

## Long-Term Ice Variability in Arctic Marginal Seas

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### ABSTRACT

Examination of records of fast ice thickness (1936–2000) and ice extent (1900–2000) in the Kara, Laptev, East Siberian, and Chukchi Seas provide evidence that long-term ice thickness and extent trends are small and generally not statistically significant, while trends for shorter records are not indicative of the long-term tendencies due to large-amplitude low-frequency variability. The ice variability in these seas is dominated by a multidecadal, low-frequency oscillation (LFO) and (to a lesser degree) by higher-frequency decadal fluctuations. The LFO signal decays eastward from the Kara Sea where it is strongest. In the Chukchi Sea ice variability is dominated by decadal fluctuations, and there is no evidence of the LFO. This spatial pattern is consistent with the air temperature–North Atlantic Oscillation (NAO) index correlation pattern, with maximum correlation in the near-Atlantic region, which decays toward the North Pacific. Sensitivity analysis shows that dynamical forcing (wind or surface currents) dominates ice-extent variations in the Laptev, East Siberian, and Chukchi Seas. Variability of Kara Sea ice extent is governed primarily by thermodynamic factors.

### 1. Introduction

Arctic sea ice plays an important role in the global climate system. Export of Arctic ice to lower latitudes is an effective regulator of the intensity of large-scale ocean overturning, with consequences for the global thermohaline circulation (see Aagaard and Carmack 1994 for further discussion). Arctic ice controls the high-latitude heat balance by moderating heat exchange between the atmosphere and the ocean.

Numerous changes have occurred in the Arctic over the last few decades: Arctic surface air temperature (SAT) has exhibited rapid increases (Martin et al. 1997; Rigor et al. 2000), and sea level pressure (SLP) has decreased, and atmospheric cyclonicity increased in the late 1980s through the early 1990s, relative to any time in the past several decades (Walsh et al. 1996). Concurrent with these atmospheric changes are reductions in Arctic ice extent (Johannessen et al. 1995; Maslanik et al. 1996; Parkinson et al. 1999) and a decrease of ice thickness (Rothrock et al. 1999; Tucker et al. 2001).

Observations show an average decrease in ice cover over the whole Arctic by 2.9% decade<sup>-1</sup> during 1979–96 (Cavalieri et al. 1997), with a stronger reduction of 4%–6% decade<sup>-1</sup> in summer (Chapman and Walsh

1993; Maslanik et al. 1996; Cavalieri et al. 1997; Parkinson et al. 1999; Deser et al. 2000) and a much smaller decline of 0.6% decade<sup>-1</sup> in winter (Chapman and Walsh 1993; Deser et al. 2000). However, it has been emphasized by Deser et al. (2000) that on a regional basis winter trends are comparable with summer trends. At timescales from weeks to decades, sea ice conditions are controlled by changes in the atmospheric circulation patterns manifested locally by SAT and wind variability (Walsh and Johnson 1979; Overland and Pease 1982; Fang and Wallace 1994; Slonosky et al. 1997; Prinsenberg et al. 1997; Mysak and Venegas 1998; Deser et al. 2000). Modeling studies have also demonstrated that winds may be responsible for substantial changes in ice conditions (Häkkinen 1993; Tremblay and Mysak 1998; Proshutinsky and Johnson 1997; Polyakov et al. 1999; Zhang et al. 2000; Polyakov and Johnson 2000).

Submarine-based sonar observations of Arctic ice draft provide valuable information about temporal variability of ice drafts in the central Arctic. Depending on the time period and geographical location, some investigators have reported thinning of Arctic ice (Wadhams 1994), whereas other studies find no convincing evidence of a trend (McLaren et al. 1994; Shy and Walsh 1996). All researchers found large interannual and spatial variability. The same conclusion has been reached by Haas and Eicken (2001), who found a significant (up to 1 m) difference between drill-hole records of ice thickness taken in consecutive years (1995 and 1996)

