GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L12607, doi:10.1029/2005GL022728, 2005

Observational evidence of alternating zonal jets in the world ocean

Nikolai A. Maximenko,[1] Bohyun Bang,[1] and Hideharu Sasaki[2]

Received 15 February 2005; revised 28 April 2005; accepted 20 May 2005; published 21 June 2005.

[1] Multiple zonal jets with the east-west velocity direction alternating with latitude are discovered in satellite altimetry data. The time-varying jets are shown to populate every part of the world ocean and its marginal seas and are best seen in the anomaly of geostrophic vorticity. At midlatitudes the jets have a meridional wavelength of about 300 kms with r.m.s. sea level, velocity and vorticity values of 2.4 cm, 6.9 cm/s and $1.5 \cdot 10^{-6}$ s^{-1}, correspondingly. Realistic data from the high-resolution OGCM run on the Earth Simulator are used to justify high vertical coherence of the jets structure and relevance of the jets to an evolving mesoscale eddy field. Strong coupling between the jets and mesoscale eddies is hypothesized. **Citation:** Maximenko, N. A., B. Bang, and H. Sasaki (2005), Observational evidence of alternating zonal jets in the world ocean, *Geophys. Res. Lett.*, *32*, L12607, doi:10.1029/2005GL022728.

1. Introduction

[2] A tendency of a two-dimensional (2D) (or barotropic) eddy field on a rotating sphere to form zonal jets has been evaluated in many previous studies (e.g., see the review of basic dynamics of the jets by *Rhines* [1994] and recent results of *Galperin et al.* [2004]). It has been shown that under a broad range of conditions quasi-geostrophic eddies behave like 2D turbulence and evolve into energetic alternating zonal jets. In support of the theory, jets are observed in the atmospheres of Jupiter and Saturn [e.g., *Kondratyev and Hunt*, 1982] in association with bands of clouds. Recent progress in geophysical supercomputing [*Ohfuchi et al.*, 2005] has provided multi-decadal outputs of pretty realistic eddy-resolving basin-wide or even global numerical models of the Earth's ocean. *Nakano and Hasumi* [2005] showed that zonal jets are distinct in the one-year averaged currents at 1 km depth and that they occupy the entire domain of the North Pacific model. Persistence of similar zonal structures in other numerical models, such as the OFES (OGCM for the Earth Simulator [*Masumoto et al.*, 2004]), suggests the robustness of their physics. However, to the best of our knowledge the existence of these jets in the ocean has not been confidently confirmed by observations.

[3] Although many meridional hydrographic and ADCP sections [*Wijffels et al.*, 1998; *Treguier et al.*, 2003; *Hall et al.*, 2004] do reveal alternating velocities, the horizontal extent of these structures is unknown. Moreover, similar patterns are seen in meridional velocities measured along zonal sections, which in this case are obviously formed by eddies and meandering frontal jets. Some trajectories of deep floats also indicate the prevalence of zonal currents, but their ensemble fails to resolve individual jets, if any.

[4] At present, data with sufficient horizontal and temporal resolution and coverage are only available from remote sensing and are confined to the sea surface. Attempts to detect zonal jets (ZJs) of the nature discussed above are missing in previous studies. This may be partly because the theory of 2D turbulence is more applicable to the deep ocean layers and/or because the wind-driven circulation overwhelms the upper ocean currents. Here, we describe a method to extract the surface signature of ZJs from maps of satellite altimetry. We also use the OFES output to justify the relevance of the extracted signal to deep ZJs. Both datasets are then used to evaluate properties of the jets.

2. Data

[5] The data used in this work are 513 weekly maps (from October 14, 1992 through August 7, 2002) of the sea level anomaly distributed by Aviso (CLS Archiving, Validation, and Interpretation of Satellite Oceanographic Data project) and computed using the technique suggested by *Ducet et al.* [2000]. The data are on Mercator grid with a 1/3° increment in the zonal direction and variable steps in latitude. They were optimally interpolated using merged corrected along-track sea level anomaly data from the TOPEX/Poseidon, ERS-1/2, Jason-1 and Envisat altimeters with a mapping function having a time scale of 10 (15) days poleward (equatorward) of 5° latitude and zonal (meridional) scale varying from 350 km (250 km) on the equator to 100 km (100 km) at 60° latitude. At each grid point we have subtracted the overall time mean, so that the "anomaly" (hereafter, "observed" sea level anomaly or SLA) is now defined relative to the entire period of the dataset used.

