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May 5, 2010

Statement of
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before the
Subcommittee on Space and Aeronautics
Committee on Science and Technology
United States House of Representatives

Good morning Chairwoman Giffords, Ranking Member Olson and Members of the Subcommittee. I appreciate the opportunity to appear before you today to discuss the National Aeronautics and Space Administration's (NASA's) Earth Science-related activities to monitor and study volcanic ash clouds. The recent eruption of Eyjafjallajökull highlights the different types of contributions that NASA Earth Science makes to the study of, and response to, such events. Through its fleet of satellite assets, NASA is able to rapidly generate and broadly disseminate imagery and data products on the location, heights, and densities of ash plumes and related hazards. These data products fuel a range of research investigations which enhance our knowledge of solid Earth processes, atmospheric transport and composition, and the impacts that volcanic eruptions have on the Earth system. NASA is also able to – and did – provide critical data streams from these research satellites to the National Oceanic and Atmospheric Administration (NOAA) to support that agency's operational prediction of dust plumes. In response to the intense public interest in this event, NASA has conducted focused public outreach activities regarding our research capabilities and science activities in the areas of volcano research and hazard prediction. Although NASA does not have operational responsibility for observation and analysis of volcanic gas and aerosol emissions, its fleet of research spacecraft provides data that are directly applicable to the societal hazards presented by these phenomena.

NASA has been using research satellites to study volcanic eruptions, especially their atmospheric impact, for more than three decades. NASA pioneered such activities using the Total Ozone Mapping Spectrometer (TOMS) instrument flying aboard the Nimbus 7 satellite launched in 1978. The record for the Nimbus 7 TOMS and the flight of successor TOMS instruments on other missions covers the years 1978-2003 and includes observations of a total of 274 eruptive events from 70 different volcanoes (see http://toms.umbc.edu/). Starting in 2004 and extending to the present, key successor measurements are provided by the Ozone Monitoring Instrument (OMI) flying aboard NASA's Aura spacecraft.

Information on atmospheric composition in the TOMS/OMI data is based on measurements of ultraviolet radiation; however, this is only one of the ways in which NASA uses its satellites to study the atmospheric impact of volcanic eruptions. NASA's currently operating fleet of 13 satellite missions is being used to generate several data products which provide complementary information on volcanic effects on the atmosphere through measurements obtained from different wavelength regions, viewing geometries, and employing a variety of remote sensing technologies. These products provide information not only on the location of ash clouds and sulfur dioxide (SO_2) injected into the atmosphere, but on the

height, size, and composition of the particles. Such data are critically important for the initialization and evaluation of the models that are used to predict the evolution of the gas and ash plumes associated with volcanic eruptions, as well as for direct guidance as to the location and severity of ash plumes.

Monitoring Eyjafjallajökull Using NASA Assets

NASA's satellites have observed the ash plume since the eruption of Eyjafjallajökull, providing essential data on the size and composition of the plume as it expanded and moved over Europe. For example, data acquired by the Multi-angle Imaging SpectroRadiometer (MISR), one of the instruments on NASA's TERRA spacecraft (launched in 1999) provided information on both the horizontal and vertical extents of the plume. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua (launched in 2002) satellites captured images of the eruption; the multiple wavelength measurements provided by the MODIS instruments aid researchers in separating ash plumes from clouds in the imagery. Information on the height of the ash plume was also provided by MODIS. NASA was able to validate the Terra and Aqua ash plume height observations using data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched in 2006. CALIPSO's active remote sensing (lidar) approach not only detects aerosols (small particles such as dust, smoke and pollution) and thin clouds that are often invisible to radar, but determines their heights and vertical concentration profiles. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument, also onboard Terra, is able to detect and track lava flows, as well as ash and gas plumes, with high spatial resolution. For the Eyjafjallajökull eruption, additional thermal and visible images of the plume were captured using the Atmospheric Infrared Sounder (AIRS) instrument on Aqua and the Hyperion instrument on Earth Observing-1 (EO-1), launched in 2000. The data and images are archived and available from the NASA Earth Observing System Distributed Active Archive Center. Select imagery can be accessed at: http://earthobservatory.nasa.gov/NaturalHazards/event.php?id=43253.

