THE GLOBAL S_1 TIDE AND EARTH'S NUTATION

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ABSTRACT. Diurnal S_1 tidal atmospheric oscillations induced by the cyclic heating of air masses through solar radiation elicit a small contribution to Earth's prograde annual nutation at a level of 100 μas (microarcseconds). Previously published estimates of this Sun-synchronous perturbation based on angular momentum series from global geophysical fluid models have however diverged, and within the present conventional nutation theory, the effect has been instead accounted for in an empirical manner based on analyzing residual spectra of observed celestial pole offsets. This study constitutes a first, tentative reassessment of the S_1 signal in nutation by resorting to modern-day atmospheric reanalyses as well as available hydrodynamic solutions for diurnal oceanic angular momentum changes that are driven by daily air pressure variations at the water surface. We elucidate the global character of the S_1 tide with particular regard to Earth rotation variations and investigate to which extent atmospheric and oceanic excitation terms from various sources can be superimposed. The combined influence of the principal diurnal tide on Earth's nutation, associated with both atmosphere and ocean dynamics, is found to yield a sound agreement with its observational evidence from geodetic VLBI (Very Long Baseline Interferometry) measurements.

1. INTRODUCTION

Describing Earth's orientation in space is a multidisciplinary topic that has attracted the interest of astronomers, geophysicists, and geodesists alike. The currently most accurate model of precession-nutation, i.e. the spatial motion of a conventional reference axis relative to a quasi-inertial system, has been elaborated by Mathews et al. (2002, MHB for short) as a semianalytical theory built upon both a comprehensive model for nutational motions of a non-rigid Earth as well as the assistance of VLBI observations to constrain basic Earth parameters by means of a least-squares fit. Additional effects of external geophysical fluids, such as those from gravitationally-forced ocean tides, have been accounted for in an a priori fashion or via iterative adjustment based on well-established values of oceanic angular momentum (OAM). By analogy, Mathews et al. (2002) anticipated diurnal radiational tides in the atmosphere to evoke small seasonal nutations; though—given the lack of adequate atmospheric angular momentum (AAM) estimates at that time—the authors were left incapable of constructing proper theoretical estimates of the atmosphere-induced nutations to match their observational evidence in VLBI data. As a result, particularly pronounced residuals at the order of 100 μas were registered at the prograde annual nutation frequency and ascribed to the forcing of the principal diurnal S_1 wave. Opting for an empirical but still accurate representation of this anomaly in their model, Mathews et al. (2002) subtracted the S_1 contribution from their observational data prior to adjustment and superimposed the very same values as postfit corrections to the final nutation series.

In keeping with one of the earlier fundamental recommendations (Fedorov and Smith, 1980) of the International Astronomical Union (IAU), it is still desirable to eschew a purely empirical account of the S_1 residual as in MHB's case and replace it by an unambiguous explanation in terms of angular momentum estimates from geophysical fluid models. While several studies have pursued this idea, including Brzeziński et al. (2004) or Brzeziński (2011), a sufficiently good agreement with MHB's postfit correction term has not been documented yet. This mismatch prompts the conclusion that the diurnal AAM/OAM estimates deduced from global numerical atmosphere-ocean models were of subpar quality and that a renewed consideration of the S_1 signal in nutation from the viewpoint of up-to-date geophysical fluid models is warranted. The present paper serves as a preparatory text for such a thorough investigation (Schindelegger et al., 2015) and is conceptualized to recall the nature of the global radiational S_1 tide, to assemble estimates of its impact on nutation from published and newly probed sources, and to present some initial explorations on the likely consensus between geophysical and geodetic excitation quantities at the prograde annual frequency.

2. THE ATMOSPHERIC S_1 TIDE

Solar tides in the atmosphere are ubiquitous oscillations occurring in all types of surface and vertical parameters at frequencies that evenly divide into a mean 24-hour day. Decomposition of the principal diurnal (24-hour, S_1) tide from a global domain to Fourier space reveals pronounced Sun-synchronous or so-called "migrating" waves, whose thermal forcing mechanisms through incoming solar radiation are now well understood (Hagan et al., 2003). To first order, the migrating S_1 component in surface variables is a downward-propagated, linear response of tropospheric layers to the heating associated with infrared absorption by water vapor. Figure 1, conceived as a sample climatology of diurnal surface pressure variations, reflects the Sun-locked mode both by a circular phase advancement and a persistent pressure high of about 60 Pa in the equatorial Pacific. Obvious land/ocean modulations of S_1 and local peak amplitudes of up to 180 Pa testify to the presence of additional, non-Sun-synchronous waves, which are known to be forced by latent heat release mostly in the tropics and sensible heat flux from the ground to atmospheric layers aloft.

