Monitoring capability for volcanic eruptions: Limb scanning satellites

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Monitoring of Geoengineering Effects and their Natural and Anthropogenic Analogues

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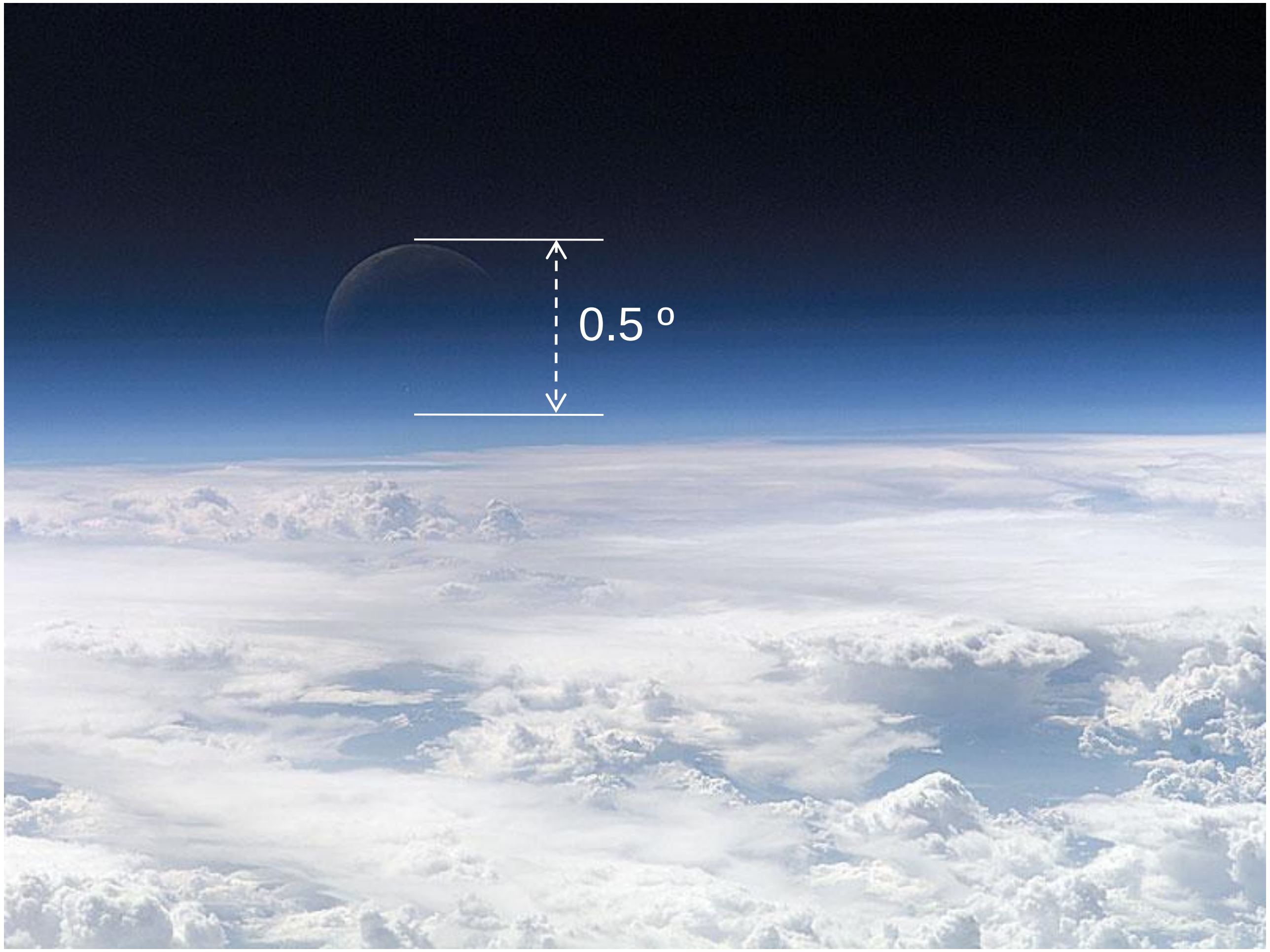
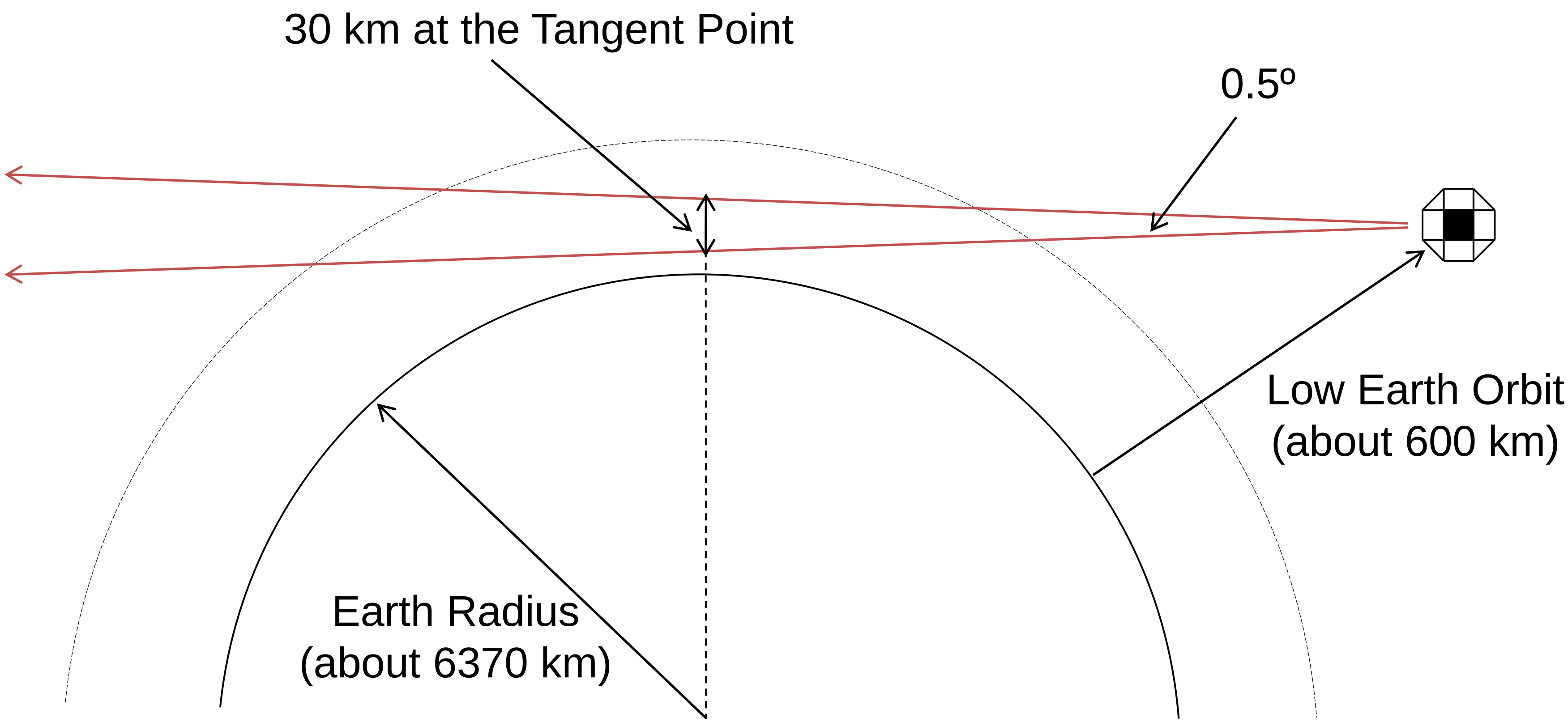
The Limb View



A view of the Earth's limb from the ISS

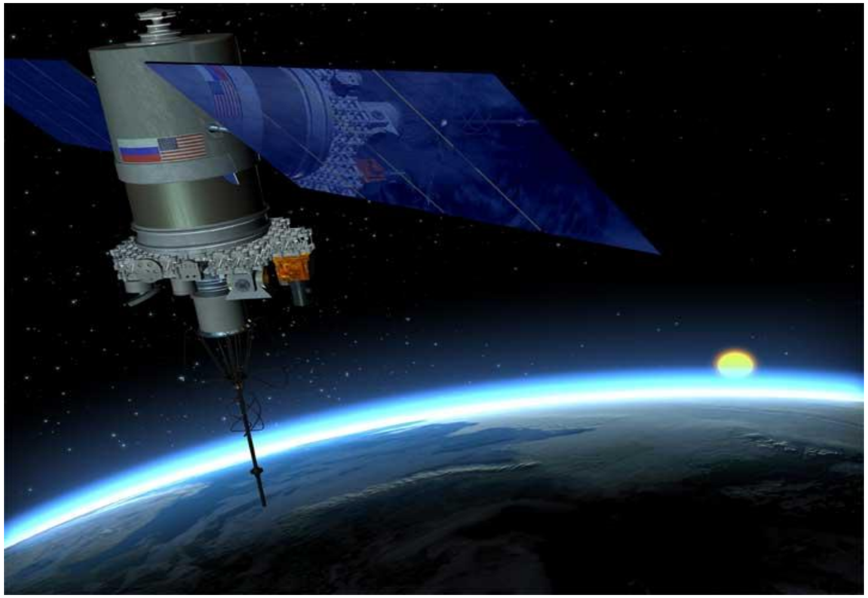
The Limb View of the Atmosphere



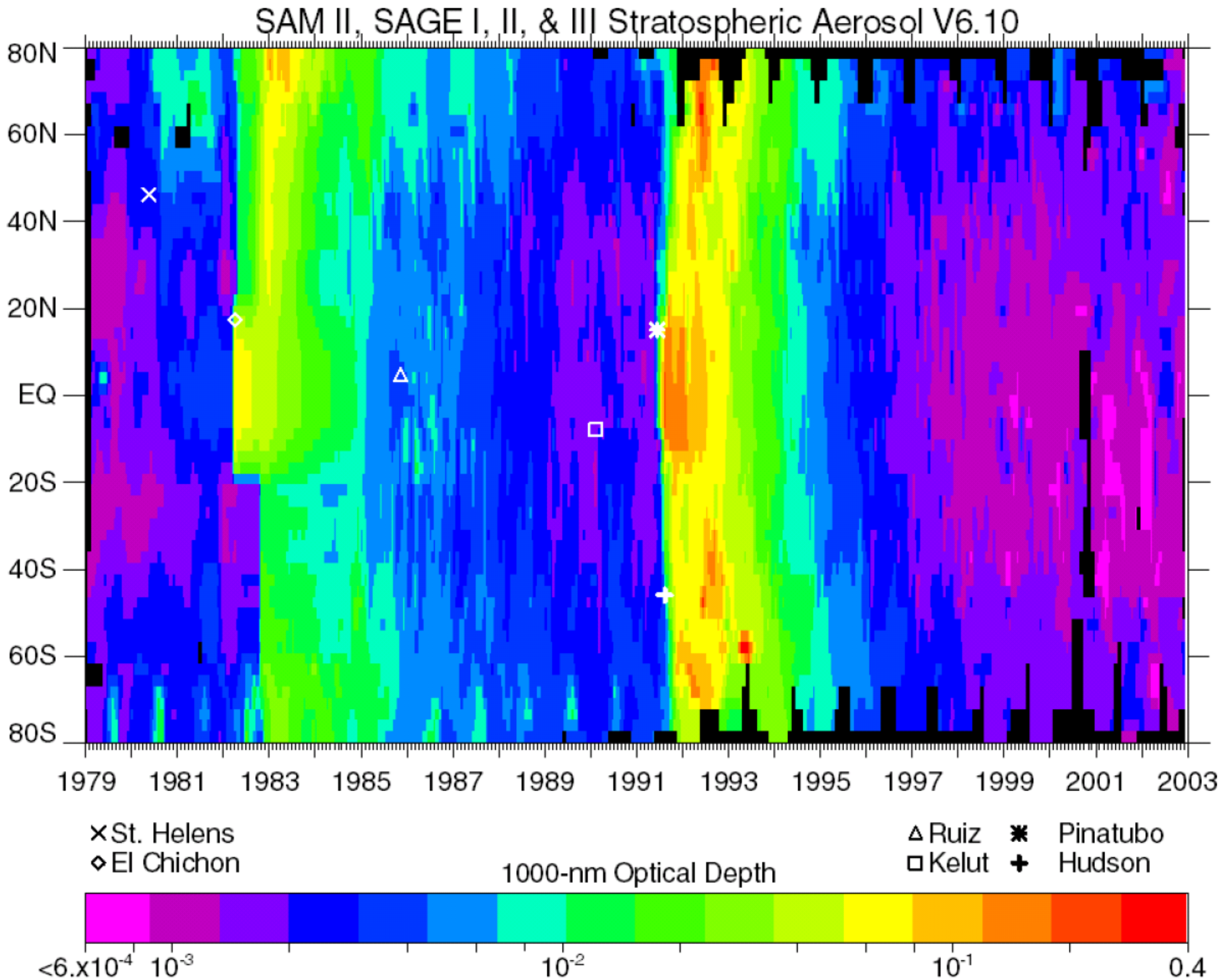
Rule of Thumb: 1 arcminute ≈ 1 km at the tangent point

Solar Occultation

- A long term measurement standard (1970's) for ozone and aerosol profiles
- Stability – inherent calibration and pointing information
- High vertical resolution (around 1 km)
- Relatively poor global coverage
    - Two profiles per orbit: observed sunrise and sunset
- Solar Occultation Missions
    - SAM II, 1978 – 1993
    - SAGE II, 1984 – 2005
    - SAGE III, 2002 – 2006
    - HALOE, 1991 – 2005
    - POAM II/III, 1993 – 2005
    - ACE, 2003 – current
- The future?
    - SAGE III on ISS in 2014
    - CASS (ACE-FTS2 + OSIRIS2) ?



