On the importance of mid-latitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation

Hisashi Nakamura,[1, 2] Takeaki Sampe,[3] Atsushi Goto,[4] Wataru Ohfuchi,[5] and Shang-Ping Xie[3]

Received 19 March 2008; revised 16 June 2008; accepted 1 June 2008; published 13 August 2008

[1] Observations indicate that midlatitude weather systems are organized into "stormtracks" near oceanic frontal zones with pronounced sea-surface temperature (SST) gradients. A pair of atmospheric general circulation model experiments with zonally-uniform SST profiles prescribed show that their observed collocation is not fortuitous. In one experiment, a stormtrack is anchored around a midlatitude SST front that maintains near-surface thermal gradients and energizes eddies. Westerly momentum transport by eddies produces a well-defined polar-front jet (PFJ) along the front, even in winter when a subtropical jetstream intensifies. In the other experiment, removal of the SST front leads to a substantial weakening in eddy activity and the PFJ especially in winter. It also leads to a weakening of the annular mode—the dominant mode of westerly jet variability—and its notable structural distortion in winter. Though idealized, our experiments suggest the importance of midlatitude oceanic fronts for the tropospheric circulation and its variability. **citation:** Nakamura, H., T. Sampe, A. Goto, W. Ohfuchi, and S.-P. Xie (2008), On the importance of midlatitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation, *Geophys. Res. Lett., 35,* L15709, doi:10.1029/2008GL034010.

1. Introduction

[2] Midlatitude migratory cyclones and anticyclones that bribg changes in daily weather are an important element of the tropospheric general circulation and climate system. Moving warm and cold air masses, they transport heat from the subtropics into higher latitudes to maintain the tropospheric thermal structure against the differential radiative heating [*e.g., Hartmann,* 1994]. Their transport of westerly momentum from the subtropics maintains a deep westerly jet-stream in midlatitudes [*Lee and Kim,* 2003], called the polar-front jet (PFJ). Surface westerlies are particularly strong over the midlatitude oceans with marked storminess [*Sampe and Xie,* 2007], driving ocean currents [*Trenberth et al.,* 1990], whose heat transport acts to confine sharp sea-surface temperature (SST) gradients into narrow frontal zones.

[3] While conceptual models of extratropical atmospheric general circulation have been developed without special attention to surface thermal conditions except the gross equator-pole temperature difference [e.g., *Palmén,* 1951], midlatitude storms have been known to forecasters to rapidly amplify preferentially off the east coasts of Asia and North America near the major SST fronts associated with the Kuroshio and Gulf Stream, respectively [*Sanders and Gyakum,* 1980]. Indeed, evidence is emerging from recent observations that major stormtracks and attendant PFJs are organized along or just downstream of major oceanic frontal zones [*Nakamura et al.,* 2004]. A typical example is shown in Figure 1 for the South Indian Ocean, where a prominent SST front, called the Antarctic Polar Frontal Zone (APFZ) [*Colling*, 2001], forms at ~45°S along the warmer flank of the Antarctic Circumpolar Current (ACC), marked as a zone of tight SST gradient based mainly on satellite measurements [*Reynolds and Smith,* 1994]. Climatological fields in Figure 1 from an atmospheric reanalysis (JRA-25) [*Onogi et al.,* 2007] indicate that the core of the Southern Hemisphere (SH) stormtrack, marked by zonal maxima of precipitation and poleward heat flux by subweekly disturbances, is anchored along the SST front, in agreement with a synoptic analysis of cyclogenesis [*Sinclair*, 1995]. The stormtrack core is collocated with a surface westerly jet that drives the ACC [*Nakamura et al.,* 2004].

[3] Those previous studies and Figure 1 suggest a potential importance of the SST distribution on stormtrack activity and mean westerlies. *Hoskins and Valdes* [1990] hypothesized a self-maintenance mechanism of a midlatitude stormtrack with emphasis on moisture supply from a warm ocean current into individual cyclones and associated latent heat release as forcing of the westerlies. Recent numerical experiments by *Brayshaw et al.* [2008] indicate high sensitivity of a westerly jet and stormtrack to extratropical SST profile. In this study, we assess the influence of midlatitude oceanic frontal zones on the mean state and low-frequency variability of the tropospheric circulation, using an atmospheric general circulation model (AGCM). We show that the observed collocation of the SST front, stormtrack and surface westerly jet in Figure 1 is a consequence of high baroclinicity near the surface maintained by cross-frontal contrast in heat supply from the ocean.

