The Gradient Genesis of Stratospheric Trace Species in the Subtropics and around the Polar Vortex

KAZUYUKI MIYAZAKI
Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

TOSHIKI IWASAKI
Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan

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ABSTRACT

Mechanisms that control the formation and decay of meridional gradients in stratospheric trace species in the subtropics and around the polar vortex are investigated using a gradient genesis equation that uses mass-weighted isentropic zonal means. Application of this method to global nitrous oxide (N₂O) data output from a global chemical transport model shows that mean vertical transport increases the meridional tracer gradient from the subtropics to midlatitudes through the shearing deformation, particularly related to overturning of the Brewer–Dobson circulation. Mean meridional transport advects the subtropical tracer gradient toward midlatitudes, while the eddy stairstep effect, steepening at the edge of the well-mixed region because of a meridional gradient in the diffusion coefficient, increases the tracer gradient in the subtropics and around the polar vortex. Mechanisms controlling the evolution of the tracer gradients in the subtropics differ between spring and autumn. The autumnal subtropical tracer gradient maximum is generated mainly from shearing deformation of the mean vertical transport, but less from mean and eddy meridional fluxes. In spring, the eddy stairstep effect also contributes to the generation of the subtropical tracer gradient maximum. Strong divergence forces stretching deformation that causes the springtime subtropical tracer gradient to decay. The gradient genesis mechanism around the Antarctic polar vortex is significantly different from that in the subtropics. Development of the tracer gradient around the Antarctic polar vortex is mostly controlled by mean meridional stretching motion in the middle stratosphere. Vertical advection and eddy smoothing effects flatten the tracer gradient as the polar vortex decays.

1. Introduction

Past studies have revealed transport barriers in the stratosphere in the subtropics and at the edge of the polar vortex. These transport barriers play important roles in determining the meridional distributions of long-lived chemical species and age of air in the stratosphere (e.g., Hall and Plumb 1994). Tropical air is isolated from midlatitude air in the stratosphere; this isolation is supported by observed distributions of trace constituents (Jones and Pyle 1984; Volk et al. 1996; Randel et al. 1998), aerosol distributions (Trepte and Hitchman 1992; Hitchman et al. 1994), the “tape recorder” in the tropical lower stratosphere (Mote et al. 1996), and tracer–tracer relationships (Plumb and Ko 1992; Volk et al. 1996). Sharp isentropic gradients in trace species imply barriers to isentropic mixing in the subtropics (Bowman 1996); diabatic relaxation helps form the subtropical edge of the surf zone (Polvani et al. 1995). Air within the polar vortex is also surrounded by a “surf zone” (McIntyre and Palmer 1983, 1984) and remains isolated from lower latitudes in the winter stratosphere. Isentropic mixing due to planetary wave breaking occurs more rapidly within the surf zone than in other regions (Juckes and McIntyre 1987). Accordingly, diffusive transport across the circumpolar vortex is much rarer than transport within the surf zone because the strong polar night jet acts as a barrier to eddy mixing (Haynes and Shuckburgh 2000). The mixing barrier is located near the core of the polar jet stream.
and is usually collocated with the steep tracer gradient (Nakamura and Ma 1997).

However, stratospheric airmass exchange between the tropics and extratropics does occur (e.g., Trepte and Hitchman 1992; Boering et al. 1994, 1996; Volk et al. 1996). Randel et al. (1993) used satellite observations in the subtropics to confirm the existence of strong meridional gradients in observed trace species. They also described planetary-scale tongues of tropical stratospheric air that extended into midlatitudes, suggesting irreversible mixing from the tropics into midlatitudes. The transport from the tropics is a consequence of Rossby wave breaking that causes filaments of tropical air to be drawn into midlatitudes (Waugh 1996). Wave-breaking events are observed from autumn to spring when stratospheric westerlies are common in midlatitudes. Tongues of tropical air are also associated with disturbances in the stratospheric polar vortex (Waugh 1993). Observational studies have described filaments around the polar vortex and isentropic mixing across its edge. Similarly, a tracer–tracer relationship analysis developed by Plumb and Ko (1992) has explored diffusive transports across the polar vortex (Waugh et al. 1997; Plumb et al. 2000; Jost et al. 2002; Morgenstern et al. 2002).

