Chapter 7

Conclusion

7.1 Discussion

The Atlantic Ocean interacts intensively with the other basins of the World Ocean. Most of the exchange takes place via the Southern Ocean. It is here that the Atlantic issues its North Atlantic Deep Water (NADW) for distribution over the entire World Ocean. And it is here that other water masses are drawn into the Atlantic, as part of the global thermohaline circulation system. This exchange of water masses, each with its own temperature, salinity, and other constituents, makes the Atlantic Ocean a unique and complex blending system, that makes its influence felt worldwide. On the other hand, the thermohaline structure of the Atlantic is largely determined by processes in other parts of the World Ocean.

The interest in the exchange between the Atlantic and the rest of the World Ocean was spurred by a recent debate in the oceanographic literature. This was started by Gordon (1985, 1986), who argued that most of the water supplying the Atlantic for NADW formation is derived from the Pacific and Indian thermoclines. This water enters the Atlantic via a process called Agulhas Leakage, a highly intermittent exchange between the thermoclines of the South Indian and South Atlantic Oceans. Rintoul (1991), on the other hand, argued that most of the water compensating for NADW export is derived from fresh and cold Subantarctic water masses. This water enters the Atlantic sector of the Southern Ocean via Drake Passage, and it finds its way north mainly as so-called Antarctic Intermediate Water (AAIW).

The water masses involved in these two routes for NADW renewal contrast highly with respect to their thermohaline characteristics. Obviously, the ratio with which the two scenarios supply water for NADW formation largely influences the heat and salt balance of the Atlantic. Gordon et al. (1992) suggested that Agulhas Leakage may have a *dynamical* effect on the strength of the Atlantic overturning circulation; its input of salty thermocline water salinifies the Atlantic surface waters, and preconditions them for deep convection in the northern polar region, and associated formation of NADW. This hypothesis has large implications for studies of past and future climate; since the process of Agulhas Leakage probably depends critically on characteristics of the Indian Ocean wind climatology (De Ruijter et al. 1999), it may be sensitive to relatively small changes in climate. Indeed, paleoceanographic records indicate that Agulhas Leakage may have been strongly reduced or even absent during the major glaciations of the Pleistocene (Howard and Prell 1992; Flores et al. 1999). And it is not known how Agulhas Leakage will react to future climate changes.

The studies presented in this dissertation focussed on the question whether the Atlantic overturning circulation itself is influenced by the heat and salt fluxes brought about by interocean exchange. The results of these studies all suggest that these fluxes do have considerable influence on the Atlantic thermohaline circulation. Especially the heat and salt input by Agulhas Leakage turns out to have a considerable stimulating impact on the strength of the overturning. The results thus support the hypothesis of Gordon et al. (1992). However, the response in our models is not primarily caused by the stimulating effect of enhanced Atlantic surface salinities on the convective activity in the source areas of NADW. The 2D model studies of Chapters 4 and 5, as well as the 3D model study of Chapter 6, show that the heat and salt fluxes influence the stratification and the pressure field of the entire Atlantic to such an extent that it impacts on the strength of the overturning circulation. In fact, the overturning strength in these models turns out to be linearly related to characteristics of the meridional pressure gradient, in line with the results of Hughes and Weaver (1994) and Rahmstorf (1996).

The 2D model studies also show the role of energy conversions in generating the overturning response. The lateral fluxes (Chapter 4) and sources (Chapter 5) of heat and salt, representing the interocean exchange, supply the Atlantic with potential energy. This energy is readily converted into kinetic energy of the flow, establishing a direct connection between the interocean buoyancy fluxes and the overturning strength. In fact, this energy supply turns out to *control* the flow strength; the linear relation between the meridional pressure gradient and the overturning strength is established accordingly. In the real ocean, work must be done outside the Atlantic to make this energy available. If this work is done by buoyancy driven upwelling alone, as is the classical notion about the thermohaline circulation (e.g., Stommels and Arons 1960), then the extra-Atlantic energy loss would cancel the Atlantic energy gain. In this case, the sensitivity of the circulation strength is probably overestimated by the approach of modelling the Atlantic circulation only. However, recent investigations point at the possibility that a part of this work is done by wind-driven upwelling (Toggweiler and Samuels 1993ab; Shriver and Hurlburt 1997; Döös and Coward 1997). This would make this energy really available for the Atlantic overturning circulation (Toggweiler and Samuels 1998). Unfortunately, the importance of the energy balance, as displayed by the 2D models, could not be confirmed in the 3D model context.

The heat and salt fluxes brought about by Agulhas Leakage almost cancel with respect to density, and the resulting buoyancy flux is consequently small. Crucial for generating a response of the overturning strength is a physical mechanism that allows for the development of density anomalies. Only then can the pressure field of the Atlantic be affected, and can a response in the overturning circulation be generated. Indeed, thermal anomalies are in general rapidly attenuated by intense heat exchange with the overlying atmosphere (Haney 1971; Rahmstorf et al. 1996).