2. Experimental Design

[4] The AGCM we use is called AFES (AGCM for the Earth Simulator) [*Ohfuchi et al.,* 2007]. Its horizontal resolution corresponds to ~150 km grid spacing (T79) with 48 vertical levels. Reducing the resolution by half leads to notable weakening of stormtrack activity. As in *Brayshaw et al.* [2008], we perform a pair of idealized AGCM experiments by placing the model atmosphere above a hypothetical water-covered globe with zonally uniform SST. This "aqua-planet" setting simplifies the problem by eliminating planetary-scale atmospheric stationary waves forced by land-sea thermal contrasts and orography as observed in the Northern Hemisphere (NH). Thus, our experiments are more applicable to the SH. In our control (CTL) experiment, the climatological SST profiles

---

[1] Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan.

[2] Frontier Research Center for Global Change, JAMSTEC, Yokohama, Japan.

[3] International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI.

[4] Climate Prediction Division, Japan Meteorological Agency, Tokyo, Japan.

[5] Earth Simulator Center, JAMSTEC, Yokohama, Japan

Paper number 2008GL034010.

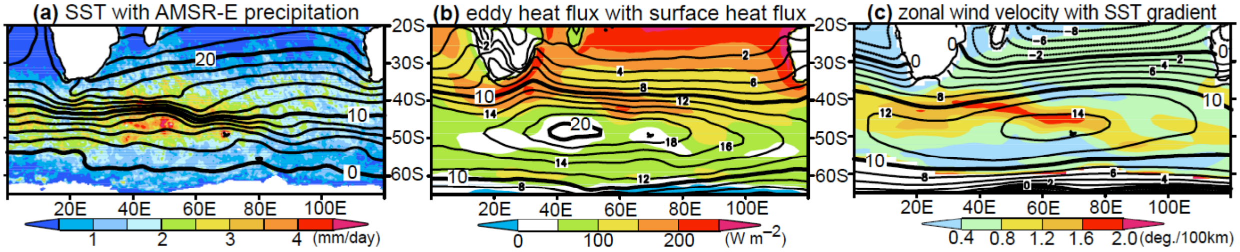

Figure 1. Climatologies for austral winter (Jun.-Aug.) over the South Indian Ocean of (a) SST (every 2°C) and satellite-measured (AMSR-E) precipitation (mm/day; color), (b) stormtrack activity measured as 850-hPa poleward eddy heat flux (every 2 K m/s) and turbulent flux of sensible and latent heat from the surface (W/m^2; color) and (c) 925-hPa westerly wind velocity (every 2 m/s; negative for easterly) and local equatorward SST gradient (deg./100 km; colored).

observed over the South Indian Ocean (60~80°E) for austral summer (Dec.-Feb.) and winter (Jun.-Aug.) are prescribed in the model NH and SH, respectively. In the resultant profile (Figure 2), SST peaks in the NH tropics, where the ascending branch of a Hadley cell is simulated with stronger subtropiccal subsidence in the SH, a winter-summer asymmetry typically observed. The model NH and SH thus correspond to the summer and winter hemispheres, respectively. In each hemisphere the SST profile is charac- terized by sharp gradients at 45° latitude associated with APFZ, which is in contrast to *Brayshaw et al.* [2008], who assigned hypothetical non-frontal SST profiles. In the other (NF) experiment, SST poleward of the front is artificially raised to relax the gradients (Figure 2). To highlight the sensitivity of PFJs, no modifications were added to subtropical SST, to which the intensity of a subtropical jet (STJ) is sensitive [*Brayshaw et al.*, 2008]. The frontal feature in the SST profile was thus eliminated with the equator-pole difference kept the same between the two experiments, each of which was performed for 60 months with insolation fixed to the boreal summer solstice condition for robust statistics.

3. Mean stormtracks and westerly jets

[5] Figures 3a and 3b compare the mean states of stormtrack activity between the CTL and NF experiments. The activity was evaluated daily as the longitudinal variance of 250-hPa meridional velocity (v) and the covariance between 850-hPa v and temperature (T) fluctuations, both associated with subweekly eddies. The latter is equivalent to the eddy heat flux in Figure 1b. In each hemisphere for the CTL experiment, the main stormtrack marked as a well-defined activity maximum is located slightly poleward of the SST front, as observed (Figure 1). In the NF experiment, the midlatitude stormtrack activity is reduced by ~50% in the upper troposphere (Figure 3a) and by 70~75% in the lower troposphere (Figure 3b). The hemispherically-averaged time-mean eddy heat flux is reduced by ~50%, as a consequence of reduced low-level available potential energy (APE) that is proportional to the latitudinal integral of the squared difference between local time-mean and hemispheric-mean temperatures.