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in the Eurasian Basin. Summarizing available ice draft data from submarine cruises, Rothrock et al. (1999) documented a 1.3-m reduction of ice thickness in the central Arctic in the 1990s relative to the 1950s–70s. They also pointed to continued thinning of Arctic ice in the 1990s at a rate of  $0.1 \text{ m yr}^{-1}$ . This research has been complemented by Wadhams and Davis (2000), who reported a thinning of Arctic ice in the area between Fram Strait and the North Pole. However, Winsor (2001), extending the Rothrock et al. data through the 1990s with data from three additional submarine cruises, argued that there was no decrease in ice thickness during the 1990s. Later, Tucker et al. (2001) reported thinning of sea ice in the western Arctic in the recent decades, but found no evidence of a similar trend near the North Pole between the mid-1980s and early 1990s agreeing with Shy and Walsh (1996) but disagreeing with Rothrock et al. (1999) and Wadhams and Davis (2000). This diversity of conclusions may indicate a fundamental statistical sampling problem in analyzing highly variable (both spatially and temporally) Arctic ice thickness using existing time series. For example, Fig. 5b from Polyakov and Johnson (2000) shows that the simulated ice thickness for the central Arctic (approximately the area of the Scientific Ice Expeditions experiment) can vary by up to 0.6–1.0 m (30% or more of the total ice thickness) within 3–4 yr due to decadal variability. Holloway and Sou (2002), using their coupled ice–ocean model, showed that the problem may stem from undersampling and that most ice loss in the recent decades was due to wind-forced ice export from the central Arctic.

This research is devoted to the assessment of long-term Arctic sea ice variability, with a special focus on multidecadal fluctuations [low-frequency oscillation (LFO)] with a period of 50–80 yr, which has played an important role in recently observed changes in the Arctic environment (Polyakov and Johnson 2000). Newly available long-term Russian observations of sea ice extent and fast ice thickness from the Kara, Laptev, East Siberian, and Chukchi Seas offer the possibility for new insights into trends and variability of Arctic ice.

## 2. Data

Russian historical records of Arctic sea ice extent and thickness extend back to the beginning of the twentieth century. There are several distinct periods in the history of Russian sea ice observations. Occasional ship observations of summer ice edge started in the first decade of the 1900s when the first Russian hydrographic surveys and commercial shipping routes along the Siberian coast began. These data have been analyzed by the Russian climatologist, Vize (1944). Some data for this period have also been obtained from Russian navigation books. Starting in 1929, when the Soviet Polar Aircraft Fleet was created, aircraft-based observations began, which improved the quality of the data substantially. However, systematic aircraft and ship observations of

sea ice from the Kara Sea to the Chukchi Sea only began in 1932, when the Northern Sea Route was created. There were information gaps during World War II (1942–45). The missing data have been reconstructed using statistical (regressionlike) models relating atmospheric processes (SLP gradients and SAT) to ice extent (Kovalev and Nikolaev 1976; Yulin 1990). Aircraft ice-edge observations continued until 1979, when the satellite era began, but until recently a combination of satellite and aircraft summer ice-edge observations was used. Since 1990 all ice-extent observations have been satellite based.

In this study, we use August ice extent for the four seas (the regions from which the data were collected are shown in Fig. 1). The errors in defining ice-edge position from ship and aircraft are about 2–10 km. These data were mapped, and the ice-covered area was estimated. Generalization of this information for the whole domain may introduce rather large errors if only a few measurements of ice-edge position are available. Also, it is rather difficult to evaluate possible errors introduced by this generalization into the total ice-extent estimate. This is especially true for the beginning of the twentieth century, when observational data were extremely scarce. While these data may have substantial errors, they are unique in indicating important changes in the Arctic environment since the dawn of the industrial era.

Five locations where measurements are available of fast ice thickness (motionless sea ice anchored to the seafloor and/or the shore) are shown in Fig. 1 by stars; these data extend back to 1936. The observations were carried out at Russian polar stations, where observers drilled holes in ice and directly measured thickness, a rather precise method of observation (though not necessarily representative of the areal average and may include uncertainties due to ice formed from snow). Measurements of fast ice thickness are also invaluable because they provide an opportunity to separate, to some extent, the contribution of thermodynamical and dynamical factors in the formation of Arctic ice since they measure “pure” thermodynamical ice growth. The annual maximum ice thickness typically reached in May is analyzed.

In our analysis we also used SAT and SLP observations from coastal stations. The data, methods of analysis, and processing techniques have been described in a companion paper (Polyakov et al. 2003). SLP observations from five stations (Fig. 1, red dots) have been used to calculate pressure gradients as a measure of geostrophic winds along the red arrows in the map (characterizing possible wind-driven ice inflows–outflows). The SAT data were also used to prepare composite temperature records for two regions. The first region includes areas of the Kara and Laptev Seas and the surrounding maritime zone, the second is a combination of data from the area of the East Siberian and Chukchi Seas and coastal regions (not shown). All of the above time series are longer than 65 yr.

