GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L03605, doi:10.1029/2007GL032760, 2008

Click Here for Full Article

Indian Ocean Rossby waves detected in HYCOM sea surface salinity

David M. Heffner,[1] Bulusu Subrahmanyam,[1,2] and Jay F. Shriver[3]

Received 21 November 2007; accepted 31 December 2007; published 5 February 2008.

[1] Rossby waves have been well identified in satellite derived sea surface height (SSH), sea surface temperature (SST) and ocean color observations. Studies of Rossby waves have yet to include sea surface salinity (SSS) as a parameter, largely because presently available in situ measurements of salinity lack sufficient spatial and temporal coverage, and as of now no methods are available for measuring salinity from a satellite. In this paper, we demonstrate that Rossby waves can be observed in SSS in the Indian Ocean by using simulations of the 1/12° global Hybrid Coordinate Ocean Model (HYCOM). HYCOM results compared favorably to SSS data provided by Argo floats and the World Ocean Atlas 2005 (WOA05) in selected grid boxes in the Indian Ocean. Hovmöller diagrams of HYCOM SSS anomalies and gradient show the distinct westward propagating signature of Rossby waves, with a steeper slope in longitude/time plots further from the equator. The propagation speeds, calculated from a 2D Radon Transform are comparable with new theoretical speeds for Rossby waves. Annual westward propagating signals in the SSS simulations at most of the latitudes in the Indian Ocean coincide with previous studies. We hope that future studies of Rossby waves in SSS using model results and eventually satellite measurements of salinity data will allow a better understanding of Rossby wave dynamics. **Citation:** Heffner, D. M., B. Subrahmanyam, and J. F. Shriver (2008), Indian Ocean Rossby waves detected in HYCOM sea surface salinity, *Geophys. Res. Lett.*, *35*, L03605, doi:10.1029/2007GL032760.

1. Introduction

[2] Although planetary wave theory has been around since the late 1800s, and was heavily improved upon by Carl-Gustav Rossby in the 1930s and 40s, it wasn't until the advent of satellite altimetry that oceanographers were able to observe Rossby waves throughout the world's oceans [*Chelton and Schlax*, 1996; *Cipollini et al.*, 2000]. *Chelton and Schlax* [1996] were not only the first to show the presence of Rossby waves throughout the world using sea surface height observations from TOPEX/Poseidon (T/P) altimetry, but also demonstrated that the standard linear theory for Rossby wave propagation was lacking, as it could not account for the observed phase speeds which were in general faster, by a factor greater than 2 in some parts of the ocean. *Killworth et al.* [1997] extended the theory to account for the mean background flow and *Killworth and Blundell* [2003a, 2003b] (hereinafter referred to as KB2003) further extended it to include the combined effect of mean flow and topographic slope. These extensions, especially the mean flow, resolve most of the discrepancy between theory and observation.

[3] Rossby waves have been well identified in sea surface height (SSH) measurements from Geosat and T/P altimetry [*Perigaud and Delecluse*, 1992; *Chelton and Schlax*, 1996; *Cipollini et al.*, 1997; *Subrahmanyam et al.*, 2001]. Recent studies showed that aside from SSH, Rossby waves have also been detected by satellite in sea surface temperature (SST) [*Cipollini et al.*, 1997; *Hill et al.*, 2000], and ocean color data [*Cipollini et al.*, 2001; *Uz et al.*, 2001; *Killworth et al.*, 2004]. Rossby waves are generally easier to identify in the SSH measurements from altimetry than SST or ocean color observations because altimetry is an all weather sensor not disrupted by clouds. Although Rossby waves have been observed in SSH, SST, and ocean color, studies on Rossby waves have yet to include sea surface salinity (SSS) as a parameter, largely because presently available in situ measurements of salinity lack sufficient spatial and temporal coverage.

