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Atmospheric contributions to nutations and implications for the estimation of deep Earth's properties from nutation observations

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SUMMARY

We propose a new estimation of the atmospheric contributions to Earth's nutations based on three reanalyses of atmospheric global circulation models (GCM), namely the two reanalyses of the National Center for Environmental Prediction (NCEP) and the ERA-40 reanalysis of the European Center for Medium-Range Weather Forecasts (ECMWF). We estimate the complex amplitudes of the periodic terms in the atmospheric forcing and convolve them with a transfer function for a three-layers Earth with an anelastic mantle and dissipative couplings at the fluid core boundaries. Unlike previous estimations based on operational GCMs, the results we obtain here from the three reanalysis GCMs are in good agreement, which makes them more reliable. From a joint inversion of the three atmospheric models on their common time span (from 1979 to 2002.3), we estimate the atmospheric contributions to nutations to be -38.2 ± 0.4 µas in-phase (ip) and 65.1 ± 0.4 µas out-of-phase (op) on the prograde annual term (S_1), -64 ± 5 µas ip and 29 ± 5 µas op on the retrograde annual term (ψ_1), and -11.3 ± 0.3 µas ip and 41.5 ± 0.3 µas op on the prograde semi-annual term (P_1). As the atmospheric contributions to nutation vary in time, we also compute their time-variability on the time span from 1979 to 2010. In particular, we show that the contribution to ψ_1 has a very large time variability but that these variations are well determined by the atmospheric models that we use. Finally, we explore the implications of the atmospheric contribution to ψ_1 on the estimation of Earth's deep interior properties from nutation observations. We show that this contribution is too small to affect significantly the estimation of these properties.

Key words: Reference systems; Earth rotation variations; Core, outer core and inner core.

1 INTRODUCTION

Nutations are variations in the orientation of the Earth's rotation axis with periods larger than two days in a celestial reference frame. The nutations with the largest amplitudes (about 8 arcsec) are driven by the gravitational torque applied on the ellipsoidal Earth by the other celestial bodies. Other nutations are generated by interactions between the solid Earth and the external geophysical fluids, although their amplitudes are smaller by several orders of magnitude.

In an Earth-fixed reference frame, nutations correspond to quasi-diurnal retrograde (clockwise) variations so that it is the diurnal cycle in the geophysical fluids dynamics that is responsible for exciting the motion. This diurnal cycle originates from two different mechanisms: the gravitational tides, generated by the luni-solar gravitational torque acting directly on the atmosphere and ocean, and the atmospheric 'thermal' tides, arising from the diurnal cycle in solar heating. The largest contribution of the external geophysical fluids to nutations (about 1 mas) comes from the ocean gravitational tides (Chao *et al.* 1996). A smaller but significant part (about 0.1 mas) comes from the atmosphere, mainly from the thermal tides, as Bizouard & Lambert (2002) showed that the effect of the atmospheric gravitational tides were negligible. Whereas the atmospheric contributions to nutations are relatively small, they are much larger than the current precision of the observations, which is between 5 and 40 µas (Herring *et al.* 2002), and thus need to be included in nutation models.

The atmospheric effects on nutations are both direct and indirect. Directly, the atmosphere interacts with the solid Earth through non-homogeneous pressure field acting on the topography, gravitational attraction between atmospheric and solid Earth masses and wind friction on the surface. Indirectly, the atmosphere pressure and wind fields act over the ocean, changing the water pressure acting on its bottom topography, which in turn interacts with the solid Earth. As suggested by de Viron *et al.* (2004) and Brzeziński *et al.* (2004), the contribution of the indirect atmospheric effects, also called the 'non-tidal ocean' effects, can be as large (or even larger) than the direct effect. The evaluation of the atmosphere direct contribution requires a precise knowledge of the atmospheric diurnal dynamics. It is thus quite complicated to estimate as this is a part of the spectrum where the atmospheric global circulation models (GCMs) are not the most precise. The atmosphere indirect contribution is even more difficult to estimate, as it requires both a precise knowledge of the atmospheric forcing and a good knowledge of the ocean response. In this paper, we focus on the direct atmospheric effects.

The contributions of the atmosphere (both direct and indirect) to Earth's rotation, and in particular to nutations, can be estimated using two different approaches, both deriving from the angular momentum budget equation (see Munk & MacDonald 1960; Wahr 1982). In the 'angular momentum approach', the atmosphere/solid Earth is considered to be a closed system so that its total angular momentum is conserved and the change in the Earth's rotation can be estimated directly from the change of atmospheric angular momentum (AAM). In the 'torque approach', the fluid layer is considered to be external to the system, and Earth's rotation changes are estimated as the rotation response of the solid Earth to the torque exerted on it by the atmosphere. Theoretically, both approaches are equally valid. However, in practice, several studies have shown that, due to the lack of precision of the GCMs in the diurnal frequency band, the torque approach was not able to give results with the required precision (de Viron *et al.* 2001; de Viron & Dehant 2003; Marcus *et al.* 2004; de Viron *et al.* 2005). Consequently, we focus here on the angular momentum approach.

A first estimation of the direct atmospheric effects on nutations, based on the angular momentum approach, was given by Bizouard *et al.* (1998), from the National Center for Environmental Prediction (NCEP) reanalysis atmospheric model (Kalnay *et al.* 1996). Using the same atmospheric model along with an oceanic model [the CLIO model from Goosse *et al.* (1999)], de Viron *et al.* (2004) estimated the total atmospheric and non-tidal oceanic effects on nutations, and found results very close to what was expected from nutation observations. Another estimation of the combined atmospheric and non-tidal oceanic effects was performed by Brzeziński *et al.* (2004), using another oceanic model and a different approach, and they found that the agreement with nutation observations was not better than for atmospheric contributions alone. On the other hand, Yseboodt *et al.* (2002) used different atmospheric GCMs and concluded that the estimation of the atmospheric contributions to nutations differs largely from one model to another. This is consistent with the results of de Viron *et al.* (2005), who showed that, at diurnal timescales, the large scale features of the surface pressure distribution differ strongly from one GCM to the other.

Because of these strong differences from one GCM to the other, estimations of atmospheric contributions to nutations are not considered to be reliable and most nutation models do not use them. In particular, in the nutation model of Mathews *et al.* (2002), atmospheric and non-tidal oceanic effects are assumed to affect only the prograde annual nutation term (S_1) and their contribution to this term is considered as an unknown parameter which is estimated from nutation observations. Whereas the atmosphere and non-tidal ocean are known to affect other frequencies as well (Bizouard *et al.* 1998), the contributions to these other terms are not taken into account. This can be problematic for the estimation of Earth's interior properties from nutation observations. Indeed, as Mathews *et al.* (2002) nutation model depends on parameters describing physical properties of the Earth's interior, this model has been used to estimate these properties from nutation observations (Mathews *et al.* 2002; Koot *et al.* 2008; Koot *et al.* 2010). However, if the atmospheric/non-tidal oceanic contributions are not properly taken into account, they are absorbed by the Earth's interior parameters, leading potentially to erroneous values of the Earth's interior physical properties. A precise knowledge of the atmospheric/oceanic contributions is thus necessary to isolate the contribution of the Earth's interior, allowing to further interpret the nutation data in terms of internal geophysics.

In this paper, we want to readdress the problem of estimating atmospheric contributions to nutations from GCMs. Our first purpose concerns the problem of the large discrepancies from one GCM to the other observed by Yseboodt *et al.* (2002). We explore the possibility that these inconsistencies come from the use of operational GCMs which are not reliable for use over a long time period. Indeed, these operational models show, over the time period used, a lot of changes in the models (they always use the best available models at the time of the run) and in the data assimilation method, as well as long gaps without any data. However, to overcome these inconsistencies, the atmospheric analysis centers also compute 'reanalysis' models by using one single model (as recent and complete as possible) that assimilates all the meteorological observations available on a given time span. These reanalysis time-series are thus much more consistent for long term studies. In this paper, we estimate the atmospheric effects on nutations from three different reanalysis data sets independently and show that they are in much better agreement than the estimations obtained by Yseboodt *et al.* (2002), and even in very good agreement for some of the periodic terms. This result makes the estimated atmospheric contribution to nutations more trustworthy than previously.

The second purpose of our paper is to include in the nutation model of Mathews *et al.* (2002) our estimation of the atmospheric contributions and to re-estimate the Earth's interior parameters of the model. Whereas the atmospheric contribution to S_1 and to the semi-annual prograde nutation are not expected to affect the estimation of the Earth's interior parameters, the contribution to the annual retrograde term (ψ_1) can have an important effect. This is because ψ_1 has a frequency very close to that of the Free Core Nutation (FCN) normal mode. The amplitude of the ψ_1 term has thus an important role in the estimation of the complex frequency of the mode, and hence of the physical properties of the deep Earth. We perform an estimation of the Earth's interior parameters, taking into account the atmospheric contribution to ψ_1, and determine to what extend these parameters are affected and the implications for our knowledge of the deep Earth.