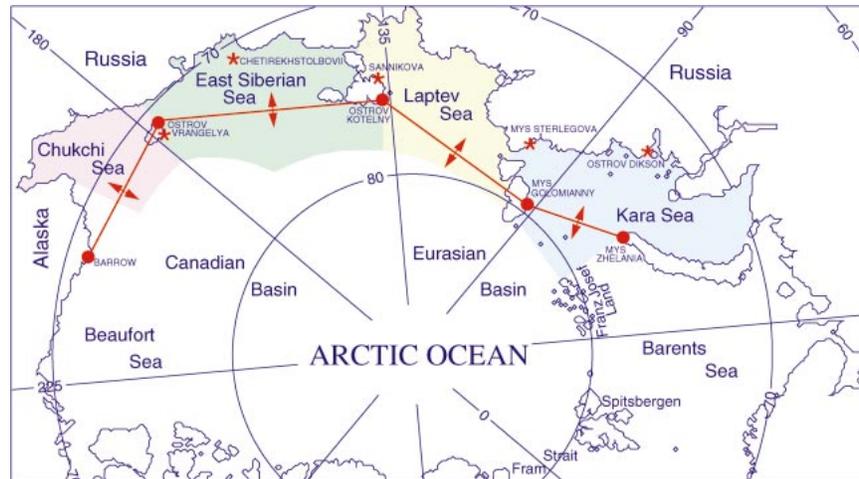


FIG. 1. Map of the Arctic Ocean, with colors denoting ice extent analysis regions. Locations of sea level pressure observations are shown by red dots. Red stars denote stations where ice thickness data were collected. Red lines denote locations of cross sections used for analysis of the modeling ice and water transports.

### 3. Variability of August ice extent

The century-long time series are used to evaluate trends and long-term variability of August ice extent in Arctic marginal seas (Fig. 1, color). The ice-extent time series show a combination of decadal and interdecadal variability, with lower values prior to the 1920s, in the late 1930s–40s, and in recent decades, and higher values in the 1920s through the early 1930s and in the 1960s–70s (Fig. 2, top). This is consistent with the multidecadal LFO found in instrumental records of Arctic SAT and SLP (Polyakov et al. 2003), simulated ice thickness and ice/freshwater transport through Fram Strait, observed and simulated salinity in the upper Barents Sea (Polyakov and Johnson 2000), and observed ice extent in the Nordic Seas (Vinje 2001, manuscript submitted to *J. Climate*). For example, a decrease of ice extent in the late 1930s–40s and in recent decades is well correlated with periods of LFO-driven Arctic warming (see Fig. 2 from Polyakov et al. 2003). The wavelet transform of the ice-extent time series compares favorably with two negative and two positive LFO phases superimposed on the decadal-scale variability (Fig. 2, top right).

There are, however, some important regional differences in ice-extent variability. The LFO amplitude tends to decrease from the Atlantic sectors toward the Pacific sectors of the Arctic. In the Kara Sea, which is closest to the North Atlantic, the LFO signature is most pronounced (Fig. 2). In the Chukchi Sea, the farthest of the seas from the North Atlantic, ice-extent variability is dominated by a relatively high-frequency decadal mode, in agreement with Yi et al. (1999), and there is no evidence of the LFO. This is perhaps because the LFO is related to fluctuations in the thermohaline circulation of the North Atlantic (Delworth and Mann 2000). Observations display distinct basinwide patterns

of multidecadal sea surface temperature variability centered in the North Atlantic that appear to maintain large-scale SLP anomalies expressed by the North Atlantic Oscillation (NAO) index (Deser and Blackmon 1993; Kushnir 1994; Mann and Park 1996; Delworth and Mann 2000). The correlation pattern between monthly air temperature from coastal stations and the NAO index supports the coupling between the processes in the western Arctic (closest to the North Atlantic) and North Atlantic, with maximum correlation in the near-Atlantic region, decaying toward the North Pacific (see Fig. 3 from Polyakov et al. 2003). Note an anomalously high ice extent in the late 1920s through the early 1930s, evident from both ice-extent time series and wavelet transforms. SAT records show warming, so the air temperature cannot be the reason for this ice extension. However, instrumental records show a substantial SLP decrease (see Fig. 2 from Polyakov et al. 2003) associated with a positive, cyclonic LFO phase which may explain this observed reduction in ice extent.

