

Patterns of Sea Ice Retreat in the Transition to a Seasonally Ice-Free Arctic

PATRICIA DEREPENTIGNY AND L. BRUNO TREMBLAY^a

McGill University, Montreal, Quebec, Canada

ROBERT NEWTON

Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

STEPHANIE PFIRMAN

Barnard College, Columbia University, New York, New York

(Manuscript received 29 September 2015, in final form 27 May 2016)

ABSTRACT

The patterns of sea ice retreat in the Arctic Ocean are investigated using two global climate models (GCMs) that have profound differences in their large-scale mean winter atmospheric circulation and sea ice drift patterns. The Community Earth System Model Large Ensemble (CESM-LE) presents a mean sea level pressure pattern that is in general agreement with observations for the late twentieth century. The Community Climate System Model, version 4 (CCSM4), exhibits a low bias in its mean sea level pressure over the Arctic region with a deeper Icelandic low. A dynamical mechanism is presented in which large-scale mean winter atmospheric circulation has significant effect on the following September sea ice extent anomaly by influencing ice divergence in specific areas. A Lagrangian model is used to backtrack the 80°N line from the approximate time of the melt onset to its prior positions throughout the previous winter and quantify the divergence across the Pacific and Eurasian sectors of the Arctic. It is found that CCSM4 simulates more sea ice divergence in the Beaufort and Chukchi Seas and less divergence in the Eurasian seas when compared to CESM-LE, leading to a Pacific-centric sea ice retreat. On the other hand, CESM-LE shows a more symmetrical retreat between the Pacific, Eurasian, and Atlantic sectors of the Arctic. Given that a positive trend in the Arctic Oscillation (AO) index, associated with low sea level pressure anomalies in the Arctic, is a robust feature of GCMs participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5), these results suggest that the sea ice retreat in the Pacific sector could be amplified during the transition to a seasonal ice cover.

1. Introduction

Significant changes in the Arctic sea ice cover have been observed in recent years, particularly at the end of summer (Stroeve et al. 2007). The decline in minimum sea ice extent has accelerated from approximately -2.2% decade⁻¹

between 1978 and 1996 to -10.1% decade⁻¹ between 1996 and 2007 (Comiso et al. 2008; Serreze and Stroeve 2015). In addition to the loss of area of perennial ice (Tucker et al. 2001), there has been an overall thinning of the Arctic ice cover (Kwok and Rothrock 2009), with a significant decrease in the oldest and thickest ice within the multiyear ice pack (Pfirman et al. 2004; Maslanik et al. 2007). A thin ice cover is more vulnerable to strong summer retreat under anomalous atmospheric forcing or increasing ocean heat transport to the Arctic (Maslanik et al. 1996; Holland et al. 2006; Stroeve et al. 2012b). Moreover, the decrease in areal extent promotes a positive ice–albedo feedback (Perovich et al. 2007a).

The spatial variability of sea ice retreat may also impact global weather patterns. Several studies have associated Arctic sea ice loss with increased storm surge activity and cold winter extremes in North America, Europe, and

 Denotes Open Access content.

^a Additional affiliation: Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York.

Corresponding author address: Patricia DeRepentigny, Department of Atmospheric and Oceanic Sciences, McGill University, 805 Sherbrooke Street West, Montreal, Quebec H3A 0B9, Canada.
E-mail: patricia.derepentigny@mail.mcgill.ca

DOI: 10.1175/JCLI-D-15-0733.1

northern Asia (Maslanik et al. 1996; Petoukhov and Semenov 2010; Francis and Vavrus 2012; Inoue et al. 2012; Tang et al. 2013; Vermaire et al. 2013; Vihma 2014; Francis and Vavrus 2015; Gervais et al. 2016), although the exact nature of this link is still an active area of debate (Barnes 2013; Barnes et al. 2014). While model simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5) offer some evidence that future Arctic warming and sea ice loss may have an effect on the midlatitude jet stream, the net circulation response is unlikely to be explained primarily by Arctic amplification (Barnes and Screen 2015; Barnes and Polvani 2015).

As the summer sea ice retreats, industrial and commercial interests are evolving. Travel time between Europe and the northern ports of Asia can be reduced by 50% when the Northern Sea Route is free of ice (Peters et al. 2011). The length of the navigation season of the Northern Sea Route and Northwest Passage is projected to increase by 173% and 156%, respectively, by the end of the twenty-first century (Khon et al. 2010; Smith and Stephenson 2013). Although oil and gas activity is currently at a relative low, the Arctic holds a large fraction of undiscovered energy resources, which will be increasingly accessible as sea ice retreats and thins (Gautier et al. 2009; Blanken et al. 2015, 2016, manuscript submitted to *Mar. Pollut. Bull.*). The rate and patterns of change of the Arctic ice cover will be of high importance for planning and development, resource management, species preservation, national security, and international environmental monitoring programs (Campbell et al. 2007; Byers 2010).

Many studies have investigated the thermodynamic and dynamic mechanisms driving the observed sea ice retreat (Serreze et al. 2007). For instance, prior to the record sea ice extent minimum of 2007, the oceanic heat fluxes through the Bering Strait reached about twice the average of the prior 7 years, enough to melt one-third of the 2007 estimated total sea ice loss (Steele et al. 2010; Woodgate et al. 2010). In 2007, the Arctic dipole anomaly (with a high-pressure system over the arctic regions of North America) persisted throughout the summer. It led to a strengthening of the Transpolar Drift Stream and ice export through the Fram Strait, leaving open water off the shores of Alaska and Siberia, and to cloud-free skies, allowing for more surface solar heating of the ocean (L'Heureux et al. 2008; Kay et al. 2008; Schweiger et al. 2008; Zhang et al. 2008; Wang et al. 2009; Screen et al. 2011; Overland et al. 2012). Nonetheless, Lindsay et al. (2009) found that the 2007 ice mass loss followed the trend, as the area of thin ice at the beginning of the melt season and the total volume of ice in the summer have been steadily decreasing since 1987.

The large-scale pattern of sea level pressure in the Arctic can be characterized, to first order, by the Arctic Oscillation (AO) (Thompson and Wallace 1998), the first EOF of Northern Hemisphere sea level pressure, or by the northern annular mode (NAM) (Thompson and Wallace 2001), a closely related high-latitude pattern. Rigor et al. (2002) showed that the AO explains 52% of the variance of sea level pressure over the Arctic Ocean during winter. They also suggest that the summer sea ice concentration is correlated with the AO index of the previous winter, reflecting the dynamical influence of the wintertime sea level pressure on thickness distribution. Likewise, Rigor and Wallace (2004) found that more than half of the variance in summer sea ice extent can be explained by the age of the ice pack, a proxy for ice thickness. More recently, Williams et al. (2016) linked the phase of the mean winter (December–March) AO index and the divergence of sea ice away from the Eurasian and Alaskan coastlines ($r = 0.59$). Coastal divergence in turn leads to the formation of thin first-year ice that melts more readily in early summer and a smaller September sea ice extent ($r = -0.66$) (Williams et al. 2016). These results reinforce the idea of potential predictability of the September sea ice extent based on the previous winter mean sea ice circulation (Holland and Stroeve 2011).

Seasonal predictions of Arctic sea ice have been based on a variety of modeling, statistical, and heuristic approaches (Guemas et al. 2014). Stroeve et al. (2014b) found that sea ice concentration is the most important predictor of September sea ice extent between 2008 and 2013 for lead times of 2 months or less, but for longer lead times ocean temperature and sea ice thickness come into play as reemergence mechanisms (Blanchard-Wrigglesworth et al. 2011a; Chevallier and Salas-Méla 2012; Chevallier et al. 2013). Atmospheric variability also provides an inherent limit on sea ice predictability (Guemas et al. 2014; Serreze and Stroeve 2015), making interannual departures from the long-term trend hard to predict (Tietsche et al. 2013; Stroeve et al. 2014b). Even with a “perfect model” assumption, under which ensemble integrations are initialized from a reference model, initial-value predictability of sea ice area is only significant for up to 1–2 years (Blanchard-Wrigglesworth et al. 2011b; Tietsche et al. 2013). Beyond 3 years, predictability is dominated by climate forcing rather than initial conditions (Blanchard-Wrigglesworth et al. 2011b). In addition, the long-term predictive capability of the September minimum sea ice extent decreases as the ice pack gets thinner (Blanchard-Wrigglesworth et al. 2011a; Holland et al. 2011; Tietsche et al. 2013). Nonetheless, Holland and Stroeve (2011) looked at climate model projections through the end of the twenty-first century

and found that the correlation between September sea ice extent anomalies and winter–spring predictors such as the area of the Arctic Basin covered by thin ice increases as the pack ice transitions from perennial to seasonal ice cover. At the same time, they also found that the variance of modeled sea ice extent explained by summer large-scale atmospheric circulation over the Arctic Ocean decreases from the late twentieth century to the middle of the twenty-first century.

A positive AO (or NAM) index is characterized by low sea level pressure anomalies over the Arctic, a small Beaufort Gyre, and increased coastal divergence in the East Siberian and Laptev Seas (Dickson et al. 2000; Rigor et al. 2002). Moreover, it can lead to a higher number of storms entering the Arctic through the Nordic seas, which can favor the inflow of warm Atlantic waters and enhance the winter sea ice retreat north of Scandinavia (Bengtsson et al. 2004; Sorteberg et al. 2005; Sorteberg and Kvingedal 2006). GCMs simulate a steady positive trend in the NAM (Fyfe et al. 1999; Rauthe and Paeth 2004; Miller et al. 2006), suggesting either that the observed return to a negative phase since the nineties is a manifestation of internal variability or results from a mechanism not resolved by models (Gillett and Fyfe 2013; Jin-Qing et al. 2013). In particular, Gillett and Fyfe (2013) show that CMIP5 models on average simulate an increase in the NAM in every season by 2100, with the largest increases in autumn and winter.

GCMs that have a reasonable late-twentieth-century Arctic climate predict ice-free summers before 2100 for a business-as-usual emission scenario (Holland et al. 2006; Stroeve et al. 2012a). Even though these models agree on the decline of sea ice extent and the likelihood of a seasonal Arctic sea ice cover, the pattern of the predicted sea ice loss varies widely (Bitz et al. 2005). Recently, Stroeve et al. (2012a) showed that predicted trends from the models participating in CMIP5 are consistent with observations, but they nevertheless exhibit declines that are smaller than the observed value. Although the mean thickness distributions from GCMs are in good agreement with observations, there are large differences in the spatial patterns of sea ice thickness in CMIP3 and CMIP5 models (Bitz et al. 2002; Stroeve et al. 2014a). Such disparities can be the result of relatively small biases in atmospheric circulation patterns that drive the movement of sea ice. Nevertheless, all models agree on the dominant role of sea ice melt in the simulated volume loss (Holland et al. 2010).

