IMPACT OF ATMOSPHERIC TIDES SIMULATED IN A CHEMISTRY-CLIMATE MODEL ON SUB-DIURNAL VARIATIONS IN UT1

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ABSTRACT. Sub-diurnal variations in Earth rotation parameters as obtained from time-series of space geodetic observations contain substantial variability even after correcting for the effects of oceanic tides. These residuals are in particular apparent at frequencies of 1, 2 and 3 cycles per solar day, where atmospheric tides, principally excited by water vapor absorption and ozone heating in the middle atmosphere, are known to occur. By means of hourly data of the chemistry-climate model WACCM, the potential of atmospheric tides on the excitation of UT1 variations is re-assessed. Tidal signals are separated into migrating and non-migrating zonal waves for individual height levels. Only standing waves of wavenumber zero are found to be effective in exciting UT1 variations, which are subsequently discussed in terms of their characteristic surface pressure and vertically varying wind amplitudes.

1. INTRODUCTION

The Earth's atmosphere exhibits periodic variations in its global temperature, pressure and wind fields that are principally induced by the diurnal cycle of solar energy absorption. Those variations, commonly referred to as thermal or atmospheric tides, are by a factor of 20 larger than the gravitational lunisolar tides in the atmosphere (Volland, 1988), and cover also variations due to the absorption of solar energy at the surface and corresponding radiative or convective vertical transfer processes. Since these tides are primarily excited by the daily variation of solar irradiation, signals at periods of 24 h and corresponding higher harmonics occur, that are additionally slightly altered by seasonal modulations.

Analyses of continuous VLBI campaigns designed to observe sub-diurnal tidal variability in Earth rotation parameters revealed substantial residuals at periods of 8, 12, and 24 h for example in UT1-TAI on the order of a few μs, even after correcting for the effects of ocean tides (Artz et al., 2010). Those residuals, although eventually affected by sun-synchronous systematic errors like thermal deformations of the antennas or temperature dependent delays in the receiving electronics (see Sovers et al., 1993), are often hypothesized to be related to atmospheric tides (e.g. Brzezinski, 2008).

Atmospheric data considered for analyzing the atmospheric contributions to rotational changes of the Earth are usually obtained from numerical weather prediction models. The most recent reanalysis from ECMWF, ERA-Interim, for example, is limited in its vertical extend to a level of 1 hPa. Thus, processes relevant for the excitation of tides in the middle atmosphere, where peak heating per unit mass via absorption of solar ultraviolet radiation by ozone occurs (Covey et al., 2011), are not adequately resolved in such models.

We therefore analyze a recent experiment from the Whole Atmosphere Community Climate Model (WACCM; Garcia et al., 2007) that is discretized on a regular horizontal grid with 1.9° x 2.5° and extends well into the thermosphere up to an altitude of 140 km. The simulation was performed within the SPARC-CCMVal activity under the REFB1 scenario and has been forced by observed sea surface temperatures, solar irradiances, greenhouse gas concentrations and ozone depleting substances as well as the observed, nudged Quasi-Biennial Oscillation (Matthes et al., 2010). For the year 2002, hourly

		wave number						
		s=3	s=2	s=1	s=0	s=-1	s=-2	s=-3
diurnal	$n = 1$	DW3	DW2	DW1	D0	DE1	DE2	DE3
semi-diurnal	$n = 2$	SW3	SW2	SW1	S0	SE1	SE2	SE3
ter-diurnal	$n = 3$	TW3	TW2	TW1	T0	TE1	TE2	TE3

Table 1: Naming convention for individual zonal waves contributing to the atmospheric tides. Waves with $s = n$ and zonal phase speeds $C_\phi = -\omega$ (i.e., DW1, SW2 and TW3) are called migrating tides to distinguish them from the remaining non-migrating components with $s \neq n$ (after Forbes, 2003).

three-dimensional fields of temperature, zonal and meridional wind, geopotential, and surface pressure are available, allowing us to assess the regional contributions to variations in UT1.

2. ZONAL WAVES RELEVANT FOR UT1 VARIATIONS

Periodic variations with n cycles per solar day of length $1/\omega = 24$ h can be described for an atmospheric state variable G at any location given by latitude φ, longitude λ, and pressure p from locally analyzed amplitudes A and phases ϕ as

$$G_n(\varphi, \lambda, p, t) = A_n(\varphi, \lambda, p) \cos(n\omega t - \phi_n(\varphi, \lambda, p). \tag{1}$$

However, tidal motions are generally not excited locally, but originate from a resonant motion of the laterally unbounded atmosphere. Given that the primary energy source is varying with the incidence angle of solar insulation, it is straightforward to represent tidal motions as a sum of zonal waves with different wave numbers s which include travelling waves towards east ($s < 0$) and west ($s > 0$), as well as standing waves ($s = 0$) (Forbes, 2003):

$$G_n(\varphi, \lambda, p, t) = \sum_{s=-\infty}^{s=\infty} A_{n,s}(\varphi, p) \cos(n\omega t + s\lambda - \phi_{n,s}(\varphi, p)). \tag{2}$$

