and volcanically disturbed stratospheric aerosols. The interactive evolution and climate effects of the aerosol from Mt. Pinatubo and from a prehistoric strong eruption in northern midlatitudes (Laacher See) will demonstrate the effect of the volcanic setting on the evolution of the aerosol cloud. Simulations of physicochemical processes in a volcanic eruption plume with the ATHAM model show the effect of environmental and volcanic conditions on the injection of volcanic gases($H_2O$, $SO_2$, $H_2S$, HCl, HBr) into the stratosphere.

### U31A-10 1145h INVITED

### Depletion of the Ozone Layer Following the Pinatubo Eruption: A Case Study for Ozone/Chlorofluorocarbon/Aerosol Chemistry

Susan Solomon (3034973483; solomon@al.noaa.gov)

NOAA Aeronomy Laboratory, 325 Broadway, Boulder, CO 80305, United States

The abundance of stratospheric ozone decreased substantially over much of the globe following the eruption of Mt. Pinatubo. This spectacular eruption provided direct evidence for chemical perturbations to the reactive nitrogen and chlorine families and hence to ozone loss rates. This talk focuses on the large seasonal and latitudinal variations in the ozone response and their relationship to chlorofluorocarbon chemistry. Finally, the recovery of the stratosphere following the eruption is as important as the depletion, and recent observations of the ozone layer and its relationship to stratospheric aerosols will also be shown to demonstrate the key role of chlorine/aerosol interactions in modifying the state of the stratospheric ozone layer.

## U32A MC: Hall D Wednesday 1330h

## Ten Years of Science From the 1991 Mount Pinatubo Volcano Eruption II

*Presiding:* **A Robock,** Rutgers University**; C Newhall,** USGS**; J Power,** USGS

### U32A-0001 1330h POSTER

### Distal Volcano-Tectonic Earthquakes (DVT's): Diagnosis and use in Eruption Forecasting

Randall A White[1] (650-329-4746; rwhite@usgs.gov)

John A. Power[2] (907-786-7426; jpower@usgs.gov)

[1]U.S. Geological Survey, 345 Middlefield Road, MS 910, Menlo Park, CA 94025, United States

[2]John A. Power, Alaska Volcano Observatory, USGS, 4200 University Dr, Anchorage, AK 99503, United States

Volcano-tectonic earthquake swarms occurred 5-6 Km from the summit months prior to the catastrophic eruptions of Mt. Pinatubo (1991) and Nevado del Ruiz (1985). Similar earthquake swarms probably occurred beneath distal portions of Mt. St. Helens (1980), El Chichon (1982), and Soufriere Hills (1995-98) months to years prior the eruptions there. Thus these Distal Volcano-Tectonic (DVT) earthquakes were probably the longest-term precursors to those eruptions. Based on close correlation with observed volcanic activity, we show that DVT's result from magma intrusion. Although DVTs are brittle-failure earthquakes along faults, they are generally distinguishable from tectonic sequences by clustering features, most notably a slowly increasing to roughly constant moment release rate. Total seismic moments for DVT swarms appear constrained by magma viscosity, with the largest moments associated with basalts. DVT swarms occur from $<3$ to $>30$ Km from summits of volcanoes. Maximum depths increase roughly as the distance out to 10 km then gradually level off, as do depths to the brittle-ductile transition near active volcanoes.

We interpret DVTs as resulting from injection of magmatic fluids into closed aquifers near the base of the brittle zone, over-pressurizing the aquifers out several to many kilometers horizontally. The overpressure may trigger faulting in areas where the intruding magma increased the static stress. We show that the DVT moment rate is proportional to the fluid injection rate and is apparently delayed by only minutes to tens of minutes depending on distance, owing to the rapid hydraulic transmission of pore-pressures. Thus DVT earthquake swarms can provide early warning for major eruptions while possibly providing constraints in near-real time on magma viscosity, depth and ascent rate during intrusion.

### U32A-0002 1330h INVITED POSTER

### Precise Correlation-Based Phase Repicking of Pinatubo Pre-Eruption Seismicity Illuminates Families of Repeating Earthquakes and a Refined Image of Precursory Hypocenter Locations.

Charlotte A. Rowe[1] (608-262-5567; char@geology.wisc.edu)

Clifford H. Thurber[1] (608-262-6027; clifft@geology.wisc.edu)

John A. Power[2] (907-786-7426; jpower@usgs.gov)

[1]University of Wisconsin, Department of Geology and Geophysics, 1215 W. Dayton St., Madison, WI 53706, United States

[2]Alaska Volcano Observatory, U.S. Geological Survey, 4200 University Drive, Anchorage, AK 99508, United States

We applied waveform cross-correlation and hierarchical clustering methods to volcanic seismicity recorded at Mount Pinatubo between 1 May and 14 June, 1991, identifying 155 clusters of up to 50 similar earthquakes each. Relative corrections of initial P-wave picks were as large as 0.563 s within similar event families, although the mean adjustment at our master station was only 0.04 s, with a standard deviation of 0.05 s. Final, absolute picks were obtained by applying an Akaike Information Criteria autopicker to stacks of the aligned waveforms within each cluster. We demonstrate enhanced phase identification for noisy arrivals by application of the cross-correlation, clustering and stacking strategy, and we show refined hypocenter locations following the automatic phase repicking.

Station PIE (6 km ENE of the summit) was selected as our master station because of its longevity and high signal quality. Waveforms for brittle-failure events display great similarity at PIE for much of the activity during May, 1991. Over 80% of the picked seismograms at PIE recorded before 3 June fall into clusters originating some 5 km northwest of the crater. Consistent waveforms at this and other stations suggest similarity in mechanism; however, clear reversals in P-wave polarity within these families at station PPO ( 5 km NNW of the summit) indicate near-nodal arrivals at this station and my help to constrain focal mechanisms. Families of shallow volcano-tectonic (VT) events beneath the summit begin to dominate on 3 June. Long-period events, mixed with continued shallow VT events beneath the summit, begin to dominate the digital record at PIE from 12 to 14 June, when correlatable signals ceased prior to the station's demise in the 15 June cataclysmic eruption.

### U32A-0003 1330h POSTER

### Spatial Variations in the Frequency-Magnitude Distribution of Earthquakes at Mount Pinatubo Volcano.

John J Sanchez[1] (907-474-7309; jjalaska@giseis.alaska.edu)

Stephen R McNutt[1] (907-474-7131; steve@giseis.alaska.edu)

Max Wyss[1] (907-474-5529; max@giseis.alaska.edu)

John A Power[2] (907-786-7426; jpower@usgs.gov)

[1]Geophysical Institute, University of Alaska Fairbanks, 903 N. Koyukuk Drive, Fairbanks, AK 99775, United States

[2]Alaska Volcano Observatory, U.S. Geological Survey, Anchorage, Alaska, 4200 University Drive, Anchorage, AK 99508, United States

The frequency-magnitude distribution of earthquakes measured by the b-value is mapped in 3 dimensions at Mount Pinatubo, Philippines, down to a depth of 6 km below the summit. We analyzed 1892 well-located earthquakes with magnitudes ML $>=1.4$, recorded from May 7 through August 7 1991, and used both the weighted least squares and maximum likelihood methods.

With the weighted least squares method, we found that generally b-values are higher than normal (b=1.0), with values between b=1.1 and b=3.6. The computed b-values are lower in the areas adjacent to the vent and directly underneath it, whereas high b-values are found in patches located E-SE, and NW of the vent. Two prominent regions of anomalously high b-values ($b>2.4$) are resolved, the first is located roughly 3 km E-SE of the vent, at depths between 3 and 7 km; the second is located roughly 3 km NW of the summit, at depths between 3 and 8 km. There is also some indication of a deeper high b-value anomaly NE of the summit at depths between 12 and 16 km. The statistical differences between selected regions of low and high b-values are established at the 99% confidence level.

