What will NASA do in response to the next major volcanic eruption?

Hal Maring
Paul Newman
Ken Jucks

The Volcano Workshop
17-18 May 2016

Abstract: Based on history, it is reasonable to expect a major volcanic eruption in the foreseeable future. **By “major volcanic eruption”, we mean an eruption that injects a substantial amount of material, gases and particles, into the stratosphere** as a result of one eruption event. Such a volcanic eruption can impact weather, climate, and atmospheric chemistry on regional, hemispheric and global scales over significant time periods. Further, such an eruption can be an unintended analog for a number of geo-engineering schemes for mitigating greenhouse warming of the Earth. In order to understand and project the consequences of a major eruption, it is necessary to make a number of observations from a variety of perspectives. Such an eruption will occur, in the immediate sense, unexpectedly. Therefore, it is wise to have a thoughtfully developed plan for executing a rapid response that makes useful observations. In this seminar, Paul Newman will relate on the outcome of a workshop held on 17-18 May 2016 at NASA GSFC. **The goal of the workshop was to develop an observation strategy that can be quickly implemented in response to a major volcanic eruption**, to characterize the changes to atmospheric (especially stratospheric) composition following a large volcanic eruption. To be clear, eruptions having only local effects, no matter how severe, are not of interest in this context. The workshop was attended by about 30 experts from NASA, NOAA, USGS, and several universities.

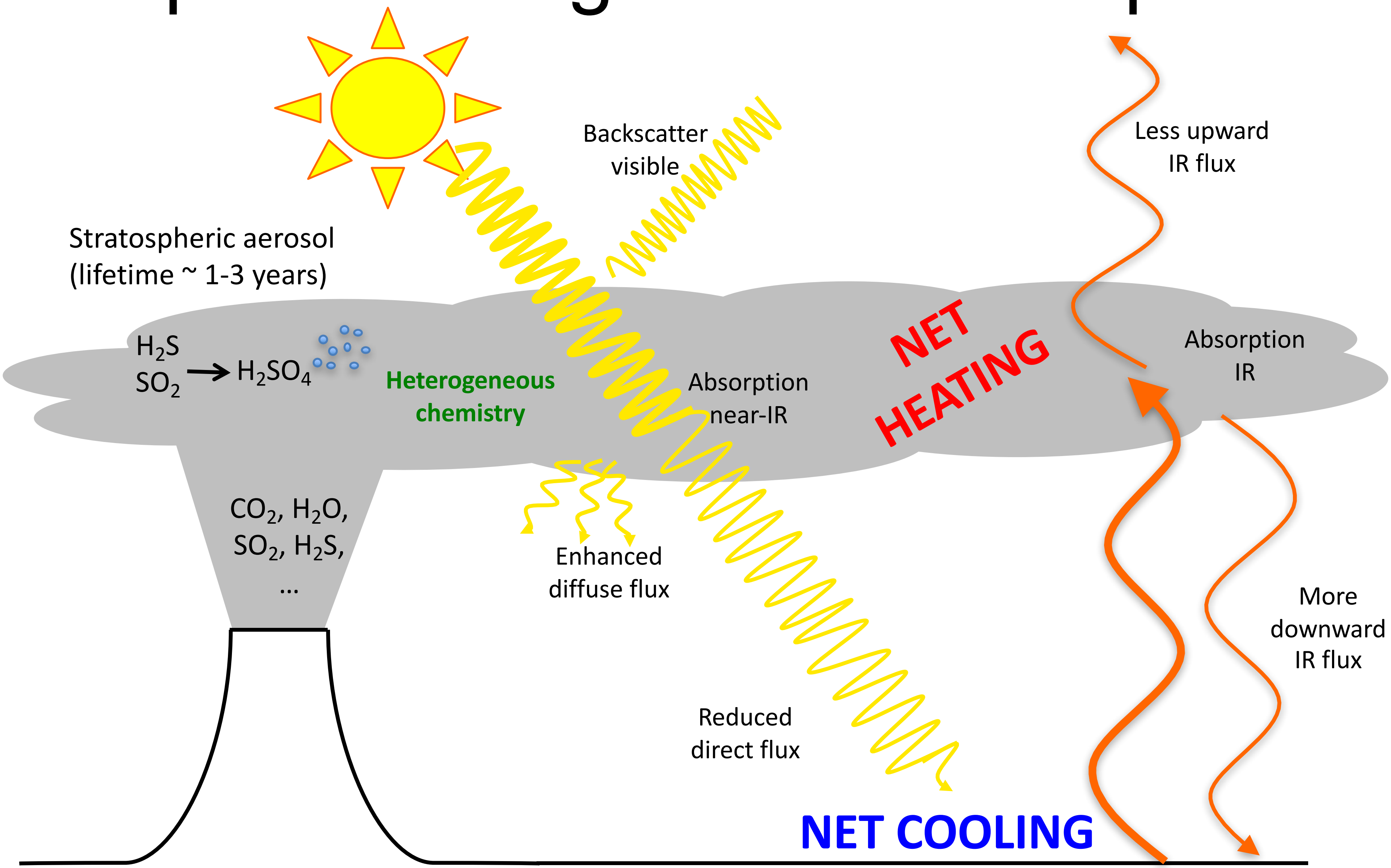
Agenda

- Framing the issue:
  - Jack Kaye - HQ
  - Brian Toon & Pat McCormick - Historic
  - Valentina Aquila & Allegra Legrande - Modeling
  - Jean-Paul Vernier, Ross Salawitch – Atmos Comp
- Working groups
  - Aerosol impacts (Hal Maring – Dave Fahey)
  - Radiative, Dynamical and Climatic impacts (Paul Newman)
  - Chemical impacts. (Ken Jucks)
- Report Outline formed

The HQ Perspective
(Kaye)

- We are here to ask the essential questions:
  - **What would we do if the big one blew?**
  - **How would we respond if we look at the existing assets?**
  - What can we anticipate for future eruptions? Is there any data emerging from volcano science studies?
  - Want to focus on the things we know vs. the things we could possibly obtain from different platforms
- **Have a plan in our pocket as to what we would do** – and establish a place where we could investigate
  - Wouldn't be starting the approval process, but at least could establish realistic plans of action
  - Think about stocking up on balloons, etc.
  - We want a NASA-centric, but US-wide approach to research and then we can branch out into global needs
- **No budget** for this – if we know what we are looking at, we can alert management, and make a budget at that time

Impacts of large volcanic eruptions



Modified from Robock (2000)

Major eruptions

Volcanic eruption	Year	Global optical depth, Source	Estimated RF, Wm^{-2}	SO_2 (Mt) Carn et al. (2015)**
Well above tropopause		***Sato****		
La Soufriere, Santa Mari	1902	0.08	−2	
Novarupta (Katmai)				
Mt. Agung				
Mt. Fuego				
El Chichón others				(+2)
Mt. Pinatub				18
Near tropopause		***Santer****	***Santer***	
Cerro Hudson	1991			4
Misc.	2006	~0.003		0.8
Kasatochi	2008		~ −0.025	2
Sarachev	2009	~0.002		1.2
Nabro	2011	~0.003	~ −0.04	2

A major eruption would have > 5 Mt SO_2, yielding:

~.08 optical depth

~ 2 W/m^2 radiative forcing

Toon

Constraining the climate effects of a major volcanic eruption

Question	Geophysical Parameters	Measurement Requirements	Current Capabilities		
			Ground	In situ	Space
What is the volcanic forcing of the climate system?	Injection timing, vertical profile	w/in 24 hours, plume top/bottom	Platform capability		
	Injection Composition	S, Cl, Br, H_2O, ash, …			
	Gas to particle conversion rate	e.g., SO_2 -> SO_4^-			
	Aerosol optical properties	particle size, shape, composition			
	Aerosol loading	Spectral AOT, extinction, backscatter			
What is the stratospheric response to volcanic forcing?	Temperature	up to ±4K (GEOS-5)			
	Water vapor	up to +0.5ppmv (GEOS-5)			
	Long-lived tracers	Up to 50 ppbv (N_2O GEOS-5)			
	Stratospheric winds				
	NO_x, ozone, …				

Aquila

Historical Summary
(Toon and McCormick)

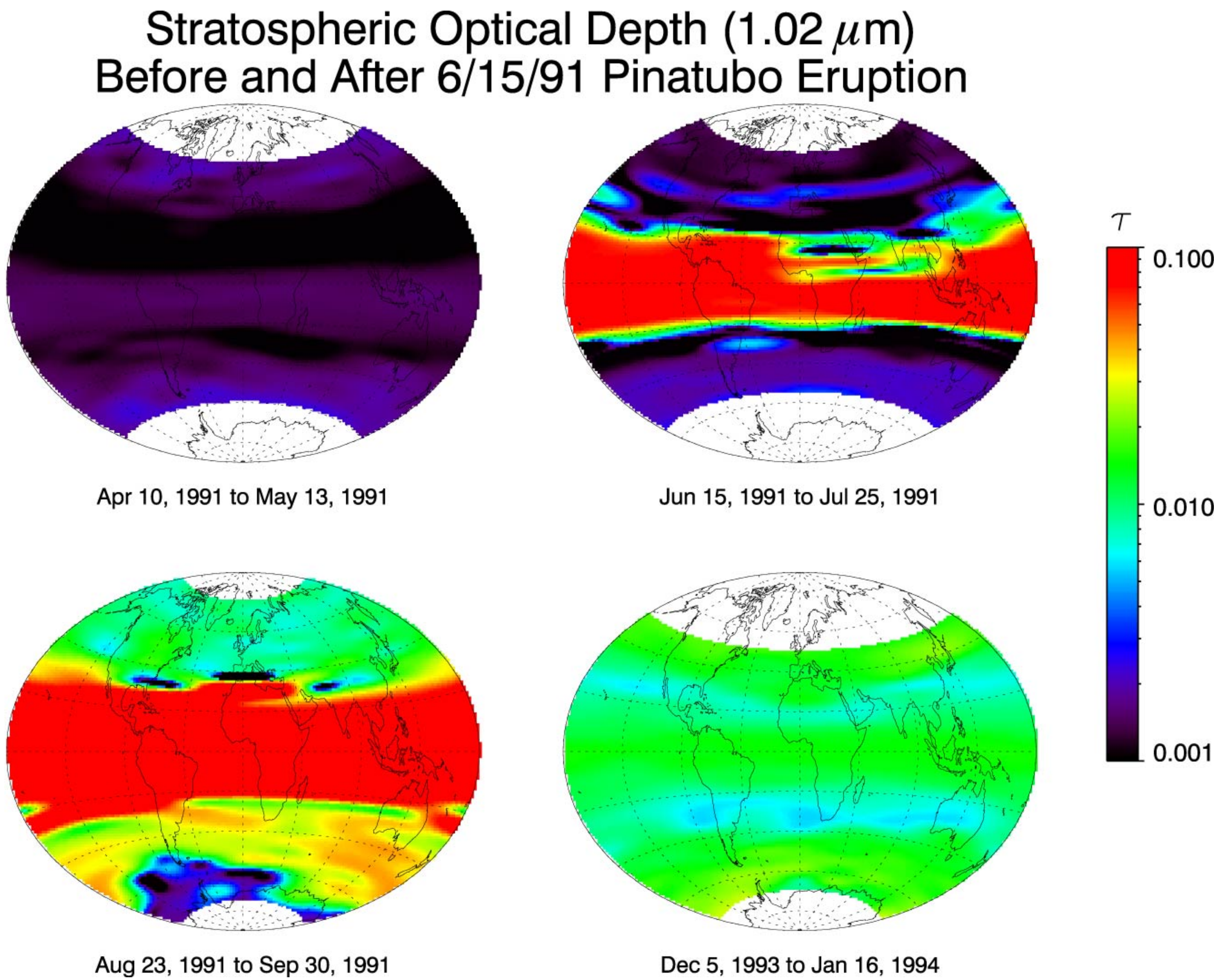
- Instruments and platforms developed for reasons other than studying volcanic clouds
- Many instruments developed to ground truth satellites
- Balloons are highly mobile
- Aircraft can respond quickly if co-located with instruments
- Aircraft campaigns can succeed within a year of eruptions

