Computing Atmospheric Excitation Functions for Earth Rotation/Polar Motion

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Abstract. The weather forecasting and data assimilation systems resident at the world's large meteorological centers are used to produce analyses of meteorological parameters from which excitations of earth rotation/polar motion are calculated. The meteorological systems involve up to three procedures generally known as the model, assimilation, and initialization steps. The weather data that are assimilated into the systems are taken by a heterogeneous group of instruments, which are ground-, air- and space-based. Earth rotation excitation functions are in fact calculations of the angular momentum of the atmosphere, and as such are derived from the surface pressure and wind fields; winds are more related to the axial, length of day, component and pressures to the polar motion component. The pressure-based angular momentum may be modified by the actions of the ocean, the degree to which it acts as an inverted barometer. The world's major meteorological centers produce the fields necessary to produce these quantities, both in an operational and in a retrospective way, known as reanalysis. Measures of wind-based polar motion are especially investigated for their strong subdiurnal variability.The atmospheric community investigates as well models that are only driven by boundary conditions to see how well they may simulate the atmosphere; we use the diagnostics of atmospheric excitations of Earth rotation/polar motion to check if such models are successful. Other lengthy simulations of atmospheric models provide an indication of changes in angular momentum in the past and possible increases in the future related to climate variability and potential greenhouse gas increases.

Introduction – Weather Forecasting and Data Assimilation Systems

The atmosphere has been described by a number of numerical modeling systems over the last several decades. These have grown in complexity with the increases in computer power, advances in atmospheric physics and in the number and variety of observations. The world's major weather centers run such meteorological systems for the purposes of weather forecasting and analysis. In the typical system there is a cycle consisting of three basic steps:

1. Model: Advances the state of a forecast model, usually through six hours, obtaining forecasted fields of the atmospheric parameters

Characteristics of a model include the description of the general physical laws, that is the equation of motion, the thermodynamic equation, the continuity equation (conservation of overall mass), and the conservation of water substance. Atmospheric physics that are vital to models also include descriptions of clouds, especially the treatment of sub-gridscale parameterization of cumulus clouds. Secondly, the way the atmosphere treats radiation, both the incoming, shortwave and the outgoing, longwave radiation are issues. Very important as well is the model physics at the lower boundary, where the atmosphere exchanges momentum, heat, and moisture with the land or ocean surface below.

Details of the numerics of a model are relevant here: Models are either cast in grid point or spectral space. In grid point space, the distance between points are often regular in latitude and longitude, but some models are irregular, taking advantage of the decreasing distance between the same longitude spread with increasing latitude. The spectral space models are spherical harmonics ranging up to a certain truncation in either triangular or rhomboidal limits. In the case of spectral space, fields are then converted to a grid point format, sometimes in a way that is consistent with the spherical functions; the so-called Gaussian grid are zeros in latitude of the spherical harmonics and the most convenient formats for such conversions.

Lastly, the numerical approach of advancing the state of the atmosphere in time is variable, involving a number of techniques (explicit, implicit, semi-implicit).

2. Assimilation: Combines the various observations within a time window in an optimal way, based upon the error characteristics of the data sources, with the advanced state of the atmosphere.

A variety of different types of data are available to assimilate together, with the forecasted field. In areas of limited observations, thus, the forecast becomes relatively more important. The current methods of data assimilation are known as optimal interpolation approaches in which all observations are used, though their weights are based on the error characteristics of the observation source. These are combined with those of the forecasted state to determine the best fit to the data, considering the data distribution. In spectral space, a statistical spectral interpolation method is used which projects all data onto harmonic modes of the atmosphere and optimally determines the mode amplitudes with the least errors. The data assimilation methods are done multi-variately, that is, getting the optimal solutions to a set of atmospheric variables (e.g., temperature, geopotential, wind, moisture).

Research on advanced types of assimilation like the 4-D state of the atmosphere has been done. One such method is to combine the data for a period by running a model and its inverse, or adjoint, in both temporal directions to minimize the solution for the entire time period. This computer –intensive approach is not currently operational at meteorological centers.

