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Temperature changes over storms from measurements of spacecraft TIMED

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In the present work we have studied changes of mesospheric temperature over the powerful storms Wilma, Haitang, and Katrina using measurements of the space vehicle TIMED. We have found the temperature increasing at the altitude range 80–100 km. We have found the explanations for the obtained results by the dissipation of the gravity waves. Propagation of atmospheric gravity waves in a non-isothermal, windless atmosphere, with taking into account the viscosity and the thermal conductivity, has also been modelled in this work. We have determined that the maximum of amplitude of the atmospheric-gravity waves at the considered characteristics corresponds to altitudes of near 90 km (mesopause). It was found that the main factor influencing propagation and dissipation of the wave in such cases is the vertical temperature gradient. Viscosity and thermal conductivity have less influence on the wave amplitude.

Key words: pressure, density, and temperature; ionosphere-atmosphere interactions; wave propagation; middle atmosphere dynamics; thermospheric dynamics; tropical meteorology

INTRODUCTION

Nowadays there is much evidence of the existence of atmospheric-gravity waves (AGW) in the neutral Earth's atmosphere. Among the observed facts one may discern: wave structures on the tropospheric and noctilucent clouds; variations of the surface pressure at microbarogrammes; wave variations of ozone concentration and other impurities in the middle atmosphere; wave structures obtained by the ionosphere's radiosounding method, etc. [16, 18, 20, 24].

There are tens of possible sources of AGW, among which the most potent are: tropospheric cyclons and frontal systems; solar terminator; hurricanes; storms; nuclear tests; large-scale anthropogenic disasters; earthquakes; volcanic eruptions; supersonic rockets' flight etc. [11, 29].

The spectrum of gravity waves in atmosphere is very wide. They can have periods from a few minutes up to tens of hours [10, 27]. As the AGW propagates upwards in the adiabatic regime, the AGW amplitude increases as density decreases [15, 24, 42]. Meanwhile, as the altitude increases, the adiabatic condition of the wave propagation breaks. Such an effect mostly leads to the loss of durability of these waves and to their dissipation.

Investigation of AGW at altitudes of 80–100 km and identification of the source of the AGW meets a range of difficulties [13]. It is particularly difficult studying this problem by ground-based imaging techniques. Short horizontal wavelength AGWs reach the airglow region a few hundred kilometres from their source, which means that the ground-based imagers must be placed close to the source region. However, the periods of intensive convective activity are also periods of considerable cloudiness, which often precludes imaging observations. Then, there is some evidence that the AGWs, which are seen in imagers, may be ducted a considerable horizontal distance from their source, making it difficult to determine the origin of these waves [40]. Finally, until recently, there were almost no space-based instruments capable to make images of AGWs above the troposphere. Nevertheless, there were several studies attempting to determine specific AGW sources. They could be separated into two classes: those regarding AGWs which travel directly from the convective source to the observation height, and those regarding the ducting or trapping of AGWs.

There are only a few such reports of the first *former* category. The first one was a ground-based study by Taylor and Hapgood [37], which observed curved wave fronts with a centre approximately 200 to 500 km from the observed wavefronts. They used the estimates of the wind and temperature profiles from the limited satellite and model data available

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for analysis. The horizontal wavelength was about 25 km, and the intrinsic period was found to be approximately 17 min. From meteorological charts and lightning data it was shown that there were transient thunderstorms present in the studied region, which were found to be the source of these AGWs.

Another study was based on space-based observations by Dewan et al. [4]. It used infrared data collected by the Midcourse Space Experiment satellite, originating at altitudes of 40 km which showed circular wave-fronts with a horizontal wavelength of approximately 25 km. The source of these waves was also identified as a thunderstorm.

The final study was by Sentman et al. [31], who observed nearly concentric wavefronts emanating from a tropospheric source region (thunderstorm).

In the second category, there were a number of investigations that attempted to explain the prevalence of AGWs in airglow imagers with horizontal wavelength values which are typically several tens of kilometres, have ground-based periods of ten to several tens of minutes, and are imaged a long distance away from a specific convective source [5, 12, 13, 23, 26, 36, 38, 40]. Walterscheid et al. [40] presented the idea that this was due to ducting of the AGWs in a thermal duct present in the upper mesosphere and lower thermosphere. Hecht et al. [13] later suggested that modifications of this thermal duct by winds must also be considered and the waves may be trapped rather than purely ducted.

