Warming of the arctic ice-ocean system is faster than the global average since the 1960s

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[1] Model results and observations both indicate warming of the world ocean from 1955 to 2003. Forced by reanalysis data, the model also shows that the warming of the arctic ice–ocean system is faster than the global average since the 1960s; there is a small but widespread increase in heat content of the Arctic Ocean's waters and a larger increase of latent heat embodied in the ocean's decreasing ice cover. From 1966 to 2003 the modeled mean world ocean temperature in the upper 700 m increased 0.097°C and by 0.137°C according to observations (Levitus et al., 2005); the modeled mean temperature adjusted for sea ice in the corresponding layer of the Arctic Ocean increased 0.203°C. The warming of the world ocean is associated with an increase in global surface air temperature, downward longwave radiation, and therefore net heat flux. The faster warming of the arctic ice–ocean system is associated with an amplified increase in arctic surface air temperature, downward longwave radiation, and net heat flux. **Citation:** Zhang, J. (2005), Warming of the arctic ice-ocean system is faster than the global average since the 1960s, *Geophys. Res. Lett.*, *32*, L19602, doi:10.1029/2005GL024216.

1. Introduction

[2] Significant changes in arctic climate have been observed recently [*Hassol*, 2004]. One is the substantial decline of sea ice [e.g., *Rothrock et al.*, 1999; *Comiso*, 2002]. Another is the increased presence of warm, salty Atlantic water (AW) in the Arctic Ocean (AO) in the 1990s [e.g., *Morison et al.*, 1998]. Recent observations from the North Pole Environmental Observatory show that the AW signature has lessened, but is still stronger than the pre-1990s level (J. Morison, per. comm.). The changes in the arctic ice–ocean system are linked to changes in the atmospheric circulation often characterized by the North Atlantic Oscillation, as well as to an increase in surface air temperature (SAT) in the northern polar region [*Rigor et al.*, 2000].

[3] The recent arctic SAT increase appears to be part of the global SAT increase, but the arctic SAT increases more rapidly than the global average [e.g., *Alley et al.*, 2003; *Johannessen et al.*, 2004]. This is reflected in the spatial distribution of the linear SAT trends (Figure 1) over the period 1955–2003, based on NCEP/NCAR reanalysis data. Except for a few areas of decreasing SAT, temperatures have increased over the world ocean, most notably over the AO. Over the northern hemisphere the pattern of change in the reanalysis-based SAT since the 1950s agrees quantitatively with the observations and analysis of *Johannessen et al.* [2004]. According to the reanalysis data for the period 1955–2003, the average SAT increase is 0.044°C yr^{-1} over the AO (consisting here of the Arctic Basin and the Barents Sea) and 0.010°C yr^{-1} over the world ocean (Figure 2a). The SAT increase coincides with an increase in the reanalysis surface downward longwave radiation (SDLR, Figure 2b). The spatial distribution of the linear SDLR trends is similar to that of SAT (not shown). Again the arctic SDLR increases faster than the global average.

[4] The world ocean heat content in the upper 300, 700, and 3000 m increased from 1955 to 2003 for most individual ocean basins [*Levitus et al.*, 2005, hereinafter referred to as L05]. Has the heat content of the arctic ice–ocean system increased under the condition of a steeper increase in arctic SAT and SDLR? If so, to what degree? Diagnostic tests of a coupled global Parallel Ocean and sea Ice Model (POIM) [*Zhang and Rothrock*, 2003] forced with the reanalysis surface data offer an explanation.

2. Model Description

[5] The global POIM couples the Parallel Ocean Program developed at the Los Alamos National Laboratory and a multicategory thickness and enthalpy distribution sea-ice model [*Zhang and Rothrock*, 2003]. The model is driven by daily NCEP/NCAR reanalysis forcing fields, including 10-m winds, SAT, specific humidity, SDLR, surface downward shortwave radiation (SDSR), precipitation, and evaporation. Initial ocean temperatures and salinities are from the Levitus climatological data. Model spin-up consists of an integration of 30 years using 1948 forcing fields repeatedly. After this spin-up the model proceeds to simulate the period 1948–2003. To compare observational estimates from L05 with model results, the period 1955–2003 is presented here.

