Climate impacts of systematic errors in the simulation of the path of the North Atlantic Current

Scott R. Weese$^1$ and Frank O. Bryan$^1$

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[1] Experiments employing an adjustment of the pressure field in the ocean component of a coupled climate system model are undertaken in both ocean-only and coupled experiments to assess the climatic impacts of reducing the systematic errors in the North Atlantic Current. This conservative and adiabatic adjustment process substantially decreases North Atlantic Ocean SST biases and locally reverses the associated surface heat flux balance in both model configurations. Ice concentrations in the Labrador Sea increase as the oceanic surface heat fluxes are displaced by the adjustment. Downstream, in the Nordic Seas, the subsurface ocean responds favorably to this adjustment, as the vertical profiles of potential temperature and salinity converge towards the observations. Atmospheric stationary wave patterns show a modest improvement, with a slight weakening of the excessively deep Icelandic low. Further unresolved errors in the coupled model framework potentially contribute to the continued presence of biases in the North Atlantic.


1. Introduction

[2] Many global coupled climate models and coarse resolution ocean models exhibit a systematic error in the simulation of the pathway of the North Atlantic Current (NAC). This error is most evident southeast of Newfoundland, as exemplified by the near surface current simulated by the Community Climate System Model version 3 (CCSM3) [Collins et al., 2006a]. In the simulation, as the Gulf Stream passes the tail of the Grand Banks near 50°W, it continues to flow zonally across the Atlantic basin near 40°N (Figure 1). In contrast, the observed circulation path as revealed by surface drifters [see Flatau et al., 2003, Figure 6a] has a sharp northward turn east of the Grand Banks of Newfoundland and an eventual resumption of the zonal flow near 50°N. This incorrect simulation of the NAC path by the CCSM results in an absence of warm temperature advection into the region east of Newfoundland, as the model current is oriented nearly 180° to the observed current. A sea surface temperature (SST) bias in excess of 10°C forms due to this erroneous configuration of the circulation.

[3] The path of the NAC is very similar in a simulation of the ocean component model alone forced with observed atmospheric conditions, so we can reliably attribute the systematic error to a misrepresentation of the dynamics in the ocean component of the coupled system. A few recent high-resolution ocean simulations [e.g., Smith et al., 2000] have succeeded in simulating realistic paths of the NAC, but the dynamics of the current remain obscure, and use of these models in a coupled system would be prohibitively expensive.

[4] Our goal in this study is to investigate the broader scale atmospheric and ocean impacts in the coupled simulation of this error in the simulation of the NAC path through an ad hoc adjustment of the ocean component model. Specifically, we will investigate the response of the water mass properties in the Nordic Seas and Arctic Ocean, and the atmospheric circulation in the North Atlantic sector to an improved representation of the NAC path. The displacement of the northward flowing branch of the NAC to the eastern side of the basin prevents the exposure of warm SST's to cold air advection flowing from the North American continent, potentially impacting the water mass transformation in the subpolar Atlantic and the meridional overturning circulation. In nature, the warm NAC contributes to the establishment of diabatic heat fluxes that strengthen preexisting weather disturbances, forming a recognizable storm track over the North Atlantic Ocean [Hoskins and Valdes, 1990]. Errors in the surface heat fluxes resulting from the poor simulation of the NAC may thus impact the large-scale atmospheric circulation. Poleward ocean heat transport at high latitudes, through its influence on the sea ice distribution, significantly impacts climate sensitivity through the ice-albedo feedback mechanism that drives polar amplification, as Holland and Bitz [2003] estimate that Arctic warming in coupled climate models ranges from 1.5 to 4.5 times the mean global warming trend.

[5] Here we show that a present-day, coupled climate system simulation with a spurious NAC path can be successfully forced into a more climatologically accurate position through an adjustment of the pressure field, thus allowing for an appraisal of the broad scale and remote climate impacts of this bias. The adjustment is first employed in an ocean general circulation model (OGCM) forced with observed atmospheric conditions, and then into a fully coupled global circulation model (AOGCM).

