Geophysical Research Letters, **31**, 2004, doi: 10.1029/2004GL019532, in press.

Tropospheric Influence on the Diminished Antarctic Ozone Hole in September 2002

Kazuaki Nishii and Hisashi Nakamura[1]

Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan.

Abstract. In late September of 2002, the first recorded major sudden stratospheric warming occurred over Antarctica, leading to sudden breakdown of the cold polar vortex and the collapse of the ozone hole. Our diagnosis reveals that the warming was associated with propagation of a Rossby wavepacket from a prominent tropospheric blocking ridge over the South Atlantic into the stratospheric polar-night jet that had already weakened unusually. The blocking developed from anomalies that had formed as a component of another Rossby wavetrain that appeared to be forced in mid-September by anomalous deep cumulus convection in the South Pacific Convergence Zone.

1. Introduction

As opposed to a recent tendency toward a deeper ozone hole over Antarctica associated with a cold polar vortex, ozone depletion in spring of 2002 was the least since the first appearance of the hole in the mid-1980s [*Allen et al*., 2003; *Sinnhuber et al*., 2003]. The reduced depletion was attributable to quite unusual conditions of the atmospheric circulation in 2002, including a sudden stratospheric warming (SSW) that occurred in late September [*Baldwin et al*., 2003; *Krüger et al.,* 2004; *Newman and Nash*, 2004]. It was the first recorded major SSW event for the Southern Hemisphere (SH). In that winter, the stratospheric polar-night jet (PNJ) had unusually weakened by mid-September after three minor SSW events associated with enhanced wave-activity propagation from the troposphere since late August (Figures 1a-b), which is considered to be a crucial preconditioning for the major SSW event [*Baldwin et al*., 2003; *Krüger et al.,* 2004; *Newman and Nash*, 2004].

It has been established theoretically that a SSW event is caused by the amplification of stratospheric planetary waves due to wave-activity propagation from the troposphere [*Matsuno*, 1971]. Some studies have suggested a possible link between a SSW event and a tropospheric blocking phenomenon [*Quiroz*, 1986; *Mechoso et al.,* 1988; *Naujokat et al.*, 2002]. However, no successful attempt has been made thus far to objectively pinpoint a particular blocking ridge as the tropospheric source of upward-propagating Rossby waves that led to a given SSW event. In this study, through wave-activity flux diagnoses, we show that upward-propagating Rossby waves that contributed to the major SSW event in 2002 originated from a blocking ridge that developed over the South Atlantic. We also show that the blocking formation was contributed to by a Rossby wavetrain that appeared to be forced by anomalous deep cumulus convection in the South Pacific Convergence Zone (SPCZ).

[1]Also at IGCR, Frontier Research System for Global Change, Yokohama, Japan.

Paper number 2004GL019532.
0094-8276/01/2004GL019532$05.00

2. Data and diagnostic method

Daily data of air temperature, horizontal wind and geopotential height on a regular latitude-longitude grid with 2.5° intervals at the 17 standard pressure levels from 1000 to 10 hPa are used. They are based on a reanalysis project by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) [*Kalnay et al.,* 1996]. The data time series at each grid point have been filtered with a 5-day running mean to remove fluctuations associated with migratory transient eddies especially in the troposphere.

To diagnose group-velocity propagation of Rossby waves, we utilized two flux formulae of wave-activity pseudo-momentum, a dynamical quantity that is conserved, in theory, following a Rossby wavepacket under the so-called non-acceleration condition. One of them is for stationary Rossby waves propagating through zonally-homogeneous westerlies [*Plumb*, 1985; hereafter P85], and the other is for those waves propagating through zonally-inhomogeneous westerlies [*Takaya and Nakamura*, 2001; hereafter TN01]. The flux of P85, defined for the instantaneous zonal-mean westerlies as the background flow and the zonal asymmetries as the wave component, is suited for diagnosing stratospheric planetary waves during SSW events. In contrast, the flux of TN01 defined for the time-mean flow is not, because drastic changes that occur in the background westerlies during a SSW event can lead to the breakdown of WKB-type approximations used in the derivation of the flux. No such drastic changes occur in the background westerlies in the troposphere. Rather, propagation of tropospheric quasi-stationary Rossby waves with submonthly time scales, whose wavelengths are shorter than those of the stratospheric planetary waves, depends rather sensitively on the locations of local waveguides associated with westerly jets that are more persistent than those tropospheric waves. A tropospheric flow is thus more suited for our application of the flux of TN01, in which 31-day running-mean fields are regarded as the background flow and 5-day running mean departures (or anomalies) from the 31-day mean fields as fluctuations associated with quasi-stationary Rossby waves. Both the zonally asymmetric component and anomalies of geopotential height have been multiplied with a factor [sin (45°S)/sin (lat.)] to mimic wave-associated streamfunction fields.

