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Modeling Arctic Ocean heat transport and warming episodes in the 20th century caused by the intruding Atlantic Water

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Abstract This study investigates the Arctic Ocean warming episodes in the 20th century using both a high-resolution coupled global climate model and historical observations. The model, with no flux adjustment, reproduces well the Atlantic Water core temperature (AWCT) in the Arctic Ocean and shows that four largest decadal-scale warming episodes occurred in the 1930s, 70s, 80s, and 90s, in agreement with the hydrographic observational data. The difference is that there was no pre-warming prior to the 1930s episode, while there were two pre-warming episodes in the 1970s and 80s prior to the 1990s, leading the 1990s into the largest and prolonged warming in the 20th century. Over the last century, the simulated heat transport via Fram Strait and the Barents Sea was estimated to be, on average, 31.32 TW and 14.82 TW, respectively, while the Bering Strait also provides 15.94 TW heat into the western Arctic Ocean. Heat transport into the Arctic Ocean by the Atlantic Water via Fram Strait and the Barents Sea correlates significantly with AWCT ($C = 0.75$) at 0-lag. The modeled North Atlantic Oscillation (NAO) index has a significant correlation with the heat transport ($C = 0.37$). The observed AWCT has a significant correlation with both the modeled AWCT ($C = 0.49$) and the heat transport ($C = 0.41$). However, the modeled NAO index does not significantly correlate with either the observed AWCT ($C = 0.03$) or modeled AWCT ($C = 0.16$) at a zero-lag, indicating that the Arctic climate system is far more complex than expected.

Key words Arctic Ocean, heat transport, warming episodes, modeling.

the 1930s, 70s, 80s, and 1990s, with the 1990s being the largest and longest and the 1930s being the second (see Fig. 5 of Thompson and Wallace 1998[1] and Fig. 8 of Wang *et al.* 2005[3]). Polyakov *et al.* (2002)[4] found that the 1930s and 1990s warmings were comparable in magnitude in the Arctic maritime SAT and may be attributed to natural multi-decadal variability[2]. Bengtsson *et al.* (2004)[5] investigated a possible mechanism of the 1930-40 warming. These warming episodes are generally attributed to the Arctic Oscillation (AO)[1,3] or the North Atlantic Oscillation (NAO).

The Atlantic Water is considered the heat engine that persistently supplies heat to the Arctic Ocean via Fram Strait and the Barents Sea to maintain the Arctic Ocean heat balance[6-11]. Therefore, the Atlantic Water/Layer in the Arctic Ocean is a key parameter to measure the Arctic warming episodes. Polyakov *et al.* (2004)[12] revealed the long-term variability of the Atlantic Water core temperature (AWCT) using historical measurements over the last 100 years. They found similar warming episodes in the 1930s and 1990s with comparable magnitude in the Arctic intermediate Atlantic Water. Wang *et al.* (2005)[3] proposed a decadal time scale Arctic climate feedback loop, in which the Atlantic Water intrusion into the Arctic Ocean is a key component in the Arctic climate system.

There have been many efforts to investigate the Arctic Atlantic Water using regional ocean-ice models, primarily for the short-term variability[13]. Regional ocean-ice models have difficulty in reproducing the natural variability due to the following limitations: 1) the southern boundary cuts off the interaction between the Arctic and the subpolar oceans such as the Atlantic Ocean and Bering Sea[3], 2) flux adjustment and/or restoring of temperature and salinity to climatological values in the interface, the ocean interior and boundaries have to be prescribed to avoid a model's drift away from climatology, which has been shown to be a damping factor for long-term variability[14], and 3) long-term integration of regional models is always problematic because the energy (heat) and mass (freshwater) budgets are not closed. It is also a great challenge even for global climate models to simulate the Arctic Water of the Atlantic origin due to model resolution, numerical accuracy, and a lack of understanding of physical processes. Most global models use the so-called flux adjustment or restoring in order to perform a long-term integration. Nevertheless, there have been no reports that the Atlantic Water was successfully reproduced.

