A GLOBAL PERSPECTIVE ON VOLCANOES AND ERUPTIONS

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Geologists have identified ~1500 volcanoes worldwide as probably active in the past 10,000 years. Many form conspicuous, lofty cones; others include depressions, fissures, and areas peppered with vents. Most of these volcanoes reside on land or protrude above water. An additional, much larger number remain unwatched at depth beneath the sea, but their eruptions seldom break the surface. Towards the poles in places like Iceland, eruptions under thick glacial ice can melt an opening, allowing energetic discharges directly into the atmosphere. Volcanoes often occur in linear belts or chains; those along the Pacific Rim tend to erupt explosively. Many Asian air routes pass portions of Indonesia, the Philippines, and Japan, countries collectively home to over one-third of the known active volcanoes. Earth's active volcanoes include ~10-15 erupting (discharging solid material) nearly continually. At any one time, these are joined by several others, often those that have erupted in the recent past. During each year of the 1990s, ~50-60 volcanoes erupted. Across the spectrum of explosive eruptions, smaller eruptions predominate. Many noteworthy eruptions started suddenly (over one-third reached climax within the first day; one-fifth in the first hour); however, in noteworthy cases years of milder eruptions preceded a climactic one. Such factors as the erupted material's volume, discharge rate, viscosity, and volatile content influence the eruption's size, character, and ash column height. No one phenomenon spawns large ash clouds. It is often difficult to gauge the ultimate size of an eruption at the onset. Although a growing ash column would hopefully trigger an immediate report to a VAAC, factors may thwart this effort (e.g., bad weather, darkness, limited infrastructure, damage, lack of diagnostic satellite coverage), thus halting clear, timely assessments. Half the world's 1500 active volcanoes reside in developing nations; many of the world's volcanoes lack dedicated monitoring instruments.

PROMISE AND PITFALLS IN ERUPTION FORECASTING

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"The problem with weather forecasting is that it's right too often for us to ignore it and wrong too often for us to rely on it." (Patrick Young) The same holds true for eruption forecasting.

Weather forecasting, though not perfect, has improved greatly in recent decades. Volumes of data from ground, air, and space based sensors and sophisticated numerical models complement older methods. Daily trials in every forecast area help to refine the models. Hurricane (typhoon) and tornado forecasting carry greater uncertainties, limited by fewer data and opportunities for testing forecasts.

Volcanic eruption forecasting has also improved in recent decades. Though uncertainties remain high, probably even higher than uncertainties in hurricane and tornado forecasts, dozens of successful eruption forecasts have been made since 1980 that saved tens of thousands of lives. True, volcanologists are handicapped by being limited to proxy or indirect measurements at the earth's surface rather than having direct measurements of the rising magma. True, only a few trials per year allow us to refine forecast methods. True, numerical forecast models are a dream of the future. However, today's and certainly tomorrow's eruption forecasts are important wake-up calls for plume detection and the variety of other ash-hazard mitigation measures described elsewhere in this volume.

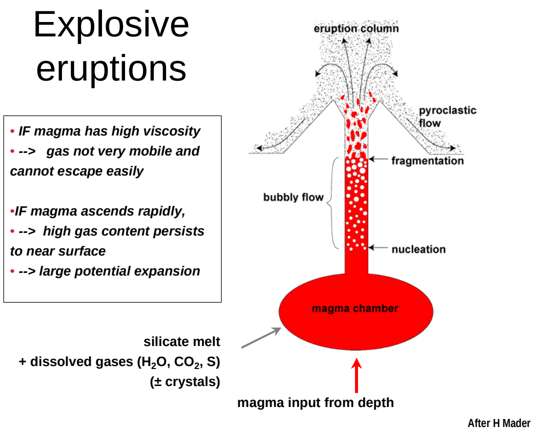
In this paper I'll say a few words about why volcanoes erupt, the basis for eruption forecasts, the relative reliability of various types of eruption forecasts, and some potential pitfalls of which you should be aware.

First, what are eruptions? Eruptions are ejections of molten or solid rock, as flows or fragments, into the air or onto the earth's surface. In most cases the starting material of eruptions is molten rock (magma) that has risen from many miles depth, through the crust of the earth. If magma and its hot gases heat groundwater in the surrounding crust to sufficiently high temperatures and pressures, natural steam explosions will pulverize the older crust around the magma and cause that already solid rock to erupt as well. Many eruptions begin with such steam ("phreatic") explosions and then become "magmatic" if magma itself reaches the surface.

Phreatic explosions generate ash by pulverizing the rock through which they explode. Magmatic explosions generate ash by fragmenting the magma itself. Gases that are dissolved comfortably in magma at depth exsolve (i.e., un-dissolve) near the earth's surface, pressurize, and blow the magma into tiny sand- and silt-size fragments that we know as volcanic ash *(fig. 1)*. Aside from minor differences in composition and shape, phreatic ash and magmatic ash are the same, i.e., tiny rock fragments, lofted into the air in thermals generated by the heat of exploding steam and magma. Small explosions may loft ash a few hundred or a few thousand feet above a vent; giant eruptions like that of Mount St. Helens in 1980 or Pinatubo in 1991 loft ash 60,000-100,000 feet. A curtain of ash then rains out of an eruption plume, back down through all elevations.

Ideally, forecasts of eruptions would specify their location, onset date, explosive magnitude, and duration or ending date. The most important for aviation safety are location, onset, and explosive magnitude (eruption column height, ash concentrations), joined soon after by ash trajectories. Current forecasts of duration or ending date are too imprecise to be helpful to the aviation community.

To forecast the location of volcanic eruptions is relatively simple if there is an adequate network of monitoring instruments. Nearly all eruptions are from preexisting volcanoes, and most though not all volcanoes that have erupted in recent history are monitored well enough to detect signs that might lead to an eruption (see Ewert and Newhall, this volume). As magma pushes its way toward the surface, it breaks the crust to make way. This process is recorded as tiny earthquakes by nearby seismometers. It also causes the earth's surface to bow slightly upward, detectable by sensitive surveying instruments including high-precision GPS stations. As gases that are dissolved in the magma at depth begin to exsolve, some leak out and can be detected by a variety of "gas sniffers"



Explosive eruptions

- *IF magma has high viscosity*
- *--> gas not very mobile and cannot escape easily*

- *IF magma ascends rapidly,*
- *--> high gas content persists to near surface*
- *--> large potential expansion*

Fig. 1. From Magma to Ash. Molten rock that contains dissolved gases (mostly, CO2 and H2O) rises buoyantly through a volcanic conduit. As it rises, confining pressure decreases (as when the cap of a carbonated drink is opened), bubbles form, expand, and eventually turn the top of the magma column into a magma foam. Rapid depressurization causes the foam to explode and pulverize tiny minerals and quenched (glass) bubble walls into volcanic ash. Heat from the hot ash causes the cloud to rise like a strong thermal.

at the surface. Nearly always, we know which monitored volcanoes are restless and COULD erupt.

To forecast the onset of an eruption is more difficult but sometimes possible. Some volcanoes exhibit exponentially escalating unrest and the onset of an eruption can be forecast to within a few hours or days (small eruptions of Mount St. Helens after the famous May 18 1980 events, a moderate-size initial eruption of Redoubt in December 1989, and progressively larger and eventually giant Pinatubo eruptions of June 1991). Sometimes, volcanoes also show a sudden, distinctive cessation of seismicity or gas emission, or a sudden tilting of ground very near a vent, that are extra signs that an eruption is imminent. Fortunately, volcanoes that have been quiet for many years and that are the most dangerous are usually the easiest at which to forecast eruption onset. Unfortunately, volcanoes that erupt frequently can erupt again with little notice, and volcanoes that have already been restless for an extended period can also erupt with little further notice (e.g., Mount St. Helens, May 18 1980).

Forecasts of the explosive magnitude of an eruption are fraught with uncertainty. Two approaches are usually combined. The first is to review prior eruptions of that volcano and to assume that future eruptions will be of similar magnitude(s). Because many volcanoes erupt with a wide range of explosive magnitudes, we may have only statistical odds of one explosive magnitude vs. another. These odds can be refined slightly by factoring in the number of years the volcano has been quiet and the degree to which long quiescence at that volcano makes subsequent eruptions more explosive. Not all volcanoes behave alike, though, and some volcanoes even change their general eruptive style from decade to decade or century to century.

A second way to forecast explosive magnitude looks for telltale indications in precursory unrest. Some indicators include the speed with which magma is rising (faster speed correlates with higher eventual explosivity), recent gas emissions (to judge whether the new magma remains gas-charged or has already lost its fizz and explosive potential), and, perhaps, the apparent volume of rising magma as indicated by bowing up of the ground surface. Truth be told, though, we have had very few opportunities to test the consistency and thus reliability of these indicators.

At best, explosive magnitude can be forecast to the nearest order of magnitude of how much magma will be fragmented into ash (e.g., 0.01, 0.1, 1, 10, or 100 cubic miles of magma) and the nearest 20,000 or 30,000 feet of eruption column height. Many volcanologists use a shorthand index of explosive magnitude, called the Volcanic Explosivity Index or VEI (Newhall and Self, 1982). Successively higher VEI values refer to roughly one order of magnitude greater ash volume and successively higher maximum column heights. Of the 60 or so non-submarine volcanoes around the world that are active each year (Wunderman and others, this volume), most are producing VEI 2 eruptions from which ash rises between 3,000 and about 20,000 feet. VEI 2 eruptions generally don't threaten commercial jet traffic at cruise altitude but can certainly cause problems for low-flying aircraft, planes on ascent or descent, and for airports themselves. VEI 3 and higher eruptions, of which there are typically several per year worldwide, generally do send ash to cruise altitudes and are serious aviation hazards. If a volcano is expected to erupt and is known to produce VEI 3 and larger eruptions, it would be prudent to assume that the impending eruption could be that large until proven otherwise. Satellite imagery combined with a measure of seismic tremor associated with an eruption (McNutt, 1994) can often give an estimate of column height within an hour after eruption onset, supplanting whatever was forecast, but be aware that eruptions often increase or decrease in VEI from hour to hour and day to day. In more than 90 % of eruptions, the climax (maximum explosive magnitude) is reached in the first 24 hours (Simkin and Siebert, 1984), but tall eruption columns can also pop up later in eruptions!

What determines the ultimate explosive magnitude of an eruption? In a word, gas! More precisely, explosivity is controlled by how much gas was originally contained in the magma and how much of that has bled off before the magma reached near the earth's surface. The analogy between magmas and soda pop is actually quite good. Gas-charged soda pop will explode if opened suddenly, but if opened slowly its gas will just bleed off. Without trying here to quantify these parameters, we can generalize that if magma is relatively fluid and/or is rising slowly, most of its gas may be able to bleed off before that magma nears the surface. Its resulting explosive potential will be low. This is true of fluid Hawaiian magmas and of very viscous magmas beneath some lava domes. In contrast, if gas-rich magma is too viscous to let gases escape easily and if it rises fast enough that the gases can't bleed off before nearing the surface, the explosive potential will be high. This is characteristic of most volcanoes of the Circum-Pacific "Ring of Fire" and most volcanoes in Italy, Greece, and Iceland. Some volcanoes like Soufrière Hills on Montserrat exhibit both behaviors -- non-explosive dome growth when the supply and ascent rate of magma is slow and explosive eruptions when it is high. At a few volcanoes like Stromboli in Italy, the ascent rate is just right to maintain constant small explosions -- high enough to not lose all of its gas enroute to the surface yet low enough to lose enough gas to keep explosions small.

I should add words of caution about “non-explosive” dome building eruptions and secondary explosions. Even though lava domes may grow without explosions, those that are actively growing, especially if on steep slopes, tend to collapse and produce what we call dome-collapse pyroclastic flows. These are hot avalanches and have significant dust (ash) clouds. Because the lava is hot, these winnowed ash clouds can rise in thermals to thousands, even several tens of thousands of feet, i.e., up into cruise altitudes. Dome collapse and associated ash clouds are very difficult to forecast and, at this point, the best that can be done for warning of these is near-real time detection and tracking, alerted by the seismicity of the collapse. “Secondary explosions” occur where pyroclastic flow deposits are thick and remain hot for months or even years and groundwater seeps into the deposit, is heated, and flashes into steam. Most such events are too small for aviators to worry about, e.g., lofting ash only a few hundred feet at Redoubt Volcano in 1990, but the largest secondary explosions from thick deposits on the slopes of Mount Pinatubo occurred months after the main eruption, with only rainfall as warning, and sent ash 80,000 feet into the air and damaged at least one commercial jet.

Conventional wisdom is that after an eruption, magma that remains in the volcano's conduit cools and solidifies ("freezes"), forming a plug that will have to be cracked or blasted out before the volcano can erupt again. Such "closed-vent" behavior is characterized by infrequent, often explosive eruptions. However, many volcanoes exhibit "open-vent" behavior in which magma in the conduit does not solidify between eruptions but, instead, churns in a kind of lava-lamp-like convection. Rising, gas-rich magma grows less and less dense as gas bubbles grow in it, eventually turning into a magma foam not far below the surface. Foams are permeable and most of the gas escapes, feeding persistent gas plumes from such volcanoes. The degassed foam collapses, becomes dense, and sinks back down through the fresh rising magma, driving the convection process. If the reservoir of gas-rich magma is large enough, this activity can persist and feed small eruptions for years or even decades, e.g., Stromboli, Italy and Yasour, Vanuatu. Some volcanologists think the same is occurring beneath other volcanoes that in recent years have produced a lot of gas and not much else, e.g., Popocatépetl in Mexico.

Closed-vent behavior makes eruptions relatively easy to forecast. Fresh magma working its way to the surface must break through the plug or surrounding rock, generating earthquakes and swelling of the ground. Gas leaks may or may not be detected at the surface. The most easily measured gas, sulfur dioxide, may be absorbed into and hidden in groundwater and thus not reach gas instruments on the surface. Fortunately, most VEI 3 and larger eruptions are going to follow closed-vent behavior and thus will give at least some warning of reawakening.

Open-vent behavior tends to bleed off the gas and thus reduce explosive potential. Thus, most eruptions during this behavior will be VEI 2 and smaller. However, be careful, because there are some cases in which either the convection speeds up (increasing explosive potential) or is temporarily stopped (trapping gas and thus also increasing explosive potential). Eruptions from volcanoes in open-vent behavior are generally difficult to forecast because there is virtually no plug to break through. Seismic and ground deformation precursors will be minimal.

Emission of CO_2, SO_2, and other volcanic gases may increase notably, but these don't indicate likely onset time very precisely. Ground deformation (e.g., tilt) measurements right on crater rims can warn of fresh-arriving slugs of magma and thus of explosions or dome collapse to follow within hours to a few days, but very few volcanoes have instruments close enough to their vents to detect such changes. So, in general, eruptions during open-vent behavior will be difficult to forecast. As an example, after the vent of Mount Spurr, Alaska, was opened in June 1992, a second eruption in August began without clear seismic precursors.

Throughout this paper I have been referring to eruption forecasts as if they are issued in a standard format. In reality, they are not. Three related formats illustrate.

One format of eruption forecasts explicitly states one or several progressively narrower time windows, e.g., 2 weeks, 1 day, etc., within which an eruption is expected to begin (e.g., Swanson and others, 1983; Punongbayan and others, 1996). Very few forecasts are this explicit, although one successful one from Pinatubo (1991) was instrumental in saving many lives. Equally few specify the exact magnitude of an impending eruption; more often, forecasts give a range of likely magnitudes.

A second format estimates relative and absolute probabilities of all likely outcomes, usually in the form of a probability tree that applies to a specified timeframe (Aspinall and others, 2002; Newhall and Hoblitt, 2002; Marzocchi and others, *in press*).

The third, most common format (with many variants) is a color or numerical code that is shorthand for the intensity of seismic and other unrest, level of volcanologists' concern, OR proximity of the onset of an eruption. Most such codes have 3-6 levels of which the lowest is background activity and the highest is a dangerous explosive eruption in progress. Steps between these two extremes represent increasing hazard but may not specifically "forecast" an eruption. Rather, they represent DECREASING ASSURANCE that an eruption will NOT occur. Although this might seem like a fine distinction I think it is an important one, as there are still many instances in which we know that present unrest COULD presage an eruption but could equally well stop without eruption. Volcanologists try very hard to avoid false alarms, i.e., to not "cry wolf," and color codes that can be raised or lowered are more flexible than forecasts of when a volcano WILL erupt. The International Civil Aviation Organization (ICAO, 2004) describes its color-code scheme, and task groups within the US Geological Survey (Gardner, *this volume)* and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) are exploring whether wider standardization is possible.

The three formats of forecasts are broadly related. Yellow or similar codes indicate elevated but not intense unrest, and generally do not imply that an eruption will occur. Indeed, more often than not, yellow unrest will stop without an eruption. Many instances of orange or similar unrest typically are followed by an eruption within days to weeks, so there is an implication, tacit or explicit, that an eruption could and in some cases probably will begin within that timeframe. The highest level of alert, red or similar, may indicate that an eruption is likely within hours or has already begun. Please note use of the terms "could" and "likely," rather than "will occur." Observatories may use different formats for different audiences or to emphasize time of onset, type of eruption, or simplicity and possible relation to response plans, respectively.

Weather forecasters track how often their forecasts are correct or incorrect. Can we do the same for eruption forecasts? Of 224 moderate-size explosions during a 1987-1991 test period at Sakurajima Volcano, 162 were successfully forecast and 62 were missed (Kamo and others, 1994). An automated algorithm produced only a few false alarms. Twenty (20) post-climactic, mostly dome-building eruptions of Mount St. Helens were successfully forecast between 1980 and 1986 without false alarms or misses (Swanson and others, 1983; Swanson, 1990).

