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Mesospheric non-migrating tides generated with planetary waves: II. Influence of gravity waves

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Abstract

In Part I, we demonstrated with the numerical spectral model (NSM) that non-linear interactions between planetary waves (PWs) and migrating tides could generate in the upper mesosphere non-migrating tides that have amplitudes comparable to those observed. The NSM incorporates Hines' Doppler spread parameterization (DSP) for small-scale gravity waves (GWs), which affect the dynamics of the mesosphere in numerous ways. The latitudinal (seasonal) reversals in the zonal circulation and temperature variations above 70 km, largely caused by GWs, contribute to the instabilities that generate the PWs, and the circulation filters the waves. The PWs in turn are amplified by the momentum deposition of upward propagating GWs, as are the migrating tides. The GWs thus affect the migrating tides and PWs, the building blocks of non-migrating tides. In the present paper, we present the results of two computer experiments, which indicate that the GWs also contribute significantly to the process of non-linear coupling between PWs and tides. In one, we turn off the GW source to show the effect on the non-migrating tides. In the second case, we demonstrate the effect on the standing non-migrating diurnal tide by selectively suppressing, for comparison, the time dependence of the GW momentum source for zonal wave number $m = 0$.
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1. Introduction

In the mesosphere, the diurnal and semidiurnal tides have been observed with the UARS spacecraft (e.g., Hays et al., 1993, 1994; Shepherd et al., 1993; McLandress et al., 1996; Burrage et al., 1995a, b) and with ground-based measurements (e.g., Avery et al., 1989; Manson et al., 1989; Vincent et al., 1989; Jacobi et al., 1999). These observations mainly refer to the dominant migrating tides, but the non-migrating tides are also found to be important in the region. Based on observations and supported by modeling studies, a large body of evidence has been accumulated over the years, which shows that the non-migrating tides represent a major part of the phenomenology that characterizes the mesosphere and lower thermosphere (e.g., Manson et al., 1989; Lieberman, 1991; Miyahara et al., 1993; 1999; Miyahara and Miyoshi, 1997; Forbes et al., 1995a, b, 2003a, b; Hagan et al., 1997; Talaat and

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Lieberman, 1999; Hagan and Roble, 2001; Hagan and Forbes, 2002, 2003; Pancheva et al., 2002; Huang and Reber, 2003, 2004).

As reviewed in Part I, the inferred phase progression of the non-migrating tides suggests that they propagate up from below (Lieberman, 1991; Talaat and Lieberman, 1999). But the sources for these tides in the troposphere and stratosphere are not sufficient to reproduce the observed amplitudes in the mesosphere (e.g., Miyahara et al., 1993; Hagan et al., 1997). Teitelbaum and Vial (1991) thus proposed that non-linear interactions between migrating tides and planetary waves (PWs) could generate non-migrating tides. This mechanism was invoked for example by Forbes et al. (1995a, b) to explain the large westward propagating 12-h wave observed in radar measurements near the South Pole. Miyahara et al. (1999) also concluded that non-linear interactions involving PWs could generate the non-migrating tides in their GCM, and Hagan and Roble (2001) found that the process produced such tides in the TIME-GCM model.

We recently demonstrated for the $m = 0$ diurnal tide in the NSM that the planetary wave mechanism could generate amplitudes comparable to those observed in the mesosphere (Mayr et al., 2003). In the accompanying paper (Mayr et al., 2005), we discuss this mechanism more fully for the non-migrating diurnal and semi-diurnal tides and describe their seasonal variations. In the study presented here, we focus on the influence of gravity waves (GWs). We discuss two modeling studies to show (1) the effect of GWs on the non-migrating tides, and (2) that GWs contribute significantly to the process of non-linear coupling between PWs and westward propagating migrating tides.

2. Mesospheric gravity wave processes

In Fig. 16 of Part I (for short Fig. 16I), with emphasis on GW processes, we illustrate and enumerate some of the dynamical interactions that contribute to generate, directly or indirectly, the non-migrating tides in the NSM. Solar heating drives (a) the westward migrating tides, and (b) the mean zonal circulation and associated temperature variations (with zonal wave number $m = 0$). As demonstrated first by Lindzen (1981), GWs cause the zonal winds and latitudinal (seasonal) temperature variations to reverse at higher altitudes in the mesosphere (item 1, Fig. 16I). The waves have also been shown to cause the observed reversal in the phase of the semiannual oscillation (SAO) at low latitudes (Dunkerton, 1982). The GW-induced changes in the temperature, pressure and wind fields produce instabilities that have been invoked to generate PWs in the mesosphere (e.g., Plumb, 1983). Filtered by the seasonally varying global-scale zonal circulation, upward propagating GWs deposit momentum in the tides and thus contribute to the observed seasonal variations, and GWs were invoked to account in part for the non-linear coupling between the diurnal and semidiurnal tides (item 2, Fig. 16I). Migrating diurnal and semi-diurnal tides produce through non-linear interaction ter-diurnal tides, and GW processes are likely involved in that too. Apart from the important role GWs play in generating the PWs through the mean zonal circulation (item 1, Fig. 16I), they are also involved in amplifying them (item 3, Fig. 16I). Gravity wave breaking causes momentum deposition in vertical wind shears, which is the process that generates the quasi biennial oscillation (QBO) and contributes to produce the large (SAO)s in the middle atmosphere at low latitudes (item 4, Fig. 16I).