The objective of this study is to evaluate long-term natural variability of the intermediate Atlantic Water of the Arctic Ocean intrinsic to the coupled atmosphere-ocean-sea ice climate system using a high-resolution, coupled global climate model with no restoring or flux adjustment constraint.

2 CCSR/NIES/FRCGC climate model

The CCSR/NIES/FRCGC coupled atmosphere-ice-ocean climate model is the Model for Interdisciplinary Research on Climate (MIROC) version 3.2, which was developed by the Center for Climate System Research (CCSR), University of Tokyo, National Institute for Environmental Studies (NIES), and Frontier Research Center for Global Change (FRCGC)[15]. This model was configured in the Earth Simulator (ES) and has the following features: 1) the atmosphere model has T106 ($\sim 1.1°$) spectral resolution with 56 vertical levels, 2) the ocean model resolution is $1/4° \times 1/6°$ with 48 levels with the north pole rotated to Greenland, 3) the sea ice model uses a single level ice model with elastic-plastic-viscous rheology[16]. The model was parallelized with a message-passing interface (MPI) on 80 processors for the atmosphere model and 608 processors for the ocean-ice model. The initial ocean temperature and salinity use the climatology of Levitus and Boyer (1994)[17]. The coupled model was spun up for 109 years under the climate forcing of 1900, including atmospheric (greenhouse gases, solar radiation, aerosol, volcano eruptions, etc.). Then the model was integrated from 1900 to 2000. Note that throughout the spinup and simulation, neither restoring method nor flux adjustment was used[18].

3 Atlantic Water variability and warming episodes in the 20th century

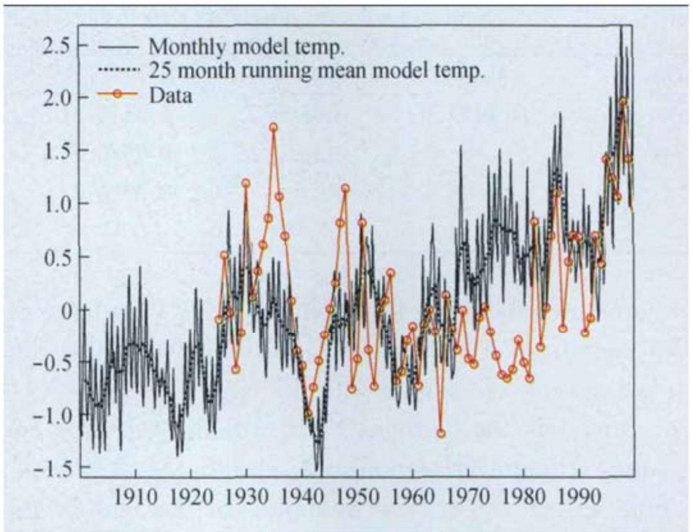

Fig. 1 Time series of the normalized anomalies of the AWCT simulated by the model (black, with the 25-month running mean in yellow) and by observation (in red)[12]. The correlation is 0.49, above the 95% significance level of 0.35 determined by the Monte Carlo simulation[26]).

Figure 1 shows the simulated 100-year time series of the normalized AWCT and observed AWCT, using the same regionally-normalized method as Polyakov *et al.* (2004)[12], who defined the AWCT anomaly as the maximum temperature anomaly in the water column below 50 m, divided by its standard deviation. Over the 20th century, the modeled AWCT compares very well with the observations, with a temporal correlation of 0.49 (see Table 1). For example, the model reproduces the 1930s warming with a smaller amplitude than the observation. The model also reproduces three consecutive warming episodes in the late 1970s, 1980s, and 1990s, with the 1990s warming being the largest and longest[10], which may extend to 2004[8]. However, the model shows a warming event in the 1970 s, opposite to a cooling event in the observation. This could be due to the fact that the data used to calculate the AWCT were taken in the deep ocean, while the warming episode in the 1970s in the model occurred in the shallow seas, as shown and discussed shortly. The model captures very well the warming episodes in the 1980s and 90s, even with a larger magnitude.

