Variability in Arctic sea ice drift

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[1] Analysis of Arctic sea ice drift from 1979–1997 using a Lagrangian perspective shows the complexities of ice drift response to variations in atmospheric conditions. Changes in ice dynamics influence the redistribution of ice, and any transported material, from different source areas. Sources of ice exported to Fram Strait shifted in about 1986/87 from dominance of the Kara Sea and Severnaya Zemlya to the New Siberian Islands, East Siberian Sea, and Chukchi Sea. Average travel time of multiyear ice within the perennial pack of the central Arctic Basin, reached a maximum in 1987/88, and decreased by at least 1 year between 1984–1989 and 1990–1997. Consistent with the observations of other investigators, this decrease in ice travel time occurred following a major export or "surge" of old ice to Fram Strait from the Beaufort Gyre in 1988 through 1990, which decreased the fraction of thick, ridged ice within the central basin. *INDEX TERMS:* 9315 Information Related to Geographic Region: Arctic region; 1863 Hydrology: Snow and ice (1827); 4215 Oceanography: General: Climate and interannual variability (3309); 4207 Oceanography: General: Arctic and Antarctic oceanography. **Citation:** 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.

1. Introduction

[2] The decrease in Arctic sea ice thickness in the 1990s [*Rothrock et al.*, 1999; *Tucker et al.*, 2001; *Rothrock et al.*, 2003] has been attributed to a combination of dynamic and thermodynamic factors. Along with warming of the atmosphere and ocean, there was a change in ice dynamics in 1989 in response to a weakening of the Beaufort high pressure system and a strengthening of the European Arctic low (a shift from lower North Atlantic Oscillation/Arctic Oscillation to higher NAO/AO index) [*Walsh et al.*, 1996; *Proshutinsky and Johnson*, 1997; *Kwok*, 2000; *Zhang et al.*, 2000; *Rigor et al.*, 2002]. This led to a decrease in multiyear ice travel time as recirculation in the Beaufort Gyre slowed and more ice was advected towards Fram Strait [*Tucker et al.*, 2001; *Rigor et al.*, 2002]. Decreased formation of ridged ice in the central Arctic [*Tucker et al.*, 2001; *Rigor et al.*, 2002; *Makshtas et al.*, 2003], was coupled with export to Fram Strait of thick, old ice that had been recirculating in the Beaufort Gyre [*Arfeuille et al.*, 2000; *Koberle and Gerdes*, 2003]. This increased the volume flux through Fram Strait [*Vinje et al.*, 1998; *Kwok and Rothrock*, 1999], at the same time that there was increased export through the Barents Sea [*Kwok*, 2000]. *Tucker et al.* [2001] and *Koberle and Gerdes* [2003] noted that the origin of ice exported through Fram Strait changed during this period, from the Kara and Laptev Sea to East Siberian Sea sources. Clearly, thickness and circulation patterns within the Arctic interior condition the response of Fram Strait ice export to atmospheric changes [*Walsh and Chapman*, 1990; *Tremblay and Mysak*, 1998; *Arfeuille et al.*, 2000; *Kwok*, 2000; *Zhang et al.*, 2000; *Koberle and Gerdes*, 2003].

[3] To explore these changes from the perspective of the ice itself, we use a Lagrangian approach to track multiyear ice as it drifts across the Arctic Basin and is exported through Fram Strait. We examine how large-scale changes in driving forces affect the trajectories of multiyear ice and any transported constituents.

2. Methods

[4] Trajectories of probable ice drift from January 1979 to September 1997 were estimated from monthly fields of ice motion obtained from the International Arctic Buoy Program (IABP). The fields were analyzed using an optimal interpolation procedure that combined monthly observations of ice motion from buoys, supplemented by geostrophic winds [e.g., *Pfirman et al.*, 1997]. The large scale features of ice sources and travel times in the perennial pack (Figure 1) were evaluated based on back trajectories computed for a high resolution (5 km × 5 km) grid of points. We use the term travel time rather than age, because the oldest ice at the surface of the floes is lost annually to summer melt. The back trajectory for each grid point in the ice pack was traced until it intersected the multi-year mean mid-September ice edge based on NASA bootstrap data [*Comiso*, 1995]. The longitude of the intersection gives the sea of origin, and the number of time steps in the trajectory gives the travel time estimate. The computation was performed for every month

