CIRCULATION DEDUCED FROM AEROSOL DATA AVERAGED BY SEASON AND PHASE OF THE QUASIBIENNIAL OSCILLATION

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ABSTRACT. Aerosol measurements obtained from the Stratospheric Aerosol and Gas Experiments (SAGE I and II), for the periods 1979-81 and 1984-91, are averaged by season and by the phase of the quasibiennial oscillation (QBO). Largest values of aerosol extinction ratio are found in the tropical lower stratosphere. Latitude-altitude distributions suggest the existence of an upper and a lower transport regime out of this tropical reservoir. Above 25 km upward detrainment occurs more readily in the subtropics during summer and fall. Detrainment poleward and downward occurs within ~5 kilometers above the tropopause most readily during the austral winter and spring and during the boreal fall, winter and spring. Ascent associated with QBO easterly shear favors detrainment in the upper regime, while relative descent and poleward spreading during QBO westerly shear favors detrainment in the lower regime.

1. Introduction

The stratosphere has many links with the troposphere, including modulation of solar radiation by ozone and aerosols, its role in the greenhouse effect, and as a chemical processor. Many uncertainties in forecasting stratospheric climate into the next century arise from a poor understanding of constituent transport mechanisms. Several order-one questions have yet to be answered: 1) How do constituents enter the stratosphere? (Is the net upward molecular drift in the tropics due to a Lagrangian pumping mechanism above cumulus convection? Is it primarily laminar in nature, controlled by the global pattern of gravity and Rossby wave absorption in the lower stratosphere?) 2) Why do tracer distributions in the tropical stratosphere appear rather homogeneous compared to other regions? 3) How do constituents leave the tropical stratosphere? In this paper we will attempt to give partial answers to the last two questions by considering the distributions of

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sulfate aerosols, as seen in a decade of satellite observations, binned by season and by the phase of the QBO.

2. Data and Analysis

The Stratospheric Aerosol and Gas Experiments (SAGE I, 1979-81 and SAGE II, 1984-91), employing the limb-viewing solar occultation technique on polar orbiting satellites, have yielded near-global long-term self-calibrated measurements of extinction near 1 μm (McCormick et al. 1979). The ratio of measured extinction to Rayleigh extinction near 1 μm (hereafter extinction ratio, β; Russell et al. 1981) provides an estimate of the distribution of stratospheric sulfate aerosols, suspended liquid droplets of radius 0.01-1.0 μm composed of sulfuric acid and water. The latitude-altitude distribution of β is a useful indicator of air motions at altitudes from near the tropopause to ~15 km above the tropopause (Trepte and Hitchman 1992). Although aerosols precipitate, relative vertical air motions may be inferred because temperature perturbations associated with the motions exert only a minor effect on coagulation and evaporation (Kent et al. 1985).

Extinction ratio profiles, with 1 km vertical resolution, range from 79°S to 79°N, although during winter months measurements are not taken poleward of ~50° (McCormick et al. 1979). Due to the sampling pattern and data gaps, spatially coherent distributions could be obtained only for a season or longer. Each profile was binned in latitude at 5° resolution, and then binned either by season or by phase of the QBO. There are typically ~500 profiles corresponding to each latitude for each season, ranging from ~230 to ~7000 per latitude bin. Values of β less than 1.5 were not contoured and profiles were truncated at the climatological tropopause.

The record of stratospheric zonal wind profiles at Singapore (1°N, 104°E) was examined to establish the phase of the QBO. Each profile of β was assigned to the easterly shear (westward wind increasing with altitude) or westerly shear category according to the observed predominant shear over the altitude range 20-30 km. From theory and models it is known that westerly shear coincides with descent and easterly shear with ascent (e.g., Plumb and Bell 1982). Easterly shear is more common: 59% of all profiles are contained in that category.

Aerosol amounts varied considerably during the data record, reflecting the random history of volcanic injections. Major tropical eruptions include those of El Chichon in April 1982 (during the data gap between SAGE I and II), Mt. Ruiz in November 1985, and Mt. Kelut in February 1990. Although some minor biases in seasonal trend and latitudinal distribution persist in the record-long averages shown in Figs. 1 and 2, we interpret them as being useful climatological distributions.

