

Geographic muting of changes in the Arctic sea ice cover

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[1] The seasonal cycle in Arctic sea ice extent is asymmetric. Its amplitude has grown in recent decades as the ice has retreated more rapidly in summer than in winter. These seasonal disparities have typically been attributed to different physical factors operating during different seasons. Here we show instead that the seasonal asymmetries in Arctic sea ice extent are a geometric consequence of the distribution of continents. Coastlines block southward ice extension during winter, thereby muting changes in ice extent, but they have relatively little effect at the time of summer minimum extent. We suggest that the latitude of the Arctic sea ice edge, averaged zonally over locations where it is free to migrate, is the most readily interpretable quantity to describe the Northern Hemisphere sea ice cover. We find that the zonal-mean sea ice edge latitude during the 1978–present era of satellite measurements has been following an approximately sinusoidal seasonal cycle that has been migrating northward at an approximately annually constant rate of 8 km/year. These results suggest a change in perspective of the most critical quantities for understanding changes in Arctic sea ice. **Citation:** Eisenman, I. (2010), Geographic muting of changes in the Arctic sea ice cover, *Geophys. Res. Lett.*, 37, L16501, doi:10.1029/2010GL043741.

1. Introduction

[2] The Northern Hemisphere sea ice extent, defined as the area with a fractional sea ice cover of at least 15%, can be inferred from passive microwave satellite observations since the late 1970s. The ice extent reaches a minimum each year in September and approximately doubles by the winter maximum in March. The seasonal decay of sea ice extent is gradual during early summer and then accelerates during the remaining summer months, whereas wintertime growth is most rapid in early winter [Parkinson *et al.*, 1999; Parkinson and Cavalieri, 2008] (Figure 1a). A standard explanation suggests that this asymmetry between seasonal growth and decay is caused by rapid temperature changes driven by air masses from the Eurasian continent [Peixoto and Oort, 1992].

[3] Seasonal asymmetries in sea ice extent become more striking when rates of recent retreat are considered. Arctic sea ice retreat is typically discussed in terms of the linear trend in ice extent for each month scaled by the 1979–2000 mean extent [e.g., Serreze *et al.*, 2007]. Calculated in this

manner, the sea ice extent each September has followed a downward trend of 10.9% per decade during 1979–2009, equivalent to an average loss of 34% of the perennial sea ice cover during the 31-year record. Each winter the sea ice has largely recovered the previous year's extent, albeit with a thinner ice cover [Maslanik *et al.*, 2007; Rothrock *et al.*, 2008], and the downward trend in March sea ice extent during the same period is only 2.9% per decade (Figures 1b and 1c). The year-to-year variability around the linear trend (Figure 1d) is also largest in September, such that the retreat is relatively constant throughout the year when expressed in units of detrended standard deviation [Meier *et al.*, 2007].

[4] This difference between September and March rates of retreat has often been explained in terms of a thin winter ice cover reforming where temperatures are below freezing, only to be quickly lost during the following summer melt season [e.g., Meier *et al.*, 2005]. Furthermore, trends in different elements of the climate system have been suggested to dominate the rate of ice retreat during different seasons. The gradual retreat of March sea ice extent has been attributed to changes in wind patterns and surface temperature [Comiso, 2006; Francis and Hunter, 2007; Nghiem *et al.*, 2007], whereas September ice retreat has been suggested to be driven predominantly by anomalies in downward longwave radiation fluxes [Francis and Hunter, 2006], with other dynamic and thermodynamic factors also contributing [Stroeve *et al.*, 2005; Serreze *et al.*, 2003; Rigor and Wallace, 2004; Ogi *et al.*, 2010]. However, unraveling the causal connection between wintertime air temperatures and sea ice cover is difficult because the ice cover strongly influences surface air temperature by impeding air-sea heat fluxes.

[5] Arctic sea ice extent reached a record low in September 2007, when the ice extent was 40% below the mean 1979–2000 September value (lowest red point in Figure 1e). The September 2007 sea ice low has been attributed to an unusual concurrence of events [Perovich and Richter-Menge, 2009]. The ice cover had thinned and was susceptible to rapid loss [Nghiem *et al.*, 2007; Maslanik *et al.*, 2007; Kwok, 2007], an unusual pattern of atmospheric circulation persisted through the summer with strong southerly winds advecting warm temperatures [Comiso *et al.*, 2008; Stroeve *et al.*, 2008], and a strengthened wind-driven transpolar drift caused large amounts of ice to either exit the Arctic Ocean through Fram Strait or pile up at the edge of the basin [Zhang *et al.*, 2008; Kwok, 2008]. Although this explanation is physically consistent, it hinges on a confluence of factors that are not obviously related.

