At present only the first version of the CORE forcing (CF1), updated through 2004, is being distributed through the Geophysical Fluid Dynamics Laboratory (http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html). The main differences are that wind direction is unaltered and the humidity adjustment is made to relative humidity such that there is a drying in the equatorial Pacific instead an increase in specific humidity. CF1 includes a single annual cycle of «Normal Year Forcing» that is constructed to give the same climatological pseudo fluxes to transition smoothly when used for repeat annual forcing and to retain high frequency storm events. An alternative forcing, based on the 15 year ECMWF reanalysis, is described by Roske (2006). It places a higher premium on resolution, uses reanalysis radiation, as well as precipitation over both ocean and land, and can't be updated beyond 1993. The data set is «closed» using the inverse procedure of Isemer et al. (1989), so it is not independent of observed ocean tranport estimates.

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Design Considerations for Coordinated Ocean-Ice Reference Experiments

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1. Introduction

Simulations with coupled ocean-ice models are commonly used to assist in understanding climate dynamics, and as a step towards the development of more complete earth system models. Unfortunately, there is little consensus in the global modelling community regarding the design of ocean-ice experiments, especially those run for centennial and longer time scales. Furthermore, differences in forcing methods can lead to large deviations in circulation behaviour and sensitivities.

Members of the CLIVAR Working Group for Ocean Model Development (WGOMD) have been addressing various aspects of the issue of forcing ocean-ice models. The result of this effort is the *Coordinated Ocean-ice Reference Experiments* (COREs). COREs do not resolve problems related to forcing global ocean-ice models. Rather, COREs highlight difficulties, and provide a means to lift disparate modelling efforts onto a common plateau from which alternative experimental designs and forcing data sets can be systematically explored.

2. Boundary fluxes for ocean-ice models

A coupled ocean-ice model requires momentum, thermal, and hydrological fluxes to drive the simulated ocean and ice fields. When decoupling the ocean and sea ice models from the atmosphere, one must introduce a method to generate these fluxes. Three general approaches have been used. The first is to damp sea surface temperature (SST) and salinity (SSS) to prescribed values. This approach is reasonable since SST anomalies experience a negative feedback in the climate system (Haney, 1971), whereby they are damped by interactions with the atmosphere. Unfortunately, the thermohaline fluxes generated can be quite unrealistic (Killworth et al., 2000; Large et al., 1997). A complement is to use undamped thermohaline fluxes from a dataset. However, fluxes from observations and/or reanalysis products have huge error bars (Taylor, 2000; Large and Yeager, 2004). Running ocean-ice models for decades or longer with such large uncertainties, especially absent a restoring flux, leads to unacceptable model drift (Rosati and Miyakoda, 1988). A third approach prognostically computes turbulent fluxes for heat, moisture, and momentum from a planetary boundary layer scheme (Parkinson and Washington, 1979; Barnier et al., 1995; Barnier, 1998), in addition to applying radiative heating, precipitation and river runoff. Turbulent fluxes are computed from bulk formulae as a function of the ocean surface state (SST and surface currents) and a prescribed atmospheric state (air temperature, humidity, sea level pressure, and wind velocity or wind speed).

The third method is proposed for COREs since it is closest to what is used in earth system models. Hence, it is important to recognize its limitations. A fundamental problem relates to the use of a prescribed and nonresponsive atmosphere that effectively has an infinite heat capacity and infinite moisture capacity. This situation is the converse to what occurs in Nature, where the ocean has a far larger heat and moisture capacity than the atmosphere. We summarize two problems that arise when running ocean-ice models with a fixed atmospheric state.

2.1. Salinity fluxes and mixed boundary conditions

Relatively strong salinity restoring, analogous to the effective restoring of SSTs arising from bulk formulae, can reduce drift in the ocean-ice simulations. However, salinity restoring has no physical basis. It is thus desirable physically to use weak restoring. Weak restoring also has the benefit of allowing increased, and typically more realistic, variability in the surface salinity and deep circulation. Unfortunately, when the restoring timescale for SSS is much longer than the effective SST restoring timescale, the thermohaline fluxes move into a regime commonly known as *mixed boundary conditions* (Bryan, 1987). Stommel (1961) showed that ideal thermohaline systems forced with mixed boundary conditions admit multiple equilibria. Mixed boundary condition simulations can be susceptible to unrealistically large amplitude thermohaline oscillations, as well as a polar halocline catastrophe, in which a fresh cap develops in high latitudes of the North Atlantic and shuts down the overturning circulation (Zhang et al., 1993; Rahmstorf and Willebrand, 1995; Rahmstorf et al., 1996; Lohmann et al., 1996).