We have argued (Mayr et al., 2001a, b) that GW processes affect significantly the tides and PWs of the mesosphere, and that GWs produce non-linear interactions between some of the other dynamical features. Gravity wave filtering appears to be a natural candidate for generating non-linear interactions between the QBO and SAO to produce inter-seasonal variations, and between the QBO and AO (annual oscillation) to produce quasi-decadal oscillations. Having shown in Part I that non-linear coupling between migrating tides and PWs generates non-migrating tides with substantial amplitudes in the NSM, we ask the question of how important the GWs are specifically for the nonlinear process itself that produces the interaction (item 5, Fig. 16I).

With Fig. 1 of the present paper we illustrate how GW filtering may produce non-linear coupling between PWs and migrating tides to generate non-migrating tides. In this scenario, we consider upward propagating GWs that encounter a quasi-stationary long-period PW and deposit some of the eastward momentum into the eastward (positive) phase of the PW wind oscillation. The wave momentum thus given to the PW is then missing in the GWs when they encounter the migrating tide higher up, which is illustrated with an arrow to the left (indicating reduced eastward momentum). This PW-induced deficit in the GW momentum is then not available to amplify the eastward phase of the migrating tide, causing it to be a weaker relative to the westward phase. A similar argument can be applied to the westward winds of the PW that would cause a relative reduction in the westward phase of the tide. The net result of this interaction is that the tide, its periodicity virtually intact, is modulated by the PWs, with GWs producing the apparent non-linear coupling. This may illustrate the non-linear process involving the temporal variations of PWs and migrating tides—and similar arguments could be applied to describe the non-linearity that couples the longitudinal variations. Obviously, the non-linear process discussed here is fundamentally different from the more traditional

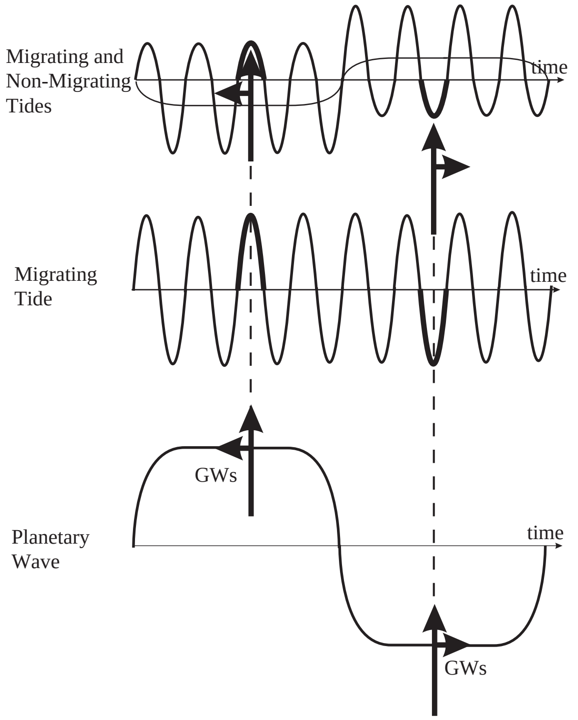

Fig. 1. Schematic, showing how GW filtering can be involved to generate the non-linear coupling that produces non-migrating tides from planetary waves (PW) and migrating tides as illustrated with item 5 in Fig. 16I.

nonlinearities, associated for example with advection, that develop in a fluid (and are accounted for in our non-linear model). Given a set of migrating tides and PWs, one would expect then that such a GW-induced nonlinear interaction would increase the amplitudes of the resulting non-migrating tides and affect their dynamical properties.

3. Numerical spectral model

The numerical spectral model (NSM), discussed in greater detail in Part I, extends from the Earth's surface up into the thermosphere, and its design and applications have been described in the literature (e.g., Chan et al., 1994; Mengel et al., 1995; Mayr et al., 2000, 2002a). This model incorporates the Doppler spread parameterization (DSP) for small-scale gravity waves (GW) developed by Hines (1997a, b), with a GW source in the troposphere that is taken to be independent of latitude and season. The tides are only driven by the westward migration thermal excitation sources in the troposphere and stratosphere (Forbes and Garrett, 1978), i.e., the important non-migrating sources associated with topography and convection are not accounted for in the present study. The planetary waves (PWs) are solely excited by the instabilities associated with the mean zonal circulation and temperature variations, and they are amplified by GWs. The present 3D version of the NSM reproduces qualitatively the observed zonal jets and accompanying latitudinal temperature variations near the tropopause, which affects the PWs and in turn the non-migrating tides that are generated.

4. Non-linear coupling generated by gravity wave filtering

Considering that GW processes contribute, through a number of channels, to produce the non-migrating tides as illustrated in Fig.16I, it is difficult to completely isolate their specific role in generating the non-linear coupling that is involved. Notwithstanding this problem, we performed a numerical experiment in which we simply eliminated the GW source after integrating the model sufficiently long to reach equilibrium. The idea is that the inertia in the mean zonal circulation and associated temperature variations (for $m = 0$) may be sufficient to maintain nearly at full strength, for a limited time, the PWs and the migrating tides. Given similar tidal and PW amplitudes, the effect on the non-migrating tides, through the process of non-linear coupling (item 5, Fig. 16I), would then become apparent.

