Talking Points Volcanoes and Volcanic Ash Part 1

Slide 1 - Title **Page** and intro to authors.

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Slide 2 (6) – WHY?

Slide 2, Page 2 - Volcanic Ash and Aviation Safety: Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety – 1991 - Introductory Remarks by Donald D. Engen

(Vice Admiral) Donald D. Engen – a legend in aviation, aviation education, and aviation history. U.S. Navy from 1942 (as a Seaman Second Class) - retiring in 1978 as a Vice Admiral. Also, – General Manager of the Piper Aircraft Corporation – a member of the National Transportation Board; appointed Administrator of the Federal Aviation Administration by President Ronald Reagan, and was also appointed Director of the Smithsonian Air and Space Museum, where he served until his death (1999 – glider accident).

Slide 2, Page 3 – What to call this volcano? Eyjafjallajökull - phonetically "Eye a Fyat la yu goot" However, this volcano is also known as "Eyjafjöll" which is pronounced "Eva logue" And finally, this volcano is, thankfully, also known as "E15." (or the basic "Iceland Volcano").

Some statistics concerning Eyjafjallajökull volcano. The volcano in Iceland erupts explosively April 14 after a two day hiatus (originally beginning rather benignly March 20, 2010).

Point 1: That translates to nearly $200 million loss per day

Point 2: That represents 10 percent of the entire global air traffic system!

Point 3: (65,000 in the ten day period mentioned above) throughout Europe

Point 5: In locations far from the erupting volcano, (ie the United States, India, and southeast Asia), travel was significantly affected.

Slide 2, Page 4 – From USGS. Relatively large area affected - Mount St. Helens Ash Distribution from (just) the May 18th Eruption.

Slide 2, Page 5 – Comparisons of various past eruptions over the lower 48. Mount St. Helens; Long Valley Caldera; Yellowstone Caldera; and Crater Lake Volcano eruptions. This is what could (will) happen at an unknown point in the future.

Slide 2, Page 6 – Map of potentially active volcanoes across the western portion of the USA…which also answers the question as to "WHY?"

Slide 3 (5) – Group of material showing HYSPLIT 48 hour trajectory forecasts for **hypothetical** eruptions that could have started on the evening of July 20th (00Z July 21)2010. The period selected for the run was purely random – with no preconceived ideas. The (hypothetical) sites are as follows:

Page 1 – Mount Rainier

Page 2 – Mount Lassen

Page 3 – Mount Shasta

Page 4 – Long Valley Caldera

Page 5 – Yellowstone Caldera

Point out the far reaching effects in each of these hypothetical events. Also point out that there will be more concerning the HYSPLIT model itself (and these hypothetical events) later in the session.

Slide 4 – Objectives

Slide 5 (1) – Intro to Volcano and eruptive types.

Slide 6 (1) – Cinder cone example - Recent example of a Cinder Cone Volcano. **Parícutin Volcano in Mexico. Pari koo ten (Located west of Mexico City)**

Cinder Cone Volcano: The simplest type of volcano. They are built from particles and blobs of congealed lava ejected from a single vent. As the gas-charged lava is blown violently into the air, it breaks into small fragments that solidify and fall as cinders around the vent to form a circular or oval cone. Most cinder cones have a bowl-shaped crater at the summit and rarely rise much more than a thousand feet or so above their surroundings. Cinder cones are numerous in western North America as well as throughout other volcanic terrains of the world.

Famous volcano that initially erupted back in 1943. The volcano began as a fissure in a cornfield owned by a P'urhépecha farmer, Dionisio Pulido on February 20, 1943. Pulido, his wife, and their son all witnessed the initial eruption of ash and stones first-hand as they plowed the field. The volcano grew quickly, reaching five stories tall in just a week, and it could be seen from afar in a month. Much of the volcano's growth occurred during its first year, while it was still in the explosive pyroclastic phase. Nearby villages Paricutín (after which the volcano was named) and San Juan Parangaricutiro were both buried in lava and ash; the residents relocated to vacant land nearby.

At the end of this phase, after roughly one year, the volcano had grown 336 meters (1,102.36 ft) tall. For the next eight years the volcano would continue erupting, although this was dominated by relatively quiet eruptions of lava that would scorch the surrounding 25 km² (9.65 mi²) of land. The volcano's activity would slowly decline during this period until the last six months of the eruption, during which violent and explosive activity was frequent. In 1952 the eruption ended and Parícutin went quiet, attaining a final height of 424 meters (1,391.08 ft) above the cornfield from which it was born. The volcano has been quiet since. Like most cinder cones, Parícutin is believed to be a monogenetic volcano, which means that now that it has finished erupting, it will never erupt again. Any new eruptions in a monogenetic volcanic field erupt in a new location.

Slide 7 (1) – **Compostie Volcano - Mount St Helens** - May 18, 1980

Composite (strato) Volcano: Typically steep-sided, symmetrical cones of large dimension built of alternating layers of lava flows, volcanic ash, cinders, blocks, and bombs and may rise as much as 8,000 feet above their bases. Some of the most conspicuous and beautiful mountains in the world are composite volcanoes, including Mount Fuji in Japan, Mount Cotopaxi in Ecuador, Mount Shasta in California, Mount Hood in Oregon, Mount St. Helens and Mount Rainier in Washington.

Slide 8 (1) – **Shield Volcano** - **Mauna Loa Hawaii**

Shield Volcano: Are built almost entirely of fluid lava flows. Flow after flow pours out in all directions from a central summit vent, or group of vents, building a broad, gently sloping cone of flat, domical shape, with a profile much like that a a warrior's shield. They are built up slowly by the accretion of thousands of flows of highly fluid basaltic (from basalt, a hard, dense dark volcanic rock) lava that spread widely over great distances, and then cool as thin, gently dipping sheets. Lavas also commonly erupt from vents along fractures (rift zones) that develop on the flanks of the cone. Some of the largest volcanoes in the world are shield volcanoes. In northern California and Oregon, many shield volcanoes have diameters of 3 or 4 miles and heights of 1,500 to 2,000 feet. The Hawaiian Islands are composed of linear chains of these volcanoes including Kilauea and Mauna Loa on the island of Hawaii -- two of the world's most active volcanoes. The floor of the ocean is more than 15,000 feet deep at the bases of the islands. As Mauna Loa, the largest of the shield volcanoes (and also the world's largest active volcano), projects 13,677 feet above sea level, its top is over 28,000 feet above the deep ocean floor.

Mauna Loa - the largest volcano on Earth in terms of volume and area covered and one of five volcanoes that form the Island of Hawaii in the U.S. state of Hawaii in the Pacific Ocean. It is an active shield volcano, with a volume estimated at approximately 18,000 cubic miles (75,000 km3),[2] although its peak is about 120 feet (37 m) lower than that of its neighbor, Mauna Kea. The Hawaiian name "Mauna Loa" means "Long Mountain". Lava eruptions from Mauna Loa are silica-poor, thus very fluid: and as a result eruptions tend to be non-explosive and the volcano has relatively shallow slopes.

The volcano has probably been erupting for at least 700,000 years and may have emerged above sea level about 400,000 years ago, although the oldest-known dated rocks do not extend beyond 200,000 years.[3] Its magma comes from the Hawaii hotspot, which has been responsible for the creation of the Hawaiian island chain for tens of millions of years. The slow drift of the Pacific Plate will eventually carry the volcano away from the hotspot, and the volcano will then become extinct within 500,000 to one million years from now.

Slide 9 (1) –Eruption Types:

Definitions:

Info from **"*Volcanoes*" by Peter Francis and Clive Oppenheimer**

Large volume basaltic eruptions are almost exclusively **effusive** (these types of eruptions are the ones you can walk up to and observe on your vacation, Poas volcano in Costa Rica, etc. Large volume silicate eruptions are almost exclusively **explosive**. (the ones that come to mind are recent the Okmok and Kasatochi volcanoes in Alaska, the Chaiten volcano in Chile, and of course, the eruption of Mt. Saint Helens in 1980). For the most part, we are primarily concerned with volcanic eruptions that exhibit explosive activity.

Slide 10 (1) – Eruption Mechanisms:

Phreatic eruption (explosion): An explosive volcanic eruption caused when **water and heated volcanic rocks** interact to produce a violent expulsion of steam and pulverized rocks. **Magma is not involved**. **Example: Mount Saint Helens.**

Phreatomagmatic eruptions: are defined by the interaction between **water and magma**, providing for explosive thermal contraction of magmatic particles under rapid cooling from contact with water. **Example: Mount Okmok.**

Magmatic eruptions: eruptions caused by **rapid decompression of the magma** - therefore releasing dissoved gases quickly (explosively) causing familiar fountains and flowing associated with shield volcanoes. **Example: Mauna Loa.**

Slide 11 (2) – The Okmok Example: Image of an **explosive type/phreatomagmatic eruption for Okmok**, taken Sunday, **July 13, 2008**, by flight attendant Kelly Reeves during Alaska Airlines flights 160 and 161.Picture Date: July 13, 2008

Image Creator: Reeves, Kelly;
Image courtesy of Alaska Airlines.

Slide 11, Page 2 - Here are the two eruption examples within the Okmok caldera. The diagram shows a hypothetical **phreatomagmatic** eruption (top) - a result of interaction between water and magma that releases both magmatic gases and steam - caused by the contact of the magma with groundwater or ocean water. The extreme temperature of the magma causes near-instantaneous evaporation to steam resulting in an explosion of the steam along with water, ash, rock, and volcanic bombs. (Below) – **Magmatic eruption (also called a Strombolian eruption) -** characterized by huge clots of molten lava bursting from the crater to form luminous arcs through the sky. The explosions are driven by bursts of gas slugs that rise faster than surrounding magma.

Figure taken from Beget, J.E., Larsen, J.F., Neal, C.A., Nye, C.J., and Schaefer, J.R., 2005, Preliminary volcano-hazard assessment for Okmok Volcano, Umnak Island, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2004-3, 32 p., 1 sheet, scale 1:150,000.Picture Date: July 13, 2008
Image Creator: Larsen, Jessica;

Image courtesy of the AVO/ADGGS.

Slide 12 (1) – Intro to the Hazards: Volcanic eruptions and ash production can cause great hardship to those local and regional communities which lay under the direct effects of a volcano. These effects range widely from property damage to health hazards. Volcanic eruptions with plumes of drifting ash clouds not only cause substantial delays in flight operations around the world, but can also produce significant damage to both aircraft and equipment.

Eyjafjallajökull volcano, Iceland is erupting with lava, ash—and lightning - April 16th, 2010

Photo : Photo: Stomboli Online @ http://www.swisseduc.ch/stromboli/ - **Marco Fulle**

Slide 13 (1) – The Dangers: Point out obvious hazards. Less obvious definitions are below. There are also further examples and definitions of both pyroclastic flow and Lahar in the next two slides.

Tephra: is a general term for fragments of volcanic rock and lava regardless of size that are blasted into the air by explosions or carried upward by hot gases in eruption columns or lava fountains. Such fragments range in size from less than 2 mm (ash) to more than 1 m in diameter. Large-sized tephra typically falls back to the ground on or close to the volcano and progressively smaller fragments are carried away from the vent by wind. Volcanic ash, the smallest tephra fragments, can travel hundreds to thousands of kilometers downwind from a volcano.