3. Results

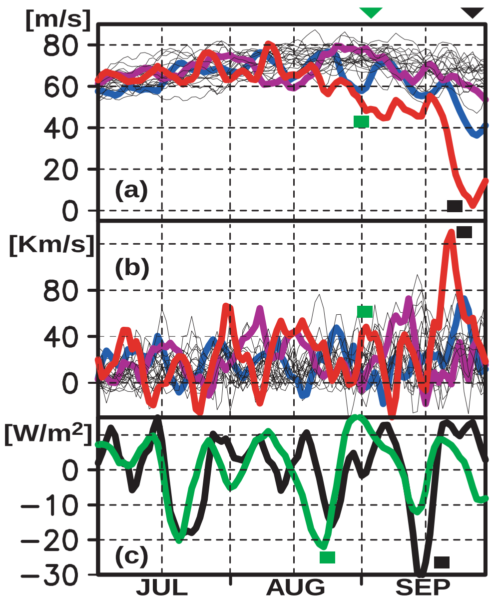

Figure 1. (a) Time series of 20-hPa zonal-mean zonal wind [m s^{-1}] at 60ºS. A red line is for 2002, a blue line for 1988 and a purple line for 1997. Thin black lines are for other years from 1979 to 2001. (b) As in (a), but for zonal-mean poleward heat flux at 60ºS [K m s^{-1}] across the 100-hPa level, equivalent to the upward E-P flux. (c) Time series of OLR anomalies [W m^{-2}] for 2002, averaged over the South Pacific areas [160ºE~170ºW, 15ºS~30ºS] (black) and [140~170ºE, 5ºS~30ºS] (green). Black squares denote a major SSW event in late September, 2002 in (a), the corresponding enhanced upward wave-activity flux in (b), and related enhanced cumulus convection in (c). Green squares denote the same but for a minor SSW event in early September, 2002.

Though much weaker than in other recent winters (Figure 1a), the SH stratospheric PNJ in the 2002 winter was almost circumpolar until it was disturbed markedly during the major SSW event in late September. The three-dimensional structure of the amplified planetary waves during the event is shown in Figure 2. On 23 September, the zonally asymmetric component of 20-hPa height was characterized by strong cyclonic and anticyclonic eddies both situated in the 50~65°S band (Figure 2a). The wave-activity flux defined by P85 was diverging eastward out of the cyclonic eddy (denoted by **Ls** in Figure 2) to the large-scale anticyclonic eddy (denoted by **Hs** in Figure 2). Below the cyclonic eddy (**Ls**), the flux was strongly upward across the 100-hPa surface. In a cross section along the 50°S circle (Figure 2b), the anticyclonic eddy (**Hs**) was confined to the stratosphere. The cyclonic eddy (**Ls**), in contrast, extended deep into an intense tropospheric cyclone over the western Indian Ocean (denoted by **L** in Figure 2). Immediately upstream, over the southeastern Atlantic, wave activity propagated upward from a developed anticyclone confined to the troposphere (denoted by **H** in Figure 2) through the deep westward-tilting cyclonic eddy in the lower stratosphere into the mid-stratospheric anticyclonic eddy (**Hs**). The westward phase tilt was consistent with upward wave-activity propagation, which was initiated 2 days before. At that time (21 Sep.; Figure 2c), the cyclonic (**Ls**) and anticyclonic (**Hs**) eddies in the stratosphere were substantially weaker, whereas the tropospheric anticyclone (**H**) was almost at its full intensity. This evolution is also consistent with the upward group-velocity propagation of the Rossby waves.