To perform this experiment, the standard computer solution after 5 model years was continued for another 3 months but, for comparison, without the GW source. Computed with (solid line) and without (dotted) GW forcing, the resulting amplitudes for the meridional and zonal winds of the $m = 1$ diurnal tide, westward and eastward propagating, are shown in Fig. 2 for an altitude of 100 km at 18° latitude (Gaussian point). For the westward tide, the meridional winds (a) without GW source are larger than those with GW interaction, but the opposite is true for the zonal winds (c). Given the importance of GW processes, it is expected that the solutions are different. It is not understood however why the zonal and meridional winds of the migrating tide, a global oscillation, respond differently. In contrast to the migrating tide, the GW effect on the weaker eastward tide is more consistent: with GW forcing, the meridional (b) and zonal winds (d) are significantly larger at least during the first $1\frac{1}{2}$ months.

In Fig. 3 we present the meridional and zonal winds for the $m = 1$ PWs computed again with (solid line) and without (dotted) the GW source. The wind velocities for the two solutions are significantly different, but their amplitudes are comparable in magnitude. Finally, the non-migrating $m = 0$ tide is presented in Fig. 4, which is generated by the dominant migrating tide in Fig. 2 and by the PWs in Fig. 3. This shows that the GW

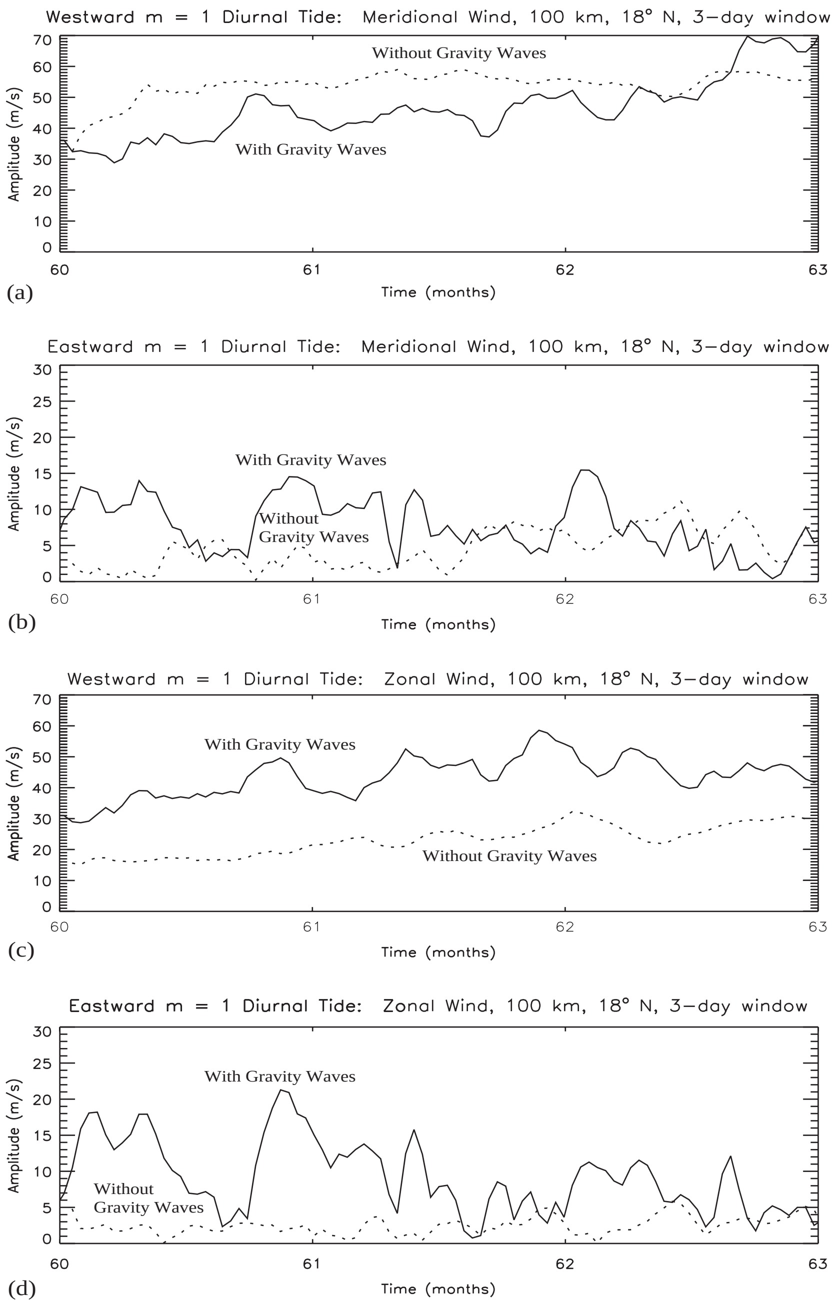

Fig. 2. Diurnal tides, westward and eastward propagating, for meridional (a, b) and zonal (c, d) winds respectively at 100 km and 18°N, computed for a time period following solstice after 5 model years (60 months). The standard model is presented in solid lines, and for comparison a solution is shown with dotted lines in which the GW source is suppressed (reduced by a factor of 30). For the dominant westward tide, the GW forcing produces significant differences but they go in opposite directions for the zonal and meridional winds. The weaker eastward tides are in general amplified by the GW source.