Meridional gradients of stratospheric trace species vary with time and altitude because of the flattening effect of isentropic mixing and the steepening effect of diabatic advection (Holton 1986; Plumb and Ko 1992; Plumb 2002, 2007). The mean age of air, which is estimated from passive tracer calculations, can also be determined from the relative importance of two pathways in the extratropical stratosphere. These two pathways are rapid quasi-horizontal transport from the tropics forced by mean motions and eddies and downwelling of air from higher altitudes in the mean meridional circulation (Andrews et al. 2001). The relative importance of the two pathways depends on season and altitude. For example, isentropic mixing dominates for the subtropical constituent gradient in the lower stratosphere, whereas mean meridional transport is important in the middle stratosphere (Gray and Russell 1999). However, scant information is available to describe formation and decay mechanisms of the trace species gradient associated with meridional transports. In particular, it remains unclear how the transport barrier (or cross-barrier transport) affects the development of the trace species gradient. Major problems precluding better understanding include the complicated eddy (diffusion) transport term that is difficult to estimate directly and exactly using conventional analysis methods (Miyazaki and Iwasaki 2005). However, a detailed understanding of how the gradients develop is important for a comprehensive understanding of stratospheric processes that include meridional transports of anthropogenic chemicals from the tropics to higher latitudes. These transports control chemical concentrations near the poles, and the concentrations are particularly related to the ozone hole and to climate change.

This study will yield insights into how gradients in stratospheric trace species develop in the subtropics and around the polar vortex. We conducted an exact analysis of tracer gradient genesis using a gradient genesis equation based on the mass-weighted isentropic zonal means. Such a formulation has advantages over conventional methods in expressing mean and eddy transport terms, and the analysis describes the formation and decay mechanisms controlling the gradient of the trace species. The trace species considered in this study is global nitrous oxide ($\text{N}_2\text{O}$), for which data were obtained from a global chemical transport model and were used as a tracer in the gradient genesis analysis. Two-dimensional (2D) model results revealed the roles of the mean meridional circulation in the genesis of the gradient.

2. Data

Data used in this study were obtained from an objective analysis that included chemical constituents. The system is formulated with the help of a 3D chemical transport model (CTM) developed at the Meteorological Research Institute (MRI) of Japan (Shibata et al. 2005). The MRI–Japan Meteorological Agency (JMA) 1998 general circulation model (GCM; Shibata et al. 1999) drives the MRI CTM. The model has T42 spectral truncation in the horizontal and 68 levels in the vertical from the surface to 0.01 hPa. Model chemistry includes 72 gas-phase reactions, 32 photolysis reactions, and 8 heterogeneous reactions on polar stratospheric clouds and sulfate aerosols. Horizontal wind and temperature fields from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Simmons and Gibson 2000) data were assimilated into the GCM using the nudging technique (Hoke and Anthes 1976; Miyazaki et al. 2005b) to reproduce past meteorological fields. The nudging relaxation time was optimized to reproduce the mean meridional circulation in the objective analysis with a smaller temperature bias in the nudged GCM. The relaxation time was 1 day for horizontal winds and 5 days for temperature (Miyazaki et al. 2005b). A 5-yr simulation from 1997 to 2001 was run. Transport analysis was computed on the model eta coordinate system. Computing transport in the model coordinate system
allows for a more accurate analysis of gradient genesis because interpolation errors from model to pressure or isentropic surfaces are reduced. Also, 2-hourly snapshot data were used to include atmospheric disturbances with short time scales in the analysis.

Global N$_2$O data were used in the gradient genesis analysis. N$_2$O is representative of most passive tracers in the stratosphere and troposphere. It has a very long lifetime, except in the upper atmosphere where it can photodissociate. Figure 1 compares zonal-mean N$_2$O distributions in the model and in climatological data obtained from the Cryogenic Limb Array Etalon Spectrometer (CLAES) on board the Upper Atmosphere Research Satellite (UARS; Randel et al. 1994). Both model results and observations show strong meridional gradients of N$_2$O in the subtropics and around the polar vortex. Strong meridional N$_2$O gradients in the subtropics extend from about 50 hPa to the upper stratosphere. Stronger gradients are lower in the polar vortex but are still above about 100 hPa. The model reproduces the main features of the observed N$_2$O distribution but slightly underestimates the meridional N$_2$O gradient in the Northern Hemisphere. Note that CLAES N$_2$O data compose an operational period of less than 2 yr, from December 1991 to May 1993, and these data are strongly influenced by interannual variations in the strength of the polar vortex and general circulation, particularly in the Northern Hemisphere. This may explain differences between the simulated climatological N$_2$O fields and the CLAES observations, particularly around the Arctic polar vortex. Disagreements may also reflect insufficient model resolution or degraded accuracy in the transport calculation.

The model reproduces subtropical maxima in the meridional N$_2$O gradient during early spring and autumn in both hemispheres (Fig. 2). The steep N$_2$O gradient in the subtropics has a narrower latitudinal range in winter than in other seasons, as noted by Neu et al. (2003).
and the region of the steep gradient shifts to lower latitudes in winter and to higher latitudes in summer. These simulated seasonal variations agree with CLAES observations in the Southern Hemisphere. Both model output and CLAES observations show local maxima in the meridional N$_2$O gradients near 30°S from January to March and near 20°S from September to November. In the Northern Hemisphere, in contrast, the observed maximum gradient in June was not reproduced by the model. Both model and observations do reveal a gradient maximum from January to March around 25°N. CLAES observations show a strong meridional gradient in N$_2$O near 60°S from June to November. This gradient surrounds the Antarctic circumpolar vortex. Seasonal variations in the gradient around the Antarctic are relatively small in the model output, probably because of errors in the circulation fields and transport calculations.

