IS ARCTIC SEA ICE RAPIDLY THINNING?

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ABSTRACT

Reports based on submarine sonar data have suggested Arctic sea ice has thinned nearly by half in only recent decades. Such rapid thinning is a concern for detection of global change and for Arctic regional impacts. Re-examining the inferred thinning while including atmospheric timeseries, ocean currents, rivers runoff, and modelled physics of ocean-ice-snow, we find that inferred rapid thinning was unlikely. Varying winds, which rapidly redistribute Arctic ice, create a difficult sampling problem, dominated by a recurring pattern where ice is expelled from the central Arctic while thickening in the Canadian sector. Timing and cruise tracks of the submarine surveys missed this mode of Arctic variability.

INTRODUCTION

Concern for possible global warming focuses attention on the Arctic as a bellweather region where changes may become apparent more quickly than at lower latitudes. Moreover, changes to Arctic sea ice are part of the mechanism of projected climate change on account of ice-albedo feedback, the insulating effect of sea ice on winter atmosphere, and the stability of oceanic thermohaline overturning.

Since the satellite era, observations of areal extent of sea ice have showed a statistically confident decrease at about 3% per decade, within uncertainty near 1% per decade (Cavalieri et al., 1997; Johannessen et al., 1999; Parkinson et al., 1999; Vinnikov et al., 1999; Serreze, et al., 2000). An earlier study spanning 1973-1976 showed small interannual change (Carsey, 1982).

Changes to ice thickness have been more difficult to observe and assess. Sundry observations near the North Pole, taken at various times of year by various means (Shy and Walsh, 1986; McLaren et al., 1992), do not show a statistically significant trend. Progress at thickness estimation over the larger Arctic domain has resulted submarine-based sonar profiling (Bourke and Garrett, 1987; Bourke and McLaren, 1992; Rothrock et al., 1999; Wadhams and Davis, 2000; Winsor, 2001). A startling result, reported by Rothrock et al. (1999) and supported by Wadhams and Davis (2000), was that average thickness decreased more than 40 % over a few decades. Specifically, Rothrock et al. found that, averaging over five cruises in autumns of 1958, 1960, 1962, 1970 and 1976 and averaging over three cruises in autumns of 1993, 1996 and 1997, the latter average showed 42% less ice volume than the former average. Comparing single cruises in 1976 and 1996, Wadhams and Davis found a strikingly similar reduction in ice volume by 43% over 20 years, this near a region where Wadhams (1990) also reported 15% loss of ice volume between 1976 and 1987.

Reported rapid loss of Arctic sea ice attracted widespread attention in popular media and among environmental scientists. The IPCC 2001 assessment concluded that loss of autumn sea ice by more than 40% was "likely" (66% to 90% likelihood). Although Winsor (2001) subsequently report that six submarine cruises in the Canada Basin during 1991 through 1997 showed no average thinning, this may not contradict the earlier reports given the different time period and location. Overall, a perception is that volume of Arctic sea ice is in precipitous decline, and that this further evidences global warming.

Is such rapid decline of Arctic ice volume physically plausible? Rothrock et al. suggested two possibilities. First, warming may enhance ice melt and reduce ice growth. Second, changing wind-driven ice export at Fram Strait alters the ice volume remaining within the Arctic. There are many uncertainties such as varying winds or changes of radiative forcing or poorly known heat transport by ocean currents. There are uncertainties estimating "observed" ice thickness due to different methods of sonar operation, non-coincident cruise tracks and differences of seasonal timing among cruises, cf. Rothrock et al. and Wadhams (1997). Nevertheless, the apparently strong "signal" of rapid decline invites examination.

INFERENCE FROM DYNAMICS?

To complement sparse observations, we invoke the dynamically consistent framework of a large scale numerical model. Our efforts, like modeling studies of many other investigators, suffer uncertainties stemming in parts from poorly known initial, boundary and forcing conditions, from incomplete physics, and from inaccuracies of numerical representations. Cautiously we develop model-based inferences as a "best guess" at physical consistency.