2. Methods and Model Description

[6] Because the dynamical shortcomings of the model leading to errors in the NAC path remain obscure, we utilize an ad hoc method that forces the model currents toward observed conditions. The “semi-prognostic” method proposed by Greatbatch et al. [2004] is an adiabatic
adjustment of the advective characteristics of an ocean GCM, without requiring any flux corrections. Eden et al. [2004] demonstrated significant decreases in the systematic errors induced by the false NAC pathways, by employing the semi-prognostic technique in a regional, eddy-permitting ocean GCM. In this study a suite of experiments with the fully coupled CCSM, and the ocean component alone, with and without the semi-prognostic method, have been carried out to explore the broader scale climate impacts of the systematic NAC path error.

[7] The OGCM integration consists of an active ocean model, the Parallel Ocean Program (POP) [Smith and Gent, 2004], configured with a horizontal resolution of approximately 1° on a displaced dipole grid, with the northern pole located in Greenland, and 40 vertical levels [Danabasoglu et al., 2006]. For the ocean only experiments, the model is forced with a repeating annual cycle of precipitation, radiation, and atmospheric state information based on a synthesis of NCEP/NCAR reanalysis and remote sensing products [Large and Yeager, 2004]. A control integration was initialized using the salinity and potential temperature climatologies from Steele et al. [2001], and run for 130 years. The semi-prognostic simulation was branched at year 100 and run out for 30 years.

[8] The AOGCM employs the fully active models for each component of CCSM3: the Community Atmosphere Model, (CAM) [Collins et al., 2006b], the Community Sea Ice Model (CSIM) [Holland et al., 2006], and the Community Land Model (CLM) [Dickinson et al., 2006], in addition to POP. In these experiments, POP is configured identically to the ocean only experiments described above. The sea ice model has the same resolution as POP, CAM, and CLM have triangular spectral truncation at wave number 42, for a horizontal grid resolution of approximately 2.8°.

[9] A control integration for present-day conditions (greenhouse gas and aerosol concentrations for 1990) was run for 1001 years [Collins et al., 2006a]. The corresponding semi-prognostic run was initialized as a branch at year 600 from the present-day control, and integrated for 50 years.

[10] In the semi-prognostic method, the hydrostatic equation is reformulated following Greatbatch et al. [2004] to utilize a blended density, with contributions from the model calculated density ($\rho_m$) and a climatological density ($\rho_c$):

$$\frac{\partial p}{\partial z} = -g[(1 - \alpha)\rho_m + \alpha \rho_c]$$

(1)

This semi-prognostic density thus influences the pressure gradient force in the momentum equation and brings the geostrophic flow into closer alignment with observations. Focusing on the NAC led to the subjective definition of the domain of application of the semi-prognostic method as a region of radius $L = 4000$ km, centered on 48°N, 40°W. The parameter $\alpha$ is given by:

$$\alpha = \begin{cases} 
\frac{1}{4} [1 + \cos(\pi r/L)] & r < L \\
0 & r \geq L.
\end{cases}$$

(2)

where $r$ is the distance between a given grid point and the center of the domain. In this study the parameter $\alpha$ is limited to a maximum of 0.5 at the domain center with a gradually decreasing influence of the climatological density as one moves further from the center of the NAC region, so that the model calculated densities predominate in the pressure gradient computation. The high-resolution World Ocean Atlas (WOA) climatology of monthly mean salinity and temperature of Stephens et al. [2002] is provided on a 0.25° grid for 33 standard depth levels (0–5500 m), and interpolated to the model grid to facilitate the calculation of the climatological density. Note that the semi-prognostic method is applied over the full depth range within the region defined above.

[11] Distinct advantages are realized from the use of the semi-prognostic method over the more traditional nudging of temperature and salinity. Currents driven by the model dynamics in response to the modified pressure gradient force establish the temperature and salinity distributions, preserving heat and freshwater conservation in the system and avoiding any short-circuiting of climate feedbacks.

3. Results

[12] Examining the annual average OGCM response in the North Atlantic Ocean at year 129, the SST error in the control run exhibits a large bias relative to the WOA analysis (Figure 2a). This error is manifested southeast of Newfoundland with SST’s more than 6°C colder than the observed values. The predominantly zonal flow and lack of northward penetration of subtropical water by the NAC in the OGCM accounts for the large deviation in SST. Viewing the surface heat flux field reinforces this assertion, as large heat fluxes into the ocean are co-located with the largest SST error near the Flemish Cap at approximately 45°N, 45°W. The spatial orientation of the SST bias is mimicked by the surface heat flux pattern. Introduction of the semi-prognostic method greatly reduces the spatial extent and magnitude of the error in the OGCM (Figure 2b): maximum SST errors are less than 4°C, and the cold bias between 40°N and 45°N is eliminated as the NAC is forced into alignment with the observed path. Heat now fluxes out of the ocean into the atmosphere near the Flemish Cap, and into the ocean over a smaller area near the Grand Banks due
Near 45°/C176N, 45°/C176W, fluxes in the OGCM control exceeded 80 W/m² from the atmosphere to the ocean, while the heat flux in the OGCM semi-prognostic experiment reverses direction and increases in magnitude to over 160 W/m².

