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Evidence of Tropospheric Effects on the Ionosphere

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A new paradigm in upper atmospheric and ionospheric physics has begun to emerge, starting with discoveries from observations taken with the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite in 2002. These discoveries [*Immel et al.*, 2006] show that the entire ionosphere, sometimes referred to as "the inner edge of space," regularly responds to the tropospheric weather systems below. The likely mechanism for effectively carrying tropospheric energy upward to the edge of space to modify the ionosphere is the generation and upward propagation of large-scale waves, known as atmospheric tides. The coupling of these tides to the ionosphere is inferred from the strong similarity in longitudinal structure of the tidal winds and the ionospheric densities at low latitudes. However, the appearance of this behavior in the upper ionosphere is surprising because the tides that are forced by tropospheric weather are believed to dissipate at the base of the ionosphere and are expected to have little effect at higher altitudes.

This article shows an example of the strong longitudinal variability in peak plasma density near the equator and describes one hypothetical mechanism for how atmospheric tides may produce this effect. Although such forcing by tidal winds might provide a plausible mechanism, a new satellite mission concept has been proposed to experimentally test this hypothesis and to understand other recent findings that intimate consistent and strong coupling of energy and momentum across all layers of the atmosphere.

Coupling From Below

Ionospheric studies have focused primarily on the variability of the height and peak density of prominent ionospheric layers. That variability could often be attributed to changes in solar irradiance or magnetospheric electric fields from above. New findings show that atmospheric tides are more variable than had been thought earlier [*Forbes et al.*, 2008], and they are now recognized as carrying a significant and complex dynamic forcing from below. As yet, though, there is no comprehensive understanding of these tidal drivers and how they produce global-scale effects in the ionosphere.

Near the equator, the ionosphere grows very dense during the day, when a neutral wind-driven electric field lifts the equatorial plasma by hundreds of kilometers, perpendicular to the arched magnetic field. The plasma also flows down along the magnetic field and accumulates astride the magnetic equator in two dense bands called