3. Increasing Global Ocean Heat Content, Increasing SAT and SDLR

[6] Anomalies of world ocean heat content for the upper 300, 700, and 3000 m simulated by the model and estimated by L05 agree (Figure 2), showing a generally increasing global ocean heat content during the period 1955–2003, more strongly since 1966. The largest model–data discrepancy occurs in the early years of the model integration (the 1950s) when the model may be under the influence of initial condition uncertainty and the spin-up process. The observational estimates of the global ocean heat content also increase more rapidly than model estimates in the early 2000s. Nevertheless, the model results are highly correlated with the L05 data after 1966, with a correlation of 0.86 for the upper 700 m of the ocean. Over 1966–2003, the model

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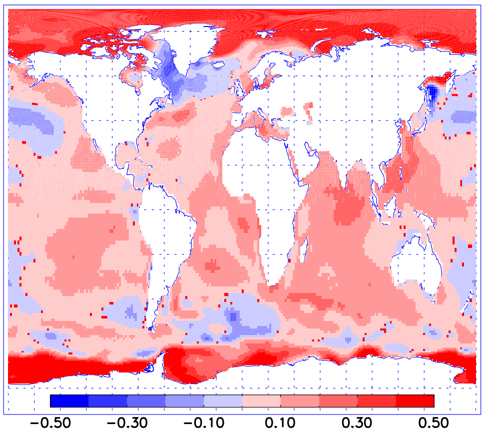

Figure 1. Linear trend (1955–2003) of SAT (°C decade^{-1}) over the world ocean, based on the NCEP/NCAR reanalysis data.

largely replicates the positive trend in observations of the heat content in all layers.

[7] Figure 3 compares the linear trend of zonally integrated ocean heat content for the world ocean computed by 100-m thick layers. The model agrees with the estimates of L05 to show positive trends over the period 1955–2003 at most latitudes with the largest trend in the surface layer of the equatorial region. Ocean heat content also increases significantly in the regions of 20–40°S and 20–40°N. However, unlike the observations, an increase occurs in areas near the Antarctic continent. Like the observations, the model creates a large negative trend in the subsurface layers of the equatorial region (Figure 3), which corresponds to areas of strong reduction in heat content in the equatorial Pacific (Figure 4). Further south, model results also show significant cooling in the upper 1500 m at 50–60°S, while the observations show cooling only below 1000 m depth.

[8] Modeled and observed global ocean heat content is closely correlated to the global average of the reanalysis SAT and SDLR (Figure 2) because of air–sea interactions. Over 1966–2003, the correlation between the SAT or SDLR and the model (observational) estimate of the global ocean heat content for the upper 700 m is 0.79 (0.63) or 0.82 (0.65). However, the simulation of a warming world ocean is linked directly to the simulation of an increasing global downward surface net heat flux (SNHF, Figure 2c). The simulated SNHF consists of downward net longwave and shortwave radiation and downward sensible and latent heat flux, but its upward trend is dominated by an increasing net longwave radiation because of the growing SDLR. There is no significant trend in the simulated net shortwave radiation because of the relatively flat reanalysis SDSL forcing (not shown), while the increasing SAT does not cause the downward sensible heat flux to increase significantly because of the simulation of a warming sea surface. The simulated global SNHF is comparable in magnitude and more or less correlated with the changes in modeled (r = 0.75) and observed (r = 0.29) global ocean heat content for the upper 700 m.

4. Increasing Arctic Ocean Heat Content

[9] The model simulates a positive trend in heat content everywhere in the AO except some areas in the Barents and Kara seas (Figures 3 and 4). The observation-based trends are mixed in the region north of 65°N; the overall trend for the AO is not clear. A close-up view (Figure 5) of the simulated ocean temperature trend in a transect across the Arctic shows that warming occurs in most of the upper 1500 m from 1955 to 2003, with the greatest warming off the Alaska coast, while significant cooling occurs in a limited area in the Eurasian Basin. The simulated upward trend of the AO heat content or temperature is closely linked to the