The SST error pattern associated with the NAC path error in the coupled model control experiment is similar to that in the OGCM, now reaching more than 10°C, and embedded in a broader scale cold bias extending across the subpolar Atlantic between 40°N and 55°N (Figure 3a). The reduction in the maximum SST errors between the AOGCM control case (Figure 3a) and the AOGCM semi-prognostic case (Figure 3b) is smaller than was obtained in the ocean alone experiments, but the shift of the maximum error to the north and large reduction of the error between 40°N and 45°N is the similar. In the AOGCM control case (Figure 3a), the largest SST error coincides with a large surface heat flux into the ocean near the Flemish Cap. In the AOGCM semi-prognostic experiment, surface heat fluxes in excess of 40 W/m² into the ocean are confined to the area over Grand Banks. Heat fluxes at 45°N, 45°W again show a reversal in sign, as the 80 W/m² heat flux into the ocean in the AOGCM control becomes over 160 W/m² into the atmosphere in the AOGCM semi-prognostic case. Comparing the 10% ice concentration contour in the AOGCM control and semi-prognostic experiments shows increasing ice coverage in the Labrador Sea, and a slight reduction north of Iceland in the latter. The control simulation has too extensive sea ice in the Labrador Sea when compared to the observations [Cavalieri et al., 1997], and the problem is exacerbated in the semi-prognostic experiment. A substantial reduction in the oceanic heat flux in the Labrador Sea is noticed in the semi-prognostic AOGCM that corresponds with the largest ice concentration gains. Less improvement in SST is demonstrated in the AOGCM framework than in the OGCM, yet the surface heat flux response is consistent across both simulations and sufficient response is displayed to permit an analysis of the impacts of NAC errors in the fully coupled climate system.

The downstream ocean impacts are succinctly studied with basin averaged, time averaged (year 129 for the OGCM and years 630 to 649 for the AOGCM), vertical profiles of potential temperature and salinity. Changes in Atlantic layer water (the stratum of subducted NAC water lying between 200 and 1000 m depth in the Nordic Seas and Arctic Ocean [e.g., Coachman and Barnes, 1963]), due to the adjustment from the semi-prognostic method can be tracked with these plots. Figures 4a and 4b show the vertical profiles of potential temperature and salinity in the Labrador Sea in the AOGCM semi-prognostic experiment becoming slightly closer to the WOA analysis than in the AOGCM control. Biases in the OGCM semi-prognostic run are also diminished with respect to the control, but tend to be slightly too cold below 400m depth. The error reduction over the Atlantic layer in the Greenland-Iceland-Norwegian (GIN) Sea in the AOGCM semi-prognostic integration is more substantial: the salinity error (Figure 4d) is reduced by approximately 0.25 psu and the potential temperature (Figure 4c) drops by 0.5°C fairly uniformly over the vertical.
Between 200m and 400m, the OGCM semi-prognostic experiment is remarkably in line with the potential temperature observations, but again becomes too cold in the deeper ocean by as much as 0.5°C. The OGCM semi-prognostic profile of salinity is a consistent improvement over the control throughout the Atlantic layer. Waters in the Arctic Ocean exhibit a high degree of improvement in the AOGCM semi-prognostic potential temperature field, with a maximal change of roughly 0.7°C noticed between 250 m and 1000 m depth (Figure 4e). Cooling prevails in the OGCM semi-prognostic temperatures, but is restricted to under 0.2°C maximum over the 200m to 800m layer. Figure 4f displays mixed results in the AOGCM salinity profile of the Arctic Ocean, with the semi-prognostic experiment Atlantic layer salinity little improved over the control case relative to the observations.

