ATMOSPHERIC ANGULAR MOMENTUM RELATED TO EARTH ROTATION STUDIES: HISTORY AND MODERN DEVELOPMENTS

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ABSTRACT. It was noted some time ago that the angular momentum of the atmosphere varies, both regionally as well as in total. Given the conservation of angular momentum in the Earth system, except for known external torques, such variability implies transfer of the angular momentum across the atmosphere's lower boundary. As nearly all is absorbed by the Earth below, the solid Earth changes its overall rotation from this impact. Due to the large difference between in the moments of inertia of the atmosphere and Earth, relatively big differences in the atmosphere are translated as relatively very small differences in the Earth, measurable as changes in Earth rotation rate, and polar motion. The atmospheric angular momentum (AAM) is that due to the motion of the winds and to the changes in mass distribution, closely related to the atmosphere pressure patterns; its variability in the atmosphere is mirrored in the Earth rotation rate and polar motion. This connection between the global solid Earth properties and the global and regional atmosphere on a number of time scales, especially seasonal and interannual, was much appreciated by Barbara Kolaczek, with Jolanta Nastula, at the Space Research Center in Warsaw, and this was a subject of our collaborative studies. Many calculations were made of atmospheric angular momentum, leading to a service under the Global Geophysical Fluids Center of the IERS based on calculations using both operational meteorological series, determined for weather forecasting purposes, and retrospective analyses of the atmosphere. Theoretical development of the connection between the AAM, Earth rotation/polar motion, and also the angular momentum of the other geophysical fluids occurred at the same time that space-based observations and enhanced computer power were allowing improved skills for both weather analysis and forecasting. Hence better determination of the AAM became possible, which could be used as a measure for forecasting Earth rotation. Today we are looking at the atmosphere in combination with the ocean and other fluids, and also assessing the implications of climate variability on Earth rotation through climate model research. According to models of the Earth system, significant changes in winds appear to be a possible result of climate change, with implications for the Earth rotation parameters.

1. INTRODUCTION

Variations in the angular momentum of the atmosphere have been shown to be strongly related to changes in the Earth orientation parameters due to the conservation of angular momentum in the Earth system. The atmosphere (and the ocean) can be modeled based on physical equations. We discuss how atmospheric angular momentum is measured and calculated and its relationship to climate signals. Angular momentum of the atmosphere varies on a number of important timescales, including seasonal, sub season, and inter annual, and all of these manifest in the related Earth orientation signal.

Dynamically, angular momentum in a system changes by means of torques upon the system, and this is true in the exchange of angular momentum between the atmosphere and the solid Earth. Specifically, the main mechanisms causing these torques are normal torques against topography by varying atmospheric pressure, and tangential torques from the lowest level of the winds upon the Earth's surface.

Long-period models of the atmosphere and ocean show what has happened and might happen in the future to angular momentum. The Coupled Model Intercomparison Project (CMIP) is an effort to run multiple climate models, and determine the physical parameters in the future. Potential global change in the winds and pressures point to changes in Atmospheric Angular Momentum throughout the past and present centuries.

This presentation is dedicated to the memory of Prof. Barbara Kolaczek of the Space Research Institute, Warsaw, Poland, with whom I collaborated with for many years. I was inspired by her scientific insight and curiosity, determination, and genuine kindness.

2. METHODS TO DETERMINE ATMOSPHERIC ANGULAR MOMENTUM

Concerning the atmosphere, we need to have observations from the surface, upper air, and from space. In order to use all of theses observations, there are a number of methods of combining them with each other and with modeled information. The model itself is based on physical principles. The backbone of the meteorological data is the radiosonde network of instruments that are launched at a network of weather stations around the globe. In addition data from microwave instruments in polar or oblique orbits, and infrared observations from geostationary satellites are needed used as well. Information from GPS receivers yields temperature and moisture data. Data from the nosecones of aircraft flying through their scheduled routes are also brought into the mix. Additionally ocean measurements such as those from buoys, and expendable bathythermographs are used.

To put the information together, the observations are merged into an analysis whose basic state is the short-term (typically 6-hour) forecast of a meteorological model. Geodetic functions are calculated from the raw parameters of the new fields. Also, these fields become the base of new forecasts both to carry on until the next assimilation time 6-hours later, or for more extended weather forecasts, often out to 10 days or so.