In this paper, we expand on the work of Williams et al. (2016) and link projected decadal trends of regional (Pacific and Eurasian sectors) summer sea ice extent loss in the Arctic to trends in sea ice drift patterns from the previous winter. We look at two GCMs that have

important differences in their late-twentieth-century large-scale mean winter atmospheric circulation: one that is similar to observations [Community Earth System Model Large Ensemble (CESM-LE)] and one that exhibits a positive AO bias [Community Climate System Model, version 4 (CCSM4)]. As a result, CCSM4 simulates larger divergence in the sea ice field in the Beaufort and Chukchi Seas compared to CESM-LE, leading to a Pacific-centric sea ice retreat. On the other hand, CESM-LE has a mean winter atmospheric circulation in the twentieth- and twenty-first century that is similar to the observed late twentieth century, leading to a more symmetrical retreat between the Pacific, Eurasian, and Atlantic sectors of the Arctic. Given that a positive trend in the AO index is a robust feature of GCMs participating in CMIP5, our results suggest that sea ice retreat in the Pacific sector could be amplified during the transition to a seasonally ice-free Arctic.

2. Data

a. Observations

We use the National Snow and Ice Data Center (NSIDC) Polar Pathfinder Daily 25-km Equal-Area Scalable Earth Grid (EASE-Grid) Sea Ice Motion Vectors, version 3 (Tschudi et al. 2016), for the period of January 1990 to May 2015. This dataset is constructed using an optimal interpolation of sea ice motion vectors from the Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I), Advanced Microwave Scanning Radiometer-EOS (AMSR-E), Advanced Very High Resolution Radiometer (AVHRR), drifting buoys from the International Arctic Buoy Program (IABP), and free drift estimates derived from the 10-m winds of the NCEP–NCAR reanalysis data. For this analysis, we do not consider the satellite-derived velocities from SMMR (1979–87) because of a reported low bias in sea ice velocity before the change from SMMR to SSM/I in July 1987 (NSIDC 2016). In this dataset, IABP data are considered as truth and are used with a weight of unity that decreases to zero outside a radius of influence of approximately 200 km. Sea ice drift vectors have been derived using a maximum cross-correlation method applied to brightness temperature data (Emery et al. 1997; Meier et al. 2000; Fowler et al. 2004; Meier and Dai 2006). The process results in a sparse field of ice drift vectors, where features can be tracked from one image to the next. Satellite-derived daily ice motion vector fields were interpolated on the 25-km EASE-Grid (Brodzik et al. 2012) and averaged over a one-week and one-month time period, resulting in low root-mean-square errors and making long-term

Lagrangian tracking possible (Meier and Maslanik 2001; Sumata et al. 2015b).

We use sea ice concentration data derived from passive microwave brightness temperatures between January 1990 and December 2014 from the National Oceanic and Atmospheric Administration (NOAA)/NSIDC Climate Data Record (CDR), version 2 (Meier et al. 2015). The sea ice concentration is defined as the fraction of a grid-cell area covered by sea ice. CDR concentration estimates are derived using the NASA Team (NT) algorithm (Cavalieri et al. 1984) and the Bootstrap (BT) algorithm (Comiso 1986). The CDR algorithm then blends the NT and BT output concentrations by selecting, for each grid cell, the higher concentration value (Peng et al. 2013; Meier et al. 2014). The sea ice concentrations were interpolated onto the same 25-km EASE-Grid.

Monthly mean sea level pressure is obtained from ERA-Interim, a product of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011), for the period of January 1979 to December 2015, as well as from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP–NCAR) between January 1948 and December 2014. Sea level pressures were interpolated onto the same 25-km EASE-Grid.

We also use the NSIDC IABP drifting buoy data product that includes 12-h latitude/longitude positions from 1988 to 2011 (Rigor 2002).

b. Global climate models

This study utilizes monthly mean fields of the u and v components of sea ice velocity, sea ice concentration, and sea level pressure between 1900 and 2100 (historical and RCP8.5 simulations) from the six ensemble members of the CCSM4 provided by NCAR (Gent et al. 2011).

We also use monthly mean u and v components of sea ice velocity, sea ice concentration, and sea level pressure between 1920 and 2100 from the 40 ensemble members of the CESM-LE with historical and RCP8.5 forcings (Kay et al. 2014). CESM-LE uses the latest version of the Community Atmosphere Model (CAM5), which has undergone substantial improvements in the representation of physical processes in the atmosphere (e.g., parameterizations of diabatic processes, interactive carbon–nitrogen cycling, and treatment of water substances and aerosols) (Hurrell et al. 2013). Of importance to the Arctic are the resulting improvements in the representation of the total cloud percentage (Barton et al. 2012; Kay et al. 2012).

Although the land, ocean, and ice components, as well as the spatial resolution are the same for both models, CESM-LE tends to produce thicker ice, which may be a result of the reduced twentieth-century warming in CAM5 (Hurrell et al. 2013). CESM-LE also has stronger

climate feedbacks, leading to a higher climate sensitivity compared to CCSM4 and greater warming in the twenty-first century (Meehl et al. 2013).

3. Methodology

Our goal is to assess the spatial patterns of future sea ice retreat on decadal time scales given the projected changes in large-scale atmospheric circulation patterns over the Arctic Ocean. To this end, we quantify the divergence of sea ice in different regions of the Arctic using a Lagrangian model to backtrack a selected set of points (virtual ice floes) from the approximate time of melt onset to their prior positions throughout the previous winter. A similar approach has been used successfully to track ice age over several years (Fowler et al. 2004; Pfirman et al. 2004; Rigor and Wallace 2004; Maslanik et al. 2007), and results compared well with ice thickness data, a proxy for ice age (Maslanik et al. 2007).

In this analysis, we use the ice drift vectors to backtrack an imaginary line at 80°N latitude and quantify sea ice divergence in two separate regions: the Pacific sector (Beaufort and Chukchi Seas) and the Eurasian sector (East Siberian, Laptev, and Kara Seas) of the Arctic. All Lagrangian trajectories are initialized on 1 June, the approximate start of the melt onset. At the beginning of the integration, each selected grid cell is considered an independent Lagrangian particle and is advected using weekly averaged sea ice motion vectors. After each time step, the gridded ice velocity is interpolated at the new particle location. This procedure is done repeatedly until 1 November of the previous year, when the Arctic Basin is still fully ice covered. We then calculate the fluxes of ice along the 80°N line in both regions (see example in Fig. 1). We do not include the Barents Sea in the analysis of the Eurasian sector because the ice edge in this region is strongly affected by ocean heat fluxes (Bitz et al. 2005). In section 4, we present an error analysis to quantify the biases in sea ice drift associated with the use of the Lagrangian model and the increased temporal resolution of the observational data (weekly) when compared with model data (monthly).

The advection of individual ice parcels is done using a first-order finite-difference approximation of the ice velocity:

$$\frac{x(t + \Delta t) - x(t)}{\Delta t} = v\left(t + \frac{1}{2}\Delta t\right) = \frac{dx}{dt}\bigg|_{t+1/2\Delta t}, \quad (1)$$

where $v(t + 1/2\Delta t)$ is the mean sea ice velocity at time $t + 1/2\Delta t$, $x(t)$ is the location of the particle at time t , and Δt is equal to one week and one month for the observations and models, respectively.

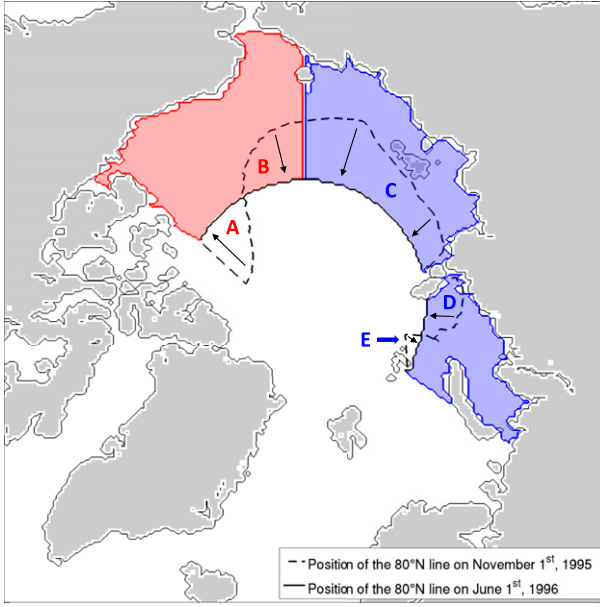


FIG. 1. Example of a Lagrangian trajectory for the year 1996 using member #001 of CESM-LE. The 80°N line was backtracked from 1 Jun 1996 (black solid) to 1 Nov 1995 (black dashed) in order to quantify the change in area from the Pacific ($A_B - A_A$) and the Eurasian ($A_C + A_D - A_E$) sectors. The original areas (before backtracking) of the Pacific and Eurasian sectors are defined as A_{red} and A_{blue} , respectively. The arrows indicate the direction of motion of the 80°N line forward in time from 1 Nov to 1 Jun.

To calculate the mean divergence over a given region, we use the two-dimensional divergence theorem:

$$\iint_R \nabla \cdot \mathbf{u} dA = \oint_C (\mathbf{u} \cdot \hat{\mathbf{n}}) dS. \quad (2)$$

This can be rewritten in terms of the rate of change in area provided by the Lagrangian backtrajectory model [see p. 6 of Vallis (2006)]:

$$\overline{\nabla \cdot \mathbf{u}} = \frac{1}{A} \oint_C (\mathbf{u} \cdot \hat{\mathbf{n}}) dS = \frac{1}{A} \frac{dA}{dt}. \quad (3)$$

For instance, the sea ice divergence from the Pacific and Eurasian sectors can be written as

$$\overline{\nabla \cdot \mathbf{u}} = \begin{cases} \frac{1}{A_{\text{red}}} \frac{A_B - A_A}{\Delta t} & \text{Pacific sector} \\ \frac{1}{A_{\text{blue}}} \frac{A_C + A_D - A_E}{\Delta t} & \text{Eurasian sector} \end{cases}, \quad (4)$$

where A_{red} and A_{blue} are the original areas (before backtracking) of the Pacific and Eurasian sectors, respectively, and A_A , A_B , A_C , A_D , and A_E are the areas of regions A, B, C, D, and E enclosed between the original position of the 80°N line (black solid line) and its backtracked position (black dashed line) (Fig. 1).

We have opted to calculate the divergence as a rate of change in area instead of spatial derivatives of the velocity because it gives an intuitive way of looking at the same process and highlights aspects of the divergent field that are not readily obvious when using ice motion vectors. In addition, calculating spatial and temporal averages of the Lagrangian trajectories decreases the errors associated with the vector field (Sumata et al. 2015b).

