Tutorial Review

Global propagation of gravity waves generated with the whole atmosphere transfer function model

Hans G. Mayr\textsuperscript{a,b,}\textsuperscript{*}, Elsayed R. Talaat\textsuperscript{a}, Brian C. Wolven\textsuperscript{a}

\textsuperscript{a}Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
\textsuperscript{b}Emeritus, NASA Goddard Space Flight Center, Greenbelt, MD, USA

\textbf{A B S T R A C T}

A brief review is presented of the Transfer Function Model (TFM) [e.g., Mayr et al., Space Science Reviews, 1990], which describes acoustic gravity waves (AGW) that propagate across the globe in a dissipative and static (no winds) background atmosphere with globally uniform temperature and density variations extending from the ground to 700 km. Unique among existing models, the TFM can be placed between the analytical approach on one end, and the rigorous numerical approach of general circulation models (GCM). The time consuming numerical integration of the conservation equations is restricted to compute the transfer function (TF) for a broad range of frequencies and spherical harmonics. Given TF, the atmospheric response for a chosen source configuration is then obtained in short order. Computationally efficient, the model is well suited to serve as experimental and educational tool for simulating propagating wave patterns across the globe. By design, the TFM is also semi-analytical and therefore well suited to explore the different wave modes that can be generated under different dynamical conditions.

\textsuperscript{*}Corresponding author at: Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, United States. Tel.: +1 443 778 9107.
\textit{E-mail addresses:} hans.mayr@jhuapl.edu, hmayer@verizon.net (H.G. Mayr).

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literature (e.g., Beer, 1974; Hines and Colleagues, 1974; Yeh and Liu, 1974; Francis, 1975; Gossard and Hooke, 1975; Hunsucker, 1982; Fritts, 1984, 1989; Hocke and Schlegel, 1996; Fritts and Alexander, 2003).

In broad terms, there are two classes of theoretical models that describe acoustic gravity waves (AGW). On one end are analytic/numerical hybrid models (e.g., Vadas and Fritts, 2005; Vadas, 2007; Vadas and Liu, 2009; Vadas and Nicolls, 2012). In this kind of model, the derivation of the local dispersion relation is fully analytical, and so is the analysis of convective wave generation. For waves generated in the thermosphere and troposphere, the numerical part of the model then applies ray tracing to describe the propagation through the time and spatially varying temperature and wind fields of the background atmosphere. The analysis also accounts for the generation of secondary waves. On the other end of gravity wave models are those that provide rigorous numerical solutions of the non-linear Navier Stokes equations like GCMs (e.g., Sato et al., 1999; Piani et al., 2000; Lane et al., 2001; Walterscheid et al., 2001; Miyoshi and Fujiwara, 2008). This class of models provides a comprehensive description of the physical processes that influence the propagation of AGW and their interactions with the background atmosphere, of critical importance for the climatology.

The numerical Transfer Function Model (TFM) discussed here (e.g., Mayr and Volland, 1976; Mayr et al., 1984, b, 1987, 1990) can be placed between the analytical approach and the rigorous numerical models. In the TFM, the time consuming integration of the fluid-dynamic equations is restricted to derive the transfer function for a broad range of frequencies and spherical harmonics. For a chosen time dependent source, the global wave response is then obtained in short order. In this review of the model, the waves are taken to originate at high latitudes in the auroral region, which is a prolific source of gravity waves, observed in temperature and wind measurements on the AE-C and DE-2 satellites (Spencer et al., 1976, 1981, 1982), illustrated in Fig. 1. The waves are generated by precipitating particles, and by Joule heating and momentum coupling due to solar wind induced electric fields (e.g., Chimonas and Hines, 1970; Testud, 1970).

In Section 2, we discuss the theoretical concept of the TFM and the physical processes applied. In Section 3, we discuss some properties of the transfer function and related gravity wave modes. In Section 4, examples are presented of impulsive wave perturbations simulated with the model. A brief summary is presented in Section 5.