Seasonal variations in the simulated subtropical gradient of N$_2$O can be compared to methane (CH$_4$) profiles obtained from satellite measurements from the Halogen Occultation Experiment (HALOE). These CH$_4$ values are from version 19 data (Russell et al. 1993) and include observations from 1993 to 2004 (Fig. 3).
HALOE data cover a longer time period than the CLAES data and therefore include more realistic climatological features in the constituent gradient in the subtropics. Niwano and Shiotani (2001) and Niwano et al. (2003) described the methods used in this study to construct zonal and monthly averages. In the middle stratosphere, CH$_4$ can be treated as a passive atmospheric tracer even though the chemical lifetime of CH$_4$ is somewhat shorter than that of N$_2$O. In fact, meridional gradients of HALOE CH$_4$ resemble both CLAES N$_2$O and model N$_2$O gradients in the Southern Hemisphere. In contrast, model N$_2$O output shows better agreement with HALOE CH$_4$ than with CLAES N$_2$O in the Northern Hemisphere. HALOE CH$_4$ data show maxima in gradients in March and October, which are consistent with simulated N$_2$O output but different from CLAES N$_2$O observations. These comparisons indicate that seasonal variations in the trace species gradient in the subtropics in both hemispheres are reproduced accurately by the model.

There are also interannual variations in trace gas transports and in meridional gradients of trace gases, which can be related to, for example, the quasi-biennial oscillation (QBO; Hasebe 1983; Jones et al. 1998; Gray and Russell 1999; Gray 2000; Shuckburgh et al. 2001). Tracer distribution can be related to changes in the QBO circulation and to the location of the zero wind line at low latitudes (Neu et al. 2003); however, the focus of this study was the examination of the seasonal cycle and climatological features of the tracer gradient genesis.

3. Analysis method for the genesis of the meridional gradient

a. Gradient genesis analysis

We assessed the formation and maintenance of the meridional gradient of a tracer using a gradient genesis equation that was newly formulated using a mass-weighted isentropic formulation. Past studies have shown that a zonal symmetric transport equation using mass-weighted isentropic zonal means can accurately separate meridional transports of chemical constituents into mean and eddy flux terms and can express the conservative nature of minor constituents (Iwasaki 1989; Miyazaki et al. 2005a; Miyazaki and Iwasaki 2005; hereinafter, we refer to this method as “MI diagnosis”). In particular, the eddy transport term can be exactly and simply estimated in the MI diagnosis. Such a diagnosis considers mass weighting for the mixing ratios of minor constituents, as well as the mean meridional circulation.

We used a gradient genesis equation, derived here from the zonal symmetric transport equation of the MI diagnosis. The equation can quantify the tendency of the meridional gradient of the tracer as forced by mean and eddy transports:

$$\frac{\partial}{\partial t} \left( \frac{\partial r^\circ}{\partial \phi} \right) = \frac{\partial}{\partial \phi} \left( \frac{\partial r^\circ}{\partial t} \right) = \frac{\partial}{\partial \phi} \left( \frac{\partial r^\circ}{\partial t} \right) + \frac{\partial}{\partial \phi} \left( \frac{1}{a \cos \phi} \frac{\partial (r'v') \cos \phi}{\partial \phi} - \frac{\partial r}{\partial z} \frac{\partial z}{\partial \phi} \right) + \frac{\partial Q^\circ}{\partial \phi},$$

where $r$ is the mixing ratio of the chemical constituent, $v$ is the meridional wind velocity, $w_z$ is the vertical wind velocity, $a$ is the earth’s radius, $\phi$ is the latitude, and $Q$ is a net chemical production/loss term. The overbar and asterisk indicate zonal averages on an isentropic surface and mass weighting, respectively.

The mean transport term is further decomposed into four terms to yield insights into the gradient genesis. The four mean transport terms can be interpreted as forcings that change the meridional gradients by shearing (rotational) deformation, stretching deformation, and advections, in a manner similar to the frontogenesis equation (Hoskins 1982):

$$\text{MEAN} = -\frac{1}{a^2} \frac{\partial v}{\partial \phi} \frac{\partial r}{\partial \phi} - \frac{1}{a^2} \frac{\partial v}{\partial \phi} \frac{\partial r}{\partial \phi} - \frac{1}{a} \frac{\partial w_z}{\partial \phi} \frac{\partial r}{\partial \phi} \frac{\partial z}{\partial \phi}.$$

Figure 4 uses a schematic to show how gradient development is forced by mean transport terms as defined by Eq. (2). The first term is meridional stretching deformation (MEY1) that arises from meridional mass convergence. This term concentrates meridional gradi-
ents of tracers along a latitudinal axis. The second term is meridional advection (MEY2) by which the mean meridional flow horizontally advects the tracer slope. The third term is shearing deformation (MEZ1), which arises because of meridional shear in the mean vertical velocity. This shear gives a rotational effect, that is, stretching along a vertical axis and shrinking along a latitudinal axis. This term is important for diagnosing the effects on the tracer gradient of overturning in the mean meridional circulation. The fourth term is vertical advection (MEZ2), which diagnoses changes in meridional tracer gradients that arise through vertical advection of meridional gradients.

