deviation of the 5000 different least square linear fits. For each Monte Carlo run, trends are randomly chosen from a Gaussian distribution covering the error estimates of the X and Y values in the linear regression. The fitted relationships is significant at a level of 94%.

3. Evaluation of a subset of CMIP5 models

3.1. Arctic sea ice properties (distribution, area, thickness)

In this section, Northern Hemisphere sea ice properties in six CMIP5 models are assessed, including the simulated export of sea ice in the Fram Strait (Fig. 1). Both the seasonal cycle, inter-annual variance, and long-term trends of the different variables are presented. The spatial distributions of the simulated sea ice cover for March and September are shown in Fig. 2. For March, when the sea ice cover is at the annual maximum, all models show a fully sea ice covered Arctic Ocean for the period 1979–2005. All models correctly simulate an ice free area in the Norwegian and Barents Seas, except MRI-CGCM3 that has a sea ice cover extending too far south in the Atlantic sector (Fig. 2a). In the Pacific sector, the sea ice in CNRM-CM5 also advances too far south. The sea ice in both of these models cover regions that have never been sea ice covered during the satellite era.

In September, the observed sea ice retreats north towards the Arctic Ocean proper, apart from the Fram Strait. In contrast to the observed sea ice, some models (NorESM1–M, CNRM-CM5, MRI-CGCM3, ACCESS1–3) have a larger sea ice cover in all or some of the following regions: the Barents Sea, Kara Sea, Nordic Seas, and in the Baffin Bay west of Greenland (Fig. 2b). These models, except NorESM1–M, have a smaller sea ice covered region than the observed sea ice in the Beaufort, Chukchi Sea, and East Siberian Sea. Hence, NorESM1–M is the model with largest overestimate of the sea ice cover in September.

The seasonal cycle of the Northern Hemisphere sea ice area averaged over the period 1979–2005 is shown for the six models in Fig. 3. The timings of the maximum and minimum sea ice area in the models are similar to the observed timings; maximum in February or March and minimum in August or September. This is no surprise, as the seasonal cycle is largely forced by the strong seasonal cycle of solar radiation. Since CNRM-CM5 and MRI-CGCM3 have a too extensive March sea ice cover, these models have the largest overestimation of the seasonal cycle amplitude (Fig. 3). On the other hand, NorESM1–M is the one that most largely underestimates the seasonal cycle amplitude, due to the too large sea ice cover in the Atlantic sector in September. For the other

---

**Fig. 5.** Time series of Northern Hemisphere March sea ice area for six CMIP5 models, showing all ensemble members (grey lines). The coloured lines highlight one ensemble member from each model, where the time series have been smoothed by a 11-yr running mean. These lines demonstrate the long-term trend in the sea ice area, whereas the grey lines illustrate the interannual variability. The vertical end bars show 2 standard deviation of the ensemble member with the lowest and highest variance, whereas 2 standard deviation of the satellite observations (NSIDC) is shown as the middle bar. The standard deviations are calculated for the detrended time series in the period 1979–2005. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 6.** Time series of Northern Hemisphere September sea ice area for six CMIP5 models, showing all ensemble members (grey lines). The coloured lines highlight one ensemble member from each model, where the time series have been smoothed by a 11-yr running mean. These lines demonstrate the long-term trend in the sea ice area, whereas the grey lines illustrate the interannual variability. The largest negative trend is shown by the green curve (member #10 from CNRM-CM5), whereas the red dashed curve shows the largest positive trend (member #3 from MRI-CGCM3). Table 2 gives the trends for the other ensemble members in the period 1979–2005. The vertical end bars show 2 standard deviation of the ensemble member with the lowest and highest variance, whereas 2 standard deviation of the satellite observations (NSIDC) is shown as the middle bar. The standard deviations are calculated for the detrended time series in the period 1979–2005, and are given for all ensemble members in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

three models, the seasonal cycle is well reproduced (Fig. 3). However, the spatial distribution of the September sea ice cover is not well simulated in some regions as discussed above.

A Taylor diagram for the seasonal Northern Hemisphere sea ice area is shown in Fig. 4. All six models have a correlation higher than 0.99 with the observational data. Most of the models have a larger variance in the seasonal cycle than the observational data. This is particularly the case for MRI-CGCM3 (cf. Fig. 2 and Fig. 3). The same models that have the largest variance, also have the largest rms error compared to the observed seasonal cycle.

The temporal evolution of the simulated and observed March Northern Hemisphere sea ice area is shown in Fig. 5, and for September in Fig. 6. For comparison with the observed sea ice area, we focus on the period 1979–2005, which is covered by the passive microwave satellites. The 1979–2005 average of sea ice area for our six models appears quite similar in March (Fig. 5). On the other hand, the spread in September sea ice area (Fig. 6) is smaller than the spread in extent for the 20 models.

The simulated declining trend of the September sea ice area is not straightforward to read from Fig. 6, and the rate of change per decade for the period 1979–2005 is therefore given in Table 2.

