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CONNECTION BETWEEN TOTAL OZONE FIELDS AND LOWER STRATOSPHERIC DYNAMICS

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ABSTRACT

It is expected from theoretical considerations that synoptic-scale variations in total ozone should be correlated with the absolute vorticity field near the tropopause. This paper tests the theory, using TOMS total ozone fields and vorticity derived from ECMWF analyses. A good correlation is found, except during winter - suggesting that other sources of variability in total ozone are active at this time. The correlation with potential vorticity is also investigated. This shows two maxima in the correlation coefficient in winter and spring, one near the tropopause and the other in the region of 420K. A study of the residuals from a linear regression of vorticity with total ozone during January reveals a similar structure to the 450K potential vorticity field.

1. INTRODUCTION

The relation between total ozone and vorticity that forms the basis of this paper was derived by Vaughan and Price (1991). The total column of ozone in the atmosphere, N, may be written as

$$N = \int_0^{\infty} n(z)dz = -\int_{\theta_s}^{\infty} \frac{x(\theta)}{Mg}\frac{\partial p}{\partial \theta}\, d\theta$$

where n is the ozone number density, x its volume mixing ratio, M the mass of an air molecule, θ the potential temperature and θ_s its surface value. We can substitute for $\partial\theta/\partial p$ from the expression for potential vorticity Q, to obtain

$$N = \frac{1}{M}\int_{\theta_s}^{\infty} \frac{x(\theta)}{Q(\theta)}\, \xi_\theta\, d\theta \qquad (1)$$

where ξ_θ is the absolute vorticity on an isentropic surface. The ratio x/Q varies slowly with latitude and height since x and Q are strongly correlated between the tropopause and 21km (Danielsen, 1985; Gidel and Shapiro, 1980), where most of the ozone column is found. If the correlation holds up to a potential temperature θ_p,

$$N = \frac{1}{M}\frac{\overline{[x]}}{[Q]}\int_{\theta_t}^{\theta_p} \xi_\theta\, d\theta + N_t + N_u \qquad (2)$$

where θ_t is the potential temperature at the tropopause, N_t is the column of ozone in the troposphere and N_u is the residual column total above θ_p where x and Q are no longer positively correlated.

Synoptic-scale disturbances decay with height in the lower stratosphere, with no phase progression. Thus, variations in vorticity on this scale (and smaller) near the tropopause will be coherent with those at all heights in the lower stratosphere, provided there are no processes generating variability on such scales in the stratosphere itself. Consequently, total ozone should correlate with the isentropic vorticity at tropopause levels. This may be understood qualitatively by noting that air columns stretch on entering regions of high vorticity (such as troughs) because of the need to conserve potential vorticity (PV). They therefore present more total ozone to the TOMS instrument.

A further influence on total ozone columns is the height (or potential temperature) of the tropopause. Different air masses, with different depths of stratosphere, will contain different total ozone even though the absolute vorticity is the same. Air mass differences may be identified by differences in PV, therefore total ozone should also correlate with the PV distribution in the lower stratosphere. The purpose of this paper is to investigate the correlation of total ozone with potential and absolute vorticity. The study is based on GRID-TOMS ozone fields and meteorological data from ECMWF assimilation fields for midday. The latter provided winds and temperatures on 11 pressure levels extending up to 50 mb, with a horizontal resolution of 1.125°.

2. GRID CORRELATIONS BETWEEN ABSOLUTE VORTICITY AND TOTAL OZONE

Correlations were calculated every five days from 1st Jan to the 14th August 1987 for the region from 30°N to 60°N and 30°W to 30°E. The latitude range was chosen because equation (2) is not valid in the subtropics (Vaughan and Price 1991) and

TOMS measurements are unreliable poleward of 60°N in winter because of the high solar zenith angles. A restricted longitude range was chosen to ensure a close correspondence in time between the two data sets. GRID-TOMS data in this region were derived from three passes of the NIMBUS-7 satellite, within about 3 hours of 12h.

