Pathways to Predicting Atmospheric Composition

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Abstract - With advances in our observational, modeling and data assimilation capabilities, accurate atmospheric composition forecasts can be achieved with significant benefits to society. This paper will highlight some of what is needed to realize this goal, such as expanded scientific knowledge, advanced remote sensing capabilities and modeling.

I. Introduction

The atmosphere serves as a global "commons," linking the other components of the Earth system, including the oceans, land, terrestrial and marine plants and animals, and the frozen regions. Indeed, the atmosphere links the natural system and all elements of human societies of all nations. Because of these linkages, the atmosphere is a *conduit of change*. For example, natural events and human activities can change atmospheric composition and hence the Earth's radiative (energy) balance. Subsequent responses by the climate system and the stratospheric ozone layer can influence the well being of human and natural systems.

Global change research and observations have shown that changes in the composition and chemistry of the atmosphere spread over very large areas very quickly—that the atmosphere is the "fast mixer" in the Earth system. Because of the rapid and often global dispersal of chemical emissions, observations of changes in the atmosphere are among the very earliest harbingers of global changes. And the very long atmospheric residence times of some emissions imply virtually irreversible global changes over decades, centuries, and millennia—for all countries and populations, not just the pollutant emitters. Finally, the emerging capability of modeling the composition of global atmosphere as a whole is pointing to the relationships between issues once considered separately and independently, such as continental air quality and climate change.

Prediction of the evolution of atmospheric trace constituent composition is intimately linked to that of the meteorological conditions under which chemical and transport processes occur and the ability of models to capture the essential physical and chemical processes, which transform chemical species. The composition of the atmosphere is also affected by biological processes and can affect the biosphere in ways that impact human well being. Atmospheric changes which have had the greatest impact on human health are air pollution (gases and aerosols) and increases of ultraviolet radiation. The chemical constituent of greatest interest is ozone. In the stratosphere, ozone protects the Earth from biologically damaging solar ultraviolet radiation. In the troposphere ozone is an active chemical pollutant that affects both plant and animal life. Ozone responds (for both production and destruction) to the concentration of many precursor species coming from both natural and anthropogenic sources. Accurate modeling of atmospheric composition requires knowing or forecasting the future evolution of these chemical forcings, as well as relevant changes in climatic conditions. In the case of sufficiently large changes in atmospheric composition, interactions with resulting changes in atmospheric circulation and physical properties cannot be ignored (e.g. the chemistry of the polar stratosphere affects the atmospheric transport). Processes of particular importance for assessments of potential atmospheric chemical composition impacts include the long range transport of material from natural and man made sources; the formation of aerosols and cloud particles and their interactions with constituents.

With advances in our observational, modeling and data assimilation capabilities, accurate atmospheric composition forecasts can be achieved with significant benefits to society. This paper will highlight some of what is needed to realize this goal, such as expanded scientific knowledge, advanced remote sensing capabilities, and modeling.

II. Monitoring Future Stratospheric Ozone Levels

The depletion of stratospheric ozone observed over the past two decades is of considerable concern because of the resulting increase in UV radiation at the Earth's surface, and because of the deleterious effects of increased UV radiation. It is now well established that stratospheric ozone depletion is due in large part to synthetic chlorine-containing chemicals. International agreements, developed under the Montreal protocol, led to an international phase-out of these chemicals, and atmospheric observations over the past decade indicate compliance. Anthropogenic chlorine concentrations in the lower atmosphere leveled off in the late 1990s and have now begun to decrease. Because the most abundant chlorine-containing compounds have long atmospheric lifetimes, it is expected that ozone will take several decades to recover. The critical question is whether the stratospheric ozone actually will recover.

The reason for this remaining uncertainty is that greenhouse warming of the Earth's surface is expected to cause cooling and moistening of the stratosphere over the next decades. Current models indicate that these climate changes will enhance the ozone-depletion capability of stratospheric chlorine and may at least partially offset the benefits of decreasing chlorine levels. Growing aircraft traffic, including, possibly, a supersonic fleet of aircraft further complicates the assessments of future changes in ozone over the next decades. Ozone depletion arising from large volcanic eruptions adds another layer of uncertainty.

NASA can contribute to better understanding of stratospheric ozone trends over the next decades through high-quality satellite observations of ozone and related chemical species, and through the development of a new generation of atmospheric chemistry models including the coupling to climate change. Through this effort, it will be possible to gauge quantitatively the success of the Montreal protocol and to accurately assess the effects of aircraft. Increased confidence in our understanding of stratospheric chemistry will enable better and more cost-effective regulation of new industrial chemicals and lead us towards an era of management of human effects on the stratospheric ozone layer.

III. Monitoring & Short-Term Forecasting of Pollution Episodes

Monitoring the cleanliness of Earth's air and water is of prime importance to the health of the general public and to the protection of its food sources. Global monitoring is needed to assure that international air pollution treaties are being honored. Monitoring for pollution events must be done on a timely basis—as frequently as hourly—to detect episodic or point releases of contaminates. Hourly to daily predictions of the transport and concentration levels of air and water borne pollutants is required to give the public time to mitigate the impacts of air/water quality pollution episodes that occur over short time intervals from hours to a few days. Oil spills, toxic gas releases from a chemical plant, municipal waste treatment plant failure, power plant meltdown are a few examples of pollution episodes. The vision is to enable reliable and timely predictions of air and water quality and to predict the evolution of the pollution plume as it interacts with the atmospheric or aqueous processes.