[6] The OFES model, described in detail by *Masumoto et al.* [2004], is based on the MOM3 with 54 vertical levels and a horizontal grid spacing of 1/10°. It was run starting from the World Ocean Atlas 1998 annual mean for 50 model years, forced by the NCEP/NCAR climatology. Used in this study are nine years (January 1, Model Year 42 through December 31, MY50) of daily snapshots of the sea surface height and six years (January, MY45 through December, MY50) of monthly mean horizontal velocity at the 1041 m level (hereafter, 1 km). To reduce the computational load, all grids were reduced to ½° horizontal resolution by taking spatially weighted averages.

3. Zonal Jets in the Altimeter Data

[7] An example of the observed SLA h'_o smoothed over 18 weeks around the period centered on September 10, 1997 is shown in Figure 1a. This map reveals dominant signals associated with large-scale intra- and interannual

---

[1] International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii, USA.

[2] The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology, Kanazawa-ku, Yokohama, Japan.

0094-8276/05/2005GL022728$05.00

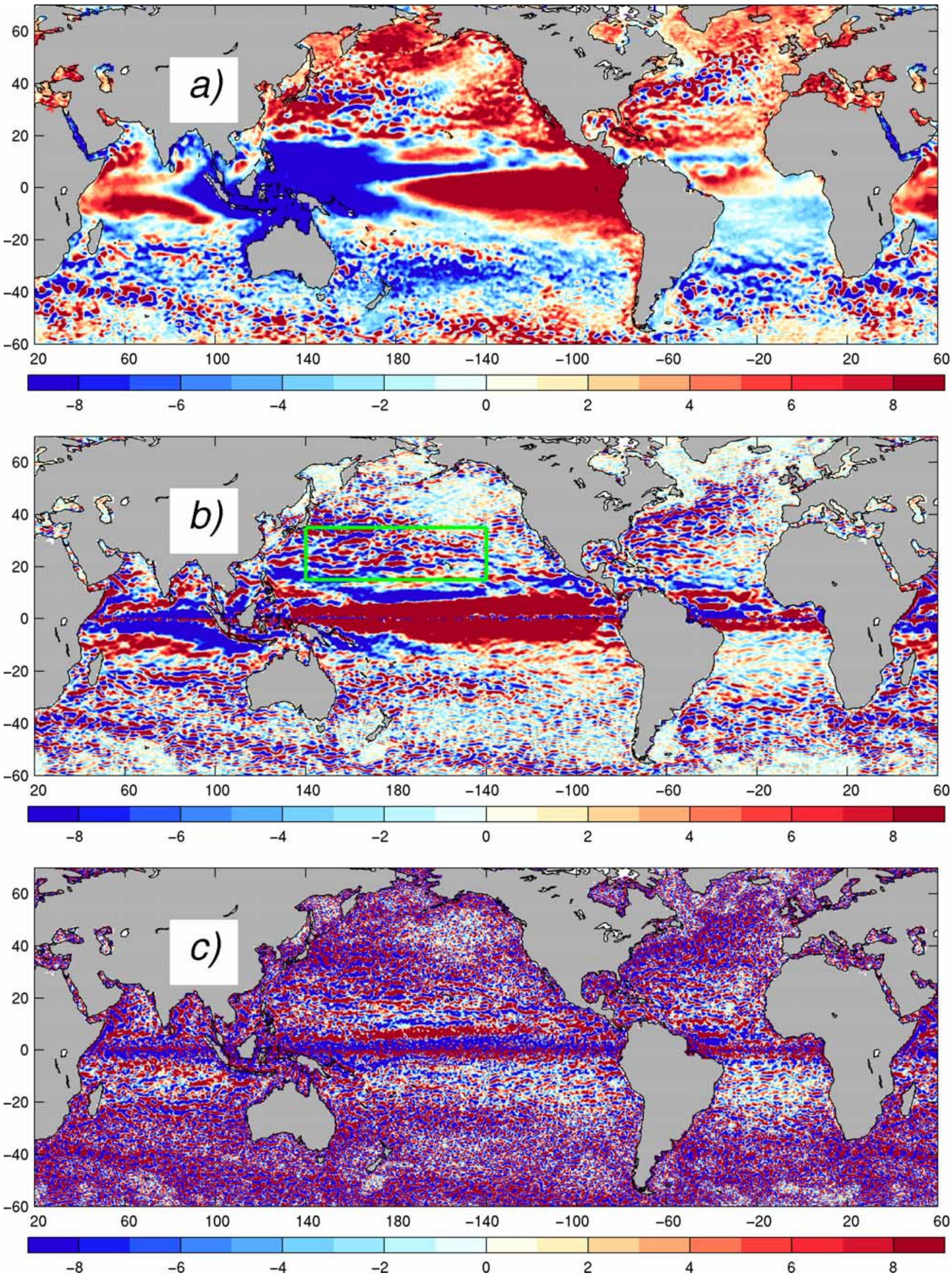

Figure 1. 18-week averages of Aviso 10-year anomalies of sea level h'_o (*a*, cm), geostrophic velocity U'_o (*b*, cm/s) and geostrophic vorticity ζ'_o (*c*, 10^{-7} s^{-1}). Rectangle (*b*) marks domain of Figure 3.

processes, such as the ENSO [*Neelin et al.*, 1998], the Indian Ocean dipole [*Saji et al.*, 1999] and the Pacific decadal oscillation [*Polovina et al.