# The GGFC Special Bureau for the Atmosphere of the International Earth Rotation and Reference Systems Service

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## 1 Introduction

The mass and the angular momentum of the atmosphere are properties whose variability relates to both geodetic and climate signals. Total atmospheric dry mass is very nearly conserved, but water substance is exchanged with the oceans and Earth below. The horizontal distribution of atmospheric mass changes on a number of time scales, and varies both meridionally and zonally, often related to climate modes. Such variability is important to the overall terrestrial mass signal measured by the new "Gravity Recovery and Climate Experiment (GRACE)" satellite system. Atmospheric pressure, moreover, loads the crust, leading to small vertical deformations and thus impacts the geodetic reference frame.

The angular momentum of the atmosphere is a signal that changes on many climatic time scales due to the motion of winds and to atmospheric mass redistribution; angular momentum is exchanged, moreover, across the atmosphere's lower boundary. The atmospheric angular momentum signal responds to certain signals like the El Nino, which is observed in some geodetic properties such as Earth's rotation rate, reckoned by the small changes in the length of day, and the motions of the pole.

Global analyses, like that produced by the NCEP-NCAR reanalysis system, capture both mass and angular momentum signals with considerable success; additionally general circulation models have been used to simulate past variability and forecast future changes in these quantities. Relevant diagnostics are calculated, collected, analyzed, and archived by the "Special Bureau for the Atmosphere (SBA)" of the International Earth Rotation Service (IERS), and include: atmospheric angular momentum in the axial and equatorial directions, torque interactions that exchange angular momentum across the lower interface, and harmonics of surface pressure, including the global mean surface pressure.

## 2 Atmospheric Mass

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# 3 Atmospheric Angular Momentum

The angular momentum of a parcel of air in the perpendicular plane about an axis is given as its mass multiplied by the length of the radius arm to the reference axis, multiplied by the component of the velocity of the parcel in that plane, normal to the radius arm. The angular momentum of the global atmosphere about such an axis is the integration of all such parcels. When the axis is that of the Earth's rotation, then changes in the angular momentum of the atmosphere are compensated by those of other portions of the Earth, most notably the solid Earth itself; nevertheless a lesser amount does get exchanged with the oceans and between the ocean and solid Earth. Variability of angular momentum about the other two axes, namely in the equatorial plane may be related to the wobble of the Earth, causing motions of the Earth's pole.

Angular momentum variations in the atmosphere can be conveniently separated into those due to mass fluctuations, absolute angular momentum due to solid body rotation, and those due to the winds, the angular momentum relative to the solid Earth. An explicit formulation for the angular momentum that excites both variations of Earth's rotation rate, reckoned as length of day changes, as well as polar motion, were derived by Barnes et al. (1983). An additional element of importance here concerns the so-called inverted barometer (IB) hypothesis, in which the variability of the atmospheric pressure over the oceans is reduced by their isostatic response that quickly readjusts sea level in response to the overlying atmospheric load. A correction for the IB involves substituting the mean value of the atmospheric pressure over the oceans for atmospheric surface pressure at every point over the oceans. These excitations for the length of day and polar motion, given for mass, mass as corrected by the inverted barometer, and motion, are the basic angular momentum values collected by the SBA and are reviewed in Salstein et al. (1993; see that paper's Fig. 1 and 2 for formulas, and sample angular momentum series).

The SBA collects such excitation terms from several of the world's large weather centers, currently consisting of the U.S. National Centers for Environmental Prediction, the European Center for Medium-Range Weather Forecasts, the Japan Meteorological Agency, and the United Kingdom Meteorological Office. Besides analyses for a given time, forecasts are collected as well, out to 10 days. Such values are used operationally for navigation, especially involving that of planetary spacecraft, because the knowledge of the exact orientation, as well as projections into the future, are necessary and are helped by the angular momentum terms. Besides these operational series, values from reanalyses are collected so that there can be relative consistency among these excitation terms for Earth motions. Based on the NCEP-NCAR reanalysis, atmospheric angular momentum quantities were computed by Sal-

stein and Rosen (1997) staring in 1948. These datasets are available from the Special Bureau for the Atmosphere at <[1]>.

We note first that the motions of the pole are related strongly to the pressure (inverted barometer) excitations. On subseasonal variations, moderate correlation exists between the excitations and the polar motion values. Values on longer time scales may be interesting, involving both the seasonal scale, and a natural response of the Earth at around 430 days, the Chandler wobble. The polar motions involve both the oceans and the atmosphere. On seasonal scales, climate modes can force polar motions because of the anomalous pressure patterns connected with such modes. Variability in certain regions due to the pressure patterns on a range of weather and climate time scales are stronger than others: those in the middle latitudes influence the motions of the poles the most because of geometric factors (Barnes et al., 1983). Nastula and Salstein (1999) have noted that fluctuations over Eurasia and North America have impacted polar motions most strongly. On very short time scales, we have noted that fluctuations as short as 8 and 12 hours are noted in both the atmospheric excitation terms for polar motion, and in polar motion as determined methods depending on Global Positioning Systems measurements (Weber et al., 2001).