In [1, 13, 38, 41] the results obtained indicated that the short-period, short-horizontal wavelength AGWs are produced by convective activity. However, these studies also indicate that AGWs with somewhat longer wavelengths (up to several hundred kilometres) may also be produced. Furthermore, Walterscheid et al. [41] suggest that acoustic waves with periods of a few minutes may also be present in the region above the storm.

In spite of a large number of works, so far there is no clearance in understanding what mechanisms and at which heights are involved in the wave attenuation.

OBSERVATIONS

Echoes in the upper atmosphere on large-scale weather formations can become apparent in temperature variations, vector of wind speed, emissions, etc.

In the capacity of researching sources of atmospheric disturbances, hurricanes were chosen. These powerful vortex flows of air masses arise above the warm water basins of the ocean from the powerful tropical cyclones, inside which the pressure is dropping towards the centre. Meanwhile, the air flows move from the periphery to the cyclone's centre. The rotating component of the wind speed inside the cyclone is caused by the Coriolis force. Due to the condensation of water vapour a large amount of heat is extracted, which increases upstreams and results in turbulence. Although hurricanes form in the lower atmosphere and expand only for approximately twenty kilometres in height, they carry enough energy to considerably influence the structure of the upper layers.

The effects of three hurricanes were studied, which occurred from July till October 2005. They are as follows: Katrina (23.08.2005–31.08.2005), Wilma (15.10.2005–25.10.2005) and Haitang (11.07.2005–19.07.2005). Hurricanes Katrina and Wilma developed above the Atlantic Ocean, Haitang above the Pacific Ocean.

We analysed temperatures values above these hurricanes measured by the satellite TIMED and particularly by its device TIDI.

The results are presented in Fig. 1, the temperatures are represented on a grey colour scale. Temperature changes were analysed in the altitude range of 70–110 km prior to the appearance of the hurricane (left column), during the most powerful stage of the hurricane (middle column), and following its complete dissipation (right column).

It can be seen from the figures that the temperature increases above the hurricane regions by 25–40 K at the mesopause level. Obtained temperature changes cannot be explained by the features of solar and geomagnetic activity.

NUMERICAL MODELLING OF PROPAGATION AND DAMPING OF THE ATMOSPHERIC GRAVITY WAVES

Since AGW are considered to be a possible mechanism responsible for the energy transport from the lower atmospheric layers upwards, we decided to perform a numerical modelling of AGW propagation in the Earth atmosphere. Our method is based mainly on the method of solution of the Navier-Stokes equations, described in [6, 7]. It is similar to the multi-layer methods, which were firstly considered by Midgley and Liemohn [22]. AGW, while propagating in an inhomogeneous atmosphere, can dissipate its energy both by self-damping and by redistribution via various dissipative processes (viscosity, thermal conductivity etc.). Calculations of Midgley and Liemohn [22] are based on the assumption that energy redistribution between gravity waves and dissipative processes in the lower atmosphere is negligibly small, so that waves can be considered as of gravity type only. The iterative scheme used in this method is valid until dissipative processes dump much faster than atmospheric-gravity waves. Volland [39] showed that viscosity and thermal conductivity may be important at upper atmospheric levels. He admits that the gravity-wave dominated solution used for lower altitudes, will be gravity-wave dominated at high altitudes also.