[6] The CTL experiment simulates realistic jetstreams (Figures 3c and 3d). Reflecting its eddy-driven nature, a PFJ with strong surface westerlies is collocated with the main stormtrack slightly poleward of the front in either hemisphere, as observed (Figure 1b). Vigorous poleward eddy heat transport acts to relax the meridional air temperature gradient, which is equivalent to the westerly acceleration near the surface under thermal wind balance. As observed in the SH [*Nakamura and Shimpo,* 2004], eddies maintain the well-defined PFJ and surface westerlies even in winter when the STJ strengthens at the terminus of the strong Hadley cell. As argued by *Hoskins* [1991], the surface westerly axis is simulated on the poleward flank of the SST front, where a zonal chain of air parcels cooled by the ocean is forced to shrink toward higher latitudes. The resultant westerly acceleration maintains the westerlies against surface friction. In the NF experiment, the reduced stormtrack activity causes a marked weakening of midlatitude westerlies. In the upper troposphere, the PFJ core displaces equatorward by 10° in summer, while it diminishes in winter. The surface westerly axis also moves equatorward by 10° or more, which could alter ocean currents. Despite no changes added to the subtropical or tropical SST, the removal of the midlatitude SST front causes an unrealistic equatorward displacement of the subtropical high-pressure belt, marked by the latitude of zero near-surface zonal wind, and the weakening of the tropical easterly Trades (Figure 3d). The associated weakening of angular momentum exchange with the solid earth is consistent with reduced lateral mixing of the momentum by eddies due to the removal of the SST front.

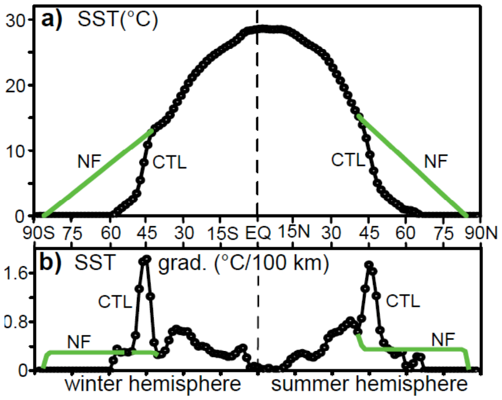

Figure 2. Latitudinal profiles of (a) SST and (b) its meridional gradient, prescribed as the lower- boundary condition for an AGCM experiment with midlatitude SST fronts (black, "CTL"). Partially modified profiles are shown for another experiment without the fronts (green, "NF").

[7] As evident in Figure 3f, the main stormtrack is anchored firmly on the poleward flank of the SST front in each hemisphere, but it becomes much more wobbling without the front. The front maintains tight meridional gradient in surface air temperature (SAT) necessary for recurrent storm development. As observed (Figure 1), the ocean warms the overlying atmosphere through upward turbulent heat flux on the warmer side of the front, while it is downward on its cooler side (Figure 3e). The flux is proportional to local SST-SAT difference,

