The Influence of Nontidal Sea Level Height and Current Changes on the Earth's Rotation and Polar Motion During 1992-1994

by

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- Use products of Ocean General Circulation Models (OGCMs) to evaluate effects of ocean current and bottom pressure changes on length-of-day and polar motion during 1992–1994
  - Princeton Modular Ocean Model (MOM)
  - Miami Isopycnal-Coordinate Ocean Model (MICOM)
- Compare model-predicted effects with observations of length-of-day and polar motion excitation
  - After removing atmospheric effects
VARIATIONS IN EARTH'S ROTATION

- POLAR MOTION: THE QUASI-PERIODIC PROGRADE MOTION OF THE ROTATION AXIS AROUND THE NORTH POLE (scale ~ 10 meters)
- LENGTH OF DAY VARIATION: VARIATION IN THE ROTATIONAL SPEED (~ 1 m/sec day)

MILESTONE
- DYNAMICS BY EULER 1752
- CHANDLER'S DISCOVERY OF POLAR MOTION 1931
- ASTROME OBSERVATION BY ILS (International Latitude Service) SINCE 1900
- ADVENT OF ATOMIC CLOCK IN 1950s
- NEW OBSERVATION TECHNIQUES: SATELLITE DOPPLER, SATELLITE LASER RANGING, VERY-LONG-BASELINE INTERFEROMETRY SINCE 1970s

POSSIBLE CAUSES:
- ATMOSPHERIC OCEANIC CIRCULATION?
- SEISMIC ACTIVITIES?
- IMANTLE CONVECTION?
- CORE-MANTLE COUPLING?
- SOLAR ACTIVITIES?

SCIENTIFIC SIGNIFICANCE:
- TO IMPROVE UNDERSTANDING OF EARTH'S GLOBAL DYNAMICS
- INference FOR EARTH'S INTERIOR STRUCTURES
LONG PERIOD LIOUVILLE EQUATION

Conservation of angular momentum expressed within rotating, body-fixed reference frame:

\[ \frac{\partial \mathbf{L}}{\partial t} + \omega \times \mathbf{L} = \tau \]

where the angular momentum vector \( \mathbf{L} = \mathbf{I} \cdot \mathbf{w} + \mathbf{h} \)

Assume rotation is small perturbation from state of uniform rotation at rate \( \Omega \). Keeping terms to first order results in long period Liouville equation

\[ \mathbf{m}(t) - t \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{m}}{\partial t} = \psi(t) \]

\[ = \chi(t) - \frac{i}{\Omega} \frac{\partial \chi}{\partial t} \]

where: \( \mathbf{m} = (\mathbf{w} + i \mathbf{w})/\Omega \) (terrestrial location of rotation pole)

\( \psi(t), \chi(t) \) are the polar motion excitation functions

\( \sigma_{cw} \) is complex-valued frequency of Chandler wobble

Written in terms of reported polar motion parameters \( \mathbf{p}(t) = x_p(t) - i y_p(t) \)

in first equation:

\[ \mathbf{p}(t) + \frac{i}{\sigma_{cw}} \frac{\partial \mathbf{p}}{\partial t} = \chi(t) \]

\[ = \frac{1.61}{\Omega (C - A)} \left[ h(t) + \frac{\Omega \sigma(t)}{1.44} \right] \]

\( h(t) \) is

\[ \mathbf{p}(\sigma) = \frac{\sigma_{cw}}{\sigma_{cw} - \sigma} \chi(\sigma) \]
OCEAN ANGULAR MOMENTUM (OAM)

- Angular momentum of oceans changes due to:
  - Frictional drag on the ocean surface by atmospheric currents
  - Rotation of ocean changes in oceans' angular momentum

- Under principle of conservation of angular momentum, the rotation of the solid Earth changes as OAM is exchanged with the solid Earth