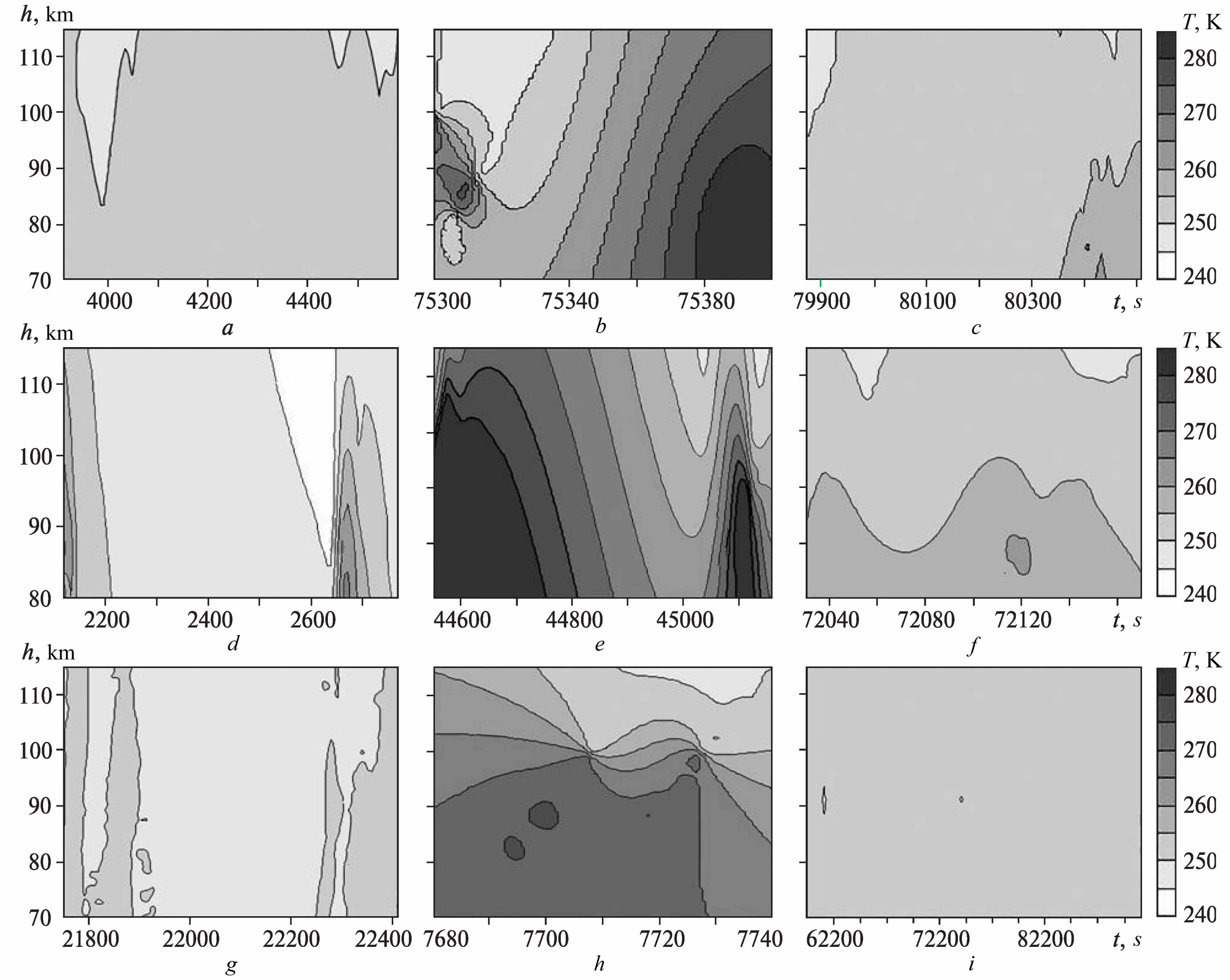

Fig. 1: The distribution of temperature by time and height: before (a), during (b) and after (c) the hurricane Katrina (August 2005); before (d), during (e) and after (f) the hurricane Wilma (October 2005); before (g), during (h) and after (i) the hurricane Haitang (July 2005).

In this work we solve the Navier-Stokes equation taking into account dissipative processes. We consider a plane-parallel atmosphere consisting of homogeneous layers with constant temperature T_0, mass M, adiabatic constant γ, gravity g, viscosity to density ratio μ/ρ_0 and thermal conductivity to density ratio λ/ρ_0. We linearize the system of equations relative to the unperturbed steady state of the atmosphere:

$$\begin{cases} \rho_0 \dfrac{\partial u_i''}{\partial t} = -\dfrac{\partial p''}{\partial x_i} + \rho'' g_i + \\ \quad + \dfrac{\partial}{\partial x_i}\left[\mu\left(\dfrac{\partial u_i''}{\partial x_j} + \dfrac{\partial u_j''}{\partial x_i} - \dfrac{2}{3}\delta_{ij}\nabla\cdot\mathbf{u}''\right)\right], \\ \dfrac{\partial \rho''}{\partial t} + \nabla\cdot(\rho_0\mathbf{u}'') = 0, \\ \dfrac{\rho_0 R_a}{(\gamma-1)M}\dfrac{\partial T''}{\partial t} = \nabla\cdot(\lambda\nabla T'') - \rho_0\nabla\cdot\mathbf{u}'', \end{cases} \tag{1}$$

