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# Assessing Information Content of CLARREO Measurements to Size-Dependent Dust Emissions: An OSSE Study

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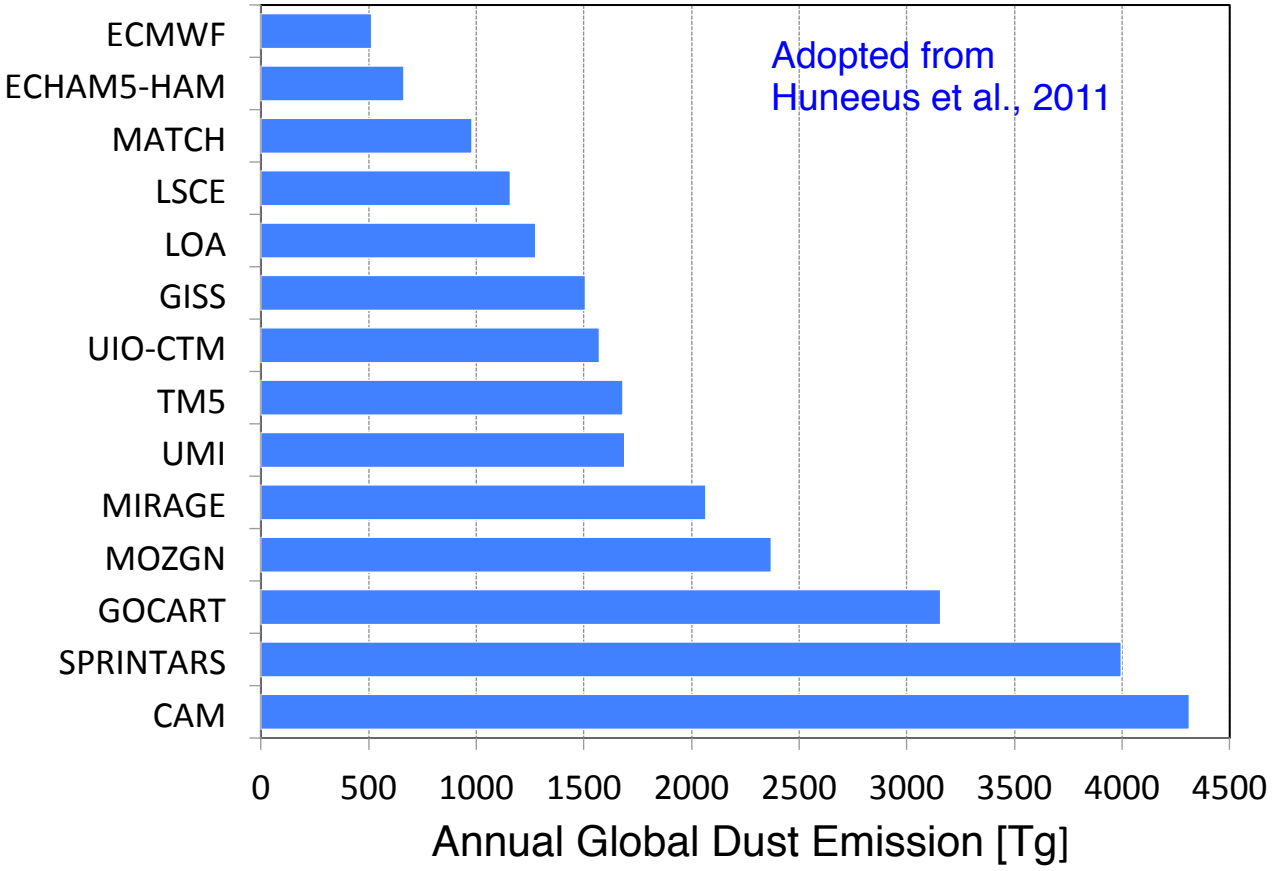
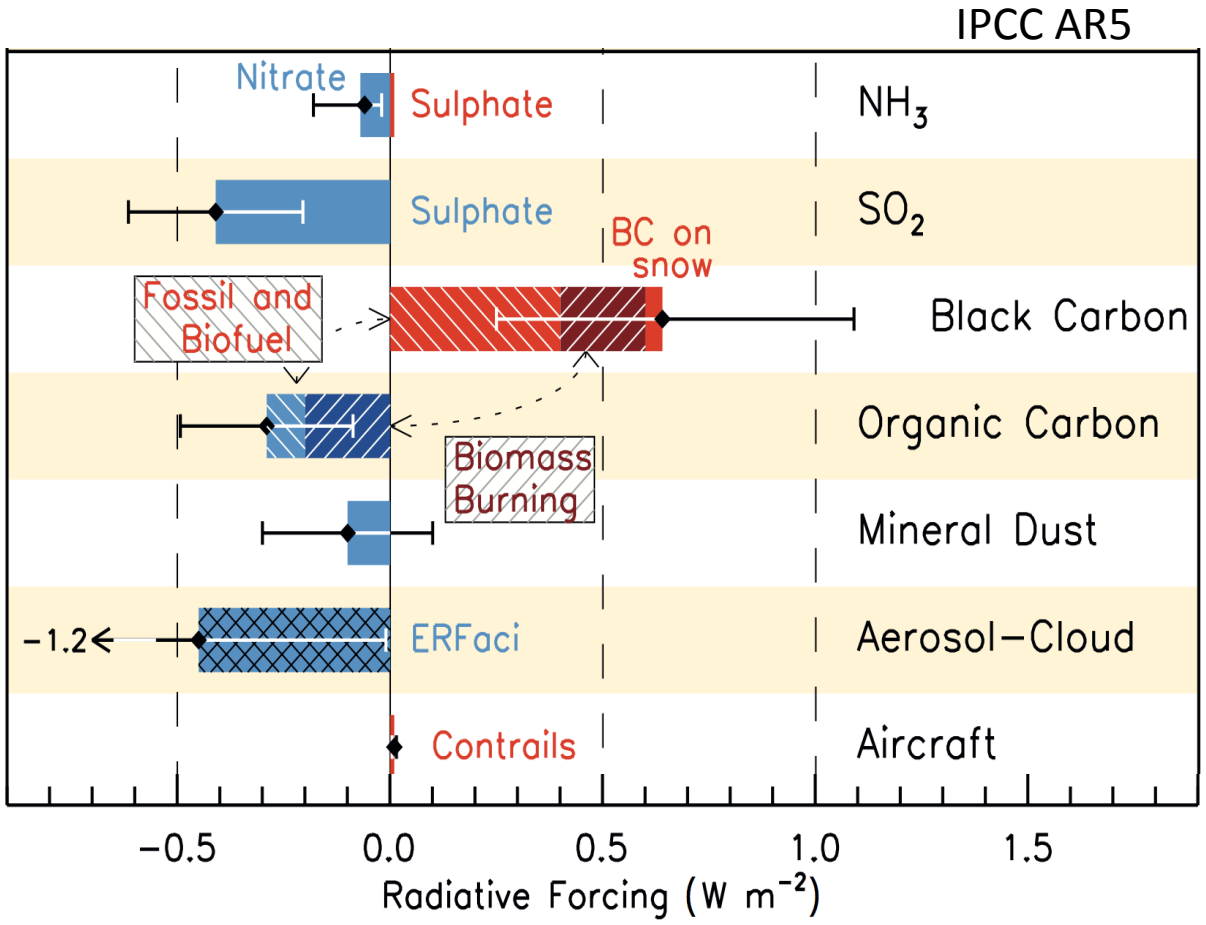
# Outline

- Motivation and objectives
- The design of observing system simulation experiment (OSSE)
- Results:
  - Information content of CLARREO measurements to dust optical depths (DOD)
  - OSSE on size-dependent dust emissions
- Future work

# Diversity of dust emissions & uncertainty of dust radiative forcing

**Global dust emission inter-comparison in AeroCom**




**The sign of dust forcing is still unknown.**

# How are dust emission modeled?

**Inputs: Wind speed, friction velocity ($u_*$), soil texture and moisture, Land surface properties**

↓

**Ideal threshold wind friction v:**

$$u_{*t} = f(D_0, \rho_p)$$

↓

**Threshold wind friction affected by <u>drag partition</u> and <u>moisture inhabitation</u>:**

$$u_{*t}(\theta, z_{0,m}) = u_{*t} \cdot f(\theta) \cdot f(z_{0,m})$$

↓

**Horizontal saltation flux:**

$$Q_s(u_{*t}; u_*) = \begin{cases} \frac{C_k \rho_a}{g} u_*^3 \left(1 - \frac{u_{*t}}{u_*}\right)\left(1 + \frac{u_{*t}}{u_*}\right)^2, & \text{if } u_* > u_{*t} \\ 0, & \text{if } u_* \le u_{*t} \end{cases}$$

**Dust emissions are distributed among different particle size bins with a pre-described function**

**Vertical entrainment flux:**

$$F_{d,j} = T_0 f_{\text{bare}} S \alpha Q_s \sum_{i=1}^{3} M_{i,j}$$

| | |
|---|---|
| $f_{bare}$ | Fraction of bare soil |
| $S$ | Soil "erodibility" (GOCART) |
| $\alpha$ | Sand blasting efficiency factor (<u>Fixed</u>) |
| $M_{i,j}$ | Mass fraction of dust bin $j$ from parent soil mode $i$ |

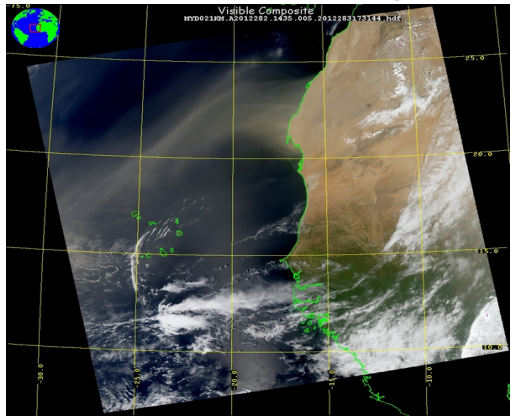
Zender et al [2003]
Iversen and White [1982]
Marticorena and Bergametti [1995]
Fairlie et al [2007]

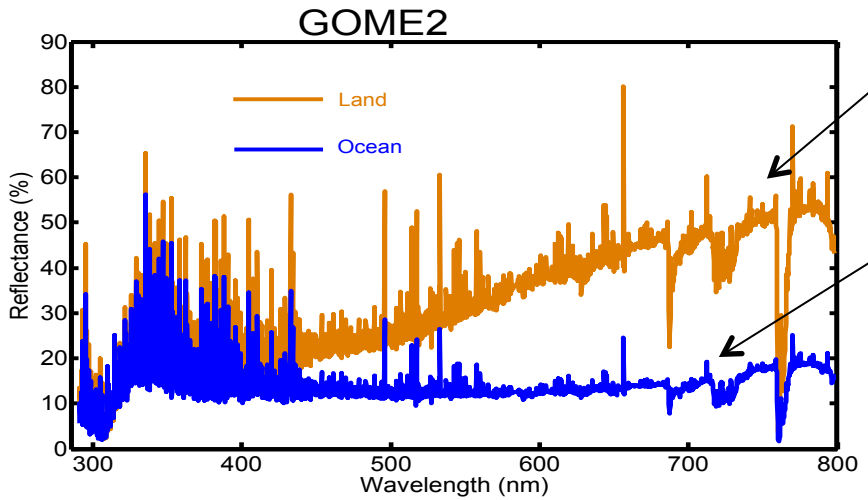
# Dust spectral signature

**In shortwave, spectrally flat; In infrared, negative slope in BT in 820-920 cm$^{-1}$ (12.2 -10.87 $\mu$m).**

**We think dust can be best characterized by using SW (UV+blue in particular) + IR. CALERRO is well suited for this.**

MODIS Visible Composite

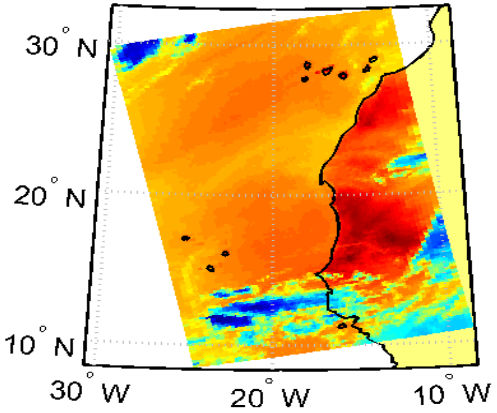


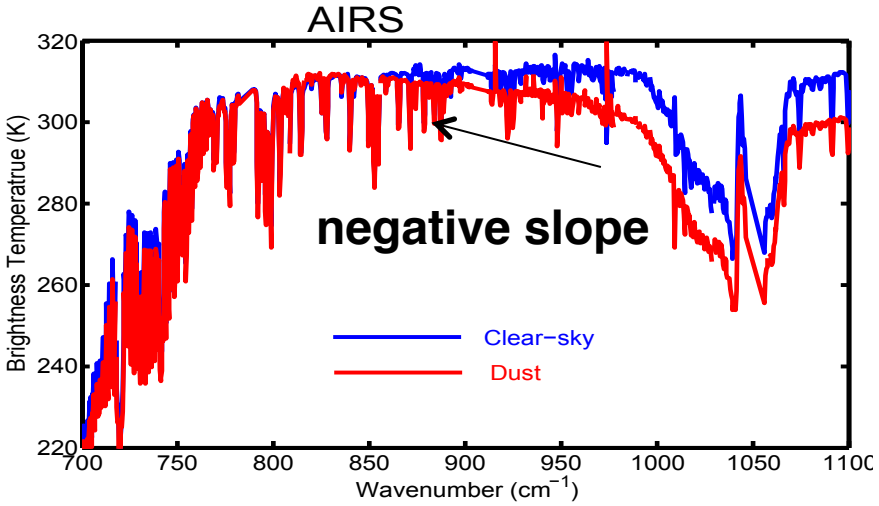



**dominated by surface ref.**

**Dominated by dust**

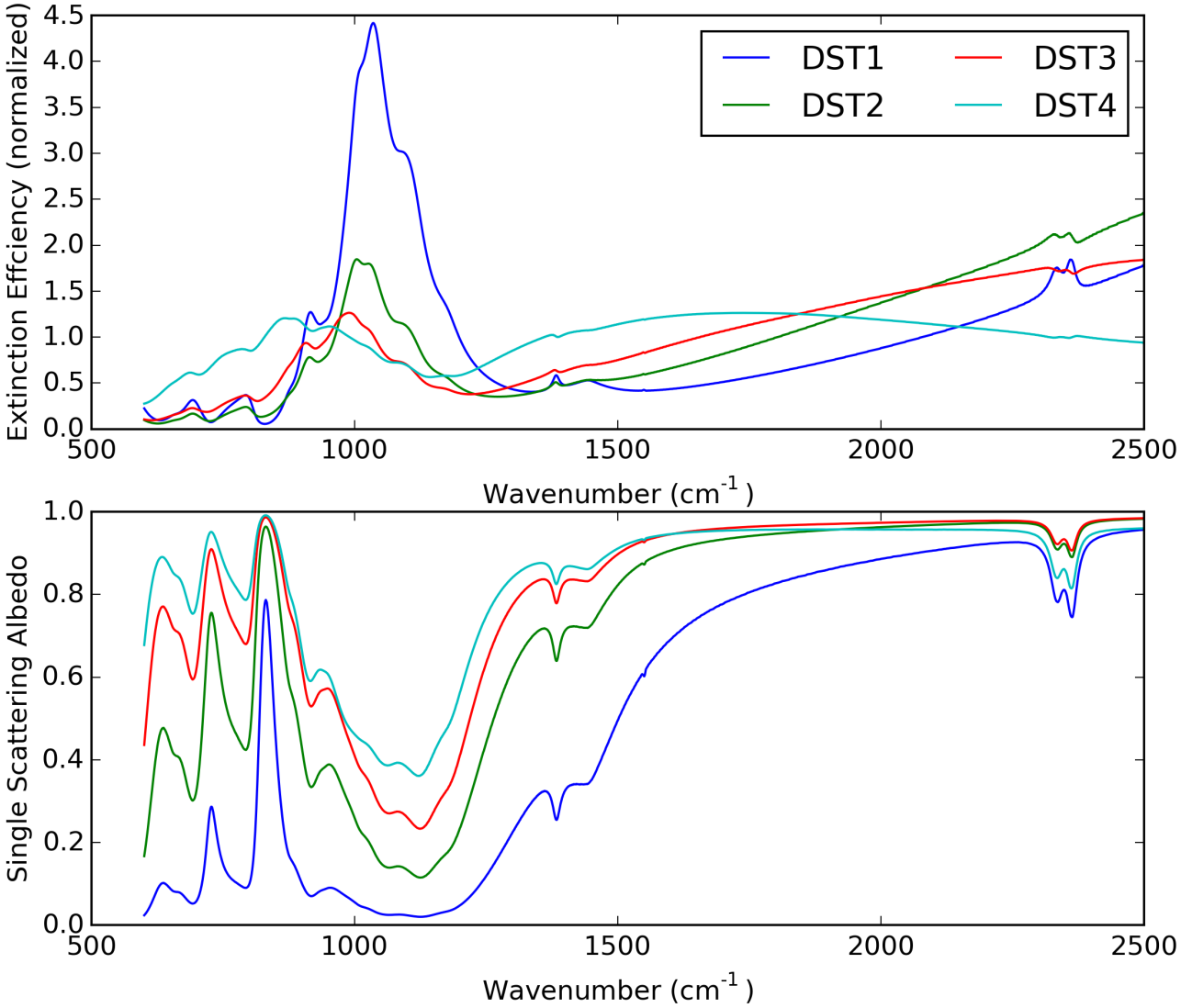
AIRS Level 1B 11 $\mu$m BT




**Dust produces negative slope of BT 820-920 cm$^{-1}$**

# Dust optical properties in IR




Shortwave refractive index adopted from Patterson et al., 1977, and IR refractive index from Di Biagio et al., 2014. lognormal size distribution for each bin.