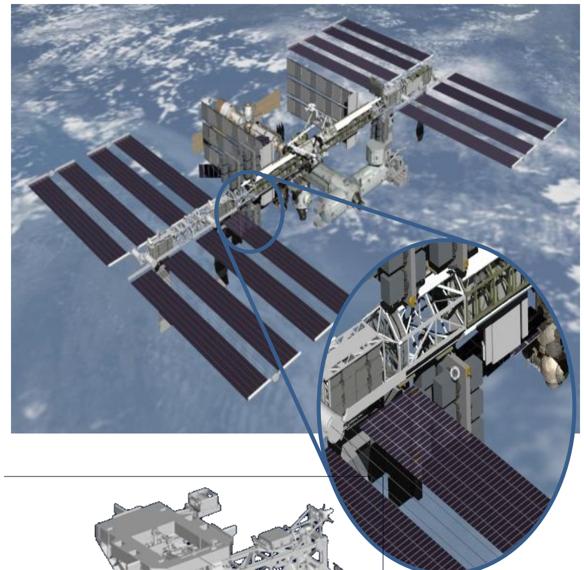
Solar Occultation

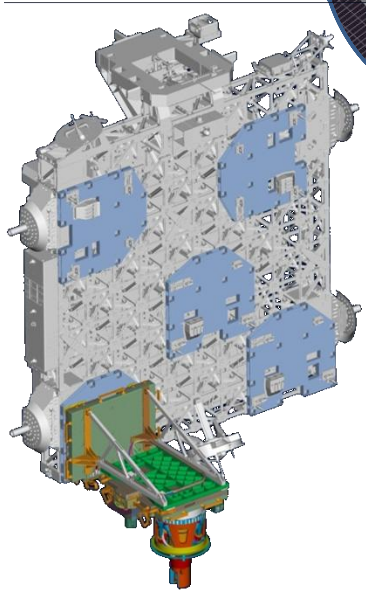


From Assessment of Stratospheric Aerosol Properties, SPARC Report, Ed. Thomason

SAGE III on ISS

www-sage3oniss.larc.nasa.gov





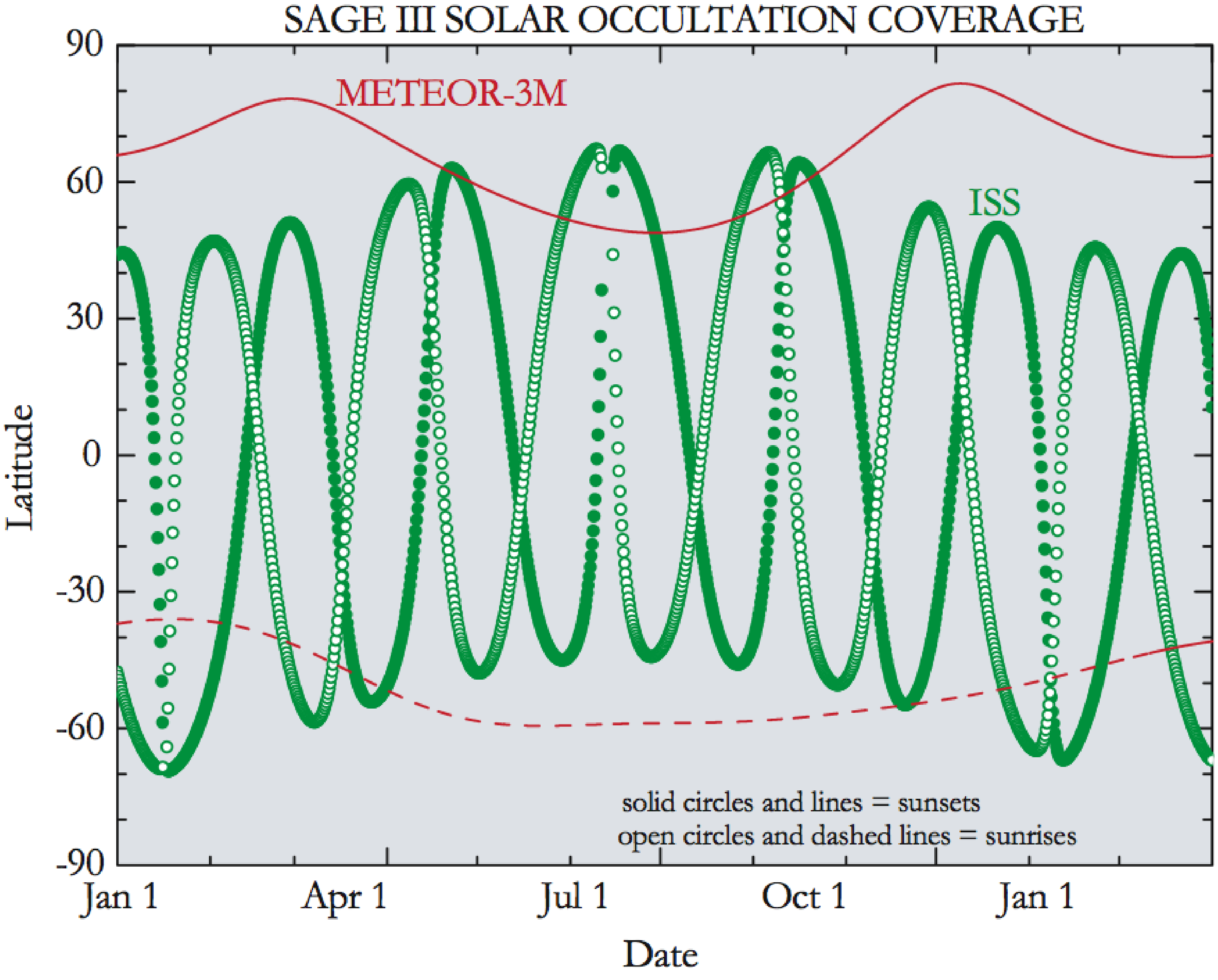
SAGE III on ISS directly supports NASA Strategic Goals to extend and sustain human activities across the solar system; expand scientific understanding of the Earth and the universe in which we live

Primary Science Objective:

Monitor the vertical distribution of aerosol, ozone and other trace gases in Earth's stratosphere and troposphere to enhance understanding of ozone recovery and climate change processes in the upper atmosphere

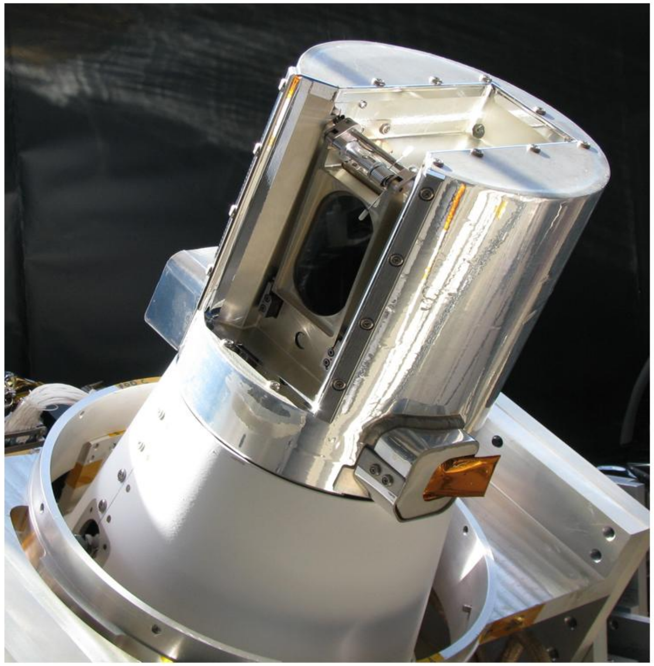
Mission Implementation	
Partners	**LaRC** (Science; Project Management; System Engineering and Mission Design; SMA; I&T; Launch Support; Mission Operations; Science Data Processing and Delivery) **JSC/ISSP** (System Engineering Support, Hexapod Pointing System and ISS mounting adaptors, ISS Mounting Location, Launch Processing and Access to Space, Infrastructure and Telemetry Data)
Launch	August 2014 (Space X)
Orbit	ISS Mid-Inclination orbit
Life	3 years (nominal) / ISS manifest through 2020 for extended mission
Payload	Sensor Assembly (LaRC), Hexapod (ESA), CMP (LaRC), ExPA (JSC/ISS), ICE (LaRC), HEU (ESA), IAM (LaRC), DMP (LaRC), Nadir Viewing Platform (LaRC)
Data	Solar Occultation: Multi-wavelength Aerosol Extinction, O_3, NO_2, H_2O Lunar Occultation: O_3, NO_2, NO_3 Limb Scatter: Multi-wavelength Radiance

The Inclined ISS Orbit is Ideal for SAGE III measurements

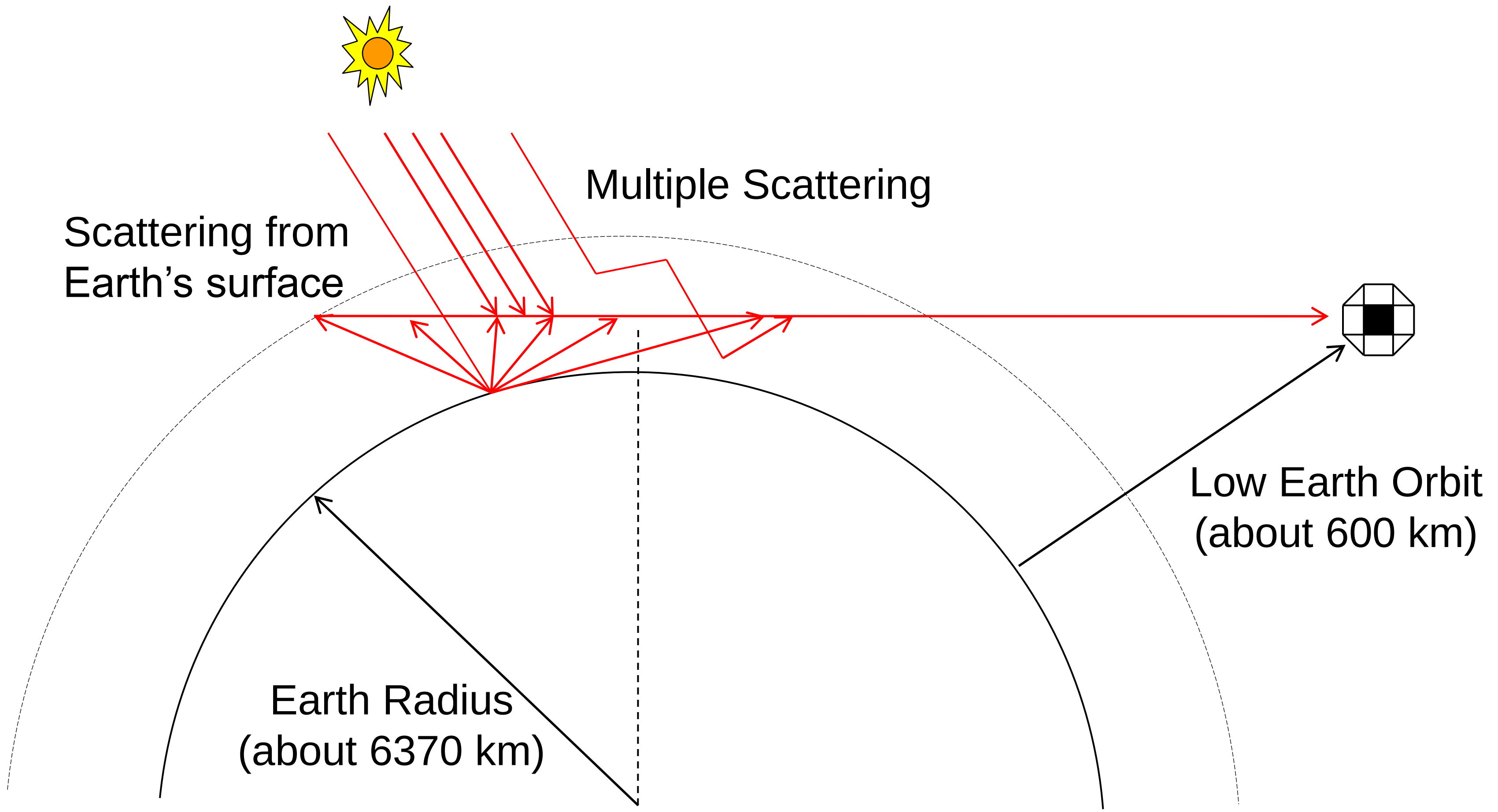


Mission Foundation is Based on Existing Flight Hardware

- SAGE III has been maintained at NASA LaRC
- Hexapod has been maintained at Thales / Alenia in Turin Italy

	
Sage III Instrument	Hexapod Pointing System

A measurement of the intensity of sunlight scattered from the atmosphere



Measuring Aerosols with Limb Scatter

- **A non-linear inverse problem**

The physics of limb scattered sunlight

All other inputs

$$\mathbf{y} = \mathbf{F}(\mathbf{x},\ \mathbf{b})$$

The measured spectra

Our desired parameter (the aerosol state)

- **What is the physics? The Radiative Transfer Equation**

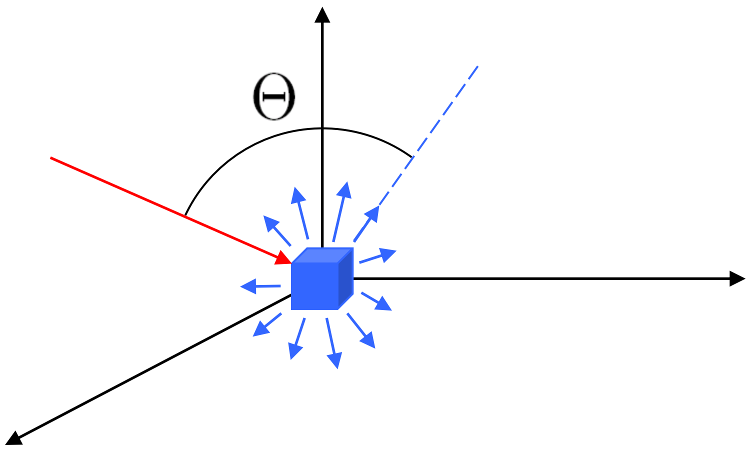
$$I(\vec{r}_0, \hat{\Omega}) = \int_{s_1}^{0} J(s, \hat{\Omega})\, \mathrm{e}^{-\tau(s,0)}\, \mathrm{d}s + \tilde{I}(s_1, \hat{\Omega})\, \mathrm{e}^{-\tau(s_1,0)}$$

$$J(s, \hat{\Omega}) = k_{\mathrm{scat}}(s) \int_{4\pi} I(s, \hat{\Omega}')\, \bar{p}(s, \Theta)\, \mathrm{d}\Omega'$$

The source term arises from the incident sunlight:

$$J(s,\hat{\Omega}) = k_{\text{scat}}(s)\int_{4\pi} I(s,\hat{\Omega}')\,\bar{p}(s,\Theta)\,\mathrm{d}\Omega'$$

At a scattering volume, the sun is incident from exactly one direction:



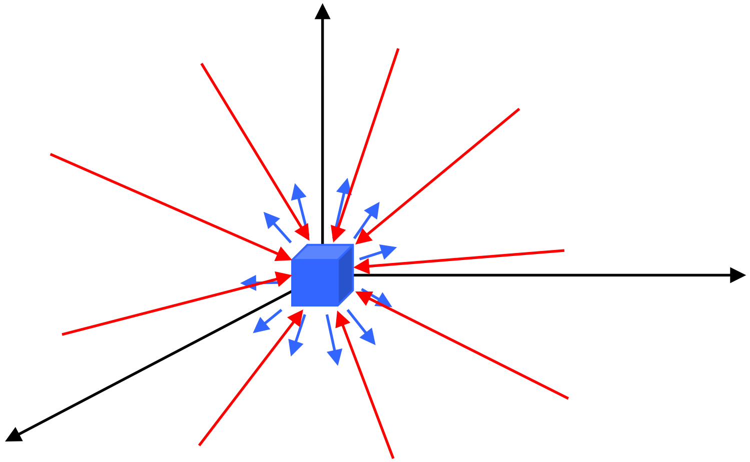
The source term results from scattering of incoming radiation into all directions.

The phase function, $\bar{p}(s,\Theta)$, defines the probability of scattering in a direction.

The source term is radiation scattered from atmosphere and earth surface:

$$J(s,\hat{\Omega}) = k_{\text{scat}}(s) \int_{4\pi} I(s,\hat{\Omega}')\,\bar{p}(s,\Theta)\,\mathrm{d}\Omega'$$

At a scattering volume, radiation is coming from all directions.



The total source term is the sum of the scattering of radiation from every incoming direction into every outgoing direction.

Ray tracing computer model: discretize the parameters and the integrals.

SASKTRAN Radiative Transfer Model

A fast, fully spherical, 3D, successive orders, discrete ordinates model.

A subdivision of the source terms (and ground radiance) by scattering order:

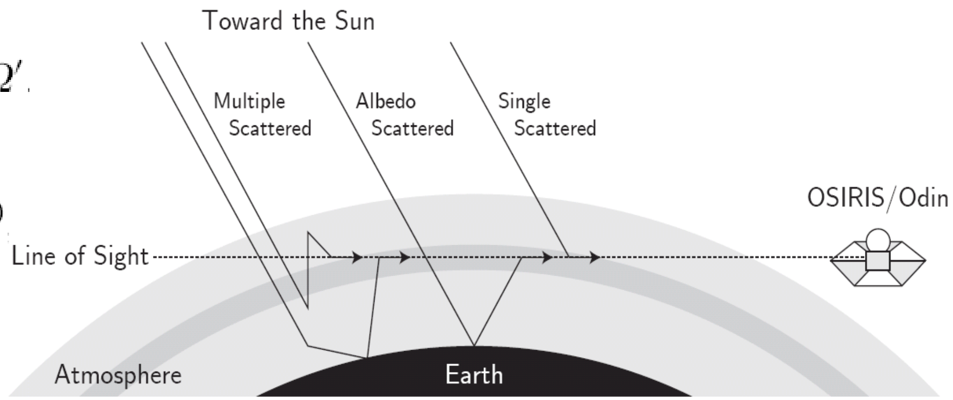
$$I(\vec{r}_0, \hat{\Omega}) = \int_{s_1}^{0} \left[J_1(s, \hat{\Omega}) + J_2(s, \hat{\Omega}) + \sum_{i=3}^{\infty} J_i(s, \hat{\Omega}) \right] \mathrm{e}^{-\tau(s,0)}\, \mathrm{d}s + \left[\tilde{I}_1(s_1) + \tilde{I}_2(s_1) + \sum_{i=3}^{\infty} \tilde{I}_i(s_1) \right] \mathrm{e}^{-\tau(s_1,0)}$$

A recursive calculation for n-order multiple scattering:

$$J_i(s, \hat{\Omega}) = k_{\mathrm{scat}}(s) \int_{4\pi} [I_{i-1}(s, \hat{\Omega}')]\, \bar{p}(s, \hat{\Omega}, \hat{\Omega}')\, \mathrm{d}\Omega'$$

$$I_i(\vec{r}_0, \hat{\Omega}) = \int_{s_1}^{0} J_i(s, \hat{\Omega})\, \mathrm{e}^{-\tau(s,0)}\, \mathrm{d}s + \tilde{I}_i(s_1)\, \mathrm{e}^{-\tau(s_1,0)}$$

