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Key Points:
- Sea ice seasons have shortened by at least 5 days/decade over most of the Arctic
- Across 1.9 million km^2 ice seasons have shortened by at least 25 days/decade
- Counter to most of the Arctic ice seasons have lengthened in the Bering Sea

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3

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Spatially mapped reductions in the length of the Arctic sea ice season

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Abstract Satellite data are used to determine the number of days having sea ice coverage in each year 1979–2013 and to map the trends in these ice-season lengths. Over the majority of the Arctic seasonal sea ice zone, the ice season shortened at an average rate of at least 5 days/decade between 1979 and 2013, and in a small area in the northeastern Barents Sea the rate of shortening reached over 65 days/decade. The only substantial non-coastal area with lengthening sea ice seasons is the Bering Sea, where the ice season lengthened by 5–15 days/decade. Over the Arctic as a whole, the area with ice seasons shortened by at least 5 days/decade is 12.4×10^6 km^2, while the area with ice seasons lengthened by at least 5 days/decade is only 1.1×10^6 km^2. The contrast is even greater, percentage-wise, for higher rates.

1. Introduction

Arctic sea ice has received considerable attention in recent years because of the downward trend in both the areal extent [e.g., *Parkinson et al.*, 1999; *Stroeve et al.*, 2012] and the thickness [e.g., *Rothrock et al.*, 1999; *Kwok and Rothrock*, 2009] of the ice cover. The decreasing ice cover coincides with significant Arctic warming [e.g., *Jeffries et al.*, 2013; *Ding et al.*, 2014], and indeed the positive feedback between the ice and the temperature—with warming leading to ice reductions that in turn lead to more warming because of the resulting decreased surface albedo—is thought to be a principal reason why the Arctic region has warmed more than the global average [e.g., *Screen and Simmonds*, 2010].

Passive-microwave satellite data have provided the primary data source for the quantification of the decreasing areal extent of the ice. These data have important advantages for sea ice monitoring. Among them: the microwave signature of ice is quite different from the signature of liquid water, allowing a clear identification of the ice edge and an estimation of ice concentration; the microwaves are coming from within the Earth system, and thus the data can be collected during periods of darkness as well as sunlight; and at selected microwave frequencies, the microwave radiation can pass through clouds nearly unaffected. These advantages allow a monitoring of the ice cover under all lighting and most weather conditions. This has enabled a robust determination of the areal coverage of the Arctic sea ice since the beginning of the multi-channel satellite passive-microwave record in late 1978.

Decreases in the areal extent of the Arctic sea ice as determined from the multi-channel satellite record were pointed out in the late 1980s, although with due cautions in view of the brevity of the record and the minor nature of the decreases up to that point [*Parkinson and Cavalieri*, 1989]. The decreases became more convincing in the 1990s [e.g., *Johannessen et al.*, 1995; *Parkinson et al.*, 1999] and have accelerated in the 21st century [e.g., *Meier et al.*, 2007; *Cavalieri and Parkinson*, 2012; *Stroeve et al.*, 2012], although with continuing interannual variability [e.g., *Screen et al.*, 2011].

Important as the quantification of the ice extent decreases are, they fail to tell the full story of what the satellite passive-microwave data can reveal about the changing Arctic sea ice cover. They allow quite thorough temporal detail, even down to showing changes on a daily timescale, but much less spatial detail. In this paper, instead of looking at the extent changes, the focus is on changes in the length of the sea ice season, defined (for each pixel and each year) as the number of days with sea ice coverage. The season-length calculations cannot show the temporal detail of the ice-extent calculations, as they aggregate to yearly values, but they show much greater spatial detail, down to the pixel level. The two measures hence complement each other nicely.