[4] Satellite measurements of SST using passive (infrared) and active (microwave) radiometers have been available since the 1970s, but as of the writing of this paper, no methods are available for measuring SSS from a satellite, although there are two planned satellite missions-Aquarius and SMOS. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission has been designed to observe soil moisture over the Earth's landmasses and salinity over the oceans. The SMOS satellite launch is scheduled for 2008 (http://www.esa.int/esaLP/LPsmos.html). Aquarius/SAC-D is a space mission developed by NASA and the Space Agency of Argentina (Comisión Nacional de Actividades Espaciales, CONAE), which is planning to launch in 2009.

[5] Despite the importance of the Indian Ocean in the global climate system, in situ data in this region is quite sparse both in time and space. Development of a systematic observing system in the Indian Ocean is well behind those in the Pacific and Atlantic Oceans. We hope that the combination of SMOS and Aquarius salinity missions will provide detailed SSS observations for the Indian Ocean from which Rossby wave signals can identified. Rossby waves are prominent in the southern Indian Ocean, existing as an annual westward propagating signal between 10°S and 12°S [*Perigaud and Delecluse*, 1992; *White*, 2000; *White et al.*, 2004], and as semiannual signals between 20° and 35°S [*Morrow and Birol*, 1998; *Birol and Morrow*, 2001]. *Quartly et al.* [2003] compared Rossby waves at various latitudes in the Indian Ocean, and found that between 15°S and 29°S, planetary wave signals in ocean color, SSH, and SST data were in phase with each other, while at 34°S,

[1]Department of Geological Sciences, University of South Carolina, Columbia, South Carolina, USA.
[2]Marine Science Program, University of South Carolina, Columbia, South Carolina, USA.
[3]Naval Research Laboratory, Stennis Space Center, Mississippi, USA.

0094-8276/08/2007GL032760$05.00

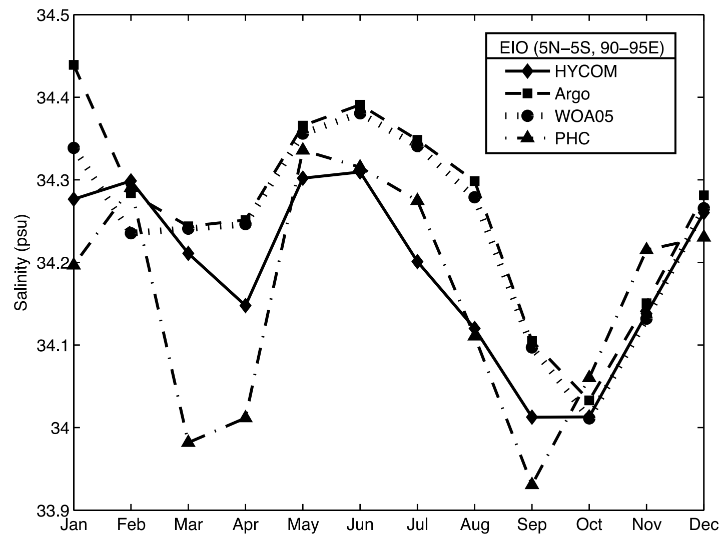

Figure 1. Annual variation of HYCOM, Argo, and World Ocean Atlas 2005 (WOA05) sea surface salinity in the EIO box (5°N–5°S, 90°–95°E) during 2003–2006.

ocean color lagged SSH by a quarter of a cycle, and SSH lagged SST by a quarter of a cycle.

[6] The purpose of this study is to demonstrate that Rossby waves can be observed in SSS. Up until this point, nobody has shown that Rossby waves can be seen in SSS at least in the Indian Ocean, largely because there is currently no easy way to acquire basin wide salinity data. This paper demonstrates that Rossby waves can be identified in the sea surface salinity (SSS) signal, using HYbrid Coordinate Ocean Model (HYCOM) simulations as a proxy for the awaited SSS data.

2. HYCOM Model Simulations

[7] The HYbrid Coordinate Ocean Model (HYCOM) is isopycnal in the open, stratified ocean, but uses the layered continuity equation to make a dynamically smooth transition to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas [*Bleck*, 2002]. It maintains the significant advantages of an isopycnal model in stratified regions while allowing higher vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics.