interaction makes a large difference. The amplitudes for this non-migrating tide are much larger for the standard model with GW forcing. Given that the PW amplitudes are comparable (Fig. 3) and the differences between the westward migrating tides do not reveal a well-defined trend (Figs. 2a and c), we are led to the tentative

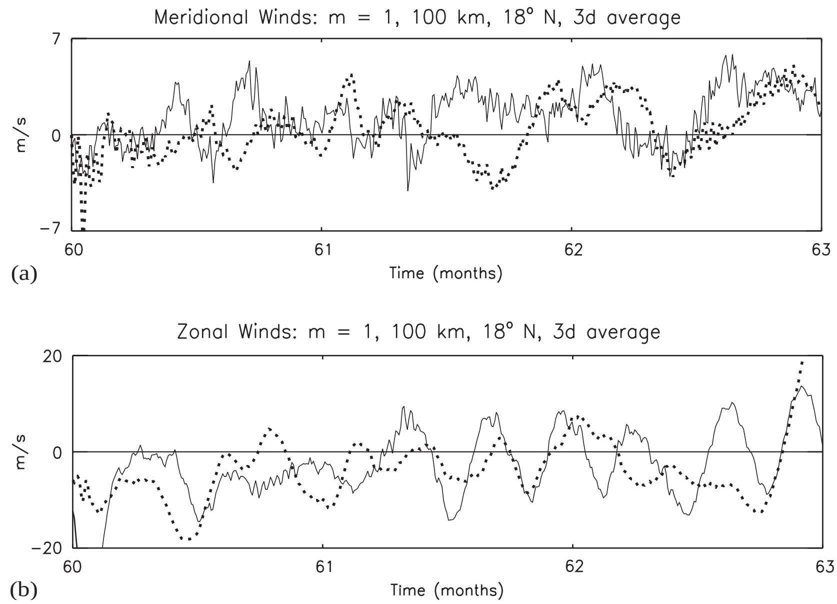

Fig. 3. Analogous to Fig. 2 but for the $m = 1$ PWs computed with (solid lines) and without (dotted lines) GW forcing.

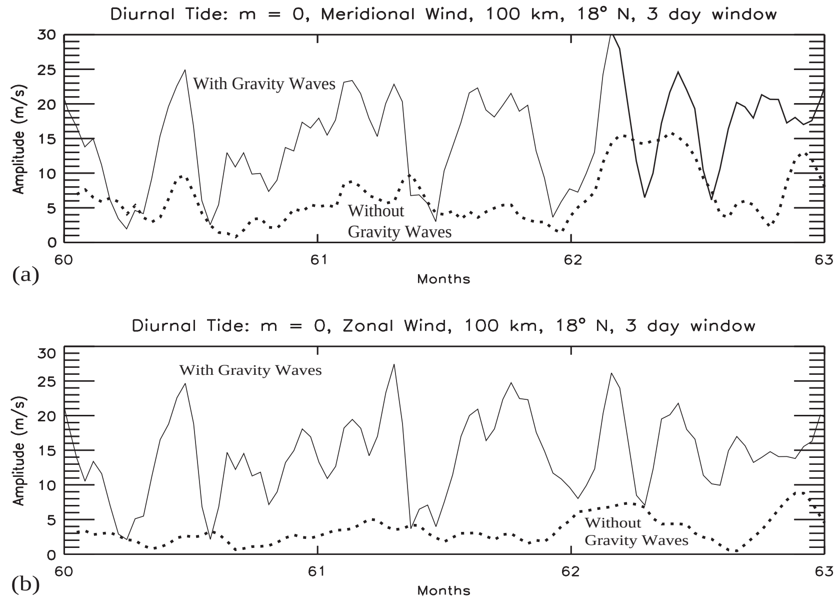

Fig. 4. Analogous to Fig. 2 but for the $m = 0$ non-migrating diurnal tide that is generated by non-linear coupling between migrating tide (Fig. 2) and PWs (Fig. 3). The differences are large and reveal the importance of GW interactions. Since the differences for the tides (Fig. 2) are not systematic, and the differences for the PW amplitudes (Fig. 3) are relatively small, this suggests that the GWs are important for the non-linear coupling.

conclusion that a significant part of the differences in the $m = 0$ non-migrating tide (Fig. 4) must be attributed to the process of non-linear coupling by GW filtering (item 5, Fig. 16I) that is illustrated in Fig. 1.

The above discussed computer runs clearly show how important GW processes are. But given the many channels in which the waves come into play (Fig. 16I), we cannot be certain about the specific role GW filtering plays to generate the non-linear interactions involved. For this reason, we have carried out another computer experiment, which specifically targets the GW interaction for the $m=0$ non-migrating tide. In this case, we ran the standard model for perpetual equinox, with the Sun fixed at the equator. After 18 model months, sufficient to reach equilibrium, we then ran the model in such a way that the GW momentum source for $m=0$ was forced to remain constant. That is, the time dependence of the GW source was artificially suppressed, which includes variations with a period of 1 day that could contribute to generate the $m=0$ non-migrating diurnal tide. In this experiment, the time-independent GW momentum source for $m=0$ is retained so that it can maintain the global-scale temperature and wind fields that filter the migrating tides and contribute to generate the PWs through instabilities. The idea is to produce migrating tides and PWs commensurate with the standard model under the influence of GW interactions—but to generate the $m=0$ non-migrating tides without the GW momentum source that specifically contributes to the non-linear processes involved. Such a model would essentially retain all the GW interactions, i.e., items 1–4 in Fig. 16I—but not the one that accounts for the non-linear GW momentum source (item 5). As was shown by Teitelbaum and Vial (1991), non-migrating tides such as the one for $m=0$ can be generated generically by non-linear interactions, and our non-linear model would account for such processes even without GW interaction. As emphasized