Similarly, the eddy meridional transport term is decomposed into two terms using a diffusion coefficient to clarify the physical meaning of the eddy transport. Eddy meridional flux convergence can be approximated using a flux-gradient relationship with the horizontal diffusion coefficient $K_{yy}$ as

$$- \frac{1}{a \cos \phi} \left( \frac{\partial (r' u')}{\partial \phi} \cos \phi \right)$$

$$= - \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} \left( K_{yy} \frac{\partial r^*}{a \partial \phi} \cos \phi \right).$$

Accordingly, the eddy meridional transport in the gradient genesis equation can be expressed as two terms,
Figure 5 shows schematic descriptions of gradient genesis by eddy transport. The first term is the stairstep effect (EDY1) related to the meridional gradient in the diffusion coefficient $K_{yy}$. For a case of mixing around the stratospheric surf zone, the stairstep effect will flatten the tracer gradient within the surf zone, which is defined as the region surrounded by the maximum $K_{yy}$ gradient, and will steepen the tracer gradient at the boundary of the surf zone. The boundary is the region between the edge of the mixed region (nonzero $K_{yy}$) and the maximum $K_{yy}$ gradient. The tracer gradient tendency forced by the stairstep effect is also influenced by the shape of the tracer slope. The second term is a smoothing effect (EDY2), which describes a reduction in skewness in the meridional tracer gradient that arises through isentropic diffusion as depicted in Fig. 5.

$$\frac{\partial}{\partial \phi} \left\{ \frac{1}{\cos \phi} \frac{\partial (r^y)^s \cos \phi}{\partial \phi} \right\}$$

$$= - \frac{\partial}{\partial \phi} \left\{ \frac{1}{\cos \phi} \left( \frac{\partial K_{yy}}{\partial \phi} - \frac{\partial r^y \cos \phi}{\partial \phi} \right) \right\}$$

$$- \frac{\partial}{\partial \phi} \left\{ \frac{1}{\cos \phi} \left[ K_{yy} \frac{\partial}{\partial \phi} \left( \frac{\partial r^y \cos \phi}{\partial \phi} \right) \right] \right\}. \quad (4)$$

b. Verification of the gradient genesis analysis

The gradient genesis equation [Eq. (1)] is applied to N$_2$O data output from the MRI CTM. Tendencies of meridional gradients in N$_2$O computed with Eq. (1) are compared to the CTM output to validate the accuracy of the gradient genesis analysis. Figure 6a shows sea-
sonal variations and time tendencies of the monthly averaged meridional $N_2O$ gradient. The time tendencies in the gradient genesis analysis were obtained by summing all terms in the gradient genesis equation [on the right side of Eq. (1)]. The sign of the tendencies in the Northern Hemisphere is reversed so that an increase in the meridional gradient has a positive value, as in the Southern Hemisphere. Analysis error for the gradient genesis analysis is

$$
\epsilon = \left[ \frac{\partial}{\partial t} \left( \frac{\partial \sigma^*}{\partial \phi} \right) \right]_{CTM} - \text{RHS of Eq. (1)}. \tag{5}
$$

The gradient genesis analysis shows good agreement with the CTM, and the analysis error $\epsilon$ is quite small (Figs. 6 and 7); analysis errors are typically less than 25%. However, some larger analysis errors can arise because of temporal and spatial truncations and numerical errors, particularly around the polar vortex. Analysis error is very sensitive to the time intervals of the meteorological and constituent data used in the gradient genesis analysis.

4. Analysis of the meridional $N_2O$ gradient

a. Annual mean; slope equilibrium state

This section assesses the contributions of each gradient genesis term on the right side of Eq. (1) to the genesis of a meridional gradient of $N_2O$. Figure 7 shows the result for the gradient genesis analysis at 20 hPa. The Brewer–Dobson circulation in the stratosphere makes the $N_2O$ distribution uniform. The upward branch of the circulation carries air rich in $N_2O$ from the troposphere into the tropical stratosphere, and the downward branch carries air depleted of $N_2O$ from higher altitudes, steepening the meridional gradient of $N_2O$ in the extratropics. As a result of transport by the Brewer–Dobson circulation, the gradient tendency by the mean transport (advection) term is negative at low latitudes and positive at mid- and high latitudes; the gradient tendency vanishes near the region of maximum $N_2O$ gradient in the subtropics.

