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Adrift in the Beaufort Gyre: A Model Intercomparison

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Abstract. Output from six regional sea ice-ocean climate model simulations of the arctic seas is compared to investigate the models' ability to accurately reproduce the observed late winter mean sea surface salinity. The results indicate general agreement within the Nordic seas, strong differences on the arctic continental shelves, and the presence of a climate drift that leads to a high salinity bias in most models within the Beaufort Gyre. The latter is highly sensitive to the wind forcing and to the simulation of freshwater sources on the shelves and elsewhere.

Introduction

Recent evidence suggests that winter sea surface salinity (SSS) is an important indicator of climate change in the Arctic Ocean [*Steele and Boyd*, 1998] (hereinafter referred to as SB98). In fact, long-term changes in this quantity have been predicted by global climate models for some time [e.g., *Manabe and Stouffer*, 1994]. This is perhaps not too surprising, given the crucial role that SSS spatial/temporal variability plays in the freshwater budget of the region and in the stability of the water column at these cold temperatures. It is particularly unfortunate, however, since SSS is notoriously difficult to accurately simulate in climate models, owing to its lack of negative feedbacks at the ocean surface (unlike, for example, sea surface temperature).

So how well do numerical models simulate arctic SSS? Here we address this question by performing an intercomparison of some of the most sophisticated coupled sea ice-ocean models presently available. We focus here on long-term mean SSS fields, which we compare with newly available climatologies. Subsequent studies will focus on temporal variability.

The Models

There is a model intercomparison project, or "MIP," for nearly every component of the earth's climate system. Each MIP has a different strategy for comparing disparate model output and observations. The present study is one of several sub-projects currently underway as part of the Arctic Ocean Model Intercomparison Project (AOMIP). Our philosophy in this early "pilot" stage of AOMIP was to minimize the workload for each modeling group by comparing existing output. The only requirement was that each model's domain include the Arctic Ocean. This meant that the atmospheric and other forcings were in general different, as were physical and numerical parameters such as albedos and spatial resolution. However, all simulations were forced with data from the latter half of the 20th century, and in particular with atmospheric forcing from 1979 through the 1990s. A summary of ocean model parameters and atmospheric forcings is provided in Table 1. (Every model discussed here includes a dynamic-thermodynamic sea ice model. Details about this component may be found in the references provided in the table.) Future AOMIP work will involve coordinated simulations with common forcing data. Participation from a broader community of modeling centers will also be actively pursued. More information about AOMIP may be found at: http://fish.cims.nyu.edu/~holland/project_aomip/overview.html.

River discharge provides the largest freshwater signal to the Arctic Ocean [*Aagaard and Carmack*, 1989; *Steele et al.*, 1996]. Table 1 shows the wide range of parameterizations currently used, from no discharge to a full accounting for rivers and "ungauged" flows. In all of these, the discharge affects the nearest coastal ocean grid cell as a salinity flux at the surface, exactly like precipitation. The NPS model also accounts for heat inputs to the ocean. None provide a discharge volume or momentum flux, nor do they account for potentially significant effects arising from land fast ice [e.g., *Macdonald and Carmack*, 1991].

Those models with little or no explicit river discharge can simulate a freshwater flux into the coastal regions by using climate restoring. This is an artificial term added to the prognostic equation for salinity S that partially counteracts the cumulative effect of model errors by dragging the solution back to a climatological mean state S_c over an e-folding time τ, i.e.,

$$\frac{\partial S}{\partial t} = \ldots - \frac{(S - S_c)}{\tau} \quad . \tag{1}$$

Near river mouths this represents a freshwater flux that mimics the effect of river discharge, albeit with severely limited variability. Restoring is often used even when an observationally reasonable discharge flux is imposed. This is because other factors exist that also influence oceanic freshwater storage and transport, including ice melt and growth, advection/diffusion, precipitation/evaporation, and numerical inaccuracies.