3. Seasons

Figure 1 shows the distribution of extinction ratio from 60°S to 60°N, 10 to 35 km for boreal winter, spring, summer and fall. Note that there is little data poleward of 50° in winter. Average values of β range from less than 1.5 in the upper stratosphere to as much as 15 in the tropical lower stratosphere. The tropical maximum is bounded by strong meridional gradients near 20°N and S, a rapid downward decrease toward the tropopause, and a more gradual decrease upward. For sulfate aerosols to exist there must be sufficient ultraviolet light and sulfur precursors (from direct volcanic injection of SO_2 and ascent of tropospheric SO_2 and COS through the tropical tropopause), and sufficiently cold temperatures. The rapid downward decrease toward the tropical tropopause may be due to a combination of aerosol-poor air ascending from the tropopause and insufficient ultraviolet light below the ozone layer for precursor photolysis (Yuk Yung, personal communication). The decrease upward from the maximum is due primarily to evaporation, as parcels gain heat and gradually ascend to higher levels in the stratosphere.

From maxima near 21 km over the equator, high values extend upward between 30°S and 30°N above 25 km in an "upper regime", and poleward and downward within ~5 km of the tropopause in a "lower regime". This general pattern, frequently called the Brewer-Dobson circulation, is compatible with the net drift of molecules inferred from the distribution of water vapor (Brewer 1949), total ozone (Dobson 1956), net heating rates (Murgatroyd and Singleton 1961), radioactive debris (Feely and Spar 1960; Telegadas and List 1969), and the pattern of diminution of insolation following the eruption of Mt. Agung in 1963 (Dyer and Hicks 1968).

The upward extent of the 2.5 contour varies with season, reaching the highest altitudes near 10-15°S during boreal winter. One may infer a preference for lofting in the subtropics during summer and fall, especially in the southern hemisphere. Factors which could affect the shape of the upper regime include vertical motions and subtropical 'scavenging' by extratropical planetary scale Rossby waves via quasi-isentropic exchange of aerosol-poor air from higher latitudes. Lofting during the summer and fall is expected from the pattern of radiative heating and the meridional circulation spun up by the pattern of gravity wave and Rossby wave absorption over the middle atmosphere. In the winter and spring hemispheres, values may be smaller due to descent, a lack of ascent, or to poleward transport and dilution in association with wave motions.

In the lower stratosphere the 5 contour extends farthest poleward and downward during the austral winter and spring and the boreal fall, winter and spring. It extends poleward the least during boreal summer. Tropospheric baroclinicity is smallest during summer. Furthermore, summer easterlies tend to keep Rossby