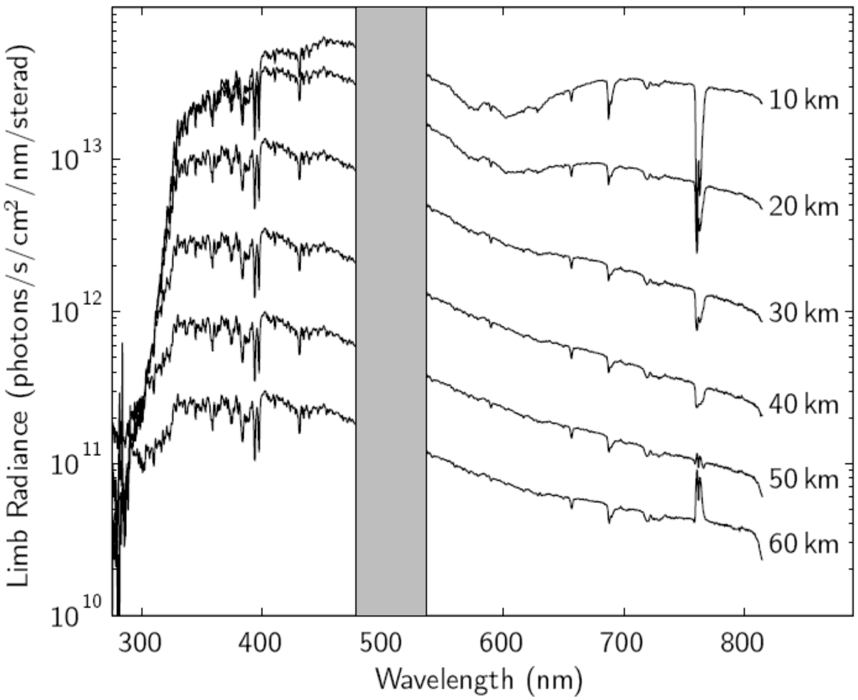
$$\tilde{I}_i(s_1) = \frac{a}{\pi} \int_{2\pi} I_{i-1}(s_1, \hat{\Omega}') \cos(\theta')\, \mathrm{d}\Omega'$$

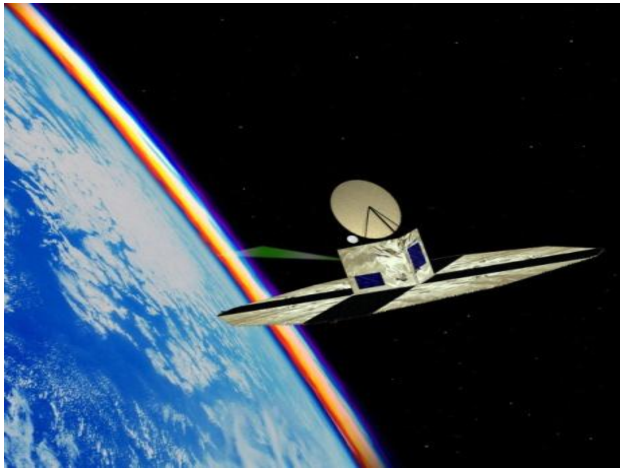


Optical Spectrograph and Infrared Imager System (OSIRIS)

OSIRIS does limb scanning and limb imaging

1) Optical Spectrograph
   - Single line of sight, narrow horizontal slit
   - Grating spectrograph, 280-810 nm, 1 nm res
   - Auto-exposed limb scan
2) Infrared Imager
   - Three channel filtered vertical imager
   - 1.26 and 1.27 μm O_2(1D) emission
   - 1.53 μm OH emission and scattered sunlight

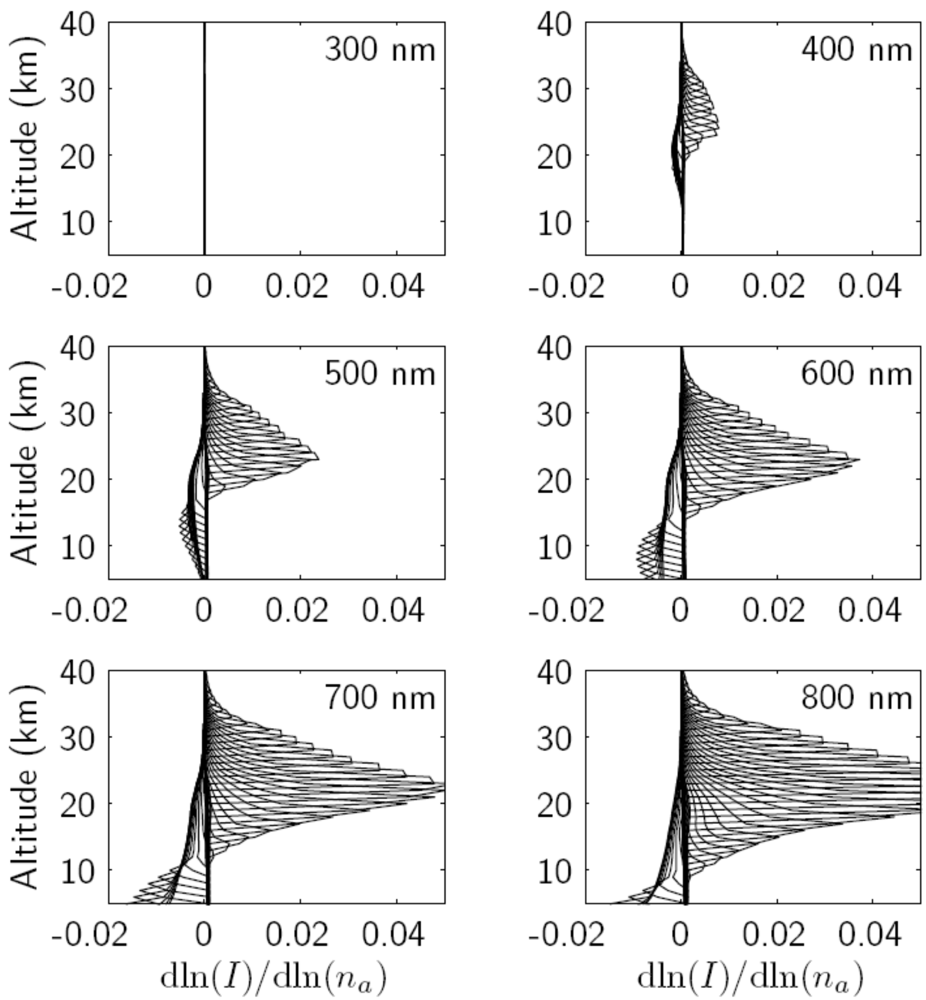




Launch 2001 – 100% aeronomy measurements since 2007
MART Version 5.0 retrievals fully processed including aerosol extinction coefficient at 750 nm

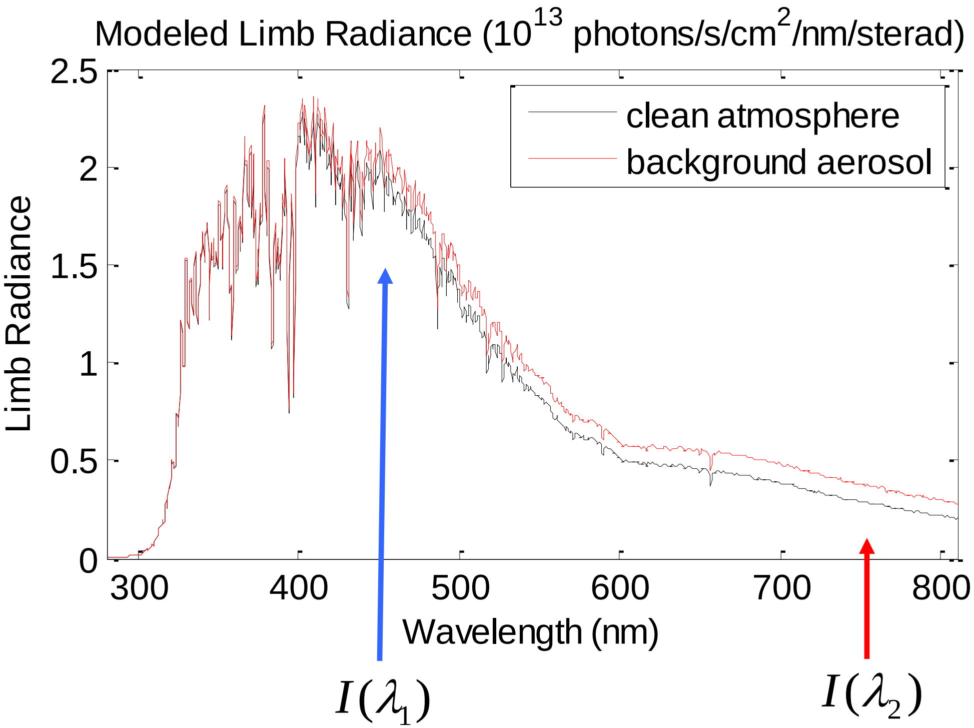
The Limb Scatter Signature of Stratospheric Aerosol

Aerosol Weighting Functions (Jacobian)



- Visible/NIR stratospheric aerosol signal is well characterized by Mie scattering (liquid droplets around 0.1 to 0.3 micron radius)
- Cross section spectrum is a relatively weak function of wavelength
- Enhancement and attenuation effects that depend on (aerosol) optical depth

Typical limb spectrum at 22 km tangent altitude calculated with the SASKTRAN Radiative Transfer Model



The Measurement Vector

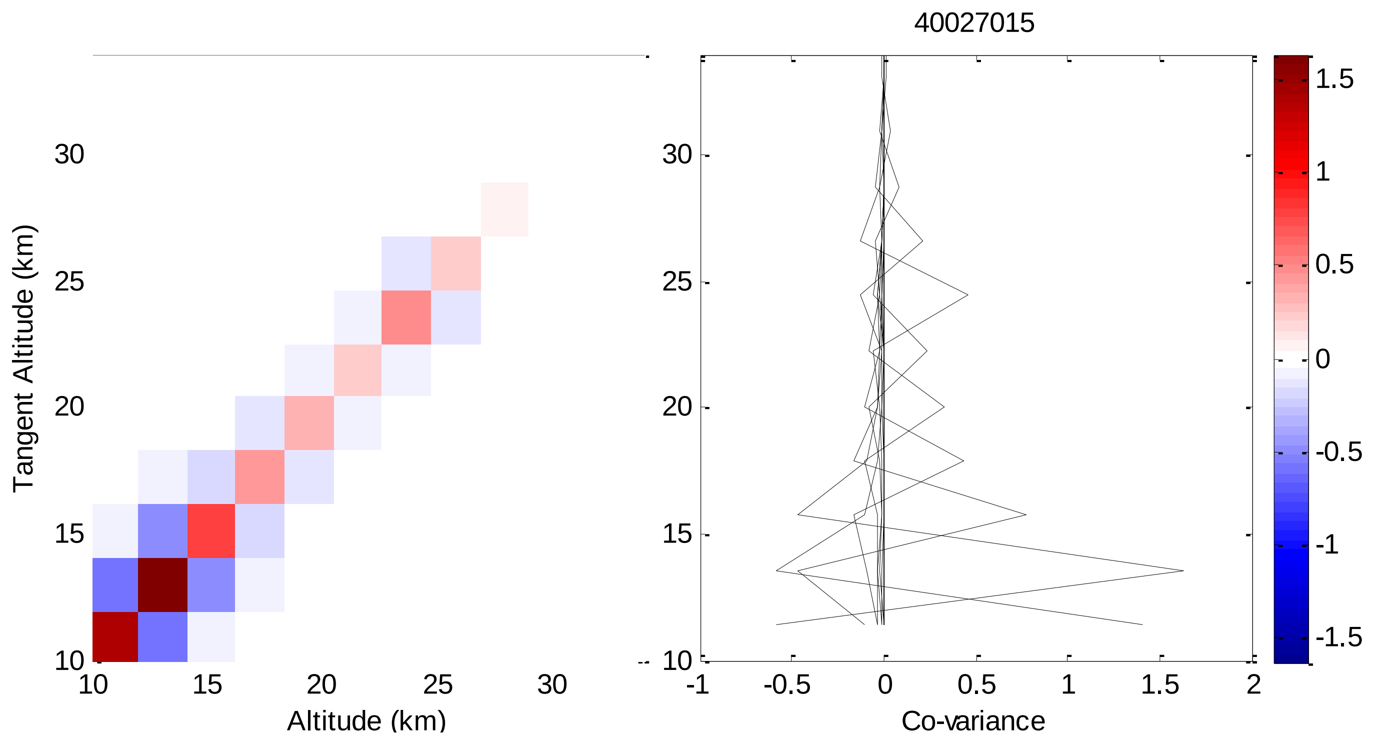
$$y = \log\left(\frac{I(\lambda_2)}{I(\lambda_1)}\right) - \log\left(\frac{I_R(\lambda_2)}{I_R(\lambda_1)}\right)$$

$I_R(\lambda) \equiv$ Model with no aerosol

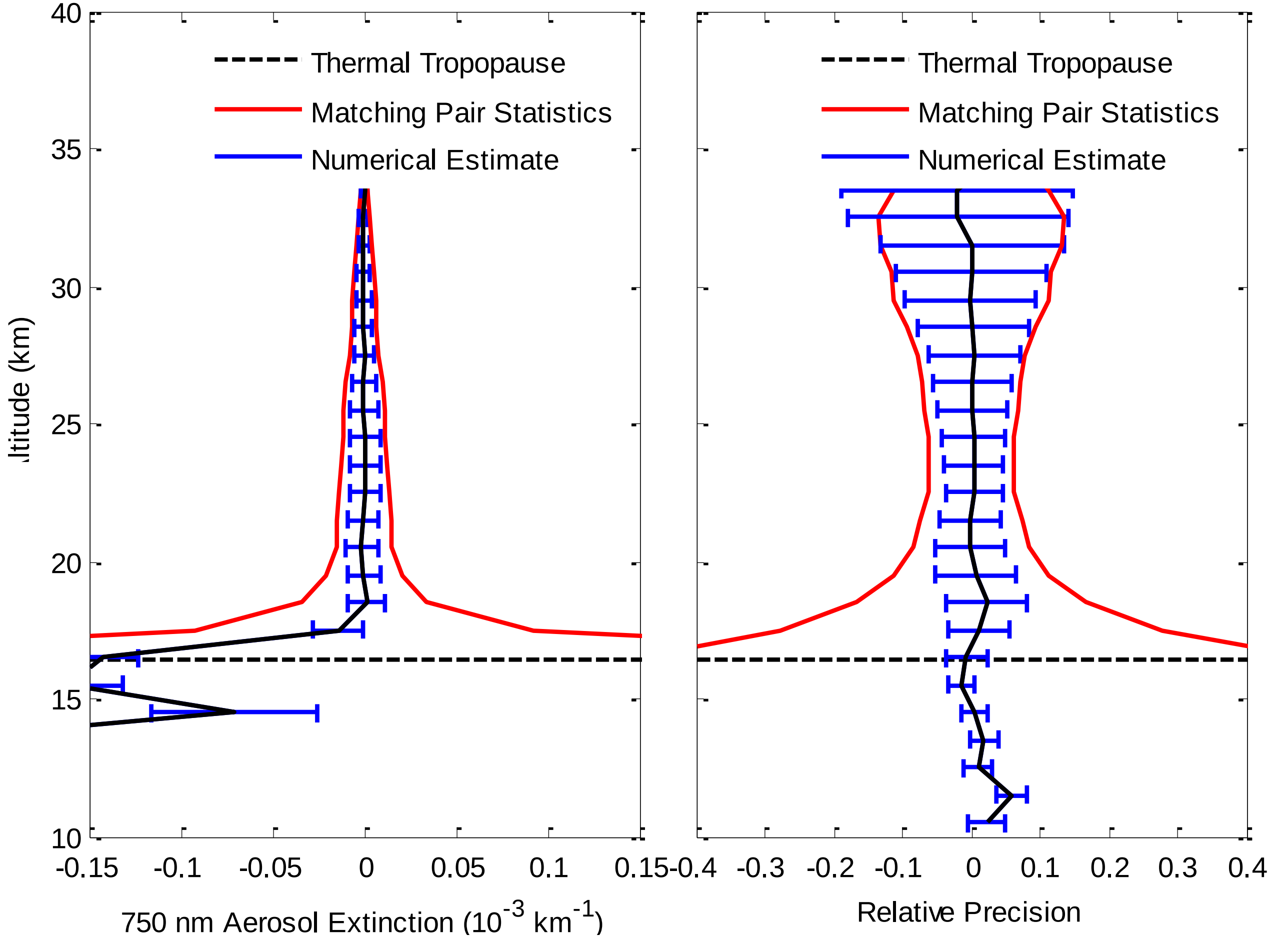
Effectively a measure of the residual scattering (positive Jacobian required)

