Spatial and temporal variations in the age structure of Arctic sea ice

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[1] Spatial and temporal variations in the age structure of Arctic sea ice are investigated using a new reverse-chronology algorithm that tracks ice-covered pixels to their location and date of origin based on ice motion and concentration data. The Beaufort Gyre tends to harbor the oldest (>10 years old) sea ice in the western Arctic while direct ice advection pathways toward the Transpolar Drift Stream maintain relatively young ($\leq$5 years) ice in the eastern Arctic. Persistent net losses ($-4.2\%\ yr^{-1}$) in extent of ice >10 years old (10+ year age class) were observed during 1989–2003. Since the mid-1990s, losses to the 10+ year age class lacked compensation by recruitment due to a prior depletion of all mature (6–10 year) age classes. Survival of the 1994 and 1996–1998 sea ice generations reestablished most mature age classes, and thereby the potential to increase extent of the 10+ year age class during the mid-2000s. **Citation:** Belchansky, G. I., D. C. Douglas, and N. G. Platonov (2005), Spatial and temporal variations in the age structure of Arctic sea ice, *Geophys. Res. Lett.*, *32*, L18504, doi:10.1029/2005GL023976.

1. Introduction

[2] Satellite observations since the late 1970s document pronounced variability and striking reductions in the extent of Arctic perennial (multiyear) sea ice [*Stroeve et al.*, 2005; *Belchansky et al.*, 2005]. Changes in sea ice distributions and dynamics are associated with changes in atmospheric circulation patterns across a breadth of temporal and spatial scales [*Polyakov and Johnson*, 2000; *Kwok*, 2004]. In the late 1980s and early 1990s, very low atmospheric pressure anomalies over the Arctic strengthened the polar vortex [*Walsh et al.*, 1996] and commenced a decade of concomitant changes in sea ice motion [*Rigor et al.*, 2002], area [*Belchansky et al.*, 2005], thickness [*Rothrock et al.*, 2003], melt [*Belchansky et al.*, 2004], and age [*Rigor and Wallace*, 2004].

[3] Recent studies by *Fowler et al.* [2004] and *Rigor and Wallace* [2004] found that the Arctic's sea ice age structure has become younger. To estimate ice age, *Rigor and Wallace* [2004] advected parcels of ice through time using monthly fields of ice motion derived from extrapolations of drifting buoy and manned station locations. Similarly, *Fowler et al.* [2004] inferred ice age using weekly ice motion vectors averaged from an optimally integrated synthesis of daily infrared and passive microwave satellite imagery and drifting buoy locations [*Fowler*, 2003]. In this paper, we analyze *Fowler*'s [2003] monthly-averaged ice motion vectors using a reverse-chronology tracking strategy [*Pfirman et al.*, 2004] to estimate age, and we present elaborated examinations of age structure evolution and age class survivorship.

2. Methods

[4] Sea ice age maps were independently generated for each January 1989–2003 by tracking every ice-covered pixel (25 km $\times$ 25 km), one at a time, in reverse chronology to their locations and dates of origin. Our reverse chronology algorithm (RCA) utilized two data sets from the National Snow and Ice Data Center: monthly mean (1979–2003) ice motion vectors [*Fowler*, 2003] and monthly masks of sea ice extent delineating $\geq$15% average daily ice concentration [*Comiso*, 2003]. For all masks, sea ice was assumed contiguous inside the North Pole gap undetected by the satellite sensors. Starting in January, each pixel's location was iteratively advected backwards and aged by one month, until the corresponding sea ice mask indicated water at the pixel's respective position (or until duration of the input data was exhausted). Monthly age estimates were merged into annual classes following World Meteorological Organization criteria that ice formed during autumn becomes first-year ice in January; hence, ice 0–4 months old was classified as 1-year ice, 5–16 months as 2-year ice, etc. Although the RCA is capable of commencing in any month, we elected to examine 11 age classes (1–10, and 10+ years) so results were limited to 1989–2003 by temporal range of the ice motion data. To prevent loss of pixels during reverse tracking, the RCA was executed (and results summarized) over the full hemispheric extent of ice motion data [*Fowler*, 2003], although our illustrations just show the Arctic basin to economize page-space.