[6] Here we focus on four central features of the observed Arctic sea ice extent evolution: (i) the asymmetry between seasonal growth and decay (Figure 1a), (ii) the seasonal disparity in the rate of recent retreat (Figure 1c), (iii) the seasonal differences in year-to-year variability about the

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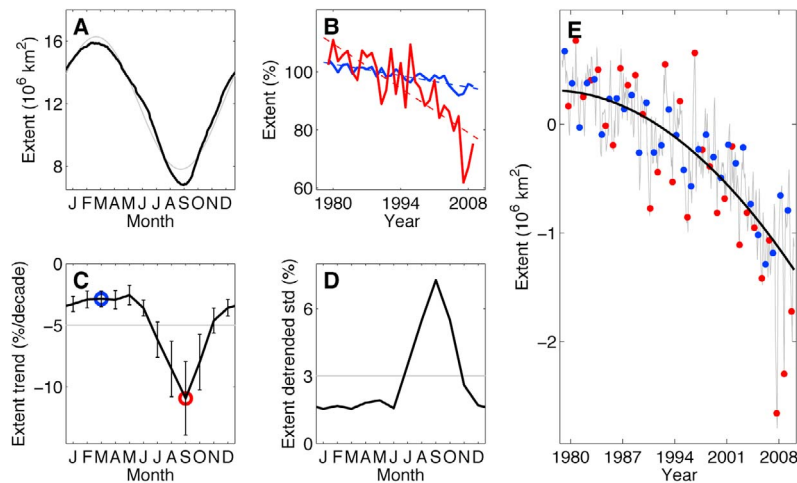


Figure 1. Evolution of Arctic sea ice extent (i.e., area with at least 15% sea ice cover), which is commonly used to assess sea ice changes. (a) Mean seasonal cycle during 1979–2000 (black line) with a sinusoidal fit (gray line; see auxiliary material) to emphasize the asymmetry between growth and decay. (b) Evolution of September (red) and March (blue) ice extent (solid lines), also including linear trends (dashed lines). (c) Linear trends for each month during 10/1978–1/2010, with rates at the time of winter maximum and summer minimum ice extent indicated by blue and red circles, respectively, and a gray horizontal line indicating the annual mean. Trend rates are computed by linear regression ignoring months with missing data, with error bars indicating estimated 95% regression confidence intervals. (d) Year-to-year standard deviation of the detrended ice extent, with a gray line indicating the annual mean. The trend and standard deviation are considerably larger in September than in any other month of the year. Following the standard convention, ice extents are expressed as percentages of the 1979–2000 mean for each month in Figures 1b–1d. (e) Ice extent monthly time series during 10/1978–1/2010 with the mean 1979–2000 seasonal cycle subtracted. The values in each March and September are indicated by blue and red circles, respectively, for reference. An optimal polynomial trend line (see auxiliary material) is included (black line) to illustrate the long-term mean changes.

long-term trend (Figure 1d), and (iv) the extreme outlier in September 2007 (Figure 1e).

2. Influence of Coastline Geometry

[7] The spatial structure of the sea ice seasonal cycle is shown in Figure 2a. In September, sea ice is confined to high northern latitudes and is largely contained within the Arctic Ocean (red shading in Figure 2a). Since the Arctic Ocean is bounded by land in most directions, during winter the sea ice cover extends to the shores and can only extend

further southward in limited regions (Fram Strait, the Bering Sea, the Barents Sea, Baffin Bay, Hudson Bay, and the Sea of Okhotsk). At the time of winter maximum ice extent (blue shading in Figure 2a), coastlines have blocked the southward extension of sea ice at most longitudes. Hence when the ice edge migrates a given distance southward at the end of the winter growth season, the change in total hemispheric sea ice extent is relatively small.

[8] A cartoon of the Arctic coastline distribution is shown in Figure 2b. This schematically illustrates how geometric constraints of Arctic coastlines cause changes in the location

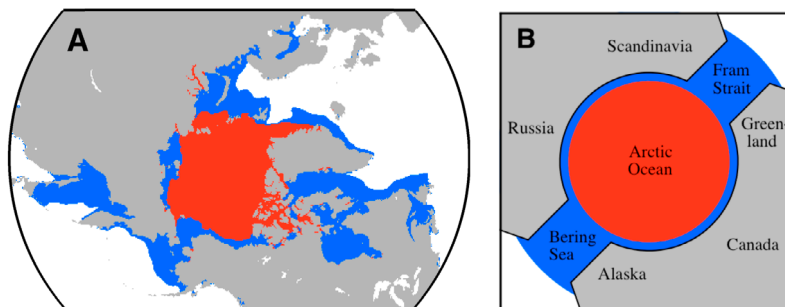


Figure 2. Spatial structure of sea ice seasonal cycle. (a) Mean 1979–2000 sea ice cover in September (red) and additional area covered by sea ice in March (blue). The data are plotted on a polar stereographic projection with ice-covered areas identified as grid cells which have at least 15% sea ice cover in the 22-year averages for March or September. (b) Cartoon of the Arctic coastlines illustrating how geometric constraints cause displacements of the sea ice edge near the winter maximum (blue) to have a muted effect on areal extent, in contrast to ice edge displacements near the summer minimum (red).