The axial angular momentum of the global atmosphere, and particularly the relative term due to the winds is an index that mirrors many climate phenomena. Lengthy analysis of such values, since 1970, based on the NCEP-NCAR reanalysis demonstrates both the prominent seasonal and interannual signals present in the series. The seasonal signature, yielding maxima and minima in zonal mean belts (Rosen and Salstein, 1983) during boreal winter and summer, respectively, are due to the larger annual signature of the winds and hence the zonal angular momentum in the Northern Hemisphere compared to the Southern. Superimposed on the annual signal is a semi-annual one in which the boreal summer typically has a particularly steep minimum and the winter has a dip during the middle months.

The maxima in the interannual signatures occur during occurrences of El Nino when anomalous westerly zonal flow throughout much of the tropics and subtropics occur, sometimes moving as well into higher latitudes; the events in 1983 and 1997–98 are contain record high values of the angular momentum index. The global maxima derive from momentum anomalies that often start in the lowest latitudes and propagate toward poleward (e.g., Dickey et al., 1997) in the band-pass filtered analysis of belts (Rosen and Salstein, 1983) from NCEP-NCAR reanalysis data. In that analysis, the very strongest values occurred during the 1997–98 El Nino, in the subtropics of each hemisphere; interestingly a rapid transition occurred between positive and negative anomaly at the end of this event in middle of 1998. The global axial angular momentum is very strongly connected to values in the length of day; such connections occur on time scales between days and several years. Such common fluctuations relate to the annual and semiannual terms. Also noteworthy here, too, are subseasonal fluctuations, including the 30–60 day fluctuations associated with the Madden-Julian oscillation.

The atmosphere-solid dynamic link is the subject of a large number of studies that were related to the atmospheric series produced by the Special Bureau for the Atmosphere and other groups in the International Earth Rotation Service. Lengthy series of atmospheric angular momentum produced by our data center to geodesists have helped unravel several questions involving excitations of free oscillations, of the Chandler wobble, the role of diurnal and semidiurnal tides, and signals of atmospheric normal modes in the dynamics of the Earth (Brzezinski et al., 2002).

[1] http://www.aer.com/groups/diag/sb.html

# 4 Torque interactions

There are a number of torque mechanisms usually considered for the overall transfer of angular momentum from the atmosphere to the solid Earth. These involve the normal forces of surface pressures against topography, typically known as mountain torques. Those torques usually fluctuate on fairly rapid time scales, reflecting the weather systems that move across mountain ranges in the order of several days. A second torque is known as a friction torque, involving the tangential forces by the winds upon the Earth's surface. These appear to be somewhat steadier and with lower amplitude than the mountain torques. An additional torque seen in atmospheric models is gravity wave drag torque, which is a value created to simulate the frictional effects, typically near uneven topography, generated by gravity waves; this is a contribution from scales smaller than model grid resolution.

Another torque depends on gravitational interaction that depends on the changing mass of the atmosphere. It is only important on the equatorial directions, not in the axial, and reduces the amount of mountain, or pressure, torque in that plane. The difference between the angular momentum approach and the torque approach can be striking, leading to questions about the best formulation of the problem that investigates the difference between angular momentum of the atmosphere and the solid earth.

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# References

Barnes, R.T.H., R. Hide, A.A. White, and C.A. Wilson 1983: Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, Proc. R. Soc. London A387, 31–73.

Brzezinski, A., C. Bizouard, and S. D. Petrov, 2002: Influence of the atmosphere on Earth rotation: what new can be learned from the recent atmospheric angular momentum estimates? Surv. Geophys. 23, 33–69.

Dickey, J.O., S.L. Marcus, R. Hide, 1992: Global propagation of interannual fluctuations in atmospheric angular momentum. Nature, 357, 484–488.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, et al., 1996: The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc., 77, 437–471.

Nastula, J. and D.A. Salstein, 1999: Regional atmospheric angular momentum contributions to polar motion excitation, J. Geophys. Res. 104, 7347–7358.

Rosen, R.D. and D.A. Salstein, 1983: Variations in atmospheric angular momentum on global and regional scales and the length of day. J. Geophys. Res., 88, 5451–5470.

Salstein, D.A., D.M. Kann, A.J. Miller, and R.D. Rosen, 1993: The subbureau for atmospheric angular momentum of the International Earth Rotation Service: A meteorological data center with geodetic applications. Bull. Amer. Meteor. Soc. 10, 67–80.

Salstein, D.A., and R.D. Rosen, 1997: Global momentum and energy signals from reanalysis systems, in Proc. 7th Conference on Climate Variations, Amer. Met. Soc., Boston, 344–348.

Weber, R., J. Nastula, B. Kolaczek, and D. Salstein, 2001: Analysis of rapid variations of polar motion determined by GPS, International Association of Geodesy General Assembly, Budapest.