Modes of Variability in High-Frequency Atmospheric Excitation for Molar Motion

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Abstract
Excitation of polar motion is related to the redistribution of atmospheric mass. Such a change is detected in atmospheric pressure, whose fluctuations are connected to observed climate patterns. Here we determine modes of the atmospheric excitation functions for polar motion by complex eigenvector analysis as a prelude to understanding a relation between atmospheric excitation and climate patterns. Examined are sub-seasonal variations of pressure, and of pressure as modified by the inverted barometer (IB) relationship, of atmospheric excitation for polar motion, computed in 108 geographic sectors for the period 1948-1999, from (NCEP/NCAR) reanalysis data. In the case of pressure the first two modes have maxima over the North Atlantic-Europe region, the North Pacific and the South Pacific. Applying the IB correction results in the dominance of the Eurasian landmass instead.

Introduction
Although the important role of atmospheric and oceanic signals for polar motion excitation has been well documented, it is clear, however, that even the combined atmospheric and oceanic forcing as determined from data currently available data do not explain all of the observed polar motion signals [see reviews by Eubanks, 1993; Ponte, 1998].

Studies of regional variability in the atmospheric excitation functions fields are necessary, as a way to understand the processes involved. To do so, we use a spatial decomposition of the atmospheric excitation functions spanning the globe. The regional variations of atmospheric excitation functions have already been computed in several papers. Salstein & Rosen (1989) used a set of two-dimensional sectors to determine that subseasonal fluctuations of atmospheric mass in such areas as the North Atlantic, North Pacific, and the whole southern oceans strongly influence the global excitation functions for polar motion. Using an 8-year data set, Nastula (1997) partly confirmed that result. Some of the regions identified by Salstein & Rosen were found to be important, but subseasonal variations of polar motion were strongly coherent only with the pressure over midlatitude land areas [Nastula 1997; Nastula et al., 1997]. When the inverted barometer (IB) relationship is included, spatial structure in the atmosphere over the oceans is eliminated and temporal variability is much reduced. Thus, applying the IB correction to the pressure leads to the dominance of Eurasia and America instead, with nearly all Southern Hemisphere contributions disappearing. Most recently Nastula & Salstein (1999) used a much longer and more reliable data set to expand upon the earlier results, isolating most clearly the Eurasian, North American and other regions as important for exciting high-frequency polar motion with Eurasia especially prominent in this regard.

Our goals are to confirm the important role of some regions for excitation of sub-seasonal polar motion and, more importantly, to examine if variations over the most important regions are associated with climate patterns. To do so we attempt to estimate modes of the atmospheric excitation functions by complex eigenvector analysis (Complex Empirical Orthogonal Functions Analysis). Techniques like this CEOF analysis are often used to derive patterns of climate variability.

Atmospheric Data
A commonly used technique for comparing the polar motion excitation with atmospheric phenomena is through the determination of the so-called atmospheric excitation functions for polar motion, $\chi_{i}^{e}$ and $\chi_{i}^{A}$, describing the
effective changes in the angular momentum components about two equatorial axes conventionally taken to point towards the Greenwich and 90° E meridians, respectively [Barnes et. al., 1983].

For this study we use two regional data sets of atmospheric excitation functions for polar motion, computed in 108 equal-area sectors by Nastula & Salstein [1999] from four-times daily gridded data produced by the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses system [Salstein et al. 1993]. The basic data include atmospheric surface pressure and the vertical distribution of the horizontal components of wind velocity on a 2.5° x 2.5° latitude-longitude grid. To produce equal-area sectors we divide the globe, placing meridional boundaries every 30° of longitude and zonal boundaries at 6.4, 19.5, 33.7, 51.1° and 90° north and south [see Figure 1 in Nastula & Salstein, 1999]. In this paper, we attempt a characterisation of patterns in excitations of subseasonal polar motion. So oscillations with periods longer than 150 days are removed from the time series in every sector by the use of a higher-order sine high-passed Butterworth filter [Otnes & Enochson, 1972] and a cut-off period equal to 150 days. Additionally, because we are focused here on oscillations with periods longer than 20 days, the atmospheric time series at every sector were averaged over 10 days to decrease the number of points.

