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A review of vertical coupling in the Atmosphere–Ionosphere system: Effects of waves, sudden stratospheric warmings, space weather, and of solar activity

Erdal Yiğit [a,*], Petra Koucká Knížová [b], Katya Georgieva [c], William Ward [d]

[a] Department of Physics and Astronomy, George Mason University, Fairfax, Virginia, USA
[b] Institute of Atmospheric Physics, Czech Academy of Sciences, Czech Republic
[c] Bulgarian Academy of Sciences, Department of Space Weather, Bulgaria
[d] University of New Brunswick, Canada

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ABSTRACT

This brief introductory review of some recent developments in atmosphere–ionosphere science is written for the “Vertical Coupling Special Issue” that is motivated by the 5th IAGA/ICMA/SCOSTEP Workshop on Vertical Coupling in the Atmosphere–Ionosphere System. Basic processes of vertical coupling in the atmosphere–ionosphere system are discussed, focusing on the effects of internal waves, such as gravity waves and solar tides, sudden stratospheric warmings (SSWs), and of solar activity on the structure of the atmosphere. Internal waves play a crucial role in the current state and evolution of the upper atmosphere–ionosphere system. SSW effects extend into the upper atmosphere, producing changes in the thermospheric circulation and ionospheric disturbances. Sun, the dominant energy source for the atmosphere, directly impacts the upper atmosphere and modulates wave-induced coupling. The emphasis is laid on the most recent developments in the field, while giving credits to older works where necessary. Various international activities in atmospheric vertical coupling, such as SCOSTEP's ROSMIC project, and a brief contextual discussion of the papers published in the special issue are presented.

1. Introduction to the atmosphere–ionosphere system

The atmosphere–ionosphere system describes Earth's whole atmosphere environment extending from the lower atmosphere to the upper regions of the topside ionosphere ($\sim$1000 km). In the upper portion of this system ($z > 70$ km) increasing amount of ionization, primarily by solar ultraviolet (UV) and extreme ultraviolet (EUV) radiation, forms the partially ionized plasma environment of the atmosphere, the ionosphere, that coexists with the thermosphere, the hottest neutral atmospheric region. The atmosphere–ionosphere system thus includes various atmospheric and ionospheric layers that are governed by a variety of complex nonlinear chemical, dynamical, electrodynamical, and radiative processes. Overall, the structure of the atmosphere–ionosphere system is influenced by internal and external processes, such as, by internal atmospheric waves from below (Fritts and Alexander, 2003; Kazimirovsky et al., 2003; Laštovička, 2006; Forbes et al., 2009; Becker, 2011; Pancheva et al., 2012; Oberheide et al., 2015; Yiğit and Medvedev, 2015) and magnetospheric, solar and geomagnetic processes from above (e.g., Thayer and Semester, 2004; Johnson and Heelis, 2005; Kopp and Lean, 2011; Prölss, 2011; Yamazaki et al., 2015), as illustrated in Fig. 1. Internal atmospheric waves are composed of a broad spectrum of waves generated in the lower atmosphere, possessing scales ranging from small scales of 10 to 100 km (e.g., gravity waves) to large scales (planetary scale) of several thousands of km (e.g., tides and Rossby waves). Overall, the state and evolution of the atmosphere–ionosphere is influenced from below and above. The atmosphere and the ionosphere are tightly (two-way) coupled by plasma–neutral interactions during quiet and as well as geomagnetically disturbed conditions. In this context, “two-way” does not indicate upward–downward directions in the atmosphere; namely it means that neutrals can impact plasma processes as well as plasma can drive neutral dynamics, depending on the latitude. Such plasma-neutral interactions lead to frictional heating of the neutral atmosphere by Joule heating, which significantly influences the structure of the upper atmosphere (Yiğit and Ridley, 2011). Interestingly, the significance of the neutral atmosphere for the plasma dynamics has been appreciated in earlier studies of the

* Corresponding author.
E-mail address: eyigit@gmu.edu (E. Yiğit).

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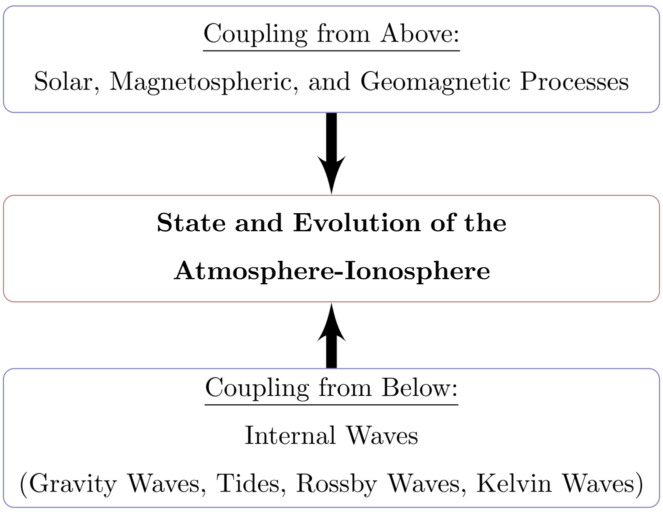

Fig. 1. Vertical coupling: the atmosphere–ionosphere system is under the influence of lower atmospheric forces (internal waves) from below and external forcings (solar, magnetospheric, and geomagnetic) from above.

atmosphere–ionosphere research also in the context of planetary science, e.g., in magnetospheric physics on Jupiter (Huang and Hill, 1989). An adequate description of the neutral upper atmosphere is crucial for studies of magnetospheric wave propagation.