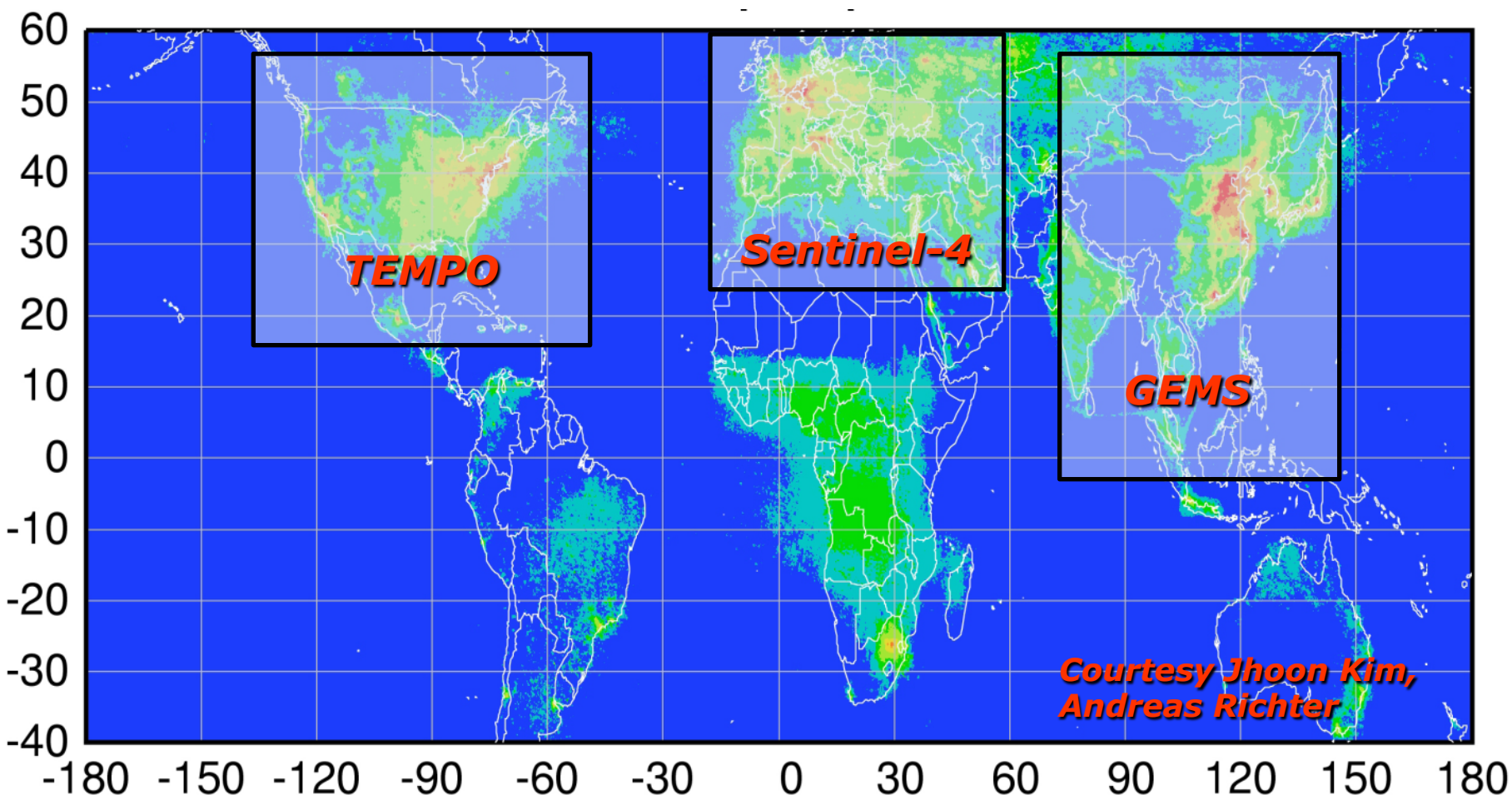
Dust size bin (um):

- DST1: 0.1 – 1 (reff = 0.7)
- DST2: 1 – 1.8 (reff = 1.5)
- DST3: 1.8 – 3 (reff = 2.5)
- DST4: 3 – 6 (reff = 4.0)

# Some spectrometers from polar orbiting platform

| Instruments | Spatial | Spectral range | Spectral resolution | Available for |
|---|---|---|---|---|
| GOME-1 on ERS-2<br>GOME-2 on Metop-A/B | 40x320 $km^2$<br>40x80 $km^2$ | 240–790 nm<br>240–790 nm | 0.2–0.4 nm<br>0.26-0.51 nm | 1996 – 2011<br>2006 – present |
| SCIAMACHY/ENVISAT | 32 x 215 $km^2$ | 240–2380 nm | 0.24–1.48 nm | 2002 – 2012 |
| AIRS on Aqua | 50 (3x3 13.5-km) | 645–2700 $cm^{-1}$ | 1200-resolving | 2002 – present |
| IASI on Metop-A/B | 50 (2x2 12.0-km) | 645–2760 $cm^{-1}$ | 0.25 $cm^{-1}$ | 2006 – present |
| CrIS on Suomi-NPP | 50 (3x3 13.0-km) | 645–2700 $cm^{-1}$ | 0.6 $cm^{-1}$ | 2011 – present |
| TropOMI | 7 X (28 or 7) $km^2$ | 270-320; 310-495<br>405-495; 675-775<br>2305-2385 nm | 0.25-0.5 nm | 2016 - |
| HyspIRI | 30 * 30 m2 ? | 380 - 2500 nm | 10 nm | 2020?- |
| CLARREO<br>(SW/IR spectrometers) | 0.5-km SW<br>25-km IR | 320–2300 nm<br>200–2000 $cm^{-1}$ | 8 nm<br>0.5 $cm^{-1}$ | 2020? – |

# Hyperspectral shortwave measurement from GEO platform




**Policy-relevant science and environmental services enabled by common observations**

- Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, *e.g.*, observations to support the United Nations Convention on Long Range Transboundary Air Pollution

# Objectives

- Identify the spectral fingerprint of mineral dust in the space-based **shortwave** and **infrared** measurements (from CLAERRO)
- Assess the capability of CLARREO measurements for the recovering of **dust sources** in the climate time scales (OSSEs).

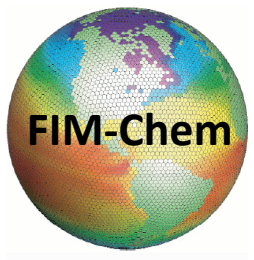
Question to answer: What are the advantages of CLARREO measurements (combined **shortwave** and **infrared** spectrally-resolved radiances) for determining dust emissions?

# Ideal OSSE:
## using spectral radiance measurements

**Forward modeling &**
**Adjoint analysis**

**Satellite & sun emulator:**
- Orbital / sampling configurations
- Radiometric definitions

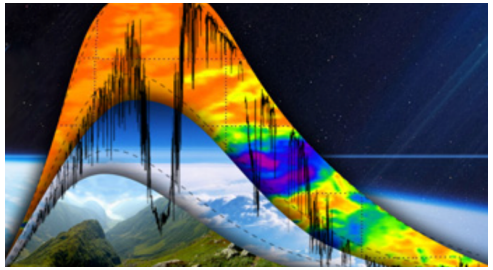
**Dust emissions:**
- Spatial-resolved
- Size-resolved
- Monthly scale



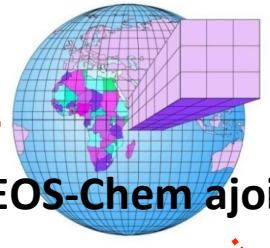

**Atmosphere:**
- T, P, $H_2O$, cloud
- Trace gases
- Mineral dust
- Other aerosols

**UNL-VRTM**
- HITRAN gas absorption
- Mie/T-matrix scattering
- Surface BRDF
- **Spectral radiance/flux**
- Jacobians of radiance to aerosol properties

**CLARREO Measurements**



**Analysis:**
- Size-dependent dust emissions



**GEOS-Chem ajoint**

$$\frac{\partial \text{ spectra}}{\partial \text{ emissions}} = \frac{\partial \text{ AODs}}{\partial \text{ emissions}} \times \frac{\partial \text{ spectra}}{\partial \text{ AODs}}$$

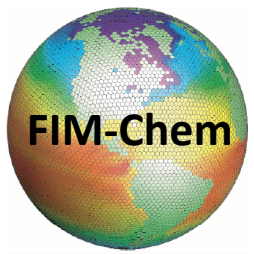
# Simplified OSSE:
## size-binned dust optical depths (DOD) as observation constraints

**Steps**

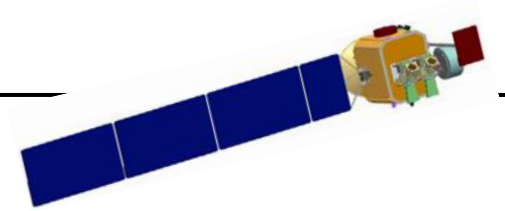
1. **Perform nature run**
2. **Characterize DOD errors**
3. **Perform the inversion from DOD**

**Satellite & sun emulator:**
- Orbital / sampling configurations
- Radiometric definitions

**Dust emissions:**
- Spatial-resolved
- Size-resolved
- Monthly scale

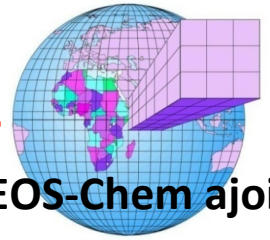



**Atmosphere:**
- T, P, $H_2O$, cloud
- Trace gases
- Mineral dust
- ~~Other aerosols~~



**CLARREO DOD**
- Size-binned DOD as observations
- Observation errors determined by the selection of spectra (RS-only, IR-only, and RS+IR)

**Analysis:**
- Size-dependent dust emissions

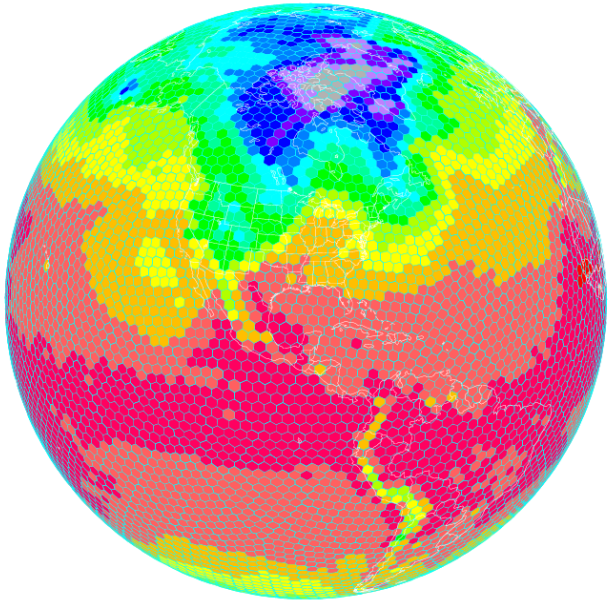


**GEOS-Chem ajoint**

**Assimilation of DOD is equivalent to the assimilation of radiances, given the DOD errors are characterized by radiance measurements.**

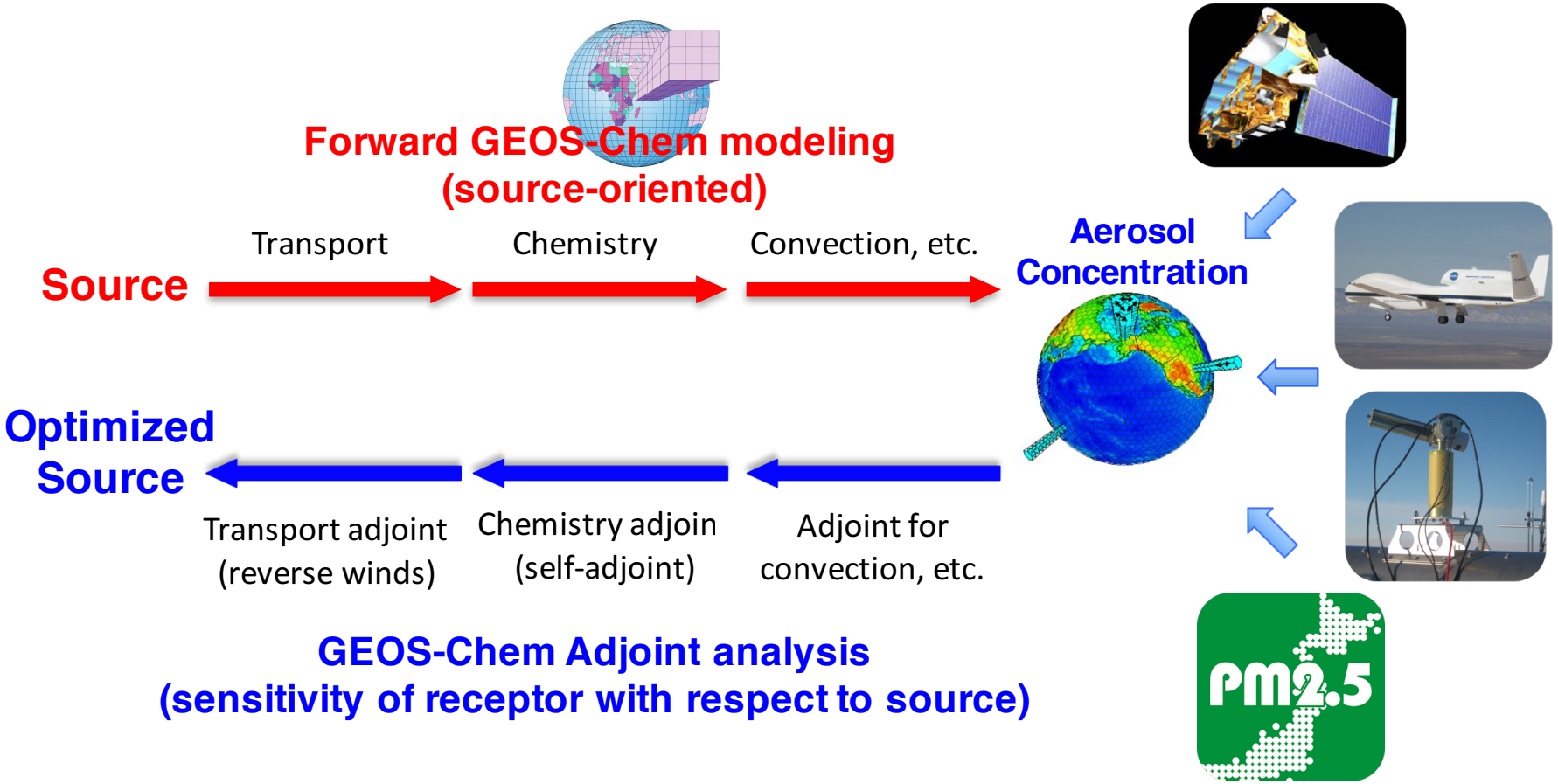
**No radiative transfer calculation involved in the adjoint run.**