With the pair of intense anticyclonic (**H**) and cyclonic (**L**) eddies embedded, the mid-latitude westerlies in the upper troposphere meandered strongly over the South Atlantic just before the major SSW event (Figure 3a). The cyclone (**L**) and anticyclone (**H**) constituted a blocking flow configuration that accompanied a marked split of the westerlies. Those eddies were so strong as to be recognizable as large-amplitude anomalies embedded in the 31-day mean field (Figure 3b). In fact, they were as about 3 times strong as the local standard deviation of intraseasonal fluctuations in 400-hPa height (cf. Figure 5). The blocking anomalies (**H** and **L**) were not localized within the South Atlantic. Rather, they developed near the leading edge of a Rossby wavetrain propagating from the southeastern Pacific. Feedback forcing by migratory synoptic-scale eddies, evaluated as in *Nakamura et al.* [1997], also contributed substantially to the blocking development (not shown). In a manner consistent with its eastward group velocity, the

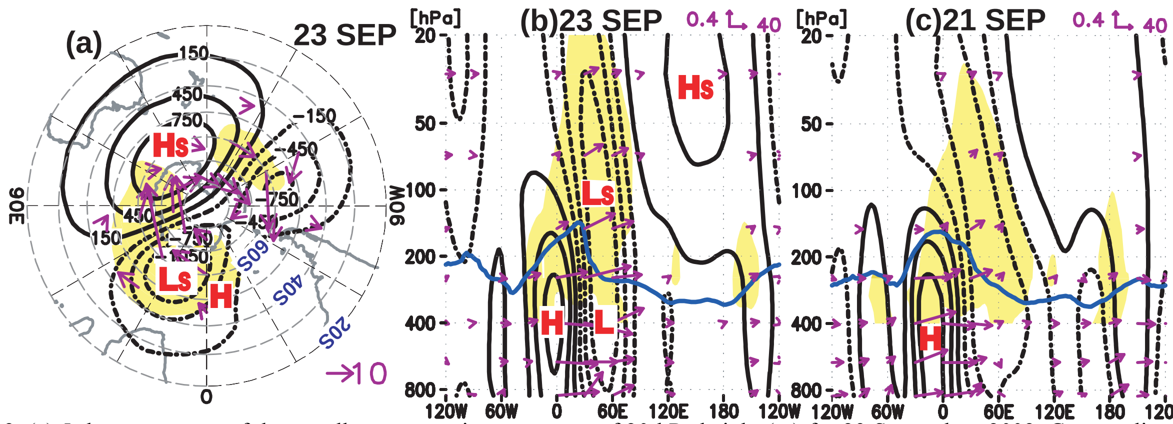

Figure 2. (a) 5-day mean map of the zonally-asymmetric component of 20-hPa height (m) for 23 September, 2002. Contour lines (black): wave-associated cyclonic (dotted) and anticyclonic (solid) eddies. Purple arrows: horizontal component of 20-hPa wave-activity flux (P85) with scaling (unit: $m^2 s^{-2}$) at the lower-right corner. Yellow shading: the upward flux component across the 100-hPa surface exceeding 0.04 ($m^2 s^{-2}$). (b, c) As in (a), but for zonal sections at 50°S for (b) 23 and (c) 21 September. Height anomalies are normalized by pressure. Blue line: tropopause. Purple arrows: Zonal and vertical components of the wave-activity flux (P85), with scaling ($m^2 s^{-2}$) at the upper-right corner. Yellow shading: the upward flux component exceeding 0.04 ($m^2 s^{-2}$).

Geophysical Research Letters, **31**, 2004, doi: 10.1029/2004GL019532, in press.