3. Spatial and Temporal Age Variability

[5] The eastern Arctic is dominated by relatively young ice 1–5 years old while the western Arctic harbors nearly all ice >10 years old (Figure 1). The time series in Figure 1 shows a pronounced loss of old ice in the high-latitude western Arctic and an increased prevalence of young ice in the Beaufort Sea. These results are consistent with those reported by *Rigor and Wallace* [2004], who attributed the loss of old ice to sea ice motion anomalies associated with the strong positive phase of the Arctic Oscillation (AO) during the early 1990s. Under the high-index AO conditions, lower than average sea level pressure (SLP) in the Eurasian Arctic favored a westward shift in the Transpolar Drift Stream [*Rigor et al.*, 2002] that facilitated advection of older ice from the high-western Arctic toward Fram Strait.

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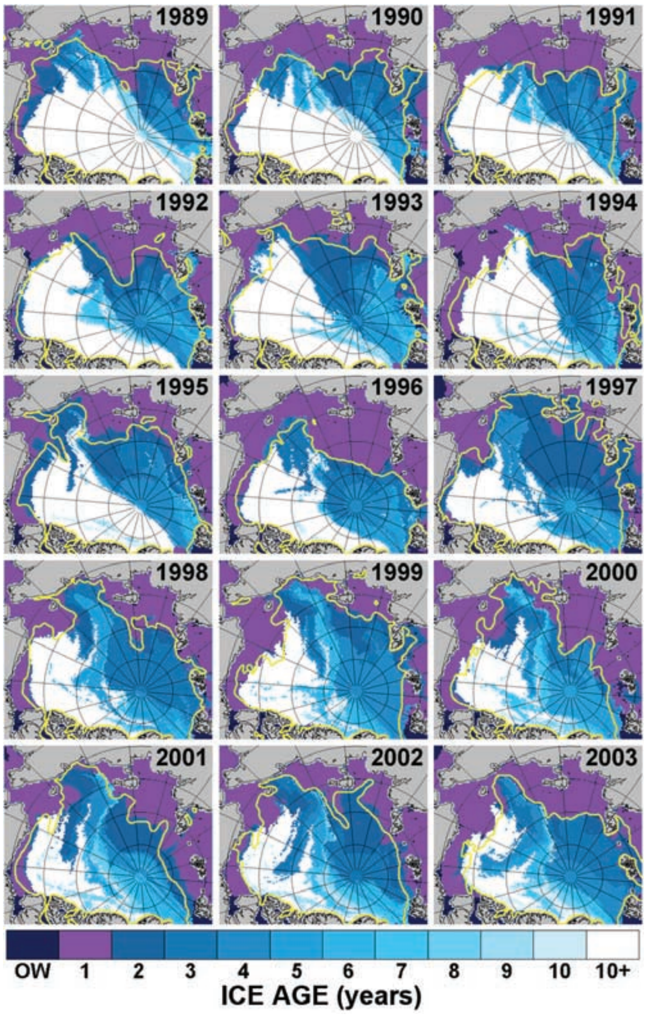

Figure 1. Sea ice age distributions in the Arctic Ocean, January 1989–2003. Yellow contours delineate January extent (≥15% concentration) of multiyear ice from *Belchansky et al.* [2005].

In the western Arctic, more prevalent low SLP anomalies weakened the Beaufort Gyre and increased the likelihood of entraining young ice from the Chukchi Sea [*Rigor and Wallace*, 2004].

[6] In the linear average, extent of 10+ year ice declined 4.2% annually ($S > 95\%$, Student's T-test) during 1989–2003. The 10+ year age class comprised almost half (49.8%) of the total perennial ice extent in 1989, but only one-fifth (20.7%) by 2003 (Figure 2). Combined extent of all age classes was relatively constant across years (Figure 2a) because first-year ice growth each winter replenished the Arctic basin to a fairly uniform total ice extent [*Parkinson and Cavalieri*, 2002]. By comparison, the combined extent of all multiyear (≥2 years) age classes (Figure 2b) shows the recent variability and overall decline in the Arctic's perennial ice cover [*Belchansky et al.*, 2005].