3. Initialization: Makes analysis useful as a consistent initial state for the forecast model.

If analyses, the first product of the data assimilation step, are used as initial states of a forecast model, they may be out of balance with the modes (usually the spherical harmonics) comprising the forecast model itself, and thus may generate spurious waves that are linearly unstable. In the initialization step the modes of the forecast model will be determined, and the analyzed state projected onto each mode, up to a certain limit. The sum of such projections is the new initial state; this method is akin to a low-pass filtering technique. It should be noted that in statistical spectral interpolation, in use at US National Centers for Environmental Prediction (NCEP), because the optimal analysis is performed itself in spectral space, the first analysis is automatically initialized, and no further initialization need occur.

Data used by assimilated by weather forecasting models

The primary data that are the observables of a weather forecasting system come from the surface and radiosonde network. Such locations available to weather centers include the large number of land based reports in the populated areas of northeast U.S., Europe, southern Canada, east Asia and much of Australia. Much of the rest of the globe is not so well served. Ships in the North Atlantic and North Pacific especially supplement this datasets that is the backbone of the system.

Besides the radiosonde and surface observations, both on land and by ship at sea, are the following alternate observations that are used as input to data assimilation systems: Buoys, which are fairly well distributed throughout the world's oceans, aircraft-based observations, which follow principal air routes, observations by geostationary satellites, centered currently at five locations on the equator, wind profiler data, and the following special satellite-based systems: SSM/I, the passive microwave system, scatterometer, measuring winds above the ocean surface, by active microwave, and both ATOVS and AIRS, polar orbiting systems with radiance measurements from which temperature and moisture can be derived.

Characteristics of a weather forecast system: the current state of the European Centre for Medium-Range Weather Forecast

As an example of features in a weather forecast system, we relate those of the ECMWF. Others, like the NCEP system, have alternate types of physical treatments in models. The weather forecast systems do, though, receive essentially the same basic observational set. In the ECMWF system, synoptic hours considered are four times daily, at 00, 06, 12, and 18 UTC and global 10-day forecasts are started from 12 UTC data. Its numerical scheme is TL511L60, meaning that the spherical harmonics have triangular truncation of 511 waves, and at 60 levels. This very high resolution, when saved appropriately at the surface, is equivalent to 20,911,680 points, with a mean grid distance of 39 km.

The variables considered are wind, temperature, humidity, cloud fraction, water/ice content, and ozone. Four surface and subsurface levels allow for vegetation cover, and a model of surface runoff. Stratiform and convective precipitation are considered in clouds. Carbon dioxide is fixed at 345 ppmv, and a full radiation suite deals with both short- and longwave processes. Orographic drag is considered, including gravity wave-drag. The global analysis of wind temperature, surface pressure and humidity (from www.ecmwf.int).

Overview of equations for excitations of length of day and polar motion

The excitations are a vector that can conveniently be decomposed (Barnes et al. 1983) into portions related to the motion of the winds (relative angular momentum), and the mass term (closely identified with surface pressure). The first and second, equatorial, components of that vector (χ1 and χ2 relate to polar motion, and the third, axial, component (χ3) relates to variations in length of day. Besides the standard pressure excitation, excitations may be modified for the inverted barometer (IB) response of the ocean, which would isostatically adjust the surface of the whole world ocean to the distribution of overlying atmospheric pressures. We use this traditional decomposition in the excitations that are available from our Special Bureau for the Atmosphere of the International Earth Rotation and Reference Frames Service (IERS). With data sets with the current formulations available through the IERS-SBA from four weather centers and reanalyses back to 1948 (Salstein et al. 1993). Updated constants and formulations that have been advised at the Chandler Wobble Workshop (Wahr, 2004; and others) will be addressed at the SBA in the coming year.

The excitations for one year, which are given in Fig. 1, show that the wind signals for polar motion have large subdiurnal fluctuations; these are discussed below. The pressure fluctuations do not have such high frequency variability, but overall the varability is decreased for the IB formulation. For the length of day component, the axial, wind term has a very strong signal, with the pressure term playing a less important role. Power series of such variability for lengthy series reveals strong annual and lesser semiannual fluctuations. Notable, especially for the axial, wind-term, is variability at the subseasonal scale from Madden Julian oscillation (Chao and Salstein 2004).

The NCEP-NCAR reanalysis (Kalnay et al. 1996) has been run for over a fifty-year period, by assimilating data back to 1948 with a consistent analysis system. Although the lengthy records are more consistent, avoiding discontinuities when newer systems were introduced, at present the reanalysis model is based on considerably less resolution than the current NCEP operational system.