2. Transfer function model (TFM)

The Transfer Function Model (TFM) computes the wave perturbations in a static (no winds) background atmosphere with
For a chosen time dependent excitation source varying horizontally, \( q(t, \theta, \phi) \), the related source spectrum, \( q(L, \omega) \), is then folded into \( TF(z, L, \omega) \) to produce the global wave response. The synthesis of source and transfer function is very efficient computationally. Given the transfer function, the wave response is obtained in essence instantaneously. Computationally efficient, the TFM is therefore well suited to serve as experimental and educational tool for simulating propagating wave patterns on the globe. Separating the transfer function from the horizontal excitation source, the model is also semi-analytical and therefore well suited to explore the different wave modes that can be generated under different dynamical conditions.

The TFM does not account for nonlinear processes and wave mean flow interactions, which are the hallmark marks of general circulation models (GCM). In a class of its own, however, the numerical TFM is a versatile and efficient semi-analytical tool for simulating gravity waves propagating through the whole atmosphere, and across the globe, without limitations in spatial and temporal resolutions. The gravity wave simulations of the past were carried out with FORTRAN, which remains the software of choice for the compilation of the transfer function, TF. But for the synthesis of TF with the excitation source, the Interactive Data Language (IDL) is much better suited, especially when the model is applied as an educational wave simulation tool – and with that software, efforts are underway to resurrect the TFM.

### 3. Gravity wave transfer function and wave Modes

#### 3.1. Transfer function (TF)

In the framework of the linear TFM, the transfer function (TF) describes the dynamical properties of the atmosphere divorced from the complexities of the horizontal and temporal variations of the excitation source. This is illustrated in Fig. 3, where we present the computed relative temperature variations at 300 km.
Fig. 3. Height variations A and B of heat source (a) generate for a frequency of 48 c/d the temperature transfer functions, plotted versus wave number, \( L \), which are shown in the thermosphere at 300 km (b, c), and lower atmosphere at 40 and 60 km (d). Source: (Figure taken from Mayr et al. (1990).)

(Fig. 3b and c) and at 40/60 km (Fig. 3d) for a frequency of 48 c/day (period of 30 min), plotted versus horizontal wave number, \( L \) (approximately related to the horizontal wavelength, \( \lambda = 2 \pi r/L \), \( r \) Earth radius). The amplitudes are shown for two excitation sources varying with altitude (Fig. 3a), one confined to the lower thermosphere (A), the other one (B) extending to higher altitudes with a heating rate proportional to the density above 150 km. The phase variations are presented for the source B, virtually identical to A.

As shown in Fig. 3b and c, TF exhibits amplitude maxima and associated rapid phase transitions characteristic of resonances, which are the signatures of different gravity wave modes. With a thermospheric temperature of 1000 K, the lower cut-off for propagating gravity waves (Hines, 1960) occurs at a horizontal wavelength corresponding to \( L = 25 \) for atomic oxygen and \( L = 40 \) for molecular nitrogen. For the thermospheric mixture of the two gases, these values are consistent with the rapid build up of TF at about \( L = 30 \) shown in Fig. 3c. The lowest order resonance at about \( L = 32 \), with horizontal wavelength \( \lambda = 1200 \) km, describes the quasi horizontally propagating gravity wave of the thermosphere, referred to as direct wave (Francis, 1975). The direct wave has a phase velocity of about 700 m/s, near the sound speed, which is large compared with the tidal wind oscillations in the thermosphere. The second resonance peak in TF occurs at about \( L = 47 \) (\( \lambda = 850 \) km); it is excited in the lower thermosphere. The wave...
from the lower thermosphere propagates more obliquely, and it has shorter wavelengths and lower phase velocities.

A distinct and outstanding feature of TF is the narrow resonance peak near \( L = 87 \), which is the signature of a wave with horizontal wavelength of about 450 km and horizontal phase velocity of about 250 m/s, close to the sound speed of the lower atmosphere. Based on classical gravity wave theory (Hines, 1960), this is the ducted wave that is produced through reflections from the Earth’s surface and from the temperature gradient in the lower thermosphere. The short-wavelength ducted wave propagates in the lower atmosphere virtually without viscous dissipation, and leaks back into the thermosphere where it can travel large distances from the source without much loss of power.

