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Physical Processes in Acoustic Wave Heating of the Thermosphere

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Physical processes in acoustic wave heating of the thermosphere

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[1] Upward propagating acoustic waves heat the atmosphere at essentially all heights due to effects of viscous dissipation, sensible heat flux divergence, and Eulerian drift work. Acoustic wave-induced pressure gradient work provides a cooling effect at all heights, but this is overwhelmed by the heating processes. Eulerian drift work and wave-induced pressure gradient work dominate the energy balance, but they nearly cancel at most altitudes, leaving their difference, together with viscous dissipation and sensible heat flux divergence to heat the atmosphere. Acoustic waves are very different from gravity waves which cool the upper atmosphere through the effect of sensible heat flux divergence. Acoustic wave dissipation could be an important source of upper atmospheric heating.

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1. Introduction

[2] In a previous paper [*Hickey et al.*, 2001] we discussed how the dissipation of upward propagating acoustic waves heats the thermosphere. That discussion needs to be revisited because the roles of the different physical processes (Table 1) involved in acoustic wave heating and cooling of the thermosphere were not properly identified. This note clarifies how each physical process contributes to the overall net heating. A discussion of how these effects operate in Jupiter's upper atmosphere can be found in *Schubert et al.* [2003].

[3] The problems in the interpretive discussion of *Hickey et al.* [2001] are due to their use of a different, though equivalent form of the heating equation (compare their equation (1) with the equation derivable from the terms in Table 1). They referred to the term $d/dz\left\{\overline{\rho}\, c_p \overline{T}\langle w'\theta'\rangle/\overline{\theta}\right\}$ as the sensible heat flux divergence (θ is potential temperature, and $\overline{T}$ is the mean state temperature). This term should have been identified as the potential temperature flux divergence; it can also be described as dS/dz, where S is the potential sensible heat flux. This quantity includes a heating effect of compressibility arising from $\langle w'p'\rangle$ (wave mechanical energy flux). For quasi-static gravity waves this effect is small and approximately $S = \overline{\rho}\, c_p\langle w'T'\rangle$, i.e., the sensible heat flux. However, for acoustic waves, where compressibility effects are essential, S can be much different from the sensible heat flux and dS/dz should not have been referred to as sensible heat flux divergence. The numerical results in *Hickey et al.* [2001] are correct, but the above term should have been called the potential sensible heat flux divergence. Also, other terms in equation (1) of *Hickey et al.* [2001] scramble the physical effects in Table 1.

[4] In the rest of this note we reinterpret the results in *Hickey et al.* [2001]. Again, those results are numerically correct, but they were not appropriately attributed to the relevant physical processes. Since heating by acoustic and gravity waves is qualitatively much different, it is important to elucidate the relevant physical processes for terrestrial acoustic waves, as has already been done for gravity waves. The model and model parameters are essentially the same as those in *Hickey et al.* [2001]. The background state and vertical structure of the three acoustic waves considered (a wave with a 10 s period and a horizontal wavelength of 6 km, a 2 min wave with a horizontal wavelength of 72 km, and a 4 minute wave with a horizontal wavelength of 144 km, all the waves are fast acoustic waves with horizontal phase speed equal to 600 m s^{-1}) are basically those shown in *Hickey et al.* [2001, Figures 1 and 2], and these figures are not repeated here.

2. Results

[5] Altitude profiles of all the terms that contribute to heating/cooling of the thermosphere are shown in Figure 1 for all 3 acoustic waves. Viscous heating, sensible heat flux divergence, and Eulerian drift work all contribute to heating the upper atmosphere at essentially all heights. Wave-induced pressure gradient work cools the upper atmosphere at all heights. The net influence of the acoustic wave is

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Table 1. Terms in the Energy Balance[a]