Color-code or numerical alerts do not specifically forecast dates of eruptions but, at higher levels, usually imply a timeframe of weeks or less. Within the past 20 years but not including Sakurajima and Mount St. Helens events, 60 orange, red, or similar alerts were followed by eruptions within weeks or less, 8 orange or red alerts were “false alarms,” i.e., NOT followed shortly by eruptions, and 48 eruptions were missed. Many in the last group were anticipated with a yellow alert but not with a more urgent orange or red alert.

Of roughly 150 VEI ≥ 3 eruptions that occurred from mid-1984 to mid-2004 – eruptions that are always of concern to aviation -- about 30 were successfully forecast with an orange or red alert and 50-100 were loosely anticipated by a yellow or equivalent alert, but at least several tens were not anticipated at all.

The last group occurred where volcanoes were not monitored or where the observatory failed to issue an alert. These unforetold VEI ≥3 eruptions are worrisome and unacceptable, and their source volcanoes are slowly being brought under monitoring surveillance.

Eruption forecasting is improving slowly but surely. Part of the improvement comes from expanded and better monitoring and a growing body of experience about what precursors to expect. Another part comes from improving conceptual models of how magma rise and degas, or, if not, explode. Clearly, not all eruptions are being forecast yet, but are the forecasts that are issued reliable? Since volcano observatories are careful to not issue false alarms, most orange, red, or equivalent warnings are likely to be correct and can help you to be ready for ash as soon as an explosive eruption does begin.

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STATUS AND CHALLENGES OF VOLCANO MONITORING WORLDWIDE

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Introduction

Volcanoes exhibit precursory activity that may occur hours to years before an eruption and thus allow an eruption forecast. Accurate forecasts and real-time detection of volcanic eruptions are essential to keep pilots, passengers, and planes out of ash clouds. Timely eruption reporting by volcano observatories, beginning with information about the premonitory build-up phase, allows more time for flight planning and improves response time of satellite-based ash-cloud detection. Here we describe in general terms the most commonly used volcano-monitoring techniques, and report where obvious gaps in monitoring exist, particularly with respect to aviation safety.

Most volcano-monitoring networks and observatory operations have been designed to mitigate hazards to people on the ground rather than in the air. Consequently, most volcano observatories and hence most monitored volcanoes are found where the risks to people on the ground are greatest. Notable exceptions are the monitoring of Alaskan volcanoes by the Alaska Volcano Observatory (AVO) (Murray, this volume), Kamchatkan and Kurile volcanoes by KVERT (Gordeev and others, this volume), and Anatahan volcano by the U.S. Geological Survey and the Commonwealth of the Northern Mariana Islands. At the present time, volcano-monitoring operations are conducted by about 60 institutions globally. However, of the more than 1500 active volcanoes in the world, less than a quarter have any kind of real-time monitoring, and only a few (numbering less than 50) would be considered adequately monitored for both hazard and research purposes.

Why is ground-based monitoring critical?

A recent eruption at Anatahan volcano in the Commonwealth of the Northern Mariana Islands (CNMI) in 2003, gives an example of the time lag between eruption onset and ash cloud detection that can occur in a remote area if only remote sensing is employed. On 10 June 2003, approximately five hours elapsed from the unexpected onset of eruptive activity at Anatahan and subsequent ash plume to 11 km, to the issuance of the first Significant Meteorological Advisory (SIGMET) and Volcanic Ash Advisory by the Guam Meteorological Watch Office (MWO) and Washington-Volcanic Ash Advisory Center (W-VAAC), respectively (Guffanti and others, in press). Arguably, had Anatahan been seismically monitored in real time before the start of eruptive activity, this delay likely could have been much shorter and dissemination of ash-hazard information to the aviation sector could have been more rapid. Luckily, no damaging encounters appear to have occurred.

Subsequently, real-time seismic monitoring was installed on Anatahan by the U.S. Geological Survey and the CNMI Emergency Management Office, and in March and April of 2004 notices of new eruptive activity at Anatahan were passed to the W-VAAC and Guam MWO within minutes of seismic detection (R.White, written communication).

When ground-based monitoring is in operation at a volcano, and communication links are in place between the volcano observatory and the regional MWO and VAAC, notices of heightened eruption potential and notification of eruption onset are typically more rapid than if no ground-based monitoring is in place. The eruption of remote Bezymianny Volcano, Kamchatka in June, 2004, illustrates this case. On June 16, 2004, based on increasing seismicity, the Kamchatkan Volcanic Eruption Response Team (KVERT) raised the concern color code for Bezymianny from yellow to orange (indicating an eruption is possible within a few days and may occur with little or no warning). On June 18, 1940 UTC an explosive eruption was detected seismically, and an ash column to 8-10 km was observed by a remotely operated video camera at 2040 UTC. KVERT issued an eruption notification at 2055 UTC, a little more than one hour after the eruption began. In contrast, owing to a lack of satellite coverage, the ash column was first spotted in satellite imagery approximately 4 hours after the seismically-determined eruption onset. (D. Schneider, personal communication).

Although the eruption notification was not made within five minutes of the eruption onset as airline representatives to the 2nd International Conference on Volcanic Ash and Aviation Safety suggested as a goal, the notification was much more timely than would have been possible with only satellite remote sensing owing to the ground-based monitoring by the KVERT. No damaging encounters were reported from this eruption.

Real-time volcano monitoring

An adequately monitored volcano has continuous multiparametric (a combination of seismic, deformation, geochemical, etc.) data streams that are available in real-time to an observatory facility. More commonly in the world today, if a volcano has any monitoring at all, it is by a single seismometer, standalone or within a regional network.

For the purposes of this discussion, we classify volcano monitoring techniques into two general classes; those useful for eruption forecasting and prediction, and those useful for eruption detection. We limit our discussion to those techniques and instruments that can be used in real time or near-real time, generally in a telemetered configuration. A combination of monitoring techniques and sensor types yields the most reliable results.

Eruption forecasting tools

Seismic monitoring is the mainstay of volcano monitoring operations around the world. The typical telemetered seismic station used to monitor a volcano is a single (vertical) component , short-period type, data from which are sent via analog telemetry to a central recording site. This class of instrumentation has been employed to monitor volcanoes since the early 1970s, is robust even in marginal field conditions, and the technology is accessible in developing countries. To locate seismicity, a minimum of four telemetered instruments spread around the volcano is necessary. In many cases though, only one or two instruments may be deployed close enough to a volcano to reliably detect and track the subtle changes in seismicity prior to eruption. Fortunately, useful information about the status of a volcanic system can be gleaned from one or two stations if an experienced seismologist is on hand with appropriate data processing software (McNutt, 1996).

At well-monitored volcanoes, which number less than 50 worldwide, focused, small-aperture seismic networks are arrayed within a larger aperture regional network and may consist of a mix of single and three-component stations. Focused seismic monitoring techniques can be used to infer the presence of magma as a cause of seismicity, to track the ascent of magma and other fluids toward the surface, and to determine the onset of explosive eruptions.

Other monitoring techniques used to forecast and predict eruptions include methods to measure ground movement (deformation), gas emissions, and changes in thermal characteristics. Telemetered deformation instrumentation includes (in order of increasing sensitivity) Global Positioning System (GPS) installations, which measure surface displacement in three dimensions; tiltmeters, which measure changes in near-surface ground inclination; and strainmeters, which measure minute compressional or tensional changes in strain in boreholes that are 10s to 100s of meters deep. Monitoring ground movement by remote sensing over broad areas is sometimes possible with Interferometric Synthetic Aperture Radar (InSAR). The InSAR technique lends itself to tracking slow, long-term changes that may occur months to years ahead of an eruption. Together, these deformation-monitoring techniques can detect accumulation of magma beneath a volcano and the passage of magma toward the surface (Dvorak and Dzurisin, 1997).

Carbon dioxide, sulfur dioxide and hydrogen sulfide gas fluxes can be determined by flying monitoring instruments beneath and through the volcanic gas plume near the volcano. Sulfur dioxide flux can be measured from the ground in daylight hours and the data telemetered. Changes in concentrations of gas species in soil or fumaroles can also be measured, and the data telemetered to a central receiving site. Though not measurements of the total gas flux from the magmatic system, these types of data can be useful in tracking a volcanic system moving toward eruption. These techniques can confirm the presence of an active, degassing magma body and be used to infer rise of magma to shallow levels beneath a volcano and/or boiling and disappearance of groundwater in response to increased thermal flux (Symonds and others, 1994).

The extent and intensity of thermal emissions from a volcanic source can be measured in a variety of ways including satellite, aircraft, and ground based measurements. Used in conjunction with other monitoring techniques, thermal monitoring can aid in diagnosing whether a restless volcano is progressing toward eruption.

Eruption detection tools

Explosive volcanic eruptions can create a sudden ash hazard to aircraft, necessitating the shortest possible delay between eruption detection and issuance of warnings. While satellite remote sensing offers attractive eruption detection capabilities owing to broad areal coverage and multi-spectral capabilities, uncertainties in cloud cover, eruptive column height, orbital timing of Polar Operational Environmental Satellites and scan timing of Geostationary Operational Environmental Satellites make timely detection of eruptions from space a hit or miss proposition (Mouginis-Mark and Domergue-Schmidt, 2000). Ground-based instrumental monitoring, used in conjunction with satellite remote sensing offers a much higher probability of timely detection of eruption onsets.

As with eruption forecasting, seismic monitoring is the mainstay of eruption detection at volcano observatories. Other techniques used to detect and confirm eruptions include infrasonic and lightning detection, direct human observations, weather radars and video surveillance. A combination of different sensors coupled with effective communication between observers and the aviation community offer the best chance of timely ash cloud avoidance by aircraft.

Current Status

The number of monitored volcanoes has increased in most regions since the First International Symposium on Volcanic Ash and Aviation Safety in 1991 (Casadevall, 1994). About 270 of 470 explosive volcanoes that have erupted in past 2000 years have some form of continuous monitoring in place (fig. 1). The majority have only seismic monitoring—in many cases a single sensor. Well-monitored volcanoes tend to be in wealthy countries, exhibit some level of unrest, have erupted recently, and/or pose a clear hazard to densely populated areas. The corollary is that there are about 200 recently active volcanoes with explosive potential that remain unmonitored.

With the exception of the monitoring being carried out in the Aleutian Islands by the Alaska Volcano Observatory Murray, 2004), Kamchatkan and northern Kurile volcanoes by KVERT (Gordeev, this volume), and Anatahan volcano by the U.S. Geological Survey and the CNMI, aviation risk has not been the determining factor in where volcano networks are established. Usually the first priority of the institution doing the monitoring is the safety of people in hazardous areas nearby the volcano. Volcano observatories typically issue public notifications of conditions at monitored volcanoes, but again, the focus is typically on warnings about ground hazards.

Although more volcanoes are monitored now than ever before, there are still large portions of volcanic arcs that remain un-monitored, including volcanoes that seriously threaten airways (fig. 1). The most under-monitored volcanic areas include the Northern Mariana Islands, the Kurile Islands and parts of Kamchatka, the central and southern Andes of South America, and Africa. Not surprisingly, these are areas with the smallest ground populations at risk.

Challenges

More volcanoes along busy air routes are continuously monitored now than at the time of the first Volcanic Ash and Aviation Safety Conference 13 years ago. Encounters are fewer today than 13 years ago (Guffanti and others, this volume). Yet, encounters with ash still occur. We in the volcanological community are proud of our improvements in monitoring, but we're still not satisfied and the aviation community shouldn't be either. Here are several targets toward which volcanologists, meteorologists, air traffic control, pilots, and airlines *together* should strive:

1) Add monitoring as quickly as possible to the ~200 volcanoes that are potentially active and may pose a threat to aviation, but are still unmonitored. Can we halve that number of unmonitored within the next 10 years?

2) Strengthen monitoring at minimally-monitored volcanoes, so that no eruption will be missed.

3) Ensure that communications between volcano observatories and VAACs are fast, clear, and robust. One way to improve this communication and awareness of each others' work would be to increase near-real-time data sharing. Through the internet, volcano observatories could share graphic seismic data with their VAAC(s) and VAACs could share selected satellite imagery (e.g., GOES or GMS images) with their cooperating volcano observatories.

4) A clear and worthy target is to notify pilots of an ash-producing eruption within 5 minutes of its onset. Work together to ensure adequate funding for these efforts. Specifically, pilots, airline companies, and those in air traffic control need to help volcanologists and meteorologists tally (a) encounters and details of their consequences, (b) diversions (avoided encounters) and probable savings (c) the volume of air traffic in under-monitored volcanic areas. These data are sorely needed to justify measures and expenses that each of the abovementioned players would make in the overall mitigation effort.

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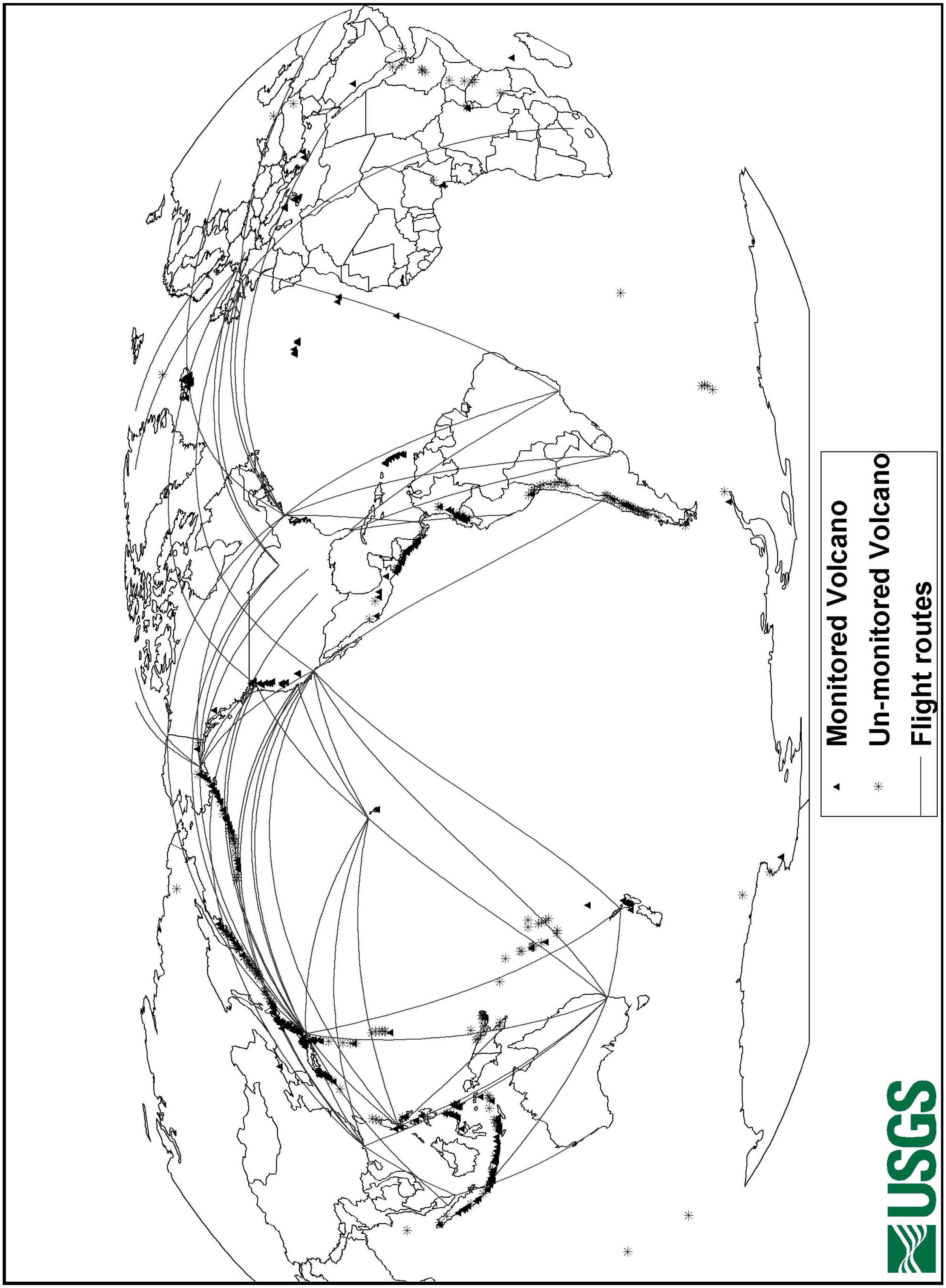
Figure 1. Map showing 468 volcanoes that have erupted explosively in the last 2000 years. Monitored volcanoes indicated by solid triangles. Un-monitored volcanoes indicated by open circles. Volcano data from Siebert and Simkin, 2002-. Flight routes from Casadevall and others, 1999. Monitoring status compiled by the authors.


▲ Monitored Volcano
✳ Un-monitored Volcano
— Flight routes
USGS

VOLCANIC ALERT SYSTEMS: AN OVERVIEW OF THEIR FORM AND FUNCTION

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Volcanic activity world wide is monitored by over 60 Volcano Observatories. Individual volcano observatories can be responsible for anywhere from one to over 40 volcanoes. They are typically set up to advise national, regional or local governments, emergency responding agencies, industry and the population. This advice is usually communicated by ‘volcano alert bulletins’ and ‘volcano alert levels’. A wide variety of needs are catered for in these systems. Two basic styles of volcano alert/warning systems have developed which relate to the status of a volcano, i.e. is it frequently in eruption or is it reawakening? Systems dealing with frequently active volcanoes have steps in them that are typically linked to the ‘current’ status of the volcanic activity, especially ongoing eruptive activity. They can carry any element of prediction, forecasting or warning and some indication of the degree of risk that the public are placed in while undertaking normal (non-restricted) activity on or about the volcano. In contrast, systems based on expected activity (reawakening) are often based on time-windows to the next expected level of unrest or the commencement of eruptive activity. The window durations are typically years, months, days or hours. The structure and responses to the alert systems vary between countries, resulting in a lack of international uniformity in our alert-warning systems, however this does not undermine the important function they achieve.