Saline anomalies, on the other hand, do not generate such an interaction, and salt anomalies have been shown to persist for decades (Dickson et al. 1988). This difference is to some extent represented by the mixed boundary conditions that were used to force our models. These conditions imply that the surface temperature is strongly restored towards a fixed value, whereas the surface salinity can freely develop under influence of a freshwater flux. However, restoring the sea-surface temperature to a fixed temperature does no justice to the fact that the atmosphere responds to changes in the sea-surface temperature (Rahmstorf and Willebrand 1995). Therefore, mixed boundary conditions are in general thought to overestimate the sensitivity of the circulation to disturbances. It is possible that the sensitivity to Agulhas heat and salt sources is somewhat smaller in ocean models that are coupled to more realistic atmosphere models. But as long as different lifetimes for thermal and saline anomalies are simulated, an impact on the overturning circulation can be expected.

The results found here contrast with the findings of Cai and Greatbatch (1995). They found that the overturning strength in a low-resolution General Circulation Model did not change when Agulhas Leakage was shut off. Rahmstorf et al. (1996) pointed at the unrealistically weak thermal relaxation that was implied by their atmosphere model. This allowed thermal anomalies to develop equally free as saline anomalies. Indeed, despite a general cooling and freshening of the Atlantic, the density field in their model was unaffected when Agulhas Leakage was shut off, leaving the pressure field and the overturning strength unchanged.

7.2 Recommendations

Although this dissertation has shed light on several issues, even more new questions seem to have been raised. Here I will address some of the topics that may become the subject of further study.

Model studies are not more than a theoretical exercise if they are not supported by observations. The validation of (future) climate scenarios is often impossible (and in most cases, undesirable) for obvious reasons. However, a lot can still be learned from paleoceanographic records, containing invaluable information of past climate. Detailed time series of the start-up of the conveyor belt circulation and Agulhas Leakage at the end of the last glacial may provide more information about causal relationships. If it could be determined that the Atlantic surface salinities really changed in response to re-establishing Agulhas Leakage, this would give more support to the hypothesis of Gordon et al. (1992) and the conclusions drawn here.

Presently, Agulhas Leakage seems to be a rather steady process, exhibiting little variability of considerable amplitude. The only event of anomalous Agulhas Leakage that was observed directly took place in the mid-80's (Shannon et al. 1990). It would be interesting to find out what happened to the SSS and SST anomalies that entered into the South Atlantic as a result of this enhanced Agulhas Leakage. Has the dispersion of these anomalies been recorded in hydrographic or remote sensing records? Did these anomalies generate baroclinic waves, and did they in some way influence the net outflow or inflow across 30°S? If these events leave their imprint on terrestrial climate records (like, for instance, rainfall statistics), then an estimate could be made of the frequency and strength of similar events in the past. It is nevertheless unlikely that these events generate anomalies that are strong enough to influence the overturning strength in the North Atlantic. Therefore, attempts to find correlations between occurrences of anomalous Leakage events and changes in the North Atlantic overturning circulation (e.g., Koltermann et al. 1999; Bersch et al. 1999) must be considered as showing little promise.

In light of the conclusion that the overturning circulation is rather sensitive to Agulhas Leakage, it is important to study the possible response of this Indian-Atlantic exchange in global warming scenarios. Since this exchange depends mainly on the position of the Subtropical Convergence and on the strength of the Agulhas Current, the focus should be laid on those features of the South Indian Ocean wind stress climatology that influence in particular these facets. It would be interesting to examine the suggestion whether feedbacks exist between the amount of Agulhas Leakage and the position of the line of zero wind-stress curl that may explain its relative stability (De Ruijter, personal communication).

The sensitivity estimate of the overturning strength to Agulhas Leakage could be refined by using more sophisticated models. As discussed in the former section, the use of mixed boundary conditions exaggerates the difference in damping time scales of thermal and saline anomalies, and more or less optimises the response of the overturning strength to the applied disturbances. Coupling the ocean model to a more active atmosphere may adjust the estimated sensitivity, probably to a somewhat smaller value. Furthermore, using more sophisticated ocean models, featuring a higher resolution and a better representation of physical processes (like inclusion of momentum advection, lower values of viscosity, or other mixing schemes), may yield an even more reliable estimate of the sensitivity.

Still an open question is how much Agulhas Leakage water ultimately participates in the overturning circulation. A part of this problem could be solved by studying the mixing processes that are involved in the decay of Agulhas Rings. Studying the path of drifters, deployed in newly shed Agulhas Rings, could also help in determining the ultimate fate of Agulhas Leakage water. Theoretical and model studies could help to identify the processes that control the amounts of thermocline and intermediate water that are drawn north for NADW renewal.

Currently, the MARE (Mixing of Agulhas Rings Experiment) project is in progress, aimed at understanding and quantifying the decay processes of Agulhas Rings. This project, a cooperation between the Universities of Utrecht and Cape Town, the Royal Netherlands Meteorological Institute (KNMI) and the Netherlands Institute for Sea Research (NIOZ), combines hydrographic surveys (the same Agulhas Ring will be visited three times), data assimilation techniques, regional and global modelling studies, and paleoceanographic research, to assess the impact of Agulhas Leakage for regional and global climate issues in the present and past. This will contribute to our understanding of the role of Agulhas Leakage in shaping Atlantic and global climate.