OSIRIS Aerosol Retrieval: Error Analysis

- Newly developed precision analysis for MART V5.01 Processing
- Numerical estimate of the co-variance matrix
  - Propagation of the Level 1 error bar (random error) to the state parameter
  - Linearization of the inversion about the retrieved state

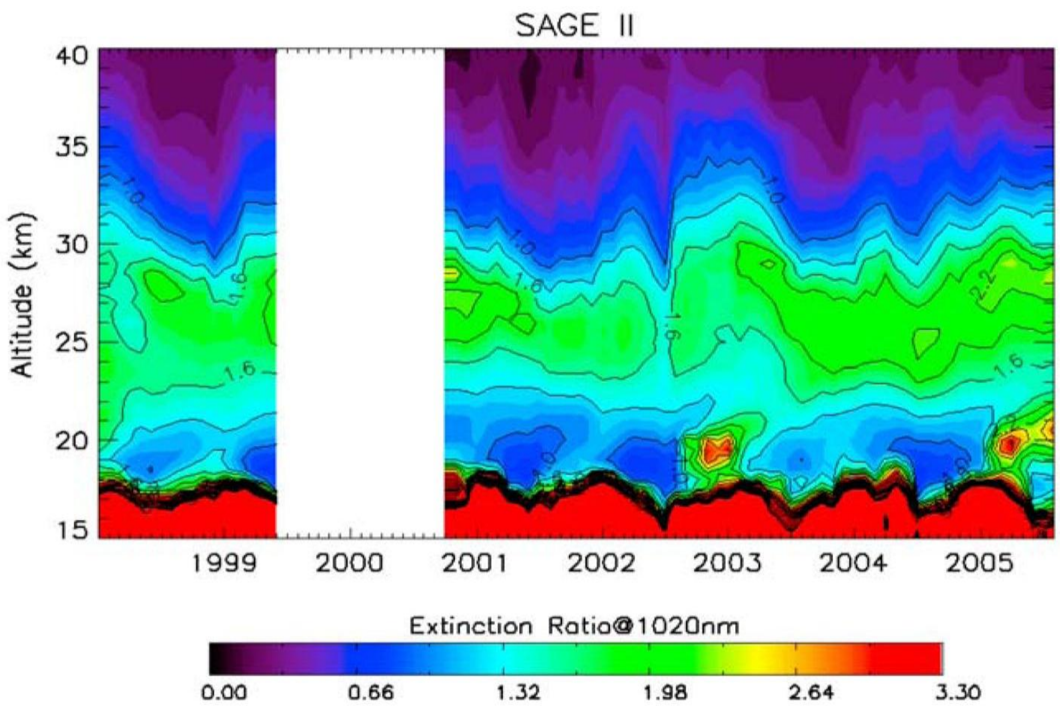


Statistics for 765 “Matched Pairs” in 2008 for latitudes 0 to 10 N



Comparison with SAGE II

Figure 8 from Vernier et al., JGR, 2009: SAGE II zonal mean 1.0 micron extinction ratio (20 N to 20 S); 1998-2006



Lower stratospheric volcanic eruptions:
- Raventador, Ecuador, September, 2002
- Manam, Papua New Guinea, February, 2005

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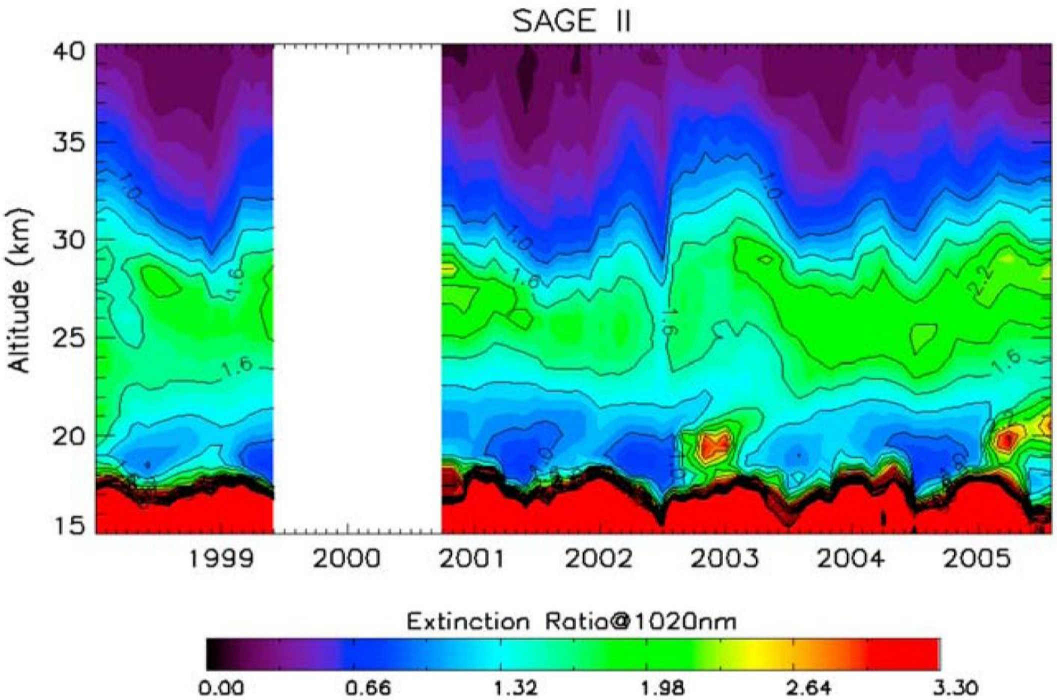

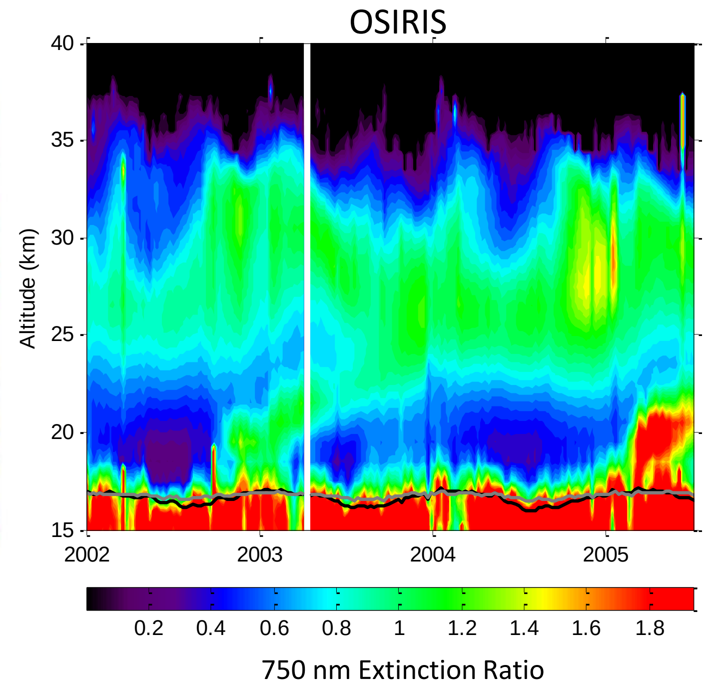

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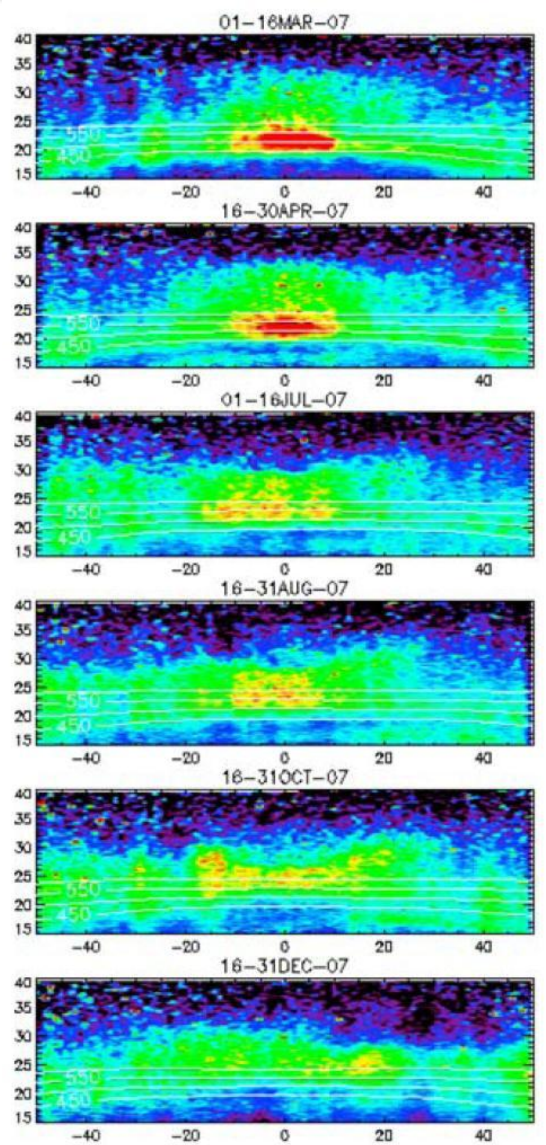
Comparison with CALIPSO

Figure 9 from Vernier et al., JGR, 2009: CALIOP zonal average scattering ratio for 16 day time periods throughout 2007



- Early 2007: Aerosol layer from Montserrat 10 months post-eruption confined in high altitude tropical stratospheric reservoir with relatively clean TTL
- Later 2007: Double horned vertical propagation towards subtropics in westerly phase of QBO

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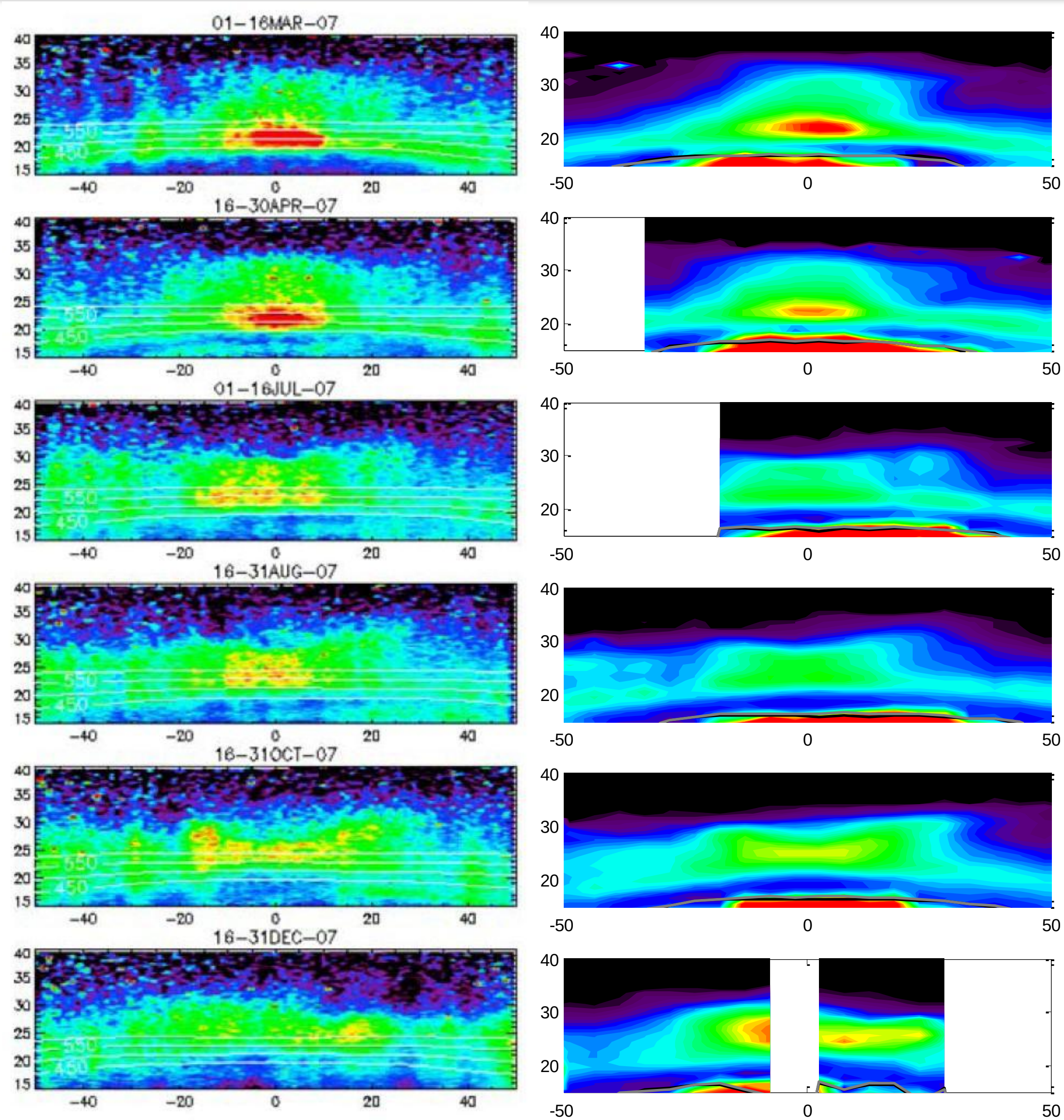
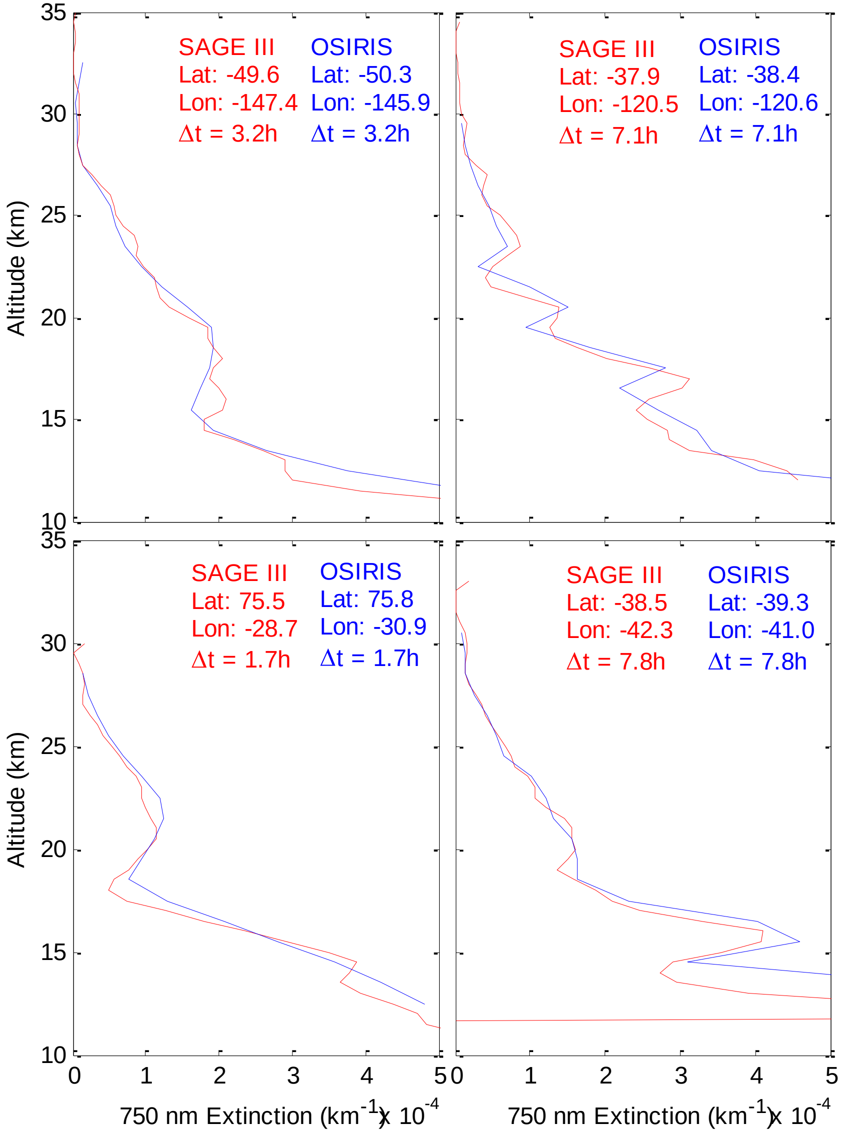
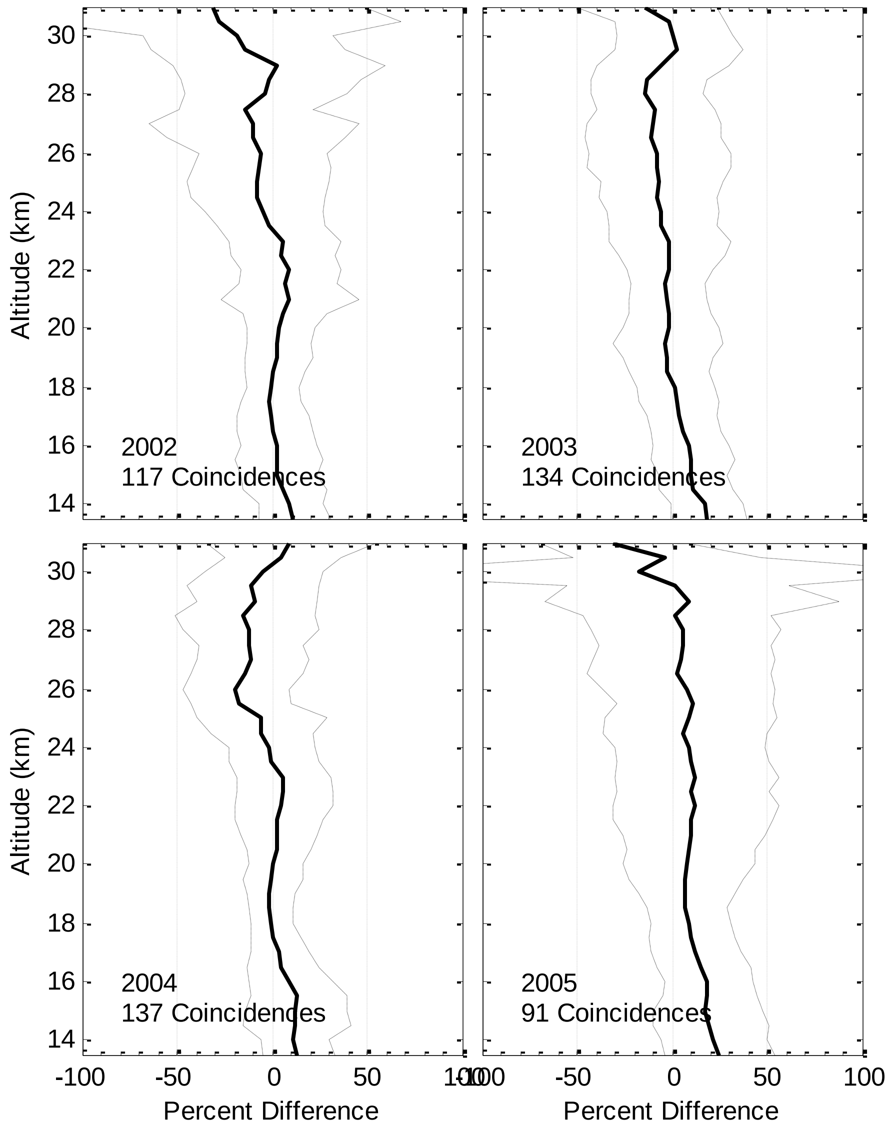