Rewriting Equation (2) in terms of local time $t_{LT} = t + \lambda/2\pi$, we obtain

$$G_n(\varphi, \lambda, p, t) = \sum_{s=-\infty}^{s=\infty} A_{n,s}(\varphi, p) \cos(n\omega t_{LT} + (s - n)\lambda - \phi_{n,s}(\varphi, p)). \tag{3}$$

For wave numbers $s = n$, variations for any given local time are independent of longitude. Those components correspond to a zonal phase speed of $C_\phi = d\lambda/dt = -n\omega/s = -\omega$, implying a westward propagation of the signal at the same angular velocity as the apparent motion of the sun with respect to a ground-based observer. Those sun-synchronous components that dominate their spectra are referred to as migrating tides in order to distinguish them from the non-migrating tides with $s \neq n$ (Table 1).

Variations in Universal Time $\mathrm{UT1_{p,w}}$ are proportional to changes in the axial component of the angular momentum due to atmospheric surface pressure variations p_s, and the relative angular momentum caused by variations in the zonal wind u, respectively (Gross, 2009):

$$\frac{\partial(\mathrm{UT1_p} - \mathrm{TAI})}{\partial t} \sim \iint p_s(\varphi, \lambda) \cos^2 \varphi \; d\lambda \; d\varphi \tag{4}$$

$$\frac{\partial(\mathrm{UT1_w} - \mathrm{TAI})}{\partial t} \sim \iiint u(\varphi, \lambda, p) \cos \varphi \; dp \; d\lambda \; d\varphi. \tag{5}$$

By considering the de-composition of atmospheric tides into zonal waves it follows that only a sub-set of waves is contributing to UT1 variations. By inserting Equation (3) into Equations (4) and (5), it is clear that contributions from all wavenumbers $s \neq 0$ vanish when integrated over the globe, leaving only standing waves $s = 0$ to contribute to changes in UT1. Those waves will be subsequently discussed in more detail.

3. STANDING WAVES FROM WACCM

Hourly WACCM output of the relevant quantities surface pressure and zonal wind were Fourier de-composed for wave numbers $|s| \leq 8$ (Figure 1). Note that the migrating tides DW1 and SW2 who dominate all other waves in amplitude (see, e.g., Figures 5 and 6 of Covey et al., 2011, for an idea) have been excluded here since they do not contribute to UT1 variations. Non-migrating tides ($s \neq n$) arrive from a wide range of processes including deep convective activity leading to variations in rain fall and corresponding latent heating, or longitudinally varying insolation absorption due to changing water vapor content at different altitudes, that is closely related to the orography and land-sea distribution (Forbes, 2003). Amplitudes for D0 reach 12 Pa in the tropics with accompanying variations in the zonal winds. Since winds are more effective in exciting UT1 variations when they occur closer to both the surface and the equator, jet-like structures seen at subtropical latitudes that extend well down into the troposphere are in particular relevant, suggesting further analysis of the simulated strong zonal winds centered at 35° N on tropopause level.