In addition to the excitations of polar motion and length of day directly, we are interested as well in the dynamic torques that effect the transfer of angular momentum across the atmosphere's lower boundary to the solid Earth or oceans below. Generally, three different torque mechanisms are computed in the context of the angular momentum transfer: The mountain torque is derived from the normal pressure gradient forces against topography; these occur on timescales of the synoptic weather systems (several days and longer) to subseasonal scales. The tangential force of winds against the Earth surface creates the friction torque, which has power at shorter, subseasonal timescales. A third torque, the gravity-wave torque is derived from subgrid scale processes, typically near topography. This effect is very small on all but annual timescales. A fourth, based on the gravitational attraction of anomalous mass distribution has been noted to be important in polar motion space, but this gravitational torque largely counters the pressure torque against the earth's oblate bulge when it is considered as a "mountain" (de Viron et al. 1999).

Subdiurnal signals in wind-based excitations of polar motion

Because of thermal tides that are present in the atmosphere, which are captured in analyses (Hsu and Hoskins 1989), the excitations that arise from the winds are very dependent on the hour of the day, with different signals in the upper (~200 hPa) and lower (~850 hPa) levels of the atmosphere. Here a vertical circulation results from the strong thermal forcing. The patterns are modulated seasonally as well, because of changing heating patterns on these scales. Because the polar motion wind-based excitation geometric weights are dependent upon wavenumber-1 in latitude and have nodes at the poles and equator, and oppositely weighted signs in middle latitudes, the tidal signature projects onto the polar motion terms. Currently, the excitations are available from atmospheric analyses for four synoptic hours: 00, 06, 12, and 18 UT, and show significant variations (Fig. 2). Proper sampling at enough synoptic hours is thus important to determine the signals, which are needed to determine those at even the seasonal and Chandler scales. Even higher (subdiurnal) temporal resolutions would be useful for the most accurate polar motion excitation signals. In principle this resolution is calculable from intermediate steps within the forecast-assimilation systems, but may not be fully independent of the 4 times daily data, as those are based on observations with lower temporal sampling. The excitation values themselves for the wind terms appear sensitive to the calculations, including the formulation for inclusion of the atmosphere near areas of topography. There appears to be power as well at the Chandler band, though at this resolution, it may be spillover from the annual frequency.

Decadal/century atmospheric modeling of angular momentum

General circulation models (GCM) are often used to simulate the state of the atmosphere. These GCMs are similar to the atmospheric models embedded within the analysis system discussed above, but are used to respond only to the boundary conditions of the atmosphere, generally the temperature of the lower ocean surface. Here the physics of the land surface, clouds, and radiation are important. We use the results of such models to determine angular momentum quantities, in part as diagnostic tools to determine the success of modeling techniques, and in part to understand climate signals, including possible future ones. We verify the 20-30 models contributing to the Atmospheric Model Intercomparison Project (AMIP) with reanalysis results. For the axial term, the seasonal cycle is generally well simulated and the interannual signal, in which for example, periods of El Niño events contain positive anomalies of atmospheric angular momentum, are reasonably well-modeled too. Two phases of AMIP based on models ca ~1993 and ~1998 showed considerably better simulations in the more recent models. Models with advanced land schemes are particularly more successful than others. Polar motion-excitations by the (later) AMIP models, over a 17-year simulation period, are generally successful in the subannual-multiannual timescale range, but much less so at shorter timescales (Nastula et al. 2003). Also, all models tend to have common levels of skill during specific time periods.

Atmospheric modeling over the entire 20th century is feasible now, and when analyzed for certain decades, we have found that the interannual variability of atmospheric angular momentum has changed, and increased in general (Rosen and Salstein 2000). Lastly, coupled models, that include both atmosphere and ocean components, and do not have imposed sea-surface temperatures, may be run with increasing CO2 to analyze the putative effects of global warming. For a 70-year simulation of future conditions, we found that the atmospheric angular momentum increases, largely because of the stronger westerly winds in the middle latitude upper troposphere and lower stratosphere. This result is consistent with an increasing length of day with increasing greenhouse gases. Implications for polar motion, including the Chandler motion, are not yet clear.