Validation Data

Plate 1 shows late winter SSS in the three existing versions of the World Ocean Atlas (WOA) produced by the National Oceanographic Data Center (NODC) [e.g., *Boyer et al.*, 1998] and in the Polar Science Center Hydrographic Climatology (PHC) [*Steele et al.*, 2000]. These climatologies include data collected mostly after 1950 and before 1990. The PHC merges WOA98 with the high-quality Arctic Ocean Atlas (AOA) produced by the Environmental Working Group [*EWG*, 1997/1998], thus providing a global product with a good

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Table 1. AOMIP Ocean Model Descriptors, Ranked by SSS Restoring, Starting at the Top with the Strongest Restoring

Institution (reference)	Restoring time constant and depth (climatology)	Domain/lateral b.c.'s	Δx	Vertical coordinate (# levels)	River discharge (total inflow)[a]	Atmosphere forcing data (years/climatology)
NPS [*Maslowski et al.*, 2000]	S: 120 d at 10 m T: 365 d at 10 m (monthly WOA94)	closed Bering Strait closed N. Atl. at 50°N restore T, S to WOA94	1/6° x 1/6°	z-coor (30 levels)	major rivers only (2012 km^3/yr)	ECMWF: reanalysis (1979–1993) + operational (1994–1998)
AWI [*Karcher et al.*, 1999]	S: 180 d at 10 m (WOA94 + AOA)[b]	closed Bering Strait ~50°N. Atl. inflow and T, S from a larger domain model	1/4° x 1/4°	z-coor (30 levels)	none	ECMWF: reanalysis (1979–1993) + operational (1994–1999)
NYU	S: 2 y over the mixed layer[c] (PHC1.0[d])	closed N. Pac. at ~60°N closed N. Atl. at ~60°N restore T, S to PHC1.0[d]	1° x 1°	ρ-coor (11 layers)	none	ECMWF reanalysis (climatological mean)
UW [*Zhang et al.*, 2000]	S: 5 y at 5 m and below 800 m T: 5 y below 800 m (annual WOA82)	Bering St. = 0.8 Sv in C. Arch. = 1.5 Sv out E/W Iceland = 0.7 Sv in restore T, S to WOA 82	40 km	z-coor (21 levels)	major rivers + ungauged (4339 km^3/yr)	IABP/POLES (1979–1998)
GSFC [*Häkkinen*, 1999]	none at 0.02–2.6 m[e]	Bering St. = 0.8 Sv in 15°N. Atl. = 0.8 Sv out restore T, S to WOA82	0.9° x 0.7°	σ-coor (20 levels)	major rivers + ungauged (4372 km^3/yr)	ECMWF + NCEP + ISCCP + others (1958–1999)
IOS [*Nazarenko et al.*, 1998]	none at 2.5 m	Bering St. = 0.8 Sv in C. Arch. = 1.0 Sv out E/W Jan Mayen = 0.2 in inflow T, S uses WOA82	1/2° x 1/2°	z-coor (29 levels)	major rivers only (2344 km^3/yr)	NCEP reanalysis (climatological mean)

[a] This is the volume discharge into the Arctic Ocean and the Nordic seas.

[b] This model uses an annual average linear combination of WOA94 and AOA similar to that in PHC.

[c] In the ice-covered arctic, April mean mixed layer mid-depth ranges in the embedded mixed layer model between 5–100 m.

[d] An early release, PHC1.0, has been superseded by the version shown in this paper, simply referred to as PHC.

[e] Grid levels vary in a sigma coordinate model. The uppermost level is provided (even when there is no restoring) for use in evaluating Plate 2.

description of the Arctic Ocean. In the PHC, the North Atlantic is salty, the waters entering the Arctic Ocean from the North Pacific are relatively fresh, and the river-influenced continental shelves are fresher still. The Canadian Basin shows a broad SSS minimum within the anticylonic Beaufort Gyre. These fields influence model results in proportion to the climate restoring time constants provided in Table 1.