# Nature run: NOAA/ESRL FIM-Chem Model



- Global Flow-following finite-volume Icosahedra Model (FIM, http://fim.noaa.gov/) coupled online with the GOCART aerosol modules.
- Icosahedral horizontal grid, mostly hexagons except for 12 pentagons.
- Uses the dust schemes of the GOCART and the Air Force Weather Agency (AFWA).
- Nature run was performed on 240-km grids, and simulations are re-gridded into 1◦X 1◦ grids.
- 64 vertical layers of the isentropic-sigma hybrid vertical coordinate

# Assimilation model: GEOS-Chem Adjoint



# Dust Size Bins in FIM-Chem and GEOS-Chem

radii

FIM-Chem

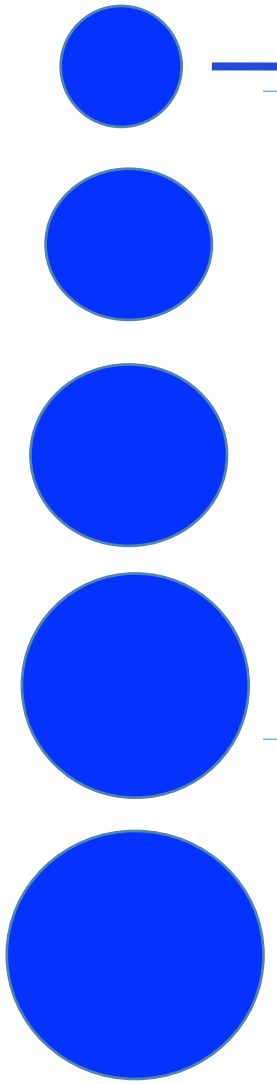
0.1– 1.0 µm
r-eff=0.7

1.0–1.8 µm
r-eff=1.5

1.8–3.0 µm
r-eff=2.5

3.0–6.0 µm
r-eff=4.0

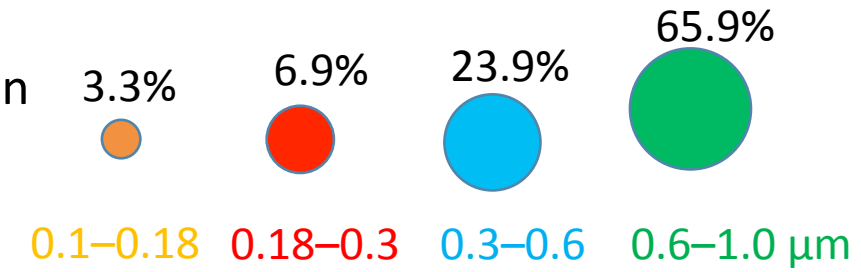
6.0–10.0 µm
r-eff=8.0



GEOS-Chem

The largest size bin is not used for consistency

For optical calculation

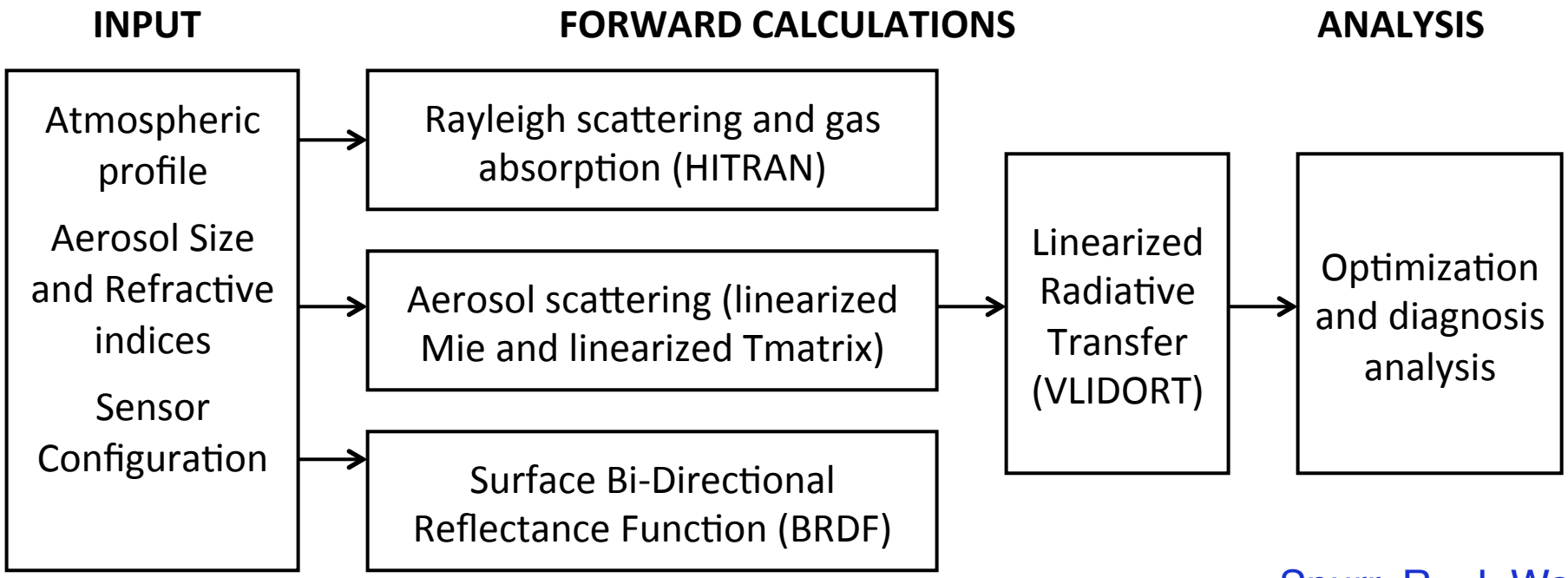



**Mass contributions of each size bin**

| | Bin 1 (%) | Bin 2 | Bin 3 | Bin 4 |
|---|---|---|---|---|
| GEOS-Chem | 12.2 | 25.3 | 32.3 | 30.2 |
| FIM-Chem | 11.35 | 11.35 | 23.30 | 54.00 |

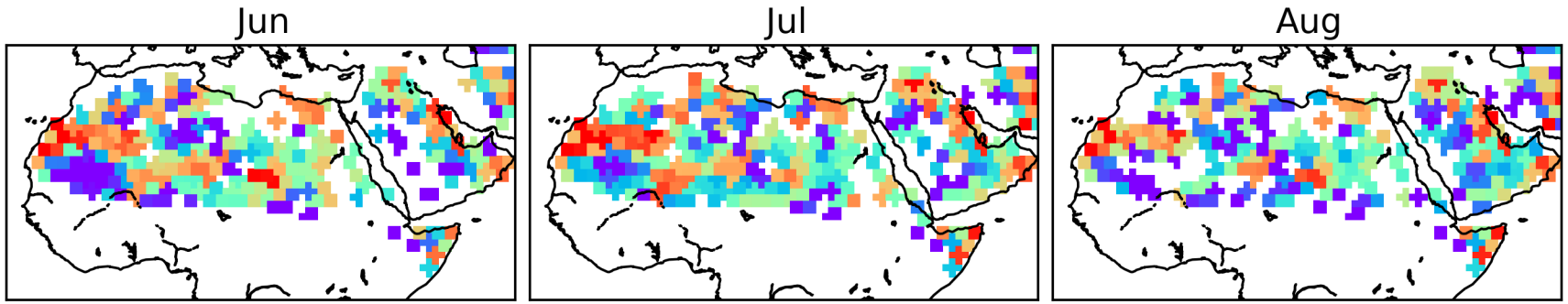
# UNified & Linearized Vector Radiative Transfer Model (UNL-VRTM)

**UNL-VRTM can calculate Jacobians of any Stokes vector with respect to any aerosol parameters, a powerful tool to assess of the information content of remote sensing observations.**

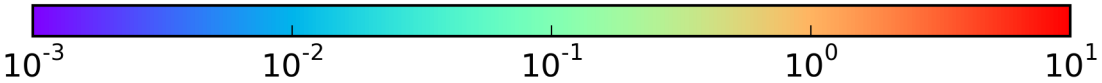



Spurr, R., J. Wang, et al., 2012
Wang, J. , X. Xu, et al., 2014
Xu and Wang, 2015

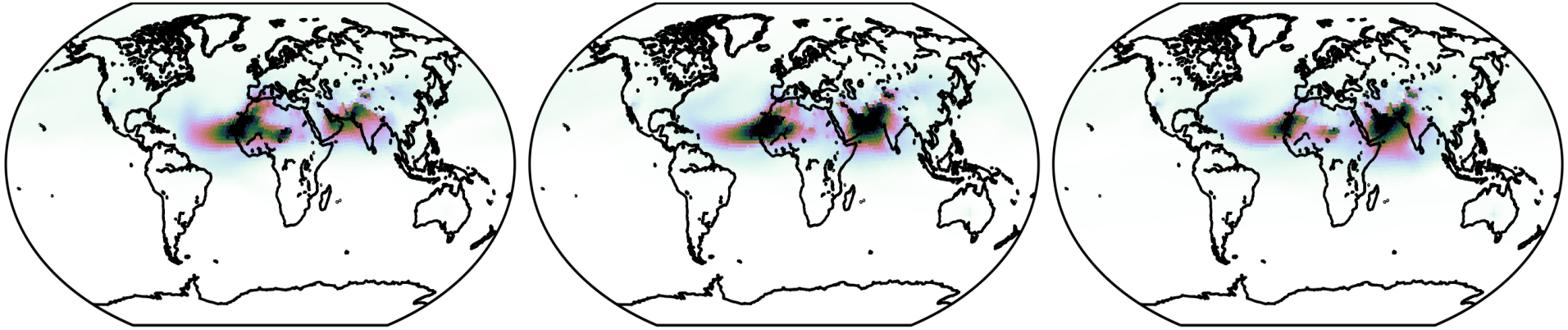
# FIM-Chem nature run: dust emissions and optical depths




2011 Jun – Aug




Dust emission flux (g/m2)



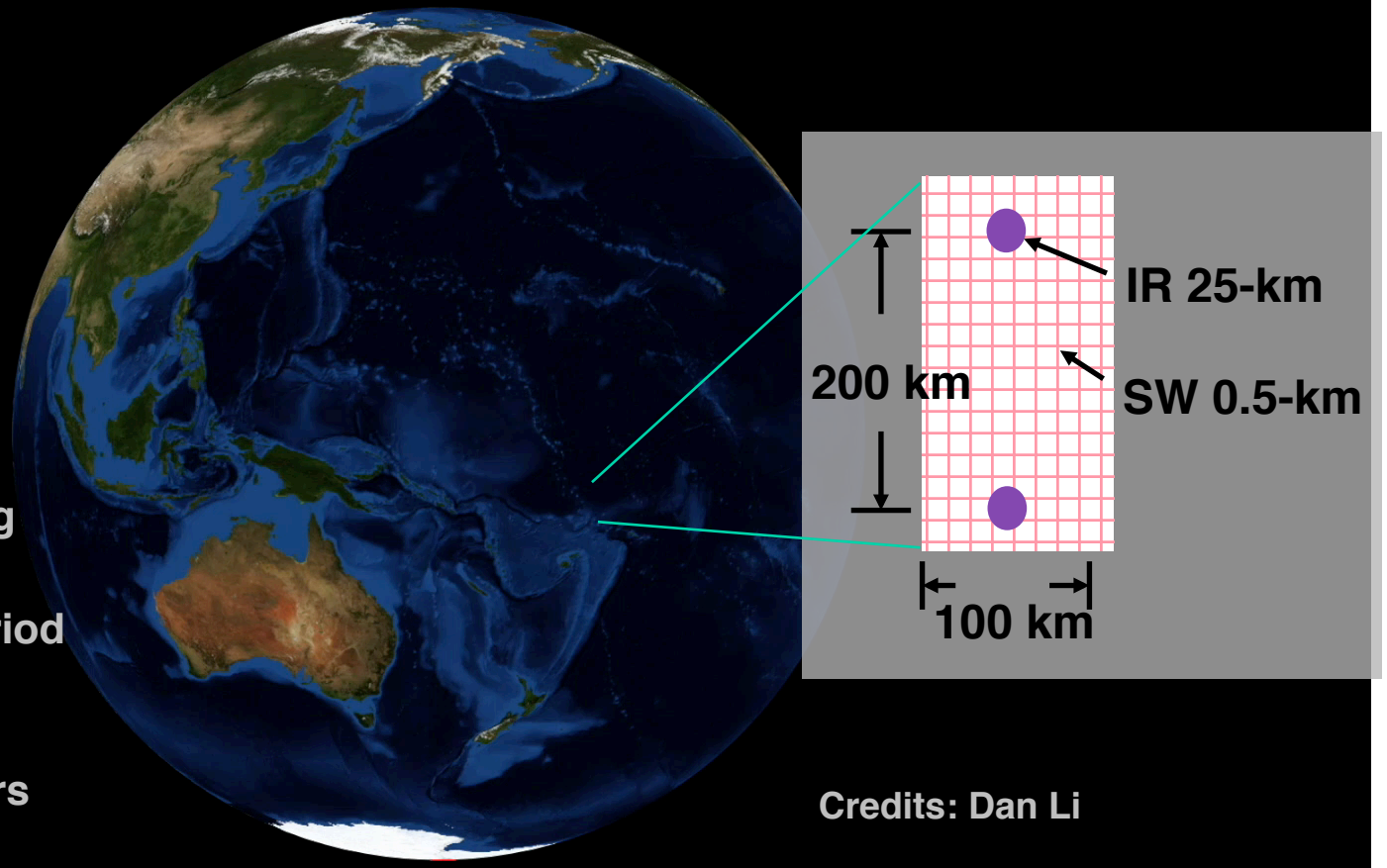
Optical depth (550 nm)