The b-value results agree fairly well spatially with those derived from earlier P-wave tomographic studies. No significant changes in b-values were found as a function of time. We speculate that the high b-value anomalies around Mount Pinatubo are regions of increased crack density, or alternatively high pore pressure, related to the presence of magma bodies nearby.

### U32A-0004 1330h POSTER

### Evidence for the Co-Ignimbrite Origin of the 15 June 1991 Mt. Pinatubo Climactic Eruption Ashcloud.

Sebastien Dartevelle[1] (906-487-1782; sdarteve@mtu.edu)

Gerald Ernst[2] (gerald.j.ernst@bristol.ac.uk)

John Stix[3] (stix@eps.mcgill.ca)

Alain Bernard[4] (abernard@ulb.ac.be)

[1]Michigan technological university, Dept. Geological Engineering, 630 Dow Env. Sc. and Eng. Building, 1400 Townsend Drive, Houghton, MI 49931, United States

[2]University of Bristol, CEGF, Dept. Earth Sciences, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, United Kingdom

[3]McGill University, Dept. Earth and Planetary Sciences, 3450 University Street, Montreal, Qc H3A 2A7, Canada

[4]Universite Libre de bruxelles, BRUEGEL, CP 160/02, 50 Av. Roosevelt, Brussels B-1050, Belgium

The Mt. Pinatubo climactic eruption on the afternoon of 15 June 1991 was one of the largest of the 20th century. The eruption has been widely studied, but the origin of the giant ashcloud remains unclear. It is most commonly assumed to have a plinian origin, but field observations indicated unusual features. To evaluate the origin of the Pinatubo climactic ashcloud, we measured new grain-size parameters of our own fall samples collected around Pinatubo, of the PHIVOLCS data, and of distal deep-sea ash samples. In addition, we systematically compared the Pinatubo fallout deposit with the unambiguously plinian 1875 Askja ashfall (Iceland) and with an integrated grain-size dataset of 600 pyroclastic deposits from many eruptive styles (plinian, subplinian, strombolian) and representing the main types of pyroclastic activity (surge, flow, fall and co-ignimbrite fall). The co-ignimbrite fallout deposits are from the 1980 Mt. St. Helens (MSH) and from the 1815 Tambora eruptions.

Instead of using the classical Phi-scale and related grain-size parameters, we calculate grain-size parameters of arithmetic mean (m) and standard deviation (e.g., sorting, m), both defined in the metric scale. We also calculate the bulk specific surface area (SSA) which is the total surface area of a set of grains to their total volume (1/m). We also introduce two new grain-size ratios: (i) SSA/Mean (1/m2) and (ii) Mean/Sorting (dimensionless). The first ratio, SSA/Mean, distinguishes coarse-grained from fine-grained deposits. The second ratio, Mean/Sorting, discriminates gravity-controlled flow from pure plinian-subplinian-strombolian fall deposits. In this SSA/Mean vs. Mean/Sorting plot, co-ignimbrite fallout deposits plot in the surge domain, not in the plinian fallout domain.

Using this approach, we demonstrate that the Pinatubo ashcloud deposit is unusually rich in breathable fine ash (less than 10 micrometers, PM10), from 5-11 wt% of PM10 in Mt. Pinatubo vicinity up to 26 wt% beyond 300km from the vent. By contrast, the plinian Askja deposit shows no PM10 up to 145 km from vent. Furthermore, the variations of metric-mean, metric-sorting and SSA versus distance differ considerably for the Askja and the Pinatubo fall deposits. In the Pinatubo case, grain-size variations with distance are more gradual, whereas they are rapid for the Askja plinian fall deposit. For instance, within 50km of source, SSA increases 100-fold for Askja, whereas it only doubles for Pinatubo. In addition, SSA of most Pinatubo proximal deposits are about 2-3 orders of magnitude higher than most proximal Askja deposits. Pinatubo metric-mean values are an order of magnitude smaller than those for Askja. All the available data indicate that the Pinatubo giant ashcloud deposited dominantly homogeneous fine ash enriched in PM10, while the Askja plinian cloud deposited coarser and heterogeneous fallouts. Last but not least, in the SSA/Mean vs. Mean/Sorting diagram, Pinatubo fallout deposits systematically plot in the co-ignimbrite domain, away from the plinian fallout domain.

From our new grain-size approach and from all the available grain-size data, we conclude that the Pinatubo climactic eruption ashcloud was mostly of co-ignimbrite origin.

## U32A-0005 1330h INVITED POSTER

### Vent-derived and Deposit-derived Pyroclastic Flow Generation and Emplacement of the 1991 Pinatubo Ignimbrite Sheet

Stephen Self[1] (Stephen.Self@open.ac.uk)

Ronnie C. Torres[2,3] (torres@higp.hawaii.edu)

[1]Dept. of Earth Sciences, Open University, Walton Hall, Milton Keynes MK76AA, United Kingdom

[2]HIGP/SOEST, University of Hawaii at Manoa, 2525 Correa Rd., Honolulu 96822, United States

[3]PHIVOLCS, C.P. Garcia St., Quezon City, Philippines

The climactic phase of the 1991 Mount Pinatubo eruption consisted of plinian activity and large-scale generation of pyroclastic flows, which were coeval for most of the 3.5 hours duration of the climax. The plinian column was maintained above 30 km high throughout this period, forming layer C1, while spawning dilute pyroclastic flows fed by partial collapses from the lower buoyant column. About an hour after onset of the plinian phase, fountaining at the base of the column generated higher-particle-concentration pyroclastic flows that flowed at an average encroachment velocity of 5-6 m/s. Simultaneous plinian fallout and co-ignimbrite ash deposition formed the C2 fall layer while transport and emplacement of fan-building flows were occurring.

Both dilute column-generated and denser fountain-generated pyroclastic flows were the sources of the vent-derived ignimbrite. Fan-building vent-derived pyroclastic flows ponded on the low-lying areas, but were unable to surmount high topographic barriers in the proximal region. Meanwhile, widespread surge deposits veneered the uplands and interfluves, and were laterally contiguous with the stratified horizons in valley-ponded ignimbrite sequence. Gravitational instability and the loose, poorly consolidated nature of the freshly emplaced ignimbrite fan sequence yielded deposit-derived pyroclastic flows. Deposit-derived flows, some up to 3 km long, occurred at Pinatubo for more than 5 years after the June 15, 1991, eruption and left prominent avalanche escarpments at their origin. Penecontemporaneous deposit-derived flows also probably occurred as indicated by buried headscarps that can be recognized at the early post-eruption stages of the ignimbrite landscape and by the change in slope between the fan and lower valley ignimbrite sequences.

The Pinatubo ignimbrite sheet represents a continuum of pyroclastic sedimentation that began during the climactic eruption on June 15, 1991 and episodically continued with decreasing frequency for several years after the eruption. Apparently, deposit-derived flows are a common mechanism for redistributing ignimbrite after initial deposition and present post-eruption hazards that should be anticipated after ignimbrite-producing events.

## U32A-0006 1330h POSTER

### Pinatubo Eruption Dynamics Inferred from Equilibrium and Kinetics Experiments

Julia E Hammer (401-863-1383; jhammer@brown.edu)

Brown University, Dept. Geological Sciences Brown University Box 1846, Providence, RI 02912, United States

The 1991 eruption of Mt. Pinatubo included dome growth, four vertical eruptions, multiple surge-producing collapsing fountains, a 9 hour climactic plinian event, caldera collapse and subsequent dome emplacement. In order to provide a more accurate picture of magma storage conditions prior to ascent and conduit processes during ascent, we conducted (1) a phase equilibria study of dacite magma storage conditions and (2) a series of decompression-induced crystallization experiments. Previous studies of the phenocryst-rich dacite erupted during the climactic phase of the 1991 Pinatubo eruption indicated that prior to eruption the magma was oxidized (NNO+1.7 $\pm$0.2), fairly cool (780 $\pm 10^{\circ}$C), and saturated with an $H_2O$-rich volatile phase at a total pressure of $\sim$220 $\pm$50 MPa. New phase equilibrium experiments at total pressures of 220 - 150 MPa (all vapor saturated with an $H_2O$-rich fluid) define the isothermal liquid line of descent for multisaturated Pinatubo dacite as a function of $P_{H2O}$. Experimental matrix glass compositions at 160 and 170 MPa bracket the natural compositions, indicating chemical equilibration occurred 50 MPa lower (or 2.8 km higher in the crust) than the storage level identified from melt inclusion volatile contents and Al-in-hornblende geobarometry (220 MPa).