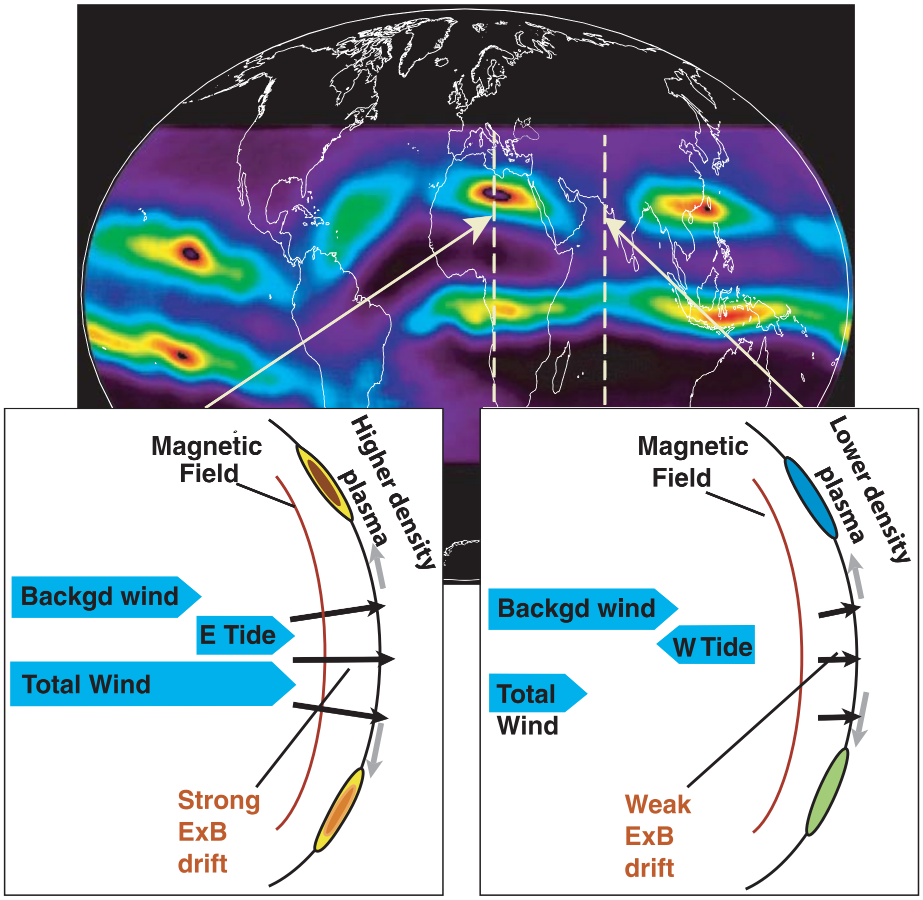

Fig. 1. Average July 2002 nighttime ionospheric density distribution measured in far ultraviolet emissions by the Global Ultraviolet Imager on board NASA's Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. A possible explanation for the strong observed longitudinal variability between regions of high and low plasma density—such as those indicated by the two vertical dashed white lines and also shown by the difference in the two insets at the bottom of the figure—is the (left) increased and (right) decreased dynamo winds. The increase in the left inset is due to the additive effect of an eastward flowing tidal wind (E tide), while the reduction in the right inset is due to a subtractive westward tide (W tide). The electric fields in daytime and their subsequently differing effects on the upward plasma lift (the ***E*** *×* ***B*** *drift that is perpendicular to both the electric and magnetic fields) produce the resultant plasma density.*

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the equatorial ionospheric anomaly (EIA). At night, production of the plasma ceases, but the banded structure of the EIA persists [*Hanson and Moffett*, 1966]. Recent space-based ultraviolet imaging of ionospheric densities has produced a new global view of the EIA [*Immel et al.*, 2006], showing unexpectedly large longitudinal changes in plasma density around the Earth, clearly visible in Figure 1. For instance, note the peaks in density over Africa and Southeast Asia, separated by a deep low centered over the Arabian Sea.

Also at these low latitudes, wave and tidal forcing is a persistent daily phenomenon. New versions of global-scale models predict tidal wind and temperature perturbations that originate in the troposphere and grow in amplitude while propagating upward, to the regions where they exceed the magnitude of tidal winds produced in situ. The formation of raindrops in extensive cloud systems over tropical rainforests releases heat that is a major source of energy for these tides [*Hagan and Forbes*, 2002]. These tides therefore vary naturally with the seasons, and they reflect the longitudinal distribution of tropospheric forcing.

Winds associated with these tides may produce significant modifications of the electric fields in the lower ionosphere (at and below 120 kilometers), as illustrated in Figure 1. Models show, for instance, that one dominant 24-hour tidal component can impose a four-peaked variation in the east-west winds at low latitudes. This would provide a straightforward explanation for the structure shown in Figure 1 and for the observation of a change in ionospheric structure with the seasons [*England et al.*, 2009]. However, recent studies have found a similar signature in almost every upper atmospheric parameter imaginable, including winds above 400 kilometers [*Lühr et al.*, 2007]. One of many open questions is, How much of the tropospheric influence is due to tidal propagation directly to the main ionospheric layer located near 300-kilometer altitude, and how much is due to the influence of tides on other important processes such as the generation of electric fields in the atmospheric wind dynamo operating near 120-kilometer altitude?

A New Observational Approach

In summary, recent efforts to understand the coupling across atmospheric regions show that neutral-ion coupling is a complex and dynamic process. Unraveling the details behind these interactions requires a satellite mission dedicated to making continuous observations of the thermospheric winds, densities, temperatures, and composition in the region 100–400 kilometers above the Earth, while simultaneously measuring ionospheric density profiles in this region during both day and night.

To address this gap in scientific understanding, a new mission concept has been developed to study the coupling between Earth's atmosphere and ionosphere. In May 2008, NASA selected the Neutral Ion Coupling Explorer (NICE) for study as a prospective new mission in the framework of the Small Explorer (SMEX) line of missions. NICE would simultaneously measure all of the key parameters that characterize the thermosphere and the ionosphere. Three optical imaging techniques would retrieve altitude profiles of neutral winds, composition, temperature, and ion density while in situ plasma measurements would retrieve the electric field that develops from the neutral-ion coupling processes.

NICE would be a single-spacecraft mission flying in an approximately 28° inclination, 550-kilometer-altitude orbit. The relatively fast precession of this orbit is favorable for frequent sampling of all combinations of latitude and local time, which is necessary for the comprehensive investigation of tidal structures that appear to dominate the low-latitude ionosphere. The NICE viewing geometry is illustrated in Figure 2. Optical instruments aboard NICE would use the "limb viewing" technique, where instruments focus on the region above the horizon to view distinct atmospheric layers from the side, providing altitude discrimination and a significant gain in brightness as layers are viewed edge on. Two limb-viewing Fabry-Perot Doppler interferometers would obtain altitude profiles of both the vector-neutral winds and temperatures on the horizon from 90- to 270-kilometer altitude by measuring orthogonal Doppler components of two airglow emission lines with minimal time separation, as shown in Figure 2.

