# WHEN STRATOSPHERIC OZONE HITS GROUND-LEVEL REGULATION

## Exceptional Events in Wyoming

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**BACKGROUND.** A nonattainment area is a geographic region that fails nationwide air quality standards set by the Environmental Protection Agency (EPA) for one or more criteria air pollutant: ozone, particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, or lead. The EPA sets an acceptable air pollution threshold value for each of the six criteria pollutants, defined as the National Ambient Air Quality Standards (NAAQS).

Compliance with the ozone NAAQS is determined by the 3-yr average of the annual fourth-highest daily maximum 8-h average ozone (MDA8), as recorded by ground-level ozone monitors. If monitors in a state exceed the NAAQS, the state may be required to submit an implementation plan that describes how future ambient ozone levels in the area will be reduced to levels below the NAAQS standard. However, the EPA's Exceptional Events Rule provides a mechanism for excluding monitor data that violates the NAAQS, if the state prepares a demonstration that meets the requirements of the Exceptional Events Rule and shows that the exceedance was caused by a stratospheric intrusion.

On 14 June 2012, the EPA approved an "exceptional event" demonstration for ozone exceedances at the Boulder and Big Piney, Wyoming, ozone monitors located in the Upper Green River basin of western Wyoming. This was the first time since the 1980s that the EPA has recognized a stratospheric intrusion as the cause of a high-ozone event. The Agency acted on the 14 June 2012 exceptional events demonstration for the Boulder and Big Piney monitoring sites because the exceedances were associated with the Upper Green River basin area, a current nonattainment area for the 2008 ozone NAAQS. A second exceptional event demonstration package for 6 June 2012 in Thunder basin, Wyoming, is still under review by the EPA. The EPA may give a lower priority to acting on the 6 June 2012 exceptional events demonstration because the affected data do not influence a regulatory decision associated with that area. Yet, the 6 June demonstration offers an interesting case study given the unusual wealth of data gathered from the event. The data were so extensive because it was the state's first submission that included the recently developed and more rigorous methodology for demonstrating a stratospheric intrusion event as the cause of an ozone exceedance in a nonattainment area. The 6 June 2012 data from Thunder basin, Wyoming, is the primary focus of this article.

Because state air regulators carefully documented the science, the Wyoming submittal is influencing the template developed by the EPA Ozone Stratospheric Intrusion (SI) Working Group. Future submissions will therefore require less effort. The SI working group includes representatives from state agencies and EPA, as well as NOAA, NCAR, and NASA researchers. The objectives of the SI working group are to develop standardized technical methods for analysis of SI; to promote collaboration and data sharing between the states, academics, and federal researchers; and to promote archiving of key datasets.

The data analysis for the 6 June 2012 event was performed by a partnership of researchers from the NASA Air Quality Applied Sciences Team (AQAST) and air quality managers in the SI Working Group. A serendipitous alignment of NASA research flights over California, which was upwind of unusually high surface ozone in Wyoming, also provided valuable

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data for this analysis. We discuss the analyses that were used to demonstrate the stratospheric cause of the events as well as the implications for other high-altitude regions of the United States.

**WYOMING EXCEPTIONAL EVENT DEMONSTRATION.** The high plains of Wyoming have served as a unique testing ground for advanced air quality research. Although Wyoming has the lowest population of any U.S. state, it is not unusual for ozone monitors to show one or more days per year with measured values of ground-level ozone near or above the NAAQS. The Wyoming Department of Environmental Quality (DEQ) has produced three exceptional event demonstrations that cite stratospheric intrusion: 30 May 2011 (South Pass monitor); 6 June 2012 (Thunder basin monitor); and 14 June 2012 (Boulder and Big Piney monitors). The two 2012 demonstrations were submitted to EPA in June 2013, and the 14 June 2012 demonstration was approved by the EPA in May 2014.[1] The EPA is currently reviewing the two other exceptional event demonstrations.

Satellite data, ground-level measurements, aircraft measurements, and global air quality models were used to identify a stratospheric intrusion as the primary cause of the 6 June 2012 ozone episode. Collaboration between air quality managers at the DEQ, researchers on NASA's AQAST, and members of the EPA SI Working Group was central to this work. The NASA AQAST is a national team of 19 researchers, with the mission of connecting air quality managers at the national, state, and local levels with NASA data—especially satellite data—and tools.

