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The standard deviation of column ozone from the zonal mean

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Abstract. The standard deviation of column ozone from the zonal mean (COSDZ) provides a measure of the longitudinal inhomogeneity in ozone and dynamical wave activities in the atmosphere. Using the Total Ozone Mapping Spectrometer (TOMS) data, we obtain latitude-season maps of COSDZ that are representative of a dynamically quiet year (1987) and a dynamically active year (1992). The spatial and temporal patterns of COSDZ show considerable similarity to the standard deviation of the 50 mb geopotential heights from the zonal mean. We point out that the simulation of this quantity by three-dimensional (3-D) models could provide a sensitive check of wave activities in the stratosphere that are responsible for ozone transport. Comparison between the observed COSDZ and the simulations of the GSFC 3-D model of ozone reveals major discrepancies between data and model in the tropical stratosphere.

Introduction

Most studies of stratospheric ozone column have emphasized the zonal averaged values (e.g. Stolarski *et al.*, 1991, 1992). However, the mean is only one of the many statistical quantities that can be extracted from observations such as the Total Ozone Mapping Spectrometer (TOMS) data. Additional information that measures the intrinsic variability of ozone is available in the higher order moments and it can provide new insights as well as tests of predictive models of the ozone layer. Indeed, the recognition of the importance of higher order moments in atmospheric chemistry is overdue in view of their successful application to climate studies [Polyak, 1996; Haskins *et al.*, 1997].

Even after monthly averaging, the global maps of total ozone display substantial deviations from zonal symmetry, especially during the winter seasons of the respective hemispheres. These deviations can be explained by the vertically propagating quasi-stationary planetary waves from the troposphere [Charney and Drazin, 1961; Matsuno, 1970] and their influence on the transport of ozone [Geller *et al.*, 1989].

We shall argue that the spatial-temporal pattern of the second order moment, the standard deviation of column ozone from the zonal mean (COSDZ), provides a useful measure of the impact of dynamical wave activities on ozone in the stratosphere. This will be illustrated by a detailed study for the years 1987 (a quiet year) and 1992 (an active year).

Data and Method

We use the high resolution (1°×1.25°) in latitude and longitude) Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) version 7 data from 1979 to 1992 [McPeters and Labow, 1996]. The total column ozone Ω can be expanded in zonal Fourier harmonics up to some zonal wave number N ($\cong$240 for TOMS ozone) representing the limit of resolution of the data [Andrews *et al.*, 1987],

$$\Omega(\theta,\phi)=\Omega_0(\theta)+\sum_{n=1}^{N}\Omega_n(\theta)\cos(n\phi+\alpha_n) \qquad (1)$$

Here θ is latitude, ϕ is longitude, α_n is the phase for wavenumber n and $\Omega(\theta,\phi)$ is column ozone as a function of θ and ϕ. We have zonal-averaged column ozone in each latitude

$$\Omega_0(\theta)=\frac{1}{2\pi}\int_0^{2\pi}\Omega(\theta,\phi)d\phi \qquad (2)$$

Previous studies of zonal-averaged column ozone trend [Stolarski *et al.*, 1991] have focused on Ω_0, which is most important for an assessment of the impact of chemistry. Information on higher wavenumbers was lost due to zonal averaging. The zonal mean standard deviation is a convenient measure of the amplitude of the zonal asymmetry. It is known that the zonal asymmetric part represents the dynamical wave activities in the atmosphere for the dynamical tracers. We will first define the column ozone standard zonal deviation (COSDZ) and derive the relationship between COSDZ and the higher wave harmonics.

Let

$$\Sigma^2(\Omega(\theta))=\frac{1}{2\pi}\int_0^{2\pi}(\Omega(\theta,\phi)-\Omega_0(\theta))^2d\phi \qquad (3)$$

We have

$$\Sigma^2(\Omega(\theta))=\frac{1}{2\pi}\int_0^{2\pi}\left(\sum_{n=1}^{N}\Omega_n(\theta)\cos(n\phi+\alpha_n)\right)^2d\phi$$
$$=\frac{1}{2}\sum_{n=1}^{N}\Omega_n(\theta)^2$$

