Atmospheric Angular Momentum related to Earth Rotation studies: History and modern developments

Atmospheric and Environmental Research
Lexington, MA, USA

Journees 2019

L’observatoire de Paris
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Dedication -- to Prof. Barbara Kolaczeck

With whom I collaborated for many years – I was inspired by her scientific insight and curiosity, determination, and genuine kindness.
Outline

History of Atmospheric angular momentum and relation to Earth rotation
Modeling of the atmosphere (and the ocean): equations based on physics

Variable Earth rotation: relationship to atmosphere
Atmospheric angular momentum (AAM)--how it is measured and its climate signals
Seasonal, subseasonal, intraseasonal, interannual time scales

Dynamical relations: torques change rotation rate

Long-period models (20th century + )
Coupled model intercomparison project (CMIP), global change results, and relationship to AAM
What do we need to know about the atmosphere (and ocean)?

1. Observations, from surface, air, space, and sea

2. Methods of combining observations with each other and with modeled information

3. How to construct a model of the atmosphere
1. Raw meteorological data

RAOBS, SURFACE

Microwave, (PO+OO)

AIRCRAFT

GPS

IR (Geostationary)
Some more ocean observations

BUOYS

XBTs

(eXpendable BathyThermographs)
2. METEOROLOGICAL DATA ASSIMILATION and FORECAST SYSTEM

Raw meteorological observations: rawinsondes, aircraft, satellites, etc.

Forecast fields from short forecast

Forecast fields to 10 days

ANALYSES on grid or spectral domain
Fields from assimilation

Compute geodetic functions from atm parameters for ANALYSES

Make forecast with model--may require initialization procedure

Compute Geodetic functions from atm parameters for FORECASTS
3. Atmospheric and ocean models: Equations of fluid motion

Expressed from physical principles:

Equation of motion (Force = Mass x acceleration) about an axis:
   in rotating frame:
Torque = Moment of inertia x angular acceleration

Equation of thermodynamics (Heat = increase in temperature x specific heat + work done by expansion)

Conservation of mass* (inflows of mass balanced by divergence out)

*both DRY air and WATER vapor
Equation of motion in fluid

\[ \frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \] Substantial derivative, follows the flow

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + 2\Omega \times \mathbf{v} \right) = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{f} \]

Mass\hspace{1cm} Acceleration\hspace{1cm} Forces

\[ \frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \cdot \nabla \mathbf{v} - 2\Omega \times \mathbf{v} - \frac{\nabla p}{\rho} + \frac{\nabla \cdot \mathbf{T}}{\rho} + \frac{\mathbf{f}}{\rho} \]

Velocity change\hspace{1cm} Advection\hspace{1cm} Coriolis accel\hspace{1cm} Pressure gradient\hspace{1cm} Edge\hspace{1cm} Body

Friction\hspace{1cm} gravity

Two equations in horizontal: \( \frac{du}{dt} = ... \hspace{1cm} \frac{dv}{dt} = ... \)

Hydrostatic balance in vertical: \( 0 = \left(\frac{1}{\rho}\right) \frac{dp}{dz} = g \) \hspace{1cm} No vertical accel.
Angular momentum fluxes in atmosphere

From: Physics of Climate, J.P. Peixoto and A.H. Oort, 1992

angular momentum = mass x velocity x distance to axis

FIGURE 11.13. Streamlines of the nondivergent component of the zonal-mean transport of relative angular momentum in the atmosphere for annual, DJF, and JJA mean conditions in $10^{18}$ kg m$^2$ s$^{-2}$. Added are some dashed contours of $|u|/\cos \phi$ in units of m s$^{-1}$, which show the counter-gradient nature of the eddy transports (from Oort and Peixoto, 1983).
Variable Earth rotation/atmospheric angular momentum (1)

Stoyko and Stoyko (1936): Annual variation of length of day: tied to air masses
Paris Observatory

Starr (1948): Statement that the atmosphere need not conserve angular momentum, and could share it with the Earth below.
Victor Starr started the “General Circulation Project” at the Massachusetts Institute of Technology (MIT)

Walter Munk and collaborators in the early 1950s: Calculations of atmospheric angular momentum [Munk and MacDonald 1960]

Lambeck and Cazenave (1973) Earth’s rotation and atmospheric variations
[Lambeck 1980]. At Paris Obs. Data from MIT

Intraseasonal variations: Feissel and Gambis (1980) (Paris Obs) for geodetic, followed by Langley et al. (1981) for AAM (MIT)
Variable Earth rotation/atmospheric angular momentum (2)

Hide et al. (1980) and Barnes, R. Hide, et al. (1983): codified the theory with relationship to lod and polar motion, using atmospheric models
-- combining atmosphere calculations and Earth responses (Love numbers etc.)