The correlation between time series of the AWCT derived from the simulations and the observation is 0.49 with the 95% significance level of 0.35 (see Table 1). The relatively low correlation may be due to the out of phase in the 1970s. It is clear that both the coupled model and the observations capture the multi-decadal (50-80 years) variability over the last century. As shown in Table 1, the modeled AWCT has very high correlation with total heat transport (0.75). The correlation with the Fram Strait heat transport alone is 0.68, implying the Barents Sea heat transport is also an important contributor. As expected, the modeled NAO index has a significant correlation (0.37) with heat transport from Fram Strait and the Barents Sea.

Table 1. Correlation and significance level using Monte Carlo simulation. Obs.-T and Mod.-T denote the observed and modeled AWCT, respectively; Mod.-NAOI is the modeled NAO index; HT denotes heat transport; and FS and BS denote the Fram Strait and the Barents Sea, respectively. The correlations were computed for the period of 1925 to 1999, due to missing data before 1925. The correlations (before slash) over the 95% significance level (after slash) are bold. The first column time series were randomized to determine the significance levels by a Monte Carlo approach

Randomized	Obs.-T	Mod.-T	Mod.-NAOI	HT/FS + BS	HT/FS
Obs.-T		**0.49**/0.35	0.03/0.25	**0.41**/0.31	**0.43**/0.31
Mod.-T			0.16/0.25	**0.75**/0.41	**0.68**/0.37
Mod.-NAOI				**0.37**/0.27	**0.35**/0.25
HT/FS + BS					**0.91**/0.33

However, the correlation between the modeled AWCT and the NAO index is only 0.16, below the 95% significance level of 0.25. This indicates that the AWCT variability in the Arctic Ocean has a weak association with the NAO, although NAO-related wind (i.e., atmospheric circulation) in the northern North Atlantic Ocean is considered the major driver of the warm, saline Atlantic Water intruding into the Arctic Ocean at the intraseasonal and interannual time scales[10,11]. For example, in the late 1990s, the NAO index dropped to around zero and even negative values, while the AWCT still experienced the prolonged warming based on both the model results and observations (see Fig. 2). In other words, the NAO has a phase difference with the heat transport and AWCT, which could be explained by the decadal feedback loop in the Arctic climate system[3]. This association is more complex than can be shown by simple 0-lag correlation. Figure 2 shows that the NAO is a much faster process than the oceanic heat flux and AWCT variability. This is a natural, fundamental difference between the atmosphere and the ocean. The Arctic climate is a fully coupled atmosphere-sea ice-ocean system and should be described by a feedback loop as proposed by Wang *et al.* (2005)[3]. In addition, the Arctic Ocean has its own time scale depending on its basin size and baroclinic (internal) Kalvin wave progression[19], which may redistribute heat content inside the Arctic Ocean. It should be noted that the 1930s warming was a natural variability at time scales of 50-80 years[12], which was captured by the climate model in terms of magnitude and phase. The coincidence of phasing is likely anomalies in the pan-Arctic were constructed for all ten decades. In the Arctic Ocean there were warming episodes in the 1930s, 1970s, 1980s, and 1990s (Fig. 3). During the 1920s, there was a cooling event, while just after the 1930s warming, a pulse of anomalous cold water intruded into the eastern Arctic Ocean via Fram Strait and the Barents Sea, while the western Arctic was still experienced the prolonged warming since the 1930s.

