JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. C9, PAGES 20,859-20,861, SEPTEMBER 15, 1999

Introduction to special section:

World Ocean Circulation Experiment: South Atlantic results

Arnold L. Gordon,[1] Bernard Barnier,[2] Kevin Speer,[3,4] and Lothar Stramma[5]

Oceanographers are increasingly urged to think globally. The World Ocean Circulation Experiment (WOCE) organized and implemented a strategy for a global view of the ocean. Yet the global ocean and its influence on the climate system consist of an interlocked array of regions. Heat and freshwater pass between component oceanic regions which, on coupling by sea-air fluxes, act in concert with atmosphere fluxes, the essence of climate. Each ocean basin plays its role, differing by virtue of its unique geometry and atmospheric coupling. Deep convection of the saline North Atlantic must balance the freshwater accumulation within the North Pacific, instilling global thermohaline circulation. Similarly, deep convection in the Southern Ocean must somehow be compensated by larger-scale thermohaline circulation.

What is the role of the South Atlantic in the global reference frame? WOCE observational (Figures 1 and 2) and model studies have done much to address this topic. The subtropical South Atlantic forms varied types of Subtropical Mode Water; shallow upwelling occurs in the eastern boundary regions and within the equator belt, as with other oceans. However, what it does uniquely is that it exposes the North Atlantic water mass products to the Antarctic Circumpolar Current, giving it global access. Equally important is the associated climate issue of the nature of the upper ocean flow that balances the export of deep water. The South Atlantic thermocline exchange with the Indian Ocean thermocline and the injection of Pacific Ocean derived Antarctic intermediate and mode water masses in Drake Passage are all part of the hotly debated "warm route, cold route" subject, echoed in this collection of WOCE based articles.

At the crux of the debate is that the South Atlantic displays the most curious feature of the global ocean: oceanic heat flux toward the equator! Warm upper waters move northward, compensating southward moving, cooler deep water. Ultimately, this heat warms the northern climes of the North Atlantic. Estimates range from 0.2 to 0.9 PW for the northward heat flux across the subtropical belt, with the error estimated in excess of 0.2 PW. There appears to be significant north-south divergence of the meridional heat flux with seasonal (large) and interannual (weaker) variability, hence a large range in heat flux estimates is to be expected. Recent attention to this issue by models and observations has not yet narrowed the range, but there is optimism that further analysis of the diverse WOCE data set will provide better estimates of the spatial and temporal variability of the meridional heat flux.

The South Atlantic is unique in its collection of diverse water masses. Within the Argentine Basin of the South Atlantic one can sample just about all of the major water masses formed in the world ocean: deep water from the North Atlantic, deep and intermediate water from the Pacific, locally derived intermediate water and mode water types, and bottom and deep water formed in the Weddell Sea. These varied water masses spread under the constraint of the bottom topography for the densest waters and vigorously mix within the eddy-rich environment at the confluence of the Malvinas and Brazil Currents. The advection of Subtropical Atlantic Water within the South Atlantic Current contributes both to the Benguela Current and the Indian Ocean. In the southeastern Atlantic, Indian Ocean water masses intrude into the South Atlantic. There a complex circulation is set up in which South Atlantic and Indian Ocean Waters intermingle. Injection of Indian Ocean Waters at the Agulhas Retroflection, into the Benguela Current, make for a unique eastern boundary regime, one where energetic western boundary eddies are found within the eastern upwelling environment. Agulhas eddies mix with surrounding waters, following a track affected by bottom topography, and travel across most, if not all of the South Atlantic.

In the equatorial region a branch of the South Atlantic South Equatorial Current passes along the coast of Brazil to enter into the Northern Hemisphere, by what is likely to be a complex pathway involving eddies and the zonal flow and

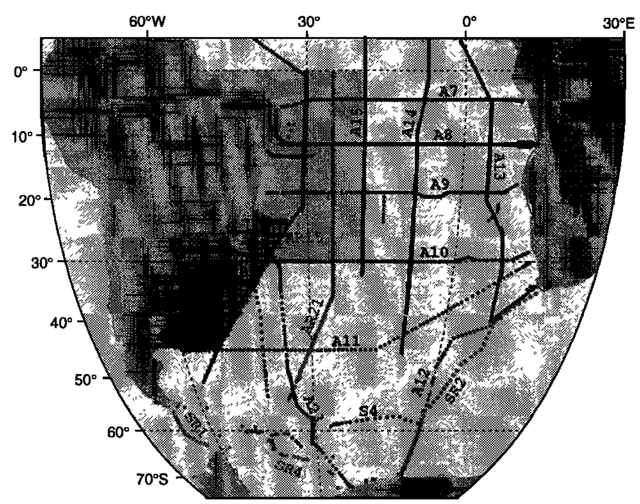

Figure 1. World Ocean Circulation Experiment Hydrographic Program one time and repeat lines within the South Atlantic Ocean. The special study areas in the western South Atlantic are shaded. Individual dots indicate conductivity-temperature-depth (CTD) station locations.