4. Error analysis

To quantify the error in drift distances from the Lagrangian model, we compare simulated sea ice drift forced with weekly and monthly mean sea ice velocities from the Polar Pathfinder dataset with the actual buoy drift trajectories from the IABP buoy data between 1988 and 2011 (Meier and Maslanik 2001). To this end, we track each individual IABP buoy from its initial position to its last recorded position for a maximum of 1 year. For each simulated trajectory, the error in modeled location compared to the actual buoy position was calculated at each time step until the final position of the buoy. The procedure allows us to estimate model errors as well as to quantify the impact of temporal resolution on the estimated errors. Recall that the observed IABP drift velocities are used to construct the Polar Pathfinder sea ice motion vectors, making a precise error estimate of the drift trajectories more strenuous. Averaging daily sea ice drift into longer time periods introduces an error in the initial velocity of the simulated trajectory. This error will grow in time as the distance between the simulated position and the actual buoy position increases.

Figure 2 shows the median, the interquartile range, and the number of trajectories used to calculate the error in drift distance using weekly and monthly time resolutions for trajectories of up to 1 year. The median is closer to the bottom of the interquartile range because the distribution is positively skewed, indicating that most buoys do not travel long distances and stay within the same area. Larger errors will arise when trying to simulate fast-drifting buoys, which represent a small portion of the data (Sumata et al. 2015a). As expected, the error growth is faster for pairs of points separated by more than 200 km, the radius of influence used for IABP data in the NSIDC interpolation scheme. Reducing the temporal resolution from weekly to monthly leads to an increase of the error in drift distance from about 83 to 128 km after a year of tracking. Given an observed mean sea ice drift speed in the Arctic Ocean of about $3\text{--}5 \text{ cm s}^{-1}$, the total mean drift after a year is approximately 1200 km. The median errors in the trajectories using weekly and monthly time resolutions are therefore 7% and 11%, and the upper-quartile error is about 16% and 26%, respectively. Note that

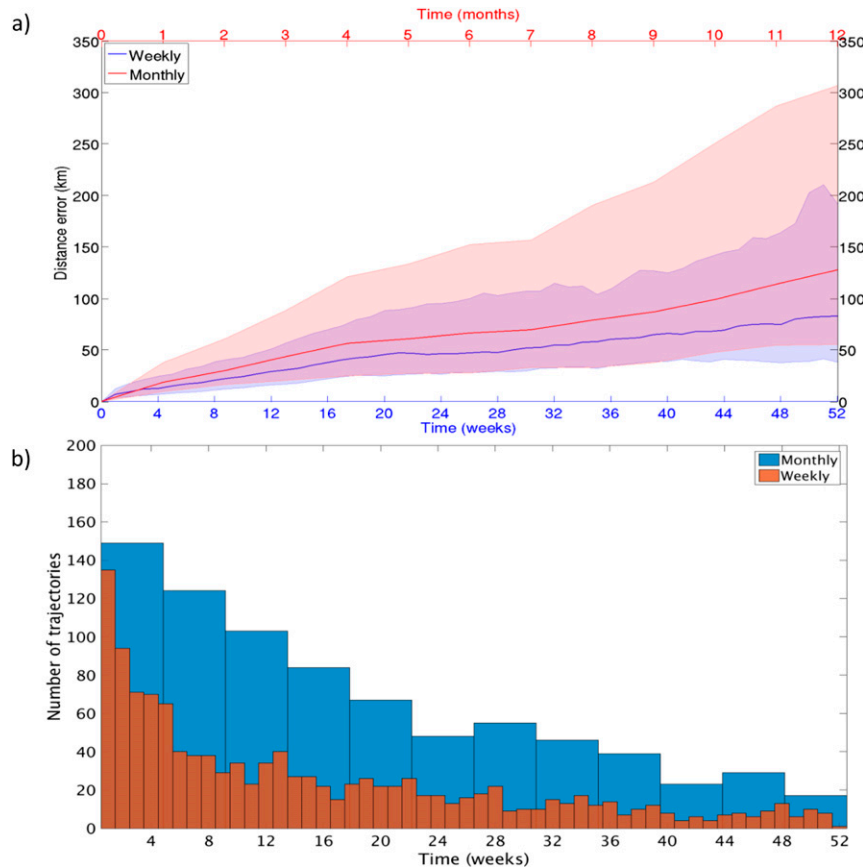


FIG. 2. (a) Median (solid) and interquartile range (shaded) of the error in drift distance of the Lagrangian ice trajectory model with two different time resolutions. The error is defined as the difference in drift distance between the tracer advected using the Polar Pathfinder sea ice drifts and the actual buoy position from IABP between 1988 and 2011. (b) Number of trajectories of each maximum time length used to calculate the error in drift distance.

weekly averaged sea ice velocities are used throughout this study for observational data.

5. Results and discussion

The winter (November–May) mean Arctic sea level pressure (above 70°N) from NCEP–NCAR, ERA-Interim, CCSM4, and CESM-LE is shown in Fig. 3. CESM-LE mean wintertime sea level pressure is similar to observations. On the other hand, CCSM4 has a bias of around -7 mb over the Arctic region when compared to observations (De Boer et al. 2012; Jahn et al. 2012), as well as larger internal variability than observed (Vavrus et al. 2012). This is indicative of a mean state with a very positive AO index. Note that the years with highest mean sea level pressure in CCSM4 are comparable to years of lowest observed values. The decreasing trend in winter mean sea level pressure in CESM-LE and CCSM4 (Fig. 3) starts in the first and second halves of the twenty-first

century, respectively, associated with a later transition to a seasonal sea ice cover in CCSM4 when compared to CESM-LE (Fig. 4) (Meehl et al. 2013).

The winter mean Arctic atmospheric circulation is characterized by a semipermanent high pressure system (Arctic or Beaufort high), flanked by two semipermanent climatological low pressure systems in the Atlantic (Icelandic low) and Pacific sectors (Aleutian low). The resulting observed winter mean sea ice drift pattern is the Beaufort Gyre, an anticyclonic circulation that redistributes thick multiyear ice north of the Canadian Arctic Archipelago (CAA) within the central Arctic, and the Transpolar Drift Stream that carries ice from the Eurasian coastline toward the North Pole and out through the Fram Strait (Figs. 5a,b).

The last decade of the twentieth century in CESM-LE is characterized by a broad Beaufort Gyre with faster sea ice drift speed when compared to observations and a smaller Transpolar Drift Stream that advects sea ice

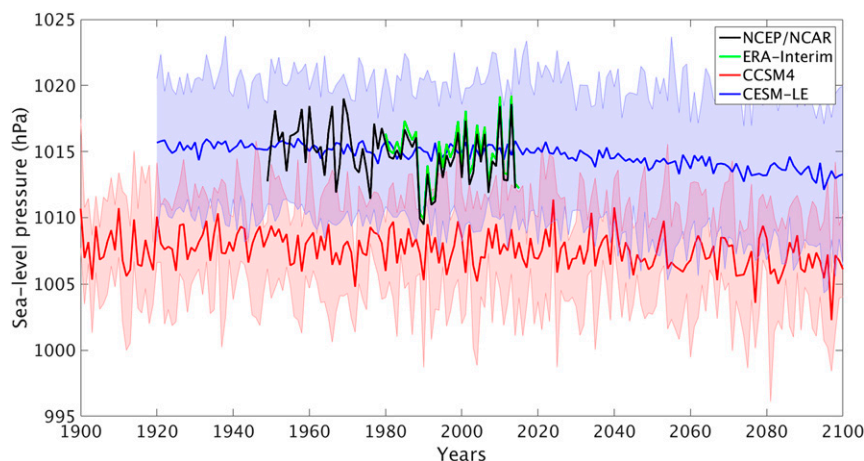


FIG. 3. Winter (November–May) mean sea level pressure averaged over the region above 70°N from 1900 to 2100 for the NCEP–NCAR reanalysis (black), ERA-Interim (green), CCSM4 (red), and CESM-LE (blue). For models, the solid line is the mean, and the shading represents the spread between all ensemble members.

from the Kara Sea to the Fram Strait and out of the Arctic Ocean (Figs. 5c,d). There is also a bias in the location of the center of the Beaufort Gyre toward the Eurasian coastline, redistributing thin ice from the East Siberian Sea and part of the Laptev Sea to the central Arctic. In contrast, there is no clear evidence of the presence of the Beaufort Gyre circulation in the winter mean sea ice velocities averaged over 1990–99 in CCSM4 (Figs. 5e,f). In this model, the Icelandic low is deeper than observed, and it penetrates farther in the eastern Arctic, resulting in a broader Transpolar Drift Stream carrying thick ice north of the CAA out through the Fram Strait (De Boer et al. 2012). This atmospheric pattern is a typical manifestation of an extremely positive AO index.

The years with high sea level pressure anomalies in CESM-LE (Fig. 6c) are characterized by a strengthening of the Beaufort Gyre circulation and a weakening of the Transpolar Drift Stream, along with a larger bias in the location of the center of the Beaufort Gyre toward the Eurasian coast. Conversely, the years with low sea level pressure anomalies see a weakening of the Beaufort Gyre circulation and a strengthening of the Transpolar Drift Stream (Fig. 6d). Note that the same features in the sea ice drift pattern are present in the observations (Figs. 6a,b), although the observed departures from the mean are of smaller amplitude compared to CESM-LE. The large internal variability of the sea level pressure in CCSM4 accounts for important interannual variability in the large-scale mean winter atmospheric circulation (Vavrus et al. 2012). In fact, the sea ice circulation shown in Fig. 5e with the absence of a clear Beaufort Gyre is the result of the average of two very different regimes. In

years with high sea level pressure anomalies (Fig. 6e), the winter sea ice velocities are very similar to the mean observed sea ice drift field (Fig. 5a). In years with low sea level pressure anomalies (Fig. 6f), the winter sea ice velocities follow a cyclonic circulation over the whole Arctic Basin, driven by an extremely deep Icelandic low, and a Transpolar Drift Stream that carries ice from the Beaufort Sea directly into the Fram Strait via the Lincoln Sea (Rigor et al. 2002). This circulation is characteristic of an extremely positive AO phase.

Future projections of sea ice extent from CESM-LE present a sea ice retreat that is relatively symmetric around the Lincoln Sea (north of Ellesmere Island)

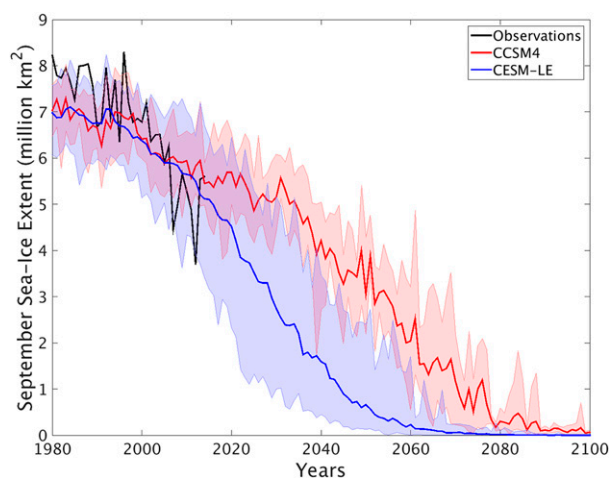


FIG. 4. September sea ice extent from 1980 to 2100 for observations (black), CCSM4 (red), and CESM-LE (blue). For models, the solid line is the mean, and the shading represents the spread between all ensemble members.