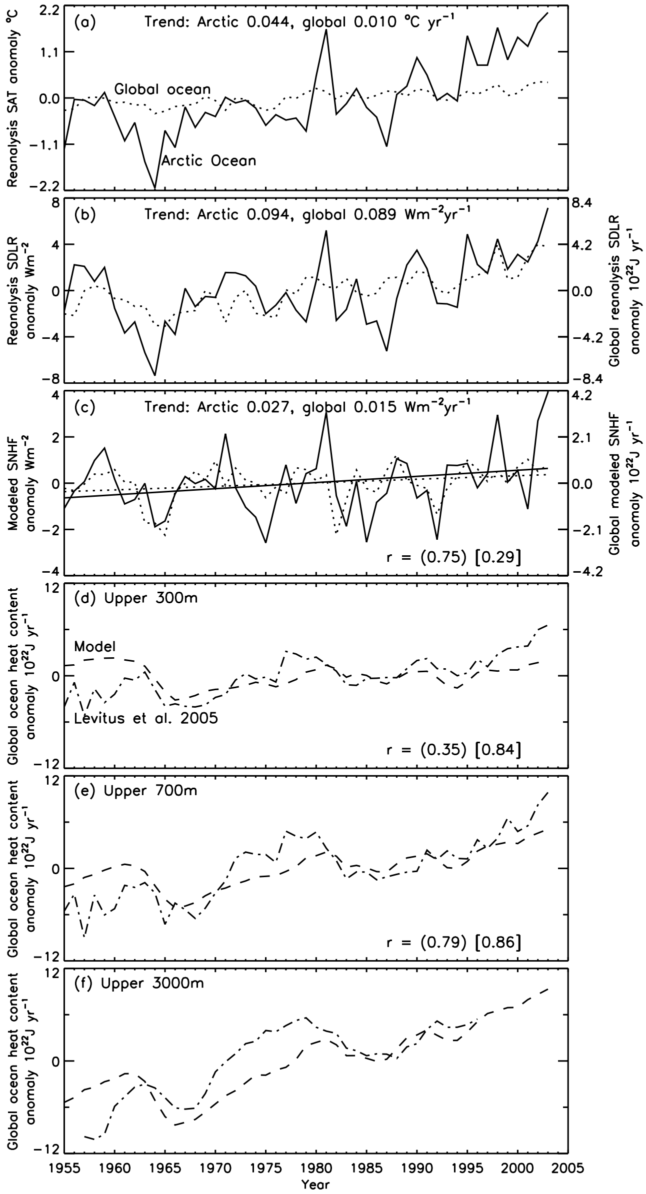

Figure 2. Anomalies. (c) Correlations between the simulated global surface net heat flux and the model (in parentheses) and *Levitus et al.* [2005] (in square brackets) estimates of changes in global ocean heat content in the upper 700 m. (d) and (e) Correlations between the model and Levitus et al. estimates for the periods 1955–2003 (in parentheses) and 1966–2003 (in square brackets). (f) Levitus et al. estimates for the upper 3000 m covers 1957–1996 only.

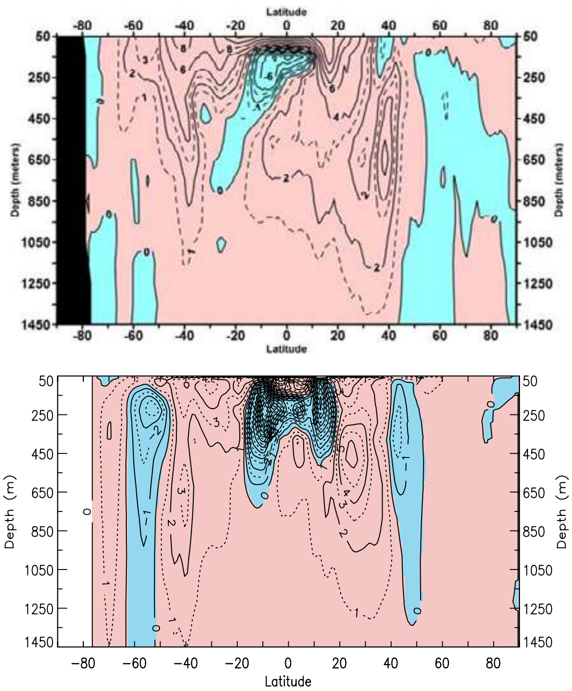

Figure 3. Linear trend (1955–2003) of the zonally integrated world ocean heat content (top) from *Levitus et al.* [2005] and (bottom) from model simulations. Contour interval is 10^{18} J year^{-1}. Pink represents positive values and blue negative.

increase in the reanalysis SAT and SDLR forcing (Figures 1, 2a, and 2b) and the simulated SNHF (Figure 2c).