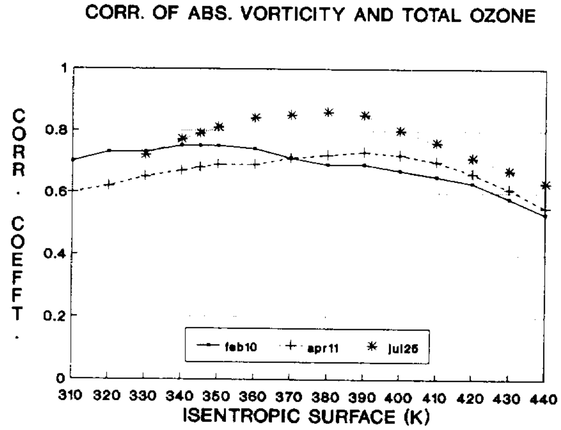

Fig. 1

Correlation coefficients were calculated for isentropic surfaces at 10K intervals between 310 and 440K (the latter was the highest surface remaining below 50 mb throughout the year). Examples are shown in fig.1, for 3 representative days. It is clear that the correlation coefficient varies slowly with height (consistent with the coherent decay of synoptic-scale disturbances in the lower stratosphere), and is higher in summer than in winter (exceeding 0.8 in July). This point is elaborated in fig.2, which shows how the correlation coefficient at three representative levels varied during the year. From March onwards, the values are roughly constant at 0.75 ± 0.07, but the correlation in winter is poor. This is consistent with the theory outlined above: the lower stratosphere is itself dynamically active in winter and this destroys the correlation with synoptic-scale features.

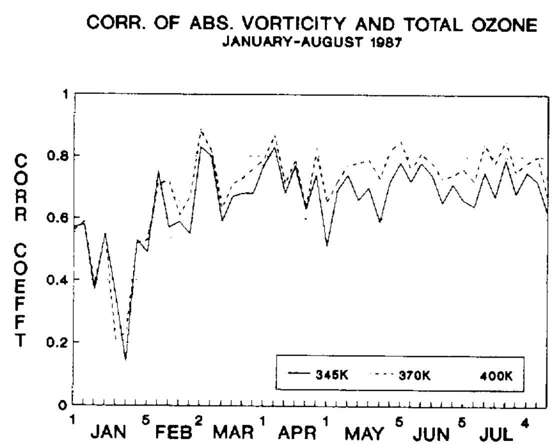

Fig. 2

3. GRID CORRELATIONS BETWEEN POTENTIAL VORTICITY AND TOTAL OZONE

The variation with height of the correlation coefficients between potential vorticity and total ozone is shown for four representative days in fig.3. In contrast to the absolute vorticity, there are very different patterns in summer and winter. In the

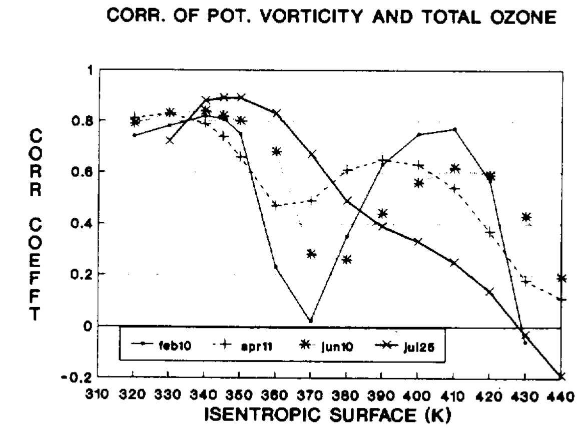

Fig. 3

summer case (July 25th) a maximum correlation of 0.85 occurs near 350K, then the correlation coefficients decrease steadily with height, becoming negative by 430K. In the other three examples a maximum correlation greater than 0.8 occurs between 330K and 340K, just above the tropopause, followed by a minimum near 370K and a second maximum near 400K. This pattern is most pronounced for the winter case (Feb 10th), where the correlation coefficient is not significantly different from zero at 370K, yet the second maximum is almost as large as the first. Above 420K in winter the correlation coefficient decreases sharply, becoming negative above 430K. The two spring profiles show a gradual evolution from the winter to the summer pattern, the latter being established by early July. This point is demonstrated more clearly by fig.4, showing the time

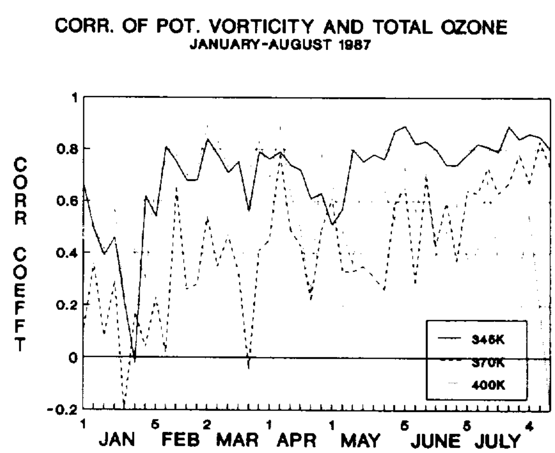

Fig. 4

a)

b)

