Contents

Chapter 19

Solar diurnal tides in the middle atmosphere: Interactions with the zonal-mean flow, planetary waves and gravity waves

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Abstract The dynamics of solar tides is investigated with regard to variations of the background atmosphere, including planetary waves (PW), and to the interaction with gravity waves (GW). (1) Using a linear model with a clear cause-effect relationship, it is shown that planetary waves play an important role in tidal dynamics, most importantly by inducing non-migrating tidal components from a migrating thermal forcing. (2) Ray-tracing simulations are used to analyze the GW force on the large-scale flow including the solar tides. In comparison to classic GW parameterizations, the inclusion of time-dependence and horizontal refraction leads to a significant decrease of the GW drag.

19.1 Introduction

The diurnal cycle of solar heating represents a forcing of the atmosphere at the diurnal period (24h) and its higher harmonics. Corresponding large-scale waves, i.e. solar tides, are emitted, with signatures in all dynamic fields, including wind and temperature, propagating upwards into the mesosphere/lower thermosphere (MLT) region (*Chapman and Lindzen*, 1970). Due to the enormous density decrease tidal amplitudes grow significantly so that they represent a major component of atmospheric variability in the MLT. Tides are very sensitive to the propagation conditions

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they encounter on their way from the forcing region. Hence, if the mean atmospheric circulation is modified by solar variability this could leave a significant footprint on the tides encountered in the MLT. Moreover, many processes, discussed in this book, by which solar variability could have an impact on the tropopause region and below, rely on dynamic coupling mechanisms between the lower atmosphere and higher regions where the influence of a varying sun acts primarily. It seems important to understand these well. Solar tides, however, are controlled just by such mechanisms so that research on tides might be helpful not only for the detection whether solar variability can influence the lower layers of the atmosphere, but also for a better understanding how this might happen. We here take the chance to summarize recent work within this framework (*Achatz et al.*, 2008; *Achatz et al.*, 2010; *Senf and Achatz*, 2011). Therein the focus mainly is on how much various processes and mechanisms contribute to the tidal signature in the MLT.

One of these is the diurnal cycle of atmospheric heating. Two of the main heating processes subject to a significant diurnal cycle, and contributing to solar tides in the MLT, are the direct absorption of solar radiation by ozone in the stratosphere and by water vapor in the troposphere. This is supplemented by the diurnal cycle of tropospheric latent heat release and convection, mostly over tropical land masses. In propagating from the regions of these source processes to the MLT solar tides encounter propagation conditions which can have a strong impact on them. Here one discriminates between the impact of the zonal mean of the atmosphere on tides, which cannot change their zonal wave number, and the interaction between tides and planetary waves, which can do so. In general, the spatial and time dependence of the signature of the solar tides in any dynamic variable X is given by

$$\left.\begin{aligned} X(\lambda,\phi,z,t) = \sum_{n=1}^{\infty} \Big\{ & A_{n,0}(\phi,z)\cos\left(n\Omega t - \Phi^{e}_{n,0}\right) \\ + \sum_{s=1}^{\infty} & \left[A^{e}_{n,s}(\phi,z)\cos\left(n\Omega t - s\lambda - \Phi^{e}_{n,s}\right) + A^{w}_{n,s}(\phi,z)\cos\left(n\Omega t + s\lambda - \Phi^{w}_{n,s}\right)\right] \end{aligned}\right\} \qquad (19.1)$$

Here λ and ϕ denote the geographic longitude and latitude, respectively. The altitude is given by z, and t is the universal time. The rotation rate of the earth is $\Omega = 2\pi/24\text{h}$. The temporal subharmonics corresponding to $n = 1,2,3$ are the diurnal, semidiurnal, and terdiurnal tide, respectively. Each is decomposed into a zonally symmetric part, with zonal wave number $s = 0$, and east- and westward traveling components at zonal wave numbers $s > 0$ with amplitudes $A^{e}_{n,s}$ and $A^{w}_{n,s}$, and phases $\Phi^{e}_{n,s}$ and $\Phi^{w}_{n,s}$, respectively, both depending both on latitude and altitude. For conciseness, a westward or eastward traveling diurnal component at wave number s will be called DW*s* or DE*s*, respectively. The name for the corresponding zonally symmetric component is DS0. Since the apparent movement of the sun around the globe is westward, a leading tidal component of each temporal subharmonic is the westward traveling one at zonal wave number $s = n$, called the migrating tide. Its horizontal propagation is synchronous with that of the sun. Since also the tidal forcing by the diurnal cycle of solar heating can be decomposed into migrating and non-migrating components, the question arises which tidal components eventually dominate when the thus forced waves propagate into the MLT. Consider the interaction between tides and large-scale stationary planetary waves in terms of wave-wave interactions, governed by the triad condition $s_2 = s_1 \pm m$, with $s_{1,2}$ being zonal wave numbers of the tide and its forcing, and m the zonal wave number of a planetary wave. Clearly, a planetary wave can lead to the emergence of a non-migrating tide in the MLT from a migrating forcing further below, while the zonal-mean part of the atmosphere, with zonal wave number $m = 0$ cannot do so. Note that these are mechanisms already captured by a linear model where the dynamics of solar tides is represented after a linearization about an atmospheric reference state containing both zonal mean and stationary planetary waves.