![Fig. 7. Annually averaged and area weighted sea ice thickness in the Arctic Basin (see shaded blue area in Fig. 1) for six CMIP5 models, showing all ensemble members (grey lines). The coloured lines highlight one ensemble member from each model, where the time series have been smoothed by a 11-yr running mean. These lines demonstrate the long-term trend in the sea ice area, whereas the grey lines illustrate the interannual variability. The largest negative trend is shown by the red curve (member #1 from NorESM1-M). See Fig. 14 for the trends in the other ensemble members. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)

### Table 2


<table>
<thead>
<tr>
<th>Model name</th>
<th>March (10^6) km(^2)</th>
<th>September (10^6) km(^2)</th>
<th>Std(^a) (10^6) km(^2)</th>
<th>Trend(^b) (10^6) km(^2/10) yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSIDC</td>
<td>13.9</td>
<td>5.2</td>
<td>0.3</td>
<td>-0.6 ± 0.1</td>
</tr>
<tr>
<td>NorESM1-M (#1)</td>
<td>13.2</td>
<td>6.8</td>
<td>0.3</td>
<td>-0.4 ± 0.1</td>
</tr>
<tr>
<td>NorESM1-M (#2)</td>
<td>13.1</td>
<td>6.8</td>
<td>0.3</td>
<td>-0.3 ± 0.1</td>
</tr>
<tr>
<td>NorESM1-M (#3)</td>
<td>13.3</td>
<td>6.8</td>
<td>0.4</td>
<td>-0.2 ± 0.1</td>
</tr>
<tr>
<td>CNRM-CM5 (#1)</td>
<td>16.5</td>
<td>5.0</td>
<td>0.6</td>
<td>-0.8 ± 0.2</td>
</tr>
<tr>
<td>CNRM-CM5 (#2)</td>
<td>15.8</td>
<td>4.3</td>
<td>0.8</td>
<td>-0.2 ± 0.4</td>
</tr>
<tr>
<td>CNRM-CM5 (#3)</td>
<td>16.2</td>
<td>4.8</td>
<td>0.6</td>
<td>-0.7 ± 0.2</td>
</tr>
<tr>
<td>CNRM-CM5 (#4)</td>
<td>15.8</td>
<td>4.7</td>
<td>0.7</td>
<td>-0.6 ± 0.3</td>
</tr>
<tr>
<td>CNRM-CM5 (#5)</td>
<td>16.1</td>
<td>4.7</td>
<td>0.7</td>
<td>-0.8 ± 0.4</td>
</tr>
<tr>
<td>CNRM-CM5 (#6)</td>
<td>16.3</td>
<td>5.0</td>
<td>0.6</td>
<td>-0.6 ± 0.6</td>
</tr>
<tr>
<td>CNRM-CM5 (#7)</td>
<td>16.9</td>
<td>4.8</td>
<td>0.8</td>
<td>-1.5 ± 0.3</td>
</tr>
<tr>
<td>CNRM-CM5 (#8)</td>
<td>16.0</td>
<td>4.6</td>
<td>0.8</td>
<td>-0.4 ± 0.2</td>
</tr>
<tr>
<td>CNRM-CM5 (#9)</td>
<td>15.7</td>
<td>4.5</td>
<td>0.7</td>
<td>-0.8 ± 0.2</td>
</tr>
<tr>
<td>CNRM-CM5 (#10)</td>
<td>16.3</td>
<td>4.9</td>
<td>0.9</td>
<td>-1.6 ± 0.5</td>
</tr>
<tr>
<td>MPI-ESM-LR (#1)</td>
<td>13.6</td>
<td>5.2</td>
<td>0.4</td>
<td>-0.4 ± 0.1</td>
</tr>
<tr>
<td>MPI-ESM-LR (#2)</td>
<td>13.6</td>
<td>5.3</td>
<td>0.5</td>
<td>+0.1 ± 0.3</td>
</tr>
<tr>
<td>MPI-ESM-LR (#3)</td>
<td>13.5</td>
<td>5.0</td>
<td>0.4</td>
<td>-0.4 ± 0.2</td>
</tr>
<tr>
<td>MRI-CGCM3 (#1)</td>
<td>18.9</td>
<td>5.2</td>
<td>0.8</td>
<td>-0.4 ± 0.4</td>
</tr>
<tr>
<td>MRI-CGCM3 (#2)</td>
<td>19.1</td>
<td>5.5</td>
<td>0.8</td>
<td>+0.1 ± 0.4</td>
</tr>
<tr>
<td>MRI-CGCM3 (#3)</td>
<td>19.0</td>
<td>5.3</td>
<td>0.6</td>
<td>+0.2 ± 0.1</td>
</tr>
<tr>
<td>MRI-CGCM3 (#4)</td>
<td>18.9</td>
<td>5.4</td>
<td>1.2</td>
<td>-0.3 ± 0.4</td>
</tr>
<tr>
<td>ACCESS1-3</td>
<td>13.9</td>
<td>5.5</td>
<td>0.6</td>
<td>-0.4 ± 0.2</td>
</tr>
<tr>
<td>NSIDC</td>
<td>13.5</td>
<td>4.7</td>
<td>0.5</td>
<td>-0.4 ± 0.2</td>
</tr>
<tr>
<td>MRI-ESM-P (#1)</td>
<td>13.5</td>
<td>4.5</td>
<td>0.7</td>
<td>-0.7 ± 0.5</td>
</tr>
</tbody>
</table>

\(^a\) Standard deviation (Std) of the detrended September sea ice area.