Another class of waves appears in the form of broad resonance maxima at higher wave numbers \( L > 90 \), which are the signatures of gravity waves reflected from the Earth’s surface (Francis, 1975). In contrast to the sharp resonance peak of the ducted wave that essentially propagates horizontally, the reflected wave propagates obliquely with lower horizontal phase velocities < 230 m/s. As expected there are no signatures of the thermospheric waves in the lower atmosphere (Fig. 3d), where the ducted and Earth reflected waves dominate for \( L > 80 \).

In the thermosphere, molecular diffusion produces large variations in the composition. To account for that, the continuity and momentum equations are solved for the individual species to derive the transfer functions of densities and associated transport velocities, allowing for collisional momentum transfer between species. The effect is shown in Fig. 4a for the density transfer function (TF) of different species at 300 km, which is generated with a frequency of 48 c/d, and with the heat source B (Fig. 3a). For comparison, TF is shown in Fig. 4b without collisions. With collisions, i.e., momentum transfer, the amplitudes of Ar and He are about a factor of 2 larger than that of the dominant O; without collisions the differences are much larger. Momentum transfer has the effect to impress the dynamic properties of the major species upon the minor ones. The individual species lose some of their identity related to mass. Besides composition effects, momentum transfer between the dominant species O and N\(_2\) affects significantly the temperature and wind fields, as shown in Fig. 4c.

### 3.2. Wave modes

The thermospheric wave modes identified in the above-discussed transfer function (TF), shown in Fig. 5a, can be readily simulated with simple source configurations. They are generated with the wave number spectra of 3° and 8° source pixels presented in the lower two panes of Fig. 5a. (A pixel with infinitely small diameter would produce an infinitely wide Dirac delta function spectrum, covering all \( L \) values with uniform amplitudes; the wider or narrower the source, the narrower or wider the wave

**Fig. 5.** (a) Shown are the temperature transfer function amplitudes (upper pane) from Fig. 3c, and spectra for 3° and 8° wide pixels of localized identical energy sources (lower panes). (b) Computed temperature perturbations (amplitude and phase), generated with source pixels in Fig. 5a. The broad 3° source (upper pane) covers the waves originating also in the lower thermosphere, which produces narrow propagation cones with shorter horizontal wavelengths. The narrow 8° source (lower pane) mainly generates the waves of the upper thermosphere, with uniformly large horizontal wavelengths.

Source: (Figures taken from Mayr et al. (1990)).
With identical amplitudes for the excitation sources, the resulting temperature response is presented in Fig. 5b along a meridian intersecting the source at 25° colatitude. The broad source extends to large $L$ values and covers the entire TF spectrum of waves excited in the upper and lower thermosphere in particular. As a result, prominent propagation cones are generated with amplitude maxima close to the source (Fig. 5b, upper pane), which are produced by the waves originating in the lower thermosphere that have shorter horizontal wavelengths. Away from the source and outside the propagation cones, the direct wave dominates that propagates quasi horizontally in the dissipative upper thermosphere. For the 8° source, the ducted wave is filtered out (upper pane), and the wavelengths are uniformly large at all latitudes.

The wave modes of the lower atmosphere are simulated with frequencies of 24 and 72 c/d (60 and 20 min respectively), which produce with heat source B (Fig. 3a) the temperature transfer functions (TF) at 300 km shown in the upper pane of Fig. 6a. Consistent with gravity wave theory, $L$ in Fig. 6a increases in proportion to the frequency, and the horizontal wavelength decreases. The wave response is generated employing the 6° and 8° source pixels shown in the lower panes of Fig. 6a. The 6° pixel is

Fig. 6. (a) Upper pane shows computed temperature transfer functions (TF) at 300 km, plotted versus $L$, generated with source B (Fig. 3a) and frequencies 24 and 72 c/d; in the lower panes, source spectra are shown for 6° and 8° wide pixels. (b) Temperature perturbations (amplitude and phase) generated with TF, applying the source spectra in Fig. 6a. With 8° source, the ducted wave for 72 c/d is generated (lower pane), which produces short horizontal wavelengths at high colatitudes near the equator. With 6° source, the ducted wave is filtered out (upper pane), and the wavelengths are uniformly large at all latitudes.