Fig. 2 illustrates the atmosphere–ionosphere system from ground up to the thermosphere–ionosphere that is bounded by the magnetosphere from above. This system is formed by the coupling between the troposphere, stratosphere, mesosphere, thermosphere, and the ionosphere. The magnetosphere is the outermost region of the geospace and is coupled to Sun by the solar wind and to the ionosphere by field-aligned currents. Internal waves, i.e., gravity waves, tides, Kelvin waves, and planetary waves, are shown as propagating from below upward away from their sources in the troposphere and tropopause (~15 km) regions. Some important physical processes are shown in red approximately indicating their place of occurrence. For example, sudden stratospheric warmings (SSW) occur at around 30 km, while polar mesospheric clouds (PMCs) are found in the upper mesosphere. At higher altitudes, in the thermosphere–ionosphere, intensive electromagnetic, electrodynamical, and chemical processes occur, such as, $\mathbf{E} \times \mathbf{B}$-drifts of ionospheric plasma, storm enhanced density events (SEDs), Joule heating (Q_j) and auroral particle precipitation (Q_A) that can produce substantial neutral gas heating as well as ionization. The turbopause (~105 km) is the hypothetical layer that separates the turbulently mixed lower and middle atmosphere (homosphere) from the upper atmosphere (heterosphere) that is dominated primarily by molecular processes. On the right hand, various (wave) dissipative processes, such as radiative damping, nonlinear interactions, molecular diffusion and thermal conduction, and ion drag, are highlighted in gray as they are discussed coherently in the work by Yiğit et al. (2008). While radiative damping plays an important role in the lower atmosphere, nonlinear interactions (Medvedev and Klaassen, 2000) and eddy viscosity are dominant dissipative processes in the middle atmosphere, while above the turbopause, the effects of molecular ion–neutral interactions, molecular diffusion and thermal conduction should be considered.

The atmosphere is a natural geophysical fluid laboratory that can sustain to a significant degree wave generation, propagation, and dissipation processes. The associated wave-mean flow interactions produce spectacular hydrodynamical phenomena. Internal waves primarily generated in the lower atmosphere by various weather systems and various nonlinear physical processes (e.g., Medvedev and Gavrilov, 1995) can propagate to higher altitudes in the atmosphere. Recently, it has been increasingly acknowledged that wave-induced vertical coupling has wider reaching implications in the momentum and energy balance of the atmosphere, in particular, at higher altitudes, than previously anticipated by the geoscience community. The physical significance of internal waves arises from their ability to transport energy and momentum

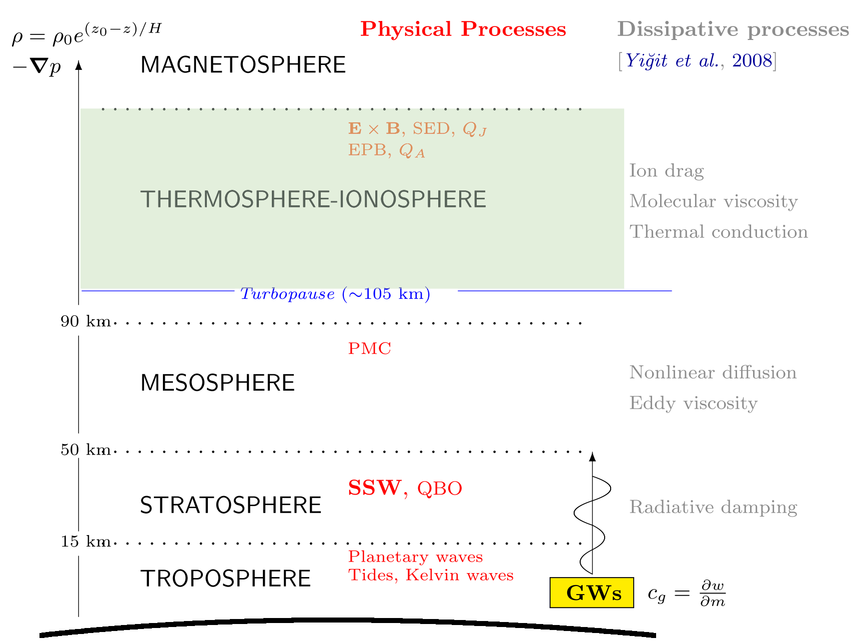

Fig. 2. Vertical structure of the atmosphere–ionosphere system from the surface up to the topside ionosphere and magnetosphere. Some physical processes are marked in red: plasma drifts ($\mathbf{E} \times \mathbf{B}$), are Joule ($Q_j$) and auroral ($Q_A$) heating, Equatorial plasma bubbles (EPB), storm enhanced density (SED), polar mesospheric clouds (PMCs), sudden stratospheric warmings (SSWs), quasi-biennial oscillations (QBOs), and internal atmospheric waves (e.g., gravity waves (GWs), and tides). Important dissipative mechanisms are represented by grey color according to their altitude where they predominantly play a role after the work of Yiğit et al. (2008). Upward energy flux due to internal waves is indicated by the group velocity c_g. Green shading represents the upper atmosphere region above the turbopause marked by the blue horizontal line. Mass density ρ decreases with increasing altitude approximately as $\rho = \rho_0 \exp[(z_0 - z)/H]$, where ρ_0 and $z_0 < z$ are the mass density and altitude at a reference level, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)