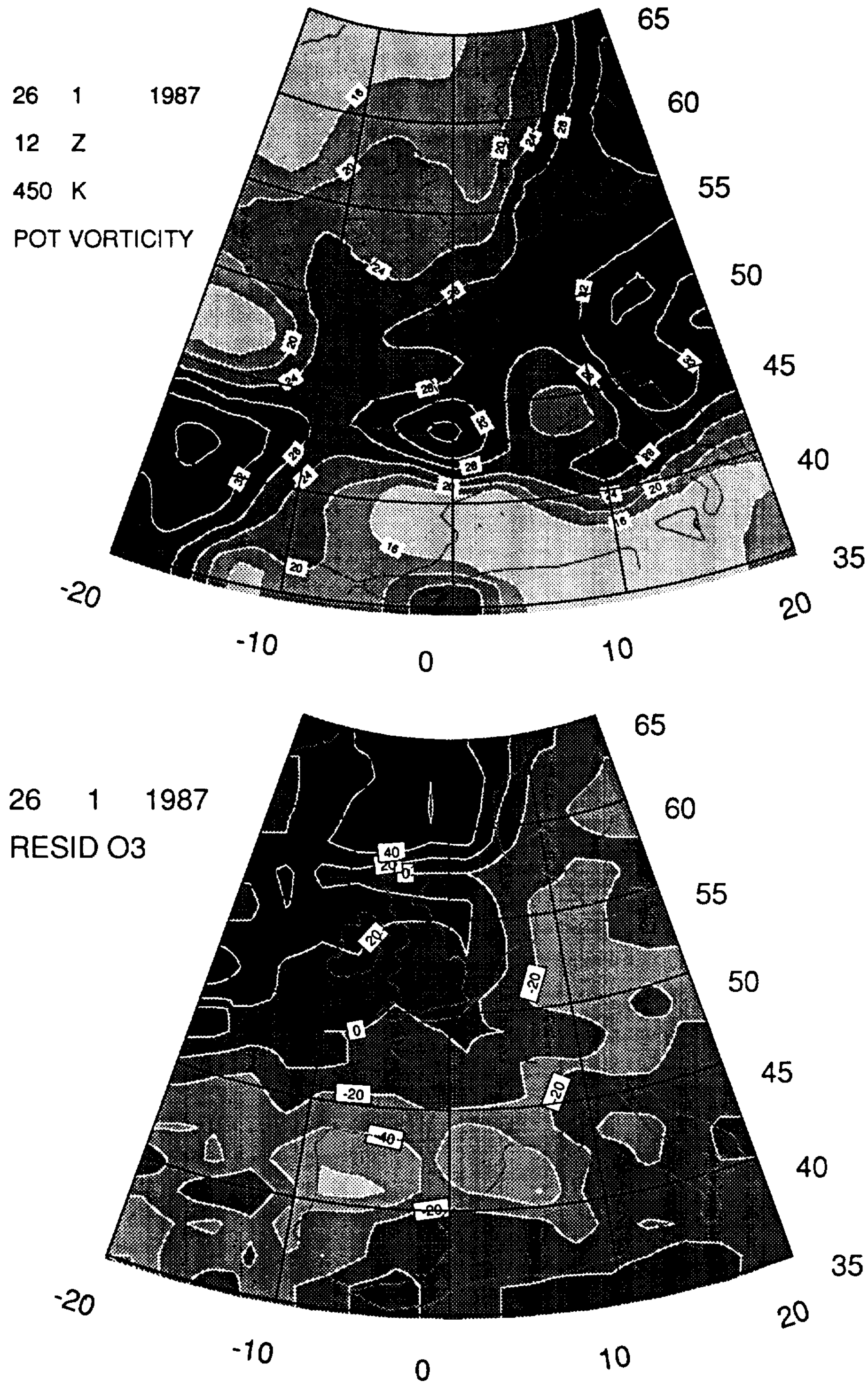

Fig.5 a)Potential vorticity field at 450 K potential temperature, 12h 26 Jan 1987 in units of $\mu Km^2(kgs)^{-1}$, derived from ECMWF operational analyses. Note the tongue of high PV extending southwestwards between 40° and 50°N.