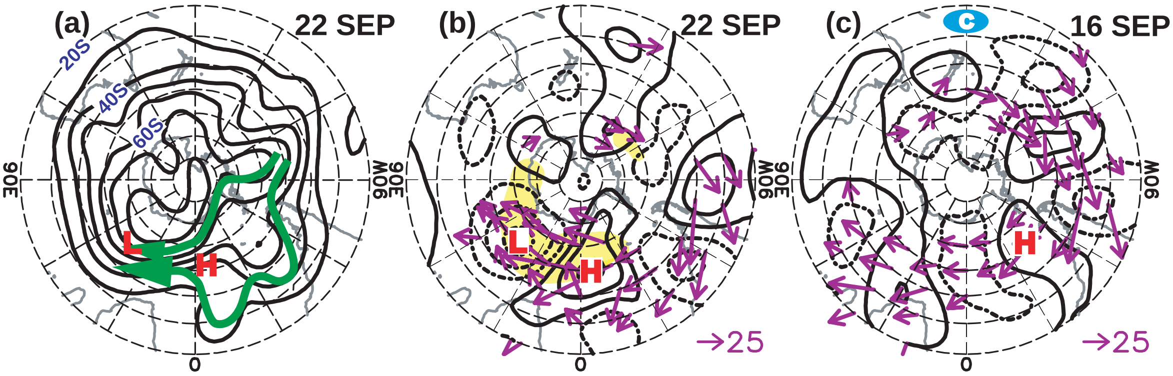

Figure 3. (a) 5-day mean map of 400-hPa height (m) for 22 September, 2002 (every 200 from 6400 to 7600, decreasing with latitude). Green arrows: the split westerlies. (b, c) 5-day mean maps of 400-hPa height anomalies for (b) 22 and (c) 16 September (black solid: anticyclonic; black dotted: cyclonic). Purple arrows: horizontal component of the associated wave-activity flux (TN01), with scaling ($m^2 s^{-2}$) at the lower-right corner. Yellow shading: upward flux component across the 100-hPa surface exceeding 0.04 $m^2 s^{-2}$. Label C (blue): active cumulus convection (see Figure 4).

most intense anomalies associated with the wavetrain observed 6 days before were over the South Pacific (Figure 3c). A Hovmöller diagram of 400-hPa height anomalies averaged between 35°S and 55°S (Figure 4a) indicates that the wavetrain traveled over ~21,000 km across the western hemisphere over a 9-day period (15~23 Sep.). This wavetrain is similar to the Pacific/South American (PSA) pattern, a dominant anomaly pattern in the SH tropospheric circulation [*Mo and Higgins*, 1998; *Renwick and Revell*, 1999].

This PSA-like pattern appeared to be linked to anomalous deep cumulus convection in the SPCZ [*Kiladis et al.,* 1989] over the tropical and subtropical western Pacific. In a region around the SPCZ [15°~25°S, 160°E~170°W], the strongest negative anomaly of outgoing long-wave radiation (OLR) in the 2002 winter (Jul. ~ Sep.) was observed in the period of 13~17 September (Figure 1c), when the wavetrain was observed over the western and central South Pacific (Figure 4a). The enhanced cumulus convection (denoted by **C** in Figure 4b) accompanied an anomalous mid-tropospheric updraft (not shown) and an anomalous upper-tropospheric divergent outflow that could act as anticyclonic vorticity forcing (denoted by **F** in Figure 4b) for the Rossby wavetrain [*Sardeshmukh and Hoskins,* 1988]. Consistently, to the northeast of Australia, the wave-activity flux of TN01 was diverging eastward out of the anticyclonic vorticity anomalies (denoted by **A** in Figure 4b) located immediately downstream of the anticyclonic forcing (**F**) along the strong subtropical jet stream.

4. Summary and discussion

In the present study, we have shown that the first recorded major SSW event over the SH in late September of 2002, which led to the collapse of the Antarctic ozone hole, was contributed to by upward propagation of a Rossby wavepacket emanating from a tropospheric blocking ridge (**H**) and associated prominent cyclonic anomalies (**L**) over the South Atlantic. The blocking flow configuration developed from anomalies that had formed as a component of a Rossby wavetrain that appeared to be forced in mid-September by the most active cumulus convection around the subtropical SPCZ in that winter. A similar association between a tropical convective anomaly and blocking development was also observed just before a minor SSW event in early September, which contributed to the weakening of the PNJ (Figure 1a) acting as a crucial preconditioning for the major