Term	Meaning	Designation
$\langle \underline{\underline{\sigma}}'_m : \nabla \underline{v}' \rangle$	Heating rate due to viscous dissipation of wave kinetic energy	$\bar{\rho}\, c_p\, Q_{\mathrm{vis}}$
$-\dfrac{d}{dz}\{c_p \bar{\rho} \langle w' T' \rangle\}$	Sensible heat flux divergence [*Walterscheid*, 1981]	$\bar{\rho}\, c_p\, Q_{w'T'}$
$\langle \underline{v}' \cdot \nabla p' \rangle$	Work done per unit time by wave-induced pressure gradients	$\bar{\rho}\, c_p\, Q_{v'\mathrm{gradp}'}$
$-\dfrac{d\bar{p}}{dz}\dfrac{\langle w' \rho' \rangle}{\bar{\rho}}$	Work done per unit time by second-order wave-induced Eulerian drift in transporting mass in the gravitational field [*Walterscheid and Hocking*, 1991]	$\bar{\rho}\, c_p\, Q_{w'\rho'}$

[a]Angle brackets denote an x, y, t average, x and y are horizontal cartesian coordinates, t is time, z is altitude, T' is wave temperature perturbation, $\underline{v}'$ is the wave velocity vector, $\underline{\underline{\sigma}}'_m$ is the molecular viscous stress tensor of the wave field, c_p is the specific heat at constant pressure, $\bar{\rho}$ is the mean state density, w' is the wave vertical velocity, p' is the wave pressure perturbation, ρ' is the wave density perturbation, primes refer to wave quantities, and overbars refer to basic state quantities. The energy equation equates $\bar{\rho}\, c_p\, Q$ to the sum of the terms in the table [*Schubert et al.*, 2003]. Q is the net or total heating or cooling rate (degrees per unit time). This energy equation neglects dissipation due to eddy viscosity which is small in the thermosphere.

heating at essentially all heights. (Below about 125 km altitude, sensible heat flux divergence has a small cooling effect and the total of all energy transfer terms yields a small net cooling. This cooling is so small that it produces a negligible change in temperature below about 125 km altitude (Figure 1).) While acoustic wave sensible heat flux divergence heats the upper atmosphere, gravity wave sensible heat flux divergence both cools and heats the atmosphere at different altitudes [*Walterscheid*, 1981; *Hickey et al.*, 2001]. Wave-induced pressure gradient cooling and Eulerian drift heating dominate the energy balance and nearly cancel each other. These terms are largest at low altitudes, increase with increasing height below about 100 km altitude, and decrease with height at greater altitudes. These two large terms essentially offset each other and only their small difference (a net cooling effect), at heights where the waves dissipate, contributes to the resultant total wave heating profile.

3. Discussion

[6] We have seen above that for acoustic waves sensible heat flux divergence produces heating at essentially all altitudes while for nearly hydrostatic gravity waves sensible heat flux divergence produces cooling at high altitudes where the waves dissipate and heating below [*Walterscheid*,