\(^b\) Trends from least squares line fit of the September sea ice area. The simulated trends that are significantly different from the observed trend are given in bold font.

The observed sea ice area is reduced by $0.6 \times 10^6$ km$^2$ per decade, whereas the models range from an increase of 0.2 to a reduction of $1.6 \times 10^6$ km$^2$ per decade. The difference in the trends among individual ensemble members for each model is an expression of the internal variability within that model. For instance, CNRM-CM5 has a large spread in the trends ($-1.6$ to $-0.3 \times 10^6$ km$^2$ per decade, Table 2) caused by the different initial conditions in the model. The ensemble member with the largest negative trend is highlighted in Fig. 6 (green curve). In addition, three of the 24 ensemble members have a positive trend in the sea ice area (Table 2). The simulated trends that are significantly different from the observed trend are given in bold in Table 2. Later we will show the 1957–2005 trends of the September sea ice area (Fig. 6), and all six of our models show a loss in sea ice. This indicates that simulated internal variability for a few decades may produce an increase in September sea ice area, but taking the longer time average produces the expected response to the external forcing – a loss of ice (Kay et al., 2011).

In the following, the focus is on the Arctic Basin sea ice (Fig. 1) instead of the Northern Hemisphere sea ice. The temporal evolution of the simulated annually averaged sea ice thickness in the Arctic Basin is shown in Fig. 7. The ensemble members cluster in two groups, with NorESM1-M having an ensemble mean thickness of 3.3 m, and the other models having an ensemble mean thickness between 1.5 and 2.0 m. Clearly, there are large differences in the sea ice thickness between the models. Apart from three ensemble members (NorESM1-M #3, MRI-CGCM3 #1 and #2), the remaining 21 members demonstrate a decline in the sea ice thickness. The overall mean thinning in the models for the period 1957–2005 is $-0.4$ m, and the range in linear trends are $-0.9$ m to $+0.2$ m for the different ensemble members. See Fig. 14 for the decadal trend in each of the ensemble members.

None of the six models are close to reproducing the estimated thinning from available thickness observations of the Arctic sea ice since the 1960s (Kwok and Rothrock, 2009). Although observations of thickness are limited, we know that the mean Arctic sea ice thickness decreased from above 3 m to $-$1.4 m from the 1960s to the 2000s (Yu et al., 2004; Kwok and Rothrock, 2009). NorESM1-M has a mean thickness close to that of the 1960s, while the others are close to today’s lower mean thickness.

### 3.2. Fram Strait ice export

The simulated seasonal Fram Strait ice area export is compared with the observed (SAR) and estimated (NCEP proxy) ice area export in Fig. 8. The observed ice export is high from October to April and low from May to September. Perhaps surprisingly, the models do reproduce this seasonal cycle with larger export during the winter, and smaller during the summer. This seasonal cycle is caused by seasonality in the ice speed related to winds and ocean currents above and below the ice, respectively, and is not directly caused by solar radiation.

![Fig. 8. Seasonal cycle of Fram Strait ice area export for satellite observations (SAR), six CMIP5 models for the period 1957–2005 (ensemble means), and NCEP proxy. Numbers in parentheses indicate the number of ensemble members and the data periods for satellite observations and proxy. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)](image1)

