Michael SCHINDELEGGER
Johannes BÖHM, David SALSTEIN

The global $S_1$ tide and Earth’s nutation

Session 4: Earth’s rotation and geodynamics
Motivation & Background

IAU2000A nutation model, Mathews et al. (MHB):

- MHB noticed a distinct gap of about 100 µas between their theory and VLBI data at the prograde annual frequency
- Residual from solar \( S_1 \) tide, subtracted prior to adjustment

“Postfit correction term” ➞ Present-day circulation models

Radiational or thermal tides:
- Caused by the daily cycle of solar heating; stratospheric \( \text{O}_3 \) and tropospheric \( \text{H}_2\text{O} \) absorb solar radiation
- Excited waves propagate to the ground; diurnal variations in surface parameters dominated by Sun-synchronous or \textit{migrating} oscillations, e.g. in ...
Radiational Tides

... Surface pressure: Global maps of $S_1(p)$

- Signature of **migrating wave**: equatorial belt of ~60 Pa in amplitude / westward increase in phase
- **Non-migrating waves**: strong oscillations over continents, repercussions of the local heat transfer from the ground
Radiational Tides

$S_1$ and nutation, important notes:

- Air pressure loads the oceans and induces oceanic angular momentum = „indirect“ atmospheric excitation

- Only the second-order tesseral spherical harmonic of pressure (~10 Pa mode) can couple to Earth rotation variations

- Wind tide effect features a better signal-to-noise ratio, e.g. in terms of $S_1$ retrograde atmospheric angular momentum (AAM):

  motion : mass contribution = 7:1

Presence of the $\psi_1^1$ normal mode, cf. Brzeziński et al. (2002)
**Time line** of atmospheric reanalyses (with fixed model configuration):

<table>
<thead>
<tr>
<th>Name</th>
<th>&quot;Generation&quot;</th>
<th>Fixation</th>
<th>Resol. (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCEP RI</td>
<td>1</td>
<td>1995</td>
<td>210</td>
</tr>
<tr>
<td>NCEP RII</td>
<td>1</td>
<td>1995</td>
<td>210</td>
</tr>
<tr>
<td>ERA-40</td>
<td>2</td>
<td>2001</td>
<td>125</td>
</tr>
<tr>
<td>JRA-25</td>
<td>2</td>
<td>2002</td>
<td>120</td>
</tr>
<tr>
<td>MERRA</td>
<td>3</td>
<td>2004</td>
<td>60</td>
</tr>
<tr>
<td>NCEP CFSR</td>
<td>3</td>
<td>2004</td>
<td>40</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>3</td>
<td>2006</td>
<td>80</td>
</tr>
</tbody>
</table>

National Centers for Environmental Prediction Reanalyses I and II

ECMWF 40-year Reanalysis

Japanese Meteorological Agency 25-year Reanalysis

Mapped to nutation by Koot & de Viron (2011), fair agreement found

Mapped to nutation by Bizouard et al. (1998)
Atmospheric Model Data

Probing the 3rd generation reanalyses:

1. **MERRA** of NASA’s Global Modeling and Assimilation Office:  
   *Modern Era-Retrospective Analysis for Research and Applications*

2. **NCEP CFSR**: Climate Forecast System Reanalysis

3. **ERA-Interim** of ECMWF

**Key numbers**

- Temporal resolution: 3h, analysis & forecast data
- Horizontal spacing: 1.25° - 2.5° (pressure level data), 0.5° (surface pressure, except for MERRA)
Crosscheck of surface pressure with empirical $S_1$ solution:

- ~7000 in situ estimates
- $1^\circ \times 1^\circ$ multiquadric interpolation

Schindelegger & Ray (2014)

- ERA-Interim amplitude snippet: almost non-existent $S_1$ tide
- Barometers suggest variations $> 100$ Pa
Crosscheck of surface pressure with empirical $S_1$ solution:

**Tibetan Plateau** “anomaly”: global numerical models (0.5° or less) too coarse to resolve the topography & associated physics:

- RMS differences in $S_1$ pressure cycle almost linearly dependent on
  \[ \Delta H = H_{\text{barometer}} - H_{\text{model}} \]
- Gradient -100 Pa/km
- Strong diurnal oscillations in valleys entailed by mountain-valley breezes
Implications of possible inadequacies in $S_1$ surface pressure for nutation estimates?

- Quick assessment based on $S_1^-$ Fourier coefficients of mass angular momentum
- Oceanic contributions diverge
- Enhanced amplitude of in situ AAM due to W-China $S_1$ tide
Implications of possible inadequacies in $S_1$ surface pressure for nutation estimates?