Comparison with SAGE III



- SAGE III (V4) 755 nm Aerosol Extinction
- OSIRIS 750 nm Aerosol Extinction
- Tight coincident scan comparison
  - 1° latitude, 2.5° longitude, 6 hours
- Good agreement of magnitude and vertical features

Comparison with SAGE III



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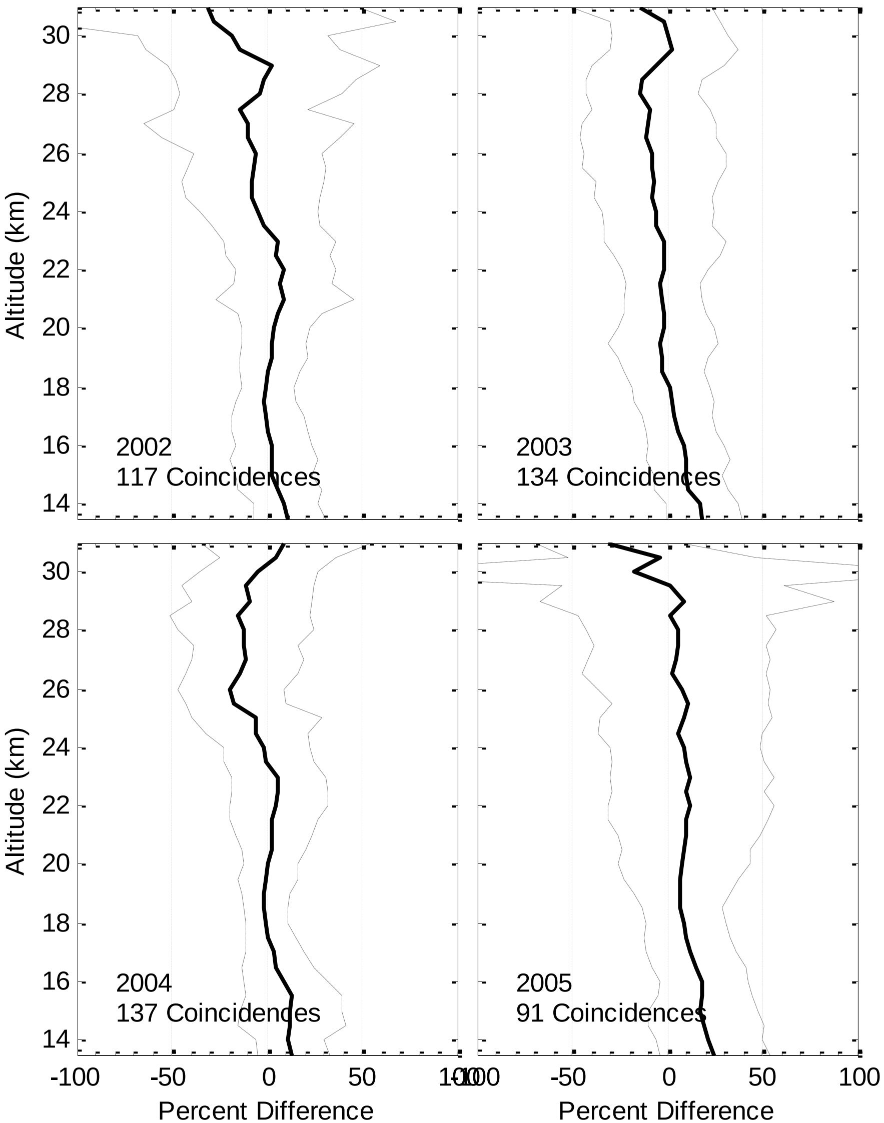
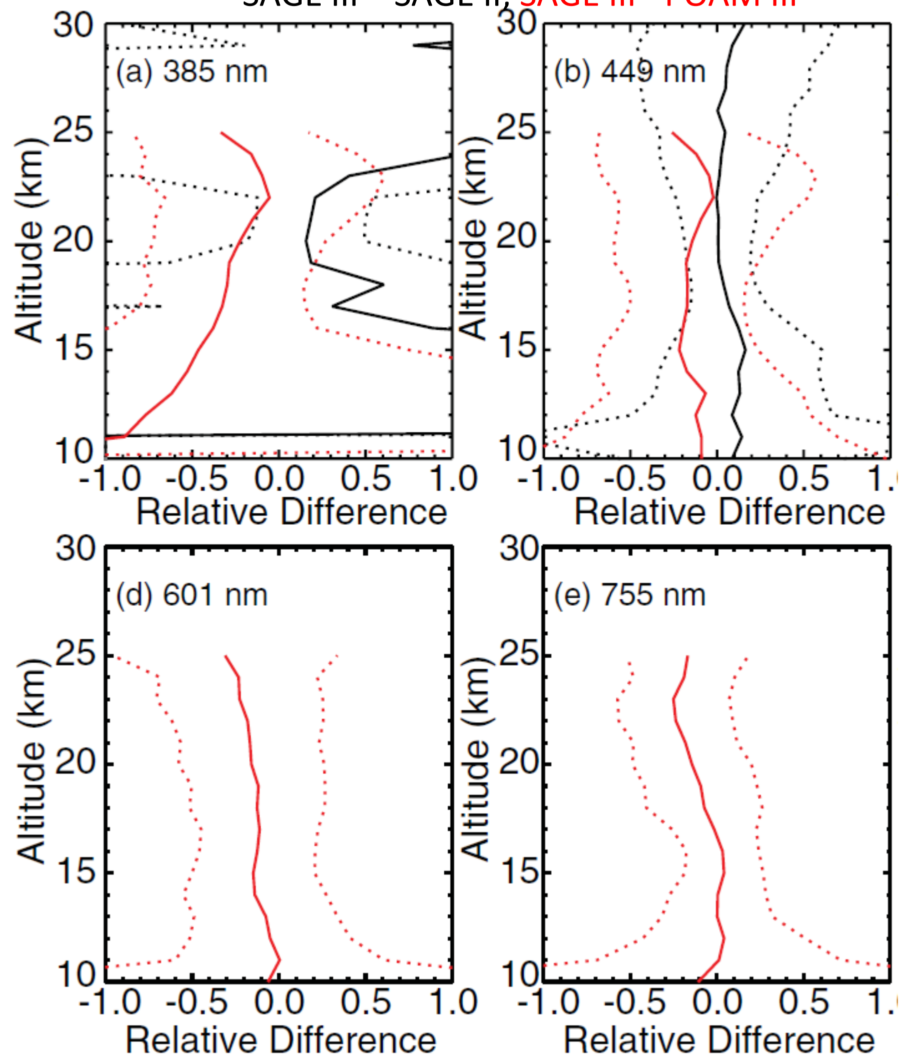


Figure 4 from Thomason et al., ACP 2010:
SAGE III – SAGE II; SAGE III - POAM III



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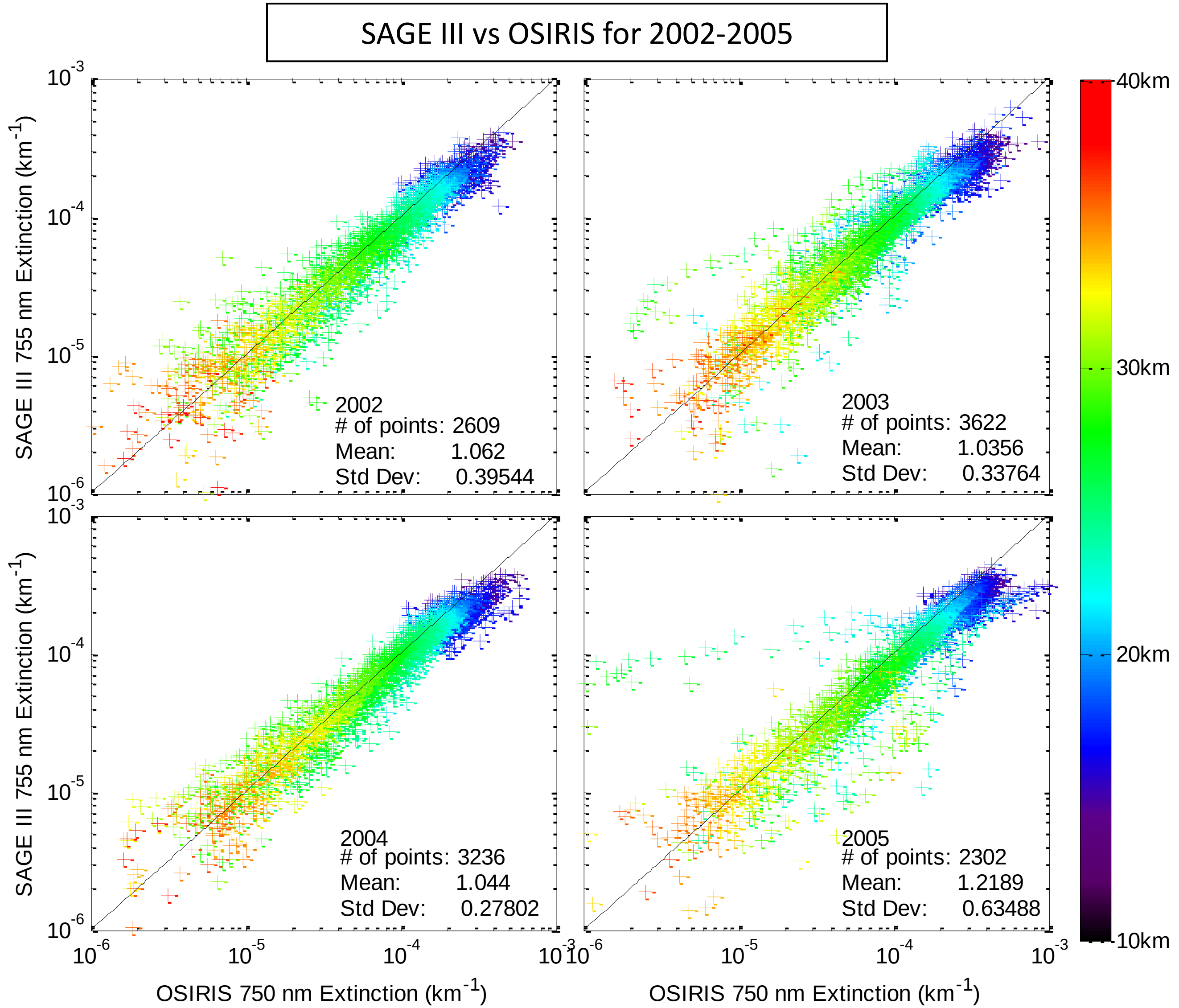
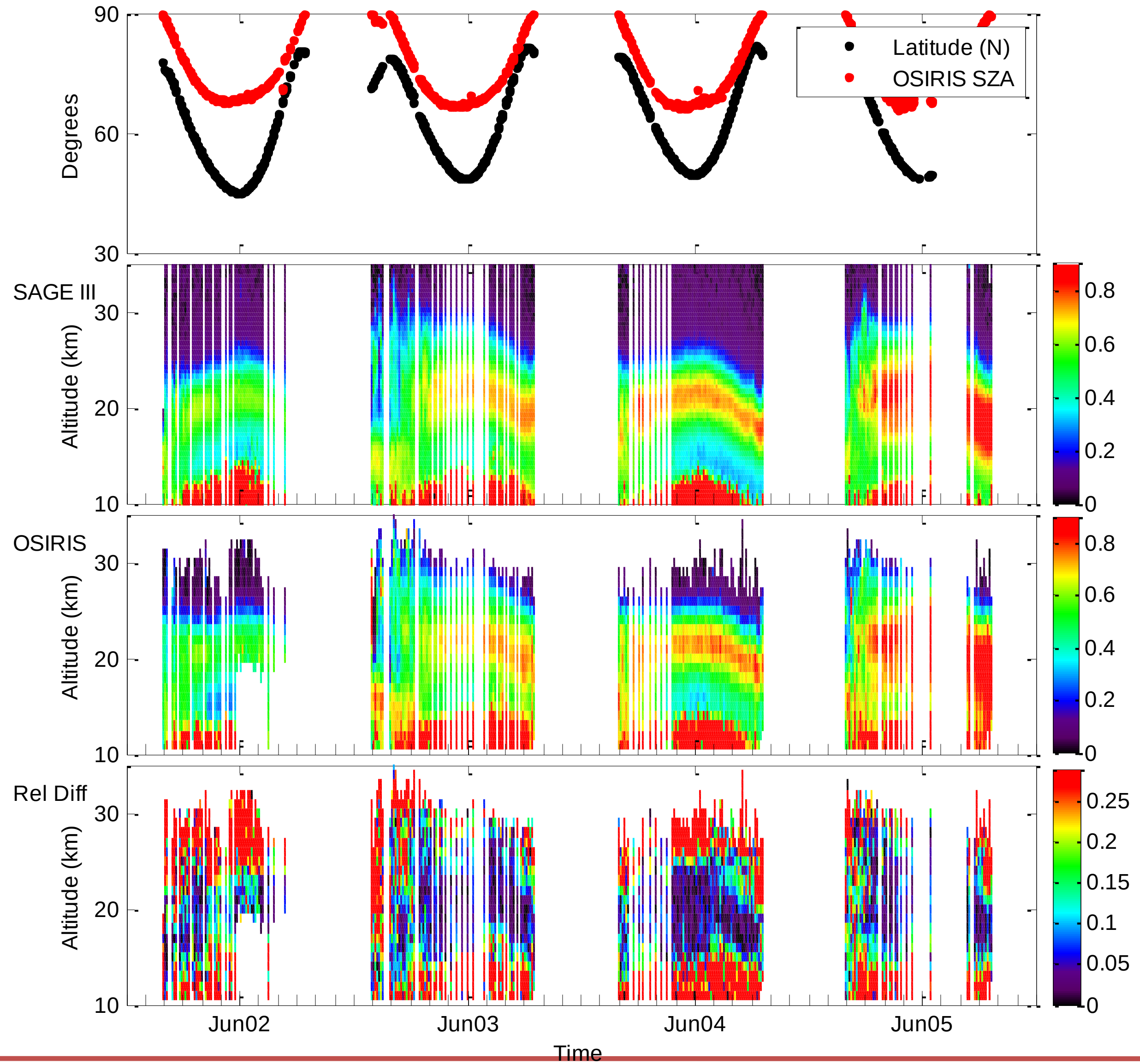
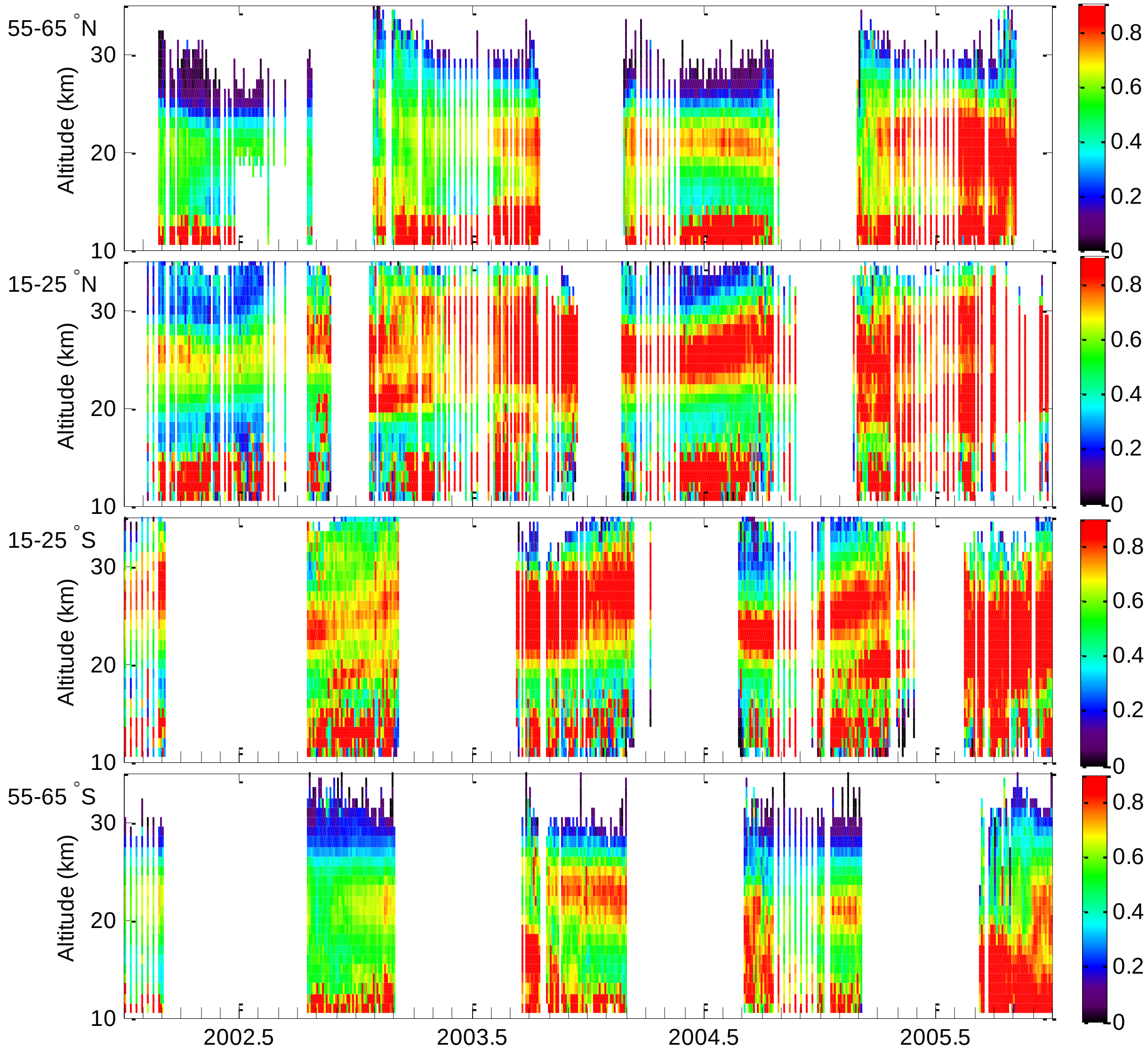