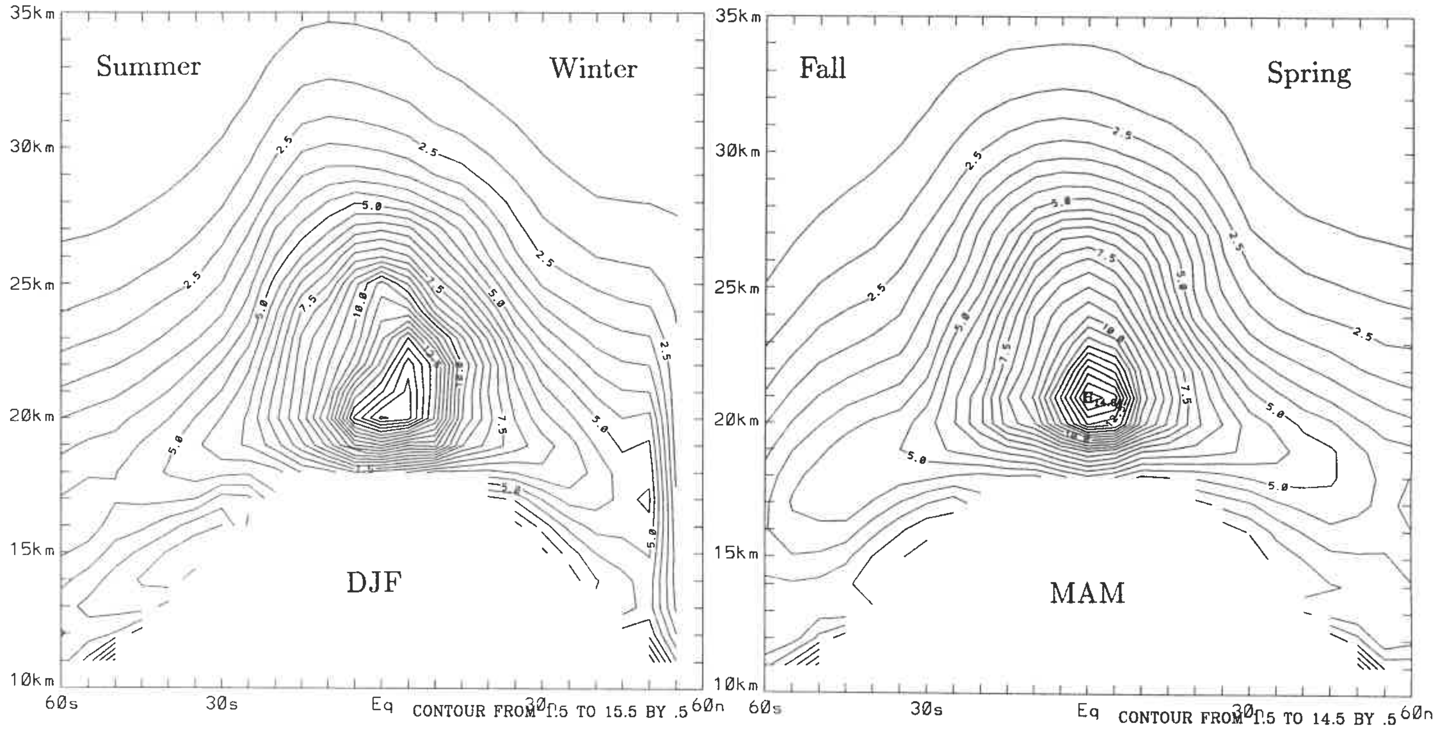

Fig. 1. Latitude-altitude sections of β at 1 μm from SAGE I (1979-81) and II (1984-91), averaged for the periods December, January and February (DJF, left), and March, April and May (MAM, right). The contour interval is 0.5, starting at 1.5.

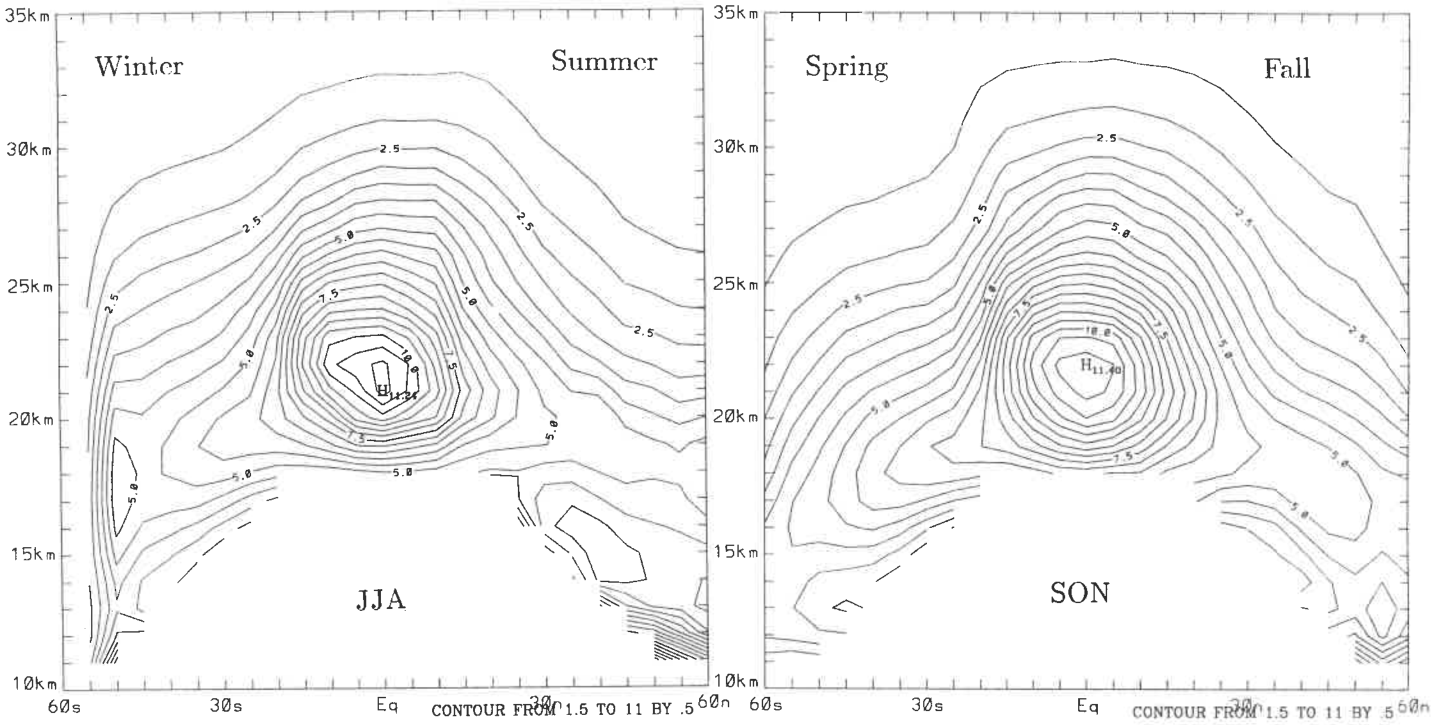

Fig. 1 (continued). Same for June, July and August (JJA, left), and September, October and November (SON, right).