Since 2011, AQAST researchers have been working to understand states' scientific needs, which are not being met by the standard air quality data provided by ground-based monitors and regional air quality models. One such need is to support the demonstration of exceptional events, especially for ozone. Unlike PM2.5, where monitored differences in composition help identify an aerosol's source, ozone's composition is the same regardless of origin. Therefore, new types of analyses are needed to attribute ozone events to source type and location.

A stratospheric intrusion occurs when ozone-rich air from the upper atmosphere is pushed downward into the troposphere where it can affect ozone at ground level. In the western United States, stratospheric intrusions are typically associated with pressure perturbations that cause the boundary between the troposphere and stratosphere to "fold," allowing dry and ozone-rich air to enter into the mid- and lower troposphere. Intrusions are difficult to identify in ground-based ozone measurements, where a peak value due to stratospheric ozone may be indistinguishable from a peak event due to chemical production from local emissions.

However, stratospheric air masses have unique characteristics that are identified with complementary data. Stratospheric air is typically depleted of carbon monoxide and water vapor compared to surface-level air masses. Since satellites can detect ozone, carbon monoxide, and water vapor, they are useful for air quality managers looking for evidence of stratospheric impact.

Satellite data have some limitations, however, such as a lack of availability when clouds are present, limited temporal coverage (typically once a day or less), and an inability to detect ambient mixing ratios—satellites can only identify either total column abundances or average mixing ratios over relatively thick layers of the upper atmosphere. Therefore, the use of satellite data for attribution of stratospheric impacts on peak ozone events must address these limitations. Typically, photochemical ozone events occur near the surface on sunny, warm days, in the afternoon, coincident with the overpass of three major NASA satellites: *Aura, Aqua,* and *Terra,* collectively known as the A-train (A is for Afternoon). When a satellite is detecting stratospheric air, its ability to measure the total column as well as the ozone mixing ratios in the stratosphere allows for estimates of how much ozone is in the lower atmosphere. While the satellite data cannot be used to quantify the ground-level ozone-mixing ratio, the data do provide a useful indicator of a possible stratospheric impact on surface ozone. This illustrates the value of satellite data for helping states to manage air quality and to meet the requirements of the Clean Air Act.

Key evidence for Wyoming's 6 June event demonstration was provided by NASA's AJAX (Alpha Jet Atmospheric Experiment; https://espo.nasa.gov/missions/ajax/content/AJAX). It was coincidental that the AJAX aircraft was gathering data on weather systems over California just prior to the ozone event in Thunder basin. AQAST researchers were track-

[1] www.epa.gov/sites/production/files/2015-05/documents/june_14_2012_strat_o3_concurrence_letter_28_march_2014.pdf

ing the Thunder basin event backward in time and discovered that there had been an AJAX flight two days before. As a result, the AJAX team came together with the EPA working group, both working in tandem ever since.

The 6 June demonstration used ozone analyses from the Real-time Air Quality Modeling System (RAQMS) model, back trajectories of air mass history from the AJAX flight, and total-column ozone retrievals from the Atmospheric Infrared Sounder (AIRS) as evidence that a stratospheric intrusion pushed ozone mixing ratios over the 75-ppb NAAQS threshold. The trajectories were initialized along the flight track at the measurement locations and were traced back to regions with high total-column ozone as observed by the AIRS instrument. RAQMS is a global general circulation model (GCM) that provides real-time predictions of atmospheric dynamics, chemistry, and aerosols. Its dynamical forecasts are initialized with the NOAA Global Data Assimilation System (GDAS) meteorological analyses, and its chemical and aerosol forecasts are initialized using chemical and aerosol analyses constrained with real-time satellite ozone and aerosol optical depth retrievals from NASA A-Train satellites. RAQMS has provided real-time global ozone and aerosol analyses and forecasts on a daily basis since January 2012 (http://raqms-ops.ssec.wisc.edu).

The 6 June demonstration helped identify the need for stratospheric intrusion forecasts to help air quality managers in the western United States identify stratospheric intrusion events. Following the 6 June demonstration, IDEA-I (Infusing Satellite Data into Environmental Applications—International) was expanded to include stratospheric intrusion forecast capability. IDEA-I was originally developed as part of a NASA- and NOAA-funded program to provide air quality managers with open-source, globally configurable tools with which to forecast air quality (both real-time and retrospectively) using satellite retrievals of aerosol optical depths (http://cimss.ssec.wisc.edu/idea-i/USaerosol). IDEA-I was developed within the framework of the Global Earth Observation Systems of Systems (GEOSS) Group on Earth Observations (GEO) Health Societal Benefit Area and was made publicly available through the National Environmental Satellite, Data, and Information Service (NESDIS) Center for Satellite Applications and Research (STAR).