Solutions for the mean S_1 pressure tide (as in Fig. 1) and its pronounced seasonal modulations are however by no means concordant when compared across different atmospheric analysis systems and globally distributed in situ observations (Schindelegger and Ray, 2014). Much of the difficulties in modeling the

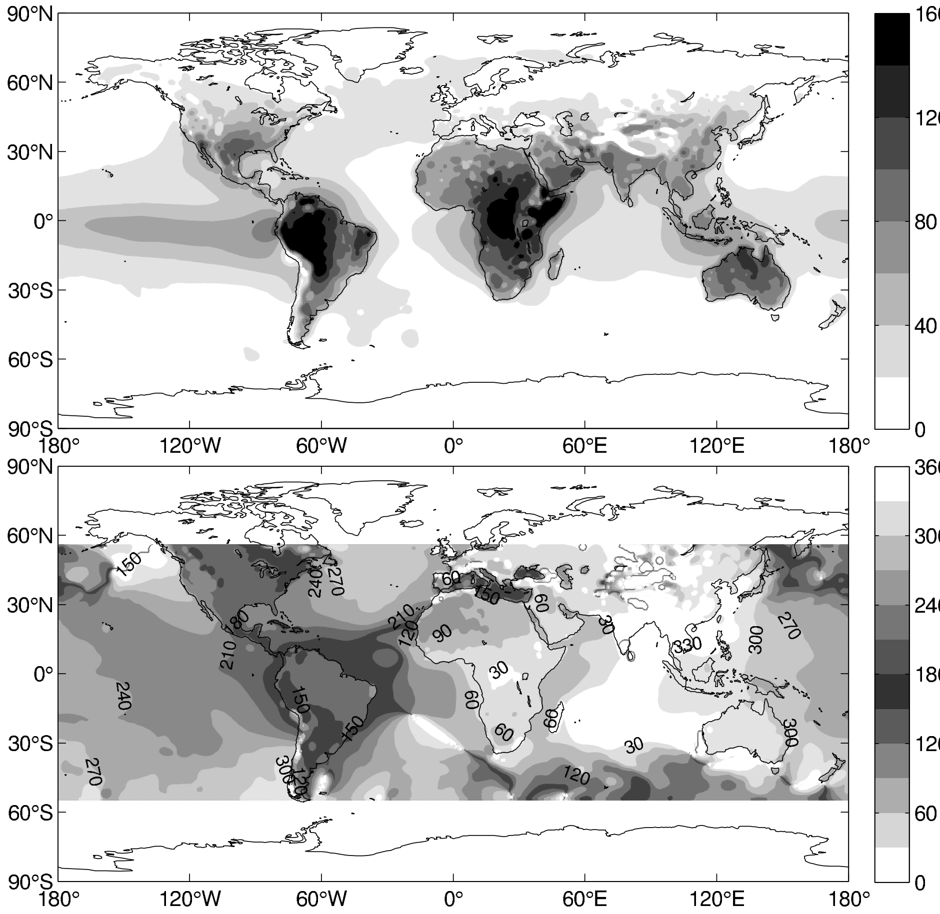

Figure 1: Long-term averages of diurnal air pressure tide amplitudes (Pa, upper panel) and corresponding Greenwich phase lags (deg, lower panel) as deduced from 10 years of ERA-Interim 3-hourly forecast data.

Name	Source	Generation	Fixation	Resolution (km)
NCEP R1	NCEP	1	1995	210
NCEP R2	NCEP	1	1995	210
ERA-40	ECMWF	2	2001	125
JRA-25	JMA	2	2002	120
MERRA	NASA GMAO	3	2004	60
CFSR	NCEP	3	2004	40
ERA-Interim	ECMWF	3	2006	80

Abbreviations: NCEP (National Centers for Environmental Prediction), ECMWF (European Centre for Medium-Range Weather Forecasts), ERA (ECMWF Reanalysis), JRA-25 (Japanese 25-year Reanalysis), JMA (Japan Meteorological Agency), MERRA (Modern Era-Retrospective Analysis for Research and Applications), GMAO (Global Modeling and Assimilation Office), CFSR (NCEP Climate Forecast System Reanalysis).

