OCEAN MODELLING IN THE AGULHAS CURRENT SYSTEM

Pierrick Penven[1], **S. Herbette**[2], **and M. Rouault**[3]

[1]*Laboratoire de Physique des Océans (UMR 6523: CNRS, IRD, IFREMER, UBO), LMI ICEMASA, Department of Oceanography, University of Cape Town, Rondebosch, South Africa*
[2]*Laboratoire de Physique des Océans (UMR 6523: CNRS, IRD, IFREMER, UBO), LMI ICEMASA, Department of Oceanography, University of Cape Town, Rondebosch, South Africa*
[3]*Department of Oceanography, University of Cape Town, Rondebosch, South Africa*

ABSTRACT

Ocean models have now reached a sufficient precision to reproduce key elements of the Agulhas Current system, such as the Agulhas Retroflection and the Agulhas Rings shedding. Nevertheless, there are still recurrent biases which are not yet totally understood. Two model solutions show different results for the processes controlling the Agulhas Leakage. Idealized numerical experiments for the subtropical gyre of the Indian Ocean are then conducted to explore the Agulhas Current / Agulhas Leakage relationship. These experiments reproduce the general patterns of the Agulhas Current System and a strong mesoscale variability. For these simulations, the Agulhas Current increases with the wind forcing, and the Agulhas Leakage increases quasi-monotonically with the Agulhas Current.

Key words: Agulhas Current; Agulhas Rings; Agulhas Leakage; numerical models.

1. INTRODUCTION

The Agulhas Current is the western boundary current of the South Indian Ocean subtropical gyre (Lutjeharms, 2006). It takes its sources in the Mozambique Channel and south of Madagascar and flows along the South-eastern coasts of Africa. It transports about 70 Sv towards the south in a narrow band of about 50 km with velocities often above 2 m s^{-1} (Lutjeharms, 2006).

A characteristic of the Agulhas Current is the presence of a retroflection at the South of the African continent, where the flow turns back on itself to return in the Indian Ocean (Lutjeharms and van Ballegooyen, 1988). Levels of eddy turbulence in the Agulhas Retroflection region are among the largest of the world Oceans (Ducet et al., 2000; Gordon, 2003). A recent analysis of subsurface floats and drifters trajectories suggests that at least 15 Sv of the incoming Agulhas Current water spreads into the South Atlantic (mostly in the forms of large anticyclonic eddies: the Agulhas Rings) (Richardson, 2007). This leakage of Agulhas Current waters into the Atlantic Ocean induces a buoyancy flux which could be critical for the global overturning circulation of the Ocean (Gordon, 1986; de Ruijter et al., 1999; Weijer et al., 1999; Biastoch et al., 2008).

This global effect has been recently confirmed by paleo-oceanographic studies which have shown that most severe glacial periods are marked by reductions in Agulhas Leakage (Bard and Rickaby, 2009; Zahn, 2009), while sharp increases in Agulhas Leakage are observed at the end of ice ages, causing a rapid return towards interglacials (Peeters et al., 2004). This shows that on top of direct effects on local climate in Southern Africa (Reason, 2001; Rouault et al., 2002), the Agulhas Current could be a key element for the global Earth climate system.

The Agulhas Current compensates an equatorward flow forced by a homogeneous positive wind stress curl over the South Indian Ocean. However, the dynamics of the region is complicated by several other elements:

1. The South Indian Ocean is not closed and the Agulhas Current is part of a Southern Hemisphere Supergyre, which connects the Pacific, Indian and Atlantic Oceans via the Indonesian Througflow, the Southern Ocean and the Agulhas Leakage (de Ruijter et al., 1999).
2. Due to the presence of Madagascar, the flow in the Mozambique Channel is dominated by eddies which propagate in the Agulhas region and affect the retroflection process (Schouten et al., 2002; Penven et al., 2006c).
3. Natal pulses, large meanders in the Agulhas Current travel sporadically along the Agulhas Current (de Ruijter et al., 1999; Rouault and Penven, 2011).
4. At the southern tip of Africa, the Agulhas Current looses the continent before reaching the latitude of 0 wind stress curl. The current detachment and subsequent Agulhas Retroflection are associated with large inertia (Ou and de Ruijter, 1986) and current

/ topography interactions (Lutjeharms and van Ballegooyen, 1984; Matano, 1996).