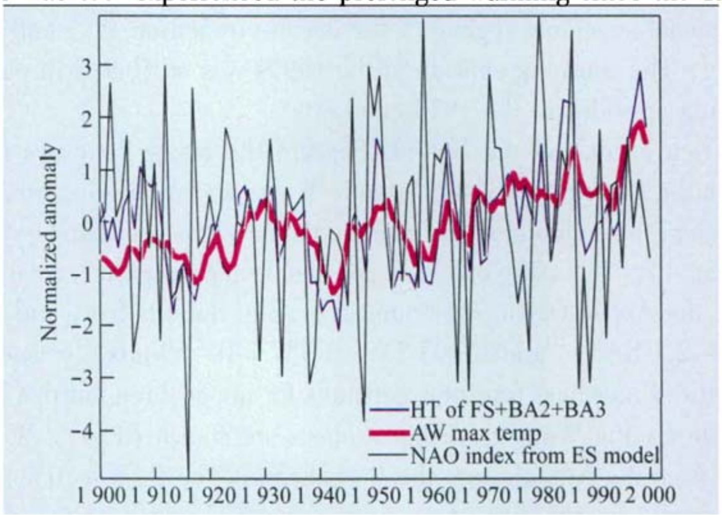

Fig. 2 Time series of normalized anomalies of modeled AWCT (pink), heat transport from both Fram Strait and the Barents Sea (blue), and the modeled winter (DJF) NAO index (black). The correlation between the NAO index and AWCT is 0.16 (not significant) and with the heat transport is 0.37 (significant).

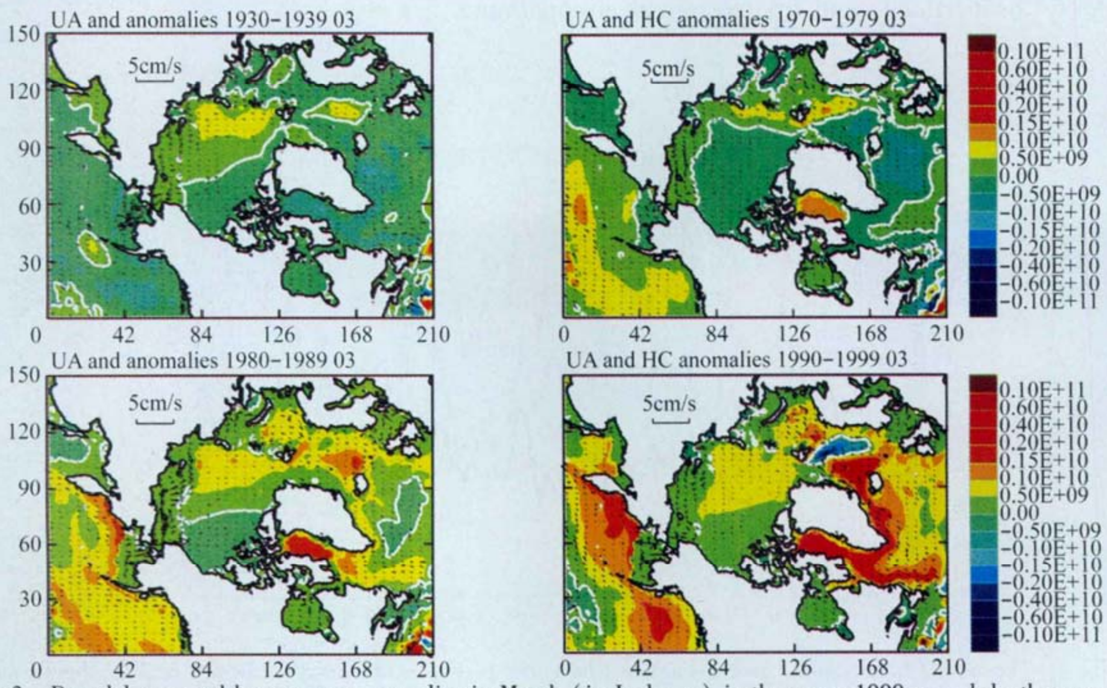

Fig. 3 Decadal averaged heat content anomalies in March (in Joules m) in the upper 1000 m and depth-averaged velocity anomalies.

Therefore, the 1930s warming episode was a relatively short event, compared to the 1990s. In the late 1970s, a pulse of warming anomaly was advected into the eastern Arctic Ocean mainly along the coast from the Barents-Kara-Laptev-East Siberian seas. This may be the reason that the measurements missed this event since the data taken were from the deep basin (see Fig. 1 of Polyakov *et al.* 2004[12]). Extending into the 1990s, a decade-long warming episode occurred throughout the Arctic Ocean and was successfully detected and simulated[10]. This warming evidently led to the retreat or collapse of the Arctic halocline layer[21], the anomalously-cyclonic regime of the ocean circulation[22], and the shrinkage of Arctic sea ice[2,3]. The warming episode in the 1990s was attributed in part to the preconditioning of warming episodes in the 1970s and 80s.