Decompression experiments with natural dacite were conducted to explore parameters controlling the kinetics of crystal nucleation with the goal of reproducing the microlite textures observed in erupted material from the pre-climactic events. Rapid isothermal decompressions of $H_2O$-saturated dacite from 170 MPa to 10 MPa failed to generate the high crystal number densities observed in the natural rocks. Several methods were attempted to boost nucleation rates, including simultaneous heating or cooling with decompression, but feldspar nucleation rates were consistently at least 3 orders of magnitude lower than in nature. Only by introducing an intermediate decompression step were high rates of crystal nucleation obtained. We interpret this stage as a necessary interval of melt reorganization that effectively "primes" it for a massive nucleation event upon final decompression.

## U32A-0007 1330h POSTER

### High Temperature Magmatic Vapor Deposition of Anhydrite Prior to the 15 June 1991 Eruption of Mount Pinatubo

Ryan T. Jakubowski[1,2] (jakubr@dnr.state.wi.us)

John Fournelle[1] (johnf@geology.wisc.edu)

Sue Welch[1] (swelch@geology.wisc.edu)

R.J. Swope[3] (rjswope@iupui.edu)

Patrick Camus[4] (pcamus@thermonoran.com)

[1]Department of Geology and Geophysics, University of Wisconsin-Madison, 1215 W. Dayton St., Madison, WI 53706, United States

[2]Present address: Wisconsin Department of Natural Resources, Bureau of Waste Management, 101 S. Webster St., Box 7921, Madison, WI 53707-7921, United States

[3]Department of Geology, Indiana University-Purdue University-Indianapolis, 723 W. Michigan St., Indianapolis, IN 46202, United States

[4]Thermo NORAN, 2551 W. Beltline Hwy., Middleton, WI 53562, United States

Mount Pinatubo's 15 June 1991 climactic eruption initiated a multi-disciplinary investigation that integrated many fields within the earth sciences. Our study followed up on one aspect of the sulfur budget analysis that was not previously studied in detail, an analysis of the anhydrite ($CaSO_4$) phenocrysts (Jakubowski et al., accepted, Am. Min). Anhydrite phenocrysts were separated from two 15 June pumice deposits and were examined by scanning electron microscope. Observations documented include micron-sized and smaller pyramids and lesser numbers of etch pits on anhydrite surfaces.

Electron backscatter diffraction patterns conclusively indicate that the pyramidal surface growths are indeed orthorhombic anhydrite and not another calcium sulfate phase. Single crystal X-ray diffraction patterns also indicate that the phenocrysts themselves are orthorhombic anhydrite. This suggests at least a portion of the Pinatubo anhydrite phenocrysts provided substrates for nucleation and epitaxial growth of anhydrite from a water-rich magmatic vapor phase. This is, we suggest, high temperature magmatic vapor deposition (MVD) of anhydrite, a previously unrecognized magmatic process. The anhydrite pyramids closely resemble products of chemical vapor deposition of metals and ceramics. This supports the suggestions of Pallister et al. (1996) and Pasteris et al. (1996) that (at least) a portion of the anhydrite phenocrysts precipitated from a separate fluid phase in the magma, rather from the melt.

We modeled the homogenous nucleation of anhydrite from a Pinatubo $H_2O$-$CO_2$-$SO_2$-rich vapor (Gerlach et al., 1996) at 500 bars and NNO+1.7, using the SOLVGAS program. If the gas had $>10^{-9}$ mol% Ca (and 4 mol% $SO_2$), anhydrite would have precipitated at $\sim$780$^{\circ}$C. An isothermal drop in pressure would cause anhydrite dissolution, consistent with a small number of etch pits on some anhydrite phenocrysts and pyramids. The small size of the pyramids suggests that their vapor deposition immediately preceded the 15 June 1991 climactic eruption. Our examination of anhydrite phenocrysts found an intimate association with apatite and magnetite (inclusions), which has never been explained.

We suggest that magmatic vapor deposition of anhydrite may be a common phenomenon and its occurrence may assist scientists in better interpreting the sulfur budget at arc volcanoes. However, samples must be collected immediately after eruption, the anhydrite separated, and examined by SEM. Evidence of anhydrite MVD could be used as an indicator of a pre-eruptive gas phase source for excess sulfur vented during explosive eruptions.

## U32A-0008 1330h POSTER

### A re-evaluation of the 1991 Pinatubo $SO_2$ emission using TOMS

Song Guo[1] (906-487-3098; sguo@mtu.edu)

Gregg J. S. Bluth[1] (906-487-3554; gbluth@mtu.edu)

Iain Matthew Watson[1] (906-487-2045; watson@mtu.edu)

William I Rose[1] (906-487-2367; raman@mtu.edu)

[1]Michigan Technological University, Geo. Enggr. and Sci. Dept 1400 Townsend Dr., Houghton, MI 49931, United States

Explosive volcanic eruptions influence the atmosphere and environment from days to years depending on the amount of sulfur species and ash erupted. Large volcanic eruptions, such as Pinatubo, have much stronger effects on the atmospheric chemistry and global climate change since huge amounts of $SO_2$ are directly erupted into the stratosphere. The June 1991 Pinatubo eruption is the largest eruption of the satellite era, and accurate retrievals of emitted sulfur and ash species are therefore crucial in understanding its atmospheric impacts. The Total Ozone Mapping Spectrometer (TOMS) is routinely used to map and quantify $SO_2$ for volcanic eruptions. Column amounts of $SO_2$ and aerosol indices (AI, which represents the ash and aerosol amount qualitatively) for each pixel can be retrieved and then a total mass of $SO_2$ within the volcanic cloud can be calculated. The $SO_2$ cloud from the Pinatubo eruption has been studied by Bluth et al. (GRL, Vol. 19, No. 2, 1992). Uncertainties from missing data, saturation, gaps and overlap between neighboring pixels may bring errors in the estimation of initially erupted $SO_2$ amounts and $SO_2$ removal rate. An iterative $SO_2$ algorithm, which was developed by scientists from NASA, is used for getting a more accurate result of total column $SO_2$ in each pixel. The gap and overlap problem of neighboring pixels is addressed by resampling the data into grids using a nearest neighbor method. Missing data problems in the TOMS datasets due to periodic transmission interruptions are treated by a variety of interpolation models. We have been analyzing the accuracy of a variety of reconstruction methods. The goals of this project include revised tonnage values for daily cloud images; this information will be used to derive a more accurate emitted sulfur dioxide mass and removal rate. Studies of gas and particle separation in the TOMS UV dataset will be supplemented by and compared to IR data analyses.