5. The levels of eddy energy associated with the Agulhas Retroflection, and the Agulhas rings are the highest in the world (Ducet et al., 2000; Gordon, 2003).

Because of these factors, modelling the Agulhas Current system is still a difficult exercise.

2. NUMERICAL MODELS OF THE AGULHAS CURRENT SYSTEM

The Agulhas Current has been successfully simulated, from its sources to the spawning of Agulhas Rings, using specifically designed regional models as well as global ocean models. In the early days of primitive equations ocean models, Boudra and Chassignet (1988) were able to produce an idealized simulation of the wind driven gyre of the South Indian Ocean at 20 km resolution. They were able to produce a retroflecting Agulhas Current and the generation of Agulhas Rings.

Agulhas Retroflection and Agulhas Rings were also reproduced in the Fine Resolution Antarctic Model (FRAM) (Lutjeharms and Webb, 1995). This first realistic simulation of the Agulhas Current system presents a behavior seen later on in several other models: a mean Retroflection position eastward (upstream) of the observed pattern, and Agulhas Rings following a straight route into the South Atlantic Ocean (Barnier et al., 2006). A similar bias has been noticed in several other model simulations : in global models at 1/10° resolution (POP and OFES) (Maltrud and McClean, 2005; Sasaki et al., 2005), in global models at 1/4° resolution (DRAKKAR and OCCAM) (Barnier et al., 2006, see figure their 12), in a Atlantic model at 1/6° resolution (CLIPPER) (Barnier et al., 2006), and in a regional model at 1/10° resolution (HYCOM) (Backeberg et al., 2009). In global models at 1/16° and 1/32° resolutions such as NLOM a similar pattern with spurious high variability upstream of the Agulhas Retroflection is still present (Wallcraft et al., 2002, see figure their 2). Such upstream variability was also found in a regional model at 1/4° resolution (SAfE) (Penven et al., 2006a). To the exception of the regional models of Biastoch and Krauß (1999); Biastoch et al. (2008) and de Miranda A. et al. (1999), almost all realistic models have encountered an equivalent bias in their representation of the Agulhas Retroflection dynamics. This bias has been reduced (or even removed) by improving the numerical precision (Backeberg et al., 2009) or the conservation properties (Barnier et al., 2006) of the momentum advection scheme, or by smoothing the topography and adding a parameterization for horizontal viscosity (Penven et al., 2006a). Nevertheless, there is not at this time a definite answer on why this type of bias occur, and if it is possible to systematically prevent it. Such recurrent biases in model simulations of the Agulhas Current system emphasize the need for a better understanding of the system.

3. MODELLING THE AGULHAS LEAKAGE

Two model simulations have suggested that the Agulhas Leakage has increased in the last decades with possible important climatic implications (Biastoch et al., 2009; Rouault et al., 2009). Although both studies agree in relating this increase to changes in winds over the Indian Ocean, there is a debate over the process involved. van Sebille et al. (2009) (and also Biastoch et al. (2009) hypotheses) imply an anticorrelation between the Agulhas Leakage and the Agulhas Current transport. In Rouault et al. (2009) simulation, an increased Agulhas Current induces an increased Agulhas Leakage. It occurs in conjunction with a warming at the surface of the Ocean, in agreement with observations. This illustrates the need of a better knowledge of the relationship between the Agulhas Current and the Agulhas Leakage.

A set of idealized numerical experiments based on ROMS (Shchepetkin and McWilliams, 2005) has been specifically designed to explore this relationship. The model generates a subtropical gyre interacting with a topographical feature representing the African continent (Figure 1). The gyre is forced by an analytical wind and a restoring towards surface temperature and surface salinity, all 3 varying only with latitude (Figure 1). After a spinup of 20 years using a basin scale model alone, a 2-way nested grid based on AGRIF (Penven et al., 2006b; Debreu et al., 2011) at 1/9° resolution is introduced (see Figure 1), and the simulation is run for 10 more years.

Although based on simplified geometry and surface forcing, this simulation is able to reproduce the general Agulhas Current properties, such as eddy kinetic energy, mean transport and temperature. Figure 2 presents the modeled temperature after 30 years at sea surface (Figure 2a) and at 500 m depth (Figure2b). For such an idealized model, the comparison with World Ocean Atlas climatology is notable, indicating that the key processes are reproduced. A characteristic is a high mesoscale variability, showing a spectral peak at 43 days (i.e. 8-9/year) for the Agulhas Leakage. This corresponds approximately to the frequency of Agulhas Rings generation (de Ruijter et al., 1999).