While already the above leads to interesting questions, i.e. how much does each tidal forcing contribute to the total tidal signal, and how do interactions between tides and zonal mean or planetary waves influence what finally emerges as tide in the MLT, this is by far not all. Upward propagating small-scale gravity waves (GWs) transport a significant amount of momentum and energy from the lower to the middle atmosphere (*Fritts and Alexander*, 2003). Again due to the density decrease the GW amplitude rises in the course of their propagation from the troposphere to the MLT so that they eventually become unstable and break. Because solar tides, mainly their horizontal winds, induce changes in the GW propagation and properties, e.g. in GW vertical wave number, the wave breaking itself and the resulting momentum deposition (*Lindzen*, 1981) are periodically modulated. This way results a diurnal variation of the GW force on the large-scale flow which can have a feedback on the tides. This effect of gravity waves on thermal tides has not been well understood so far (*Ortland and Alexander*, 2006). Many linear models for the description of solar tides incorporate it by simple Rayleigh friction, which most likely is a crude over-simplification, needing either verification or replacement by better approaches.

These issues are addressed in the work reported here. We sketch in section 19.2 some steps and results in the research on the impact of zonal-mean and planetary-wave background variations on solar tides, give an account of new findings on interaction between tides and GWs in section 19.3, and finally summarize in section 19.4. All of the work reported here exclusively addresses the diurnal tide.

19.2 The seasonal cycle of the diurnal solar tide in its interaction with zonal-mean variations and planetary waves

The effect of the interaction between tidal forcing, migrating and non-migrating, and zonal-mean atmosphere or planetary waves on the various diurnal tidal components has been an original focus of research (*Hagan and Roble*, 2001; *Grieger et al.*, 2004, e.g.). Its modulation by the seasonal cycle represents an important test of our current understanding of tidal dynamics, and therefore has more recently attracted considerable attention. The MLT amplitude of the migrating diurnal tide exhibits a strong semiannual variation with maxima at equinox and minima at solstice. *McLandress* (2002a,b) explains this in terms of the impact of the seasonally varying zonal-mean wind on the tidal propagation conditions. The seasonal cycle of the leading non-migrating tides (DE3, DS0, and DW2) in the MLT has been addressed by *Oberheide et al.* (2005, 2006). They follow a similar strategy to the one from *Hagan and Roble* (2001) in using a linear model (GSWM) and a general circulation model (TIME-GCM) for simulating the seasonal cycle. The latter has a lower boundary at 30km altitude, where a migrating diurnal tide was prescribed, as obtained from the linear model, which again has a zonally symmetric background. The TIME-GCM is then integrated with prescribed planetary wave activity at the lower boundary. To some degree the two models complement each other: The linear GSWM captures the direct effect from the non-migrating forcing in a zonally-symmetric background while the TIME-GCM, without non-migrating forcing, can only produce non-migrating tides by an interaction between migrating tides and planetary waves. The linear model is reported to reproduce the seasonal cycle of DE3. This component therefore seems to result directly from a tide being forced by non-migrating heating, due to latent heat release, and its propagation through the zonal-mean background atmosphere. An open question is which part both factors play in comparison in determining the seasonal cycle of DE3. In the same studies both the linear GSWM and the nonlinear TIME-GCM yield seasonally varying components DS0 and DW2. Therefore, the excitation of DS0 and DW2 seem to be controlled by two processes, the interaction of migrating forcing and planetary waves, and the direct non-migrating forcing in interaction with a varying zonal mean in the background atmosphere. However, the respective role of variations in the zonal-mean background and the non-migrating forcing is not clarified within GSWM. Moreover, the TIME-GCM integrations are fully nonlinear; corresponding feedbacks are not excluded. It is therefore not possible to simply add the GSWM result to the one from the GCM so as to obtain the complete tidal signal. A more conclusive picture could arise from a linear model with a background atmosphere incorporating the most important stationary planetary waves. Such analysis have been done by *Achatz et al.* (2008).