![Fig. 9. Taylor diagram of seasonal cycle of Fram Strait ice area flux for six CMIP5 models (D-I, ensemble means) over the same time periods as given in Fig. 8. Number in parentheses indicate number of ensemble members included. The x-axis is the same as the y-axis, showing the standard deviation. The root mean square (rms) difference between the simulated (D-I) and observed variable (A) is proportional to their distance apart.](image2)
Note that the seasonal cycle is averaged over different time periods for the different data, as indicated in Fig. 8. The temporal overlap of the CMIP5 simulations and the observed (SAR) ice area export is very small. However, both can be directly compared to the NCEP proxy, which covers both time periods. The NCEP proxy underestimates the ice export during winter and overestimates during summer, producing a smaller amplitude of the seasonal cycle than the observed seasonal cycle. Comparison of the NCEP proxy for the two time periods shows no qualitative differences for the climatologies of the seasonal cycle in 1957–2005 and 2004–2010, respectively. This justifies using the observed seasonal climatology (SAR) as the baseline for the CMIP5 model evaluation. Due to the limited time series of the SAR data, NCEP data is used as a proxy for the ice area export for the period 1957–2005 (Smedsrud et al., 2011). The simulated inter-annual variability of the seasonal cycle is averaged over different time series, is comparable to the variability in the NCEP proxy (Table 3). Most models overestimate the inter-annual variance, which can be up to twice the standard deviation of the NCEP based time series. The four models that have the largest inter-annual variance (Table 3), are the same models that have larger ice export during winter and early spring than the observations (cf. Fig. 8). In the long-term mean, the ice area export is overestimated in five of our six models with 32–84%, whereas MRI-CGCM3 underestimates the ice area export by 16% (Fig. 10 and Table 3). The overestimated values in the simulations are mostly caused by excess export during winter (cf. Fig. 8). Rawlins et al. (2010) evaluated nine CMIP3 models and found a similar result; the simulated export was higher than the observations available at that time (Kwok, 2009). The mean export of the older CMIP3 models is actually quite close to the new high values based on the SAR tracking between 2005 and 2010, ~0.9 × 10⁶ km²/yr (Table 3). The mean level of the new CMIP5 models is even higher, and there has thus been no improvement of ice area export between CMIP3 and CMIP5.

The simulated trends in the Fram Strait ice area export over the period from 1957 to 2005 are shown in Fig. 11., together with the simulated decline in the Arctic Basin September sea ice area for the same period. All models have a negative trend for the September sea ice area, but trends are either positive or negative for the Fram Strait ice area export, and range between a decrease of 0.04 × 10⁶ km²/yr and an increase of 0.07 × 10⁶ km²/yr per decade. The NCEP based trend gives an increase of 0.03 × 10⁶ km²/yr per decade. Eight of the 24 ensemble members have an ice export trend that is significantly different from the NCEP trend at the 95% level.

### 4. Relationship between Fram Strait ice export and Arctic Basin sea ice

The second goal of this study is to test the hypothesis that the Fram Strait ice export could be a potential driver for the decline of sea ice area or thickness within the Arctic Basin. We therefore investigate relationships between the Fram Strait ice area or

<table>
<thead>
<tr>
<th>Model name</th>
<th>Mean a [10⁶ km² yr⁻¹]</th>
<th>Std (area)b [10⁶ km² yr⁻¹]</th>
<th>Std (volume)b [10¹² m³ yr⁻¹]</th>
<th>Std (ABvolume)c [10¹² m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR (2005–2010)</td>
<td>0.90</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCEP (1957–2005)</td>
<td>0.75</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NorESM1-M (#1)</td>
<td>0.96</td>
<td>0.11</td>
<td>0.74</td>
<td>1.71</td>
</tr>
<tr>
<td>NorESM1-M (#2)</td>
<td>1.01</td>
<td>0.15</td>
<td>0.80</td>
<td>1.85</td>
</tr>
<tr>
<td>NorESM1-M (#3)</td>
<td>0.99</td>
<td>0.11</td>
<td>0.69</td>
<td>1.28</td>
</tr>
<tr>
<td>CNRM-CM5(#1)</td>
<td>1.28</td>
<td>0.14</td>
<td>0.19</td>
<td>0.93</td>
</tr>
<tr>
<td>CNRM-CM5(#2)</td>
<td>1.27</td>
<td>0.17</td>
<td>0.25</td>
<td>0.88</td>
</tr>
<tr>
<td>CNRM-CM5(#3)</td>
<td>1.21</td>
<td>0.14</td>
<td>0.22</td>
<td>1.03</td>
</tr>
<tr>
<td>CNRM-CM5(#4)</td>
<td>1.26</td>
<td>0.14</td>
<td>0.20</td>
<td>1.16</td>
</tr>
<tr>
<td>CNRM-CM5(#5)</td>
<td>1.28</td>
<td>0.16</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>CNRM-CM5(#6)</td>
<td>1.25</td>
<td>0.15</td>
<td>0.27</td>
<td>0.83</td>
</tr>
<tr>
<td>CNRM-CM5(#7)</td>
<td>1.16</td>
<td>0.16</td>
<td>0.22</td>
<td>0.99</td>
</tr>
<tr>
<td>CNRM-CM5(#8)</td>
<td>1.29</td>
<td>0.16</td>
<td>0.23</td>
<td>0.72</td>
</tr>
<tr>
<td>CNRM-CM5(#9)</td>
<td>1.28</td>
<td>0.16</td>
<td>0.23</td>
<td>0.88</td>
</tr>
<tr>
<td>CNRM-CM5(#10)</td>
<td>1.25</td>
<td>0.19</td>
<td>0.30</td>
<td>1.15</td>
</tr>
<tr>
<td>MPI-ESM-LR (#1)</td>
<td>1.25</td>
<td>0.23</td>
<td>0.48</td>
<td>0.96</td>
</tr>
<tr>
<td>MPI-ESM-LR (#2)</td>
<td>1.27</td>
<td>0.20</td>
<td>0.42</td>
<td>0.99</td>
</tr>
<tr>
<td>MPI-ESM-LR (#3)</td>
<td>1.32</td>
<td>0.19</td>
<td>0.47</td>
<td>0.96</td>
</tr>
<tr>
<td>MRI-CGCM3(#1)</td>
<td>0.65</td>
<td>0.11</td>
<td>0.10</td>
<td>1.25</td>
</tr>
<tr>
<td>MRI-CGCM3(#2)</td>
<td>0.65</td>
<td>0.14</td>
<td>0.12</td>
<td>1.17</td>
</tr>
<tr>
<td>MRI-CGCM3(#3)</td>
<td>0.64</td>
<td>0.12</td>
<td>0.10</td>
<td>1.15</td>
</tr>
<tr>
<td>MRI-CGCM3(#4)</td>
<td>0.61</td>
<td>0.12</td>
<td>0.10</td>
<td>1.40</td>
</tr>
<tr>
<td>MRI-CGCM3(#5)</td>
<td>0.66</td>
<td>0.14</td>
<td>0.11</td>
<td>1.57</td>
</tr>
<tr>
<td>ACCESS1–3</td>
<td>1.36</td>
<td>0.18</td>
<td>0.62</td>
<td>1.05</td>
</tr>
<tr>
<td>MPI-ESM-P (#1)</td>
<td>1.35</td>
<td>0.20</td>
<td>0.45</td>
<td>1.41</td>
</tr>
<tr>
<td>MPI-ESM-P (#2)</td>
<td>1.30</td>
<td>0.19</td>
<td>0.41</td>
<td>1.28</td>
</tr>
</tbody>
</table>