2.5

EXPLOSIVE ERUPTIONS OF ETNA VOLCANO SERIOUSLY THREATEN AVIATION SAFETY IN THE CENTRAL MEDITERRANEAN REGION

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Etna is a basaltic volcano located in eastern Sicily (Italy). Although it is worldwide known for lava flow eruptions that often threat the populated areas on its slopes, in the last decades explosive eruptions represent its more frequent activity either at summit craters or along fissures opened on its flanks, making Etna volcano a serious source of risk for aviation in central Mediterranean region (Fig. 1).

The frequency of Etna's eruptive phenomena in the last four centuries has increased, and particularly the explosive eruptions since 70's years (Branca and Del Carlo, 2004a). From 1979, we surveyed a large number of violent explosive events (Fig. 2) produced by summit craters, including more than 150 lava fountain episodes, characterized by: i) eruptive columns from 2 to 15 km high above the vent, ii) tephra volumes ranging from 10^4 to 10^7 m^3 and iii) magnitude from violent strombolian to subplinian. They often produced tephra fallout over eastern Sicily and the city of Catania.

Fig. 1: 2001 eruption plume of Etna in the Mediterranean Sea (NOAA courtesy).

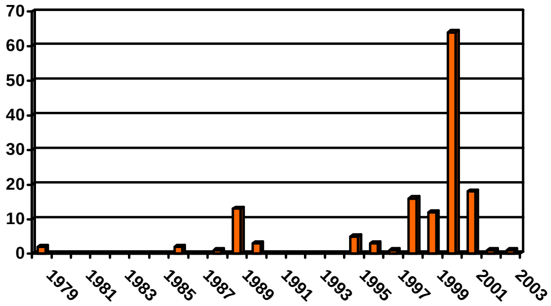

Fig. 2: Frequency of Etna's explosive eruptions occurred in the last 25 years.

At summit craters the prolonged explosive activity is generally weaker and produces limited dispersed tephra fallout, whereas violent strombolian and subplinian types episodes from summit craters are short-lived eruptions (from less than one hour to few hours) that produce widely dispersed deposits up to a few hundred km from the volcano. Due to the small volume of magma erupted they are not able to produce serious damages to the infrastructures also close to the volcano but they produce or induce several collateral damages mainly to the human health (lung ingestion of very small particles), to agriculture (lost of harvests), to the aviation (in-flight encounters with the drifting ash cloud and airport's runway contaminated with ash) and to the surface mobility (slippery roads due to a continuous ash mantle). These events are often repeated in a short time as in September 1989, when 14 episodes occurred during 16 days; in 1990 when other five episodes occurred; between November 1995 and June 1996 when ten strong fire fountain episodes were produced by North East Crater; during 1997 with other 14 episodes mainly from South East Crater; in 1998-9 when 4 episodes occurred, and finally the extraordinary activity of 2000 when 64 episodes occurred during five months causing the first serious problems to the population of eastern Sicily for the damages to aviation, to agricultures, and to roads and villages around Etna covered by an ash-mantle and almost daily cleared.

During this period, the most relevant air accident occurred on April 2000 when a commercial airplane (Airbus 320) departing from Catania airport encountered Etna's ash cloud damaging cockpit windshields.

During the last flank eruptions, occurred in 2001 and 2002-03, an exceptional and prolonged explosive activity originated from vents opened on the upper slopes of Etna was observed for the first time in the last century (INGV Research Staff, 2001; Andronico et al., 2004). Lava fountaining activity formed an ash plume 1-3 km high above the 2800 m vent (Fig. 3), causing a continuous tephra fallout for almost two months during the 2002-03 eruption.

Fig. 3: 2002-03 eruption ash plume dispersed eastward from the 2800 m vent in the S slope of Etna (Photo UFVG-INGV Sezione di Catania).

Copious lapilli and ash covered the volcano slopes and fine particles reached Rome and central Italy, western cost of Greece at and the northern coast of Libya. Because the effects of this *unusual* flank activity have been very serious on both health and economy, particularly for the respiratory diseases widely reported, and for the frequent disruption of the flight operations at Catania and Reggio Calabria airports, the explosive activity of Etna has started to draw the attention of local administrators and national politicians (Fig. 4).

Fig. 4: 2002-03 eruption plume and ash fall on Catania airport (Photo UFVG-INGV Sezione di Catania).

The critical revision of the historical reports from the last four centuries (Branca and Del Carlo, 2004b) shows that eruptions characterised by long-lasting explosive activity, such as the 2001 and 2002-03, are not so unusual. The report by abbot Recupero (1985) describes a copious tephra fallout of 4 kg per square meter in Catania in about ten days during the La Montagnola eruption in 1763, whereas during the 2002-03 eruption, we measured 2.5 kg per square meter in two days. In the 19th century, the occurrence of this type of eruption is more frequent. Eruptions occurred in 1811, 1852, 1886 and 1892 caused abundant ash fallout in the distal areas of the volcano. Therefore, the eruptive behaviour of Etna during the 2001 and 2002-03 eruptions is not a frequent phenomenon, yet at the same time it does not represent any anomaly in the eruptive history over the past centuries.

The thick volcaniclastic successions, that blanket the eastern slope of the Etna edifice, record a history of important explosive activity in Late Pleistocene and Holocene times characterised by plinian, phreatoplinian and subplinian central eruptions and violent strombolian lateral eruptions (Coltelli et al., 1998; 2000; Del Carlo et al., 2004).

The discovery of these explosive eruptions raises important issues for hazard assessment of basaltic volcanoes in almost persistent activity such as Etna, indicating that even a volcano, commonly considered non-hazardous for humans, can become very dangerous for aviation safety.

In summary, Etna's explosive eruptions observed and quantitatively described, historically reported and stratigraphically studied, represent a severe threat for aviation and economy of Sicily.

INGV staff in Catania, is in charged of the monitoring of the eruptive activity of Sicilian volcanoes, in response to this source of hazard, up to a few years ago completely ignored. It worked with Catania International Airport Direction, Italian Agency for Civil Aviation (ENAC), Meteorological Office of Italian Air Force and Italian National Civil Protection for warnings continuously the aviation authorities about the incidence of ash clouds on Sicilian airspace and the ash fallout on Catania airport depending on the intensity of the eruptive plume and the wind direction. With this aim, INGV is organizing an articulate strategy for studying in depth these eruptions, for setting an instrumental network to observe ash-cloud formation and developing, and finally for forecasting by mean of simulating computer models the ash dispersion in atmosphere and its fallout on the ground.

The lesson learned during the 2001 and 2002-03 crises was used to improve our volcanic ash cloud monitoring system, and transferred to ENAC for editing an official procedure for air-traffic and airport operations management in case of future crises at Etna, and in any case, to have a broad applicability worldwide.

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RECENT ERUPTIVE ACTIVITY IN ECUADORIAN VOLCANOES AND ITS THREAT TO AVIATION SAFETY

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Recently, Ecuadorian volcanoes have been unusually active. They are huge, tall volcanoes whose edifices rise more than 15.000 ft asl, therefore their eruptions start close to the flight corridors used by local commercial airlines. Guagua Pichincha (GGP) and Reventador (REV) have produced short lived but powerful eruptions (VEI ≥ 3), which generated superbuoyant eruptive columns and stratospheric injections of volcanic material. A distinctive characteristic is that these eruptive columns split at about the tropopause due to a 180º change in wind direction at the equatorial regions. This creates a virtual E-W ash shade for commercial routes flying N-S along the pacific coast of South America. Tungurahua (TUNG) is generating thermals since 1999 within two altitude ranges: 1) quiescent plumes related to weak strombolian activity and/or permanent gas emissions that are being propagated by prevailing westerly winds between 15.000-20.000 ft; and 2) stronger strombolian or vulcanian explosions which have been tracked by satellites to altitude levels higher than 25.000 ft. Sangay (SANG) sent its most recent ash cloud, 50 km long and traveling East at 18.000 ft, at the beginning of 2004. Thanks to the geophysical monitoring of the volcanic activity, the onset of the eruption period at GGP and TUNG was anticipated by the IG and transmitted to the responsible authorities, including commercial aviation (DAC). Once that eruption activity was correlated with seismic signals, it was possible to inform DAC about expected ash clouds or thermals beforehand. In some cases, especially during TUNG's open system venting, no seismic signals are generated and information flows in opposite direction: from ground observers and pilots to the IG through DAC. REV's eruption was sudden but the working relationship already established between IG and Washington VAAC greatly helped to establish the size and potential threat during early stages of the eruption. SANG is not monitored by the IG due to its remote location, but it poses a major threat to Guayaquil Airport and commercial routes.

THE ALASKA VOLCANO OBSERVATORY - FIFTEEN YEARS OF WORKING TO MITIGATE THE RISK TO AVIATION FROM VOLCANIC ASH IN THE NORTH PACIFIC

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Anchorage AK, USA

On December 15, 1989, a passenger wide-body jet encountered an ash cloud erupted from Alaska's Redoubt Volcano. All four engines of the aircraft ceased operation and it descended almost 15,000 feet before the engines were restarted, enabling the aircraft to land safely in Anchorage. This near disaster was a defining moment for the then year-old Alaska Volcano Observatory (AVO). Almost all of Alaska’s volcanoes lie along the 1500-mile-long Aleutian volcanic arc which parallels the busy North Pacific air routes between North America and Asia. Generally, the main threat to life and property posed by explosive eruptions of Aleutian arc volcanoes is to aircraft. Thus, most of AVO's efforts have focused on limiting the risk to aviation in the North Pacific from volcanic ash, including (1)installing new seismic monitoring networks on remote volcanoes along the Aleutian arc to provide advanced notification of volcanic activity, (2)expanding the satellite remote sensing capability of AVO and developing this into an integral part of volcano monitoring and research, (3) undertaking geologic studies of Alaskan volcanoes to determine their eruptive histories and hazards, (4) working with other Federal and State agencies in Alaska to establish protocols and procedures that enable AVO to quickly notify the aviation industry of volcanic activity and volcanic ash clouds,(5) coupling the monitoring efforts with a strong research program to better understand volcanic processes in order to provide better forecasts of volcanic activity, and (6) working with Russian scientists to establish the Kamchatkan Volcanic Eruptions Response Team (KVERT)in order to insure reports of volcanic activity in Kamchatka are broadly distributed.

GROUND-BASED REAL TIME MONITORING OF ERUPTION CLOUDS IN THE WESTERN PACIFIC

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Abstract: Ground-based observation of eruption clouds, combined with satellite imagery, is very important for understanding their properties under various volcanic and meteorological conditions. Real time monitoring contributes greatly to aviation safety, since height information is essential for dispersion model prediction. The near-infrared camera serves to improve the observation because it is less sensitive to atmospheric haze and able to detect hot anomalies. We report here the monitoring of eruption clouds at Mayon volcano in the Philippines, and Suwanosejima, Satsuma-Iojima and Sakurajima volcanoes in southwest Japan. We also discuss volcanic clouds and gas at Miyakejima near Tokyo.

1. Introduction

Volcanic clouds are often obscured on satellite imagery by meteorological cloud, or are too small-scale to detect. For aviation safety, a ground-based observation network is very useful for detecting ash ejections, and obtaining the vertical structure of the clouds. The flow and dispersion of volcanic clouds can be clarified by combined studies of ground observation and satellite images. Here we report our works in this direction concerning volcanoes in Japan and the Philippines. More details are described in the papers in a booklet of Kagoshima group [1].

2. Methods of ground-based observation

2-1. Near-infrared and visible observations

The near-infrared (NIR) band is widely used in satellite imagery, as it has quite different properties of surface reflection and atmospheric transportation compared with visible bands. The use of visible-cut filter in the cameras with CCD or CMOS sensor enables us to get NIR images in ground-based observation [2]. We are using a film type filter IR-84, which shields the light with wavelength < 840 nm. There are the following advantages for NIR over conventional visible observations, though the colour information is lacking: (i) The images are not so obscured by haze and mist. (ii) They may distinguish aerosols more clearly than visible images. (iii) They may detect very hot anomalies. (iv) They may detect vegetation damage by ash, gas and lava.

Fig. 1 shows a comparison of NIR and visible images of Takachiho peak at Kirishima volcanoes 48 km away. We may see topographic features owing to the shading in NIR image, while we only see the outline of the mountain in visible image.

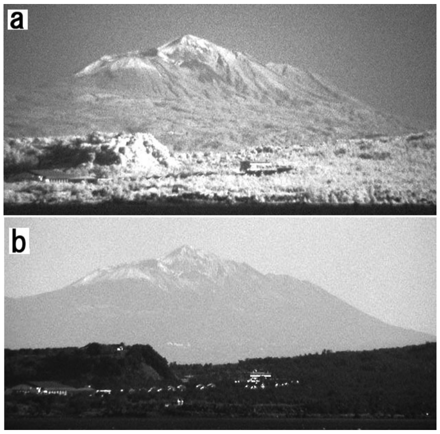

Fig. 1. Takachiho peak in Kirishima volcanoes observed from 48 km away in Kagoshima City on 14 Jan. 2004. (a) NIR image with IR-84 and ND400 filters in night-shot mode of SONY DCR-TRV30. (b) Conventional visible image.

2-2. Methods of automatic recording and monitoring

Since the features of volcanic clouds change with day and time, long period recording is necessary. Time-lapse recordings may be appropriate for the phenomena, except for very quick ones such as lightning. For this purpose, there are basically two alternatives [2] as follows.

(A) Long-time automatic camera recordings: Video camera recording for 100 days is possible in a two hour videocassette by recording 0.5 sec. with 10 min. interval. Memories with large capacity are able to store quite large number of digital camera photos for a few to several months with an hourly interval.

(B) Camera-computer system for monitoring and archiving: A web-camera with a personal computer or a network-camera alone is able to serve as a real time monitor accessible remotely via an Internet connection. For time-lapse recording and archiving, a server with enough storage capacity is necessary in the system.

For both *(A)* and *(B)*, a stable electric power supply is essential, and an uninterrupted power supply (UPS) must be used.

3. Mayon volcano

After the gigantic Pinatubo eruption in 1991, Mt. Mayon (2462 m) near Legaspi in southeast Luzon has been the most active volcano in the Philippines (Fig. 2). It erupted in 1993 and 1999-2001 with pyroclastic and lava flows, as seen by the lack of vegetation in Fig. 3. In the latter eruptions, the appearance of hot lava in nighttime was detected by a video camera by using night-shot mode.

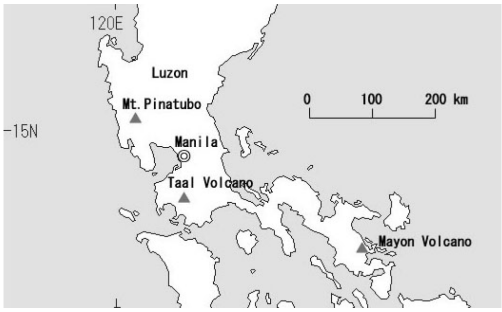

Fig. 2. Location of Mayon volcano.

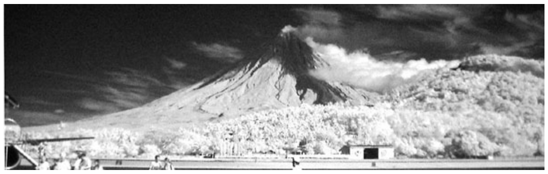

Fig. 3. NIR image of Mayon volcano observed from Legaspi airport 11.5 km south from the summit.

3-1. Interval recordings with visible-spectrum cameras

Automatic interval recording at Mt. Mayon began on 22 June 2003 as joint work of the Philippine Institute of Volcanology and Seismology(PHIVOLCS) and the Kagoshima group. Digital and video cameras were set in an observatory on Lignon Hill situated at 11 km SSE of the summit crater. Fig. 4 exhibits a few video scenes of the plume flow, which depends on the wind around the summit height. From the records for eight months, it was found that cloud-free scenes are generally limited to morning and evening, as clouds develop to cover the summit during sunny days, following the tropical diurnal mesoscale convection cycle. This indicates the difficulty of satellite monitoring of volcanic eruptions in the moist tropical areas.

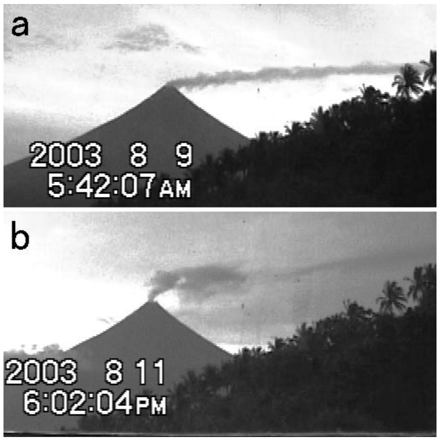

Fig. 4. Typical scenes of the plumes at Mayon volcano.
(a) Horizontal flow for fresh wind,
(b) Rise and flow under mild wind.

3-2. Network camera system to take NIR and visible images

On 24 February 2004, we installed a network camera system that has NIR and visible cameras in parallel, as shown in Fig. 5, except for the Internet connection.

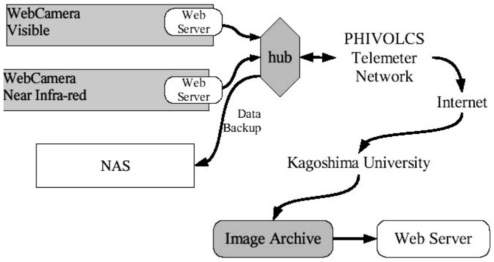

Fig. 5. Network camera system.

The system started to operate as a local network, to store visible images every ten minutes during 5:30 and 18:30, and near-infrared images every one-hour continuously in a network-attached storage (NAS).