The model follows Nazarenko et al. (1998), consisting of 3D ocean with dynamic-thermodynamic sea ice and snow on a spherical-rectangular finite difference grid. Among changes since Nazarenko et al., the present model omits "flux correction" (surface layer restoring). We apply atmospheric forcing from NCEP/NCAR (Kalnay et al., 1996) with river inflows from Becker (1995), and initial ocean conditions from PHC hydrography (Steele et al., 2001). The domain has open boundaries across Bering Strait, Baffin Bay and the Greenland-Norwegian Sea with 0.8×10^6 m^3/s inflow at Bering Strait and 1.0×10^6 m^3/s outflow through Baffin Bay. Integrations were "spun up" over 30 years of climatological annual cycle, followed by 52 years (1948 through 1999) under monthly atmospheric forcing, adjusted for daily wind variability. This effort can be compared with other studies, e.g., Polyakov and Johnson (2000) or Zhang et al. (2000) modeling ocean-ice-snow or Hilmer and Lemke (2000) modeling ice-snow only.

Because of uncertainties in model formulation, forcing specification, etc., we have explored a range of possibilities, seeking to identify robust results and a range of uncertainty about those results. For example, we find results depending substantially upon the history of windstress fields over the Arctic. Yet, within the set of NCEP atmospheric variables, there are different ways to estimate windstress history. First, NCEP provides reanalysis of windstress. Second, NCEP supplies history of 10m vector wind which, with estimated windspeed and surface parameters, can be used to estimate stress. Third, NCEP reanalyses of sea level pressure can be used with empirical parameterizations to estimate "geostrophic windstress". We have employed these three methods to reconstruct windstress histories, comparing and contrasting resulting ice fields. Similarly we have explored uncertainty to internal model parameters such as ice strength and leads fraction.

While the range of numerical experiments indicate modest reductions in ice area, similarly to satellite-derived area reduction over 1979 - 1999, the same experiments exhibit only moderate thinning. This contradicts the rapid thinning reported from submarine observations. Either the model results are systematically flawed or inferences previously drawn from submarine data are misleading. Exploring a wide range of model cases has not revealed systematic errors in model formulation. We turn to the question if we have been misled by the submarine data.

CRUISING IN VIRTUAL SUBMARINES

Loosing eight "virtual submarines" to sample the model Arctic at the times and places of the actual submarine cruises, we revisit the Rothrock et al. study. (We also deployed "virtual cruises" to compare with Wadhams and Davis and with Winsor, as summarised below.) In their study, Rothrock et al. identified 29 locations at which coincidence of tracks and adjusted seasonal timing were adequate to support comparisons. Those 29 locations are plotted in Figure 1 on a map of model difference between September ice thickness averaged over 1993, 1996 and 1997 less September thickness averaged over 1958, 1960, 1962, 1970 and 1976.

