Arctic Ocean sea ice volume: What explains its recent depletion?

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[1] Various observations and model results point to an arctic sea ice cover that was extraordinarily thin in the 1990s. This thin ice cover was caused by a strengthened cyclonic circulation of wind and ice and by unusual warmth of springtime air temperatures. Here modeled sea ice volume is decomposed into two components: first, a dynamic or wind-forced response to interannually varying winds but a fixed annual cycle of air temperature and second, a thermally forced solution responding only to interannually varying temperatures. Over the 52-year simulation from 1948 to 1999 these two components have a similar range and variance; the wind-forced component has no substantial trend, but the temperature-forced component has a significant downward trend of −3% per decade. Total ice volume shows a trend of −4% per decade. Export slightly exceeds production over the simulation. Annual export and production can differ from each other and from year to year by ±30%. This behavior seems to characterize an ice cover highly constrained by interannual variations in forcing and not in balance. The bulk (two thirds) of volume loss from the 1960s to the 1990s is a result of a striking thinning of undeformed ice. The remainder of the volume loss is due to thinning of ridged ice and reduced concentrations. The central Arctic Ocean and particularly the East Siberian Sea suffer the greatest losses (of up to 2 m); the ice north of the Canadian archipelago also thinned since the 1960s by ∼0.5 m.

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1. Introduction

[2] The sea ice cover of the Arctic Ocean was extraordinarily thin in the mid-1990s. This statement is supported by observations from submarine upward looking sonar data of ice draft [*Rothrock et al.*, 1999; *Wadhams and Davis*, 2000; *Tucker et al.*, 2001]. A number of sea ice and ocean models confirm that we can simulate many broad aspects of this behavior with our present physical understanding. Of the five models simulating the 1990s and summarized by *Rothrock et al.* [2003, Figure 12], all show extreme minima in the 1990s. Three (*Hilmer and Lemke* [2000], *Polyakov and Johnson* [2000], and the simulation of *Rothrock et al.* [2003]) show minima for their entire simulations (41–52 years). Two (*Arfeuille et al.* [2000] and *Holloway and Sou* [2002]) show 1990s minima matching previous minima (in the 1950s and 1960s). It is also apparent from *Rothrock et al.* [2003, Figure 12] that there is considerable disagreement among such simulations and that they still contain an undesirably high level of uncertainty.

[3] The causes of this thin ice cover are strengthened cyclonic wind and ice circulation patterns [*Deser et al.*, 2000; *Rigor et al.*, 2002] and warm springtime air temperatures [*Rigor et al.*, 2000; *Deser et al.*, 2000]. These mechanisms have been discussed by multiple authors, for instance, *Zhang et al.* [2000] and *Tucker et al.* [2001]. The relative contribution from wind and temperature changes has been examined in an ice-ocean model by *Köberle and Gerdes* [2003], who find in a 50-year hindcast that the temperature response is more correlated with ice volume change. Their analysis emphasizes the event-like structure of volume variations, which they describe as accumulation phases followed by export events. *Makshtas et al.* [2003] also consider the wind-driven and thermally driven changes in ice volume; two of their primary conclusions are that only 20% of the ice decrease during a 50-year simulation can be attributed to an increase in surface air temperature and that the property of the ice cover that best correlates with decreasing volume is the concentration of ridged ice. Both of these papers cast their analyses more in terms of interannual variations than in terms of trends.

[4] Here we further examine and quantify the individual contributions of the dynamic and thermal components of Arctic Ocean sea ice volume change, reporting findings entirely from model results. We address four sets of questions.

[5] 1. How do wind and thermal forcing each contribute to the reduction in the ice cover? Do both contributions vary similarly with respect to atmospheric oscillation indices?

[6] 2. How do ice export from the Arctic Ocean and production within the ocean vary interannually? Does increased export explain the decline in volume? Does production tend to replenish exported ice each year? How is production related to ice mass? If the ice gets thinner,

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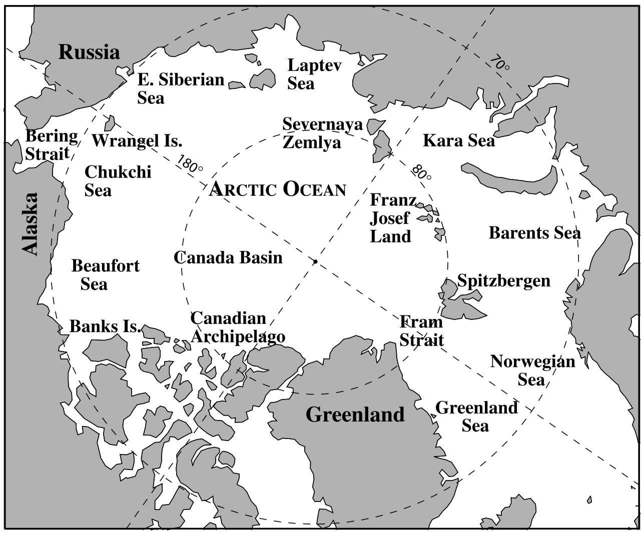

Figure 1. Arctic Ocean and neighboring seas. The model domain extends to the lower and right-hand edges of Figure 1 in the Greenland and Norwegian seas, the Bering Strait, and the Canadian archipelago as detailed in Figure 10. It excludes the waters within the archipelago, Baffin Bay, and the Bering Sea.

does production increase to compensate and to allow the thickness to recover?

[7] 3. How does the partition between younger undeformed ice and older ridged ice change? Is there a depletion primarily of ridged ice, or is there a depletion of all ice?

[8] 4. What is the change in the regions where ice mass resides? Has the ice volume actually changed little but simply changed location, perhaps being driven against the coast of the Canadian archipelago?

[9] All four of these topics are explored in sections 2–5; for all topics the forcing and the modeled response are calculated over a 52-year period from 1 January 1948 to 31 December 1999. The ice-ocean model used here is the same as used by *Rothrock et al.* [2003, Appendix A] and differs only slightly from the version used by *Zhang et al.* [2000]. Surface forcing consists of daily surface air temperature and sea level pressure from the NCEP (National Centers for Environmental Prediction) reanalysis for the entire simulation (unlike *Rothrock et al.* [2003]). The wind pattern is characterized by the 4-month mean North Atlantic Oscillation (NAO) index for January through March of the given year and December of the previous year. The domain is shown in Figure 1. The model was initialized with a 2-m ice cover over the entire domain and then was forced with conditions for 1948 repeatedly during a spin-up period of 18 years. After that initialization the simulation proceeded with the evolving NCEP forcing from 1948 on. Results reported here, unless stated otherwise, are averages over calendar years and apply to the Arctic Ocean, excluding the Kara, Barents, Greenland, and Norwegian seas.