# CLAERRO processionary orbits
# 2 days

90° inclination

609-km altitude

~ 15 daily orbital cycle



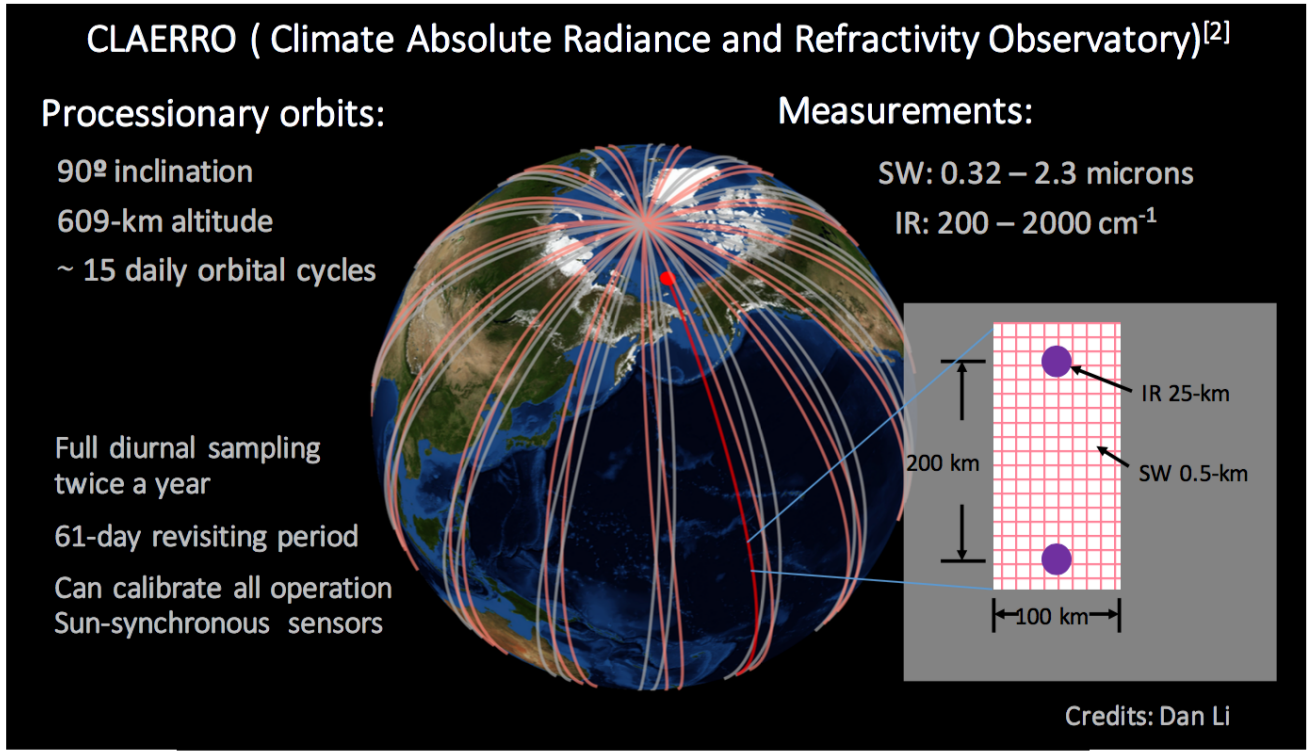

Full diurnal sampling twice a year

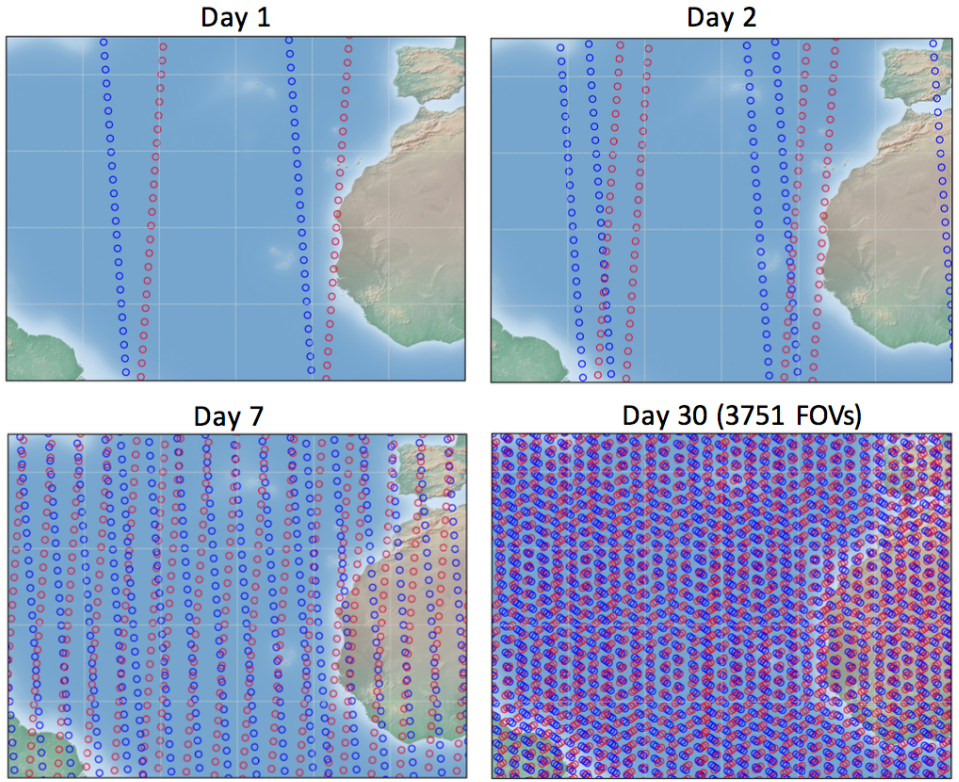
61-day revisiting period

Can calibrate all operation Sun-synchronous sensors

Credits: Dan Li

# Simulation of one-month CLARREO orbits

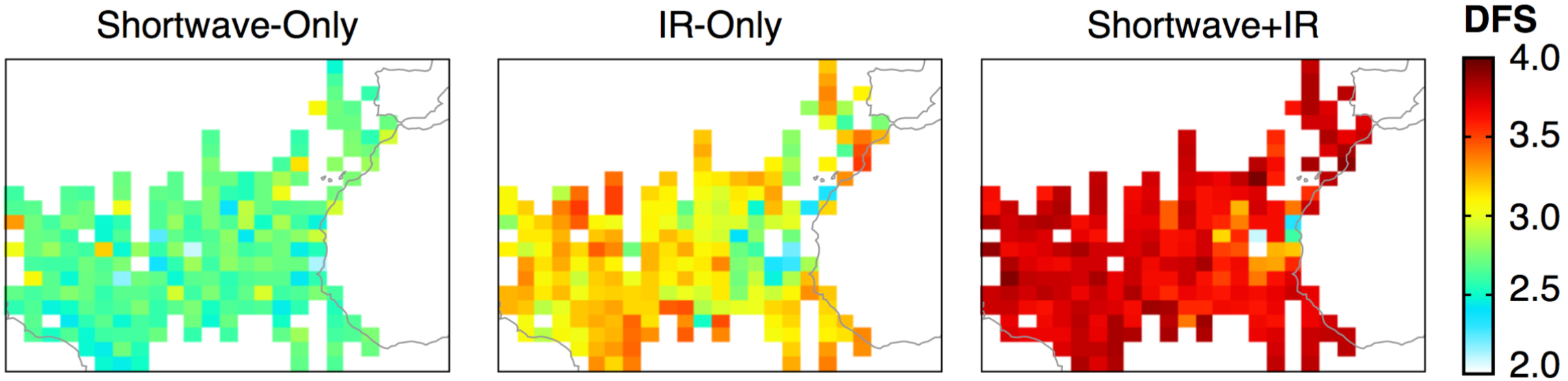


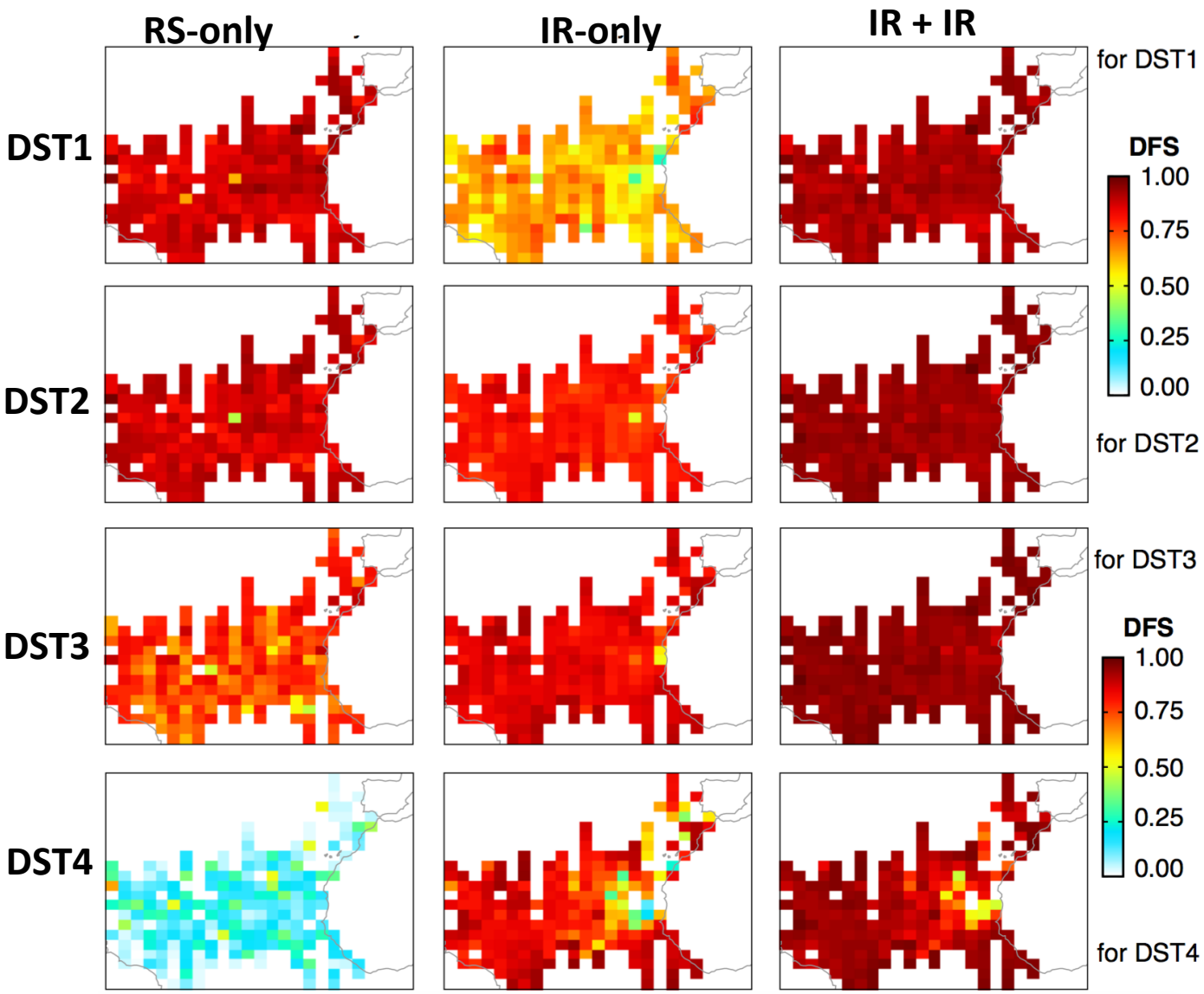

**Spatial sampling:** 25-km footprint for both IR and IS spectra scanned every 200 km.
**Spectral sampling:** 4 nm for RS and 1 $cm^{-1}$ for IR
**Spectral resolution:** 8nm for RS and 0.5 $cm^{-1}$ for IR

# DFS for Determining Dust Optical Depths of 4 Size Bins

We assume $\mathbf{S}_a = diag([0.2, 0.15, 0.1, 0.05]) \pm 50\%$; BT error is 0.4 K and reflectance error is $0.03 \pm 5\%$, both including instrument noises and model errors; observation error correlation coefficients are 0.33–0.95 for pair-wise channels.

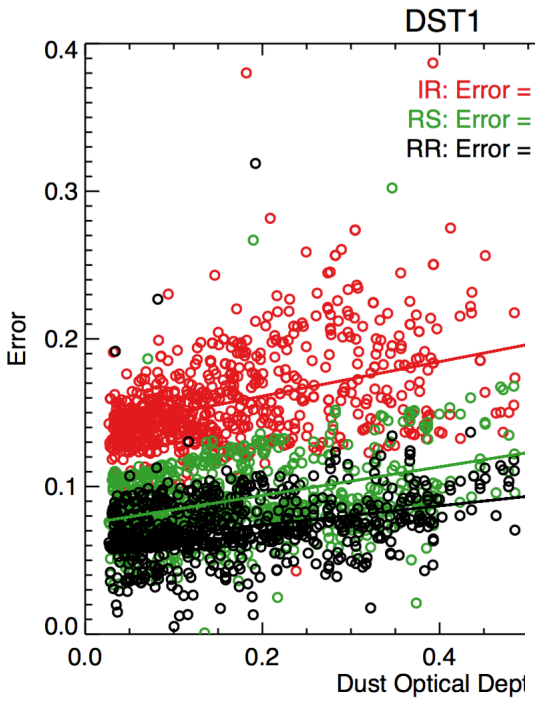


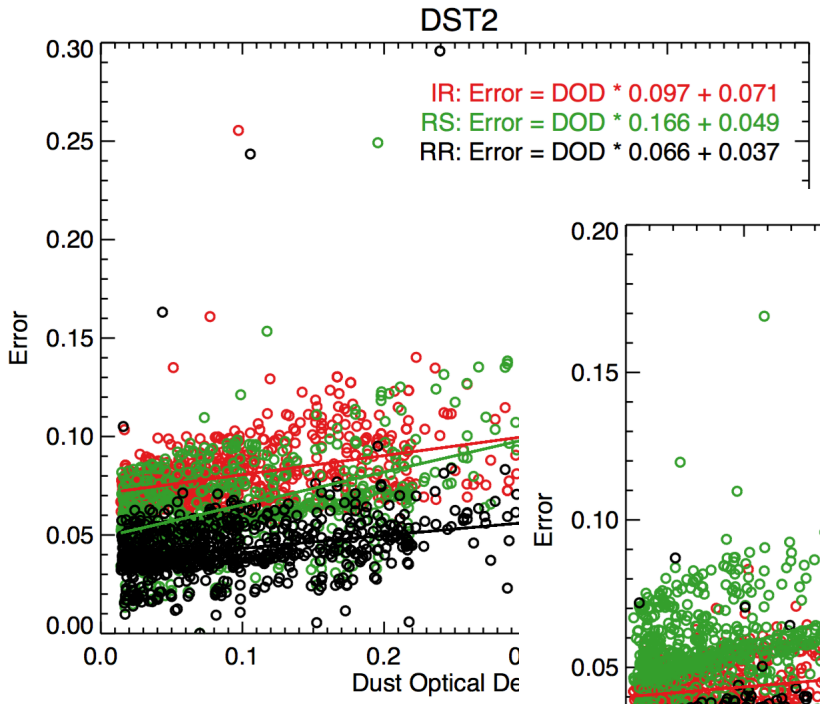
# DFS for Determining Dust Optical Depth (DOD) of each Size Bin

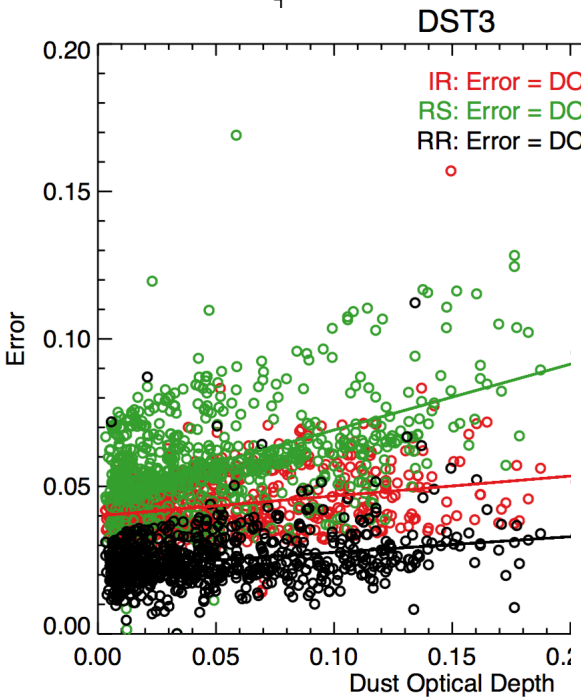


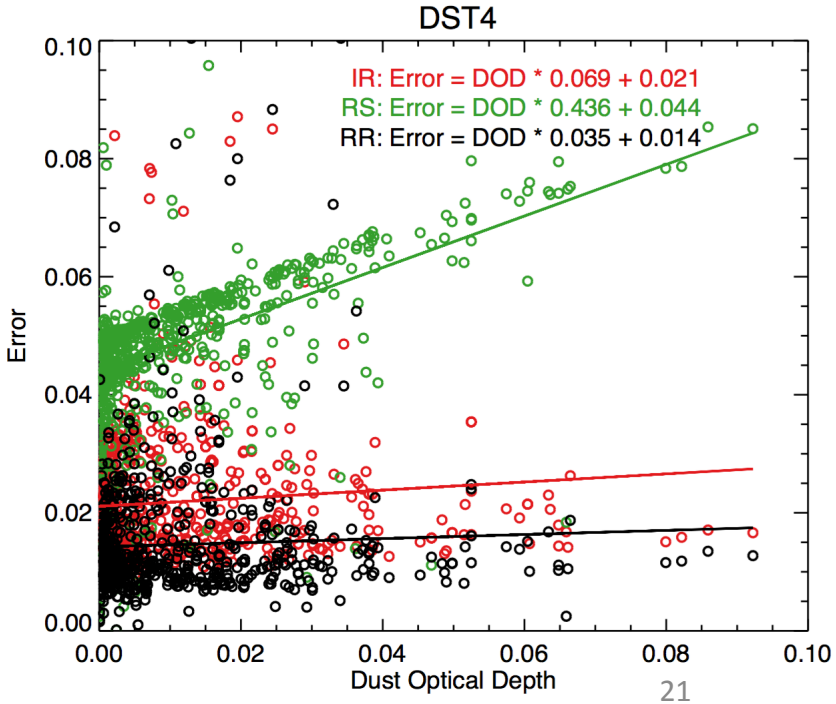

- The RS spectra are most sensitive to dust AOD of 1st size class, and the sensitivity decreases as bin size increases;
- The IR spectra are most sensitive to dust AOD the 3rd size bin least sensitive to the 1st size bin.
- Combining IR and RS spectra allows DFS for AOD in each size bin to be close to 1; information content for fully characterizing particle size is nearly 100%.