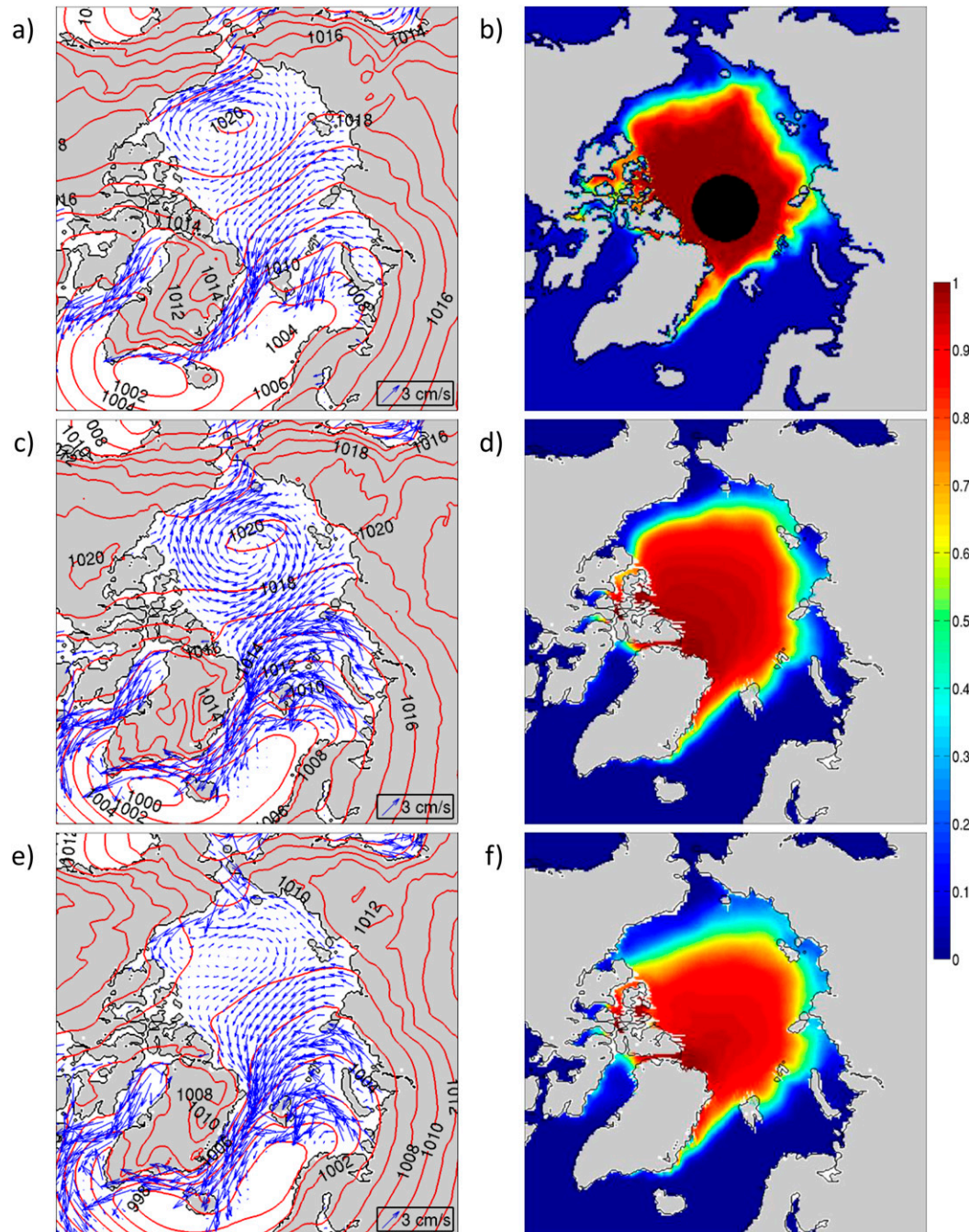


FIG. 5. (left) Winter (November–May) mean sea ice velocity field (arrows) and sea level pressure contours (red) and (right) mean September sea ice concentration during the 1990–99 period. (a),(b) Observations; (c),(d) CESM-LE 40-member ensemble average; and (e),(f) CCSM4 6-member ensemble average. Sea ice velocity vectors are capped at 4 cm s^{-1} for clarity. ERA-Interim is used for the sea level pressure contours.

(Figs. 7a,c,e), and thick ice north of the CAA is maintained by the presence of the Beaufort Gyre throughout the twenty-first century (results not shown). In CCSM4, the simulated patterns of sea ice retreat are drastically different. The positive AO state that characterizes the

large-scale mean winter atmospheric circulation results in a sea ice retreat preferentially in the Beaufort Sea (Figs. 7b,d,f). The region north of the CAA becomes ice free in September before the central Arctic (around the North Pole), with sea ice remaining in the region north

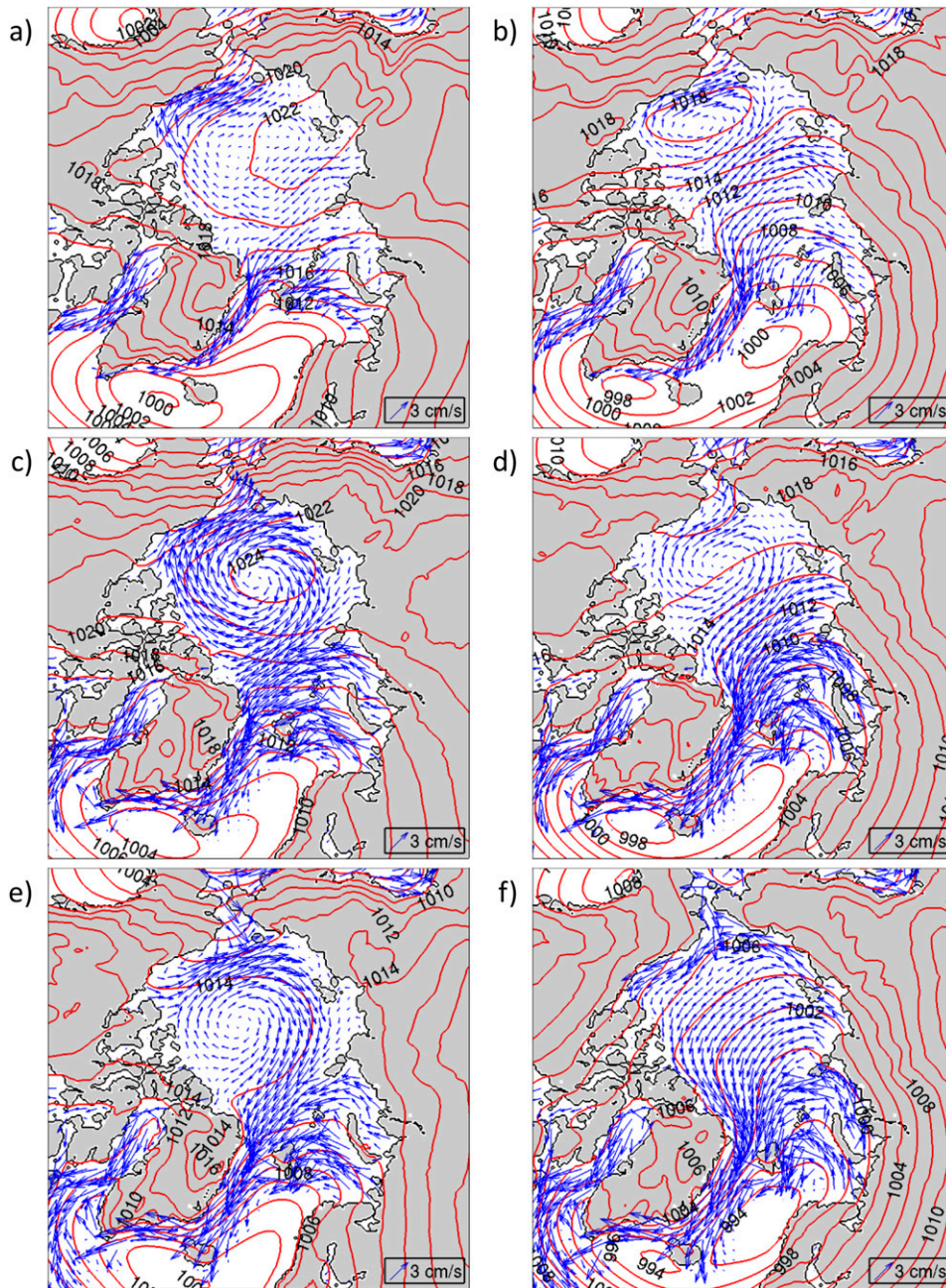


FIG. 6. Winter (November–May) mean sea ice velocity field (arrows) and sea level pressure contours (red) for years of sea level pressure anomalies (left) greater or (right) lesser than 1 standard deviation from the mean during the 1990–99 period. (a),(b) Observations; (c),(d) CESM-LE 40-member ensemble average; and (e),(f) CCSM4 6-member ensemble average. Sea ice velocity vectors are capped at 4 cm s^{-1} for clarity. ERA-Interim is used for the sea level pressure contours.

of Greenland and in the narrow channels of the CAA (Jahn and Holland 2013).