[8] In this study we used global HYCOM with 1/12° horizontal resolution (~7 km at mid-latitudes) and 32 hybrid layers in vertical. The model is configured on a Mercator grid from 78°S to 47°N, while north of this latitude an Arctic dipole patch is used to avoid the singularity at the pole.

[9] HYCOM was initialized using monthly mean temperature and salinity from the 1/4° Generalized Digital Environmental Model (GDEM3) climatology [*NAVOCEANO*, 2003] in August. This experiment was then run for 13 years using climatological monthly mean wind and thermal forcing constructed from the 1.125° European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA15) over the 1979–1993 time frame. In addition, 6-hourly variability from the ECMWF operational model over the period September 1994–September 1995 was added to the climatological wind forcing (but not the thermal forcing) to add the higher frequency variability needed for realistic simulation of the surface mixed layer. In order to keep the evaporation minus precipitation budget on track, the model weakly relaxes to monthly mean SSS from the Polar Science Center Hydrographic Climatology (PHC) SSS. The PHC climatology is chosen for its accuracy in the Arctic region [*Steele et al.*, 2001]. The actual SSS relaxation e-folding time depends on the mixed layer depth (MLD) and is (30 days × 30 m/MLD m) days, i.e. it is more rapid when the MLD is shallow and less so when it is deep. The SSS relaxation is sufficient to avoid long-term drift in SSS, but not so strong as to inhibit SSS anomaly formation. The SSS relaxation is in addition to the evaporation-precipitation budget.

[10] Once the model was determined to be equilibrated after being spun-up with climatological forcing, the simulation was then continued using 3 hourly Navy Operational Global Atmospheric Prediction System (NOGAPS) winds, heat fluxes and precipitation fields for the period 2003–2006 as the forcing. This version of the model uses the NASA Goddard Institute for Space Studies level 2 (GISS) mixed layer scheme and includes monthly river runoff from 986 global rivers. There is no assimilation of any ocean data, including SST, and no relaxation to any other data except SSS to keep the evaporation minus precipitation balance on track. A data assimilative version of this model is presently being developed as the ocean model component of an eddy resolving operational nowcast/forecast system for the Naval Oceanographic Office (NAVOCEANO).

[11] Figure 1 shows an example of a comparison of mean monthly (2003–2006) HYCOM SSS with World Ocean Atlas 2005 (WA05) salinity, PHC climatology and Argo float data in the Equatorial Indian Ocean box (EIO: 5°N–5°S, 90°–95°E). Argo and WOA05 track each other closely, with HYCOM salinities varying between ±0.15 psu compared with Argo and WOA05. The PHC climatology exhibits similar variability to ARGO, WOA and HYCOM, with the largest differences in March–April and September. When considering the limitations on the accuracy of measurements