wave activity from penetrating into the stratosphere. Synoptic charts (not shown) strongly support the concept that the lower regime seen in these zonal mean seasonal average plots represents the integrated effect of discrete transport events.

4. Quasibiennial Oscillation

Figure 2 shows the distribution of extinction ratio, minus one, averaged during times of predominant QBO easterly and westerly shear. The aerosol patterns suggest enhanced ascent over the equator during easterly shear, with relative descent over the equator and poleward motion at the base of the shear layer during westerly shear, in agreement with theoretical expectations (Andrews et al. 1987). The meridional circulation associated with the QBO has never been observed. These aerosol distributions, along with temperature and column ozone observations, contribute toward observational constraints on circulation magnitudes. Given uncertainties in microphysical properties, at present it is difficult to make quantitative estimates of vertical motions. The sign of vertical motion over the equator during QBO westerly shear is not known.

These patterns suggest that, in the upper regime above 25 km during QBO easterly shear, air is lofted more readily and made accessible for detrainment from the tropical reservoir in the upper stratosphere. In the lower regime below 25 km air is more readily detrained to higher latitudes during QBO westerly shear, with its associated relative descent and poleward flow.

5. Discussion

One may regard these climatological distributions as the average residue of tropical volcanic injections. During most of the record, aerosol distributions are clearly linked temporally with a previous eruption. To the extent that the 1979-91 period is geologically representative, a climatological aerosol distribution should be regarded as primarily volcanic in nature. The evolution of debris from the eruption of Mt. Ruiz near 4°N in November 1985 may have resulted in maximum values occuring slightly north of the equator during DJF, with a monotic decrease in maximum value and equatorial centering occurring through MAM, JJA, and SON (Fig. 1). Note also that the eruption occurred midway through a period of QBO easterly shear and the maximum values are correspondingly larger than for westerly shear (Fig. 2). Hence significance should be attached only to the differences in distributions among the seasons and phase of the QBO, rather than among absolute magnitudes. It should be emphasized that the basic differences between each season and phase of the QBO are found throughout the data record.

Figures 1 and 2 also indicate where heterogeneous reactions are likely to be important. The quantity relevant to heterogeneous chemistry is the aerosol surface