- OAM can be computed from products of OGCMs by:

  \[
  \mathbf{m}^o(t) = M_1^o(t) + M_2^o(t) = \int_{V_o} r^2 \Omega \rho(r,t) \sin \phi \cos \lambda + i \sin \lambda \, dV
  \]
  \[
  M_3^o(t) = \int_{V_o} r^2 \Omega \rho(r,t) \cos^2 \phi \, dV
  \]

- \( M_1, M_2, M_3 \) are related to angular momentum:

  \[
  \mathbf{m}^o(t) = M_1^o(t) + i M_2^o(t) = \int_{V_o} \rho(r,t) r \sin \phi u(r,t) + v(r,t) \cos \lambda + i \sin \lambda \, dV
  \]
  \[
  M_3^o(t) = \int_{V_o} \rho(r,t) r \cos \phi u(r,t) \, dV
  \]

- OAM is related to Earth rotation excitation functions by:

  \[
  \chi(t) = \chi_1(t) + i \chi_2(t) = \frac{1.61}{\Omega (C-A)} \left[ M_1^o(t) + \frac{M_2^o(t)}{1.44} \right]
  \]
  \[
  \Delta A(t) = \frac{\Lambda_o}{C_m \Omega} \left[ M_3^o(t) + 0.756 M_3^o(t) \right]
  \]

- \( \chi(t) \) and \( \Delta A(t) \) are the excitation functions related to Earth rotation.
ATMOSPHERIC ANGULAR MOMENTUM (AAM)

- Angular momentum of atmosphere changes due to:
  - pressure effects on atmospheric winds
  - change of earth rotation (along with exchanges)

- Under principle of conservation of angular momentum, the rotation of the solid earth changes as AAM is exchanged with the solid Earth

- AAM $\chi$-functions quantify the atmospheric excitation of Earth rotation

\[
\chi_1^p + i \chi_2^p = \frac{-1.00 \ a^4}{(C-A) \ g} \int p_x \sin \phi \cos^2 \phi \ (\cos \lambda + i \sin \lambda) \ d\lambda \ d\phi
\]

\[
\chi_3^p(t) = \frac{0.70 \ a^4}{C \ g} \int p_x \cos^3 \phi \ d\lambda \ d\phi
\]

- AAM $\chi$-functions under (total angular momentum)

\[
\chi_1^w + i \chi_2^w = \frac{-1.43 \ a^3}{\Omega (C-A) \ g} \int (u \sin \phi \cos \phi + i \nu \cos \phi) \ (\cos \lambda + i \sin \lambda) \ dp \ d\lambda \ d\phi
\]

\[
\chi_3^w(t) = \frac{a^3}{C \ \Omega \ g} \int u \cos^2 \phi \ dp \ d\lambda \ d\phi
\]

- AAM $\chi$-functions are computed from the operational analyses of the:
  - ECMWF
  - JMA
  - NOGEO
  - UKMO

- AAM $\chi$-functions are computed from the reanalysis systems of the:
  - NASA / GSFC Data Assimilation Office (DAO)
  - NOGEO / NOCAR
  - ECMWF
OCEANIC RESPONSE TO ATMOSPHERIC SURFACE PRESSURE FLUCTUATIONS

How do oceans transmit atmospheric surface pressure fluctuations to ocean bottom?

- The fluid column term, near-surface, is represented as a classical medium.

- Inverted barometer assumption

  - Fluid height is measured above ocean surface. Corrections are possible if density varies.
  - Density is unlikely to vary much in long periods.

- Rigid ocean (no inverted barometer) assumption

  - Pressure fluctuations are transmitted directly without attenuation.

- All pressure terms are available that have been computed under each of these assumptions.