Their model uses the primitive equations, linearized about a time-independent, but fully three-dimensional, background atmosphere, with a spectral discretization in the horizontal (T14) and 60 hybrid-coordinate layers in the vertical between the ground and about 140km altitude. Sub-grid-scale processes are parameterized crudely by vertically dependent Rayleigh friction, Newtonian cooling and horizontal diffusion. The model is forced by diurnal oscillations in the heat sources, taken, just as the background atmosphere, from the monthly climatology of a state-of-the-art GCM HAMMONIA (*Schmidt et al.*, 2006) ranging from the ground far into the thermosphere. The heat sources comprise, among others, the absorption of solar radiation, including the ultraviolet and extreme ultraviolet wavelength regime, long-wave radiation, and heating by latent heat release and convection. Instead of a brute forward integration, the equations including the forcing are Fourier analyzed in time, so that for each tidal period a system of linear equations is obtained, which are solved iteratively by a preconditioned conjugate gradient solver. The result is the complete three-dimensional tidal structure, with all migrating and non-migrating

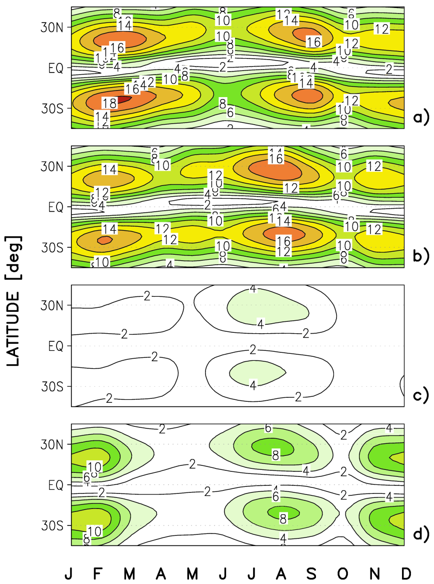

Fig. 19.1 From the linear model, the seasonal cycle in the amplitudes of the non-migrating component DW2 of the diurnal tide in the meridional wind at 95km altitude (a), the part due to variations of the background atmosphere (b), the part due to the seasonally varying part of the diurnal heat sources (c), and the corresponding contribution from the seasonal cycle of the stationary planetary waves (d). Units are m/s. Taken from *Achatz, U., N. Grieger, and H. Schmidt, Mechanisms controlling the diurnal solar tide: Analysis using a GCM and a linear model, J. Geophys. Res., 113, A08,303, 2008*. Copyright 2008 American Geophysical Union. Modified by permission of American Geophysical Union.

components. Note that the background state is three-dimensional so that the effect of stationary planetary waves is included.

The linear model is used for analyzing the seasonal behavior of the tides in the GCM, which it reproduces reasonably well. We here focus on the three most relevant non-migrating tidal components. Perhaps least surprising is the important role played by condensation and convection in the forcing of *DE3*. An analysis of the seasonal cycle near the mesopause shows that the amplitude maximum between November and February is mostly due favorable propagation conditions given then by the zonal mean. *McLandress* (2002b) argues that the decisive factor in the modulation of the migrating tide by the zonal mean is the seasonal dependence of the zonal-mean vorticity in the background atmosphere. This might as well be the case for DE3. An erroneous maximum in HAMMONIA, as compared to observations, in August is prevented in the linear model by a counteracting effect due to the seasonal cycle in the forcing. The interplay between the zonal-mean background and the forcing thus seems to be essential for explaining the complete seasonal cycle.

Around the time of its maximum (April - June) *DS0* in the linear model is mostly excited by the direct non-migrating forcing by the absorption of short-wave solar radiation and by condensational heating. Since the planetary waves are weak during this time it is no surprise that their effect is not so important then. Indeed, it is found that most of the seasonal cycle can be understood as an effect of variations in the zonal-mean background. However, this even holds between December and February when the planetary waves are strong. Closer analysis shows that the total signal is very similar to the direct non-migrating input from condensation and convection. Both, the effects from the direct non-migrating forcing by the absorption of solar short-wave radiation by tropospheric water vapor and the modulation of the migrating forcing by the planetary waves are also strong, but cancel each other. It thus seems that destructive interference effects such as here might also be an essential factor of the planetary wave effect on non-migrating tides.