Atmospheric models are expressed from physical principles. The equations of motion about an axis in the rotating frame form the most important part of the framework. In this case the torques which cause changes in angular momentum are products of the moment of inertia and the angular acceleration. A second important equation is the equation of thermodynamics, in which heat imposed on a system is the increase in temperature multiplied by the specific heat, plus the work done by expansion. A third physical law is conservation of mass in which inflows of mass are balanced by divergence in the absence of changes in local density. Conservation of mass applies to both dry air and water vapor.

3. HISTORICAL CONTEXT OF VARIABLE EARTH ROTATION CONNECTION TO ATMOSPHERIC ANGULAR MOMENTUM

The earliest observations of changes in length of day were made at Paris Observatory by Stoyko and Stoyko (1936), who observed the annual variation of length of day. In 1948, Victor Starr of the Massachusetts Institute of Technology (MIT) noted that the atmosphere need not conserve angular momentum, and could share it with the Earth below. Starr started the *General Circulation Project* at MIT, and one of its features was calculations of fluxes and changes in atmospheric angular momentum. Walter Munk and his collaborators calculated atmospheric angular momentum and wrote about connections to Earth rotation variations (Munk and MacDonald, 1960). Lambeck and Cazenave (1973) of Paris Observatory made use of the MIT data to determine the excitations of Earth rotation. Subsequently this connection was continued: Feissel and Gambis (1980) analyzed intraseasonal oscillations in geodetic study, followed by Langley et al. (1981) of the same timescales in the atmosphere.

Raymond Hide was instrumental in codifying the theory of the relationship of length of day and polar motion from atmospheric models in Barnes et al. (1980). This formalism was used for calculations by the Sub-bureau for Atmospheric Angular Momentum, an agency of the International Earth Rotation and Reference System Service (IERS). Salstein et al. (1993) organized the service based on operational weather analyses from four meteorological centers: US National Centers for Environmental Prediction, the European Centre for Medium-Range Weather Forecasts, the United Kingdom Meteorological Agency, and the Japan Meteorological Agency. The Sub-bureau was later renamed the Special Bureau for the Atmosphere of the Global Geophysical Fluids Center (GGFC/IERS). Later, the procedures were later updated in Zhou et al. (2006) using more accurate integration techniques and updated geophysical parameters. Besides calculations from operational meteorological series, during the period of operation of the special bureau, Reanalyses of the atmosphere became available and were routinely produced as well. Such series go back to use all raw observational meteorological data and in order to reconstruct the fields of the atmosphere. From the reanalyses, we were able to calculate the angular momentum parameters to produce a more consistent result. The best known of these series have been the NCEP-NCAR reanalysis (U.S. National Centers for Environmental Prediction-National Center for Atmospheric Research), the ERA (European Centre Reanalyses), the the MERRA analysis from the US National Aeronautics and Space Administration.

Efforts to use analysis and forecasts of AAM as a proxy for Length-of-day were used by Rosen et al. (1987) and at the US Naval Observatory by Johnson et al. (2005) and with later improvements by Stamatakos et al. (2018), including the use of the NAVGEM (U.S. Navy Global Environmental Model and HYCOM (Hybrid Coordinate Ocean Model). At the GeoforschungsZentrum (GFZ), Dill et al (2019) used ECMWF models, with ocean, land hydrology and sea-level models. At Vienna University of Technology, an archive was established of atmospheric information for many geodetic purposes (see Böhm and Schuh, 2013). Quite a bit of research was done on the connections between AAM and Earth rotation parameters on time scales from seasonal (e.g. Höpfner et al., 2001) and inter annual, including signals of the 2.2 year quasi-biennial oscillation and El Niño/Southern Oscillation (especially J. Dickey at the Jet Propulsion Laboratory). Exhaustive survey of these agreements was made by N. Sidorenkov in many publications and books.

4. METHODS TO DETERMINE ATMOSPHERIC ANGULAR MOMENTUM AND CURRENT THEMES

AAM has three components. The axial component is to be compared with variations in the rotation rate of the Earth, reckoned in changes in the length of day. The two components about the equatorial axes may be related with change in the motion of the Earth's pole.