# Characterization of DOD errors




**Three observation scenario:**

- Infrared radiance (IR) spectra only
- Reflected-solar reflectance (RS) only
- RS + IR

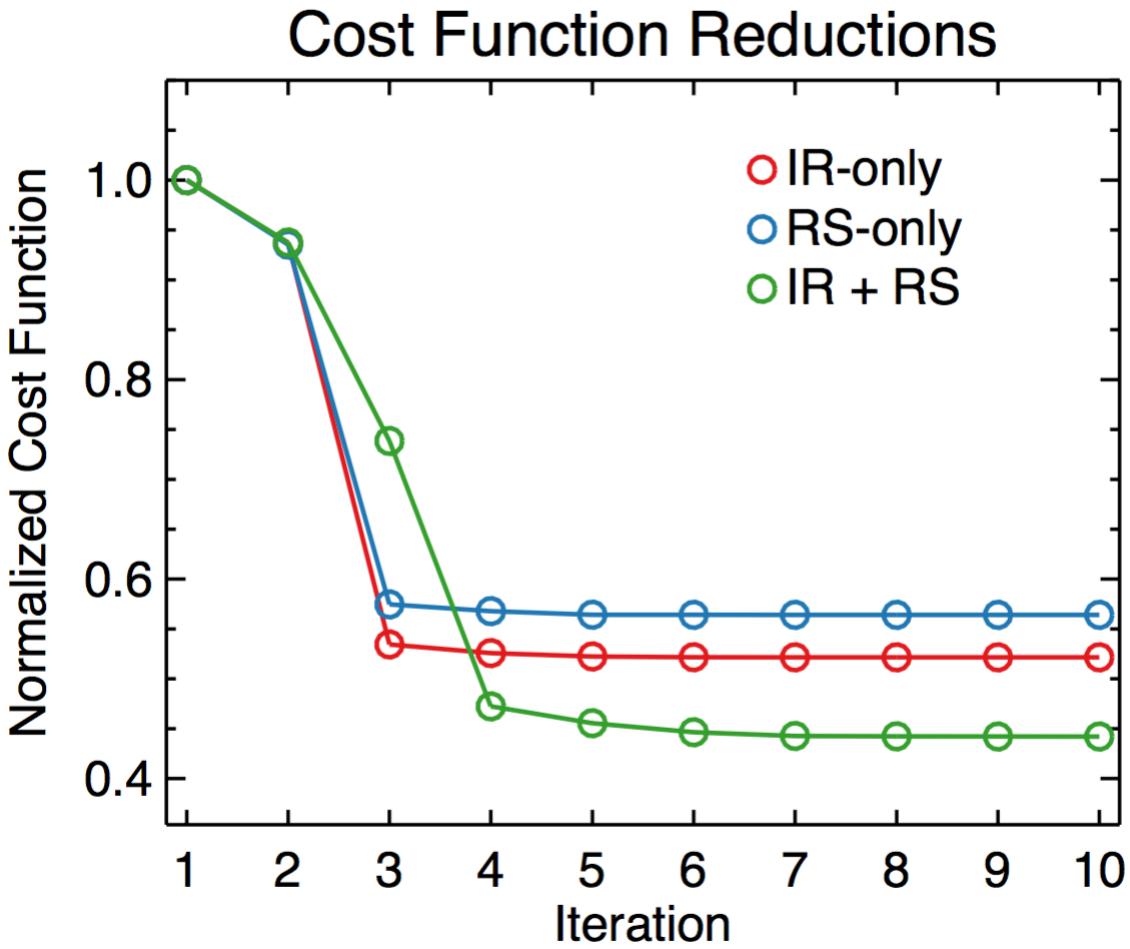
**DOD errors are estimated by the Bayesian theory:**

$$\hat{\mathbf{S}}_{\tau}^{-1} = \mathbf{K}^{T}\mathbf{S}_{\rho}^{-1}\mathbf{K} + \mathbf{S}_{\mathrm{a},\tau}^{-1}$$

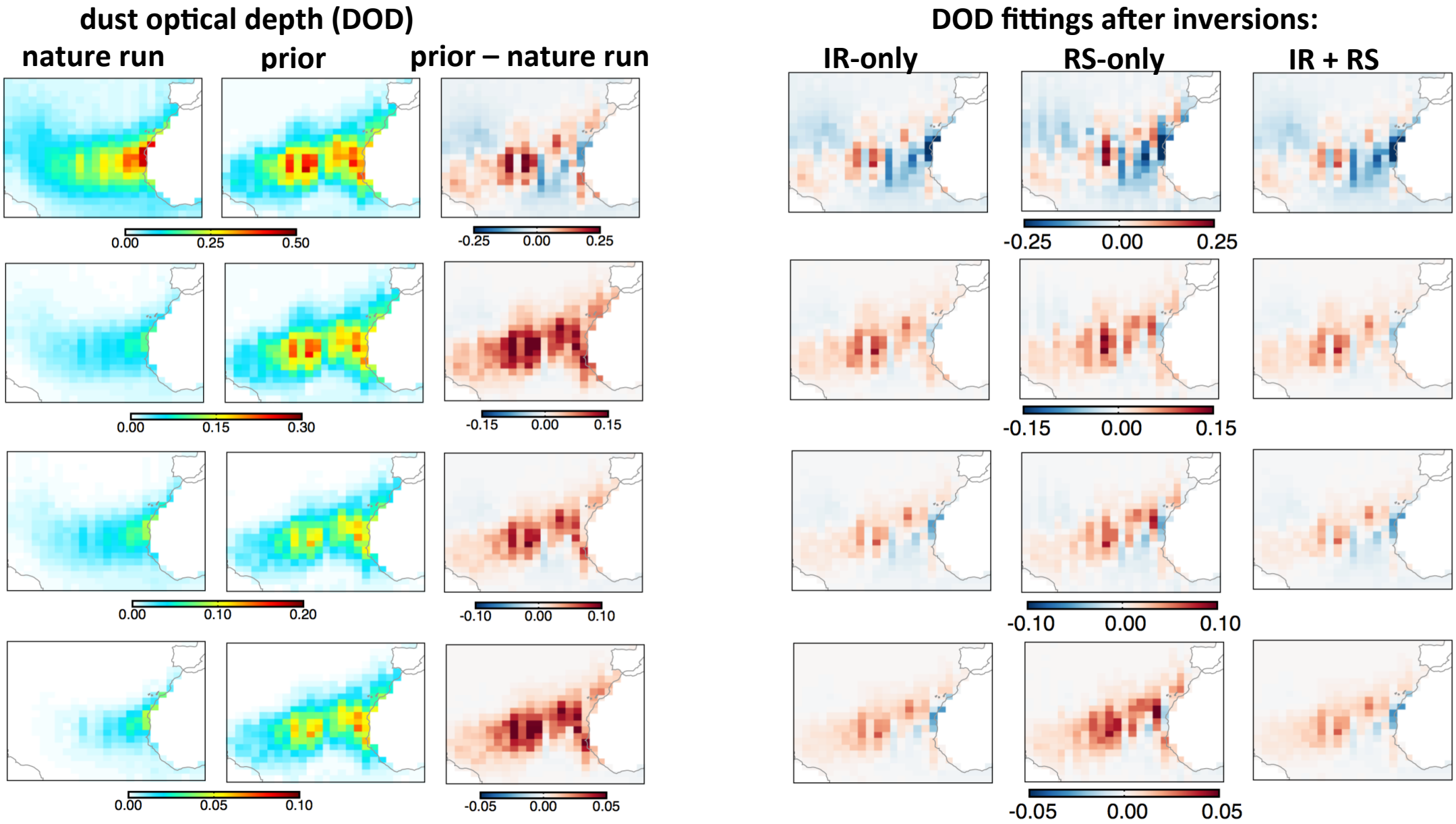
# OSSE: One-month adjoint inversion

**Model settings:**

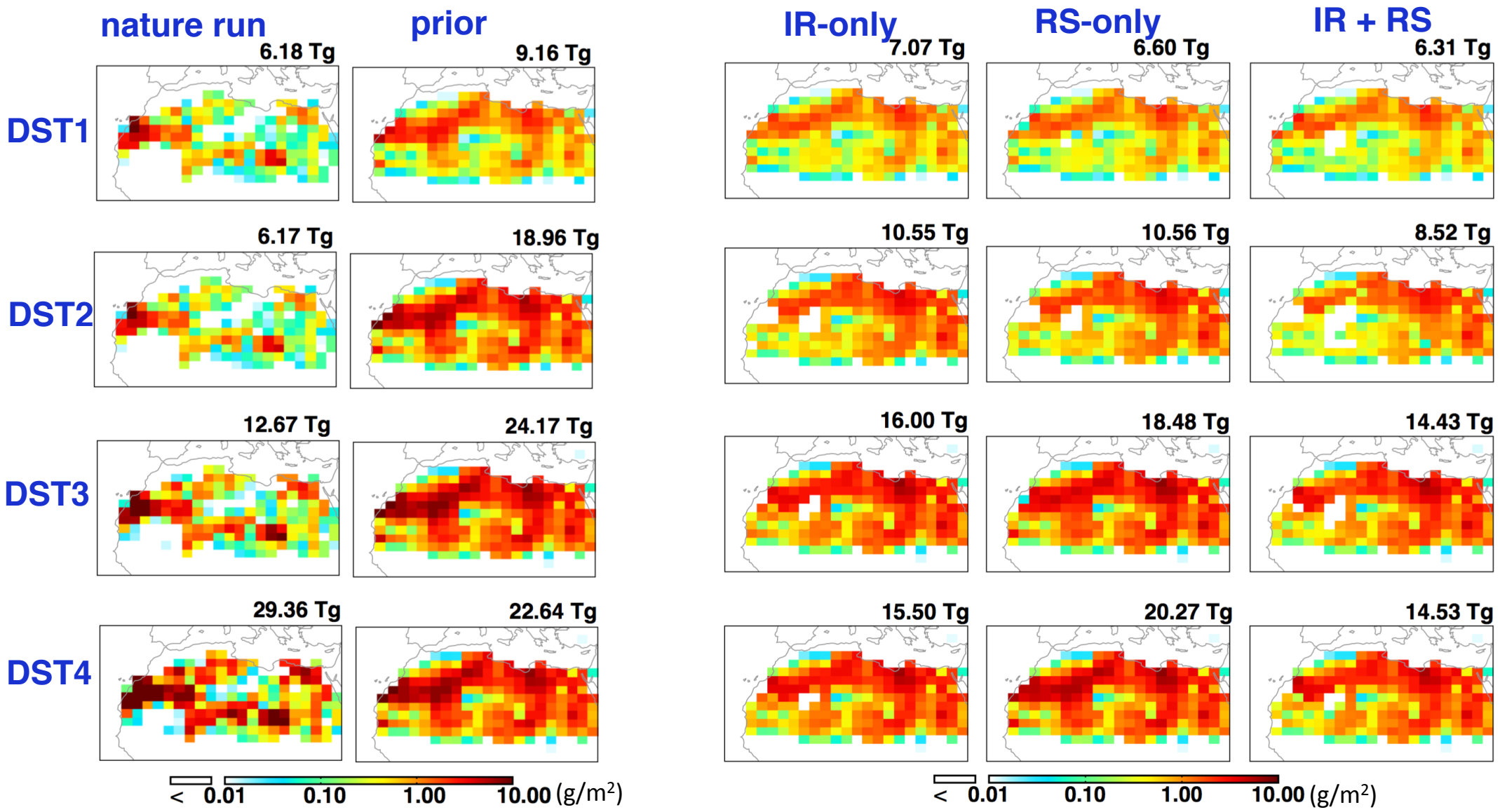
- June 2011
- Constrain dust emissions of each size bin
- 2 x 2.5 resolution
- Chemistry turned off
- No emission for tracers other than dust
- Dust emissions considering sub-grid wind



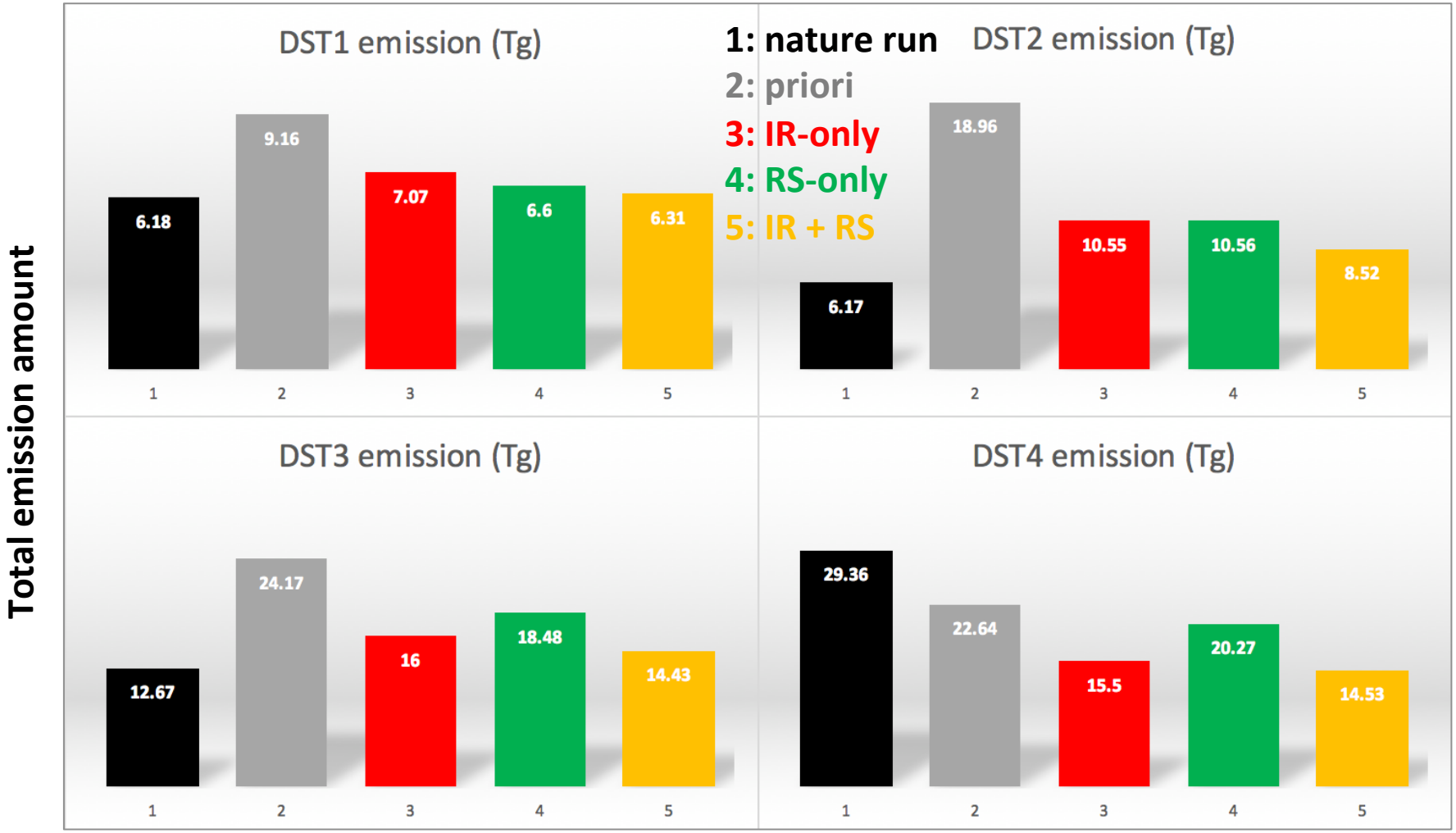
# Fitting of DOD "observations"