August ice extent in the Arctic marginal seas declined from 1961 to 1990 at a rate of  $2.7\%$  decade<sup>-1</sup> (percentages are relative to total surface area), somewhat less than for the entire Arctic (Chapman and Walsh 1993; Maslanik et al. 1996; Cavalieri et al. 1997; Parkinson et al. 1999; Deser et al. 2000). Regional trends varied widely, from  $-4.6\%$  and  $-3.5\%$  decade<sup>-1</sup>, respectively in the East Siberian and Kara Seas to  $-1.0\%$  decade<sup>-1</sup> in the Laptev Sea and  $+0.5\%$  decade<sup>-1</sup> in the Chukchi Sea. The large recent ice decline in the East Siberian Sea has also been reported by Maslanik et al. (1996) and Deser et al. (2000).

Extending the ice-extent time series back to the beginning of the twentieth century shows that the magnitude of trends tends to diminish (except in a relatively

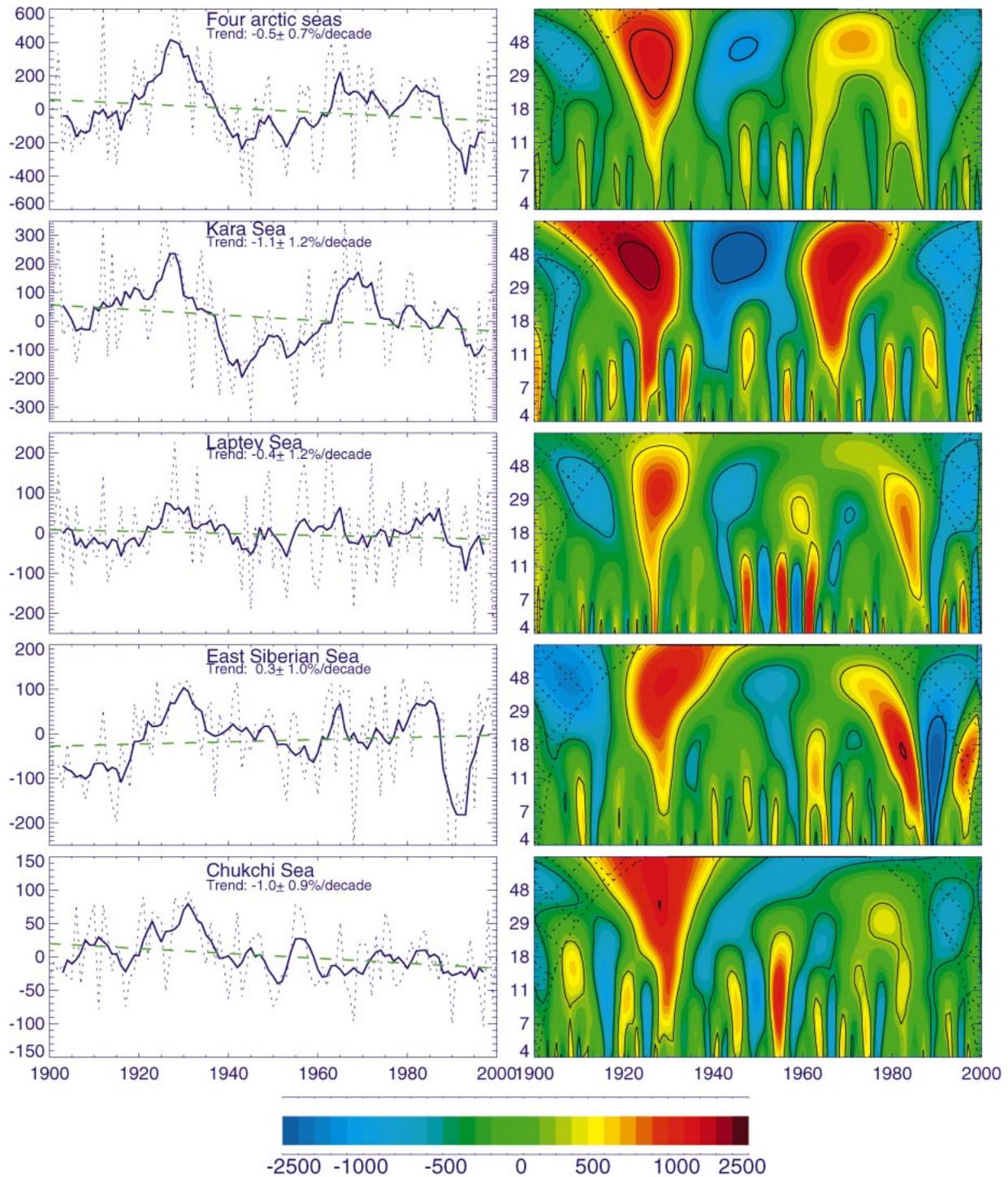


FIG. 2. (left) Time series of the Aug ice-extent anomalies ( $\times 1000 \text{ km}^2$ ) in four Arctic seas. Dotted lines show yearly Aug values, solid lines show 6-yr running means, green dashed lines show linear trends (quoted limits represent 95% confidence levels). Note axis scalings are not uniform. (right) Wavelet transform of annual ice extent using the Mexican hat ( $m = 2$ ) wavelet (Torrence and Compo 1998). Vertical axes show the period in years. The black contours are the 95% (thick) and 68% (thin) confidence levels, the black cross-hatched area denotes the region of the wavelet spectrum in which edge effects become important. The time series and wavelet transform indicate two periods of minimum ice extent associated with positive LFO phases (and warming in the 1930s–40s and late 1980s–90s) and two periods of maximum ice extent associated with negative LFO phases (and cooling prior to the 1920s and in the 1960s–70s).

TABLE 1. Correlations between ice and atmospheric–oceanic parameters. Here  $S_i^o$  and  $S_i^m$  denote ice extent derived from observations and modeling, respectively. The  $\nabla P$  is SLP gradient along the directions shown by red arrows in Fig. 1. For model description and design of the experiments see Polyakov and Johnson (2000).