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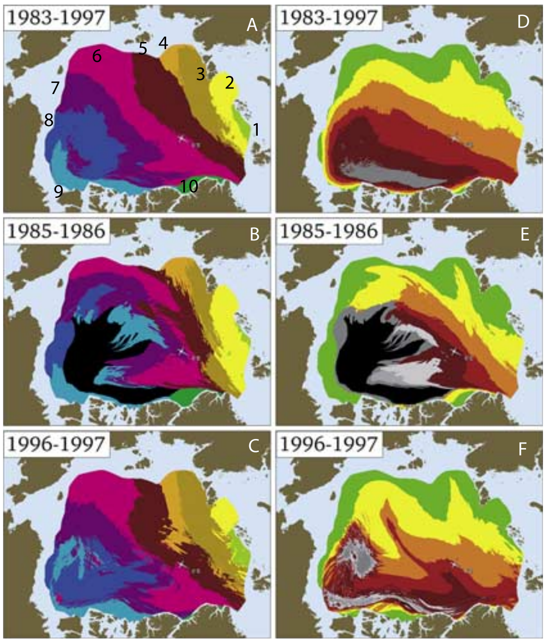

Figure 1. Modal sea of origin of multiyear Arctic sea ice: a) mean, b) 1985/86, c) 1996/97. Multiyear ice travel time: d) mean, e) 1985/86, f) 1996/97. See Figure 2 for color codes.

from 2/1/79 to 12/1/97, yielding 226 grids of travel time and longitude of origin. This analysis does not consider deformation, melting or formation of new ice enroute. Therefore, we confine our discussion to the relative strength of various sources, which is less affected by these factors.

[5] Trajectories are truncated at the coastline (not allowed to pass over land), and at the mid-September multiyear ice edge. Ice export from the Arctic Basin through the Canadian Archipelago is not resolved since only a few buoys drifted through these straights and there is not enough data to resolve the month-to-month variability of this flow. Ice exported from the shelves may have circulated for some time on the shelves before we set it to 0 as it crossed the mid-September ice boundary and so may be older than it appears in the travel time assessment. A region where this is an issue, is the recirculation of ice from north of Severnaya Zemlya into the Laptev Sea, where it is then reclassified as Laptev Sea ice with a travel time of 0 when it is re-exported northward.

[6] To assess the potential impact of changes in trajectories on ice entering Fram Strait, yearly (July to June) southward areal flux was calculated along a section at 80°N extending from Greenland to Svalbard (Figure 2). These flux estimates were computed by evaluating one month forward trajectories for each grid point and tabulating trajectories that intersected the ice edge at the outflow points. The fraction of ice with unknown, pre-1979, origin exported to Fram Strait was $\leq$5% of the total ice export after 1982/83, except for 1988/89 and 1989/90, when it was 16%, and 28%, respectively. Therefore, origins and travel times are calculated for the time period 1983–1997. All percents of total ice flux include the unknown fraction in the total.

[7] We assumed that the ice edge extended below 80°N (i.e., 100% ice coverage along this line of latitude). This assumption leads to an overestimate of transport through eastern Fram Strait especially during summer when ice cover is at a minimum. Areal fluxes calculated here track the interannual variability of *Vinje et al.* [1998] and *Kwok and Rothrock* [1999], with the exception of 1989/90 and 1990/91, when the summer ice edge was frequently north of 80°N. Our flux estimates are about 17% higher than those estimated by Kwok and Rothrock at 81°N for the period 1979/80 through 1995/96, but are similar to those determined by *Vinje et al.* [1998] at 79°N for the period 1991/92 through 1995/96.