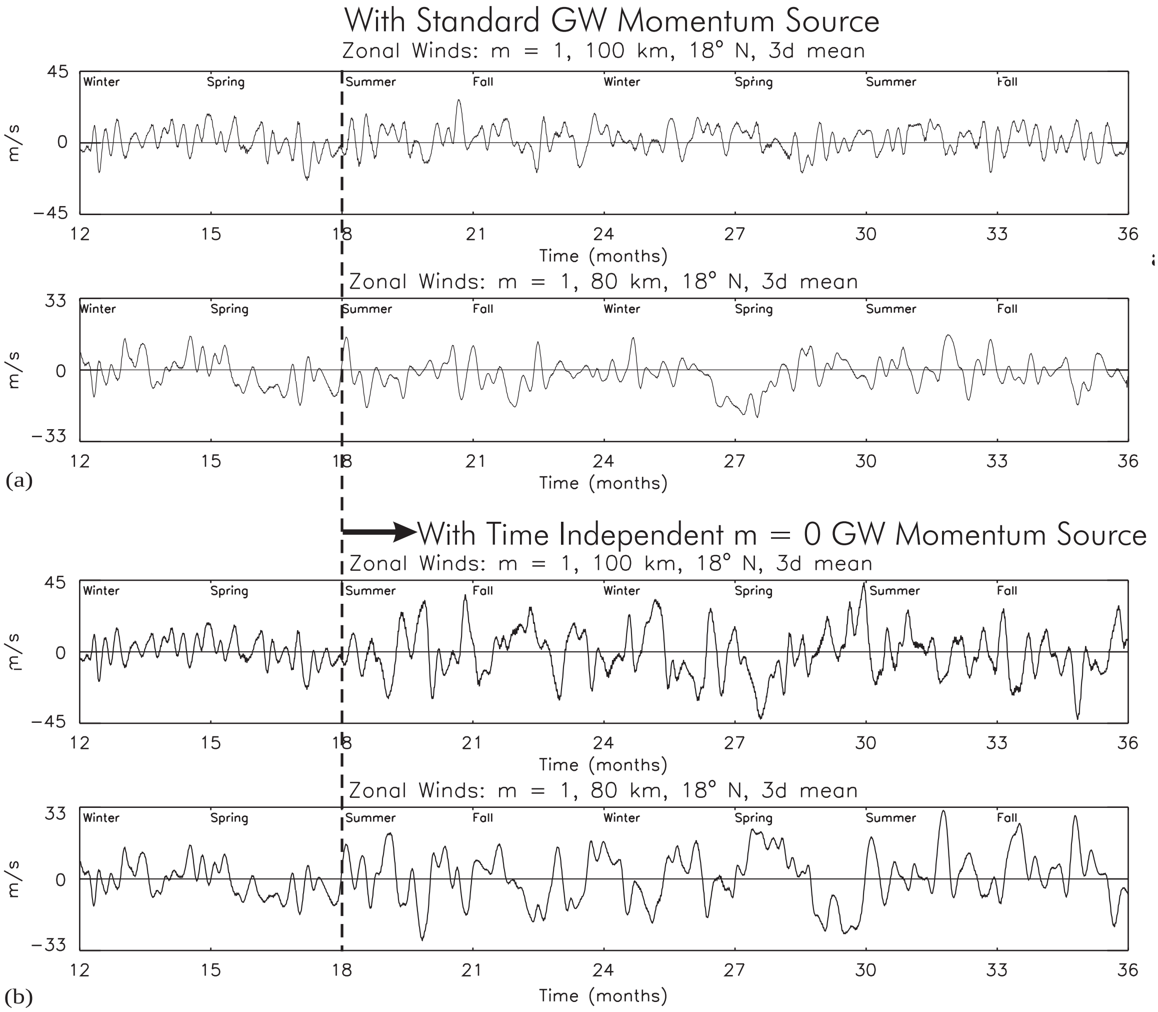

Fig. 5. Zonal winds for planetary waves with $m=1$ at 80 and 100 km and at 18°N computed for perpetual equinox. The standard solution (a) accounts for the full GW momentum source. For comparison, a solution is presented (b) in which the GW source is modified after 18 months so that the time dependence for $m=0$ is artificially eliminated. In the latter case, the amplitudes are considerably larger (after 18 months).

earlier, we explore here the question of how important GW processes are specifically for the non-linear coupling itself—and we explore the process in an application to the $m = 0$ tide.