To test the sensitivity of the Agulhas Current and the Agulhas Leakage to wind strength, 20 experiments are run with a wind multiplied by a coefficient ranging from 0.1 to 2. The leakage is measured as the westward flux at the southern tip of Africa of a passive tracer restored toward 1 in the Indian Ocean (East of 40°E), and toward 0 in the Atlantic Ocean (West of 5°E). Statistics are made using the last 8 years of each simulation. At equilibrium, the mean Agulhas transport increases linearly with the wind, following approximately the Sverdrup relation. Figure 3 presents the mean Agulhas Leakage as a function of the mean Agulhas transport using 8 years (blue) and 1 year (red) of simulation to compute the averages. These simulations produce an Agulhas Leakage larger than generally observed. The model values obtained by van Sebille et al. (2009) are added for comparison. Using 8 years averages, the Agulhas Leakage increases almost monotonically with the incoming Agulhas transport. For an Agulhas transport below 50 Sv, the slope of the curve is about 0.3, while it more than doubles to reach 0.8 above 50 Sv. There is indication of a slow down of the increase for the highest values. Using only 1 year averages, the perturbations induced by the mesoscale activity creates variations of large amplitude. These experiments present an example of a system where at statistical equilibrium, and in a closed domain, a stronger Agulhas Current could lead to more Agulhas leakage, in agreement with Rouault et al. (2009). The results obtained by van Sebille et al. (2009) are in the same order of magnitude, but the variations of Agulhas transports employed are too limited to derive general conclusions (Figure 3).

4. CONCLUSION

Ocean models have now reached a sufficient precision to reproduce key elements of the Agulhas Current system, such as the Agulhas Retroflection and the Agulhas Rings shedding. Nevertheless, there are still recurrent biases which are not yet totally understood. Two model solutions show different results for the processes controlling the Agulhas Leakage. Specific idealized numerical experiments for the subtropical gyre of the Indian Ocean are conducted to explore the processes controling the Agulhas Leakage. These simulations reproduce the general patterns of the Agulhas Current System and a strong mesoscale variability. For these simulations, the Agulhas Current increases with the wind forcing, and the Agulhas Leakage increases quasi-monotonically with the Agulhas Current. A detailed analysis of these experiments will be made to address the processes associated with the variations of the Agulhas Current and Agulhas Leakage. This idealized model configuration will be also used to test new hypotheses for past and future climate.

REFERENCES

Backeberg, B. C., Bertino, L., Johannessen, J. A., 2009. Evaluating two numerical advection schemes in HYCOM for eddy-resolving modelling of the Agulhas Current. Ocean Sci. 5, 173–190.

Bard, E., Rickaby, R. E. M., 2009. Migration of the subtropical front as a modulator of glacial climate. Nature 460, 380–383, doi: 10.1038/nature08189.

Barnier, B., Madec, G., Penduff, T., Molines, J.-M., Treguier, A.-M., Le Sommer, J., Beckmann, A., Biastoch, A., Böning, C., Dengg, J., Derval, C., Durand, E., Gulev, S., Remy, E., Talandier, C., Theetten, S., Maltrud, M., McClean, J., Cuevas, B. D., 2006. Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution. Ocean Dyn. 56, 543–567, doi:10.1007/s10236-006-0082-1.

Biastoch, A., Böning, C. W., Lutjeharms, J. R. E., 2008. Agulhas leakage dynamics affects decadal variability in atlantic overturning circulation. Nature 456, 489–492.

Biastoch, A., Böning, C. W., Schwarzkopf, F. U., Lutjeharms, J. R. E., 2009. Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies. Nature 462, 495–498.

Biastoch, A., Krauß, W., 1999. The role of mesoscale eddies in the source regions of the Agulhas Current. J. Phys. Oceanogr. 29, 2303–2317.