- AAM pressure term computed under inverted barometer assumption chosen for use here.
SPACE96 EARTH ORIENTATION SERIES

- A combination of space-geodetic Earth rotation measurements
  - LID (from JPL analysis center)
  - GULF (from University of Texas Center for Space Research analysis center)
  - U.S. from ITIS "Intensive" (both NOAA & USNO analyses), NASA's Deep Ear
  - Earth and NASA's Space Geodesy Program of GSFC
  - GNS (from GIO and JPL analysis centers and IGS combined series)

- Individual series adjusted prior to their combination
  - Long records and tidal terms removed (when necessary) from UT1 values
    - Yoder et al. [1981] model used to remove effect of all long period solid Earth tides
    - Dickman [1993] model used to remove ocean tidal corrections to the Yoder et al. [1981]
      model values at the $M_i, M'_i, M_m$, and $S_{ss}$ tidal frequencies
    - Herring [1993] empirical model used to remove effect of semidiurnal and diurnal ocean
      tides on NOAA's IRIS "Intensive" UT1 values
  - All rates of each series adjusted to be in agreement with each other
  - Standard uncertainties of each series adjusted so its residual with respect to a
    combination of all other series has a reduced chi-square of one
  - Outlying data points deleted

- Adjusted series combined using Kalman filter to form SPACE96
  - Consists of values for DMX, DMV, UT1-UTC, their formal uncertainties and
    correlations spanning September 23.0, 1976 to February 28.0, 1997 at daily intervals
SPACE96 EXCITATION FUNCTIONS

- SPACE96 consists of values for polar motion and UT1–UTC
- Kalman filter used to generate SPACE96
  - Kalman filter used to generate SPACE96
- Excitation functions used here are those estimated by Kalman filter when generating SPACE96
APPROACH

- **Earth rotation observations**
  
  Use SPACE98 Earth rotation excitation functions
  
  - SPACE96 is a Kalman filter-based combination of space-geodetic Earth rotation measurements
  - SolidEarth and ocean tidal effects have been removed from $\gamma$ values
  - Daily values at noon spanning 1976.8 -1997.1

  Form 3-day averages of daily noon values; demean and detrend

- **Remove effects of atmospheric wind and pressure**

  Use the NCEP/NCAR reanalysis atmospheric angular momentum values

  - 6-hour values spanning 1979–present
  - Pressure term used is that computed assuming oceans respond as inverted barometer to imposed atmospheric pressure changes

  Average over diurnal cycle by forming centered average of 5 successive values with weights $1/8$, $1/4$, $1/4$, $1/4$, $1/8$

  Form 3-day average of daily noon values; demean and detrend

- **Compare residual to predictions of OGCM**

  Use $\gamma_{AM}$ values computed from MCM and BICOM models run at 10$^5$ by Yi Chao

  - 3-day averaged values at noon spanning 1992–1994

  Correct term for effects of mass non-conservation

 breaking term for in-situ effect; adjustment of model to climatological forcing
# OCEAN MODELS

<table>
<thead>
<tr>
<th></th>
<th>Princeton MOM</th>
<th>Miami Isopycnal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model domain</strong></td>
<td>80°S to 80°N</td>
<td>80°S to 80°N</td>
</tr>
<tr>
<td><strong>Horizontal resolution</strong></td>
<td>2° long x 1° lat</td>
<td>2° long x 1° lat</td>
</tr>
<tr>
<td><strong>Vertical layers</strong></td>
<td>22</td>
<td>11 + mixed</td>
</tr>
<tr>
<td><strong>Surface</strong></td>
<td>rigid lid</td>
<td>free surface</td>
</tr>
<tr>
<td><strong>Bottom topography</strong></td>
<td>smoothed ETOP05</td>
<td>smoothed ETOP05</td>
</tr>
<tr>
<td><strong>Model spinup</strong></td>
<td>10 years with climatological air-sea fluxes</td>
<td>10 years with climatological air-sea fluxes</td>
</tr>
<tr>
<td><strong>Forcing</strong></td>
<td>daily NCEP winds and heat flux derived from bulk formula</td>
<td>daily NCEP winds, and heat flux derived from bulk formula</td>
</tr>
<tr>
<td><strong>P – E</strong></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>Output time resolution</strong></td>
<td>3 day averages</td>
<td>3 day averages</td>
</tr>
</tbody>
</table>
BOUSSINESQ MODELS