*, 1995]. To see whether any jet-like structure is hidden behind these monsters, a high-pass spatial filtering is necessary. A simple way to emphasize the smaller scales is to differentiate the original data along horizontal coordinates. The anomaly of zonal geostrophic velocity $U'_o = -\partial h'_o/\partial y \cdot g/f$, where g is the acceleration due to gravity and f is the Coriolis parameter, is shown in Figure 1b. In a striking contrast to Figure 1a, it does reveal a global pattern of alternating jets similar to the ones obtained by *Nakano and Hasumi* [2005] in their one-year mean model currents at 1 km depth. The jets are also distinct on the map of the anomaly of geostrophic vorticity $\zeta'_o = \Delta\ h'_o \cdot g/f$ (Δ is a Laplacian) displayed in Figure 1c. While horizontal anisotropy of U'_o can partly be attributed to a unidirectional differentiation, the operator relating ζ'_o to h'_o is fully isotropic, and, hence, the zonally elongated jet-like structures (whether realistic or fictitious) are hidden in the observed SLA.

[8] At midlatitudes (20°–40°), r.m.s. values of the anomalies of zonal velocity and vorticity, estimated from maps in Figure 1, are $R_U = 6.9$ cm/s and $R_\zeta = 1.5 \cdot 10^{-6}\ s^{-1}$, respectively. The dominant wavelength in the meridional direction can thus be estimated as $L = 2\pi R_U/R_\zeta \approx 280$ km, which agrees with a 300–400 km estimate obtained by a manual count of the jets. The r.m.s. SLA associated with the jets can be estimated as $R_H = (f \cdot R_U^2)/(g \cdot R_\zeta) \approx 2.4$ cm. Thus, although R_ζ is only 2% of the local value of f, characteristic values of R_U and R_H are both within the accuracy of modern *in situ* and remote instruments [*Le Traon and Ogor*, 1998]. However, as wind-driven currents are very strong in the upper ocean [*Niiler et al.*, 2003], the relevance of the discovered structures to the hypothetical deep ZJs ought to be justified.