## U32A-0009 1330h POSTER

### Satellite Observations of the Mt. Pinatubo Stratospheric Cloud

Patrick Hamill[1] (650-604-1710; hamill@sky.arc.nasa.gov)

Howard Houben[2] (650-604-3381; houben@humbabe.arc.nasa.gov)

Robert W. Bergstrom[3] (650-604-6261; bergstro@sky.arc.nasa.gov)

[1]Physics Department, San Jose State University, San Jose, CA 95192-0106, United States

[2]Space Physics Research Institute, 572 Hyannis Drive, Sunnyvale, CA 94087-1315, United States

[3]Bay Area Environmental Research Institute, 3430 Noriega Street, San Francisco, CA 94122, United States

The Mt. Pinatubo eruption of 1991 was one of the largest climatically significant volcanic eruptions of the 20th century. The resulting stratospheric cloud of sulfuric acid aerosol was almost entirely undisturbed by other eruptions over a ten-year period. During this time, the cloud was constantly monitored by a number of satellite missions. It thus presents an excellent case study to determine the intensity and duration of the global climatic effects of volcanoes. Of particular interest are the processes by which the stratosphere aerosol returns to its pre-volcanic state and the nature of that aerosol in the absence of large eruptions. Monthly and zonally averaged aerosol extinction measurements at five wavelengths (0.5 and 1.0 micrometers, measured by the Stratospheric Aerosol and Gas Experiment [SAGE II] on ERBS; 2.5, 3.6, and 5.3 micrometers, measured by the Halogen Occultation Experiment [HALOE] on UARS) have been combined in a two-dimensional (latitude-height) aerosol transport model, using data assimilation techniques. The results specify the time-varying aerosol size distribution, the stratospheric residual mean meridional circulation, and the background (non-volcanic) source of sulfuric acid as functions of altitude, latitude, and time.

## U32A-0010 1330h POSTER

### Did the Eruption of the Mt. Pinatubo Volcano Affect Cirrus Properties?

William Rossow[1]

Zhengzhao Luo[2] (212-678-5643; zl47@columbia.edu)

Toshiro Inoue[3]

Claudia Stubenrauch[4]

[1]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, United States

[2]Columbia University, 2880 Broadway, Rm 608, New York, NY 10025, United States

[3]Meteorological Research Institute of Japan, 1-1 Nagamine, Tsukuba, Ibaraki 305, Japan

[4]Laboratorie de Meteorologie Dynamique du CNRS, Ecole Polytechnique, Palaiseau, France

Some observations suggest that the volcanic aerosols produced by the Mt. Pinatubo eruption may have altered cirrus properties. We look for evidence that such modification of cirrus is extensive enough to be climatically significant by comparing three satellite-based cirrus datasets produced by the ISCCP analysis, the split-window analysis, and 3I analysis. Since the former two have not been compared in detail before, we conduct such a comparison here. When applied to AVHRR data, both the ISCCP and split-window analyses identify about 0.2 to 0.3 cirrus cloud amount in tropical latitudes; however, there are detailed differences of classification for about half of these clouds. The discrepancies are attributed to the simplified assumptions made by both methods. The latter two datasets are derived from infrared radiances, so they are much less sensitive to volcanic aerosols than the ISCCP analysis. After the Mt. Pinatubo eruption, the ISCCP results indicate a dramatic decrease of thin cirrus (cloud top pressure less than 440 mb and visible optical thickness less than 1.3) over ocean, accompanied by a comparable increase of altocumulus and cumulus clouds; over land, there are no significant changes. In contrast, results from the split-window and 3I analyses show little change in thin cirrus amount over either ocean or land that is associated with the volcanic eruption. The ISCCP results can, therefore, be understood as a misclassification of thin cirrus because the additional reflected sunlight by the volcanic aerosol makes the cirrus clouds appear to be optically thicker. Examination of the split-window signature and the infrared emissivities from 3I show no significant change in infrared emissivity (or optical thickness). These results indicate that the Mt. Pinatubo volcanic aerosol did not have a significant systematic effect on tropical cirrus properties, but rather produced only temporary, local effects. Hence, these results indicate that there was no significant climate feedback produced by aerosol-cirrus-radiative interactions.

## U32A-0011 1330h POSTER

### The Effects of Aerosol from Pinatubo on Remotely Sensed Global Vegetation Measurement

Liping Di[1] (301-794-5488; lpd@rattler.gsfc.nasa.gov)

Meixia Deng[1] (301-794-5091; mxd@heineken.gsfc.nasa.gov)

[1]George Mason University, 4400 University Drive, MSN 5C3, Fairfax, VA 22030, United States

The Normalized Difference Vegetation Index (NDVI) is one of important indicators of vegetation activities on land surface. There are several global NDVI time-series products available. The most popular one with longest temporal coverage is the NOAA/NASA Pathfinder AVHRR Land product (PAL) available from 1981 to 1999 with 8-km spatial resolution and 10-day time interval. The NDVI in PAL was calculated from data collected by AVHRR instruments on four satellites, NOAA-7 from 1981 to 1985, NOAA-9 from 1985 to 1988, NOAA-11 from 1989 to 1994, and NOAA-14 from 1995 to 1999. Studies on PAL or other similar products from AVHRR showed the global NDVI increases linearly with the aging of the NOAA satellites and drops when a new satellite replaces an old one. This pattern was caused by the orbital drifting of NOAA satellites. This study found the pattern was interrupted in the year of 1991, when Mt. Pinatubo erupted, and the following two years (1992, and 1993). Based on the pattern, it was estimated that the mean values of the annual global maximum dropped 0.029, 0.066, and 0.027 NDVI units from the normal pattern for years 1991, 1992, and 1993. This study proved that the most likely cause of the NDVI drops was not the reduction of global vegetation activities during those years but the aerosol brought into the stratosphere by the eruption of Mt. Pinatubo. Since the effects of volcanic aerosols on global vegetation measurement are very large, they have to be removed from the global NDVI datasets.

## U32A-0012 1330h POSTER

### Development of Volcanic Plume Tracking Model 'PUFF' using Real-time Weather Data

Hiroshi L. Tanaka (81-298-53-4502; tanaka@atm.geo.tsukuba.ac.jp)

Institute of Geoscience University of Tsukuba, 1-1-1 Tenohdai, Tsukuba 305-8571, Japan

The purpose of the study is to develop and improve the volcanic plume tracking model so-called 'PUFF' for an arbitrary volcano in the world using high quality upper air wind data predicted by the operational weather prediction centers. The centers, which provide the upper air wind data, include Japan Meteorological Agency (JMA), National Weather Service (NWS) in the USA, and European Center for Medium-range Weather Forecasts (ECMWF). The PUFF model is developed at the computer system in the University of Tsukuba Japan using the predicted gridded point values (GPV) of wind data provided by JMA, then it is transplanted to the computer system in International Arctic Research Center (IARC) using the GPV data by NWS and/or ECMWF.

The achievement of this study includes following items: (1) Quantitative evaluation of the order of the error contained in the predicted wind field in JMA, NWS, and ECMWF. (2) Further tuning of the physical parameters such as the diffusion coefficient and fall out speed of volcanic ash in the PUFF model. (3) Expansion of the model domain from the local area near Alaska and Japan to any volcano in the world. (4) Improvement of the Graphic User Interface (GUI) to describe the 3-D perspective image of volcanic ash over topography. (5) Producing hazard maps around active or possibly active volcanos as an application of the PUFF model.