Boudra, D., Chassignet, E. P., 1988. Dynamics of the Agulhas retroflection and ring formation in a numerical model. Part I: The vorticity balance. J. Phys. Oceanogr. 18, 280–303.

de Miranda A., Barnier, B., Dewar, D. K., 1999. Mode waters and subduction rates in a high resolution South Atlantic simulation. J. Mar. Res. 57, 213-244.

de Ruijter, W. P. M., Biastoch, A., Drijfhout, S. S., Lutjeharms, J. R. E., Matano, R. P., Pichevin, T., van Leeuwen, P. J., Weijer, W., 1999. Indian-Atlantic interocean exchange: Dynamics, estimation and impact. J. Geophys. Res. 104, 20885–20910.

Debreu, L., Marchesiello, P., Penven, P., 2011. Two-way embedding algorithms for a split-explicit free surface model. Ocean Model., in prep.

Ducet, N., Le Traon, P. Y., Reverdin, G., 2000. Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. J. Geophys. Res. 105, 19,477–19,498.

Gordon, A. L., 1986. Inter-ocean exchange of thermocline water. Geophys. Res. Lett. 91, 5037–5046.

Gordon, A. L., 2003. The brawniest retroflection. Nature 421, 904–905.

Lutjeharms, J. R. E., 2006. The Agulhas Current. Springer-Verlag.

Lutjeharms, J. R. E., van Ballegooyen, R. C., 1984. Topographic control in the Agulhas Current system. Deep Sea Res. 31, 1321–1337.

Lutjeharms, J. R. E., van Ballegooyen, R. C., 1988. The retroflection of the Agulhas Current. J. Phys. Oceanogr. 18, 1570–1583.

Lutjeharms, J. R. E., Webb, D. J., 1995. Modelling the Agulhas current system with FRAM (fine resolution antarctic model). Deep Sea Res., Part I 42, 523–551.

Maltrud, M. E., McClean, J. L., 2005. An eddy resolving 1/10° ocean simulation. Ocean Model. 8, 31–34.

Matano, R. P., 1996. A numerical study of the Agulhas Retroflection: The role of bottom topography. J. Phys. Oceanogr. 26, 2267–2279.

Ou, H. W., de Ruijter, W. P. M., 1986. Separation of an inertial boundary current from a curved coastline. J. Phys. Oceanogr. 16, 280–289.

Peeters, F. J. C., Acheson, R., Brummer, G.-J. A., de Ruijter, W. P. M., Ganssen, G. G., Schneider, R. R., Ufkes, E., Kroon, D., 2004. Vigorous exchange between indian and atlantic ocean at the end of the last five glacial periods. Nature 400, 661–665.

