ANALYSIS OF THERMOHALINE FEEDBACKS

JOCHEM MAROTZKE
Massachusetts Institute of Technology
Cambridge, USA

Contents

1 Introduction

2 Model formulation
   2.1 Basic equations
   2.2 Surface heat fluxes
   2.3 Surface freshwater fluxes
   2.4 Equilibrium solutions

3 Stability of the high-latitude sinking equilibrium
   3.1 Atmospheric transport anomalies
   3.2 Modelling strategy
   3.3 Thermohaline feedbacks

4 Land effects
   4.1 Basic equations
   4.2 Spatially averaged quantities
   4.3 Meridional gradients

5 Flux adjustments and climate drifts

6 The ‘neutrally buoyant mode’

7 Concluding remarks

Abstract

Feedbacks between atmospheric meridional transports and the thermohaline circulation (THC) are analysed, using a four-box ocean-atmosphere model in one hemisphere. The ocean model is Stommel’s; the atmospheric model is similar to the one developed earlier by Marotzke and Stone and gives the surface heat and freshwater fluxes as residuals of the atmospheric energy and moisture budgets, assumed in balance. Radiation at the top of the atmosphere depends linearly on surface temperature; atmospheric meridional heat and moisture transports are proportional to an arbitrary positive power of the meridional temperature gradient, which is taken to be identical to the oceanic temperature gradient. The coefficients in the power laws for atmospheric meridional transports are chosen such that all coupled models have one steady state in common. Upon linearization, a Newtonian cooling law is derived for anomalous differential surface heat flux. The timescale on which the ocean temperature gradient is restored decreases with increasing power, $n$, in the atmospheric heat...
transport parameterization. The limits, $n = 0, \infty$, correspond approximately to the uncoupled cases of fixed surface heat flux and fixed surface temperature, respectively. A power, $m$, of zero in the atmospheric moisture transport is equivalent to fixed surface freshwater flux. Stronger dependence of moisture transport on temperature gradient (increasing $m$) destabilises the THC. When moisture transport depends weakly on temperature gradients ($m \leq 1$), the THC is more stable to perturbations as $n$ decreases (weaker restoring). For $m \geq 2$, however, the THC is more unstable with smaller $n$, because the destabilising effect of anomalous moisture transport outweighs the stabilising effect of anomalous thermal forcing of the THC. If zonal mixing in the atmosphere is incomplete, the zonal mean temperature deviates from the ocean temperature. Meridional atmospheric transports are less sensitive to variations in the ocean temperature gradient if the ocean area is small, and Newtonian cooling is weaker. Simultaneously, a smaller ocean can compensate a given atmospheric energy budget imbalance only through a greater change in surface heat flux, which translates into stronger Newtonian cooling. When flux adjustments are applied to obtain the correct model climate despite incorrect atmospheric transports, the effect is that of choosing incorrect $n$ or $m$, so transient behavior and model sensitivity are wrong although the mean state is correct. It is speculated that climate drifts seen even in flux-adjusted coupled models are amplifications of residual drifts in an incomplete, uncoupled spinup. The linearised model is non-normal, which leads to amplifications of small perturbation through interference of non-orthogonal eigenfunctions. Considerable excursions in temperature and salinity gradients can occur, which are density compensated and hence are not effectively counteracted by changes in the circulation unless the atmospheric transports respond to the changes in ocean temperature.

1 Introduction

This paper provides a conceptual framework to understand some feedbacks involving meridional transports in the atmosphere and the thermohaline circulation. Along the way, a strategy is presented that could be used to assess the strength of various feedbacks in a wide range of models. The analysis is motivated by the quest for a dynamical understanding of variations in North Atlantic Deep Water (NADW) formation and Atlantic meridional overturning, which are both crucial for the northward heat transport in the Atlantic (Hall and Bryden, 1982; Roemmich and Wunsch, 1985). Paleoclimatic observations indicate that the strength of NADW formation may have varied significantly in the geologic past (see, for example, Boyle, 1990, or Sarnthein et al., 1994). Besides natural fluctuations in overturning strength, anthropogenic ones may occur in the future: The coupled climate model of the Geophysical Fluid Dynamics Laboratory (GFDL; Manabe and Stouffer, 1994) shows a temporary reduction by one half of the Atlantic thermohaline circulation, in response to a gradual doubling of atmospheric