Table 1: Compilation of available atmospheric reanalyses, including information about the meteorological agency, a "generation" or age index as assigned by the climate data community (at https://climatedataguide.ucar.edu/), the fixation or freezing date of the agency's operational model, as well as the horizontal resolution.

diurnal cycle in numerical weather prediction models relate to the existence of peak diurnal oscillations on subgrid scales as well as uncertainties attached to the daily variations in tropical convection. Mass (i.e. pressure) term estimates of the S_1 effect in nutation have thus varied considerably, handicapped also by a small signal-to-noise ratios as a result of cancellation phenomena between regional pressure maxima. By contrast, the vertically-integrated wind portion of AAM exceeds the retrograde diurnal pressure term by a factor of seven, allowing for a rather unambiguous representation of it in different atmospheric models (Koot and de Viron, 2011).

A proper assessment of seasonal variations in nutation forced by pressure and wind AAM imposes the requirement of a stable, long-term atmospheric dataset, in which possible systematics associated with frequent model updates have been eliminated. So-called "reanalyses", built upon "frozen" versions of the operational assimilation and analysis models of specific weather agencies, largely comply with this condition and have thus become the preferred means to investigate the diurnal atmospheric forcing of nutation amplitudes. Table 1 provides an overview of currently available reanalysis datasets, sorted by a qualitative generation (age) index which roughly mirrors the models' improvements in terms of physics, discretization, input data, and assimilation technique.

Most of the hitherto published S_1 estimates in nutation are based on NCEP's first-generation reanalysis R1, whose formulation and admittedly coarse resolution ($2.5° \times 2.5°$ output grids) date back to 1995. Bizouard et al. (1998) and later Brzeziński et al. (2004) used the R1 data for a first comprehensive examination of the entire atmosphere-induced nutation spectrum, while Koot and de Viron (2011) included additional AAM series from NCEP R2 and ERA-40 (Table 1) and could demonstrate a fair agreement with the results from NCEP R1. However, with the exception of ERA-Interim being probed by Brzeziński (2011), the latest, third-generation set of reanalyses has not been mapped to nutation, although such an effort should, in principle, benefit from the afore-noted model advances over the last decade. The present paper is conceived as a provisional attempt to fill this gap, using 10 years of 3-hourly AAM series (2004.0–2013.12) for MERRA and ERA-Interim (henceforth ERA). Pressure term series were inferred from a combination of analysis and forecast fields at a horizontal resolution of 0.5° (ERA) and 1.25° (MERRA), whereas the wind term integrals were computed from isobaric level data at 2.0° (ERA) and 1.25° (MERRA) latitude-longitude intervals.

Viable procedures translating AAM functions to seasonal perturbations of nutation have been described in Bizouard et al. (1998) and Koot and de Viron (2011) and usually involve an initial demodulation of the terrestrial time series to the celestial frame, low-pass filtering, an adjustment of in- and out-of-phase components referred to the fundamental arguments of nutation, as well as scaling to actual rotational variations by aid of separate transfer functions for pressure and wind terms. Here, we follow Bizouard et al. (1998)'s approach but replace their sophisticated spectral estimator by a simple least-squares fit of in- and out-of-phase terms. Mean S_1 nutation values of ERA/MERRA including three-fold formal errors are displayed in Fig. 2 together with the estimates for NCEP R1, NCEP R2, and ERA-40 from Koot and de Viron (2011). The agreement between both third-generation results is excellent and within 30 μas of the predictions from earlier reanalyses. A moderate amplitude reduction observable