## U32A-0013 1330h POSTER

### The Pinatubo Eruption in Antarctic Snow and Its Significance to Paleoclimate Research

Jihong Cole-Dai[1] (605-688-4744; jihong_cole-dai@sdstate.edu)

Yuansheng Li[2] (yshli@sh163e.sta.net.cn)

[1]South Dakota State University, Department of Chemistry and Biochemistry SDSU Box 2202, Brookings, SD 57007, United States

[2]Polar Research Institute of China, Polar Research Institute of China 451 JinQiao Road, Pudong, Shanghai, SHA 200129, China

Records of past volcanic eruptions can be found in polar ice cores, because explosive volcanic eruptions leave acidic spikes in polar snow. Analyses of Antarctic ice cores have resulted in detailed paleovolcanic records for the past several thousand years. These records are tremendously valuable to discerning the role of volcanism in climatic variations and changes. Field studies across Antarctica have detected and confirmed the presence of the sulfuric acid fallout from the 1991 Pinatubo eruption. Chemical analyses of snow samples have determined the magnitude of the Pinatubo signal, in the form of volcanic sulfate flux, and its range of variations across the Antarctic continent. More quantitative information is known about the Pinatubo signal in Antarctic snow than about any other eruptions. These results and existing ice core records, when combined with the instrumentally determined total Pinatubo aerosol mass loading, provide an unique opportunity to estimate the atmospheric mass loadings by, and therefore the climatic impact of, past explosive eruptions found in Antarctic ice cores. Here we (1) present the quantitative evidence of the Pinatubo signal in Antarctic snow, (2) determine the spatial variability of the signal across Antarctica, and (3) analyze the quantitative relationship between the aerosol mass loading of an eruption and its signal in snow. We also attempt to calculate mass loadings of about 20 eruptions recorded in Antarctic ice cores from the past 1000 years, by using an extrapolation of the relationship between mass loading and signal magnitude in snow derived from the Pinatubo studies.

## U32A-0014 1330h POSTER

### Monitoring of Post-Eruption Hazards at Pinatubo Volcano Using Multiple Remote Sensing Data Sets

Ronnie C Torres[1,3] (torres@higp.hawaii.edu); Peter Mouginis-Mark[1] (pmm@higp.hawaii.edu); Kalpana Kallianpur[1] (kalpana@higp.hawaii.edu); Harold Garbeil[1] (harold@pgd.hawaii.edu); Stephen Self[2] (Stephen.Self@open.ac.uk); Rowena Quiambao[3] (weng@phivolcs.dost.gov.ph)

[1]HIGP/SOEST, University of Hawaii at Manoa, 2525 Correa Rd., Honolulu, HI 96822, United States

[2]Dept. of Earth Sciences, Open University, Walton Hall, Milton Keynes MK76AA, United Kingdom

[3]Philippine Institute of Volcanology and Seismology, C.P. Garcia St. Diliman, Quezon City, Philippines

Since the 1991 climatic eruption of Pinatubo, various hazards have affected the surrounding areas. The most significant of these involve the re-deposition of pyroclastic flow and fall deposits as lahars, deposit-derived pyroclastic flows, and phreatic explosion ash fall. Many of these processes occurred in areas that are inaccessible for ground observation and monitoring. A case in point is the potential hazard that currently threatens the low-lying areas along the Maraunot-Bucao river system should a significant lake breakout occur from the 1991 crater.

Sequential remote sensing (RS) data sets, which include multi-temporal ERS, SIR-C, SPOT, TOPSAR/AIRSAR, Landsat 7 and Ikonos scenes, provide an unparalleled perspective to reconstruct the sequential development of the Pinatubo landscape and map the areas of the ignimbrite sheets that are being eroded as well as the encroachment of lahar fans. Multiple acquisition using different imaging techniques over the same area yields different surface albedos that can be compared with the actual ground observation. We have utilized the ENVI software package to apply principal component analysis, image subtraction, band ratio, and density slice on these data. These analytical techniques provide measurable parameters to track down the changes in the post-eruption landscape, calculate rates of erosion and deposition, and allow hazard vulnerability prediction along the timeline establish by the series of RS data sets.

The RS-derived maps agree reasonably well with the field derived maps and provide important large-area coverage and show details that unobtainable from conventional ground-based mapping. Image subtraction between scenes yields image-difference maps that show cumulative aggradation within the lahar fans of the Pasig-Potrero River and erosion and development of the drainage systems in the upstream regions. Co-registered multi-temporal scenes can also allow changes in the settlement patterns of local population to be identified, as well as the construction and modification of the engineering structures for controlling the lahar hazards. These types of information are crucial inputs for local decision-and policy-making in volcanic hazard mitigation.

## U32A-0015 1330h POSTER

### Thirteen Years of Remote Sensing of Mt. Pinatubo, the Philippines

Peter J. Mouginis-Mark[1] ((808) 956-3147; pmm@higp.hawaii.edu)

Harold Garbeil[1]

Kalapana Kallianpur[1]

Ronnie Torres[1]

[1]Hawaii Institute of Geophysics and Planetology/SOEST, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, United States

The 1991 eruption of Mt. Pinatubo, Philippines, provides a unique opportunity to study the effects of a large eruption in part because it took place after the advent of satellite-based observations. This paper reviews the great diversity of satellite and aircraft remote sensing data that has been collected over Mt. Pinatubo in the context of interpreting the evolution of the volcano. We also show the importance of a multi-year data sets that can document the evolving problem with lahars during the first few years after the eruption, as well as the hazards that still exist due to potential water over-spills from the summit caldera more than 10 years after the eruption. Prior to 1991, only one SPOT satellite image (20 m/pixel) had been obtained in 1988 that now serves as a "bench mark" against which to measure subsequent changes in drainage basin geometry. Since the eruption, a wide diversity of remote sensing data has been obtained. Imaging radar data, providing cloud-free coverage of the whole volcano, have been collected from the ERS-1, ERS-2 and RADARSAT spacecraft between 1993 and 2001, as well as two SIR-C/X-SAR Space Shuttle flights in 1994. These radar data are particularly good for mapping changes in lahar deposits. Multiple multispectral data from SPOT, Landsat 7 and ASTER over the period 1991 - 2001 allow the re-vegetation of the volcano to be monitored at a scale of 10 - 30 m/pixel. Additional photographic images have also been obtained by Space Shuttle astronauts through-out this period. Two flights of the NASA DC-8 aircraft (in 1996 and 2000) have collected very high resolution (5 m/pixel) digital elevation data for parts of the volcano, permitting erosion in some valleys to be studied. These topographic data will soon be augmented when data are released from 2000 Shuttle Radar Topography Mission (SRTM), providing the potential for erosion rates to be determined. Most recently, a very high resolution (1 m/pixel) IKONOS image for the summit caldera and western ignimbrite fan was obtained in March 2001, allowing the hazards associated with water outflow events from the summit caldera to be assessed in great detail.

## U32A-0016 1330h POSTER

### Has Dynamic Equilibrium Been Re-established for the Fluvial Landscape on the 1991 Mt. Pinatubo Ignimbrite Sheet?

John E Bailey[1,3] (1-808-956-5960; jbailey@soest.hawaii.edu)

Stephen Self[2] (Stephen.Self@open.ac.uk)

Peter J Mouginis-Mark[3] (pmm@higp.hawaii.edu)

[1]Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu, HI 96822, United States

[2]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, United Kingdom

[3]Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii, Honolulu, HI 96822, United States

Ignimbrite forming eruptions are rare events, and here report on the first study of an actively eroding ignimbrite sheet at Mt. Pinatubo (15°N, 120.5°E) deposited on the $15^{th}$ June 1991. An important question in the evolution of ignimbrite landscapes is how long do they take to reach dynamic equilibrium. At Mt. Pinatubo, the implication is that once dynamic equilibrium is reached the magnitude of risk posed by sediment-flow-related hazards is greatly reduced. Large erosional events, which generate high volume lahars, are unlikely except in the event of a major disruption to the normal pattern of erosion. This study used three images produced by the SPOT (System Pour l'Observation de la Terre) satellite. SPOT data are in three spectral bands (0.50-0.59$\mu$m; 0.61-0.68$\mu$m; 0.79-0.89$\mu$m) with a spatial resolution of one pixel equals 20m. These were used to generate five false color RGB images of the Mt. Pinatubo region), showing the pre-eruption (April 1988), early post-eruption (December 1991) and later post-eruption (December 1994, February 1996, December 1998) landscapes. Drainage networks that developed between 1991 and 1998 were delineated using these images. Geographically we concentrated on the western side of the volcano, where approximately two-thirds of the ignimbrite was deposited in just three drainage basins; Marella, Balin-Baquero and Bucao.