2 DATA USED

We use the data from three different GCM reanalyses: the reanalyses I and II of the NCEP (Kalnay *et al.* 1996; Kanamitsu *et al.* 2002), and the ERA-40 reanalysis from the ECMWF (Uppala *et al.* 2005). The NCEP I and II reanalyses are available on the intervals 1948–2010 and 1979–2007, respectively, and ERA-40 on the interval 1979–2002. The AAM time-series, with a 6 hrs sampling, were provided through the IERS Special Bureau for the Atmosphere (SBA) (Salstein *et al.* 1993; Zhou *et al.* 2006) and are available at http://www.aer.com/scienceResearch/diag/sb.html.

The AAM is classically divided into two parts. The first part, referred to as the mass or pressure term, accounts for the rotation of the atmosphere with the Earth; we denote it $\tilde{H}^p \equiv H_x^p + i H_y^p$ for the complex combination of the equatorial components. The second part, referred to as the motion or wind term, is the relative angular momentum of the atmosphere with respect to the rotating Earth; we denote it $\tilde{H}^w \equiv H_x^w + i H_y^w$. Both can be computed directly from the GCM reanalyses outputs (Barnes *et al.* 1983; Zhou *et al.* 2006). Two versions of the AAM pressure term are available, representing two types of oceanic response to the atmospheric pressure variations on its surface: the so-called Inverted Barometer (IB) ocean (see e.g. Munk & MacDonald 1960) and the rigid ocean. Since the IB hypothesis is not verified at diurnal time scales (e.g. Ponte *et al.* 1991), we use the rigid-ocean pressure term. Note also that Bizouard *et al.* (1998) found considerably better agreement with the nutation data when using the rigid-ocean pressure term.

Rather than the AAM itself, the quantities that are made available by the IERS SBA are the 'effective atmospheric angular momentum functions' (EAMF) denoted by $\tilde{\chi} \equiv \chi_x + i\chi_y$ and related to the AAM by (Barnes *et al.* 1983)

$$\tilde{\chi}^p = \frac{1}{\Omega_0(C-A)}(1+k_2')\frac{k_0}{k_0-k_2}\tilde{H}^p \tag{1a}$$

$$\tilde{\chi}^w = \frac{1}{\Omega_0(C-A)}\frac{k_0}{k_0-k_2}\tilde{H}^w, \tag{1b}$$

where Ω_0 is the Earth's mean angular rotation rate, A and C are respectively the equatorial and axial principal moments of inertia of the Earth (excluding the atmosphere), k_2 and k'_2 are respectively the tidal and load Love numbers, and $k_0 = 3(C-A)G/(\Omega_0^2 a^5)$, with G the gravitational constant and a the Earth's mean radius. The numerical values of the Love numbers used by the IERS SBA are such that $(1+k_2')k_0/(k_0-k_2) = 1.098$ and $k_0/(k_0-k_2) = 1.5913$ (Zhou *et al.* 2006). Note that the EAMF defined by eq. (1) are dimensionless quantities.

The EAMF time-series are computed in an Earth-fixed reference frame. They can be expressed in the celestial frame using the following transformation (Brzeziński 1994)

$$\tilde{\chi}'(t) = -\tilde{\chi}(t)\, e^{i[\Omega_0(t-t_0)+\Phi_0]}, \tag{2}$$

where the reference time t_0 is J2000, that is, 12 hr UT1 on 2000 January 1 and the minus sign comes from the definitions of polar motion and nutations (see Brzeziński & Capitaine 1993). The resulting $\tilde{\chi}'(t)$ is referred to as the 'celestial EAMF' (CEAMF). The numerical values of Ω_0 and Φ_0 are given in the IERS Convention 2003 and are: $\Omega_0 = (2\pi r)$ radians per solar day, where $r = 1.00273781191135448$ is the ratio of universal to sidereal time, and $\Phi_0 = 2\pi \times 0.7790572732640$ radians. Note that, prior to applying the transformation (2), we remove the mean from the EAMF time-series.

As our study focuses on nutations, we are interested in the retrograde quasi-diurnal variations in the EAMF which, by the transformation (2), are mapped into long period variations in the CEAMF. Seasonal variations in the EAMF, which are responsible for variations in the polar motion, are mapped into high frequency (quasi-diurnal) variations. Following Bizouard *et al.* (1998), we remove these high-frequency oscillations by applying a gaussian filter with a full width at half maximum of 0.025 yr. The CEAMF are also resampled with a time interval of 0.0125 yr.

3 ESTIMATION OF THE MAIN PERIODIC TERMS IN THE ATMOSPHERIC FORCING

The dominant atmospheric thermal tide has a period of one solar day in the terrestrial reference frame and is labelled S_1 because it is 'fixed to the Sun'. As the daily sunshine period varies over the year, the amplitude of the S_1 tide is not constant in time: it undergoes seasonal (mainly annual and semi-annual) modulations. When observed from the celestial frame, the S_1 tide gives rise to a prograde annual term (also called S_1), its annual modulation to a prograde semi-annual term (P_1) as well as a constant term corresponding to a constant offset of the pole, and the semi-annual modulation generates a prograde ter-annual term (π_1) and a retrograde annual one (ψ_1) (see Bizouard *et al.* 1998, appendix A). These are thus the frequencies of the nutations that are affected by atmospheric effects. As the mean amplitude of S_1 and its annual modulations are larger than the semi-annual modulations, the dominant terms in the celestial frame are the prograde annual and prograde semi-annual ones. We model the CEAMF as

Table 1. Multipliers of the fundamental arguments, periods and phases of the nutation terms. The reference epoch for the phase is J2000.

Term	Fundamental Arguments					Period	Phase
	l	l'	F	D	Ω	(solar days)	(°)
S_1	0	1	0	0	0	365.260	357.529
P_1	0	0	2	−2	2	182.621	−159.067
π_1	0	1	2	−2	2	121.749	198.462
ψ_1	0	−1	0	0	0	−365.26	−357.529

$$\tilde{\chi}'(t) = -i\sum_{j=1}^{4} a_j\, e^{i[\nu_j\,\Omega_0(t-t_0)+\varphi_j]} + c, \tag{3}$$

where ν_j takes the values $\{f_a, 2f_a, 3f_a, -f_a\}$, with $f_a = 1/366.26$. Note that the frequencies ν_j are non-dimensional as they are expressed in terms of multiples of Ω_0. They are numerically equal to the frequency given in cycles per sidereal day (cpsd). The phases $\{\varphi_j\}_{j=1}^4$ are chosen to be those of the corresponding gravitationally forced nutations. These can be computed from the phases of the so-called 'fundamental arguments' given in the IERS Convention 2003 and are listed in Table 1. With this convention for the phases, the real parts of the amplitudes a_j are in-phase (ip) with the gravitationally forced nutations and the imaginary parts are out-of-phase (op).

The complex amplitudes $\{a_j\}_{j=1}^4$ and the constant c are the unknown parameters that we estimate from the CEAMF time-series. As the model (3) is linear in these parameters, we estimate them using the classical least-squares (LSQ) method. As the EAMF time-series are provided without associated errors, we compute the error on our estimated parameters a posteriori from the residuals between the data and the fitted model, using the estimator (e.g. Aster *et al.* 2005)

$$\mathrm{Cov}(\mathbf{m}) = \frac{1}{n-p}\left(\sum_{i=1}^{n} r_i^2\right)(\mathbf{G}^T\cdot\mathbf{G})^{-1}, \tag{4}$$

where Cov(**m**) is the covariance matrix of the estimated parameters **m**, n and p are the number of data and model parameters, respectively, **G** is the normal matrix, and $\mathbf{r} = \mathbf{d} - \mathbf{Gm}$ is the residuals vector, with **d** the data vector.

We perform the LSQ estimation of the parameters on the three reanalyses data sets. As the amplitudes $\{a_j\}_{j=1}^4$ are expected to be variable in time (see Section 5.2), we perform the estimation on the common time span of the three data sets, namely 1979–2002.7. On this time span, we perform both an independent inversion of the data sets and a joint inversion (without any relative weighting of the data sets) with the three data sets together. Using the NCEP reanalysis data set, we also perform an estimation on the full time span (1979–2010) and on the time span used by Bizouard *et al.* (1998) (namely 1979–1997.3). The results are reported in Table 2, along with the values obtained previously by Bizouard *et al.* (1998). (Note that we multiplied their values by −1 to account for the different convention used by these authors for the nutation amplitudes.)

Table 2. Amplitudes of the main periodic terms in the celestial effective atmospheric angular momentum functions (CEAMF) time-series. For comparison, the results obtained by Bizouard *et al.* (1998) are also shown. The errors correspond to 1σ. Units: mas.