The length of the sea ice season was first defined and mapped from satellite data in the early 1990s. At that time, it was found that trends in the length of the sea ice season over the 1979–1986 period showed coherent patterns of shortening sea ice seasons in most of the eastern hemisphere of the Arctic seasonal ice zone and in the Greenland Sea and lengthening sea ice seasons in most of the remainder of the seasonal ice zone, particularly in Baffin Bay, the Labrador Sea, Hudson Bay, the Beaufort Sea, and portions of the Bering Sea [*Parkinson*, 1992]. (A location map appears in the supporting information, as Figure S1.) With an additional 27 years of data, the results in this paper show the area with lengthening sea ice seasons to be vastly reduced, as by now shortening sea ice seasons dominate almost the entire seasonal ice zone.

In view of the high albedo of sea ice relative to liquid water, the shortened length of the sea ice season in much of the seasonal sea ice zone results in less reflection of solar radiation back to space and more absorption of solar radiation into the ocean, providing a forcing toward further warming the system. This forcing, well known as the ice-albedo feedback [e.g., *Kellogg*, 1975; *Perovich et al.*, 2007; *Stroeve et al.*, 2012], is so impactful that calculations with the global model of the NASA Goddard Institute for Space Studies (GISS) show that, at least in that model, a full 37% of the global warming calculated for a doubling of atmospheric carbon dioxide (CO_2) is due to the inclusion of sea ice in the calculations [*Rind et al.*, 1995]. The sea ice reductions also result in increased transfer of energy between the ocean and atmosphere, a decreased strength of the Arctic atmospheric temperature inversion, and increased evaporation, with consequences to atmospheric moisture, atmospheric circulation, and precipitation [e.g., *Screen et al.*, 2013; *Vihma*, 2014].

Impacts of ice losses on the Arctic ecosystem extend all the way through the polar food web, from helping to control algal production to impacting such large animals as walruses, seals, Arctic foxes, and the iconic polar bears, whose primary hunting season shortens or lengthens in line with the sea ice season [*Post et al.*, 2013; *Tedesco and Vichi*, 2014]. Sea ice reductions affect species interactions, disease transmission, and a wealth of other aspects of the ecological system [*Post et al.*, 2013]. Humans are affected by the ice reductions through the climate and ecosystem impacts and also through such economically relevant impacts as the anticipated opening of new trans-Arctic shipping routes [*Smith and Stephenson*, 2013] and effects on proposed offshore oil and gas exploration in the Arctic [*Galley et al.*, 2013].

2. Data and Methodology

The data used for this study are from satellite multi-channel passive-microwave instruments from the National Aeronautics and Space Administration (NASA) and the United States Department of Defense (DOD). The earliest of these instruments was NASA's Scanning Multichannel Microwave Radiometer (SMMR), launched on the Nimbus 7 satellite in October 1978. This instrument provided data from November 1978 through August 1987. Fortunately, by the end of life of the SMMR instrument, the first of the DOD Special Sensor Microwave Imager (SSMI) instruments had been launched on the Defense Meteorological Satellite Program's (DMSP's) F8 satellite, in June 1987. Since June 1987, the DOD has maintained at least one SSMI or its follow-on SSMI Sounder (SSMIS) in orbit at all times. The results in this paper are from the Nimbus 7 SMMR, the F8, F11, and F13 SSMIs, and the F17 SSMIS.

The SMMR, SSMI, and SSMIS instruments are also the instruments used in many studies of the decreasing Arctic sea ice extents [e.g., *Johannessen et al.*, 1995; *Parkinson et al.*, 1999; *Meier et al.*, 2007; *Cavalieri and Parkinson*, 2012; *Stroeve et al.*, 2012]. For those studies as for this one, the data have been mapped onto a rectangular grid overlaid on a north polar stereographic projection with grid squares (or pixels) representing Earth areas of 25 × 25 km [*NSIDC*, 1992], and the results are based on the fundamental sea ice variable derived from the satellite data, the sea ice concentration. Sea ice concentration is the percent areal coverage of sea ice in each pixel. The ice concentration data were generated at NASA Goddard Space Flight Center using the NASA Team algorithm [*Gloersen et al.*, 1992]. Rigorous intercalibration was done between the SMMR and three SSMI sensors [*Cavalieri et al.*, 1999] and between the SSMI and SSMIS sensors [*Cavalieri et al.*, 2012] to create a homogeneous data set. The data are archived and available at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