Since April 2004, the network camera system is connected with the Internet, and real time access is possible from Quezon and Kagoshima. It should be noted, however, that the Internet is often disconnected by the shutdown of a server in the route whenever there are thunderstorms to avoid power surges and spikes. We are planning to construct a semi-real time homepage for worldwide access. A preliminary report of volcanic cloud observation at Mt. Mayon is given in [3].

4. Island volcanoes in southwest Japan

There is a chain of island volcanoes in the Nansei Islands in southwest Japan (Fig. 6). Among them, Suwanosejima volcano is the most eruptive in Japan in these years, while Satsuma-Iojima volcano is continuously ejecting plumes for many years.

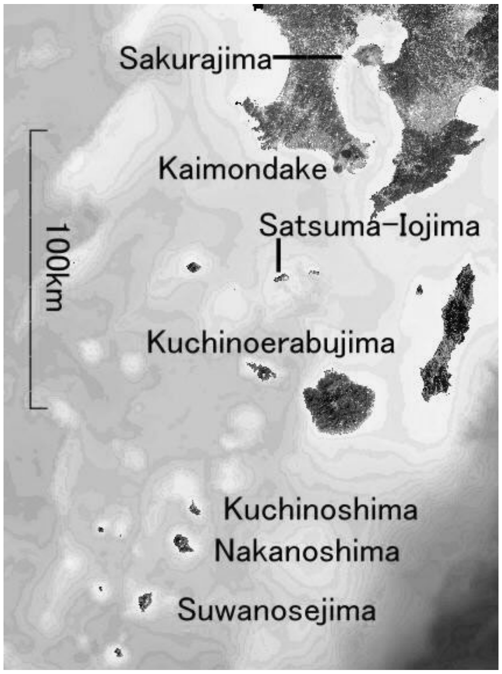

Fig. 6. Location of Suwanosejima and Satsuma-Iojima. Three small islands in between them are also volcanic islands.

4-1. Suwanosejima

There were many eruptions of Strombolian and Vulcanian types from the summit crater (799 m) at Suwanosejima in the last century. The volcano was rather dormant for five years since 1995, and resumed eruptions since the end of 2000. Eruption clouds at Suwanosejima are hazardous for low level (4-5 km) aviation, and the emitted ash frequently affects other populated islands in the vicinity. As it was difficult to have a good observation station on the island, we set a network camera at Nakanoshima, 25 km to the northeast, and connected it with the Internet on 6 August 2002.

Suwanosejima was especially active in 2002, erupting many times almost every day in August, and with 72 eruptions on 5 December. Some of them were detected by NOAA/AVHRR, EOS/MODIS and GMS/VISSR images, and reported by pilots to Tokyo-VAAC. Most of them since August were seen in the monitoring records such as shown in Fig. 7, though many of them were somewhat obscured by sea-haze. A summary of ground and satellite observations in 2002 is described in [4].

Fig. 7. Suwanosejima eruption on 14 Aug. 2002

Fig. 8. NIR monitoring camera image of Suwanosejima plume on 29 April, 2004 at 12:00 JST.

On 18 February 2004, the monitoring camera at Nakanoshima was changed from a conventional visible type to NIR type in order to minimize the sea-haze obscuration and to detect hot anomalies. Improved results have been obtained in spite of the long distance over the sea, such as shown in Fig. 8.

At the points where AC power supply is not available in Suwanosejima, we tested the interval recording by using digital camera package with rechargeable battery pack in a sealed transparent box. Such a package may be useful in long-time field observation, as it is small, lightweight and relatively expendable.

4-2. Satsuma-Iojima

Satsuma-Iojima (or Kikaijima) is a volcanic island at the NW rim of the Kikai caldera, most of which lies below the sea level formed about 7000 years ago. It has continued active ejection of gas mainly from the summit crater at Io-dake (703 m) for more than several hundred years.

Long-time automatic recording of the volcanic cloud started in July 1998 at a station about 3 km WSW of the crater, under the support of Nittetsu Mining Co. Ltd. A digital camera for hourly interval such as shown in Fig. 9, and a video camera with 0.2 sec. recording with 3 min. interval were installed. The video recording has been changed into 0.5 sec. with 10 min. interval since September 1999. In these modes, the automatic recordings are possible without changing media for about three months.

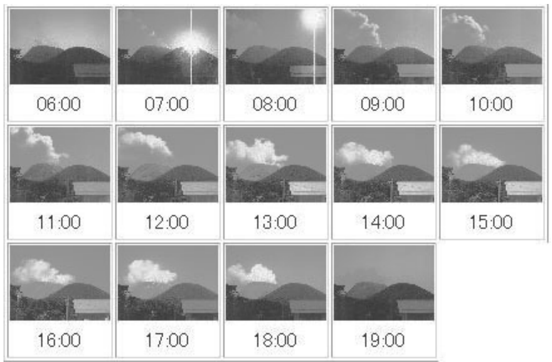

Fig. 9. Digital camera records at Satsuma-Iojima on 22 Aug. 2002.

Explosive eruptions affecting aviation have been rare at Io-dake in recent years. The ejection of volcanic plume was rather constant most of the time, with the height about 100-800 m above the summit depending on the winds. The highest heights in 2000-2002 were about1300-1500 m. Further discussions are given in [5].

For real time monitoring and archiving, a web camera system was installed in February 2003, and the camera head has been turned into NIR type since December 2003. The video camera has been turned into NIR mode since July 2003. It was found that analog connection of the telephone line was troublesome for the web-camera system. The Japan Meteorological Agency (JMA), which is responsible for volcanic disaster prevention, installed a high sensitivity camera with satellite communication line in November 2002. JMA also installed similar system at Nakanoshima for Suwanosejima monitoring in March 2003. It is desirable that different systems and modes are running in remote island volcanoes to observe various aspects of volcanic clouds and backup each other.

5. Sakurajima

Since 1972, Sakurajima volcano has been continuously active, ejecting ash plumes almost daily from the summit crater Minamidake (1040 m), mixed with Vulcanian and Strombolian eruptions occasionally. There had been many ash encounters of commercial aircrafts until 1991. The encounters have been quite reduced since then, by routing aircraft away from ash.

The Kagoshima group started interval recording of Sakurajima clouds in September 1987 at B in Fig. 10, 9.8 km WSW from the crater, and has published highlighted results on the Internet since 1997. Previous works of ground observations and satellite imagery of volcanic clouds are summarized in [6]. All of the archived records are now being converted into digital movies. Real time monitoring and archiving of the cloud images, accessible via the Internet, commenced at A in Fig. 10 in December 2000, and also at Ta and C in February and March 2003.

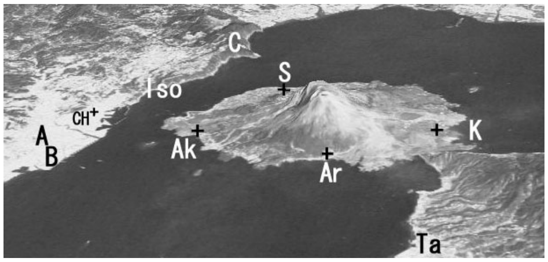

Fig. 10. The topography of Sakurajima and the surrounding Kagoshima Bay observed from southern sky (SiPSE 3D graphics). The gas monitoring stations (+), and camera monitoring points (A, B, C, Ta) are indicated.

At the foot of the volcano around the crater, there are four stations monitoring surface concentration of SO_2 and suspended particulate matter (SPM), as shown in Fig. 10, providing continuous measurement data with one-hour resolution since the 1980s. By comparing these data with the record of volcanic clouds and upper wind data, it was found that SO_2 concentrations at the foot of the volcano are high only when the winds around the summit are strong enough to create a lee wave and blow the volcanic plumes and gases down to a measuring station [7].

6. Miyakejima

Since July 8, 2000, Miyakejima volcano, about 160 km south of Tokyo (Fig. 11), has been very active, with a few big eruptions to disturb aviation in August 2000, and continuous ejection of enormous amount of poisonous gases since mid-August 2000, which compelled all of the inhabitants to evacuate from September 2000. The SO_2 flux in the ejected gas monitored by airborne Correlation Spectrometer was a few 10000s of ton/day in late-2000, and decreased gradually: it is still 4000-10000 ton/day in 2004. SO_2 was detected 100-400 km leeward in the mainland of Japan.

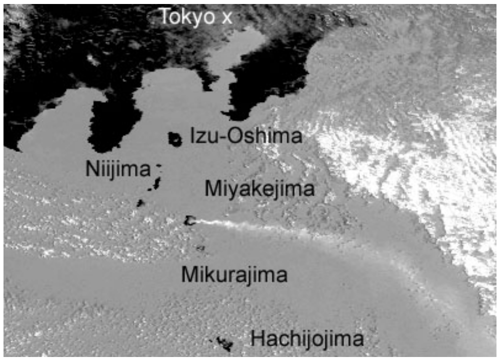

Fig. 11. Miyakejima and other Izu islands (NOAA/AVHRR image on 11 Dec. 2000, 13:25 JST).

The number of SO_2 monitoring stations at the foot of the volcano increased from three in December 2000 to fourteen in April 2004. The Kagoshima group analyzed the data, comparing with upper winds at Hachijojima, NOAA/AVHRR images and ground observation data from Mikurajima [8]. It was confirmed that, as in Sakurajima, fresh winds around the summit are responsible for the high concentration events at downstream stations [9]. The ground monitoring of the clouds is now performed by JMA at various points inside and outside the island.

7. Concluding remarks

Long-time automatic observation by the cameras from the ground, combined with satellite images, is useful for the studies of volcanic clouds and gas.

The use of NIR band has opened a new era of the ground observation.

Real time monitoring from the ground is important for aviation safety, disaster prevention of inhabitants and avoidance of ash and gas damages far away. It is especially important in order to speculate the flow of poisonous gas from the crater.

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ACOUSTIC SURVEILLANCE FOR HAZARDOUS ERUPTIONS (ASHE): A PROPOSAL FOR A PROOF-OF-CONCEPT EXPERIMENT

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SUMMARY

Ash injected into the atmosphere from volcanic eruptions poses a significant hazard to aircraft operations. In principle, infrasound monitoring will complement both seismic observation and satellite remote sensing to improve continuous monitoring of wide regions of potential eruption hazard at modest cost. This paper proposes an experiment to test both the practical utility of infrasound as a regional-scale volcanic eruption detection tool, and the feasibility of using such an infrasound system to contribute to the aviation industry timely operational alerts through Volcanic Ash Advisory Centres (VAACs). We propose a field deployment of several small prototype infrasound arrays in a suitably selected region, sending data in real time to a central data centre where algorithms for eruption detection may be prototyped. The results will be sent on a test basis to participating VAACs for comparison with the performance of existing warning systems.

Introduction

More than 80 separate incidents of interaction between aircraft and ash have been reported over the last twenty years. Incidents on international flight paths over remote areas have resulted in engine failures and significant damage and expense to commercial airlines. In order to protect aviation from volcanic ash, pilots need rapid and reliable notification of ash-generating events. Systems need to produce a minimum of false alarms to reduce additional fuel costs and delays from re-routings.

Whilst many volcanoes, particularly near population centres or in developed countries, are instrumented directly with cameras, microphones, strain and deformation meters, seismometers, etc.[1], there remain large portions of the earth's surface, particularly in remote areas or less-developed countries, where local ground-based surveillance systems are sparse or non-existent. Despite their remoteness, some of these areas lie under major intercontinental air routes. To instrument all known volcanoes with on-site sensors would be extremely expensive, both in terms of hardware and ongoing operational costs, and consequently attention is focused on using remote-sensing systems of various types to monitor broad areas in a cost-effective fashion.

Existing Broad-Area Monitoring Systems

Much research has gone into use of Earth observation satellites both for eruption detection and tracking of ash once injected into the atmosphere. Although multispectral techniques have had some impressive successes, timeliness is limited by the sampling interval of appropriate satellite images, and weaknesses remain in the ability to robustly identify ash in the presence of intervening cloud or when there is ice entrained in the ash.[2]

Since many volcanoes are in tectonically active regions where earthquakes are frequent, there are often regional seismic networks already in place. However, volcano-associated seismic signals are often of low magnitude and are difficult to detect reliably at distances of hundreds of kilometres, requiring a high density of seismometers near the volcanoes. Additionally, there is no exact correspondence between seismic and eruptive activity, resulting in possible high false alarm rates from regional seismic monitoring. Acoustic surveillance can reduce the ambiguity between eruptive and purely seismic activity in an active volcano and provide additional (and possibly more precise) estimates for the onset time of an eruption.

Use of Infrasound

The potential of using low frequency sound, or infrasound, to rapidly identify explosive volcanic eruptions has been discussed in the environmental acoustics and aviation safety communities for some time[3,4]. A direct link between the excitation of acoustic signals and the pressurized injection of ash into the atmosphere during an eruption has been demonstrated by over a century of observation[5]. The ability of sounds in the frequency range from 0.01-10 Hz to propagate for long distances in the atmosphere with little attenuation would suggest broad-area regional monitoring with a modest number of observing sites should be possible. However, progress on a demonstration of the concept has been slow, hampered by uncertainty as to the operational feasibility of the technique, lack of experience running infrasound systems for prolonged periods in remote areas, difficulties with data access, and a general lack of support for infrasound science.

Largely driven by the infrasound requirements of the Comprehensive Nuclear Test Ban Treaty (CTBT) International Monitoring System (IMS), significant practical experience has now been gained in the operation of autonomous infrasound systems in a wide range of environments from tropical jungles to polar ice sheets. In addition, low powered satellite communications systems are now available which make it feasible to install real-time communications links between data centres and remote operating locations far from civil infrastructure. Consequently, it seems an appropriate time to revisit the idea of using infrasound for remote volcano monitoring.

Although there is progress in resolving existing policies that restrict access to IMS data for civil applications[6], in practical terms the IMS network is not optimized for a volcanic monitoring role. The requirement that a 60 station infrasound network cover the globe yields stations thousands of kilometres apart with few close to areas of concern to the aviation community. Consequently, and for operational reasons, we propose deploying new infrasound arrays for the experiment, tailored for the task and free of any restrictions on data distribution.

Experimental Design

The first objective of the experiment is to test that infrasound is a practical tool for detection of ash-generating eruptions. We propose to identify a region with a number of active, well-monitored volcanoes, and deploy at least two infrasound arrays. The arrays would telemeter data in real-time to an appropriate central location where we could test various detection and identification schemes. We would seek to record and identify acoustic signals from an azimuth corresponding to a known candidate source, and ideally determine signal characteristics that would suggest a volcanic origin. Initial calculations suggest that arrays with four sensors and an aperture of 200-300 metres provide adequate azimuthal resolution over distances of several hundred kilometres. Comparison of results with on-site volcano monitoring technologies would provide ground-truth validation of results.

Although demonstrating reliable infrasound detection of an eruption is critical, an operational alert system also requires that the information be relayed rapidly to aircraft in the vicinity. Clearly, the closer one can install instruments to a source, the larger the signal[7], and the sooner it arrives. However, this must be balanced against the need to cover large areas from a reasonable number of discrete observing locations. Initial discussions with the FAA noted that while users have stated a requirement to receive notification of an eruption within 5 minutes of an eruption for an alert of airborne ash, it was felt that an alert issued within approximately 15 minutes of the time of eruption would be of significant benefit, particularly in remote and unmonitored regions of the world.[8] The International Civil Aviation Organization (ICAO) has designated a number of meteorological centres as regional Volcanic Ash Advisory Centres (VAACs) which are charged with the responsibility of issuing so-called Volcanic Ash Advisories to the aviation community, based on a synthesis of available information from pilots' reports, satellite observations, local observatories, etc. We propose to use one or more VAACs as recipients of the output of the prototype infrasound system. Feedback on comparisons of the system performance versus existing surveillance systems will provide additional feedback on system feasibility.

Conclusion and Next Steps

Recent developments in infrasound technology and expertise, automatic data processing, and satellite communications technology suggest that this is an opportune moment to revisit the concept of acoustic surveillance for detections and alerting of hazardous eruptions. A projected increase in the confidence and timeliness of an alert would help protect aircraft from the effects of ash. The next step is to identify a suitable partner organization in a country with active volcanoes that can provide technical and logistical assistance for a deployment of sufficient duration to evaluate the concepts presented in this paper.

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[7] We are neglecting here complexities introduced by atmospheric structure. Precise locations for the experiment will be chosen after detailed modelling of signal propagation.

[8] This timeframe defines a scale for the distances of the infrasound arrays from the source, considering the acoustic propagation velocity.

RECURRENCE OF EXPLOSIVE ERUPTIONS AT ETNA VOLCANO THAT PRODUCE HAZARD FOR AVIATION

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The recent activity of Etna is characterised by the occurrence of a large number of explosive eruptions, many of which have produced eruptive plume and copious ash fallout on its flanks. Since 1989 Etna summit craters have produced more than 150 fire fountain episodes, characterized by: i) eruptive columns from 2 to 12 km high above the vent, ii) tephra volumes ranging from 10^4 to 10^7 m^3 and iii) magnitude from violent strombolian to subplinian. Furthermore, in 2001 and 2002 flank eruptions, a prolonged explosive activity, forming a 1-4 km high ash column, caused continuous tephra fallout for several weeks. Lapilli and ash blanketed the volcano slopes and fine particles reached hundreds of km of distance. The effects have been very serious on both economy and health, particularly for the disruption of the operations of Catania and Reggio Calabria airports. Widening the temporal interval to the last 3 centuries, the historical record documents other five flank eruptions, comparable to the 2001 and 2002, that produced copious tephra fallout up to Malta Island and Calabria region. Furthermore, from the 18th century onwards, summit activity was characterised by several episodes of fire fountain and some short-lived sub-plinian episodes (on average two per century) that caused ash fallout on the eastern Sicily. Therefore, the eruptive behaviour of Etna observed in the last fifteen years does not represent any anomaly in the activity over the past three centuries. Nonetheless, the historical record analysis indicates an increase of the frequency of ash-plume forming eruptions from 1880 and again from 1961, highlighting Etna as certain source of risk for aviation in central Mediterranean region.