The nature of the drainage networks, combined with field-based observations, suggest there are four stages in the landscape evolution of the Mt. Pinatubo ignimbrite sheet. Stage one; The emplacement of a pristine ignimbrite surface, which in-filled the pre-eruption drainages, but did not bury all the surrounding topography. Stage two; Large amounts of unstable, excess sediment were removed. Stage three; The landscape simplified towards the stable state of dynamic equilibrium. Stage four; Erosion continues but with the landscape in a state of dynamic equilibrium, thus large erosional events are unlikely.

The Horton-Strahler classification method for drainage networks was used to find bifurcation ratios that were assumed to be representative of the complexity and development of the networks in each drainage basin. Comparison of these data suggest that the Marella and Bucao drainage basins had re-established dynamic equilibrium by 1995. However, Balin-Baquero did not appear to have re-established dynamic equilibrium by 1998 (the latest SPOT image studied). The analysis for this drainage basin was then supplemented by data from NASA airborne interferometric synthetic aperture radar instrument, TOPSAR. TOPSAR provides data with information in three spatial dimensions, allowing the generation of a DEM, which shows the volume distribution of the landscape around the volcano. The concept of a hypsometric integral was used along with the DEM data and emplaced ignimbrite volume estimates made in 1991, to estimate the volume of excess sediment that needed to be removed for the Balin-Baquero basin to enter the forth stage of evolution. Our most realistic estimate is that dynamic equilibrium was re-established in 2000 ± 1 year, which is in agreement with an extrapolation of the trend shown by the bifurcation ratios and also with recent predictions made by PHIVOLCS scientists.

## U32A-0017 1330h POSTER

### Erosion Modeling of the Pyroclastic Flow Deposits From the 1991 Eruption of Mt. Pinatubo, Philippines

Arturo S. Daag[1,2] (+(632)4261468 to 79; daag@phivolcs.dost.gov.ph)

[1]Philippine Institute of Volcanology and Seismology (PHIVOLCS), C.P. Garcia Street U.P. Campus Diliman, Quezon City 1101, Philippines

[2]International Institute for Aerospace Survey and Earth Sciences (ITC), Hengelosestraat 99 P.O.Box 6, Enschede 7500 AA, Netherlands

The June 15-16 1991 eruption of Mt. Pinatubo had emplaced approximately 6km3 of sand-size pumiceous pyroclastic flow deposits that affected 8 major watersheds surrounding the volcano. These deposits attained thickness of about 200m on deep channels and remained unconsolidated, when it rains they are the main source of lahars for several years. This study focuses on the eastern watersheds namely, Sacobia-Pasig-Abacan, because it posed the greatest risk due to lahar flow hazards being the highly developed and the most populated.

In order to study and monitor the erosions of the pyroclastic flow deposits, several methods were used. Yearly direct quantification of erosions were made using multi-temporal Digital Elevation Models (DEMs), aerial photos and satellite imageries. GIS and image processing software were used to compute erosion volumes and in determining geomorphic changes. To understand the different parameters affecting the erosiveness of in-situ deposits, a portable rainfall simulator was used. Regression modeling was utilized to determine the effect of the different parameters in the erosion such as, slope, rainfall intensity, grain size and shear strength of the deposits. Yearly rainfall events that yielded lahars were all analyzed to get the yearly deviations and relationships of the rainfall-lahar triggering thresholds.

A physically based distributed simulation model was developed using PCRaster program that simulates the catchments' response on a certain rainfall and predicts the lahar hydrographs. This model utilizes DEM and other catchment's physical parameters. The flow predicts the volumetric ratio of sediments and water using Meunier mudflow equation.

## U32A-0018 1330h POSTER

### Watershed Recovery Following Extreme Sediment Loading at Mount Pinatubo, Philippines

Karen B Gran[1] (206-543-1975; kbgran@u.washington.edu)

David Montgomery[1] (206-685-2560; dave@geology.washington.edu)

[1]University of Washington, Dept. of Earth & Space Sciences, Mailbox 351310,, Seattle, WA 98195, United States

Following the 1991 eruption of Mount Pinatubo, rivers draining the flanks of the volcano experienced extreme sediment loading leading to high post-eruption specific sediment yields. As sediment sources upstream decline or stabilize and major lahars become less prevalent, the channels are beginning to recover. Our study examines the processes by which basins recover from sediment loading in the fluvial recovery phase. We are concentrating on five basins at Pinatubo that suffered varying amounts of basin inundation by pyroclastic flow deposits (from <5% to >30%), and therefore sediment loading, in the eruption: the Pasig-Potrero, Sacobia, O'Donnell, Gumain, and Porac Rivers. From 1997-2001 we have been studying channel bed and flow conditions along a series of cross-sections. In addition, we are monitoring longitudinal changes on a subset of basins and measuring sediment transport on the Pasig-Potrero River.

Study basins with <5% cover by pyroclastic debris are recovering fastest. Cross-sections have stabilized, bed armoring is apparent, and fish have even returned. Basins with >30% cover by pyroclastic debris, including the Sacobia and Pasig-Potrero Rivers, are recovering more slowly, so the bulk of our research has concentrated on these basins. Both basins had similar amounts of sediment loading from the eruption, but the Pasig-Potrero now has a greater transport capacity from a stream capture of the upper Sacobia basin in 1993 that nearly doubled the basin area. From 1997 to 2001, changes have been observed on the Pasig-Potrero in channel form, bed composition, and sediment mobility. Bed surface grain sizes have increased through time, with the farthest upstream sites showing the most rapid coarsening. The developing low-flow armor layer is increasing roughness and decreasing sediment mobility. In 1997, sediment mobility was highly selective, with grains of increasing diameter mobilizing under flows of increasing depth. As finer grains are progressively winnowed away, the bed surface is able to coarsen. Bed coarsening can only occur, however, after the input of fine-grained sediment from upstream sources has declined significantly which could explain longitudinal variations in the rate of bed coarsening. Suspended sediment concentrations may also be important in low-flow bed mobility. In 2001, groundwater-fed braids with low suspended loads were observed under low-flow conditions on the Pasig-Potrero. These channels are fully armored and have few actively mobile clasts, in contrast to nearby braids with high suspended sediment concentrations and clasts rolling downstream. In contrast to the Pasig-Potrero, the Sacobia has shown almost no armoring or coarsening of the bed, and longitudinal changes in slope, grain size, or pumice content observed on the Pasig-Potrero are not currently present on the Sacobia. We attribute these variations primarily to differences in the relative transport capacity between the Sacobia and the Pasig-Potrero.

## U32A-0019 1330h INVITED POSTER

### Long-Term Stability of Pyroclastic Dams Around Mount Pinatubo

Norman Manuel Tuñgol[1,2] (63-2-426-1468 to 1479; norman@phivolcs.dost.gov.ph)

James A. McKean[1] (64-3-364-2987 ext 7073; j.mckean@geol.canterbury.ac.nz)

[1]Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

[2]Philippine Institute of Volcanology and Seismology, CP Garcia Ave, UP campus, Diliman, Quezon City 1101, Philippines

Many temporary lakes have been formed around Mount Pinatubo by the blockage of channels by lahar or pyroclastic-flow deposits. Many such pyroclastic dams have been observed to repeatedly form and breach, often resulting in catastrophic lahars. A few, however, have survived for many years.

We consider four conceivable mechanisms for the failure of pyroclastic dams: (1) erosion of the dam by flows along the lahar channel; (2) gravitational collapse and/or piping; (3) lake overtopping; and (4) secondary hydroeruptions.

Upper reaches of lahar channels, within about 15 km from the crater, are prone to rapid changes in channel configuration. Up to tens of meters of vertical and lateral erosion by lahars in these near-source areas have been observed to occur in hours. Pyroclastic dams formed in these areas are therefore likely to be removed or undermined by flows along the blocking lahar channel.