The length of the sea ice season is calculated for each year at each pixel by counting the number of days the pixel had at least 15% sea ice concentration. The 15% cutoff is also commonly used in the ice extent studies [e.g., *Parkinson et al.*, 1999; *Meier et al.*, 2007; *Cavalieri and Parkinson*, 2012]. Trends in the length of the sea ice season are then calculated for each pixel by obtaining the slope of the line of least squares fit through

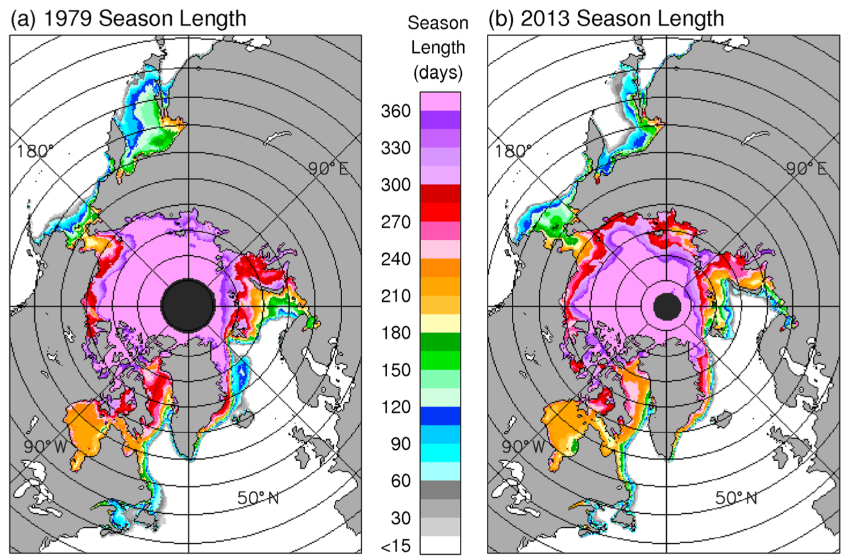

Figure 1. Length of the sea ice season for (a) 1979 and (b) 2013.

the data for the time period of interest. Trends are mapped in the Results section for the first 10, 20, and 30 years of the record and for the full 35 years 1979–2013. Due to the orbits of the satellites and the characteristics of the instruments, the data sets do not include the area in the immediate vicinity of the north pole. The SMMR data extend northward to 84.6°N, and the SSMI and SSMIS data extend northward to 87.6°N. Hence, results for the SMMR years (1979–1987) and for the trends extend only to 84.6°N, whereas results for individual years within the SSMI and SSMIS time frame (1988 and beyond) extend to 87.6°N.

3. Results

Examining maps of the length of the sea ice season for each of the 35 years 1979–2013, it is clear that many fundamentals have remained the same throughout the record. For instance, comparing the starting and ending years (Figure 1), which are typical of the early and late portions of the record: the area of year-round (or at least 360 days) ice coverage continues to include much of the central Arctic and a portion of the Canadian Archipelago; the overall outer edge of the ice area continues to reflect the strong influence of the Gulf Stream and North Atlantic Current, with year-round ice-free areas extending well into the polar region to the west and north of Scandinavia; and for any longitude, the general (although not universal) tendency is for the season length to decrease southward (Figure 1). There are also, however, some clear differences in the 2013 versus 1979 conditions, among those being the reduction in the area of year-round ice coverage and the shifting of substantial areas of the Sea of Okhotsk and the Barents Sea from being within the seasonal ice zone to being ice-free year round (Figure 1b versus 1a).