Periodic terms:			Pressure		Wind	
	Time span	Data set	ip	op	ip	op
+1 y (S_1)	1979–2010	NCEP reanalysis	0.57 ± 0.01	−0.91 ± 0.01	0.2 ± 0.1	12.3 ± 0.1
	1979–2002.7	NCEP reanalysis	0.57 ± 0.02	−0.94 ± 0.02	−0.8 ± 0.1	14.1 ± 0.1
		NCEP reanalysis II	0.68 ± 0.02	−1.18 ± 0.02	−1.7 ± 0.1	9.0 ± 0.1
		ERA40	1.55 ± 0.02	−0.89 ± 0.02	1.8 ± 0.2	11.1 ± 0.2
		Joint	0.93 ± 0.01	−1.00 ± 0.01	−0.3 ± 0.1	11.4 ± 0.1
	1979–1997.3	NCEP reanalysis	0.53 ± 0.02	−0.90 ± 0.02	−1.9 ± 0.1	14.6 ± 0.1
		Bizouard *et al.* (1998)	−0.23 ± 0.02	−1.16 ± 0.02	0.1 ± 0.1	14.2 ± 0.1
+1/2 y (P_1)	1979–2010	NCEP reanalysis	0.59 ± 0.01	−0.13 ± 0.01	2.9 ± 0.1	17.8 ± 0.1
	1979–2002.7	NCEP reanalysis	0.58 ± 0.02	−0.10 ± 0.02	2.7 ± 0.1	18.1 ± 0.1
		NCEP reanalysis II	0.60 ± 0.02	−0.09 ± 0.02	0.1 ± 0.1	15.3 ± 0.1
		ERA40	0.74 ± 0.02	−0.27 ± 0.02	3.6 ± 0.2	16.6 ± 0.2
		Joint	0.64 ± 0.01	−0.15 ± 0.01	2.2 ± 0.1	16.7 ± 0.1
	1979–1997.3	NCEP reanalysis	0.61 ± 0.02	−0.07 ± 0.02	2.8 ± 0.1	18.3 ± 0.1
		Bizouard *et al.* (1998)	0.12 ± 0.02	−0.21 ± 0.02	2.9 ± 0.1	18.5 ± 0.1
+1/3 y (π_1)	1979–2010	NCEP reanalysis	0.14 ± 0.01	−0.19 ± 0.01	0.5 ± 0.1	0.1 ± 0.1
	1979–2002.7	NCEP reanalysis	0.12 ± 0.02	−0.21 ± 0.02	0.2 ± 0.1	−0.1 ± 0.1
		NCEP reanalysis II	0.08 ± 0.02	−0.16 ± 0.02	0.4 ± 0.1	0.2 ± 0.1
		ERA40	0.11 ± 0.02	−0.14 ± 0.02	0.2 ± 0.2	0.2 ± 0.2
		Joint	0.10 ± 0.01	−0.17 ± 0.01	0.3 ± 0.1	0.1 ± 0.1
	1979–1997.3	NCEP reanalysis	0.12 ± 0.02	−0.19 ± 0.02	0.1 ± 0.1	−0.1 ± 0.1
		Bizouard *et al.* (1998)	−0.03 ± 0.02	−0.23 ± 0.02	0.4 ± 0.1	0.0 ± 0.1
−1 y (ψ_1)	1979–2010	NCEP reanalysis	−0.10 ± 0.01	0.00 ± 0.01	−1.1 ± 0.1	−1.6 ± 0.1
	1979–2002.7	NCEP reanalysis	−0.08 ± 0.02	0.01 ± 0.02	−0.9 ± 0.1	−1.4 ± 0.1
		NCEP reanalysis II	−0.11 ± 0.02	0.07 ± 0.02	−0.2 ± 0.1	−0.9 ± 0.1
		ERA40	−0.16 ± 0.02	0.08 ± 0.02	−0.9 ± 0.2	−0.8 ± 0.2
		Joint	−0.12 ± 0.01	0.05 ± 0.01	−0.7 ± 0.1	−1.0 ± 0.1
	1979–1997.3	NCEP reanalysis	−0.05 ± 0.02	0.02 ± 0.02	−0.9 ± 0.1	−1.1 ± 0.1
		Bizouard *et al.* (1998)	−0.06 ± 0.02	0.06 ± 0.02	−1.0 ± 0.1	−1.1 ± 0.1
Constant term:						
			Real	Imaginary	Real	Imaginary
	1979–2010	NCEP reanalysis	0.63 ± 0.01	0.66 ± 0.01	−16.0 ± 0.1	3.1 ± 0.1
	1979–2002.7	NCEP reanalysis	0.62 ± 0.02	0.69 ± 0.02	−16.1 ± 0.1	3.2 ± 0.1
		NCEP reanalysis II	0.52 ± 0.02	0.62 ± 0.02	−14.4 ± 0.1	−0.6 ± 0.1
		ERA40	0.65 ± 0.02	0.86 ± 0.02	−16.3 ± 0.2	2.0 ± 0.2
		Joint	0.59 ± 0.01	0.72 ± 0.01	−15.6 ± 0.1	1.5 ± 0.1
	1979–1997.3	NCEP reanalysis	0.61 ± 0.02	0.71 ± 0.02	−16.3 ± 0.1	3.3 ± 0.1
		Bizouard *et al.* (1998)	0.64 ± 0.04	−0.76 ± 0.04	−16.1 ± 0.3	5.0 ± 0.3

As expected, S_1 and P_1 are the dominant terms. For the NCEP reanalysis on the time span 1979–1997.3, our results are in good agreement with those obtained by Bizouard *et al.* (1998) for the wind term but larger discrepancies are observed for the pressure term. These differences are probably due to a reprocessing of the atmospheric data posterior to their study.

We now compare the estimates obtained independently from the three different data sets on the time span 1979–2002.7. For the pressure contribution, the π_1 and ψ_1 terms are in agreement at the 3σ level for both the ip and op components. For the wind contribution, the π_1 term op and ip and the ψ_1 op are in agreement at the 3σ level. The other terms are not in agreement in the sense that their 3σ confidence intervals do not overlap. However, this comparison in terms of the overlap of the confidence intervals depends directly on the estimated errors which themselves depend on the errors on the CEAMF data. The latter being unknown, the values obtained for the estimated errors (from eq. 4) are quite uncertain. Moreover, the process of filtering the high frequencies also implies a reduction of the noise on the data sets and the estimated errors are then likely to be underestimated. A more detailed comparison of the estimations obtained from the different atmospheric models is deferred to Section 5.

Finally, for each data set, we compute the root mean square (RMS) of the residuals. For the pressure term, we obtain a RMS of 0.6 mas for both the X and Y components and for all the data sets. For the wind term, for both the X and Y components, the RMS is 4 mas for the NCEP reanalysis data set, 3 mas for NCEP reanalysis II and 8 mas for ERA40. These values express how well the data sets can be fitted by the model (3) and are a measure of the noise on each data set. They indicate that the noise level is larger on the wind term than on the pressure term, which is consistent with the larger errors obtained for the amplitudes of the periodic terms. The larger noise level on the ERA40 wind term suggests that the quality of this data set may be a bit lower than that of the two NCEP reanalyses.

4 NUTATION TRANSFER FUNCTIONS

We consider the Earth as comprised of three different layers, an anelastic mantle, an inviscid fluid outer core and an elastic inner core, which are coupled by dissipative forces at the boundaries, such as electromagnetic or viscous forces. We derive the nutation response of such an Earth's model to changes in the AAM. We use the formalism of the Liouville equations (Sasao *et al.* 1980; Sasao & Wahr 1981; Mathews *et al.* 1991a, 2002). The couplings at the core-mantle and the inner core boundaries are included as in Mathews *et al.* (2002) by means of two complex coupling constants K_{CMB} and K_{ICB} of which the norm characterizes the strength of the coupling and the imaginary part the amount of dissipation. The deformation of the Earth and cores enter the model through the 12 'compliances' $\kappa, \gamma, \theta, \xi, \beta, \alpha, \zeta, \delta, \nu, \chi, \eta$ and λ defined by (Sasao *et al.* 1980; Sasao & Wahr 1981; Mathews *et al.* 1991a)

$$\tilde{c}_3 \equiv c_{31} + i c_{32} = A\left[\kappa \tilde{m} + \xi \tilde{m}_f + \zeta \tilde{m}_s + \chi \tilde{\phi}_L\right] \tag{5a}$$

$$\tilde{c}^f_3 \equiv c^f_{31} + i c^f_{32} = A_f\left[\gamma \tilde{m} + \beta \tilde{m}_f + \delta \tilde{m}_s + \eta \tilde{\phi}_L\right] \tag{5b}$$

$$\tilde{c}^s_3 \equiv c^s_{31} + i c^s_{32} = A_s\left[\theta \tilde{m} + \alpha \tilde{m}_f + \nu \tilde{m}_s + \lambda \tilde{\phi}_L\right], \tag{5c}$$

where $\mathbf{c}$, $\mathbf{c}^f$ and $\mathbf{c}^s$ are increments to the inertia tensor of the Earth, fluid core and inner core, respectively, $\tilde{m}$, $\tilde{m}_f$ and $\tilde{m}_s$ are incremental centrifugal potentials of the Earth, fluid core and inner core, respectively, and $\tilde{\phi}_L$ is the loading potential of the atmosphere. The numerical values of the compliances, computed from the PREM Earth's model (Dziewonski & Anderson 1981), are reported in Table 3. For the compliances κ, γ, θ, ξ, β, α, ζ, δ, ν, the values for an elastic mantle were computed by Mathews *et al.* (1991b) and the small contributions due to mantle anelasticity were computed by Koot *et al.* (2010). We computed the compliances χ, η and λ with the procedure explained in Sasao *et al.* (1980) and Sasao & Wahr (1981). The anelastic contributions are computed in the way described by Mathews *et al.* (2002).