An example where the planetary waves actually enhance the amplitude of a non-migrating tide is *DW2*, as illustrated in Fig. 19.1. This tidal component is driven to a large proportion by the non-migrating forcing due to condensation and convection. The seasonal cycle can be explained to the largest part by the seasonal variations of the zonal-mean propagation conditions of this directly forced non-migrating tide. One also has, however, a quantitatively important impact from the planetary wave modulation of the migrating tide forced in the troposphere. This holds both for the total signal as such and for the simulated seasonal cycle. In conclusion, planetary waves do seem to be a factor to be taken into account in the dynamics of solar tides.

19.3 Interaction between GWs and solar tides

In previous efforts of tidal modeling (also see *Ortland and Alexander*, 2006, and reference therein), the interaction between tides and GW parameterizations has been investigated under strong assumptions. Conventional GW parameterizations work in vertical columns which are assumed to be independent from each other, ignoring horizontal inhomogeneities in the large-scale flow (*McLandress*, 1998). Furthermore, time-dependence of the large-scale background (BG) conditions is neglected. It is supposed that GW fields just see a quasi-stationary mean flow and adjust instantaneously to its changes. In reality, however, GWs exhibit horizontal propagation and they are refracted at horizontal inhomogeneities of the BG. Time dependence of the latter changes the GW frequency. Furthermore, GWs propagate with a finite group velocity. Hence, if the time scale of the BG is short enough to get comparable to or smaller than the GW propagation time scale, significant deviations from the assumption of instantaneous adjustment appear. This might most likely be the case for solar tides in their effect on GW propagation.

In *Senf and Achatz* (2011) the effects of GW propagation and dissipation in realistic tidal fields are investigated with the help of global ray-tracing simulations, thus extending the simplified calculations by *Eckermann and Marks* (1996). In ray tracing (*Achatz et al.*, 2010, e.g), a locally monochromatic gravity wave field is propagated through a slowly changing environment. The GW field, or rather its local wave numbers and amplitudes are followed along characteristics, the so-called rays, determined from the local group velocity (*Hasha et al.*, 2008, e.g.). The time-dependence of the BG wind, in our case the effect of the diurnal tide, induces a modulation of GW observed frequency along the ray. The horizontal gradients in the BG conditions lead to changes in the horizontal GW wave numbers. Following *Grimshaw* (1975), the GW amplitude is predicted from the conservation of wave action, supplemented by a damping rate estimated via the highly simplified saturation theory (*Lindzen*, 1981). Once a GW amplitude grows beyond the threshold at which it induces local overturning of isentropes it is forced back to this convective instability threshold. Additionally, in the MLT region molecular viscosity and thermal diffusivity become more important and are included into the damping process. Our new global ray-tracer RAPAGI (RAy PArameterization of Gravity-wave Impacts) solves the ray-tracing equations on the sphere, using a small and highly idealized GW ensemble at source spectrum at 20km altitude. Each of the 14 individual and independent GW components is integrated forward separately. It has been shown by *Becker and Schmitz* (2003) that the mean residual circulation of the middle atmosphere is well reproduced in a large-scale GCM when this GW ensemble is used in a classic parameterization according to *Lindzen* (1981). We note, however, that, as that mostly resulted from tuning, this GW ensemble is just one of many possibilities. Therefore, the simple GW ensemble is viewed as a reasonably-motivated toy configuration, while the analysis of even better chosen scenarios is left for the future.

The superposition of monthly means and tidal fields from the HAMMONIA model are chosen as background for three different off-line experiments, named ”full”, ”noREF” and ”TS”, with decreasing complexity. The ”full” experiment refers to a full ray-tracing simulation without any approximations for horizontal and time dependence. Thus, changes in frequency and all wave-number components appear and are induced by mean flow changes. The geographical distribution of the GW fields is altered as well. ”noREF” (no refraction) is a simplified ray-tracing experiment in which neither horizontal refraction nor horizontal propagation are allowed. Only the vertical ray propagation is taken into account. Nonetheless, the rays have a finite group velocity and feel the transience of the BG wind. The horizontal wave-number components are constant along each ray, but frequency and vertical wave number vary to compensate temporal and vertical changes in the BG conditions, respectively. The third experiment is denoted by ”TS” (time slicing) and equivalent to a classic single-column and steady-state parameterization. Only vertical variations are taken into account. The tidal phase was fixed in 3h steps to sample the diurnal cycle, and finally the results from the different tidal phases were combined to a daily cycle. With the three experiments, effects of frequency modulation and the refraction of horizontal wave vector can be extracted. Differences between ”TS” and ”noREF” are attributed to the first, whereas differences between ”noREF” and ”full” to the latter. As the simpler simulations ”TS” and ”noREF” are obtained by successively simplifying the ”full” one, a consistent comparison of the results is possible while keeping implementation aspects the same.

