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Sea level rise in the Arctic Ocean

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Abstract. About 60 tide-gauge stations in the Kara, Laptev, East-Siberian and Chukchi Seas have recorded the sea level change from the 1950s through 1990s. Over this 40-year period, most of these stations show a significant sea level rise (SLR). In light of global change, this SLR could be a manifestation of warming in the Arctic coupled with a decrease of sea ice extent, warming of Atlantic waters, changes in the Arctic Ocean circulation, and an increase in coastal erosion and thawing of permafrost.

We have analyzed monthly mean sea level data and assessed the role that different factors may play in influencing the process of sea level change in the Arctic Ocean. Analysis of the observational data and model results shows that changes in the patterns of wind-driven and thermohaline circulation may account for most of the increase of sea level in the Arctic Ocean and their cumulative action can explain more than 80% of the sea level variability during 1950-1990.

Introduction

The Arctic Ocean comprises some of the most sensitive elements of the global environment which are considered to respond rapidly to climate change. But selecting a representative environmental parameter which can reflect both the short- and long-term variability of arctic climate is difficult because of a lack of continuous basin-wide observations. Sea ice extent has long been recognized as an important indicator of the state of the Arctic climate system in observational and modeling studies. Among recent publications, the paper by *Vinnikov, et al.* (1999) can serve as an example of such an approach. Another parameter which has been widely used for global climate change detection is the variability in sea level. Sea level is a natural integral indicator of climate change. It reflects changes in practically all dynamic and thermodynamic terrestrial, oceanic, atmospheric, and cryospheric processes. This paper assesses its role as an indicator of Arctic climate change.

About 60 tide-gauge stations in the Kara, Laptev, East-Siberian and Chukchi Seas (Siberian Seas) have recorded the sea level changes from the 1950s through 1990s (Figure 1). The sea level data were collected by the Arctic and Antarctic Research Institute, St. Petersburg, Russia. Over this 40-year period, most of these stations have shown a positive trend in sea level or sea surface heights (SSH) with an acceleration of SLR in 1970s-1990s. Data from four representative stations are shown in Figure 1.

In light of global warming, the increase and acceleration of the rate of SLR could be a manifestation of warming in the Arctic. As a consequence of a global warming scenario, *Shaw et al.* (1998) anticipate that a 0.65 m increase in sea level will occur in the Canadian Arctic in the 21st century. *Dvorkin* (1991) estimated the rate of SLR (during 1950-1985) from 0.02 to 0.6 mm/year and attributed this SLR to vertical crustal movements. He predicted a 12 mm increase in sea level due to this factor for 1990-2005.

Miller and Russel (2000) determined the fresh and salt water budgets of the Arctic Ocean estimated by a global climate model. Two 150-year simulations were used to examine how this budget might change if the quantity of atmospheric greenhouse gases (GHGs) were increased. The model indicated a SLR of 31 mm during 1950-1999 in the Arctic Ocean due to the GHG increase. This represents nearly half the 80 mm SLR which observations showed along the Russian coastline during 1950-1990 (Figure 1). They project an increase in sea level of 201 mm for the period 2000-2049, and of 534 mm for the period 2050-2099. According to these authors, the SLR in the Arctic Ocean is mainly due to the steric expansion associated with warmer water (20.18 mm or 66%) and a reduction in salinity (10.91 mm or 33%).

Pavlov and Pavlov (1999) reported a dramatic SLR acceleration in the 1980s (Figure 1). *Pavlov* (2000) concluded that the major cause of this phenomenon was due to a change in the thermohaline circulation. In contrast, *Proshutinsky et al.* (2000) found that the SLR during this period could be explained by changes in the atmospheric circulation, which in turn could effect the barotropic ocean circulation causing it to become more cyclonic, decreasing the SLP (inverted barometer effect), and increasing precipitation and river runoff.