Landslide: large masses of rock and soil that fail, fall, **Slide**, or flow very rapidly under the force of gravity down a slope.

Pyroclastic flows: **(examples follow…so be brief here)** are high-density mixtures of hot, dry rock fragments and hot gases that move away from the vent that erupted them at high speeds. They may result from the explosive eruption of molten or solid rock fragments, or both.

Lahar: (examples follow…so be brief here) a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano.

Slide 14 (2) – **Pyroclastic Flow**: Mayon Volcano, Philippines. (Maximum height of the eruption column was 15 km – 9.32 miles - above sea level). Photograph by C.G. Newhall on September 23, 1984

Pyroclastic flows: are high-density mixtures of hot, dry rock fragments and hot gases that move away from the vent that erupted them at high speeds. They may result from the explosive eruption of molten or solid rock fragments, or both.

How: Explosive volcanic eruptions can produce fast-moving (gravity) flows or currents of hot gas and rock (collectively known as tephra – which is really a plasma of sorts), which can travel away from the volcano at speeds generally as great as 700 km/h (450 mph). The gas can reach temperatures of around 1,000 deg C (1,830 deg F). These flows normally hug the ground as they accelerate downhill, spreading laterally (if the terrain is shaped appropriately) under gravity. Sort of the rocky analogy of a meteorological combination – the collapse of the ventilation column (collapse of a thunderstorm) due to the weight of the tephra (similar to a downburst) and then the acceleration downslope of the dense material (similar to a katabatic wind). Their speed depends upon the density of the current, the volcanic output rate, and the gradient of the slope. Obviously, inhaled ash particles from within a hot, dense pyroclastic flow will almost always result in death(from severe burns and/or asphyxiation).

Slide 14, Page 2 -: USGS photo archive **- Pyroclastic Flow Mt. St. Helens, August 7, 1980**

Slide 15 (2) – Lahar: a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano.

Lahar: Mount St. Helens, The depth (height) that the St Helens Lahar attained – nearly 25 ft!

Slide 15, Page 2 - Left Over by a Lahar: USGS, Mt. ST. Helens – Sept. 16, 1980

Slide 16 (3) – The **Hazards: Hazards in the Air**

Ash causes significant damage to… at the worst end, it can cause in-flight engine loss (accumulation of melted and resolidified ash on interior engine vents reduce the effective flow of air through the engine, causing it to stall), it is abrasive, mildly corrosive, and conductive. Potential to put human lives at stake. Repair and replacement associated with encounters are costly (Example: Between 1980 and 2004, more than 100 jet aircraft sustained damage after flying through volcanic ash clouds. The repairs cost more than $250 million. At least 7 of these encounters resulted in temporary engine failure, with 3 aircraft losing power from all engines. These engine failures have occurred at distances ranging from 150 to 600 miles from the erupting volcano. Aircraft damage from these volcanic ash encounters has been reported from as far as 1,800 miles from the volcano.)

Slide 16, Page 2 – **Hazards to Aircraft**. In addition to what is on the slide – the ash particles also damage the external and aerodynamic surfaces of an aircraft…especially the windscreen (is a very common occurrence). Windscreens can become totally obscurred (etching) or even crack due to the ash's hardness and the speeds of the aircraft. As a matter of fact, documentation of the frequency and cost of damage to the windscreen helped to spark alert system development.

Slide 16, Page 3 - **Ground Hazards**: Explosive eruptions that destroy vegetation and deposit volcanic rocks and ash over wide areas create conditions that (1) promote increased rates of surface runoff during rainstorms; (2) dramatically increase the availability of loose debris that can be eroded and transported into river valleys. Significant ash fall can lead to accelerated rates of erosion on hill/slopes and in valleys, above normal stream flow in rivers during rainstorms, and increased deposition of sediment along riverbeds and valley floors.

Slide 17 (5) – Volcanic Ash

(Photo: **Mount Redoubt – December 1989) Interest: KLM Flight 867 (see next page).**

Slide 17, Page 2 – **Synopsis of KLM Flight 867.** Additional Info (story) below.

On 15 December 1989, KLM Flight 867 en route to Narita International Airport, Tokyo from Amsterdam was descending into Anchorage International Airport, Alaska when all four engines failed. The Boeing 747-400, less than 6 months old, flew through a thick cloud of volcanic ash from Mount Redoubt (above), which had erupted the day before.

As the crew of KLM Flight 867 struggled to restart the plane's engines, "smoke" and a strong odor of sulfur filled the cockpit and cabin. For five long minutes the powerless 747 jetliner, bound for Anchorage, Alaska, with 231 terrified passengers aboard, fell in silence toward the rugged, snow-covered Talkeetna Mountains (7,000 to 11,000 feet high). All four engines had flamed out when the aircraft inadvertently entered a cloud of ash blown from erupting Redoubt Volcano, 150 miles away. The volcano had begun erupting 10 hours earlier on that morning of December 15, 1989. Only after the crippled jet had dropped from an altitude of 27,900 feet to 13,300 feet (a fall of more than 2 miles) was the crew able to restart all engines and land the plane safely at Anchorage. The plane required $80 million in repairs, including the replacement of all four damaged engines.

Such dangerous and costly encounters between aircraft and volcanic ash can happen because ash clouds are difficult to distinguish from ordinary clouds, both visually and on radar. Also, ash clouds can drift great distances from their source. **This makes forecasting for these catastrophic events extremely difficult.** For example, in less than 3 days, the ash cloud from the June 15, 1991, eruption of Mount Pinatubo in the Philippines traveled more than 5,000 miles to the east coast of Africa. This ash cloud damaged more than 20 aircraft, most of which were flying more than 600 miles from the volcano.

Slide 17, Page 3 – Volcanic Ash Problems During WW2 (as if they needed more problems) - eighty-eight (88) B-25 aircraft of the USAF were buried in volcanic ash from the eruption of Mt Vesuvius in Italy March 1944 which rendered the machines completely useless for further operations.

Slide 17, Page 4 – Volcanic Ash – What it is: (see slide) More info below.

There are three mechanisms of volcanic ash formation: gas release under decompression causing magmatic eruptions; thermal contraction from chilling on contact with water causing phreatomagmatic eruptions and ejection of entrained particles during steam eruptions causing phreatic eruptions. The violent nature of volcanic eruptions involving steam results in the magma and solid rock surrounding the vent being torn into particles of clay to sand size.

Volcanic ash forms during explosive eruptions when gases dissolved in the molten rock and under great pressure, expand and escape violently into the air. The force of the escaping gas then fiercely shatters the airborne, solidifying rocks.

Once in the air, and due to acquired momentum along with buoyancy effects, the hot ash (and other escaping gases) quickly rises and forms an eruption column that often reaches to more than 30,000 feet in elevation.

Listed as "mostly" insoluble because although silica and other silica rich minerals will not dissolve in water, many times the ejecta of volcanoes are coated in sulfide salts which will, through oxidation, form corrosive sulfuric acid solutions. Also, in the atmosphere, sulfur dioxide will oxidize in the presence of water to form falling acidic solutions…aka "acid rain." These acidic solutions, along with the hard ash itself (traveling at over 500 mph) can easily etch the cockpit windscreen…resulting in near total obscuration.

Slide 17, Page 5 - **Mount St. Helens' ash** cloud reached nearly 90,000 ft in about 30 minutes…well above the trop/strat cap. Ash made its way around the world in about two weeks, with over 1000 commercial flights cancelled (compared to over 60,000 flights in europe during the recent Eyjafjallajökull eruption). While this was a much more violent eruption than that of Eyjafjallajökull, it happened in an area that was rather remote (and with favorable weather patterns) to major airports – and allowed for relatively easy re-routing of flights.

Slide 18 (1) – Volcanic Ash Hazards: see slide.

Slide 19 (4) – Health Hazards:

Photo: Clark Air force Base, June 29, 1991 – E. W. Wolfe

Collapsed roofs due to heavy ash fall. Long term exposure to breathable ash particles, generally less than 10 microns in size, will result in acute symptoms, such as: nasal irritation, throat irritation , dry coughing. For people with pre-existing respiratory problems, severe bronchitis may result…with symptoms lasting from weeks to months after the ashfall. Eye and skin irritation and damage (to varying degrees) are also common side effects of exposure to airborne ash.

Slide 19, Page 2 – VOG: - NOAA-15 Satellite, July 10, 2008, Kilauea Volcano – ash and gas "cloud."

Volcanic smog (vog) is formed when SO2 and other gases emitted by an erupting volcano mix with O2 and moisture in the presence of sunlight. The term is often applied to the island of Hawaii, where the Kilauea volcano has been erupting continuously since 1983. Kīlauea emits an estimated 2,000 tons of vog every day.

Vog, similar to smog, in that both contain harmful chemicals that can damage the environment, human health, and the health of other animals. However, they are different. Vog is formed when sulfur oxides emitted by a volcano react with moisture to form an aerosol. The aerosol particles scatter light and so make the vog visible. Smog is formed largely from the incomplete combustion of fuel, reacting with nitrogen oxides and ozone produced from carbon monoxide by reactions with sunlight. The result is also a visible aerosol.

Slide 19, Page 3 – Pyroclastic Flow - Inhaled ash particles from within a hot, dense pyroclastic flow will almost always results in death from burns or asphyxiation.

Close-up view of **Pyroclastic Flow** from the Mayon Volcano, Philippines (September 23, 1984)

Slide 19, Page 4 – Volcanic Gases: Background picture (above) - Mammoth Mountain, California – 1990 results of CO2 poisoning: Dead and dying trees on the south side of Mammoth Mountain were first noticed in 1990. Since then, about 170 acres of trees have died on all sides of the volcano, especially near Horseshoe Lake. When the soil was surveyed in 1994 for carbon dioxide gas, exceptionally high concentrations of gas were found in the soil beneath the trees. What caused such high concentrations of carbon dioxide gas? The most likely sources of the carbon dioxide gas include (1) magma that intruded beneath Mammoth Mountain during an earthquake swarm in 1989; and (2) limestone-rich rocks beneath Mammoth Mountain that were heated by the hot magma.

The gases are listed in descending order of abundance: HCL and HF are strong acids.

Together with the tephra and entrained air, volcanic gases can rise tens of kilometers into Earth's atmosphere during large explosive eruptions. Once airborne, the prevailing winds may blow the eruption cloud hundreds to thousands of kilometers from a volcano. The gases spread from an erupting vent primarily as acid aerosols (tiny acid droplets), compounds attached to tephra particles, and microscopic salt particles.

The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are sulfur dioxide, carbon dioxide, and hydrogen fluoride.

The most hazardous volcanic clouds are those produced by explosive magmatic eruptions of silicic volcanoes (These involve hot, viscous magma that is disrupted explosively by high internal gas pressures as it ascends – producing hot, fine-grained ejecta that rises rapidly). The thermal energy in explosive, magmatic eruption plumes allows them to quickly reach (and usually exceed) the cruising altitudes of jet aircraft (9–11 km). Since these eruptions are driven by magmatic gases, the resultant clouds are also gas-rich, with the dominant gases typically being water vapor (H2O), carbon dioxide (CO2), and SO2 (SO2 is the volatile sulfur species favored at the low pressures and high temperatures within an erupting volcano). Of these gases, SO2 is by far the easiest to measure using remote sensing techniques.