We quantify the sea ice divergence from the Pacific and Eurasian sectors of the Arctic Ocean from November to June using the Lagrangian model (see example on Fig. 1). Figure 8 shows the net divergence from both sectors for

CCSM4 and CESM-LE from the early twentieth century to 2100. In CESM-LE, the presence of a strong Beaufort Gyre circulation leads to a net convergence of ice in the Pacific sector. On the other hand, the extremely positive AO phase in CCSM4 prevents the redistribution of thick ice north of the CAA into the Beaufort and Chukchi Seas

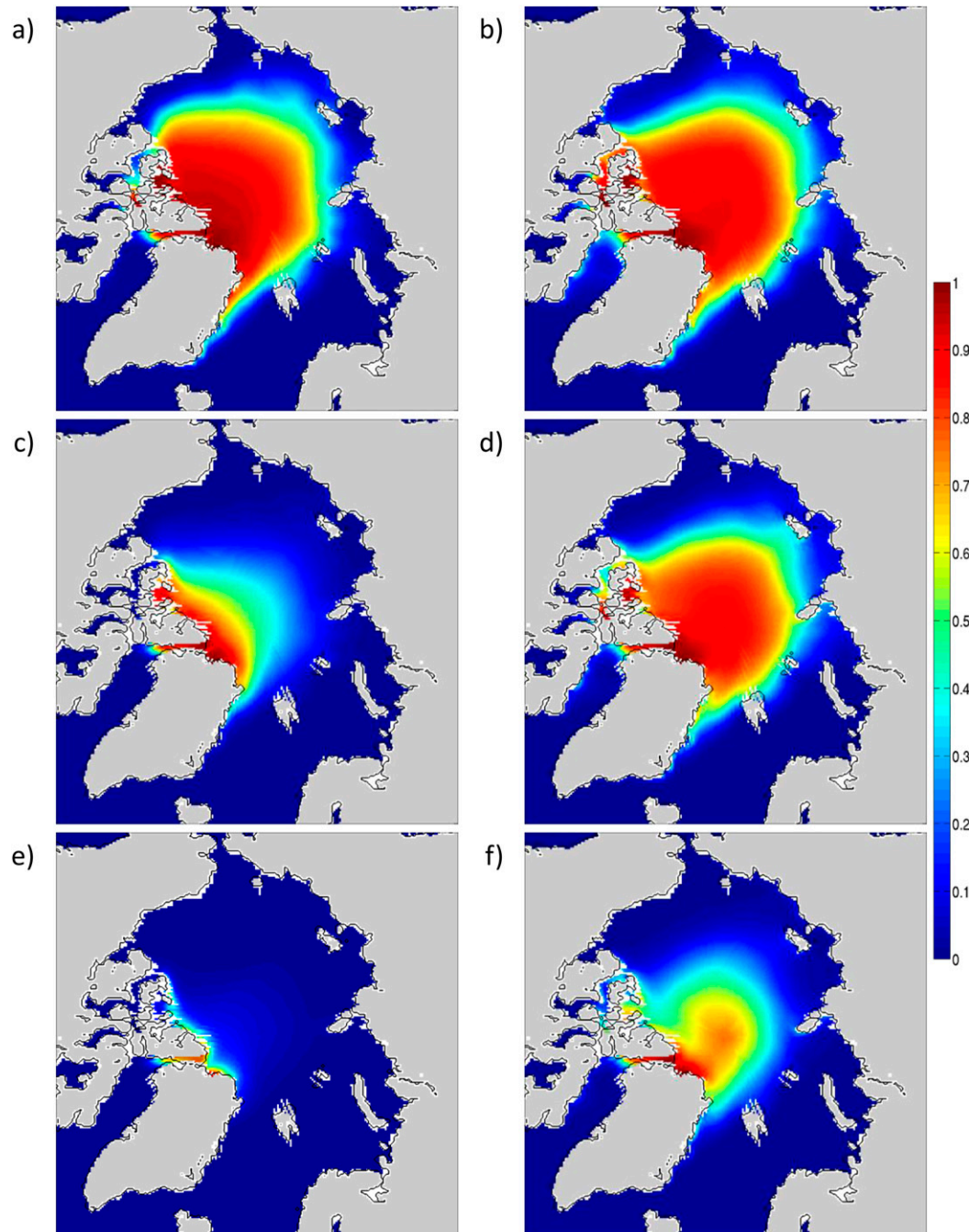


FIG. 7. Projected mean September sea ice concentration for (left) CESM-LE and (right) CCSM4: (a),(b) 2010–19; (c),(d) 2030–39; and (e),(f) 2050–59.

so that the net divergence of sea ice is approximately zero (Fig. 8b). Conversely, divergence of sea ice is somewhat more important in CESM-LE than in CCSM4 in the Eurasian sector since the strong anticyclonic circulation of the Beaufort Gyre in CESM-LE carries ice away from the Eurasian coastlines toward the North Pole (Fig. 8a). This highlights the importance of the different large-scale

atmospheric circulation patterns on projected Arctic sea ice conditions (Liu et al. 2013; Meehl et al. 2013).

In the observations, the first decade of the twenty-first century has seen successive record low sea ice extent minima (Stroeve et al. 2012b), most dramatically visible in the sea ice retreat in the Beaufort, Chukchi, East Siberian, and Laptev Seas (Fig. 9b). The

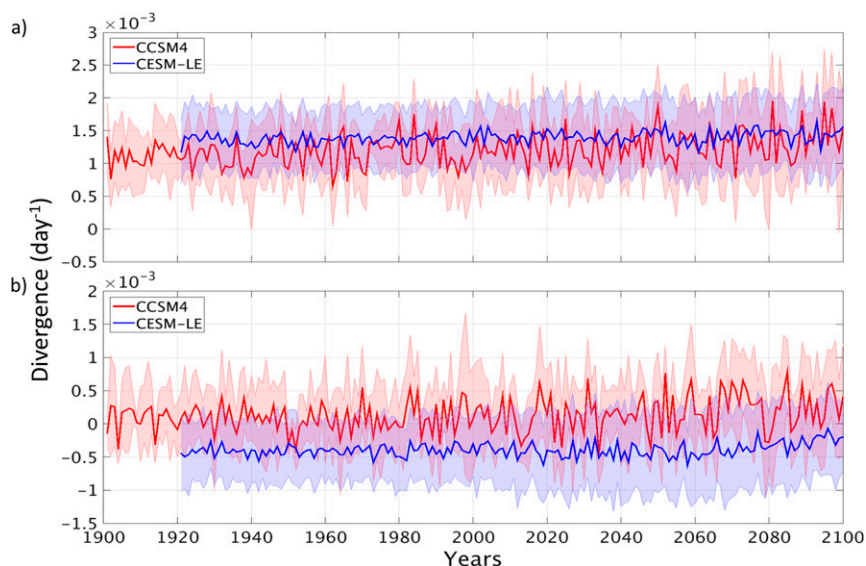


FIG. 8. Ensemble mean (solid line) and standard deviation (shaded) of sea ice divergence in the (a) Eurasian and (b) Pacific sectors of the Arctic Ocean from November to June using our Lagrangian backtrajectory model forced with sea ice drift vectors from CCSM4 (red) and CESM-LE (blue) between 1900 and 2100.

general thinning of the ice pack has led to an overall increase in sea ice velocities across the Arctic Ocean and a more mobile ice pack, except for the area north of the CAA (Fig. 9a). The increase in ice drift speed along the Alaskan coastline has strengthened the anticyclonic circulation in the Pacific sector. We again use our Lagrangian model to evaluate the observed divergence from the Pacific and the Eurasian sectors. We calculate the net sea ice divergence from the first week of February to the first week of June (approximate beginning of the melt season). Several studies have shown this period to have the highest correlation between the September sea ice extent anomaly and sea ice thickness distribution (Nikolaeva and Sesterikov 1970; Chevallier and Salas-Mélia 2012; Williams et al. 2016).

Since the early nineties, we observe a significant positive trend in the net divergence in the Eurasian sector [in accord with the trend found by Alexandrov et al. (2000)], but no significant trend in the Pacific sector, where the retreat has been greatest (Fig. 10). Clearly, ice advection is not the only factor driving the sea ice retreat in this sector. Note that the trend in sea ice divergence in each individual sea within a given sector is the same as that of the sector itself (results not shown). This result puts into question the idea of a potential predictability of the sea ice retreat on the regional scale. For instance, Rigor and Wallace (2004) found that the AO index can explain as much as 64% of the variance in summer sea ice extent in the Eurasian sector, while it explains less

than 20% of the variance in the region north of Alaska. The Pacific region is greatly influenced by oceanic heat inflow through the Bering Strait (Bitz et al. 2005; Steele et al. 2010; Woodgate et al. 2010). Southerly winds associated with the Arctic dipole can also indirectly lead to enhanced surface ocean warming by pushing the ice out of the Arctic Ocean, which lowers the albedo and allows for more shortwave radiation input (Wang et al. 2009; Overland et al. 2012). The increase in sea ice velocity along the Alaskan coast favors the upwelling of warm summer Bering Sea waters due to Ekman pumping divergence (Zhang et al. 1998; Yang 2006). These factors can be amplified by positive feedbacks, such as the ice-albedo feedback (Holland et al. 2006; Maslanik et al. 2007; Perovich et al. 2007a) and the radiative feedback associated with the presence of melt ponds at the surface of first-year ice (Perovich et al. 2007b). Finally, changes in multiyear ice concentration explain over 50% of the variance in sea ice extent in the Beaufort/Chukchi region (Rigor and Wallace 2004). Multiyear ice, compared to thin first-year ice, is preferentially advected into the Pacific region when there is a strong Beaufort Gyre circulation. Since the intensity of the Beaufort high decreases with a more positive AO index, it is possible that, even though the correlation with sea ice divergence has recently been weak in this sector, the predictive value of the AO may nonetheless be significant, operating through a divergence of mass rather than area alone. However, this is beyond the scope of this study. Nevertheless, our results show no significant trend in the

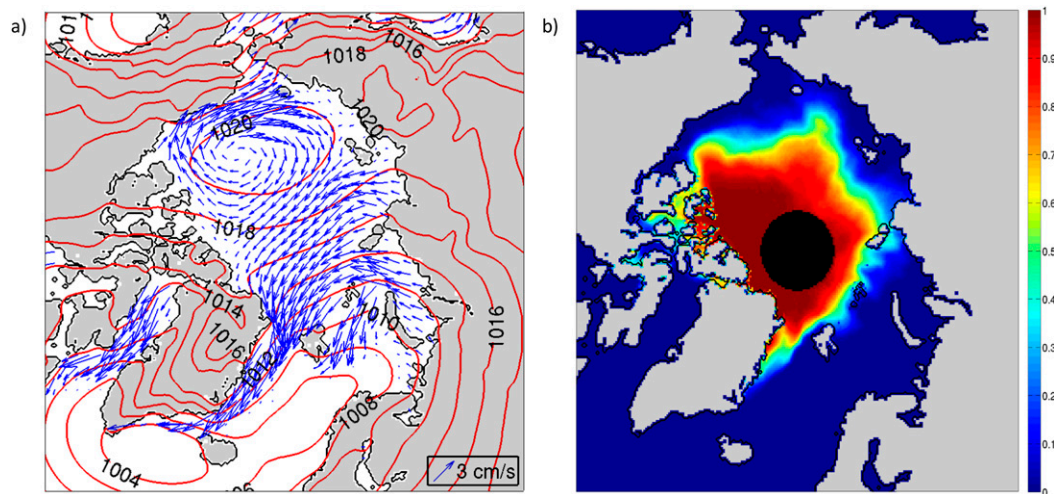


FIG. 9. Observations: (a) Winter (November–May) mean sea ice velocity field (arrows) and sea level pressure contours (red) and (b) mean September sea ice concentration during the 2000–14 period. Sea ice velocity vectors are capped at 4 cm s^{-1} for clarity. ERA-Interim is used for the sea level pressure contours.

divergence for any of the model's ensemble members during the twenty-first century (Fig. 8) that could relate to the predicted negative trend in the overall thickness of the Arctic ice cover (Holland et al. 2010), suggesting that the signal primarily comes from wind stress and not as much from the thickness distribution. Furthermore, since the early nineties, there has been no significant trend in the AO in the observational record (Overland and Wang 2005), and considering that the departures from the mean observed large-scale atmospheric circulation are of smaller amplitude than the ones from the GCMs previously analyzed, we expect a more subtle

relationship between observed large-scale wind pattern and local divergence.