One can see that disagreement exists among the different scientists not only on the rates of SLR, but also on its causes. The problem is compounded because existing observations are concentrated along the Siberian coastline and they may not reflect changes in sea level across the whole Arctic Ocean. In assessing the net influence of all these processes on climate change, it is essential to consider the impact of each of the various factors individually, and to then combine their separate contributions to provide estimates of future conditions. It is necessary to construct a hydrological

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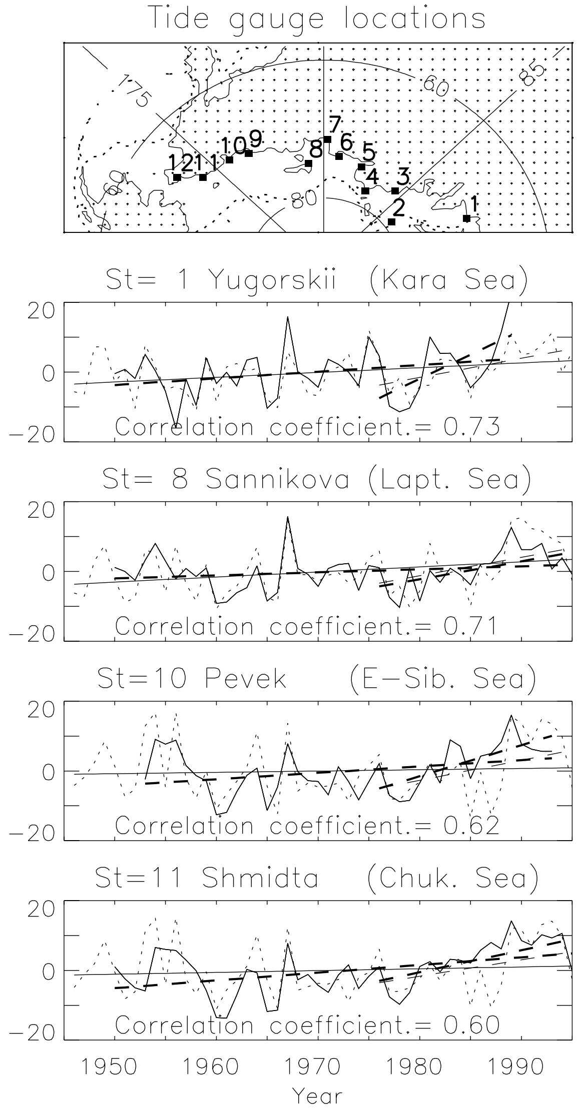

Figure 1. Tide gauge locations (upper figure). Numbers show location of stations discussed in the paper. The thick dotted line shows location of the shelf break (200 m). Observed (solid) and simulated (dotted) annual mean sea level time series are shown in lower figures. The dashed thick line shows the observed trend during the period of observations and during the last 15 years. The solid thin line and the thin dashed line show simulated trends for the period of simulation and for the last 15 years, respectively. Numbers show correlation coefficient between observed and simulated time-series.

and geophysical budget for the various contributors to local and global sea level changes.

In this paper, we analyze only the major contributors, wind stress, inverted barometer effect and thermohaline forcing and compare their estimated inputs with observations.

Wind stress and inverted barometer effects

We have investigated the role of wind stress and the gradient of SLP (the inverted barometer effect, hereinafter, IBE) on sea level variability and evaluated their relative contribution in terms of sea level change. A 2-D coupled barotropic ice-ocean model having a resolution of 55.5 km [*Proshutinsky*, 1993] was used for numerical experiments. The atmospheric forcing fields were obtained from the National Center for Atmospheric Research's CDROM containing a selected subset of the National Meteorological Center Northern Hemisphere octagonally gridded daily surface pressure data. The model was calibrated based on hourly sea level data for the stations mentioned above. The model was run for the period from 1946 through 1997 with and without the IBE and with and without the wind stress effect (WSE) to assess their role on sea level change. The correlation between the annual mean observed and simulated sea level variability (full forcing experiment (FFE) when both WSE and IBE were included) for selected stations is shown in Figure 1. Numerical experiments with and without IBE (not shown) demonstrated that wind stress was responsible for about 60% of the sea level variability with IBE providing the remainder. Note the significance of each of these effects depends on the distance of the measuring station from the shelf break. The importance of wind stress on sea level variability increases with width of the shelf (Figure 1). There is a significant disagreement between observed and simulated sea level in the East-Siberian and Chukchi Seas in 1985 and 1987. Wind and inverted barometer effects were not dominating at that time and thermohaline factors were more important (Figure 2).