Many volcanic clouds have been studied with aircraft or balloons

Quick response				
Volcano	**Location, date**	**Platform**	**What was measured?**	**Key to success**
Agung (8S, 115E) 3/17/63	Australia, 11/4/63-7/4/64	Air Force U2, Balloon	Dust	On-going stratospheric radionuclide sampling HARP
Mt. St. Helens (46°N, 122°W, 5/18/80)	5/19/-Oct/80 5/20-21/80 US	NASA U2 DOE WB57 LARC UW balloon	Extensive Dust,SO_4 lidar	On-going SAGE validation ;Ak,Panama/HARP /instruments and plane co-located "
Mystery cloud, Nyamuragira (1.4°S, 12/26/1981)		NASA U2, DOE WB-57		On-going SAGE validation, HARP/instruments and plane co-located
Hekla (64°N, 2/26/00)		NASA DC-8		Accidental on way to polar mission
Campaign				
El Chichon (17°N, 3/28/1982+)	Acapulco	Convair 990	Extensive payload	
El Chichon	various	Air Force U2, balloons UW balloon		Project HARP/Ashcan
Mt. Pinatubo (15°N, 6/15/91)	Arctic, 1992	NASA DC-8, ER-2, UW balloon		Incidental during polar mission,
Kelu (7.9°S, 2/14/2016)		GHawk UW balloon	?	Incidental to field mission Quick response

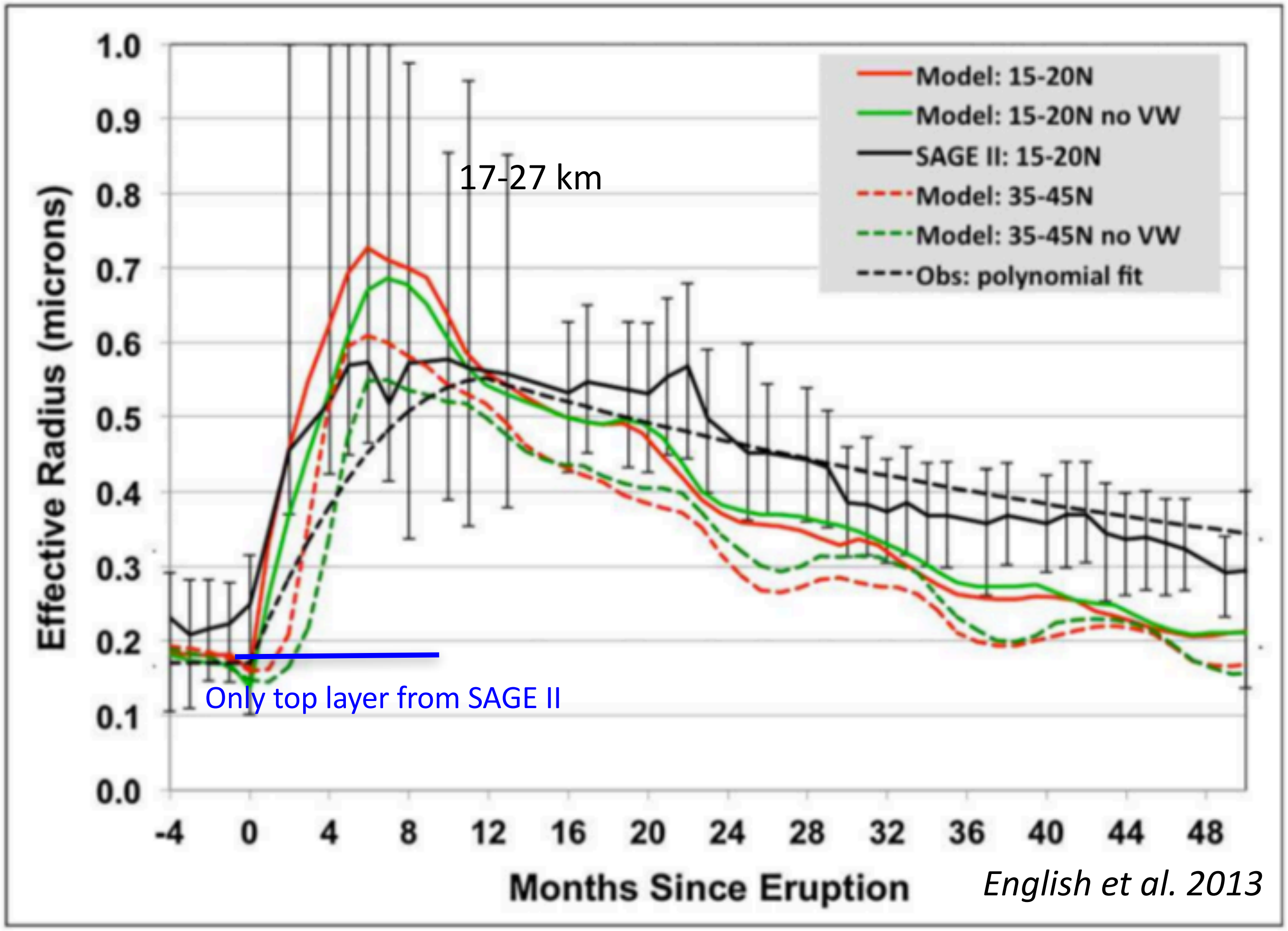
Toon

SAGE II



McCormick

Microphysical evolution of Mt Pinatubo: What do we know ?



- Large uncertainties in SAGE II retrieved Effective Radius first year (no information from SAGE II extinction ratio if aerosol radius greater than 0.5 micron)
- WACCM tends to be lower limit of Effective Radius 1 to 2 years after eruption
- Model limitations (Initial condition/ simple sulfur chemistry no interaction with ash)

Vernier

Gap Summary
(Vernier and Salawich)

- Space-based measurement gap for the next 10 years after a large volcanic eruption (e.g. of SAGE II after Mt Pinatubo)
- Volcanic eruption types of the last 10 years (small scale models for the next big event?): The persistence of ash in volcanic plumes not addressed in simulations.
- Balloon-borne In situ/remote measurements in the next large volcanic plume: for gap fillings and understand plume microphysics (sulfate/ash)
- Preparedness level required for balloon deployment based upon past campaigns and future deployments to study small volcanic eruptions (model for large one) and UTLS aerosol in background conditions (Transport of pollution in the UTLS by the SE Asian Monsoon).

Science Questions

1) When and where is heterogeneous loss of NO_x and activation of ClO_x by reactions other than N_2O_5+H_2O(sulfate) important?

2) How much BrO is present in the lowermost stratosphere?

Measurement Recommendations:

Priority 1a:

- p, T, O_3, H_2O, N_2O, SSA

Priority 1b:

- Long-lived: CFCs, NO_y (or HNO_3), CH_3Br, Halons
- Short-lived: NO and/or NO_2, ClO, HCl, BrO
- Actinic flux

Priority 2:

- $ClONO_2$, CH_4, CO, HCHO, OH, HO_2

Chemistry (related to SO_2 & H_2SO_4)

- Covered in great detail in Toon's draft white paper
- Likely mechanism leading to SSA:
  $SO_2 + OH + 3H_2O \rightarrow H_2SO_4\,(aq) + HO_2$

Key science issues:

1) Veracity of satellite SO_2
2) Role of H_2S in formation of SSA
3) Relation between SO_2 mass ejected and resulting particle size distribution
4) Volcanic emission of H_2O and halogens

Would therefore like to measure:

- SO_2, H_2SO_4, H_2O, H_2S, OH, & HO_2

Also useful:

- ClO, BrO, OCS

Aerosol Breakout Group (Tues PM)

(Hal Maring, Judd Welton, Brian Toon, Chuck Wilson, Rushan Gao, Charlie Mandeville, Paul Lundgren, Ben Phillips, Jean-Paul Vernier, Pat McCormick, P.K. Bhartia, David Fahey, Ralph Kahn, Pete Colarco)

1. Specify key/prioritized science questions and uncertainties

- Aerosol **background** description
  - Including population of sub-0.1 micron aerosol (satellites can't measure), but it can significantly affect final surface area of volcanic particles
- Aerosol formation
  - primary injection of gases and aerosols (sulfate and ash distinction, water, halogens)
  - SO2 oxidation rate
  - aerosol nucleation and growth from H2SO4
  - aerosol evolution of size and composition
- Aerosol effects on chemistry, radiation (energy budget), and dynamics
- What is the partitioning of perturbed stratospheric ***aerosol loss mechanisms***, including gravitational settling, cloud nucleation, poleward transport and high-latitude precipitation, tropopause folds, etc.?

  - aircraft effects (operations, window damage, ….)
  - ash and SO_2 mixture confuses algorithm

2. Identify a set of existing satellite remote sensing data to be collected

- **Lidar** (need more than one wavelength to get size distribution constraint, need polarization for shape)
  - CALIPSO (CALIOP lidar)
  - CATS (space station)
  - EarthCARE (future)
  - ICESAT-2
  - wind (ADM-Aeolus) (future)
- **Limb scattering** instruments
  - OMPS, OSIRIS, SAGE-III (ISS)
- **Occultation** (solar and lunar)
  - SAGE-III
- **Multi-angle**
  - MISR
  - MAIA (future)
  - 3MI (future)
- **Mappers**
  - MODIS
  - VIIRS
  - OMI
  - OMPS
- **Geostationary**
  - GOES
  - HIMAWARI (Japanese)
  - METEOSAT (ESA)
  - MTSAT (Australian)
  - LALPANA (Indian)
- **IR absorption**
  - IASI (METOP-1,2,3)
  - AIRS
  - CrIS

3. Review status and lessons of models that have been used to simulate near-term eruption impacts/evolution and characterize the observational quantities best needed to constrain models of the eruptions' future evolution and global atmospheric (climate, chemical) impacts

Aerosol model needs:

- **For prediction of initial plume evolution we need injection parameters: aerosol mass and aerosol precursor vertical profiles (e.g., SO_2) representative of the eruption event itself**
- **For validation of prediction we need observations to constrain simulated:**
  - aerosol mass and number profile
  - mass extinction & absorption efficiency
  - size distribution
  - composition (distinguish ash from sulfate)
  - shape (non-spherical)
- **Above fields are needed to constrain longer term impacts (aerosol climate effects) predicted by model; similar kinds of things needed for chemistry**

4. Develop a prioritized deployment plan for any potentially needed sub-orbital campaign including specification of platform(s), sensor payload(s), flight plans and generic deployment location(s)