6. Conclusions

In this study, we analyzed the winter mean sea ice motion in order to gain insight on future patterns of sea ice retreat in the Arctic Ocean. The wintertime sea level pressure is directly linked to the large-scale mean atmospheric circulation, the main driver of sea ice motion. Two different GCMs were used in this analysis: CCSM4 has an important low bias (-7 mb) in the wintertime sea

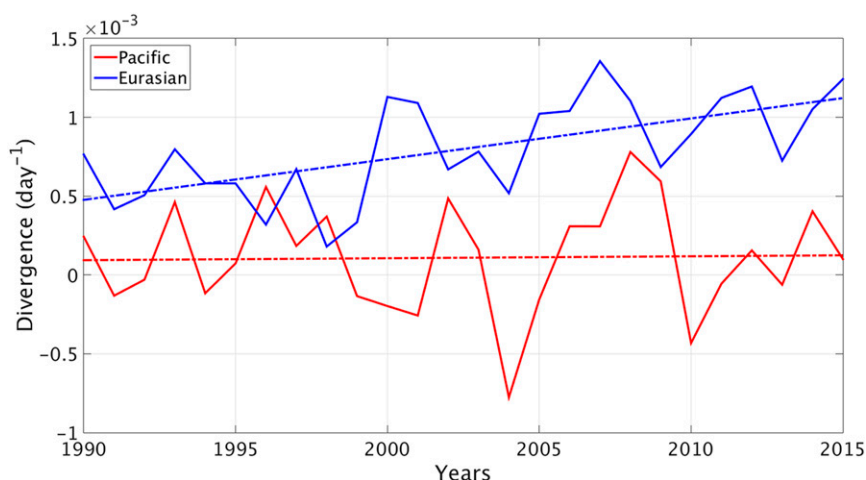


FIG. 10. Observations: Late winter (from the first week of February to the first week of June) divergence from 1990 to 2015 using our Lagrangian backtrajectory model for the Pacific (red) and Eurasian (blue) sectors. For each sector, the dashed–dotted line shows the linear trend. Note that the linear trend in the Eurasian sector is significant to the 99.9% level of confidence. There is no significant trend in the Pacific sector.

level pressure over the Arctic, characteristic of an extremely positive AO index, and CESM-LE presents a strong Beaufort Gyre circulation, with the center of the Beaufort high shifted toward the Eurasian coast, a pattern typical of a low-to-neutral AO index.

To quantify the potential for sea ice retreat, we looked at sea ice divergence from the Pacific and Eurasian sectors using our Lagrangian backtracking model. Sea ice divergence is related to formation of first-year ice, which is more likely to melt in the summer (Rigor et al. 2002; Rigor and Wallace 2004; Williams et al. 2016). The absence of a Beaufort Gyre circulation in CCSM4 leads to a net divergence of approximately zero in the Pacific sector, compared to convergence in CESM-LE. Divergence in the Eurasian sector is slightly more important in CESM-LE, along with a broad Beaufort high pushing the ice north of Siberia toward the North Pole. The positive trend in the AO index predicted by CMIP5 models (Gillett and Fyfe 2013) suggests that the Beaufort and Chukchi Seas could continue to lead in future sea ice retreat.

We do not claim that the mechanism applied here to two sets of climate output offers a full explanation of the dynamics underlying the future patterns of sea ice retreat. The determinants of sea ice extent are complex, and factors other than the large-scale atmospheric circulation have an important influence on determining its details, such as ocean heat inflow from the subarctic, small-scale atmospheric anomalies, vertical heat flux through Ekman pumping, and the interaction of ice growth/melt anomalies with the ice–albedo feedback. These mechanisms may also play an important role during the transition to a seasonally ice-free Arctic.

However, from related work (Rigor and Wallace 2004; Williams et al. 2016), the mechanism applied here to climate model output is known to be correlated with approximately 50% of the interannual variance in sea ice extent. Moreover, it rests on a straightforward and well-studied physical mechanism (Rigor et al. 2002), which is a strong argument for causation. Future work will include the study of mechanisms responsible for sea ice retreat that operate more locally, within particular subareas of the Arctic system. Nevertheless, this work, which links sea ice retreat to robust large-scale atmospheric patterns, constitutes an advancement toward better predictability of the future Arctic climate.

Acknowledgments. This work was funded by the Office of Naval Research (N000141110977). Patricia DeRepentigny is grateful to the Natural Sciences and Engineering Council of Canada (NSERC) and Fonds de Recherche du Québec–Nature et Technologies (FRQNT) for their financial support through research scholarships,

as well as ArcticNet, Québec-Océan, and ArcTrain Canada. Bruno Tremblay is grateful for the financial support of ArcticNet, the NSERC Discovery Program, Environment Canada Grants and Contribution program, and the Canadian Sea Ice and Snow Evolution (CanSISE) Network funded by the NSERC Climate Change and Atmospheric Research program.

REFERENCES

- Alexandrov, V. Y., T. Martin, J. Kolatschek, H. Eicken, M. Kreyscher, and A. P. Makshtas, 2000: Sea ice circulation in the Laptev Sea and ice export to the Arctic Ocean: Results from satellite remote sensing and numerical modeling. *J. Geophys. Res.*, **105**, 17 143–17 159, doi:[10.1029/2000JC900029](https://doi.org/10.1029/2000JC900029).
- Barnes, E. A., 2013: Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophys. Res. Lett.*, **40**, 4734–4739, doi:[10.1002/grl.50880](https://doi.org/10.1002/grl.50880).
- , and L. M. Polvani, 2015: CMIP5 projections of Arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *J. Climate*, **28**, 5254–5271, doi:[10.1175/JCLI-D-14-00589.1](https://doi.org/10.1175/JCLI-D-14-00589.1).
- , and J. A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdiscip. Rev.: Climate Change*, **6**, 277–286, doi:[10.1002/wcc.337](https://doi.org/10.1002/wcc.337).
- , E. Dunn-Sigouin, G. Masato, and T. Woollings, 2014: Exploring recent trends in Northern Hemisphere blocking. *Geophys. Res. Lett.*, **41**, 638–644, doi:[10.1002/2013GL058745](https://doi.org/10.1002/2013GL058745).
- Barton, N. P., S. A. Klein, J. S. Boyle, and Y. Y. Zhang, 2012: Arctic synoptic regimes: Comparing domain-wide arctic cloud observations with CAM4 and CAM5 during similar dynamics. *J. Geophys. Res.*, **117**, D15205, doi:[10.1029/2012JD017589](https://doi.org/10.1029/2012JD017589).
- Bengtsson, L., V. A. Semenov, and O. M. Johannessen, 2004: The early twentieth-century warming in the Arctic—A possible mechanism. *J. Climate*, **17**, 4045–4057, doi:[10.1175/1520-0442\(2004\)017<4045:TETWIT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<4045:TETWIT>2.0.CO;2).
- Bitz, C., J. C. Fyfe, and G. M. Flato, 2002: Sea ice response to wind forcing from AMIP models. *J. Climate*, **15**, 522–536, doi:[10.1175/1520-0442\(2002\)015<0522:SIRTWF>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<0522:SIRTWF>2.0.CO;2).
- , M. Holland, E. Hunke, and R. Moritz, 2005: Maintenance of the sea-ice edge. *J. Climate*, **18**, 2903–2921, doi:[10.1175/JCLI3428.1](https://doi.org/10.1175/JCLI3428.1).
- Blanchard-Wrigglesworth, E., K. C. Armour, C. M. Bitz, and E. DeWeaver, 2011a: Persistence and inherent predictability of Arctic sea ice in a GCM ensemble and observations. *J. Climate*, **24**, 231–250, doi:[10.1175/2010JCLI3775.1](https://doi.org/10.1175/2010JCLI3775.1).
- , C. Bitz, and M. Holland, 2011b: Influence of initial conditions and climate forcing on predicting Arctic sea ice. *Geophys. Res. Lett.*, **38**, L18503, doi:[10.1029/2011GL048807](https://doi.org/10.1029/2011GL048807).
- Blanken, H., B. Tremblay, S. Gaskin, and A. Slavin, 2015: A numerical risk assessment for spills from oil and gas activity around the Arctic Ocean basin. *Extended Abstracts, 36th IAHR World Congress*, The Hague, Netherlands, International Association for Hydro-Environment Engineering and Research. [Available online at <http://89.31.100.18/~iahrpapers/86780.pdf>].
- Brodzik, M. J., B. Billingsley, T. Haran, B. Raup, and M. H. Savoie, 2012: EASE-Grid 2.0: Incremental but significant improvements for Earth-gridded data sets. *ISPRS Int. J. Geo-Inf.*, **1**, 32–45, doi:[10.3390/ijgi1010032](https://doi.org/10.3390/ijgi1010032).
- Byers, M., 2010: *Who Owns the Arctic? Understanding Sovereignty Disputes in the North*. Douglas & McIntyre, 192 pp.