Locally, sulfur dioxide gas can lead to acid rain and air pollution downwind from a volcano. Globally, large explosive eruptions that inject a tremendous volume of sulfur aerosols into the stratosphere can lead to lower surface temperatures and promote depletion of the Earth's ozone layer. Because carbon dioxide gas is heavier than air, the gas may flow into in low-lying areas and collect in the soil. The concentration of carbon dioxide gas in these areas can be lethal to people, animals, and vegetation. A few historic eruptions have released sufficient fluorine-compounds to deform or kill animals that grazed on vegetation coated with volcanic ash; fluorine compounds tend to become concentrated on fine-grained ash particles, which can be ingested by animals.

Additionally: $S0_2$ gas can lead to acid rain production and air pollution downwind from the volcano.

$C0_2$ gas, being heavier than air, may flow like a river into in adjacent low-lying areas and accumulate in the soil. If sufficient in depth (low mixing) and concentration, the $C0_2$ gas can be lethal to all living matter.

A few notable eruptions in the past have released enough hydrogen fluoride (HF), carried on the wind and bound to ash particles, to kill or maim animals that ate any food coated in the ash.

Slide 20 (2) – Volcanic Ash Hazards to Aircraft and Aviation: **Photo: Mt. Cleveland eruption**, May 23, 2006 - Jeff Williams, NASA.

Slide 20, Page 2 - Damage to leading edge surfaces of aircraft. • Ash ingested into jet engines results in loss of performance, and possibly complete shutdown.

Again…significant hazards to aircraft both in the air and on the ground. Volcanic ash damages windscreens, windows, and external probes that tell pilots their airspeed and altitude, and can ruin antennae for communication and navigation radios. Ash can almost instantly contaminate onboard electronic equipment, air conditioning, equipment cooling systems, the fuel system, and hydraulic systems that move flight controls and extend landing gear.

Slide 21 (2) – Volcanic Ash and Aircraft – What is enough? - Still a question that needs to answered (nobody really knows at this point). **What about the $2mg/M^3$ level?**

NASA: "**Engine Damage to a NASA DC-8-72 Airplane From a High-Altitude Encounter With a Diffuse Volcanic Ash Cloud"** August 2003 - By *Thomas J. Grindle and Frank W. Burcham, Jr.)*

As it turns out…it doesn't take too much (ash) to do damage. This is from an encounter (Feb. 2000) of a NASA DC-8-72 research airplane with a diffuse volcanic ash cloud from the Mt Hekla volcano in Iceland.

The NASA DC-8 research airplane inadvertently flew through the fringe of a volcanic ash cloud produced by the Mt. Hekla volcano in Iceland. This encounter occurred in total darkness (no moon) in the early morning of February 28, 2000. There were no indications to the flight crew, but sensitive onboard instruments detected the 35-hr-old ash plume. Upon landing there was no visible damage to the airplane or engine first-stage fan blades; but later close-up inspection of the engines revealed clogged turbine cooling air passages, etc. (Shown in photo)

Analysis of engine damage: All engines exhibited a fine white powder coating throughout. There was leading edge erosion on HPT vanes and blades, blocked cooling air holes, blistered coatings, and a buildup of fine ash inside passages. The photos in the slide above show damaged HPT blades, with clogged cooling air holes, leading edge erosion, buildup of ash in passages, and blistered blade coatings clearly visible. Total cost of refurbishment (to standard flight condition) for all four engines was $3.2 million. Even though this was a diffuse ash cloud, the exposure was long enough and engine temperatures were high enough that engine hot section blades and vanes were coated and cooling air passages were partially or completely blocked. The un-cooled blades still performed aerodynamically but necessitated expensive overhauls. The insidious nature of this encounter and the resulting damage was such that engine trending did not reveal a problem, yet hot section parts may have begun to fail (through blade erosion) if flown another 100 hr. Normally, failure would have not been an issue for at least another 1000 hours.

Later satellite data analysis of the volcanic ash plume trajectory indicated the ash plume had been transported further north than predicted by atmospheric effects. Analysis of the ash particles collected in cabin air heat exchanger filters showed strong evidence of volcanic ash, most of which may have been ice-coated (and therefore less damaging to the airplane) at the time of the encounter. Engine operating temperatures at the time of the encounter were sufficiently high to cause melting and fusing of ash on and inside high-pressure turbine blade cooling passages. There was no evidence of engine damage in the engine trending results, but some of the turbine blades had been operating in an overheated condition and may have had a remaining lifetime of as little as 100 hr. There are currently no fully reliable methods available to flight crews to detect the presence of a diffuse, yet potentially damaging volcanic ash cloud.

Slide 21, Page 2 - Ingestion of volcanic ash by engines may cause serious deterioration of engine performance due to erosion of moving parts and/or partial or complete blocking of fuel nozzles.

Volcanic ash contains particles, whose melting point is below engine internal temperature. In-flight, these particles will immediately melt if they go through an engine. Going through the turbine, the melted materials are rapidly cooled down, stick on the turbine vanes, and disturb the flow of high-pressure combustion gases.

This disorder of the flow may stall the engine, in worst cases.

Slide 22 (3) – Volcanic Ash Plumes: **Photo: USGS – Joyce Warren, Dec 15, 1989 – Redoubt.**

The explosive characteristics are manifested from the fragmentation of the magma and the high speed jet that issues from the vent. The first distinct feature is a nearly lithostatic pressure distribution, which results from the increase of the height of the fragmentation surface. The second one is the atmospheric pressure at the vent; the flow is not choked. The third one is that the relative velocity between the gas and the ash is large at the vent despite the large interaction force between the two phases. The large relative velocity is established in the fractured-turbulent regime, and is maintained in the subsequent gas–ash flow regime. Sometimes the smaller plumes can be just as problematic if close to airports.

Slide 22, Page 2 - GOAL: determine eruption height to successfully monitor and forecast volcanic ash dispersion:

1. Plume (volcanic cloud) height, like meteorological convection, is affected by wind shear and atmospheric instability. 2. Relatively weak eruptions in moist tropics can trigger deep convection columns (15-20 km) due to the extreme instability. 3. Given the same eruptive intensity – relatively dry/stable polar/subpolar environments will (generally) produce lower eruptive heights than in the moist/unstable tropics (up 8 - 10 km difference at times). 4. A higher proportion of volcanic clouds will reach aircraft cruising levels in the moist tropics than from the drier, more stable, poleward environments. 5. Eruptions in higher latitudes in dryer atmospheres are less likely to rise to cruising

altitudes as they gain their energy mainly from the volcanic source (not as much from the atmosphere). Clouds at cruising altitudes will however be richer in ash and more dangerous because ash scavenging is less significant.

Volcanic ash cloud risks for aircraft flying at cruising altitudes (10–12 km) in different environments:

1. An aircraft flying above a polar winter tropopause would expect to have a reduced chance of encountering an ash cloud, but (if) one was encountered – you would expect it to be ash-rich and highly dangerous. 2. Conversely, an aircraft in the moist tropics would have a relatively high risk of flying into or underneath a volcanic cloud, but if the eruption was relatively weak you might only smell some SO2 and not notice any fine ash (i.e. the risk that many of these clouds pose to aviation traffic will be relatively small because of the lower ash content).

Additional Points- Eruptions into moist atmospheres cause clouds that are higher but significantly poorer in ash than eruptions into dry atmospheres. Volcanic clouds in moist atmospheres have a proportionally lower ash loading and are (generally) relatively less of a risk to aviation to eruption clouds at the same heights in dry environments. In the moist tropics, because of the relatively higher ice and SO2 Content than fine ash loading, the clouds are often more difficult to detect as being volcanic using remote sensing ash detection techniques.

Material gathered from:Tupper, A., C. Textor, M. Herzog, H-F Graf, and M. Richards, 2009. Tall clouds from small eruptions: the sensitivity of eruption height and fine ash content to tropospheric instability. Nat Hazards 51:375–401

Slide 22, Page 3 - Vertical growth of the ash plume vs. Lateral Expansion of the ash plume (Mt. St Helens example). This is exactly why there is a "**need for speed**" when it comes to observation/detection, verification, and warning! In this example of a Mt St Helens type eruption (data analysis from Boeing Industries)…it only took between 6 and 8 minutes fro the ash plume to reach between 30 and 40 kft in elevation and to extend horizontally away from the volcano by nearly 50 km (27 miles).

Slide 23 (3) - Worldwide, nearly 500 airports lie within 100 km (62 miles) of active volcanoes. Active Volcanoes in red. Map : Topinka, USGS 1997

Slide 23, **Page** 2 - Next two **Slide**s together -

There are over a hundred active volcanoes in the North Pacific region (about 20% of the world's active volcanoes). Along North Pacific air routes, some of the busiest in the world, at least 15 aircraft (including KLM Flight 867) have been damaged since 1980 by flying through volcanic ash clouds. In the same period, there have been 80 such encounters worldwide, causing hundreds of millions of dollars in damage and lost revenue. Fortunately, no fatalities have yet occurred, but the growth in air traffic over volcanically active regions, such as the North Pacific, is increasing the chance of a deadly encounter.

Slide 23, **Page** 3 - Common flight routes near or over this highly active volcanic region. One can easily see the need for advanced observations and forecasting of volcanic plume movement.

More than 10,000 passengers and millions of dollars in cargo fly across the North Pacific region each day, and the area's aviation traffic is increasing about ten percent a year. This region also contains one of the most active parts of the "Ring of Fire," a belt of active volcanoes that borders much of the Pacific Ocean. About 100 potentially dangerous volcanoes lie under air routes in the North Pacific. Along the Alaska Peninsula and the Aleutian Islands there are more than 40 historically active volcanoes. Even greater numbers of active volcanoes are found to the west of Alaska on the Russian Kamchatka Peninsula and in the Kurile Islands.

Each year about 5 eruptions occur along the 2,400-nautical-mile arc from Alaska to the Kuriles. Ash clouds from volcanoes in this segment of the "Ring of Fire" are usually carried to the east and northeast, directly across busy air routes. On an average of 4 days a year in the North Pacific region, volcanic ash is present above an altitude of 30,000 feet, where most large jet aircraft fly.

Slide 24 (2) – Hazards to Airports: In addition to posing a hazard to in-flight aircraft, volcanic ash can disrupt airport operations with local to global consequences for both life and commerce. Worldwide, nearly 500 airports lie within 100 km (62 miles) of active volcanoes. The primary volcanic hazard to airports is ashfall, which causes not only loss of visibility and slippery runways, but structural damage and contamination to ground systems and stored aircraft along with slippery runways. Ash in airspace around airports has damaged in-flight aircraft and caused airport closures that can involve loss of alternate landing sites.

Recently: An American Airlines jet is parked in the tarmac covered with ash from the eruption of the Central American - Pacaya Volcano at the international airport in Guatemala City, Friday May 28, 2010. The volcano started erupting lava and rocks on Thursday afternoon, blanketing Guatemala City with ash and forcing the closure of the international airport. One television reporter has been killed and thousands of residents from villages closest to the volcano have been evacuated to shelters.

