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Contribution of a pathway through the Arctic Ocean to the recent reduction in the ice cover

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Abstract The sea ice cover in the Arctic Ocean has been reducing and hit the low record in the summer of 2007. The anomaly was extremely large in the Pacific sector. The sea level height in the Bering Sea vs. the Greenland Sea has been analyzed and compared with the current meter data through the Bering Strait. A recent peak existed as a consequence of atmospheric circulation and is considered to contribute to inflow of the Pacific Water into the Arctic Basin. The timing of the Pacific Water inflow matched with the sea ice reduction in the Pacific sector and suggests a significant increase in heat flux. This component should be included in the model prediction for answering the question when the Arctic sea ice becomes a seasonal ice cover.
Key words Arctic Ocean, ice cover, Bering Sea.

1 Introduction

As reported in recent articles, the sea ice cover in the Arctic Ocean has declined in the last 40 years and reaches the extreme condition as shown in Fig. 1 and 2, while its decadal variability has increased[1]. Then, we might imagine that the ice cover will change into a seasonal one in near future. Actually, the observed ice decrease seems faster than that in the IPCC Report prediction; i. e., the ice cover in summer is predicted to become minimal earlier than the end of the 21st century[2]. In particular, the summer ice cover hit a record low in 2007 so that some specialists may believe disappearance by 2020. On the basis of significant year-to-year variability, however, such an early disappearance might be exaggeration. We really need to examine the mechanisms crucial for the rapid ice decrease.

The Polar Vortex has more significant decadal oscillations than the trend. The recently archived data extending from clouds, the atmospheric boundary layer to biogeochemical components in the Arctic Ocean have been analyzed for providing a close insight into Arctic environmental change, which may occur in response to global warming or as part of natural variability. The preliminary results include the following signals: the cloud cover has increased and is estimated to contribute to the ice reduction through the radiation balance[3]. The atmospheric boundary layer thickness has reduced, and the stratosphere is cooling as a result of global warming. The biogeochemical data indicate ocean interior responses to the Arctic Oscillation[4].

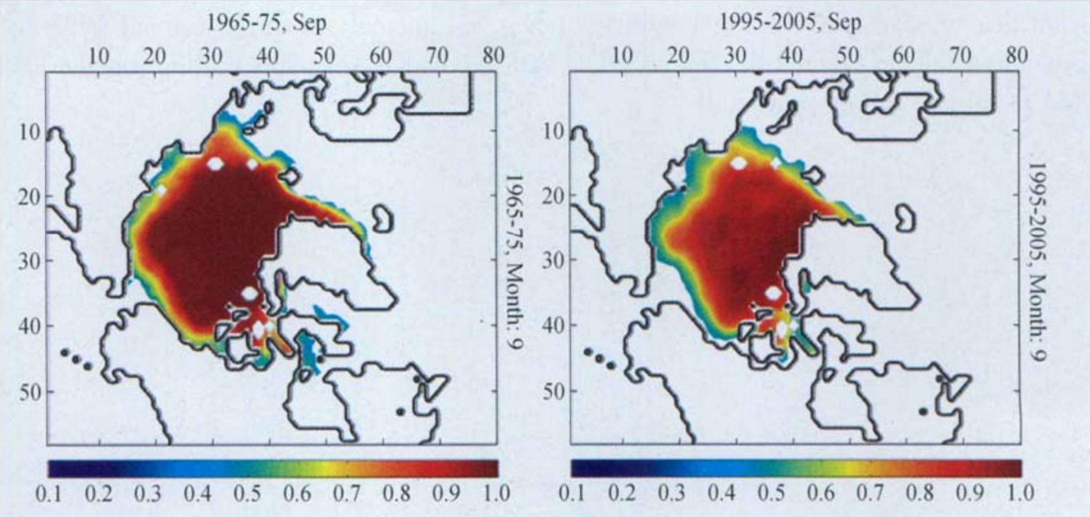

Fig. 1 Observed ice cover concentration in the Arctic Basin. Ice reduction is significant in last 30 years.