Comparison with SAGE III – Zonal Average Time Series



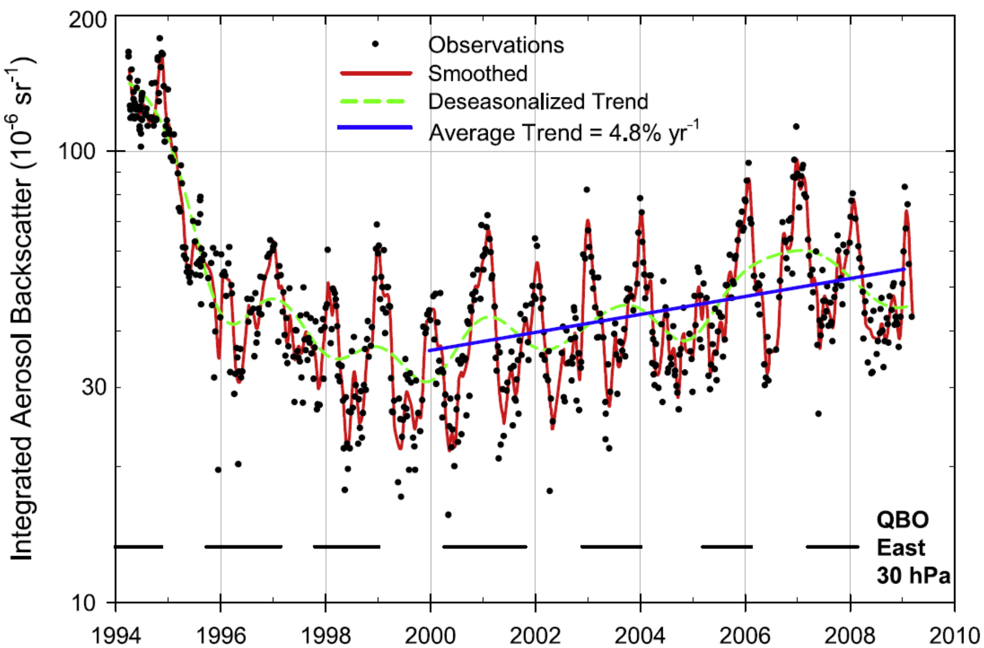
OSIRIS Measurements during the SAGE III Mission



Stratospheric Aerosol Time Series

OSIRIS retrievals (optical depth from 20-25 km) for all scans since 2002 within 700 km of Mauna Loa

Mauna Loa Observatory Integrated Lidar backscatter 20-25 km



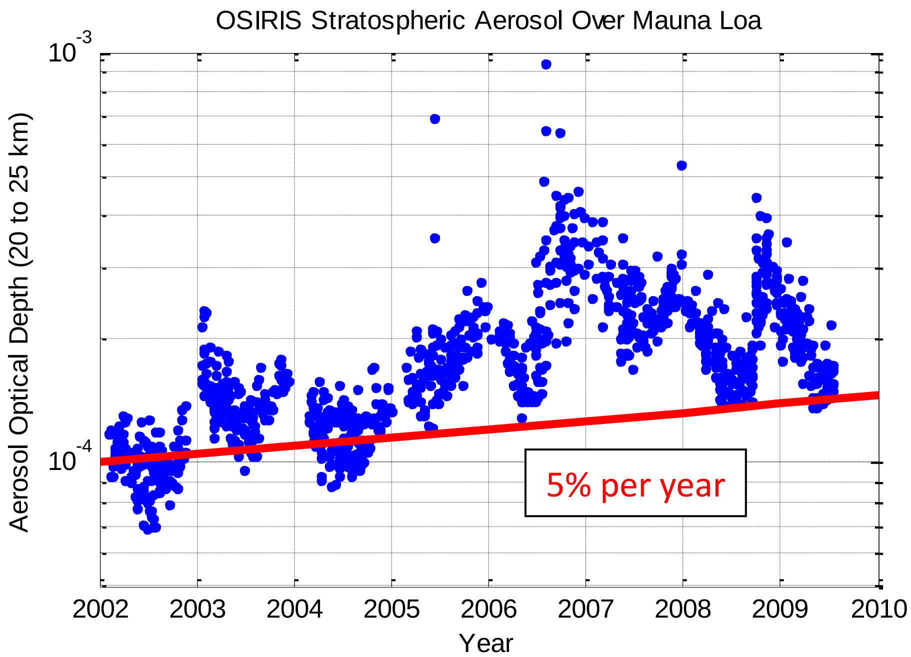
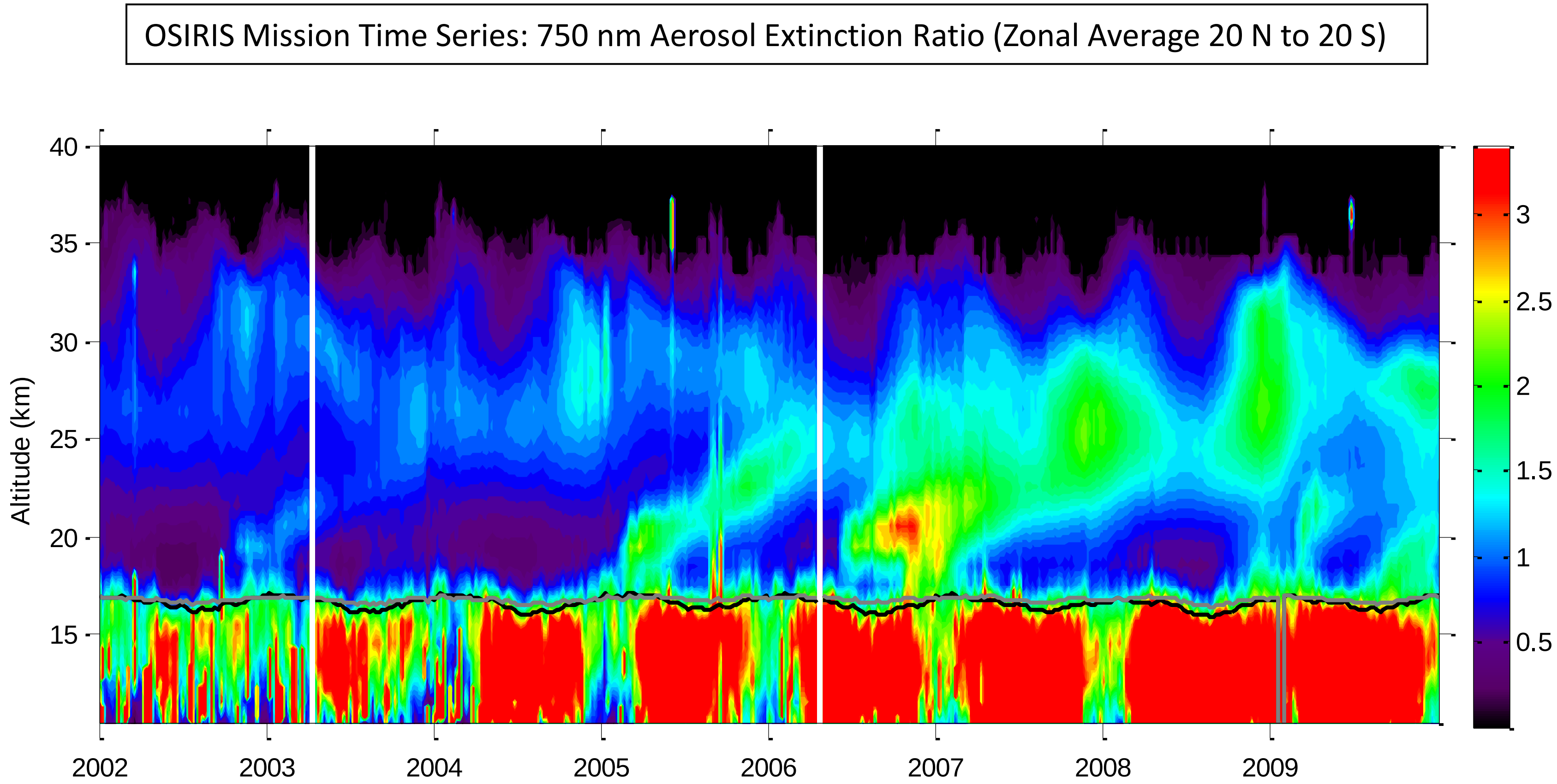
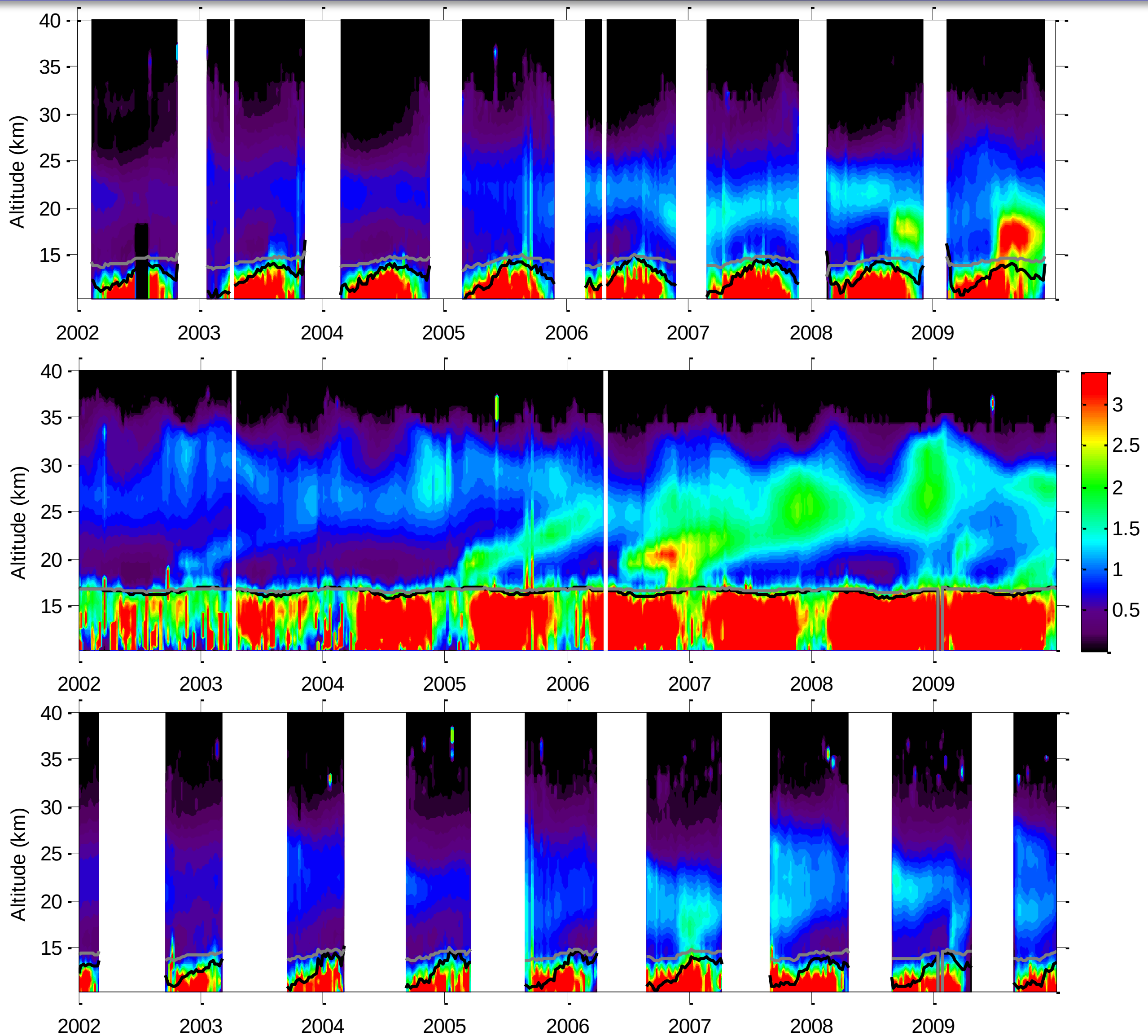