A television reporter was killed by a shower of burning rocks when he got too close to the volcano, about 15 miles (25 kilometers) south of Guatemala City. In Guatemala, the ash billowing from Pacaya has been thick and falls quickly to the ground, unlike the lighter ash that spewed from the volcano in Iceland and swept over much of Europe, disrupting global air travel. The ash here stretched for “only” hundreds of kilometers, while the plume of ash from the volcano in Iceland covered nearly all of Europe for thousands of kilometers. The original report had the ash plume at around 3,000 feet (1,000) meters high that trailed more than 12 miles (20 kilometers) to the northwest. In Guatemala City, bulldozers scraped blackened streets while residents used shovels to clean cars and roofs. The blanket of ash was three inches (7.5 centimeters) thick in some southern parts of the city.

Slide 24, Page 2 - Primary hazard: Ashfall - which can cause loss of visibility, create slippery runways, infiltrate communication and electrical systems, interrupt ground services, and damage buildings and parked airplanes (engines, surfaces and electronics). (Other airport hazards: ash in airspace around airports, lava flows, pyroclastic flows, gas emission, and phreatic explosion).

Accumulating ash - Ash does not simply disappear (like melting snow) or blow away but must be disposed of in a manner that prevents it from being remobilized by wind and aircraft and during the clean-up process itself. On average, five airports per year are impacted by volcanic activity.

Info from : "*Volcanic hazards to airports*" - Marianne Guffanti Æ Gari C. Mayberry Æ Thomas J. Casadevall Æ Richard Wunderman, Nat Hazards (2009) 51:287–302, 4 June 2008

Slide 25 (1) – Intro to Remote Sensing. Ash from Mt. Pinatubo blankets the region like snow – 11/27/1991. It can take many hours for eruptions occurring in remote regions to be recognized and assessed…while some relatively mild eruptions occurring in remote areas can even go undetected. Volcanic ash can reach commercial flight levels (30,000 ft or above) in 5 to 10 minutes and remain airborne for several days. Weak eruptions, spreading (optical thinning) of the plume, or background non-volcanic clouds can significantly reduce the visible satellite signature, making it quite difficult to correctly discern the ash cloud. Wide variability in composition and structure of ash can also cause various detection problems. Ash cloud height can be a particularly tricky problem, especially when the plume is optically thin. Aircraft radar is ineffective in locating ash clouds.

Slide 26 (1) – Volcano Monitoring: "**STATUS AND CHALLENGES OF VOLCANO MONITORING WORLDWIDE " -** John W. Ewert, U.S. Geological Survey, Vancouver, WA 98683, USA (jwewert@usgs.gov) Christopher G. Newhall, U.S. Geological Survey, Seattle, WA 98195 USA – 2004. USGS

Here is a look at a map of major flight routes of the world together with a plot of the active volcanoes of the world. The black triangles represent volcanoes with some form of monitoring going on, while the blue stared areas represent volcanoes without any structured monitoring program.

Slide 27 (1) – Real-time detection: See slide for detail of the many methods for observation and detection. We are going to (briefly) cover ash and aerosol detection as many eruptions have both ash and aerosol. There are examples in the research arena that show cases where the ash plume and aerosol plume split, but there are far too few studies that have in-situ observations to confirm that there is no ash where an SO2 signature is found and no SO2 where an ash signature is found. There is also the ever haunting question of just how much ash/aerosol poses a problem.

Slide 28 (1) - Image: Artist's depiction of GOES N(13) – Allan Kung, for NASA NOAA – from: GOES N Fact Sheet (2006)

Slide 29 (1) - Global coverage. Allows for tracking of the plume both during the day and at night. Provides information in remote locations and can be used in conjunction with other information to determine plume height and probable plume movement.

Also Important: Quick and efficient detection of an eruption (ash) plume. Monitoring of the thermal energy emitted from the volcano. Mapping of the surface deformation of a volcano, including topography and topographic change aid in producing temporal and spatial distribution of ash and gases produced a volcanic eruption. Contributing to a "baseline" data set for quantifying future changes with a given volcano. Contributing to a "model" data set that can produce future movement of ash or gases.

Slide 30 (1) – Satellite products used – see slide. Also, for more info: GOES and POES CIRA products, including - Tropical RAMSDIS online; RMTC Real-time Satellite Imagery. Many experimental GOES and POES products @: (http://www.cira.colostate.edu/cira/RAMM/Rmsdsol/ROLEX.html)

Slide 31 (4) – Observational Examples: Visible RGB product - RGB Image From: Operational Significant Event Imagery (OSEI) – MODIS AQUA RGB (Band 1, 4, 3) – 4/19/2010@13Z - Eyjafjallajokull volcano.

Slide 31, Page 2 - Visible Image View from Meteosat-9 (MSG) – Eyjafjallajokull Volcano - May 7, 2010; Image data from: EUMETSAT Data Processed by NESDIS.

Slide 31, **Page** 3 - Close-up Visible Image View from Meteosat-9 (MSG) – Eyjafjallajokull Volcano - May 7, 2010 , Image data from: EUMETSAT Data Processed by NESDIS.

Slide 31, **Page** 4 - A "false color" RGB image taken 2 hours after the initial eruption of Mount St Helens May 18, 1980. **From GOES-3…some 30 years ago!!**

Slide 32 (5) – St. Helens May 18, 1980. Showing ash flow for first 30 hours. First page – Initial eruption plus 6 minutes. From NOAA and the University of Washington – Special Collection. (GOES-3)

Slide 32, Page 2 – Initial eruption plus 1 hour

Slide 32, Page 3 – Initial eruption plus 3 hours

Slide 32, Page 4 – Initial eruption plus 6 hours

Slide 32, Page 5 – Initial eruption plus 30 hours.

Slide 33 (1) - Visible image Okmok from Terra-MODIS, July 13, 2008. High resolution. Detects albedo differences.

Interesting image: water/cloud/steam cloud easy to pick out here with rather high albedo. Ash cloud also easy in this case even with relatively low albedo. Note differing directions of flow for each type cloud. This is due to differing flow characteristics at different levels in the atmosphere. Here, the lower level flow is more northerly and the winds are backing with height…giving the mid/upr level flow more out of the northwest. Why are the two types of clouds at different heights to begin with? This can be caused from significant differences in mass and buoyancy betweent he two types of clouds…with the water vapor/gas clouds having less mass and more buoyancy than the ash cloud…even when both are exiting the crater at the same place and time. It can also have to do with the relative vertical location of where the two types of clouds are exiting the volcano to begin with…or, if there is more than one (eruptive) vent present (different locations/elevations).

Possible Problems Visible imagery: Water/ice clouds or other poor visibility can obscure volcanic cloud. Daytime only use. Ash may be difficult to discern if very low **albedo** (measure of how strongly an object(s) reflect light).

Slide 34 (1) - NOAA-19 AVHRR data – hotspots Eyjafjallajokull Volcano – 4/20/2010 – 3.7um (Shortwave IR) – **Advanced Very High Resolution Radiometer**.

Here, hotspots can be seen at the red arrows (green-blueish colored areas). Such hotspots can be identified through the use of a mid-infrared channels (e.g. AVRHH - 3.7 µm, GOES – 3.9 µm, etc.) since an increase of the temperature generally results in a high signal response in this spectral region. The intensification of the hotspots in this image indicate that Eyjafjallajokull potentially started to eject more lava and therefore less ash.

Slide 35 (1) - NOAA 18 AVHRR Channel 4 (10.3 to 11.3), Picture Date: July 13, 2008 – Okmok Volcano
Image Creator: Bailey, John
Image courtesy of AVO/UAF-GI - Alaska Volcano Observatory / University of Alaska Fairbanks, Geophysical Institute.

Longwave IR by itself can help derive cloud top temperature information. This, together with local/regional sounding data, can aid in calculating plume heights. From the data present it was determined that the ash plume was topping out at around 25, 000 feet on this day.

Slide 36 (1) - IR Image View of Eyjafjallajokull Volcano - Meteosat-9 Second Generation (MSG) – Longwave IR 11 micron – May 7, 2010 Image data from: EUMETSAT Data Processed by NESDIS

Slide 37 (4) – **Split Window Detection**. A collection of polar orbiter and geostationary satellites provide global coverage and their data enable forecasters to track a volcanic ash cloud over long distances as long as it can be distinguished from water-bearing clouds (a continuing problem). In standard visible and infrared satellite imagery, volcanic ash clouds can resemble water-bearing clouds. However, **the radiative absorption properties of the** silicate in the volcanic ash are different to those of water in the infrared wavelength range 10-12 microns. An image showing the brightness temperature difference between channels at 10.7 (or 10.8) and 12.0 microns (BT10.7 - BT12.0) can be used to distinguish volcanic ash from water-bearing clouds.

In general for Channel Differening:

BT10.8 – BT12.0 > 0 for water-bearing clouds. (Positive)

BT10.8 — BT12.0 < 0 for volcanic ash clouds. (Negative)

Volcanic ash does not have an emissivity of 1; that is, it does not emit as a blackbody (water and ice are not ideal blackbody either). The emissivity at 10.7 microns is smaller than the emissivity at 12 microns. The smaller signal received at 10.7 microns (relative to the assumed blackbody) is interpreted as a cooler emitting surface. If the blackbody temperatures at 10.7 and 12.0 microns are compared, then, values at 12.0 microns are warmer. A channel difference can be used to highlight the horizontal extent of the volcanic ash.

To watch out for: A temperature inversion (at the surface or on top of a cloud) will show up as a negative difference as well. (situational: know the vertical profile of the atmosphere)

Slide 37, **Page** 2 - Iceland ( ) 4/15/2010@15Z from OSEI – Meteosat 9 split window for Eyjafjallajokull volcano.

This eruption was more explosive than would normally be associated with this type of volcano due to its location beneath some 200m thick glacier ice. Melting ice gushing into the volcano's cater help cause it to become particularly volatile…spewing ash clouds as high as 5.5 miles into the atmosphere. The volcano's crater ice has now mostly been melted away and therefore the ash plume has according diminished to less than 2 miles AGL.

Slide 37, **Page** 3 - Meteosat-9 Second Generation (MSG) 11-12 micron image (Longwave difference) - Eyjafjallajokull Volcano Ash Cloud (**Purple – i.e. negative values**) - May 7, 2010

This image also demonstrates that a negative split window difference picks up more than just ash – particularly in arctic regions when viewing from geostationary satellites with a large viewing angle. Those other areas in the high arctic that are roughly the same "color" are not ash, but represent regions of the top of (relatively moist) stable layers. How can we tell the difference? – Mostly in terms of "context and situational awareness" – (i.e. if we know that a volcano is going off in a certain area…).

Image data from: EUMETSAT Data Processed by NESDIS

Slide 37, **Page** 4 - Show the faint ash cloud signature (**negative values in Blue** area moving south of Mt. Okmok/Umnak Island over the western tip of Unalaska Island…and out over the ocean)

Picture Date: July 13, 2008
Image CreatorBailey, John
Image courtesy of the AVO/UAF-GI (The Alaska Volcano Observatory / University of Alaska Fairbanks, Geophysical Institute)

Slide 38 (1) - Four Panel PCI - Four-panel display of component images from Okmok volcano in the Aleutian chain – 2008-07-13, Image courtesy of Don Hilger (NOAA/NESDIS) – GOES-11

PCIs-3, 2 and 5 were used to compile the previous single RGB PCI. Current product uses GOES-11 imagery, with the day-night longwave split-window (PCI-5 in image above) bands that will not be available again until the GOES-R ABI era.