The results from this computer experiment are presented in Figs. 5–8 at 18° latitude, covering a period from 12 to 36 months. In Fig. 5, the zonal winds are shown at 80 and 100 km for the $m = 1$ PWs, computed (a) with standard GW momentum source and (b) with the modified time-independent $m = 0$ source (defined above) for comparison. For the first 18 months, the solutions are identical, but then they deviate significantly after the time dependence for the momentum source has been turned off. With the time-independent GW source, the PW amplitudes are significantly larger (Fig. 5b) when compared to the standard model (Fig. 5a), and the same is true for the meridional winds shown in Fig. 6. (The differences in amplitude decrease at lower altitudes.) This is an interesting result, not yet fully understood, which apparently tells us something about the dynamical conditions that are conducive or detrimental to generate PWs in the model—and we shall later come back to discuss it.

Commensurate with the format for PWs, we present in Fig. 7 the diurnal tides for $m = 1$ at 100 km computed with the standard GW momentum source, delineating the westward (a) as well as eastward (b) components. For comparison, we show the corresponding tidal components in (c) and (d) obtained from the solution with a modified, time-independent GW momentum source for $m = 0$. Since the GW source for $m = 1$ was not modified, only the one for $m = 0$, the dominant westward migrating tides (a, c) are virtually identical in both cases, as expected. However, with the modified source, the eastward propagating tide (d) is significantly larger than that computed with the standard model (b), and this is understandable in light of the results for the PWs. The eastward propagating tide is generated in the

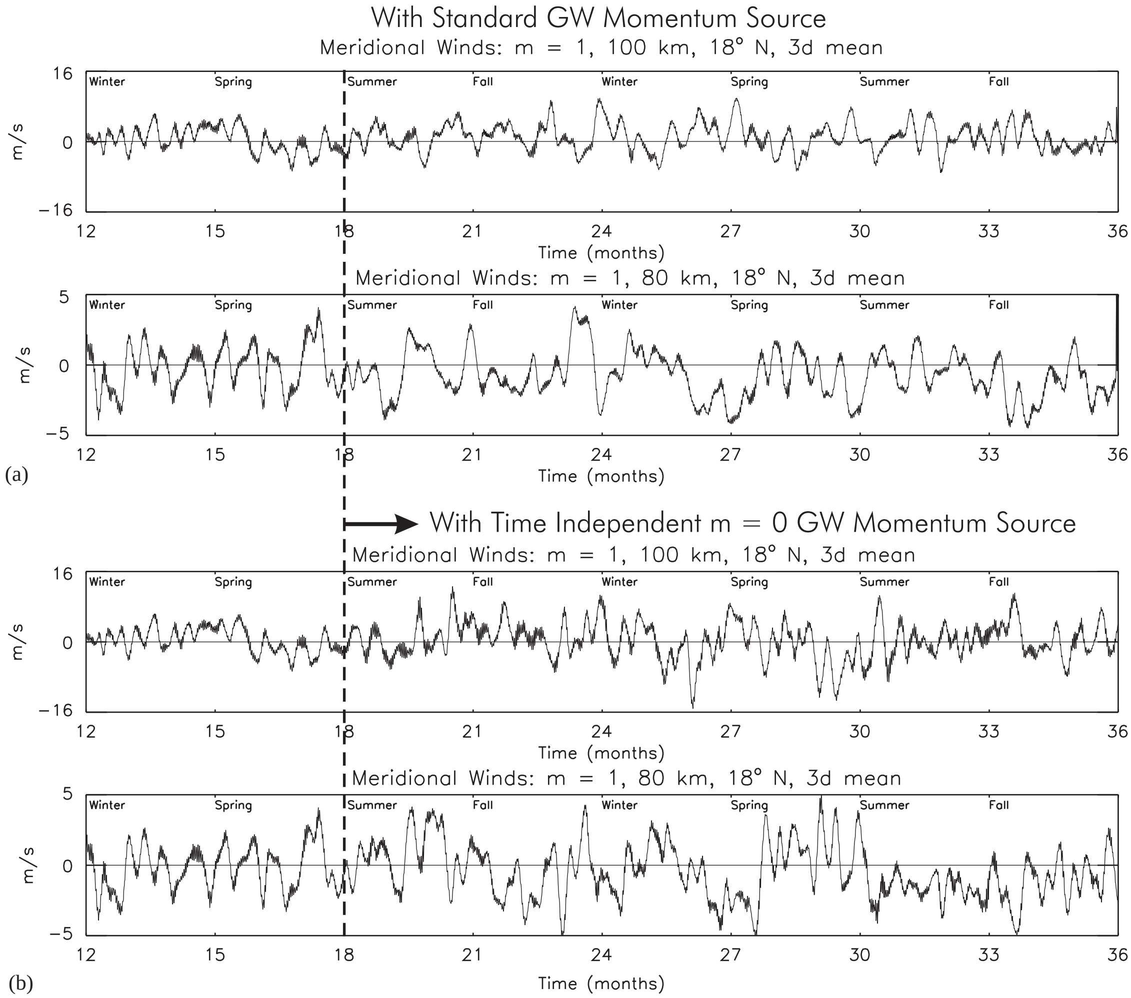

Fig. 6. Analogous to Fig. 5 but for the meridional winds.