2.2. Absence of an atmospheric response as the ice edge moves

Windy, cold, and dry air is often found near the sea ice edge in Nature. Interaction of this air with the ocean leads to large fluxes of latent and sensible heat which cool the surface ocean, as well as evaporation which increases salinity. This huge buoyancy loss increases surface density, which provides a critical element in the downward branch of the thermohaline circulation (e.g., Marshall and Schott, 1999).

When the sea ice edge and/or halocline moves, the region of large air-sea fluxes also moves when the atmosphere is allowed to evolve, as in an earth system model with an interactive atmosphere. In contrast, when the atmospheric state is prescribed and the simulated sea ice edge moves, the air-sea fluxes are spuriously shut down in the ocean-ice simulation. The ocean column becomes prone to freshwater pooling at the surface, and this provides a positive feedback on the heat flux reduction. This process is similar to the polar halocline catastrophe of mixed boundary conditions mentioned above. The net effect is to weaken the simulated thermohaline circulation.

3. A proposal for COREs

Even a perfect ocean-ice model is exposed to limitations inherent in computing fluxes from a prescribed and nonresponsive atmospheric state. Nonetheless, working under the assumption that we wish to conduct productive research and developmentwith ocean-ice models, we seek a standard modelling practice to help establish benchmark simulations, thus facilitating comparisons and further refinements to the flux data sets and experimental design.

3.1. The Large and Yeager dataset

In order to be widely applicable in global ocean-ice modelling, a dataset should produce near zero global mean heat and freshwater fluxes when used in combination with observed SSTs. This criteria precludes the direct use of atmospheric reanalysis products. As discussed in Taylor (2000), a combination of reanalysis and remote sensing products provides a reasonable choice to force global ocean-ice models. That is the approach taken by Large and Yeager (2004). Furthermore, it is desirable for many research purposes to provide both a repeating «normal» year forcing (NYF) as well as an interannually varying forcing. The Large and Yeager (2004) NYF is derived from the 43 years of interannual varying forcing. Access to the dataset, Fortran code for the bulk formulae, technical report, support code, and release notes are freely available at

nomads.gfdl.noaa.gov/nomads/forms/mom4/CORE.html

3.2. Three proposed COREs

The WGOMD has proposed three COREs, whose elements are outlined here.

- CORE-I: This experiment is aimed at investigations of the climatological mean ocean and sea ice states realized using the idealized repeating NYF of Large and Yeager (2004). Models should ideally be run to quasi-equilibrium of the deep circulation (order hundreds to thousands of years). Preliminary tests (Griffies et al., 2007) indicate that 500 years is suitable for many metrics.
- CORE-II: This experiment is aimed at investigations of the forced response of the ocean and/or ocean hindcast. It therefore employs the interannual varying dataset of Large and Yeager (2004).

- CORE-III: This is a perturbation experiment involving ideas proposed by Gerdes et al. (2006). Here, enhanced fresh water enters the North Atlantic in response to increased meltwater runoff distributed around the Greenland coast. Response of the regional and global ocean and sea ice system on the decadal to centennial time scales is the focus of CORE-III.

3.3. Status of CORE simulations

Modelling groups at GFDL, Kiel, KNMI, MPI, and NCAR have explored the CORE-I suite of experiments (Griffies et al., 2007). Each group used the CCSM bulk formulae, reflecting the approach used to develop the Large and Yeager (2004) dataset. Salinity or fresh water forcing was a frequent point of debate, largely due to difficulties raised in Section 2. Each group used their favorite salinity restoring, with restoring to the same salinity dataset.

Analyses of water mass properties, sea ice distribution, tropical circulation, overturning circulation, etc., have revealed a wide spread amongst the above models for certain metrics (e.g., overturning circulation), and general agreement for other metrics (e.g., tropical circulation). As for many other model comparison projects, these early results raise more questions than they answer. Thus, fully understanding the simulation differences will require further research. We consider this outcome a successful illustration of the CORE idea in that it (A) provided a common experimental platform to compare a wide class of global ocean-ice models, (B) has provoked many new research projects in hopes of furthering our understanding of the ocean-ice climate system.

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