Climate Change Research: Evaluation and Policy Implications
S. Zwerver, R.S.A.R. van Rompaey, M.T.J. Kok and M.M. Berk, (Eds.)

Empirical Orthogonal Function (EOF) Analysis of Ozone Variability

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Abstract

Empirical orthogonal function (EOF) analysis was applied to the monthly averages of the TOMS ozone data set from November 1978 to October 1993 for two latitude ranges.
The EOF method yields a set of orthogonal (spatial) functions (or base-patterns) wich are, unlike in most other decomposition methods (where the set is usually predefined), derived from the data itself. This is done in such a way that the EOFs, ordered by the amount of explained variance, form the most efficient basis for the variance decomposition.
In a typical case, using 15 years of monthly averaged ozone observations, rebinned to gridcels of 15° longitude × 4° latitude, up to 83 % of the total observed variance between latitudes 66°S and 66°N could be accounted for by only the first 3 EOFs. Taking into account only the tropical regions (between 30°S and 30°N), the first 3 patterns (associated with the seasonal variation and the QBO-cycle) could explain 90 % of the total variance. The fact that a small number of coefficients is sufficient to characterize the monthly averaged ozone-fields reflects the existence of only a few dominant long-term patterns.
Also the long term ozone depletion rate was analysed in terms of changes in the coefficients of the base-patterns.

1. Introduction

During the last twenty years concern has been growing about the influence of human activity on the global climate. As ozone is one of the key constituents in the stratosphere, related directly to UV-radiation and the atmospheric temperature-profile, it has been monitored extensively by ground-based and orbiting instruments. Since 1978 the Total Ozone Mapping Spectrometer (TOMS) instruments on the Nimbus 7 and Meteor 3 satellites have produced daily measurements of the ozone column with a high spatial resolution. It has been shown that the resulting global ozone time series are mainly influenced by long-term (anthropogenic) decrease in ozone, the 11-year solar cycle, the annual seasonal cycles, the quasi-biennial oscillation (QBO), and the El Nino/Southern Oscillation (ENSO). In order to separate these effects usually a multiple linear regression method is used, for which a priori information is needed about the frequency and phase of the cycles of which the coefficients are to be found. (*Herman et al.,1993* [1], *de Winter-Sorkina, 1994* [2])
By applying an EOF decomposition method instead of linear regression, no assumptions need to be made in advance, as the only requirement for the construction of each successive base-pattern is that it explain the maximum possible proportion of the variance in the data not yet accounted for. The cost is the fact that, although seasonal and QBO patterns can be easily detected, a clear identification of the less significant EOFs is not always possible.

2. EOF decomposition technique

The method of Empirical Orthogonal Function analysis, also called Principal Component analysis, is used to study the temporal variability of data over a large area. It was first introduced by Lorenz (1956), and since then has mostly been used in oceanographic and meteorological research.

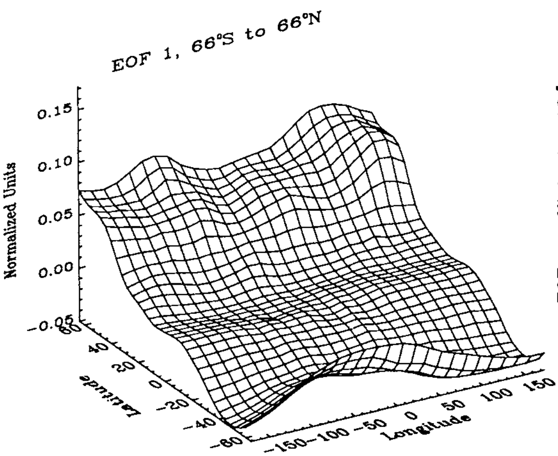
The EOFs described here are a set of orthogonal spatial patterns, which indicate the dominant deviations from the mean ozone-field. They are derived from the eigenvectors of the data covariance matrix $\mathbf{R}$: if $\mathbf{v_{mn}}$ indicates the difference of the observed ozone-column from its long-term mean at place $\mathbf{x_m}$ and time $\mathbf{t_n}$ ($m = 1 \dots M$, $n = 1 \dots N$), then $\mathbf{R}$ is defined as $\mathbf{R_{ab}} = \frac{1}{N}\sum_{n=1}^{N} \mathbf{v_{an}} \cdot \mathbf{v_{bn}}$