- Specification of platform(s)
  - light balloon packages (< 6 lbs single package or < 12 lbs two packages) for rapid (1-2 weeks) deployment: (stockpile); (Wyoming new package 12 lbs for >0.3u); Langley OPC/aerosol sampler
  - heavy balloon package for composition/total number (~1 month)
  - heavy-lift high-altitude aircraft
    - VIRGAS on WB-57 demonstrates preparedness for volcano (SO_2, O_3, water vapor, whole-air) (in future add Wilson suite, PALMS)
    - ER-2 precedent for strat flights in plumes
  - lower-altitude aircraft for lidar; optical instruments for gases (Coffey precedent SO_2, HC
  - Lagrangian balloon measurement?
- Sensor payload(s)
  - Heavy balloon: Heated/unheated OPC/CN counter (UWy, 100 lbs)
  - Below 12 lbs (6 lbs x 2) O_3/H_2O/POPS/COBALD, POPS/miniSASP (glider); sampler
  - Full size distribution (nm to micron) to have surface area and optical properties (only available from large aircraft platforms (Wilson) and heavy balloon (Deshler))
  - aerosol mass-spec for composition
  - open-path nephelometer
- Flight plans
  - Small balloon payloads for early deployment and flown coordinated with heavy-lift aircraft payloads
  - balloon flight locations more diverse (radiosonde stations) than aircraft flights
  - balloon flight frequency greater than coordinated flight frequency
  - Lidar on lower altitude aircraft to help connect satellite obs to suborbital
  - High-flyer 6 months post-eruption to see what's still there
- Generic deployment location(s): initial response
  - large flexibility since plume will be transported globally
  - aircraft: tropics: (Barbados, Costa Rica, etc), high latitudes: (AK. Punta Arenas), midlats: (North Amer, southern Africa (Namibia), New Zealand)

5. Identify existing surface-based remote and in-situ sensor data to be collected

• **GALION Networks**: EARLINET, ADNET, CIS-LINET, LALINET, CORALNET, CREST, MPLNET (global), NDACC (global) (see map on next slide)

Lidar capabilities vary within networks (examples follow)

- MPLNET is standardized, homogeneous network, but more basic capability
- EARLINET is heterogeneous but includes many sites with advanced lidar

• AERONET surface network
• SKYNET (Japanese) (similar to AERONET)
• GAW Sunphotometer network
• ARM radiometers and lidar

• No need for surface based atmospheric in-situ measurements for aerosol science

6. Develop deployment plans for additional surface-based remote and in-situ sensors, especially those needed for short time periods

• Improved coordination between existing networks, esp. international partnerships in place to facilitate rapid response
• Using models to identify/provide information on where measurements would be most valuable (i.e., Colarco’s slides on distributions over first few weeks)

MPLNET:

- Inactive
- Planned

Some areas that are currently missing sites have been visited before.

New areas are planned. SE Asia and Southern Africa are current focus.

7. Identify predictive models for flight planning and then to use the acquired satellite, sub-orbital, and ground observations to describe the consequences of the eruption

Operational GEOS-5 system supports forecasting and flight planning for, e.g., tropospheric aerosols; does not presently have representation of background stratospheric aerosol or real-time inclusion of volcanic emissions. These capabilities exist in research version of model and need transition to operational system; not in principle difficult (I think this is current state of other operational systems too)

- GEOS-5 (requires development work to be able to simulate stratospheric volcanic aerosol, which is true for other models, e.g. ECMWF, etc.)
- Langley trajectory model for CALIPSO measurements (Fairlie) to reconstruct the plume
- Flexpart for high northern latitude eruption

8. Identify what warning(s) can realistically be expected in anticipation of the eruption, and how geological and atmospheric data can best be combined to provide information about the eruption and its impacts

- Weeks to months forecast of eruption in advance from increase in seismicity, tilt meters, GPS instruments, ice pack, opening of fissures, insitu outgassing, tree kill from dissolved gases, etc
  - need background fingerprinted to improve forecasting
  - new classes of deployable gas detectors available.
- For some classes of small eruptions there is no warnings,
- Most eruptions are outside oceans
- 88/169 US volcanoes are instrumented currently and comprise the US early warning system (**1600 volcanoes world wide** – well-monitored *in situ*, e.g., in Japan, Italy, parts of Russia, but not everywhere)
- Space-based SAR can help precursor detection, but resources to monitor the data are somewhat lacking

9. Characterize what procurement mechanisms and/or stockpiling of materiel should be put into place proactively to facilitate response to a potential future eruption

- Balloon instruments that get size distribution below 100 nm diameter
- Space-borne lidar successor to CALIPSO and CATS
- Acquire stockpile of small balloon instruments (size, number, AOD) and launch systems
- Identify potential deployment sites at different latitudes, and work logistics as much as possible in advance, for balloons and/or aircraft missions

Chemistry Breakout

- What is the metric for deployment?
- What should the SO_2 and AOT thresholds value be?
- Kits for volcanic measurements to distribute to locations with ground-based measurement systems (e.g. SHADOZ)
- Need for a modeling group to perform forecast, with a previously agreed model output

Aircraft/balloon observations

- For higher altitude injections, early in-situ observations will be difficult.
  - Hence remote sensing is probably the only option during early phases from aircraft.
  - Any reasonably high altitude aircraft would be appropriate (mostly to get above clouds).
  - Balloons will be important to tie to both aircraft and satellite data.
- After transport and descent, then in-situ aircraft observations will be possible.

1. What are the effects of volcanic emissions on ozone?

Species	Satellite Instrument	Ground-based instrument	Notes
O_3	MLS, OMPS, OMI, S-5P, SAGE-III, ACE	NDACC, SHADOZ, TCCON, PANDORA, NOVAC	
H_2O	MLS, SAGE-III, ACE	NDACC, GRUAN (utls)	
NO_2	ACE, OMI/S-5P?	PANDORA, NDACC	Either NO or NO2 is sufficient
NOx	Aircraft only		Best by aircraft
NOy	Inferred from N2O/MLS or ACE		Best by aircraft
HNO_3	MLS, ACE	NDACC	
HCl	MLS, ACE	NDACC	
BrO	Challenging from satellite	NDACC, NOVAC	from satellites high uncertainty in lower stratosphere
ClO	MLS	NDACC	In situ would be important
methyl chloride	MLS, ACE		
N_2O	MLS, ACE	NDACC	
SO_4	IASI, CrIS	AERONET, ground lidars (MPLNET)	
high res. T-profile	lower resolution from weather sounders, GPSRO	NDACC, radiosondes	

2. What are the effects of volcanic gases on radiation?

Species	Satellite Instrument	Ground based instrument	Notes
ozone	MLS, OMPS, OMI, S-5P, SAGE-III, ACE	NDACC, SHADOZ, TCCON, PANDORA, NOVAC	
H2O	MLS, SAGE-III, ACE	NDACC, GRUAN (utls)	
NO2	ACE, OMI/S-5P?	PANDORA, NDACC	
CO2	GOSAT, GOSAT-II, OCO-2, OCO-3 (2018-2021)	TCCON, mobile FTS systems (few locations)	
CO	MOPITT, MLS, IASI, AIRS, ACE	IR spectrometers	
N2O	MLS, ACE	TCCON	
HDO	ACE	TCCON	
high resolution temperature profile	lower resolution from weather sounders, GPSRO	NDACC, radiosondes	

3. Which sulfur species are emitted (and SO2 conversion)?

Species	Satellite Instrument	Ground based instruments	Notes
H2SO4	IASI, AIRS?		
SO2	OMI, MLS, GOME-2, S5P, S5, TEMPO, GEMS, S4, VIIRS, MODIS, AIRS, IASI, CRiS, ASTER	PANDORA, NOVAC, NDACC	
high resolution temperature profile	lower resolution from weather sounders, GPSRO	NDACC, radiosondes	
Aerosol surface area density		AERONET (column average)	

Radiation, climate, dynamics, and radiation key science questions (1)

- What are the climate impacts of the volcanic cloud?
- How does the volcanic cloud affect the overall dynamics of the atmosphere?
  - How does the QBO, ENSO, NAO impact the volcanic cloud?
  - How does the volcanic cloud affect the QBO? ENSO? NAO? AMOC?
- How does the surface temperature and precipitation change? What are the regional impacts (monsoon, …)? Ocean impacts?
- How do the upward and down longwave flux and shortwave evolve (from surface to top of the atmosphere)?
- How do aerosols evolve and how does that impact the radiative flux?
- How do temperatures change in the stratosphere as a result of the aerosol interactions with shortwave (particularly near IR) and longwave radiation?

Radiation, climate, dynamics, and radiation key science questions (2)

- Volcanic cloud: What is a “volcanic cloud”?
  - What is in the volcanic cloud? (H_2O, CH_4, halogens, ash, SO_2)
  - How and how fast will SO_2 convert to sulfate aerosols? How will the aerosols grow? What will be the size distribution of the resulting sulfate aerosol particles?
  - How high the volcanic cloud travels? What is the 4-D structure of the volcanic cloud? How will the aerosols be transported throughout the stratosphere?
  - How much fine ash gets to the stratosphere, how long does it stay there, and what are its radiative and chemical impacts?
  - As the aerosols leave the stratosphere, and as the aerosols affect the upper troposphere temperature and circulation, are there interactions with cirrus and other clouds
- Are there large stratospheric water vapor changes associated with stratospheric aerosols? Is there an initial injection of water from the eruption?
- How do the H_2O, O_3, and CH_4 volcanic driven changes impact the surface radiative forcing?

Satellite Remote Sensing Data to be Collected

NASA Involvement	Non-NASA
Aura: MLS, OMI, TES	EARTHCARE: ATLID, CPR, BBR, MSI
Terra: CERES*, MODIS, MISR	OSIRIS
Aqua: CERES, MODIS, AIRS	Himawari-8
S-NPP: CERES, VIIRS, CriS, OMPS	SEVIRI
JPSS-1: CERES, VIIRS, CriS, OMPS	METOP: IASI, GOME-2, GRAS
JPSS-2: RBI, VIIRS, CriS, OMPS	Sentinel-4: UVN, IRS, IRS, FCI
CALIPSO	Sentinel-5: UVNS, IRS, VII, 3MI
CloudSAT	Sentinel-5 precursor: Sciamachy, UVNS, Tropomi
GPM	
GRACE	
JASON-3	
GOES-R	
SAGE 3 on ISS	
GPS	

*CERES is programmable to optimize sampling over volcano area (with 3 days notice)

Modeling in support of a Pinatubo-scale eruption

Climate, Radiation, Dynamics, and Transport

Needs

- Initial state of the atmosphere (including wind structure, aerosol background, source gases, …)
- Initial injection altitude & depth, and temporal structure
- SO2, H2O, HCl, ash amounts (& optical properties)

- Models: GISS Model-e, GEOS-5
  - Simulation of ozone, surface T, precip, …

Modeling needs

- Measure gases and aerosols in situ and with remote sensing
- Input for a data assimilation system that will include observations from remote sensing from the ground and satellites, and to separately evaluate those remote sensing observations.
- Primary goal should be to fill in the gaps in the remote sensing.
- Amount and size distribution of sulfate aerosols
- Amount and size distribution of volcanic ash (tephra).
- Airplanes can get up to about 20 km, but need to be available, and have already mounted or access to instruments that can be quickly mounted. Examples of airplanes include the NCAR G5 HIAPER, the ER-2, and the WB-57, and others, such as the DC-8, which can fly under the volcanic cloud with lidar and radiometers.
- Balloons can measure SO_2 profiles (not well) and aerosol profiles (well). Long-duration balloons can measure aerosol amounts and size distribution changes over time, which are important for calculations of radiative forcing, as well as studying gas-to-aerosol conversion and aerosol transport, to evaluate climate model simulations.