[7] Losses to the 10+ year age class since the mid-1990s lacked compensation by recruitment. Mature ice classes (6–10 years) were depleted during the early 1990s, leaving a distinct bimodal age distribution (≤5 and >10 years) in 1995–1997 (Figure 2). After 1997, improved survival of younger ice reestablished most mature age classes, and hence the potential to increase the extent of 10+ year ice in the mid-2000s.

[8] Survivorship curves of individual ice generations reveal a broad range of interannual retention times (Figure 3a). Each generation begins its tenure as 1-year ice with approximately the same areal extent, depending primarily on the amount of open water the previous autumn. Survival from the first to second year age class is highly variable, ranging in extent by as much as 2×10^6 km^2 (Figure 2b). Differential survival of 1-year ice is largely a thermodynamic response to variations in air and ocean temperature regimes [*Comiso et al.*, 2003], ice thickness [*Bitz and Roe*, 2004], and melt duration [*Belchansky et al.*, 2004]. Thickening of ice during subsequent winters buffers its risk of extirpation during intervening summers. Consequently, the 2–5 year age classes maintain relatively high survival (Figure 3a). After 5 years of age, however, survival rates often drop markedly. The increased threat to survival after 5 years roughly corresponds to the average residence time of sea ice as it traverses the Transpolar Drift Stream and becomes staged for export through Fram Strait [*Rigor et al.*, 2002].

[9] Year-to-year distributions of 3 contrasting sea ice generations (1994–1996) are spatially decomposed in Figure 3 to illustrate mechanistic aspects associated with their survival. The 1994 generation was established by ice formed during September 1993 to January 1994 (Figure 3b). One year later, a large proportion of the 1994 generation had survived its first melt season (Figure 3a), notably in the Beaufort and Chukchi Seas (Figure 3c). During subsequent years, much of the 2-year ice recruited in the western Arctic became entrained in the Beaufort Gyre (Figures 3d–3j),

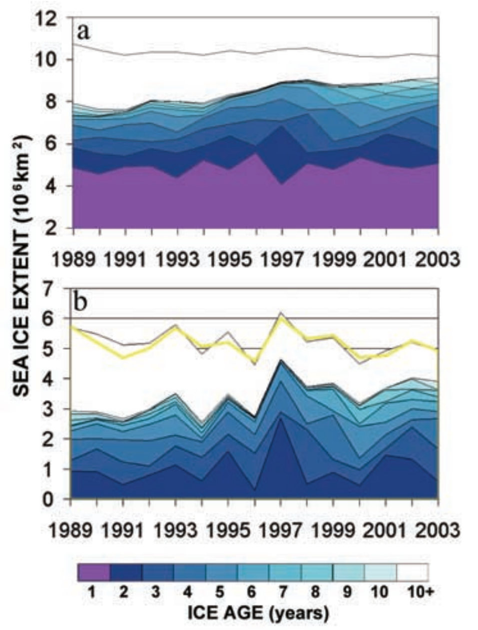

Figure 2. Cumulative histograms of Arctic sea ice age structure in January, 1989–2003. (a) All age classes, including first-year ice; (b) multiyear age classes only; yellow line is total January extent of multiyear ice from *Belchansky et al.* [2005].