All standard deviations (std) are calculated for detrended time series.

a Std and mean of ice area export.
b Std of ice volume export.
c Std of annually averaged sea ice volume in the Arctic Basin.

volume export, and the Arctic Basin sea ice area or thickness in three different ways: (1) comparison of the mean state in the ensemble members and models, (2) lagged correlations, and (3) comparison of long-term trends.

4.1. Mean state

The mean state in different decades are compared between the different ensemble members of our six models in Fig. 12. The simulated ice area export is integrated over a year, and given as a fraction of the total area of the Arctic Basin (8 \times 10^6 km^2). The total ice area export per year is between 6% and 18% of the total Arctic Basin area in the six models. The same calculation for the NCEP proxy give values between 8 and 10%. Note that if we use the area of the observed September sea ice in 2005 (about 4.5 \times 10^6 km^2, Fig. 6) instead of the area of the entire Arctic Basin, the ice area export (calculated in percent of the area) would be almost twice as high. Estimates of ice area export (from NCEP) and of the observed sea ice thickness in the Arctic Basin illustrate the

Fig. 10. Time series of annually averaged Fram Strait ice area export for six CMIP5 models, showing all ensemble members, and the NCEP proxy for the period 1957–2005. The coloured lines highlight one ensemble member from each model. The largest positive trend is shown by the green curve (member #7 from CNRM-CM5), whereas the blue curve shows the largest negative trend (member #2 from MPI-ESM-LR). See Fig. 11 for the trends in the other ensemble members. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. Trends in annually averaged Fram Strait ice area export and Arctic Basin September sea ice area in 1957–2005. The trends are shown for each ensemble member for six CMIP5 models, indicated by different colours. The grey lines illustrate the error estimates of the trends. The least square linear fit for CNRM-CM5, and the corresponding equation is shown in green. The least square linear fit is based on 5000 Monte Carlo runs to account for the uncertainty of the trends. The vertical black dashed line indicate the NCEP proxy trend (0.027 \times 10^6 km^2/year per decade). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Simulated mean sea ice thickness within the Arctic Basin and annually averaged Fram Strait area export per year for different time segments, as indicated in the legend. The ice area export is given as a fraction of the total area over the Arctic Basin (8 \times 10^6 km^2). The black markers illustrate the estimated mean thickness in the central Arctic Ocean from available observations in the periods 1958–76 (circle), 1993–97 (plus), and 2003–07 (triangle). The estimated thickness is taken from Kwok and Rothrock (2009) and represents the end of the melt season. We have added 0.5 m to this thickness to estimate the annual mean thickness.
increase in ice export and the decrease in sea ice thickness that has occurred since the 1960s (black symbols in Fig. 12).