A PROPOSED ALERT-LEVEL NOTIFICATION SCHEME FOR AVIATION AND GROUND-BASED HAZARDS AT U.S. VOLCANOES

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Introduction

The function of hazard notification schemes is to give public officials and the public warning about the proximity of a hazardous event (Scott, this volume). How precise these warnings can be depends upon the nature of the hazardous event. Prior to eruptions, volcanoes exhibit precursory behavior over a period of days to years, such that notices of impending eruptions can usually be made far enough in advance for affected groups to take mitigative action. But, volcanoes do not erupt with consistent precursors or in a uniform style; nor do all episodes of unrest end in eruption. Thus there is considerable uncertainty in assessing future volcanic behavior at restless volcanoes. These uncertainties affect the precision of volcano notification schemes and provide a challenge in developing them.

In this paper, we discuss a proposed alert-level notification scheme for activity at U.S. volcanoes monitored by the U.S. Geological Survey's Volcano Hazards Program (USGS-VHP). We discuss the motivation and goals of the scheme, the rationale for the different levels, and how it is incorporated into the USGS-VHP's overall mitigation strategy to inform the public about potential volcanic eruptions.

Proposed Notification Scheme

The U.S. and its territories have approximately 170 volcanoes that have erupted over the past 10,000 years, 80 of which have had one or more eruptions in historical time (past 250 years). Of the 80 historically active volcanoes, about 50 are monitored at varying levels of thoroughness. Some of these volcanoes are near major cities, whereas others are in remote areas hundreds to thousands of kilometers away from ground-based populations.

Under Federal law, the USGS has the responsibility to monitor U.S. volcanoes and provide timely warnings to public officials and affected communities. The USGS-VHP currently has five volcano observatories and provides assistance to the Commonwealth of the Northern Mariana Islands. Three of the five observatories have developed alert-level notification schemes in order to meet the needs of nearby populations and the aviation community. Although there are similarities among the three schemes, they are not identical. To minimize confusion from multiple schemes in the future, especially if there are simultaneous eruptions being handled by different observatories, and to avoid re-inventing schemes by observatories currently without one, a single system is explored.

The goal is to design a single system that (1) can accommodate a range of styles, sizes, and durations of volcanic activity (both precursory and eruptive); (2) will work during escalating and de-escalating activity; (3) is useful to both ground-based communities and the aviation sector; (4) does not disrupt currently effective communication between the observatories and their partners; and (5) is scientifically defensible.

These are not trivial requirements. Typical volcanic eruptions can vary in style from relatively passive events to extremely explosive ones and in size (volume of erupted material) from 0.001 km^3 to, rarely, >100 km^3. Generally, an eruption involves episodes of eruptive activity separated by non-eruptive intervals of hours to months. The duration of a single eruptive episode usually ranges from a few minutes to tens of hours, whereas the entire eruption can last for a day to many decades (Simpkin and Siebert, 1994; Wunderman et al., this volume). As a result, an observatory may need to change alert levels numerous times over the course of a volcanic eruption. Similarly, during unrest, volcanoes exhibit a wide range in precursory styles and durations. There may be several cycles of increasing and decreasing unrest, before or after an eruptive episode, or before it is clear no eruption will occur. Again, it is important that notification systems can accommodate the up-and-down pattern of many volcanic crises. Some eruptions affect only ground-based communities and others only the aviation sector, but explosive eruptions at volcanoes that are near major communities, or that are large enough that the ash falls on populated areas, will affect both. Lastly, although there are many challenges in eruption forecasting (see Newhall, this volume), an alert system must be scientifically defensible to be consistently applied.

The scheme proposed here (Fig. 1) has four levels, each assigned a color (Green, Yellow, Orange, Red), based on a modified stop-light configuration and the aviation color-code system developed by the Alaska Volcano Observatory (AVO) and recommended by the International Civil Aviation Organization (ICAO). The scheme also includes hazard terms that are used by the National Weather Service (NWS) and familiar to most ground-based emergency management personnel. The dual system of colors and terms allows the aviation and emergency management communities to use the terminology that best suits them, but only a single alert-level would be issued (e.g., Yellow/Advisory) at any time. The descriptions reflect activity **at the volcano** and can be used during escalation and de-escalation. The descriptions are general to allow for the variety of volcanic unrest and eruption and to give observatories the flexibility to expand the definitions or, if necessary, to subdivide alert levels in order to meet the needs of user groups. Any modifications, however, should reflect the overall intention of the levels as discussed in the following paragraphs.

GREEN/NORMAL is the typical non-eruptive state of a volcano. This level allows for periods of increased steaming, seismic events, deformation, thermal anomalies, or degassing, as long as the activity is within the range seen at the volcano during its monitoring history, or at similar types of volcanoes. One difficulty is how to interpret data from new monitoring techniques, such as InSAR, because there may be no comparable data to use as a baseline. Another nuance of this level is that unrest initially seen as "anomalous" -- such as the increased steam and thermal output at Mount Baker volcano in 1975, or some of the periods of elevated unrest at Long Valley caldera through the 1980s and 1990s -- may, after some time, become considered normal background or regional activity.

Figure 1. Proposed unified alert-level notification scheme for volcanic activity

Color	**Term**	**Description**
GREEN	NORMAL	Normal non-eruptive state; typical background activity
YELLOW	ADVISORY	Elevated unrest above known background activity
ORANGE	WATCH	Escalating or sustained unrest indicates eruption likely, timeframe variable. OR, eruption underway that poses a localized hazard
RED	WARNING	Hazardous eruption is underway OR expected within hours

YELLOW/ADVISORY signifies that one or more monitoring parameters are outside the "normal" range of activity. This level implies that what drives the unrest may be magmatic in origin and could be precursory to an eruption, but that we expect to see much higher levels of unrest before an eruption begins. At this level, there is a strong possibility that no eruption will occur. Stating precisely when unrest is above "normal" is often difficult, especially when unrest begins gradually. During de-escalation, the definition is the same as during escalation and implies that monitoring parameters have not yet returned to baseline levels.

ORANGE/WATCH means either that (1) sustained high levels of unrest of one or more monitoring parameters are well outside the "normal" range or, (2) an eruption is in progress but poses only a localized hazard (i.e., no communities, major airports, or overflight paths). The rationale for this dual nature primarily is the need to distinguish between hazardous eruptions and those that do not pose a significant hazard to life or property. For example, lava flows from Kilauea Volcano, Hawai'i are currently flowing through Hawai'i Volcanoes

National Park, but they are not a threat to homes or important Park structures. Using our proposed scheme, we would consider the alert level as Orange/Watch. If the lava were to start flowing through communities and threatening homes and businesses (as it has done in the past), then the alert level would be raised to Red/Warning.

Another example of a non-threatening eruption is dome growth at a remote volcano (e.g., Bezymianny, Kamchatka). In this situation, however, dome collapse could quickly change the situation from being non-threatening to potentially hazardous for air traffic. In situations like dome growth/collapse and when escalating to or de-escalating (sustained unrest) from hazardous eruptions, Orange/Watch is a warning that the situation is dynamic and could (not will) change quickly. There is no specific time frame associated with this level, but during escalation it usually implies that an eruption is more likely and more imminent (but still not guaranteed) than when in Yellow/Advisory.

We decided against using a fifth color to handle non-threatening eruptions because (1) there is no equivalent in the NWS terminology so there would be no familiar term for the ground-based communities, (2) it would be non-linear as one wouldn't necessarily escalate or de-escalate through this color, (3) it would be non-intuitive (is color A more or less of a concern than color B?), and (4) we wanted to avoid confusion with the U.S. Department of Homeland Security's five-tiered color code system.

The proposed Orange/Watch definition is similar in intent to the AVO and ICAO color code ORANGE. Like those schemes, the proposed level has a dual nature of either high unrest or a largely non-hazardous eruption. It differs primarily in that it does not define an ash plume threshold. The ash plume altitude of 25,000' was conceived as a useful threshold of concern for the North Pacific Region where many volcanoes are remote but where ash plumes above 25,000' can affect a large volume of air traffic at cruise altitudes. A concern with the 25,000' threshold for all observatories is that in places where airports are close to volcanoes, ash plumes of less than 25,000' can be very hazardous to the aviation industry. Thus we have tried to adhere to the intent and duality of the original ORANGE definition, but have deleted the specific altitude threshold so that it could be more widely applied. In some instances, observatories may want to assign an altitude or some other threshold to an alert level in order to highlight specific aviation or ground-based concerns. For example, at remote locations where there are no nearby populations or airports, an observatory may want to use an altitude, similar to that currently in use at AVO to define Orange/Watch. **Even if no ash plume threshold is assigned, any available information regarding ash plume height should be part of all alert-level notices when in Orange/Watch or Red/Warning.**

RED/WARNING means that monitoring data are at levels that suggest a potentially hazardous eruption is underway or is expected in the near future (hours). This level does not indicate whether the eruption is small, moderate, or large, or who is at risk—aviation, ground -based communities, or both. Rather it indicates that the eruption either is, or potentially is, life threatening to one or both groups, and that action to mitigate the threat is needed or should have been completed already by those groups. An observatory may choose to have sublevels within Red/Warning for explosive volcanoes that have a large range in eruption size.

Because volcanologists cannot reliably forecast eruption size, most observatories would likely raise the alert level to Red/Warning as soon as an eruption began for those volcanoes that have a history of at least some moderate explosive events (VEI $\geq$ 3; Newhall and Self 1992; Newhall this volume). Although some eruptions raised to Red/Warning may be better classified as Orange/Watch in hindsight, it may be better to be cautious than to mistake a hazardous event for a non-hazardous one.

Volcanic events are unique enough that it is impossible to predetermine a detailed set of criteria for each level that would be applicable in all situations. The above definitions are guidelines for scientists to use to categorize the level of unrest, and for public officials and the public to consider when deciding what actions they need to take. Our scheme as portrayed in Figure 1 is a way to communicate quickly our scientific judgment about the level of unrest. For more detailed information, the USGS-VHP usually issues daily, or more often if needed, updates on the status of the volcano. These communications typically give the volcano's location in latitude and longitude, height of the volcano's summit, the alert level, a short synopsis of the monitoring data, interpretation of that data, and both a short- and long-term forecast of likely activity. These daily updates are essentially the scientific rationale for the alert level assigned. If the volcano erupts, information about when the eruption began, the presence or absence of a plume, plume height and volcanic phenomena that affect ground-based activities would be conveyed along with the change in alert level.

In order for alert-notification systems to succeed, users must be aware the system exists, understand its strengths and weaknesses, and provide feedback when it works and when it fails. Communication is a critical element to mitigating any crisis. Effective communication includes two-way exchanges of information as events unfold and clear protocols for disseminating warnings when needed.

Because volcanologists do not directly measure the rise of magma during volcanic unrest, and because not all volcanoes are monitored, visual observations are an important monitoring tool. Volcanologists are located in only a few places compared to the geographical distribution of volcanoes, so observations from pilots and individuals on the ground can be vital in detecting unrest and eruptive activity. For example, a pilot was the first to note the second eruption of Crater Peak, Alaska, on 18 August 1992 and immediately informed the AVO of the event. At that time there was only a weak signal on the seismic records which would not have been interpreted as the beginning of an eruption (Eichelberger et al. 1995). It is critical that outside observers know how to contact observatories and that those observatories are receptive to outside observations in order for two-way exchanges of information to occur.

Although two-way exchanges of information are important for monitoring unrest and activity, protocols are needed to ensure that essential information is communicated efficiently and that the source of the information can be quickly verified. Every year there are many false reports of eruptions and one can only imagine the disruptions they would cause if they were all acted upon. Protocols work best if they are already in place before a crisis begins and if they are practiced regularly. The USGS-VHP is working with emergency managers and aviation personnel to set up protocols in the event of volcanic unrest and eruption. Face-to-face interactions are one of the biggest benefits of such discussions, as it is often easier to communicate openly with someone you know than with a stranger. It is not always possible to develop protocols in advance, but when they are already in place they often help diffuse many of the problems that arise during a crisis.

We digress here briefly to discuss our justification for combining the aviation and ground-based communities into one system. Perhaps the best reason for combining them is to ensure that there is a consistent message regarding the status of the volcano. One can imagine the possible confusion that could arise in populated areas if a volcano is at Red/Warning for aviation hazards but at Orange/Watch for ground hazards. All it would take would be one media or observatory report to confuse the two for a potential disaster to happen. Moreover, as restless volcanoes near populations escalate towards or de-escalate from an eruption, the information conveyed by alert levels and in daily updates is of equal importance to both communities. Many explosive eruptions may not affect both communities equally, but the differences may be slight. As long as regional airport operations are affected by ash fall, lava flows or lahars, airport-supported response and recovery efforts will be difficult or impossible to deploy. The only cases in which one community will be effected in the other not, are when volcanoes are very remote or when eruptive activity is non-explosive and far from airports. Overall we feel that there is more to be gained by combining these two groups within one system than by having two separate ones. The challenge for observatory scientists is to write eruption communications well enough so that each group can quickly identify and locate the volcanic phenomena of concern.

Closing

There are many ways to develop a volcano alert-level notification system and ours is but one of many (Scott, this volume). As stated in the title, this is a proposed system and we are in the process of testing it and evaluating it internally. Even now, we are trying to determine whether Red/Warning should only mean "hazardous eruption in progress" or stay with the current dual definition of "hazardous eruption in progress or hazardous eruption imminent." Another area of discussion is whether we should set protocols as to how long we stay in Red/Warning—only for the duration of the eruption (which may be minutes to many hours) or for a set time period, perhaps 12 hours after the eruption has ended? The latter would cover the time period when ground-based catastrophic events would have occurred and most of the tephra would have moved substantially downwind of the volcano. As we move forward with this process, we would greatly appreciate comments as to potential problems and benefits of this proposed scheme from the aviation, ground-based, and volcanological communities.

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MONITORING AND REPORTING OF KAMCHATKAN VOLCANIC ERUPTIONS

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Kamchatka is a part of Pacific volcanic ring with 29 active volcanoes. Every year 2- 3 of these volcanoes produce explosive ash clouds that spread across heavily traveled international air routes between Asia and North America. The Kamchatka Volcanic Eruption Response Team (KVERT) has since 1993 provided reports and notices of volcanic activity. In collaboration with the Institute of Volcanology and Seismology (IVS) and Kamchatkan Experimental and Methodical Seismological Department (KEMSD) of the Russian Academy of Sciences, the KVERT staff monitors active volcanoes of Kamchatka seismically, by video and visual observations, and using satellite images for ash cloud tracking and detection of thermal anomalies. As of 2003, 28 remote seismic stations are operating at 11 of the most active volcanoes in Kamchatka and North Kurile Islands. Three volcanoes, Kyuchevskoy, Sheveluch and Bezymyanny are under control by video-camera system, which makes real-time images of volcanoes available on the Internet (http://emsd.iks.ru). Seismic observations are a universal tool used to reveal the beginning of volcano unrest and to recognize volcanic blasts of frequently weather obscured volcanoes. KVERT scientists have developed methods of estimating eruption plume height from the intensity of the seismic signals. In cooperation with the Alaska Volcano Observatory, KVERT examines data from Japanese and U.S. meteorological satellites. Several times a day, images from GMS (Geostationary Meteorological Satellite), GOES (Geostationary Operational Enviromental Satellites) and polar-orbiting satellites carrying AVHRR (Advanced Very High Resolution Radiometer) are examined for volcanic activity. Since 2002, KVERT has used daily images from NOAA16 and NOAA17 satellites received by the Kamchatkan Center Communication and Monitoring (KCCM). In the future, KVERT will expand its monitoring and warning capacity by adding more seismic networks and video systems and by enhancing satellite analysis of Kamchatka and the adjacent Kurile Islands.

VOLCANO-RELATED INFORMATION AVAILABLE ON THE INTERNET: FROM CURRENT ACTIVITY TO THE PAST 10,000 YEARS

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Introduction

A wealth of information is available on the Internet about volcanoes and the ash clouds they emit, but it can be a daunting task for pilots and aviation officials to find the most pertinent information. Scientists with the US Geological Survey's (USGS) Volcano Hazards Program and the Smithsonian Institution's Global Volcanism Program (GVP) recognize that information concerning volcanic activity should be readily available to the aviation community. To that end, they provide two pages of particular relevance on their websites: the GVP/USGS Weekly Volcanic Activity Report, and the USGS Current Updates for US and Russian Volcanoes.

Worldwide Volcanic Information

Up-to-date information about significant worldwide volcanic activity is available on a weekly basis via the online GVP/USGS Weekly Volcanic Activity Report at http://www.volcano.si.edu/reports/usgs/. The report is a joint project between the Volcano Hazards Program and GVP that became available to the public on November 1, 2000.

The most significant section of the website is the brief description of the activity that occurred at the volcano during the report week. These accounts include information about (1) volcano-related activity that either did not result in an eruption or preceded and accompanied an eruption – i.e., increased seismicity, gas emissions, deformation, surficial changes, (2) eruptions, with emissions including lava flows, ash, and other fragmental volcanic material, (3) secondary activity such as mudflows/lahars and re-suspended ash, and (4) eruption impacts, including health impacts, airport closures, flights affected, and property damage. In each volcano report, volcanological terms that the general public may not be familiar with are linked to a photo glossary on the USGS Volcano Hazards Program website. In addition, acronyms and abbreviations are commonly used in the reports, so there is a link to a list with their meanings.

Background information from the GVP website is included with each volcano report that briefly summarizes the geological history of the volcano and noteworthy past eruptions. Each report also has links to maps showing the location of the report volcano in relation to nearby volcanoes and large cities, the source of the reported information when available on the Internet, and a link to more information, images, and data on the GVP website.