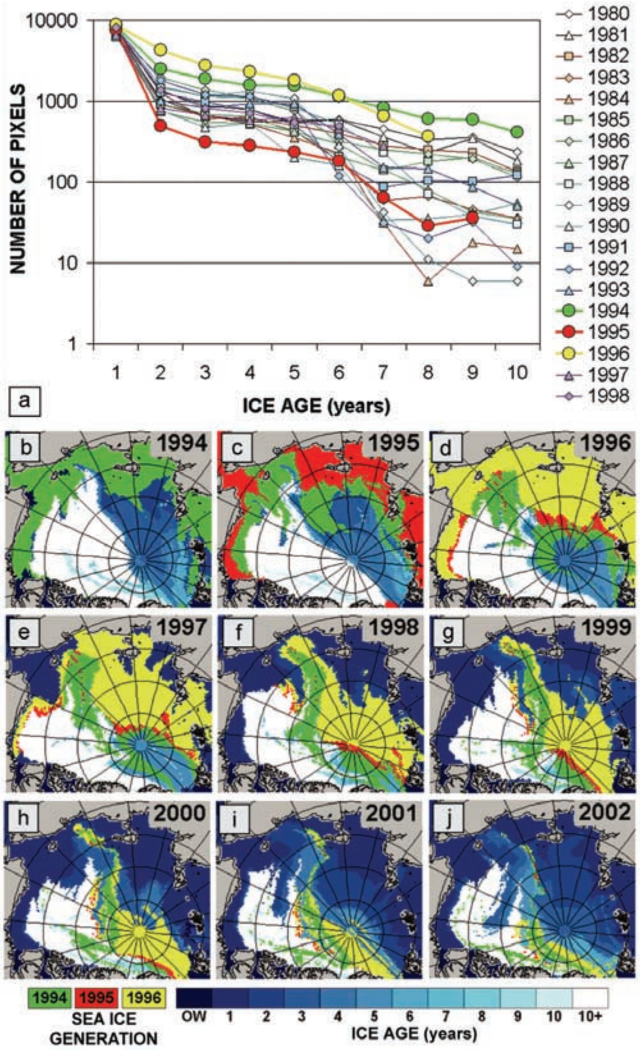

Figure 3. (a) Survivorship curves of the 1980–1998 sea ice generations. Note the logarithmic y-axis scale. (b–j) Color-coded annual distribution maps of the 1994, 1995, and 1996 sea ice generations through 9, 8, and 7 years of age, respectively.

thus reducing its depletion by export and affording the 1994 generation the highest long-term survival (Figure 3a). In contrast, little of the 1995 generation survived its first summer (Figure 3d) and only the small amount of 2-year ice in the Beaufort Sea survived to older age (Figures 3e–3j). The 1996 generation had the largest 2-year ice recruitment (Figure 3a), facilitated by a very short melt season that ended with the earliest average date of freeze onset in a 23-year (1979–2001) record [*Belchansky et al.*, 2004]. However, most 2-year ice of the 1996 generation was recruited in the eastern Arctic (Figure 3e) where it was promptly advected toward and through Fram Strait (Figures 3f–3j).

[10] Life expectancy of perennial ice is more dependent on dynamical factors associated with the Arctic's dominant patterns of sea ice motion. The location of 2-year ice recruitment is particularly important to its long-term survival. For example, the majority of sea ice from the 1980–1994 generations that survived to 10 years of age was originally formed in the Beaufort and Chukchi Seas (Figure 4). This indicates that the prominent age disparity between the eastern and western Arctic (Figure 1) also represents a general dichotomy of respective ice origin [*Pfirman et al.*, 2004], sustained by the Beaufort Gyre in the west and bifurcation of the two regions by the Transpolar Drift Stream.

4. Methodological Assessment

[11] Accuracy of the RCA ice age estimates is inherently impacted by errors in the underlying data sets of ice motion [*Kwok et al.*, 1998; *Meier et al.*, 2000] and ice concentration [*Comiso et al.*, 1997]. However, suitable data to validate the RCA's annual age estimates are lacking, so we examined indirect relationships to evaluate the algorithm's performance. Each year, the combined distribution and areal extent of ice $\geq$2 years old corresponded reasonably well with independent estimates of January multiyear ice distribution (Figure 1) and extent (Figure 2), indicating the RCA reproduces realistic delineations between the 1-year age class and all older classes.