Figure from Hofmann et al, GRL, 2009

OSIRIS Stratospheric Aerosol Time Series



OSIRIS Stratospheric Aerosol Time Series



OSIRIS Stratospheric Aerosol Time Series

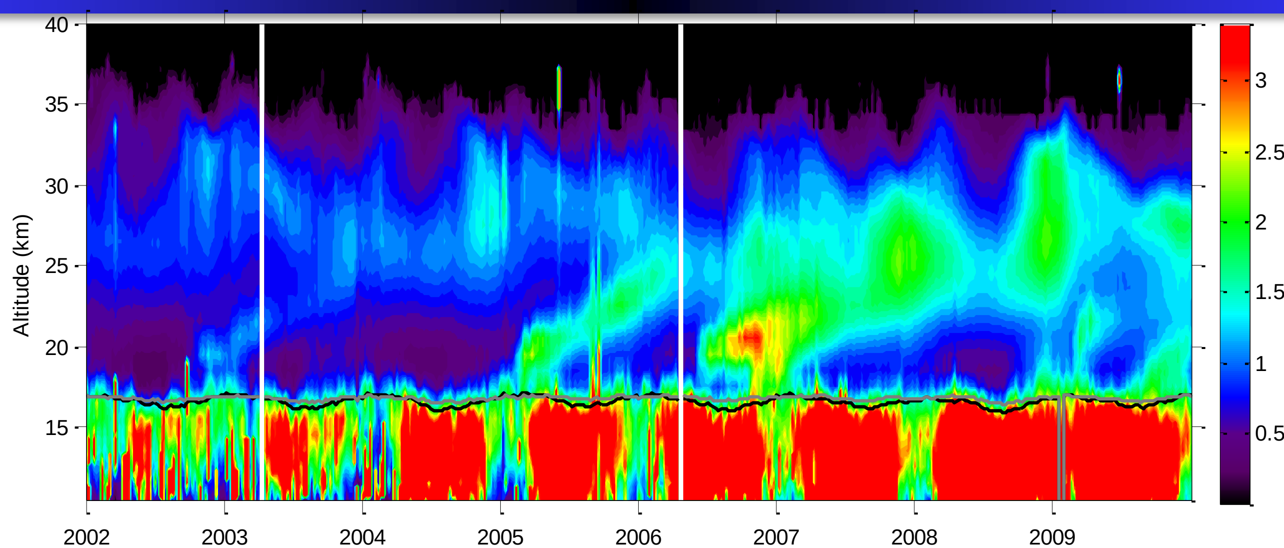
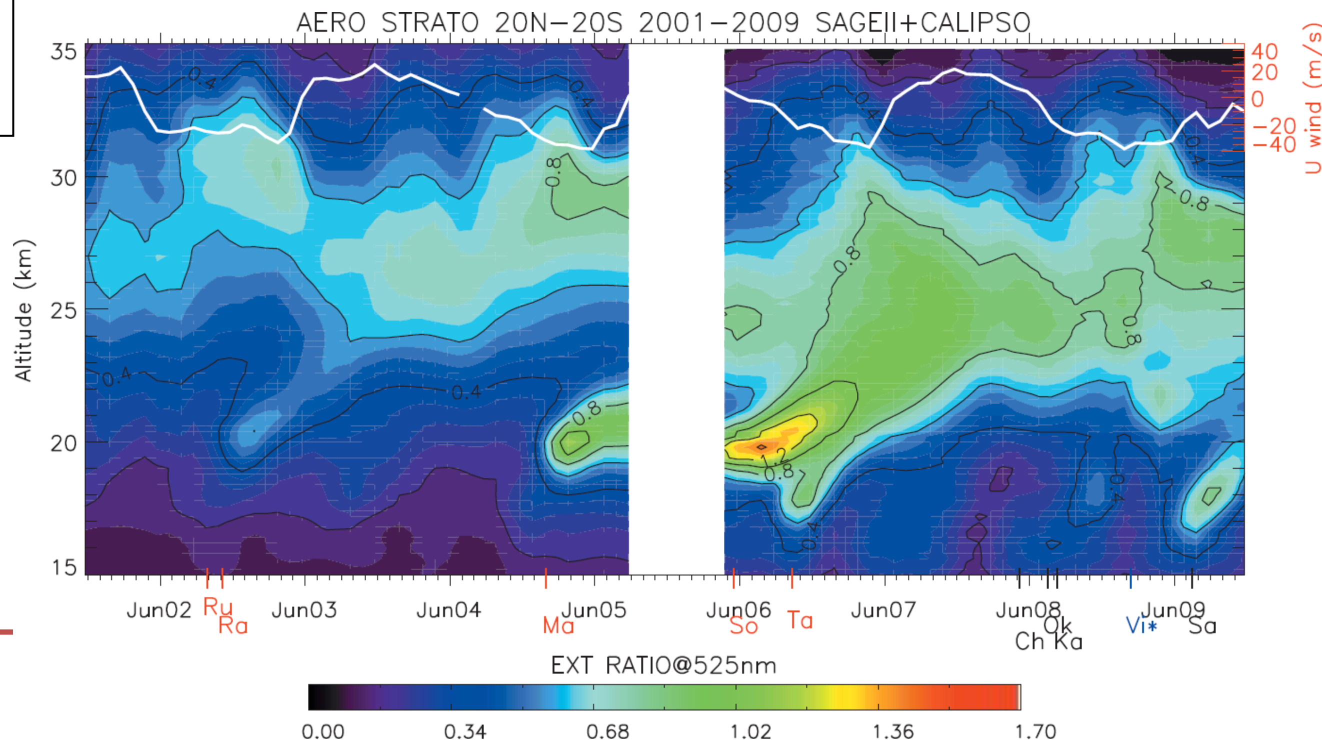
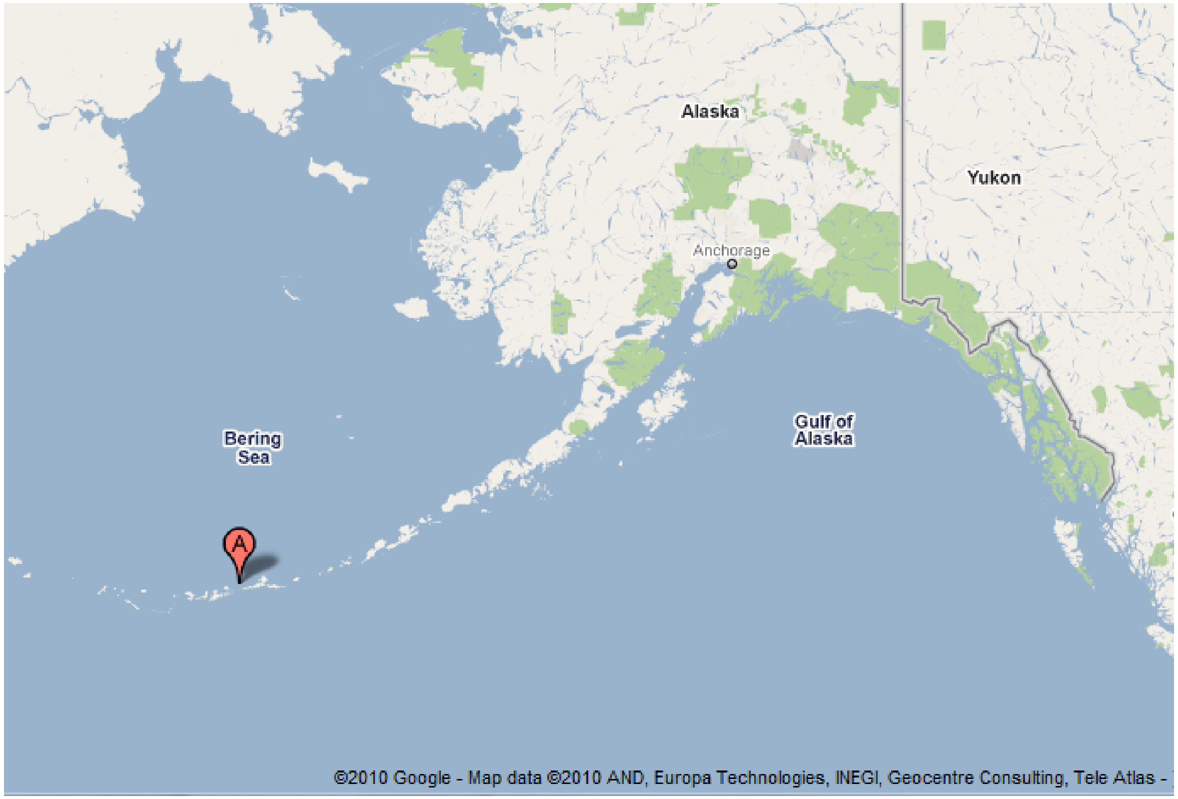


Figure 2;
Vernier et al.
GRL, 2011



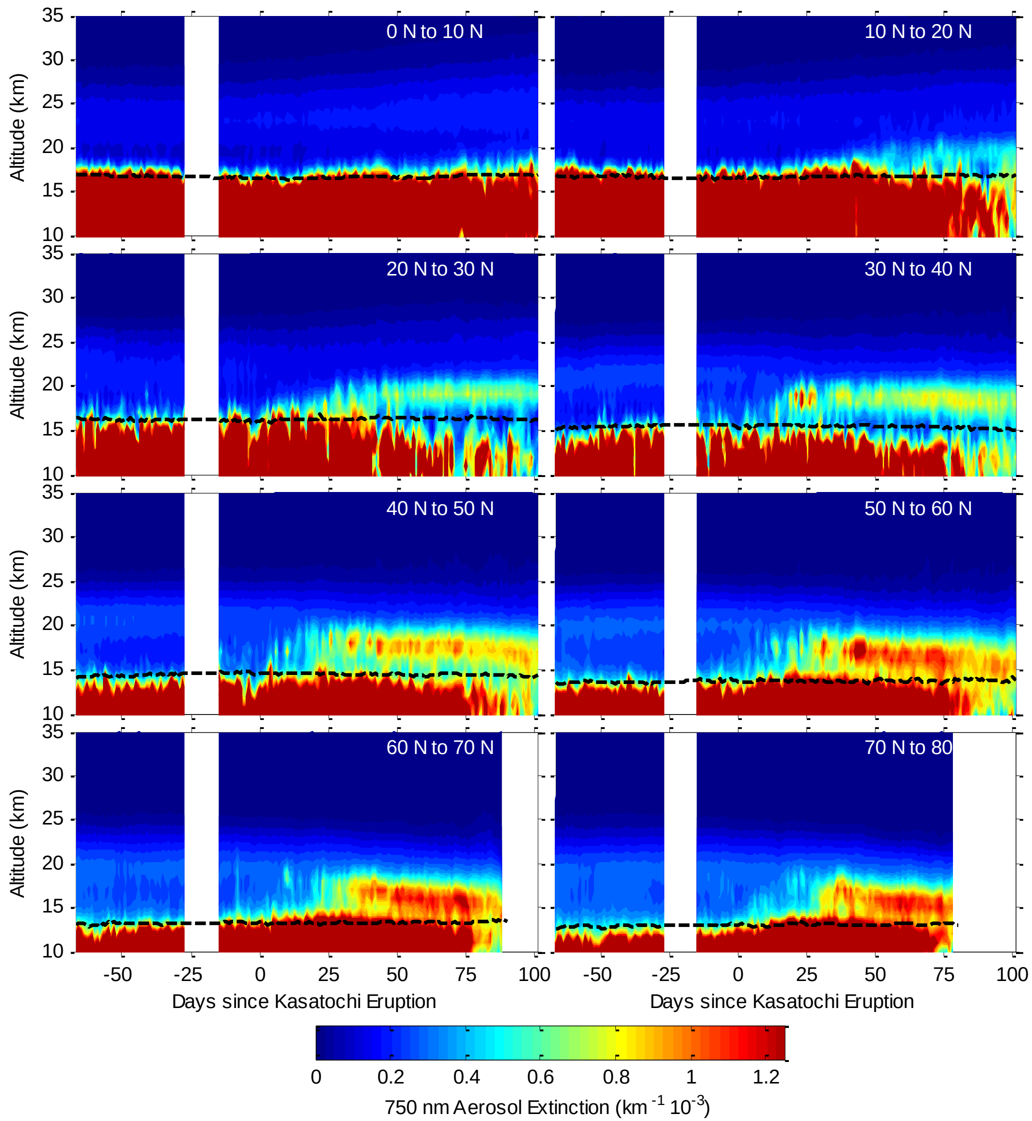
The Eruption of Kasatochi Volcano



- Kasatochi volcano (52 N, 175 W) erupted August 8,2008 (almost perfect timing for observation with OSIRIS)
- Injection of 1.2 -1.5 Tg SO_2 to altitude up to 16 km
- The largest stratospheric volcano since 1991

Retrieved Aerosol Extinction: Kasatochi Daily Time Series

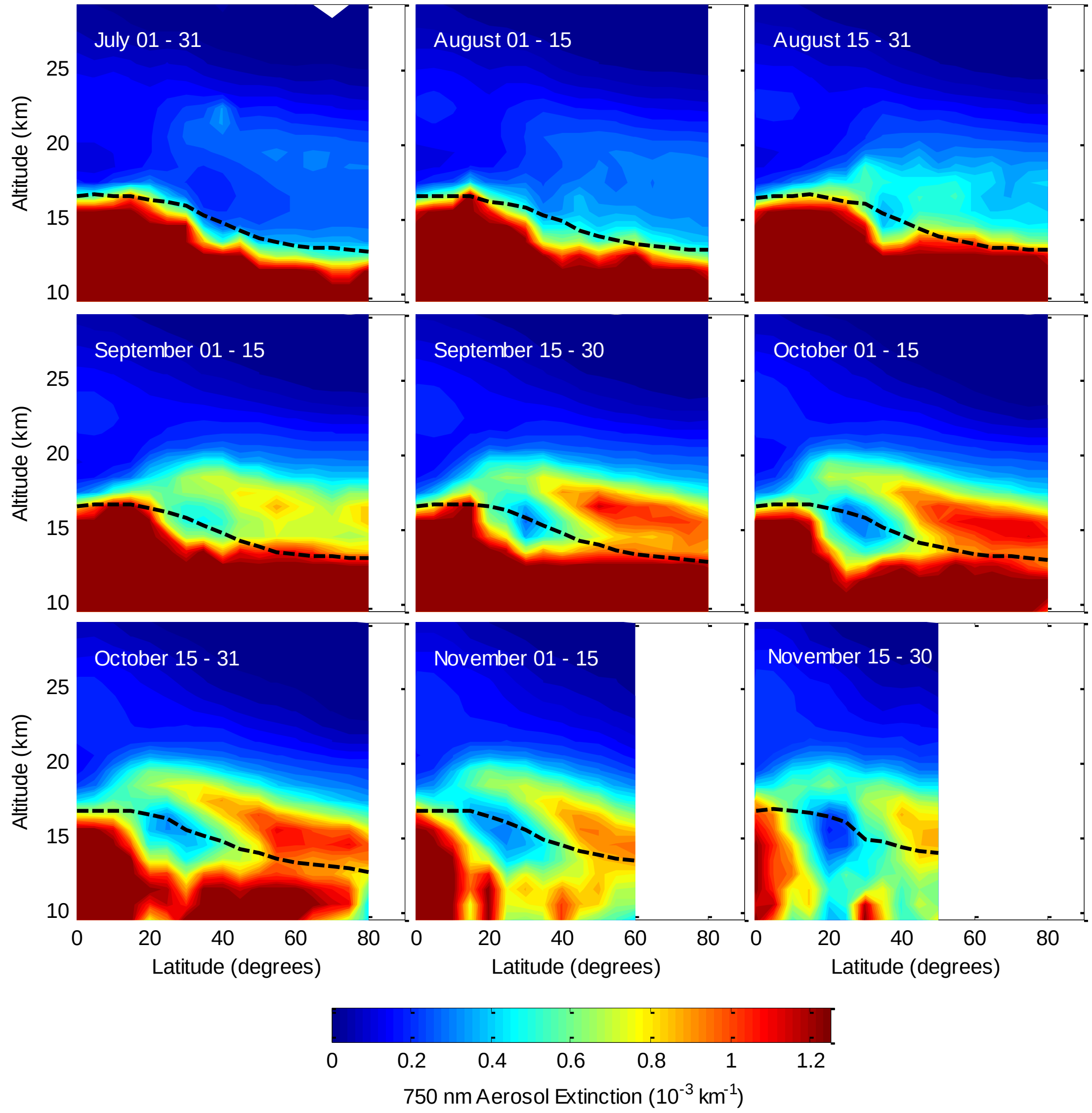
- The 380 K level of potential temperature delineates the tropical tropopause layer and the lowermost stratosphere from the deep stratosphere
- Focus analysis above 380 K
- Pre-eruption: typical background state (no effect of Okmok eruption on July 12?)
- 10 to 30 days post eruption: clear evidence of an enhanced layer with significant variability (streamers?)
- 40 days post eruption: a stable enhanced layer between 15 and 22 km at mid to high latitudes (typical e-folding conversion time of 30 days)
- No clear enhancement in the deep tropics
- 80 days post eruption: decay of the stable layer (high-latitude aerosol lifetime is less than 1 year)