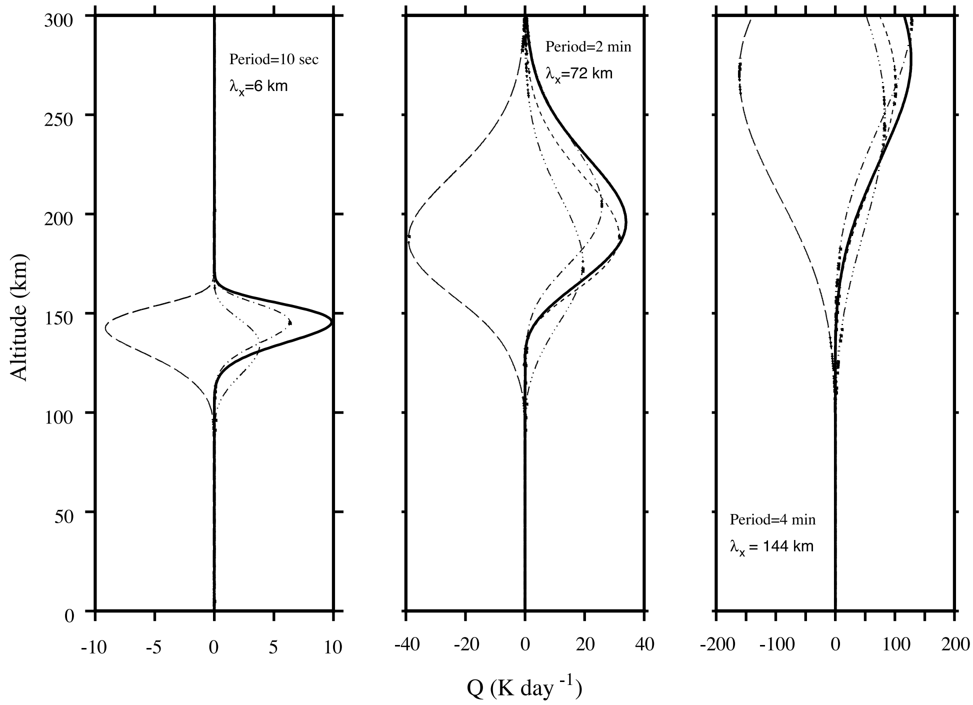

Figure 1. Altitude profiles of wave heating/cooling rates (K day^{-1}) by viscous dissipation (Q_{vis}, dashed-dotted curve), by the sensible heat flux divergence ($Q_{w'T'}$, short dashed curve), by the wave-induced pressure gradients ($Q_{v'\mathrm{gradp}'}$, long dashed curve), by the work done by second-order wave-induced Eulerian drift in transporting mass in the gravitational field ($Q_{w'\rho'}$, dashed-3 dotted curve), and total wave heating/cooling (Q_{tot}, solid curve) for the 10 s, 2 min, and 4 min acoustic waves.