First point out from PCI - 1 LWIR dominant – (looks similar to a normal cloud scene in that the high cloud is cold?) PCI – 2 Visible dominant – notice that the high cloud is bright white, the region below and slightly left is dark – "dirty" ash. PCI – 3 SWIR dominant. Points to water cloud is reflective ash cloud that likely contains water cloud as well. The normal signal for water cloud in the 3.9 um region is more highly reflective than ice cloud. We have seen this reflective ash signature with other eruption clouds. The one region below and slightly left corresponds with the darker vis region. The other region may be below higher cirrus (see what it looks like in the animation). PCI – 5 split window is dominant – corresponds to what Don labeled as water cloud.

Slide 39 (24) – Four Panel PCI Loop.

Slide 40 (1) - Three Color PCI - Three-color display of component images of volcanic ash from Okmok July 13, 2008, Image courtesy of Don Hilger (NOAA/NESDIS)

Principal Component Image (Analysis) (PCI or PCA) extracts the principal (or wanted) features of an image. These features are then integrated into a single Image (as above)…to 'compile' information from a large number of bands to lesser number of bands. PCI has ability to identify relatively fewer "features" or components that as a whole represent the full state and hence are appropriately termed "Principal Components". Often used for surface resource analysis and cloud classification.

The above PCA image (PCI), in a sense, presents more information, by compressing the information in the three of the five bands into a single "synthetic image." The idea here is to to get rid of redundancy…and only three of the five bands are needed to extract most of the information. So, as in the above example, we have to first extract information from the five bands….then a PCA is performed which from which is determined that PCI-3, 2, and 5 (seen on the next **Page**) are the most important (most of the info can be determined from these three analyses). The first PCA image (PCI-3) will contain most of the information and the information content will keep on decreasing in second, third and PCIs. In other words we can say PCA compresses multiple band information into a single image (in this case).

Real-time volcanic ash displays area created from Principal Component Imagery from current GOES-west data. The component images display different cloud and/or ash features. The principal components here, PCI-3, 2, and 5 are combined in this image using an RGB (3-color) analysis (shown as red, green, blue respectively), contain relatively little redundancy. The colors are chosen to enhance the ash cloud in this case. "Clear" (cloudless) areas in the image are deep purple; high clouds are primarily green; low clouds are mostly yellow(ish); and the ash dominate cloud is orange. Note: Higher concentration of ash in the plume (orange) south of Okmok than to the east/southeast (yellow and orange).

(Example of individual 4-panel product is on the next **Page**).

***For more information on how PCA (Principle Compent Analysis) works: http://www.nist.gov/lispix/doc/references/PCA/MAS96/paper.html

Slide 41 (24) – Three Color PCI Loop (RGB)

Slide 42 (3) - From Ken Pryor/Gary Ellrod. Comparison of three-channel (Ellrod) method using GOES-12 Bands 2, 4, 6 (right) to GOES-12 visible image (left). Combines data from the shortwave (3.9 µm) IR channel (Band 2), with two longwave window IR channels at 10.7 µm (Band 4) and either 12.0 µm (Band 5 on GOES-11) or 13.3 µm (Band 6 on GOES-12 and beyond) (Ellrod and Schreiner 2004).

Temperature differences in Bands 4 and 5 from GOES-11 (referred to as the "Split Window") can help identify areas of volcanic ash due to it's unique properties at these wavelengths.

The Band 4-6 combination on GOES-12 is not as effective for this purpose, but can help distinguish ash from cirrus.

Slide 42, Page 2 - From Ken Pryor/Gary Ellrod

Combines data from the shortwave (3.9 µm) IR channel (Band 2), with two longwave window IR channels at 10.7 µm (Band 4) and either 12.0 µm (Band 5 on GOES-11) or 13.3 µm (Band 6 on GOES-12 and beyond) (Ellrod and Schreiner 2004).

Temperature differences in Bands 4 and 5 from GOES-11 (referred to as the "Split Window") can help identify areas of volcanic ash due to it's unique properties at these wavelengths.

The Band 4(10.7 µm)-6(13.3 µm) combination on GOES-12 is not as effective as the 4(10.7 µm)-5(12.0 µm) for this purpose, but can still help distinguish ash from cirrus. (Wait for the return of 12.0 µm channel with GOES-R)

Slide42, Page 3 - The Band 4(10.7 µm)-6(13.3 µm) combination on GOES-12 is not as effective as the 4(10.7 µm)-5(12.0 µm) for this purpose, but can still help distinguish ash from cirrus. (Wait for the return of 12.0 µm channel with GOES-R) DT values between 230 and 300 are scaled to output brightness counts between 0 and 255.

(Uses 3.9, 10.7, and 12.0; other version uses 3.9, 10.7, and 13.3 The historical discriminator is incorporated in the first one BT 10.7 – 12.0 um and not in the 2nd because of the loss of the 12 µm channel on GOES-12 and later (will not return until GOES-R) The 3.9 µm channel adds hot spot detection (24hrs) and for ash detection, increased reflectance during the day. Similar to the effect of water cloud.)

Slide 43 (1) - Popocatepetl Volcano, Mexico – November 29, 1998: Showing (comparing) four different "products." Channel 4 – 10.7 µm; Channel 4 – 10.7µm; Channel 5 - 12.0µm; CIRA reflectivity product – 4 -2, 10.7um – 3.9um.

Multispectral imagery Examples: (combining more than one channel) is used to optimize ash detection. Here, panel A depicts "plain" infrared imagery that barely shows ash from an eruption of Popocatepetl (a volcano near Mexico City). Panels B, C & D use multispectral algorithms to show the ash more clearly.

Slide 44 (1) - Image and information courtesy of Scott Bachmeier – Cooperative Institute for Meteological Satellite Studies (CIMSS) – July 18, 2008.

MODIS Band 26 (MODIS 1.3 µm near-IR "cirrus detection" image) – centered on 1.375 µm - shows some promise at identifying diffuse ash clouds well after an eruption. In this example, a 17:49Z AWIPS image of the "cirrus detection" channel shows the diffuse and "streaky" volcanic plume signature heading northeastward across Idaho into northern Montana from the eruption of the Okmok volcano a few days earlier. At the time, this was well beyond the eastern boundary of the SIGMET at the time and in fact, the boundary of the Volcanic Ash SIGMET was later extended northeastward. This additional remote sensing band (which will be available on GOES-R in the future) suggests an additional way that volcanic ash may be monitored and for use in adding value to the forecast.

Additional info follows from An Introduction to Ocean Remote Sensing by Seelye Martin, Cambridge University Press 2004: MODIS channel 26 (1.375 µm) is located in the middle of a strong water vapor absorption band and much of the time the surface and near surface radiances are completely attenuated. However, because cirrus and ash clouds occur in the upper troposphere and lower stratosphere, they appear bright in contrast to the completely attenuated to the surface and to clouds in the lower troposphere whose reflectance is partially attenuated by water vapor.

Slide 45 (2) – Product Limitations – see slide

Slide 45, Page 2 – Reference Info for last two **Slide**s (not to read…except for perhaps names) from:

Casadevall, T. J., 1992: Volcanic hazards and aviation safety: Lessons of the past decade. Aviation Safety Journal, Vol. 2, No. 3, Federal Aviation Administration, Washington, DC

Davies, M. A., and W. I. Rose, 1998: Evaluating GOES imagery for volcanic cloud observations at the Soufriere Hills volcano, Montserrat. Amer. Geophys. Union Proc., in press.

Dean, K., S. Bowling, G. Shaw, and H. Tanaka, 1994: Satellite analysis of movement and characteristics of the Redoubt Volcano plume, January 8, 1990. J. of Volcanology and Geothermal Research, 62, 339-352.

Ellrod, G.P. and B. Connell, 1999: Improvements in Volcanic Ash Detection Using GOES Multi-spectral Image Data. Preprints, Conf. on Aviation, Range and Aerospace Meteorology, 10-15 January, 1999, Dallas, Texas, Amer. Meteor. Soc., Boston.

Ellrod, G.P. and A.J. Schreiner, 2004: Volcanic ash detection and cloud top height estimates from the GOES-12 imager: Coping without a 12 micrometer infrared band. Geophys. Res. Letters, 31, L15110, 11 August 2004.

Volz, F. E., 1973: Infrared optical constants of ammonium sulfate, Sahara dust, volcanic pumice and flyash. Applied Optics, 12, 564-568.

Additional Note: While the loss of the 12 µm IR band is likely to degrade the overall volcanic ash detection capability somewhat, some case studies have shown that imagery from GOES-12 and its successors will continue to prove to be a somewhat effective means of warning pilots of hazardous ash clouds in many situations.

Slide 46 (5) – Ozone Monitoring Intrument (OMI) is a nadir-viewing near-UV/Visible CCD (Charge Coule Device) spectrometer aboard NASA's Earth Observing System's (EOS) Aura satellite. Aura flies in formation about 15 minutes behind Aqua (AIRS), both of which orbit the earth in a polar Sun-synchronous pattern. Aura was launched on July 15, 2004, and OMI has collected data since August 9, 2004.

One of its missions: To detect, track and measure volcanic eruptions and degassing and anthropogenic pollution from space. Uses UV satellite data from the Ozone Monitoring Instrument (OMI) on NASA's EOS-Aura satellite and the Total Ozone Mapping Spectrometer (TOMS) to map and quantify sulfur dioxide gas (SO2) emitted by volcanoes. Also use the UV instruments to map volcanic ash and aerosol emissions, using an "Aerosol Index".

OMI measurements, in near real-time, cover a spectral region of 264–504 nm (nanometers) with a spectral resolution between 0.42 nm and 0.63 nm and a nominal ground footprint of 13 x 24 km at nadir. Essentially complete global coverage is achieved in one day and has significantly improved spatial resolution measurements as well as a vastly increased number of wavelengths observed compared to TOMS and GOME.

OMI instruments have the ability to distinguish between aerosol types, such as smoke, dust and sulfates by measuring aerosol absorption capacity in terms of aerosol absorption optical depth or single scattering albedo…which makes them them excellent for detecting and following SO2 plumes.

Above: An example of a composite OMI satellite image from August 12 showing the sulfur dioxide cloud from the August 7 eruption of Kasatochi volcano. This cloud is at a range of altitudes from 30,000 to 40,000 ft. The various colors represent the amount of gas in the atmosphere with dark orange being the highest and dark blue the lowest.

Slide 46, Page 2 – (Add info here)* - SO2 info slide.**

Slide 46, Page 3 - **July 13, 2008**
Image Creator: Schneider, Dave
Data from the OMI SO2 near real time hazard support project.

Okmok Volcano – July 13, 2008 - Ozone Monitoring Instrument (OMI) image showing sulfur dioxide concentrations (cloud) as a result of the eruption. Image data is from 2040 to 2240 UTC on July 13, 2008. The large mass over the North Pacific is presumably from the large explosion on July 12, 2008.

Slide 46, Page 4 – NASA’s Aqua, Atmospheric Infrared Sounder (AIRS) Composite Image for cumulative SO2 – Okmok volcano – between July 12 and July 20, 2008.