Quantities correlated	Kara Sea	Laptev Sea	East Siberian Sea	Chukchi Sea
$S_i^o$ vs SAT	−0.54	−0.27	−0.50	−0.20
$S_i^o$ vs $\nabla P$	−0.40	−0.55	−0.67	−0.02 (−0.50)*
$S_i^o$ vs $S_i^m$	0.47	0.54	0.51	0.45

\* The value in parentheses shows the correlation between observed ice extent and modeled surface current.

small area of the Chukchi Sea). Over the entire Siberian marginal-ice zone the century-long trend is only  $-0.5\%$  decade $^{-1}$ . In the Kara, Laptev, East Siberian, and Chukchi Seas the ice extent trends are not large either:  $-1.1\%$ ,  $-0.4\%$ ,  $0.3\%$ , and  $-1.0\%$  decade $^{-1}$ , respectively. Moreover, statistical analysis based on the bootstrap technique (Efron and Tibshirani 1993) shows that these trends, except for the Chukchi Sea, are not statistically significant. Trends in recent decades seem larger, but because of the fewer degrees of freedom in these shorter time records, they are not statistically significant either.

What drives major long-term changes in ice cover in the Arctic marginal seas? Previous studies showed that at timescales of up to a decade sea ice conditions are controlled by changes in the atmospheric circulation pattern. Our study extends this result, suggesting that even at multidecadal timescales winds remain the major contributor to ice-extent variation in the Siberian marginal-ice zone. Table 1 displays correlations of ice-extent/SAT and ice-extent/SLP gradients. It follows from Table 1 that dynamical factors (wind or surface currents) are at least of the same order of importance as thermodynamical factors in the Laptev, East Siberian, and Chukchi Seas (cf. rows 2 and 3). In the Kara Sea, ice growth/decay appears to outweigh dynamical factors. Note that prevailing easterly winds over the Chukchi Sea cannot contribute much to the northward advection of ice into the Arctic Ocean, reflecting a weak correlation between winds and ice extent. However, northward surface currents fed by Pacific waters entering the Chukchi Sea through the Bering Strait provide an effective mechanism of ice transport to the Beaufort Sea.