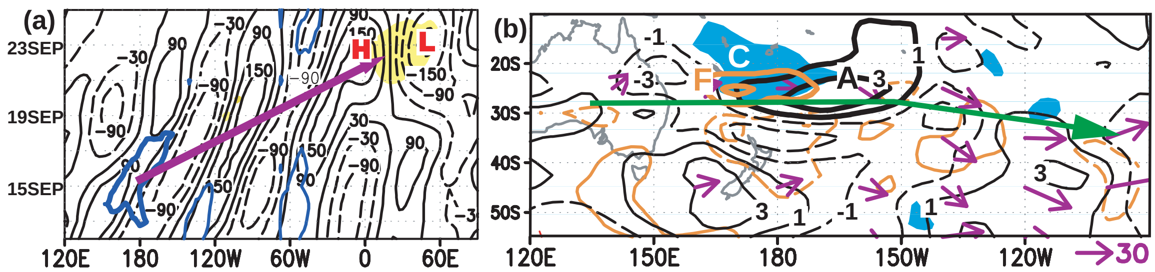

Figure 4. (a) Longitude-time section of 5-day running-mean anomalies of 400-hPa height (black solid: anticyclonic; black dotted: cyclonic) for September, 2002. Red line: eastward group-velocity propagation of the wavetrain of interest. Yellow shading: upward component of a wave-activity flux (TN01) across the 100-hPa surface exceeding 0.04 $m^2 s^{-2}$. The height anomalies and flux component have been averaged over 35°~55°S. Blue lines: OLR (averaged over 15°~25°S) below 240 W m^{-2}. Heavy blue line denotes convective anomalies as the likely source of the wavetrain. (b) Vorticity anomalies (10^{-5} s^{-1}; black dotted: cyclonic; black solid: anticyclonic) and Rossby wave source (10^{-5} s^{-1}/day; orange dotted: cyclonic forcing; orange sold: anticyclonic forcing), both at the 250-hPa level for 15 September. Blue shading: anomalous deep cumulus convection with OLR lower than its 31-day mean by at least 30 W m^{-2}. Purple arrows: horizontal component of a wave-activity flux (TN01) at the 250-hPa level, with scaling ($m^2 s^{-2}$) at the top. Green arrow: axis of the subtropical jet stream. See text for the labels A, C and F.

SSW event. The enhanced wave-activity emanation (Figure 1b) that led to the minor warming was mainly from a blocking ridge that developed over the South Atlantic. The blocking, which was somewhat weaker than that in late September, was again initiated with the formation of anticyclonic anomalies as a component of a Rossby wave train that appeared to be forced by anomalous deep convection around the SPCZ (Figure 1c), a region just northwest of the active convection in mid-September. As shown in Figure 5, the cyclonic (**L**) and anticyclonic (**H**) disturbances observed just before the major SSW event were two of the strongest tropospheric anomalies over the extratropical SH in August and September of 2002, and they were indeed among prominent anomalies over the last 25 years, which means that those blocking anomalies had the potential to act as strong sources of upward-propagating waves. However, they were not necessarily the strongest. Rather, what is striking in Figure 5 is the most profound weakness of the PNJ observed just before the development of the two prominent tropospheric anomalies in the 2002 winter, indicating the importance of the preconditioning in the PNJ for the major SSW event.

Although we have successfully pinpointed the origins of the wavetrains that led to the major and minor SSW events in the 2002 austral winter, an important issue still remaining unsolved is why the PNJ was so weak in that winter. In other words, we have to understand why Rossby wave activity was able to propagate so efficiently into the stratosphere during the 2002 winter. *Nishii and Nakamura* [2004] showed that wave-activity propagation in the wintertime SH is rather sensitive to subtle features in local overlapping between the PNJ and the tropospheric subpolar jet. *Gray et al.* [2004] argued that the anomalously strong easterlies in the equatorial upper stratosphere might have acted as a lateral boundary condition for the effective wave-activity propagation into the extratropical

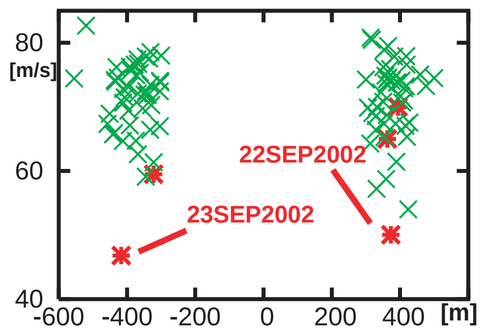

Figure 5. A scatter plot showing the relationship between the strength of positive and negative anomalies of 5-day mean 400-hPa height at their peak times [m, abscissa] and 20-hPa zonal-mean zonal wind speeds observed 10 days earlier than the peak times of the individual anomalies [m s^{-1}, ordinate]. The 10-day time lag was imposed to avoid sampling the stratospheric westerlies decelerated due to the remote influence of the tropospheric anomalies. Red symbols denote those strong anomalies in 400-hPa height observed in August and September of 2002, and black crosses denote those in other winters from 1979 to 2003. Each of the strong anomalies plotted persisted for at least 5 consecutive days within the longitudinal band between 30°S and 70°S, and the peak amplitude at its center exceeded both 300 m and 3 times the *local* standard deviation of 400-hPa height anomalies over the last 25 winters. Due to the negative kurtosis, the number of the strong anomalies shown is larger than it would be if they were normally distributed.

stratosphere. The whole dynamical picture of the 2002 major SSW event over Antarctica will not be obtained until mechanisms for the preconditioning for the effective wave-activity injection can be understood.