Source: (Figures taken from Mayr et al. [1990].)
chosen specifically so that it filters out the narrow resonance maximum at $L=130$, which describes the ducted wave in TF for 72 c/d. Fig. 6b (upper pane) shows the computed temperature amplitude and phase plotted versus colatitude along a meridian intersecting the source at $10^\circ$. The amplitude peaks inside the source. Maxima form around the source, which represent narrow propagation cones produced by waves propagating up from the lower thermosphere above discussed. As the waves propagate away from the source, the higher frequency (72 c/d) amplitudes decrease more rapidly. In the thermosphere with molecular viscosity, the shorter horizontal wavelengths produce more dissipation. As shown in Fig. 6b (lower pane), however, the wavelength of the short period wave (72 c/d) suddenly decreases away from the source above 60°, and the steep decline of the amplitude levels off – but only for the 8° source pixel. For this source (Fig. 6a), the ducted mode at $L=130$ is excited, in contrast to the 6° pixel where the wave is eliminated by a node in the spectrum. The ducted wave propagates unabated in the inviscid lower atmosphere, from where it leaks up into the thermosphere. In the thermosphere, this short-wavelength wave thus appears to propagate virtually without attenuation, so that it dominates at large distances from the source where the long-wavelength thermospheric wave has lost power due to viscous dissipation.

The above discussed wave modes are illustrated in Fig. 7. With the auroral energy source, $Q$, the model generates: (1) the direct wave that propagates horizontally with the sound speed (700 m/s) of the upper thermosphere that is large compared with the tidal wind oscillations; (2) the wave that propagates up from the lower thermosphere; (3) the ducted wave that slowly propagates horizontally (250 m/s) in the inviscid lower atmosphere, from where it propagates up into the thermosphere traversing the large temperature increase above 100 km; and (4) the wave reflected from the Earth surface.

Spacecraft data show that there is statistical evidence for the above discussed short-wavelength ducted and long-wavelength thermospheric waves that can be generated in the auroral region. Thermospheric winds give rise to traveling ionospheric disturbances (TID), which have been categorized into medium scale and large scale perturbations of order 100 and 1000 km (Georges, 1968). Based on satellite measurements on AE-C and AE-E, disturbances in the range 400–4000 km have been observed in neutral and ion densities at all latitudes across the globe (Gross et al., 1984). The observations are consistent with wave-like perturbations in the neutral composition inferred from a statistical analysis of DE-2 satellite measurements (Hedin and Mayr, 1987), which produce horizontal wavelength bands of 40–400 and 400–4000 km. The long and short wavelength bands are observed to be correlated with magnetic activity and decrease by about a factor of 3 from the pole to the equator, with the longer wavelengths amplitudes a factor of five larger. The satellite data show that the amplitudes remain large during low magnetic activity – and this is understandable because the planetary Ap index for the global current system is not a good measure of the gravity wave excitation source (Mayr et al., 1990). Localized and short duration energy deposition is more conducive for creating the resonance-like conditions that generate gravity waves. The temperature and wind fields in the lower panes of Fig. 1, for example, show large perturbations for $Ap=12$, but none for $Ap=48$.

It is important here to emphasize that gravity waves observed in the thermosphere can also originate in the lower atmosphere. This is shown convincingly in the model simulations of Vadas and Fritts (2005), Vadas (2007), Vadas and Liu (2009), and Vadas and Nicolls (2012), which demonstrate that the waves generated by tropospheric convection can produce considerable temperature and wind perturbations in the thermosphere at equatorial latitudes.

4. Impulsive perturbations

4.1. Composition effects

Under realistic conditions, an auroral source does not produce a single frequency oscillation, which was assumed for the above wave simulations shown in Figs. 5 and 6. In general, the source...
tends to be impulsive. This requires that the entire transfer function is applied with integral Fourier transformation, covering a broad range of frequencies and wave numbers. In Fig. 8 such an impulsive perturbation is generated with Joule heating for a ring source at 20° colatitude that is 5° wide. As illustrated in the top pane, the source is abruptly turned on and off, and lasts for 1 h. The resulting time variations of temperature, N₂ and He densities, and wind velocities are shown at 50° colatitude, away from the source. In agreement with DE-2 observations around 300 km (Hedin and Mayr, 1987), the variations in He and N₂ are out of phase, and the amplitudes are of comparable magnitude, caused by collisional momentum transfer between species above discussed.