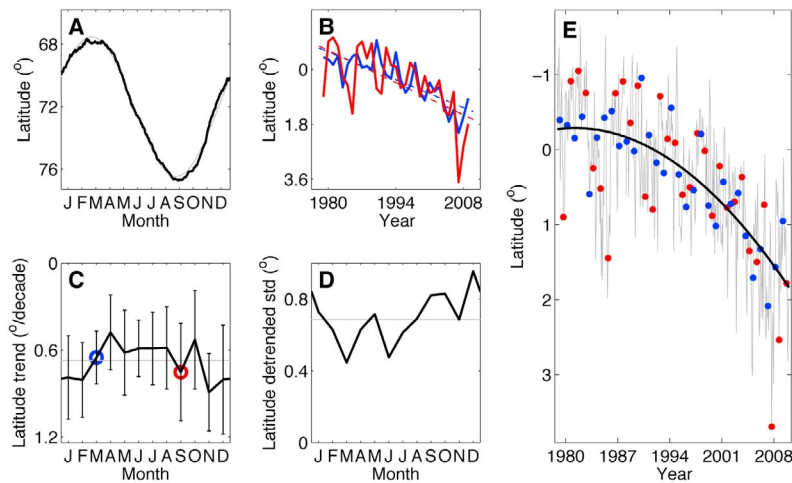


Figure 3. Evolution of the zonal-mean latitude of the sea ice edge, which is proposed here as a more readily interpretable quantity than ice extent. (a–e) As in Figures 1a–1e. The seasonal asymmetries in ice extent (Figure 1) disappear when changes are viewed from the perspective of ice edge latitude.

of the March ice edge to have relatively little effect on the areal extent compared with changes in the location of the ice edge in September.

[9] To quantify this effect, we examine changes in the location of the sea ice edge in satellite-derived observations of the Northern Hemisphere sea ice cover [Cavalieri *et al.*, 1996; Meier *et al.*, 2006; Maslanik and Stroeve, 1999]. Here we summarize the calculation, which is described in detail in the auxiliary material.¹ For each day of satellite observations, we look from the North Pole meridionally in each direction and identify the ice edge as the point with ice-covered ocean to the north and ice-free ocean to the south. Some meridians do not contain such points, instead transitioning directly from ice-covered ocean to land, and we consider these longitudes to contain no information about the ice edge latitude. We calculate the zonal-mean latitude of the sea ice edge by averaging over all longitudes in which an ice edge is identified (although as usual for zonal mean, this is merely a summary statistic, which does not imply that the ice edge latitude is zonally uniform [Bitz *et al.*, 2005]). This can be visualized in Figure 2a as the mean latitude of locations where the edge of the blue or red shading does not touch the gray shading. This leads to a time series of values for the zonal-mean ice edge latitude, which can be compared with the evolution of the ice extent.

3. Results

[10] The seasonal cycle of the ice edge latitude is plotted in Figure 3a. In contrast with the seasonal cycle in ice extent (Figure 1a), the ice edge latitude traces out a symmetric sinusoidal oscillation during the course of the year. The phase of the seasonal cycle in ice edge latitude (Figure 3a) demonstrates a rate of change approximately proportional to Northern Hemisphere insolation, with the ice edge latitude lagging behind insolation by 2.5 months. The central dif-

ference between Figure 1a and Figure 3a is that the ice edge latitude varies smoothly, whereas changes in ice extent are muted during winter when the ice cover is largely bounded by land. This demonstrates how geometric constraints from Arctic coastlines introduce seasonal asymmetry into the evolution of Arctic sea ice extent, despite seasonally symmetric changes in ice edge latitude.

[11] Next, we examine the rate of recent sea ice retreat. In contrast with the ice extent which retreats far more rapidly in September than in March (Figure 1b), we find that the ice edge latitude retreats at nearly identical rates in the two months (Figure 3b). In Figure 3c, the 1978–2010 trend in the ice edge latitude is plotted. For each month, the estimated 95% confidence interval (error bars) includes the annual-mean trend (gray line), demonstrating that observations are consistent with the ice edge retreating at an annually constant rate in regions where it is not blocked by land. The annual-mean trend is 8 km/year, implying an average northward displacement of 250 km during the 31-year record.

[12] The ice edge latitude year-to-year variability about the linear trend is also approximately uniform throughout the year (Figure 3d), in contrast with the ice extent which displays far larger variability during late summer than during the rest of the year (Figure 1d). Hence the seasonal cycle, rates of retreat, and detrended variability are all seasonally symmetric when viewed from the perspective of ice edge latitude.