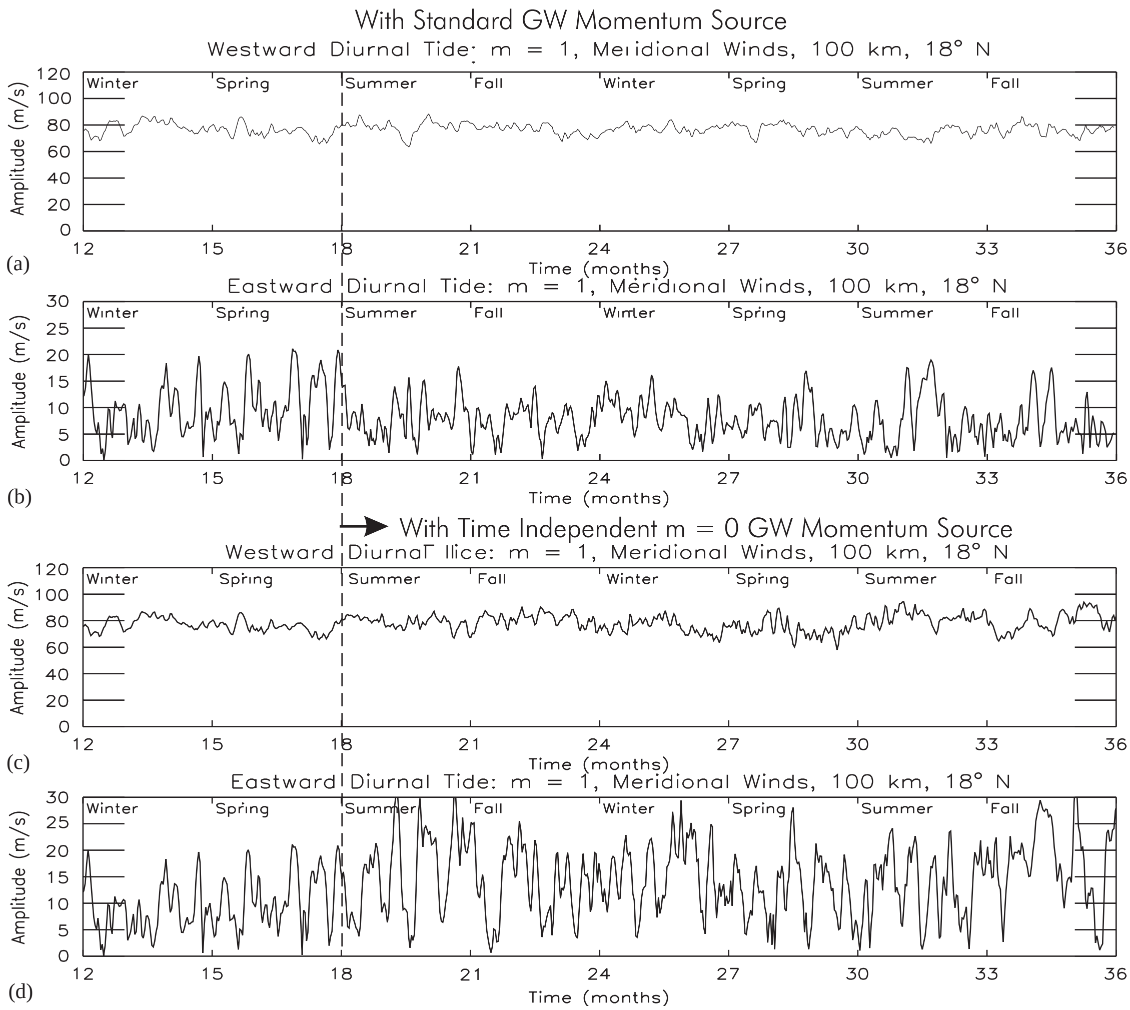

Fig. 7. Diurnal tides for $m = 1$ computed for perpetual equinox with the standard GW momentum source, (a) westward and (b) eastward propagating. For comparison, computed after 18 months with the modified time-independent $m = 0$ GW source. Note that the westward migrating tide (c) is similar in magnitude to that in (a). But the amplitudes for the eastward migrating tide (d) are larger (after 18 months) because the associated PWs for $m = 2$ (not presented) are also stronger, which is consistent with the stronger $m = 1$ PWs shown in Figs. 5b and 6b relative to Figs. 5a and 6a.

model by non-linear coupling between the migrating diurnal tide (c) and the $m = 2$ PWs. And these PWs (not shown) are found to be larger in the case where the $m = 0$ GW source is forced to be time independent, which is consistent with the larger $m = 1$ PWs in Figs. 5 and 6 (b, compared to a).

Finally, we present in Fig. 8 the non-migrating tides for $m = 0$ computed with the standard GW source (a) and, for comparison, with the time-independent $m = 0$ source (b) applied after 18 months. This shows that, relative to (a), the amplitudes are significantly smaller for the case with modified GW source (b) in which the $m = 0$ temporal variations are artificially suppressed (including the periodicity of 1 day). In this case, the decrease in the computed $m = 0$ tide occurs in spite of the fact that the involved PWs are larger than those computed with the standard GW source (comparing Figs. 5a and 6a with Figs. 5b and 6b). Since the $m = 0$ tide is generated by non-linear coupling between these PWs and the migrating tide, and the migrating tides are virtually identical (Figs. 7a and c) in both cases, we are led to the conclusion that GWs indeed play a major role in generating the non-linear coupling illustrated in item 5 of Figure 16I. In our model, GW processes not only affect the migrating tides and PWs, the building blocks of the non-migrating tides, they apparently also