Sub-bureau for Atmospheric Angular Momentum set up as an agency of the IERS in 1989. (Salstein et al. 1993) at AER and NOAA. Since 1999 called: Special Bureau for the Atmosphere of the Global Geophysical Fluids Center (GGFC/IERS)
-- Angular momentum from the following centers:
  US National Centers for Environmental Prediction (analysis AND reanalysis)
  European Centre for Medium-Range Weather Forecasts
  United Kingdom Meteorological Office
  Japan Meteorological Agency

Updated by Zhou et al. (2006) -- better integration techniques, updated Earth parameters
From Eubanks
Variable Earth rotation/atmospheric angular momentum (3)

Efforts to use analysis and forecasts of AAM and as proxy for LOD:

At US NOAA and AER: Rosen et al. (1987, 1991)
At USNO: Johnson et al. (2005), Stamatakos et al. (2011 - )
-- combine US Navy Products of NAVGEM atmosphere model and HYCOM ocean model
At GFZ: Dill et al. (2017; 2019) using ECMWF models, with ocean, land hydrology and sea-level models
At Vienna University of Technology: Archive of atmosphere excitations for many Geodetic purposes / GGOS Atmosphere
(Schindelegger et al., 2011, 2013, 2014)

Seasonal: J. Hopfner (2000) at GFZ, showing LOD, four different Met. Centers agreement
Interannual variations: Quasi-biennial signals (~2.2 years) and El Nino/Southern Oscillation (~3-4 years)
Works by several groups, including JPL (Dickey et al.) Eubanks et al. AER, Rosen et al.(1984 ...)
Russian Hydromet. Center: Sidorenkov (..., 2009, ...) exhaustive survey of agreements
LOD: 1980-2019

Excess of the length of day

C04 series of LOD, from Paris Observatory
AAM: excitation ($\chi$) vector for Earth rotation: polar motion (1,2) and rotation rate (3)

Polar motion (1,2)

\[ \chi^P = \chi_1^P + i\chi_2^P \]

\[ \chi^W = \chi_1^W + i\chi_2^W \]

Earth rotation: Length-of-Day (3)

\[ \chi_3^P = \frac{0.753 R^4}{C_m g} \iint p_s \cos^3 \phi d\lambda d\phi \]

\[ \chi_3^W = \frac{0.998 R^3}{C_m \Omega g} \iiint u \cos^2 \phi dpd\lambda d\phi \]


Atmospheric mass over the ocean depresses it very nearly 1 hPa (1 millibar) = 1 cm ocean on scales > several days
AAM (NCEP-NCAR Reanalyses) and Earth Rotation Parameters (01/2017 – 09/2019)

1. Polar motion
2. Length-of-day

ERP data and software: Paris Observatory
Where are changes coming from in the atmosphere (I.o.d.)?

Zonal winds

Variance and fractional covariance by latitude
Relevance to climate parameters (ENSO)

SOI = Southern Oscillation Index; the standardized difference between $p_s$ over Tahiti (central Pacific) and Darwin, Australia. Peaks are El Nino events

ENSO = El Nino/Southern Oscillation
Physics of Earth rotation

a. Angular momentum (\(M\)) approach
Atmospheric angular momentum = AAM

\[
\frac{dM_{\text{solid . Earth}}}{dt} = - \frac{dM_{\text{fluid . layer}}}{dt}
\]

b. Torque (\(T\)) approach

\[
\frac{dM_{\text{solid . Earth}}}{dt} = T_{\text{fluid . layer}}
\]

\[
\frac{dM_{\text{fluid . layer}}}{dt} = -T_{\text{fluid . layer}}
\]
Mountain and friction torques

\[ T_{\text{mountain}} = -R^2 \int \int p_s \frac{\partial Z}{\partial \lambda} \cos \phi d\phi d\lambda \]

\[ T_{\text{friction}} = R^3 \int \int \tau \cos^2 \phi d\phi d\lambda \]

\[ T_{\text{gravity-wave}} = \text{Frictional related to sub-grid scale Action in the atmospheric model} \]