b)Residual ozone field in DU for the same time. This was calculated by subtracting from the actual total ozone at each point (measured by TOMS) the value predicted from the regression equation between total ozone and absolute vorticity derived on the 17th January. Note negative residuals corresponding to the PV tongue in a): the polar vortex shows up as a region of lower total ozone once tropopause-level disturbances are removed.

series of correlation coefficients at three representative levels. As before, the values at 345K were low in winter (especially from 22-28th Jan, see below), but increased to around 0.75 in spring and 0.8 in summer. Values in the second maximum remained as large as those in the first until the beginning of April, by which time the minimum correlation near 370K had increased to roughly the same value.

These results may be explained as follows: below 345K good correlation is found throughout the year because these surfaces intersect the tropopause, and high PV is found on the cyclonic side of the jet stream where the tropopause is low and the stratosphere comparatively deep. The second maximum in winter and spring is then indicative of further air mass differences at a higher level - near the base of the stratospheric polar vortex. Around 360-370K in winter there is a transition region, below which isentropes slope downward towards the pole (corresponding to the low tropopause there) and above which they slope up into the polar vortex because of the strong diabatic cooling there. This will be particularly pronounced when the polar front jet stream lies below the stratospheric polar jet. In the transition region the static stability decreases poleward and tends to be anticorrelated with ξ_θ (as was verified by direct calculation); thus, the correlation between total ozone and PV disappears at this level. The gradual decay of the second maximum in fig.4 is related to the time taken to mix out the inhomogenieties set up in winter; its disappearence coincided with the establishment of the easterly polar vortex at 50mb during June.

Independent confirmation that the pattern shown in figs. 3 and 4 is not an artifact of the ECMWF assimilation is provided by the study of Vaughan and Begum (1989), who correlated total ozone and PV over Asia. Although their vorticity values were derived from ECMWF analyses, their stability was calculated directly from radiosonde profiles (and so had better vertical resolution than the present study). Their distribution of correlation coefficients between 40° and 50°N is very similar to the present results, with a second maximum in winter and spring above 380K.

4. THE PERIOD 22-28 JANUARY 1987

This period is identified in figs. 2 and 4 as one where total ozone correlated very poorly with both potential and absolute vorticity. It corresponded to a major stratospheric warming over northern latitudes, when polar air throughout most of the stratosphere shifted equatorwards resulting in a significant distortion of the total ozone field due to a change in the term N_u in equation 2. The aim of this section is to isolate this change by removing the synoptic-scale features related to tropospheric weather systems.

The method used was to calculate the linear regression equation of total ozone on absolute vorticity at 345K over the region 35°-60°N, 20°W-20°E, and look at the map of residuals from this equation. Tests during summer showed that typical residuals of 20 DU were found; this value represents a 'noise' for the method. Correlation coefficients were calculated daily from 17-30 January. The highest value (0.65) was found on 17th January, when the polar vortex was well away from the region of study. The regression equation derived for that day was then used to calculate residual fields for the rest of the period.

The results were compared with the PV fields at 450K derived from the ECMWF model (this surface was below 50 mb in winter). A reasonable agreement was found, with negative residuals corresponding to high PV at 450K, and therefore the polar vortex. An example is shown in fig. 5 for January 26. During this period a tongue of air was drawn off the vortex and moved to lower latitudes; this feature is well captured by the residual field.

5. CONCLUSIONS

This paper verifies the theoretical relationship derived by Vaughan and Price (1991) linking synoptic-scale disturbances in total ozone to the upper tropospheric absolute vorticity pattern. Additionally, correlations with potential vorticity reveal the influence of air mass differences on the ozone column: correlation coefficients from this study are high just above the tropopause at all times of the year, but show a distinct minimum near 370K and a second maximum near 400K in winter and spring. Above about 440K the correlation coefficients with PV become negative at all times of the year. A study of the residuals from a linear fit of total ozone with absolute vorticity during a stratospheric warming clearly identifies the removal of a tongue of ozone-poor air from the polar vortex, which correlates well with the 450K PV chart. Thus, TOMS data may be used to study transport processes in the stratosphere without the interference of tropospheric weather systems.

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