COMPLEX EMPIRICAL ORTHOGONAL FUNCTION ANALYSIS

The modes here are the eigenvectors of the covariance matrix formed from the data, and for each eigenvector one can derive a time series of coefficients by projecting the data onto the eigenvector. The product of the eigenvector and its associated time series, reproduces one portion of the original data, and summing up all such products will reconstruct the entire original data set.

To apply CEOF analysis to our data, we first formed the two-dimensional data matrix $F$ with complex-valued elements $f_{km}$:

$$F = \begin{bmatrix} f_{11} & f_{1r} \\ f_{21} & f_{2r} \\ \vdots & \vdots \\ f_{n1} & f_{nr} \end{bmatrix}$$

(1)

Here $f_{km} = \chi_{km} = (\chi_{1}^{k} + i \chi_{2}^{k})_{km}$ is complex-valued atmospheric excitation at 108 locations taken at times $t_k$ from 1948 to 1999, and $m=1,2,...,r$ ($r = 108$ the number of sectors), and $k=1,2,...,n$ (the number of points for the period from 1948 to 1999). This way of ordering data into a matrix is referred to as S-mode analyses [Preisendorfer, 1988; Bjornsson & A. A. Venegas, 1997].

Next, by using singular value decomposition we decompose the data matrix $F$ into the form [Marple, 1987]:

$$F = UTV^T$$

(2)

Then we form the covariance matrix $R$:

$$R = F^*TF = (UTV^T)^* (UTV^T) = V \Lambda V^T = \Lambda V^T$$

(3)

$\Lambda$ is a diagonal matrix containing the eigenvalues $\lambda_m (m=1,...,108)$ of covariance, matrix $R$. The column vectors of the unitary matrix $V$ are the eigenvectors $\text{coef}_m$ for the $R$ corresponding to the eigenvalues $\lambda_m$. The eigenvectors here are complex and can be expressed in term of magnitude and phase $|\text{coef}_m|e^{i\theta_m}$. Unlike real EOF's where each mode represents a standing wave pattern, CEOF's can resolve propagating waves [Horel, 1984; Preisendorfer, 1988]. To see how eigenvectors evolve in time one can calculate time series of expansions coefficients associated with each eigenvector from the following relation:

$$c_{km} = \sum_{l=1}^{108} \text{coef}_{ml} f_{kl}$$

(4)

The proportion of the total variance in the data explained by the $m$-th eigenvector is given by formula (5).
The magnitude of $v_m$ can provide a measure of significance of each eigenvector. Figure 1 shows percent variability explained by $eigenvalues$ versus mode number. For the case of pressure with IB correction the first four modes explain nearly 50% of the variability, with the first four modes accounting for 19.2%, 13.9%, 11.1% and 6.4% of the total variance. The first four modes, however, for the case of pressure explains only 20% with 5.6%, 5.2%, 4.6%, 4.5% of the total variance respectively.

![Figure 1](image.png)

**Figure 1.** The fraction of the total variance of the atmospheric excitation functions computed in 108 regions explained by the mode for the case of pressure and pressure with the IB. The first 50 modes are shown.

**VARIABILITY OF MODES**

Figures 2a and 2b display the first complex-valued eigenvectors as maps for both pressure and pressure IB vectorially with the length of the arrow proportional to the magnitude of the eigenvector and direction equal to the eigenvector phase at a sector. Besides arrows, different shadings represent different magnitudes.

For the case of pressure here the first mode can explain only 5.6% of the global variance but reaches strong values over the Gulf of Alaska and North Pacific. The spatial pattern contains also a connection between the regions of the North Atlantic and the Europe; the signal however is weak. Maxima over the Northern Hemisphere might be associated with North Atlantic Oscillation (NAO) and North Atlantic - Eurasia variability. The Southern Hemisphere spatial pattern is characterised by wave trains spanning the South Pacific from Australia to Argentina. The center of the pattern with very strong signals found near $60^\circ$ S and $90^\circ$W. This pattern might be associated with Southern Hemisphere extratropical patterns by Lau et al. [1993]. It is clear, however, that the modes are not well separated and needs careful study of significance to be useful in studying of atmospheric excitation.

The alternate, with the addition of the IB correction, decreases the overall variance explained but now the proportion in the first mode of this total variance is larger (19.2%) than the non-IB case, and leads to the dominance of the land areas, with Eurasia especially important. There is also some teleconnection with the Southern Hemisphere even in the IB case.