Density variations of the kind shown are common in the thermosphere, observed with satellite borne mass spectrometers (e.g., Hedin et al., 1977a, 1977b). The He concentration is much lower in summer than in winter, opposite to the N₂ and temperature variations. During magnetic storms with increasing N₂ density in the auroral source region at high latitudes, He is observed to decrease. The variations are generated by mass transport under the influence of molecular diffusion (e.g., Mayr et al. (1978)).

Controlled by the decreasing density of the major gas N₂, flow continuity requires that the winds are larger in the upper leg of the circulation relative to the reversing flow in the lower leg. Embedded in this flow field, the minor and lighter species He, with larger vertical scale height, is effectively removed by the upper leg of the circulation that diverges away from the source region. For the propagating gravity waves, the alternating wind bands produce N₂ and He oscillations respectively, in phase and out of phase with the temperature variations shown in Fig. 8.

Considering that the chosen source configuration is rather simple for the above discussed oscillations, the thermospheric wave response is relatively complicated. The response pattern has no resemblance to the impulsive excitation source, and a number processes contribute to that. As the source is turned on or off, a broad band frequency spectrum is produced. From that spectrum, waves are generated that match the ring source geometry, obeying classical gravity wave theory. About an hour after the build up of the distant source, the perturbations are seen to develop, and this agrees roughly with the time it takes for the fast thermospheric wave that propagates with a velocity of about...
The increase in the apparent wave period with progression of time could be caused in part by the ducted wave from the lower atmosphere that propagates with a much smaller velocity of 250 m/s. The ducted wave can also be taken over by the fast thermospheric wave that is reflected from the pole, the center of the ring source.

Neutral mass spectrometer measurements of thermospheric densities on Pioneer Venus (Niemann et al., 1980) reveal pronounced gravity wave perturbations, He opposite in phase with O and CO₂ (Kasprzak et al., 1987) – and the TFM reproduces the observations with an excitation source in the lower atmosphere (Mayr et al., 1988).

### 4.2. Multiple excitation sources

The simple source configurations above discussed provide a basic understanding of the processes that characterize the propagation of gravity waves. But they do not represent realistic scenarios. In the real world, the auroral source resembles a "garden hose", in which the energy is deposited in a meandering pattern. To account for this complexity, we present here a wave simulation in which the temporal and spatial variations of the source are specified separately in some arbitrary fashion. The waves are generated with 3 local source pixels illustrated in Fig. 9a. Each source is 3° in diameter and is located along a circle around 20° colatitude, along longitudes of 0°, 12° and 18°. For the time dependence, each source is impulsive and lasts 20 min, turned on at 0, 1.2, and 1.8 h, starting with the one at 0° longitude (I) and ending with the one at 18° (II). The lower panes of Fig. 9 show contour plots of the temperature perturbations generated by Joule heating (b) and the electric field momentum source (c), plotted versus time and colatitude along a meridian intersecting source I at 0° longitude. The 3 excitation sources are close together, so the waves propagating away appear to come from the same location. Moreover, the propagation velocity of the dominant thermospheric wave is about 700 m/s, and the communication time between the source pixels is only 10 min, short compared with the pulse duration. Inside the source region at 20° colatitude, the temperature perturbation with Joule heating (Fig. 9b) reveals the localized trapped component with slow decay; energy is gradually removed by heat conduction. For the momentum source without energy deposition, the trapped component is not prominent (Fig. 9c). Outside the source region, the propagation patterns in Fig. 9b and c reveal the different wave modes earlier discussed, which are labeled in order of decreasing propagation velocities: (1) the direct quasi-horizontally propagating wave that propagates with the high sound speed of the thermosphere, (2) the slower wave originating in the lower thermosphere, and (3) the ducted wave that slowly propagates with the sound speed of the lower atmosphere. The amplitudes of the waves decrease away from the source due to viscous and geometric attenuation. Dissipation is evident in the steep decay of the thermospheric wave amplitudes (1) produced by molecular viscosity, in contrast to the slow decay of the weaker ducted wave (3) that propagates up from the inviscid lower atmosphere.