Mapping the trends in the length of the sea ice season for the first 10, 20, and 30 years of the record and for the full 35 years (Figure 2) dramatically illustrates the transition in the Arctic sea ice cover. Specifically: for the first 10 years, 1979–1988, the trends show substantial regions with marked shortening of the ice season and substantial regions of lengthening sea ice seasons (Figure 2a); with an additional 10 years, the 1979–1998 trends have a noticeably larger area of shortening versus lengthening seasons (Figure 2b); and with the 30 and 35 year records, the seasonal ice zone has shortening sea ice seasons almost everywhere, the main exceptions being in the Bering Sea and portions of the Canadian Archipelago (Figures 2c and 2d). This complements well the aforementioned acceleration of the decrease in ice extents since the 1990s.

The statistical significance of the trends has increased markedly as the data set has lengthened. Trends for the first 10 years of the record are generally not statistically significant even at the 95% confidence level, with the exception of a sizeable portion of the Sea of Okhotsk and smaller portions of the northeastern Greenland

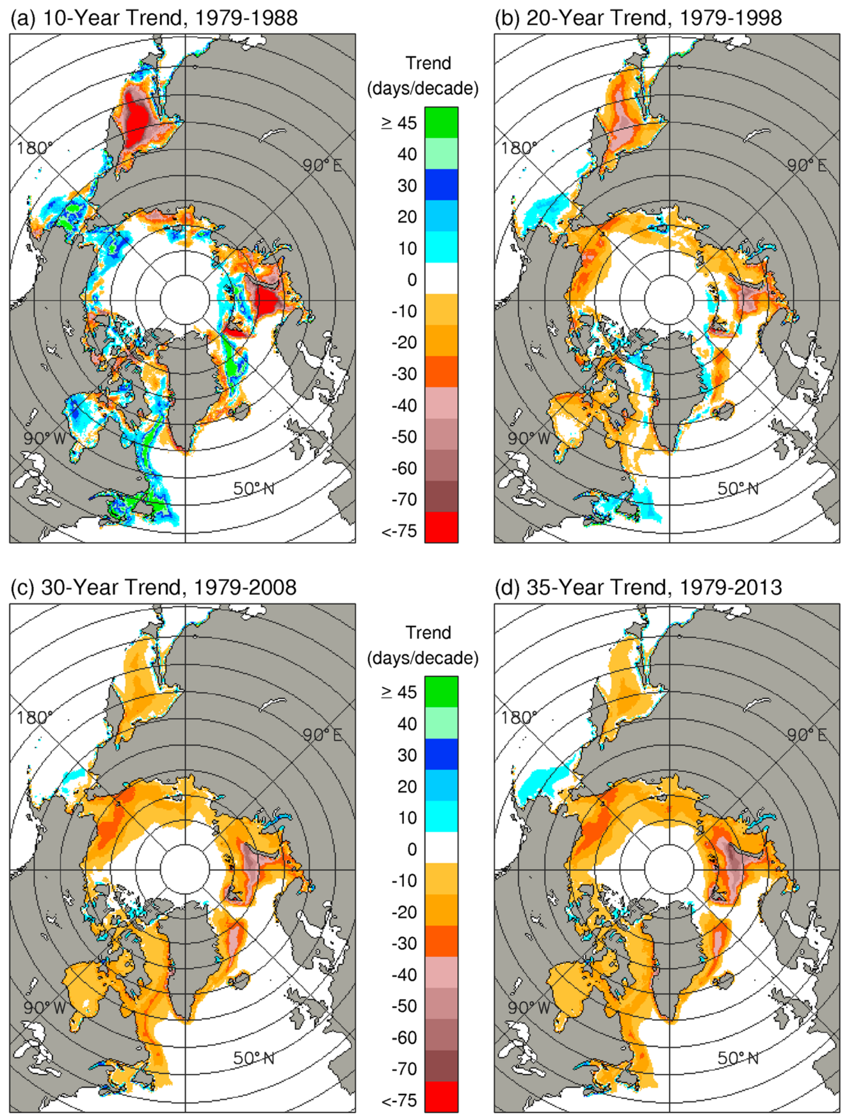

Figure 2. Trends in the length of the sea ice season for the following periods: (a) 1979–1988, (b) 1979–1998, (c) 1979–2008, and (d) 1979–2013.