The AAM is decomposed into a sum of periodic terms as

$$\tilde{H}^{(p,w)}(t) = \sum_j \hat{H}^{(p,w)}(\sigma_j)\, e^{i\sigma_j \Omega_0 t}, \tag{6}$$

where $\Omega_0 \sigma_j$ is the angular frequency in the terrestrial reference frame. As the equations are linear in the dynamical variables, they can be solved term by term for a given frequency of the forcing.

Adding the AAM to the expression of the total angular momentum of the Earth in Mathews *et al.* (1991a), the nutation $\hat{\eta}(\sigma)$ due to the atmosphere is given by

$$\hat{\eta}(\sigma) = \mathrm{TF}^p(\sigma)\, \frac{\hat{H}^p(\sigma)}{\Omega_0 (C - A)} + \mathrm{TF}^w(\sigma)\, \frac{\hat{H}^w(\sigma)}{\Omega_0 (C - A)}, \tag{7}$$

where $\mathrm{TF}^p(\sigma)$ and $\mathrm{TF}^w(\sigma)$ are called 'transfer functions' and describes the Earth's nutation response to the atmospheric (or oceanic) forcing. They are given by

$$\mathrm{TF}^p(\sigma) = \frac{e}{\tau} \frac{\left[\mathbf{M}^{-1}(\sigma) \cdot \mathbf{y}_p(\sigma)\right]_1}{1 + \sigma} \tag{8a}$$

$$\mathrm{TF}^w(\sigma) = -e \frac{\left[\mathbf{M}^{-1}(\sigma) \cdot \mathbf{y}_w(\sigma)\right]_1}{1 + \sigma}, \tag{8b}$$

where $\tau = \Omega_0^2 a^5 / (3GA)$, e is the 'dynamical ellipticity' of the Earth, defined as $(C - A)/A$, the 4×4 matrix $\mathbf{M}$ depends on Earth's interior parameters (the compliances, the equatorial principal moments of inertia of the Earth, fluid core and inner core, A, A_f and A_s, respectively, and the dynamical ellipticities of these regions, namely e, e_f and e_s) and on the frequency of the forcing. The exact expression of $\mathbf{M}$ can be found in Mathews *et al.* (1991a, 2002). The four-components vectors $\mathbf{y}_p$ and $\mathbf{y}_w$ are given by: $\mathbf{y}_p(\sigma) = [(1 + \sigma)(\tau - \chi), -\sigma\eta, -\sigma\lambda, 0]^T$ and $\mathbf{y}_w(\sigma) = [-(1 + \sigma), 0, 0, 0]^T$.

Table 3. Numerical values of Earth's interior parameters used to compute the transfer functions.

Symbol	Value	Reference
Principal moments of inertia:		
A	8.0115×10^{37} kg m^2	Mathews *et al.* (1991b)
A_f	9.0583×10^{36} kg m^2	Mathews *et al.* (1991b)
A_s	5.8531×10^{34} kg m^2	Mathews *et al.* (1991b)
Dynamical ellipticities:		
e	3.2845482×10^{-3}	Koot *et al.* (2010)
$e_f + \mathrm{Re}\,(K_{\mathrm{CMB}})$	2.6753×10^{-3}	Koot *et al.* (2010)
e_s	2.422×10^{-3}	Mathews *et al.* (1991b)
Coupling constants:		
$\mathrm{Im}\,(K_{\mathrm{CMB}})$	-1.78×10^{-5}	Koot *et al.* (2010)
K_{ICB}	$(1.01\text{-}i\ 1.09) \times 10^{-3}$	Koot *et al.* (2010)
Elastic compliances:		
κ^{el}	1.039×10^{-3}	Mathews *et al.* (1991b)
γ^{el}	1.965×10^{-3}	Mathews *et al.* (1991b)
θ^{el}	6.794×10^{-6}	Mathews *et al.* (1991b)
ξ^{el}	2.222×10^{-4}	Mathews *et al.* (1991b)
β^{el}	6.160×10^{-4}	Mathews *et al.* (1991b)
α^{el}	-7.536×10^{-5}	Mathews *et al.* (1991b)
ζ^{el}	4.964×10^{-9}	Mathews *et al.* (1991b)
δ^{el}	-4.869×10^{-7}	Mathews *et al.* (1991b)
ν^{el}	7.984×10^{-5}	Mathews *et al.* (1991b)
χ^{el}	1.063×10^{-3}	This paper
η^{el}	1.941×10^{-3}	This paper
λ^{el}	-8.554×10^{-7}	This paper
Anelastic contributions to the compliances:		
$\Delta\kappa^{AE}$	$(13 + i\,5) \times 10^{-6}$	Koot *et al.* (2010)
$\Delta\gamma^{AE}$	$(22 + i\,9) \times 10^{-6}$	Koot *et al.* (2010)
$\Delta\theta^{AE}$	$(3.7 + i\,1.5) \times 10^{-8}$	Koot *et al.* (2010)
$\Delta\xi^{AE}$	$(2.5 + i\,1.0) \times 10^{-6}$	Koot *et al.* (2010)
$\Delta\beta^{AE}$	$(7.4 + i\,3.0) \times 10^{-6}$	Koot *et al.* (2010)
$\Delta\alpha^{AE}$	$(1 + i\,0.4) \times 10^{-8}$	Koot *et al.* (2010)
$\Delta\zeta^{AE}$	$(25.1 + i\,1.2) \times 10^{-11}$	Koot *et al.* (2010)
$\Delta\delta^{AE}$	0	Koot *et al.* (2010)
$\Delta\nu^{AE}$	0	Koot *et al.* (2010)
$\Delta\chi^{AE}$	$(10 + i\,4) \times 10^{-6}$	This paper
$\Delta\eta^{AE}$	$(11 + i\,5) \times 10^{-6}$	This paper
$\Delta\lambda^{AE}$	$(2.56 + i\,1.04) \times 10^{-8}$	This paper
Parameter τ:		
τ	3.480×10^{-3}	This paper
Parameters α_i (defined by Mathews *et al.* (1991a)):		
α_1	0.9463	Mathews *et al.* (1991b)
α_2	0.8294	Mathews *et al.* (1991b)
α_3	0.0537	Mathews *et al.* (1991b)

Note that the amplitudes of the periodic terms $\hat{H}^p(\sigma)$ and $\hat{H}^w(\sigma)$ that enter eq. (7) refer to the terrestrial reference frame while the amplitudes that we have estimated in Section 3 refer to the celestial frame. These amplitudes in the terrestrial and celestial reference frames are opposed in sign (see eq. 2). The amplitudes listed in Table 2 thus have to be multiplied by -1 to use the transfer functions defined by eq. (8).

Eqs (7) and (8) are generalizations for a three-layers Earth of the expression given by Sasao & Wahr (1981). As was done by these authors, the transfer functions can also be written in the form of

Table 4. Numerical values of the rotational normal modes frequencies and strengths. The frequencies are given in cycles per sidereal day (cpsd) in the terrestrial frame. Periods are in solar days and refer to the terrestrial frame for the CW and ICW modes and to the celestial frame for the FCN and FICN modes.

	σ (cpsd)				N^p		N^w	
Mode	Real	Imag	Period (days)	Q	Real	Imag	Real	Imag
CW	0.00251794	−0.00000564	396.06	223	0.002561471	−0.000004259	0.003702480	−0.000000004
FCN	−1.00232436	0.00002539	−429.05	19736	0.000235658	0.000000612	0.000000973	−0.000000009
FICN	−0.99892016	0.00109455	923.53	456	0.000000375	0.000000017	0.000000001	—
ICW	0.00041323	0.00000045	2413.34	−458	0.000000038	—	0.000000055	—

resonance formulas, namely

$$\mathrm{TF}^{p,w}(\sigma) = \sum_{i=1}^{4} \frac{N_i^{p,w}}{\sigma - \sigma_i}, \tag{9}$$

where σ_i are the frequencies of the four rotational normal modes of a three layers Earth: the Chandler wobble (CW), the FCN, the FICN and the Inner Core Wobble (ICW). The coefficients $N_i^{p,w}$ characterize the strengths of the associated resonances. Using the numerical values of the Earth's interior parameters listed in Table 3, we have computed the numerical values of the resonance frequencies σ_i and associated strength $N_i^{p,w}$. The values are listed in Table 4.

Note that eq. (7) depends directly on the AAM themselves rather than on the EAMF given by the analysis centres. The AAM is obtained from the EAMF by eq. (1), using the numerical values given under this equation.

5 ATMOSPHERIC CONTRIBUTIONS TO NUTATION

5.1 Mean contributions

As expressed by eq. (9), the transfer functions show resonances associated with the presence of the rotational normal modes. Due to these resonances, the effect of the AAM will be amplified or diminished, depending on the frequency. In the nutation frequency band, the main resonance is the FCN, a free mode that corresponds to a rigid rotation of the outer core around an axis slightly different than that of the mantle. As was also shown by Dehant *et al.* (2005), the resonance to the FICN mode is much smaller. The values of N^p and N^w in Table 4 show that the FCN mode is much more excited (about 200 times) by the pressure term than by the wind term. This is because the pressure term is associated with a loading deformation of the CMB, which can excite a differential rotation of the fluid core relative to the mantle.