where $\mathbf{u}''$, p'', ρ'' denote a 1st-order perturbation of velocity, pressure, and density, caused by the propagation of the wave, R_a is universal gas constant, $p'' = \dfrac{\rho'' R_a T_0}{M} + \dfrac{\rho_0 R_a T''}{M}$.

We search the solution in a plane mode:

$$\frac{p''}{A_p} = \frac{T''}{A_T} = \frac{u_z'}{A_z} = \\ = \frac{u_x'}{A_x} \propto \exp\left(i\omega t - ik_x x - ik_z z + \frac{z}{2H}\right). \tag{2}$$

A_p, A_T, A_z and A_x are scaling factors. The horizontal wave vector k_x and the real frequency ω are assumed to be constant throughout the atmosphere, since the atmosphere depends neither on spatial coordinate x nor on time t. On the other hand, vertical wave vector k_z varies through the different atmospheric layers.

Substituting a plain mode solution (2) into the (1) we turn the system of differential equations into a system of algebraic equations. We join the solutions for waves in different adjacent layers by assuming continuity for vertical velocity and moment flux. For a certain ω and a horizontal wave number k_x, the scale parameters A_z, A_x, A_p, and A_T are defined by the following formula:

$$A_z = \frac{\omega}{k_x}\left[(1+\eta)k - 2i\eta\alpha + \frac{k - i\alpha}{(\gamma-1)^{-1} - \nu R}\right] - \\ - \frac{\omega}{k_x}\left[1 + \eta - \beta + 3\eta R + \frac{1}{(\gamma-1)^{-1} - \nu R}\right], \quad (3)$$

$$A_x = \frac{\omega}{k_x}\left[(1+\eta)k - i\alpha(1+3\eta) + \frac{k}{(\gamma-1)^{-1} - \nu R}\right] - \\ - \frac{\omega}{k_x}\left[(1+4\eta)R - \eta - \beta - 1 + \frac{R-1}{(\gamma-1)^{-1} - \nu R}\right], \quad (4)$$

$$A_T = \frac{T_0 k_x}{\omega}\left[\frac{A_x + kA_z}{(\gamma-1)^{-1} - \nu R}\right], \quad (5)$$

$$A_p = \frac{p_0 k_x}{\omega}\left[A_x + A_z\left(k - i\alpha\right)\right] + p_0\frac{A_T}{T_0}. \quad (6)$$

where the dimensionless parameters are: $k = (k_z + i/2H)/k_x$, $R = k^2 - i\alpha k + 1$, $\alpha = 1/k_x H$, $\beta = \omega^2/gk_x^2 H$, $\eta = i\omega\mu/3p_0$, $\nu = i\lambda T_0 k_x^2/\omega p_0$.

If the values u'_x, u'_z, p'' and T'' are valid for Eq. (2), then they are valid for the Navier-Stokes equations.

In the course of numerical modelling while using Eqs. (2)–(6) we have calculated the amplitudes of velocity disturbances (both vertical u''_z and horizontal components u''_x), pressure p'', and altitudinal measurements of temperature T'' caused by the motion of AGW with a period of 65 minutes and horizontal component of the wave vector $k_x = 10^{-5}\,\mathrm{m}^{-1}$ [11, 19]. At the period and k_x changing the scales of processes are also changing, however, the regularity of changes of atmosphere parameters in the case of AGW is still the same. For the analysis of the investigated parameters the initial conditions (temperature profiles, concentrations of all components, altitude of uniform atmosphere) were calculated using the model of MSIS [14] for the days of maximal intensities of considered storms. The presence of experimental data with temperature measurements above storms allowed us to use the value 30 K as the maximal increase of temperature as a result of the wave presence (border conditions).

In the course of the analysis we considered an atmosphere that has no wind, is non-isothermal, and is stratificated in terms of density and concentration of main components, while taking into account viscosity and heat-conductivity.