Acknowledgments. We thank the anonymous referees for carefully reading the manuscript and giving us a number of helpful comments. This study is supported by JSPS-KAKENHI (B) 15340153.

References

Allen, D. R., R. M. Bevilacqua, G. E. Nedoluha, C. E. Randall and G. L. Manney, Unusual stratospheric transport and mixing during the 2002 Antarctic winter, *Geophys. Res. Lett.,* **30**, doi: 10.1029/2003 GL017117, 2003.

Baldwin, M. A., T. Hirooka, A. O'Neill and S. Yoden, Major stratospheric warming in the Southern Hemisphere in 2002: Dynamical aspects of the ozone hole split, *SPARC Newsletter,* **20**, 2003 (available at http://www.aero.jussieu.fr/~sparc/News20/20Baldwin. html).

Gray, L., W. Norton, C. Pascoe, and A. Charlton, A possible influence of equatorial winds on the September 2002 Southern Hemisphere sudden warming event, *J. Atmos. Sci.,* **61,** 2004, in press.

Kalnay, E. and coauthors, The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc*., **77**, 437-471, 1996.

Kiladis, G. N., H. von Stroch, and H. van Loon, Origin of the South Pacific Convergence Zone, *J. Clim.,* **2**, 1185-1195, 1989.

Krüger, K., B. Naujokat and K. Labitzke, The unusual midwinter warming in the Southern Hemisphere stratosphere 2002: A comparison to Northern Hemisphere phenomena, *J. Atmos. Sci.,* **61**, 2004, in press.

Matsuno, T., Dynamical model of stratospheric sudden warming, *J. Atmos. Sci.,* **28**, 1479-1494, 1971.

Mechoso, C. R., A. O'Neill, V. D. Pope, and J. D. Farrara, A study of the stratospheric final warming of 1982 in the Southern Hemisphere, *Quart. J. R. Meteorol. Soc.,* **114**, 1365-1384, 1988.

Mo, K. C. and R. W. Higgins, The Pacific South American modes and tropical convection during the Southern Hemisphere winter, *Mon. Weather Rev.,* **126**, 1581-1596, 1998.

Nakamura, H., M. Nakamura and J. L. Anderson, The role of high- and low-frequency dynamics in blocking formation, *Mon. Weather Rev.,* **125**, 2074-2093, 1997.

Naujokat, B., K. Krüger, K. Matthes, J. Hoffmann, M. Kunze and K. Labitzke, The early major warming in December 2001 exceptional? *Geophys. Res. Lett.,* **29**, doi: 10.1029/2002GL015316, 2002.

Newman, P. A. and E. R. Nash, The unusual Southern Hemisphere stratosphere winter of 2002, *J. Atmos. Sci.,* **61**, 2004, in press.

Nishii, K. and H. Nakamura, Lower-stratospheric Rossby wave trains in the Southern Hemisphere: A case study for late winter of 1997, *Quart. J. R. Meteorol. Soc.,* **130**, 325-345, 2004.

Plumb, R. A., On the three-dimensional propagation of stationary waves, *J. Atmos. Sci.,* **42**, 217-229, 1985.

Quiroz, R. S., The association of stratospheric warming with tropospheric blocking, *J. Geophys. Res*., **91**, 5277-5285, 1986.

Renwick, J. A. and M. J. Revell, Blocking over the South Pacific and Rossby wave propagation, *Mon. Weather Rev.,* **127**, 2233-2247, 1999.

Sardeshmukh, P. D. and B. J. Hoskins, The generation of global rotational flow by steady idealized tropical divergence, *J. Atmos. Sci.,* **45**, 1228-1251, 1988.

Sinnhuber, B. M., M. Weber, A. Amankwah and J. P. Burrows, Total ozone during the unusual Antarctic winter of 2002, *Geophys. Res. Lett.,* **30**, doi:10.1029/2002GL016798, 2003.

Takaya, K. and H. Nakamura, A formulation of a phase-independent wave-activity flux for stationary and migratory quasi-geostrophic eddies on a zonally varying basic flow, *J. Atmos. Sci.,* **58**, 608-627, 2001.

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

(Received January 22, 2004; revised June 14, 2004; accepted June 27, 2004.)