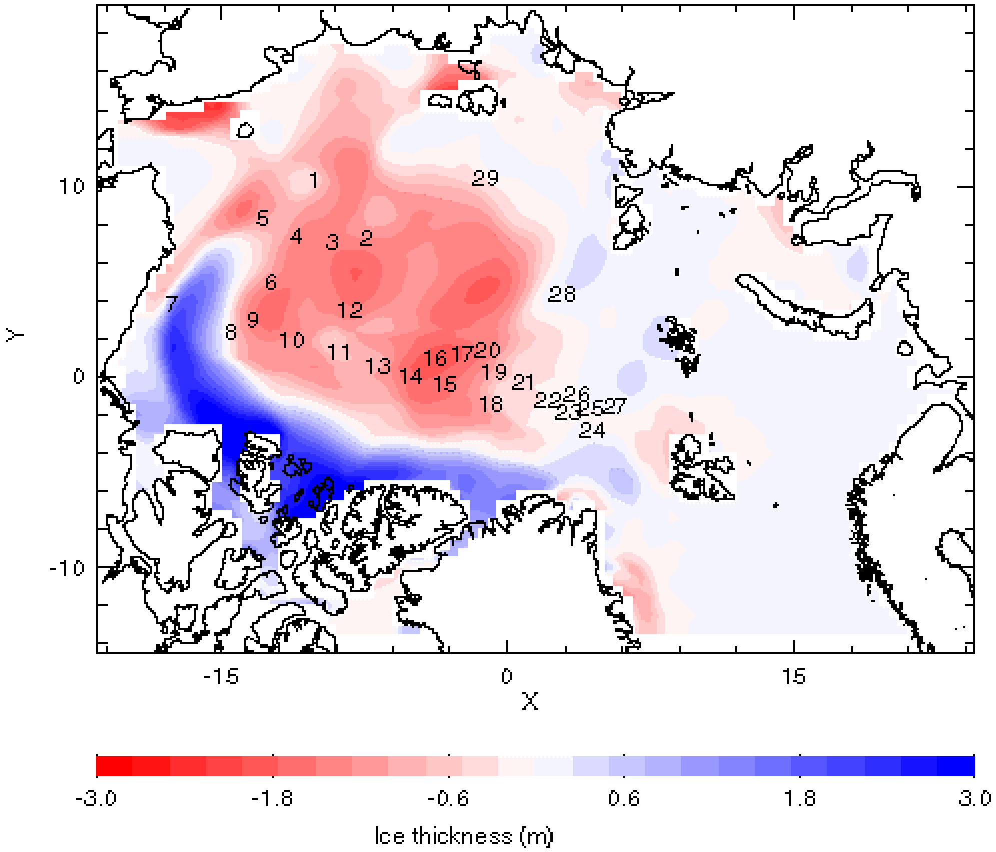

Figure 1. Change of ice thickness between latter and earlier submarine observations, with submarine evaluation locations marked.

In this case, the reduction of ice volume as sampled by virtual submarines was 45%. However, the total loss of ice volume over the Arctic domain (excluding the portions of Greenland and Norwegian Seas and the portion of Baffin Bay) is only near 12%. The figure suggests a simple explanation of large reported loss: rather than enhanced melting or export, the apparent ice loss was due to a shift of ice within the Arctic which the submarine sampling pattern missed. Moreover, this 12% loss is specific to the particular years of the submarine cruises, while a background trend over the period impies even more modest loss. Of the 12% ice loss in this case, about 9% attributes to enhanced export and only 3% is due to thermodynamics (i.e., less growth and/or more melt).

Are these numerical model results reliable? In detail, surely they are not. Over a variety of ways of estimating windstress history or radiative forcing, and for different ice leads parameters, heat and moisture exchange coefficients, etc., one obtains a range of possible results summarised in the following table.

Source	Change of thickness
Rothrock et al., as observed	-42 %
This study, at Rothrock sites	-25 to -45 %
This study, over Arctic domain	-12 to -16 %
Wadhams and Davis, as observed	-43 %
This study, at Wadhams sites	-11 to -62 %
This study, over Arctic domain	-27 to -34 %

For both the Rothrock et al. study and the Wadhams and Davis study, observed large decreases fall within the range of model-derived virtual observations. In both cases, Arctic overall change is indicated to be far more modest. As well,Winsor showed that six cruises from 1991 to 1997 indicated no signficant thinning. We find a slight, but not statistically significant, downward trend along the Winsor cruise lines during 1991 to 1997.

RESULT 1. THE WIND DID IT.

A key concern is how much depends upon uncertain detail of any particular model, and how much we can understand in a robust, nearly model-independent way. We find the pattern in Fig 1 is largely due to changing wind patterns interacting with a mobile ice cover. Examining the history of wind prior to any time of ice sampling, a question is: over how much prior time? Since we are not sure, we've varied the time window, ranging from a few winter months to the eight calendar months prior to September observations. Pictures obtained for these different intervals are broadly similar and Figure 2 can be considered representative.