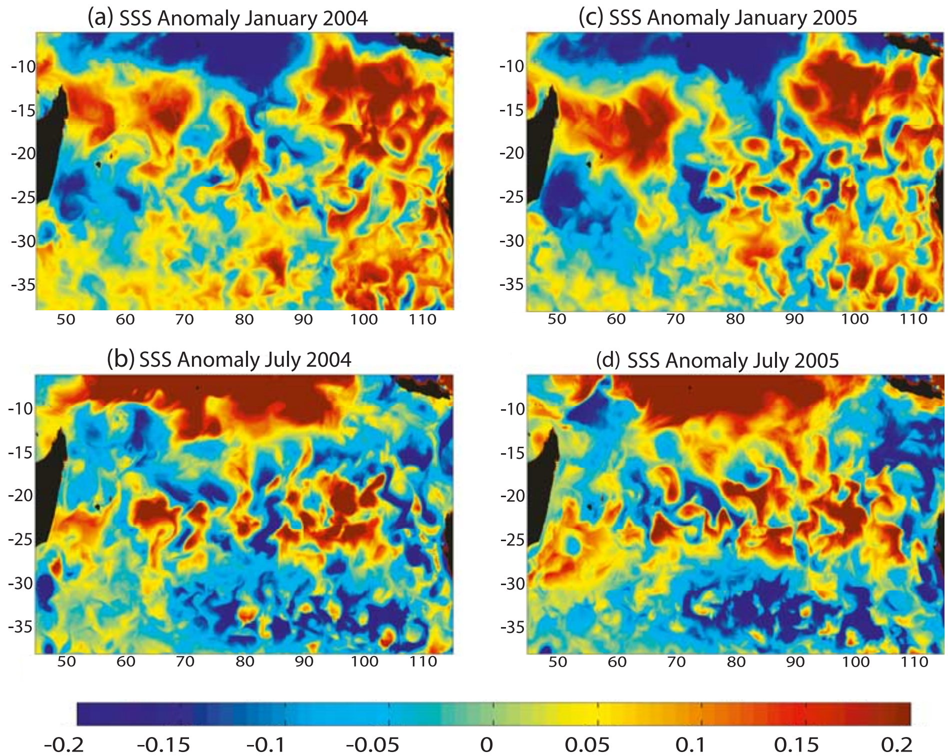

Figure 2. HYCOM sea surface salinity anomalies during (a) January 2004, (b) July 2004, (c) January 2005, and (d) July 2005.

of SSS, The differences between the 3 climatologies aren't significant. It is also evident from this figure that the SSS relaxation is sufficient to prevent large drift in SSS, but not so strong that the SSS is tightly constrained to follow PHC, thereby suppressing the SSS anomalies of interest. The correlation satisfied us that these HYCOM simulations of SSS could be used to study Rossby waves in the Indian Ocean. Comparisons have been made in other boxes throughout the Indian Ocean (not shown) where Argo data is available, which showed similar results.

3. Methods

[12] The first simple technique we used to locate Rossby waves in the HYCOM SSS simulations was to produce longitude/time plots (also know as Hovmöller diagrams) along several latitudes within the Indian Ocean. Rossby waves show up in these diagrams as westward moving diagonal features, with a decreasing slope in longitude/time plots closer to the equator. To make the waves easier to see, we removed the temporal and spatial means. From these diagrams a rough estimate of the wave speeds can be computed, however this method is quite subjective, and can be rather slow when trying to consider an entire ocean basin.

[13] In order to get more objective results, we applied a discrete 2D Radon Transform (RT) [*Chelton and Schlax*, 1996; *Cipollini et al.*, 2000; *Challenor et al.*, 2001] to the SSS gradients, which were regridded to 0.5 degrees longitude by 10 days to reduce noise [*Cipollini et al.*, 2001], and were de-trended in time and space. Rossby wave speeds aren't necessarily constant across lines of latitude [*Chelton and Schlax*, 1996; *Killworth et al.*, 1997], yet the Radon Transform identifies the most energetic source propagating at a constant speed [*Cipollini et al.*, 2000; *Challenor et al.*, 2001], so to reduce the problems this may cause, at each latitude for consideration we segmented the diagrams into 5 degree (longitude) sections, and applied the Radon Transform to each segment. We also applied a Fast Fourier Transform (FFT) to the de-trended longitude/time (L/T) plots of SSS gradient in order to get wave number and frequency to calculate Rossby wave phase speeds (not shown here). Finally we compared Rossby wave phase speeds obtained from HYCOM SSS with the new theoretical speeds of KB 2003.