In addition to providing measurements and information to aid decision-makers in responding to the volcanic event and its aftermath, these data from NASA's research satellites are being utilized in several ongoing NASA-sponsored scientific studies of solid Earth processes, atmospheric composition and air quality, Earth's radiation balance, and aviation forecasting improvement methodologies within NASA's Earth Science Division's Research and Analysis (R&A) and Applied Sciences programs.

For example, over the past several years a project competitively funded through NASA's Applied Sciences Program demonstrated reliable and accurate detection of volcanic ash clouds using observations of sulfur dioxide (SO_2) from the Ozone Monitoring Instrument (OMI) onboard the NASA Aura satellite. SO_2 is a reliable marker for fresh ash clouds from explosive magmatic eruptions as it provides a clear discrimination between volcanic plume and ordinary clouds. Since volcanic eruptions are essentially the only large sources of stratospheric SO_2, false alarms are non-existent. Satellite observations of SO_2 thus assist operational agencies to identify and locate volcanic ash clouds, in particular during the first few days after an eruption. In general the ash in a volcanic plume will drop due to gravity effects faster than the SO_2, so that some distance away from the volcano the ash and SO_2 clouds may be separated. Details of how this Applied Sciences work is now being used in an operational regime are presented in the next section.

Collaboration with U.S. and International Organization to Monitor Volcanic Ash Plumes

NASA works with other agencies to ensure that data from NASA's research satellites can be used to meet operational needs. For example, NASA, in collaboration with NOAA, provides information on volcanic sulfur dioxide (SO_2) and ash aerosols from OMI aboard the Aura satellite every three hours after the data is acquired. This information is used to supplement data from NOAA's Geostationary Operational Environmental Satellites (GOES) and Polar Operational Environmental Satellite (POES) fleets. NOAA distributes these data on-line to its Volcanic Ash Advisory Centers (VAACs) at:

http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html. Nine VAACs were founded in 1995 as a part of an international system set up by the International Civil Aviation Organization (ICAO) called the International Airways Volcano Watch (IAVW). The VAACs are charged with gathering information on the presence and motion of volcanic clouds and assessing any hazards to aviation. They issue advisories and alerts to airline and air traffic control organizations on the possible danger of volcanic clouds. VAACs assist the aviation community to utilize satellite data, pilot reports, and other sources of information to detect and track ash clouds, and to use trajectory and dispersion models to forecast the motion of ash plumes.

At the time of the latest eruption, SO_2 information was being made routinely available for sectors covering the Americas and the Pacific, through the Anchorage and Washington Volcanic Ash Advisory Centers (VAACs). However, beginning on April 19, 2010, NASA began to provide this information for sectors covering Iceland and Northwest Europe to the VAAC in London. This information is now being utilized in the formulation and validation of Volcanic Ash Advisories over Europe.

As an additional response to the eruption, the Support to Aviation Control Service (SACS), a support center for the European VAACs, is now directly linking to the Aura/OMI near-real time products (http://sacs.aeronomie.be/). The SACS SO_2 data and alert service delivers near-real time data derived from satellite measurements regarding SO_2 emissions possibly related to volcanic eruptions, and in case of exceptional SO_2 concentrations ("SO_2 events") can use the data to send out alerts by email to interested parties. When volcanic activity poses a hazard to aviation, the VAACs issue alerts to air traffic control and airline organizations to help them decide whether to reroute planes away from volcanic clouds. In the case of the Eyjafjallajökull eruption, the satellite measurements and products were also directly shared with Schiphol Airport (Amsterdam) and the Netherlands Ministry of Traffic Affairs through the OMI Principal Investigator at the Royal Netherlands Meteorological Institute.

Future NASA Assets With Volcanic Ash Monitoring Applications

Several of the research satellite missions that NASA is currently developing will be able to provide new and advanced insights into volcanic ash cloud properties.

Later this year, NASA will launch the Glory mission to study the Earth's energy budget and the presence of aerosols in the atmosphere. Glory will be able to distinguish various species of aerosols, information which will advance the study of volcanic effluent composition.