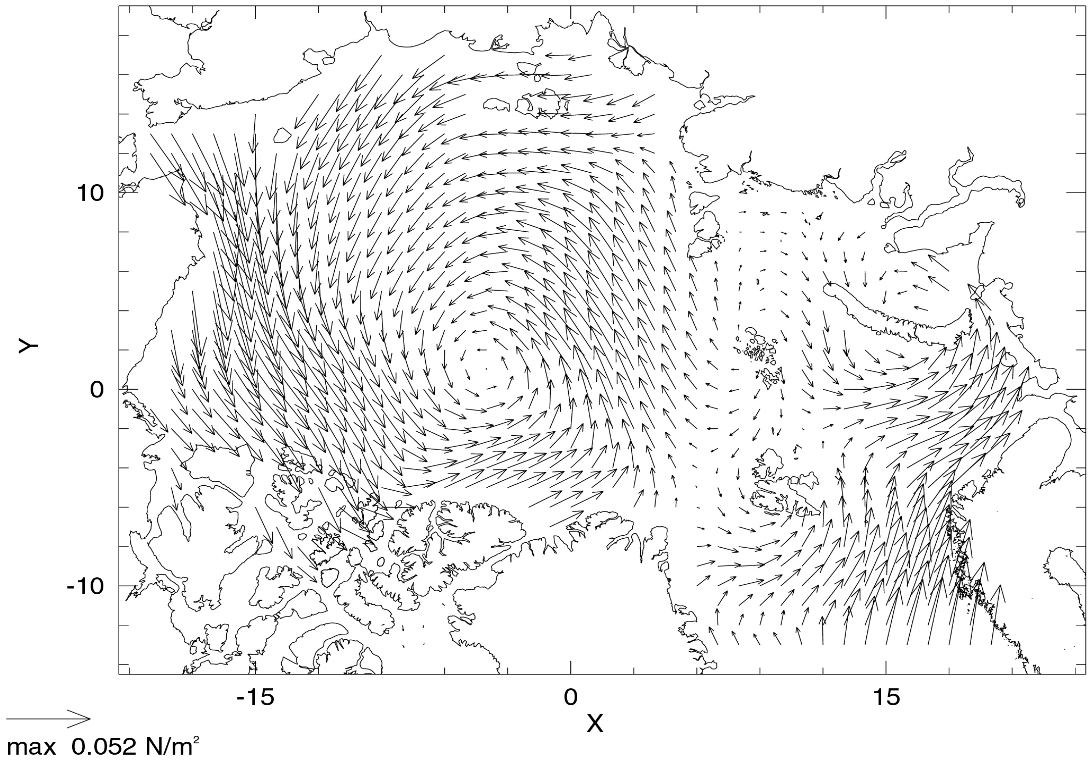

Figure 2. Difference of 8-month-mean (January through August) windstress, averaged over 1993, 1996 and 1997 minus the average over 1958, 1960, 1962, 1970 and 1976.

In fact the windstress differences in Figure 2 are themselves model-dependent insofar as the NCEP reanalysis products are model-based. We only suppose that physically plausible changes of windstress over the indicated periods may have resembled the pattern seen in the figure. Ice response to changing wind is complicated by nonlinear ice dynamics. Qualitatively however we can interpret ice distribution in Figure 1 in a quasilinear way, expecting *difference* ice to be pushed along by *difference* windstress while drifting somewhat to the right from the difference windstress. Thus, in the case of submarine sampling used by Rothrock et al., we see that when the submarines returned in 1993, 1996 and 1997, winds had largely expelled ice from the central Arctic and especially had driven ice into the Canadian sector from which U.S. submarines were politically excluded. Inferred rapid loss of ice volume was a result of undersampling, an unlucky combination of ever-varying winds and politics. Likewise the Wadhams and Davis results and the Winsor results are sensitive to happenchance of shifting winds.

We may further ask if the wind patterns underlying Figure 1 are unusual or are part of larger hemispheric patterns. The pattern of difference windstress is suggestive of patterns revealed by Thompson and Wallace (1998), characterised by Arctic Oscillation (AO) index which, in its winter manifestation, strongly correlates with North Atlantic Oscillation (NAO). One may examine winter (J-F-M) AO or averages of AO over 8 months prior to September submarine observation times. Results are similar, with the 8 month AO series shown in Figure 3.