Note very good similarities between the Aura OMI and AIRS platforms which give overall good confidence to the observations and any subsequent forecasts.

AIRS sensitivity to sulfur dioxide is low and is primarily visible in volcanic activity. However the AIRS instrument is very sensitive to atmospheric aerosols, such as dust and ash. AIRS sulfur dioxide and aerosols are not produced in geophysical units (e.g. concentration or optical thickness), but due to absorption the sulfur dioxide is expressed in terms of a temperature difference. The detection of the presence of volcanic sulfur dioxide is made by comparison of radiances

More info: Launched into Earth-orbit on May 4, 2002, the Atmospheric Infrared Sounder, AIRS, moves climate research and weather prediction into the 21st century. AIRS is one of six instruments on board the Aqua satellite, part of the NASA Earth Observing System. AIRS along with its partner microwave instrument, Advanced Microwave Sounding Unit (AMSU-A), represents the most advanced atmospheric sounding system ever deployed in space. Together these instruments observe the global water and energy cycles, climate variation and trends, and the response of the climate system to increased greenhouse gases.

AIRS uses cutting-edge infrared technology to create 3-dimensional maps of air and surface temperature, water vapor, and cloud properties. With 2378 spectral channels, AIRS has a spectral resolution more than 100 times greater than previous IR sounders and provides more accurate information on the vertical profiles of atmospheric temperature and moisture. AIRS can also measure trace greenhouse gases such as ozone, carbon monoxide, carbon dioxide, and methane.
AIRS and AMSU-A share the Aqua satellite with the Moderate Resolution Imaging Spectroradiometer (MODIS), Clouds and the Earth's Radiant Energy System (CERES), and the Advanced Microwave Scanning Radiometer-EOS (AMSR-E). Aqua is part of NASA's "A-train", a series of high-inclination, Sun-synchronous satellites in low Earth orbit designed to make long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans.

Slide 46, Page 5 - OMI measurements on April 29, 2010 12Z - show SO2 emissions south of Eyjafjallajökull. High SO2 column amounts are observed SW of the volcano, probably due to light winds (indicated by the Keflavik radiosonde sounding – next **Slide**) and reduced dispersion of the volcanic plume.

Slide 46, Page 5 - Keflavik radiosonde sounding – April 29, 2010 12Z

Slide 47 (5) - July 13, 2008
Image Creator: Schneider, Dave
Data from the OMI SO2 near real time hazard support project.

(MAIN ERUPTION WAS JULY 12, 2008)

Okmok Volcano – July 13, 2008 - Ozone Monitoring Instrument (OMI) image showing sulfur dioxide concentrations (cloud) as a result of the eruption. Image data is from 2040 to 2240 UTC on July 13, 2008. The large mass over the North Pacific is presumably from the large explosion on July 12, 2008.

Aura-OMI (Ozone Monitoring Instrument) - OMI Instruments can distinguish between aerosol types, such as smoke, dust, and sulfates (excellent for detecting and following SO2 plumes).

Info for subsequent images – July 14, 15, 16, 17

Slide 47, Page 2 - July 14

OMI image showing the extent of the sulfur dioxide gas cloud from the eruption of Okmok Volcano. The large red mass is from the main explosive phase on 12 July at 2130 UTC and is at an estimated height of 50,000 ft above sea level. The north-south dimension of this cloud is about 850 miles. Current emissions from the volcano are at a lower altitude of approximately 30,000 to 35,000 feet. Other OMI data (not

shown) indicate that volcanic ash is mixed with the sulfur dioxide cloud.Picture Date: July 14, 2008 UTC
Image Creator: Schneider, Dave;
Data provided through the OMI near-real-time decision support project funded by NASA.

Slide 47, Page 3 - July 15 (2 day composite)

OMI composite image from NOAA showing the extent of the sulfur dioxide gas cloud from the eruption of Okmok Volcano imaged at about 12:17PM AKDT on July 15, 2008. The large red mass is from the main explosive phase on 12 July, 2008. The image also shows a small sulfur dioxide plume extending east of the volcano at the time of the image. Good for presenting spatial and temporal continuity. Picture Date: July 15, 2008 UTC
Image Creator: Wessels, Rick;
Data provided through the OMI near-real-time decision support project funded by NASA.

Slide 47, Page 4 - July 16

OMI composite image from NOAA showing the extent of the sulfur dioxide gas cloud from the eruption of Okmok Volcano imaged at about 12:00 PM AKDT on July 16, 2008. The large red mass is shows the sulfur dioxide cloud from the main explosive phase on 12 July, 2008. OMI data acquired over Okmok at 1:48PM AKDT (2248 UTC), July 16 (not in this mosaic) show no sulfur dioxide emitting from Okmok volcano.Picture Date: July 16, 2008 UTC
Image Creator: Wessels, Rick;
Data provided through the OMI near-real-time decision support project funded by NASA.

Slide 47, Page 5 - July 17

OMI composite image from NOAA showing the extent of the sulfur dioxide gas cloud from the eruption of Okmok Volcano imaged at about 12:00 PM AKDT on July 17, 2008. The large red mass shows the location of the high altitude sulfur dioxide cloud from the main explosive phase on 12 July, 2008. OMI data acquired during this time over Okmok show no sulfur dioxide emitting from the volcano.Picture Date: July 17, 2008 UTC
Image Creator: Wessels, Rick;
Data provided through the OMI near-real-time decision support project funded by NASA.}}}

Slide 48 (1) - Example of Meteostat Combined (Multispectral) Product for finding Ash and SO2. April 20, 2010 0943Z – Meteosat-9: From German Aerospace Center (DLR)

Eyjafjallajökull volcano in Iceland emitted large quantities of ash and sulfur dioxide into the atmosphere. Sulfur dioxide and ash particles differ in their radiative properties and through the use of suitable combinations of channels at 10.8 microns and 12 microns (longwave differencing) – you get ash (highlighted in yellow) and from the differencing of the 8.7 micron channel and the 12 micron channel – we get SO2 (marked in blue). The grey background represents brightness temperature at 10.8 microns. Ongoing dilution of the “plume” or overlying clouds makes detection quite difficult. Therefore, ash-free classified areas are not necessarily a safe airspace.

Slide 49 (1) – Schematic, Ash/SO2 Cross section.

Here, two (tephra) dispersal models were used to simulate the climactic 1991 eruption of Mt. Pinatubo. The simulations indicated that the majority **of ash** was advected away from the source at the level of the tropopause (~ 17 km). Several other eruptive pulses injected both ash and SO2 gas to higher altitudes (~ 25 30 km), but these pulses represented only a small fraction (~ 1 %) of the total erupted material released during the simulation. Comparison with TOMS (Total Ozone Mapping Spectrometer) images of the SO2 cloud after 71 and 93 h indicated that the SO2 gas "originated" at an altitude of around 25 km near the source and then descended to an altitude of around 22 km as the cloud moved across the Indian Ocean. The results of this study demonstrate that the largest concentration of ash was transported at a level significantly below the maximum eruption column height (~ 40 km) and was thus controlled by atmospheric circulation patterns near the regional tropopause. In contrast, the movement of the SO2 cloud occurred at higher levels, along slightly different trajectories, and may have resulted from gas/particle segregations that took place during the intrusion of the Pinatubo umbrella cloud as it moved away from source and into the stratosphere. This also shows that even if the horizontal (plan) location of both ash and SO2 were the same…that they may still be well separated from each other in the vertical.

Slide 50 (3) - Poster Image GOES-R from NOAA – Continuous Environmental Monitoring

Slide 50, Page 2 - A suite of GOES-R products will detect and monitor volcanic ash as well as sulfur dioxide (SO2), which is often co-located with ash in volcanic clouds. Current GOES operational volcanic cloud products are qualitative, primarily due to sensor limitations. Improved spatial resolution and a

large selection of spectral channels will enable the GOESR ABI to generate more advanced quantitative volcanic cloud products. The SO2 Detection product will automatically detect volcanic clouds during very early stages when an ash signal is generally obscured by liquid water/ice. The Volcanic Ash product will provide objective estimates of ash cloud coverage, height, mass, and particle size,

which are necessary to issue Significant Meteorological Information (SIGMET) advisories for aircraft and accurately forecast the dispersion of ash clouds. (NASA/NOAA GOES-R Aviation Products Volcanic Ash and SO2 Detection – October 2009)

Slide 50, Page 3 - The GOES-R Volcanic Ash and SO2 Detection products will be generated from infrared radiances, which are day/night independent. ABI channels centered at 7.3, 8.5, 11, 12, and 13.3 µm are used in the algorithms. The 8.5, 11, and 12 µm channels provide information on cloud particle size and composition, the 13.3 µm channel detects ash cloud height, and the 7.3 µm channel detects SO2 clouds. These algorithms are unique because they account for background conditions such as surface temperature, surface emissivity, atmospheric temperature, and water vapor on a pixel-by-pixel basis. Consideration of background conditions results in greater sensitivity to thin ash and consistent algorithm performance from the tropics to the high latitudes.

Slide 51 (1) - GOES-R benefits. (in a nutshell)

The advanced spectral, spatial, and temporal resolution of the GOES-R ABI will be utilized to generate a complete set of volcanic cloud detection and monitoring products, resulting in improved air and ground safety as well as economic savings.

The GOES-R products will also be used to improve the modeling of volcanic ash clouds, which will allow for more accurate ash cloud dispersion and ash fall forecasts.

Slide 52 (1) - Example Ash Products:

From NASA/NOAA GOES-R Aviation Products Volcanic Ash and SO2 Detection – March 23, 2009 – (Jim Gurka, Steve Goodman, Mike Pavolonis and Gary Hufford) – Redoubt Eruption.

Slide 53 (1) – Aircraft Obs – Photo: Okmok 08/03/2008

View of Mount Saint Helens, initial eruption May 18, 1980.

Excellent airborne perspective. Great viewing distance and aspect. Can also use cameras.

However, there is limited nighttime use. Also, water/ice cloud or other poor visibility can obscure volcanic cloud. Requires some local infrastructure and reliable communications. Limited nighttime use. ***Pilot weather radar is not sensitive to volcanic ash.

Slide 54 (3) – Ground Obs – Photo: View of the eruption (Okmok) plume as seen from Fort Glenn (ranch building in foreground) on 8-03-2008. The small peak to the left is Tulik, an extra-caldera stratocone.
Picture Date: August 03, 2008 by Jessica Larsen.
Image courtesy of the Jessica Larsen, Alaska Volcano Observatory / University of Alaska Fairbanks, Geophysical Institute.

On the plus side – can be a source of "remote access" for direct observations (direct or by video camera). In addition, this technology is on the lower side and much cheaper. You also have the power of local/subjective interpretation. Nighttime observations are also available in the form of thermal infrared Heat/night-time measurements – however, this technology is much more expensive.

On the down side: Water/ice cloud or other poor visibility can obscure volcanic cloud. Requires locally developed infrastructure and reliable communications. Automated systems are prone to vandalism or theft. In areas without thermal infrared capability - daytime use only. Water/ice cloud or other poor visibility can obscure volcanic cloud.

Slide 54, Page 2 – Ash laden turbulent "mammatus" ash clouds from Mount St. Helens volcano move over Ephrata airport in Washington on the day following the initial eruption (May 18, 1980) - Monday, May 19, 1980.