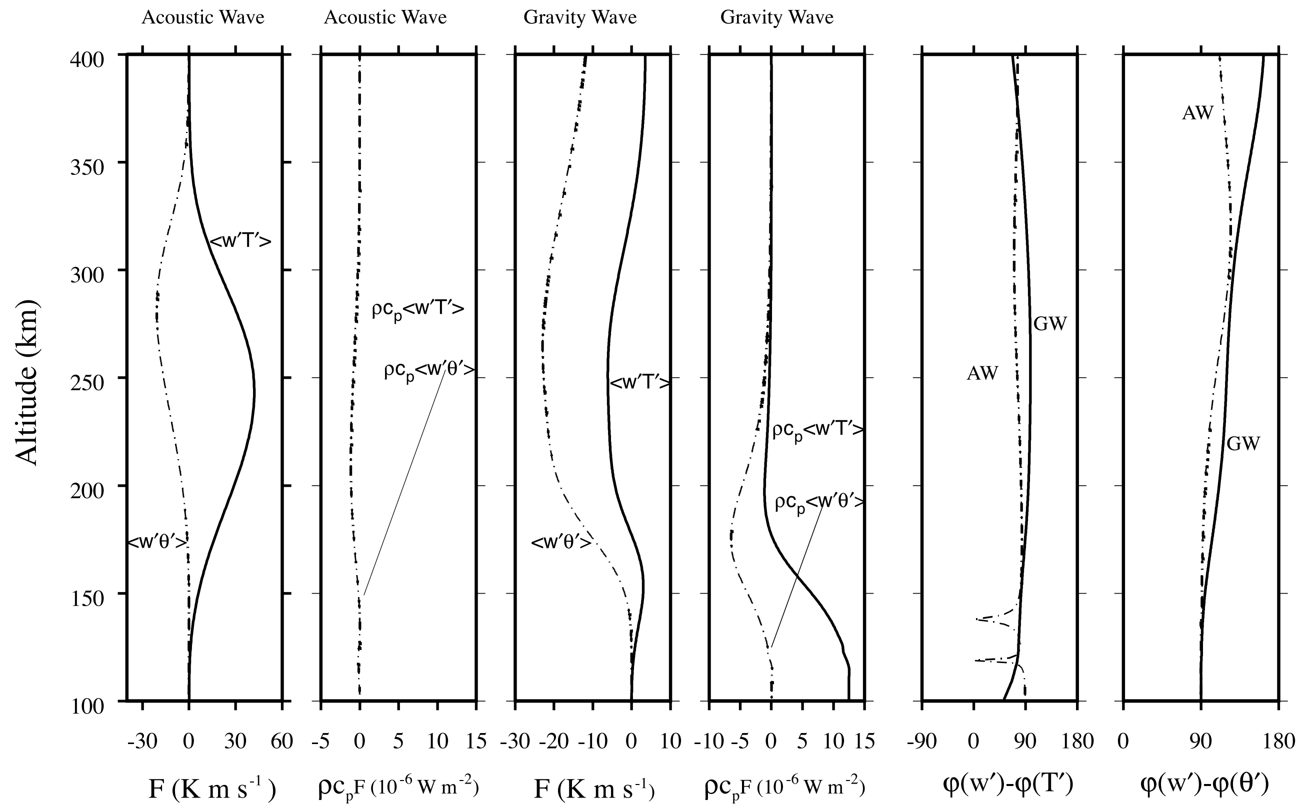

Figure 2. Altitude profiles of the fluxes F of sensible heat and potential temperature and the relative phases φ between the wave vertical velocity and the wave temperature and potential temperature for the 4 minute acoustic wave and a gravity wave with period 60 minutes and horizontal wavelength 720 km.

1981]. Figure 2 helps to explain these differences. It shows altitude profiles of the sensible heat flux, the sensible potential temperature flux, and the phase differences between wave vertical velocity w' and wave temperature T' and potential temperature θ' perturbations for the 4 minute acoustic wave and a gravity wave with a period of 60 minutes and a horizontal wavelength of 720 km. For the acoustic wave, the sensible potential temperature flux is negative and the sensible heat flux is positive. The acoustic wave tranfers sensible heat upward and deposits it at high altitudes where the wave dissipates. For the gravity wave, the sensible potential temperature flux is also negative, but the sensible heat flux changes sign between 100 and 400 km altitude. The gravity wave sensible heat flux is negative between about 175 km and 325 km altitude and positive at greater heights. This leads to gravity wave cooling at high altitude with gravity wave heating below. Figure 2 shows that for both the acoustic wave and the gravity wave, w' is nearly in quadrature with both T' and θ'. Despite these near quadrature relationships, the wave fluxes of potential temperature and sensible heat are nonzero at almost all altitudes.

[7] The negative divergence of sensible heat flux is shown in Figure 3. It is seen that for the acoustic wave $Q_{w'T'}$ is a heating term at essentially all heights with a broad maximum around 260 km altitude (there are negligible cooling effects below about 125 km altitude). For the gravity wave however, it can be seen that $Q_{w'T'}$ is a heating term below about 200 km altitude and a strong cooling term above.

[8] Figure 4 compares the total heating rate profiles of all the acoustic waves studied. The maximum heating rate and the altitude of maximum heating increase with wave period. The maximum volumetric heating rate decreases

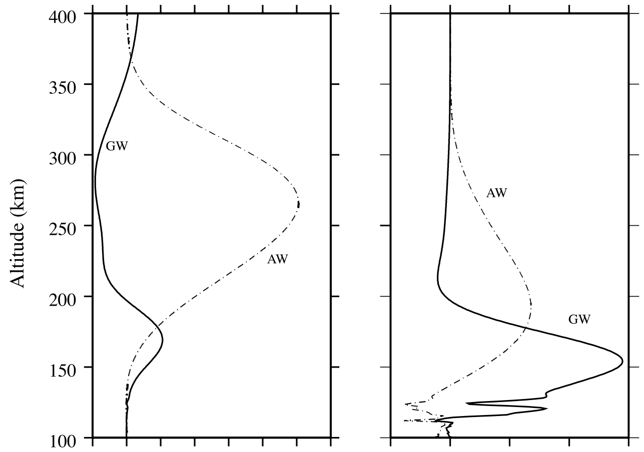

Figure 3. A comparison of altitude profiles of the heating/cooling from sensible heat flux divergence for the acoustic wave and gravity wave of Figure 2. Gravity wave sensible heat flux divergence leads to both heating and cooling at different altitudes while acoustic wave sensible heat flux divergence leads to heating at essentially all altitudes.

