How reasonable is the Arctic/subArctic Ocean in historical CMIP5 simulations?

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The ocean plays a key role in the heat budget of Arctic climate through its regulation of surface thermodynamic and radiative fluxes, and potentially through advective exchanges with lower latitudes. While meteorological aspects of Arctic climate are receiving increasing attention in recent years understanding of the ocean's interaction with the atmosphere has been limited by the historical observation set. Here we provide some insight into the ocean's and sea ice's interaction with the overlying atmosphere on seasonal timescales through examination of historical simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project. We are interested in exploring those features of the models which are realistic, but also in understanding how differences in model physics and numerics may lead to differences in their evolution. This work is an extension of Dr. Yanni Ding's 2014 dissertation (*Ding, 2014*), which additionally includes an examination of the ocean's response to volcanic aerosols. In this paper we mainly show results for one model, CCSM4.

1. Background

Warm salty water enters the Arctic Ocean from the Atlantic at a rate of ~8Sv (1Sv = 10^6 m^3/s) while somewhat less than 1Sv of cooler, fresher water enters the Arctic through Bering Strait from the Pacific. This observed input of mass is balanced by outflow of cool water primarily through Fram Strait, and the East Greenland Current [*Serreze et al., 2006*]. It is also known that there is more Pacific water entering the Arctic Ocean from the Bering Strait and less Arctic water outflow from Fram Strait in summer. However, the contribution of these ocean heat flux convergences to seasonal ocean temperatures is still unclear. Observed heat storage in the Arctic Ocean comes in the form of warming of the seasonal thermocline, generally confined to the upper 100m. At the surface temperature undergoes a modest seasonal cycle of less than 2°C in ice-free regions [*Chepurin and Carton, 2012*], decreasing in amplitude with depth.

The maximum net solar radiation at the surface (insolation) is delayed and reduced in strength relative to top-of-the-atmosphere radiation by the scattering and absorption effects of sea ice, aerosols, and clouds. Both cloud cover and sea ice vary seasonally but variations of the latter dominate, lowering the average albedo in summer/fall and enhancing the absorption of sunlight. In summer the combination of downward net solar radiation minus longwave cooling and thermodynamic fluxes exceeds 100 Wm^{-2} into the ocean. In late fall through early spring the ocean loses heat to the atmosphere through an almost equal combination of turbulent and longwave flux at a rate of roughly 75 Wm^{-2}. Where this heat is stored seasonally (e.g. the seasonal thermocline), and whether or not ocean het transport convergence contributes are interesting questions for us.

A striking feature of the historical record of sea ice cover is the shrinkage of the seasonal minimum extent at a rate of 13% per decade during 1979-2014 according to the National Snow and Ice Data Center, with an even greater loss of sea ice mass. How the retreat of the seasonal sea ice pack during the 21st century will alter seasonal insolation, surface temperature, as well as moisture sources for the Arctic atmosphere are questions also very much of interest to this study.

2. Models and Methods

The study examines multiple sets of simulation ensembles (numbers of ensembles given in parentheses) from 14 CMIP5 models: CanESM2 (5), CCSM4 (6), CNRM-CM5 (10), GFDL-CM3 (5), GFDL-ESM2G (2), GFDL-ESM2M (3), GISS-E2-R (6), HadCM3 (10), HadGEM2-ES (4), IPSL-CM5A-MR (3), MIROC5 (5), MPI-ESM-LR (3), MRI-CGCM3 (3), and NorESM1-M (3). Most were obtained from the online archive (pcmdi3.llnl.gov/esgcet/home.htm). All output is reduced to monthly resolution and calculations based on individual ensemble members were averaged. Vertical resolution varies among models with NorESM1-M having the finest vertical resolution (70 layers), and HadCM3 have the coarsest (20 layers). Most models have approximately horizontal 1°×1° spatial ocean resolution except for IPSL-CM5A-MR, whose resolution is approximately 2°×2°.

3. Results

The results are divided into two parts. The first is a presentation of the time mean surface meteorology (winds and sea level pressure), and ocean temperature, salinity, and currents. The second is a presentation of seasonal surface fluxes averaged 63°N-90°N.

i) Mean fluxes and circulation

In some fundamental ways the CMIP5 models do reproduce key aspects of the mean state in the Arctic such as sea ice cover. However a more detailed examination suggests that the processes controlling those aspects may differ. For example, two key features of the sea level pressure fields are the Beaufort high in sea level pressure (Polar High) and the corresponding Aleutian low. Several widely used models have weak or displaced Polar Highs. As a result they have distorted ocean circulations and an inability to store reserves of freshwater in the Beaufort gyre (an important aspect of the observed ocean hydrology). Shifts in the strength and position of the Aleutian low, closely related to the North Atlantic Oscillation, also differs among models. These differences affect aspects of synoptic meteorology and the relative importance of surface fluxes versus ocean heat transport convergence! Finally, the models have strong vertical exchanges that allow the heat entering the Arctic from the Atlantic to escape to the surface more rapidly than is seen in historical observations.

ii) Seasonal fluxes and circulation

Averaged over the spherical cap 63°N-90°N many of the CMIP5 models show surface fluxes that are qualitatively similar to observations. For example, **Fig. 1** shows a comparison of monthly fluxes and the linear trend in monthly fluxes for CCSM4 in comparison to similar calculations for the ERA40 reanalysis. Both show the dominance of insolation in summer. Longwave, and turbulent flux components always act to cool the ocean. Longwave is reduced somewhat in late summer due to enhanced humidity and clouds.