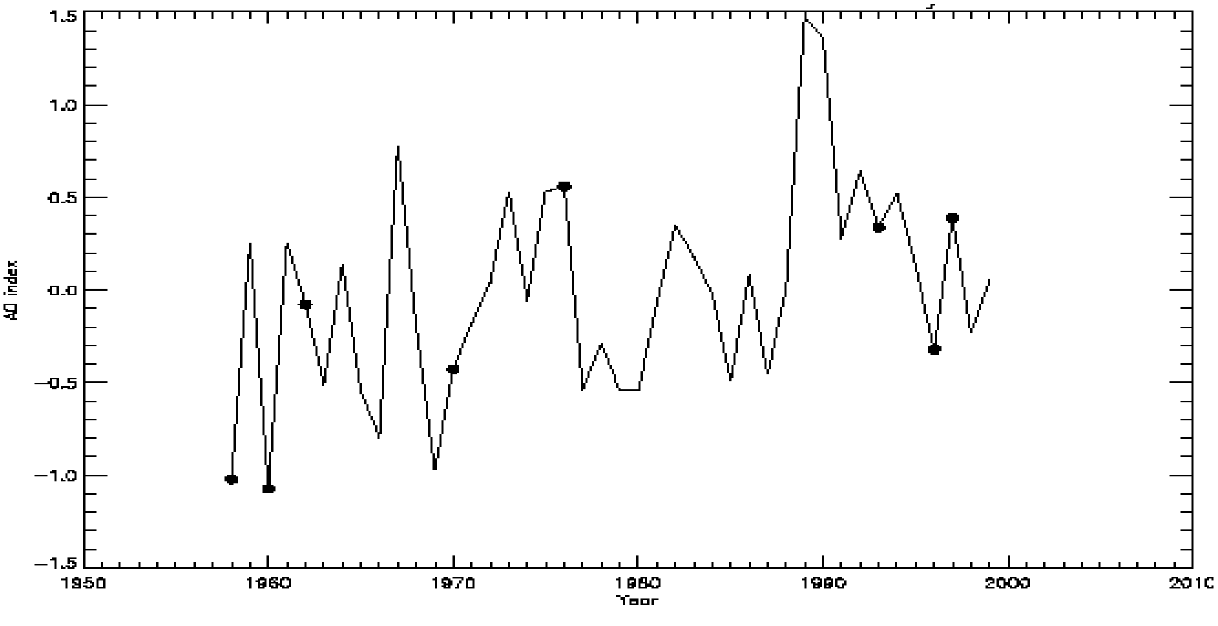

Figure 3. Timeseries of AO averaged over the first 8 calendar months each year, with the years of submarine observations used by Rothrock et al. (1999) indicated.

During the years of later cruises the 8-month AO was an average 0.57 index points higher than during the earlier period. Corresponding results using only winter (J-F-M) AO show increase by 1.9 index points in winters prior to the submarine surveys. More positive values of AO during the later surveys correspond to more cyclonic windstress, as seen in Figure 3.

RESULT 2. TIMING IS CRUCIAL.

In the previous section we saw that the pattern of submarine surveys misrepresented the pattern of changed ice thickness. Outcomes are also highly sensitive to the particular years of the submarine surveys as illustrated in Figure 4. Employing model output, we imagine the 29 locations identified by Rothrock et al. to have been occupied continuously over 50 years. The figure shows a continuous average of thickness over those 29 locations, with the timing of Rothrock et al. analyses marked. It is interesting that, if one supposed a climatic trend toward reduced ice volume, then one might better realize the "signal" by extending the analysis interval. Yet if we supposed the five earlier cruises had occurred just one year earlier (Sept 1957, 1959, 1961, 1969 and 1975) and the three later cruises had occurred one year later (Sept 1994, 1997 and 1998), model-based results would have showed very little thinning rather than the 42% loss as reported. It is a caution about undersampling in time as in the previous section in space.