[15] A large, excessively deep Icelandic surface low pressure system is evident in the climatological winter season average sea level pressure distribution in the present-day AOGCM control simulation (Figure 5a). The central pressure drops below 990 hPa, while the NCEP Reanalysis [Kalnay et al., 1996] central pressure exceeds 994 hPa (Figure 5c). The extent of the deep low in the control is much broader than in the reanalysis, and promotes enhanced surface pressure gradients and wind stresses over the North Atlantic Ocean. The AOGCM semi-prognostic integration over the same region shows a slight weakening of the Icelandic low, with central pressures rising roughly
3 hPa (Figures 5b and 5d). Weaker meridional flow over the Labrador Sea is present in the semi-prognostic simulation relative to the control, as the sea level pressure gradient is diminished. This moderate change is correct in direction, but weak in magnitude, and only somewhat diminishes the strength of the surface low pressure. Zonal flow dominates the region where the semi-prognostic method is applied in both the experiments and observations, with winds in both the control and semi-prognostic runs too strong relative to the observations. The Azores high is also too strong in both the control and semi-prognostic simulations, with little change between the experiments. The upper atmosphere shows minimal change in response to the semi-prognostic forcing of the NAC. The 500 hPa geopotential height surfaces for both the control and AOGCM simulations (not shown) exhibit deep troughs over the North Atlantic ocean, and weak downstream ridging. A predominately zonal pattern of 500 hPa height surfaces prevails in the semi-prognostic forcing domain, with strengthening winds equatorward.

4. Discussion and Conclusions

[16] Comparison of the OCGM and AOGCM ocean surface heat flux distribution reveals a coherent outcome. Large fluxes originate from the ocean near the Flemish Cap in both semi-prognostic integrations, associated with displaced and diminished SST biases. Distinct SST errors persist in the fully coupled semi-prognostic experiment, suggesting that correction of the NAC path inaccuracies exposes additional model defects. These errors may be of opposite sign to the NAC induced bias, leading to compensatory interactions in the control runs that mask the individual errors.

Figure 5. Climatological winter (DJF) mean sea level pressure (hPa) for (a) AOGCM control, (b) AOGCM semi-prognostic, (c) NCEP/NCAR reanalysis, and (d) difference (hPa) between AOGCM semi-prognostic and AOGCM control. Map projections show the North Pole to 35°N, with 15° interval latitude lines.
The weakening of the Icelandic low pressure in the AOGCM semi-prognostic experiment can be interpreted with potential vorticity concepts discussed by Kushnir et al. [2002]. The SST correction in the northwest corner induced by the semi-prognostic forcing acts as an anomalous heat source. This heating generates a maximum in potential vorticity below the heating and increases the static stability of the layer. The shallow heating anomaly weakens with height, and works to reduce the static stability above the heat source as a sink of potential vorticity forms above the heating. The pressure gradient of the Icelandic low and corresponding high pressure region to the south imply primarily zonal atmospheric winds. This zonal flow in a shallow heating anomaly dictates a downstream baroclinic warm core feature, implying rising pressure in the vicinity of the Icelandic low pressure system. The bottom panel of Figure 4 from Kushnir et al. [2002] shows the geopotential height perturbation induced by a shallow heating anomaly, as decreased heights exist west of the anomaly and increased heights are generated to the east. This SST correction induces a very weak linear heating response and the pressure increase is slight but explains the reduction of the AOGCM Icelandic low pressure center values. The impact on GCM’s of SST perturbations in the extratropics tends to be small when compared with tropical anomalies and intrinsic atmospheric variability, as the heating profile tends to be much shallower than those associated with the other mechanisms [Kushnir et al., 2002]. Weak pressure rises in the AOGCM Icelandic low pressure system are induced by this slight potential vorticity forcing mechanism. Upper atmospheric levels remain unaffected due to the superficial nature of the SST anomaly, as demonstrated by Kushnir et al. [2002] in an idealized ω-channel experiment showing the quasigeostrophic response to shallow heating in a westerly flow.

The North Atlantic Current path errors contribute to the biosphere in the simulation of the water mass properties in the subpolar North Atlantic Ocean and the Nordic Seas. The fully coupled modeling system has a more modest SST bias reduction when the semi-prognostic method is employed than was the case for the ocean alone experiments, but exhibits a surface heat flux response that is more similar in magnitude. Atmospheric stationary wave patterns are also slightly impacted by this NAC path error, but further unidentified sources of error impart a significant degree of bias in this region. Future integrations may demonstrate convergence of the model towards the observations, as the transient solution continues to evolve.

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References


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