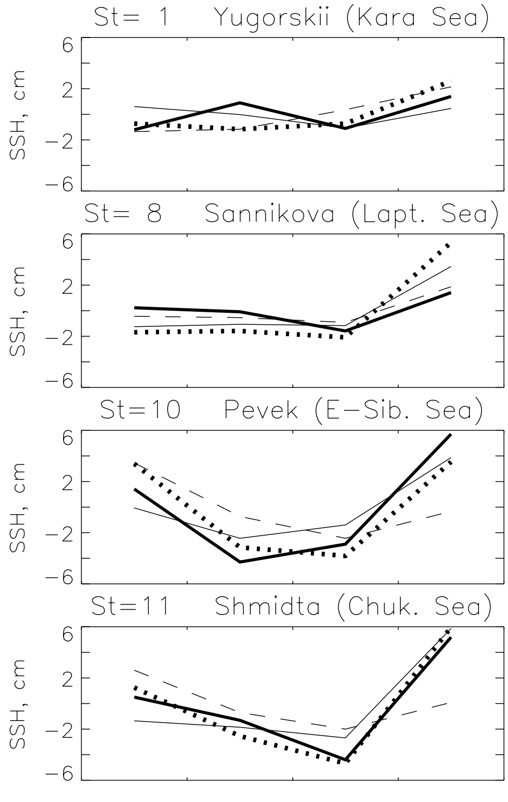

Figure 2. Decadal sea level for 1950s, 1960s, 1970s and 1980s from observations (thick solid line), and simulations based on thermohaline factors only (thin solid line), atmopsheric forcing only (dashed line), and combined on thermohaline and atmospheric forcing (dotted line). Note that thermohaline forcing in the Laptev, East-Siberian and Chukchi Seas explains more than 70% of the sea level change.

Table 1. Observed and simulated sea level rise rates

Station	Obs-1 [a]	FFE [b]	WFE [c]	IBE [d]	Obs-2 [e]	FFE-2 [h]	TFE-2 [f]
1	0.19	0.14	0.08	0.06 (42%)	0.25	0.18	0.16
2	0.25	0.07	0.01	0.06 (86%)	0.30	0.08	0.03
3	0.19	0.06	-0.01	0.07 (100%)	0.57	0.27	0.10
4	0.12	0.06	0.00	0.06 (100%)	0.72	0.08	0.32
5	0.09	0.09	0.03	0.06 (67%)	0.21	0.03	0.54
6	0.03	0.09	0.03	0.06 (67%)	0.71	0.10	0.45
7	0.26	0.07	0.01	0.06 (86%)	0.45	0.17	0.48
8	0.09	0.15	0.09	0.06 (40%)	0.29	0.28	0.46
9	0.32	0.08	0.03	0.05 (63%)	0.92	0.25	0.52
10	0.18	0.04	0.00	0.04 (100%)	0.86	0.21	0.53
11	0.22	0.05	0.03	0.02 (40%)	0.96	0.21	0.86
12	0.26	0.08	0.07	0.01 (12%)	0.81	0.28	0.76
average	0.18	0.08	0.03	0.05 (62%)	0.58	0.18	0.40

[a] Observed trend 1950-1990, cm/year

[b] Simulated trend under Full Forcing Experiment (FFE), cm/year

[c] Simulated trend under Wind Forcing Experiment (WFE), cm/year

[d] Simulated trend under Inverted Barometer Experiment (IBE), cm/year. Percentage relative to FFE is shown in brackets.

[e] Observed trend between 1970s and 1980s, cm/year

[h] Simulated trend between 1970s and 1980s under FFE, cm/year

[f] Simulated trend between 1970s and 1980s under Thermohaline Forcing Experiment (TFE), cm/year

The relative contribution of each factor (wind stress, ice extent, inverted barometer effect) is also different for different seasons. Our results show that during January-March the variability of sea level is dominated by the inverted barometer effect because vast areas of these seas are covered by fast and pack ice and the direct effect of wind stress on water motion is damped. Thus the relative importance of the inverted barometer effect is regulated by the presence of fast or compact sea ice.