Since both Fram Strait and the Barents Sea are the major pathways for the advective heat transport from the Fram Strait of the Atlantic Water and the Bering Strait is the pathway for the Pacific Water, we calculated the modeled time series of year-to-year variability of heat transport (Fig. 4). The 100-year averaged net heat transports (relative to 0℃ water temperature) into the Arctic Ocean via Fram Strait, the Barents Sea, and Bering Strait are 31.32, 14.82 (BA2 + BA3), and 15.93 TW (1 TW = 10^{12} Watts), respectively (see Table 2). The Atlantic Water heat transport accounts for about three fourth (3/4) of the total transport, while the Pacific Water contributes about one fourth (1/4). We also calculated the heat transport from the Atlantic into the Barents Sea (see BA1 section), which is 129.11 TW. In other words, nearly 89% of the heat is released to the atmosphere in the Barents Sea on the way to the Arctic Ocean, indicating that the Barents Sea is the most active region in terms of air-sea interactions. Heat transport from Bering Strait (15.93 TW) is comparable to that from the Barents Sea (14.82 TW). Thus, the Bering Sea contribution to the Arctic heat balance and sea ice retreat is important.

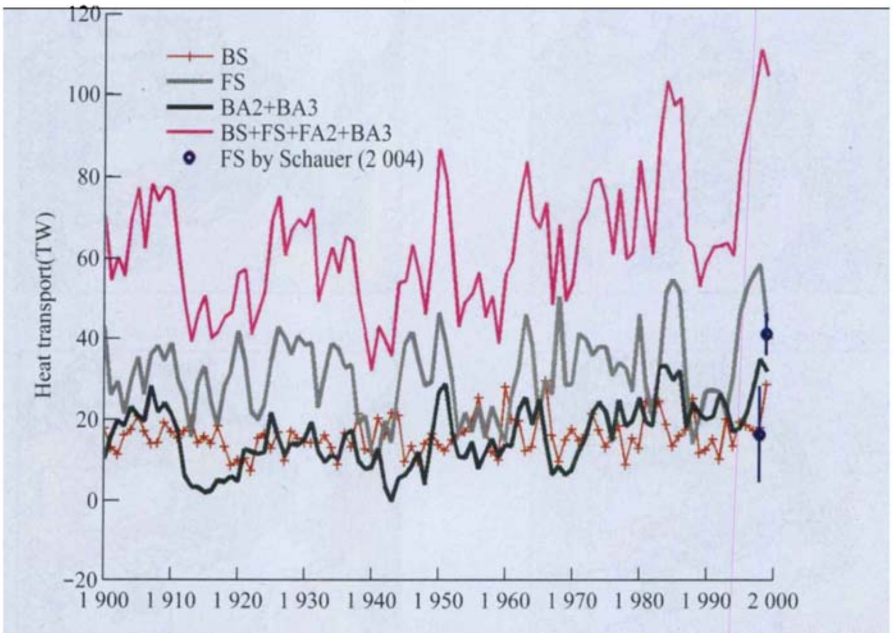

Fig. 4 The annual time series of model-simulated heat transports (in units of 10^{12} Watts, or TW) from Fram Strait (gray), the Barents Sea (black), Bering Strait (red), and the total (pink). The observations in Fram Strait with the standard deviations by Schauer *et al.* (2004)[6] were in blue.

The observed heat transport during 1997/98 was lower than the model results, even in terms of standard deviations[6], while the observed heat flux during 1998/99 was comparable to the model results (Fig. 5). Note that heat flux derived from the measurements also contains errors due to horizontal and vertical resolutions of the measurement arrays and the methods used to calculate the geostropic velocity based on ship-based measured temperature and salinity[23]. Walczowski *et al.* estimate that the heat flux into the Arctic Ocean from the West Spitsbergen Current was as high as 70 TW with a transport of 11.6 Sv (1 Sverdrup $= 10^6\ m^3 s^{-1}$) in the summer of 2003.