4. Results

[14] The SSS anomaly (SSSA) for the months of January and July for the years 2004 and 2005 are presented in Figure 2. These snapshots were selected because they illustrate the large seasonal and interannual variability that occurs in Indian Ocean SSS, and a strong Rossby wave signal can be seen propagating throughout that time period, across various latitudes (Figure 3). The southern tropical Indian Ocean exhibits positive SSSA in Austral Summer (January) and negative SSSA in Austral winter (July). The surface salinity distribution highlights the presence of low salinity waters (negative SSSA) from the eastern basin, entering the Indian Ocean through the Indonesian Through-Flow (ITF) between 5°S and 15°S (July 2004 and 2005, Figure 2). In January, 2004 and 2005, the ITF signature in the southeastern region (10–15°S and east of 90°E) is nearly absent. The absence of the ITF signature in January and its presence in July (in both the years) is related to the seasonal variation in the magnitude of the ITF [*Gordon and Fine*, 1996]. The flow of low salinity ITF

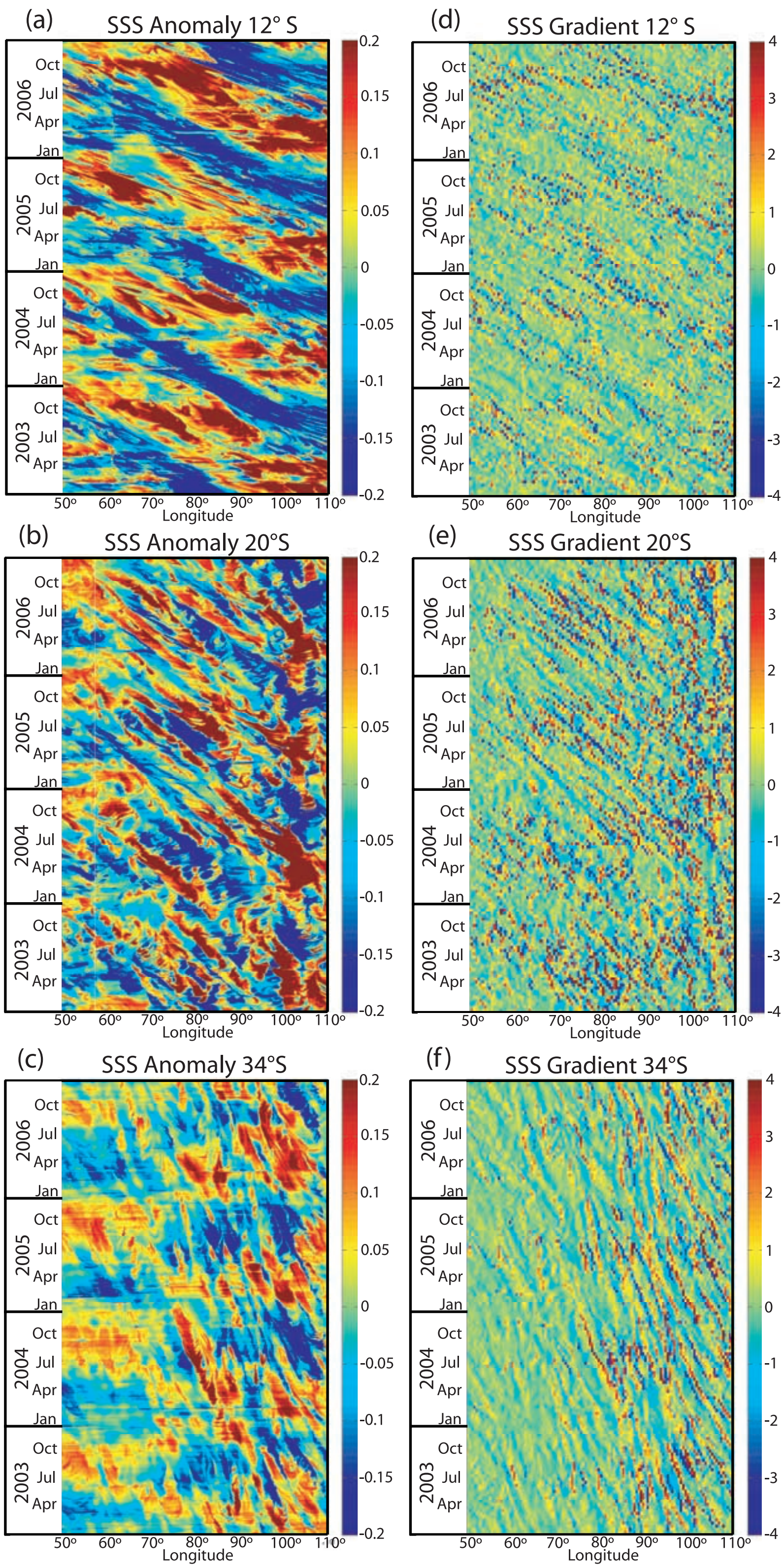

Figure 3. Longitude/Time plots of (left) sea surface salinity anomaly and (right) sea surface salinity gradient at 12°S, 20°S, and 34°S.