A high correlation between atmospheric forcing and sea level variability along the Siberian coastline is noted but the observed sea level trend (thick dashed line) is greater than the simulated trend (thin solid line). Analysis of the FFE, WFE and IBE experiments (Table 1) demonstrated that on average the IBE explains 60% of the simulated SLR along coastlines, and that over this 40 year period it is closely related to a trend of a decreasing atmospheric pressure in the Arctic Ocean. Note that the wind stress is more responsible for the short-term variability (60%) and does not cause any significant trends in SLR during 1950-1990.

Thermohaline forcing and thermohaline circulation

In order to investigate the sea level variability generated by changes in thermohaline forcing, we have used a 3-D baroclinic model with a free surface [*Pavlov and Pavlov*, 1999]. A set of diagnostic simulations of water circulation and sea level fields was carried out for the 1950s, 1960s, 1970s and 1980s using only temperature and salinity fields for these decades from the Joint U.S.-Russian Atlas of the Arctic Ocean (1998). Figure 2 shows that observed decadal sea level variability is highly correlated with the simulated sea level change due to variability of thermohaline factors. This correlation steadily improves from the Kara Sea to the East-Siberian and Chukchi Seas where it reaches more than 80%. In the Kara Sea, atmospheric forcing is more important than the change in thermohaline circulation (Figure 1). In the Laptev Sea both effects are important but in the East-Siberian and Chukchi Seas the SLR is clearly more related to the change of thermohaline circulation. It is interesting that in winter, the maximum trend in SLR is located in the center of the ocean (about 8 cm/40 years, not shown) and in summer, this maximum (not shown) is located in the marginal seas as might be expected from increased river runoff, or from increased water temperature because of the reduction of sea ice concentration and subsequent increase in accumulation of solar radiation and ocean heat content. Areas of decreasing sea level (negative trend, not shown) are located along the continental slope and in the Alaskan/Canadian Arctic and on average this lowering trend compensates for the SLR along the coastlines and in the center of the ocean.

Conclusions

Most of the SLR observed along the Siberian coastline during the 1950s to 1980s can be explained by atmospheric forcing and by changes in the thermohaline circulation due to changes in the T-S distribution in the ocean. Thermohaline and wind-driven effects are equally important in influencing the ocean circulation and both significantly contribute to the SLR in the Arctic Ocean over this 40-year period. Our investigation shows that in the Kara Sea (and somewhat in the Laptev Sea) the variation in atmopsheric pressure is more responsible for the SLR than the change in thermohaline circulation. In the East-Siberian and Chukchi Seas, the change in thermohaline forcing prevails over wind effects and the inverted barometer effect. This suggests that warming of the Arctic is responsible for the SLR but not directly through land-ice melting as one might expect. The rise in sea level is an integrated effect due to processes associated with global warming which have changed the intensity and direction of the atmospheric circulation, ice distribution, rates of sea ice melting and freezing, and temperature and salinity fields.

Many secondary effects have not been taken into account in this research. Interaction of the Arctic Ocean with the North Pacific and North Atlantic Oceans in terms of sea level variability will be investigated in a future study using correlation analysis among sea level time series in the Arctic Ocean and in the Bering, Norwegian and Greenland Seas.

The sea level change due to variability in precipitation, evaporation and river runoff must be estimated accurately as well. An example of the complexity of this estimate can be gleaned from the interplay between storms and river runoff. An increase of precipitation in the central Arctic, associated with the passage of cyclonic storms, will likely lead to a reduction in river runoff from land because the trajectories of the cyclones will be shifted towards the central Arctic causing less precipitation to be expected over Siberia.

In addition, geological effects on sea level variability must be estimated, perhaps based on the theory of glacial isostatic adjustment (*Peltier*, 1999).

The formulation and development of a conceptual model of the long term variability in Arctic Ocean sea level is fundamentaly important for understanding future sea level changes under differing global warming scenarios. This paper provides a step in this effort.

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