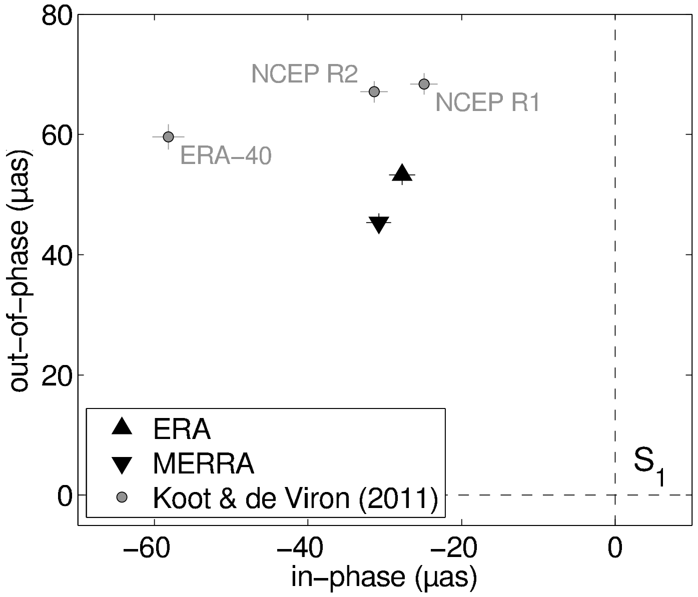

Figure 2: Total (pressure + wind) atmospheric contribution to the prograde annual nutation (S_1) obtained from ERA and MERRA during 2004.0–2013.12 in comparison to the estimates from Koot and de Viron (2011) from earlier generation models for the period 1979.0-2002.7.

Model	Resolution	Atmospheric forcing	in-phase (μas)	out-of-phase (μas)
FES2012	5–75 km	ECMWF operational (mean field)	−11.7	51.9
Ray & Egbert	0.25°	ECMWF operational (mean field)	11.6	62.3
CLIO	1.5°	NCEP R1 (time-variable)	8.0	57.0
OMCT	1.875°	ERA-Interim (time-variable)	−29.4	30.3

Model abbreviations and references: FES (Finite Element Solution, Carrère et al., 2012), Ray and Egbert (2004), CLIO (Coupled Large-Scale Ice-Ocean model, de Viron et al., 2004), OMCT (Ocean Model for Circulation and Tides, mapped to nutation by Brzeziński et al., 2012).

Table 2: Compilation of ocean models that provide a hydrodynamic S_1 solution from forward integration using either a constant forcing or time-variable atmospheric data. FES2012 and the model of Ray and Egbert (2004) are barotropic formulations, whereas CLIO and OMCT are baroclinic models.

for ERA and MERRA likely relates to the use of 3-hourly atmospheric data which resolve semi- and ter-diurnal solar tides and are thus void of folding effects as present in the 6-hourly AAM series of Koot and de Viron (2011). The analysis window of this reference study (1979.0-2002.7) is however disjoint from the one employed here, and a more admissible comparison between the various reanalyses will require a retrospective extension of the ERA/MERRA series by at least one decade.

3. THE OCEANIC S_1 TIDE

As evident from Fig. 2, the atmospheric contribution to the prograde annual nutation is at the level of 60 μas and therefore not the solitary explanation for the S_1 residual in VLBI data (about 100 μas; cf. Section 1). A second substantial geophysical driving arises from the small S_1 ocean tide, which is an "anomalous" phenomenon inasmuch as its gravitational excitation is minor as against the effect of pressure loading associated with the diurnal atmospheric tide (Ray and Egbert, 2004). Nonetheless, the spatial pattern of this "meteorological" ocean tide resembles those of gravitational diurnal tides, including large magnitude oscillations (> 15 mm) in the Gulf of Alaska, the Okhotsk Sea, the Indian Ocean, and the shallow Arafura Sea; cf. the amplitude chart of a modern-day S_1 representation in Fig. 3.

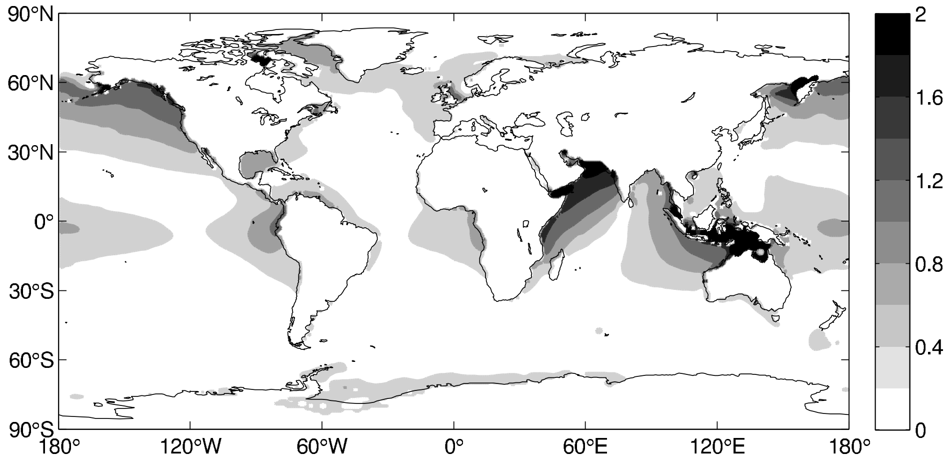

Figure 3: Tidal heights (cm) of the radiational S_1 tide in the global ocean as predicted by the FES2012 model (Carrère et al., 2012) based on a data-free hydrodynamic forward integration forced by a 10-year pressure tide mean from 3-hourly ECMWF operational data.

