A call for interdisciplinary science focusing on how particle precipitation from the magnetosphere affects Earth's atmosphere

Truly interdisciplinary science has the potential to create new paradigms and discover exciting links between phenomena that occur across disciplines, thereby changing our understanding of the system as a whole. This kind of holistic treatment has been highly successful in other sciences, even in our sister fields of Planetary and Earth science. Time and again, interdisciplinary investigations have led to real breakthroughs. Traditionally, Heliophysics has conducted research using a more compartmentalized model. As an example, even the form to fill out before submitting this white paper requires a Primary and Secondary categorization from within the firmly established sub-disciplines. When studying how particles from the Sun are processed by Earth's magnetosphere and provoke a response in Earth's atmosphere, would one define the Primary subject to be Heliosphere, Magnetosphere or ITM science? As we look forward to thirty years from now, we should intentionally shift away from this kind of siloed science and toward a more interdisciplinary approach to understanding the Sun-Earth system.

The atmospheric effects of particle precipitation

To this end, we pose a specific long-standing science question that connects multiple regions of geospace, yet is still not understood. Energetic particle precipitation, known as EPP, is the primary source of nitrogen oxides (NO and NO_2), collectively known as NO_x, in the polar upper atmosphere. These NO_x constituents are known to catalytically destroy stratospheric ozone. But the contribution to polar ozone loss of NO_x produced by EPP, and the consequent effects on temperature and winds, are poorly quantified. The atmosphere is necessary for the existence of life on Earth, yet we still don't understand a critical component of this region: how energy from the Sun and from near-Earth space is absorbed and transported in the middle and lower layers of the atmosphere. Earth's atmosphere is made up of a system of concentric layers that exchange energy in multiple, complex ways. Atmospheric variability is driven from below by chaotic, tropospheric weather and anthropogenic inputs, as well as from above by geomagnetic forcing - itself originating from solar wind driving of Earth's ionosphere-thermosphere-magnetosphere (ITM) system. The atmosphere responds to these drivers through intricate and coupled processes involving chemistry and the transport of energy and momentum from one atmospheric layer to another.

NO_x produced by EPP (EPP-NO_x) can be created directly in the stratosphere by high-energy particles, or at higher latitudes in the middle and lower thermosphere by lower energy particles. The downward transport of EPP-NO_x is controlled by an unknown combination of diffusion, large-scale circulation, and confinement in the polar vortex, with winds and waves modifying these elements. Due to this complexity, we cannot currently predict which geomagnetic storms will lead to ozone depletion occurrence or how extensive that depletion will be. Investigating the processes that drive the redistribution of atmospheric energy is challenging and **requires simultaneous observations of both the upper and middle regions of the atmosphere, as well as the flux of precipitating particles.**

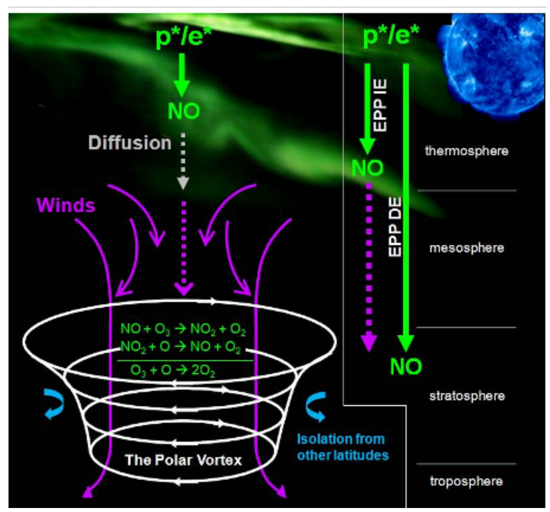

Figure 1: Direct and indirect effect of EPP on the atmosphere. Polar vortex and dynamics play a strong role.

A highly-sophisticated whole-atmosphere model, WACCM (Whole Atmosphere Community Climate Model) has been successfully used for years to investigate the effects of EPP on the atmosphere during relatively quiet periods. Studies have shown that WACCM (and other atmospheric models) underestimate EPP-NO_x during high NO_x-yield events by at least two orders of magnitude. Suggestions were made long ago that EPP could couple the magnetosphere and atmosphere[1,2,3], and evidence for this coupling abounds[4]. However, with the limited observations currently available, we only poorly understand the nonlinear feedbacks that amplify the effects of solar and magnetospheric energy inputs and act to couple all the layers of Earth's atmosphere.

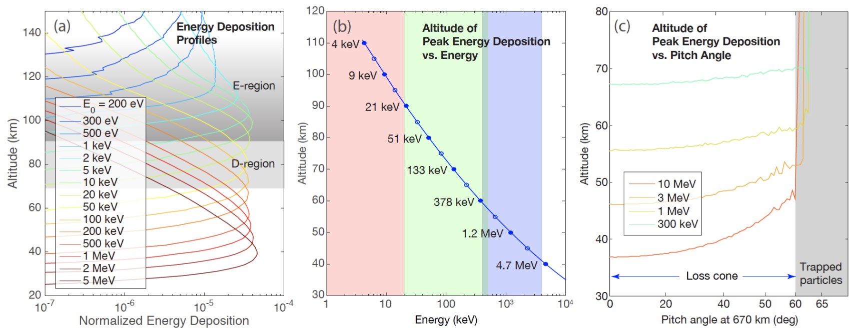

Figure 2: (a) Energy deposition versus altitude for precipitating electrons in Earth's atmosphere; (b) Peak energy deposition altitudes from (a) plotted versus electron energy; c) Peak energy deposition altitudes versus pitch angle within the loss cone.