Since GW fields in the MLT region are periodically modulated by tidal winds, they produce a periodic force acting back on the diurnal tides. The relevant forc-

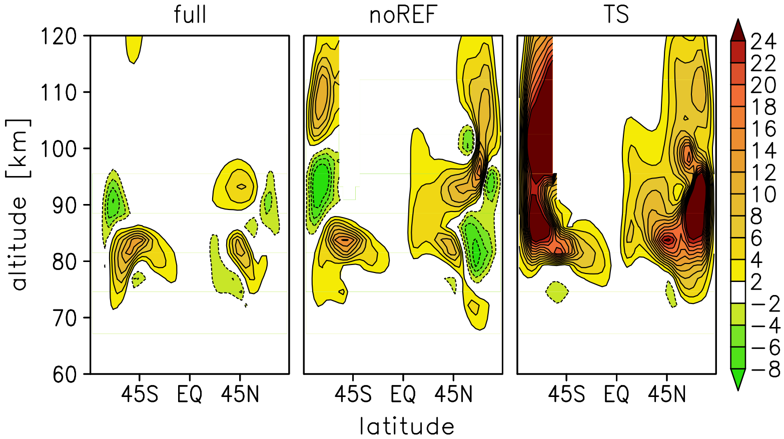

Fig. 19.2 The zonally averaged real part of the equivalent Rayleigh friction coefficient for the three different experiments: "full" (left), "noREF" (middle) and "TS" (right). The shading interval is $2 \times 10^{-6}\ \mathrm{s}^{-1}$.

ing of the mean flow, in our case temporally averaged flow plus diurnal tides, is given by the divergence of the pseudo-momentum fluxes from all 14 GW ensemble members. The diurnal amplitude of the zonal force can be analyzed most conveniently on the basis of equivalent Rayleigh friction coefficients (ERFs). These have been introduced in the context of GW-tidal interaction by e.g. *Miyahara and Forbes* (1991) and further discussed e.g. by *McLandress* (2002a). With the help of ERFs, the effects of GWs can be incorporated into a linear tidal model. Effectively, the tidal component of the GW force is approximated by $f_\lambda \approx -\gamma_R u_T - \frac{\gamma_I}{\Omega} \partial_t u_T$, where u_T is the tidal wind, and γ_R and γ_I are the real and imaginary part of the ERFs, respectively. Positive real parts of the ERFs indicate regions of tidal damping and vice versa. The imaginary part of ERF acts on the tidal phase structure. A reduction of tidal vertical wave length is a very robust result in previous investigations, whereas the GW effect on tidal amplitudes is controversial (*Ortland and Alexander*, 2006, and references therein). The real parts of ERFs are shown in Fig. 19.2 for the three simulations. For the reference simulation "TS" in Fig. 19.2(c), large positive peaks up to $60 \times 10^{-6} s^{-1}$ occur. The damping of tidal amplitudes is a quite typical result of Lindzen saturation parameterization. Others show qualitatively different effects on tides (e.g. *Ortland and Alexander*, 2006). For the "noREF" experiment, in Fig. 19.2(b), the magnitude of γ_R is reduced. As analyzed in *Senf and Achatz* (2011) this results from an avoidance of critical levels, due to the time dependence of the tidal fields. The latitude-altitude structure is wave-like with a vertical wave length comparable to the tidal wave length. In Fig. 19.2(a), the magnitude of the ERF is further decreased. The influence of γ_R is drastically lowered at high latitudes and in the thermosphere. This is mostly due to the meridional refraction of the GW horizontal wave number by the mean wind gradients and the corresponding horizontal GW propagation (*Senf and Achatz*, 2011). The bottom line of this is that frequency modulation and horizontal refraction by the tidal background significantly reduces the GW forcing in the MLT.

19.4 Conclusions

The dynamics of solar tides is still a challenging field. We have here reported progress on the linear modeling of these forced waves. This approach has the advantage that cause-effect relationships can be established which would remain hidden in an all-nonlinear approach. We are able to trace back characteristics of the seasonal cycle of important components of the diurnal solar tide to the impact of either migrating and non-migrating diurnal heating, or the impact of planetary waves on the tidal propagation. The latter can lead to a non-migrating signal in the mesosphere, caused by migrating forcing in the troposphere. An important problem remains the GW-tidal interaction. So far we are able to show that it is incorrectly described on the basis of single-column and steady-state GW parameterization approaches. The time dependence of the solar tides, and the spatial gradients set by the background atmosphere tend to reduce the GW impact much below what has been assumed so far. The feedback on the tides, however, remains to be examined.

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