[1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York.
[2]Laboratoire des Ecoulements Géophysiques et Industriels, UMR 5519 CNRS/UJF/INPG, Grenoble, France.
[3]Laboratoire de Physique des Oceans, IFREMER/CNRS/UBO, Plouzane, France.
[4]Department of Oceanography, Florida State University, Tallahassee.
[5]Institut fuer Meereskunde, Kiel, Germany.

Paper number 1999JC900186.
0148-0227/99/1999JC900186$09 00

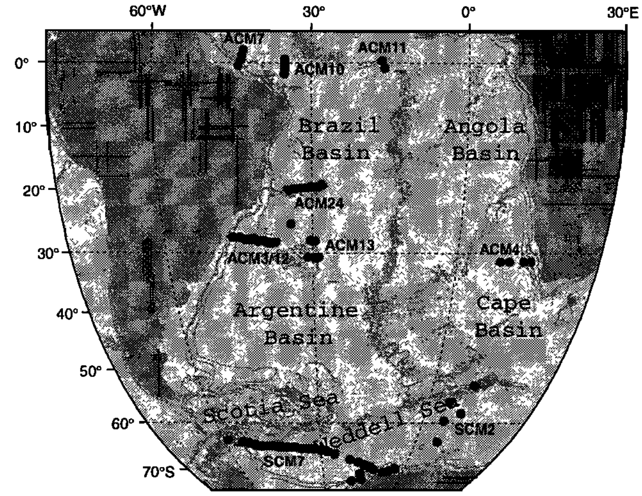

Figure 2. World Ocean Circulation Experiment current meters positions within the South Atlantic, with topography and basin names.

upwelling characteristic of the equatorial belt. Much progress had been made during the WOCE period in the equatorial region as direct velocity profiles (Acoustic Doppler Current Profiler (ADCP) and lowered ADCP (LADCP)) became operational and provided velocity sections to overcome the shortcomings of geostrophy at all latitudes, particularly near the equator. A large cyclonic gyre occupies the eastern tropical region of the South Atlantic. Variations of the size of this gyre may represent an Atlantic "El Niño." In the deep equatorial Atlantic, southward transport of North Atlantic Deep Water within the Deep Western Boundary Current displays large transport variability, recirculation cells, and branching near the equator, in which part advects eastward while the major part continues southward as a deep western boundary current.

The 22 papers in the present collection of WOCE based South Atlantic articles touch upon all of the topics mentioned above. They are organized as follows: an overview paper by Stramma and England; four papers dealing with large-scale and interactions with adjacent ocean; then, regional topics, the eastern South Atlantic and Agulhas eddies (five papers, including that by *Beismann et al.* [1999], which was inadvertently published in an earlier issue *of Journal of Geophysical Research-Oceans*), the Brazil/Malvinas and southwest South Atlantic (eight papers), and the tropics (four papers).

There have been numerous South Atlantic articles published in JGR and elsewhere in recent years, including the excellent volume by *Wefer et al* [1996], most of which are based on WOCE observational or modeling efforts. The reference list herein includes many South Atlantic articles published from 1997 to 1999 [*Andrie et al.*, 1998; *Arhan et al.*, 1998, 1999; *Barnier et al.*, 1998; *Beismann et al.*, 1999; *Boebel et al.*, 1997, 1999, *De Miranda et al.*, 1999; *Florenchie and Verron*, 1998; *Gan et al.*, 1998; *Garzoli et al*, 1997; *Glorioso and Flather*, 1997; *Goni et al.*, 1997; *Gründlingh*, 1999; *Hogg and Owens*, 1999; *Hogg and Zenk*, 1997; *Jones et al.*, 1998; *Larque et al.*, 1997; *Maamaatuaiahutapu et al.*, 1998; *Marchesiello et al.*, 1998; *Matano et al.*, 1998; *Oudot et al.*, 1998; *Polzin et al.*, 1997; *Rhein et al.*, 1998; *Schott et al.*, 1998; *Smythe-Wright and Bosell*, 1998; *Smythe-Wright et al.*, 1998; *Stramma and Schott*, 1999; *Stutzer and Krauss*, 1998; *Thompson et al.*, 1997; *Van Leeuwen*, 1999; *Venegas et al.*, 1997, 1998; *You*, 1999; *Zavialov et al.*, 1998]. Our South Atlantic collection does not reflect the total WOCE contributions to the South Atlantic. One can safely anticipate continued production of science results stemming from the rich WOCE data set.