In the Arctic, the most pronounced atmospheric pattern is the Northern Annular Mode (NAM), which was first reported as the Arctic Oscillation by Thompson and Wallace (1998)[5]. A difference between this mode and the North Atlantic Oscillation (NAO) has been discussed from the viewpoints of statistics and dynamics: which mode is dynamically meaningful. The horizontal pattern is the intensified/weakened Polar Vortex with distinct coherence from the surface to the stratosphere. The decadal signal had a clear peak around 1990 with strong Polar Vortex in Fig. 3. The less ice anomalies occurred around this peak, propagating from the Beaufort-Chukchi Sea, the East Siberian-Laptev Sea to the Barents-

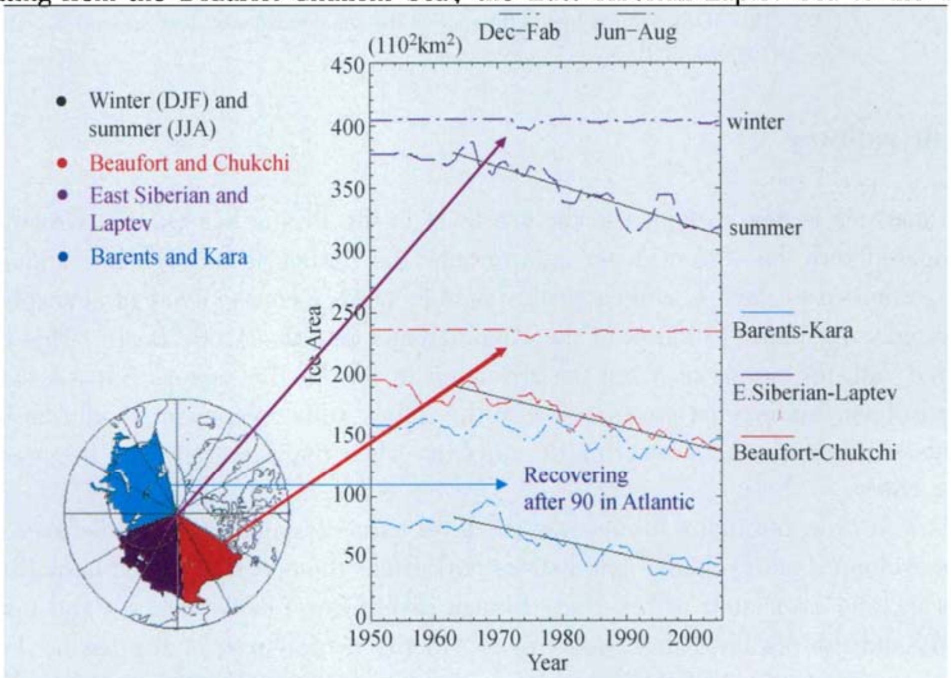

Fig. 2 Ice cover trends and decadal variability in three regions, the Beaufort-Chukchi Sea, the East Siberian-Laptev Sea and the Barents-Kara Sea.

Kara Sea in several years. In contrary, a less ice anomaly occurred around 1998 in the Beaufort-Chukchi Sea but did not correlate with a positive AO. This finding was the motivation to initiate the present study.