# Inversion of dust emissions



# Inversion of dust emissions

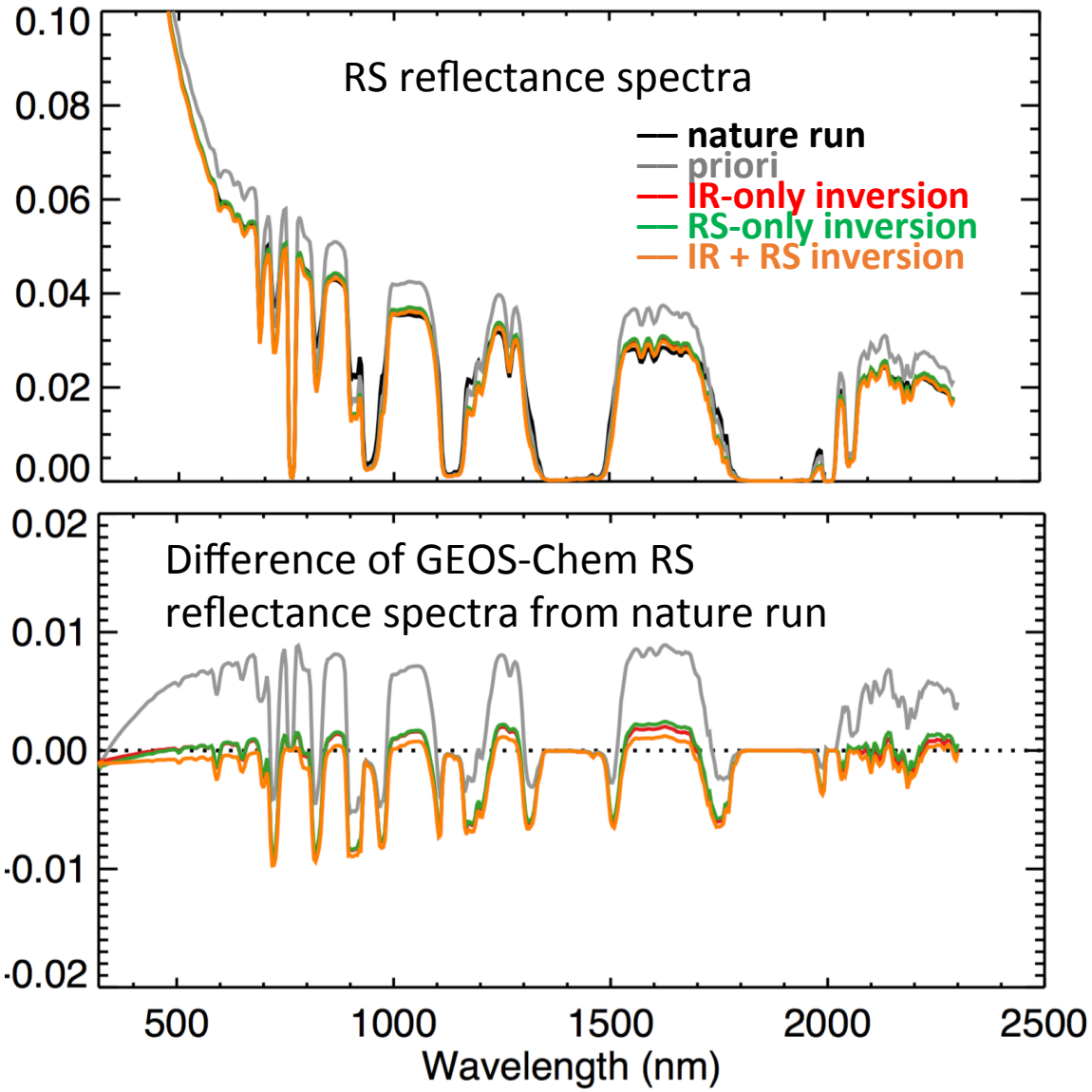


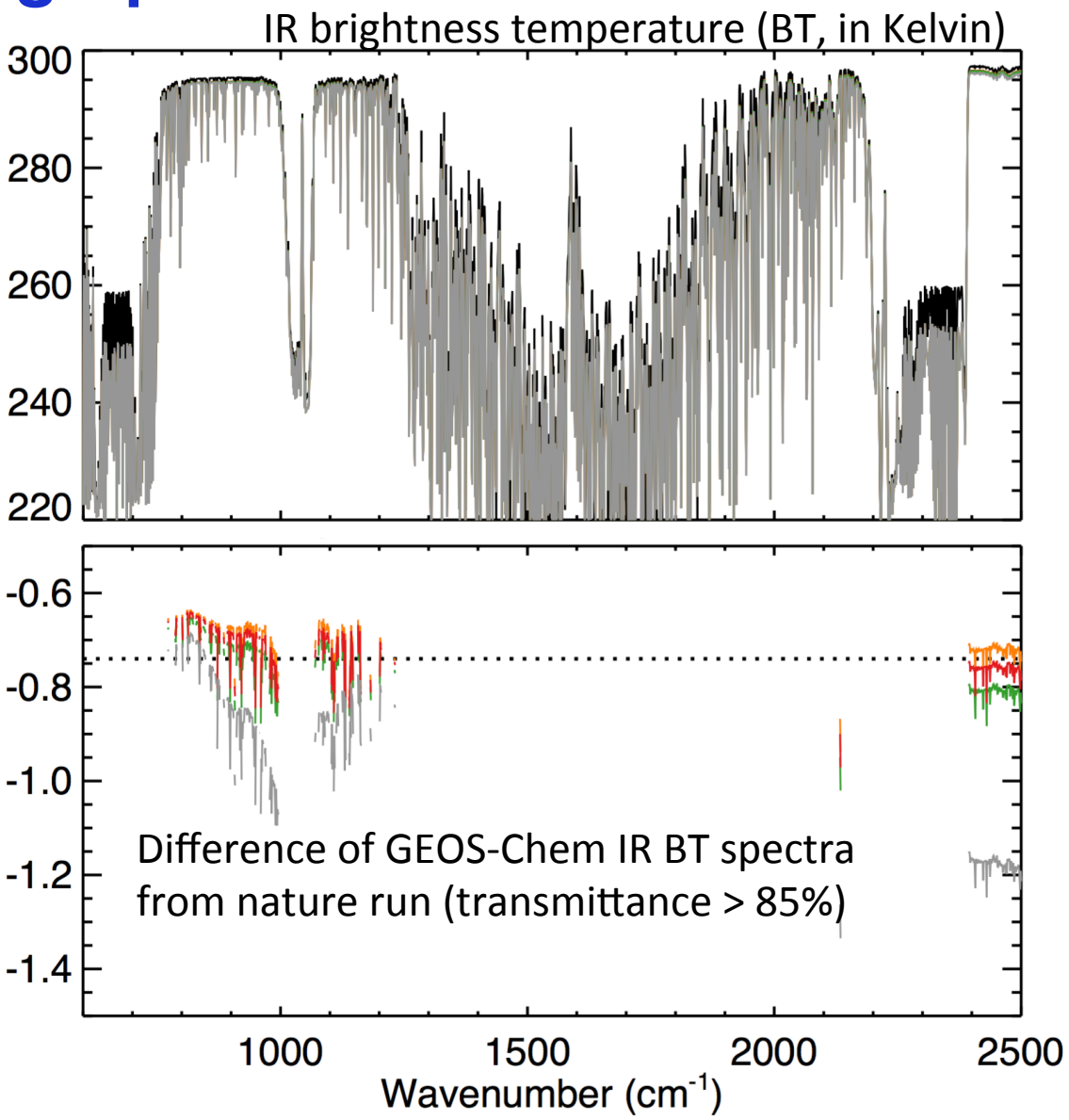

RS spectra yield better emission estimates for DST1, while IR yield better estimates for DST3.

RS + IR yield best emission estimates for DST1–DST3.

Emission for DST4 are underestimated, possibly because dust aerosol dry/ wet deposits faster in nature run.

# Spectral Fingerprint



# Summary

- The RS spectra are most sensitive to dust AOD of 1$^{st}$ size class, and the sensitivity decreases as bin size increases; Therefore, RS spectra yields better emission estimates for the 1$^{st}$ size bin.
- The IR spectra are most sensitive to dust AOD the 3$^{rd}$ size bin least sensitive to the 1$^{st}$ size bin. Emissions of the 3$^{rd}$ size bin are well constrained by IR spectra.
- Combining IR and RS spectra allows DFS for AOD in each size bin to be close to 1; information content for fully characterizing particle size is nearly 100%. Such combination allows a better characterization of dust emissions for most size classes.

# Back-up slides begin here!

# Assimilation of DOD is equivalent to the assimilation of radiances

## To assimilate DOD:

$$J = \frac{1}{2}[\tau_\mathrm{o} - \tau_\mathrm{m}]^T \hat{\mathbf{S}}_\tau^{-1}[\tau_\mathrm{o} - \tau_\mathrm{m}] + \frac{1}{2}\gamma[\mathbf{p} - \mathbf{p}_\mathrm{a}]^T \mathbf{S}_\mathrm{a}^{-1}[\mathbf{p} - \mathbf{p}_\mathrm{a}]$$

$$\hat{\mathbf{S}}_\tau^{-1} = \mathbf{K}^T \mathbf{S}_\rho^{-1} \mathbf{K} + \mathbf{S}_{\mathrm{a},\tau}^{-1}$$

DOD observation errors are estimated from spectral radiances

## Replace $S_\tau$ in the cost function:

$$J = \frac{1}{2}[\mathbf{K}(\tau_\mathrm{o} - \tau_\mathrm{m})]^T \mathbf{S}_\rho^{-1}[\mathbf{K}(\tau_\mathrm{o} - \tau_\mathrm{m})] + \frac{1}{2}\gamma[\mathbf{p} - \mathbf{p}_\mathrm{a}]^T \mathbf{S}_\mathrm{a}^{-1}[\mathbf{p} - \mathbf{p}_\mathrm{a}]$$

$$\rho_\mathrm{o} = \mathbf{K}\tau_\mathrm{o}; \rho_\mathrm{m} = \mathbf{K}\tau_\mathrm{m}$$

In our OSSEs, same aerosol optical properties are assumed for both forward and inverse modeling.

$$J = \frac{1}{2}[\rho_\mathrm{o} - \rho_\mathrm{m}]^T \mathbf{S}_\rho^{-1}[\rho_\mathrm{o} - \rho_\mathrm{m}] + \frac{1}{2}\gamma[\mathbf{p} - \mathbf{p}_\mathrm{a}]^T \mathbf{S}_\mathrm{a}^{-1}[\mathbf{p} - \mathbf{p}_\mathrm{a}]$$

**= To assimilate radiances**

$\tau_\mathrm{o}$ : observed DOD

$\tau_\mathrm{m}$ : modeled DOD

$\mathbf{S}_\tau$ : DOD error covariance

$\rho_\mathrm{o}$ : observed radiances

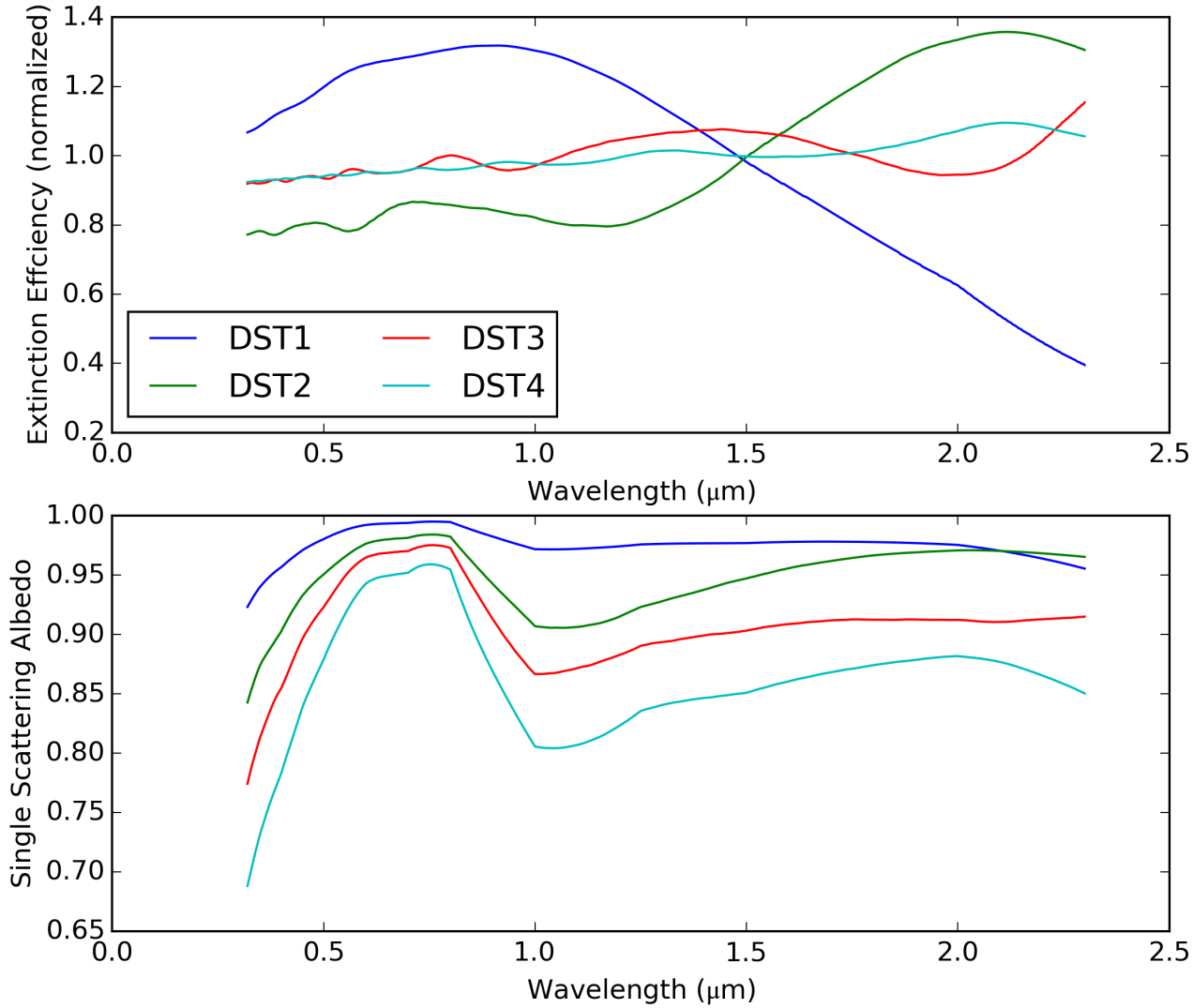
$\rho_\mathrm{m}$ : modeled radiances

$\mathbf{K}$ : Jacobian of radiance wrt DOD

$\mathbf{S}_\rho$ : radiance obs. error covariance

$\mathbf{S}_{\mathrm{a},\tau}$ : DOD a priori error covariance

# Dust optical properties in solar spectrum



# The OSSE

## Observing-Systems Simulation Experiments: Past, Present, and Future

Charles P. Arnold, Jr.[1] and Clifford H. Dey[2]