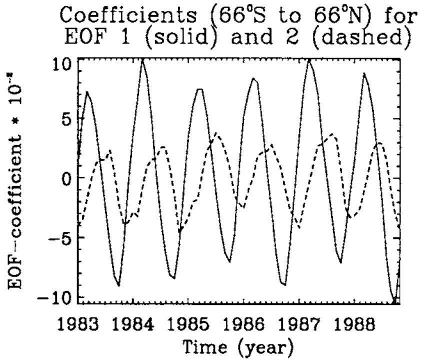
It can be shown that for each EOF the corresponding eigenvalue is a direct measure of the explained fraction of the total amount of variance in the data. In the following sections the EOFs will be sorted by this criterion, index 1 indicating the most significant EOF. After finding the EOFs, the observed ozone-fields can be rewritten as linear combinations of these EOFs, by calculating each EOF's contribution to the total field at any time. The resulting coefficients represent the time dependence of the EOFs. A comprehensive description of the EOF technique is given in Preisendorfer et al., 1981 [3].

3. The ozone-field from 66°S to 66°N

The EOF-analysis of the monthly averages of the TOMS ozone data set from November 1978 to October 1993, gridded at a resolution of 15° longitude × 4° latitude, yields a very strong first component, explaining 60.1 % of the total variability. This pattern can clearly be identified to the main seasonal variation (at midlatitudes typically in the order of some 100 Dobson Units) by its characteristic North/South asymmetry *(fig. 1)*, and by the cyclic nature of its coefficient *(fig. 2)*. At higher latitudes the longitudinal variation strongly suggests the influence of planetary waves, wich are known to affect the distribution of ozone (*Garcia and Hartmann, 1980* [4]). The coefficients of the second and third EOF, explaining 13.4 % and 8.9 % of the total variance respectively, also clearly show a yearly periodicity (EOF 2 more clearly than EOF 3), but with smaller amplitudes, and some 90° out of phase (in *quadrature*) with regard to the first EOF. These second and third base-patterns, with the same frequency as (but independent of) the first one, can be interpreted as phase-corrections to the main seasonal variation: The combination of the first three EOFs not only gives the amplitude but also the phase of the seasonal ozone-cycle for each gridcel, explaining 82.4 % of the total variance.

The remaining EOFs have much less significance (e.g. EOF 4 explains 2.6 % of the variance, EOF 10 only 0.5 %), and their association with some specific physical process is not evident.

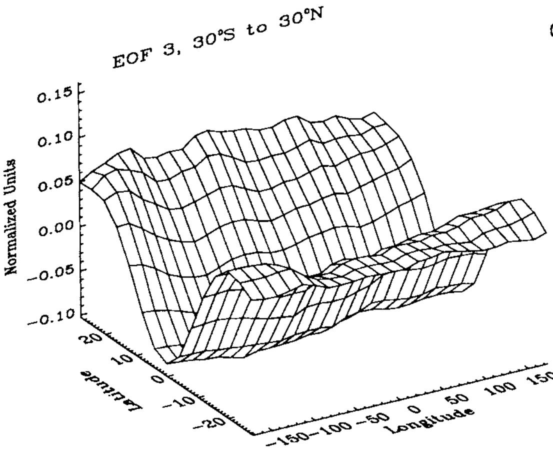


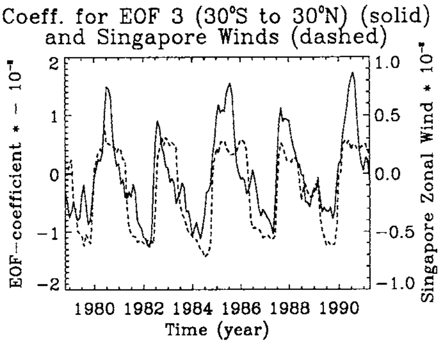


figures 1 and 2, showing EOF 1, and the timedependence for EOF's 1 and 2

4. The ozone-field from 30°S to 30°N

Using the same spatial resolution and time-frame as before, the EOF-analysis of only the tropical regions results in three dominant EOFs, explaining 90.0 % of the total variance. The first two, both with a very strong year-periodicity, but in quadrature with one another, again describe the amplitude and phase of the seasonal variation. As was expected this signal is somewhat weaker then in the case where higher latitudes were included, reflecting the fact that in the tropics the ozone-layer is less influenced by the seasons. The third EOF *(fig. 3)* can clearly be associated with the QBO cycle: it is very symmetric with respect to the equator, and its coefficient shows a periodicity of somewhat over two years, closely matching the Singapore (2°N) 30 mbar zonal wind values *(fig. 4)*.





figures 3 and 4, showing EOF 3 and its time-depence compared with tropical zonal winds.