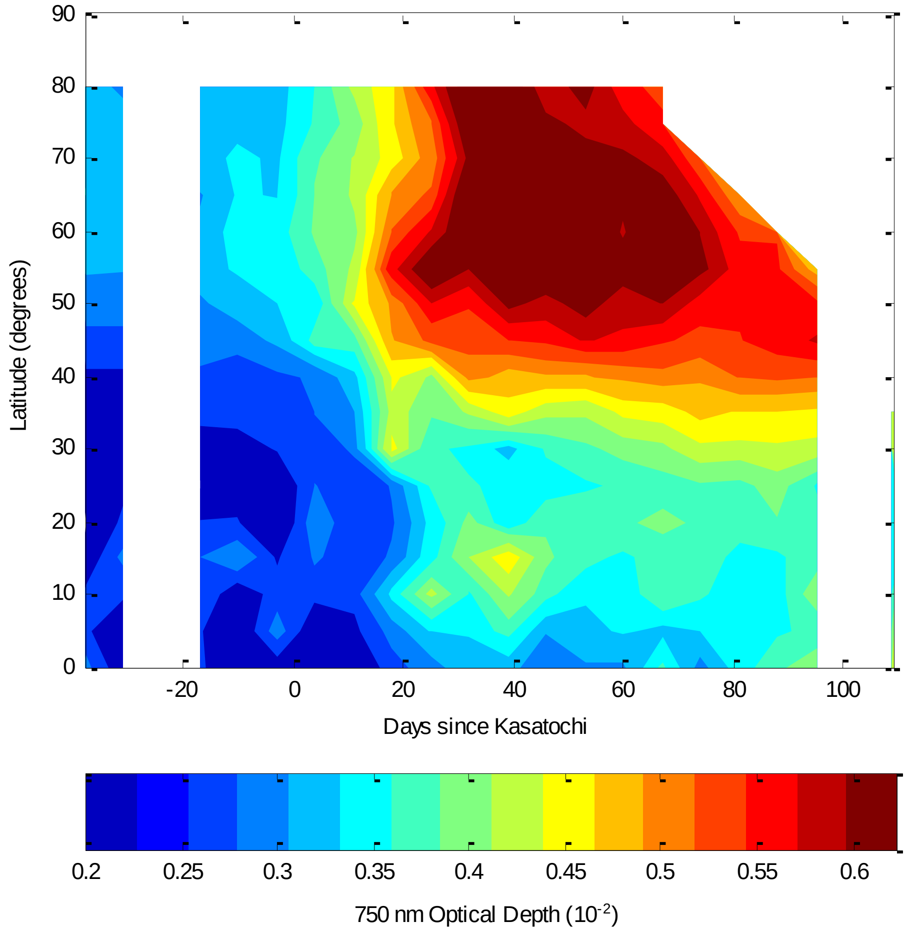
OSIRIS Aerosol Extinction: Kasatochi Zonal Average Time Series

- Northern hemisphere zonal averages
- Again focus analysis above 380 K
- Pre-eruption: Junge layer
- Maximum enhancement in the lower stratosphere (not *lowermost*) in early October of up to 5 times background values
- A remarkable delineation of the 380 K level in the aerosol distributions
- Clear transport to the tropics (2 way leaky tropical pipe)
- No mixing into the tropical stratospheric reservoir
- Remarkable mixing barrier above the subtropical jet

Bourassa et al., JGR, 2010



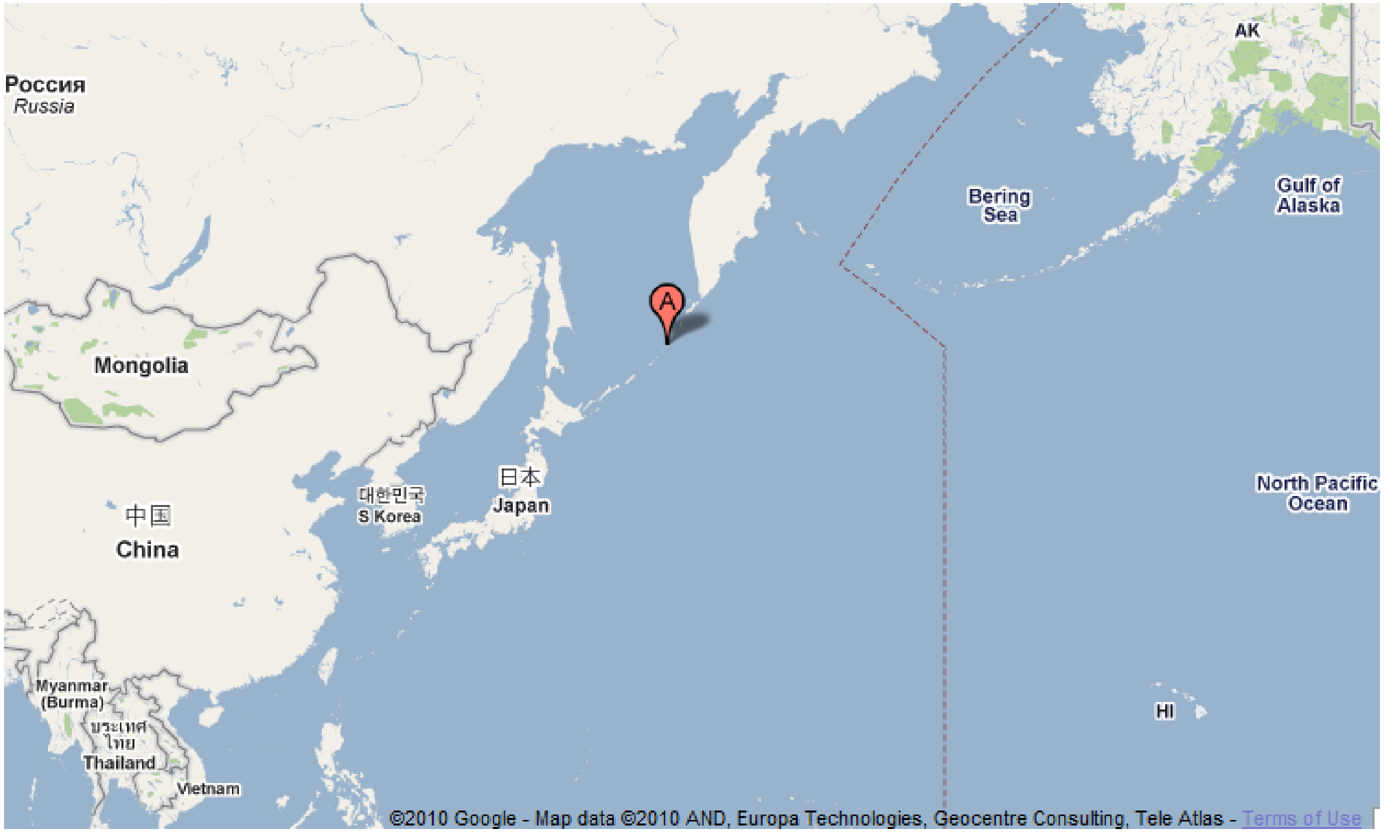
Kasatochi Climate Effects: Model Simulations



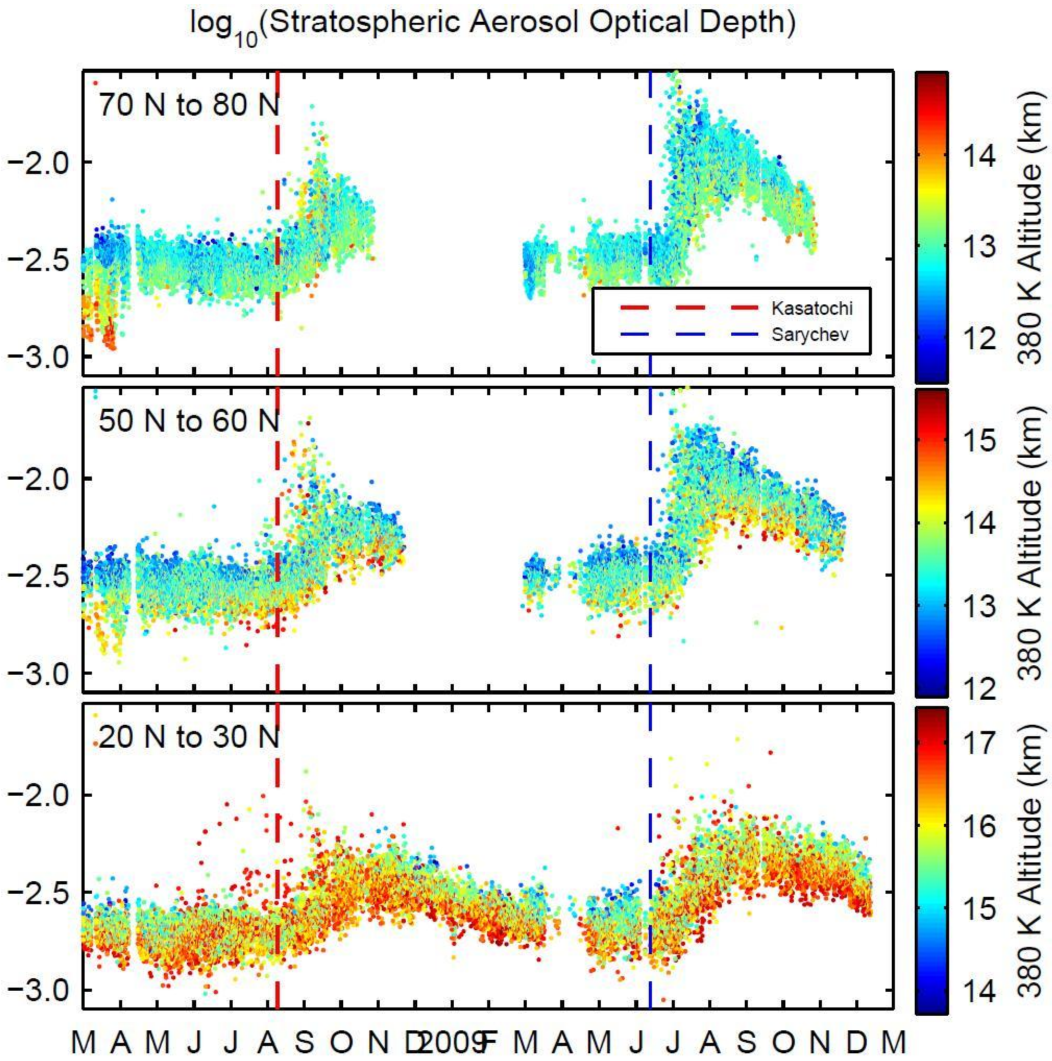
Kravitz et al., JGR, 2010

- OSIRIS retrievals of zonal average vertical stratospheric aerosol optical depth from 380 K
- Compared to simulations of a 1.5 Tg Kasatochi eruption using NASA GISS ModelE (a coupled atmosphere-ocean general circulation model) performed by Kravitz and Robock
- The spatial and temporal distributions of the volcanic aerosol enhancement agree very well
- The optical depth predicted by the model is an order of magnitude larger
  - total column, wavelength, particle size, injection characteristics

- Sarychev Peak, Kuril Islands, June 12, 2009, 1.2 Tg SO_2 up to 16 km



The Eruption of Sarychev Peak



- Sarychev Peak, Kuril Islands
- June 12, 2009
- 1.2 Tg SO_2

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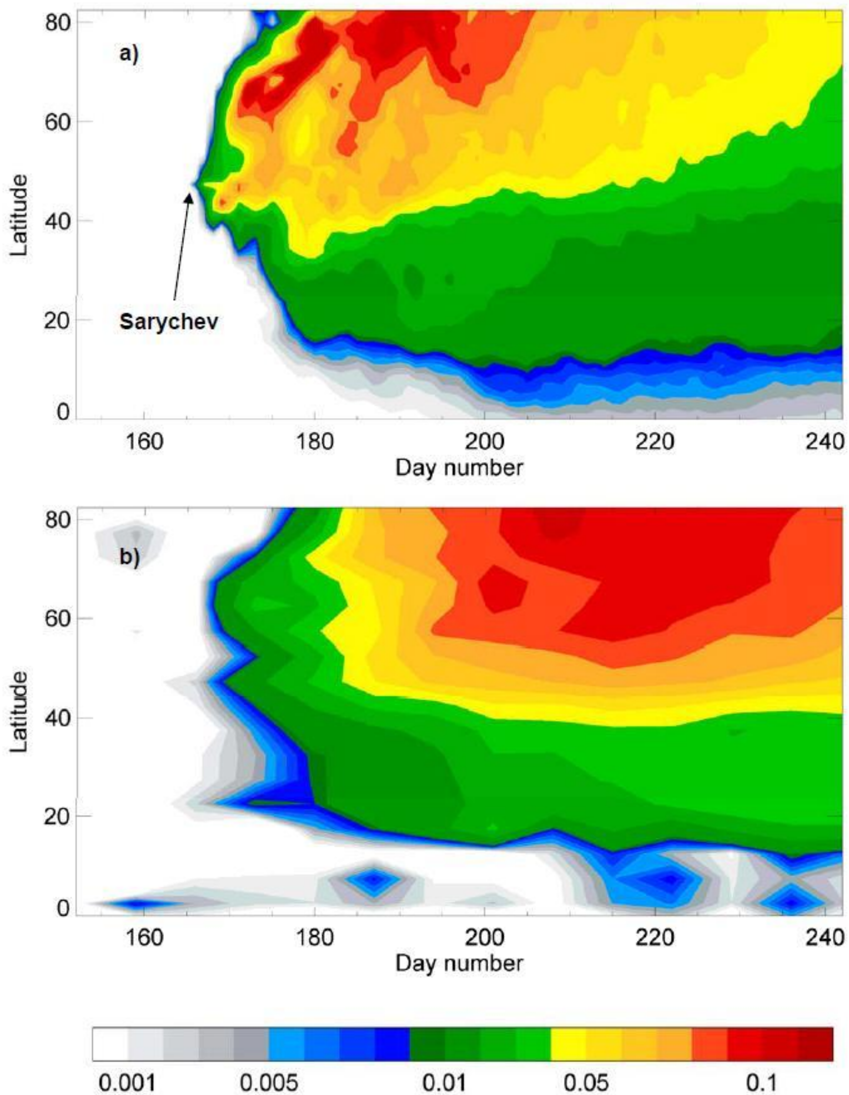
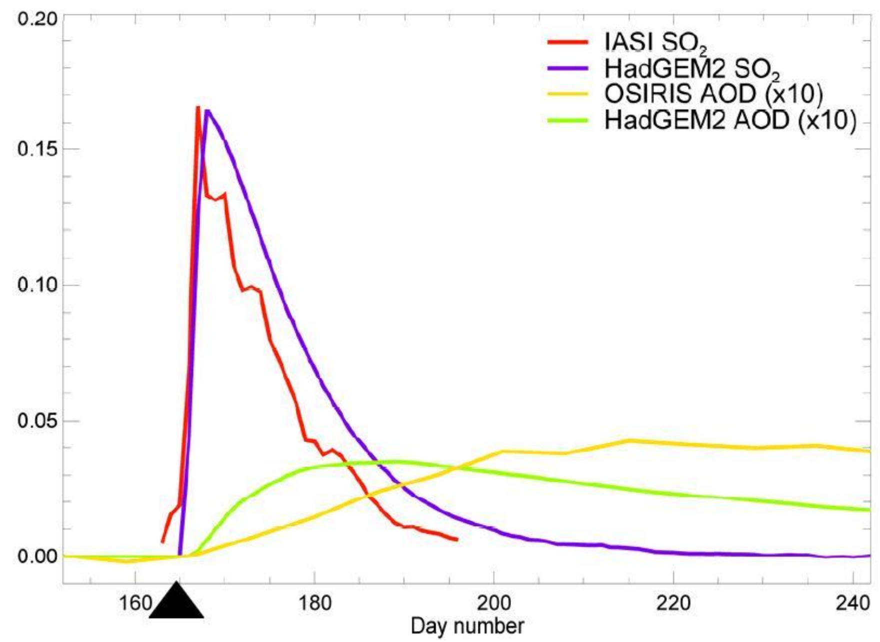


- Sarychev Peak, Kuril Islands, June 12, 2009
- 1.2 Tg SO2
- Effects of the eruption modeled with a nudged version of HadGEM2 climate model
    - work by Haywood et al, Hadley Center, U.K.
    - published in JGR, 2010



OSIRIS Aerosol Optical Depth Movie: 2008-2010