The results of numerical modelling of the change with the altitude of vertical and horizontal components of AGW velocity, pressure, and temperature, as a result of waves passing, are shown in Figures 2–5. We should note that the disturbances of temperature and pressure as a result of AGW spreading are put onto the usual view of changes of pressure and temperature with the altitude.

It can be seen that for the chosen set of the modelling parameters, the waves propagate to heights of approximately 120 km and reach a maximum amplitude in the range of 90 to 100 km.

DISCUSSION AND CONCLUSION

Analysing the changes of the upper atmosphere temperature over hurricanes we found that the local temperature increases to some marked extent at the mesopause heights. We modelled propagation of atmospheric gravity waves in a windless, non-isothermal atmosphere with a stratification of density and main components, but while taking into account viscosity and thermal conductivity. Our main conclusions are:

- An AGW has its maximum amplitude at the mesopause level.
- The altitude at which the waves reach maximum amplitude depends essentially on the height temperature gradient in that area.
- The waves begin to dampen from altitudes 100 km above sea level.
- Wave amplitude depends mainly on viscosity and thermal conductivity. Dependence of the dissipation height on these parameters is much lower.
- Propagation of AGWs disturbs the mesopause so that the vertical component of the velocity changes by approximately 1–2 m/s, the horizontal component—by 6–10 m/s, and the pressure — by 60–100 mPa, while the temperature changes by 15–30 K.

The obtained results are found to be in good agreement with works of numerical modelling of amplitude values of temperature variations from orographic waves at altitudes of 80–90 km over mountain [9], and temperature disturbances from a tsunami (increasing by 10–12 K [35], wave periods are ~ 30 min [2]), and also are in good correspondence by order of magnitude to experimental estimations [1, 13, 32, 33, 34, 38, 41].

In addition, the results of this work agree with the results of previous studies [19, 20, 29].

Note that nowadays there are researches in which the existence of the inverse connection is discussed, i. e. when the AGWs starting their spread from auroral ionosphere regions have an influence onto extratropical cyclones [28].

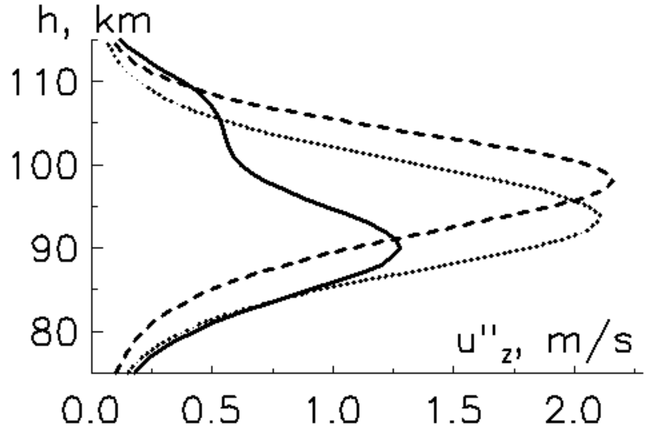

Fig. 2: Vertical AGW velocity dependence on height (solid line for July 18, 2005, dotted line for August 28, 2005, dashed line for October 19, 2005).

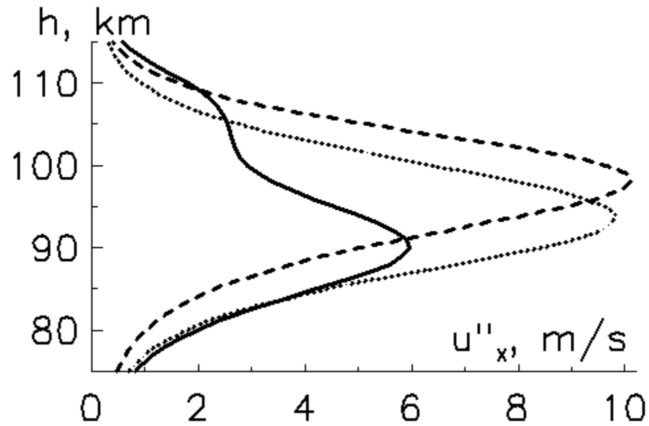

Fig. 3: Horizontal AGW velocity dependence on height (solid line for July 18, 2005, dotted line for August 28, 2005, dashed line for October 19, 2005).