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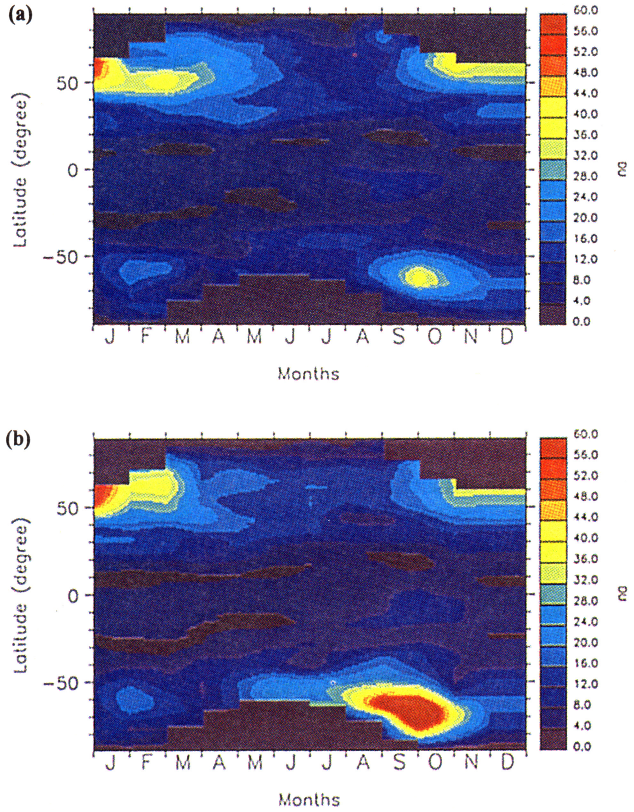

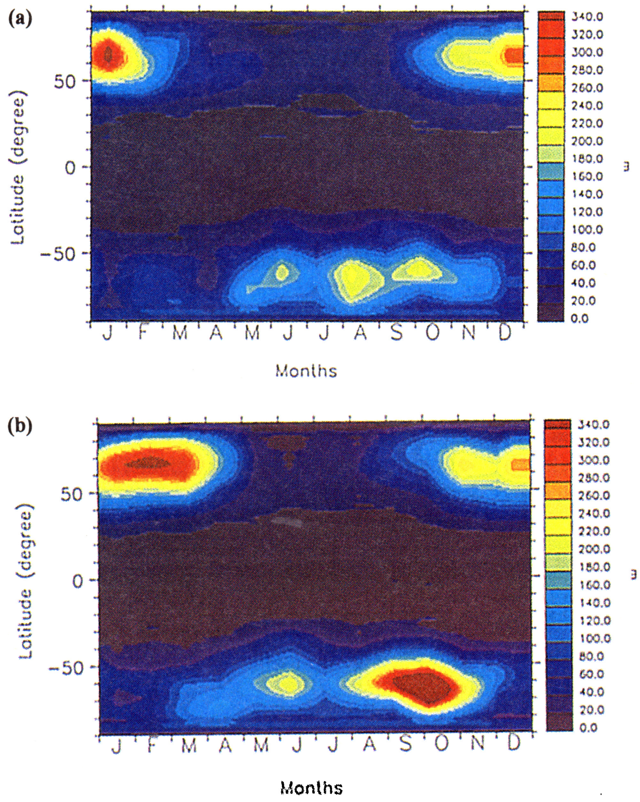

Figure 2. (a) Geopotential height standard zonal deviation (GHSDZ) in meter at 50 mb level in 1987; (b) Geopotential height standard zonal deviation (GHSDZ) in meter at 50 mb level in 1992.

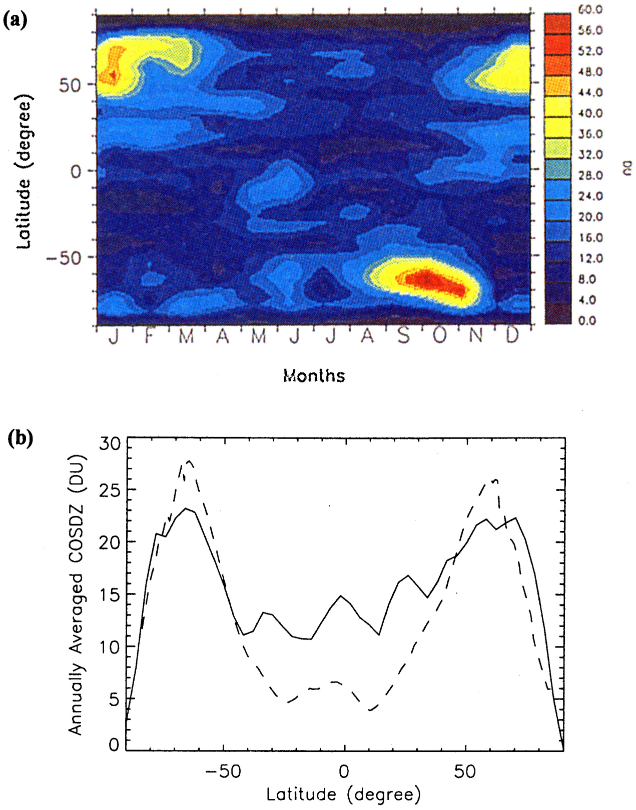

Figure 3. (a) Model COSDZ from September 11, 1991 to September 8, 1992 (Data from output of the Goddard model [Douglass *et al.*, 1996]); (b) Annual average of model COSDZ (solid line) and TOMS COSDZ in 1992 (dash line).