Slide 54, Page 3 - Of course, if you were (un)lucky enough to observe the St Helens eruption from the wrong location, it could be hazardous to your health. This shot was taken from the streets of Yakima, Washington at around 3:00 PM on May 18, 1980. Light gray volcanic ash covered the streets and passersby wore masks to avoid breathing the ash.

Slide55 (1) – Radar Obs – Image: Mount Augustine 01/13/2006

From: 14th Symposium on Meteorological Observation and Instrumentation, WSR-88D OBSERVATIONS OF VOLCANIC ASH, by Jefferson Wood* and Carven Scott (NOAA/National Weather Service) and David Schneider (U.S. Geological Survey-Alaska Volcano Observatory) January 2007.

– From same paper, "The ability of the radar to provide near real-time updates on the position and altitude of volcanic ash clouds can be vital in providing timely and accurate forecasts and warnings. One of the most significant contributions made by the radar data is in short term aviation forecasting. Radar cross sections were also routinely used for diagnosing the vertical disposition of ash clouds during events. These observations, in tandem with pilot reports, were used to ascertain the vertical extent of the ash clouds and issue timely advisories to the aviation community. The ability to track the volcanic ash in the short-term was also vital to issuing timely and location-specific volcanic ashfall advisories."

Strength - Can measure height and position (and help forecast projection and timing of ash plume) of larger particles in ash cloud. However, you need relatively expensive ground radar stations (in the right place) and even these have limited range. Portable radar units are also expensive to purchase and can be quite hard to get to a good "viewing" location. Will not detect smaller particles well (unless sufficiently dense). Observations can be obscured by heavy rain. Requires advanced local infrastructure/ communications and must be well staffed.

Slide 56 (3) - **From: "Early Detection of the 5 April 2005 Anatahan Volcano Eruption using the Guam WSR-88D" - Timothy P. Hendricks, National Weather Service Forecast Office, Guam**

PGUA 0.5 degree reflectivity image for 1726 UTC 5 April 2005 - 50 to 55 dBZ observed at 9 km (30,000 ft) over Anatahan.

NEXRAD WSR88D Radar is especially good (if within 250nm) at early detection of volcanic eruptions – particularly in remote regions and at night. It also excels at getting good echo top measurement for plume height estimates. At the time of the image here…plume height was already above 30kt ft…with the 1.5 degree scan (next frame) showing echoes to over 50kt ft!

Anatahan erupted at approximately 1610 UTC. Within minutes, the PGUA WSR-88D signaled the onset of another major eruption. Since Anatahan is located within the range of the PGUA WSR-88D, early detection of major eruptions of the volcano is not only possible, but is likely. The PGUA 0.5 degree reflectivity at 1616 UTC (six minutes after eruption began) shows a faint echo directly over Anatahan between 20 and 30 dBZ. – with the plume tops already at least 9 km (30,000 ft) AGL. Less than an 1.5 hrs later, echoes were being pick up by the 1.5 deg tilt, showing plume tops over 50,000 ft (next **Slide**).

Slide 56, Page 2 - As in previous **Slide**: except at 1.5 deg tilt.

PGUA 1.5 degree reflectivity image for 1732 UTC 5 April 2005. At the peak of the eruption, 40 to 45 dBZ echo to 15 km (50,000 ft) over

Anatahan.

Slide 56, Page 3 - As previous 2 **Slide**s: Except combination image.

GOES-9 10.7um image and PGUA 0.5 degree reflectivity image for 1725 UTC 5 April 2005. The low level plume can be seen trailing off to the southwest under influence of northeast trade winds. Northerly winds aloft are steering the high level plume toward Tinian and Saipan.

Overlaying both satellite imagery with radar (AWIPS) imagery, gives much more confidence to analyzing the event and figuring out what the observations are telling us. As in this example, in the tropical western Pacific, volcanic clouds can contain or entrain moisture easily, making them difficult to distinguish from meteorological clouds. However, the combination of PGUA WSR-88D and GOES-9 infrared (IR) imagery can be beneficial in tracking the extent and migration of the ash plume. The 1725 UTC PGUA-RADAR/GOES-9 IR combination shows the low level plume trailing off the southwest, essentially trapped underneath the trade-wind inversion. However, a southward drift was discerned at the higher levels. The low level plume is typically not a problem for commercial jets arriving from Japan, Korea, Taiwan or Southeast Asia, as flight levels at descent are commonly near 6 km (20,000 ft) at that range from Guam and Saipan International airports. However, the high level plume is a serious hazard, which was relayed in Washington VAAC advisories and WFO Honolulu SIGMETS.

Slide 57 (2) - Lidar: The cross polarized signal on April16, 2010 above Paliseau France showing the main part of the ash cloud from Eyjafjallajökull volcano as irregular particles originally at 6km at 16UTC descending and thinning out to 3km by the end of the day.

Lidar (Light Detection And Ranging) is the visible light analog of radar. Very short laser pulses of light are sent into the atmosphere, are scattered back to the lidar by gases and aerosols in the air, and from the time out to these scatterers and the time to return back to the lidar, the position, concentration and some information on the properties of the scatters are determined. In the most common configuration of lidars in Europe in the EARLINET component of GALION, light at 355, 532 and 1064 nm (ultraviolet, green and infrared) wavelengths is emitted vertically. Lidars can also be carried by satellites.

Currently there is a lot of interest in the transport of volcanic emissions. Layers of the volcanic ash plume over Europe are detected as a function of time from 22 fixed stations by the Europe lidar network EARLINET (see web **Page** for details) and several in Russia. The two figures show the backscatter for parallel and cross-polarized light at 1064nm from the Paliseau, France, station of GALION. The cross-polarized signal allows discrimination between normal pollution which tends to be small spherical particles and the ash which, though small, is irregular in shape.

The aerosol properties observed include the identification of aerosol layers, profiles of optical properties with known and specified precision (backscatter and extinction coefficients at selected wavelengths, lidar ratio, Ångström coefficients), aerosol type (e.g. dust, maritime, fire smoke, urban haze), and microphysical properties (e.g., volume and surface concentrations, size distribution parameters, refractive index). Observations are planned to be made with sufficient coverage, resolution, and accuracy to establish comprehensive aerosol climatology, to evaluate model performance, to assist and complement space-borne observations, and to provide input to forecast models of "chemical weather".

Slide 57, Page 2 - The ash layers above Paliseau France the next day (on April17) showing descending layers from 3 to 2km and a more diffuse layer of dust up to 7km. The features at 9-10km are cirrus clouds.

Slide 58 (3)- Observational Strengths and weaknesses.

IR Weaknesses: Observed temperature can be misleading - Has to do with the same problem as that with which you have in the detection of (optically) thin clouds. Thin clouds may have warmer brightness temperatures than the actual physical temperature of the clouds. This effect occurs because the satellite is "seeing through" the thin clouds to warmer clouds or to the warmer surface below. (Thus, a thin clouds tend to have calculated heights that are “too low,” because the temperature matching technique (algorithm) matches them with a temperature that is higher (lower height) than the physical cloud temperature.

Slide58, Page 2 - More Strengths and weaknesses.

Slide 58, Page 3 - More Strengths and weaknesses.

Slide59 (1) – See Slide (Also, Ambiguity in atmospheric data due to the regional conditions of the Earth’s surface below – i.e. very hard to tell differences between the two levels…low contrast, similar apparent temperatures, etc.)

Slide 60 (2) – MODELING. Puff model run valid for May 5, 2010 08Z - WebPuff Version 2.2 – Run at University of Alaska.

Numerical models of ash-cloud movement can forecast locations of ash-clouds and, in principle, can forecast ash concentrations in a quantitative manner that is not possible through most remote sensing or other observational means. However, the accuracy of such models hinges in large part to their input data (what goes in determines what comes out…i.e crap in, crap out), which historically has not been well understood during eruptions.

Slide 60, Page 2 – The PUFF and HYSPLIT Models.

(FYI - Dr. Craig Searcy developed and rewrote Dr. Tanaka’s version of PUFF as part of his PhD program. An updated version is currently used by the National Weather Service (NWS), the Alaskan Volcano Observatory, and the Volcanic Ash Advisory Center to track volcanic ash clouds. There are also two other North American models used to predict ash movement – the HYSPLIT and the CANERM, or Canadian Emergency Response Model.)

*****POINTS TO REMEMBER:** regardless of the particular model used, several types of input related to the volcanic source must be known or estimated during an eruption:
— ***Height of the volcanic plume.*** This is the most important volcanic input, as it determines whether ash exists at typical jet cruise altitudes and in what wind fields and weather systems it disperses. Plume heights can range from less than a kilometer to nearly 50 km. They can be estimated from several satellite techniques, radar, or observations by ground observers or pilots. All these observations have uncertainties. Where multiple estimates of plume height are available, they commonly vary by several kilometers.

Mass eruption rate, or rate at which ash is pumped into the atmosphere. Ash concentration in volcanic clouds is directly related to this rate, which ranges over more than five orders of magnitude for historical events. The mass eruption rate cannot be determined directly during an eruption; it can only be estimated by correlation with plume height. There is considerable scatter in the relationship of mass eruption rate and plume height, which reflects both real variance and measurement error. A plume height of 10 km correlates best with an eruption rate of about 1.8 million kg/s; but within the 1 standard-deviation error it could range from ~0.7 million kg/s to 8 million kg/s—more than an order of magnitude. Deviations from this trend are especially common among small eruptions in tropical regions, where plume height is boosted by the latent heat of rising moist air.

Mass distribution of material in the plume by elevation. . Volcanic plumes are driven upward by buoyancy of hot gas and air. Large eruptions pump out so much heat that ash columns can ascend over 100 km per hour to an elevation at which their density equals that of the surrounding atmosphere. These rapidly rising columns are unlikely to be bent over by wind, thus forming a straight or “strong” plume that spreads laterally near its top to form an umbrella cloud. Most mass is concentrated at this elevation. In contrast, small eruptions rise slowly and are easily affected by wind to form a bent or “weak plume”. Weak plumes distribute mass over a wider range of elevation in the atmosphere. Sometimes it is possible to distinguish these plume types during an eruption and adjust model input.

Fragment size and rate of fallout. Erupted fragments, which are known as tephra, range in size from meters to less than a micrometer (micron); ash is tephra that is less than 2 mm (2000 microns) in diameter. Individual fragments may rise to many kilometers and then fall out as they travel downwind. Fragments larger than several tens of microns can fall at a meter per second or faster, reaching the ground within several hours and usually within a few hundred kilometers of the volcano. Micron-sized fragments would theoretically fall at centimeters per second or less, staying in the atmosphere for days. The fraction of the erupted mass that consists of these small particles is not well understood because most of our knowledge comes from deposits that fall from the ash cloud—not the cloud itself.

Slide 61 (1) – The PUFF Model. Puff simulates the transport, dispersion and sedimentation of volcanic ash. It requires horizontal wind field data as a function of height on a regular grid covering the area of interest. Puff output includes the location (in 3 dimensions), size, and age-since-eruption of representative ash particles. It can also produce gridded data of relative and absolute ash concentration in the air and on the ground. Puff is a fast and efficient research and operational tool for predicting the trajectories of ash particles, and is considered an essential tool for hazard assessment.