The ‘1960s state’ with low ice area export and thick sea ice is exemplified by NorESM1-M, and within the different ensemble members a linear inverse relationship appears where higher ice area export is associated with lower ice thickness. The recent thinner state with higher export is exemplified by MPI-ESM-LR, MPI-ESM-P, CNRM-CM5, and ACCESS1–3 (Fig. 12). These models export 1–7% more than NorESM1-M and have a mean thickness of 1.5–1.8 m, or that of the ‘2000s state’. A transition to higher ice export and thinner mean sea ice thickness has occurred in nature, but the models do not show this transition. However, among the models, except MRI-CGCM3, there appear to be a linear inverse relationship between the ice export and sea ice thickness. MRI-CGCM3 has an ice area export comparable to the 1960s level, and yet a sea ice thickness comparable to 2000s conditions. Some other processes must maintain a low ice thickness in the mean state, despite the also low ice export. Note that this model is the one that poorly reproduces the seasonal cycle of the ice export (Fig. 8), and that overestimates the winter sea ice cover (Fig. 2a). These characteristics make this model an outlier in our analysis.

The situation in the five other models (NorESM1-M, MPI-ESM-LR, MPI-ESM-P, ACCESS1–3, and CNRM-CM5) confirms earlier sensitivity studies using column models. Björk (1997) found that a doubling of the ice area export leads to a loss of about 1 m of sea ice in a steady state climate based on Arctic boundary conditions of the 1990s. Smedsrud et al. (2008) found that a mean Arctic Basin sea ice thickness of about 1 m could be maintained in a steady state solution of this model when forced with a 35% increase in sea ice area export, 40 TW of increased ocean heat transport, and a moderately increased level of long-wave radiation due to global warming. With only the global warming related long-wave forcing the ice thickness increased to about 2 m over 10 years (Smedsrud et al., 2008).

4.2. Inter-annual variability

From lagged correlations, a relationship between the Fram Strait ice area export and the Arctic Basin sea ice thickness was found. The correlations are significant but low for all six models (upper panel in Fig. 13); an increase in the ice export is followed by a decrease in the sea ice thickness. Ice export leads with one year for four models, two years for MRI-CGCM3, and five years for MPI-ESM-P. The highest significant negative correlation is −0.37, and the lowest is −0.13. Ice export through Fram Strait is only one process beside a number of other processes (e.g., freezing, melting, ice dynamics) that steer Arctic Basin sea ice variations on an inter-annual time scale, and accordingly explains only a moderate part of the variance on this time scale. The relative strength of these processes on longer times scales might scale differently, however, and will be investigated in Section 4.3. If the sea ice thickness is replaced with the sea ice volume, the lagged correlations show more or less the same result. This means that the inter-annual variability of the sea ice volume is caused by changes mainly in the sea ice thickness, and not the sea ice area.

There is also a significant negative correlation between the Fram Strait ice area export during spring and summer (March–August) and the September sea ice area in the Arctic Basin (not shown). The maximum correlations are now mainly found at zero time lag, but the correlations are of similar magnitude as for those
above, except for MPI-ESM-P and ACCESS1–3. There is no significant negative correlation for MPI-ESM-P, whereas the negative correlation for ACCESS1–3 increases to −0.59. These correlations become lower for annually averaged time series. This ‘fast response’ for the sea ice area compared to sea ice thickness could be related to the fact that open water due to removal of sea ice refreezes quickly, whereas thick sea ice takes longer time to grow.

The significant negative correlation between the ice area export and sea ice thickness, also holds for the ice volume export in a similar way (lower panel in Fig. 13). The largest significant negative correlation is −0.40, and the lowest is −0.13. However, for CNRM-CM5 there is no significant negative correlation. The correlations are slightly higher between ice area export and thickness than for ice volume export and thickness. In addition, there is a significant positive correlation for three out of six models between sea ice thickness and the ice volume export, where the thickness leads by 1–2 yrs. This finding is more intuitive, stating that an increase in the sea ice thickness within the Arctic Basin leads a higher ice volume export through the Fram Strait with one to two years lag. In this way the ice volume export is potentially both a response to changes within the Arctic Basin, as well as a boundary condition (i.e., the ice export) that drives the changes within the Arctic Basin. However, the more intuitive relationship (with positive correlation) can oppose the relationship with the negative correlation; higher export leads to thinner sea ice, and when the sea ice becomes thinner, the export becomes lower.

In order to directly compare the volume anomalies of the Fram Strait ice export and the Arctic Basin sea ice volume, the standard deviation of the two are given in Table 3. The variations in annual ice volume export are 29% of the sea ice volume variations for the ensemble mean. For some ensemble members it is higher than 50%. The largest ice volume export anomalies vs sea ice volume anomalies is found in NorESM1-M and ACCESS1–3. Considering only CNRM-CM5, the ensemble mean would be 25%, similar to the ensemble mean of all six models. From the evaluation of the six models in Section 3, MRI-CGCM3 is the model that represents most poorly the Northern Hemisphere sea ice both in terms of the seasonal cycle and long-term trend of the sea ice area. If we disregard this model from Table 3, the variations in annual ice volume export becomes 35% of the the sea ice volume variations for the ensemble mean. This means that the variations in the Fram Strait ice volume export are significant compared to the variations in the Arctic Basin sea ice volume.