Research Aircraft and Deployment Scenarios

DC-8

- Lidar: HSRL
  - Amount and location of the volcanic cloud
  - Size distribution information
- DIAL: O_3, T, H_2O profile
- Column amounts: AOD, SO_2, O_3, N_2O, H_2O
- 4Star, BBR, SSFR, CAFS
- Polarimeter(s)
- Long-range, upper troposphere

High Altitude (WB-57F, ER-2)

- Remote sensing:
  - BBR, SSFR, CAFS
  - Lidar (upward & downward): aerosol concentration, vertical distribution, size distribution, shape (depolarization)
  - CAR, AirMSPI, RSP, …
- In-situ
  - O_3, H_2O, SO_2, T, P, winds, N_2O, SF_6, CO_2
  - Aerosols: concentration, size distribution, composition

Deployment strategy

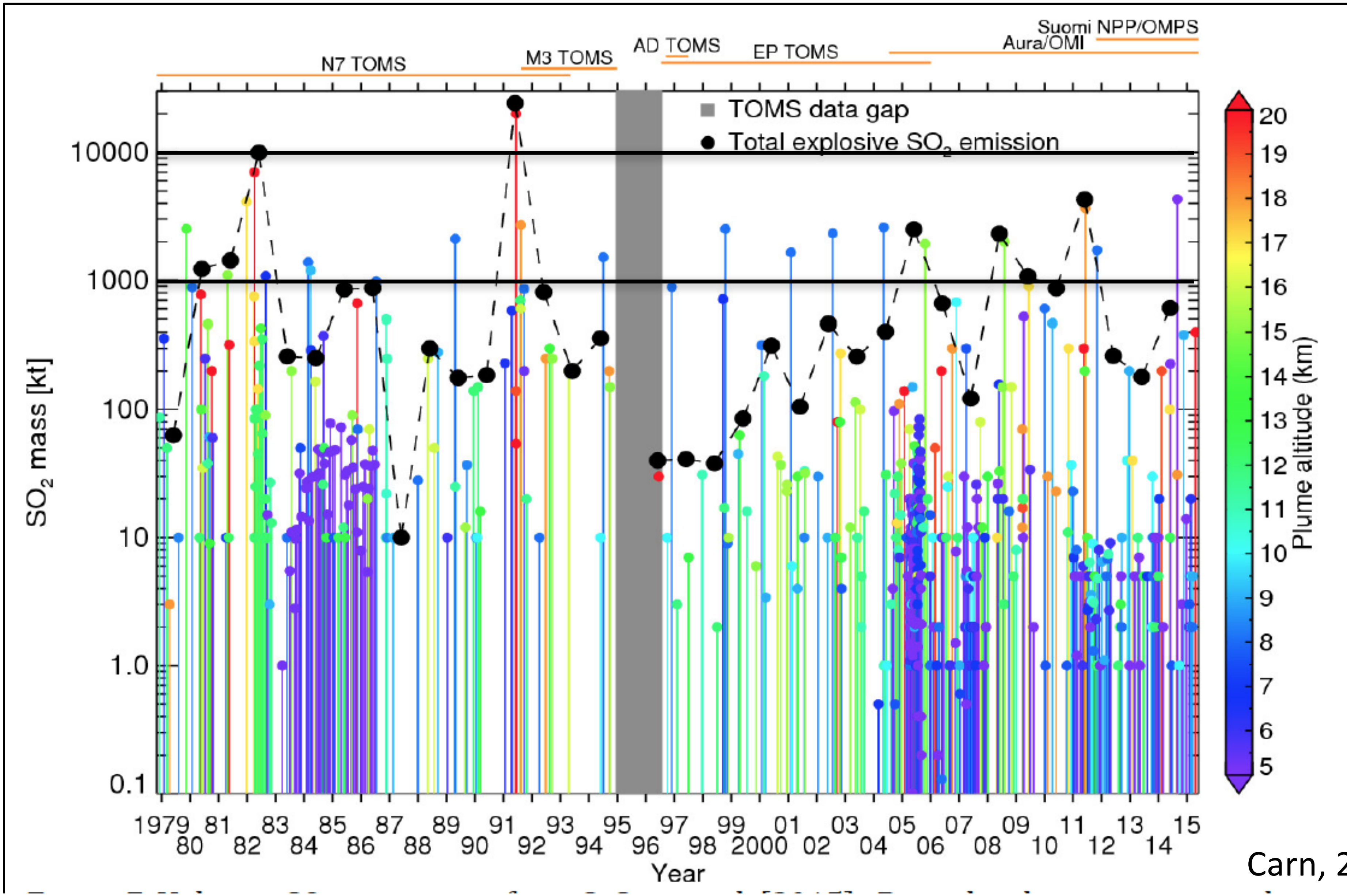
- Balloon
  - Where: approximate latitude of the eruption, plus 3-4 additional latitudes
  - When:
    - Within first few weeks: profiles of SO_2 & aerosols
    - Balloon payload: once per week for 2 years
- Aircraft
  - 4 deployments spaced 3 months apart: 2-3 week deployments (7 flights per deployment). 1st deployment two months after eruption (or as early as possible).
- Ground: deploy MPL & sun photometer, etc. to remote site – as early as possible

Surface Measurements for Climate and Radiation Relevant for Volcanic Eruption

- Networks and Mobile Facilities: ARM Mobile facility, GSFC and LaRC, Ship measurements
- Surface Radiation:
  - Broadband solar and thermal infrared; direct/diffuse solar (BSRN (including NOAA SurfRad), ARM, NOAA-ESRL/GMD), FluxNet
  - Sun photometry: AERONET (sun photometer, CIMEL), NOAA-ESRL/GMD
  - Spectral solar: total, direct, diffuse (SurfRad – MFRSR, ARM)
- Surface Rain Gauge: NCEI, GPCC
- Surface temperature & meteorological: Land - NCEI, Ocean - ARGO, Buoy (WHOI) & Ship
- Surface turbulent energy fluxes: FluxNet
- Column/Profile Temp & Humidity: Lidar (GALION => MPLnet, LALINET, etc.), DIAL (mobile?), RAMAN (ARM)
- Column/Profile Aerosol: AERONet, Lidar (MPLnet, LALINET), RAMAN (ARM)
- Column/Profile Chemistry: Ozone (Spectrometers, DIAL, etc.)

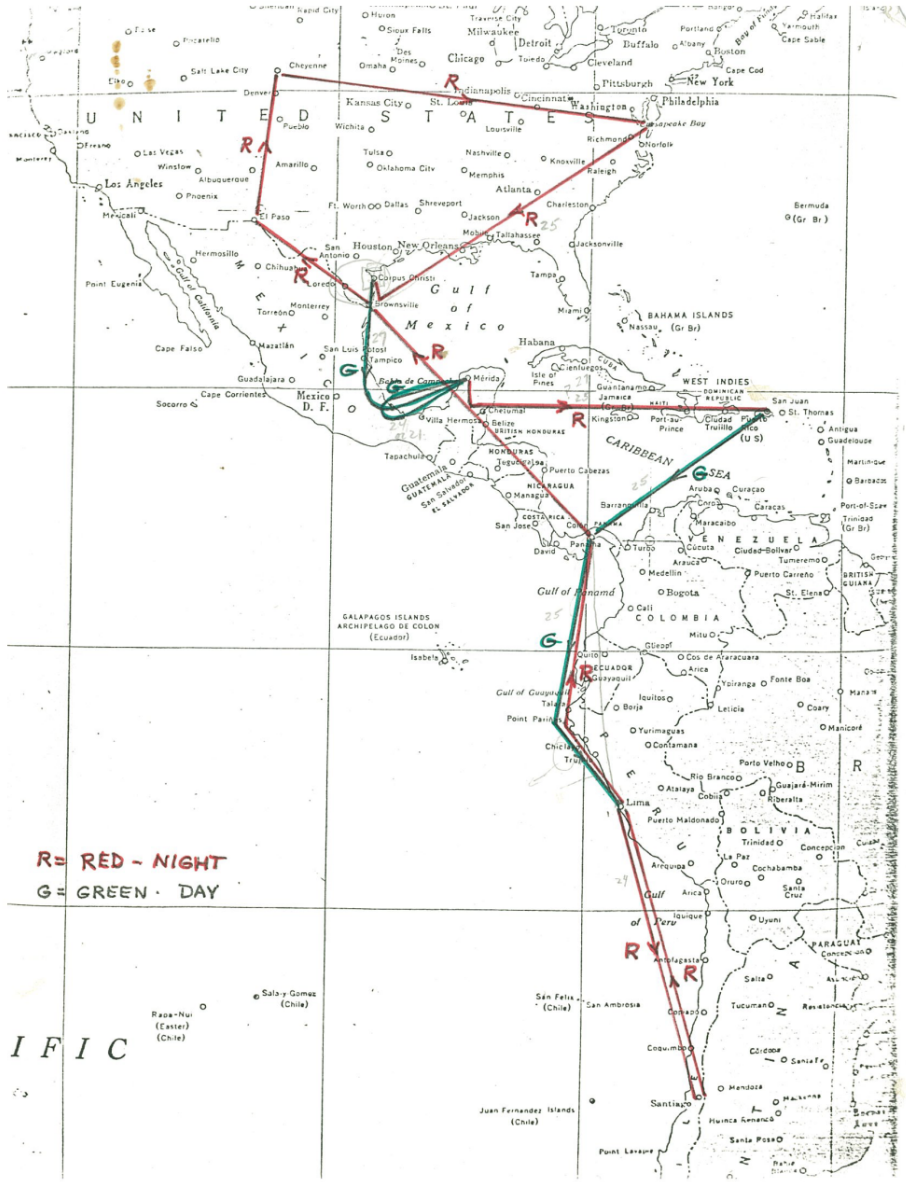
Back Up

What is a major eruption?