- Campbell, K. M., and Coauthors, 2007: The age of consequences: The foreign policy and national security implications of global climate change. CSIS–CNAS Tech. Rep., 124 pp.
- Cavalieri, D. J., P. Gloersen, and W. J. Campbell, 1984: Determination of sea ice parameters with the NIMBUS 7 SMMR. *J. Geophys. Res.*, **89**, 5355–5369, doi:10.1029/JD089iD04p05355.
- Chevallier, M., and D. Salas-Mélia, 2012: The role of sea ice thickness distribution in the Arctic sea ice potential predictability: A diagnostic approach with a coupled GCM. *J. Climate*, **25**, 3025–3038, doi:10.1175/JCLI-D-11-00209.1.
- , D. Salas y Mélia, A. Voldoire, M. Déqué, and G. Garric, 2013: Seasonal forecasts of the pan-Arctic sea ice extent using a GCM-based seasonal prediction system. *J. Climate*, **26**, 6092–6104, doi:10.1175/JCLI-D-12-00612.1.
- Comiso, J. C., 1986: Characteristics of Arctic winter sea ice from satellite multispectral microwave observations. *J. Geophys. Res.*, **91**, 975–994, doi:10.1029/JC091iC01p00975.
- , C. L. Parkinson, R. Gersten, and L. Stock, 2008: Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.*, **35**, L01703, doi:10.1029/2007GL031972.
- De Boer, G., W. Chapman, J. E. Kay, B. Medeiros, M. D. Shupe, S. Vavrus, and J. Walsh, 2012: A characterization of the present-day Arctic atmosphere in CCSM4. *J. Climate*, **25**, 2676–2695, doi:10.1175/JCLI-D-11-00228.1.
- Dee, D., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, doi:10.1002/qj.828.
- Dickson, R., and Coauthors, 2000: The Arctic Ocean response to the North Atlantic Oscillation. *J. Climate*, **13**, 2671–2696, doi:10.1175/1520-0442(2000)013<2671:TAORTT>2.0.CO;2.
- Emery, W., C. W. Fowler, and J. Maslanik, 1997: Satellite-derived maps of Arctic and Antarctic sea ice motion: 1988 to 1994. *Geophys. Res. Lett.*, **24**, 897–900, doi:10.1029/97GL00755.
- Fowler, C., W. Emery, and J. Maslanik, 2004: Satellite-derived evolution of Arctic sea ice age: October 1978 to March 2003. *IEEE Trans. Geosci. Remote Sens. Lett.*, **1**, 71–74, doi:10.1109/LGRS.2004.824741.
- Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.*, **39**, L06801, doi:10.1029/2012GL051000.
- , and —, 2015: Evidence for a wavier jet stream in response to rapid Arctic warming. *Environ. Res. Lett.*, **10**, 014005, doi:10.1088/1748-9326/10/1/014005.
- Fyfe, J., G. Boer, and G. Flato, 1999: The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophys. Res. Lett.*, **26**, 1601–1604, doi:10.1029/1999GL000317.
- Gautier, D. L., and Coauthors, 2009: Assessment of undiscovered oil and gas in the Arctic. *Science*, **324**, 1175–1179, doi:10.1126/science.1169467.
- Gent, P. R., and Coauthors, 2011: The Community Climate System Model version 4. *J. Climate*, **24**, 4973–4991, doi:10.1175/2011JCLI4083.1.
- Gervais, M., E. Atallah, J. R. Gyakum, and L. B. Tremblay, 2016: Arctic air masses in a warming world. *J. Climate*, **29**, 2359–2373, doi:10.1175/JCLI-D-15-0499.1.
- Gillett, N., and J. Fyfe, 2013: Annular mode changes in the CMIP5 simulations. *Geophys. Res. Lett.*, **40**, 1189–1193, doi:10.1002/grl.50249.
- Guemas, V., and Coauthors, 2014: A review on Arctic sea-ice predictability and prediction on seasonal to decadal time-scales. *Quart. J. Roy. Meteor. Soc.*, **142**, 546–561, doi:10.1002/qj.2401.
- Holland, M. M., and J. Stroeve, 2011: Changing seasonal sea ice predictor relationships in a changing Arctic climate. *Geophys. Res. Lett.*, **38**, L18501, doi:10.1029/2011GL049303.
- , C. M. Bitz, and B. Tremblay, 2006: Future abrupt reductions in the summer Arctic sea ice. *Geophys. Res. Lett.*, **33**, L23503, doi:10.1029/2006GL028024.
- , M. C. Serreze, and J. Stroeve, 2010: The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models. *Climate Dyn.*, **34**, 185–200, doi:10.1007/s00382-008-0493-4.
- , D. A. Bailey, and S. Vavrus, 2011: Inherent sea ice predictability in the rapidly changing Arctic environment of the Community Climate System Model, version 3. *Climate Dyn.*, **36**, 1239–1253, doi:10.1007/s00382-010-0792-4.
- Hurrell, J. W., and Coauthors, 2013: The Community Earth System Model: A framework for collaborative research. *Bull. Amer. Meteor. Soc.*, **94**, 1339–1360, doi:10.1175/BAMS-D-12-00121.1.
- Inoue, J., M. E. Hori, and K. Takaya, 2012: The role of Barents Sea ice in the wintertime cyclone track and emergence of a warm-Arctic cold-Siberian anomaly. *J. Climate*, **25**, 2561–2568, doi:10.1175/JCLI-D-11-00449.1.
- Jahn, A., and M. M. Holland, 2013: Implications of Arctic sea ice changes for North Atlantic deep convection and the meridional overturning circulation in CCSM4-CMIP5 simulations. *Geophys. Res. Lett.*, **40**, 1206–1211, doi:10.1002/grl.50183.
- , and Coauthors, 2012: Late-twentieth-century simulation of Arctic sea ice and ocean properties in the CCSM4. *J. Climate*, **25**, 1431–1452, doi:10.1175/JCLI-D-11-00201.1.
- Jin-Qing, Z., L. Wei-Jing, and R. Hong-Li, 2013: Representation of the Arctic Oscillation in the CMIP5 models. *Adv. Climate Change Res.*, **4**, 242–249, doi:10.3724/SP.J.1248.2013.242.
- Kay, J. E., T. L'Ecuyer, A. Gettelman, G. Stephens, and C. O'Dell, 2008: The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum. *Geophys. Res. Lett.*, **35**, L08503, doi:10.1029/2008GL033451.
- , M. M. Holland, C. M. Bitz, E. Blanchard-Wrigglesworth, A. Gettelman, A. Conley, and D. Bailey, 2012: The influence of local feedbacks and northward heat transport on the equilibrium arctic climate response to increased greenhouse gas forcing. *J. Climate*, **25**, 5433–5450, doi:10.1175/JCLI-D-11-00622.1.
- , and Coauthors, 2014: The Community Earth System Model (CESM) Large Ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, **96**, 1333–1349, doi:10.1175/BAMS-D-13-00255.1.
- Khon, V., I. Mokhov, M. Latif, V. Semenov, and W. Park, 2010: Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century. *Climatic Change*, **100**, 757–768, doi:10.1007/s10584-009-9683-2.
- Kwok, R., and D. Rothrock, 2009: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophys. Res. Lett.*, **36**, L15501, doi:10.1029/2009GL039035.
- L'Heureux, M. L., A. Kumar, G. D. Bell, M. S. Halpert, and R. W. Higgins, 2008: Role of the Pacific–North American (PNA) pattern in the 2007 Arctic sea ice decline. *Geophys. Res. Lett.*, **35**, L20701, doi:10.1029/2008GL035205.
- Lindsay, R., J. Zhang, A. Schweiger, M. Steele, and H. Stern, 2009: Arctic sea ice retreat in 2007 follows thinning trend. *J. Climate*, **22**, 165–176, doi:10.1175/2008JCLI2521.1.
- Liu, J., M. Song, R. M. Horton, and Y. Hu, 2013: Reducing spread in climate model projections of a September ice-free Arctic. *Proc. Natl. Acad. Sci. USA*, **110**, 12 571–12 576, doi:10.1073/pnas.1219716110.
- Maslanik, J. A., M. C. Serreze, and R. G. Barry, 1996: Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophys. Res. Lett.*, **23**, 1677–1680, doi:10.1029/96GL01426.