Sea and the eastern Barents Sea (Figures S2a and S3a for 95% and 99% confidence levels, respectively). However, the area of statistical significance is larger for the 20 year trends, 1979–1998 (Figures S2b and S3b) and much larger for the 30 year (Figures S2c and S3c) and 35 year (Figures S2d and S3d) trends. The 30 year trends, 1979–2008, show statistical significance at the 95% level over most of the seasonal sea ice zone (Figure S2c) and at the 99% level over a lesser but still substantial portion of it (Figure S3c). The 35 year trends, 1979–2013, show statistical significance at the 95% level over almost the entire seasonal sea ice zone (Figure S2d) and at the 99% level over most of it (Figure S3d).

Figure 3 presents histograms quantifying the area of shortening and lengthening sea ice seasons. Summing the relevant values in the histograms, for the 10 year 1979–1988 record, the area with ice seasons that lengthened by at least 5 days/decade is 5.7×10^6 km^2, and the area with ice seasons shortened by at least 5 days/decade is only 14% greater than that, at 6.5×10^6 km^2 (Table 1). Adding another 10 years, the 20 year record has a far greater difference, with values of 2.5×10^6 km^2 and 9.1×10^6 km^2, respectively. The difference is even greater for the 30 year and 35 year records; and the contrast in areas of shortened versus lengthened sea ice seasons over the full 35 year record increases even further, percentage-wise, when considering some of