2. Effect of Variable Atmospheric Forcing

[10] Changes in arctic surface pressure patterns (which define the wind field) were described by *Walsh et al.* [1996] and have come to be summarized by the NAO index [*Hurrell*, 1995] and Arctic Oscillation or Northern Annular Mode [*Thompson and Wallace*, 1998]. The corresponding changes in ice and ocean surface circulation have been characterized by alternating anticyclonic and cyclonic regimes [*Proshutinsky and Johnson*, 1997], by a changing cross-basin gradient of sea surface height (the Arctic Ocean Oscillation) [*Proshutinsky et al.*, 1999], and by shifting ice mass (the east-west arctic anomaly pattern) [*Zhang et al.*, 2000; *Holloway and Sou*, 2002]. These changes are recognized by the above authors and others to be responses to both winds and temperatures. The proportion and nature of the sea-ice response to each of these factors is the focus here.

[11] The modeled ice volume $V(t)$ within the Arctic Ocean is shown in Figure 2a. The first 4 or 5 years can be regarded as a period of adjustment to the initial condition. The mean over the simulation period, denoted by $\overline{V}$, is 22.5×10^3 km^3, with a maximum of 28.1×10^3 km^3 in 1966 and a minimum of 17.7×10^3 km^3 in 1999. The response is striking in the strength and breadth of the 1966 maximum, the local maximum in 1987, and the general decline through 1999. The range is surprisingly large; the final low is 37% less than the 1966 maximum. Note, however, that the 1999 value is only ~17% less than the value at the end of the model adjustment period in mid-1950s. The volume has a downward trend of 0.089×10^3 km^3 yr^{-1} or 4% of $\overline{V}$ per decade, similar to the oft-quoted loss rate of 3% per decade that satellites show since 1978 for hemispheric ice extent [e.g., *Parkinson et al.*, 1999].

2.1. Separating Wind and Thermal Forcing

[12] How do the wind forcing and the thermodynamic forcing each contribute to the interannual variability of

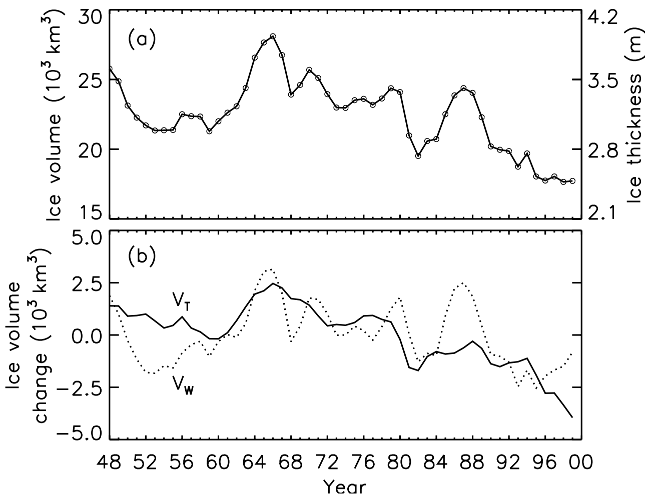

Figure 2. (a) Modeled ice volume within the Arctic Ocean domain. The 52-year mean annual ice-covered area of 6.91×10^6 km^2 is used to convert volume to an approximate thickness scale on the right axis; the annual value of this conversion factor has a standard deviation of 2%. (b) Wind-forced volume change $V_W(t)$ (dotted line) and the temperature-forced component $V_T(t)$ (solid line), as defined in the text.

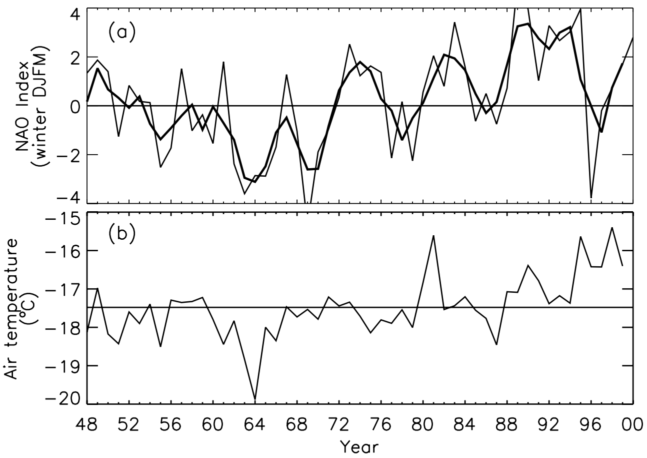

Figure 3. Interannual variation in the wind and temperature forcing of the model. (a) North Atlantic Oscillation index, an indicator of the surface wind field pattern, and its 3-year running mean and (b) mean annual surface air temperature over the Arctic Ocean domain.

the ice cover? The variability of the atmospheric forcing by winds and by surface air temperature is illustrated in Figure 3. Generally, periods of high NAO index have a strong Icelandic low-pressure cell that increases cyclonic motion in winds and ice motion in the eastern longitudes of the Arctic Ocean and advects warmer air into Eurasia and on into the Arctic Ocean [*Rigor et al.*, 2000]. Periods of low NAO index show a well-developed and large region of anticyclonic winds and ice drift in the Beaufort and Chukchi seas and the Canada Basin, tending to recirculate ice within the Arctic Ocean. The NAO index values (Figure 3a) are modest in the first decade of the simulation period, are low in the 1960s, and exhibit increasing maxima in the 1970s, 1980s, and 1990s. Mean air temperatures (Figure 3b) show a notable minimum in the 1960s, an upsurge in the early 1980s, and a substantial increase from the late 1980s through the 1990s. In fact, the temperature is rather stationary until the warm years starting in 1995. The temperature trend (assuming an autoregressive process of order 1) is +0.03° ± 0.01°C yr^{-1} (or +1.5°C per 50 years).