- , C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery, 2007: A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. *Geophys. Res. Lett.*, **34**, L24501, doi:[10.1029/2007GL032043](https://doi.org/10.1029/2007GL032043).
- Meehl, G. A., and Coauthors, 2013: Climate change projections in CESM1 (CAM5) compared to CCSM4. *J. Climate*, **26**, 6287–6308, doi:[10.1175/JCLI-D-12-00572.1](https://doi.org/10.1175/JCLI-D-12-00572.1).
- Meier, W. N., and J. A. Maslanik, 2001: Improved sea ice parcel trajectories in the Arctic via data assimilation. *Mar. Pollut. Bull.*, **42**, 505–511, doi:[10.1016/S0025-326X\(00\)00195-8](https://doi.org/10.1016/S0025-326X(00)00195-8).
- , and M. Dai, 2006: High-resolution sea-ice motions from AMSR-E imagery. *Ann. Glaciol.*, **44**, 352–356, doi:[10.3189/172756406781811286](https://doi.org/10.3189/172756406781811286).
- , J. A. Maslanik, and C. W. Fowler, 2000: Error analysis and assimilation of remotely sensed ice motion within an Arctic sea ice model. *J. Geophys. Res.*, **105**, 3339–3356, doi:[10.1029/1999JC900268](https://doi.org/10.1029/1999JC900268).
- , G. Peng, D. J. Scott, and M. H. Savoie, 2014: Verification of a new NOAA/NSIDC passive microwave sea-ice concentration climate record. *Polar Res.*, **33**, 21004, doi:[10.3402/polar.v33.21004](https://doi.org/10.3402/polar.v33.21004).
- , F. Fetterer, M. Savoie, S. Mallory, R. Duerr, and J. Stroeve, 2015: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, version 2. National Snow and Ice Data Center. Subset used: January 1990 to December 2014, accessed 30 May 2014, doi:[10.7265/N55M63M1](https://doi.org/10.7265/N55M63M1).
- Miller, R., G. Schmidt, and D. Shindell, 2006: Forced annular variations in the 20th century Intergovernmental Panel on Climate Change Fourth Assessment Report models. *J. Geophys. Res.*, **111**, D18101, doi:[10.1029/2005JD006323](https://doi.org/10.1029/2005JD006323).
- Nikolaeva, A. J., and N. P. Sesterikov, 1970: A method of calculation of the ice conditions (on the example of the Laptev Sea). *Ice Forecasting Techniques for the Arctic Seas*, B. A. Krutskikh, Z. M. Gudkovic, and A. L. Sokolov, Eds., Amerind Publishing Co. Pvt. Ltd., 150–230.
- NSIDC, 2016: Ice Motion from passive microwave: SMMR, SSM/I, SSMIS, and AMSR-E. National Snow and Ice Data Center, accessed 15 January 2016. [Available online at http://nsidc.org/data/docs/daac/nsidc0116_icemotion/smmr_ssmi.html.]
- Overland, J. E., and M. Wang, 2005: The Arctic climate paradox: The recent decrease of the Arctic Oscillation. *Geophys. Res. Lett.*, **32**, L06701, doi:[10.1029/2004GL021752](https://doi.org/10.1029/2004GL021752).
- , J. A. Francis, E. Hanna, and M. Wang, 2012: The recent shift in early summer Arctic atmospheric circulation. *Geophys. Res. Lett.*, **39**, L19804, doi:[10.1029/2012GL053268](https://doi.org/10.1029/2012GL053268).
- Peng, G., W. Meier, D. Scott, and M. Savoie, 2013: A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring. *Earth Syst. Sci. Data*, **5**, 311–318, doi:[10.5194/essd-5-311-2013](https://doi.org/10.5194/essd-5-311-2013).
- Perovich, D. K., B. Light, H. Eicken, K. F. Jones, K. Runciman, and S. V. Nghiem, 2007a: Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback. *Geophys. Res. Lett.*, **34**, L19505, doi:[10.1029/2007GL031480](https://doi.org/10.1029/2007GL031480).
- , S. V. Nghiem, T. Markus, and A. Schweiger, 2007b: Seasonal evolution and interannual variability of the local solar energy absorbed by the Arctic sea ice–ocean system. *J. Geophys. Res.*, **112**, C03005, doi:[10.1029/2006JC003558](https://doi.org/10.1029/2006JC003558).
- Peters, G., T. Nilssen, L. Lindholt, M. Eide, S. Glomsrød, L. Eide, and J. Fuglestad, 2011: Future emissions from shipping and petroleum activities in the Arctic. *Atmos. Chem. Phys.*, **11**, 5305–5320, doi:[10.5194/acp-11-5305-2011](https://doi.org/10.5194/acp-11-5305-2011).
- Petoukhov, V., and V. A. Semenov, 2010: A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents. *J. Geophys. Res.*, **115**, D21111, doi:[10.1029/2009JD013568](https://doi.org/10.1029/2009JD013568).
- Pfirman, S., W. F. Haxby, R. Colony, and I. Rigor, 2004: Variability in Arctic sea ice drift. *Geophys. Res. Lett.*, **31**, L16402, doi:[10.1029/2004GL020063](https://doi.org/10.1029/2004GL020063).
- Rauthe, M., and H. Paeth, 2004: Relative importance of Northern Hemisphere circulation modes in predicting regional climate change. *J. Climate*, **17**, 4180–4189, doi:[10.1175/JCLI3140.1](https://doi.org/10.1175/JCLI3140.1).
- Rigor, I. G., 2002: IABP drifting buoy pressure, temperature, position, and interpolated ice velocity, version 1. Polar Science Center, National Snow and Ice Data Center. Subset used: 1988–2011, accessed 12 June 2014, doi:[10.7265/N53X84K7](https://doi.org/10.7265/N53X84K7).
- , and J. M. Wallace, 2004: Variations in the age of Arctic sea-ice and summer sea-ice extent. *Geophys. Res. Lett.*, **31**, L09401, doi:[10.1029/2004GL019492](https://doi.org/10.1029/2004GL019492).
- , —, and R. L. Colony, 2002: Response of sea ice to the Arctic Oscillation. *J. Climate*, **15**, 2648–2663, doi:[10.1175/1520-0442\(2002\)015<2648:ROSITT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2).
- Schweiger, A., J. Zhang, R. Lindsay, and M. Steele, 2008: Did unusually sunny skies help drive the record sea ice minimum of 2007? *Geophys. Res. Lett.*, **35**, L10503, doi:[10.1029/2008GL033463](https://doi.org/10.1029/2008GL033463).
- Screen, J. A., I. Simmonds, and K. Keay, 2011: Dramatic interannual changes of perennial Arctic sea ice linked to abnormal summer storm activity. *J. Geophys. Res.*, **116**, D15105, doi:[10.1029/2011JD015847](https://doi.org/10.1029/2011JD015847).
- Serreze, M. C., and J. Stroeve, 2015: Arctic sea ice trends, variability and implications for seasonal ice forecasting. *Philos. Trans. Roy. Soc. London*, **A373**, 20140159, doi:[10.1098/rsta.2014.0159](https://doi.org/10.1098/rsta.2014.0159).
- , M. M. Holland, and J. Stroeve, 2007: Perspectives on the Arctic's shrinking sea-ice cover. *Science*, **315**, 1533–1536, doi:[10.1126/science.1139426](https://doi.org/10.1126/science.1139426).
- Smith, L. C., and S. R. Stephenson, 2013: New trans-Arctic shipping routes navigable by midcentury. *Proc. Natl. Acad. Sci. USA*, **110**, E1191–E1195, doi:[10.1073/pnas.1214212110](https://doi.org/10.1073/pnas.1214212110).
- Sorteberg, A., and B. Kvindal, 2006: Atmospheric forcing on the Barents Sea winter ice extent. *J. Climate*, **19**, 4772–4784, doi:[10.1175/JCLI3885.1](https://doi.org/10.1175/JCLI3885.1).
- , N. G. Kvamstø, and Ø. Byrkjedal, 2005: Wintertime Nordic Seas cyclone variability and its impact on oceanic volume transports into the Nordic Seas. *The Nordic Seas: An Integrated Perspective*, *Geophys. Monogr.*, Vol. 158, Amer. Geophys. Union, 137–156.
- Steele, M., J. Zhang, and W. Ermold, 2010: Mechanisms of summertime upper Arctic Ocean warming and the effect on sea ice melt. *J. Geophys. Res.*, **115**, C11004, doi:[10.1029/2009JC005849](https://doi.org/10.1029/2009JC005849).
- Stroeve, J. C., M. M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophys. Res. Lett.*, **34**, L09501, doi:[10.1029/2007GL029703](https://doi.org/10.1029/2007GL029703).
- , V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier, 2012a: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.*, **39**, L16502, doi:[10.1029/2012GL052676](https://doi.org/10.1029/2012GL052676).
- , M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik, and A. P. Barrett, 2012b: The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change*, **110**, 1005–1027, doi:[10.1007/s10584-011-0101-1](https://doi.org/10.1007/s10584-011-0101-1).
- , A. Barrett, M. Serreze, and A. Schweiger, 2014a: Using records from submarine, aircraft and satellite to evaluate climate

- model simulations of Arctic sea ice thickness. *Cryosphere*, **8**, 1839–1854, doi:[10.5194/tc-8-1839-2014](https://doi.org/10.5194/tc-8-1839-2014).
- , L. C. Hamilton, C. M. Bitz, and E. Blanchard-Wigglesworth, 2014b: Predicting September sea ice: Ensemble skill of the SEARCH sea ice outlook 2008–2013. *Geophys. Res. Lett.*, **41**, 2411–2418, doi:[10.1002/2014GL059388](https://doi.org/10.1002/2014GL059388).
- Sumata, H., R. Gerdes, F. Kauker, and M. Karcher, 2015a: Empirical error functions for monthly mean Arctic sea-ice drift. *J. Geophys. Res. Oceans*, **120**, 7450–7475, doi:[10.1002/2015JC011151](https://doi.org/10.1002/2015JC011151).
- , R. Kwok, R. Gerdes, F. Kauker, and M. Karcher, 2015b: Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data. *J. Geophys. Res. Oceans*, **120**, 5285–5301, doi:[10.1002/2015JC010810](https://doi.org/10.1002/2015JC010810).
- Tang, Q., X. Zhang, X. Yang, and J. A. Francis, 2013: Cold winter extremes in northern continents linked to Arctic sea ice loss. *Environ. Res. Lett.*, **8**, 014036, doi:[10.1088/1748-9326/8/1/014036](https://doi.org/10.1088/1748-9326/8/1/014036).
- Thompson, D. W., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297–1300, doi:[10.1029/98GL00950](https://doi.org/10.1029/98GL00950).
- , and —, 2001: Regional climate impacts of the Northern Hemisphere annular mode. *Science*, **293**, 85–89, doi:[10.1126/science.1058958](https://doi.org/10.1126/science.1058958).
- Tietsche, S., D. Notz, J. H. Jungclauss, and J. Marotzke, 2013: Predictability of large interannual Arctic sea-ice anomalies. *Climate Dyn.*, **41**, 2511–2526, doi:[10.1007/s00382-013-1698-8](https://doi.org/10.1007/s00382-013-1698-8).
- Tschudi, M., C. Fowler, J. Maslanik, J. Stewart, and W. Meier, 2016: Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, version 3. NSIDC. Subset used: January 1990–May 2015, accessed 16 May 2016, doi:[10.5067/O57VAIT2AYYY](https://doi.org/10.5067/O57VAIT2AYYY).
- Tucker, W. B., J. W. Weatherly, D. T. Eppler, L. D. Farmer, and D. L. Bentley, 2001: Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s. *Geophys. Res. Lett.*, **28**, 2851–2854, doi:[10.1029/2001GL012967](https://doi.org/10.1029/2001GL012967).
- Vallis, G. K., 2006: *Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation*. Cambridge University Press, 769 pp.
- Vavrus, S. J., M. M. Holland, A. Jahn, D. A. Bailey, and B. A. Blazey, 2012: Twenty-first-century Arctic climate change in CCSM4. *J. Climate*, **25**, 2696–2710, doi:[10.1175/JCLI-D-11-00220.1](https://doi.org/10.1175/JCLI-D-11-00220.1).
- Vermaire, J. C., M. F. Pisarcic, J. R. Thienpont, C. J. Courtney Mustaphi, S. V. Kokelj, and J. P. Smol, 2013: Arctic climate warming and sea ice declines lead to increased storm surge activity. *Geophys. Res. Lett.*, **40**, 1386–1390, doi:[10.1002/grl.50191](https://doi.org/10.1002/grl.50191).
- Vihma, T., 2014: Effects of Arctic sea ice decline on weather and climate: A review. *Surv. Geophys.*, **35**, 1175–1214, doi:[10.1007/s10712-014-9284-0](https://doi.org/10.1007/s10712-014-9284-0).
- Wang, J., J. Zhang, E. Watanabe, M. Ikeda, K. Mizobata, J. E. Walsh, X. Bai, and B. Wu, 2009: Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent? *Geophys. Res. Lett.*, **36**, L05706, doi:[10.1029/2008GL036706](https://doi.org/10.1029/2008GL036706).
- Williams, J., B. Tremblay, R. Newton, and R. Allard, 2016: Dynamic preconditioning of the minimum September sea-ice extent. *J. Climate*, doi:[10.1175/JCLI-D-15-0515.1](https://doi.org/10.1175/JCLI-D-15-0515.1), in press.
- Woodgate, R. A., T. Weingartner, and R. Lindsay, 2010: The 2007 Bering Strait oceanic heat flux and anomalous Arctic sea-ice retreat. *Geophys. Res. Lett.*, **37**, L01602, doi:[10.1029/2009GL041621](https://doi.org/10.1029/2009GL041621).
- Yang, J., 2006: The seasonal variability of the Arctic Ocean Ekman transport and its role in the mixed layer heat and salt fluxes. *J. Climate*, **19**, 5366–5387, doi:[10.1175/JCLI3892.1](https://doi.org/10.1175/JCLI3892.1).
- Zhang, J., W. Hibler III, M. Steele, and D. Rothrock, 1998: Arctic ice–ocean modeling with and without climate restoring. *J. Phys. Oceanogr.*, **28**, 191–217, doi:[10.1175/1520-0485\(1998\)028<0191:AIOMWA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1998)028<0191:AIOMWA>2.0.CO;2).
- , R. Lindsay, M. Steele, and A. Schweiger, 2008: What drove the dramatic retreat of Arctic sea ice during summer 2007? *Geophys. Res. Lett.*, **35**, L11505, doi:[10.1029/2008GL034005](https://doi.org/10.1029/2008GL034005).