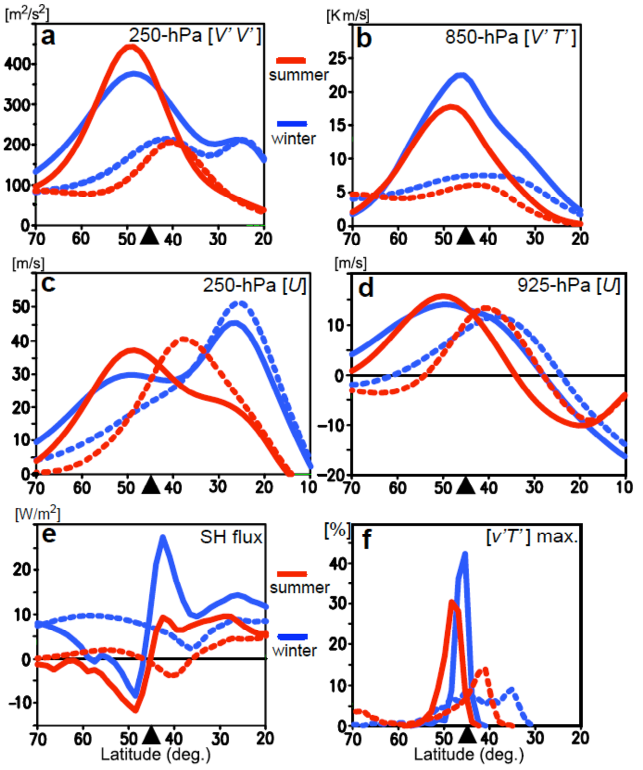

Figure 3. Meridional profiles of the mean states of (a) longitudinal variance of 250-hPa meridional wind fluctuations (m^2/s^2), (b) 850-hPa poleward eddy heat flux (K m/s), both associated with subweekly disturbances, (c) 250-hPa zonally-averaged westerly wind velocity [*U*] (m/s), (d) 925-hPa [*U*] (m/s; negative: easterly), (e) turbulent sensible heat flux (W/m^2) from the surface (positive: upward), and (f) probability density of 850-hPa stormtrack axis (maximum eddy heat flux), based on the 60-month AGCM integrations with (solid, CTL) and without (dotted, NF) SST fronts (triangle) for the summer (red) and winter (blue) hemispheres, as indicated.

which is particularly large on the frontal flanks. A lag correlation analysis was performed between the 850-hPa poleward eddy heat flux at 45° latitude as the reference index and the cross-frontal differences in each of the SAT and sensible heat flux between 42° and 48° latitudes. It reveals that, after being relaxed by the eddy heat transport, the SAT gradients can be restored within 2~3 days through the enhanced cross-frontal differential heat supply from the ocean, which is what may be called "oceanic baroclinic adjustment".

4. Annular variability of the westerly jets

[8] Our experiments also suggest that midlatitude SST fronts can significantly influence the atmospheric variability. We focus on the annular mode [*Thompson and Wallace,* 2000], the dominant mode of low-frequency variability in the extratropics recognized as a meridional seesaw in zonally-averaged westerly wind speed [*U*]. The model annular mode has been extracted statistically as the first empirical orthogonal function (EOF) of 11-day mean anomalies (as deviations from the 60-month mean) in 250-hPa [*U*] poleward of 20° latitude for each hemisphere. The first EOF defines a profile of [*U*] anomalies that accounts for the largest fraction of their hemispheric variance, and the amplitude timeseries (PC1) was used for identifying the events for the composites in Figure 4.

[9] In the CTL experiment, the annular mode is dominant, accounting for about half of the total [*U*] variance in either hemisphere. The winter and summer modes represent seesaws in [*U*] between the latitudes of 55° and 37° and of 60° and 42°, respectively, with their nodes anchored around the mean joint axes of a PFJ and stormtrack, as observed in the SH [*Thompson and Wallace,* 2000]. While the summer mode represents meridional migration of the PFJ (Figure 4b), the positive and negative phases of the winter mode correspond to PFJ-STJ double-jet and STJ-dominant regimes, respectively (Figure 4a), as observed in SH winter [*Aoki et al.,* 1996]. The model annular mode is essentially the coupled variability between the PFJ and stormtrack, as in the observations [*Lorenz and Hartmann,* 2001]. In winter, for example, increases in the midlatitude eddy activity and associated momentum transport cause westerly acceleration and deceleration poleward and equatorward of the PFJ, respectively.

[10] In the NF experiment, however, stormtracks lose their anchor with the SST fronts and thus become wobbling (Figure 3f), while their activity and associated poleward momentum transport both weaken markedly. Consequently, the annular mode becomes weaker and less well defined in its spatial structure in either hemisphere (Figure 4). Particularly, the winter mode is unrealistic, basically representing the STJ variability with no well-defined center of action in midlatitude [*U*] anomalies, consistent with *Eichelberger and Hartmann* [2007]. In this situation, the double jet regime is no longer realized (Figure 4c). The removal of the SST front weakens [*U*] fluctuations markedly in each hemisphere, with a loss of two distinct midlatitude peaks in the [*U*] variance that signify the dominance and robustness of the annular mode.