[13] In principle, the volume of ice $V(t)$ can be thought of as having a component of response $V_W(t)$ due purely to variations in wind forcing, another component $V_T(t)$ due purely to variation in thermal forcing, and a nonlinear component $V_{WT}(t)$ when both winds and temperatures vary together. Computing $V_W(t)$ is straightforward: One retains the interannually varying winds and replaces the temperatures with the average annual cycle of temperature (at each point). Evaluating the volume change V_T due to interannually varying thermal forcing without the interannual variation of wind stress is more complicated. Unlike temperature the winds cannot be averaged to provide an average annual cycle of wind forcing; wind stress is quadratic in the wind speed, so such an average would give too weak a wind forcing. This case of varying thermodynamic forcing with fixed annual winds has been computed by *Köberle and Gerdes* [2003]. Their procedure for computing $V_T(t)$ was to retain the daily wind stress anomalies about each monthly mean and to substitute for the monthly means the climatological monthly means. They found the surprising result that these two components of change, $V_W(t)$ and $V_T(t)$, add to give a very good approximation to the change in volume itself, $V(t) - \overline{V}$; the nonlinear component V_{WT} that one would have expected because of interaction between the wind-driven and thermally driven changes is negligible.

[14] We define the change in volume $V_W(t)$ as the difference between the wind response and its 52-year mean. $V_W(t)$, computed with the temperatures reduced to an average annual cycle, is shown as the dotted curve in Figure 2b. The wind-forced volume change shows a 52-year range of 5.7×10^3 km^3 or about two thirds the range of $V(t)$. (The corresponding range in wind-forced mean thickness is 0.8 m.) The trend of $V_W(t)$ is not significantly different from zero. The two strongest minima occur at the end of the spin-up period and in the early 1990s. After reaching its minimum in 1995 the wind-forced volume increased by $\sim 1.7 \times 10^3$ km^3 to its 1999 (ending) value.

[15] To evaluate the volume change V_T due to interannually varying thermal forcing without the interannual variation of wind stress, we invoke the result of *Köberle and Gerdes* [2003] and simply compute $V_T(t)$ as a residual between the total volume change and the wind-forced change,

$$V_T(t) = V(t) - \overline{V} - V_W(t). \qquad (1)$$

The total volume is now decomposed into its mean $\overline{V}$, the wind-forced component V_W, and the thermodynamically forced component V_T. The temperature response V_T is shown in Figure 2b by the solid curve. The local minimum in 1981–1982 is forced by the very warm temperatures in 1981. V_T trends downward at a rate of -0.07×10^3 km^3 yr^{-1} (significant at the 95% confidence level), which is 3% of $\overline{V}$ per decade.

2.2. Partition of Variance

[16] How much of the variance in V is explained by each of the components V_W and V_T? The 52-year variance of V is 6.5 $(10^3$ $km^3)^2$ and is equally distributed among the wind-forced component, the temperature-forced component, and twice the covariance between the two. (Recall that $\mathrm{var}(V_W + V_T) = \mathrm{var}(V_W) + \mathrm{var}(V_T) + 2\mathrm{cov}(V_W, V_T)$, which evaluates to 2.1 + 2.1 + 2.3 in units of $(10^3$ $km^3)^2$.) We conclude that the variance in V is due equally to wind- and temperature-forced responses.

[17] Given that the wind and temperature forcing tend to vary somewhat in phase (Figure 3), it is no surprise that V_T and V_W tend to vary in phase (with a correlation of 0.55). However, the temperature response clearly has a smoother structure and a tendency to decline over the last 30 years of the simulation. As *Köberle and Gerdes* [2003] explain, there is only weak linkage between V_T and V_W in determining events of accumulation and decline. Either response (V_T or V_W) can dominate either type of event. Looking at the three strong declines (Figure 2a), rather different contributions are evident (Figure 2b): In the 1960s the wind response is dominant, around 1980 both wind and temperature contribute, and in the late 1980s and the 1990s the

Table 1. Mean Volume of Ice Export Through Various Passages[a]

Passage Name and/or Location	Modeled 52-Year Mean Export	Standard Deviation of Modeled Annual Mean Export	Observed Export
Fram Strait, between Greenland and Spitzbergen	2.6	0.7	2.4
Between Spitzbergen and Franz Josef Land	0.2	0.2	0.1
Between Franz Josef Land and Severnaya Zemlya	−0.1	0.2	−0.1
Proliv Vilkitskogo, between Severnaya Zemlya and the Russian mainland	∼0.0	∼0.0	—
Total excluding Fram Strait	0.10	0.3	−0.04
Total	2.7	0.8	2.4

[a]Volume is in 10^3 km^3 yr^{-1}. Negative values indicate flow into the Arctic Ocean. Observations are for 1978–1995 [*Rothrock et al.*, 2000].

wind response leads, and then the temperature response becomes more important.

3. Ice Volume Change as an Imbalance Between Production and Export

[18] We use the word "export" to mean the net export E through the four passages in our model (see Table 1 and Figure 1). For practical purposes this export E is the same as the export through Fram Strait. For comparison the right column of Table 1 gives observations of the fluxes through these passages tracked from passive microwave satellite imagery from the years 1978–1995, assuming an ice thickness of 2 m [*Rothrock et al.*, 2000]. Over the long term the export (in units of 10^3 km^3 yr^{-1}) through the minor passages (0.10) is 4% of that through Fram Strait (2.6). In any given year the export through the three minor passages varies (±0.3) by ∼11% of the mean flow through Fram Strait. Our model allows no ice exchange through the Bering Strait or the Canadian archipelago. The annual change in sea ice volume ΔV must arise from an imbalance of annual production P and export E in the equation

$$\Delta V = P - E, \tag{2}$$

where P and E are averages over the year and ΔV is the difference from the first day of the year to the first day of the next year.

[19] Is the Arctic Ocean in balance? In our model it is not. P and E are closely but not quite in balance over the 52 years of our simulation. In units of 10^3 km^3 yr^{-1} the long-term mean production $\overline{P}$ is 2.63, and the mean export $\overline{E}$ is 2.77. These can be compared with the 52-year mean volume $\overline{V}$ of 22.5×10^3 km^3. As a fraction of mean volume $\overline{V}$, export $\overline{E}$ is 12.3% yr^{-1}; that is, just over 12% of the ice volume in the Arctic Ocean is exported each year. However, a bit less than 12% is produced; $\overline{P}/\overline{V}$ is 11.7% yr^{-1}. Over our 52-year simulation, $\overline{P}$ and $\overline{E}$ are very slightly out of balance. Export is ∼105% of production, or production is 95% of export. The imbalance (mean loss rate) in volume is ∼5% of the source $\overline{P}$ or sink $\overline{E}$ and ∼0.6% yr^{-1} of the volume $\overline{V}$.