5. Warming of the Arctic Ice–Ocean System is Faster Than the Global Average

[10] The heat of fusion in sea ice is much smaller than the ocean heat content on a global scale [*Levitus et al.*, 2001] and was not considered in the analysis of global ocean heat content. It cannot be ignored, however, when considering the heat budget of the AO. The simulated ice volume and heat of fusion (Figure 6a) maximum occurs in 1966 after a dip in both the arctic and the global SAT and SDLR in the previous two years (Figure 2a). Model results show that 1966 is also the year of minimum global ocean heat content (Figure 2). After 1966 the ice volume generally decreases while both SAT and SDLR increase, and 2003 is the year of minimum ice volume for the period 1955–2003. From 1966 to 2003, the change in the total heat of fusion is close to 4×10^{21} J (Figure 6a), representing a significant change in the heat budget of the arctic ice–ocean system.

[11] If the latent heat of fusion of sea ice is not taken into account, the mean temperature of the water column of the AO increases more slowly than that of the world ocean (Figure 6), even though the recent increases in arctic SAT and SDLR are more significant than the global average. The ice cover insulates the ocean from the cold polar atmosphere by regulating the surface heat exchange; it absorbs much of the impact of changes in the air–sea heat exchange, thus reducing the sensitivity of the underlying ocean to changes in the atmosphere.

[12] Adding the latent heat of fusion of arctic sea ice (Figure 6a) as a negative term to the heat content of the AO yields an "adjusted ocean temperature" of the arctic ice–ocean system. This adjusted arctic mean ocean temperature increases more rapidly than the adjusted global mean ocean temperature over the period 1955–2003 (Figure 6). In fact, the adjusted AO temperature increases even more rapidly than the estimates of L05 since the 1960s, although the model, compared with the observations, underestimates the increase in temperature and heat content of the world ocean. This indicates that the arctic ice–ocean system has warmed faster than the global average since the 1960s when arctic sea ice is taken into account.

6. Discussion and Conclusions

[13] There are uncertainties with the NCEP/NCAR reanalysis data and the model, but the model forced by the data supports the observational estimates of a significant increase in heat content of the world ocean during the period 1955–2003 when the reanalysis data show increasing SAT and SDLR. From 1955 to 2003 the mean world ocean temperature in the upper 700 m increased 0.146°C based on L05 and 0.071°C based on the model (Figure 6d). According to the model, the increase in SDLR plays a dominant role in

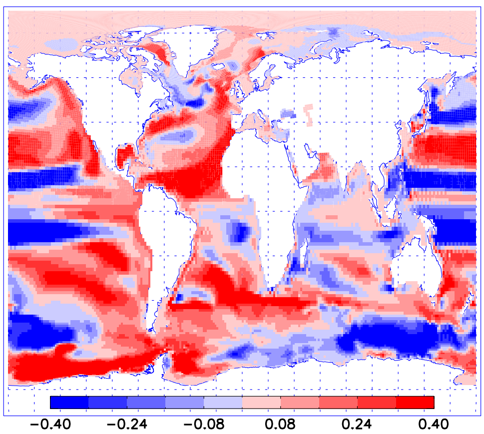

Figure 4. Linear trend (1955–2003) of modeled ocean heat content per unit area (10^9 J m^{-2} decade^{-1}) in the upper 700 m.

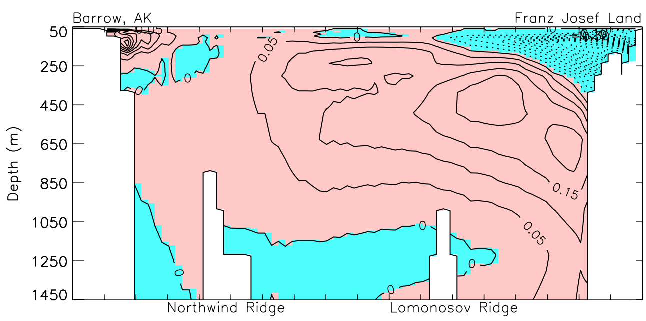

Figure 5. Linear trend (1955–2003) of the simulated ocean temperature across a transect between Barrow, AK, and Franz Josef Land in the Arctic Ocean. The contour interval is 0.05°C century^{-1}. Pink represents positive values and blue negative.