Results

Plate 2 shows a comparison of mean April SSS from each model. This is the time of year used by SB98 to demonstrate the sensitivity of the upper Arctic Ocean to climate change. As the last full month of winter in much of the Arctic Ocean, it allows us to compare model output at a time of minimal freshwater flux from rivers and ice melt/growth. We use the 1979–1988 April mean from those models with interannual variability in order to compare with climatology.

The model results have been ordered as in Table 1, i.e., by the strength of the restoring time constant on surface salinity. Most models realistically capture the northward transport of salty (and relatively warm) North Atlantic waters into the eastern Arctic Ocean. This accuracy is partly a result of the climatological lateral inflow boundary condition, especially in those models with higher latitude North Atlantic boundaries. Most models also predict low salinity waters on the riverine-influenced continental shelves, although large amplitude differences are evident here.

Perhaps the most obvious difference between model simulations appears in the western Arctic Ocean, where the climatological observations from the Beaufort Gyre (PHC, Plate 1) show it to be relatively fresh compared to its surroundings by about 1 psu. The simulations show a wide range of properties in this region, from a slightly too fresh gyre (NPS) to little spatial variability (UW, IOS) to a salty anomaly in the gyre and very fresh shelves (GSFC). These differences are linked to differences in the entire ice-ocean system. *Zhang et al.* [1998] (hereinafter referred to as Z98) have shown the profound changes that result when restoring is varied within a single model. For example, a fresh gyre enforces anticyclonic baroclinic ocean circulation (in part created by the wind forcing) while a salty gyre weakens or even reverses this anticyclonic motion (see Figure 13 from Z98).

Figure 1 shows the mean April SSS from each model simulation, as sampled within the circular region of 200 km radius in the Beaufort Gyre shown in Plate 2. Also shown are the average values in this region from two climatologies. Not surprisingly, models with strong restoring (less than 1/2 year) closely reproduce the observational mean. Models with weaker restoring produce values outside of the 40-year historical maximum and minimum observations (Figure 1). Reducing the strength of the restoring term (i.e., increasing the restoring time constant τ) generally leads to increasing salinities in the Beaufort Gyre. This confirms the sensitivity studies of Z98. Future intercomparisons should probably include an analysis of the restoring flux, a term which is not often saved by these models.

Discussion

Why are (most of) the model simulations biased towards overly salty values in the Beaufort Gyre? They all initialize with climatological SSS fields (e.g., Plate 1) that generally have a

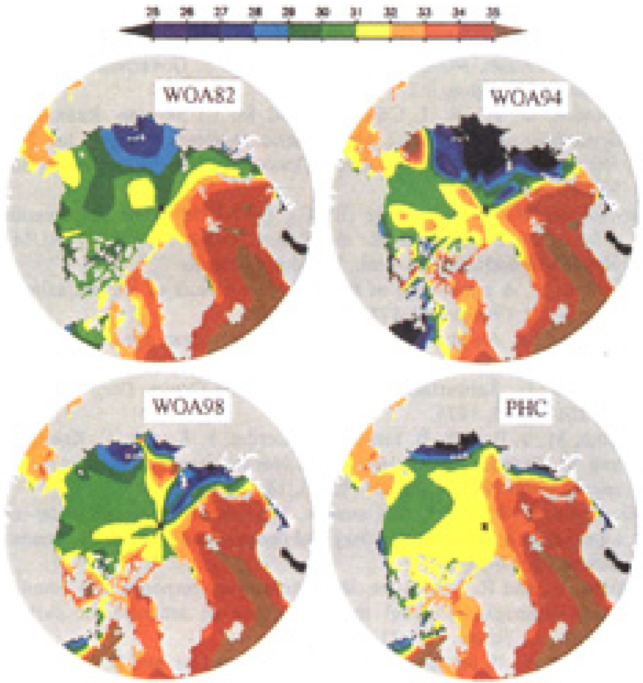

Plate 1. April mean sea surface salinity in four climatologies. The World Ocean Atlas (WOA) was produced in 1982, 1994, and 1998 [e.g. *Boyer et al.*, 1998]. The Polar Science Center Hydrographic Climatology (PHC) [*Steele et al.*, 2000] combines WOA98 with previosly unavailable Russian and western data [*EWG*, 1997/1998]. The March mean for WOA82 is shown here since April means were not provided. The north Pole is marked with '×.'