3. Multiyear Ice Origins

[8] Large amounts of sea ice form over shallow Arctic shelves, are transported across the central basin and are exported primarily through Fram Strait, and to lesser degrees, the Barents Sea and Canadian Archipelago [*Gordienko*, 1958; *Colony and Thorndike*, 1984; *Pfirman et al.*, 1997; *Rigor et al.*, 2002]. In a paper published in 1985, Colony and Thorndike showed that the Laptev (including part of the Severnaya Zemlya and New Siberian Islands fluxes separated out in Figure 1) and East Siberian seas were the main sources of ice to the Transpolar Drift Stream and the Eurasian Basin. Note that they did not include the Kara Sea in their analysis.

[9] Most previous studies of ice origin relied on an analysis of the mean field or on the statistics of independent trajectories. The present study considers realizations of contemporaneous trajectories, providing a synoptic view of ice origin and travel time. In the mean, this analysis comes up with similar results: the large scale circulation patterns of the Transpolar Drift Stream and Beaufort Gyre are clearly seen in the 1983–97 distribution of modal sea ice origins (Figure 1a). Ice from the western Siberian Seas (Kara, Severnaya Zemlya and Laptev) is entrained in the Transpolar Drift Stream and exported into the Barents Sea and eastern Fram Strait. Sea ice formed along the shelves of the eastern Arctic is largely influenced by the presence of the Beaufort Gyre, and the East Siberian Sea contributes ice

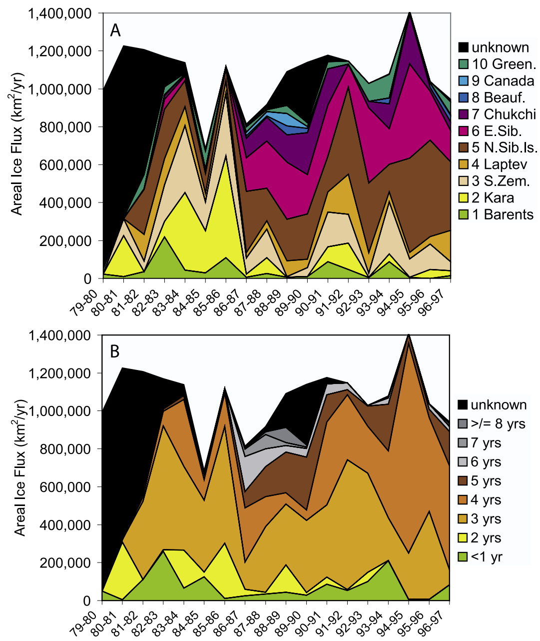

Figure 2. Fram Strait multiyear sea ice a) origins, b) travel times.

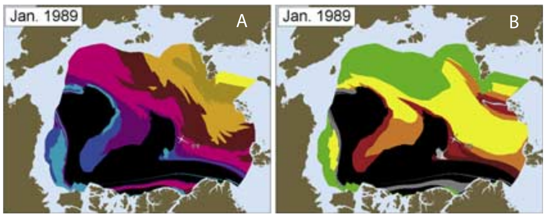

Figure 3. January 1989 multiyear sea ice a) origin and b) travel time during "surge" of old sea ice (black: pre-1979) from the Beaufort Gyre through Fram Strait.

to both regimes. Over the time period examined, ice from the Kara and Laptev seas exits the Arctic primarily through either Fram Strait or the Barents Sea; these seas are not dominant sources of ice to the Beaufort Gyre. Ice exported from the Kara Sea influences primarily the Barents Sea, Svalbard region, and eastern portions of Fram Strait. Laptev Sea ice generally melts north of Svalbard or is advected through Fram Strait and into the East Greenland Current. In 1988/89 and 1989/90, much more Laptev Sea ice entered the Barents Sea than in other years (Figure 3).

[10] Sea ice originating in the East Siberian Sea is transitional between the two large-scale circulation patterns of the Transpolar Drift Stream and Beaufort Gyre. Ice exported from the East Siberian Sea advects towards the North Pole. It then either continues southwards through Fram Strait, or some ice branches off and drifts westward in the Beaufort Gyre (Figure 1).

[11] After recirculating in the Beaufort Gyre, ice from the western Arctic is exported through western portions of Fram Strait and perhaps the Canadian Archipelago [*Tremblay and Mysak*, 1998] (although we are not able to resolve export through the Archipelago in this study). *Vinje et al.* [1998] noted a small increase in ice thickness to the west in Fram Strait, coupled with a marked increase in the standard deviation of monthly mean ice draft (from 2.5 to 4 m), consistent with export of older [*Colony and Thorndike*, 1985], and more extensively ridged ice [*Makshtas et al.*, 2003], in the western reaches of this passage.