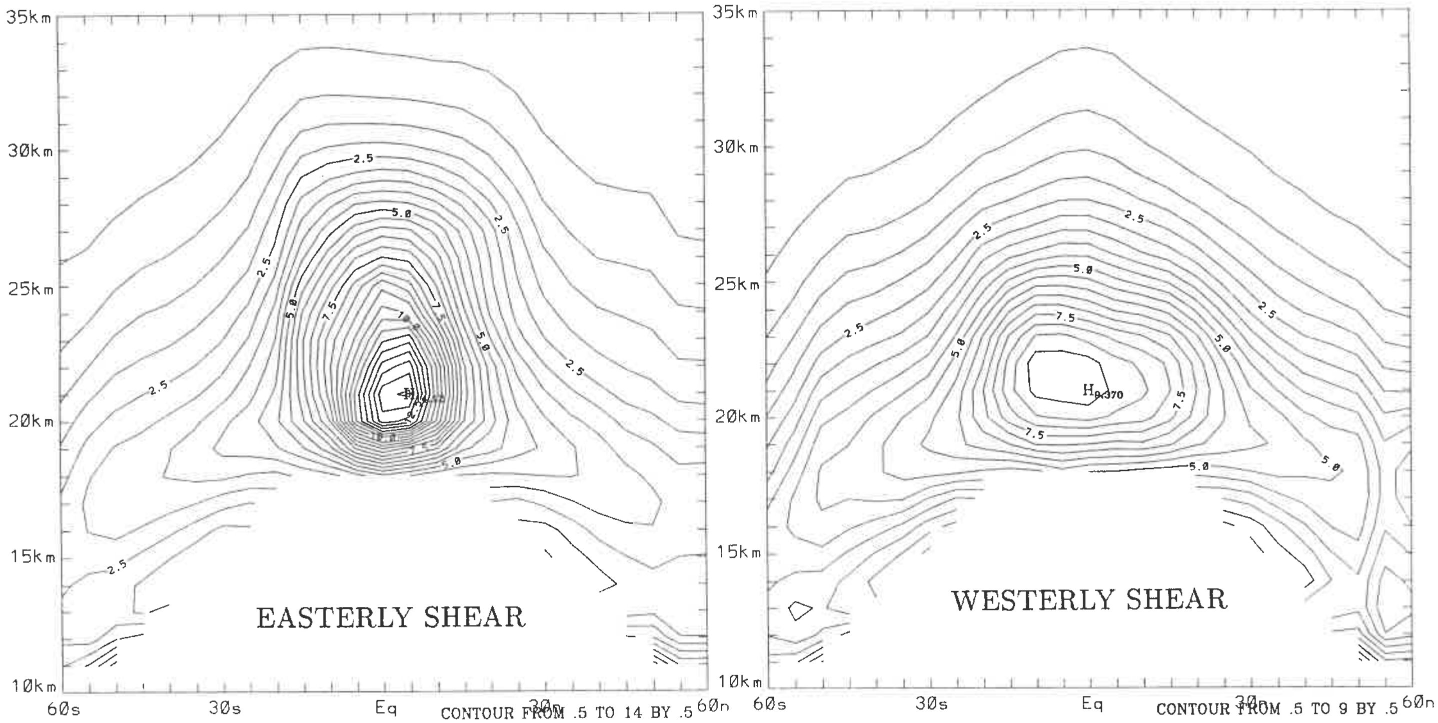

Fig. 2. Latitude-altitude sections of β-1 at 1 μm from SAGE I (1979-81) and II (1984-91), averaged by phase of the QBO: predominant easterly shear (left) and westerly shear (right) of zonal wind at Singapore in the layer 20-30 km. The contour interval is 0.5, starting at 0.5.

density. This may be calculated from extinction, which peaks at lower altitudes than extinction ratio due to the lack of normalization by air density. Nevertheless Figs. 1 and 2 suggest that sequestering of odd nitrogen and liberation of odd chlorine (Hofmann and Solomon 1989) will occur preferentially in the lower regime during QBO westerly shear, during the boreal fall, winter and spring, and during the austral winter and spring. In the upper regime heterogeneous processes may be less important, but would exert the strongest influence in the subtropics during summer and fall and during QBO easterly shear. One may also expect that the pattern of diminution of total radiation and biologically active ultraviolet radiation would also be modulated by the seasonal and quasibiennial changes in aerosol distribution.

The tropical stratosphere appears to act as a temporary containment vessel, with air entering the middle atmosphere in a two-step process. From consideration of synoptic charts, a mechanistic numerical model, and theory the following picture may be hypothesized. Constituents that enter the tropical lower stratosphere through the tropical tropopause or by direct volcanic injection are redistributed within the tropics by meridional overturning associated with the QBO. Mixing within the tropics may be enhanced by synoptic perturbations and associated inertial instability. These processes alone would tend to yield strong meridional gradients in β, but the gradients may be enhanced by extratropical disturbances mixing aerosol-poor air into the subtropics. Detrainment into the rest of the middle atmosphere is controlled by season and phase of the QBO. During westerly shear air is more readily available for transport in the lower regime, while easterly shear favors the upper regime. Easterlies tend to keep Rossby waves from penetrating into the tropical reservoir.

It is likely that detrainment occurs in discrete synoptic events. Trepte et al. (1992), in case studies of the behavior of debris from the eruptions of Mt. Pinatubo in June 1991 (McCormick and Veiga 1992), have shown that aerosols are advected poleward in rather narrow tongues around subtropical anticyclones. O'Sullivan and Hitchman (1992) have studied inertial instability in a three dimensional mechanistic model of the middle atmosphere. They found that extratropical planetary waves which reach the subtropics organize the distribution of potential vorticity (PV) such that inertial instability occurs preferentially in certain longitude bands. The meridional accelerations and overturning that result from inertial instability promote latitudinal exchange and mixing of PV and constituents. In the model, inertial instability occurs preferentially on the equatorward side of anticyclones and it is in these regions where material is detrained from the tropics. Further study is required to better understand the nature of transport phenomena in the tropical stratosphere.

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