Using the estimated amplitudes of the periodic terms in the CEAMF listed in Table 2 and the values of the transfer functions, we compute the atmospheric contributions to nutation for the three data sets as well as for the joint estimation. The results are listed in Table 5 and illustrated on Fig. 1.

Whereas, for all the frequencies, the amplitudes in the atmospheric forcing are larger for the wind term than for the pressure term (see Table 2), the results in Table 5 show that the main contribution to the nutation comes, by far, from the pressure term, due to the resonance effect explained above. Moreover, the ψ_1 term, for which the atmospheric forcing was much smaller than for the S_1 term, has a nutation amplitude of the same order because it is largely amplified due to its proximity to the FCN resonance.

As can be seen from Fig. 1 and Table 5, the results obtained from the three data sets are in good agreement (at the 3σ level) for the ψ_1 and π_1 terms, both for the ip and op components. For S_1 and P_1, the 3σ confidence intervals do not overlap but, as explained before, the estimated errors are likely to be underestimated. To quantify the importance of the discrepancies between the atmospheric models for S_1 and P_1, we can compare them with the precision of the corresponding nutation terms obtained from very long baseline interferometry (VLBI) measurements. The VLBI nutation measurements errors are listed in Table 5 and shown on Fig. 1. For S_1, the largest discrepancy between the data sets is 33 μas ip and 9 μas op. With a VLBI precision of 7 μas (Herring *et al.* 2002), the estimations can be considered in good agreement for the op component, the ip component shows a larger but still reasonable discrepancy. For P_1, the largest discrepancy is of the order of 6 μas on the ip-component and 7 μas on the op-component. The VLBI precision for this term is 5 μas (Herring *et al.* 2002). The agreement between the data sets is thus clearly sufficient for nutation studies.

This overall good agreement between the atmospheric models is rather new as the study of Yseboodt *et al.* (2002) shows strong inconsistencies between the results obtained from the different data sets they used. The reason for this is that our study relies only on reanalyses data sets, which are much more reliable for long term studies. We also use longer data sets, which makes the estimation more robust. Note that, due to the time-variability of the atmospheric contributions to nutation (see Section 5.2), a part of the discrepancies observed in Yseboodt *et al.* (2002) also comes from comparing estimations performed on different time spans.

Note finally that our results reported in Table 5 for the NCEP reanalysis on the period 1979–1997.3 are different from those obtained by Bizouard *et al.* (1998). This is partly because of the differences in the CEAMF amplitudes described in Section 3 and partly because of the different transfer functions that we use.

5.2 Time variability

Due to the time variability of the atmospheric thermal tides, the atmospheric contributions to nutation are not stable in time. The complex amplitudes that we have estimated in the previous section are thus average values on the time span used. In this section, we want to estimate the time variability of this contribution. We do the same analysis as presented in the previous sections but using a 3-yr sliding-window. The results are presented on Fig. 2.

The results shown on Fig. 2 confirm the agreement between the data sets for the ψ_1 and π_1 terms. For these terms, the temporal variations are larger than the differences from one data set to the other, which suggests that these temporal variations reflect real physical processes and are reliable. For the S_1 and P_1 terms, the temporal variations are comparable in magnitude to the discrepancies between the data sets, which means that these variations are not very well constrained by the data sets we use.

Table 5. Atmospheric contributions to nutations. For comparison, the results obtained by Bizouard *et al.* (1998) are also shown. The errors correspond to 1σ. For each term, the precision of the VLBI observations (from Herring *et al.* 2002) is also shown. Units: μas.

			Pressure		Wind		Total	
	Time span	Data set	ip	op	ip	op	ip	op
+1 y (S_1)	1979–2010	NCEP reanalysis	−23.0 ± 0.5	36.1 ± 0.5	0.4 ± 0.2	27.2 ± 0.2	−22.7 ± 0.6	63.3 ± 0.6
	1979–2002.7	NCEP reanalysis	−23.1 ± 0.6	37.3 ± 0.6	−1.8 ± 0.2	31.1 ± 0.2	−24.9 ± 0.6	68.4 ± 0.6
		NCEP reanalysis II	−27.5 ± 0.6	47.2 ± 0.6	−3.9 ± 0.2	19.9 ± 0.2	−31.4 ± 0.6	67.1 ± 0.6
		ERA40	−62.2 ± 0.5	35.1 ± 0.5	4.0 ± 0.4	24.5 ± 0.4	−58.2 ± 0.7	59.6 ± 0.7
		Joint	−37.6 ± 0.4	39.9 ± 0.4	−0.6 ± 0.2	25.2 ± 0.2	−38.2 ± 0.4	65.1 ± 0.4
	1979–1997.3	NCEP reanalysis	−21.2 ± 0.7	35.7 ± 0.7	−4.3 ± 0.2	32.3 ± 0.2	−25.5 ± 0.7	68.0 ± 0.7
		Bizouard *et al.* (1998)	9.0 ± 1.0	46.8 ± 0.7	0.2 ± 0.3	29.2 ± 0.3	9.3 ± 0.7	76.0 ± 1.0
	1σ error on the VLBI data:						7	7
−1 y (ψ_1)	1979–2010	NCEP reanalysis	−50.3 ± 6.8	4.6 ± 6.8	−4.4 ± 0.4	−6.1 ± 0.4	−54.7 ± 6.9	−1.5 ± 6.9
	1979–2002.7	NCEP reanalysis	−40.0 ± 7.8	9.0 ± 7.8	−3.5 ± 0.4	−5.1 ± 0.4	−43.4 ± 7.8	4.0 ± 7.8
		NCEP reanalysis II	−58.5 ± 7.8	42.1 ± 7.8	−1.0 ± 0.3	−3.4 ± 0.3	−59.6 ± 7.8	38.6 ± 7.8
		ERA40	−84.4 ± 7.2	46.8 ± 7.2	−3.6 ± 0.7	−3.1 ± 0.7	−88.0 ± 7.2	43.7 ± 7.2
		Joint	−61.0 ± 5.0	32.6 ± 5.0	−2.7 ± 0.3	−3.9 ± 0.3	−63.7 ± 5.0	28.8 ± 5.0
	1979–1997.3	NCEP reanalysis	−27.1 ± 9.1	12.2 ± 9.1	−3.4 ± 0.4	−4.0 ± 0.4	−30.5 ± 9.1	8.2 ± 9.1
		Bizouard *et al.* (1998)	−37.7 ± 11.5	36.5 ± 11.5	−6.0 ± 0.7	−6.2 ± 0.7	−43.7 ± 12.3	30.3 ± 12.3
	1σ error on the VLBI data:						11	13
+1/2 y (P_1)	1979–2010	NCEP reanalysis	−14.9 ± 0.3	3.2 ± 0.3	6.6 ± 0.2	40.1 ± 0.2	−8.2 ± 0.4	43.3 ± 0.4
	1979–2002.7	NCEP reanalysis	−14.7 ± 0.4	2.5 ± 0.4	6.1 ± 0.2	40.9 ± 0.2	−8.6 ± 0.4	43.4 ± 0.4
		NCEP reanalysis II	−15.2 ± 0.4	2.2 ± 0.4	0.3 ± 0.2	34.6 ± 0.2	−14.9 ± 0.4	36.8 ± 0.4
		ERA40	−18.7 ± 0.3	6.6 ± 0.3	8.1 ± 0.4	37.5 ± 0.4	−10.6 ± 0.5	44.2 ± 0.5
		Joint	−16.2 ± 0.2	3.8 ± 0.2	4.9 ± 0.2	37.7 ± 0.2	−11.3 ± 0.3	41.5 ± 0.3
	1979–1997.3	NCEP reanalysis	−15.3 ± 0.4	1.6 ± 0.4	6.3 ± 0.2	41.4 ± 0.2	−9.1 ± 0.5	43.0 ± 0.5
		Bizouard *et al.* (1998)	−3.0 ± 0.5	5.2 ± 0.5	6.0 ± 0.3	39.8 ± 0.3	3.1 ± 0.7	45.0 ± 0.7
	1σ error on the VLBI data:						5	5
+1/3 y (π_1)	1979–2010	NCEP reanalysis	−2.5 ± 0.2	3.3 ± 0.2	1.2 ± 0.2	0.3 ± 0.2	−1.3 ± 0.3	3.6 ± 0.3
	1979–2002.7	NCEP reanalysis	−2.1 ± 0.3	3.7 ± 0.3	0.4 ± 0.2	−0.2 ± 0.2	−1.7 ± 0.3	3.5 ± 0.3
		NCEP reanalysis II	−1.4 ± 0.3	2.9 ± 0.3	0.8 ± 0.2	0.4 ± 0.2	−0.6 ± 0.3	3.3 ± 0.3
		ERA40	−1.9 ± 0.2	2.5 ± 0.2	0.6 ± 0.4	0.5 ± 0.4	−1.4 ± 0.5	3.0 ± 0.5
		Joint	−1.8 ± 0.2	3.1 ± 0.2	0.6 ± 0.2	0.2 ± 0.2	−1.2 ± 0.2	3.3 ± 0.2
	1979–1997.3	NCEP reanalysis	−2.2 ± 0.3	3.4 ± 0.3	0.2 ± 0.2	−0.2 ± 0.2	−2.1 ± 0.4	3.3 ± 0.4
		Bizouard *et al.* (1998)	0.5 ± 0.3	4.3 ± 0.3	1.0 ± 0.3	0.0 ± 0.3	1.5 ± 0.6	4.2 ± 0.6
	1σ error on the VLBI data:						5	5

6 IMPLICATIONS FOR THE ESTIMATION OF DEEP EARTH'S PROPERTIES FROM NUTATION DATA

The atmospheric contribution that is the most important to study Earth's interior properties from nutation data is that to ψ_1. This contribution is also the one which exhibits the largest time variability (see Fig. 2). This is due to the proximity of this term to the FCN resonance, which amplifies small variations in the CEAMF. The good agreement between the data sets found in our study for this term allows us to determine with a good reliability the influence of the atmospheric contribution to ψ_1 on the determination of deep Earth's physical properties from nutation observations.