[20] On a year-by-year basis, how far out of balance do P and E become? The annual production P, export E, and imbalance ($\Delta V = P - E$) are shown in Figure 4. The interannual variations in P and E have a standard deviation of ∼30% of the mean $\overline{P}$ and $\overline{E}$. These substantial variations in the source and sink terms give the annual imbalance a standard deviation of 1.3×10^3 km^3 yr^{-1} or 10 times its 52-year mean $\overline{\Delta V}$. The sign of ΔV can be positive or negative for years at a time (Figures 3a and 4c). If a state of near-balance $P \sim E$ existed even for different total amounts of ice, then we would expect P and E to be correlated (as found by *Steele and Flato* [2000]), but in our model, annual values of P and E are somewhat anticorrelated ($r = -0.3$). So the notion of balance does not seem particularly helpful for characterizing the state of the Arctic Ocean ice volume over periods of 1 year to decades.

[21] We might have expected that in a year when volume is low, production would be enhanced and/or export reduced to recapture the equilibrium state, that is, to maintain $\Delta V \sim 0$. This behavior is not observed. Neither production nor export shows significant correlation with volume. There is

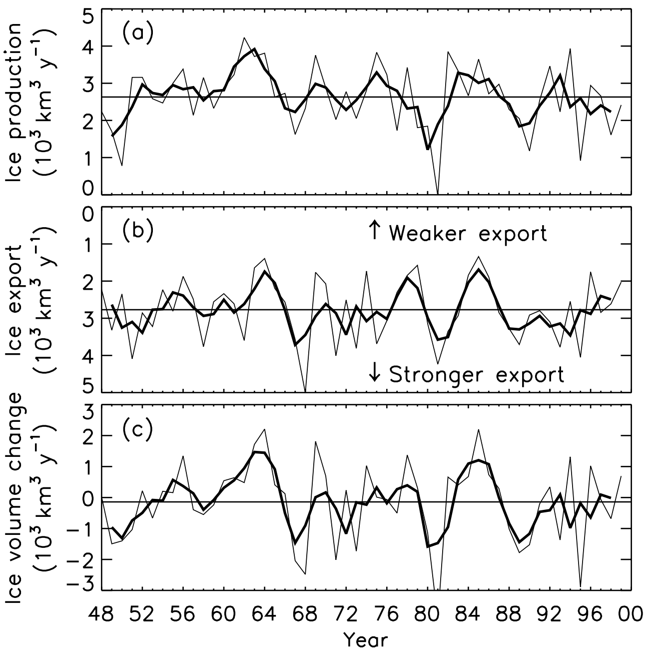

Figure 4. (a) Annual production P, (b) annual export E, and (c) annual change in volume ΔV in the Arctic Ocean domain of the simulation. The heavy curves are 3-year running means. Export has an inverted scale so that visually, Figures 4a and 4b add to give Figure 4c. The horizontal lines in Figures 4a–4c are the 52-year means.

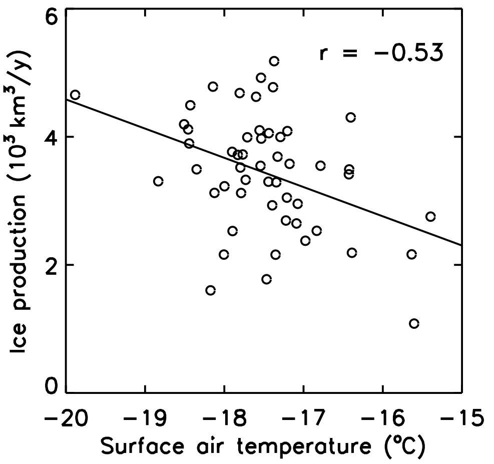

Figure 5. Ice production versus surface air temperature for annual averages over the Arctic Ocean, along with the least squares fit (straight line) and correlation *r*.

no tendency for the ice cover to rebalance itself annually by adding production in years of depleted volume or high export.

[22] Rather than a system in which production and export tend to quickly redress anomalies of volume, we see a system in which production is controlled by mean temperatures and export is controlled by local conditions at Fram Strait. The scatterplot of production versus air temperature (Figure 5) shows significant negative correlation (−0.53), so the production rate appears to be responding more strongly to the forcing by basin average air temperature than to the ice state (volume). Production declines as temperature rises; that is one of the strongest relationships we can find in our model simulation, although there is almost as strong a correlation between production and open water formation.

[23] The export E (mostly at Fram Strait) is controlled most strongly by the local winds in Fram Strait, which are characterized by the surface atmospheric pressure difference across Fram Strait (dp_{FS}). We decompose the annual export E into a velocity (U_{FS}) and a mean thickness (H_{FS}) at Fram Strait. The correlation of E with dp_{FS} is 0.67; of course, this correlation derives mostly from the correlation of velocity U_{FS} with dp_{FS}, which is 0.75 (Figure 6). The thickness H_{FS} of ice delivered to Fram Strait and available for export at any given moment is a complicated product of the history of ice mass balance and advection within the entire Arctic Ocean and is not controlled locally. H_{FS} is equally and weakly correlated with the NAO index (0.26) and dp_{FS} (0.23). The model shows no trend in export.

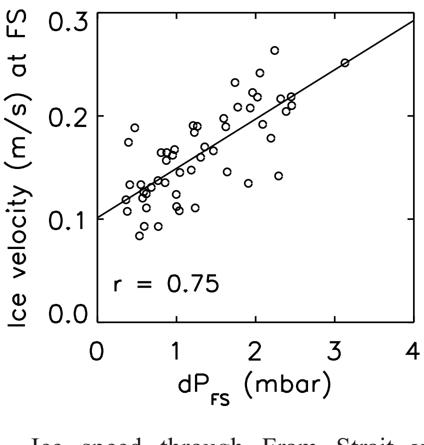

Figure 6. Ice speed through Fram Strait versus the pressure difference across Fram Strait for annual averages over the Arctic Ocean, along with the least squares fit (straight line) and correlation *r*.