Infinite-slope stability analysis indicates that pyroclastic dams are generally stable against gravitational slope collapse, owing largely to their long (typically few kilometers), gentle (<5%) downstream faces. The gentle slope and unconfined groundwater denote exit gradients for subsurface water far less than the critical hydraulic gradient of the dam material, thus rendering piping failure unlikely.

Boundary shear stress considerations, supported by field observations, show high streambed mobility of channels on pumiceous deposits, mainly due to the dominantly sand-sized composition and low density of the deposits. Similarly composed pyroclastic dams are prone to rapid breach erosion by overtopping flows. However, material lost to erosion along the breach-channel may be compensated for by sediments delivered onto the dam by lahars and/or local runoff. This is easily achieved where the dam is in an aggrading environment, as in an active lahar fan. Once sediment supply to the dam is cut off, e.g., due to the depletion of source sediments, by revegetation, or by stream beheading, the dam is predicted to fail by breach erosion. It can thus be expected that, barring engineering intervention, all pyroclastic dams around Mount Pinatubo will eventually fail, as suggested by their absence before the 1991 eruptions.

Secondary hydroeruptions and secondary pyroclastic flows/avalanches have been known to accompany the breaching of pyroclastic dams, where the dams are partially or wholly formed by hot pyroclastic flows. These phreatic phenomena may trigger dam-breaching, or they may occur once breach erosion has reached the hot sections of the dam deposits. If they do occur, they invariably accelerate breaching. The above analyses, though, show that they are not required for pyroclastic dams to fail.

## U32A-0020 1330h POSTER

### The Natural and Political Caldera-lake crisis of Mount Pinatubo, Philippines, 2001

Kelvin S Rodolfo[1,2] (312-243-8241; krodolfo@uic.edu)

[1]Dept. of Earth & Env. Sciences, University of Illinois 845 W. Taylor, Chicago, IL 60607, United States

[2]National Institute of Geological Sciences, University of the Philippines, Quezon City 1101, Philippines

In 1991 Mount Pinatubos eruptions produced a caldera with a 5.4 km2 catchment that ever since has gathered a lake with a surface that has risen roughly 10 m every rainy season. The rim is lowest at 960+ masl in the northwest, at the Maraunot notch, named after the stream into which overtopping lake water would drain, thence along the Balin Baquero and Bucao to the town of Botolan and the South China Sea 40 km downstream. In December 2000, with only 10 m of remaining notch freeboard, Philippine government geologists and American colleagues were aware of the potential for catastrophic breaching, because the surface 20 m of rock beneath the rim is highly erodible breccia. A breakout of as much as 60 x 106 m3 is considered possible. Easily eroded eruption debris is abundant in the path of the flood, which could bulk up into worst-case lahars with a volume of 3 x 108 m3. Government engineers discussed lowering the lake with siphons or a tunnel, or scraping down and strengthening the notch, but did nothing. Only in August, three months into a very wet monsoon season, when only about 5 m of freeboard remained, did the government inform the 46,000 Botolan inhabitants of the danger. It did so only after Oxfam GB, a humanitarian organization, issued a report written by private geological consultants familiar with Pinatubo and its lahars. The crisis, still evolving, unfortunately is pitting government attitudes and policies – strict control of information and decisions regarding hazards – against those of academic science, and of some NGOs concerned with community development and empowerment. In August, the government abruptly abandoned its initial denials of a serious threat, and decided to build a canal with which to induce a breach at a propitious time. Poorly paid and supervised aborigine labor has inadvertently reduced the freeboard to only 2 m,

and the government is announcing that it will evacuate Botolan and induce the breach as early as September 5. Spontaneous breaching during rainstorms remains very possible.

### U32A-0021 1330h POSTER

## The Crater Lake and Hydrothermal System of Mount Pinatubo, Philippines: Evolution in the Decade After Eruption

James A Stimac[1] (632-845-8478; jstimac@unocal.com); Fraser Goff[2]; Dale Counce[2]; Adrienne CL Larocque[3]; David R Hilton[4]; Uwe Morgenstern[5]

[1]Philippine Geothermal Inc., 12th Floor Citibank Tower, 8741 Paseo de Roxas, Makati, Philippines

[2]LANL, EES-6, MS-D462, Los Alamos, NM 87545, United States

[3]Univ. of Manitoba, Dept. of Geol. Sci., Winnipeg, MB RT3 2N2, Canada

[4]Scripps Institution of Oceanography, Geoscience Research Division, La Jolla, CA 92093-0244, United States

[5]IGNS, 69 Gracefield Rd., P.O. Box 30368, Lower Hutt, New Zealand

We document a decade of change in the lake and hydrothermal system of Mount Pinatubo, Philippines following the climactic eruption of 1991. A shallow lake formed by early Sept. 1991 and has shown a long-term trend of growth even during dry periods ($\sim$1 m/month). It was initially dominated by meteoric influx and the residuum of the pre-eruptive hydrothermal system, but quickly became more acid (pH $\sim$2-3) as magmatic discharges continued to condense into the rapidly accumulating water. Acidity and rock dissolution peaked in late 1992, during and immediately after eruption of a lava dome on the crater floor (July-Oct. 1992). The pH of the lake remained $\sim$3.0 to 3.3 from late 1992 to early 1999, whereas temperature showed a slow decline from $\sim$40 to 30$^o$C. Samples taken since cessation of dome growth suggest that magmatic degassing and rock dissolution have declined significantly relative to magmatic-hydrothermal brine and meteoric input. This is indicated by trends toward higher Cl, Na, K, Li and B and lower Mg, Ca, Fe, SO4 and F with time. Samples taken in 2001 indicate dilution, increase in pH (5.5), and decline in temperature ($\sim$27$^o$C) resulting from a growing contribution of meteoric water. The rapid transition from a small and hot acid lake to moderately large and warm near-neutral pH lake is related to the rapid cessation of direct magmatic degassing, large size of the catchment, and large volume of hydrothermal input compared to lakes hosted by more restive andesitic volcanoes.

The pre-existing hydrothermal system was invaded by an increased flux of magmatic gas and eventually by magma itself. As the impermeable caprock of the system was progressively fractured, extensive boiling and steam loss occurred. A dry conduit system that conducted volcanic gases and magma to the surface was maintained locally until late 1992. As the magmatic flux waned and the magmatic system plugged itself, a liquid hydrothermal system encroached on this direct pathway. Current hydrothermal input is neutral-Cl fluid that equilibrated with rocks at $\sim$200$^o$C and has similarities to geothermal fluids in wells drilled below the same area prior to eruption. This indicates that either very rapid fluid/rock interaction has occurred, or hydrothermal outflow that previously flowed south from the volcano now vents through the ruptured cap of the system.

Considering evidence for declining magmatic input, edifice failure and due to rising lake-level and consequent lahars pose the greatest present risk to local populations. Two low areas on the crater rim, the Maraunot Notch and the O'Donnell River headwall are a few meters above lake level (late Aug. 2001), but the water level will probably top these points sometime in late 2001 or 2002. Several meters of ash deposits from the 1991 eruptions can be easily eroded from these areas if overtopping occurs. The most likely failure point is along structurally controlled zones of weakness and hydrothermal alteration that control the Maraunot Notch.