5. Summary and discussion

[11] In this study, a comparison between our AGCM experiments with zonally uniform SST prescribed with and without its frontal gradients suggests a potentially important role of the oceanic frontal zones in maintaining the tropospheric circulation, including the PFJs and Trades, by energizing stormtrack activity through enhancing low-level APE and anchoring that activity by restoring sharp cross-frontal

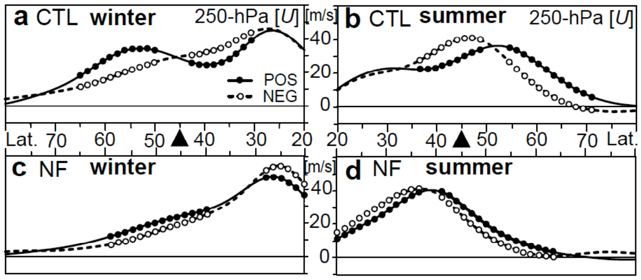

Figure 4. Typical latitudinal profiles of 250-hPa [*U*] (m/s) for the positive (solid) and negative (dashed) phases of the annular mode for the (a) winter and (b) summer hemispheres in the CTL experiment. (c) and (d): As in (a) and (b), respectively, but for the NF experiment. Based on the composites for 17~29 events in which the mode index (PC1) exceeds its 3 standard deviations in magnitude. Circules denote [*U*] anomalies significant at the 95% confidence level.

SAT gradients via the oceanic baroclinic adjustment. The SST fronts also help maintain the intensity and structure of the eddy-driven annular mode throughout the year as actually observed in the SH. Its year-round robustness may be essential for the troposphere-stratosphere linkage of anomalies from winter to early summer, including the possible downward influence of the Antarctic ozone depletion [*Gillett and Thompson,* 2002]. Our results also have certain implications to the warmed climate in future. They are useful for interpreting an increasing trend in wintertime stormtrack activity over the Far East concurrent with a weakening of the westerlies around 30°N both in recent observations [*Nakamura and Sampe,* 2002] and an AGCM simulation of global warming [*Inatsu and Kimoto,* 2005]. Since the SST gradient in our NF profile may be over-relaxed with the unrealistically warm subpolar ocean, however, our results should therefore be regarded as an upper bound of potential impacts by the SST fronts.

[12] The midlatitude ocean has been viewed as responding passively to atmospheric variability without much feedback. However, *Minobe et al.* [2008] and the present study suggest that midlatitude SST fronts may play a fundamental role in shaping the tropospheric circulation. Maintained by eddy momentum transport, surface westerly wind stress is particularly strong near the oceanic fronts, driving currents that generate the fronts in the first place through cross-frontal differential thermal advection, but further study is needed on mechanisms that maintain the fronts. *Thomas and Lee* [2005] indicated that strong cold advection by the cross-frontal Ekman flow and resultant convection lead to secondary circulation to maintain the front. Suggestive of their interaction, the collocation of the SST front, stormtrack and PFJ is observed throughout the year in the South Indian Ocean and the North Atlantic [*Nakamura et al.,* 2004], where the influence of the Hadley cell and STJ is weak. Given the possible feedback as above, our study calls for a new framework that treats those features as interactive components of an extratropical coupled atmosphere-ocean system. Though dry dynamics is essential in our framework, moisture supply from a warm current is important in energizing the stormtrack activity, as emphasized by *Hoskins and Valdes* [1990], since heat exchanges with the ocean act to damp thermal anomalies associated with individual weather systems.

[15] **Acknowledgments.** We used the Earth Simulator in support of JAMSTEC. We thank J.M. Wallace and an anonymous referee for reading the manuscript carefully and giving us insightful comments. We also thank T. Enomoto, A. Kuwano-Yoshida, N. Komori, and Y. O. Takahashi for their advice, and K. Takaya, M. Honda, J.P. McCreary, B. Qiu, B.J. Hoskins, D.L. Hartmann and W.A. Robinson for their valuable comments. This work is supported in part by the Grant-in-Aid #18204044 of the Ministry of Education, Culture, Sports, Science and Technology and by the Global Environment Research Fund (S-5) of the Ministry of the Environment, Japan. The JRA-25 dataset has become available through a cooperative research project by the Japan Meteorological Agency and Central Research Institute of Electric Power Industry, Japan. This is IPRC publicastion #531.

References

Aoki, H., M. Shiotani, and I. Hirota (1996), Interannual variability of the tropospheric circulation in relation to the stratosphere in the Southern Hemisphere, *J. Meteorol. Soc. Jpn., 74*, 509–523.

Brayshaw, D., B. J. Hoskins, and M.J. Blackburn (2008), The storm track response to idealised SST perturbations in an aquaplanet GCM, *J. Atmos. Sci., 65*, in press.

Colling, A. (2001), *Ocean Circulation,* 2^{nd} ed., 286 pp., The Open University, Butterworth-Heinemann, Oxford, U.K.