weak minimum within the Beaufort Gyre surrounded by saltier values in the Eurasian Basin and the Chukchi Sea, and by very fresh waters in the East Siberian Sea and (in some climatologies) near the Mackenzie River delta. (Summer climatologies are generally fresher but show the same regional variations.) The surface waters then converge under the anticyclonic wind and sea ice forcing, which eliminates the initial freshwater dome, replacing it with a flat field of SSS (UW and IOS models) or even a salt "bowl" (GSFC model and Z98).

Clearly, the simulations are missing a source of freshwater to the surface layers of the Beaufort Gyre. Here we discuss some possibilities that will hopefully provoke further work towards a definitive answer. One freshwater source might be melting of sea ice. However, there is net growth of sea ice over the year in much of the deep Arctic Ocean [Z98; *Steele and Flato*, 2000] which represents a freshwater sink. Another possibility might be that net precipitation less evaporation is underestimated in the forcing used by these models. This could be true, given the uncertainty in this quantity that exists in the Arctic and, indeed, globally. We deem it unlikely, however, since the central arctic value used by, for example, the UW model is the best estimate of approximately 15 cm yr^{-1} (water equivalent) as provided by extensive Russian observations and moisture flux convergence from reanalysis products [e.g., *Bromwich et al.*, 2000]. Another possibility might be inadequate river discharge, but this also seems unlikely since several AOMIP models (UW, GSFC) use values at the high end of the estimated mean [*Shiklomanov et al.*, 2000]. Yet another possibility is the eddies of 10–20 km diameter that transport warm, fresh waters from the Bering and Chukchi Seas into the western Arctic Ocean [e.g., *Hunkins*, 1974]. These are poorly resolved by even the highest resolution model in our study. However, they are mostly a sub-mixed layer phenomenon and thus are not particularly collected into the Beaufort Gyre by Ekman convergence.

One likely candidate is the simulation of arctic shelf processes, which differs widely in these models (Plate 2). Even when river discharge is reasonable, the mechanisms for exchange across these shelves and into the deep basins may be inadequately captured. For example, freshwater may be lost via simplified flux boundary conditions that neglect river volume inflow to the oceans [*Roullet and Madec*, 2000]. Also, the models might be injecting fresh riverine waters into the deep basins below the surface, which could contribute to the differences seen between Plates 1 and 2. Such issues will be explored in detail in future AOMIP studies of the heat and freshwater budgets. Here we simply note that overly salty SSS implies (by static stability) overly salty waters at depth.

Another possibility lies in the wind forcing. The SSS minimum within the Beaufort Gyre arises from a combination of surface Ekman convergence and a freshwater source. Our experience indicates that some models are sensitive to changes in the wind forcing that drives this convergence. An example is provided in Figure 1, where the two IOS simulations differ only