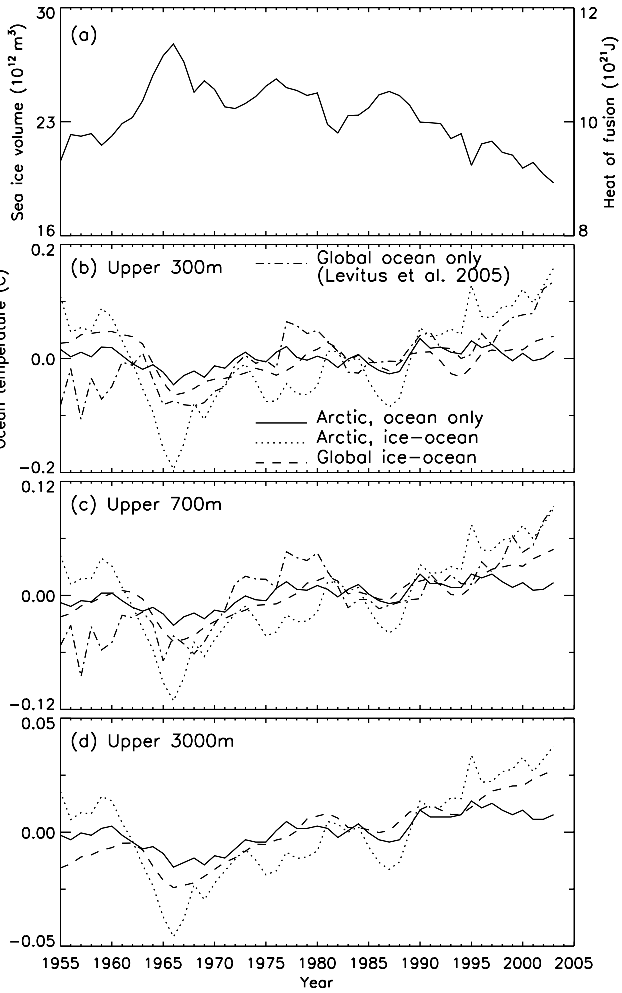

Figure 6. (a) Modeled annual mean arctic sea ice volume and the corresponding heat of fusion. (b)–(d) Anomaly of the world ocean mean temperature converted from the *Levitus et al.* [2005] estimated heat content and anomaly of model simulated mean ocean temperature for the Arctic Ocean, the arctic ice–ocean system, and the global ice–ocean system. Here the ocean temperature for either ice–ocean system is called "adjusted ocean temperature," which is calculated by subtracting the total heat of fusion of sea ice from the total ocean heat content and then dividing the reduced heat content by the total volume of the ocean.

causing an increase in SNHF, which contributes directly to the warming of the world ocean. The warmer world ocean, having vast heat content, warms up the atmosphere concurrently, leading to an increase in SAT and SDLR, as may be reflected in the reanalysis. Such air–sea interactions lead to a warming global atmosphere–ocean system over 1955–2003, which is ultimately attributed to anthropogenic influences [*Levitus et al.*, 2001, 2005].

[14] The model also reveals a small but widespread increase in the heat content of the AO from 1955 to 2003. The widespread increase is attributed to the widespread increase in SAT and SDLR (Figures 1 and 2), which may be attributed in turn to the intensification of the meridional atmospheric circulation and warming of the sea surface. The small increase is attributed to the mediterranean nature of the AO that has limited channels to communicate with the rest of the world ocean and therefore is unlikely to undergo large changes in ocean heat transport. Nevertheless, the increase in heat content of the AO may be linked to the increasing AW inflow and its heat carried into the Arctic through Fram Strait and the Barents Sea in recent years [e.g., *Zhang et al.*, 1998].

[15] The model further reveals that warming of the arctic ice–ocean system has been faster than the global average since the 1960s (Figure 6). From 1966 to 2003 the mean world ocean temperature in the upper 700 m increased 0.097°C according to the model and 0.137°C according to observations (L05), while the simulated sea-ice adjusted mean temperature in the upper 700 m of the AO increased 0.203°C (Figure 6c). Such a faster warming lies in the fact that the arctic reanalysis SAT and SDLR, and therefore the simulated SNHF (Figure 2c), have increased more significantly in recent years than the global average. Under the warming atmospheric and oceanic conditions, the simulated ice cover has declined considerably since the 1960s, resulting in a significant change in the latent heat of fusion of sea ice. Globally, the total sea ice heat of fusion is negligible compared to the total heat content of the ocean. Considering the AO only, however, the change in the heat of fusion of sea ice is of the same order of magnitude as that in the heat content of the upper 3000 m ocean layer. Since the 1960s the heat of fusion of the arctic ice cover has declined by about 4×10^{21} J, representing a significant warming of the arctic ice–ocean system. The reduced sea ice cover modifies the air-sea heat exchange and amplifies the warming of the whole arctic atmosphere-ice-ocean climate.

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