Eichelberger, S. J., and D. L. Hartmann, 2007: Zonal jet structure and the leading mode of variability, *J. Clim., 20,* 5149–5163.

Gillett, N. P., and D. W. J. Thompson (2003), Simulation of recent Southern Hemisphere climate change, *Science, 302,* 273–275.

Hartmann, D. L. (1994), *Introduction to Physical Climatology*, 411pp., Academic Press, New York.

Hoskins, B. J. (1991), Towards a PV-θ view of the general circulation, *Tellus A, 43*, 27-34.

Hoskins, B. J., and P. J. Valdes (1990), On the existence of storm tracks, *J. Atmos. Sci., 47,* 1854–1864.

Inatsu, M., and M. Kimoto (2005), Two types of interannual variability of the mid-winter storm-tracks and their relationship to the global warming, *SOLA, 1*, 061-064.

Lee, S., and H.-K. Kim (2003), The dynamical relationship between subtropical and eddy-driven jets, *J. Atmos. Sci., 60*, 1490–1503.

Lorenz, D. J., and D. L. Hartmann (2001), Eddy-zonal flow feedback in the Southern Hemisphere, *J. Atmos. Sci. 58*, 3312–3327.

Minobe, S., A. Kuwano-Yoshida, N. Komori, S.-P. Xie, and R. J. Small (2008), Influence of the Gulf Stream on the troposphere, *Nature*, *452*, 206-209.

Nakamura, H., and T. Sampe (2002), Trapping of synoptic-scale disturbances into the North-Pacific subtropical jet core in midwinter, *Geophys. Res. Lett.*, *29(16),* doi:10.1029/2002GL015335.

Nakamura, H., and A. Shimpo (2004), Seasonal variations in the Southern Hemisphere storm tracks and jet streams as revealed in a reanalysis dataset, *J. Clim.*, *17*, 1828–1844.

Nakamura, H., T. Sampe, Y. Tanimoto, and A. Shimpo (2004), Observed associations among storm tracks, jet streams and midlatitude oceanic fronts, in *Earth's Climate: The Ocean-Atmosphere Interaction, Geophys. Monogr. Ser.,* Vol., 147*,* edited by C. Wang, S.-P. Xie and J. A. Carton, pp.329–345, AGU, Washington D. C.

Ohfuchi, W., H. Sasaki, Y. Masumoto, and H. Nakamura (2007), "Virtual" atmospheric and oceanic circulations in the Earth Simulator, *Bull. Am. Meteorol. Soc., 88,* 861–867.

Onogi, K., *et al.* (2007): The JRA-25 Reanalysis, *J. Meteor. Soc. Jpn., 85,* 369–432.

Palmén, E. (1951), The role of atmospheric disturbances in the general circulation, *Q. J. Roy. Meteorol. Soc., 77*, 337–354.

Reynolds, R. W., and T. M. Smith (1994), Improved global sea surface temperature analysis using optimum interpolation, *J. Clim., 7*, 929–948.

Sampe, T., and S.-P. Xie (2007), Mapping high sea winds from space: A global climatology. *Bull. Am. Meteorol. Soc., 88,* 1965–1978.

Sanders, F., and J. R. Gyakum (1980), Synoptic-dynamic climatology of the "bomb", *Mon. Weather Rev., 108*, 1589–1606.

Sinclair, M. R. (1995), A climatology of cyclogenesis for the Southern Hemisphere, *Mon. Weather Rev., 123*, 1601–1619.

Thomas, L. N., and C. M. Lee (2005), Intensification of ocean fronts by down-front winds, *J. Phys. Oceanogr., 35,* 1086–1102.

Thompson, D. W. J., and J. M. Wallace (2000), Annular modes in the extratropical circulation. Part I: Month-to-month variability, *J. Clim.*, *13*, 1000–1016.

Trenberth, K. E., W. G. Large, and J. G. Olson (1990), The mean annual cycle in global ocean wind stress, *J. Phys. Oceanogr., 20,* 1742–1760.

A. Goto, Climate Prediction Division, Japan Meteorological Agency, Tokyo, 100-004, Japan.

H. Nakamura, Department of Earth, Planetary Science, University of Tokyo, Tokyo, 113-0033, Japan (hisashi@eps.s.u-tokyo.ac.jp).

W. Ohfuchi, Earth Simulator Center, JAMSTEC, Yokohama, 236-0001, Japan.

T. Sampe, and S.-P. Xie, International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI 96822.