The mean transport term is balanced by eddy transport, and constituent fields are in a slope equilibrium state as noted by Holton (1986) and Plumb (2002). The flattening effect of the mean transport term almost compensates for eddy transport at low latitudes. In midlatitudes, eddy transport produces a flattening effect. Subtropical steepening and extratropical flattening of the gradient by eddy transport is the stairstep effect that will be discussed in section 4c. The large positive tendency forced by the mean transport at high latitudes in the Southern Hemisphere corresponds well to the region of maximum $N_2O$ gradient around the Antarctic polar vortex. This tendency is related to stretching deformation and is discussed in section 4b. Chemical processes do not have significant effects on the development of $N_2O$ gradients because $N_2O$ is a good passive tracer in the middle stratosphere.

b. Gradient genesis by the mean transport

This section considers the evolution of the meridional $N_2O$ gradient as forced by the mean transport in the middle stratosphere. The analysis of the mean me-
ridional transport term shown in Fig. 8 shows flattening of the meridional N₂O gradient near 15° latitude and steepening near 30° latitude in both hemispheres from autumn to spring. Mean meridional transport also forces a reduction in the meridional N₂O gradient in Southern Hemisphere midlatitudes and an increase in the gradient around the Antarctic polar vortex. In contrast, mean vertical transport increases the meridional N₂O gradient in a broad region from 20° to 60° latitude. This transport helps generate the steep N₂O gradient in the subtropics in both hemispheres (Fig. 8b). In particular, the springtime maximum of the meridional N₂O gradient in the subtropics was formed principally by mean vertical transport, although the mean vertical transport weakens the subtropical N₂O gradient in late spring and reduces the N₂O gradient around the Antarctic as the polar vortex decays from August to November.

A more detailed analysis made with the gradient genesis equation [Eq. (2)] helps explain the physical meaning of the gradient tendency forced by the mean transport. Figure 9 shows the gradient genesis analysis as forced by each mean transport term. Steepening of the subtropical N₂O gradient by the mean vertical transport is forced mainly by shearing (rotating) deformation MEZ1 (Fig. 9c) that is associated with the meridional shear of the mean vertical velocity. The mean vertical velocity (Fig. 10b) shows a large seasonal variation with strong meridional shear around the subtropics; mean vertical velocity is downward from late autumn to early spring and upward from late spring to early autumn. These changes contribute to the increase in the subtropical N₂O gradient, particularly those gradient changes that are related to the overturning of the mean meridional circulation. A distinguishing feature of the shearing deformation is that the meridional N₂O gradient from the subtropics to midlatitudes is notably strengthened by enhanced wintertime descent in the
extratropics (Rosenlof 1995). During summer, in contrast, flattening by the shearing deformation is insignificant, possibly resulting in weak gradients of subtropical tracers as commonly described in some observational studies (Hitchman et al. 1994; Luo et al. 1994).

Strong mean poleward flow in the Brewer–Dobson circulation extends from the tropics to midlatitudes (Fig. 10a). MEY2 associated with the circulation transports the sharp N$_2$O slope from the subtropics to midlatitudes (Fig. 9b). In particular, from autumn to winter, the meridional N$_2$O gradient is significantly changed by strong poleward flow in the subtropics. Meridional advection also increases the N$_2$O gradient in the midlatitudes of the Southern Hemisphere, but this increase is nearly balanced by decreases forced by shearing deformation and eddy transport. The other mean meridional transport term is stretching induced by meridional convergence MEY1 (Fig. 9a). Figure 10a shows that divergence is common in meridional flow in the subtropics. Stretching deformation reduces the N$_2$O gradient around the subtropics through the divergence.

Mean transport terms significantly influence gradient genesis around the Antarctic polar vortex as well. Stretching and shearing deformation associated with strong airmass convergence increases the N$_2$O gradient around the edge of the Antarctic polar vortex. The gradient is weakened by MEZ2 (Fig. 9d) as the polar vortex decays. Vertical advection leads to a flatter gradient because downward motions around the Antarctic strengthen as the polar vortex breaks down (Fig. 10b); these stronger downward motions transport air with a flatter meridional N$_2$O gradient from the upper stratosphere to the middle stratosphere.

c. Gradient genesis by the eddy transport

Eddy meridional transport plays an important role in the genesis of a tracer gradient (Fig. 8c). The eddy meridional transport term is strongly influenced by Rossby wave breaking in the subtropics and extratropics from autumn to spring. Such wave breaking therefore effectively changes the meridional N$_2$O gradient (Waugh 1996). The eddy meridional transport term steepens

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Fig. 8. As in Fig. 6, but for the time tendency of the meridional N$_2$O gradient by (a) mean meridional transport, (b) mean vertical transport, (c) eddy meridional transport, and (d) eddy vertical transport.
and sharpens the subtropical gradient of \( N_2O \) in the spring, and the term flattens the subtropical \( N_2O \) gradient in autumn. Results also show that the steep tracer gradient around Antarctica is significantly influenced by eddy transports that increase gradients during winter and decrease gradients during spring. During the summer, less active wave motions likely substantially limit the contributions of the eddy transport term, particularly in the Northern Hemisphere (Wagner and Bowman 2000). Adiabatic processes dominate eddy trans-

**FIG. 9.** As in Fig. 6, but for the time tendency of the meridional \( N_2O \) gradient by (a) mean meridional transport, MEY1; (b) mean meridional transport, MEY2; (c) mean vertical transport, MEZ1; and (d) mean vertical transport, MEZ2.