*Bulletin American Meteorological Society* 689

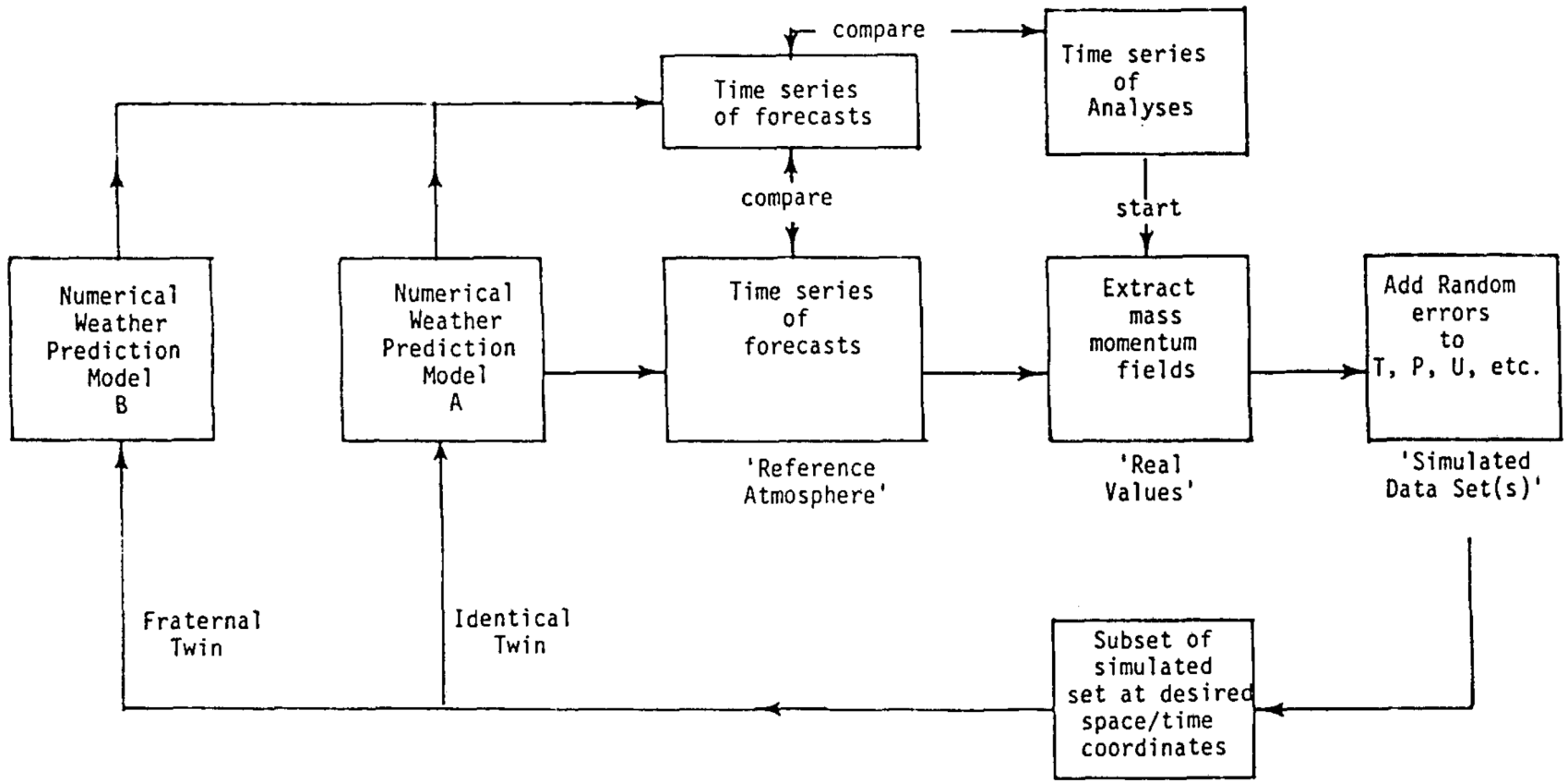
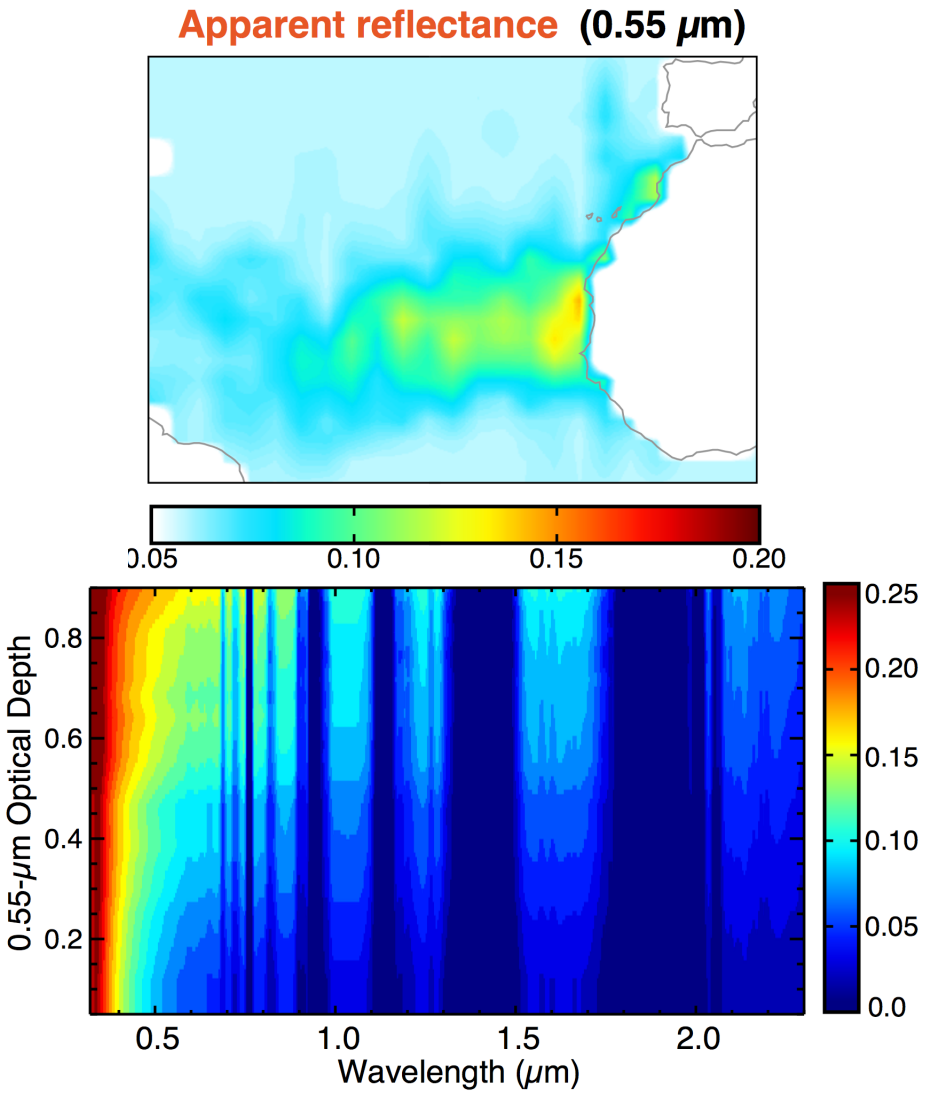
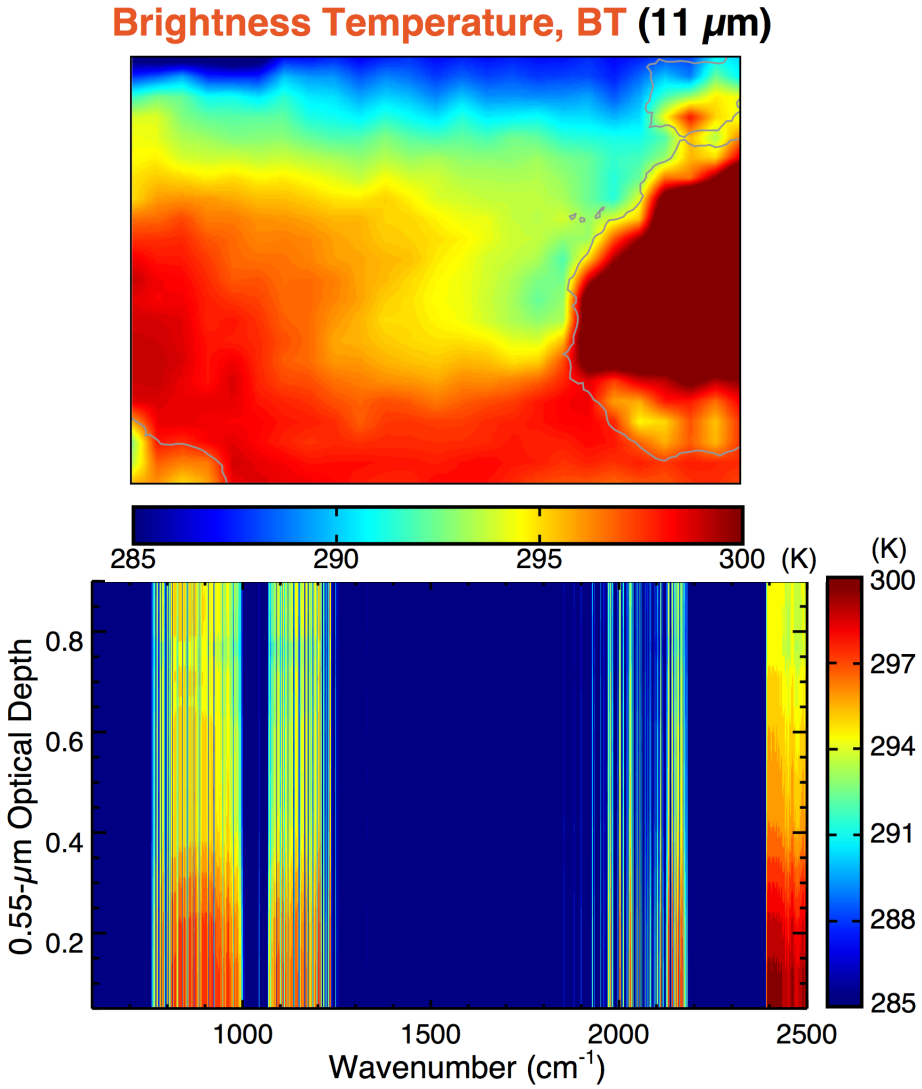


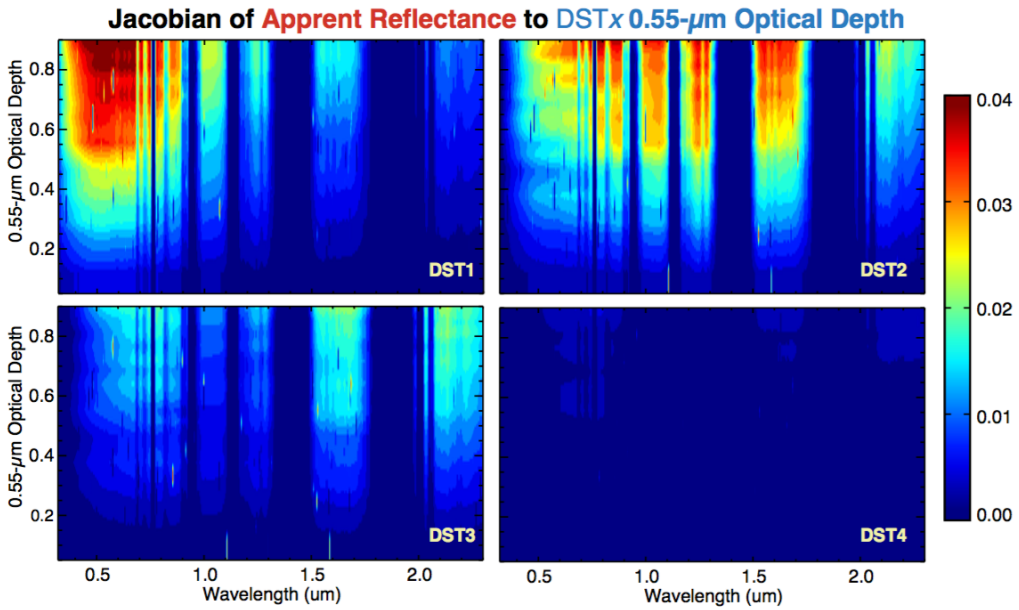

FIG. 1. Types of simulation experiments.

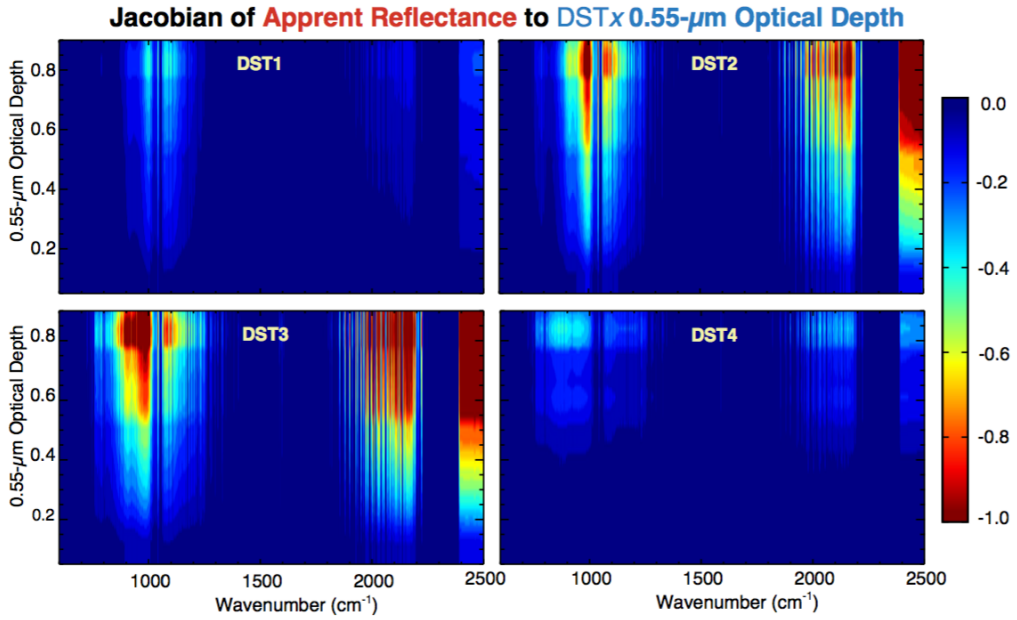
# Simulated CLARREO SW reflectance and IR brightness temperature