waters towards western Australia in July 2005 is more pronounced than in July 2004. The dominant positive SSS anomalies in July between 8S and 12S can be attributed to the upwelling (divergence) in the region of a thermocline ridge [*Annamalai and Murtugudde*, 2004]. The other important features are the occurrence of negative SSSA off southeastern Madagascar in January (both in 2004 and 2005) and the opposite variation in July in the same region.

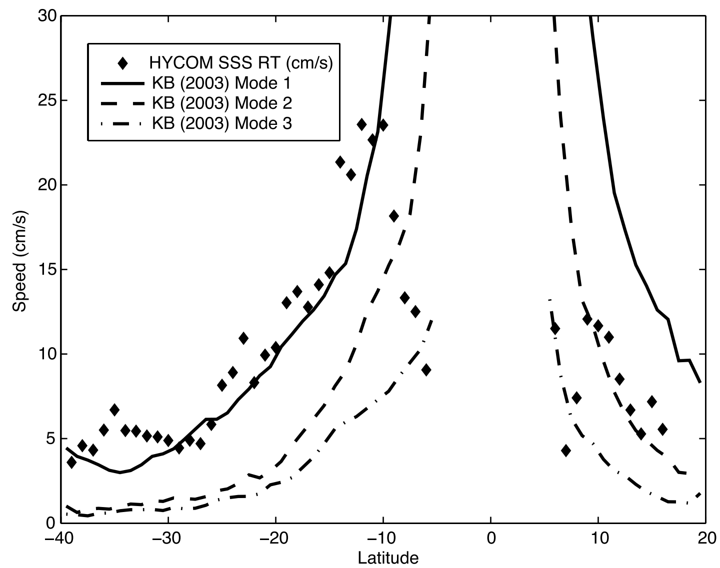

Figure 4. Comparison of HYCOM SSS Rossby wave speeds with the speeds predicted by *Killworth and Blundell* [2003a, 2003b].

The more negative SSSA off Madagascar in January may be related to the local precipitation, while the positive SSSA in July in the same region may be related to the coastal upwelling. South of 15°S, one encounters the sub-tropical high salinity zone extending from the South Africa coast to the eastern basin. The strong north-south salinity gradients would lead to strong lateral mixing between the high salinity waters and low salinity waters. In this strong gradient zone, the propagation of low frequency Rossby waves can be seen as westward moving salinity anomalies.

[15] The model results exhibit Rossby waves at all the latitudes from 40°S-20°N in the Indian Ocean, however the Rossby waves are not clear in the salinity signal north of 12°N. Figure 3 shows SSS anomalies as a function of time (left) and SSS gradients (right) along the latitudes 12°S, 20°S, and 34°S. The Rossby waves in Figure 3 are largely generated once per year, with the expected decrease in phase speed with increasing latitude. The dominance of annual Rossby waves is consistent with *Birol and Morrow* [2001]. From these measurements, a rough estimation of speed can be calculated, roughly 19 cm/s at 12°S, 8.8–9.6 cm/s at 20°S, and 3.1–3.2 cm/s at 34°S. While it is easier to visualize the Rossby waves in the SSS anomaly figures (Figures 3a, 3b, and 3c) the westward propagating features can also be seen in the gradient figures (Figures 3d, 3e, and 3f) that were used in the Radon Transform.