In 2011, NASA is scheduled to launch the NPOESS Preparatory Project (NPP). The Visible/Infrared Imager Radiometer Suite (VIIRS) instrument on NPP is designed as an operational follow-on to the research-grade MODIS instrument on Terra and Aqua. The Ozone Mapping and Profiler Suite (OMPS) on NPP will provide data that to continue support for the detection of volcanic ash clouds using SO_2 observations, currently performed by Aura/OMI. Operational availability of VIIRS data will continue on the Joint Polar Satellite System, scheduled for launch in 2015.

The 2007 National Research Council (NRC) Decadal Survey recommended several missions that promise to advance future volcano research. The **Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI)** mission, a Tier 1 mission, has as a key mission objective to improve the determination of the likelihood of earthquakes, volcanic eruptions, and landslides. This will enhance our ability to anticipate future eruptions, whereas the response to the Eyjafjallajökull eruption was reactive. Likewise, the Tier 2 **Hyperspectral Infrared Imager (HyspIRI)** mission would include measurements over a range of optical and infrared wavelengths useful for detecting volcanic eruptions, determining the ash content of volcanic plumes, and identifying the occurrence and effects of associated landslides. The **Geostationary Coastal and Air Pollution Events (GEO-CAPE)** mission, also a Tier 2 mission, would measure

aerosols and allow the tracking of pollutants being transported in the atmosphere. Similarly, data from the Tier 2 **Aerosol-Cloud-Ecosystems (ACE)** mission would be able to distinguish volcanic aerosols from other aerosol types and clouds, and will track the dispersion of volcanic plumes in three dimensions on a global basis.

Improvements to Volcanic Ash Plume Modeling

NASA-developed global models can be used to simulate the emission of volcanic ash and SO_2 into the atmosphere, and to track its subsequent transport and dispersion on regional and global scales. NASA also routinely uses air parcel trajectory modeling to estimate the source regions of features seen in satellite data that are suspected to have a volcanic origin. However, such model runs are generally undertaken after an eruption has taken place in order to advance scientific understanding, leading to improvements in the accuracy of the models. At present, our understanding of solid Earth processes and our ability to obtain adequate global measurements to initiate the models are both insufficient for generating routine, accurate predictions.

The mandate of NASA's Earth Science program is to increase scientific understanding of Earth processes as an integrated system. NASA thus does not produce routine, operational predictions of volcanic ash and SO2 cloud transports and evolution. Because there is a lack of immediately available information on the quantity and characteristics of emissions from any particular volcano, any forecasts of ash and SO_2 emission and propagation are relatively crude. With the present "state of the art," estimates of SO_2 cloud transport and characteristics are based heavily on estimates of emitted SO_2, and while model results usually match well with observed cloud dispersion and distribution, they do not produce reliable estimates of SO_2 concentrations. At this time, air parcel trajectory models, in which columns of air parcels are initialized over erupting volcanoes at the time of the eruption and then tracked as the parcels are transported away from the volcano location by forecast wind fields, estimate the evolution of the ash cloud but do not consider important loss processes such as fallout, rainout, and washout, precluding a reliable forecast of ash cloud mass loading.

The Global Modeling and Assimilation Office at NASA Goddard Space Flight Center generates weather forecasts for the NASA research community, using the Goddard Earth Observing System – Version 5 (GEOS-5) Data Assimilation System. This system includes an aerosol model, Goddard Chemistry Aerosol Radiation and Transport (GOCART), as part of its routine twice-daily weather forecast. GOCART must be forced with appropriate emissions and produces 3-dimensional distributions of aerosols during the forecast period. At present, the GEOS-5 system includes an inventory of continuously outgassing volcanoes, but episodic volcanic eruptions are not included.

Routine forecasts of the propagation of volcanic ash and SO2 clouds following an eruption using the GEOS-5 system would be possible given some modifications. More detailed observations of the constituents of the ejecta and their vertical distribution are required. Observations need to include information about the timing and duration of the eruptions, the injection altitudes as a function of time, and the particular characteristics of the emissions (amount, size, type). The information would need to be made available or converted to machine-readable data files with time of eruption, location, plume height and strength of the emission in terms of SO_2 and ash. The GOCART aerosol model would need to be modified explicitly to include a volcanic ash constituent. A third area of improvement is the development of statistical models of uncertainty useful to decision makers. For this, an ensemble forecasting technique would be necessary, spanning likely scenarios of ejecta and their vertical distribution as well as weather forecast uncertainty.