4.3. Long-term trends

A comparison of the simulated long-term trends (1957–2005) in the Fram Strait ice area export and Arctic Basin September sea ice area is shown in Fig. 11. All 24 ensemble members demonstrate a loss of September sea ice area over this period, although the weakest trend is close to zero. In the period 1957–1979 there seems to be little change in the observed September sea ice extent (Stroeve et al., 2012). The long-term trends for sea ice area are generally not the same as for sea ice extent. However, assuming that this trend is also true for the September sea ice area, an estimated long-term “observed” decline in sea ice area is 0.32 ± 0.06 km² per decade. The ensemble members in Fig. 11 both underestimate this “observed” decline.

Generally, a large positive trend in ice area export is associated with a large loss of September sea ice area (Fig. 11). And vice versa, a negative trend in ice export is associated with a small loss of September sea ice area. The error bars of the trends in Fig. 11 are relatively large, and as mentioned earlier, only eight of the 24 ensemble members have an ice export trend that is significantly different from the NCEP trend at the 95% level. Regarding the Arctic Basin sea ice area, there are 15 ensemble members that are significantly different from the weakest trend.

In the following discussion we mainly concentrate on CNRM-CM5, which is the model with the largest number of ensemble members (10). This model ensemble therefore allows us to do some more robust statistics on the relationship between Arctic Basin sea ice area and Fram Strait ice export (compared to the other models that have a maximum of five ensemble members). Focusing only on the ten ensemble members from CNRM-CM5, there is a linear inverse relationship between the long-term trends of the two variables (green line in Fig. 11, calculated according to Section 2.5). Although the error bars are large, the robustness of the linear inverse relationship is fairly good. The coefficient of determination for the least square fit is $R^2 = 0.28$. The corresponding physical interpretation is that for the long-term trends, variations in the ice export trends in the ten CNRM-CM5 ensemble members explain 28% of the variations in sea ice area for this model.

A comparison of the long-term trends of Arctic Basin sea ice thickness and Fram Strait ice export is shown in Fig. 14. All ensemble members show a thinning of the Arctic Basin sea ice cover, except for three ensemble members that show a weak increase in the thickness. Comparable to the sea ice area, there are 13 ensemble members that have a trend significantly different from the maximum (positive) trend. The least square fitting of the CNRM-CM5 ensemble members above, is also done for this model’s Arctic Basin sea ice thickness and Fram Strait ice export. The overall pattern is the same as for the trends in September sea ice area, a linear inverse relationship; a large positive trend in the ice export is associated with a strong thinning of the Arctic basin sea ice thickness (see green line in Fig. 14). The differences in the ice export trends are found to explain 28% of the differences in the sea ice thickness for the ten CNRM-CM5 ensemble members (similar to the sea ice area).

We should ideally have had several different models with a large number of ensembles available – to test the robustness of the found relationship across different models. Due to the lack of a sufficient number of ensemble members, we will in the following make some physical interpretations based on CNRM-CM5 alone. The least square linear fit of CNRM-CM5 (green line, Fig. 14) shows that when there is no change in the Fram Strait ice export, the decline in the Arctic Basin sea ice thickness would be 0.09 m per decade. If the simulated Fram Strait ice export had increased with $0.027 \times 10^6$ km²/year per decade (same as the NCEP trend), the decrease in the mean sea ice thickness would be 0.11 m per decade, i.e. an additional thinning of the Arctic Basin sea ice thickness of $19 \pm 11\%$. This means that if the different ensemble members had reproduced a more realistic ice export trend (instead of close to zero or negative), the simulated thinning of the Arctic Basin sea ice would likely be improved for those ensemble members. Similar results from CMIP3 models suggest that an increased ice export would bring those models closer to the observed sea ice thinning (Yu et al., 2004; Rampal et al., 2011). However, to be able to reproduce all of the estimated thinning from available observations, the Fram Strait ice export should be higher than $0.08 \times 10^6$ km²/year per decade (outside the domain in Fig. 14).

In a similar way as for sea ice thickness, an increase in the ice export similar to the NCEP proxy would imply an additional $18 \pm 11\%$ decrease of the September sea ice area. However, the spread of the different models do caution against regarding the sensitivity of Arctic Basin sea ice to Fram Strait ice export established by CNRM-CM5 as correct. This sensitivity is conditioned to the correct representation of the various feedback mechanisms influencing Arctic Basin sea ice besides the Fram Strait ice export. Considering the well-known deficiencies of climate models, such as parameterization of subgrid scale processes (e.g., Liu et al.,...
2003), and also the weak coupling between ice state and ice kinematics that has been found in these models (Rampal et al., 2011), we can expect substantial differences among the various climate models with regard to the modeling of this sensitivity.