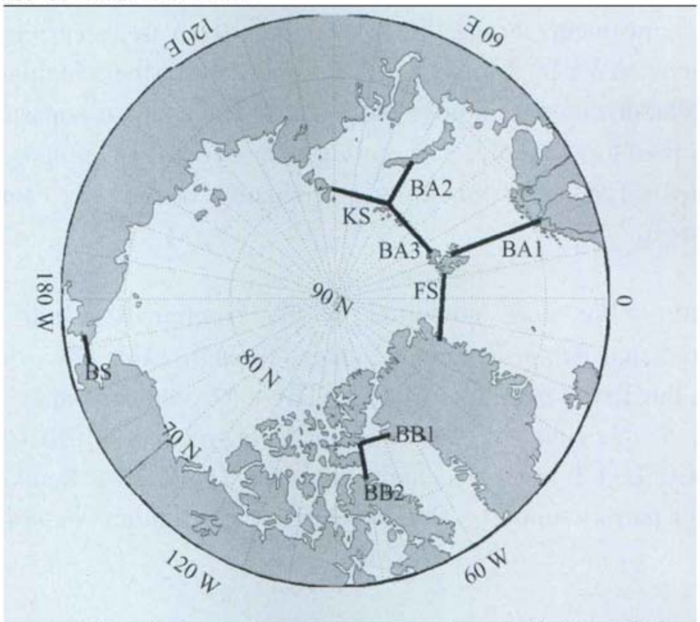

Fig. 5 Arctic Ocean transects for calculating heat flux transport (see Table 2): FS-Fram Strait, BA-Barents Sea, KS-Kara Sea, BS-Bering Strait, and BB-Baffin Bay.

Table 2. Simulated heat flux transport (TW) and standard deviation in selective transects (see Fig. 5 for locations)

	FS	BA1	BA2	BA3	KS	BS	BB1	BB2
Mean	31.32	129.11	18.58	-2.77	7.67	15.94	0.03	1.52
STD	17.85	32.03	15.12	4.70	7.81	20.47	1.17	2.83

4 Conclusions

Several warming episodes of the Arctic Ocean at a decadal time scale in the 20th century have been reproduced by the CCSR/NIES/FRCGC high-resolution climate model with no flux adjustment. The finding was validated by AWCT historical measurement. The 1930s warming was shown to be short-lived compared to the 1990s warming. The 1990s warming brought the ocean temperatures to their highest levels of the century because of the preconditioning of the prior two consecutive warming episodes in the later 1970s and the 1980s. The 1970s warming mainly occurred along the coastal seas in the Barents-Kara-Laptev-East Siberian seas. The unprecedented high temperatures in the 1990s were associated with retreat or collapse of the Arctic Ocean halocline, an anomalously-cyclonic circulation regime, and sea ice shrinking and thinning. The results imply the Arctic environment is changing and may be heading to a new state[24,25]. This study sheds new light on the warming episodes associated with Atlantic heat flux transport into the Arctic Ocean, which has been related to the NAO-related wind forcing. Based on the computation of heat flux transport, Fram Strait is the major pathway (31.32 TW), while the Barents Sea (14.82 TW) is the second as a pathway for the Atlantic Water intrusion. The Pacific Water also contributes 15.94 TW to the western Arctic. This high-resolution model run in the Earth Simulator, for the first time, reproduces these episodes that are validated by observations. This represents a major advance in simulating a coupled system with no constraint by the so-called restoring conditions or flux adjustment. Since the NAO index has a weak correlation with both the modeled and observed AWCT (Table 1) at a zero-lag, we further calculated the lag correlation. The lag correlations do not improve the results. The coupled atmosphere-sea ice-ocean coupled system is therefore complex. The climate feedback loop proposed by Wang *et al.* (2005)[3] provides a framework for future investigation of the very complex nature of the Arctic climate system.

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