The societal payoff from air pollution forecast improvements, and consequent improvements in air quality will be enormous. An improved efficiency of only 10-20% in applying environmental regulations could lead to $15B-$25B savings in government regulatory costs. Improved weather forecasts could reduce health risks, material exposure, and crop damage with potential cost reductions in the $50B-$100B range. Improved weather forecasts with concomitant policy changes could change regulatory procedures such that industry and the public sector would be able to design their emission limits based on predicted value rather than static thresholds that may or may not be prudent for current conditions. While improvements in weather forecasts and their utilization are generally incremental, only small improvements in air pollution forecasts can open up entire new welcome paradigms in societal responses and regulatory policies.

The measurement and modeling capabilities needed to address these needs include improved weather forecasting capabilities, plus global tropospheric constituent observations with timeliness, temporal and spatial resolution similar to meteorological measurements, and new, highly sophisticated, 4-D chemical transport models, that are fully coupled with meteorology, will be required to assimilate real-time measurements from satellites, ground networks. New approaches to global data handling, similar to those noted for weather forecasting, will also be required. As with other aspects of the Earth Science Vision, new level of interagency communication will be required.

IV. New Observational Vantage Points for Earth Science

Two specific challenges need to be addressed to effectively investigate tropospheric chemical processes: horizontal/vertical resolution and temporal sampling. Tropospheric composition is expected to show considerable vertical stratification and fine horizontal structures that contain information on the origin and age of important species. Likewise, the altitude distribution of upper tropospheric water vapor and ozone is a critical parameter in climate models. Temporal and horizontal variability is also important, including significant diurnal variations. The current vision for meeting these measurement challenges involves a combination of approaches. Active remote-sensing (lidar) observations from low Earth orbit could provide high vertical resolution to observe ozone and aerosols layers, and quantify the chemical, transport and radiative consequences of these vertical structures. Spectral imaging from geostationary, L-1 orbit could provide the necessary high temporal and horizontal resolution to observe rapidly evolving chemical events and quantify export from large source regions to the global atmosphere. High-power UV lasers and deployable telescopes are among the technological developments that are needed to make such measurements a reality.

Low-Earth orbiting (LEO) satellites will likely remain an important element in our strategy for global observations. However, part of the plans for future Earth-Science missions calls for observations using spectral imaging from novel vantage points that can provide the necessary high temporal and horizontal resolution to observe rapidly evolving chemical events and quantify export from large source regions to the global atmosphere. Observations of the Earth from the Lagrange-1 and Lagrange-2 points (L-1 and L-2, 1.5 million kilometers in front or behind the Earth, respectively, on the Earth-Sun line) afford a unique vantage points for atmospheric science. Geostationary (GEO) orbits, which have up to now been used for meteorological observations, are now thought of as having great potential for high temporal and spatial resolution observations of atmospheric chemical species.

Multispectral UV, visible, and infrared images of the Earth's Atmosphere made from L-1, offer unprecedented opportunities for examining atmospheric chemistry in a fundamentally different way. Most points on the sunlit side of the surface and atmosphere will be viewed simultaneously from sunrise to sunset with high temporal and spatial resolutions. Such a continuous global view and related retrievals provide a way to study how fast atmospheric dynamics, such as tropical mesoscale convective systems, hurricanes and mid-latitude storm tracks, help to determine the regional ozone, aerosol and cloud distributions in the planet.

GEO satellites can also be exploited to monitor and study quantities and processes that can vary rapidly in time in the atmosphere, such as aerosols, tropospheric ozone, water vapor, and storm and cloud development. GEO instruments have the ability to stare at the same spot on the Earth for extended periods, allowing for long integration times, high spatial (< 10 km x 10 km), removing cloud effects, by waiting for the clouds to move into/out of the field-of-view and using the sunrise/sunset data for stratospheric/tropospheric retrieval inversions. Current technological development in large well depth, large format array detectors for both the UV and IR is currently ready to support measurements from geostationary orbit. Instrument designs can be scaled up from LEO versions.

While infrared observations of the Earth's night-side disk can be performed from a variety of satellite orbits (e.g., geostationary, low Earth orbit) to obtain total column amounts of different molecular species, only occultation measurements can obtain high spatial resolution (~2 km) altitude profiles. Spectral observation of the Earth's atmosphere using solar occultation techniques in the near infrared (1 to 4 microns) provides one of the most accurate methods of passively sensing altitude profiles of the major species (CO_2, O_3, O_2, CH_4, H_2O, N_2O). While traditional polar orbiting occultation measurements can obtain about 14 measurements per day (2 per orbit), solar occultation observations from the Lagrange-2 point will yield hourly profile measurements at all latitudes. The expected spatial resolution is 2 km in altitude, 0.5 degrees in latitude, and 2 degrees in longitude. The result from 24 hours of observations will be a 3-dimensional map of atmospheric composition.