Taking into account the atmospheric contribution to ψ_1, we re-estimate the Earth's interior parameters entering Mathews *et al.* (2002) nutation model. We perform the inversion of nutation observations exactly as in Koot *et al.* (2010), except that, prior to the inversion, we remove from the nutation observations the atmospheric contribution to ψ_1. We use the nutation data provided by the Goddard Space Flight Center (GSFC) on the time period 1979–2010 and we use the atmospheric contribution to ψ_1 obtained on the same time period from the NCEP reanalysis time-series. We perform two inversions: one with the mean atmospheric contribution to ψ_1, namely −54.7 μas ip and −1.5 μas op, and another with the time-variable contribution computed in Section 5.2.

Amongst the parameters that are estimated, only the dynamical ellipticity of the fluid core e_f and the coupling constants K_{CMB} and K_{ICB} are affected by the atmospheric contribution. This is because these parameters determine the complex frequency of the FCN mode. Their values are reported in Table 6. The values of the other estimated parameters can be found in Koot *et al.* (2010). Table 6 also shows the values of the frequencies and quality factors of the FCN and FICN modes, computed from the values of e_f, K_{CMB} and K_{ICB}. For comparison, the results obtained in Koot *et al.* (2010) without atmospheric contribution to ψ_1 are also listed in Table 6.

Table 6 shows that the atmospheric contribution to ψ_1 indeed affects the values of the coupling constants K_{CMB} and K_{ICB} but the effect is relatively small. The time-variable contribution, because of the larger values involved, has a larger effect than the mean contribution, but still, the effect is small.

The coupling constants K_{CMB} and K_{ICB} reflect directly the physical properties of the CMB and ICB. We thus want to determine how much the estimation of these physical properties is affected by the atmospheric contribution. To infer these properties from the coupling constants, we follow the study of Koot *et al.* (2010) and we refer the reader to that paper for more details.

The value of $\mathrm{Im}\,(K_{\mathrm{CMB}})$ can be explained by an electromagnetic (EM) coupling between the outer core and the base of the mantle (Buffett *et al.* 2002). The value of the electrical conductivities of the fluid core and lowermost mantle are fixed to that of iron under core

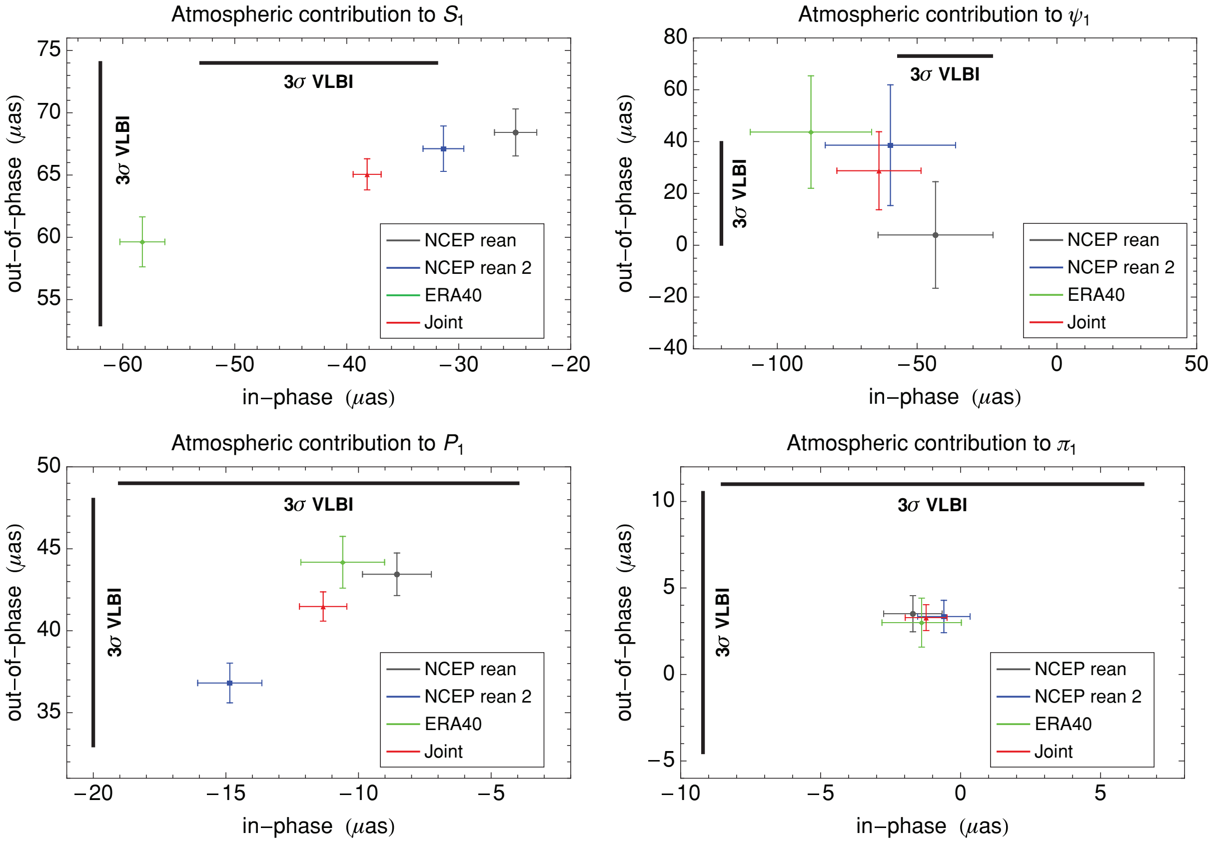

Figure 1. Total atmospheric contributions to the prograde annual (S_1), retrograde annual (ψ_1), prograde semi-annual (P_1) and prograde ter-annual (π_1) nutation terms obtained from the three data sets and the joint inversion, on the period 1979–2002.7. The error bars are the 3σ errors, corresponding to 99.7 per cent confidence intervals. For comparison, the thick black lines show the 3σ errors of the VLBI nutation measurements.

condition, namely 5×10^5 S m^{-1} (Stacey & Anderson 2001). The RMS strength of the dipolar radial magnetic field at the CMB is fixed to what can be inferred from magnetic field surface observations, namely $\bar{B}_r^D = 0.209$ mT (based on CHAOS-2s from Olsen *et al.* 2009, at year 2000). Then the value of Im(K_{CMB}) can be used to infer the RMS strength of the total radial field $\bar{B}_r$ at the CMB. The values are listed in Table 7. These results show that the value $\bar{B}_r =$ 0.668 mT, obtained without taking atmospheric effects into account, becomes 0.675 mT for the mean atmospheric contribution to ψ_1 and 0.687 mT for the time-variable atmospheric contribution.

Surface magnetic field observations suggest that $\bar{B}_r = 0.35$ mT at the CMB (Olsen *et al.* 2009). The value obtained from nutation observations without taking into account atmospheric effects, namely 0.668 mT, is almost twice as large. Taking into account the atmospheric contribution to ψ_1 does not change significantly this value. Clearly, it does not help reducing the discrepancy between the nutation inferred magnetic field and the surface magnetic field observations.

The value of K_{ICB} cannot be explained by a purely EM coupling and an additional coupling mechanism, such as the friction of the viscous core fluid on the ICB, is necessary (Koot *et al.* 2010). The electrical conductivities of the outer and inner cores are fixed to 5×10^5 S m^{-1}. The other physical quantities affecting the coupling are the RMS strength of the radial magnetic field and the kinematic viscosity of the outer core close to the ICB (see Mathews & Guo 2005). These can be inferred from K_{ICB} although the solution is not unique (see Koot *et al.* 2010). Ranges of values for which a solution exists can be determined and are listed in Table 7.

The strength of the magnetic field at the ICB can be compared to the values suggested by geodynamo models, namely around 2-3 mT (Christensen & Aubert 2006). The fluid core viscosity at the ICB can be estimated from laboratory measurements (Rutter *et al.* 2002) and 'ab initio' computation (Alfè *et al.* 2000), both suggesting values of the order of 10^{-6} m^2 s^{-1}. Without atmospheric contribution to ψ_1, the magnetic field inferred from nutation is in the range 6–6.7 mT, which is larger than suggested by geodynamo models and the outer core viscosity is around 10 m^2 s^{-1}, several orders of magnitude larger than estimations from laboratory measurements and 'ab initio' computations. Results in Table 7 show that taking into account the atmospheric contribution to ψ_1 reduces both the magnetic field and the viscosity of the fluid outer core at the ICB but the changes are too small to affect significantly the results.