Acknowledgments. We greatly acknowledge the assistance of Lewis M. Rothstein and his JGR staff at the University of Rhode Island in the preparation of the WOCE South Atlantic collection. We thank Roberta Boscolo of the WOCE International Project Office in Southampton for providing the figures.

References

Andrie, C, J F. Ternon, M.J. Messias, L. Memery, and B. Bourles, Chlorofluoromethane distributions in the deep equatorial Atlantic during January-March 1993, *Deep Sea Res., Part 1, 45*, 903-931, 1998.

Arhan, M., H Mercier, B. Bourles, and Y. Gouriou, Hydrographic sections across the Atlantic at 7°30' N and 4°30' S, *Deep Sea Res., Part I, 45*, 829-872, 1998.

Arhan, M., K. Heywood, and B. King, The deep water from the southern ocean at the entry to the Argentine Basin, *Deep Sea Res., Part II, 46*, 475-500, 1999.

Barnier, B., P. Marchesiello, A.P D. Miranda, J.M. Molines, and M. Coulibaly, A sigma-coordinate primitive equation model for studying the circulation in the South Atlantic, 1, Model configuration with error estimates, *Deep Sea Res., Part 1, 45*, 543-572, 1998.

Beismann, J.-O., R.H Kase, and J R.E Lutjeharms, On the influence of submarine ridges on translation and stability of Agulhas rings, *J. Geophys. Res., 104*, 7897-7906, 1999

Boebel, O, C. Schmid, and W. Zenk, Flow and recirculation of Antarctic Intermediate Water across the Rio Grande Rise, *J. Geophys. Res., 102*, 20,967-20,986, 1997

Boebel, O., C. Schmid, and W. Zenk, Kinematics elements of Antarctic Intermediate Water in the western South Atlantic, *Deep Sea Res., Part II, 46*, 355-392, 1999

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

Florenchie, P., and J Verron, South Atlantic Ocean circulation: Simulation experiments with a quasi-geostrophic model and assimilation of TOPEX/POSEIDON and ERS 1 altimeter data, *J. Geophys Res, 103*, 24,737-24,758, 1998.

Gan, J., L.A. Mysak, and D.N Straub, Simulation of the South Atlantic Ocean circulation and its seasonal variability, *J. Geophys. Res., 103*, 10,241-10,252, 1998.

Garzoli, S.L., G.J. Goni, A.J Mariano, and D B. Olson, Monitoring the upper southeastern Atlantic transports using altimeter data, *J. Mar Res. 55*, 453-481, 1997.

Glorioso, P.D, and R A. Flather, The Patagonian Shelf tides *Prog. Oceanogr., 40*, 263-283, 1997.

Goni, G J., S L. Garzoli, A J. Roubicek, D B. Olson, and O.B. Brown, Agulhas ring dynamics from TOPEX/POSEIDON satellite altimeter data, *J. Mar Res., 55*, 861-883, 1997.

Gründlingh, M., Surface currents derived from satellite-tracked buoys off Namibia, *Deep Sea Res., Part II, 46*, 453-474, 1999.

Hogg, N G., and W.B Owens, Direct measurement of the deep circulation within the Brazil Basin, *Deep Sea Res., Part II, 46*, 335-354, 1999.

Hogg, N.G, and W. Zenk, Long-period changes in the bottom water flowing through Vema Channel, *J. Geophys. Res., 102*, 15,639-15,646, 1997.

Jones, M.S., M. Allen, T. Guymer, and M. Saunders, Correlation between altimetric sea surface height and radiometric sea surface temperature in the South Atlantic, *J. Geophys. Res., 103*, 8073-8088, 1998.