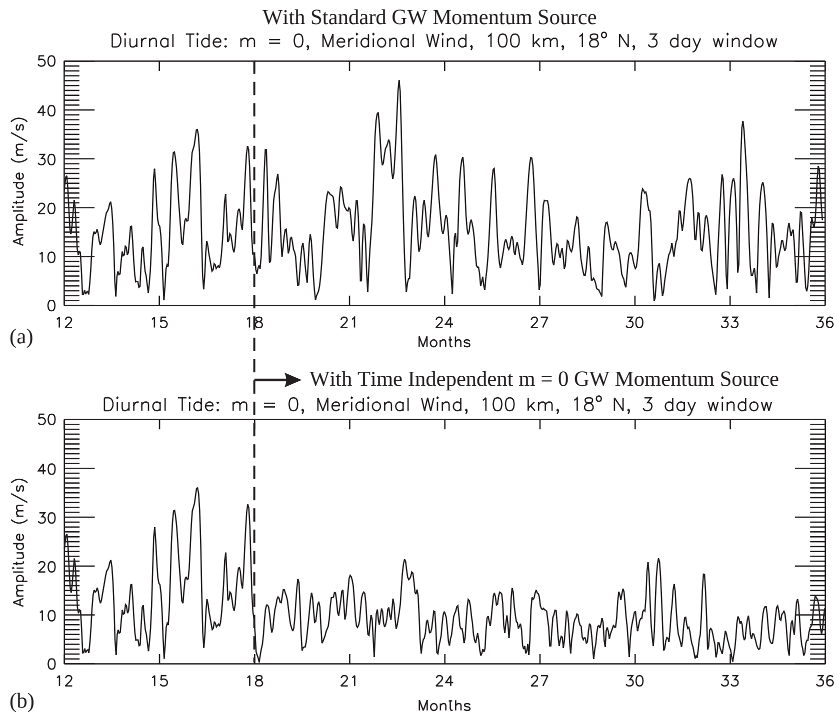

Fig. 8. (a) Diurnal tides for $m = 0$, generated by non-linear interactions between PWs and migrating tides with the standard GW momentum source. In this case, the PWs involved are represented in Figs. 5a and 6a, and the migrating tide in Fig. 7a. (b) For comparison a solution is presented with a source in which the time dependence of the $m = 0$ GW source is suppressed, including the 1-day periodicity. In this case, the PWs involved are represented in Figs. 5b and 6b, and the migrating tide in Fig. 7c. With similar migrating tides, the $m = 0$ tides in (b) are much weaker than in (a) although the PWs involved are significantly stronger. This is interpreted as evidence for the importance of GW-induced non-linear coupling.the figure is identical to Fig. 4 in Mayr et al., 2003).

contribute significantly to the process of non-linear coupling itself that produces the non-migrating $m = 0$ tide.

5. Summary and conclusion

In Part I we demonstrated that non-linear coupling between PWs and migrating tides can generate in the NSM non-migrating tides with amplitudes comparable to those observed in the upper mesosphere and lower thermosphere. Here we discussed two computer experiments to show that GWs are also important for the process of non-linear coupling itself. When the GW momentum source is turned off, the $m = 0$ non-migrating diurnal tide is reduced significantly (Fig. 4). Since the GW interaction in this case did not affect the PWs much (Fig. 3) and did not produce a systematic effect in the zonal and meridional winds of the diurnal migrating tide (Fig. 2), the differences in the non-migrating tide appear to be caused in part by the non-linear coupling (item 5, Fig. 16I) that is associated with GW filtering as illustrated in Fig. 1.

In the second experiment, the standard model was run to equilibrium for perpetual equinox with the Sun fixed at the equator. The time dependence of the $m = 0$ GW momentum source was then artificially suppressed to investigate its specific effect on the non-linear coupling that produces the $m = 0$ diurnal tide. As expected, this modification of the GW source, limited to $m = 0$, does not affect the migrating diurnal tide for $m = 1$ (Figs. 7a and c), but it produces a significant increase in the PW amplitudes (Figs. 5 and 6b, compared to a). In spite of this increase of the PWs, we find that the magnitude of the non-migrating $m = 0$ tide decreases significantly (Fig. 8). This leads to the conclusion that GW filtering of the kind illustrated in Fig. 1 contributes significantly to the process of non-linear coupling between migrating tide and PWs to generate the $m = 0$ diurnal tide. And the same may hold for the other non-migrating tides.

What causes the reduction in the PW amplitudes (Figs. 5 and 6), which is associated with the time dependence in the $m = 0$ GW momentum source that was artificially suppressed in the above discussed computer experiment? Formulating the question differently, one may ask why the time dependence of the

$m = 0$ GW momentum source interferes with the instabilities that exclusively generate the PWs in the NSM. We do not have a good answer but believe that the following might be happening. With the time-independent $m = 0$ GW source, the instabilities may be able to develop more fully to generate the PWs. When the time-dependent variations of the GW source (with a period of 1 day included) are present in the standard model, the instabilities may be disturbed or partially broken up. As a consequence, the PWs then are weakened. One could argue perhaps that a sort of conservation principle is involved: the non-migrating tides being generated in part at the expense of the PWs. GW momentum is conserved in Hines' Doppler spread parameterization. The GW momentum not expended in generating and amplifying the PWs becomes available to generate non-migrating tides through the process of non-linear coupling by wave filtering.

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