It remains unclear if the overall increase in Fram Strait ice area export is connected to global warming, as it is mainly caused by changes in number of atmospheric lows entering the North Atlantic region (Smedsrud et al., 2011). The large differences in the ice export trends among the ensemble members in Fig. 11 and Fig. 14, indicate that the variability in the ice export is driven by internal variability. If it is mostly driven by long-term internal variability, the ice area export might again decrease. What will happen in the next decade if the ice area export goes back to the lower levels of the 1960s? According to CNRM-CM5, this would contribute to a slowing down of both the loss of September sea ice area and Arctic Basin sea ice thickness.

In nature the area between Fram Strait and the North Pole are generally covered with sea ice thicker than the mean over the Arctic Ocean (Haas et al., 2010), and it is this ice that is primarily exported southwards. The simulated sea ice thickness in this region, over the period 1979–2005, is either similar or larger than the mean Arctic Basin sea ice thickness (not shown). Bentsen et al. (2012) shows a NorESM1-M sea ice thickness between 3 and 4 m north of Fram Strait, which is quite close to the observed values. The other models thus seem to be on the thin side north of Fram Strait compared to NorESM1-M (not shown), reflecting the overall differences in mean thickness (cf. Fig. 7). Regardless of the thickness of the simulated ice export, the effect will be a thinning of the Arctic Basin sea ice thickness (cf. negative correlations in Fig. 13b). This is because the exported area will initially leave behind an area of open water with zero ice thickness. However, if the exported ice is very thick it should have a stronger effect on the remaining mean thickness than if the exported ice is thinner. Since the Arctic Basin sea ice thickness is gradually thinning (cf. Fig. 7), a gradually thinner export is also expected to be the case.

5. Conclusions

We have analyzed six of the General Circulations Models, or Earth System Models, from the new Coupled Model Intercomparison Project 5 (CMIP5) for the period 1957–2005. This is a first attempt to analyze Fram Strait ice export in these models, and the role it has played for Arctic Basin sea ice area and thickness. The simulated Fram Strait ice area export in the six models has been evaluated against SAR and reanalysis data (from NCEP). Perhaps surprisingly, five of the six models do reproduce the seasonal cycle with larger export during the winter and smaller during the summer. For these five models the year-to-year variability in Fram Strait ice volume export carries 35% of the year-to-year variability of the Arctic Basin sea ice volume, indicating that the size of ice export changes is significant compared to changes in the Arctic Basin sea ice volume. On the other hand, the different ensemble members do not reproduce the same positive long-term trend as the NCEP data, but have a spread of both negative and positive trends for the ice export.

On inter-annual time scales, the simulated Fram Strait ice area export has a significant negative correlation with the simulated Arctic Basin sea ice thickness. The ice export leads by one year for most of the models. The correlations are weak, emphasizing that the Arctic Basin sea ice variability is mainly steered by other factors on shorter time scales. Our analysis on long-term trends (1957–2005), indicate that the Fram Strait ice area export plays a more important role on longer time scales. The model with the largest number of ensemble members, CNRM-CM5, suggests a linear inverse relationship between the long-term trends of the ice area export and Arctic Basin sea ice area/thickness. For instance, according to this model, an increase of the ice area export similar to the estimated trend (from NCEP) can explain almost 20% of the total simulated decline in sea ice area and thickness. This makes it likely that if the NCEP trend had been captured by the different ensemble members (instead of a trend close to zero or negative), the simulated thinning of the Arctic Basin sea ice would also be closer to the observed thinning for those ensemble members.

Once more available simulations give more confidence, there could be some potential in using the ice area export as a predictor for the Arctic Basin sea ice area/thickness. For this purpose, it is necessary to have a sufficient number of ensemble members from each model to capture the models' internal variability. Our study shows the value of having a large number of ensemble members in order to obtain relative robust statistics for the relationship between the Arctic Basin sea ice and ice area export. In order to better understand the variability in the ice area export, a more thorough investigation of what causes changes in the large-scale atmospheric circulation would be required. A possible, but speculative, interpretation is that the increase in the ice area export is caused by decadal internal variability, and that it will decrease in the future.

Acknowledgements

This study was partly funded by the Centre for Climate Dynamics at the Bjerknes Centre and NFR BlueArc (207650), and is publication A408 from the Bjerknes Centre for Climate Research. We thank two anonymous reviewers for helpful suggestions, Natalia Ivanova for help with processing the NSIDC data, and Anders Sirevaag, Pierre Rampal, and Laurent Bertino for helpful discussion and comments.

We acknowledge the NSIDC for providing satellite data of sea ice concentration and the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP. We also thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organisations for Earth System Science Portals.

References

Johannessen, O.M., Bengtsen, L., Miles, M.W., Kuzmina, S.I., Semenov, V.A., Alekseev, G.V., Nagurny, A.P., Zakharov, V.F., Bolyaeva, I.P., Pettersson, L.H.,
Hasselmann, Cattle, H.P., Arctic climate change: observed and modelled temperature and sea-ice variability. Tellus A 56, 328–341.