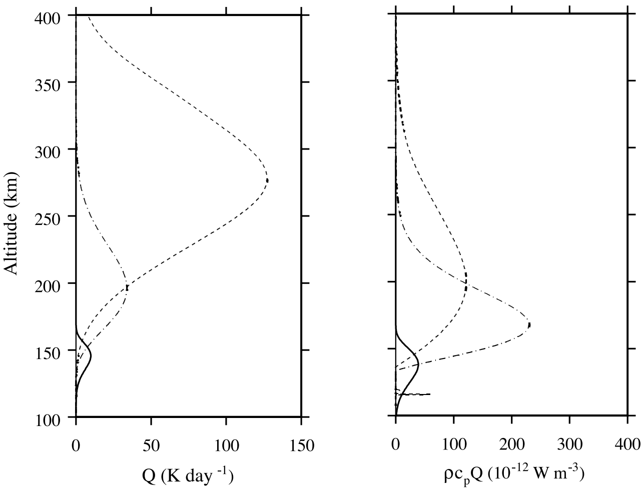

Figure 4. Altitude dependence of total heating for the three acoustic waves studied in this paper in units of K day^{-1} and W m^{-3} (solid curve – 10 s wave, dash-dot curve – 2 min wave, short dash curve – 4 min wave).

with increasing wave period. The heating rate in K day^{-1} increases with an increase in wave period because the longer period waves dissipate at higher altitudes where the energy they deposit has a larger effect on temperature because of the lower density. All the acoustic waves studied carry the same energy upward. The heating rates are identical to those reported in *Hickey et al.* [2001]. The scaling of the wave amplitudes is discussed in that paper and the derived heating rates are shown to compare favorably with observational estimates of acoustic wave heating. As discussed in *Hickey et al.* [2001], the combined effects of geometric spreading, and intermittent and spatially localized wave sources will reduce the effectiveness of acoustic wave heating as a thermospheric heat source. On the other hand, the superposition of waves generated by widespread, albeit isolated storms (as in the Earth's tropics) would counteract the intermittency, localization and spreading associated with individual storms.

[9] Some insight into the differences between acoustic and gravity wave sensible heat fluxes can be obtained from the relation

$$\bar{\rho}\, c_p \langle w'T' \rangle = \langle w'p' \rangle + \frac{g}{N^2}\, \bar{\rho}\, \langle \theta' Q' \rangle \tag{1}$$

where g is the acceleration of gravity, N is the Brunt-Väisälä frequency, and Q' is the diabatic heating per unit mass. This relation follows from the definition of θ and the first law of thermodynamics and is the same as the one found by *Walterscheid* [1981] except that the first term on the right of equation (1) does not appear in the earlier result because it was obtained in pressure coordinates. In pressure coordinates the energy flux contribution is contained in the sensible heat flux.

[10] Equation (1) shows that the sensible heat flux is the sum of an energy flux term F_E (wave mechanical energy flux) and a heating-induced term F_Q (second term on the right side of equation (1)). The energy flux term is unrelated to the viscous heating term which is sometimes modeled in terms of the energy flux. The term F_E may be approximated as the product of the vertical group velocity times the wave energy density. Thus, for the same energy density the contribution to the sensible heat flux from F_E is much greater for acoustic waves than for gravity waves since the vertical group velocities of acoustic waves are much larger than the vertical group velocities of gravity waves. For typical gravity waves the sensible heat flux is significant only when F_Q is large and F_E can be neglected. The term F_Q contributes to cooling where strongly dissipating waves extract heat from a region.

[11] The relative dominance of F_E for acoustic waves results in a fundamental difference between the sensible heat flux for gravity and acoustic waves. Acoustic wave heating is primarily a consequence of the attenuation of an already large sensible heat flux, whereas for gravity waves the heating is caused by heat fluxes that are small except where the wave is dissipating. In this respect heating due to acoustic waves is similar to wave momentum forcing. In both cases the flux is generated where the wave is generated and is transferred up with constant magnitude and zero effect until the wave is dissipated.

[12] The relative importance of F_Q and F_E can be altered by wave reflection from evanescent barriers or wind and thermal gradients. In the extreme case of standing waves resulting from complete trapping, the wave energy flux is nil; in less extreme cases it can be strongly reduced. This can cause regions to exist where the competition between the terms F_Q and F_E is altered in favor of the former term, giving regions of acoustic wave cooling as for gravity waves. This explains the acoustic wave cooling below about 125 km altitude for the 2 minute and 4 minute acoustic waves as discussed next.