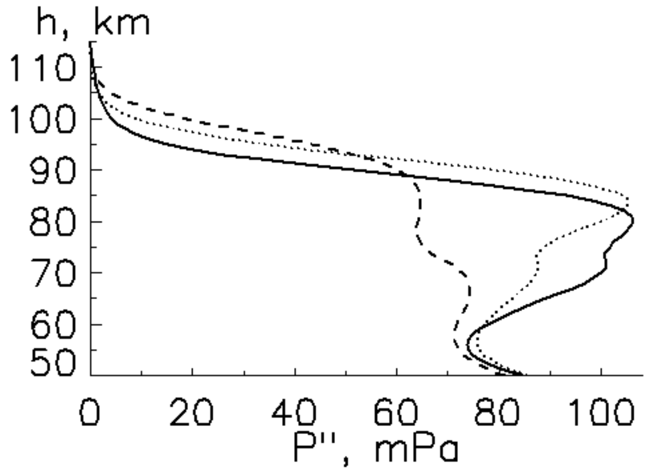

Fig. 4: Pressure variations due to propagating wave (solid line for July 18, 2005, dotted line for August 28, 2005, dashed line for October 19, 2005).

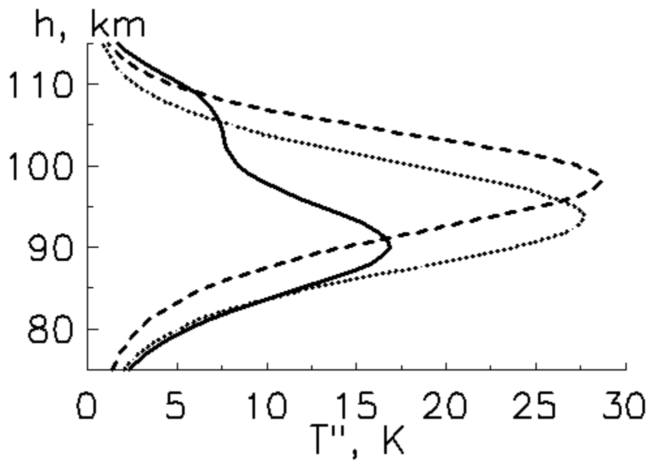

Fig. 5: Temperature variations due to propagating wave (solid line for July 18, 2005, dotted line for August 28, 2005, dashed line for October 19, 2005).

At that it is suggested that the solar-wind-generated auroral AGWs contribute to processes that release instabilities and initiate slantwise convection thus leading to cloud bands and growth of extratropical cyclones. Also, if the AGWs are ducted to low latitudes, they could affect the development of tropical cyclones. The gravity-wave-induced vertical lift may modulate the slantwise convection by releasing the moist symmetric instability at near-threshold conditions in the warm frontal zone of extratropical cyclones. In this case the Joule heating or Lorentz forcing is responsible for auroral AGWs generation.

As an evidence that the effect is observed from AGWs coming from the cyclone but not spreading from above could serve the fact that the effect to be observed at height of 90–100 km. We did not detect any significant deviations from the background value over 110 km. At the same time according to works Luhman [21] and Cole [3] gravity waves launched by the auroral electrojet generally do not cause significant perturbation of the wind fields in the middle atmosphere. However, at altitudes 110–120 km, upward and downward vertical winds in excess of 30 m/s have been observed at high latitudes during moderately-disturbed geomagnetic conditions [25]. Rees et al. [30] identified sources at high latitudes of strong vertical winds of more than 100 m/s, resulting from local geomagnetic energy input and subsequent generation of thermospheric gravity waves.

As was mentioned in introduction the stability of AGWs is breaking with increasing altitude, and they dissipate. The dissipation of wave energy at mesopause altitudes causes heat flows comparable with solar ones [8]. As a result the turbulent layers appear in atmosphere, which are generally observed in regions with highly deflected profiles of the temperature and wind velocity [19]. In troposphere the life time of such layers is longer, and they can exist for long time after "turning off" wave source of the turbulence [17]. These turbulized regions can, in turn, be sources of AGWs (secondary AGW) that propagate from the regions of primary wave dissipation. The possible generation of secondary gravity waves during wave front breaking and wave decay at mesopause altitudes is considered in [43].

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