All volcano reports are archived on the Internet by volcano and report date, so that they are easily accessible. In the 4 years that the GVP/USGS Weekly Volcanic Activity Report has been available to the public (November 1, 2000 to November 2, 2004), there have been reports written about 146 volcanoes in 33 different countries and island nations (note that all reports document the minimum amount of activity in any given week due to under-reporting). A majority of reports (53) discuss small eruptions at volcanoes that had not erupted for at least 3 months (Table 1). Small eruptions include ash emissions that did not rise higher than approximately 5 km above the volcano. Most of the remaining reports cover non-eruptive volcanic activity (48) and ongoing activity (25) not considered anomalous.

Table 1. Types of activity reported in the GVP/USGS Weekly Volcanic Activity Report during November 1, 2000 to November 2, 2004.

Type of Activity	**Number of Volcanoes**
Non-eruptive, Precursory Activity	48
Ongoing Activity	25
Small New Eruptions	53
Large Eruptions	13
Evacuations	20
Deaths	2
Injuries	2
Aviation Impacted	12

Reports were written about 13 large eruptions – i.e., produced ash clouds that rose higher than 5 km above the volcano and had significant impacts on populations or aviation (Table 2). Eight of these eruptions led to evacuations of residents near the volcanoes; eruptions at 12 other volcanoes led to evacuations when large eruptions did not occur (20 evacuations total since November 1, 2000.) Eruption-related deaths were reportedly caused by two eruptions. Injuries were reported from two eruptions, and numerous incidents occurred where people's health was adversely affected by ash and gas

Table 2: List of the 13 large eruptions reported in the GVP/USGS Weekly Volcanic Activity Report during November 1, 2000 to November 2, 2004.

Volcano, Country	**Eruption Date**
Popocatépetl, México	Dec. 2000
Cleveland, USA	Feb. 2001
Merapi, Indonesia	Feb. 2001
Etna, Italy	May-Aug. 2001 Oct. 2002
Mayon, Philippines	June, July 2001
Nyiragongo, D. R. Congo	Jan. 2002
Pago, Papua New Guinea	Aug. 2002
Tungurahua, Ecuador	Oct. 2002
Reventador, Ecuador	Nov. 2002
Bezymianny, Russia	July 2003 Jan. 2004
Anatahan, Mariana Islands	May 2003
Manam, Papua New Guinea	Oct. 2004
Grímsvötn, Iceland	Nov. 2004

Ash from eruptions at 12 different volcanoes disrupted activities at airports and/or affected aircraft in flight (See Guffanti et al., this volume). The GVP/USGS Weekly Volcanic Activity Report provides valuable information about ash and aircraft/airport incidents by consistently documenting them in a timely manner

Timely reporting of volcanic activity does not always allow time for in-depth verification of information by scientists in the field or by GVP/USGS Weekly Volcanic Activity Report editors. Therefore, false reports can sometimes be included. Six false reports of eruptions have been included in the GVP/USGS Weekly Volcanic Activity Report, and were corrected once new information was received.

The GVP/USGS Weekly Volcanic Activity Report utilizes the wealth of volcano-related information available on the GVP website at http://www.volcano.si.edu/ by providing links to data about the report volcano on the website. While the GVP/USGS Weekly Volcanic Activity Report has provided brief updates on significant volcanism around the world for the past four years, the Smithsonian GVP has provided information since 1968 about Earth's current eruptions and those that occurred in the past 10,000 years. Monthly newsletters discussing current activity have been produced since 1975, and have been posted on the Internet since 1994.

For more than three decades, GVP has compiled descriptions, data, maps, and images of volcanoes and their eruptions in order to better understand the full range of Earth's eruptive activity and to make these resources available to the ever-broadening community interested in volcanism (Siebert and Simkin, 2002). Two previous hardcopy versions of the GVP volcano and eruption data (Simkin et al., 1981 and Simkin and Siebert, 1994) have been published, but in 2002 the data became accessible on the GVP website (Venzke, et al., 2002). The development of the world wide web has made possible much wider and faster dissemination of these data, which are frequently updated.

U.S. Volcanic Information

For users specifically interested in current activity at volcanoes in the United States and Russia, the USGS Volcano Hazards Program website compiles daily-to-monthly volcano updates from all five volcano observatories in the United States and an observatory in Kamchatka. The USGS Current Updates for US and Russian Volcanoes page is available at http://volcanoes.usgs.gov/update.html. The page also has links to each individual observatory website where detailed information about the volcanoes within the observatory's region of responsibility can be found.

Summary

The GVP/USGS Weekly Volcanic Activity Report, with links to the GVP website, and the USGS Current Updates for US and Russian Volcanoes page place air traffic controllers, pilots, and airport authorities abundant information regarding volcanic activity around the world literally at their fingertips to help them quickly make informed decisions when planning flight routes.

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VOLCANIC TREMOR AND ITS USE IN ESTIMATING ERUPTION PARAMETERS

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Volcanic tremor, a continuous seismic signal, accompanies virtually all eruptions. Several published studies have examined relations between tremor reduced displacement (DR, a normalized amplitude measure; Aki and Koyanagi, 1981; Fehler, 1983) and the Volcanic Explosivity Index (VEI; Newhall and Self, 1982) or ash plume height. The goals of these studies are to determine the physical relationships between tremor and eruptions and to use DR values to provide real-time estimates of eruption parameters.

This study examines tremor for 50 eruptions from 31 volcanoes. This is a significant expansion of the data set from an earlier study of 21 eruptions from 14 volcanoes (McNutt, 1994). Several new trends are observed when DR is plotted versus VEI (Figure 1): 1) large eruptions produce stronger tremor than small ones; 2) fissure eruptions produce stronger tremor than circular vents for the same fountain height (F in Figure 1); 3) eruptions with higher gas content (H in Figure 1) produce stronger tremor than those with low gas content (L in Figure 1); and 4) phreatic eruptions produce stronger tremor than magmatic eruptions for the same VEI (P in Figure 1).

The three volcanoes with varying gas content are Redoubt 1989-1990, based on eruption type (vertically oriented pumice eruption versus dome collapse; Miller, 1994); Mount Spurr in 1992 based on SO2 measurements (Bluth et al., 1995); and Shishaldin volcano in 1999 based on presence or absence of large explosions on a pressure sensor (Caplan-Auerbach and McNutt, 2003).

Using tremor DR to estimate eruption parameters is a statistical problem with several factors contributing to uncertainties. First, tremor occurs when volcanoes do not erupt as well as when they do. Based on a worldwide sample, 60-80 percent of tremor episodes accompany eruptions, while 20-40 percent of episodes do not. Thus, there is a significant chance that no eruption is occurring. Second, for each VEI, there is a range of DR, so it is possible to overestimate or underestimate the VEI. Hence there will always be a false alarm rate (~10 percent). Improvements can be made in the estimates if the types of eruptions, shapes of vents, and gas contents are known in advance. These can be estimated from previous eruptions or measured near-real-time from independent data. However, adding additional information takes time, delaying forecasts. A primary benefit of seismic data is that they are real-time, are not affected by darkness, and are usable during poor weather, although the signal-to-noise ratio can be worsened. Monitoring tremor DR is therefore an effective way to characterize eruptions in progress.

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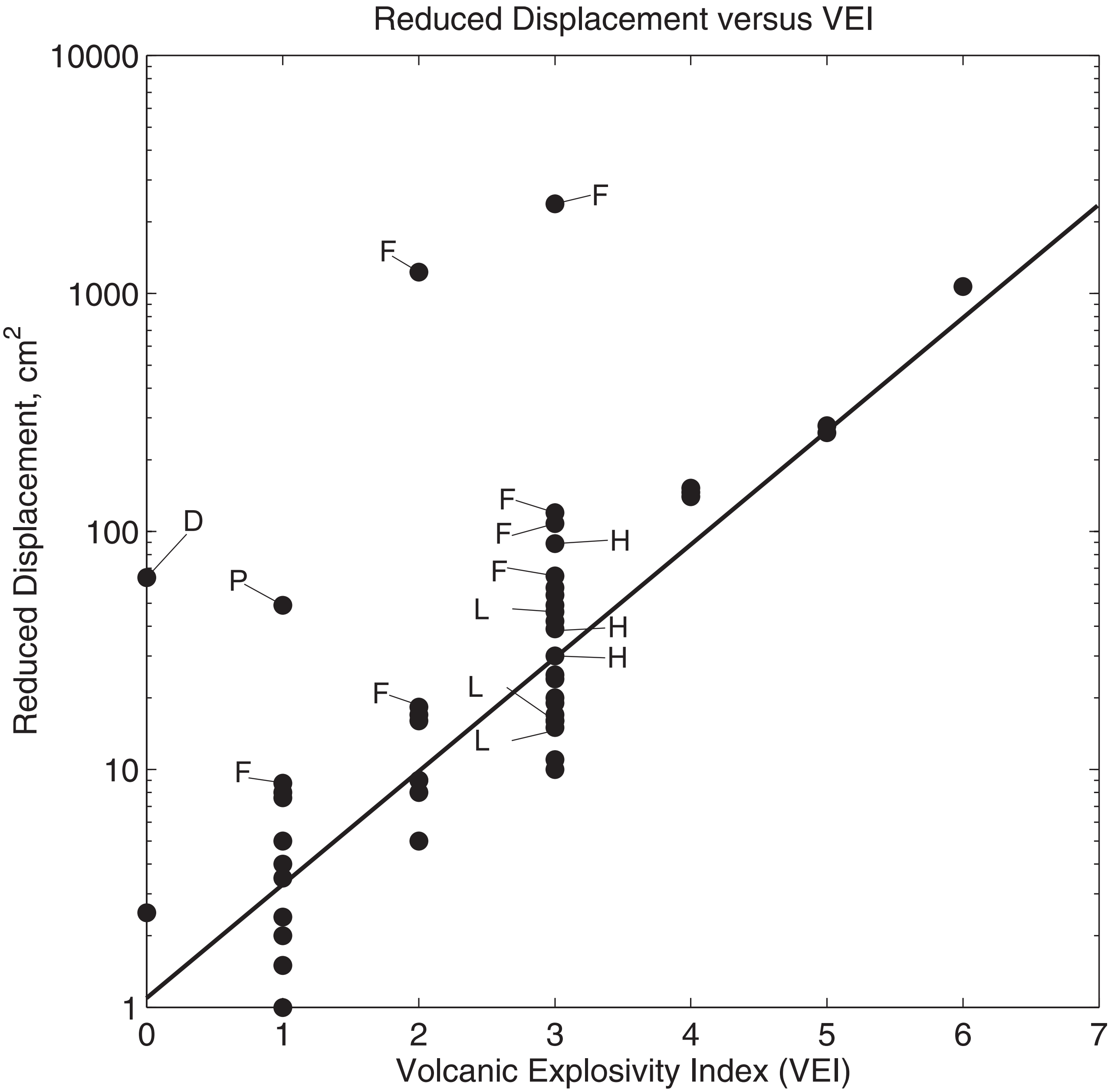

Figure 1. Reduced displacement, a normalized measure of amplitude, versus the Volcanic Explosivity Index for 50 eruptions at 31 volcanoes. The regression line is from McNutt (1994) based on a smaller data set and is shown for comparison. Fissure eruptions are labeled F; a phreatic eruption is labeled P; deep (40 km) tremor from Kilauea is labeled D (no eruption for this one); and three pairs of values from VEI=3 eruptions with high and low gas content are labeled H and L, respectively.

SURPRISE/SUDDEN ONSET ERUPTIONS: THE CASE OF REVENTADOR VOLCANO-ECUADOR, 03-NOVEMBER, 2002

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Not all volcanoes show a progressive build up over weeks and months of precursory activity prior to a major eruption. Several of these include Redoubt (1989) and most recently Reventador in eastern Ecuador. Prior to Reventador's VEI 4 subplinian eruption on 03 November, 2002, 10 seismic events were registered on 06 October, 2002 by the two telemetered seismic stations closest to the active cone. Superficial manifestations observed from a nearby construction camp were minor. On the day of the eruption only seven hours of tremor and >100 local earthquakes preceded the paroxysmal eruption at 09H12 (LT) that resulted in a 17 km high ash-rich column and 5 andesitic pyroclastic flows which descended 9 km down valley. Ash clouds entered the populated InterAndean Valley and ash began falling between 12H00 and 16H00 depositing a 5-15 mm thick layer. Quito's International Airport, 100 km west of the volcano, was closed officially at 12H45, hence most aircraft remained at the airport and were completely covered by the ash. Reventador has had at least 7 eruptive periods since 1900. In this most recent episode, the rapid ascent of volatile-rich magma was mainly aseismic. Only telemetered seismic stations operating directly on the cone may have provided a clearer warning of the impending eruption. Reventador is similar to several other active volcanoes in Ecuador which have minimal or no monitoring because of the "low" direct risk they present to important population centers. Airlines and local Civil Aviation could opt to contribute to establish more intense monitoring of these volcanoes to maximize eruption predictive capacity and at the same time have plans in place to deal with unexpected-surprise eruptions.

ASHFALL SCENARIOS AND AVIATION IMPACTS OF FUTURE ERUPTIONS OF COTOPAXI VOLCANO-ECUADOR

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Cotopaxi is a 5900 meter high stratocone on the eastern edge of the densely populated InterAndean Valley. In November, 2001 Cotopaxi’s monitoring network began to display frequent and intense anomalous seismic events. Although this activity has mostly subsided, it may be a long-term warning that a slow awakening is occurring. The volcano’s last important eruption was in June, 1877. Covered by ~14 km^2 of ice and snow, Cotopaxi is well known for its destructive lahars that have traveled down all 3 main drainages. Ashfalls also had important consequences for the agriculturally-based communities during the 13 notable VEI 3-4 magnitude eruptions of the 18th and 19th centuries. Extensive field mapping of 10 main ash fall units of the Holocene shows that the bulk of the coarser tephra has been deposited to the W-NW of the cone and that in only two cases have important ash/pumice layers been deposited to the east. As seen during recent eruptions of other Ecuadorian volcanoes, windshearing is common after the column enters the stratosphere, directing the fines-component of ash clouds eastward. Historic accounts following Cotopaxi eruptions report fine ash falls as far north as Pasto- Colombia, to Piura- Perú, to the south, and westward upon coastal Ecuador where ash falls often persisted 4 to 5 days. Future eruptions are likely to be of similar VEI 3-4.5 magnitude, producing plinian columns and pyroclastic flows, which have the effect of injecting ash-rich clouds high into the stratosphere, potentially affecting national and international airline traffic for many days in all of Ecuador, and perhaps on a regional scale. In all probability, the three main international airports- Quito, Latacunga and Guayaquil will suffer some consequences of ashfalls.

P2.9

AIRBORNE ASH HAZARD MITIGATION IN THE NORTH PACIFIC: A MULTI-AGENCY, INTERNATIONAL COLLABORATION

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More than 100 active volcanoes bordering the Pacific Ocean from southern Alaska, along the Aleutians, Kamchatka and through the Kuriles, pose a significant risk to aviation. To address this problem, scientific institutes, federal and state/regional governmental agencies, international organizations, and private industry work together to ensure effective volcanic hazard warnings. The principal earth science agencies responsible for detecting and issuing warnings of volcanic unrest in Alaska and Russia are the Alaska Volcano Observatory (AVO) and the Kamchatka Volcanic Eruption Response Team (KVERT). AVO and KVERT utilize real-time seismic networks, satellite remote sensing of ash and thermal anomalies, and visual observations to detect and characterize volcanic activity. Warnings are issued as quickly as possible by phone, fax, and the Internet to an established recipient list. Information is also rapidly posted on the Internet. AVO works closely with the National Weather Service, the Federal Aviation Administration, and others to ensure that formal operational guidance to the aviation community contains all critical volcanic hazard information. KVERT has a similar relationship with the regional aviation and meteorological authorities in Kamchatka. AVO and KVERT also issue weekly status reports on all seismically monitored volcanoes and conduct scientific studies in support of hazard assessments. Both groups utilize a 4-level, color-coded alert scheme to summarize the severity of volcanic unrest and hazard. Agency responsibilities, relationships, and operational protocols for eruptions in Alaska are formalized in the “Alaska Interagency Operating Plan for Volcanic Ash Episodes”. Frequent review of response protocols is necessary to maintain proficiency and to meet demands for increasingly rapid communication of volcanic hazards.

GROUND-BASED DETECTION OF VOLCANIC ASH AND SULPHUR DIOXIDE

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We present the first thermal infrared image data showing detection and discrimination of volcanic ash and sulphur dioxide gas emitted from erupting volcanoes. The images are acquired from a new multichannel uncooled thermal imaging camera suitable for deployment within ~10 km of an active volcano. Algorithms for ash and SO_2 detection are described. Images from the system, named G-bIRD (Ground-based InfraRed Detector) are acquired rapidly (within a few seconds), analysed and transmitted via satellite or landline to a computer with access to the Internet and utilising a standard web browser. Tests of the system have been undertaken at Etna and Stromboli, Italy, at Anatahan, NMI and at Tavurvur, Rabaul and results will be presented. G-bIRD offers a new means for monitoring hazardous volcanic substances from the ground and could provide complementary information for providing volcanic ash and SO2 warnings to the aviation industry.