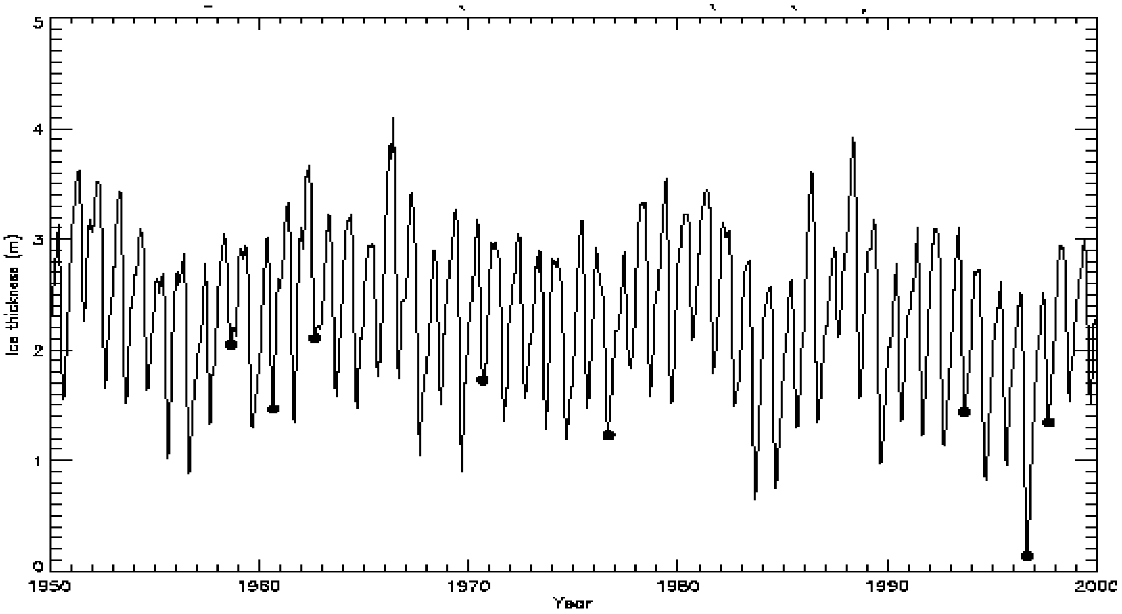

Figure 4. Timeseries of average ice thickness at 29 locations shown in Figure 1.

RESULT 3. A NATURAL MODE OF ARCTIC ICE VARIABILITY

Finally, regarding the picture of changed ice thickness shown in Figure 1, we ask if this pattern of change is common or unusual. The question can be addressed within the context of model results by decomposing thickness variations (relative to mean annual cycle) over 50 model years (1950 through 1999) into principal components or "EOF"s. The first EOF, accounting for 30% of thickness variance, is shown in Figure 5 along with the timeseries of the amplitude coefficient of this EOF.

Notably, the shape of the EOF is quite similar to the pattern of change seen in Figure 1. Thus the change in Figure 1 is very typical of the sorts of changes that occur in the Arctic. Timing of the Rothrock et al sampling, as marked, shows the coefficient having shifted to more negative values during the 1990s, corresponding to thinning in the central Arctic with thickening in the Canadian sector. While there is a statistically significant negative trend over this 50 year timeseries, it is seen that a large jump to negative values occurred in 1989-1990 coincident with the strongly positive peak in AO seen in Figure 3. Since 1990 the timeseries of this EOF coefficient suggests a trend for ice thickness to return from the Canadian sector more to the central Arctic.