[24] In summary, production is controlled most strongly by temperature over the entire Arctic basin. Export is controlled locally by winds at Fram Strait. These relationships dominate any dependence of P and E on ice volume V that might be apparent if the climatic forcing were steady. There is no requirement for annual production and export to be in balance, and they are not, neither year by year nor in the long term. Over the 52 years of our simulation they are out of balance by ~0.6% of mean volume per year. On a year-by-year basis the imbalance can be 10 times as large. It seems most useful to think of the ice cover as not in balance but strongly constrained by and continually adjusting to changing atmospheric forcing. As one reviewer put it, the equilibrium point is a moving target.

4. Undeformed and Ridged Ice

4.1. Diagnosis

[25] Was there less ridged ice in the 1990s than previously, and if so, does this explain the reduction in ice volume? Figure 7 shows the total ice volume and the volumes of undeformed ice and of ridged ice. The model carries two separate thickness distributions for these two kinds of ice. There are roughly 2–2 1/2 times as much undeformed ice as ridged ice.

[26] The amount of ridged ice rose to maxima in the 1960s and in the late 1980s, declining after that. The minimum ridged volume in 1999 is no lower than that in 1952. The range of 2.8×10^3 km^3 is modest in value but considerable as a percentage: ~40% of the mean. Ridged ice is not the primary cause of ice volume variability.

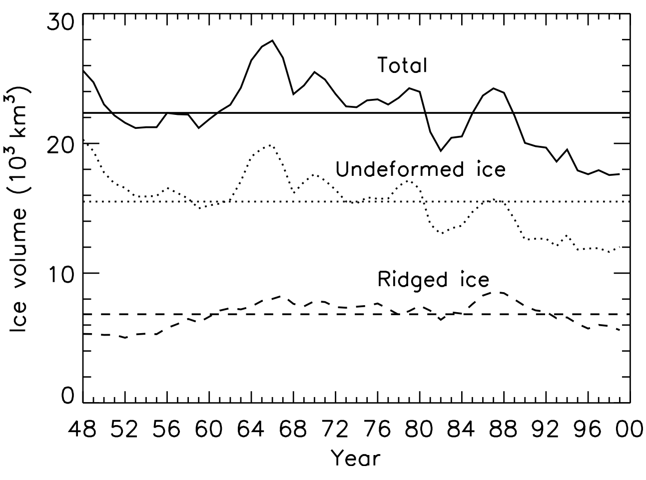

Figure 7. Annual mean volume of undeformed and ridged ice and their sum, the total ice volume within the Arctic Ocean. The horizontal lines indicate the 52-year means.

Table 2. Volume Yield v, Ice Type Thicknesses H, and Concentrations C Averaged Over the Arctic Ocean[a]

		Undeformed			Ridged		
	Total v	v_u	H_u	C_u	v_r	H_r	C_r
Average 1964–1967	3.81	2.71	3.26	0.83	1.10	9.16	0.12
Average 1986–1989	3.28	2.15	2.69	0.80	1.12	8.64	0.13
Average 1996–1999	2.41	1.62	2.08	0.78	0.79	7.88	0.10
Change from 1960s to 1990s			$\Delta H_u = -1.18$	$\Delta C_u = -0.05$		$\Delta H_r = -1.28$	$\Delta C_r = -0.02$
Change from 1960s to 1990s	$\Delta v = -1.39$	$\Delta v_u = -1.08$	$\Delta H_u \overline{C}_u = -0.95$	$\Delta C_u \overline{H}_u = -0.13$	$\Delta v_r = -0.31$	$\Delta H_r \overline{C}_r = -0.14$	$\Delta C_r \overline{H}_r = -0.17$

[a]Volume yield and ice type thicknesses H are given in meters. The values for each time period are an average of four annual means; change between the decades refers to 4-year ranges of 1964–1967, 1986–1989, and 1996–1999. The area of the modeled Arctic Ocean is 7.069×10^6 km^2.

[27] The more remarkable change is in the volume of undeformed ice. It grew from the 1950s to a maximum in 1966 and then fell intermittently but quite substantially to a minimum at the end of our simulation in 1999. That minimum is $\sim 3 \times 10^3$ km^3 less than the minimum in 1959. The range is 7.9×10^3 km^3, which is close to 3 times the range for ridged ice volume. Therefore to answer our leading questions, there was less ridged ice in the 1990s than in several previous decades, but this is not the major explanation for the reduction in ice volume in the 1990s; ice volume variability derives much more from undeformed than from ridged ice. This result is certainly contrary to our intuition and expectation.

[28] Table 2 shows how the volume change breaks down into undeformed and ridged components for selected years in the 1960s, the 1980s, and the 1990s and to what extent the changes are attributable to thickness and to concentration. Although we are focused here on interannual variations over 5 decades, the three periods were selected to capture several major events in the record: the maxima in the mid-1960s and the late 1980s and the minimum in the 1990s. Ice amount is expressed here as volume yield or volume per unit area v (whereas Figure 7 gives the volumes themselves). Volume yield and mean ice thickness are equivalent and are additive: The total volume yield is the sum of that for undeformed ice v_u and that for ridged ice v_r. The second column of Table 2 reflects the large decline in total volume yield from the 1960s through the 1980s and even more rapidly into the 1990s. The large depletion in undeformed ice is due primarily to a thinning (of H_u) by nearly 1.2 m; far less significant is the decrease in its concentration C_u by -0.05. The effect of thickness and concentration change on Δv_u is given by a few lines of algebra as

$$\Delta v_u = \Delta H_u \cdot \overline{C}_u + \Delta C_u \cdot \overline{H}_u, \quad (3)$$

where the Δ denotes the difference between two states and the overbar denotes the mean of the two states. These terms are evaluated in Table 2.