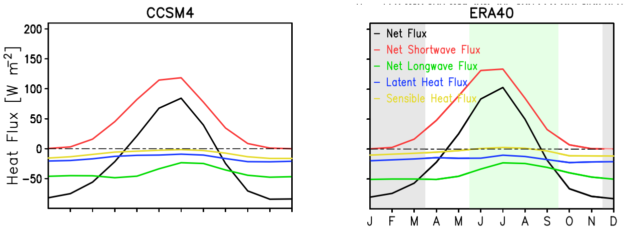

Fig. 1 Comparison of monthly surface flux components for the CMIP5 historical simulation CCSM4 and the reanalysis ERA40 for the spherical cap 63°N-90°N. Monthly fluxes are averaged from 1957 to 2002.

Net surface heating is primarily balanced by heat storage in sea ice and ocean temperatures, as shown in **Fig. 2**. Ocean heat is stored from April to September, with the maximum rate of heat storage in mid-summer. Ocean cooling is most pronounced in late fall/early winter.

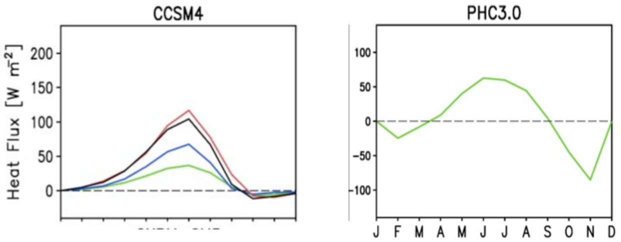

Fig. 2 seasonal heat storage in comparison to net surface flux for the CMIP5 historical simulation CCSM4 averaged 63°N-90°N. Curves are adjusted so that they have a value of zero in January. Black curve is reproduced from **Fig. 1**. Corresponding ocean heat storage computed from the PHC3.0 climatology is shown for comparison.

When heat storage in ocean and sea ice are combined they nearly balance net surface heat flux, suggesting that seasonal heat transport convergences within the ocean are of secondary importance. One region where seasonal transports may be important is in the marginal Barents Sea. As shown in **Table 1**, Volume transports nearly double in winter, bringing additional warm water to the Barents and helping to keep this sea partially ice-free even in winter.

Table 1 Volume transport through the Fram Strait and the Barents Sea Opening in summer (DJFM) and winter (JJAS). Units are Sv.

Models	**Fram Strait**		**Barents Sea Opening**	
	Summer	Winter	Summer	Winter
CCSM4	-1.0	-2.1	1.6	2.7

As discussed above, seasonal sea ice plays a key role in the heat budget of the Arctic Ocean currently, raising the question of how the heat budget may change as the seasonal sea ice declines. One of the impacts of declining sea ice will be to reduce summer insolation, as shown in **Fig. 3**. Interestingly, the strength of this effect is model-dependent. Some models such as CNRM-CM5 and CCSM4 show a powerful relationship between ice cover and insolation. Others such as GISS-E2-R show little relationship. Differences in these atmosphere-ocean-sea ice feedback processes must affect how these models respond to enhancements in greenhouse gasses.

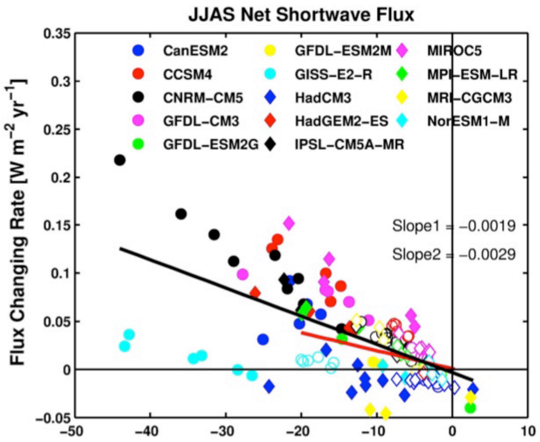

Fig. 3 Seasonal feedbacks: rate of change of net shortwave heat flux (JJAS) versus annual rate of change of sea ice extent for various flux components (10^3km^{2}yr^{-1}). Open marks are calculated from 1861 to 2005; closed marks are calculated from 1950 to 2005. Negative slope shows the decrease in insolation corresponding to an increase in sea ice cover.

4. Summary

The first part of this talk discusses differences in the time mean behavior of a set of 14 CMIP5 models in the Arctic. Among the differences we highlight are:

1) Differences in represent of the Polar High in sea level pressure affects surface winds, surface ocean currents, Ekman transport, and thus the ability of some CMIP5 models to store freshwater in the Beaufort gyre (as observed).
2) Differences in vertical stratification which allows ocean heat to more communicate easily with the atmosphere than observed.

The second part of this talk discusses the behavior of the models on seasonal timescales, focusing primarily on the surface heat budget and the way the modelled oceans handle heat storage and transport. Among the findings we highlight:

1) Local storage balances net surface heat flux, while seasonal heat flux convergence is weak.
2) The balances must alter as seasonal sea ice declines later in this century. Different models seem to react differently to these declines.

References

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