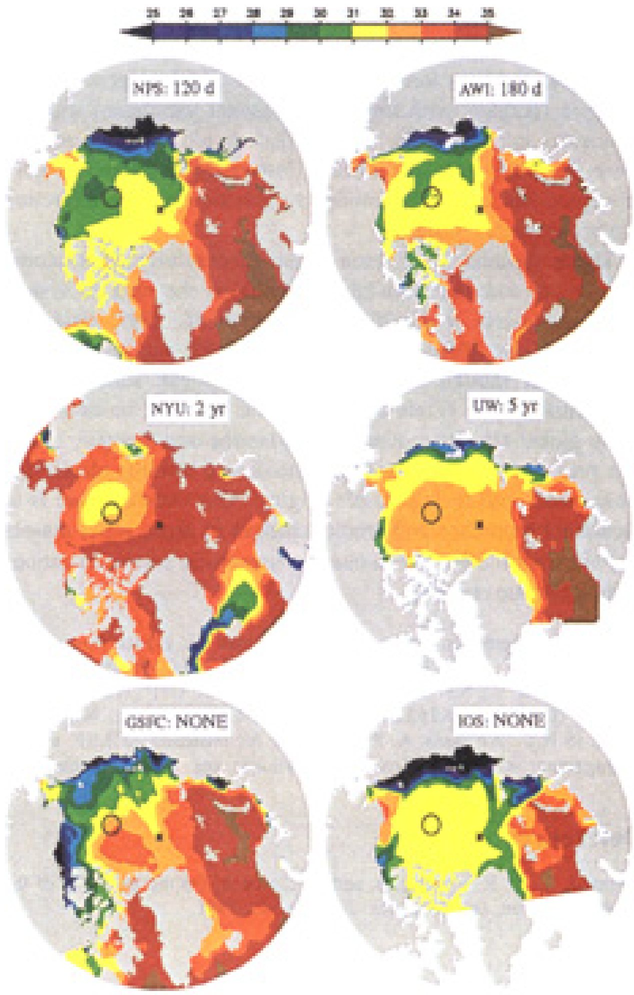

Plate 2. April mean sea surface salinity and its restoring time constant in six model simulations. Surface depth in each model (and other information) is provided in Table 1. Model output from NPS, AWI, UW, and GSFC is averaged over years 1979–1988, while output from NYU and IOS uses climatological average forcing. Values within the 200 km radius circles (centered at 160°W, 80°N) are plotted in Figure 1.

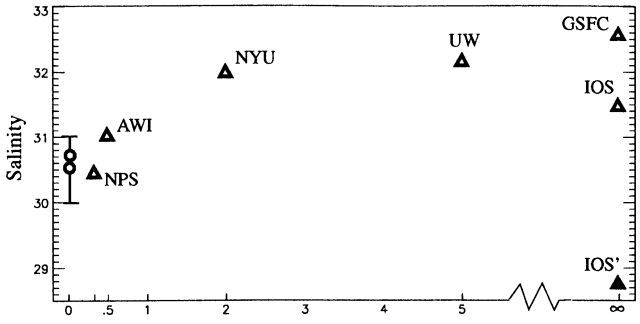

Figure 1. Mean sea surface salinity (triangles) within the 200 km radius circles shown in Plate 2. Also shown are mean salinities within this region from the PHC (upper circle) and WOA98 (lower circle) climatologies (Plate 1), and the 40-year maximum and minimum April salinities from the AOA climatology (horizontal bars). Relative SSS values remain qualitatively similar if a larger 400 km radius circle is used (not shown). Most simulations use atmospheric surface pressure fields to derive a wind stress. The exception is IOS' (filled triangle) which uses reanalysis stress vectors that are grossly similar in direction, but more than twice the magnitude relative to those derived by IOS using the pressure field.

in their wind stress forcing. The degree of convergence within the gyre (perhaps with important seasonal variations) strongly influences the SSS field, a point that should probably receive more attention in future work. Convergence within the gyre integrates and thus may amplify systematic errors in advection and/or freshwater sources.

These models have been used successfully to examine interannual and interdecadal variability in the climate system [e.g., *Maslowski et al.*, 2000; *Karcher et al.*, 1999; *Häkkinen*, 1999; *Holland*, 2000; *Nazarenko et al.*, 1998; and *Zhang et al.*, 2000] even though their unconstrained mean states exhibit substantial biases (Plate 2). The same situation holds true in many global climate models [e.g., *Manabe and Stouffer*, 1994]. The present study represents one small step towards identifying these biases and their possible origins. Our eventual goal is to accurately reproduce and predict changes in arctic water masses and circulation using a minimum of unrealistic parameterizations such as climate restoring.

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