### U32A-0022 1330h POSTER

## Mount Pinatubo's Volcanic Lake Geochemistry

Cami A. Apfelbeck[1] (425-778-5711; capfelbeck@mindspring.com)

Christopher G. Newhall[1] (206-616-1933; cnewhall@geophys.washington.edu)

Mark S. Ghiorso[1] (206-685-2482; ghiorso@u.washington.edu)

Laurie S. Balistrieri[2] (balistri@ocean.washington.edu)

[1]Department of Earth and Space Sciences, University of Washington 63 Johnson Hall, Box 351310, Seattle, WA 98195-1310, United States

[2]School of Oceanography, University of Washington Box 357940, Seattle, WA 98195-7940, United States

A geochemical investigation of Mount Pinatubo's volcanic lake indicates mixing between neutral chloride spring discharge from springs in the crater walls and meteoric waters from precipitation and runoff. I originally hypothesized that the lake water is a mixture of deep hydrothermal acid sulfate fluid representative of magmatic input into the hydrothermal system, neutral chloride fluid representative of the hydrothermal input directly into the lake via crater wall springs, and meteoric water. Lake water was periodically sampled and analyzed for temperature, pH, major element concentration, and isotopic composition. This study utilizes lake samples collected in 1992, 1994, 1999, 2000 and 2001. Solution speciation and mixing models do not support the mixing scenario originally hypothesized. Further investigation of major element concentrations and isotopic composition supports mixing between the neutral chloride spring discharge and meteoric water. A series of Cl vs. major element plots of end member solutions and sampled lake waters delineate a mixing line between the meteoric water and the neutral chloride spring discharge. For conservative elements such as Li, Na, and K, lake samples plot on or near this mixing line. For less conservative elements such as Mg, Ca, Fe, Mn, and $SO_4{}^{2-}$, lake samples plot between the two end members but above or below the mixing line indicating enrichment or depletion in the lake. The significant enrichment of Ca and $SO_4{}^{2-}$ in the 1992 lake sample and less-enriched later samples can be explained by initial anhydrite dissolution in the early lake followed by elimination of source anhydrite and dilution from meteoric water in more recent lake samples. A strong correlation between Ca and $SO_4{}^{2-}$ supports this hypothesis. Further, the slope of a regression line on a Ca vs. $SO_4{}^{2-}$ plot of the lake samples is $\sim$2.8 in good agreement with the expected $SO_4{}^{2-}$ to Ca ratio of $\sim$2.5 in anhydrite. The slight deviation can be accounted for via substitution of Mg for Ca. This is supported by a similar enrichment of Mg and a strong, positive correlation between Ca and Mg. Redox conditions in the lake are such that Fe and Mn depletions can likewise be explained through precipitation of secondary Fe and Mn oxides. A Cl vs. $\delta$D plot also delineates a mixing line between meteoric water and neutral chloride spring discharge and, along with $\delta$O-18 vs. $\delta$D data, negates any acid sulfate hydrothermal influence on the lake chemistry. Although this mixing scenario can reasonably explain the major element concentrations and isotopic composition of the lake water, it does not account for periods of extreme acidity and temperature fluctuations. The pH fluctuated from an initial 6.0 in October 1991 to its most acidic, 1.9, in December 1992 before neutralizing to 6.2 by January 2001. There is evidence of a gas phase bubbling through Pinatubo's volcanic lake. I observed surface bubbling, an area of upwelling, and an extreme inverted temperature profile over the submerged dome in August 2000. Modeling with previously published $CO_2$, $SO_2$, $H_2O$, and Cl gas ratio and flux data will illuminate the feasibility of explaining pH and temperature fluctuation via volcanic gas flux through the lake.

# U32B MC: 134 Wednesday 1330h

## Biogeophysics of Global Warming Mitigation

*Presiding:* **M Hoffert,** New York University; **K Caldeira,** Lawrence Livermore National Laboratory; **J Edmonds,** Pacific Northwest National Laboratory

### U32B-01 1330h

## Influence of Geoengineered Climate on the Biosphere

Donald Wuebbles[1] (217-244-1568; wuebbles@atmos.uiuc.edu)

Vaishali Naik[1] (217-333-6296; vnaik@uiuc.edu)

Jon Foley[2] (608-265-5144; jfoley@facstaff.wisc.edu)

[1]Department of Atmospheric Sciences, University of Illinois 105 S. Gregory St., Urbana, IL 61801, United States

[2]Department of Atmospheric and Oceanic Sciences, University of Wisconsin 1225 W. Dayton St., Madison, WI 53706, United States

Several geoengineering schemes have been proposed to counteract anthropogenic climate change by reducing the solar radiation incident on the Earths surface. It has been shown in a recent study (Govindaswamy and Caldeira, 2000) that geoengineering schemes that involve reduction of solar radiation incident on the Earths surface could noticeably diminish regional and seasonal climate change from increased atmospheric carbon dioxide (CO2). However, the response of terrestrial biosphere to reduced solar radiation in a CO2 rich climate has not been explored. Atmospheric CO2 and incident solar radiation are critical prerequisites for photosynthesis in plants. Studies have indicated that elevated CO2 in the atmosphere stimulates photosynthesis resulting in increased primary production of land vegetation. On the contrary, diminished solar radiation would not only affect plant metabolism through photosynthesis but also leaf morphology, as temperature of plants is light-controlled. In this study, we use a dynamic global ecosystem model, IBIS (Integrated Biosphere Simulator) to simulate the response of terrestrial ecosystem to a geoengineered climate conditions. Particularly, we analyze the influence of reduced solar luminosity in a CO2 rich climatic conditions on the terrestrial carbon balance (e.g., net primary productivity, net ecosystem exchange, and soil carbon) and vegetation structure (biomass, leaf area index, and vegetation composition).

### U32B-02 1345h

## Enhanced Carbonate Weathering: Helping Nature Capture and Sequester Carbon Dioxide

G H Rau[1,2] (9254237990; rau4@llnl.gov)

K G Knauss[2]

K Caldeira[2]

[1]Institue of Marine Sciences, University of California, Santa Cruz, CA 95064, United States

[2]Energy and Environment Directorate, Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550, United States

Various methods have been proposed for mitigating anthropogenic $CO_2$ release to the atmosphere, including ocean storage via enhanced biological uptake and via deep-sea injection of captured $CO_2$. We propose an alternate capture and sequestration method that we believe would be less expensive and more environmentally friendly than the proceeding methods. Specifically, it is suggested that $CO_2$-rich power-plant gases be hydrated with seawater to produce a carbonic acid solution that in turn is reacted on-site with limestone to form $Ca^{2+}$ and $HCO_3^-$. This calcium bicarbonate solution is then released and diluted in the ocean where it would add minimally to the existing, large pool of these ions in the sea. Such a process simply speeds up natural carbonate weathering and dissolution which will otherwise consume anthropogenic $CO_2$, but over many millennia.

Using a schematic model of ocean chemistry and transport we show that this process would increase ocean alkalinity, effectively neutralizing $CO_2$ acidity and isolating anthropogenic carbon from the atmosphere. Relative to atmospheric release or direct $CO_2$ injection, this method would greatly expand the capacity of the ocean to store anthropogenic carbon while minimizing environmental impacts of this carbon on ocean biota. This technique also is less energy intensive and less expensive than other abiotic $CO_2$ capture and sequestration schemes. We calculate an energy penalty that may be $<$2% with a $CO_2$ capture efficiency which may exceed 50%. Estimated sequestration costs could be as low as \$12 per tonne $CO_2$ sequestered, dependent on reactor configuration and on limestone and water availability and transport. These compare with \$90 to \$180/tonne $CO_2$ and $>>$20% energy penalties estimated for direct ocean $CO_2$ injection.

### U32B-03 1400h

## Control of Global Warming by Enhancement of the Albedo and Longevity of Low-Level Maritime Clouds

John Latham (303-497-8182; latham@ucar.edu)

NCAR/MMM, 3450 Mitchell Lane, Boulder, CO 80301, United States

A technique is proposed for controlled and significant enhancement of the droplet concentration in low-level maritime clouds, with a corresponding increase in their albedo for incoming sunlight and their longevity. The concomitant cooling effect could be regulated and sufficiently powerful to neutralise global warming. The technique involves dissemination at the ocean surface of small seawater droplets which, if in sufficient quantities and with appropriate salt mass, can act as the dominant cloud condensation nuclei (CCN) on which droplets form in marine stratocumulus. It has a short response time and low ecological impact, requiring only seawater and air as raw materials.