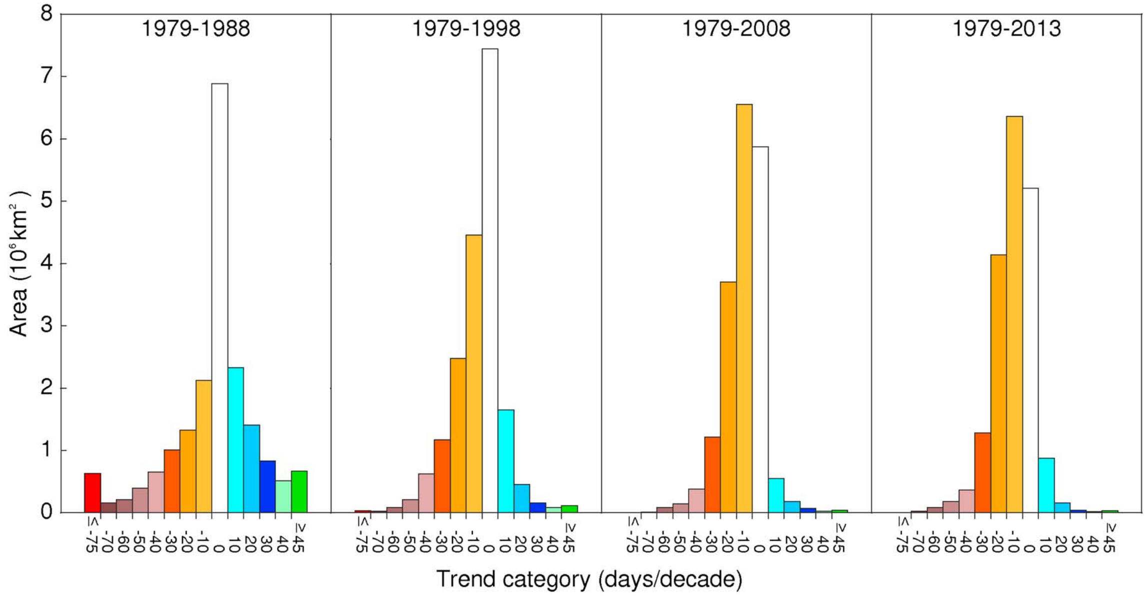

Figure 3. Histograms of the area of the Arctic region with trends in the length of the sea ice season ≤ −75 days/decade, between −75 and −65 days/decade, between −65 and −55 days/decade, and on up to between 35 and 45 days/decade, and ≥ 45 days/decade. Histograms are shown for the 10 year, 20 year, 30 year, and 35 year periods, corresponding to Figures 2a, 2b, 2c, and 2d, respectively. (In constructing the histograms, only pixels with an average of at least 1 day of ≥ 15% sea ice coverage per year are included.)

the higher rates. For instance, for the 35 year record, 1.9×10^6 km^2 had ice seasons shortened by at least 25 days/decade while only 78,000 km^2 had ice seasons lengthened by at least 25 days/decade (Table 1).

The season-length trends are affected very little by the selection of 15% for the ice concentration cutoff used in the calculations. A higher ice concentration cutoff would require more ice to be present before including a given day in the ice season and hence would mean shorter ice season lengths overall in each year of the record. However, sensitivity studies on the ice concentration cutoff yield very little effect on the trends. This is illustrated in Figure 4 with results for a 50% ice concentration cutoff. With a 50% cutoff, the season length throughout the seasonal sea ice zone is naturally shorter than with a 15% cutoff (Figure 4a versus Figure 1b, illustrating for the 2013 case), but when trends are calculated, results with a 50% cutoff are very similar to those with a 15% cutoff, retaining the basic pattern of the trends and confirming the primary conclusion of the dominance of shortening sea ice seasons (Figure 4b versus Figure 2d).

Table 1. Areal Extent of Arctic Sea Ice Coverage in Different Trend Categories, Presented for the 10 Year, 20 Year, 30 Year, and 35 Year Trends in the Length of the Sea Ice Season

Trend Category (Days/Decade)	1979–1988 (10^6 km^2)	1979–1998 (10^6 km^2)	1979–2008 (10^6 km^2)	1979–2013 (10^6 km^2)
Positive trends:				
≥ 5	5.73	2.46	0.85	1.10
≥ 15	3.41	0.80	0.30	0.23
≥ 25	2.00	0.35	0.12	0.08
≥ 35	1.17	0.20	0.06	0.04
≥ 45	0.67	0.11	0.04	0.03
Negative trends:				
≤ −5	6.50	9.07	12.09	12.44
≤ −15	4.37	4.60	5.53	6.08
≤ −25	3.04	2.13	1.83	1.94
≤ −35	2.03	0.96	0.61	0.65
≤ −45	1.39	0.33	0.23	0.29
≤ −55	0.99	0.13	0.09	0.11
≤ −65	0.79	0.05	0.01	0.02
≤ −75	0.63	0.03	0.003	0.002

4. Discussion and Conclusions

This paper examines changes in the length of the sea ice season over the period 1979–2013, showing a large predominance of shortening versus lengthening ice seasons (Figure 2). These results complement the more frequently discussed decreases in ice extent, showing much greater spatial detail although not nearly as much temporal detail as is shown in