**FIG. 10.** Seasonal variations of the mean meridional and mean vertical velocities \( u^* \) and \( w^* \) at 20 hPa averaged over 1997 to 2001. Contour intervals of mean meridional and vertical velocities are 0.03 m s\(^{-1}\) and 0.15 mm s\(^{-1}\), respectively. Negative values (southward or downward motion) are shaded.
port in the stratosphere, and eddy transport flux occurs along isentropic surfaces. Therefore, the vertical component of eddy transport is unimportant in the genesis of tracer gradients (Fig. 8d).

Eddy meridional transports associated with $K_{yy}$ force the genesis of gradients through two terms: EDY1, related to the gradient of the diffusion coefficient $K_{yy}$; and EDY2, that smooths the skewness of the tracer slope [Eq. (4)]. A flux-gradient relationship for the horizontal diffusion coefficient $K_{yy}$ yields an adequate representation of the evolution of the meridional $N_2O$ gradient both in the subtropics and around the polar vortex (Fig. 11). However, in regions in the tropics and the summer hemisphere where $K_{yy}$ cannot be defined because of very small meridional gradients in $N_2O$, the flux gradient relationship will not yield good results.

In the winter stratosphere, $K_{yy}$ is large in midlatitudes and small in low and high latitudes (Fig. 11a). This structure is also reflected in calculations of effective diffusivity (Haynes and Shuckburgh 2000; Allen and Nakamura 2001). Although effective diffusivity yields more insight into mixing processes than conventional Eulerian diffusion, the gradient genesis analysis proposed in this study allows a simple quantification of the relative importance of mean and eddy transports on tracer gradient development using an Eulerian diffusion coefficient. The strong latitudinal gradient of the $K_{yy}$ in the subtropics and at the edge of the polar vortex

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**Fig. 11.** Meridional cross sections of (a) the logarithm of the horizontal diffusion coefficient $K_{yy}$ (m$^2$ s$^{-1}$) and (b) time tendency of the meridional $N_2O$ gradient (ppmv m$^{-1}$ s$^{-1}$) by the eddy meridional transport, averaged over June, July, and August 1997 to 2001. The time tendency by the eddy meridional transport (b) is decomposed into (c) EDY1 and (d) EDY2 with the horizontal diffusion coefficient $K_{yy}$ [see text and Eq. (4) for details].
means that the stairstep effect in eddy meridional transport EDY1 can increase the meridional N₂O gradient at low (around 15°S) and high (55°S) latitudes (Fig. 11c), which correspond to the edges of the surf zone. EDY2 decreases the N₂O gradient around 20° and 50°S (Fig. 11d), and this effect somewhat balances steepening by EDY1.

The tracer gradient tendency diagnosed by eddy transport is controlled by the relative importance of the stairstep and smoothing effects, yet these two effects nearly balance each other (Fig. 12). A large smoothing effect controls the decay of the autumnal subtropical N₂O gradient because of large \( K_{yy} \); steepening of the springtime subtropical N₂O gradient is forced by the stairstep effect. Around the Antarctic polar vortex, the smoothing effect is weaker than the steepening stairstep effect during winter, but flattening by the smoothing effect dominates during spring. The latter effect reduces the meridional N₂O gradient within the decaying polar vortex (Fig. 12b), since large eddy poleward flux moves to higher latitudes as the Antarctic polar vortex decays. At northern high latitudes, active isentropic mixing across the polar vortex edge enhances the smoothing effect, and the meridional N₂O gradient is insignificant (not shown).

### d. Evolution mechanisms

This section focuses on evolution mechanisms of the meridional tracer gradient in the subtropics and at the edge of the polar vortex. Sections 4b and 4c used a detailed analysis of gradient genesis to provide a comprehensive picture of mechanisms forcing the formation and decay of meridional tracer gradients in the middle stratosphere. This picture was achieved by considering the roles of transport barriers and the relative importance of each transport term in the gradient genesis (Fig. 13). Nakamura and Ma (1997) reported from modified Lagrangian mean diagnostics that the steep tracer gradient are generally collocated with mixing barriers, but the strength of the barrier is not necessarily proportional to the tracer gradient. This reflects the influence of the mean transport, as clearly shown above in the gradient genesis analysis. The strongest tracer gradient in the subtropics occurs twice in both hemispheres in the middle stratosphere, in early spring and in autumn. Mechanisms controlling the evolution of the subtropical tracer gradient differ between these two seasons. The analysis suggests that the autumnal maximum of the subtropical tracer gradient is generated largely by shearing deformation MEZ1 that dominates other transport terms, such as stretching deformation and stairstep effects induced by the meridional transport barrier, from late summer to early autumn. Transport barriers for both mean and eddy fluxes do not substantially influence the generation of the steep tracer gradient in the subtropics in autumn. The autumnal tracer gradient then weakens because of the smoothing effect of the eddy meridional transport EDY2 that accompanies active wintertime mixing. The springtime maximum of the subtropical tracer gradient is forced by the eddy transport stairstep effect EDY1 because of the mixing barrier and by MEZ1 associated with strong meridional shear in the mean vertical velocity from winter to early spring. Strong divergence forces stretching deformation MEY1 that causes the springtime tracer gradient to decay. Upward vertical
advection in summer carries air characterized by a flatter tracer gradient from lower altitudes and helps to reduce the tracer gradient in the subtropics in spring through MEZ2.