[13] The divergence of the acoustic sensible heat flux produces cooling below about 125 km altitude for the 2 minute wave. This cooling is not expected for the dissipation of acoustic waves propagating in an isothermal atmosphere. In a non-isothermal atmosphere cooling can result from the reflection of a wave. In this case the 2 minute acoustic wave is reflected from about 125 km altitude where the wave first becomes evanescent as its phase speed turns subsonic [*Hickey et al.*, 2001]. This leads to standing wave behavior below 125 km altitude [*Hickey et al.*, 2001]. The amplitudes of the perturbation vertical velocity and temperature are shown as a function of altitude for the 2 minute wave in Figure 5. The standing wave behavior is apparent, and it can be seen that for altitudes at and below about 125 km, the nodal structure in w' is approximately out-of-phase with the nodal structure in T'. This leads to a local increase of $\langle w'T' \rangle$ with increasing altitude below about 125 km altitude and hence to cooling at those altitudes. At greater heights $\langle w'T' \rangle$ decreases with increasing altitude, leading to heating associated with the sensible heat flux divergence.

4. Concluding Remarks

[14] We have revisited an earlier study to elucidate the relevant physical processes involved in the acoustic wave heating and cooling of the terrestrial thermosphere and how each process contributes to the net heating. At low thermospheric altitudes the cooling effect of the work done by

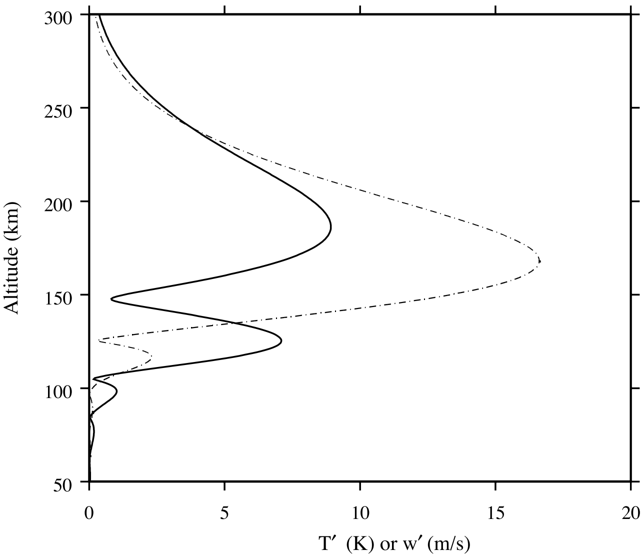

Figure 5. Altitude structure of the wave vertical velocity w' and temperature T' of the 2 min acoustic wave (solid curve – w', dash-dot curve – T').

wave-induced pressure gradients exactly cancels the heating of the work done by the wave-induced Eulerian drift. The net heating considering all terms is small. A small cooling can result from the effects of wave reflection below ~125 km altitude. At higher thermospheric altitudes, contributions due to viscous heating and sensible heat flux divergence come into play and heating can be significant, ~10^2 K per day. We argue that acoustic waves generated by extensive areas of deep convection can be a particularly important source of acoustic wave heating.

[15] For all the acoustic waves considered, the viscous heating, sensible heat flux divergence and Eulerian drift work all contribute to heating the upper atmosphere. Where heating can be significant, the dominant heating processes are viscous heating and sensible heat flux divergence.

[16] We find that acoustic waves and gravity waves heat (cool) the atmosphere in fundamentally different ways due to the different nature of the sensible heat flux for these waves. For gravity waves the heat flux is small except where the waves dissipate and induce a downward sensible heat flux. Cooling occurs where dissipating waves extract heat from a region and warming occurs where the heat is deposited. For acoustic waves compressibility effects dominate and the waves transfer sensible heat upward at all heights in the form of a wave energy flux and deposit it at high altitudes where the waves dissipate. Heating due to acoustic waves is similar to wave momentum forcing in the respect that in both cases the flux is generated at the wave source and transferred up with constant magnitude and zero effect until the wave dissipates.

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