\( R = \text{Earth radius, } p_s = \text{surface pressure, } Z = \text{topographic height} \)
\( \tau = \text{frictional stress, related to winds and roughness (model)} \)
\( \phi = \text{longitude, } \lambda = \text{latitude} \)
Mountain and friction torques
4 May 08 - 3 May 09

Different continental areas
US NOAA, following Iskenderian and Salstein, and Weickmann et al.
Climate of the 20th Century, based on surface pressure

El Nino of 1919, wind anomaly


Abarca del Rio and Salstein, 2011
Climate of the 20th Century vs. NCEP-NCAR reanalysis (NCAR) 1958-2010

**GLOBAL NH + SH TROPOSPHERE**

**INTERANNUAL**

**OTHER LOW FREQUENCIES**

**INTERANNUAL TIME SCALES**

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AAM of the 20\textsuperscript{th} century (ERA-20C data)

Veerman and van Heerwaarden, 2019)
Coupled model intercomparison project

Uses climate models with Greenhouse gas and other forcing: basis of the assessment reports by the Intergovernmental Panel on Climate Change.

Many climate models available.

CMIP 3
Previously IPCC scenarios were chosen based on population, economic growth, and technological developments:

- **A2**: Rapid growth
- **A1B**: “Middle of the road” scenario
- **B1**: GHG emissions stabilized

CMIP5
Updated IPCC scenarios have quantitative RCP’s (Representative Concentration Pathways) that span the climate space of radiative forcing: RCP 2.6, 4.5, 6.0, 8.5

CMIP6
SSPs: Shared societal pathways (combination: Bohm and Salstein, poster, this meeting)
Greenhouse gas and warming scenarios from CMIP models

CMIP3

CMIP5
Trend in Earth rotation excitation by winds, CMIP3 and CMIP5

Salstein and Quinn
Atmospheric excitation functions under different scenarios (CMIP3)

Pressure-IB

Wind

A2, A1B, B1

Salstein and Quinn
Atmosphere component, coupled model CMIP5, chi 3-wind

More on this topic in updated experiments: Poster of Bohm and Salstein
Trends in zonal means – $\chi_{3w}$
Height-Latitude cross section

Zonal mean trend (per century) by latitude and pressure level (hPa), weighted by zonal area and pressure: $(10^{-25}/m^2/hPa/century)$. Contour lines: 20C3M zonal mean $\chi_{3w}$, similar weighting $10^{-25}/m^2/hPa$.

Salstein and Quinn
Nastula, Salstein, Kolaczek (2009)
Regional contributions to polar motion at different time scales: from the NCEP/NCAR Reanalyses
Excitation polar motion by mass: Annual – Atmosphere, ocean, land hydrology masses

Nastula, Salstein Gross (2012)
SPACE RESEARCH CENTRE
Polish Academy of Sciences
ul. Bartycka 18A, 00-716 Warsaw, Poland

OBSERVATOIRE DE PARIS
Departement d'Astronomie Fondamentale
URA 1125 CNRS
61, Av. de l'Observatoire, 75014 Paris, France

EARTH ROTATION, REFERENCE SYSTEMS
IN GEODYNAMICS AND SOLAR SYSTEM

JOURNEES 1995
SYSTEMES DE REFERENCE SPATIO-TEMPORELS

Warsaw, Poland, 18-20 September, 1995

Barbara Kolaczk contributions
Short period variations of Earth Rotation
(B.Kolaczeck, Journees 1995)
The impact of El Niño and other low-frequency signals on Earth rotation and global Earth system parameters
David A. Salstein, Barbara Kolacze, Daniel Gambis (eds.)(IERS Technical Note ; 26), 1999

IDENTIFICATION OF EL NIÑO SIGNALS WITH SATELLITE ALTIMETRY (PDF, 1MB)
D.P. Chambers, J.L. Chen, and B.D. Tapley

ATMOSPHERIC ANGULAR MOMENTUM DURING THE 1997-98 EL NIÑO EVENT (PDF, 991KB)
David A. Salstein

SIGNATURE OF EL NIÑO IN LENGTH OF DAY AS MEASURED BY VLBI (PDF, 1MB)
John M. Gipson and Chopol Ma

EL NIÑO IMPACT ON ATMOSPHERIC AND GEODETIC EXCITATION FUNCTIONS OF POLAR MOTION
(PDF, 287KB)
B. Kolacze, M. Nuzhdina, J. Nastula, and W. Kosek

THE 1997-1998 EL NIÑO EVENT: INSIGHT VIA SPACE GEODESY (PDF, 886KB)
Jean O. Dickey, Pascal Gégoout, and Steven L. Marcus