[13] The ice edge latitude can be directly compared with ice extent by defining the “equivalent extent” as the total surface area, including land, north of the zonal-mean ice edge latitude. The equivalent extent is hence proportional to the sine of the ice edge latitude (see auxiliary material). The extent and equivalent extent are approximately equal in September but differ considerably during the rest of the year when geographic muting due to the ice cover evolution being blocked by coastlines becomes large (Figure 4).

[14] Because it evolves in an annually uniform manner, the ice edge latitude derived here provides a consistent year-round view of the evolution of the Arctic sea ice cover. Ice

¹ Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/gl/2010gl043741>. Other auxiliary material files are in the HTML.

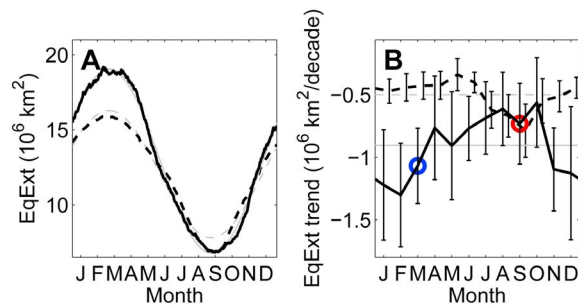


Figure 4. Evolution of the equivalent extent, defined as the total surface area, including land, north of the zonal-mean sea ice edge latitude. (a) Mean seasonal cycle as in Figure 1a. (b) Linear trends for each month as in Figure 1c. The ice extent is included as dashed black and gray lines for comparison in each panel; note that it is shifted slightly to the right in panel B to differentiate the error bars. In both Figures 4a and 4b, the equivalent extent is similar to the extent near the time of annual minimum (September), but the two quantities differ considerably near the time of annual maximum (March). Because the equivalent extent weighs ice edge deviations around low latitudes more heavily than high latitudes, the rate of retreat for the equivalent extent (solid line in Figure 4b) shows more seasonal structure than the ice edge latitude (Figure 3c), with changes being most rapid in wintertime. The difference between September and March ice extent trends shown here (dashed black line in Figure 4b) is approximately half as large as in Figure 1c because it is not scaled by the 1979–2000 mean seasonal cycle.

edge latitude anomalies from the mean seasonal cycle are plotted in Figure 3e. Perturbations decay quickly. The decorrelation time in units of the sampling period can be approximated as $\tau = -1/\log r$, where r is the lag-one autocorrelation value. Ice edge anomalies from the polynomial trend in Figure 1e have $r = 0.55$ at a lag of 1 month, implying a decorrelation time of $\tau = 1.7$ months.

[15] Viewed from this perspective, the September 2007 minimum (lowest red point in Figure 3e) is not the largest anomaly from the accelerating long-term retreat (black line), but it is the largest anomaly to occur in September (see auxiliary material), when changes in the ice edge latitude have the largest effect on ice extent. Hence it is a significant outlier when viewed from the perspective of ice extent (Figure 1e). In other words, similarly large negative ice edge anomalies have occurred previously during months when a considerable fraction of the ice edge was blocked by continents and the associated changes in ice extent were muted. This implies that the unprecedented minimum sea ice extent in September 2007 may simply be part of a noisy but annually constant retreat, with the relative change in ice extent being amplified through aliasing of the noise by the geographic effects described here. Hence such an extreme outlier in September ice extent could occur again in the future. This result may help explain why September 2007 appeared as an outlier from the perspective of ice extent while apparently lying near the trend line from the perspective of ice thickness [Lindsay *et al.*, 2009].

[16] Considering the zonal-mean ice edge latitude instead of ice extent may also be useful in the interpretation of

global climate model simulations. To facilitate calculation of the ice edge latitude from ice extent, an approximate relationship is given in the auxiliary material.

4. Conclusions

[17] These results suggest that the seasonal asymmetries in the evolution of Arctic sea ice extent are overwhelmingly the consequence of blocking by coastlines. When viewed instead from the perspective of zonal-mean ice edge latitude, the asymmetries disappear. Hence while the ice extent is useful for describing the climate response to changes in the sea ice cover, the zonal-mean ice edge latitude proposed here may provide a more readily interpretable description of the response of sea ice to climate changes. We find that the observed ice edge latitude traces out a seasonal cycle consistent with a linear response to hemispheric insolation, and that it has been retreating in recent decades at an annually constant rate. Attention on Arctic sea ice retreat has previously been focused on the summer minimum (September), when ice extent diminishes most rapidly. Our results show that the location of the sea ice edge has been receding just as rapidly during wintertime, but that geometric effects of Arctic coastline geography have caused the retreat during much of the year to appear muted in previous analyses which have focused on ice extent.

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