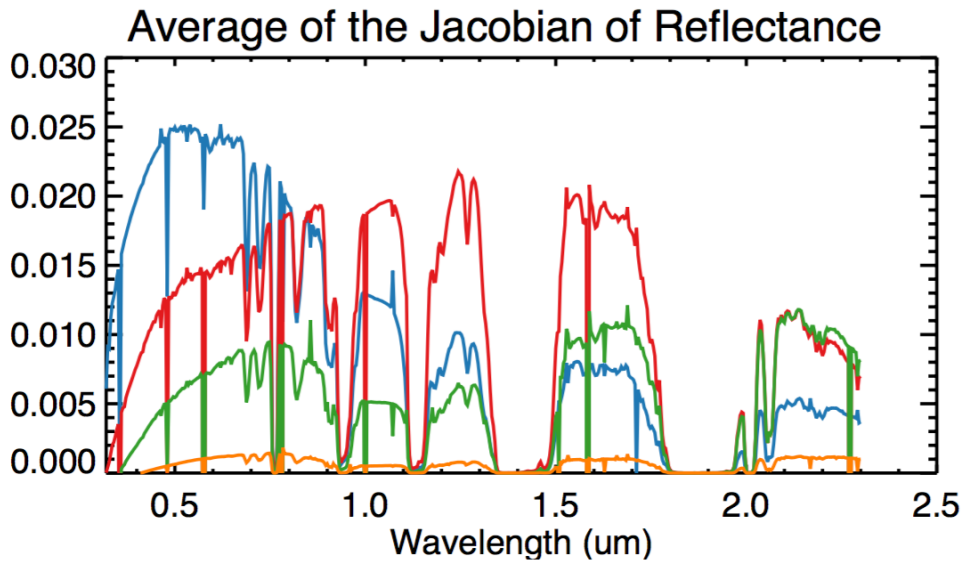


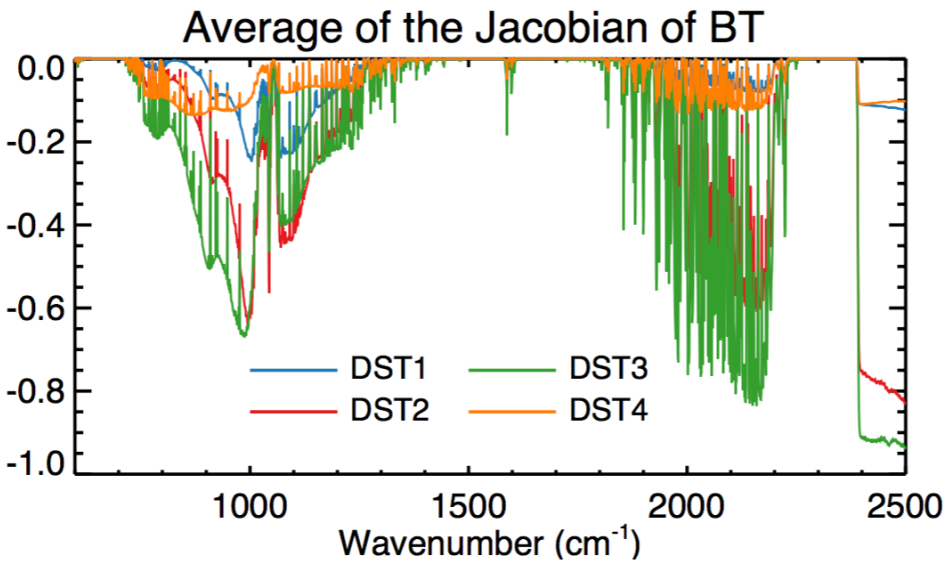



# Jacobians of Measurements to Optical Depth of each Size Bin



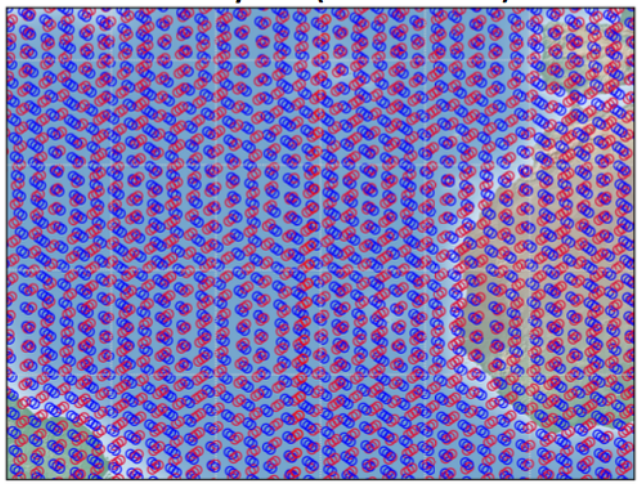



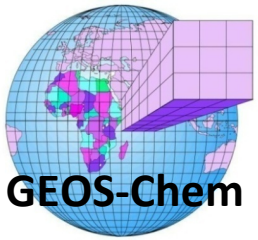



# GEOS-Chem VS. FIM-Chem: dust optical depths

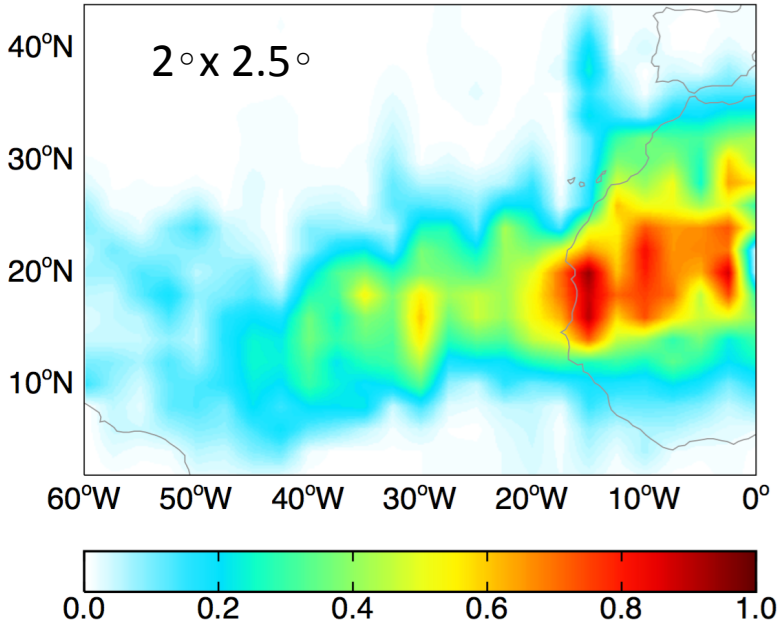
30-day CLARREO Samplings

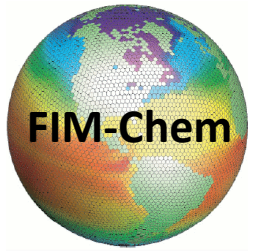
Day 30 (3751 FOVs)



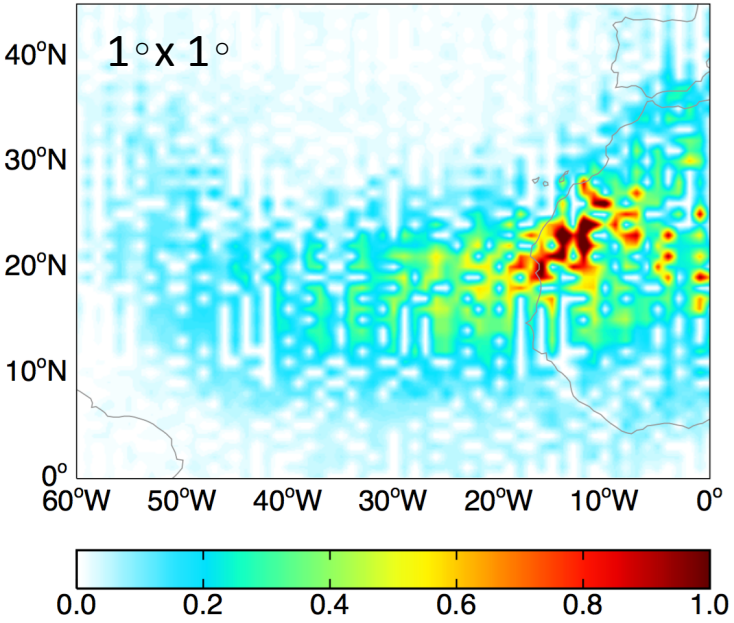
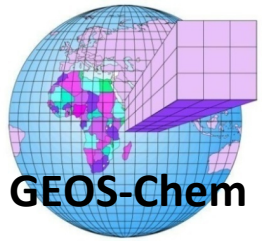
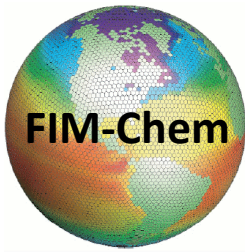
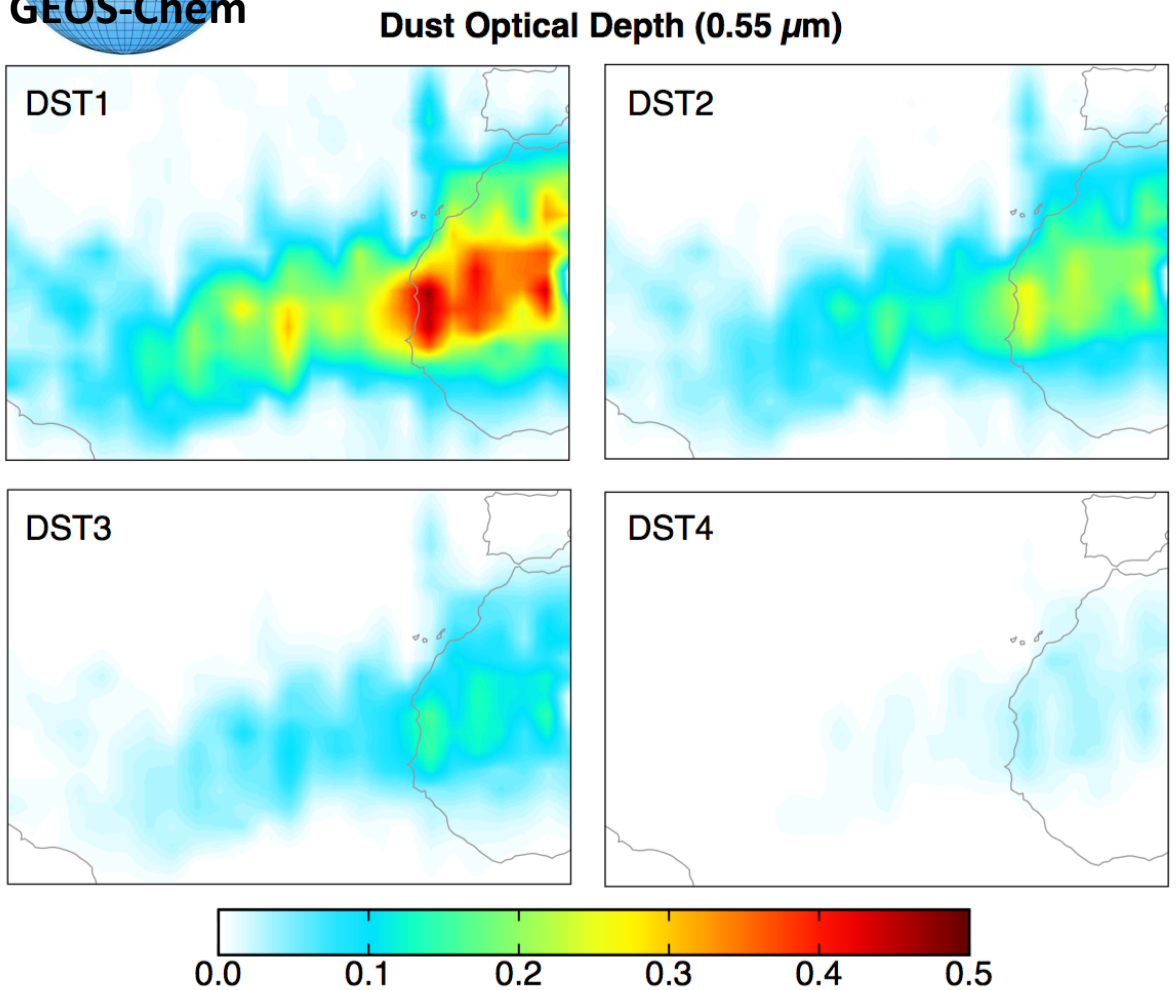
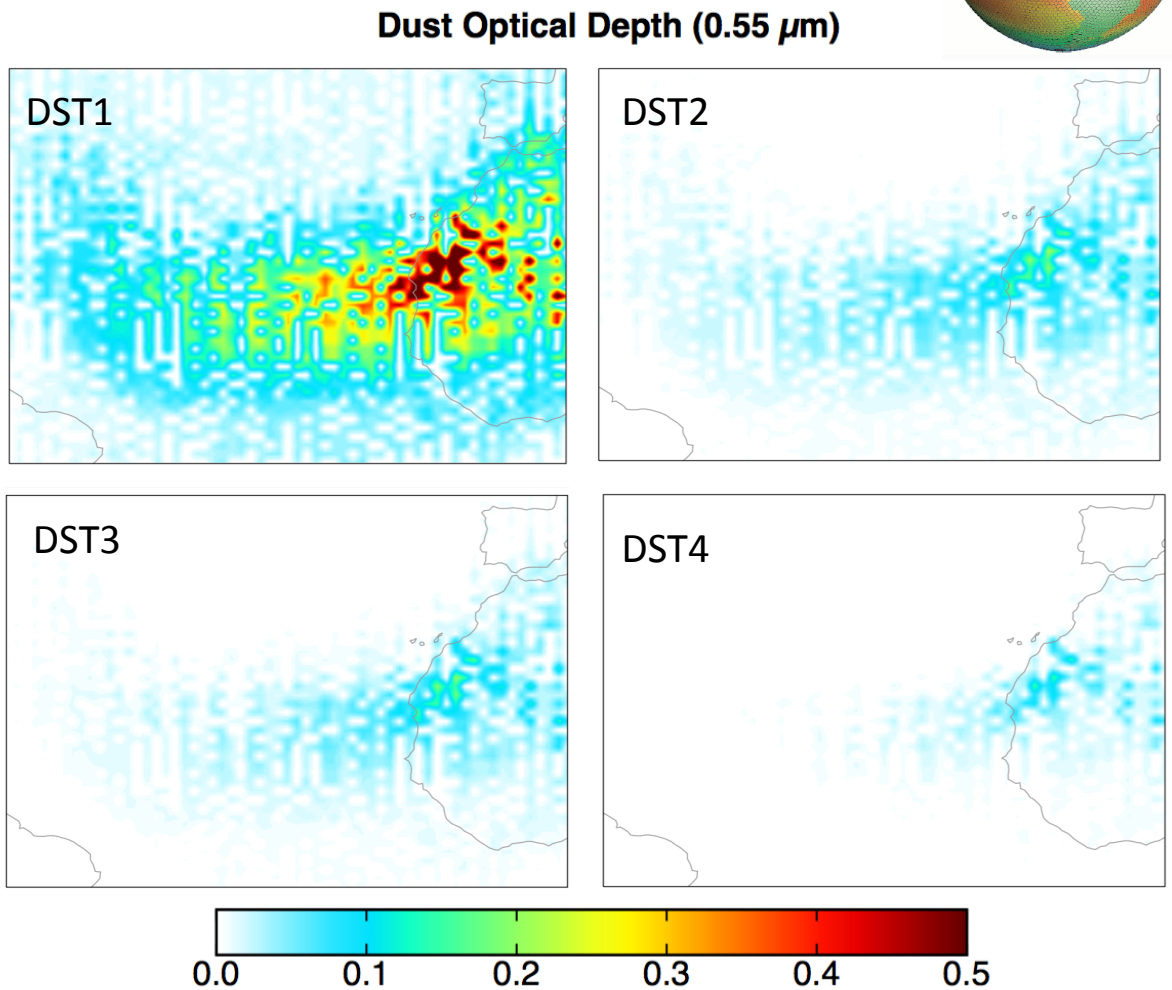



Total Dust Optical Depth (0.55 um)




Total Dust Optical Depth (0.55 um)



# GEOS-Chem VS. FIM-Chem: dust optical depths