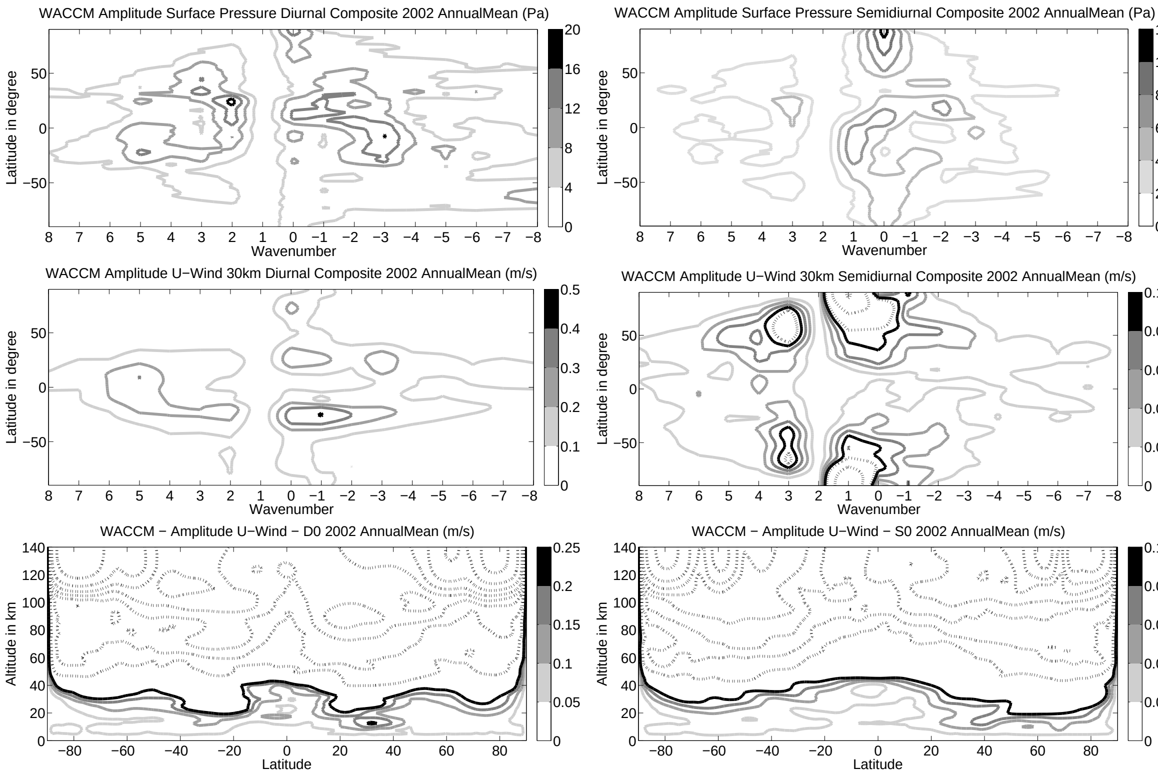

Figure 1: Wave number de-composition of diurnal (left) and semi-diurnal (right) oscillations in the mean atmospheric surface pressure (top) and the zonal wind at 30 km altitude (middle), as well as the vertical distribution of standing wave amplitudes D0 and S0 in the zonal wind (bottom), all obtained from one year of hourly WACCM data. Values out of range of the greyscale are marked by dashed lines that represent doubled amplitudes for each increment.

For the semidiurnal standing wave S0, surface pressure amplitudes are around 8 Pa in the tropics and even higher at the North Pole, where, however, the potential to excite UT1 variations is very small. For the same reason, strong wind amplitudes simulated in the polar vortex are of limited effect only. However, hemispheric assymmetries in the S0 wind amplitudes are more pronounced than for D0, calling for further analyses of the simulated low-level wind amplitudes at moderate latitudes in WACCM.

Amplitudes and phases of the standing waves D0, S0, and T0 are subsequently integrated into UT1 contributions and compared to estimates from WACCM data that has not been Fourier de-composed (Table 2). Apart from the semi-diurnal band, where the migrating component SW2 is particularly strong and affects the de-composition, standing waves indeed dominate the changes in UT1 due to variability in both wind, and surface pressure. Variability is generally decreasing with increasing frequency, consistent with energy distribution considerations. For all frequencies, wind and pressure contributions partly

		$UT1_p$ (μs)		$UT1_w$ (μs)		$UT1_{p+w}$ (μs)	
		sin	cos	sin	cos	sin	cos
diurnal	D0 only	0.092	0.25	-0.30	-0.56	-0.21	-0.31
diurnal	not decomposed	0.088	0.19	-0.27	-0.54	-0.18	-0.35
semi-diurnal	S0 only	0.17	0.013	-0.14	-0.021	0.034	-0.0085
semi-diurnal	not decomposed	0.22	0.040	-0.18	-0.023	0.041	0.017
ter-diurnal	T0 only	0.00083	-0.0032	0.0024	0.0066	0.0032	0.0034
ter-diurnal	not decomposed	0.00058	-0.0032	0.0030	0.0073	0.0036	0.0041

Table 2: Annual mean contributions of atmospheric tides at diurnal, semi-diurnal and ter-diurnal frequencies to variations in UT1, as separated into contributions from wind and atmospheric surface pressure from both the standing waves D0, S0 and T0 as obtained from a Fourier de-composition, as well as from the original wind and pressure distributions as simulated by WACCM.

compensate each other, which is in line with earlier studies based on data from numerical weather prediction models (Schindelegger, 2011).

4. SUMMARY AND CONCLUSIONS

Wind and pressure distributions available for one year of a simulation with the chemistry-climate model WACCM were used to calculate the annual mean contribution of atmospheric tides to variations in UT1. Although processes relevant for the excitation of tides are more complete in WACCM than in numerical weather prediction models, amplitudes are, however, substantially lower than current residuals from space geodetic techniques and also previously analyzed numerical models (Artz et al., 2010), suggesting that atmospheric tides even from modern chemistry-climate models are not able to fully account for this gap between theory and observation. However, since standing zonal waves were shown to be primarily responsible for the atmospheric contribution to UT1 variations, it is possible to focus now on the validation of these waves by means of auxiliary observations. Besides utilizing in-situ records from weather stations and radiosondes that are always afflicted by sampling limitations, different satellite instruments provide valuable data-sets on high altitudes tidal variations. In addition, seasonal modulations of atmospheric tides need to be considered in more detail, in particular when UT1 residuals calculated from observations of a limited time period are to be interpreted.

5. REFERENCES

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