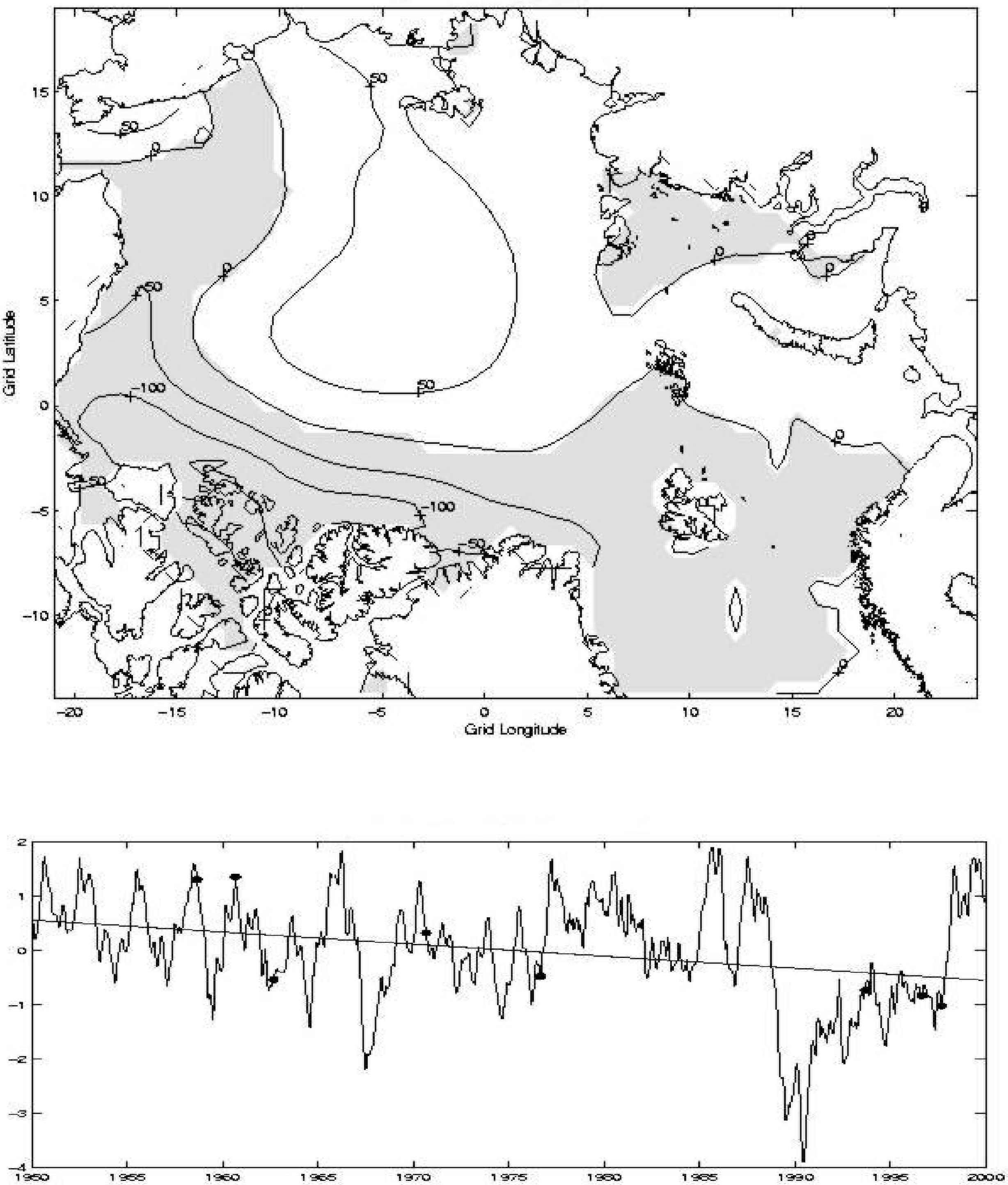

Figure 5. The first EOF of ice thickness variation and timeseries of its amplitude coefficient.

CONCLUSION

Everywhere environments change, and ability to sample those changes is limited. Inferences from sparse observations can be misleading. Additional information concerning atmospheric forcing together with the demand that inferences be physically consistent within the capability of modern ocean-ice-snow modeling helps refine inferences.

Previous reports that Arctic sea ice volume decreased nearly by half in recent decades have been widely cited in popular media and scientific considerations, e.g., IPCC 2001. We find instead, consistently with submarine data, with estimated atmospheric forcing, and with physics expressed in ocean-ice-snow modeling, that Arctic sea ice volume has decreased more slowly. Misleading inferences of rapid ice loss were a result of variable windstress forcing a natural component of sea ice variability. In particular a dominant mode of variability moves ice between the central Arctic and the Canadian sector, suggestive of the modes of Arctic ice motion discussed by Proshutinsky and Johnson (1997) or Kwok (2000). We find that the pattern of submarine surveys missed a major shift of ice thickness which may have occurred in 1989-1990 (and may be slowly relaxing since 1990).

Given uncertain estimates of atmospheric forcing, and imperfect model representation of ocean-ice-snow physics, we do not assign a confident estimate to the rate of sea ice volume change. It is somewhat reassuring that our results resemble those of independent model studies by Polyakov and Johnson (2000) or Zhang et al. (2000). We conclude that observations and model results together suggest only modest reduction of ice volume, like the modest decline in ice areal extent. Previously inferred rapid loss of ice volume is unlikely. Further analyses from yet-unpublished submarine data, from altimetric satellite data (Seymour Laxon, personal communication), and from moored sonar (Humfrey Melling, personal communication) will support more accurate assessments in the future.

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