THE NEW ZEALAND VOLCANO ALERT LEVEL SYSTEM – ITS PERFORMANCE IN RECENT ERUPTIVE ACTIVITY

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In November 1994, the New Zealand Ministry of Civil Defence introduced a new annex entitled ‘Volcanic Impacts’ into the National Civil Defence Plan. This was based on a five level volcanic alert system that encompassed all volcanoes in New Zealand. The newly introduced volcano alert system received its first significant test with eruptions at Ruapehu volcano from December 1994-April 1995; we learnt some important lessons that highlighted several operational problems with the system. A revised system was introduced in August 1995 by the Ministry. On 18 September 1995, a major episode of eruptive activity commenced from Crater Lake, Mt Ruapehu with large explosions expelling the crater lake, producing lahars through ski fields and an eruption plume over 10 km high; activity continued for weeks, testing the revised system. The revised volcano alert system is based on six levels and has two separate schemes that clearly differentiate between frequently active volcanoes and reawakening activity at a dormant volcanic centre. The system provides an indication of eruptive status and is not intended to be predictive. This revised system has been effectively used during the 1995 and 1996 eruption episodes at Ruapehu and during recent eruptions at White Island (1998-2001). The introduction of a volcano alert level system has produced a uniform platform for responding agencies like central and local government, critical industries/services, aviation and the public to focus their response on. Based on experiences with the Ruapehu eruptions, volcano contingency planning now uses the alert levels as the basic building block for that process. This presentation will outline aspects of the recent eruptions, the interaction with the alert levels and comment on our experiences.

STATUS OF MONITORING ACTIVE VOLCANOES OF THE KURILE ISLANDS: PRESENT AND FUTURE

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Abstract

Important international air routes from Asia to North America are located immediately above and to east of the Kurile Islands. There are thirty six volcanoes within the Kurile Island chain which are considered to be active, explosive, and capable of sending volcanic ash to altitudes used by commercial airliners. The remoteness and the lack of communication links hinder the development of the ground-based monitoring of the active volcanoes of the Kuriles. Therefore, the efficient use of satellite imagery and coordinated multi agency efforts in response to volcanic events are required to reduce the risk for aviation.

Part of the "Pacific Rim of Fire", the 1250-km-long chain of Kurile Islands extends from Kamchatka Peninsula, Russia to Hokkaido Island, Japan. It consists of 68 volcanic centers, among which 36 are considered to be active, i.e. have records of historic eruptive activities (Figure 1). On average, large eruptions (VEI 4) have occurred in the Kuriles every 33 years; moderate-large (VEI 3) eruptions every 22 years; moderate eruptions (VEI 2) every 11 years; and small eruptions (VEI 1) every 1-5 years. Sixty eruptions were recorded in the Kuriles during the 20th century, among which the most significant were the eruptions of Tiatia, Grozny, Sarychev, Severgin, Raikoke, Ebeko, and Alaid (Gorshkov, 1967; Simkin & Siebert, 1994). The most recent examples include the eruption of Chikurachki volcano in April-June 2003 and the eruption of Chirinkotan volcano in July 2004. Eruptions are typically explosive and capable of sending volcanic ash to an altitude of 11 km (36,000 ft) and higher, thus posing a potential danger to aviation.

Although the population of the Kuriles is quite sparse, there are several permanent settlements on the southern islands of Kunashir, Iturup and Shikotan, as well as on the northern islands of Paramushir and Shumshu. With the exception of the settlement on the Shikotan Island, all others are located in the vicinity of active volcanoes, and eruptions may also cause a significant impact on a population and infrastructure of the settlements.

The most reliable method of volcano monitoring includes the use of ground-based seismic networks providing real-time data on the seismicity beneath active volcanoes. An increase in seismicity may be used as an early warning of an eruption. Unfortunately, there are no permanent seismic networks in the Kuriles. At present, there are only four single component seismic stations in the entire Kurile arc (on the flank of the Alaid volcano, in Kurilsk, Yuzhno-Kurilsk, and Severo-Kurilsk settlements). These stations provide rudimentary seismic data for a few volcanoes, whereas the majority of the active volcanoes are tens to hundreds of kilometers from the nearest station. Installation of the permanent local seismic networks is expensive and feasible only for a few volcanoes which pose a threat to local communities (i.e. Tiatia, Mendeleev, Grozny, Baransky, Chirip, Ebeko, Chikurachki, and Alaid). Remoteness and the lack of communication links will likely preclude the establishment of the regular seismic monitoring (and/or ground observations) for most of the Kuriles for the next few decades.

It appears that remote sensing is the most convenient and cost-effective approach to regular volcano monitoring of the Kuriles. At present, two major sources of the satellite data are used by our group in daily observations: (1) AVHRR data from the NOAA series of polar orbiters and (2) MODIS data from Terra and Aqua satellites.

From 1995 to 2000, AVHRR data from NOAA-12 and NOAA-14 satellites have been acquired locally by the Institute of Marine Geology and Geophysics (IMGG) using the "ScanEx" receiving station made by the Research & Development Center ScanEx, Moscow (http://www.scanex.ru). Although there were a few confirmed small eruptive events during this period of observation the low spatial resolution of AVHRR imagery did not allow their detection. For instance, according to visual observations by on site observers a phreatic eruption of Kudriavy volcano on October 7, 1999 produced a small volcanic ash cloud, which reached an elevation of 1000 meters above sea level. The temperature of a small, hydrothermally heated area at the volcano reached 30°C with the temperatures of emissions from individual fumaroles exceeding 900°C. This activity was not detectable in either the visual, or infrared bands of AVHRR imagery. Meanwhile, the larger scale ash producing eruptive events in the neighboring Kamchatka have been reliably detected and reported to our Kamchatkan colleagues, e.g. 1995 eruption of Bezymianny (Abdurakhmanov et al. (2001).

Since 2001 MODIS data have been acquired by the DalInformGeoCenter of the Ministry of Natural Resources of Russia in Yuzhno-Sakhalinsk using the "UniScan" ground receiving station made by the aforementioned R&DC ScanEx. Compared to AVHRR, MODIS data has significantly improved spectral and spatial resolutions, i.e. 36 channels in visual, NIR and IR spectrums with 250, 500 and 1000 meter resolutions, respectively. Since the launch of Aqua satellite in 2002, we have been able to acquire two swaths daily for the Kuriles. The entire station mask covers the area from the Arctic regions to Taiwan Island and from the Anadyr Bay to the Western Siberia (Figure 2). In 2003, the DalInformGeoCenter resumed the acquisition of NOAA AVHRR data. At present, more than twenty two swaths are received daily for the Kuriles from NOAA-12, 14, 15, 16, and 17 satellites. Our monitoring capabilities will improve following the anticipated upgrade of the receiving station by summer 2004, which will allow acquisition of MSU-E and MSU-SK data from the Meteor-3M satellite with 35-m and 250-m ground resolutions respectively.

Beginning in January 2003, our Sakhalin-based group of scientists from IMGG and DalInformGeoCenter has performed satellite observations of the Kurile Islands on a regular basis. The high spatial resolution of MODIS imagery complemented by the high temporal resolution of AVHRR data allowed us to observe the 2003 Chikurachki eruption (Figure 3) as well as the manifestations of moderate volcanic activity, i.e. steam plumes at Sinarka and Severgin volcanoes, mud flows from Tiatia volcano (Figure 4), and most recently the gas and ash plume at Chirinkotan volcano. Because of a high volume of the original data, it is first processed at the receiving stations of DalInformGeoCenter, which includes (1) acquisition of the raw data from satellites, pre-processing and calibrating, (2) georeferencing the data, (3) extracting the sub sectors covering the Kuriles (Figure 2), and (4) converting data to BMP and JPEG formats. This allows us to reduce the MODIS data to three files totaling 5 Mb in size (Table 1). As soon as processing is completed, these images are sent via email to the Volcanological Laboratory of the IMGG, where they can be interpreted by volcanologists.

Over the course of the next year, we hope to streamline this process to improve the timeliness of observation and reporting. We also intend to incorporate any information from Kurile seismic stations and ground observers and eventually distribute Kurile Volcano Information Statements to aviation and meteorological authorities for wider distribution in support of aviation safety. At present, we are still gathering financial and organizational support and working with colleagues at the Alaska Volcano Observatory and KVERT to develop reliable communication protocols.

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Table 1. MODIS bands used to produce the color-composite images used in our daily monitoring

MODIS file name (example)	Spatial resolution (meters)	Bands	Wavelength range	Image size (Mb)	Application
MOD02QKM.A0403040013r	250	1 2	620-670 nm R,B 811-876 nm G	3	Volcanic clouds
MOD02HKM.A0403040013r	500	3 5 7	469-479 nm B 1230-1250 nm G 2105-2155 nm R	1,5	Volcanic clouds and thermal anomalies
MOD021KM.A0403040013r	1000	20 22 23	3,66-3,84 um B 3,929-3,989 um G 4,020-4,080 um R	0,6	Thermal anomalies

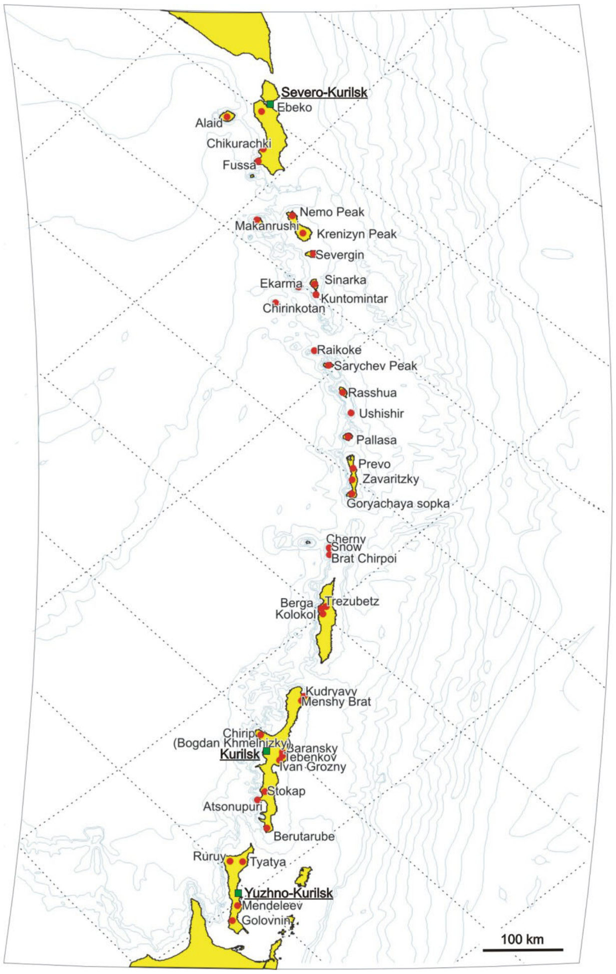

Figure 1 Map of Kurile Islands. The locations of active volcanoes are indicated by solid dots, main settlements are indicated by solid boxes with their names underlined.

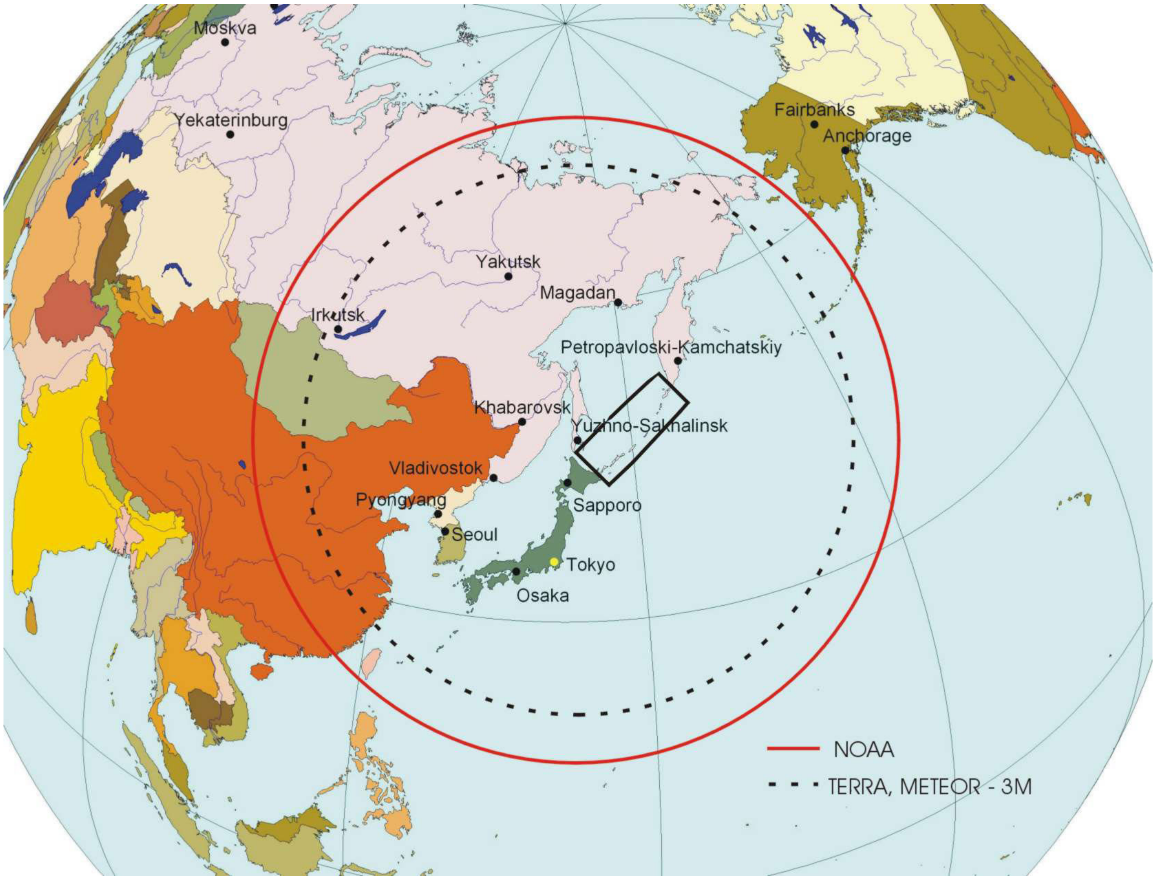

Figure 2 The DalInformGeoCenter's station mask for NOAA series polar orbiters (red circle) and for Terra, Aqua, and Meteor-3m satellites (black dotted circle). The Kuriles sub sector is shown by a black open rectangle.

Figure 3 Color-composit MODIS image of the erupting Chikurachki volcano acquired on April 22, 2003.

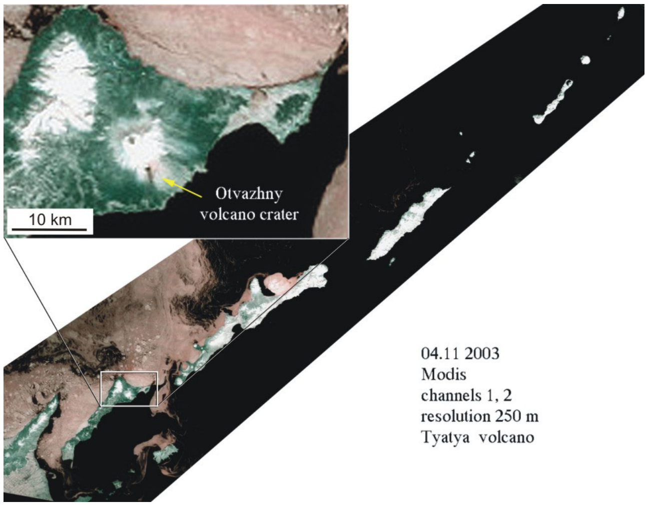

Figure 4 Color-composit MODIS image acquired on April 11, 2003 showing the mud flow from the Otvazhny crater of Tyatya volcano.

TOTAL WATER CONTENTS IN VOLCANIC ERUPTION CLOUDS AND IMPLICATIONS FOR ELECTRIFICATION AND LIGHTNING*

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1. INTRODUCTION

The fundamental role of ice particle collisions in the separation of electric charge and generation of lightning in thunderclouds is now reasonably well established (Latham, 1981; Williams, 1985; Saunders, 1995). Charge separation and lightning are also prevalent in volcanic eruptions. A recent literature survey by McNutt and Davis (2000), and its recent extension, has shown more than 150 incidents of volcanic lightning. The efficacy of the ice-based process in thunderclouds has raised the interest in the possible applicability of the same process to a class of explosive volcanic eruptions. This study is concerned with an evaluation of volcanic eruptions as atmospheric ice factories.

The behavior of water in magma within the Earth is reasonably well understood in volcanology, and the behavior of water in the atmosphere is adequately understood in meteorology. The perceived gap in understanding lies in the transition from Earth to atmosphere. This study is aimed at bridging this gap.

2. WATER CONTENT IN EXPLOSIVE MAGMA

Volatiles in magma have been well studied (Johnson et al, 1993; Wallace and Anderson, 2000; Wallace, 2004). The volatiles of greatest scientific interest have been H_2O, CO_2, and SO_2, but water is dominant in total mass by more than an order of magnitude. The solubility of water in magma is known to increase with pressure, and this physics is basic to explosive volcanism (Wilson et al, 1980). The water contents of magmas are traditionally estimated as a percent by weight of the magma. Numbers in the literature in a wide variety of studies, sampled in Table 1, are remarkably consistent.

Volcano	Water Content (Wt %)	Investigator
Bezymianni (1955)	4	Markinen (1962)
Cerro Negro	3 – 6	Roggensack et al (1997)
Fuego	1 – 6	Sisson and Layne (1993)
Mt. St. Helens	4.6 – 6.1	Carey et al (1995) Gardner et al (1995)
Pinatubo (1991)	5	Wallace and Gerlach (2004)
Vesuvius (79 AD)	3.5 – 4.7	Cornell (1987)

Table 1: Water Content of Explosive Magma

The water contents in Table 1 are large from a meteorological perspective. For example, a cubic meter of magma at depth with mean magma density 2.5 gm/m^3 and with 4% water by weight contains 100 kilograms of water. In condensed form, this is 100 liters of liquid. Following the Clausius-Clapeyron relation, this amount in vapor form is sufficient to saturate 4000 m^3 of tropical atmosphere at a temperature $T=30^oC$. At a temperature $T= -50^oC$ typical of conditions at the tops of Plinian eruption clouds, the same mass of water vapor is sufficient to ice-saturate more than 10^7 m^3 of atmosphere.