7 DISCUSSION AND CONCLUSION

The effect of the climate system on the nutation is, at present, one of the important missing pieces of the non-rigid Earth nutation theory puzzle. Estimating the atmospheric part of it is the easiest of them all, but it is still challenging, as the diurnal cycle is still not well modelled in the atmospheric GCM, and because the atmosphere dynamics that is efficient for causing nutation (the degree 2 order 1 component in spherical harmonics) is orthogonal to the main diurnal dynamics of the atmosphere (which is of degree 1 order 1). The good agreement obtained here is very encouraging, but can be interpreted in two different ways. If we are optimistic, we

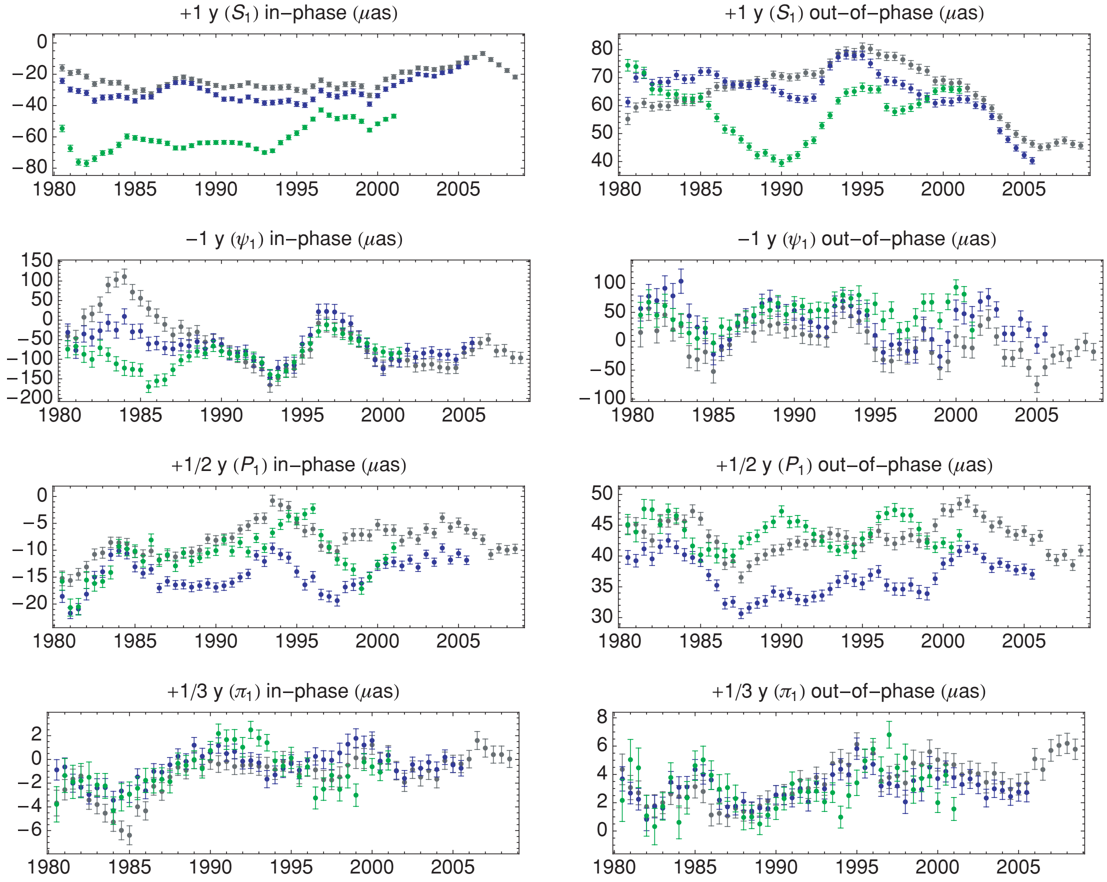

Figure 2. Time variability of the atmospheric contributions to nutations for the NCEP reanalysis (grey), NCEP reanalysis II (blue) and ERA40 (green) atmospheric models. The error bars are the 1σ errors.

Table 6. Numerical values of the coupling parameters e_f + Re(K_{CMB}), Im(K_{CMB}), Re(K_{ICB}) and Im(K_{ICB}), obtained from an inversion of nutations observations, taking into account the atmospheric contribution to ψ_1 computed from the NCEP reanalysis data set. The results are presented both for the mean contribution and the time-variable one. The corresponding periods and Q of the FCN and FICN modes are also given. The errors correspond to 1σ.

Coupling Parameters				FCN		FICN	
e_f + Re(K_{CMB}) (10^{-3})	Im(K_{CMB}) (10^{-5})	Re(K_{ICB}) (10^{-3})	Im(K_{ICB}) (10^{-3})	Period (days)	Q	Period (days)	Q
No atmospheric contribution:							
2.6751 ± 0.0001	−1.80 ± 0.01	0.99 ± 0.01	−1.06 ± 0.02	−429.09 ± 0.02	19641 ± 90	904 ± 10	467 ± 10
Mean atmospheric contribution from NCEP reanalysis ($-54.7 - i\,1.5$ µas):							
2.6729 ± 0.0001	−1.83 ± 0.01	0.98 ± 0.01	−0.99 ± 0.02	−429.55 ± 0.02	19416 ± 90	897 ± 10	502 ± 10
Time-variable atmospheric contribution from NCEP reanalysis:							
2.6715 ± 0.0001	−1.89 ± 0.01	0.96 ± 0.01	−0.95 ± 0.02	−429.82 ± 0.02	19042 ± 90	883 ± 10	526 ± 10

can think that, as different sources agree on this effect, it probably means that the result is robust, and that we present here a robust estimates of the main atmospheric effect on the nutation. If we are pessimistic, we can think that the diurnal cycle in the atmosphere is so under-determined that only the lowest level of the GCM (namely the basic physical equations of the model and not the assimilated data), which is probably common to all the models, plays a role in the results obtained here, and the good agreement does not mean much. However, this pessimistic view is not consistent with the results of Yseboodt *et al.* (2002). Consequently, it seems reasonable that the good agreement obtained here indicates a real robustness of the evaluation.

Our estimation of the atmospheric contribution to S_1 on the period 1979–2010, $(-22.7 + i63.3) \pm 0.6$ µas, can be compared to the residual between the nutation observations and models for that wave, namely $(0 + i\,107) \pm 4$ µas (Koot *et al.* 2010). The disagreement of these two estimations confirms that the direct atmospheric effects are not the only missing contribution to S_1 in the nutation model. As shown by de Viron *et al.* (2004) and Brzeziński *et al.* (2004), the non-tidal ocean contribution is expected to be at least as important. The hydrology may also play a role, although it should not be very large at the diurnal timescale. Note that any other 'Sun-synchronized' effect, such as the diurnal solar heating of the VLBI antennas, can also contribute to S_1 (Herring *et al.* 1991). On the other hand, the

Table 7. RMS strength of the radial magnetic field at the CMB and ICB and outer core kinematic viscosity at the ICB, inferred from the coupling constants given in Table 6.

$\bar{B}_r$ at the CMB (mT)	$\bar{B}_r$ at the ICB (mT)		Viscosity at the ICB ($m^2\,s^{-1}$)	
	Minimum	Maximum	Minimum	Maximum
No atmospheric contribution:				
0.668 ± 0.002	6.0	6.7	9	28
Mean atmospheric contribution from NCEP reanalysis ($-54.7 - i1.5$ μas):				
0.675 ± 0.002	5.8	6.6	7	24
Time-variable atmospheric contribution from NCEP reanalysis:				
0.687 ± 0.002	5.6	6.4	6	21

estimation of the atmospheric contribution to S_1 still needs to be improved as the agreement between the atmospheric models, in particular for the time variations, is not perfect. Enhanced high frequency atmospheric GCMs, maybe with higher time sampling of the atmosphere, and in particular of the pressure distribution, would help improving the estimation of the atmospheric contribution to S_1.

Whereas the largest atmospheric contribution to nutation is on S_1, from the point of view of internal geophysics, the most important contribution is on the ψ_1 term. Indeed, we can cope with a not so precise S_1 nutation effect, as it does not affect much our knowledge of the Earth's interior and it can be estimated from the residuals between the nutation observations and model. Contrarily, the geophysical fluids contribution to ψ_1 cannot be inferred from nutation observations because it cannot be separated from the Earth's interior parameters. This implies that any missing effect in the geophysical fluids contribution is absorbed by the Earth's interior parameters. The precision of these parameters depends thus directly on the precision of the geophysical fluids contribution to ψ_1. An important result of our paper is that the atmospheric contribution to ψ_1 is very consistent through the atmospheric GCM reanalyses. Both the mean contribution over a given time span and the temporal variations, which are very large, are in good agreement from one atmospheric model to the other. This estimation thus seems robust and allows us to determine reliably the effect of this contribution on nutation models. In particular, we have shown that the atmospheric contribution to ψ_1 does not affect significantly the estimation of Earth's interior properties from nutation observations.