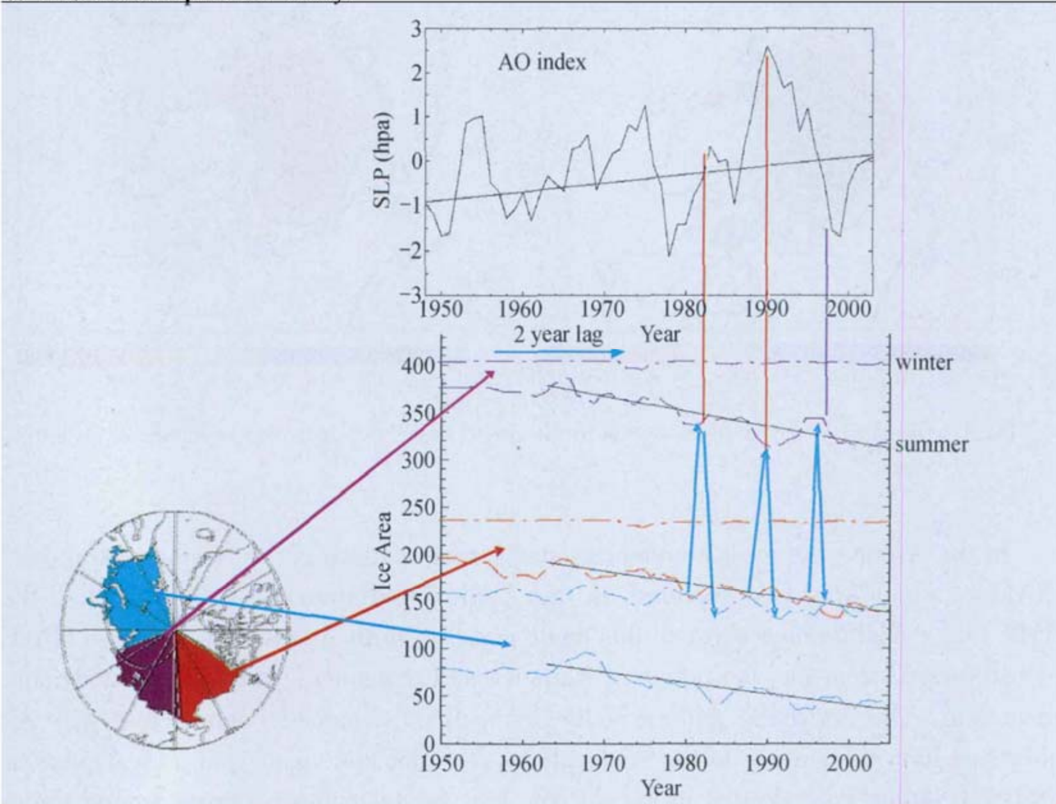

Fig. 3 Decadal variability in the Arctic Oscillation and sea ice cover produced by the AO. The AO is defined by a difference in the zonal mean sea level pressure between 70°N and 85°N.

2 Arctic pathway

An analysis is now extended to the sea level in the Bering Sea vs. the Greenland Sea and compared with the current meter data through the Bering Strait. The interannual variability is examined to show whether a peak was induced as a consequence of atmospheric circulation and contributed to inflow of the Pacific Water into the Arctic Basin. This idea will be verified with the timing of a sea ice reduction in the Pacific sector. Since a significant increase in heat flux may be associated with the inflow, this component should be included in the model prediction for answering the question when the Arctic sea ice becomes a seasonal ice cover.

It is well accepted that a basin-scale sea level varies responding to wind-driven circulation. As cyclonic (anticyclonic) wind stress curl drives the ocean, the first baroclinic mode develops in time associated with surface Ekman divergence (convergence) and propagates westward, and the sea level descends (rises) in the central part of the basin. Following this simple concept, the NCEP/NCAR data were processed over the Bering Sea and also the East Greenland Sea for 50 years. Both analysis domains have zonal lengths of 40 degrees and meridional lengths of 20 degrees. As shown in Fig. 4, a multi-decadal variability is evident over the Bering Sea, while it is mainly decadal over the East Greenland Sea.