- The Boussinesq approximation is commonly used in ocean general circulation models (OGCMs)
  - Density variations in oceans are small
    - Usually less than \( \pm 2.5\% \) of average density
  - Under Boussinesq approximation, density variations are ignored except in the gravitational buoyancy force
    - Density is not constant but changes as temperature, pressure, and salinity changes

- Boussinesq models conserve volume, not mass
  - Under Boussinesq approximation, conservation of mass equation \( \nabla \cdot (\rho u) = 0 \) reduces to \( \nabla \cdot u = 0 \) (conservation of volume)

- In Boussinesq ocean models, imposed heat flux can lead to model mass changes
  - Imposed heat flux \( \rightarrow \) temperature changes \( \rightarrow \) density changes via equation of state
  - Since model volume is constant, model mass must change to accommodate density change
    - Boussinesq models do not properly represent steric sea level, but can be corrected to do so (Greatbatch, 1994; Mellor & Ezer, 1995)

- Must account for mass non-conservation
  - Here, \( \rho^c(t) \) applies to a factor designed to ensure mass conservation:
    \[
    p^c(t) = p^u(t) + \Delta p(t) = p^u(t) + p^u(t) \frac{\Delta m(t)}{m(t)} = \frac{p^u(t)}{m(t)} <m>
    \]
  - where: superscript \( c \) (\( u \)) denotes corrected (uncorrected) parameter \( p(t) \), \( \Delta p(t) \) is the correction applied, \( m(t) \) is model mass at time \( t \), \( <m> \) is time-averaged model mass \( = m(t) + \Delta m(t) \)
OCEANIC EXCITATION OF POLAR MOTION

MICOM (42 mas$^2$) motion term (0.56) MOM (156 mas$^2$)

MICOM (122 mas$^2$) mass term (0.56) MOM (165 mas$^2$)

MICOM (210 mas$^2$) motion + mass term (0.61) MOM (499 mas$^2$)
MOM AND M COM ON T=RM

psd in db (mas**2/cpy)

frequency in cycles/year
POLAR MO-ION EXCITATION SERIES

- SPACE96 - AAM\(w+b\) (333 mas\(^2\))

- MICOM (305 mas\(^2\))
- motion+mass term
- MOM (744 mas\(^2\))

- MICOM (260 mas\(^2\))
- residual
- MOM (564 mas\(^2\))
POLAR MOTION EXCITATION SERIES

SPACE96 (519 mas²)

AAM+MICOM (497 mas²)
motion + mass term
AAM+MOM (865 mas²)

AAM+MICOM (260 mas²)
residual
AAM+MOM (564 mas²)
Polar Motion Excitation Series

SPACE96 (1248 mas²)

AAM+MOM (1102 mas²)  motion + mass term  AAM+MOM (1597 mas²)

AAM+MICOM (458 mas²)  residual  AAM+MOM (844 mas²)
## CORRELATION BETWEEN SPACE96 & AAMOAM SERIES

<table>
<thead>
<tr>
<th>AAM / OAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAM wind</td>
<td>0.46</td>
<td>0.55</td>
<td>0.50</td>
</tr>
<tr>
<td>AAM ib</td>
<td>0.36</td>
<td>0.65</td>
<td>0.59</td>
</tr>
<tr>
<td>MICOM current</td>
<td>0.26</td>
<td>0.13</td>
<td>0.23</td>
</tr>
<tr>
<td>MICOM height</td>
<td>0.52</td>
<td>0.31</td>
<td>0.39</td>
</tr>
<tr>
<td>AAM w+ib</td>
<td>0.59</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td>MICOM c+h</td>
<td>0.48</td>
<td>0.30</td>
<td>0.37</td>
</tr>
<tr>
<td>AAM+MICOM</td>
<td>0.74</td>
<td>0.80</td>
<td>0.78</td>
</tr>
</tbody>
</table>