[12] Averaging over 1983–97, the dominant source of ice to Fram Strait was the New Siberian Islands, comprising 26% of ice exported (Figure 2). However, prior to 1986/87 Kara Sea and Severnaya Zemlya sources dominated. After 1986/87 sources to the east were predominant [*Arfeuille et al.*, 2000; *Kwok*, 2000; *Tucker et al.*, 2001; *Koberle and Gerdes*, 2003]. Ice from the New Siberian Islands, East Siberian Sea and Chukchi Sea combined, average 64% of areal ice export through Fram Strait from 1986/87 through 1996/97, before they averaged just 13%. Percent export from the Kara Sea is negatively correlated with export from the East Siberian Sea.

4. Multiyear Ice Travel Times

[13] The maximum resolvable travel time for any time t, is $(t - t_o)$, where t_o is January 1, 1979. Mean travel times for the 1984–1997 period have a distribution similar to that of *Colony and Thorndike* [1985] with a maximum along the northern flank of the Canadian Archipelago (Figure 1d). However, there are large interannual differences (Figures 1e and 1f). Within the central Arctic, ice travel time averaged 4.0 ($t_{\max} = t - t_o$ or 6–10 years) years from 1984–85 through 1988–89, and 3.0 years from 1990–91 through 1996–97 (Figure 4). The 1 year decrease occurred primarily because ice from the New Siberian Islands, East Siberian Sea and Chukchi Sea that formerly recirculated in the Beaufort Gyre, was transported more directly to Fram Strait (Figure 2) [e.g., *Tucker et al.*, 2001; *Koberle and Gerdes*, 2003]. This increased travel times somewhat north of Fram Strait (Figure 4a), because the exported ice came from sources across the basin, rather than the adjacent Kara Sea.

[14] The maximum ice travel time of 4.4 years occurred in 1987/88 (Figure 4b), consistent with *Zhang et al.*'s [2000] central Arctic ice volume peak in 1987. The minimum since 1989 was 2.9 years in 1996/97. Comparing the distribution of 1996/97 with that of 1984/85, large areas of the central Arctic saw a decrease in travel time of 2 or more years during the 1990s (Figure 4a).

[15] Because ice thickens over time and tends to become more ridged as it drifts [*Makshtas et al.*, 2003], increased areas of young ice in the central and eastern Arctic (Figures 1e and 1f) coupled with the overall decrease in ice travel time (Figure 4), could be partly responsible for the sea ice thinning observed between the 1980s and 1990s [*Rothrock et al.*, 1999; *Tucker et al.*, 2001; *Rigor et al.*, 2002; *Rothrock et al.*, 2003]. Ice in the vicinity of the North Pole had only small changes in travel time, consistent with minor changes in ice thickness in this area [*Shy and Walsh*, 1996; *Tucker et al.*, 2001].

[16] The shift to export through Fram Strait of ice from more distant sources changed the travel time distribution (Figure 2b). The fraction of ice with 4 year travel time increased to an average of 44% during the period 1990/91–1996/97, with a maximum of 78% in 1994/5. This change is consistent with the observations of *Vinje et al.* [1998]

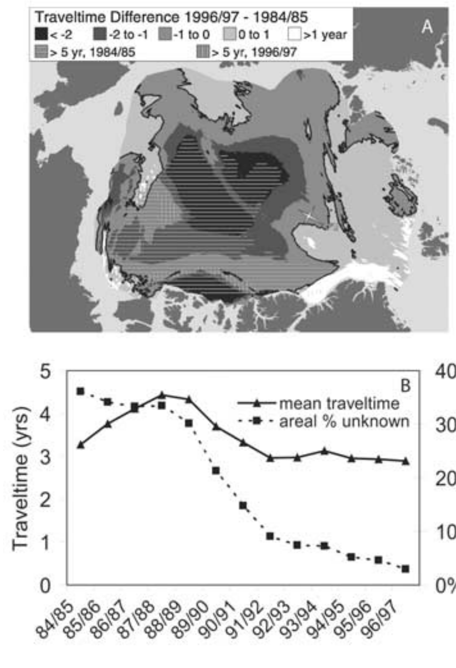

Figure 4. a) Travel time difference for 1996/97–1984/85. Unknown and >5 yr travel times set to 5 yrs. b) Mean travel time of multiyear sea ice in the central Arctic and areal % unknown (pre-1979).

that thicker ice was exported through Fram Strait in the 1990s.