[12] Theoretically, the total area of a sea ice generation cannot increase over time. That is, assuming no net changes due to divergence/convergence or import, extent of an ice age class i ($2 \leq i \leq 10$ years) in year y must be less than or equal to the extent of age class i-1 in year y-1. Positive slopes in the survivorship curves (Figure 3a) illustrate violations to this rule. Of the 171 total age class transitions (1–10 years) among all sea ice generations (1980–2002) in our study, we detected 22 (12.9%) violations. All violations occurred in age classes $\geq$4 years, most (14 of 22) were proportionally small in magnitude (implausible net increases were <15%), and the remaining 8 occurred exclusively in the older (8–10 year) less abundant age classes. Given that the RCA was independently executed each January, its ability to reconstruct a fairly stable numerical history of age class transitions suggests the estimates possess relative demographic integrity; however the possibility of age bias cannot be dismissed.

[13] The 15% ice concentration threshold used to define our monthly sea ice masks tends to conserve pixels for subsequent aging by the RCA. A pixel containing as little as 15% ice cover is retained with equivalent status as one with 100% cover. The net consequence is manifest, for example,

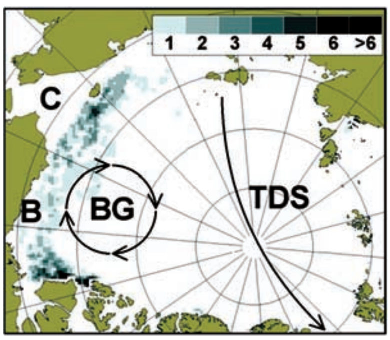

Figure 4. Origin location of 1-year ice, from the 1980–1994 generations, that survived to 10 years in age. Shading denotes overlap frequency of multiple generations. Transpolar Drift Stream (TDS), Beaufort Gyre (BG), Beaufort Sea (B), and Chukchi Sea (C).

in the expansive areas of 10+ year ice in the southern Beaufort Sea (Figure 1). The RCA concludes that at least some (≥15%) of this ice has persisted for >10 years; it does not imply the entire area is solely comprised of 10+ year ice. In the central Arctic especially, recruitments of first year ice within small openings and leads created by ice divergence are not detected by the RCA, owing to the algorithm's coarse spatiotemporal resolution and because it analyzes pixels independently so the net effects of divergence (and convergence) are not internally quantified.

[14] Although the RCA tends to portray an older representation of ice age, relative changes in age class abundance and distribution over time remain robust because the RCA is consistently executed each year. Similar to *Rigor and Wallace* [2004], we detected a decline in very old ice and more young ice entrained within the Beaufort Gyre, but overall, our age distribution maps depict a comparatively older ice pack. Rigor and Wallace's forward chronology algorithm required parcels of ice in September to fall inside a ≥90% ice concentration mask in order to be aged by 1 year. Their 90% threshold would tend to be more restrictive than the RCA in allowing ice in the marginal zones to age, which may be responsible in part for their more frequent depictions of younger ice distributions.

5. Conclusions

[15] Integrated analyses of ice concentration and ice motion data provide a quasi-empirical approach to investigate recent spatiotemporal changes in sea ice age structure. Reconstructing year-to-year survivals of individual sea ice generations provides insights into the underlying dynamic and thermodynamic mechanisms. Survival of the 1-year age class is affected by multiple factors including the location, extent, and thickness of winter growth, the degree of convergence and ridging, and the intensity and duration of summer melt. Consequently, annual recruitment of the 2-year age class is highly variable. Ice motion plays a dominant role in long-term survival. In the eastern Arctic, direct advection pathways toward Fram Strait maintain a young ice pack (≤5 years), in contrast to the western Arctic where the Beaufort Gyre often entrains and ages the ice for >10 years.

[16] Atmospheric circulation anomalies in the early 1990s induced a pronounced change in age structure by facilitating a disproportionate loss (export) of the Arctic's oldest (>10 year) ice [*Rigor and Wallace*, 2004]. Our results corroborate this loss, and further reveal that a concurrent depletion of the 6–10 year age classes prolonged net losses to the 10+ year age class by precluding compensatory recruitments through at least 2003. The observed evolution of sea ice age structure during this study period illustrates how advection anomalies can deplete the extent of old ice more rapidly than the time required for its restoration.

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