4. Zonal Jets in the OFES Data

[9] Similarly to results of *Nakano and Hasumi* [2005], the OFES solution demonstrates a clear tendency to form deep ZJs. Therefore, the OFES data were used to analyze the vertical structure of the jets. Results of an application of the procedure described in Section 3 to the OFES data are shown in Figure 2. Deep ZJs are apparent in Figure 2a, which shows a map of the model anomaly of zonal velocity U'_{m1km} at 1 km. Characteristics of the jets analogous to the ones described in Section 3 are $R_U = 1.8$ cm/s, $R_\zeta = 3.8 \cdot 10^{-7}\ s^{-1}$, $L = 309$ km, and $R_H = 0.7$ cm.

[10] The model anomaly U'_m of geostrophic zonal velocity at the sea surface shown in Figure 2b contains the same or similar jet-like features with $R_U = 7.4$ cm/s, $R_\zeta = 1.7 \cdot 10^{-6}\ s^{-1}$, $L = 267$ km, and $R_H = 2.3$ cm. Between latitudes 20° and 55° in both hemispheres it correlates with U'_{m1km} at coefficient 0.67 (0.62 for vorticity), and the width and the strength of the jets in U'_m are in qualitative agreement with Figure 1b for the observed U'_o. This example illustrates that a time-variable part of ZJs is highly coherent in the vertical and most energetic at the sea surface, where the signal is a factor of three to four stronger than at the 1 km level.

5. Properties of the Jets

[11] Successful detection of the ZJ signal in the set of quasi-continuous global satellite altimeter maps collected since 1992 provides a unique opportunity for comprehensive study of the jets' dynamics. Presented here are the preliminary results of the first approach to the problem.

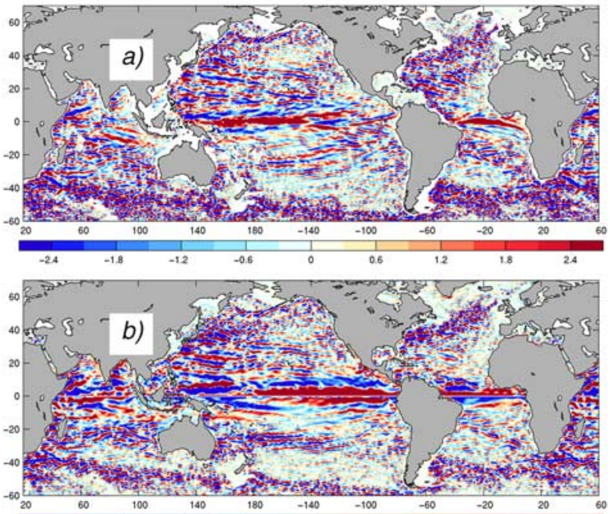

Figure 2. Anomalies (in cm/s) of the OFES model zonal velocity U'_{m1km} at 1 km depth (*a*) and geostrophic zonal velocity at the sea surface U'_m (*b*) averaged over four months centered on March, MY48.

[12] Zonally elongated structures are seen in almost every part of Figure 1b including even such isolated basins as the South China, Japan, Okhotsk and Mediterranean seas. Their widths differ from place to place and generally decrease poleward. In some regions, the jets seem to be not exactly zonal. For instance, in the Gulf Stream extension (around 40°N, 60°W) they are systematically tilted from the west-southwest to the east-northeast. Seasonal variations of the jets properties, if any, are not obvious. Correspondence of the jets' width to the *Rhines* [1975] scale $L_R = (2U/\beta)^{1/2}$, where U is a characteristic eddy velocity and β is a meridional gradient of planetary vorticity, is good in some regions but vague in others. For instance, as expected from the Rhines theory, the jets in Figure 1b are broader in the Kuroshio Extension, where eddy energy is among the highest in the world, than in the eastern North Pacific, where eddy activity is typically low. On the other hand, the jet width seems to be steady or monotonically increasing all the way south from the Kuroshio Extension to the North Equatorial Current in contrast to simultaneous monotonic increase of β and large (by an order of magnitude) variations in U.