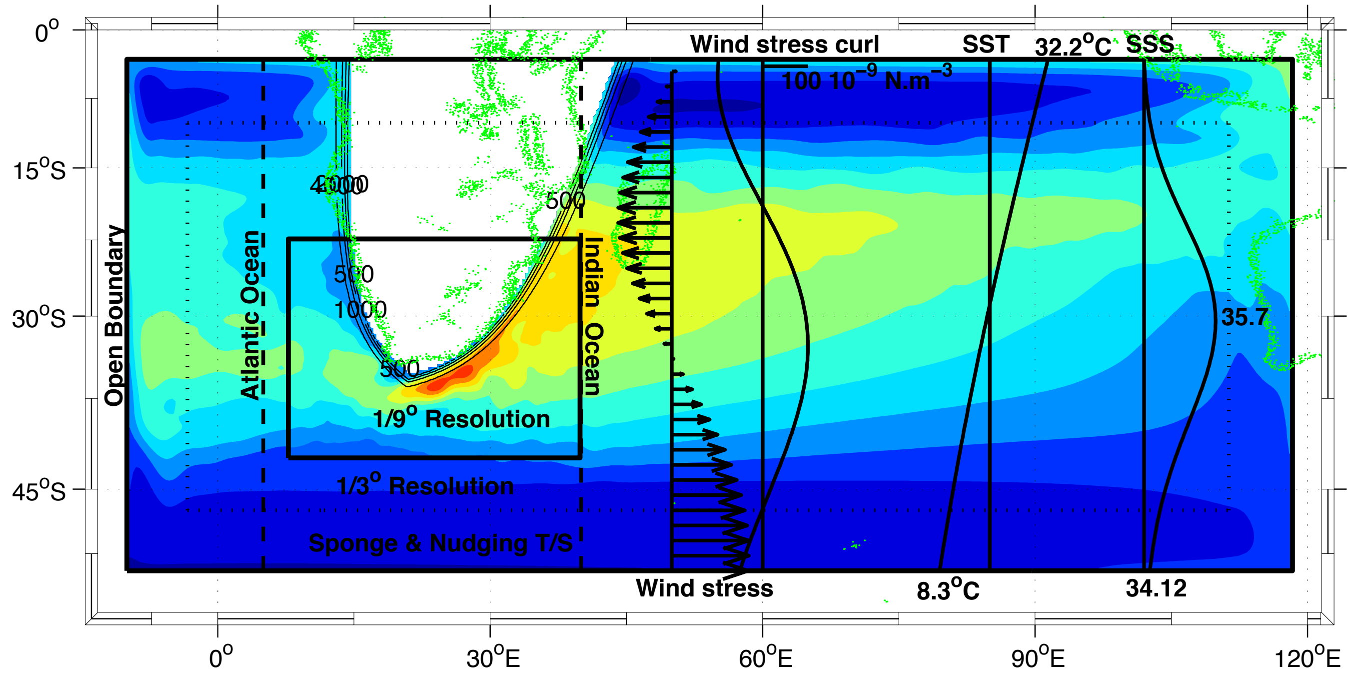

Figure 1. Model grid, bottom topography, surface forcing (wind stress, wind stress curl, sea surface temperature and sea surface salinity) and mean sea surface elevation (1 contour / 10 cm)

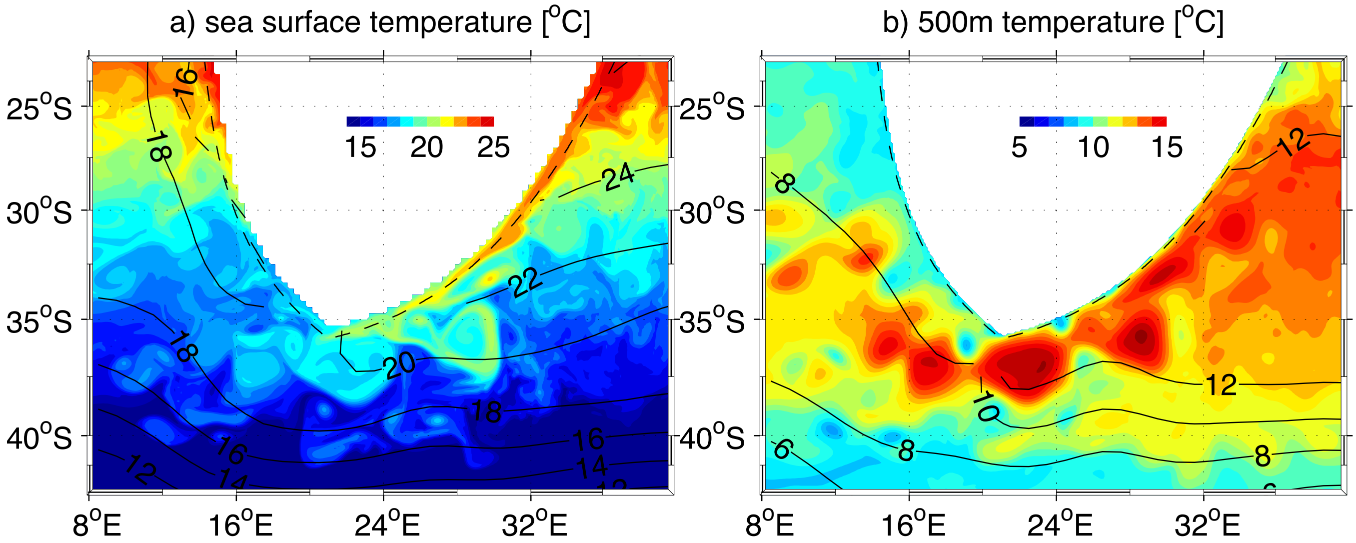

Figure 2. Model temperature for 1 January of year 30 at sea surface (a) and at 500 m depth (b). The contours represents the annual mean from World Ocean Atlas 2005 climatology.