The stretching deformation forced by the mean meridional circulation MEY1 around the Antarctic polar vortex mainly increases the tracer gradient there from late autumn to winter. The eddy meridional transport stairstep effect EDY1 also concentrates the tracer gradient because the vortex edge is generally collocated with the edge of the well-mixed region. The Antarctic polar vortex thus acts as a transport barrier for both mean and eddy transports during the formation of the steep tracer gradient. Decreases in the tracer gradient around the Antarctic polar vortex mainly arise from the smoothing effect EDY1 and vertical advection MEZ2 during spring. The eddy-mixing barrier erodes as the Antarctic polar vortex breaks down, hastening the smoothing effect around the Antarctic. Flattening by vertical advection is associated with strong downward motion around the Antarctic. Again, downward motion strengthens as the polar vortex breaks down, and the downward motion moves air characterized by flatter tracer gradients from the upper stratosphere to the middle stratosphere during spring.

5. Roles of the mean meridional circulation: A 2D model study

This section describes results derived from 2D model output. The goal was to assess the impact of only the mean meridional circulation on gradient genesis. The 2D model was constructed using the zonal-mean transport equation of Miyazaki and Iwasaki (2005). Mean meridional circulation fields diagnosed from MRI–JMA GCM output were used in the 2D model calculations that excluded the eddy meridional and vertical transport terms from the zonal-mean transport equation. The 2D model was integrated from an initial state that was obtained from the zonal-mean distribution of the 3D CTM on 1 June through 31 July for the five-member ensemble for 1997–2001. Figures 14 and 15 show monthly mean N₂O distributions averaged for July. The N₂O distribution calculated from the 2D model differs from that calculated from the 3D CTM in the subtropics during winter, and the difference increases with decreasing altitude. This result suggests...
FIG. 14. Meridional cross sections of N$_2$O distribution, averaged over July for five ensemble 2D model runs during 1997 to 2001, initialized on 1 Jun. Solid lines are zonal-mean N$_2$O mixing ratio obtained from the 3D CTM; dotted lines are from the 2D calculation. Contour interval of N$_2$O mixing ratio is 0.03 ppmv.

FIG. 15. (top) Latitudinal distribution of N$_2$O mixing ratio and (bottom) the absolute value of the meridional N$_2$O gradient at 20 hPa, averaged over July. Contour intervals are as in Fig. 14.
that eddy (diffusive) transport is dominant in the genesis of gradients particularly in the lower stratosphere as also noted by Gray and Russell (1999) and Neu et al. (2003). The 2D model produces a maximum N$_2$O gradient around 30°S in the middle stratosphere, which is steeper and at higher latitudes than in the 3D CTM.

Consider the implications of the formation mechanisms of the subtropical tracer gradient during winter. Shearing deformation steepens the tracer gradient in the subtropics, and meridional advection transports it to higher latitudes (cf. Fig. 8). These mean meridional circulation terms produce a large tracer gradient at midlatitudes in the 2D model. In the case of the 3D CTM, eddy meridional transport additionally provides a stairstep effect, reducing the tracer gradient at midlatitude and shifting the tracer gradient to the subtropics. For a hypothetical example, assume that a tracer is transported by the mean meridional motion along with eddy meridional and vertical transports (calculated with the diffusion coefficient diagnosed from the 3D CTM). Neglect only mean vertical motion. The tracer gradient maximum is located in the subtropics, but the gradient is smaller than in the 3D CTM because the 2D model does not include the steepening effect forced by shearing deformation of the mean vertical transport (dotted line in Fig. 16). In a case where the mean meridional transport is neglected (a tracer is transported by the mean vertical motion along with eddy meridional and vertical transports), a large tracer gradient is produced mainly by mean vertical transport, but the gradient is located at latitudes lower than observed (broken line in Fig. 16). This result indicates that mean meridional transports also importantly affect the gradient genesis by advecting the slope in the tracer poleward. Mechanisms described in the 2D simulation agree with the gradient genesis analysis presented in section 4.