[29] The variations in ridged ice are more evenly attributable to both thickness and concentration; ridged ice concentration C_r changed little from the 1960s to the 1980s and then fell strongly during the 1990s. The ridged ice thickness H_r fell moderately during the whole period from the 1960s to the 1990s. The contributions to reduced ice volume yield (mean ice thickness) from the 1960s to the 1990s are -0.95 and -0.14 m from thickness of undeformed and ridged ice, respectively, and -0.13 and -0.17 m from the concentrations of undeformed and ridged ice, respectively. Combining the contributions from undeformed and ridged ice from the bottom row of Table 2, we find that of the 1.39-m loss in volume yield from the 1960s to the 1990s, about four fifths was due to thinning,

$$\Delta H_u \overline{C}_u + \Delta H_r \overline{C}_r = -1.09 \text{ m}, \quad (4)$$

and about one fifth of the loss was due to reduced concentration,

$$\Delta C_u \overline{H}_u + \Delta C_r \overline{H}_r = -0.30 \text{ m}. \quad (5)$$

4.2. Attribution

[30] To what are these changes attributable? We reconsider the components of the volume change forced by wind variability V_W and the volume change forced by temperature variability V_T and examine the volumes in undeformed and in ridged ice in each of these components. The decomposition is shown in Figure 8. What becomes quite apparent is that thermal forcing causes both undeformed and ridged ice volumes to trend down after the 1960s (Figure 8a); this suggests slowing thermal growth, strengthening melt, or both and is in keeping with the rising temperature

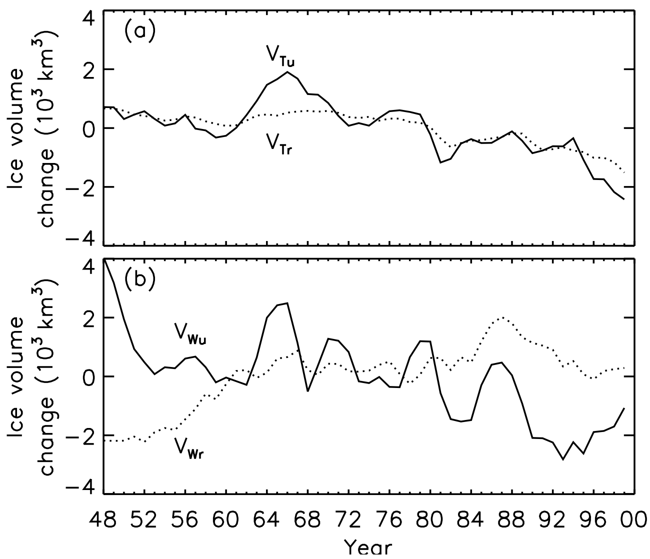

Figure 8. Annual mean volume of (a) the thermally forced component V_T and (b) the wind-forced component V_W of ice volume variations decomposed into the undeformed (V_{Wu}, V_{Tu}) and ridged ice portions (V_{Wr}, V_{Tr}).

Figure 9. Undeformed ice volume yield v_u (volume per unit area in meters) in the (a) thick and (b) thin periods and (c) their difference. Ridged ice volume yield v_r in the (d) thick and (e) thin periods and (f) their difference. Mean ice thickness for (g) the thick ice period 1964–1967 and (h) the more recent thin ice period 1996–1999 and (i) their difference. Ice thicker than 4 m has vertical hatching; ice thinner than 2 m has diagonal hatching.

(Figure 3b) starting in 1964 and the recent increase in the length of the melt season [*Smith*, 1998].

[31] The response to wind forcing is different for undeformed and ridged ice (Figure 8b). Undeformed ice volume V_{Wu} varies in opposition to the NAO index with a correlation of −0.39. The correlation is weakest at the beginning and end of the simulation period. High NAO is concomitant with strong cyclonic winds and ice circulation in the eastern arctic that deplete older and thicker ice from the East Siberian and Laptev seas [*Polyakov et al.*, 1999]. Periods of negative NAO tend to be associated with an increase in both the undeformed and ridged ice components of V_W: 1962–1966, 1968–1979, 1977–1979, 1985–1987, and 1996. This seems to fit quite well for undeformed ice but less well for ridged ice. Periods of high NAO can be but are not always related to declining V_W: 1973–1976, 1981–1984, 1987–1995, and 1998–1999. The exceptions seem more notable for ridged ice (V_{Wr}) than for undeformed ice (V_{Wu}). *Köberle and Gerdes* [2003] characterize these as periods of accumulation and export events.

4.3. Spatial Changes

[32] To conclude this topic, we examine the spatial pattern of changes in undeformed and ridged ice volume yield (Figure 9). Figures 9a, 9d, and 9g show the three volume yields during 4 years in the 1960s; Figures 9b, 9e, and 9h show the same for the 1990s; and Figures 9c, 9f, and 9i show the change from the 1960s to the 1990s. Undeformed ice thickness (Figures 9a–9c) was relatively uniform across the ocean at about 2.75–3.25 m in the 1960s. By the 1990s it was 1 m thinner toward Canada and 1.5 m thinner in the East Siberian Sea. The difference field shows

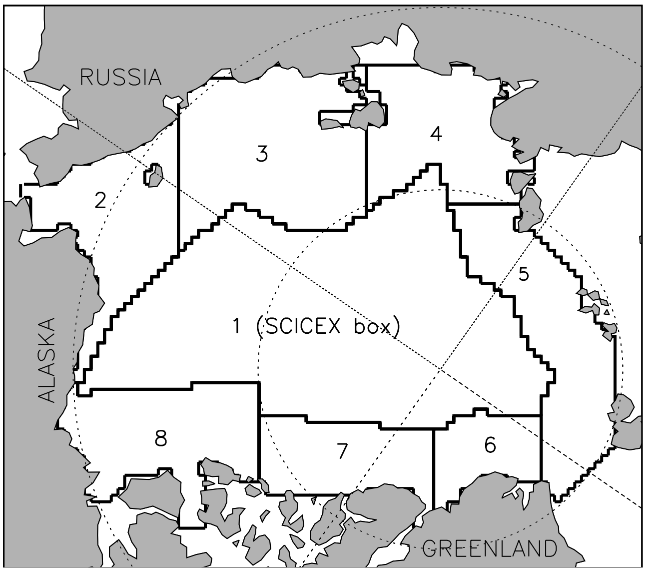

Figure 10. Eight regions of the Arctic Ocean. See text (section 5) for description. Region 1 is the Scientific Ice Expedition (SCICEX) box, the area from which originally classified submarine ice draft data could be declassified for public release. SCICEX is a series of unclassified U.S. naval submarine cruises during the 1990s.

the gradient in the change; the strongest decline was in the eastern longitudes of the ocean, with a maximum in the East Siberian Sea.