EPP effects on the atmosphere are divided into two categories: direct and indirect[5,6] (Figure 1). The direct effect of EPP refers to the local ionization and consequent production of chemically reactive odd nitrogen (NO_x = N + NO + NO_2) and odd hydrogen (HO_x = H + OH + HO_2), both of which catalytically destroy ozone (O_3)[7]. This occurs near the time and location where the precipitating electrons and protons, and the secondary electrons they generate, deposit their energy[1,4,7−9]. As shown in Figure 2, the EPP ionization altitude varies according to the energy of the precipitating energetic particles. Episodic precipitation of radiation belt electrons with energy above ∼1 MeV is associated with peak ionization in the stratosphere[10−12]. Ionization by so- called "medium energy electrons" (MEEs, ∼30 keV – 1 MeV)[13], which are associated with the radiation belts and ring current, peaks in the mesosphere or D-region from ∼60-90 km. Ionization by auroral electrons (< 30 keV) peaks at altitudes above ∼90 km. Auroral precipitation is generally associated with magnetotail and ring current processes and occurs routinely, although with varying intensity, over the solar cycle[14].

The EPP indirect effect (EPP-IE) occurs when chemical constituents produced by the direct effect are transported in the atmosphere. Empirical evidence for the EPP-IE has been cited by numerous investigators in the past few decades[15−21]. Of particular interest is the descent of EPP-NO_x at polar latitudes in winter, when the NO_x lifetime in the MLT is long (weeks)[4], as predicted more than three decades ago[22]. Once in the stratosphere, EPP-NO_x can significantly modify stratospheric O_3 levels[4,23−29]. Large uncertainties exist in how much NO_x in any given space weather event actually reaches the stratosphere, since we still aren't sure what energies are significant to this process. But analyses of observational data suggest that the EPP-IE might supply as much as ∼40% (10%) of the NO_x in the polar (global) stratosphere[6,30], with the remainder produced by the oxidation of N_2O originating at the surface.

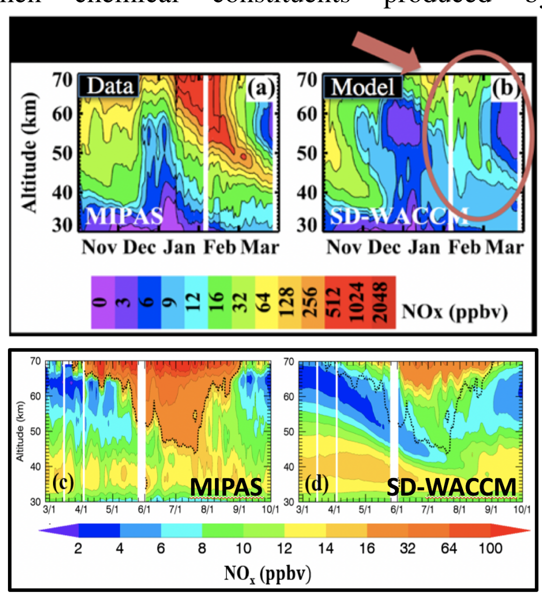

Figure 3: (a) Energy deposition versus altitude for precipitating electrons in Earth's atmosphere; (b) Peak energy deposition altitudes from (a) plotted versus electron energy; c) Peak energy deposition altitudes versus pitch angle within the loss cone.

Despite overwhelming evidence of the EPP-IE, accurate simulations are elusive. In the Arctic spring of 2004, for example, an enormous influx of reactive odd nitrogen from the mesosphere and lower thermosphere was observed to enter the polar stratosphere. NO_x mixing ratios in the upper stratosphere increased, causing localized catalytic reductions in O_3 of more than 60%, with effects persisting for at least five months[25,31]. As shown in Figure 3, the WACCM model underestimated the EPP-induced NO_x enhancements in 2004 by as much as a factor of four. Figure 3 shows that WACCM also underestimates the EPP-IE in the Antarctic region, where the vortex and thus downward transport are better constrained. Even under conditions of much lower geomagnetic activity than in 2004, significant fluxes of EPP-NO_x have been observed descending into the stratosphere[5,18,32]. These results suggest that coupling between the heliosphere, magnetosphere and atmosphere is highly uncertain with regard to both the direct production of NO_x via EPP and the transport of EPP-NO_x once produced. This is a problem that can only be solved with an interdisciplinary approach that crosses the boundaries of the solar wind, magnetospheric, and atmospheric communities.

What is needed to answer this science question?

To address this more than 60-year-old problem, high-fidelity observations of both the precipitating particle spectrum and the atmospheric constituents and dynamics must be collected across local times and latitudes during the polar winter. Using inputs from these in situ and remote sensing observations, WACCM and other atmospheric models can perform simulations that will test our current assumptions about how these systems work. Through these measurement and modeling efforts, we can understand: (1) how EPP modifies the distribution of NO_x in the atmosphere, (2) how transport affects that distribution at middle and high latitudes, (3) how ozone, zonal winds and temperature gradients are affected by EPP, and (4) how solar wind and geomagnetic driving affect EPP and thus atmospheric coupling.

Currently and previously available EPP measurements have proven to be insufficient to answer these questions. Why? First, the measurement accuracy and resolution of global, long-term particle observations have not been high enough to provide a robust picture of the precipitating energy spectrum. Second, there has not been concurrent measurements of the atmospheric constituents and dynamics required to understand the relationship between the two, specifically in the polar night where the NO_x is long-lasting.

We need a comprehensive, continuous set of these measurements to fully understand this last link in the Sun-Earth system. It requires researchers from both the magnetospheric and atmospheric fields working together. And it will require support from the greater communities and funding agencies to help build and maintain those bridges.

References

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