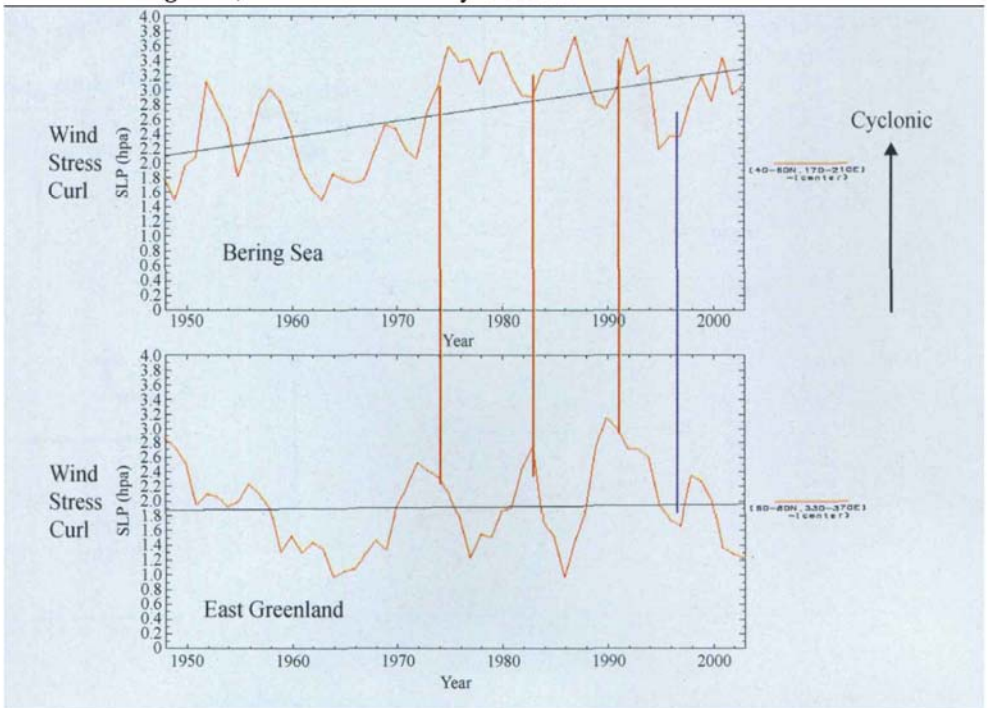

Fig. 4 Wind stress curl over the Bering Sea and the East Greenland Sea.

The wind-driven general circulation is established as a non-dispersive, first baroclinic Rossby wave, whose phase speed is determined to be about 0.01 ms-1 from the stratification in the Bering Sea. Within the analysis domain with a 2500 km zonal length, the sea level is essentially similar to the reversed wind stress curl smoothed in time and lagged by 2-to-3 years. Fig. 5 shows the sea level in the Bering Sea with a distinct peak around 1998, following a generally low sea level for the period of 1975 through 1995. This peak is also shown in the altimeter data in the Bering Sea so that the wind-driven sea level may be meaningful and interpreted to cause the low ice anomaly in the Pacific sector. An analysis of World Ocean Atlas indicates a growing trend, whereas the recent data are not ready yet. The current meter data are unfortunately missing for the peak, although the trough around 2002 is consistent with the trough in the altimeter data.

An interesting feature is an earlier high sea level all way through 1960s in a consistent manner with the steric height. This anomaly could be related to the Great Salinity Anomaly (GSA), during which freshwater was exhausted toward the Greenland Sea and the entire northern North Atlantic in late 1960s to early 1970s[6].

3 Discussion

The thermodynamic effect is estimated for the pathway transport. Once it increases the transport by 10% (10^5 m^3s^{-1}) of the Pacific Water at 3℃, extra heat flux melts 2 m thick sea ice over 10^5 km^2 in a year. An effective process would be melting sea ice from its bottom in winter, and then, the albedo-ice feedback works in summer and melts more ice.