[16] The results of the discrete Radon Transform (Figure 4) compared quite well with the new theoretical speed for Rossby waves given by *Killworth and Blundell* [2003a, 2003b]. As can be seen in Figure 4, latitudes 40°S to 10°S match the predicted speed for baroclinic first mode Rossby waves, yet interestingly none of the northern latitudes matched the predicted first mode baroclinic Rossby wave speeds. The Radon Transform results between 9°N and 16°N matches the predicted travel speeds for second mode baroclinic Rossby waves. The northern and southern hemisphere (NH and SH, respectively) baroclinic mode phase speed differences likely resulted from our application of the Radon Transform in the NH not considering the Bay of Bengal and the Arabian Sea basins separately. These two basins have different physical characteristics (specifically in salinity) that result in the phase speed differences between NH and SH.

5. Conclusions

[17] A global version of the Hybrid Coordinated Ocean Model (HYCOM) is used to investigate if Rossby waves can be seen in sea surface salinity (SSS) in the Indian Ocean. As of this writing, this question has not been addressed due to temporally and spatially sparse observations of SSS. Our analysis of HYCOM SSS shows that realistic Rossby wave signals can be observed in SSS throughout the Indian Ocean. Not only do the speeds of the signals match well to the *Killworth and Blundell* [2003a, 2003b] theoretical speeds, but they also compared very well with previous work on the Indian Ocean [*Perigaud and Delecluse*, 1992; *Morrow and Birol*, 1998; *Subrahmanyam et al.*, 2001].

[18] In the future we hope the SMOS and Aquarius salinity missions will help us to identify and detect these Rossby waves more easily, although it may be a bit of a challenge, depending on whether these satellite measurements can identify any small-scale salinity gradients. In future studies, we plan to investigate further the dynamical processes by which Rossby waves affect SSS. These processes will be examined using satellite derived parameters such as SSH, SST, ocean color, along with results from HYCOM.

[19] **Acknowledgments.** This work was supported in part by the NASA Physical Oceanography Program under Grant NNG06GJ22G awarded to BS. JS was supported by the 6.1 project "Global and Remote Littoral Forcing in Global Ocean Models" sponsored by the Office of Naval Research (ONR) under program element 601153N. The HYCOM model results were obtained under grants of challenge and non-challenge computer time from the Department of Defense High Performance Computing Program at the Naval Oceanographic Office, Stennis Space Center, MS. We wish to give special thanks to Jeff R. Blundell for providing helpful comments and discussion that greatly enhanced this paper. We would also

like to thank Peter Killworth for making the theoretical Rossby wave speed data available, and Paolo Cipollini for valuable discussions. Finally, the authors would like to express their deep appreciation to two anonymous reviewers for their detailed comments, which significantly improved the quality of this paper.

References

Annamalai, H., and R. Murtugudde (2004), The role of the Indian Ocean in regional climate variability, in [bno]*Earth Climate: The Ocean-Atmosphere Interaction*[/bno], *Geophys. Monogr. Ser.*, vol. 147, pp. 213–246, AGU, Washington, D. C.

Birol, F., and R. Morrow (2001), Source of the baroclinic waves in the southeast Indian Ocean, *J. Geophys. Res.*, *106*, 9145–9160.

Bleck, R. (2002), An oceanic general circulation model framed in hybrid isopycnic—Cartesian coordinates, *Ocean Modell.*, *37*, 55–88.

Challenor, P. G., P. Cipollini, and D. Cromwell (2001), User of the 3D Radon Transform to examine the properties of oceanic Rossby waves, *J. Atmos. Oceanic Technol.*, *18*, 1558–1566.

Chelton, D. B., and M. G. Schlax (1996), Global observations of oceanic Rossby waves, *Science*, *272*, 234–238.

Cipollini, P., D. Cromwell, M. S. Jones, G. D. Quartly, and P. G. Challenor (1997), Concurrent altimeter and infrared observations of Rossby wave propagation near 34°N in the Northeast Atlantic, *Geophys. Res. Lett.*, *24*, 889–892.