The atmospheric contribution to ψ_1, which was not taken into account in nutation models because it could not be estimated reliably, is shown here to be small enough to be safely neglected. In particular, it is too small to be responsible for any of the discrepancies observed between the interior parameters inferred from nutation observations and from other types of observations.

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REFERENCES

Alfè, D., Kresse, G. & Gillan, M.J., 2000. Structure and dynamics of liquid iron under Earth's core conditions, *Phys. Rev. B,* **61,** 132–142.

Aster, R.C., Borchers, B. & Thurber, C., 2005. *Parameter Estimation and Inverse Problems,* Elsevier Academic Press, Burlington, MA.

Barnes, R.T.H., Hide, R., White, A.A. & Wilson, C.A., 1983. Atmospheric angular momentum fluctuations, length-of-day changes and polar motion, *R. Soc. Lond. Proc. Series A,* **387,** 31–73.

Bizouard, C. & Lambert, S., 2002. Lunisolar torque on the atmosphere and Earth's rotation, *Planet. Space Sci.,* **50,** 323–333.

Bizouard, C., Brzeziński, A. & Petrov, S., 1998. Diurnal atmospheric forcing and temporal variations of the nutation amplitudes, *J. Geod.,* **72,** 561–577.

Brzeziński, A., 1994. Polar motion excitation by variations of the effective angular momentum function, II: extended-model, *Manuscr. Geod.,* **19,** 157–171.

Brzeziński, A. & Capitaine, N., 1993. The use of the precise observations of the celestial ephemeris pole in the analysis of geophysical excitation of earth rotation, *J. geophys. Res.,* **98,** 6667–6675.

Brzeziński, A., Ponte, R.M. & Ali, A.H., 2004. Nontidal oceanic excitation of nutation and diurnal/semidiurnal polar motion revisited, *J. geophys. Res.,* **109,** 11407, doi:10.1029/2004JB003054.

Buffett, B.A., Mathews, P.M. & Herring, T.A., 2002. Modeling of nutation and precession: effects of electromagnetic coupling, *J. geophys. Res.,* **107,** 2070, doi:10.1029/2000JB000056.

Chao, B.F., Ray, R.D., Gipson, J.M., Egbert, G.D. & Ma, C., 1996. Diurnal/semidiurnal polar motion excited by oceanic tidal angular momentum, *J. geophys. Res.,* **101,** 20 151–20 164.

Christensen, U.R. & Aubert, J., 2006. Scaling properties of convection-driven dynamos in rotating spherical shells and application to planetary magnetic fields, *Geophys. J. Int.,* **166,** 97–114.

Dehant, V., de Viron, O. & Greff-Lefftz, M., 2005. Atmospheric and oceanic excitation of the rotation of a three-layer Earth, *Astron. Astrophys.,* **438,** 1149–1161.

Dziewonski, A.M. & Anderson, D.L., 1981. Preliminary reference Earth model, *Phys. Earth planet. Inter.,* **25,** 297–356.

Goosse, H., Deleersnijder, E., Fichefet, T. & England, M.H., 1999. Sensitivity of a global coupled ocean-sea ice model to the parameterization of vertical mixing, *J. geophys. Res.,* **104,** 13 681–13 696.

Herring, T.A., Buffett, B.A., Mathews, P.M. & Shapiro, I.I., 1991. Forced nutations of the Earth: influence of inner core dynamics. 3. Very long baseline interferometry data analysis, *J. geophys. Res.,* **96,** 8259–8274.

Herring, T.A., Mathews, P.M. & Buffett, B.A., 2002. Modeling of nutation-precession: very long baseline interferometry results, *J. geophys. Res.,* **107,** 2069, doi:10.1029/2001JB000165.

Kalnay, E. *et al.*, 1996. The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.,* **77,** 437–472.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S., Hnilo, J.J., Fiorino, M. & Potter, G.L., 2002. NCEP-DOE AMIP-II Reanalysis (R-2), *Bull. Am. Meteorol. Soc.,* **83,** 1631–1643.

Koot, L., Rivoldini, A., de Viron, O. & Dehant, V., 2008. Estimation of Earth interior parameters from a Bayesian inversion of very long baseline interferometry nutation time series, *J. geophys. Res.,* **113,** 8414, doi:10.1029/2007JB005409.

Koot, L., Dumberry, M., Rivoldini, A., de Viron, O. & Dehant, V., 2010. Constraints on the coupling at the core-mantle and inner core boundaries inferred from nutation observations, *Geophys. J. Int.,* **182,** 1279–1294.

Marcus, S.L., de Viron, O. & Dickey, J.O., 2004. Atmospheric contributions to Earth Nutation: geodetic constraints and limitations of the torque approach, *J. Atmos. Sci.,* **61,** 352–356.

Mathews, P.M. & Guo, J.Y., 2005. Viscoelectromagnetic coupling in precession-nutation theory, *J. geophys. Res.,* **110,** 2402, doi:10.1029/2003JB002915.

Mathews, P.M., Buffett, B.A., Herring, T.A. & Shapiro, I.I., 1991a. Forced nutations of the earth: influence of inner core dynamics. 1. Theory., *J. geophys. Res.,* **96,** 8219–8242.

Mathews, P.M., Buffett, B.A., Herring, T.A. & Shapiro, I.I., 1991b. Forced nutations of the Earth: influence of inner core dynamics. 2. Numerical results and comparisons., *J. geophys. Res.,* **96,** 8243–8258.

Mathews, P.M., Herring, T.A. & Buffett, B.A., 2002. Modeling of nutation and precession: new nutation series for nonrigid Earth and insights into the Earth's interior, *J. geophys. Res.,* **107,** 2068, doi:10.1029/2001JB000390.

Munk, W.H. & MacDonald, G.J.F., 1960. *The Rotation of The Earth: A Geophysical Discussion,* Cambridge University Press, New York, NY.

Olsen, N., Mandea, M., Sabaka, T.J. & Tøffner-Clausen, L., 2009. CHAOS-2-a geomagnetic field model derived from one decade of continuous satellite data, *Geophys. J. Int.,* **179,** 1477–1487.

Ponte, R.M., Salstein, D.A. & Rosen, R.D., 1991. Sea level response to pressure forcing in a Barotropic Numerical Model, *J. Phys. Ocean.,* **21,** 1043–1057.

Rutter, M.D., Secco, R.A., Uchida, T., Liu, H., Wang, Y., Rivers, M.L. & Sutton, S.R., 2002. Towards evaluating the viscosity of the Earth's outer core: an experimental high pressure study of liquid Fe-S (8.5 wt.% S), *Geophys. Res. Lett.,* **29**(8), 080000–080001, doi:10.1029/2001GL014392.

Salstein, D.A., Kann, D.M., Miller, A.J. & Rosen, R.D., 1993. The Sub-bureau for atmospheric angular momentum of the International Earth rotation service: a meteorological data center with geodetic applications., *Bull. Am. Meteorol. Soc.,* **74,** 67–80.

Sasao, T. & Wahr, J.M., 1981. An excitation mechanism for the free ''core nutation'', *Geophys. J. R. astron. Soc.,* **64,** 729–746.

Sasao, T., Okubo, S. & Saito, M., 1980. A simple theory on dynamical effects of stratified fluid core upon nutational motion of the Earth, in *Proceedings of the IAU Symposium,* Vol. 78, pp. 165–183. Hingham, MA.

Stacey, F.D. & Anderson, O.L., 2001. Electrical and thermal conductivities of Fe-Ni-Si alloy under core conditions, *Phys. Earth planet. Inter.,* **124,** 153–162.

Uppala, S.M. *et al.*, 2005. The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.,* **131,** 2961–3012.

de Viron, O. & Dehant, V., 2003. Tests on the validity of atmospheric torques on Earth computed from atmospheric model outputs, *J. geophys. Res.,* **108,** 2068, doi:10.1029/2001JB001196.

de Viron, O., Marcus, S.L. & Dickey, J.O., 2001. Diurnal angular momentum budget of the atmosphere and its consequences for the Earth's nutation, *J. geophys. Res.,* **106,** 26747–26760.

de Viron, O., Boy, J.-P. & Goosse, H., 2004. Geodetic effects of the ocean response to atmospheric forcing in an ocean general circulation model, *J. geophys. Res.,* **109,** 3411, doi:10.1029/2003JB002837.

de Viron, O., Schwarzbaum, G., Lott, F. & Dehant, V., 2005. Diurnal and subdiurnal effects of the atmosphere on the Earth rotation and geocenter motion, *J. geophys. Res.,* **110,** 11404, doi:10.1029/2005JB003761.

Wahr, J.M., 1982. The effects of the atmosphere and oceans on the earth's wobble - I. Theory, *Geophys. J. R. astron. Soc.,* **70,** 349–372.

Yseboodt, M., de Viron, O., Chin, T.M. & Dehant, V., 2002. Atmospheric excitation of the Earth's nutation: comparison of different atmospheric models, *J. geophys. Res.,* **107,** 2036, doi:10.1029/2000JB000042.

Zhou, Y.H., Salstein, D.A. & Chen, J.L., 2006. Revised atmospheric excitation function series related to Earth's variable rotation under consideration of surface topography, *J. geophys. Res.,* **111,** 12108, doi:10.1029/2005JD006608.