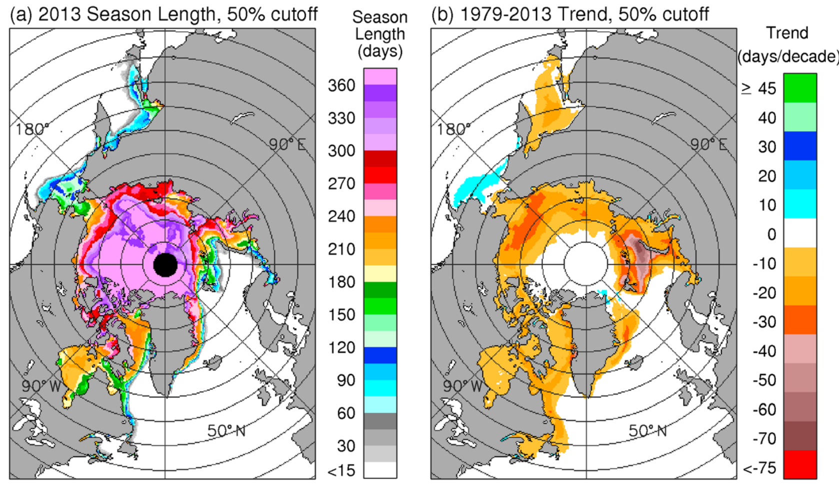

Figure 4. (a) Length of the 2013 sea ice season when considering a location to have ice only when the ice concentration is at least 50% (versus the 15% ice-concentration cutoff used in Figures 1 and 2). (b) Trends in the length of the sea ice season over the period 1979–2013 when using a 50% ice-concentration cutoff.

the ice-extent results. The season lengths show, on a pixel-by-pixel basis, at 25 × 25 km resolution, how much of the year has an ice cover (Figure 1) and how that ice-season length has changed over time (Figure 2).

Defining the length of the ice season simply as the number of days of ice coverage avoids the considerable complication of establishing start and end dates of ice coverage. Throughout the seasonal ice zone, both the autumn onset of ice coverage and the spring/summer disappearance of ice can involve multiple appearances and disappearances, some quite transitory. Simply counting the days of ice coverage gives a pure accounting of the portion of the year with a reflective, insulating ice cover present and has resulted in trend maps that show a high degree of spatial coherence, with almost no speckling. Throughout the entire grid, adjacent pixels show very similar results (Figure 2). Furthermore, the 35 year trends are statistically significant over almost the entire seasonal sea ice zone (Figures S2 and S3).

Several studies have examined the related issue of the length of the melt season and in doing so have tackled the problem of determining dates of melt onset and freezeup [*Smith*, 1998; *Belchansky et al.*, 2004; *Stroeve et al.*, 2014]. *Stroeve et al.* [2014] in particular define the melt season as extending either from early melt onset to continuous freezeup (the outer melt season) or from continuous melt onset to early freezeup (the inner melt season). The mapped 1979–2013 trends in the length of the melt season [*Stroeve et al.*, 2014] show considerably more speckling than appears in Figure 2, but the overall pattern of trends corresponds well, with the melt season having lengthened over much of the Arctic region except for the Bering Sea [*Stroeve et al.*, 2014], in line with the opposite trends for the length of the sea ice season (Figure 2).

Sea ice decreases matter to both the polar climate system and the polar ecosystem. The shortened sea ice seasons throughout much of the Arctic provide opportunities for shipping and increased air-sea exchanges, increase the region's absorption of solar radiation, force polar bears in some locales onto land for a longer portion of the year, and necessitate many additional adjustments within the polar ecosystem. They are both an indicator of and an influence on the rapidly changing Arctic.

Furthermore, the impacts of sea ice decreases are not confined to the polar regions, as illustrated by the aforementioned *Rind et al.* [1995] study in which 37% of the global warming simulated from a doubling of atmospheric CO_2 was due explicitly to the inclusion of sea ice in the calculations. The highly interconnected nature of the Earth system ensures that major changes in one region will have at least some impact on adjacent regions. In fact, considerable evidence has been compiled to link changes in the Arctic to consequent changes in weather conditions at lower latitudes [e.g., *Francis and Vavrus*, 2012; *Vihma*, 2014], and conversely, changes in lower latitudes have been viewed as forcings on recent Arctic warming [*Ding et al.*, 2014]. Although there are different approaches, at times leading to different conclusions on the specifics [e.g., *Barnes*, 2013; *Screen and Simmonds*, 2013], there is no controversy that the Earth system is interconnected and that major changes in one region are likely to propagate beyond.

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