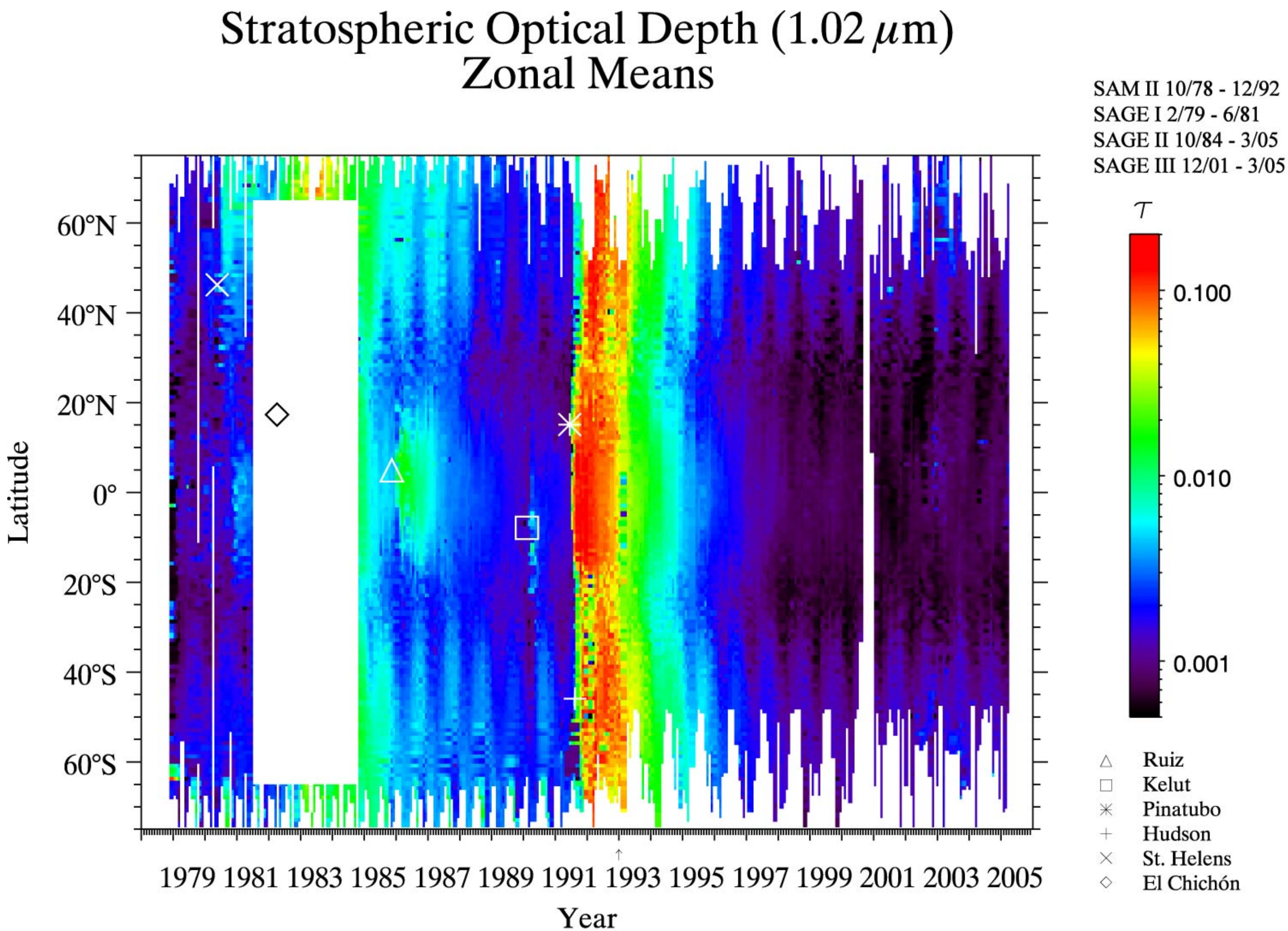
Carn, 2015

El Chichon A/C Flight Oct - Nov 1982



McCormick

SAM II, SAGE I/II/III

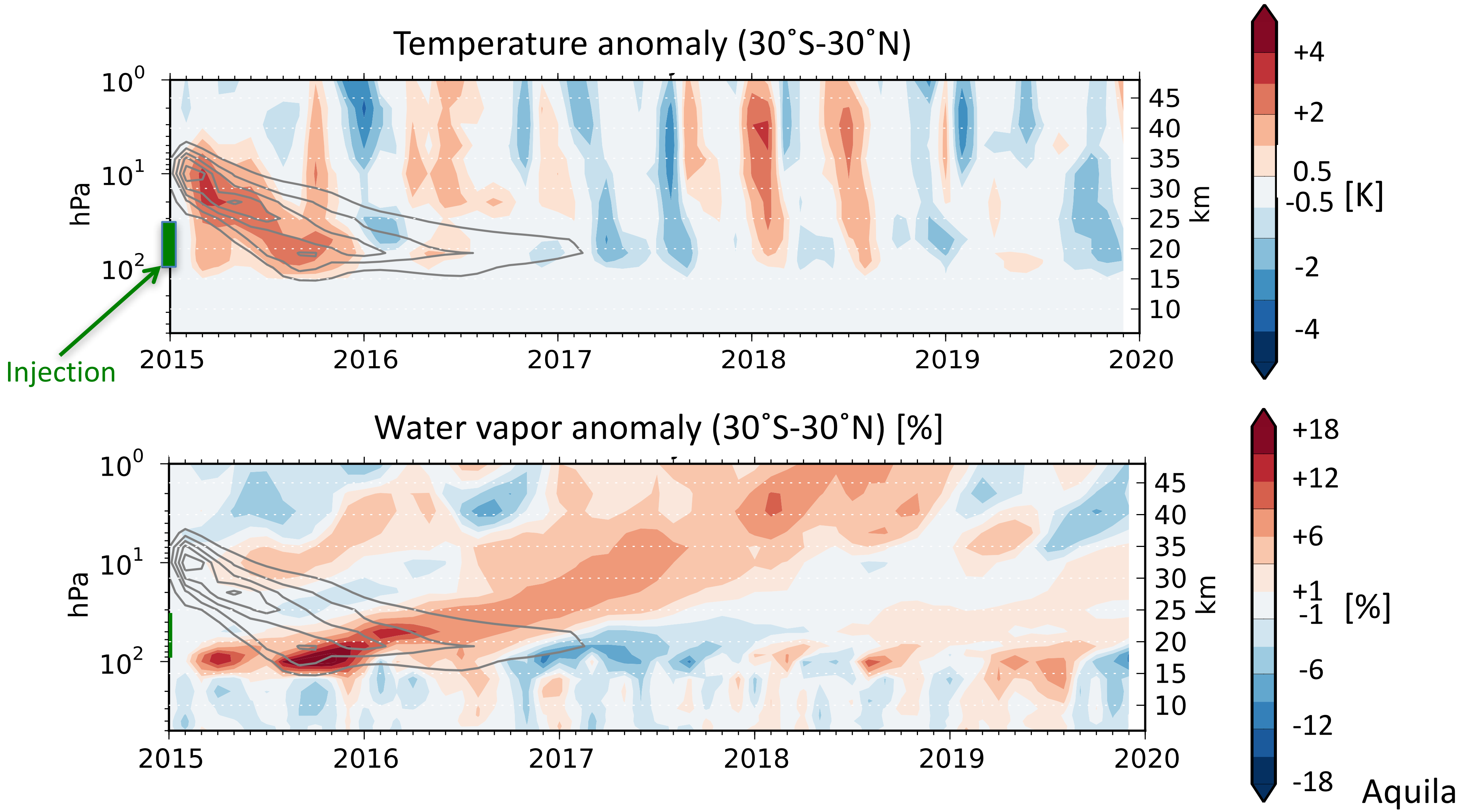


McCormick

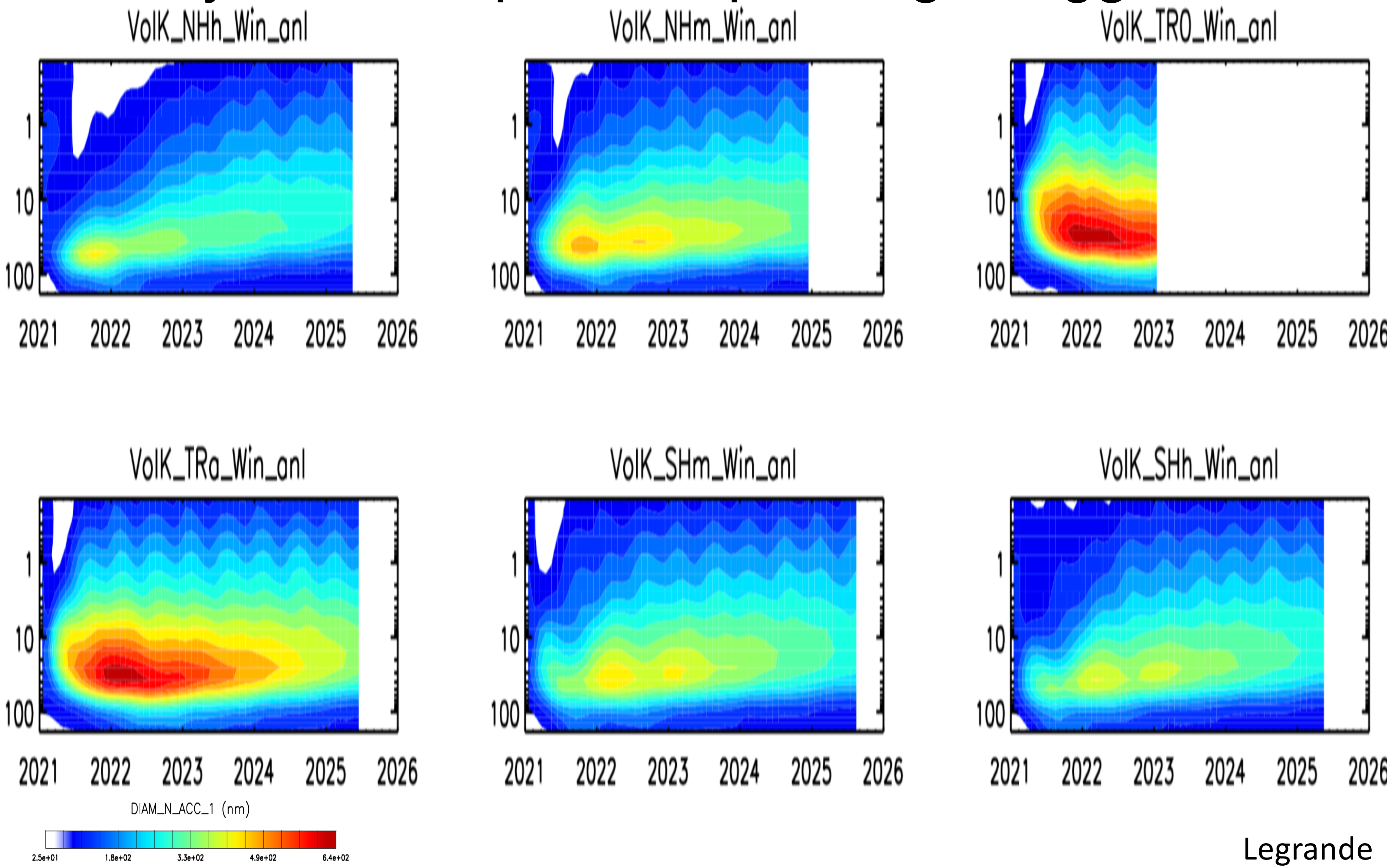
Increase in stratospheric water vapor

GEOS-5 simulations of a January tropical eruption

Contours: aerosol extinction