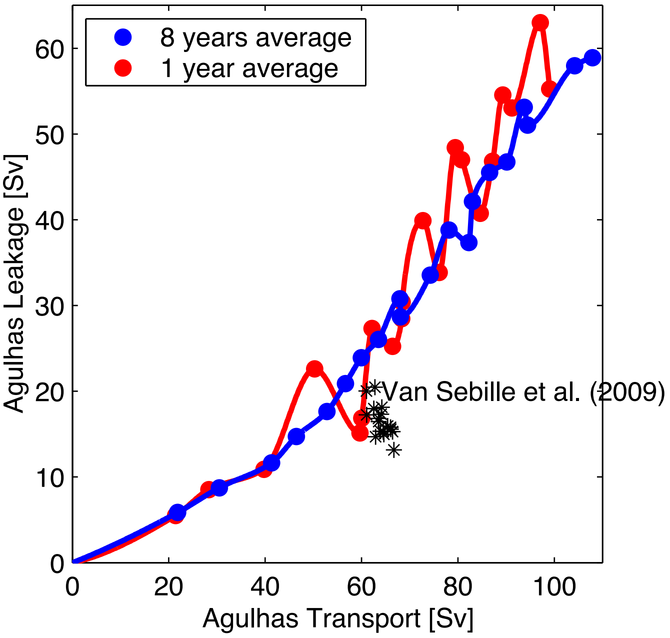

Figure 3. mean Agulhas leakage [1Sv = 10^6 $m^3.s^{-1}$] as a function of the incoming mean Agulhas Current transport [Sv]. Blue: statistics made using 8 years of experiment. Red: statistics made using 1 year of experiment. Stars: results obtained by van Sebille et al. (2009).

Penven, P., Chang, N., Shillington, F., April 2-7 2006a. Modelling the Agulhas Current using SAfE (Southern Africa Experiment). In: Proc. EGU General Assembly, Vienna, Austria.

Penven, P., Debreu, L., Marchesiello, P., McWilliams, J. C., 2006b. Application of the ROMS embedding procedure for the central California Upwelling System. Ocean Model. 12, 157–187.

Penven, P., Lutjeharms, J. R. E., Florenchie, P., 2006c. Madagascar: a pacemaker for the Agulhas Current system? Geophys. Res. Lett. 33, L17609, doi:10.1029/2006GL026854.

Reason, C. J. C., 2001. Evidence for the influence of the Agulhas Current on regional atmospheric circulation patterns. J. Clim. 14, 2769–2778.

Richardson, P. L., 2007. Agulhas leakage into the Atlantic estimated with subsurface floats and surface drifters. Deep Sea Res., Part I 54, 1361–1389.

Rouault, M., Penven, P., 2011. New perspectives on Natal Pulses from satellite observations. J. Geophys. Res.In revision.

Rouault, M., Penven, P., Pohl, B., 2009. Warming in the Agulhas Current system since the 1980's. Geophys. Res. Lett. 36, L12602, doi:10.1029/2009GL037987.

Rouault, M., White, S. A., Reason, C. J. C., Lutjeharms, J. R. E., Jobard, I., 2002. Ocean-atmosphere interaction in the Agulhas Current region and a South African extreme weather event. Wea. Forecasting 17, 655-669.

Sasaki, H., Komori, N., Takahashi, K., Masumoto, Y., Sakuma, H., 2005. Fifty years time-integration of global eddy-resolving simulation. Tech. rep., Earth Simulator Center, Yokohama, Japan.

Schouten, M. W., de Ruijter, W. P. M., van Leeuwen, P. J., 2002. Upstream control of Agulhas ring shedding. J. Geophys. Res. 107.

Shchepetkin, A. F., McWilliams, J. C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. 9, 347–404.

van Sebille, E., Biastoch, A., van Leeuwen, P. J., de Ruijter, W. P. M., 2009. A weaker Agulhas Current leads to more Agulhas leakage. Geophys. Res. Lett. 36, L03601, doi:10.1029/2008GL036614.

Wallcraft, A. J., Hurlburt, H. E., Rhodes, R. C., Shriver, J. F., 2002. 1/32° global ocean modeling and prediction. Tech. rep., Naval Research Laboratory, Stennis Space Center, MS 39529-5004.

Weijer, W., de Ruijter, W. P. M., Dijkstra, H. A., van Leeuwen, P. J., 1999. Impact of interbasin exchange on the Atlantic overturning circulation. J. Phys. Oceanogr. 29, 2266–2284.

Zahn, R., 2009. Climate change: Beyond the CO2 connection. Nature 460, 335–336, doi: 10.1038/460335a.