5. Trend analysis

The TOMS-data show a global long-term ozone depletion of about 0.3 % per year. This trend, however, has a strong geographical dependence. In the tropics little or no change has been detected during the last fifteen years, whereas at higher latitudes areas can be found where a very significant depletion has occurred. The EOF-decomposition can model this ozone-depletion pattern by calculating the linear trend of each of the EOF-coefficients. Multiplication by this trend transforms each EOF into a pattern of derivatives. By combining only the first three EOFs the ozone depletion map can be approximated quite well *(fig. 5)*, showing again that a few coefficients (the linear trends for EOF 1 to 3) are sufficient to characterize a major part of the large scale ozone variability.

6. Conclusions

These first applications of the EOF-technique to analyse the variability of observed atmospheric ozone, allow us to conclude that the decomposition in empirically found base-patterns as described above, is highly efficient, and that the most significant EOFs appear to be physically meaningfull. This suggests that at a large scale (in both space and time) the ozone sytem has only a limited number of degrees of freedom, a conclusion which would be in agreement with recent results of P. Yang et al. (1994, [5]), who applied nonlinear dynamical theory to the behavior of the ozone-layer and found evidence of low-dimensional attractors.

It is expected that, apart from producing efficient parametrizations, further EOF-analysis of the TOMS-data for different geographical ranges, different time-frames, and different spatial and temporal resolutions will also give some understanding of how the complex chemical and physical processes that produce, distribute, and destruct the ozone, are related to the basic global patterns of variability. This might help to identify those variables and equations that are essential in the simulation of long-term stratospheric ozone behavior.

fig. 5a, Ozone depletion trend nov. 1978 to oct. 1994 from the TOMS data [DU / year]

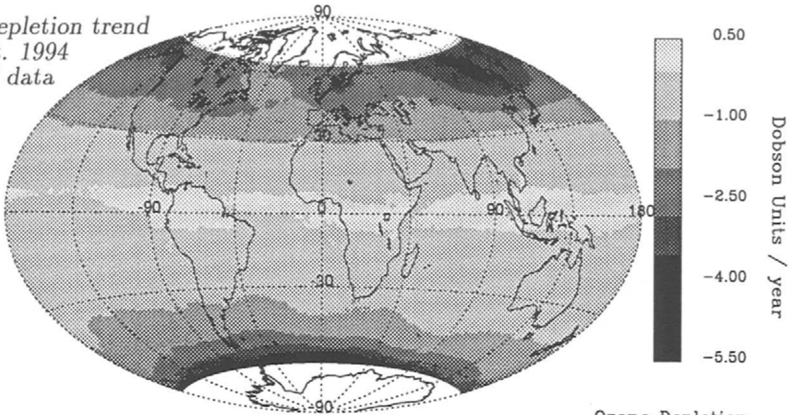
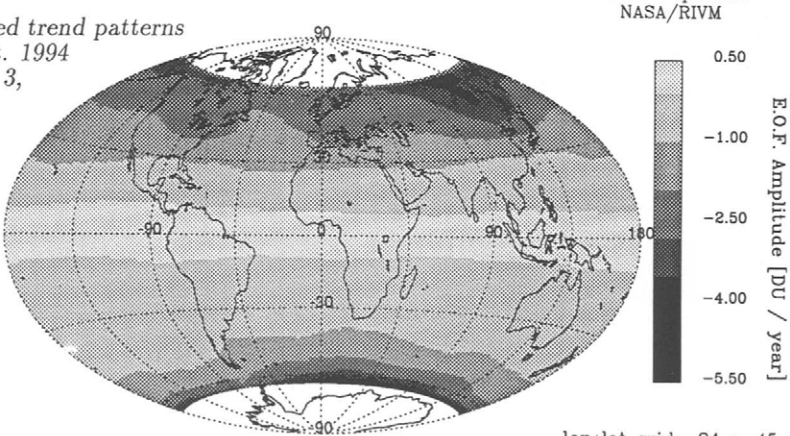


fig. 5b, Combined trend patterns nov. 1978 to oct. 1994 from EOFs 1 to 3, [DU / year]



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