Cipollini, P., D. Cromwell, G. D. Quartly, and P. G. Challenor (2000), Remote sensing of oceanic extra-tropical Rossby waves, in *Satellites, Oceanography, and Society*, edited by D. Halpern, pp. 99–123, Elsevier, New York.

Cipollini, P., D. Cromwell, P. G. Challenor, and S. Raffaglio (2001), Rossby waves detected in global ocean colour data, *Geophys. Res. Lett.*, *28*, 323–326.

Gordon, A. L., and R. A. Fine (1996), Pathways of water between the Pacific and Indian Oceans in the Indonesian Seas, *Nature*, *379*, 146–149.

Hill, K. L., I. S. Robinson, and P. Cipollini (2000), Propagation characteristics of extratropical planetary waves observed in the ASTR global sea surface temperature record, *J. Geophys. Res.*, *105*, 21,927–21,945.

Killworth, P. D., and J. R. Blundell (2003a), Long extratropical planetary wave propagation in the presence of slowly varying mean flow and bottom topography. Part I: The local problem, *J. Phys. Oceanogr.*, *33*, 784–801.

Killworth, P. D., and J. R. Blundell (2003b), Long extratropical planetary wave propagation in the presence of slowly varying mean flow and bottom topography. Part II: Ray propagation and comparison with observations, *J. Phys. Oceanogr.*, *33*, 802–821.

Killworth, P. D., D. B. Chelton, and R. de Szoeke (1997), The speed of observed and theoretical long extratropical planetary waves, *J. Phys. Oceanogr.*, *27*, 1946–1966.

Killworth, P. D., P. Cipollini, B. M. Uz, and J. R. Blundell (2004), Physical and biological mechanisms for planetary waves observed in satellite-derived chlorophyll, *J. Geophys. Res.*, *109*, C07002, doi:10.1029/2003JC001768.

Morrow, R., and F. Birol (1998), Variability in the southeast Indian Ocean from altimetry: Forcing mechanisms for the Leeuwin Current, *J. Geophys. Res.*, *103*, 18,529–18,544.

NAVOCEANO (2003), Database description for the generalized digital environmental model (GDEM–V) Version 3.0.OAML–DBD–72, 34 pp., NAVOCEANO Oceanogr. Data Bases Div., Stennis Space Center, Miss.

Perigaud, C., and P. Delecluse (1992), Annual sea level variations in the southern tropical Indian Ocean from Geosat and shallow-water simulations, *J. Geophys. Res.*, *97*, 20,169–20,178.

Quartly, G. D., P. Cipollini, D. Cromwell, and P. G. Challenor (2003), Rossby waves: Synergy in action, *Philos. Trans. R. Soc. Ser. A*, *361*, 57–63.

Steele, M., R. Morley, and W. Ermold (2001), A global ocean hydrography with a high quality Arctic Ocean, *J. Clim.*, 2079–2087.

Subrahmanyam, B., I. S. Robinson, J. R. Blundell, and P. G. Challenor (2001), Indian Ocean Rossby waves observed in TOPEX/POSEIDON altimeter data and in model simulations, *Int. J. Remote Sens.*, *22*, 141–167.

Uz, B. M., J. A. Yoder, and V. Osychny (2001), Pumping of nutrients to ocean surface waters by the action of propagating planetary waves, *Nature*, *409*, 597–600.

White, W. B. (2000), Coupled Rossby waves in the Indian Ocean on Interannual Timescales, *J. Phys. Oceanogr.*, *30*, 2972–2988.

White, W. B., K. A. Gloersen, F. Marsac, and Y. M. Tourre (2004), Influence of coupled Rossby waves on primary productivity and tuna abundance in the Indian Ocean, *J. Oceanogr.*, *60*, 531–541.

D. M. Heffner and B. Subrahmanyam, Department of Geological Sciences, University of South Carolina, 701 Sumter Street, EWS 617, Columbia, SC 29208, USA. (sbulusu@geol.sc.edu)

J. F. Shriver, Naval Research Laboratory, Code 7323 Building 1009, Stennis Space Center, MS 39529-5004, USA.