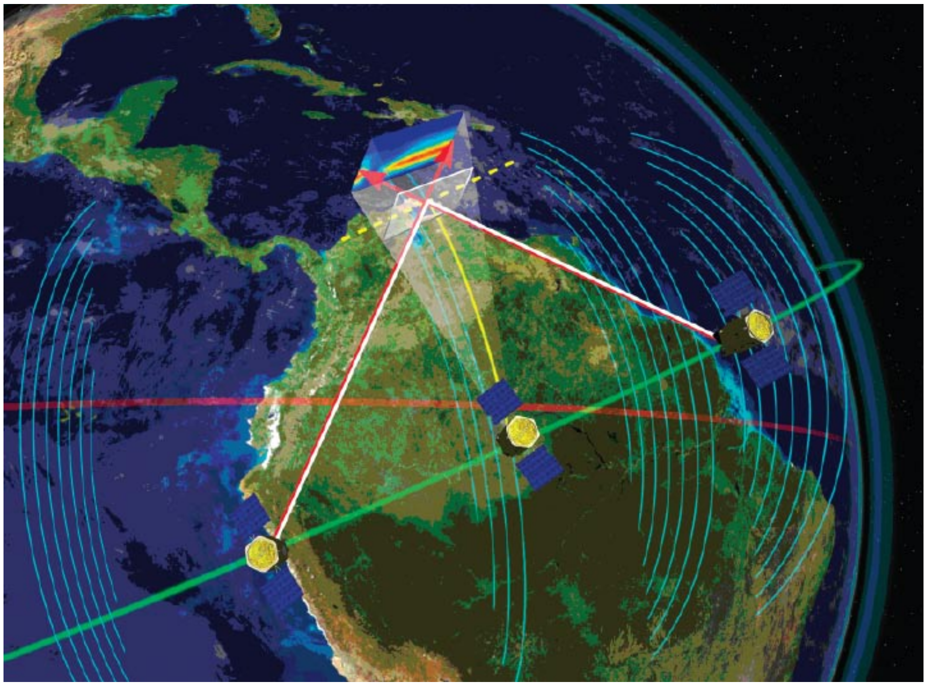

Fig. 2. The Neutral Ion Coupling Explorer (NICE) satellite would travel eastward (green line; orbit altitude, 550 kilometers) making a comprehensive set of measurements. The fore- and aft-viewing Fabry-Perot Doppler interferometers (red and white lines) on board the satellite would measure the horizontal components of the neutral wind (red arrows) as a function of altitude. The far ultraviolet and extreme ultraviolet instruments would take a set of horizon images of the atmosphere and ionosphere (illustrated as a colored plane) near the footprint of NICE's magnetic field line (yellow line). The orbit track of the footprint is shown as a dashed yellow line. In situ drift meter measurements of the ion velocity could be directly related to the electric field at both the spacecraft and the remotely observed region. The geographic equator is shown by the red line.

Two limb-viewing spectrometers measuring the extreme ultraviolet and far ultraviolet airglow would obtain altitude profiles of neutral density and composition and of ion density in the same region as the wind and temperature measurements. These instruments would produce a continuous image of the horizon parallel to the orbit track. Together, these measurements would make up the set of parameters that largely govern the generation of electric fields by neutral-ion coupling. Because even weakly ionized plasma is highly conductive along the magnetic field, the electric field will be transmitted up along magnetic fields, to a region often in the vicinity of the spacecraft (see Figure 2). NICE would take advantage of this geometry by also making in situ ion drift measurements. At the altitude of the satellite, the electric field $\mathbf{E}$ can be accurately described as $\mathbf{E} = -\mathbf{u} \times \mathbf{B}$, where $\mathbf{u}$ is the measured ion drift velocity and $\mathbf{B}$ is the Earth's magnetic field, the latter of which is well known. Thus, NICE would obtain a measure of the remote electric field as well. Because of the choice of orbit and viewing geometries, NICE would frequently measure in situ electric fields and remote neutral and ion parameters that are connected by the same magnetic field line.

Understanding the coupling of energy and momentum between the neutral and ionized components of weakly ionized gases is of critical importance to a number of applications, ranging from planetary atmospheres to astrophysical accretion disks. The 2007–2016 NASA Science Plan explicitly highlights the task to "understand coupling between planetary ionospheres and their upper atmospheres mediated by strong ion neutral interactions." Earth provides a natural analog of neutral-ion coupling effects that are observed where plasma is strongly influenced by background neutral gas, as exists in the Martian and Jovian ionospheres and in the solar photosphere.