3. EXPLOSIVE ERUPTIONS AND THE RELAXATION VOLUME

Water is widely recognized as the working substance of explosive volcanic eruptions. Water dissolved in magma at depth, and with typical weight % values given in Table 1, is exsolved to vapor in bubbles as the magma ascends and the pressure declines (Wilson et al, 1980). If the vapor phase remains disconnected in the magma, typical of isolated bubble inclusions in the magma matrix and typical of explosive eruptions over subduction zones, large confined gas pressures can develop. When the highly viscous magma fractures at a

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* This work was sponsored by the National Aeronautics and Space Administration (NASA) Contract No. F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Government.

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critical porosity (Gardner et al, 1996), the stored energy is released explosively, with an ultimate relaxation of the elevated pressure to ambient atmospheric pressure P_o.

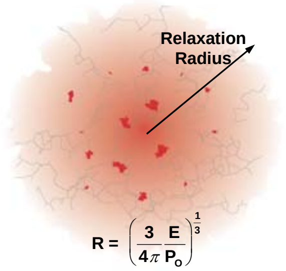
Conservation of energy for a simple spherical explosion equates the available energy E and the pressure-volume work performed against the ambient atmospheric pressure P_o:

$$E = P_o\,(4\pi R^3/3) \qquad (1)$$

A rough estimate for the explosion radius R, the so-called 'relaxation radius' (Few, 1980), is then given by:

$$R = (3E/4\pi P_o)^{1/3} \qquad (2)$$

This process is illustrated in Figure 1. Though ignored in this simple calculation, the relaxation volume will invariably be highly turbulent and involve a homogenization of the exploding material with the ambient atmosphere. Figure 1 also provides numerical estimates for different kinds of explosions. Detonations of small Chinese firecrackers have relaxation radii of centimeters, whereas energetic Fourth of July 'bombs' show relaxation smoke clouds of order meters. For a Krakatoa-level explosive eruption with estimated total energy 10^{17} joules, the relaxation radius is more than 4000 m. These scales are commensurate with the updraft widths of thunderstorm supercells (Williams, 2001), the largest and most violent form of convection known to terrestrial meteorology.



Source	E (joules)	R (m)
Chinese Firecracker	30 joules	2×10^{-2} m
Stick of Dynamite	2×10^{6} joules	0.6 m
1 kT Explosive	4.2×10^{12} joules	220 m
Krakatoa Eruption	10^{17} joules	4300 m

Energy E of explosion invested in expansion against ambient pressure P_O

$$P_O\left(\frac{4}{3}\pi R^3\right) = E$$

Figure 1: The eruption bomb based on water substance: illustration of the physical process of the relaxation radius, and some calculated values.

The relaxation radius concept was developed initially to treat the cylindrical explosions around lightning channels (Few, 1980), with the aim of estimating the dominant acoustic frequency of thunder. The dominant acoustic wavelength is of the order of the relaxation radius. For this reason, Chinese firecrackers emit in the acoustic range for human hearing and exhibit a sharp 'crack', whereas much longer wavelengths are dominant for explosions in the category of volcanic eruptions, inaudible at distance. Hence there is current interest in detecting volcanic eruptions worldwide with infrasonic methods (Bass et al, 2004).

4. THE WATER CONTENT AND TEMPERATURE IN ERUPTION CLOUDS

The relaxation volume together with estimates of magma water content and temperature enable estimates of both the average water content and temperature of eruption clouds. In both cases, it is assumed that the magma property is distributed homogeneously within the ultimate relaxation volume.

The water content is considered first. A lower bound on cloud water content is considered by assuming the ambient atmosphere to be completely dry. The favorable assumption is also made that all of the water dissolved at depth is released to the atmosphere in the explosion. This assumption is supported by the observations that the porous (water vapor) phase is connected (Gardner et al, 1996) in post-explosive tephra. Under this assumption, the mean cloud water content (MWC) is simply:

$$\mathrm{MWC} = \frac{\text{total water in magma}}{\text{relaxation volume}} \qquad (3)$$

$$= \frac{(\text{wt\%})(\text{total tephra mass})}{(E/P_o)} \qquad (4)$$

$$= \frac{(\text{wt\%})M\,P_o}{E} \qquad (5)$$

A useful reference point for total energy E is the design threshold for the Comprehensive Test Ban Treaty (CTBT) network (Sullivan, 1998): a bomb yield of 1 kiloton (1 kT = 4.2×10^{12} joules). The total energy on the scale of Volcanic Explosivity Index (VEI) (Simkin and Siebert, 1994) is not specified, but if the gravitational potential energy of the lofted tephra is 1% of the total energy, then a 1 kT event is at the low end of the VEI scale (VEI~0) where the tephra volume M ~10^4 m^3. Following Figure 1, the relaxation radius for a 1 kT total energy is ~220 meters.

If M is proportional to energy, the general assumption in considerations of VEI (Simkin and Siebert, 1994), and wt% is independent of eruption magnitude (broadly supported by the results in Table 1), then it follows that:

$$MWC = (wt\%)\ (620) \quad gm/m^3 \quad (6)$$

And for a representative value of wt% = 5 (based on Table 1):

$$MWC \sim 30\ gm/m^3 \qquad (7)$$

From a meteorological perspective, this number is again large. It exceeds by 50% the value needed to saturate air at 30°C. It exceeds by more than two orders of magnitude the value needed to saturate the upper troposphere at typical ambient temperatures. These comparisons suggest that the assumption of a dry entrained atmosphere is not a bad one, because the entrainment of a realistic moist atmosphere would not change the estimates appreciably. The magma water dominates the water budget.

Here it has been assumed that the eruption cloud will have the same temperature as the atmospheric environment in which it is mixed. Such is not strictly the case, but the cloud temperature can be estimated from similar considerations of the relaxation volume.

If the pre-explosive hot porous magma causing a volcanic explosion has temperature T_M and volume V_M, then the average temperature of the eruption cloud can be estimated from the volume mixing law:

$$V_M T_M + V_A T_A = (V_M + V_A)\ T_C \quad (8)$$

$$T_C = \frac{V_M T_M + V_A T_A}{(V_M + V_A)} \qquad (9)$$

V_M is directly related to the VEI (Simkin and Siebert, 1994) and V_A is essentially the relaxation volume. Taking values for the nominal 1 kiloton explosion, VEI = 0 case, we have $V_M = 10^4\ m^3$, $V_A = 4.2 \times 10^7\ m^3$, $T_M = 1000^oC$, $T_A = 30^oC$, we obtain a mean cloud temperature from equation (1):

$$T_C \sim 30.2^oC \qquad (10)$$

which is only 0.2 °C warmer than the atmospheric environment. This modest temperature perturbation is expected in general because $V_M << V_A$, despite the large temperature contrast between magma and atmosphere.

This result suggests that the rapidly rising cumuliform towers in explosive eruptions are caused primarily by the kinetic energy of the explosions (on the way to the relaxation radius), rather than by cloud buoyancy forces set up by cloud-atmosphere temperature contrasts. This conclusion must be considered tentative however, as it is based on a thorough mixing of the explosion emission over the entire relaxation volume. In the case of the 1980 Mt St Helens eruption, the lateral blast that initiated the eruption was clearly NOT well mixed with environmental air (Kieffer, 1981), and substantial enhancements of temperature (>100 °C) were documented. Modelling studies of eruptions (e.g., Woods and Self, 1992) show 20-30 ° C temperature contrasts between plume and environment. Furthermore, Pack et al (2000) have documented thermal anomalies from space indicative of strong temperature perturbations in Plinean eruptions, but more interpretation of these anomalies is needed. For the calculations here, we are not concerned with the short time scales of the initial blast, however, but rather the disposition of temperature and water substance at the time of 'relaxation'.

5. SUPPORTING OBSERVATIONS OF WATER SUBSTANCE IN VOLCANIC ERUPTION CLOUDS

The foregoing calculations suggest that condensation of water vapor to the liquid and solid phase should be a common occurrence in explosive volcanic eruptions. How do these simple predictions square with available observations?

Regarding the evidence for liquid water in volcanic eruptions, Clarke (1821) describes observations of the May 31, 1806 eruption of Vesuvius in Italy: "two places were deluged with a thick black rain, consisting of a species of mud filled with sulphureous particles". In the case of the more recent Mt St Helens eruption in 1980, Waitt (1981) reports, "…dark gray pisolitic mud fell from the second high-level cloud", and Thompson (2000) notes "…mud balls the size of a half-dollar fell like rain for several minutes". In tropical eruptions, wet conditions have also been documented, though in these cases the interpretation is less clear-cut, owing to the abundance of moisture and the prevalence of natural precipitating convection that may be processing atmospheric water vapor rather than magma water. Nevertheless, the reports form the tropics are worth noting in light of the predictions. In the case of the Rabaul volcano, Rose et al (1995) reported, "some of the ash fallout was very wet, and a 'rain of mud' occurred in some areas around Rabaul". For the Pinatubo (Philippines) eruptions in 1991, Oswalt et al (1996) reported: "Tephra fall continued throughout the day…varying from completely dry ash through a cement-like mud, to muddy water". Paladio-Melosantos et al (1996) document Pinatubo conditions as follows: "An area of about 2000 square kilometers was blanketed by 10 to 25 centimeters of rain-soaked tephra." Note that a typhoon accompanied the Pinatubo eruption so some of the water came from the typhoon.

In addition to this evidence for liquid water, ice has been reported in volcanic eruptions in a few instances. Owing to the lower saturation thresholds and the prevalence of subfreezing conditions in the upper troposphere, ice is expected to be the most prevalent fate of magmatic water. In the case of the Surtsey volcano in Iceland, Thorarinsson (1966) reported, "…fallout of icy pyroclasts onto local ships was described as hail showers with a grain of ash within each hailstone". Using remote sensing methods on the Rabaul volcano, Rose et al (1995) "…report the detection, using a satellite-borne infrared sensor, of >million tons of ice in the cloud". For the 1980 eruption of Mount St. Helens, Hoblitt (2000) states, "upon the arrival of the yellow cloud, ice and ice-cold mudballs began to fall…". Of the same eruption, Thompson (2000) notes: "ice-cube sized chunks of glacier ice began pelting the ground…". In the latter case, the interpretation is again fuzzy, as the ice particles could have originated from glacial ice on the volcano slope, rather than from magmatic water. Note the small number of cases cited here. Ironically, these observations, which are key for lightning studies, are not made systematically for volcanoes.

6. IMPLICATIONS FOR MICROPHYSICS IN VOLCANIC CLOUDS

The evidence for an abundance of water in all three phases in eruption clouds has important implications for the cloud microphysics occurring therein. Textor et al (2003) have already treated some of these processes in numerical simulations of volcanic clouds.

Firstly, the fine volcanic ash particles will serve as nuclei for condensation—cloud condensation nuclei for the liquid phase of water and ice nuclei for the solid phase (Mason, 1971; Hobbs, 1975). The high concentrations of such nuclei in volcanic clouds in comparison to the concentration of natural aerosol in thunderclouds will likely serve to keep the nucleated cloud droplets and ice crystals small, thereby suppressing the precipitation process (by either coalescence or by riming).

Secondly, the classical Bergeron process involving the liquid and solid phases of water is expected to be active in the mixed phase region of volcanic eruptions where the in situ temperature lies between 0^{o}C and -40^{o}C. This process will stimulate the growth of ice crystals at the expense of the liquid droplets.

Thirdly, given the presence of supercooled water droplets and ice particles, the riming process should occur for the larger, faster-falling tephra particles, with consequent accretion of ice on the surfaces of these particles, so long as the supercooled droplets are not too small. In eruptions clouds with extreme updrafts, substantially larger than those in thunderclouds, the available time for riming is expected to be shorter. Nevertheless, the collection action of nucleation and riming are expected to coat the volcanic particles with water substance in ether liquid or solid form, with considerable efficiency. This widespread coating of the volcanic debris would seem to preclude mechanisms for charge separation based on tribo-electrification of silicate mineral surfaces. At least within the mixed phase region, often half the depth of the troposphere, ice particle collisions need to be considered in the electrification process.

7. GROSS ELECTRICAL DIPOLE STRUCTURE OF VOLCANIC ERUPTIONS

A characteristic feature of ordinary thunderstorms is their gross positive dipolar structure—positive charge in upper levels and negative charge at lower levels of the ice region. A weak test of whether ice is responsible for the charge separation in volcanic eruptions is the inquiry into the gross charge structure of eruptions. The available observations summarized in Table 2, show gross positive dipole structure and so pass this weak test. The test is 'weak' because one has a 50-50 chance of being correct.

Anderson et al (1965), Surtsey volcano
"…downwind, there is a region of negative charge beneath the region of positive charge."

Cobb (1980) Mt. St. Helens volcano
"the measurements always indicated a positively charged plume"

Hobbs and Lyons (1983), Mt. St. Helens volcano
"negatively charged particles at lower altitudes, and positively charged particles higher up"

Hoblitt (1994), Redoubt volcano
"the flash polarity tended to change through time from negative to positive"

Lane and Gilbert (1992), Sakurajima volcano
"positive charges develop in the gas-rich top and negative charges in the ash-rich part of plume"

Gilbert and Lane (1994), Sakurajima volcano
"positive charges dominate at the top of the plume and negative charges dominate at the base"

McNutt and Davis (2000), Mt Spurr volcano
"thunderstorms…and eruptions…both show the same sequence of first negative, then positive…"

Table 2: Gross Dipole Polarity of Eruption Clouds

Eruptions such as Mt St. Helens in May 1980 (Cobb, 1980) grow to heights greater than the tallest thunderclouds, and given the foregoing calculations, are expected to be rich in ice in upper levels. Some of the eruption clouds documented in Table 2, however, have insufficient depth to penetrate the cold part of the troposphere, and in this case, their inclusion in the table may not be appropriate. It is however useful to consider in this context a meteorological entity composed of dry silicate minerals—the small vigorous vortices developing in desert environments called 'dust devils'. The desert conditions typically involve dry air (20% relative humidity or less), and deep boundary layers in which condensation and cloud do not occur. There can be little doubt that dust devils involve collisions between dry silicate minerals only—no liquid water and no ice is available. Electrical measurements show that the gross dipole polarity of dust devils is negative—i.e., negative charge in upper levels and positive charge at lower levels (Freier, 1960; Crozier, 1964; Ette et al, 1971). Freier (1960) refers to the dust devil dipole as an 'inverted thunderstorm'. This dust devil polarity is not consistent with any of the results in Table 2, even for the smaller eruptions (i.e., Sakurajima volcano) that are most likely NOT to contain ice.

The polarity behavior noted for cloud-to-ground lightning discharges from volcanic eruptions also bears a similarity with thunderstorms, as noted also in Table 2. Both Hoblitt (1994) and McNutt and Davis (2000) have noted a sequence of activity involving ground flashes of negative polarity followed by ground flashes with positive polarity. This behavior is characteristic of thunderclouds as they transition from their mature phase to their dissipating stage (Moore and Vonnegut, 1977; Williams and Boccippio, 1993).

8. IMPLICATIONS OF PREDICTIONS FOR THE SATELLITE-DETECTION OF ERUPTION CLOUDS

Satellite remote sensing of volcanic ash clouds has focused on the split window technique (Prata, 1989), based on the differential infrared response of dry volcanic ash. Ice is well known to show the opposite response (Prata, 1989). Ice-coated ash particles are expected to respond as ice. Given the calculations in the present study, one can expect difficulties with the split window technique in distinguishing thunderclouds from explosive volcanic eruptions. This expectation is borne out by the observations (Simpson et al, 2000; Tupper et al, 2004), and in many instances the dry ash signature will not appear strongly until the ice near the tops of eruptions clouds has sublimated to expose the dry ash.

'Dry' eruptions are referred to in the literature (Ellrod et al, 2002), but this is a relative term only. Given the water-based physics believed responsible for explosive eruptions, it is difficult to see how any eruption can be dry. Further observations of volcanic eruptions with fine time resolution from the earliest stages are needed to throw more light on this issue.

9. CONCLUSIONS

Calculations have been presented which treat the transferal of magma water in the Earth to eruptions clouds in the atmosphere. Volcanic lightning appears to be widespread, and the high water contents of magmas may be key to electrification processes. Under favorable assumptions, water in both its condensed phases is expected to be abundant in large Plinean eruptions. Further evidence involving gross electrical structure and lightning behavior is identified for a fundamental role for ice and lightning production in large eruptions. However, basic information on water and ice contents in volcanic plumes is poorly known. Instrumental electrical data and direct sampling of the water contents of ash columns and adjacent atmosphere are needed for at least a few case studies.

REFERENCES

The page limitation for this submission did not allow inclusion of references. These will be supplied on request from earlew@ll.mit.edu or steve@giseis.alaska.edu.

ACKNOWLEDGEMENTS

We appreciate discussions and correspondence on these issues with Marcia Baker, Gary Ellrod, Gerald Ernst, John Ewert, Fred Frey, Jennie Gilbert, Tim Grove, Marianne Guffanti, Paul Herzegh, Peter Hobbs, Rick Hoblitt, Patricia Mothes, Chris Newhall, Scott Oswalt, Dee Pack, Alex Proussevitch, Carl Rice, Bill Rose, Danny Rosenfeld, Tom Shaw, Lee Siebert, Tom Simkin, Inna Sofonova, Edna Sugihara, Christiane Textor, Andrew Tupper, Paul Wallace, Richard Waitt, Mark Weber and Rick Wunderman.

This research was supported by FAA's Oceanic Weather Program and by the NASA program on Advanced Satellite Aviation Products. We acknowledge Gloria Kulesa, Pete Kirchoffer, and John Murray for their support.

We thank Cynthia Woods and Nancy Bonanno for their kind assistance in the processing of the manuscript.