In discussing length of day, it is noted that the excess length of day has had variations on many time scales, from the century to decadal to the very high frequency. The C04 series of Earth rotation, from Paris Observatory maintains the long term stability of this series. Variations on sub-decadal scales down to a few days have been noted to be related to AAM. Formulas relating the atmospheric series (Barnes et al., 1983) include volume integrals through the atmosphere for the wind terms (known as u, the axial, or eastward or westerly, wind, and v, the meridional, or northward or southerly, winds). Integrals on the surface of the Earth relating to the surface pressure (or ps), approximate the mass term, because the total mass above a point on the surface, per area, multiplied by the gravitation field, is approximately equivalent to the surface pressure, given an assumption of hydrostatic equilibrium. Lastly, the so-called inverted barometer approximation has generally been invoked to estimate the effect of a modified mass term in the ocean that counteracts the changes in atmospheric mass over each point in the ocean. However, the equilibrium time for the inverted barometer to hold is generally a few days or more.

The axial AAM is determined from different geographical regions in the manner as noted above. In the annual mean, most of the atmosphere is positively oriented, which is to say that the mean winds are from the west to the east. This movement of the air has positive angular momentum by convention. These mean westerlies exist thought the subtropics, middle latitudes, and peak in the 30-40 degree latitude zone in both hemispheres, near the 200 hPa level due to jets at these areas. In contrast, negative values of the angular momentum occurs in the mean between the subtropics of each hemisphere and the tropics in the lower part of the atmosphere. There winds flow predominantly from east to west, and are often known as the trade winds.

An important interannual signature is known as the El Niño/Southern Oscillation, whose basic characteristics are warm ocean surface temperatures in the upper levels of the Pacific off the coast of South America (El Niño) accompanied by a vacillation of atmospheric mass across the breadth of the Pacific Ocean (Southern Oscillation). The oscillation period is approximately 4 years. Some El Niño events are stronger than others, but in recent decades particularly important ones occurred in 1982-83, 1997-98, and 2014-16.

Whereas angular momentum is exchanged between the solid Earth and the geophysical fluids, leading to the equivalence of AAM and LOD variations, there must be a dynamic mechanism to effect such changes. Torques do exist to foment the changes in angular momentum. Typically two principal torque mechanisms occur either as normal or as tangential forces over the Earth surface. The so-called mountain or topographic torque occurs when differential pressure on opposite side of topographic features yield a force and interpreted as a torque at the distance to the Earth's axis. These occur largely on the time scales when weather phenomena are changing, on the order of several days to a week. A second type of torque is a result of winds blowing across the surface, where tangential friction is a drag force between the atmospheric fluid and the solid Earth. It has time scales from the highest frequency of days, to sub-seasonal. A third torque is derived as gravity-wave drag that simulates the forces on spatial scales smaller than the grid points of models in use.

On long time scales, from decadal to century, the angular momentum of the Earth, and hence the Length-of-Day, have varied in part due to tidal exchanges from the moon, and exchanges of angular momentum with the Earth's liquid core. However, the atmosphere also has variability on the decade-to-century scales. A dedicated project known as the Climate of the 20th Century, is based only on atmospheric surface pressures back to approximately 1870; this is the only consistent observational data set back that far.

Currently, an important theme of research is running experiments with climate models to determine what the future might be under certain scenarios. The Climate Model Intercomparison Project (CMIP) uses atmosphere and ocean models coupled to each other, and in cases, land-surface models as well to examine the state of the atmosphere based on possible changes in the composition of the atmosphere for sociological and economic reasons, mostly due to the imposition of new greenhouse gases. We have taken the mass and motion fields from the atmospheric portion of the CMIP project to determine that under increased carbon dioxide in the atmosphere, the composition of the winds in the atmosphere may change (Salstein et al., 2012). In particular, increases in the westerly winds, especially at the high altitude levels will be accompanied by increased axial angular momentum. Such increases may occur up to about 10% of the current relative angular momentum of the atmosphere by the end of the 21st century. Further explanations and results are given in the proceedings of this meeting in the paper of Böhm and Salstein.

Variations in polar motion have also been driven by the geophysical fluids, the atmosphere and the ocean. There were many efforts to determine the origins of atmosphere-driven polar motion variations. Links especially were found to areas over Eurasia and North America where weather systems bring strong variations of mass in the form of fluctuations of weather systems (Nastula et al., 2005). In addition, mass changes from land-based hydrology, have been noted as being important to excitations of polar motion. Such information has been determined from atmospheric analyses, land hydrology models, and fields from the Gravity Recovery and Climate Experiment (GRACE) (Nastula et al., 2007).

In conclusion, the atmosphere is a mobile and variable component of the Earth system. Even though it is so much less massive than the solid Earth, the changes are visible in the angular momentum of the solid Earth, and hence the Earth rotation parameters itself.

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