Understanding the dynamic properties of the ionosphere also has important societal implications. After sunset, the tropical ionosphere experiences the electromagnetic equivalent of the Rayleigh-Taylor instability, producing what are sometimes called convective ionospheric storms (CISs) [*Kelley et al.*, 2006]. This instability produces sharp density irregularities in the ionosphere that affect radio propagation—including Global Positioning System signals—and can lead to increased errors and, in severe cases, navigation failures that adversely affect a variety of critical applications. The instability is well known to be affected by the solar cycle and season, but the day-to-day variations have resisted prediction for 50 years. The recent global ionospheric images supported by models that point to strong tropospheric influences on the tropical ionosphere present an opportunity to reconsider this stubborn yet fundamental problem in ionospheric physics. The prediction of CIS occurrence is a major goal of another NASA mission, the Global-Scale Observations of the Limb and Disk (GOLD) mission (R. Eastes et al., GOLD mission will explore forcing of Earth's space environment, submitted to *Eos*, 2008). The thermospheric wind drivers that would be measured by NICE would characterize the environment in which these large CISs erupt. In turn, the global-scale thermospheric imaging of GOLD would provide an excellent global context for the comprehensive measurements made by NICE.

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Ocean Bottom Array Probes Stagnant Slab Beneath the Philippine Sea

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Global seismic tomography has revealed the existence of a now-stagnant subducted slab (Figure 1c, inset) in the mantle transition zone (MTZ) of the western Pacific Ocean [e.g., *Fukao et al.*, 2001], where the old Pacific plate subducts at the Kuril/Japan/Mariana Trench system. *Fukao et al.* [2001] showed that a stagnant slab is a common feature of many subduction systems around the world, although it is still not well understood why and how a subducted slab may or may not become stagnant. In addition to a subducted slab itself, water entrained with the slab may also accumulate in the MTZ in association with stagnation. The MTZ has been thought to play a key role in the Earth's water cycle, with water transported to the MTZ possibly being released and supplied to the upper mantle to drive back-arc volcanism [e.g., *Ichiki et al.*, 2006].

To investigate the stagnant slab of the western Pacific Ocean in more detail, the Stagnant Slab Project (SSP)—a 5-year cross-disciplinary project involving geophysical observations, high-pressure experiments, and computer simulations—was initiated in 2004 and concludes in March 2009. This article presents a progress report for an ocean bottom array study conducted as a part of the SSP. This study had been conducted mainly in the Philippine Sea, from October 2005 until December 2008, by using broadband ocean bottom seismometers (BBOBSs) and ocean bottom electromagnetometers (OBEMs). The study was done in three phases, with each phase consisting of a 1-year deployment, resulting in a 3-year time series of data available. Of the 39 BBOBSs and 37 OBEMs deployed, only one instrument was lost—a BBOBS in phase 3, which responded but never surfaced—indicating the high reliability of instrumentation. The locations of observation sites are shown in Figure 1c. Some selected sites operated for all three phases, while others operated for one or two phases.

BBOBS and OBEM Instrumentation

The BBOBS used in this study (Figure 1a) was originally developed by the ocean bottom seismology group of the Earthquake Research Institute (ERI), University of Tokyo. The BBOBS uses a titanium alloy pressure housing (65-centimeter diameter), which allows for a maximum operating depth of 6000 meters. The BBOBS, which has a three-component CMG-3T broadband sensor (Güralp Systems, Ltd.), continuously records data sampled as 24-bit and 100 hertz resolution and stores data in two 40-gigabyte hard disk drives. The housing includes the broadband sensor with a leveling unit, data recorder, acoustic transponder, and 80 DD-size lithium cells that allow for 1 year of operation.

The OBEM used in this study (Figure 1b) was originally developed by ERI's ocean bottom electromagnetic group. The OBEM measures three components of geomagnetic field variations using a fluxgate magnetometer, and it also measures two horizontal components of electric field variations using two mutually orthogonal pairs of electrodes separated by a distance of 5 meters. The tilt of the instrument is also measured. All measurements are recorded to a flash memory card at a sampling interval of 1 minute. The OBEM's magnetic sensor, electronic circuits, data recorder, and power supply unit are housed in two glass spheres. The OBEM can be deployed for more than 1 year at a time.

Task of the Experiment

In 1999–2000, prior to the current study, our group conducted an 8-month-long trans–Philippine Sea array (TPA) study using 15 long-term OBSs and six OBEMs. In 2002, a borehole broadband seismic observatory (WP-1; Figure 1c) was activated. On the basis of analysis of the available data, *Suetsugu et al.* [2005] suggested the existence of a significant topographic variation of the 660-kilometer discontinuity between the northern and southern parts of the Philippine Sea around the WP-1. Although this variation is likely to be a feature related to the stagnant Pacific slab, no further investigation was pursued, due to the limited number of sites and amount of data, until the current study. The 17 BBOBS sites in the present