The London VAAC runs a version of the Numerical Atmospheric-dispersion Modeling Environment (NAME) model (http://www.metoffice.gov.uk/aviation/vaac/eruption_detection.html). The London

VAAC has used the OMI aerosol index (AI) to validate their dispersion model output, although their main source of satellite data has been the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) infrared instrument on the European geostationary Meteosat Second Generation (MSG) satellite, which has better temporal resolution than the polar-orbiting OMI. However, their automatic system based on SEVIRI detects only about 2/3 of the eruptions. Using near real time ultraviolet data, such as OMI Aerosol Index and SO_2 (as an ash proxy) in addition to thermal infrared data could improve early (thick) volcanic plume detection, not visible in the infrared.

NASA recently began providing OMI near real time SO_2 and AI data to Operations Department of the European Centre for Medium Range Weather Forecasts (ECMWF) for evaluation in assimilation tests. The goal is to create an advanced operational data assimilation system that will: (1) reasonably model a volcanic plume (given the uncertainties in injection height, and composition of the plume); (2) assimilate available satellite near-real-time data to constrain the model forecast; and (3) provide forecasts for the VAACs.

It is important to note that the North American-Asia air traffic routes overfly the volcanic arcs of the North Pacific from Tokyo, Japan to Anchorage, Alaska. These are among the most violent and active volcanoes on Earth. The Washington and Anchorage VAACs, operated by NOAA, have a stellar record of tracking, monitoring and warning of volcanic ash dispersion. These VAACs run NOAA's HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. They utilize operational NOAA GOES and POES satellite data, NASA research observations, as well as data leveraged from European, Japanese, Indian, and other environmental satellites. The Washington and Anchorage VAACs' areas of responsibility extend from South America through the Caribbean and cover the continental United States, Alaska, and most of the Pacific.

Airborne Assets With Volcano-Monitoring Capabilities

Volcano remote sensing researchers have a strong need for *in situ* sampling of eruption plumes and drifting ash clouds to improve, calibrate and validate ash dispersal models. Airborne assets are uniquely qualified to measure the gas and ash content of volcanic plumes at altitude. However, sampling a volcanic plume is also a hazardous procedure given the dangers that volcanic-ash contamination poses to aircraft engines.

The United States maintains both research and operational airborne assets that could be used to monitor future eruptions. However, NASA's research aircraft and unmanned aerial vehicles are typically engaged in coordinated field campaigns investigating other science research questions, but could be diverted to a hotspot on an emergency basis. Such a decision would constitute an interruption to the baseline mission profile and would require at least a one week lead time in order to position the aircraft, instruments, and crew.

One such asset is NASA's ER-2 aircraft, which could be instrumented with the Cloud Physics Lidar (CPL) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) in order to study atmospheric particles. In the future, NASA's new high-altitude, long-endurance, heavy-lift Global Hawk unmanned aerial system might also be utilized for volcanic plume monitoring. The Global Hawk is still in its development phase, so rapid response use will be limited for the next few years as NASA gains operational experience with the Global Hawk and integrates new instruments onto the platform.

Conclusion

As the Eyjafjallajökull eruption has shown, volcanic eruptions have a significant impact on the Earth's atmosphere and the planes that travel through that airspace. Although NASA does not have an

operational requirement to monitor and predict volcanic ash plumes, existing and planned NASA assets provide essential data on volcanic emissions that can be used by operational agencies around the world to determine if there are hazards to aircraft. NASA's satellites and associated research programs have added significantly to our ability to observe not just the position of volcanic ash plumes, but to understand their composition, height, and properties. Through the NASA Applied Sciences Program, we can facilitate the use of the data collected by NASA's research satellites in operational regimes. NASA researchers are developing and improving models that can be used to predict how volcanic ash plumes will propagate. While there are still areas for improvement, NASA's Earth Science Division supports this work through new instruments and satellites and continued work in its Applied Sciences and Research Programs.