[33] The ridged ice volume yield (Figures 9d–9f) is also rather uniform in the 1960s: 1.5 m across the central parts of the ocean. By the 1990s a gradient of ~0.5 m developed across the ocean. By 1996 the supply of older and heavily ridged ice to the eastern longitudes of the Arctic Ocean had been choked off by the weakening of the Beaufort Sea anticyclone [*Zhang et al.*, 2000; *Rigor et al.*, 2002]. The difference field in Figure 9f shows a gradient similar to that for undeformed ice, with a maximum decrease of 1.0 m in the East Siberian Sea and an increase of up to 0.5 m on the Canadian side. Ridged ice volume increased near Canada but less than undeformed ice decreased. Everywhere else, both undeformed and ridged ice were depleted.

5. Regional Changes in Ice Thickness

[34] Does ice volume change significantly or does the spatial distribution of volume change much more than total volume? A case has been made that incomplete observations by submarines give the illusion that total volume changes substantially, whereas, in fact, changes in different regions are out of phase and tend to cancel, and changes in total volume are minimal [*Holloway and Sou*, 2002].

[35] We consider the 52-year history of ice volume in eight regions within the Arctic Ocean (Figure 10). Region 1 is the central part of the Arctic Ocean for which submarine data have been released (the "Scientific Ice Expedition (SCICEX) Box"); these data show substantial thinning [*Rothrock et al.*, 1999; *Tucker et al.*, 2001]. Regions 2–5 include the Chukchi Sea, seas over the Russian continental shelf, and the eastern longitudes of the Arctic Ocean. Regions 6–8 lie between region 1 and the Canadian archipelago. (In units of 10^6 km^2 the areas of regions 1–8 are 2.643, 0.643, 0.976, 0.627, 0.760, 0.277, 0.466, and 0.677; together, their area is 7.069.) Figure 11 shows the volume in these regions stacked and summed; Figure 12 gives the volumes in each region separately and sums for eastern arctic regions (2–5), for the Canadian regions (6–8), and for all eight regions.

[36] Most notable is the considerable variation in total volume and the minimum of 17.7×10^3 km^3 in 1999. The decrease from 1987 to 1999 is most substantial in regions 1 and 3. There were only small decreases in volume in other regions. The eastern regions (2–5) lost some 3×10^3 km^3 from 1987 to 1999. The central region (1) lost over 2×10^3 km^3 during the same period. Of the three Canadian regions, regions 6 and 7 vary minimally; only region 8 shows substantial variability, with a range of 1.5×10^3 km^3, and variations somewhat out of phase with those of other regions as described by *Zhang et al.* [2000] and *Holloway and Sou* [2002]. As regions 1–5 lost ice starting in 1987, region 8 gained for 5 years and then lost that gain by 1999. This simulation shows no region that compensated for the substantial decline in the central and eastern Arctic Ocean.

[37] Figures 9g and 9h show mean thickness fields for two periods: a thick period (1964–1967) and a thin period (1996–1999). In the thick period, ice over 4 m thick (vertical hatching) extends right across the ocean from Canada to the East Siberian Sea, and thin ice (<2 m thick, diagonal hatching) is relegated to the southern Chukchi and the Barents and Kara seas. In the thin period, thick ice is found only near the Canadian archipelago north of Banks Island, and thin ice extends far north of Wrangel Island, far into the East Siberian Sea, and over all of the Kara, Laptev, and Barents seas. In the late 1990s the ice is 1–2 m thinner than in the mid-1960s over much of the Arctic Ocean (Figure 9i), and the ice is thicker almost nowhere.

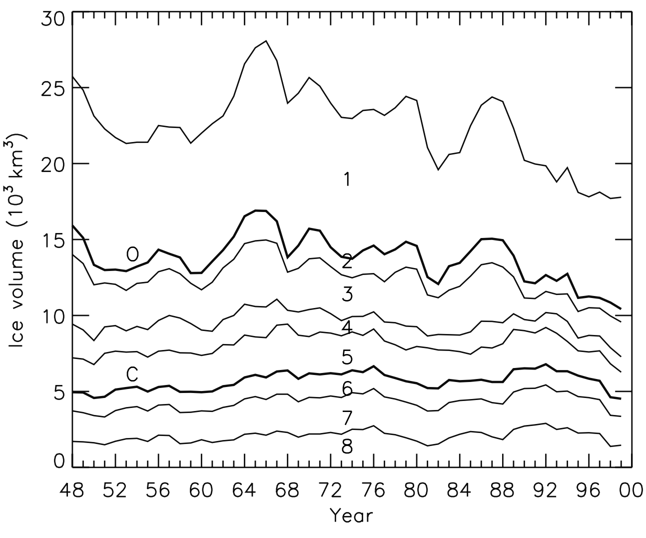

Figure 11. Ice volume simulated in the eight regions in Figure 10. The volumes are summed: region 8, regions 7 and 8, etc. The bold curve indicated by C gives the total volume in Canadian and Greenland regions 6, 7, and 8 together. The bold curve indicated by O denotes the volume in all regions outside the SCICEX box. The topmost curve gives the total volume in all eight regions.