Summary

Atmospheric analyses are based on a comprehensive set of observations and three basic steps: model, assimilation and initialization. The atmospheric reanalyses currently provide the best lengthy series for Earth rotation/polar motion excitations and torques, but operational analyses are state-of-the-art products. For polar motion, although the mass terms dominate the variability on low frequencies, the motion (wind) terms, which are dependent upon a seasonally modulated thermal subdaily tidal signature are important to sample properly; power around the Chandler band exists in this series. Modeling alone represent a means of determining how to simulate the atmosphere and we have used Earth rotation/polar motion excitations to measure the quality of models by comparing such parameters with those from analyses.

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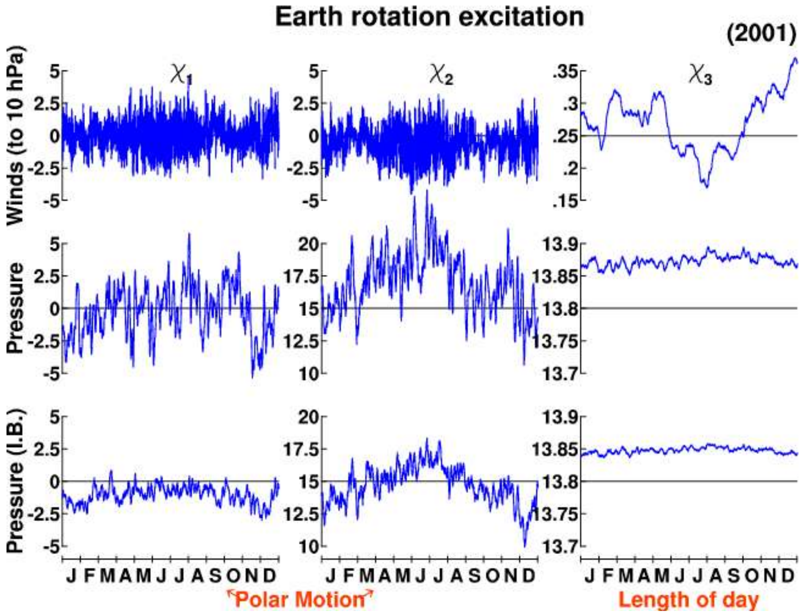

Fig. 1. Polar motion excitations (χ1 and χ2) and length of day (χ3) from the NCEP-NCAR reanalyses for wind, pressure, and pressures related to inverted barometer, taken four times per day.

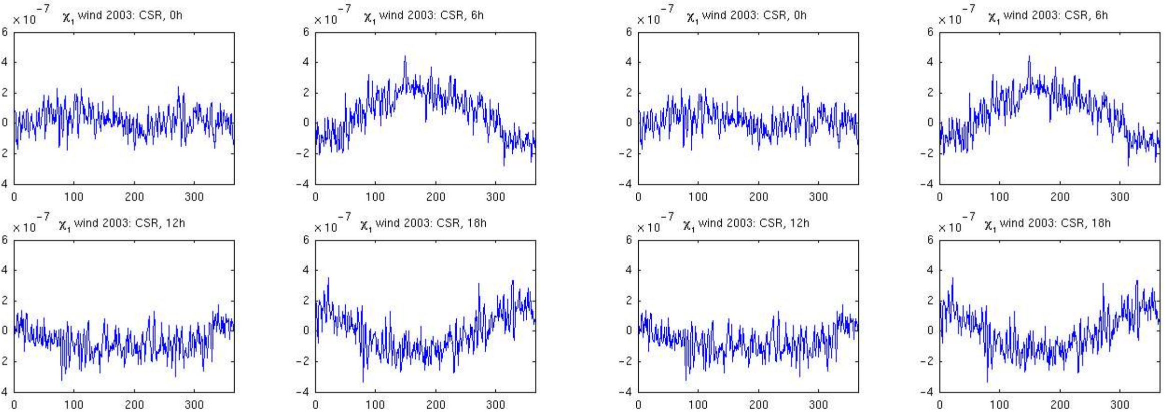

Fig. 2. Excitations of polar motion based on winds (χ1, right four panels and χ2, right four panels), each at the different hours 00, 06, 12, and 18 hours UTC for the year 2003, based on the NCEP-NCAR reanalyses.