5. 1988 Through 1990 Sea Ice "Surge"

[17] An export episode of older ice to Fram Strait from the Beaufort Gyre extending from March 1988 through March 1989, and August 1989 through November 1990 (Figure 3), depleted the central Arctic of its thicker ice fraction. In 1989/90 the fraction of ice exported to Fram Strait with a travel time ≥5 years was 58%. In 1988/89 and 1989/90, the areal flux of this older ice represented more than 500,000 km^2; more than double its 220,000 km^2 mean (Figure 2). Much of this older ice came from the Beaufort Gyre and was of pre-1979, unknown origin (16% in 1988/89 and 28% in 1989/90).

[18] *Arfeuille et al.* [2000] and *Koberle and Gerdes* [2003] modeled this flux through Fram Strait in the late 1980s as one of the largest volume export events since 1958, perhaps second only to the 1965 one that triggered the Great Salinity Anomaly. *Kwok* [2000] observed that the Barents Sea also experienced an increase in flux of older ice at this time.

[19] A later peak in ice export in 1994/95 [*Vinje et al.*, 1998; *Kwok and Rothrock*, 1999; *Arfeuille et al.*, 2000; *Koberle and Gerdes*, 2003], contained more ice that originated in the western Arctic: the Kara through East Siberian seas, because the atmospheric forcing was oriented at 45° to the 1989 event [*Hilmer et al.*, 1998]. Also, less of an ice volume anomaly was exported in proportion to the forcing because there was no prior accumulation of old ice available to tap (Figure 2b) [*Arfeuille et al.*, 2000] and the forcing was of shorter duration [*Koberle and Gerdes*, 2003].

[20] Similar to a glacial surge, major export events involving old, thick ice draw down the Arctic sea ice reservoir. Years of accumulation in a strong Beaufort Gyre [*Arfeuille et al.*, 2000; *Koberle and Gerdes*, 2003], are required for the central pack to accumulate a mass of thick, ridged ice once more [*Walsh and Chapman*, 1990; *Makshtas et al.*, 2003].

6. Conclusions

[21] This analysis of potential trajectories of sea ice incorporated in the central Arctic pack between 1979 and 1997 shows extensive changes in the fate of sea ice exported from the Arctic shelves. Ice sources east of the Laptev Sea increased in importance starting in 1986/87 and there was a "surge" of old ice out of the Beaufort Gyre in 1988–1990 [*Arfeuille et al.*, 2000; *Kwok*, 2000; *Koberle and Gerdes*, 2003]. As a result, travel times of ice within the central Arctic Basin decreased by at least 1 year, at the same time that the fraction of ice with 4 year travel times exported through Fram Strait increased. Ice from distant sources that formerly recirculated in the Beaufort Gyre under lower NAO/AO conditions of the 1980s, was exported more directly through Fram Strait in higher NAO/AO conditions of the 1990s. These changes partially explain the decrease in thick and ridged ice observed over the central region [*Rothrock et al.*, 1999; *Zhang et al.*, 2000; *Tucker et al.*, 2001; *Makshtas et al.*, 2003; *Rothrock et al.*, 2003]. A thin Arctic ice cover could be sustained by the continued direct export of ice from the East Siberian and adjacent seas.

[22] Changes in trajectories of ice with different origins are important, because they affect advection and release of any transported material. Under lower NAO/AO index conditions, sea ice exported through Fram Strait contains the sediments, contaminants, driftwood and other biological materials that were entrained in the Kara or Laptev seas, and these constituents differ markedly from those of the East Siberian and Chukchi seas exported under higher NAO/AO conditions.

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