Thus

$$\Sigma(\Omega(\theta)) = \sqrt{\frac{1}{2}\sum_{n=1}^{N}\Omega_n(\theta)^2} \qquad (4)$$

Therefore, $\Sigma(\Omega(\theta))$ represents the sum of intensity of all higher wavenumbers in the Fourier harmonics. In the following, we will refer $\Sigma(\Omega(\theta))$ as COSDZ.

Results and Discussion

The TOMS monthly averaged data are used in our analysis. The net result of monthly averaging is to filter out the short period transient components. We have carried out analysis of COSDZ from 1979 to 1992, but only the results of two representative years will be shown in this paper. Fig. 1 shows the latitude-seasonal plots of COSDZ in 1987 and 1992. 1987 is a quiet year with a deep Antarctic ozone hole, while 1992 is a very active year with a shallow ozone hole. In both years, the well-defined seasonal cycle of quasi-stationary waves in the northern hemisphere shows strong activities throughout the winter-spring season, typically from October to the finally warming in March. COSDZ reaches peak value of about 50 DU in the Arctic winter. These wave activities are essentially absent through the summer months [Plumb, 1989]. COSDZ is low in the tropics, where typical values are about 2 DU, with little seasonal variation. This is due to the lack of planetary wave activities near the equator. In the southern hemisphere, the seasonal cycle of COSDZ shows a large peak of about 40

DU in 1987 and 60 DU in 1992 near the edge of the polar vortex during the southern winter. This peak moves poleward in the austral spring during the final warming. The dramatic differences in dynamical activities between 1987 and 1992 are clearly revealed in COSDZ values in the southern polar region.

To relate our results for COSDZ to atmospheric dynamics, we compute the geopotential height standard zonal deviation (GHSDZ) at 50 mb using the dynamical fields archived by the Data Assimilation System (GEOS DAS) of Goddard Space Flight Center [Schubert *et al.*, 1993]. This pressure level was chosen as representative of the lower stratosphere, where the bulk of ozone resides. Fig. 2 shows the GHSDZ in 1987 and 1992. They show patterns that are strikingly similar to those of COSDZ in Fig. 1. Recent work by Salby and Callaghan (1993) and McCormack and Hood (1997) demonstrated the close connection between geopotential height and the ozone column. We have extended the previous work to include results on the second moments of these quantities.

We shall argue that COSDZ provides a valuable check for the 3-D models of stratospheric ozone. Unfortunately, there are no published model results for COSDZ to compare with Fig 1. We compute the values for COSDZ from the Goddard 3-D model for stratospheric ozone [Douglass *et al.*, 1996] from September 11, 1991 to September 8, 1992. This model uses winds from the Goddard Earth Observing System Data Assimilation System (GEOS DAS) for transport [Schubert *et al.*, 1993]. The results are presented in Figs. 3a and 3b. Compared with Fig. 1b, it is clear that the Goddard model correctly simulates the general pattern of COSDZ observed by TOMS, including the high winter polar peaks and the low values in the the summer poles. The minimum in COSDZ in the tropics is not reproduced in the model, in spite of the reasonable agreement between the modeled zonal mean total ozone and TOMS observations as reported by Douglass *et al.* [1996]. The large difference of annually averaged COSDZ between model and TOMS can be seen also from Fig. 3b. The COSDZ provides a more quantitative measure of the excess variability found particularly in the model tropics and subtropics. This excess variability is produced not by the chemistry and transport model but by the noisy assimilation wind fields that are inputs to the model. Efforts are underway both to improve the Goddard assimilation procedure in the tropics, thereby reducing the nonphysical variability, and to improve the usage of the assimilation fields in the model.

We should point out that the above discrepancy between the observed and the model values for the second order moments is not a surprise. When similar comparisons were made between GCMs and data for climate variables, the results reveal major model inadequacies, especially in the tropics [Polyak, 1996] and over regions with clouds [Haskins *et al.*, 1997]. Our results point to a new direction for major model improvements for transport in the tropical stratosphere in a 3-D model.

Conclusion

The intricate coupling between atmospheric chemistry, radiation, climate and dynamics has recently been discussed in a seminal paper by McElroy *et al.* [1992], but there is no definitive evidence for the coupled changes. In this paper we point out the potential usefulness of the standard deviation of column ozone from the zonal mean (COSDZ) as a key index of change of the stratosphere and troposphere.

The pattern of COSDZ extracted from Version 7 of TOMS data (Figs. 1a and 1b) reveals a complex seasonal cycle of dynamics (Figs. 2a and 2b) in determining the variability of stratospheric ozone. A state-of-the-art 3-D model (Figs. 3a and 3b) captures some features of the observed pattern but fails to account for the observations in the tropical stratosphere. It remains a challenge to 3-D models to reproduce both the climatological mean of the observed COSDZ and its decadal trend, and further determine the causes of this change, along lines that have proved to be fruitful in climate studies [Polyak and North, 1997a,b].

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