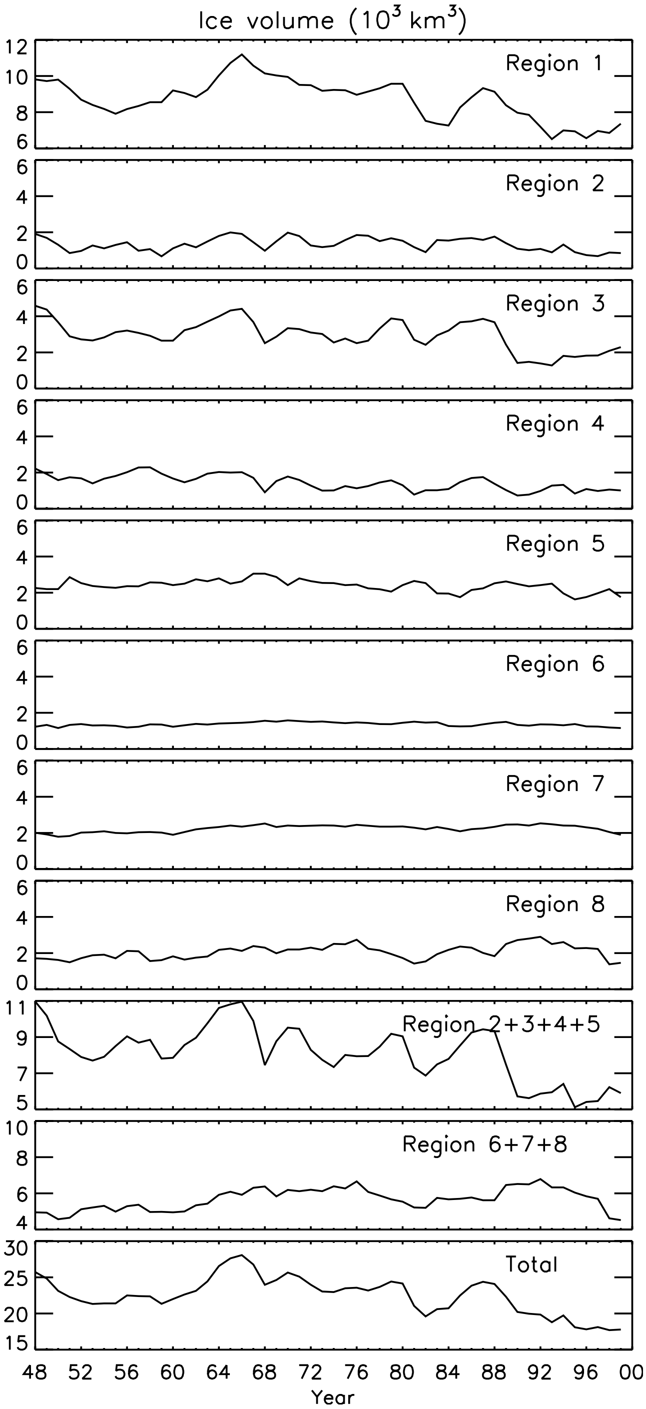

Figure 12. Ice volume in each region in Figure 10 in two groups of regions (the Russian side and the Canadian side) and the total. Except for the total, all plots have the same range of 6×10^3 km^3.

[38] With regard to the calculation by *Holloway and Sou* [2002] we note the striking difference between our two simulations (which serves to highlight the uncertainties in model results generally). The contours of the 30-year change in their Figure 2 have a similar pattern to those in our Figure 9i, but their simulation shows changes ranging from +2.2 to −2.6 m, whereas ours shows changes ranging from 0 to −2.5 m. Another comparison between these two model simulations is that a portion of the ice buildup in their Figures 2 and 5 (top) includes islands and landfast ice in passages in the Canadian archipelago. In our view these areas would not exchange significant amounts of ice with the interior of the Arctic Ocean and are better left to a discussion of ice within the archipelago. They are excluded from our model domain.

6. Conclusions

[39] An ice-ocean model has been used to describe and to diagnose the interannual changes that occurred in the Arctic Ocean ice cover during the 52-year period 1948–1999. Over that period, ice volume experienced a trend of -0.089×10^3 km^3 yr^{-1} or −4% per decade. What explains the reduction in ice thickness? By separating the wind component and the temperature component of the interannual forcing we find that even though the variance in volume derives equally from the wind and temperature responses, only the thermal component V_T seems to have a significant downward trend: -0.07×10^3 km^3 yr^{-1} or −3% of $\overline{V}$ per decade. Although from the late 1980s through the mid-1990s the wind was the dominant factor in the rapid decline in ice thickness, overall the wind appears to cause large oscillations but not a multidecadal downward trend. The volume response to rising temperatures, on the other hand, seems to be more steadily downward, accounting for a reduction of over 25% in volume over 5 decades.

[40] The annual ice mass production and export are typically out of balance year to year by ±30% but very nearly in balance over decades. The slight imbalance over 5 decades gives a loss rate of -0.14×10^3 km^3 yr^{-1}, or about −6% of mean ice volume per decade. (This imbalance matches the volume change from the beginning to the end of the simulation, as distinct from the volume trend.) Annual imbalances between production and export are not reversed from one year to the next but tend to persist for several years, dismissing the notion of a short-term balance of the ice cover. Because the primary export of ice through Fram Strait is controlled locally whereas the production of ice depends on forcing over the entire Arctic Ocean, these two quantities would not necessarily be in balance. Our model shows no unusually large and persistent export in recent decades that would have drawn down the volume of sea ice in the Arctic Ocean.

[41] Examining the behavior of undeformed ice and of ridged ice, we find, contrary to our expectation, that the largest change in ice volume derives from a thinning of undeformed ice. This is the dominant cause, accounting for about two thirds of the decrease in ice volume since the 1960s. Another 10% is due to thinning of ridged ice. The remaining 22% of ice reduction is due to lower concentrations of both undeformed and ridged ice. Another way to summarize the depletion is that the total ice volume decreased by 36% since 1966, and this was accomplished by a loss of 28% of the ridged ice and 40% of the undeformed ice.

[42] Our findings differ somewhat from those presented by *Makshtas et al.* [2003]. Theirs is a two-level ice model (not coupled to an ocean model) with a single variable thickness for undeformed ice and a fixed thickness (12 m)

for ridged ice; that model attributes most of the decrease of ice volume to a replacement of ridged ice area by undeformed ice. The present model with its two 12-category thickness distributions, one for undeformed and one for ridged ice, attributes the change from the 1960s to the 1990s to roughly equal declines in the thickness and concentration of ridged ice and to a much stronger decline in the thickness of undeformed ice.

[43] By separating the ice response into thermally and wind-forced components we find that the thermal component of the response shows the volume of both undeformed and ridged ice rather steadily declining since the 1960s. The wind-forced component unexpectedly does not exhibit a decrease of ridged ice, but it does exhibit a highly varying but continually decreasing amount of undeformed ice.

[44] As for the regional distribution of change, it is the central Arctic Ocean and the East Siberian Sea that experience the greatest decrease in ice volume up until 1999. The regions near the Canadian archipelago contribute more weakly and neutrally (regions 6, 7, and 8 in Figures 10–12). From the maximum in the mid-1960s to the minimum in the 1990s (Figure 9i), ice in the entire Arctic Ocean became thinner by up to 2 m in the East Siberian Sea and by at least 0.5 m toward the Canadian archipelago.

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