As an aid to monitoring techniques, the PUFF ash tracking model has been developed for predicting ash movement. These forecasts provide information on the location and extent of the ash cloud when observations are not available. Results are also used to alert concerned parties in near-real time of potential ash cloud location usually, in less than an hour after an eruption.

The PUFF model is mainly concerned with the tracking of "young" eruption clouds. Young clouds are defined here as less than 48-60 hours old. These are especially dangerous to aircraft since concentrations are highest during this period. The North Pacific region includes some of the heaviest air traffic in the world, mostly in the form of cargo flights. Young eruption clouds offer great potential for loss of life, equipment, productivity and commerce during an eruption.

Lagrangian: Describe changes which occur as you follow a fluid particle along its trajectory.

Eulerian: Describe changes as they occur at a fixed point in the “fluid.”

More info (Than you probably need): PUFF is a dynamic pollutant tracer model developed to simulate the behavior of young ash clouds. For emergency-response applications, it requires near real-time forecast wind data to predict the movement of the ash cloud. The model is based on the three-dimensional Lagrangian formulation of pollutant dispersion. PUFF initializes a collection of discrete ash particles representing a sample of the eruption cloud and calculates transport, turbulent dispersion and fallout for each particle.

In Lagrangian form, given a time step Dt, the position vector for each particle is updated from time t to time t + Dt by the equation:

Ri(t + Dt) = Ri(t) + W(t)Dt + Z(t)Dt + Si(t)Dt

(1) where Ri is the position vector of the ith ash particle at time t, W is the local wind velocity, Z is a vector representing turbulent dispersion and Si is the terminal gravitational fallout vector, dependent on the ith particle's size. The particles are driven by subsampling wind from a four-dimensional mesoscale model at a particle's position and calculating its next position according to the above formulation.

Lagrangian random walk formulations have been used successfully in a variety of numerical applications. Subsampling wind data in a Lagrangian formulation as in the PUFF model allows a higher resolution for tracking ash clouds during the first critical few hours. The Lagrangian method also requires no estimate of the mass distribution of the cloud which would not be available in real-time during an eruption.

For more on the PUFF model: http://pafc.arh.noaa.gov/puff/jvgr/puffpaper.html

Slide 62 (6) Pages 2 thru 6 – Example of hypothetical Okmok eruption valid for May 4-5, 2010.

Generated from PuffWeb v2.2, NOAA/NWS Alaska Region Headquarters, Anchorage Alaska.

Slide 63 (1) – Characteristics of the HYSPLIT Model

The transport and dispersion of a pollutant is calculated by assuming the release of a single puff with either a Gaussian or top-hat horizontal distribution or from the dispersal of an initial fixed number of particles. A single released puff will expand until its size exceeds the meteorological grid cell spacing and then it will split into several puffs. The Hysplit_4 approach is to combine both puff and particle methods by assuming a puff distribution in the horizontal and particle dispersion in the vertical direction. The resulting calculation may be started with a single particle. In this way, the greater accuracy of the vertical dispersion parameterization of the particle model is combined with the advantage of having an expanding number of puffs represent the pollutant distribution as the spatial coverage of the pollutant increases. Air concentrations are calculated at a specific grid point for puffs and as cell-average concentrations for particles. A concentration grid is defined by latitude-longitude intersections. The HYSPLIT model is also useful in predicting ash plume concentrations as they forward in time.

However - Dispersion models used operationally have a number of set parameters that can produce over or under estimates of the amount of ash in the atmosphere. It is a standard practice for the US VAACs to compare the model's output to what we can see or infer from satellite interpretation. This quality control often times produces the best combination of forecast tools with observed VA. This assessment is done qualitatively and on-the-fly as time is critical for the issuance of the VAA and VAG (graphical VAA)

On January 25, 2005, NOAA NCEP began running HYSPLIT for volcanic ash dispersion modeling. HYSPLIT replaced the VAFTAD operationally in 2007

More, in depth - http://www.epa.gov/scram001/9thmodconf/draxler.pdf

Slide 64 (1) - Example of HYSPLIT Trajectory (Ensemble).

Hypothetical HYSPLIT Ensemble Trajectory forecast for the lower 48 – if the Super-volcano were to erupt from Yellowstone (May 5, 2010). This is a 48 hour forcast. **Model run above was run using the WRF 12km run initialized on May 5, 2010@12Z.**

Trajectory Ensemble option starts multiple trajectories from the first selected starting location (Yellowstone in this case). Each member of the trajectory ensemble is calculated by offsetting the meteorological data by a fixed grid factor. This results in 27 members for all-possible offsets in 3 dimensions.

Advantage to ensemble: Give a decent approximation of the plume using a group of trajectories. Since a single trajectory cannot properly represent the growth of a pollutant cloud when the windfield varies in space and height, this simulation is, instead, conducted using many volcanic ash particles (separate trajectories).

Slide 65 (2) - Examples of HYSPLIT Layer Dispersion Forecast **18Z April 26, 2010 through 12Z April 27**. Eyjafjallajokull Volcano – 18 hour forecast.

Read across from left to right.

Slide 65, Page 2 - Examples of HYSPLIT Layer Dispersion Forecast 18Z April 27, 2010 through 12Z April 28. Eyjafjallajokull Volcano

Read across from left to right.

Slide 66 (1) - Example of HYSPLIT **Mass Dispersion** Forecast

Slide 67 (9) – 9 forcast Slides - **HYSPLIT Mass Dispersion** Forecast valid for 00Z April 26, 2010 to 12Z April 27, 2010. Eyjafjallajokull Volcano

Slide 68 (1) - Example of HYSPLIT **Particle Dispersion** Forecast

Slide 69 (9) – Forecast slides - HYSPLIT **Particle Dispersion** Forecast valid for 00Z April 26, 2010 to 12Z April 27, 2010. Eyjafjallajokull Volcano

Slide 70 (2) - The CANERM - Above is an example of Eyjafjallajokull (ay-yah-FYAH'-plah-yer-kuh-duhl) run for possible effect to Europe April 26-27, 2010.

The Canadian Emergency Response Model (CANERM) is a 3-dimensional numerical transport and dispersion model that calculates advection and diffusion, but also simulates wet and dry depositional processes. CANERM was initially designed to model the transport of radioactive contaminants in the atmosphere. However, it has been adapted for volcanic ash and is now used as an emergency forecast tool for predicting the movement of volcanic ash clouds that may threaten Canadian air space.

CANERM is a fully operational model at the Montreal Volcanic Ash Advisory Center (VAAC) which operates as part of the Canadian Meteorological Center (CMC). Daily forecasts are produced for active or potentially active volcanoes and are ready to be administered to proper aviation weather forecasting authorities if needed. The model can also be executed by the on-duty meteorologist at the CMC on a 24-hour basis. A simulation can be produced for any volcano in the world.

Slide 70, Page 2 - Hysplit model run – Starting April 26, 2010 00Z and run to April 27, 2010 12Z (36hrs) for Eyjafjallajokull (ay-yah-FYAH'-plah-yer-kuh-duhl) Volcano for same time period as CANERM.

Slides 71 through 78 - Use if time allows…or with recorded audio version…otherwise skip to **Slide 78**.

Slide 71 - May 7th **Visible** (Meteosat 9)

Slide 72 – Loop of Visible

Slide 73 - May 7th **Close-up Visible** (Meteosat 9)

Slide 74 – Loop of Close-up visible

Slide 75 - May 7th **Longwave IR** (Meteosat 9)

Slide 76 – Loop of Longwave IR

Slide 77 - May 7th example **Split Window Longwave Difference**.

Slide 78 – Loop of Split Window Longwave Diffrerence

Slide 79 – **Model Runs (Particle Dispersion) over CONUS July 21, 2010 00Z to July 23, 2010 00Z.**

Slide 80 – Mount Lassen Title Page – **Last erupted May 22, 1915**

Slide 81 HYSPLIT Model – Particle Dispersion for Mt Lassen starting July 21, 2010 (48hrs).

Slide 82 – Mt. Shasta Title Page

Slide 83 - **HYSPLIT Model – Particle Dispersion for Mt Shasta starting July 21, 2010 (48hrs).**

Slide 84 – Long Valley Caldera Title Page

Slide 85 - **HYSPLIT Model – Particle Dispersion for Long Valley Caldera starting July 21, 2010 (48hrs).**

Slide 86 – Mount Rainier Title Page

Slide 87 - **HYSPLIT Model – Particle Dispersion for Mt Rainier starting July 21, 2010 (48hrs).**

Slide 88 – Yellowstone caldera Title Page

Slide 89 - **HYSPLIT Model – Particle Dispersion for Yellowstone Caldera starting July 21, 2010 (48hrs).**

Slide 90 (1) – What's coming in part 2 of Volcanoes and Volcanic Ash.

Slide 91 (1) – **End Part 1**.

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Slide 92 (14) – Eyjafjallajökull Image Montage – (use as time allows)

14 Image montage to show while delivering the following info (or other). Optional at end of recorded session.

The Eyjafjallajökull volcano in Iceland last began erupting during the winter of 1821-1822 – an eruption that lasted for more than a year. 188 years later (March 20, 2010) the eruption began again with widely varying results (and ironic twists) to the economies and populations in and near the European continent.

The first eruptive cycle, which began on March 20th 2010 and Lasted until April 12th of the same year, was a boon (tourist boom) for recession-weary Iceland, whose banking system collapsed 18 months earlier, capsizing the economy and sending unemployment soaring. As Eyjafjallajokull volcano began erupting – threatening floods and earthquakes all along - thousands of adventurous tourists clamored to the region bringing desperately needed cash. Icelandic tour companies and other service industries made a small fortune during this period as drivers, hikers and other gawkers caused unprecedented traffic jams in what is normally a sparsely populated rural area. Even airlines were making out well as charter airline - Iceland Express – showed as its business rose by some 20 percent since the eruption began. The Icelandic Tourist Board said that 26,000 overseas visitors came to the country in March, a record for a usually quiet month (when Iceland is still in its winter hibernation). But, as they say, all good things must come to an end. And it did.

By April 12th the main magma chamber of the volcano became blocked – which killed the first eruption, but which caused intense pressure to build. Then, less than two days later the second eruption began – this time with a vengeance. This new eruption had been thought to have been about 10 times stronger than the first – melting glacier ice in and around the crater much quicker than before which helped in causing this eruption to be much more explosive than the first (phreatomagmatic). Through at least the first week after the second eruption began, billions of tons of ash (a rate of around 750 tons per second) from the eruption had been shot into the atmosphere – disrupting air travel all over northern Europe, with flights that were grounded or diverted (over 90,000 flights total) due to the risk of engine damage from sucking in particles of ash from the volcanic cloud. As of April 24th (first 10 days after) the total loss of revenue to only the airline industry was around 3.0 billion dollars! Of course, the toll to stranded passengers (worldwide) as well as all the various cargo importations – (and loss of revenue to many businesses) has since climbed into the 5 to 6 billion dollar range. Quite ironic in the difference between the two eruptions over a month’s time. And – another very scary repercussion of all this still awaits on the horizon – that this eruption could help trigger Mt Katla, a much more powerful volcano nearby – and one that covered by a much thicker ice sheet – AND, one that is overdue - for an eruption!!!