ANGULAR MOMENTUM AND TORQUES DURING THE 1982-83 EL NIÑO (PDF, 545KB)
Rui M. Ponte and Richard D. Rosen

FLUCTUATIONS OF THE EARTH ROTATION AND EL NIÑO EVENTS (PDF, 736KB)
V. Frège and P. Mazega

TROPICAL PACIFIC OCEAN LONG WAVES CONTRIBUTION TO LENGTH OF DAY DURING ENSO IN
1980-1997 (PDF, 359KB)
Rodrigo J. Abarca del Rio, Boris Dewitte, Yvon duPenhoat, and Daniel Gambis

EL NIÑO SIGNAL IN LOCAL AND GLOBAL ATMOSPHERIC TORQUES (PDF, 703KB)
O. de Viron, V. Dehant, P. Paquet, and D.A. Salstein

ATMOSPHERIC-OCEANIC INFLUENCE ON INTERANNUAL LENGTH-OF-DAY VARIABILITY LINKED TO
EL NIÑO/SOUTHERN OSCILLATION (PDF, 1MB)
Laura I. Fernández and Elisa Felicitas Arias

CORRELATION OF INTRASEASONAL LENGTH OF DAY AMPLITUDE MODULATION WITH ENSO (PDF,
1MB)
Zhong Min, Zhu Yao-zhong, and Gao Bu-xi
Possible influences of core processes on the Earth's rotation and the gravity field
H. Greiner-Mai, H. Jochmann, F. Barthelmes, L. Ballani
Pages 343-358
Progress in understanding momentum exchange process—another look at the role of mass transports
Jin-Song von Storch
Pages 359-367
Chandler and annual wobbles based on space-geodetic measurements
Joachim Höpfner
Pages 369-381
Empirical patterns of variability in atmospheric and oceanic excitation of polar motion
J. Nastula, D.A. Salstein, R.M. Ponte
Pages 383-396
El Nino-related variations in atmosphere–polar motion interactions
B. Kolaczek, J. Nastula, D. Salstein
Pages 397-406
Polar motions with a half-Chandler period and less in their temporal variability
Joachim Höpfner
Pages 407-422
Solar activity and earth rotation variability
Pages 423-443
Summary

• Atmosphere angular momentum is an important driver of Earth rotation variations, given conservation of angular momentum in the Earth system
• Atmospheric angular momentum (AAM) is a fundamental measure of the atmosphere, relating to seasonal and climate signatures and Earth rotation measurements
• Atmosphere and ocean can be modeled based on the equations of physics and forecast in time. With data assimilation → series of AAM from models
• Torques are the means of angular momentum transfer between atmosphere and Earth -- normal force against mountains, and tangentially by friction
• Modeled trend in AAM increased somewhat in the 20th century and expected to increase more in the 21st century depending upon the warming scenario. Source: zonal wind changes in upper troposphere/lower stratosphere in the subtropics
• Many researchers were involved in AAM over the last decades

• FOND MEMORY OF AND GRATITUDE TO BARBARA K!
State, thermodynamic, conservation equations

\[ p = \rho R_d T \]

Change in water = sources

Continuity of dry air

\[ \frac{c_v}{v} \frac{dT}{dt} + \frac{p}{v} \frac{d\alpha}{dt} = q + f \]

Equation of state

Thermodynamic eq.

\[ \frac{D\rho}{Dt} = -\rho \nabla \cdot v \]

Continuity of dry air

\[ \frac{Dq}{Dt} = S \]

Change in water = sources

\[ \frac{\partial q}{\partial t} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} + \text{Evaporation} - \text{Condensation} \]
Can model changes in time from equations

We showed that from physics we have, for property M:

\[
\frac{\partial M}{\partial t} = M_{\text{rate}}
\]

For \( M = \) u (zonal wind, from west to east)
\( v \) (meridional wind, from south to north)
T (temperature)
q (water vapor)

So we can the relationship as the basis of a "**Forecast model**":

\[
M_t + \Delta t = M_t + \Delta t \times M_{\text{rate}}
\]

Perform this sequentially at points on a grid
Reanalysis Earth rotation excitation (2002)

IB=Inverted Barometer

Polar motion

Mass

Mass--IB

IB=Inverted Barometer

Length of day
Trends in zonal means – zonal winds

Units: m/s/century

Contour units mean over 20th century in m/s

Salstein and Quinn also Paek and Huang