In addition, the meridional N$_2$O gradients around the lower stratospheric polar vortex are somewhat smaller and at lower latitudes in the 2D model than in the 3D CTM. The stairstep effect associated with the eddy meridional transport likely influences the gradient genesis by steepening and shifting the tracer gradient. During summer when mixing is weak, the mean meridional circulation alone reproduces the tracer gradient in the middle and upper stratosphere.

6. Discussion and conclusions

Large meridional gradients of long-lived chemical species exist in the subtropics and around the polar
vortex in the stratosphere. This paper has investigated formation and maintenance mechanisms of these tracer gradients using a newly developed gradient genesis equation based on the mass-weighted isentropic zonal means. The gradient genesis equation includes shearing and stretching deformations and meridional and vertical advections. These terms yield insights into mechanisms that help form gradients. Data used were global objective analyses of meteorological fields and N$_2$O data (used as a tracer) obtained from MRI CTM output.

Estimates of terms in the gradient genesis equation are used to clarify formation and decay mechanisms controlling the meridional gradients of tracers. In the middle stratosphere, mean transport weakens the meridional tracer gradient at low latitudes and strengthens the gradient at mid- and high latitudes. The mean transport is predominantly the meridional component at low latitudes and both vertical and meridional components at mid- and high latitudes. Shearing deformation of the mean vertical transport increases the meridional tracer gradient from the subtropics to midlatitudes because of meridional shear of the mean vertical velocities. Mean meridional advection transports the subtropical tracer gradient toward midlatitudes. This decreases (increases) the meridional tracer gradient on the equatorial (polar) side of the sharp tracer slope in the subtropics. In contrast, the stairstep effect of the eddy meridional transport (steepening at the end of the well-mixed region owing to the meridional gradient of the diffusion coefficient) increases (decreases) the meridional tracer gradient on the equatorial (polar) side of the sharp tracer slope in the subtropics. This effect shifts the subtropical sharp tracer slope to lower latitudes and nearly compensates for the reduction in gradient due to the mean transport terms around the subtropics. The horizontal diffusion coefficient has a large gradient in the subtropics and at the polar vortex edge and that large coefficient gradient and the eddy meridional transport cause the stairstep effect.

Figure 13 shows the mechanisms that control the seasonal evolution of the tracer gradient as revealed by the gradient genesis analysis in this study. The subtropical tracer gradient is largest in early spring and in autumn. Our analysis finds that evolution mechanisms on the subtropical tracer gradient differ between the two seasons. Development of the autumnal subtropical tracer gradient maximum is mostly controlled by shearing deformation. Thus the subtropical tracer gradient in autumn does not arise from transport barriers for both mean and eddy fluxes. The autumnal tracer gradient subsequently weakens mainly because of the smoothing effect of the eddy meridional transport as influenced by active wintertime mixing. In contrast, development of the springtime subtropical tracer gradient maximum is controlled by the eddy transport stairstep effect and by shearing deformation associated with strong meridional shear in the mean vertical velocity. Subsequent gradient decay in spring is hastened by stretching deformation and vertical advection, along with smoothing effects from the eddy meridional transport. In particular, stretching deformation effectively reduces the tracer gradient in the springtime because of strong divergence in the mean meridional flow in the subtropics during spring. The Antarctic polar vortex acts as a transport barrier for both mean and eddy fluxes during winter. The stretching deformation of the mean meridional circulation associated with strong airmass convergence is the main generation mechanism for the steep tracer gradient around the Antarctic polar vortex in the middle stratosphere. The stairstep effect in the eddy transport also steepens the tracer gradient around the Antarctic polar vortex. The tracer gradient around the Antarctic polar vortex is weakened by the eddy transport smoothing effect and vertical advection as the polar vortex decays. Flattening by vertical advection is associated with strong downward motion that transports air with a flatter tracer gradient from the upper stratosphere to the middle stratosphere.

Calculations with a 2D model were also used to investigate the influence of the mean meridional circulation on gradient genesis. These calculations ignored the eddy transport term. The mean meridional circulation alone in the 2D model can reproduce the steep tracer gradient in the subtropics in the middle and upper stratosphere during summer. In the winter, however, the tracer gradient in the subtropics calculated from the 2D model is steeper and is located at higher latitudes than the gradient calculated in the 3D CTM. Isentropic diffusion shifts the subtropical sharp tracer slope toward lower latitudes. The results suggest that around the Antarctic polar vortex, the eddy meridional transport stairstep effect plays an important role in gradient genesis, especially in the lower stratosphere.

Gradient genesis has been investigated using realistic constituent data. However, the influence of small-scale transport (unresolved in the present model) on gradient genesis remains unclear. Furthermore, uncertainties remain in the transport scheme and circulation fields in current CTMs (e.g., Eluszkiewicz et al. 2000). Further analysis using more realistic high-resolution data is warranted to improve understanding of gradient genesis.

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REFERENCES


——, D. W. Waugh, and M. P. Chipperfield, 2000: The effects of