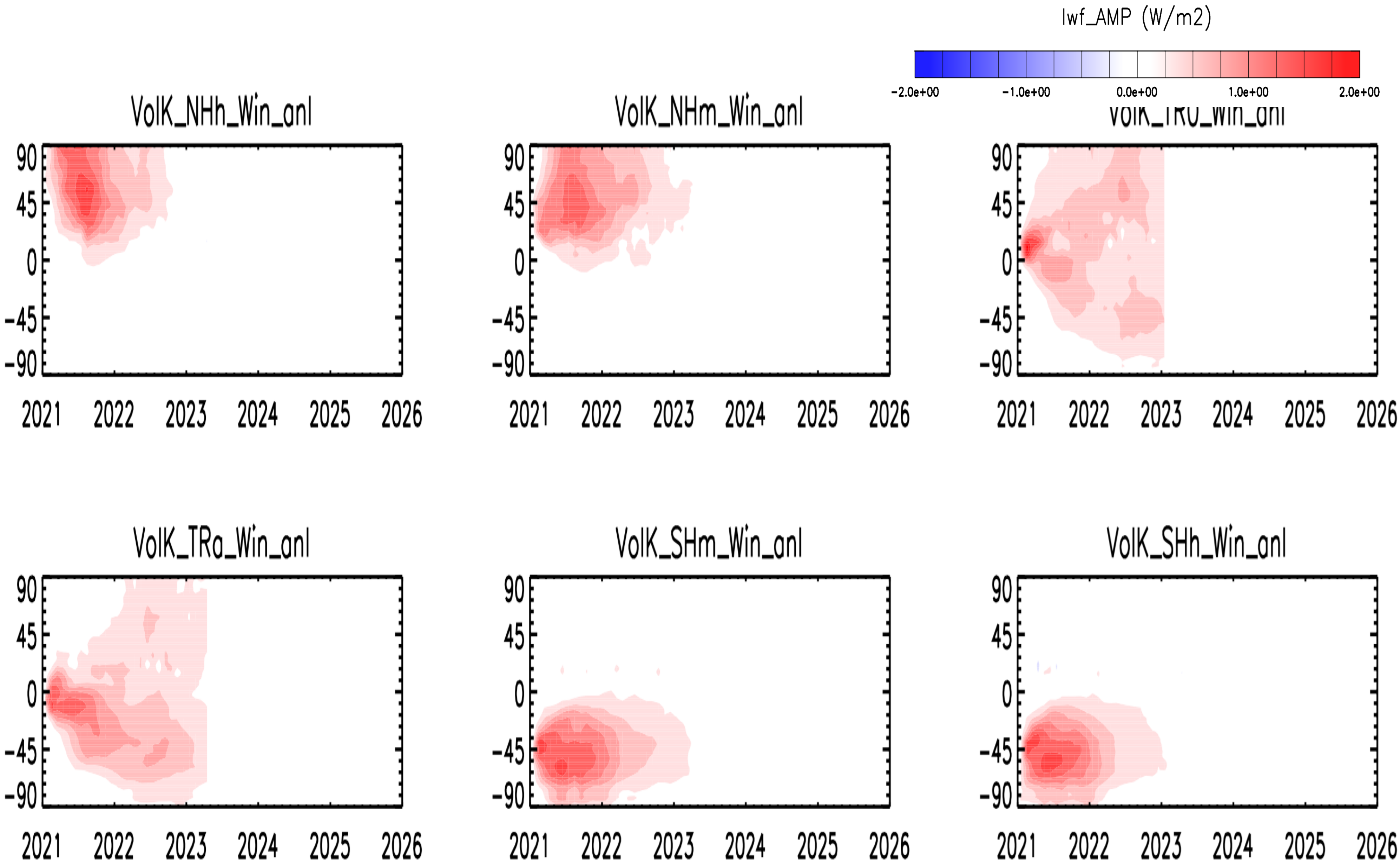


Sulfate reaches a maximum after a few years – tropical eruptions get bigger



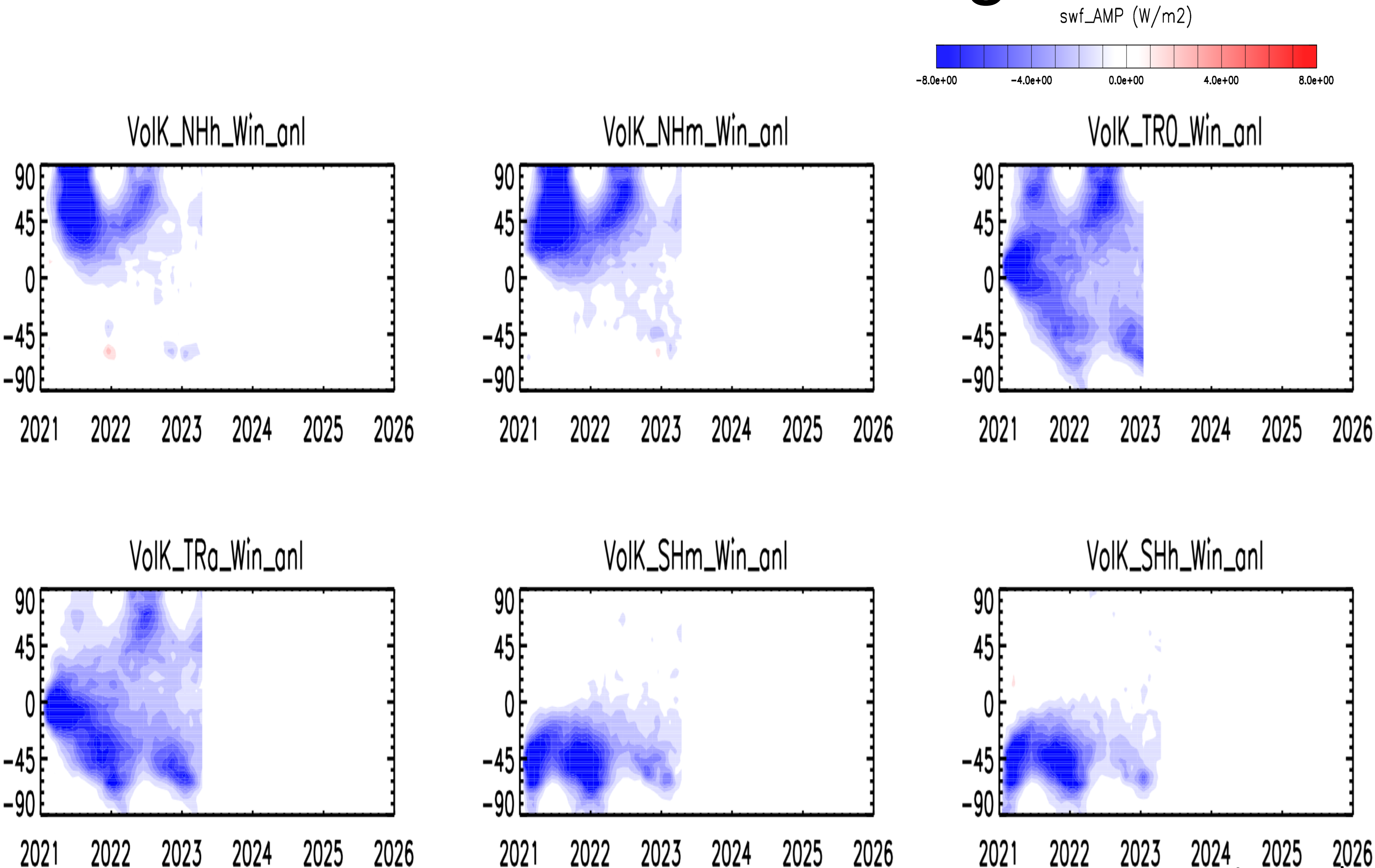
Legrande

Longwave Forcing



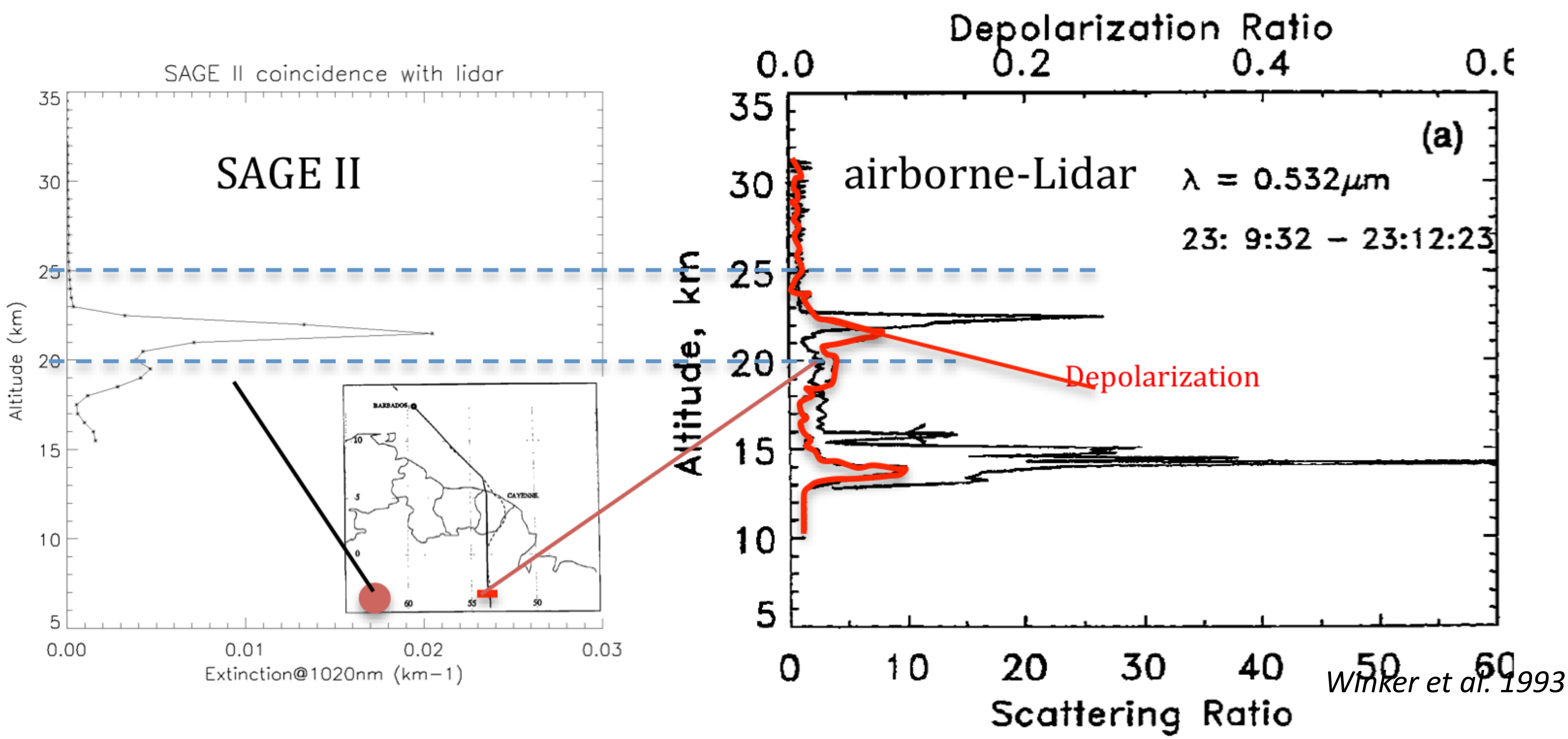
Legrande

Shortwave Forcing



Legrande

Microphysical evolution of Mt Pinatubo:

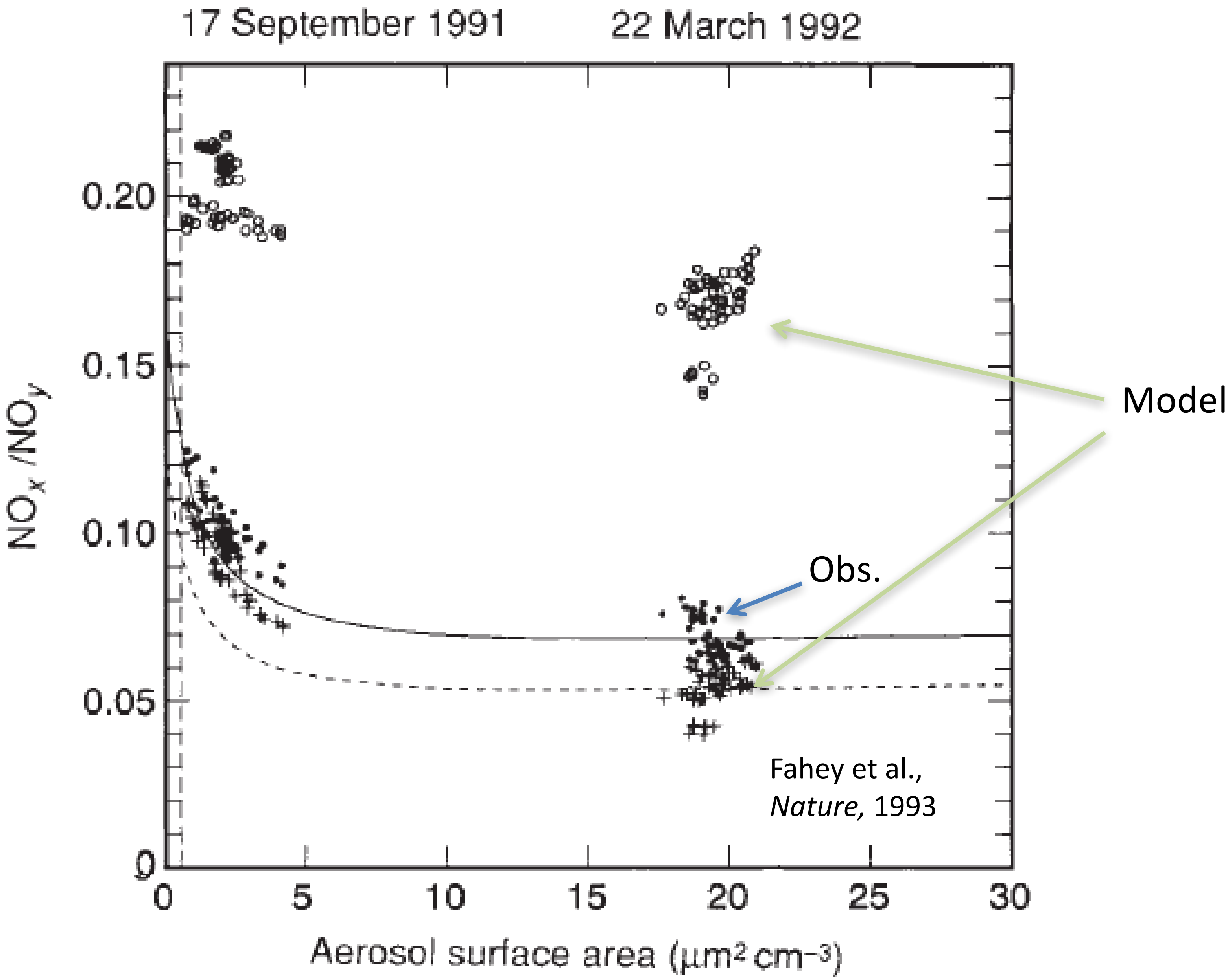


- Near-coincident observations of a sunrise occultation from SAGE II on 13 July 1991 and airborne lidar profiles at 23 UTC on 12 July 1991
- Depolarization measurements indicate the presence of volcanic ash at ~22km in the Mt Pinatubo plume a month after the eruption /large particles at the bottom of the plume.

Vernier

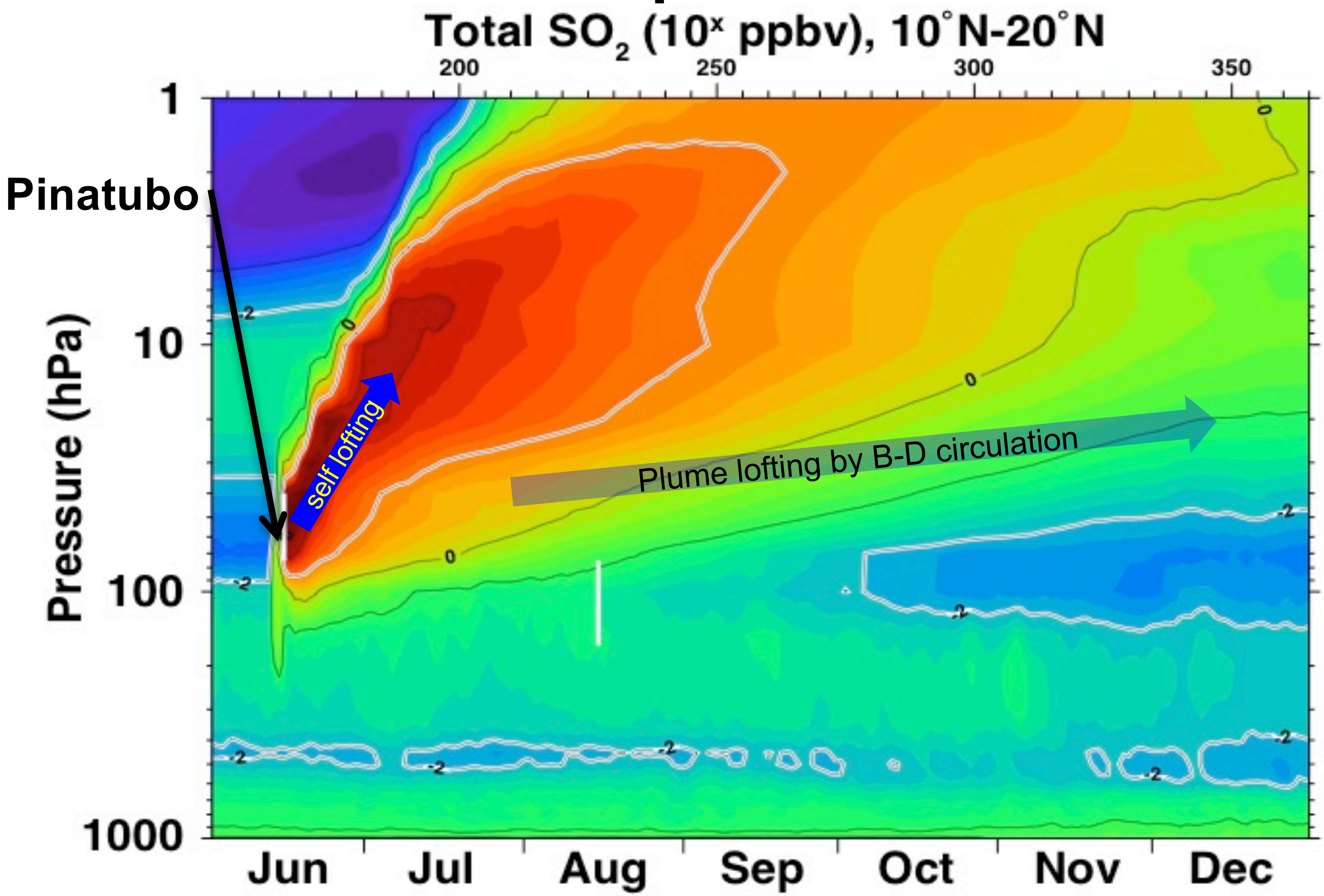
Heterogeneous chemistry:

As stratospheric aerosol rises, NO_x/NO_y drops due to $N_2O_5+H_2O$



Salawitch

Self-lofting of the volcanic plume



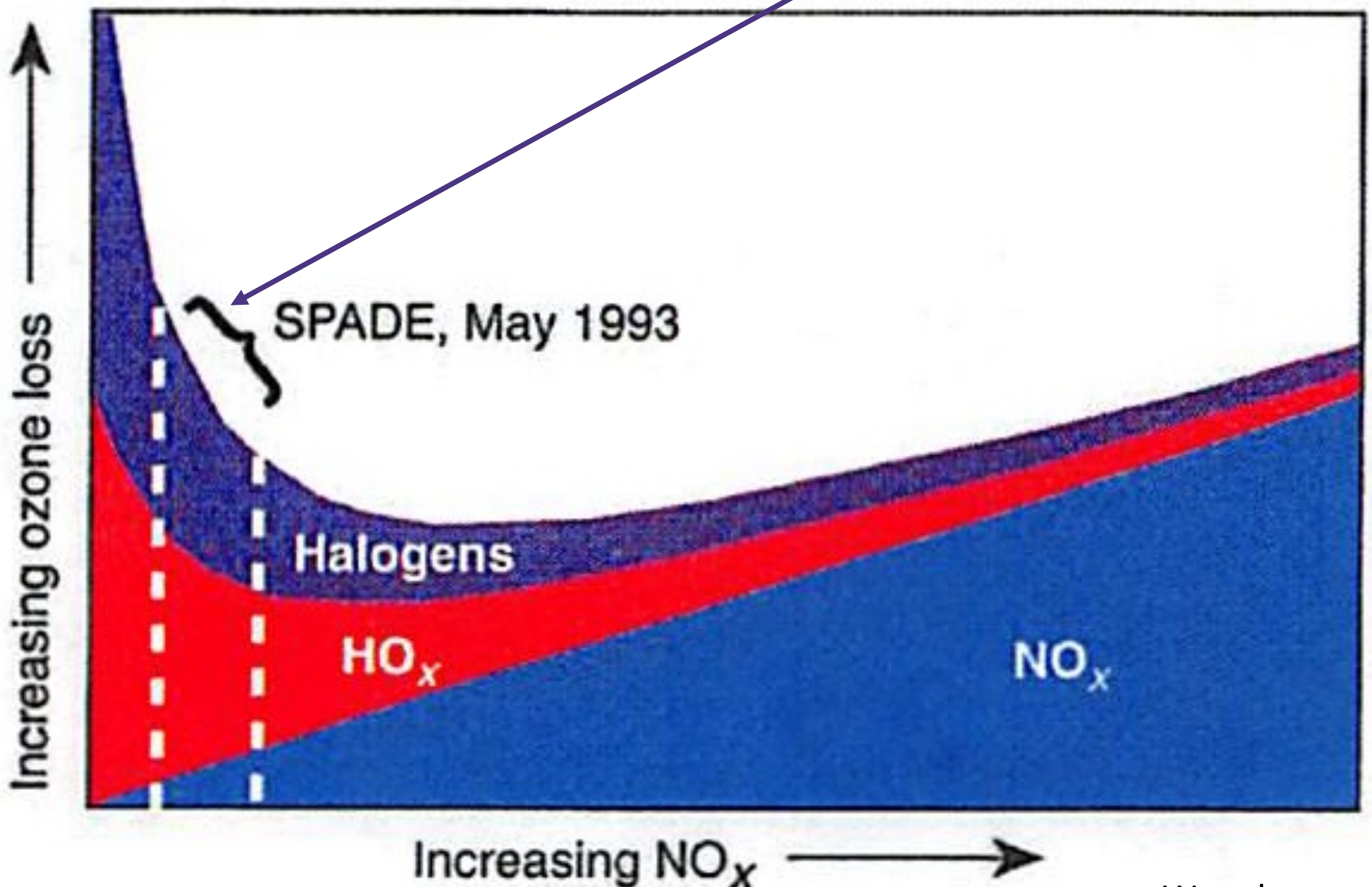
GEOS-5 Pinatubo simulations

Slide by P. Newman

Aquila

Heterogeneous chemistry:

- As stratospheric aerosol rises, NO_x/NO_y drops due to N_2O_5+H_2O
- ClO & HO_2 rise as NO_x falls
- In lower stratosphere, O_3 loss increases [i.e., O_3 is depleted more efficiently] due to the volcanically induced drop in NO_x

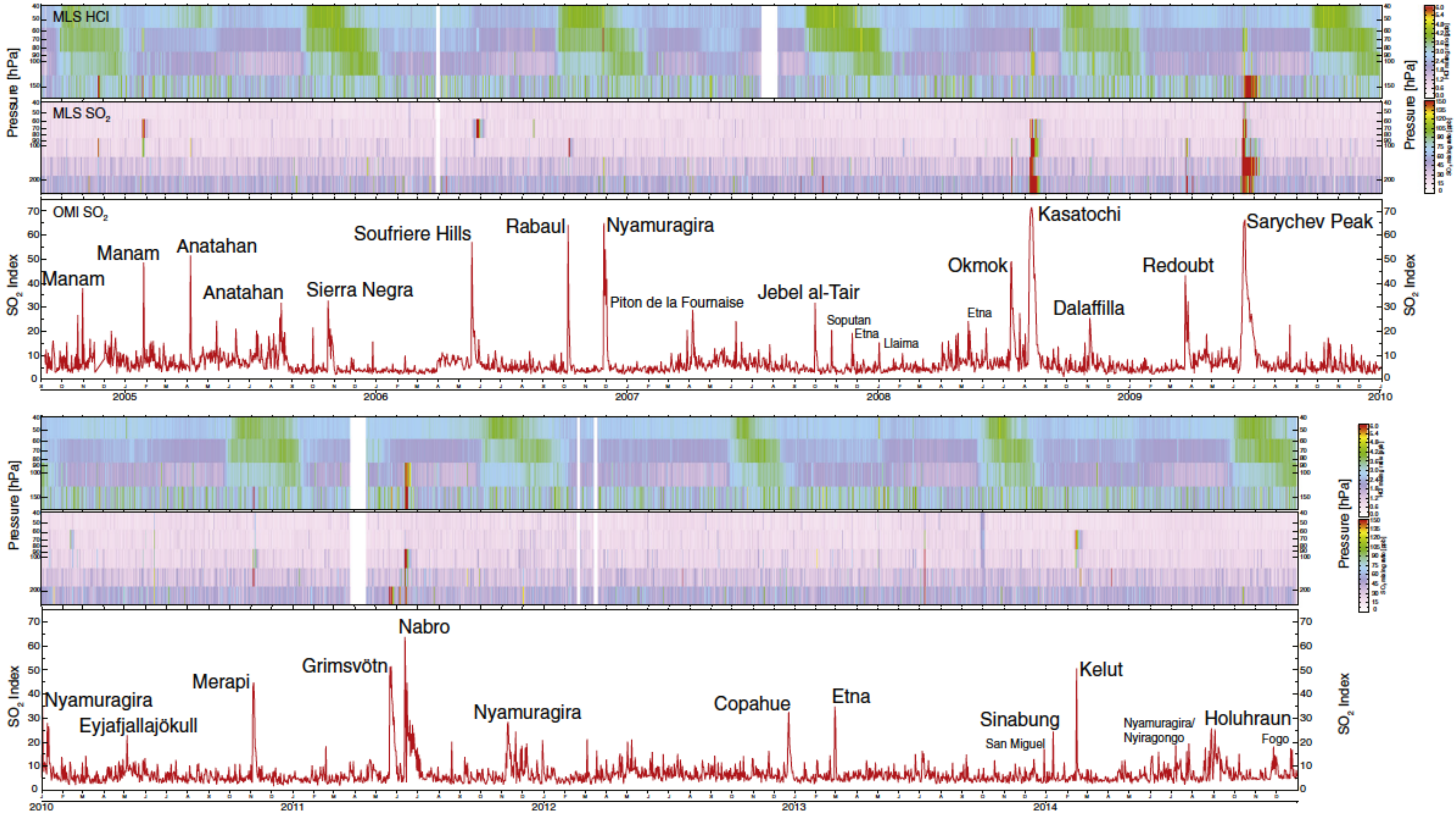


Wennberg et al., *Science*, 1994

Salawitch

MLS measurements of volcanically enhanced SO_2 and HCl in the UTLS

Carn et al. [*J. Volcanol. Geotherm. Res.*, 2016]



- Time series from September 2004 through December 2014 of maximum daily OMI SO_2 index and maximum daily MLS UTLS SO_2 and HCl as a function of pressure
- Explosive eruptions frequently inject HCl (up to ~6 ppbv) into the stratosphere
- Very strong volcanic perturbations allow detection in MLS SO_2 and HCl at retrieval levels outside the generally recommended range (e.g., at p > 100 hPa for HCl)

Constraining the climate effects of a major volcanic eruption

Question	Geophysical Parameters	Measurement Requirements	Current Capabilities		
			Ground	In situ	Space
What is the volcanic forcing of the climate system?	Injection timing, vertical profile	w/in 24 hours, plume top/bottom	Platform capability		
	Injection Composition	S, Cl, Br, H_2O, ash, …			
	Gas to particle conversion rate	e.g., SO_2 -> SO_4^-			
	Aerosol optical properties	particle size, shape, composition			
	Aerosol loading	Spectral AOT, extinction, backscatter			
What is the stratospheric response to volcanic forcing?	Temperature	up to ±4K (GEOS-5)			
	Water vapor	up to +0.5ppmv (GEOS-5)			
	Long-lived tracers	Up to 50 ppbv (N_2O GEOS-5)			
	Stratospheric winds				
	NO_x, ozone, …				

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	NO_x, ozone, …				

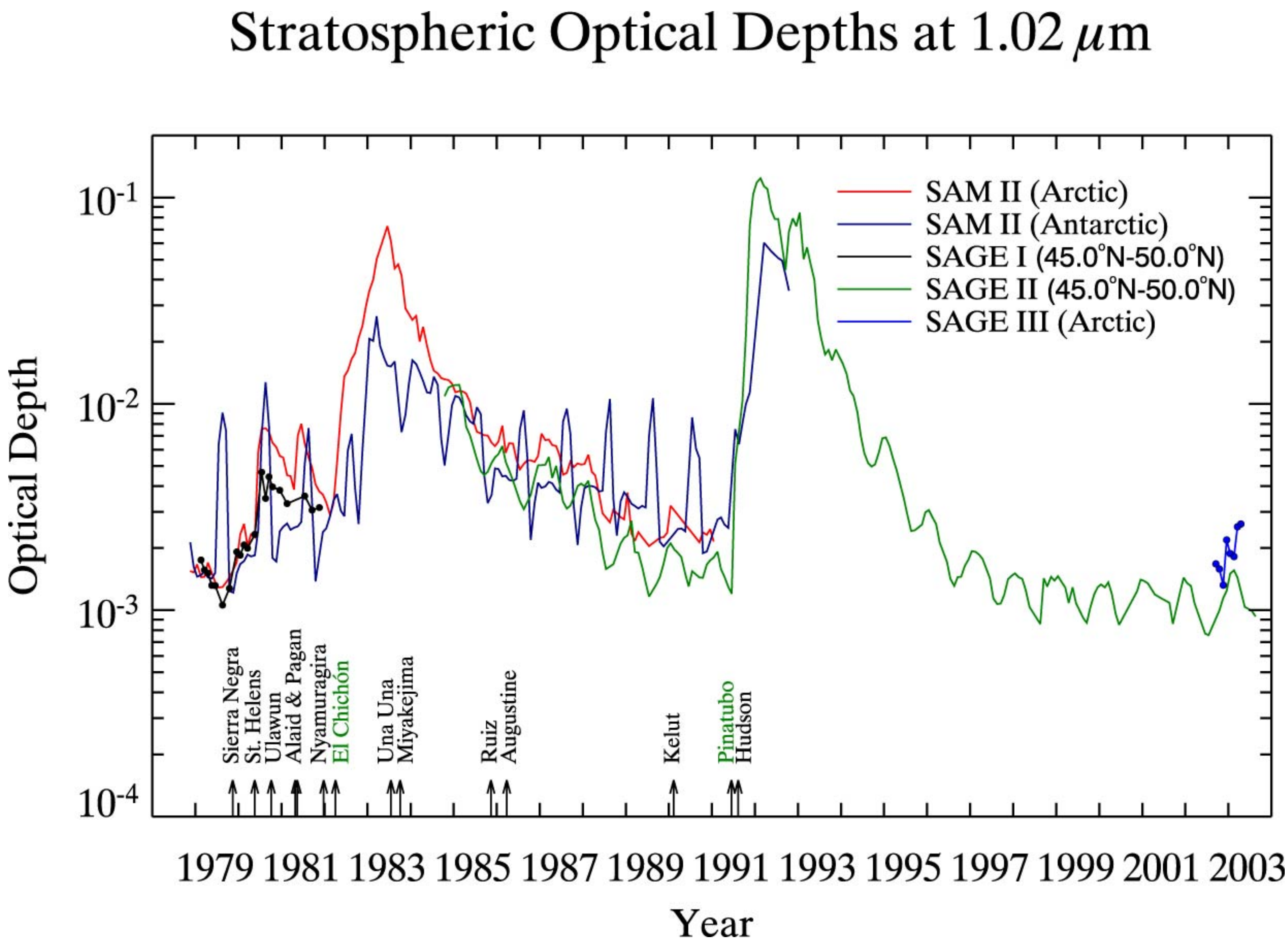
Report Outline

- Executive summary
- Need introduction – Brian, Paul N, Alan., Florian
  - What is a major volcano?
  - Science questions
  - Define the timeline: identify goals
- Need section that outlines overall behavior of volcanic clouds
  - Historic perspective (Brian, Pat, & Allegra)
  - Hypothetical model simulations (Pete, Valentina, Allegra, Kostas)
  - What are the available instruments, assets? (see next page)
  - Traceability matrices (post June 30) Paul, Hal, Ken
- Plans according to the eruption time-scale: 5 plans for each sub-section: model, ground, AC, balloon, satellite (see next page)
  - Pre-eruption. How well can we predict a major eruption, & how far in advance?
  - 0-30 days
  - 1month to 3 years

This is the end, beautiful friend
This is the end, my only friend, the end
Of our elaborate plans, the end
Of everything that stands, the end
No safety or surprise, the end
I'll never look into your eyes, again

- End of the Night, The Doors (1967)

SAM II, SAGE I/II/III



McCormick

Next steps

- Rewrites of section ppt's (initial writers). May 27
- Drafting of instrument tables: June 30

  Lidar/Sunphotometer –

  Satellite –

  Balloons (large and small) –

  Aircraft –

  Modeling
- Formulation of plans June 30
  - Modeling - Allegra, Valentina, Pete
  - Ground - Judd, Paul S
  - Aircraft - Brian, Paul N, Mike C, Hal, Ken
  - Balloon - Ru-shan, Jean-Paul
  - Satellite - Ralph, Norm, PK, Michelle
- 1st draft on 1 Sept.