## BETWEEN SPACE96-AAM RESIDUAL & OAM SERIES

<table>
<thead>
<tr>
<th>OAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICOM current</td>
<td>0.45</td>
<td>0.41</td>
<td>0.42</td>
</tr>
<tr>
<td>MICOM height</td>
<td>0.53</td>
<td>0.44</td>
<td>0.47</td>
</tr>
<tr>
<td>MICOM c+h</td>
<td>0.59</td>
<td>0.52</td>
<td>0.54</td>
</tr>
</tbody>
</table>

## BETWEEN SPACE96-OAM RESIDUAL & AAM SERIES

<table>
<thead>
<tr>
<th>AAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAM wind</td>
<td>0.49</td>
<td>0.49</td>
<td>0.37</td>
</tr>
<tr>
<td>AAM ib</td>
<td>0.59</td>
<td>0.74</td>
<td>0.70</td>
</tr>
<tr>
<td>AAM w+ib</td>
<td>0.65</td>
<td>0.78</td>
<td>0.74</td>
</tr>
</tbody>
</table>
% VARIANCE EXPLAINED
OF SPACE96 BY AAM / OAM SERIES

<table>
<thead>
<tr>
<th>AAM / OAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAM wind</td>
<td>20.0</td>
<td>20.1</td>
<td>20.1</td>
</tr>
<tr>
<td>AAM ib</td>
<td>9.0</td>
<td>40.9</td>
<td>31.9</td>
</tr>
<tr>
<td>MICOM current</td>
<td>3.7</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>MICOM height</td>
<td>27.0</td>
<td>9.9</td>
<td>14.8</td>
</tr>
<tr>
<td>AAM w+ib</td>
<td>34.7</td>
<td>48.7</td>
<td>44.8</td>
</tr>
<tr>
<td>MICOM c+h</td>
<td>14.3</td>
<td>7.7</td>
<td>9.5</td>
</tr>
<tr>
<td>AAM+MICOM</td>
<td>50.0</td>
<td>62.4</td>
<td>58.8</td>
</tr>
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OF SPACE96-AAM RESIDUAL BY OAM SERIES

<table>
<thead>
<tr>
<th>OAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICOM current</td>
<td>19.8</td>
<td>14.8</td>
<td>16.5</td>
</tr>
<tr>
<td>MICOM height</td>
<td>27.9</td>
<td>19.1</td>
<td>22.2</td>
</tr>
<tr>
<td>MICOM c+h</td>
<td>21.9</td>
<td>26.5</td>
<td>24.9</td>
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OF SPACE96-OAM RESIDUAL BY AAM SERIES

<table>
<thead>
<tr>
<th>AAM series</th>
<th>PMX</th>
<th>PMY</th>
<th>CMPLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAM wind</td>
<td>0.1</td>
<td>17.6</td>
<td>12.9</td>
</tr>
<tr>
<td>AAM ib</td>
<td>33.0</td>
<td>64.7</td>
<td>49.3</td>
</tr>
<tr>
<td>AAM w+ib</td>
<td>41.7</td>
<td>59.2</td>
<td>54.5</td>
</tr>
</tbody>
</table>
SOLID EARTH - ATMOSPHERE RESIDUAL (detrended)

MICROSECONDS

YEARS AFTER 1900

LOD - NCEP (Wind to 10mb)
LOD - IMA (Wind to 10mb)
LOD FORCING: CURRENTS (detrended)

MICROSECONDS

YEARS AFTER 9999
LOD FORCING: MASS (detrended)

MICROSECONDS

YEARS AFTER 1900.

MOM model
MICOM Model
Conclusions

By making proper allowance for climate and mass drifts, angular momentum variations produced by 2 substantially different OGCMs were shown to be very similar

- Both current and mass terms agree

Comparisons with geodetic and atmospheric data show that the model-simulated OAM series can significantly improve closure of the Earth’s axial angular momentum budget

- Results enhance confidence in robustness of model simulations

High-quality geodetic measurements have the potential to serve as benchmarks for validating and improving complex geophysical models

- Benefits to both geodetic studies and ocean/atmosphere modeling
ACKNOWLEDGMENTS

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