- Quick assessment based on $S_1$ Fourier coefficients of mass angular momentum
- Oceanic contributions diverge
- Enhanced amplitude of in situ AAM due to W-China $S_1$ tide
- ERA-Interim AAM with inserted in situ grid over W-China increases by $\approx 0.2 \cdot 10^{23} \text{ kgm}^2\text{s}^{-1}$
  $\triangleq 13 \mu\text{as in nutation}$
Nutation: Atmospheric Excitation

**S₁ nutation estimates** obtained from standard procedure:

1) Demodulation to celestial AAM functions
2) Low-pass filtering
3) Fit of in- and out-of-phase components w.r.t. fundamental arguments
4) Convolution (Brzeziński transfer function)

- Good agreement with 1ˢᵗ/2ⁿᵈ generation reanalyses but amplitude reduction for **ERA** and **MERRA**

**CFSR deviation:** $S_1(p)$ anomaly of ~35 Pa in Subantarctic Ocean
Nutation: Atmospheric Excitation

$S_1$ nutation estimates, temporal variability:

- Partition between mass & motion effects in ERA and MERRA about 55:45
- Estimation repeated with 3-year sliding window

Interannual variability of up to 40 µas …

... Is this noise or a real physical signal?
**Nutation: Atmospheric Excitation**

**S₁ nutation estimates**, temporal variability - arguments for noise:

- Little coherence among all three reanalyses
- No residual pattern of the same size (40 µas) at the prograde annual frequency in celestial pole offsets:

  **IERS series, Morlet wavelet analysis**

  ![Wavelet Analysis](image)

  - **MHB fitting period**
  - **Amplitude (µas)**
  - **T = +365^d**

⇒ Atmospheric contribution rather harmonic and well-covered by the MHB empirical correction term (?)
Substantial contribution of radiational $S_1$ oceanic tide:

Collection of estimates - from heights & currents, or already published papers:

<table>
<thead>
<tr>
<th>phase (µas)</th>
<th>in</th>
<th>out-of</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FES2012</strong></td>
<td>-11.7</td>
<td>51.9</td>
</tr>
<tr>
<td><strong>Ray &amp; Egbert (2004)</strong></td>
<td>11.6</td>
<td>62.3</td>
</tr>
<tr>
<td><strong>de Viron et al. (2004): CLIO</strong></td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td><strong>Brzeziński et al. (2012): OMCT</strong></td>
<td>-29.4</td>
<td>30.3</td>
</tr>
</tbody>
</table>

**FES2012 tidal heights** (1 cm = 100 Pa)

- FES: Finite Element Solution
- CLIO: Coupled Large-Scale Ice-Ocean Model
- OMCT: Ocean Model for Circulation and Tides (1.875°)
Superposition of atmospheric & oceanic effects:

- Not fully consistent w.r.t. surface pressure forcing fields
- In terms of RMS differences at sea surface, MERRA fits well to ECMWF input data of both *Ray & Egbert (2004)* and FES2012

<table>
<thead>
<tr>
<th>phase (µas):</th>
<th>in</th>
<th>out-of</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA</td>
<td>-30.2</td>
<td>51.4</td>
</tr>
<tr>
<td>MERRA</td>
<td>-38.3</td>
<td>40.6</td>
</tr>
<tr>
<td>(CFSR</td>
<td>-42.7</td>
<td>85.6)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>phase (µas):</th>
<th>in</th>
<th>out-of</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERRA + FES</td>
<td>-50.0</td>
<td>92.5</td>
</tr>
<tr>
<td>MERRA + Ray</td>
<td>-26.7</td>
<td>102.9</td>
</tr>
<tr>
<td>VLBI observ.</td>
<td>-10.4</td>
<td>108.2</td>
</tr>
</tbody>
</table>

Similar conclusion in *de Viron et al. (2004)*: CLIO + NCEP, but apparent anomaly (40 µas) in atmospheric out-of-phase estimate
Summary and conclusion:

- Atmospheric pressure term probably the “bottleneck” in explaining the observed prograde annual nutation, even if examined by aid of 3rd generation reanalyses

- Total (mass + motion) excitation varies with time in a rather spurious manner

- Critical role of averaging period

- Uncertainty in atmospheric contribution therefore likely to be in the range of 20 μas ≈ accuracy of VLBI estimates
Thank you for your attention!

e-Mail: michael.schindelegger@tuwien.ac.at

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ψ\textsubscript{1} retrograde annual nutation: mean estimates 1994.0 - 2010.12

- Inter-model disparities of about 100 µas (!)
- Large formal errors indicative of “noise-like” character of the ψ\textsubscript{1} tide:
**ψ₁ retrograde annual nutation:** temporal variability

- Estimation repeated with 3-year sliding window
- Large-magnitude fluctuations, probably non-physical
- Partition between mass & motion effects about **95:5**