[13] *Are these structures real jets or are they propagating eddies smoothed in time?* Mesoscale eddies are known to move westward [*Cushman-Roisin et al.*, 1990]. Although meridional motions are also observed [*Morrow et al.*, 2004], they are much weaker. The signal of a typical individual eddy, when smoothed in time, would produce a zonally elongated structure with its width corresponding to the eddy size and its length defined by the displacement of the eddy. The maps of U'_o in Figure 3 show for the central part of the North Pacific Subtropical Gyre that, indeed, jets are more coherent in the zonal direction when data are averaged over longer time periods. However, the jets are recognizable even

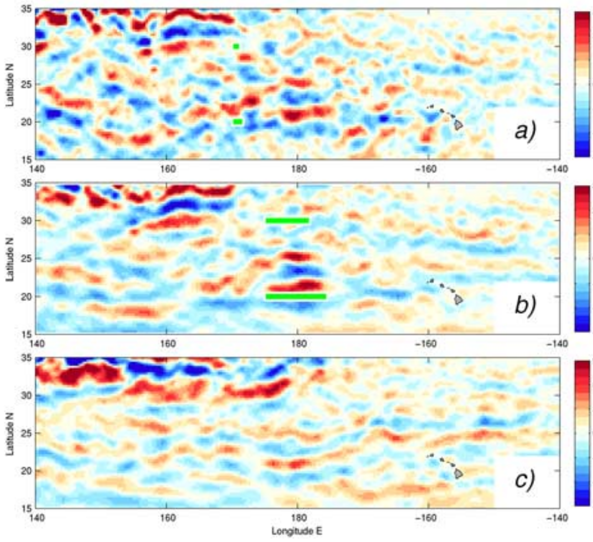

Figure 3. Maps of U_o' (cm/s) in the region marked in Figure 1: (*a*) September 10, 1997 snapshot, (*b*) 18-week average, and (*c*) 200-week average. Green horizontal bars mark estimated displacements of mesoscale eddies.

on individual weekly maps of U_o', without any additional smoothing. Green horizontal bars in Figures 3a and 3b mark characteristic westward displacements of mesoscale eddies anticipated for the effective average time. As the Aviso mapping function has temporal scale of 15 days, the "weekly" snapshot shown in Figure 3a is effectively an average over four weeks. The corresponding time scale of Figure 3b is 18 + 4 = 22 weeks. These times were then multiplied by velocity values of 7.5 and 5.0 cm/s at latitudes of 20 and 30°N suggested by studies of J. Small and J. Hafner (personal communication, 2005) and *Chelton and Schlax* [1996]. It is evident from Figure 3 that the characteristic near-zonal length of the jet exceeds the estimated displacement of the eddy by a factor of 3–5 on the weekly map (Figure 3a) and 2–2.5 for the 18-week average (Figure 3b).

[14] In addition, the jets remain pretty distinct even after averaging over 200 weeks (or almost four years; Figure 3c). During this long time period numerous eddies that have passed through the area should have largely canceled the effects of each other. The fact that this is not happening means that paths of individual eddies are not completely random. We reckon that the presence of the jets regularizes the formation process of new eddies. In return, the eddies feed back to maintain the jets. Verification of this, presently speculative, hypothesis is a challenge for our future study.

[15] **Acknowledgments.** The authors thank Boris Galperin and Peter Rhines for valuable discussions of early results of this study and Diane Henderson for help in preparing this article. Comments from two anonymous reviewers greatly helped to improve the paper. The Aviso data were downloaded from ftp://ftp.cls.fr/pub/oceano/enact/msla/. The OFES simulation was conducted on the Earth Simulator (ES) of Japan, and the Asia-Pacific Data-Research Center (APDRC) of the IPRC provided access to the OFES output. This research was partly supported by the Japan Agency for Marine-Earth Science and Technology through its sponsorship of the International Pacific Research Center. IPRC/SOEST contribution Nos. 331/6588.

References

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

Cushman-Roisin, B., E. P. Chassignet, and B. Tang (1990), Westward motion of mesoscale eddies, *J. Phys. Oceanogr.*, *20*, 97–113.