### 4.3. Simulation of satellite observations

A model simulation is presented of temperature and vertical wind velocities that match the Dynamics Explorer (DE)-2
measurements (Spencer et al., 1981) shown in Fig. 10a. The data come from a magnetic storm on December 25, 1981, when the planetary magnetic index was $Ap = 200$ for a short period of less than 3 h. Simultaneous measurements of electric fields (Maynard et al., 1981), magnetic fields (Farthing et al., 1981), and precipitating particles (Winningham et al., 1981), all show disturbances confined to latitudes near 65°. An image of auroral emissions (Frank et al., 1981), taken from DE-1 4 h earlier, indicates a ring-like source geometry. Based on these observations, a simple model was constructed (Mayr et al., 1985) that is presented in Fig. 10b. Around the magnetic pole, a ring source is chosen with 2500 km radius and 500 km wide. The source is turned on and off over 10 min and lasts for 1 h. In the lower panes of Fig. 10b, the model simulations are shown for the temperature and vertical velocities, plotted versus colatitude relative to the magnetic pole. The computed perturbations closely resemble the DE-2 observations (Fig. 10a), except for the amplitudes of the vertical velocities that are smaller than those observed. The model results are presented for 2 instances in time, 24 min and 36 min (labeled 1 and 2, respectively) after the source is turned on. Displayed in Fig. 10b, these time spots show that two wave patterns are generated. One wave propagates towards the equator (1 followed by 2), the other one to the pole. As the temperature wave propagates to the pole, the center of the ring source, a saddle like pattern is generated by geometric amplification (Fig. 9b). As the wave converges at the pole, the amplitude increases. At a later point in the time evolution (not shown), the amplitude will peak at the pole, and the impulsive wave will then propagate out of the polar region towards low latitudes. An important property of the TFM is that it enables wave simulations across the globe. The formulation with spherical harmonics eliminates the numerical problems, encountered in grid-point models, which are produced by indefinite terms with vanishing denominator, $1/\sin$, that arise in the governing differential equations at polar latitudes.

5. Summary

Acoustic gravity waves (AGW) are ubiquitous in the Earth's atmosphere and contribute significantly to the observed variability. Models of AGW have therefore increasingly come to the forefront of atmospheric science, and in this brief review a concise summary is provided of the Transfer Function Model (TFM).

Conceptually different from the analytic/numerical hybrid models and general circulation models (GCM), the TFM can provide a valuable complementary role. The linear TFM describes acoustic gravity waves propagating across the globe in a dissipative and static (no winds) background atmosphere with globally uniform temperature/density variations. The model accounts for collisional momentum transfer between atmospheric species, which affects significantly the wave perturbations of temperature, densities, and wind fields. Compared to GCMs, the TFM does not account for nonlinear processes, in particular for the wave interactions with temperature and wind fields like atmospheric tides. But the model is not limited in temporal and spatial resolutions. By design the model is semi-analytical, separating the transfer function from the excitations source. The model is thus well suited to explore and identify different wave modes that can be generated under different dynamical conditions, discussed in Section 3. In the TFM, the time consuming integration of the conservation equations is restricted to derive the transfer function. For a chosen time dependent excitation source, the global wave response is then obtained in short order, illustrated with simulations of impulsive wave perturbations shown in Section 4. The model is therefore also well suited to serve as experimental and educational tool.

It is well established that the large perturbations observed in the auroral region of the thermosphere are gravity waves, which are generated by Joule heating and momentum coupling associated with solar wind induced electric fields and precipitating particles. The TFM discussed has been employed to explore and simulate the waves excited by the auroral source. But the model extends from the ground to the exosphere above 400 km and can be readily applied to describe also the gravity waves that are generated in the lower atmosphere, as is shown in model simulations applied to Mars and Venus (Mayr et al., 1992).

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