Detection of a lightning influence on tropical tropospheric ozone

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Detection of a lightning influence on tropical tropospheric ozone

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Abstract. Empirical orthogonal functions (EOFs) are used to analyze a 14-year record of tropical tropospheric ozone columns (TTOCs) determined from satellite measurements. The first EOF explains 54% of TTOC variance and represents biomass burning in Africa and South America. The second EOF explains 20% of the variance and has a distinct lightning signature.

Introduction

Ozone (O₃) in the tropical troposphere plays a key role in determining the oxidizing power of the atmosphere and is an important greenhouse gas. Production of O₃ in the tropical troposphere is believed to be controlled by the supply of nitrogen oxide radicals (NOₓ ≡ NO + NO₂) originating from lightning, biomass burning, and soils [Jacob et al., 1996]. Global model calculations suggest that most of the NOₓ in the tropical troposphere is from lightning [Lamarque et al., 1996], but to date there are no clear observations of large-scale O₃ enhancements associated with emissions of NOₓ from lightning. This is in contrast to the large springtime enhancements of O₃ in the southern tropics caused by NOₓ emissions from biomass burning [Thompson et al., 1996; Schultz et al., 1999].

Part of the problem in detecting a lightning influence on O₃ may be that most of the lightning NOₓ is released in the upper troposphere where O₃ production is slow even though the number of O₃ molecules produced per unit NOₓ consumed is high. If so, the advent of global observation capability from satellites should greatly facilitate detection.

We present here evidence of a large-scale lightning influence on tropical tropospheric O₃ using a 14-year record of monthly tropical tropospheric ozone columns (TTOCs) determined by Ziemke et al. [1998] from the Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus 7 satellite. We show that empirical orthogonal functions (EOFs) of TTOCs relate significantly to lightning NOₓ emissions.

EOFs represent an orthogonal basis upon which the monthly spatial fields of TTOCs can be decomposed, offering an objective analysis of the spatial and temporal patterns of variability.

Data and Methods

We used monthly-mean TTOCs over the period 1979–1992 (inclusive) derived by Ziemke et al. [1998] from Nimbus 7 TOMS observations using the convective cloud differential method. The central assumption of this method is that cloud tops over the equatorial Pacific usually extend to the tropopause. Since longitudinal variability in stratospheric column O₃ is small in the tropics, stratospheric O₃ columns can be derived by averaging above-cloud column O₃ amounts over the equatorial Pacific. The resulting monthly TTOCs are reported by Ziemke et al. [1998] on a 5° × 5° grid between 15S and 15N (Figure 1).

Because the convective cloud differential method does not rely upon other satellite O₃ measurements, its error is reduced over that of TOMS-SAGE [Fishman and Brueckett, 1997] or TOMS-SBUV [Fishman et al., 1996]. An alternative retrieval of TTOCs from TOMS observations has been reported by Hudson and Thompson [1998], but provides a continuous record from only 9S to 7N during 1979–92.

Our analysis compares the TTOCs from Ziemke et al. [1998] to global lightning NOₓ emission estimates available from Price et al. [1997] on a 2.5° × 2.5° grid with monthly resolution. The latter estimates parameterize lightning frequencies and intensities as a function of cloud top data at 5 km resolution in 1983–91 from the International Satellite Cloud Climatology Project (ISCCP) [Rossow and Schiffer, 1991].

Figure 2 illustrates the seasonal variation in tropical lightning NOₓ as derived by Price et al. [1997]. Lightning occurs mainly over continents since the relatively weak updrafts in marine storms result in considerably fewer electrical discharges. Lightning NOₓ emissions vary with seasonal solar heating and are highest during DJF (JJA) in the southern (northern) tropics. We find that 28% of lightning NOₓ in the 15S to 15N latitudinal band is produced over Africa, 34% over South America, and 38% over southeast Asia and Oceania.

We averaged the monthly TTOCs from Ziemke et al. [1998] over the 14-year period (1979–92) to yield one year of...
monthly means that are representative of TTOC seasonal variation. The EOFs were calculated from the monthly mean TTOCs, $\mathbf{T}$, after weighting them by $\sqrt{\cos \phi}$ of the latitude to adjust for the poleward decreasing area of each grid box [Chung and Nigam, 1999], a minor adjustment for the tropics. The spatial loading patterns or EOFs are the eigenvectors, $\mathbf{e}^{(i)}$, of the temporal covariance matrix of TTOCs. The $i$-th eigenvalue defines the fraction of TTOC variance accounted for by $\mathbf{e}^{(i)}$. The corresponding seasonal variation $\mathbf{s}^{(i)}$, commonly referred to as the principal component, is the product of $\mathbf{e}^{(i)}$ and the weighted monthly mean TTOCs with their annual mean, $\mathbf{T}$, removed

$$\mathbf{s}^{(i)} = (\mathbf{T} - \mathbf{T}_a) \mathbf{e}^{(i)}. \quad (1)$$

With this definition, $\mathbf{s}^{(i)}$ is the $i$-th vector of 12 components (one for each month) which describes the seasonal variation in the $i$-th EOF. The original monthly mean TTOCs for a given month ($m$) can then be expressed as a function of the annual mean, the ensemble of EOFs, and the corresponding monthly component of $\mathbf{s}^{(i)}$

$$\mathbf{T}(m) = \mathbf{T} + \sum_i \mathbf{s}^{(i)}(m) \mathbf{e}^{(i)}. \quad (2)$$

We find that Varimax rotated EOFs [e.g., Kim and Wu, 1999] have similar spatial loading patterns and seasonal variation as the unrotated EOFs presented here.