From Figures 2c and 2d one can see that the second modes magnitudes have generally similar patterns to those for the first modes. In case of pressure there are some differences between the first and the second modes patterns in the Southern Hemisphere. While in the case of pressure + IB one can see in the second mode pattern two maxima over
Europe and Asia instead of one strong maximum over West Europe for the first mode. For the pressure case the second mode explains 5.2% of the global variance and for pressure with IB this mode can explain 13.2%.

Figure 2. Dimensionless maps of (a, b) first and (c, d) second eigenvector of complex-valued atmospheric (a, c) pressure and (b, d) pressure+IB excitation functions for polar motion for the spectral band 20–150 days, expressed in terms of magnitude and phase. Note the changing shadings for the magnitude. Phase are plotted every point indicated by direction of the line segment; the length of the line segment is proportional to the magnitude of the eigenvector.
The phase exhibits large-scale patterns. The patterns for pressure+IB appear to be associated with wave propagation east for the first mode and with both east and west for the second mode (Figs. 2b and 2d). Modes for pressure are difficult to interpret as one wave (Figs. 2a and 2c). The pattern of the first and second modes appears to be one associated with wave propagation both zonally and meridionally.

COMPARISON WITH POLAR MOTION EXCITATION

To determine the extent to which the atmosphere participates in forcing polar motion, we compare the atmospheric excitation function with the function required to explain Earth's observed polar motion. The latter, termed the geodetic polar motion excitation function is determined from daily values of geodetic observations of pole position using a time domain deconvolution formula [Wilson, 1985; Nastula & Salstein, 1999]. For our analyses, we used the EOP C04 data set of polar coordinates from the International Earth Rotation Service [IERS, 1999] and a time deconvolution formula [Wilson, 1995] to compute values of for over the period from 1962 to 1999. The geodetic functions were averaged over 10-days and they were high-pass filtered by use of the Butterworth filter for consistency with the atmospheric ones.

![Figure 3. Correlation coefficients between the complex-valued components of geodetic and atmospheric excitation functions for polar motion, computed over five-years intervals, starting each eighth of a year, since 1962. Solid lines show "real" correlation while dotted lines show a partial correlation after two first modes are removed from a relation between polar motion and global atmosphere.](image)

To examine the time variations of the polar motion/atmosphere relation, we calculate correlation coefficients between complex-valued components of geodetic and atmospheric functions. The coefficients were computed over five-year intervals, starting each eighth of a year, since 1962 (Fig. 3). This correlation coefficient will be defined for later purposes as a "real" correlation. In order to estimate influence of the modes on the "real" correlation, we first evaluate time series of expansions coefficients associated with and. Next we eliminate its contributions from the "real" correlation by computation a partial correlations [Panofsky & Brier, 1958].

After considering Figure 3 it is clear that the "real" correlation has improved since 1980's (result also found by Nastula & Salstein, 1999). The IB correction, when included in the pressure term of the atmospheric excitation function, increases the correlation somewhat but does not change the general tendency. These disagreements are likely due to less accurate polar motion or atmospheric data before the period considered here.
Focusing on comparisons between "real" and partial correlations, one can see that the first two modes seem to be important in the case of pressure with the IB correction. The "real" correlation between polar motion and atmospheric excitation with IB might be driven by patterns associated with the modes. While in the case of the pressure term, an impact of the first two modes on "real" correlation seems to be not significant.

CONCLUSIONS

The CEOF technique has proven to be a valuable tool in analysis of relationships between atmospheric excitation for polar motion and climate variability. Further study of the modes significance is needed, however, before relation between the modes of atmospheric excitation variability and climate patterns is fully determined. For the case of pressure the first two modes contain patterns with strong variations over southern oceans over the Gulf of Alaska and North Pacific. The spatial pattern contains also a connection between the regions of the Northern Hemisphere. The addition of the IB correction leads to the dominance of land areas, with the Eurasia especially important. There are also some teleconnections with the Southern Hemisphere even in the IB case. Using the CEOF we have reconfirmed the earlier results of Salstein & Rosen [1989] and Nastula & Salstein [1999] who found maxima in the atmospheric excitation function over similar regions. The modes of pressure with IB terms of atmospheric excitation are more significant for polar motion excitation than those of pressure non-IB; however the non-IB modes may be important indicators for atmospheric variations.

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