The newly released IDEA-I stratospheric intrusion forecasts (http://cimss.ssec.wisc.edu/idea-i/USozone/index.php?action=view_preview) help air quality managers uncover stratospheric intrusions based on satellite retrievals of ozone, temperature, and water vapor profiles. This information can then be used as the starting point for trajectory forecasts.

These types of forecasts can predict whether or not intrusions are likely to impact surface ozone levels over the ensuing 48 h, and where those impacts might be felt. IDEA-I stratospheric intrusion provides twice-daily trajectory forecasts that show when and where upper tropospheric air with high ozone mixing ratios are likely to descend toward the surface of the Earth. The trajectory forecasts are initialized soon after satellite overpass using the A-Train's ability to directly broadcast data to the University of Wisconsin—Madison's Space Science and Engineering Center (SSEC). However, IDEA-I stratospheric intrusion forecasts do not predict the surface ozone mixing ratios.

**BEYOND WYOMING.** In 2013, the AJAX flights were coordinated to intercept potential stratospheric intrusion events over California and Nevada. The EPA SI Working Group is in the process of determining when and where stratospheric intrusions may have occurred during 2013 and 2014. The team is trying to determine whether stratospheric intrusion events influenced elevated ozone levels measured at the surface, but it has not yet finished analyzing all of the data.

The collaboration between AQAST, NASA's AJAX team, EPA, NOAA, and air quality managers in Wyoming, Colorado, and other states has been valuable in identifying, predicting, and conducting retrospective analysis of stratospheric intrusions. Furthermore, AQAST scientists have worked with the EPA SI Working Group to develop user-friendly tools that could reduce the burden on the Wyoming DEQ and other air quality managers whose states experience stratospheric intrusions. These tools use satellite measurements of ozone to identify where stratospheric intrusions may occur and to predict whether intrusions will affect surface ozone levels. The tools range from simple trajectory-based forecasts to complex satellite data assimilation and forecasting systems. The outputs from these tools are posted online to give air quality managers easy access to the data provided by these powerful resources.

EPA's stratospheric intrusion working group is currently testing additional tools that provide operational support for air quality managers. The Atmospheric Infrared Sounder (AIRS) was the first hyperspectral infrared instrument to be used for satellite ozone profile retrievals, and the Cross-track Infrared Sounder (CrIS) is the newest instrument with these capabilities. Satellite retrievals from AIRS and CrIS provide the basis for predicting where stratospheric intrusions could affect ground-level air quality. In the future, satellite tools may be further enhanced with additional airborne measurements, such as the European In-service Aircraft for a Global Observing System (IAGOS; www.iagos.org) program, which uses instruments mounted on commercial aircraft to measure atmospheric composition.

AIRS and CrIS represent the next generation of forecasting tools. Air quality managers and researchers can download them by navigating to the SSEC International MODIS/AIRS Processing Package (IMAPP) page and choosing to download the Hyperspectral Sounder Stratospheric Ozone Intrusion Forecast and Analysis Software Package (http://cimss.ssec.wisc.edu/imapp/ideai_ozone_v1.0.shtml). Visitors to the site will be able to pick the domain of their choice to do their own forecasting exercises.

Finally, NASA's Global Modeling and Assimilation Office (GMAO) has recently expanded its high-resolution modeling capabilities to simulate the detailed chemical signatures of stratospheric intrusions (http://gmao.gsfc.nasa.gov/research/composition/modeling/stratospheric_intrusions). For instance, Bryan Duncan, an AQAST member from NASA's Goddard Space Flight Center, contributed to the development of the Goddard Earth Observing System Model, Version 5 (GEOS-5), which can be used to predict the frequency, seasonality, and life cycle of stratospheric intrusions. Some of these tools, such as RAQMS and IDEA-I forecasts, may be utilized now by air quality managers to predict when exceptional events will cause elevated ozone levels. Global RAQMS and GEOS-5 ozone analyses are available, upon request from SSEC and GMAO, to help air quality managers demonstrate cases in which the ozone standard would not have been exceeded without the uncontrollable stratospheric contribution. Wyoming may soon become the first state to apply this cutting-edge research to demonstrate NAAQS compliance and provide an example for other states to follow.

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