Larque, L., L.K. Maamaatuaiahutapu, and V. Garcon, On the intermediate and deep water flows in the South Atlantic Ocean, *J Geophys. Res., 102*, 12,425-12,440, 1997

Maamaatuaiahutapu, K., V. Garcon, C. Provost, and H. Mercier, Transports of the Brazil and Malvinas Currents at their Confluence, *J. Mar. Res., 56*, 417-438, 1998.

Marchesiello, P., B Barnier, and A.P De Miranda, A sigma-coordinate primitive equation model for studying the circulation in the South Atlantic, 11, Meridional transports and seasonal variability, *Deep Sea Res., Part II, 45,* 573-608, 1998

Matano, R.P., C.G. Simionato, W.P. de Ruijter, P.J. van Leeuween, P.T. Strub, D B. Chelton, and M.G. Schlax, Seasonal variability in the Agulhas Retroflection region, *Geophys. Res. Lett., 25,* 4361-4364, 1998.

Oudot, C., P. Morin, F Baurand, M Wafar, and P.L. Corre, Northern and southern water masses in the equatorial Atlantic: distribution of nutrients on the WOCE A6 and A7 lines, *Deep Sea Res,. Part I, 45,* 873-902, 1998

Polzin, K., J.M Toole, J.R Ledwell, and R W. Schmitt, Spatial Variability of Turbulent Mixing in the Abyssal Ocean, *Science, 276,* 93-96, 1997

Rhein, M , L Stramma, and G Krahmann, The spreading of Antarctic Bottom Water in the tropical Atlantic, *Deep Sea Res., Part I, 45,* 507-527, 1998.

Schott, F.A , J Fischer, and L. Stramma, Transports and pathways of the upper-layer circulation in the western tropical Atlantic, *J. Phys. Oceanogr , 28,* 1904-1928, 1998

Smythe-Wright, D , and S Bosell, Abyssal circulation in the Argentine Basin, *J. Geophys Res , 103,* 15,845-15,851, 1998

Smythe-Wright, D., P. Chapman, C D Rae, L.V. Shannon, and S.M. Boswell, Characteristics of the South Atlantic subtropical frontal zone between 15° W and 5° E, *Deep Sea Res , Part I, 45,* 167-192, 1998

Stramma, L. , and F. Schott, The mean flow field of the tropical Atlantic Ocean, *Deep Sea Res., Part II, 46,* 279-304, 1999

Stutzer, S., and W Krauss, Mean circulation and transports in the South Atlantic Ocean. Combining model and drifter data, *J Geophys. Res., 103,* 30,985-31,002, 1998

Thompson, S.R, D P Stevens, and K Doos, The importance of interocean exchange south of Africa in a numerical model, *J. Geophys. Res., 102,* 3303-3316, 1997

Van Leeuwen, P.J., The time-mean circulation in the Agulhas region determined with the ensemble smoother, *J. Geophys. Res., 104,* 1393-1404, 1999.

Venegas, S.A., L A Mysak, and D N Straub, Atmosphere-ocean coupled variability in the South Atlantic, *J. Clim., 10,* 2904-2920, 1997

Venegas, S A , L.A. Mysak, and D N. Straub, An interdecadal climate cycle in the South Atlantic and its links to other ocean basins, *J Geophys. Res , 103,* 24,723-24,736, 1998

Wefer, G , W H Berger, G. Siedler, and D.J Webb (eds.), *The South Atlantic Present and Past Circulation* 644 pp., Springer-Verlag, New York, 1996

You, Y., Dianeutral mixing, transformation and transport of Antarctic Intermediate Water in the South Atlantic, *Deep Sea Res., Part II, 46,* 393-436, 1999

Zavialov, P.O , R D Ghisolfi, and C.A.E. Garcia, An inverse model for seasonal circulation over the South Brazilian Shelf. near-surface velocity from the heat budget, *J. Phys. Oceanogr., 28,* 545-562, 1998.

B. Barnier, Laboratoire des Ecoulements Géophysiques et Industriels, UMR 5519 CNRS/UJF/INPG, BP53, 3804 Grenoble,France

A.L Gordon, Lamont-Doherty Earth Observatory, Columbia University, Route 9W, Palisades, NY 10964 (agordon@ldeo.columbia.edu)

K Speer, Department of Oceanography, Florida State University, Tallahassee FL 32306

L Stramma, Institut fuer Meereskunde, Duesternbrooker Weg 20, 2405 Kiel, Germany

(Received June 17, 1999, accepted June 18, 1999.)