Accurate determinations of the oceanic S_1 tide originate from hydrodynamic time-stepping models forced by strictly harmonic or time-variable atmospheric pressure (and occasionally wind) data containing the diurnal cycle. A brief tabulation of relevant modeling efforts of that kind is given in Table 2 with emphasis on the model resolution and the respective nutation estimates. Two of the considered numerical solvers (FES, Ray and Egbert) are barotropic (2D) formulations and were rendered to nutation estimates in the frame of this study following the same procedure as in Section 2, whereas CLIO and OMCT results have been extracted from the publications referenced in Table 2. With the exception of OMCT, in- and out-of-phase components of all models agree reasonably well, although the CLIO estimates might be fortuitous, considering that a low-resolution baroclinic (3D) formulation has been used to model a barotropic response characterized by small-scale oscillations.

Given the close inter-model agreement documented for the atmospherically-driven prograde annual nutation (Fig. 2) as well as the barotropic oceanic contribution (FES, Ray and Egbert), a superposition of both effects seems to be warranted. However, such an attempt violates requirements of dynamical consistency, since the forcing climatologies of the hydrodynamic models are different from those inherent to ERA and MERRA. To some extent, these restrictions are weakened by the fact that our pressure tide solutions share strong similarities with those of FES and the Ray model, as evidenced for instance by a global RMS difference of only 4 Pa (average over all pelagic points equatorward of 60°). Moreover, if converted to in- and out-of-phase components of prograde annual nutation, the pressure tide maps of especially the Ray model yield excitation values (-33.9 μas in-phase, 22.7 μas out-of-phase) that conform to the mass term results from reanalyses (e.g. -30.4 μas in-phase, 15.0 μas out-of-phase for MERRA). Bearing in mind this level of inconsistency, combined nutation estimates from both AAM and OAM comply well with the S_1 residual from VLBI observations (Table 3). In particular, oceanic excitation values from Ray and Egbert (2004) superimposed to either ERA or MERRA match the observation to within 10 μas, surpassing the rather approximate agreement noted in predecessor studies (Brzeziński et al., 2004, 2012).

4. DISCUSSION AND OUTLOOK

Present-day determinations of the global S_1 tide in atmospheric and oceanic models have been mapped to nutation signals and were found to yield an accurate account of the empirical prograde annual correction term of the current IAU nutation model (Mathews et al., 2002). This balance is tentative, though, since (a) no allowance has been made for insufficiencies of the MHB model regarding small secondary prograde annual nutations, such as those elicited by mantle anelasticity or the gravitational S_1 ocean tide; (b) only a mean atmospheric contribution has been inferred from 10 years of reanalysis data without exploring the temporal variability of pressure and wind effects over a longer time span; and (c) inconsistencies have been incurred in adding up atmospheric and oceanic excitation estimates from different sources.

	ERA-Interim nutation (μas)		MERRA nutation (μas)	
Model Combination	in-phase	out-of-phase	in-phase	out-of-phase
Atmosphere-only	-27.8	53.3	-30.8	45.3
Atmosphere + FES2012	-39.5	105.2	-42.5	97.2
Atmosphere + Ray and Egbert	-16.2	115.6	-19.2	107.6
VLBI estimate (MHB)	-10.4	108.2	-10.4	108.2

Table 3: Combined effect of atmosphere and oceans on the prograde annual nutation, taking into account ERA and MERRA as well as the two barotropic ocean models cited in Table 2. All estimates given with respect to the fundamental arguments of nutation.

Resolving the latter issue will require the development of a medium-resolution, barotropic time-stepping model in the fashion of Ray and Egbert (2004) which can be forced by the pressure tide solutions of ERA and MERRA, either as long-term averages or as constantly updated "real-time" fields. Extensions of the utilized set of reanalyses, both in time (back to 1994) and by a third state-of-the-art model in the form of CFSR are envisaged and will likely contribute to a more comprehensive picture of the global S_1 tide and its impact on nutation.

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