#### 4. Variability of fast ice thickness

Ice dynamics makes detection of climate change using ice thickness data most difficult. The simplest effect of warming may be seen in thickness of fast ice. Wadhams (1994) emphasized that “in assessing likely climate change impacts . . . the fast ice zone . . . should show a definitive thinning in response to warming because ice thickness here is chiefly determined by air temperature.” Figure 3 shows five 65-yr-long time series of

fast ice measurements from the four Arctic marginal seas. The unsmoothed time series show strong year-to-year variability, with a dominant period of 2–3 yr, which has been found in various meteorological, ice, and oceanographic parameters (Gudkovich et al. 1972). Consistent with ice-extent variations, long-term fast ice thickness variability is strongest in the western Arctic (Kara Sea), and is modulated by multidecadal and decadal-scale fluctuations. In the Kara Sea, the fast ice thickness reaches its maximum in the 1960s–70s and is at its minimum in the 1940s and 1980s–90s, which compares favorably with one negative (cold) and two positive (warm) LFO phases (Polyakov et al. 2003). At station Sannikova (Laptev Sea), variability at longer periods ( $>30$  yr) is dominated by a downward trend that is manifested in wavelet transforms by a change of color from red–yellow to green–blue. In the Chukchi Sea fast ice thickness variability is dominated by decadal-scale fluctuations whereas multidecadal variability, though weak, shows an opposition to the LFO found in the Kara Sea, with two maxima in the 1950s and in recent decades, and a minimum in the 1970s. The tendency of climate variations to be of opposite phase in the eastern Arctic (Chukchi and East Siberian Seas) and western Arctic (Kara and Laptev Seas) has been known for a long time (Zakharov 1976). However, we must exercise caution to reach the same conclusion based upon a single time series, especially when the *ice-extent* records from the Chukchi and Kara Seas do not exhibit a similar opposition.

The fast ice records do not show a significant trend (Fig. 3). In the Kara and Chukchi Seas trends are positive, and in the Laptev and East Siberian Seas trends are negative. In all of the seas the trends are relatively small, about 1 cm decade $^{-1}$ , close to the resolution of the measurements. These trends are not statistically significant at the 95% confidence level. Thus, using these data we cannot conclusively identify the possible moderating role of sea ice in the apparent lack of polar amplification of global warming in the century-long Arctic SAT time series (see Polyakov et al. 2002 for details).

#### 5. Conclusions

In recent decades, large-scale changes have been observed throughout the Arctic atmosphere–ice–ocean system, sparking discussion as to whether these changes are episodic events, or long-term shifts in the Arctic environment. The lack of long-term observations in the Arctic makes it impossible to reach a definitive conclusion. Long-term records are now available due to recently released Russian ice observations from the Siberian marginal-ice zone.

Examination of records of fast ice thickness and ice extent from four Arctic marginal seas (Kara, Laptev, East Siberian, and Chukchi) indicates that long-term trends are small and generally statistically insignificant,