**Results**

The three leading EOFs Figure 3 together explain almost 90% of the seasonal TTOC variability. The 4th EOF (not shown) represents less than 6%. Figure 3a shows the spatial loading pattern of each EOF, with corresponding seasonal variation in Figure 3b. Our analysis does not account for interannual variability of TTOCs which Ziemke and Chandra [1999] found to be driven primarily by the El Niño-Southern Oscillation in the Pacific and secondarily by the quasi-biennial oscillation in the Atlantic. Independent calculations of EOFs that included and excluded El Niño years showed little difference relative to the results in Figure 3.

The first EOF (EOF1) captures 54% of TTOC variability with an unequivocal biomass burning signature that peaks in September and October over Brazil and the southern tropical Atlantic. Ozone concentrations in the southern tropics reach their seasonal maxima in September and October [Olson et al., 1996] due to widespread biomass burning in Brazil and southern Africa [Thompson et al., 1996]. Ozone production in that time of year is thought to be enhanced by proximal deep convective systems in southern Africa [Jenkins et al., 1997]. Biomass burning decreases with the onset of the wet season in concurrence with TTOCs in the positive region of EOF1.

The second EOF (EOF2) explains 20% of TTOC variability and is seasonally in phase with lightning, peaking in the north (south) during the boreal (austral) summer. The prominent features of a maximum in Oceania during DJF and a maximum in Central America during JJA replicate similar features in the lightning NO$_x$ source distribution (Figure 2). We projected the spatial distribution of EOF2 (Figure 3a) upon the monthly gridded lightning NO$_x$ emissions of Price et al. [1997] by calculating their product (Eq. 1). The monthly variation of this lightning projection correlates significantly with the seasonal variation of EOF2 ($r = 0.88$, $p < 0.0005$, $n = 12$) supporting our attribution of EOF2 to a lightning source of O$_3$.

We examined the EOFs of the lightning NO$_x$ emissions of Price et al. [1997] to provide an alternate perspective. The first EOF (Figure 4) accounts for 76% of the variance. It features a broad maximum during DJF (JJA) in the south (north) and correlates significantly with EOF2 ($r = 0.89$, $p < 0.0005$, $n = 12$). The results from extended EOFs [e.g., Kim and Wu, 1999] of both lightning and O$_3$ also support the relationship between EOF2 and lightning NO$_x$ emissions. The third EOF (EOF3) explains 15% of the TTOC variance with a maximum in March-April and a secondary maximum in October. The March-April maximum appears to reflect the Southeast Asian biomass burning season [Liu et al., 1999] and meridional transport from the northern extratropics where O$_3$ is at its seasonal peak. The physical meaning of the October secondary maximum is unclear.
Discussion

Other known factors of tropical O\(_3\) variability do not correlate with EOF2. The Walker Circulation over the equatorial Pacific is most active in DJF [Webster and Yang, 1992] with associated rapid convective overturning that enhances destruction of O\(_3\) in the tropospheric column [Leiweke and Crutzen, 1994]. EOF2 has the opposite seasonal pattern. Emission of NO\(_x\) from tropical soils peaks in the dry season [Bakwin et al., 1990], again inconsistent with EOF2.

EOF2 is slightly distorted by the biomass burning season south of the Congo Basin that peaks in June and July [Justice et al., 1996]. Figure 1 illustrates the tropical Atlantic O\(_3\) enhancement concurrent with the June-July biomass burning season south of the Congo Basin. This small biomass burning signal appears in EOF2 due to its temporal correlation with the seasonal variation in lightning NO\(_x\).

EOFs calculated separately for the continental regions of South America, Africa, and Indonesia (not shown) provide further support to the hypothesis of lightning NO\(_x\) influencing the distribution of TTOCs. Because each continent has slightly different biomass burning seasons, performing the calculation separately on each continent allows EOF1 to more accurately represent biomass burning. As a result, in each case EOF2 more clearly represents the latitudinal variation associated with the seasonal movement of lightning activity. The TTOC variances explained by EOF2 for South America and Indonesia increase to 24% and 34%, respectively. In Africa where lightning NO\(_x\) is weaker and the biomass burning season more intense, the variance explained by EOF2 decreases to 17%.

Remarkably, the TTOCs from TOMS show no O\(_3\) enhancement over northern (sub-Saharan) Africa during the biomass burning season between December and March. In situ observations in that region show that high aerosol and O\(_3\) concentrations from biomass burning are largely confined to the lower troposphere by a strong inversion [Marenco et al., 1990; Andreae et al., 1992]. The collocation of aerosols with high O\(_3\) in the northern tropics would reduce the sensitivity of TOMS to O\(_3\) from biomass burning. In contrast, during the Southern Hemisphere biomass burning season, O\(_3\) is enhanced in the middle and upper troposphere where it is not associated with aerosols because of scavenging [Browell et al., 1996]. Although a correction for aerosols has been included in the TOMS retrieval algorithm [Torres and Bhartia, 1999], it may not be sufficient. Furthermore, the TOMS retrieval algorithm is generally insensitive to O\(_3\) variability in the lower troposphere due to Rayleigh scattering and the assumption of a standard O\(_3\) profile [McPeters et al., 1996]. These uncertainties probably affect regions other than northern Africa. The EOFs presented here are therefore more indicative of middle and upper tropospheric variability than of lower tropospheric variability.

The EOF analysis is a linear decomposition but the dependence of O\(_3\) on NO\(_x\) is nonlinear. Although the 20% contribution of EOF2 to the O\(_3\) variance does imply a significant effect of lightning on tropical tropospheric O\(_3\), it does not mean that lightning accounts for 20% of the O\(_3\) variance. Quantitative interpretation of the EOF information in terms of the O\(_3\) budget must be done within the framework of a global three-dimensional model. Reproducing the observed EOFs represent a critical test of the ability of a model to capture the dominant patterns of O\(_3\) variability.

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