Ducet, N., P. Y. Le Traon, and G. Reverdin (2000), Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2, *J. Geophys. Res.*, *105*(C8), 19,477–19,488.

Galperin, B., H. Nakano, H.-P. Huang, and S. Sukoriansky (2004), The ubiquitous zonal jets in the atmospheres of giant planets and Earth's oceans, *Geophys. Res. Lett.*, *31*, L13303, doi:10.1029/2004GL019691.

Hall, M. M., T. M. Yoice, R. S. Pickart, W. M. Smethie Jr., and D. J. Torres (2004), Zonal circulation across 52°W in the North Atlantic, *J. Geophys. Res.*, *109*, C11008, doi:10.1029/2003JC002103.

Kondratyev, K., and G. Hunt (1982), *Weather and Climate on Planets*, Elsevier, New York.

Le Traon, P.-Y., and F. Ogor (1998), ERS-1/2 orbit improvement using TOPEX/Poseidon: The 2 cm challenge, *J. Geophys. Res.*, *103*, 8045–8057.

Masumoto, Y., et al. (2004), A fifty-year eddy-resolving simulation of the world ocean—Preliminary outcomes of OFES (OGCM for the Earth Simulator), *J. Earth Simulator*, *1*, 35–56.

Morrow, R., F. Birol, D. Griffin, and J. Sudre (2004), Divergent pathways of cyclonic and anti-cyclonic ocean eddies, *Geophys. Res. Lett.*, *31*, L24311, doi:10.1029/2004GL020974.

Nakano, H., and H. Hasumi (2005), A series of zonal jets embedded in the broad zonal flows in the Pacific obtained in eddy-permitting ocean general circulation models, *J. Phys. Oceanogr.*, *35*(4), 474–488.

Neelin, J. D., D. S. Battisti, A. C. Hirst, F.-F. Jin, Y. Wakata, T. Yamagata, and S. Zebiak (1998), ENSO theory, *J. Geophys. Res.*, *103*(C7), 14,261–14,290.

Niiler, P. P., N. A. Maximenko, and J. C. McWilliams (2003), Dynamically balanced absolute sea level of the global ocean derived from near-surface velocity observations, *Geophys. Res. Lett.*, *30*(22), 2164, doi:10.1029/2003GL018628.

Ohfuchi, W., H. Sasaki, Y. Masumoto, and H. Nakamura (2005), Mesoscale resolving simulations of the global atmosphere and ocean on the Earth Simulator, *Eos Trans. AGU*, *86*(5), 45–46.

Polovina, J. J., G. T. Mitchum, and G. T. Evans (1995), Decadal and basin scale variation in mixed layer depth and the impact on biological production in the central and North Pacific, 1960–88, *Deep Sea Res., Part I*, *42*, 1701–1716.

Rhines, P. B. (1975), Waves and turbulence on a beta-plane, *J. Fluid Mech.*, *69*, 417–443.

Rhines, P. B. (1994), Jets, *Chaos*, *4*(2), 313–339.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata (1999), A dipole mode in the tropical Indian Ocean, *Nature*, *401*, 360–363.

Treguier, A. M., N. G. Hogg, M. Maltrud, K. Speer, and V. Thierry (2003), The origin of deep zonal flows in the Brazil Basin, *J. Phys. Oceanogr.*, *33*, 580–599.

Wijffels, S. E., M. M. Hall, T. Joyce, D. J. Torres, P. Hacker, and E. Firing (1998), Multiple deep gyres of the western North Pacific: A WOCE section along 149°E, *J. Geophys. Res.*, *103*(C6), 12,985–13,009.

B. Bang and N. A. Maximenko, International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii, 1680 East West Road, POST #401, Honolulu, HI 96822, USA. (bohbang@hawaii.edu; nikolai@soest.hawaii.edu)

H. Sasaki, The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology, 3173-25, Showa-machi, Kanazawa-ku, Yokohama, 236-0001, Japan. (sasaki@jamstec.go.jp)