Mapping atmospheric constituents at high spatial resolution to understand their influence on Earth's climate

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1. *What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*

As the effects of climate change become more pronounced, it becomes critical to understand the influence of atmospheric constituents on Earth's energy budget. These include methane (CH_4) and carbon dioxide (CO_2), the two anthropogenic greenhouse gases most important to climate change. For both gasses, the majority of anthropogenic emissions are emitted from concentrated point sources. These emissions are expected to continue rising and their impacts are significant. Although the cause of increased atmospheric CH_4 remains unclear, CH_4 is an important source of ozone production and photochemical smog. Water vapor (H_2O) contributes around 60% of the Earth's greenhouse gas warming effect and concentrations will increase with rising global temperatures. Volcanic sulphur dioxide (SO_2) emissions affect human, animal, and plant health and can result in aerosols, which represent the largest uncertainty in the global energy budget.

2. *Why are these challenge/questions timely to address now especially with respect to readiness?*

Existing satellite sensors used to measure these atmospheric constituents are limited by coarse spatial resolutions (i.e. kilometers). A spaceborne imaging spectrometer with a spatial resolution of 30 m or less would provide coverage of large areas, resolve individual point sources, and permit characterization of emissions at resolutions fine enough to catalog the most important point sources. This includes attribution of natural/anthropogenic emissions to regions of increasing concern like megacities (CH_4, CO_2, aerosols) and oil/gas fields (CH_4), both projected to grow in size and number. Many source categories of anthropogenic emissions are underestimated and represent effective targets for mitigation. Individual point sources would also be characterized, including emissions from energy production like power plants (CO_2), and from natural sources such as volcanos (SO_2, aerosols). Imaging spectrometers are particularly well suited because adjacent pixels within scenes are acquired nearly instantaneously, thereby providing spatial context important in interpreting results. In addition to direct attribution to individual point source locations, these measurements will permit emission flux estimates of both point and regional emission sources. High spatial resolution water vapor maps would allow quantification of evapotranspiration from agriculture and natural vegetation, understanding of sub-scale variability relevant to weather and climate models, and fine scale characterization of cloud properties as they relate to radiative forcing.

3. *Why are space-based observations fundamental to addressing these challenges/questions?*

Given the global distribution and great number of point sources like megacities, oil/gas fields, power plants, and volcanos, space-based observations are an effective method for characterizing emissions from these sources. While airborne imaging spectrometers have been used in the past, mapping large regions by aircraft is challenging given limited access to airspace and the high cost of airborne campaigns (particularly if repeat coverage is required). A satellite with a revisit time of 16 days or less would permit baseline measurements and enable statistically robust sampling to track variations with time (i.e. growth rate, assessing questions of persistent versus intermittence).

a. *Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?*

Existing and planned U.S. and international satellite missions are limited by coarse spatial resolutions (5x5 km^2) or a narrow swath (less than 20 km). For example, CO_2 measurements have 2x2 km^2 spatial resolution with a swath less than 20 km (OCO-2, OCO-3, and TanSat), while CH_4 measurements will have the coarser resolution of 7x7 km^2 with a swath greater than 2,000 km (Sentinel-5p and Sentinel-5). A spaceborne imaging spectrometer designed with the right balance of spectral, spatial (30 m or less), and temporal (revisit time of 16 days or less) resolution requirements would resolve individual point sources within scenes and offer the ability to track emission sources over time.

b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs;

These high spatial/temporal resolution records could be compared directly with additional satellite measurements obtained at coarser spatial resolutions (i.e. atmospheric sounders). In addition, results from airborne imaging spectrometers could be used to validate satellite measurements of atmospheric constituents from point sources and regions of interest like megacities or oil/gas fields. Finally, in situ airborne or ground based measurements (tower networks) could be used to validate flux estimates derived from satellite measurements.

c. The anticipated scientific and societal benefits; and

By improving our understanding of Earth's energy budget, carbon cycling, greenhouse gas budgets, as well as permitting identification and mitigation of emissions sources, these measurements would have significant scientific and societal benefits with relevance to policy makers and regulators. These measurements are the best way to enable a comprehensive global catalog of trace gas emissions; they are timely and important to the health of the Earth and its inhabitants. In addition, it is important to understand how rising temperatures and increasing concentrations of the greenhouse gas water vapor will effect global radiative forcing. Quantification of evapotranspiration from agriculture and natural vegetation has implications for a future where freshwater is scarcer, while an improved understanding of cloud properties and water vapor could improve weather forecasts and climate models. Characterization of volcanic SO_2 emissions are important not only because they have immediate effects on health, but volcanic eruptions have lasting effects on the environment, climate, and the economy. A greater understanding of the influence of aerosols is of particular importance given they represent the largest uncertainty in the global energy budget.

d. The science communities that would be involved.

These measurements would provide a unique dataset critical to understanding the influence of atmospheric constituents on Earth's energy budget. This spans the atmospheric, climate, modelling, carbon cycle, and natural hazards scientific communities. In addition, water vapor and cloud data at this unprecedented spatial resolution (30 m or less) would be particularly relevant for weather and climate modelers. Given potential application towards informing mitigation strategies, regulatory approaches, and policy development, involvement would also include the environmental, political, and economic science communities.