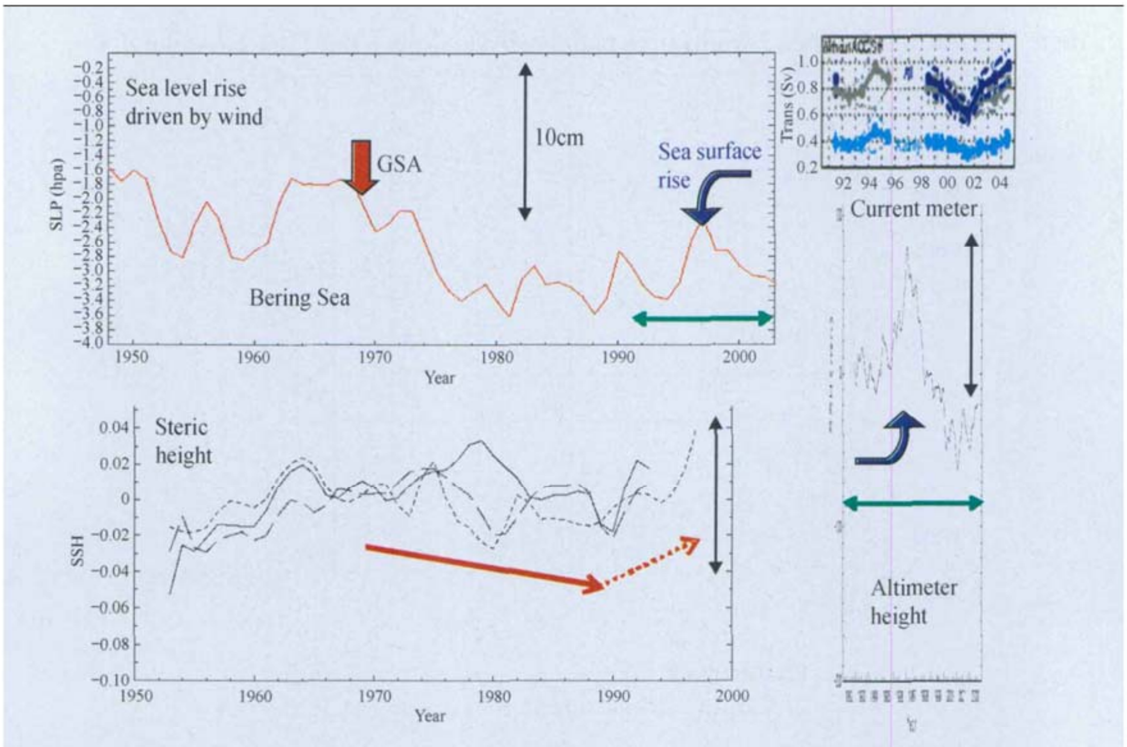

Fig. 5 Sea level in the central part of the Bering Sea estimated from the wind stress curl over the Bering Sea. It is compared with the steric height in the Bering Sea produced from World Ocean Atlas, the TOPEX/POSEIDON altimeter height in the Bering Sea during the ice-free season and the current meter data in the western Bering Strait[8].

In this paper, a higher sea level in the Bering Sea was suggested to be one of the causes of a less ice anomaly in the Pacific sector. A wind-driven general circulation was shown to be related to the sea level variability. It is noted that this view is based on the assumption that pressure field is horizontally uniform in the lower ocean. However, there is a topographic barrier between the Bering Sea and the Arctic Ocean. A further study is needed for clarifying validity of the steric height concept. One of the possible methods is to use a global ocean model to simulate the sea surface heights in the Bering Sea and the Arctic Ocean, which are connected all way across the Pacific and Atlantic equatorial regions and the Antarctic Circumpolar Current region. Various processes in these regions are well imagined to produce a pressure difference in the lower parts of the Bering Sea and the Arctic Ocean.

Shimada *et al.* (2006) pointed out importance of the Pacific Water inflow in summer for ice reduction and made an additional suggestion that this inflow worked as a trigger for a more influential mechanism of ice reduction through air-sea interactions[7]. The inflow of the Pacific Water increased in 1990s and may be effective on the ice reduction in the Pacific sector[8]. In addition to sea level variability in the Bering Sea, a wind stress along the Bering Strait must play some roles on the pathway, as suggested by Woodgate *et al.* (2005)[9]. Actually, the pathway transport increased from 2002 to 2004[8]. It is an urgent task to evaluate which is dominant for the pathway transport, sea level in the Bering Sea or wind stress along the Bering Strait.

A more fundamental question is how crucial wind-driven ice motion is for a less ice anomaly in the Pacific sector. Once a southerly wind pushes sea ice away from the coastal region in summer, solar radiation effectively heats the ocean and accelerates ice melting. This effect is considered to be a major one for the record low in summer of 2007[10].

Coupled ice-ocean models have been used for simulating the signals in the Arctic seas, and in turn verified in comparison with the data. The models well duplicate the ice cover variability in the Arctic Ocean, the Labrador Sea and the Okhotsk Sea for seasonal cycle and decadal variability. Both modeling and observational approaches should be coordinated so that more reliable tools may be provided for predicting future change in the Arctic seas. An ultimate attempt is to use a coupled ice-ocean-atmosphere model, in which crucial mechanisms should be tackled and enables us to find answers for the questions when the Arctic sea ice becomes a seasonal ice cover.

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