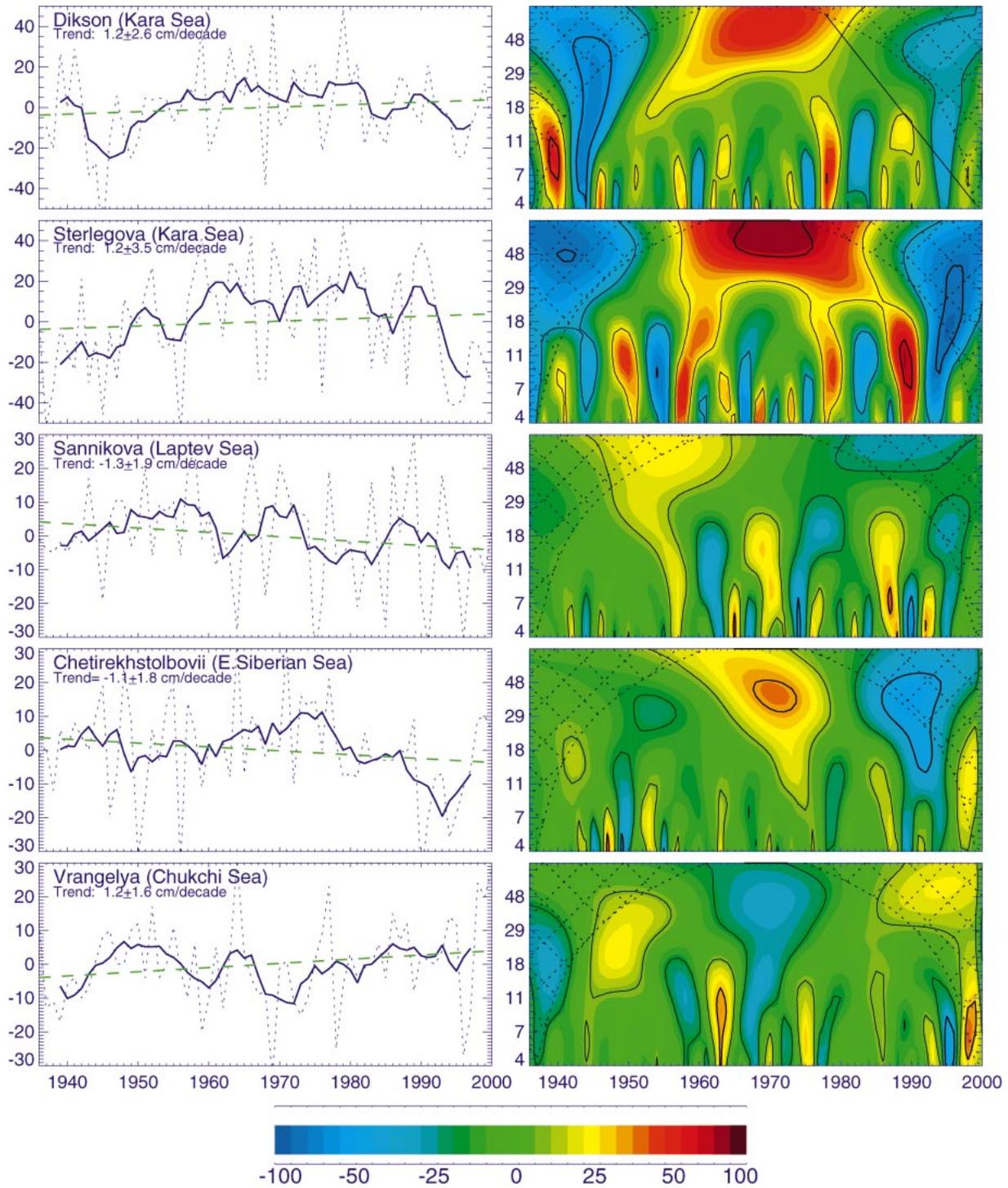


FIG. 3. (left) Time series of May fast ice thickness anomalies (cm) at five locations. Dotted blue lines show yearly May values and solid blue lines show 6-yr running means, green dashed lines show linear trends (quoted limits represent 95% confidence levels). (right) Wavelet transform of annual fast ice thickness. Vertical axes show the period in years. Plot legend is given in Fig. 2 caption. The time series and wavelet transform at Dikson and Sterlegov (Kara Sea) and Chetirekhtolbovii (East Siberian Sea) indicate two periods of minimum ice extent associated with positive LFO phases and one period of maximum ice extent associated with a negative LFO phase.

while trends for shorter records are not indicative of the long-term tendencies due to strong low-frequency variability in these time series, which places a strong limitation on our ability to resolve long-term trends. Ice variability in the Arctic marginal-ice zone is dominated by the multidecadal LFO and, to a lesser degree, by decadal fluctuations. This variability is complicated by geographical differences: the LFO signal decays eastward, and is strongest in the Kara Sea, whereas in the Chukchi Sea, ice-extent and fast ice variability is dominated by decadal fluctuations, and there is no evidence of the LFO. This is consistent with the Arctic SAT/NAO index correlation pattern, which shows maximum correlation in the near-Atlantic region, decaying toward the North Pacific.

Correlation analysis shows that dynamical forcing (wind or surface currents) is at least of the same order of importance as thermodynamical forcing for the ice-extent variability in the Laptev, East Siberian, and Chukchi Seas. Prevailing easterly winds over the Chukchi Sea cannot contribute much to ice advection across the open boundary, but surface currents provide an effective mechanism of ice transport from the sea into the central Arctic Ocean. In the Kara Sea, thermodynamical factors outweigh dynamical factors in controlling ice-extent variability. This analysis implies that deficiencies of present-day models, such as the oversimplification of ice dynamics, make simulation of fundamental ice–albedo feedback most difficult.

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