Aerosol complexity and implications for predictability and short-term forecasting

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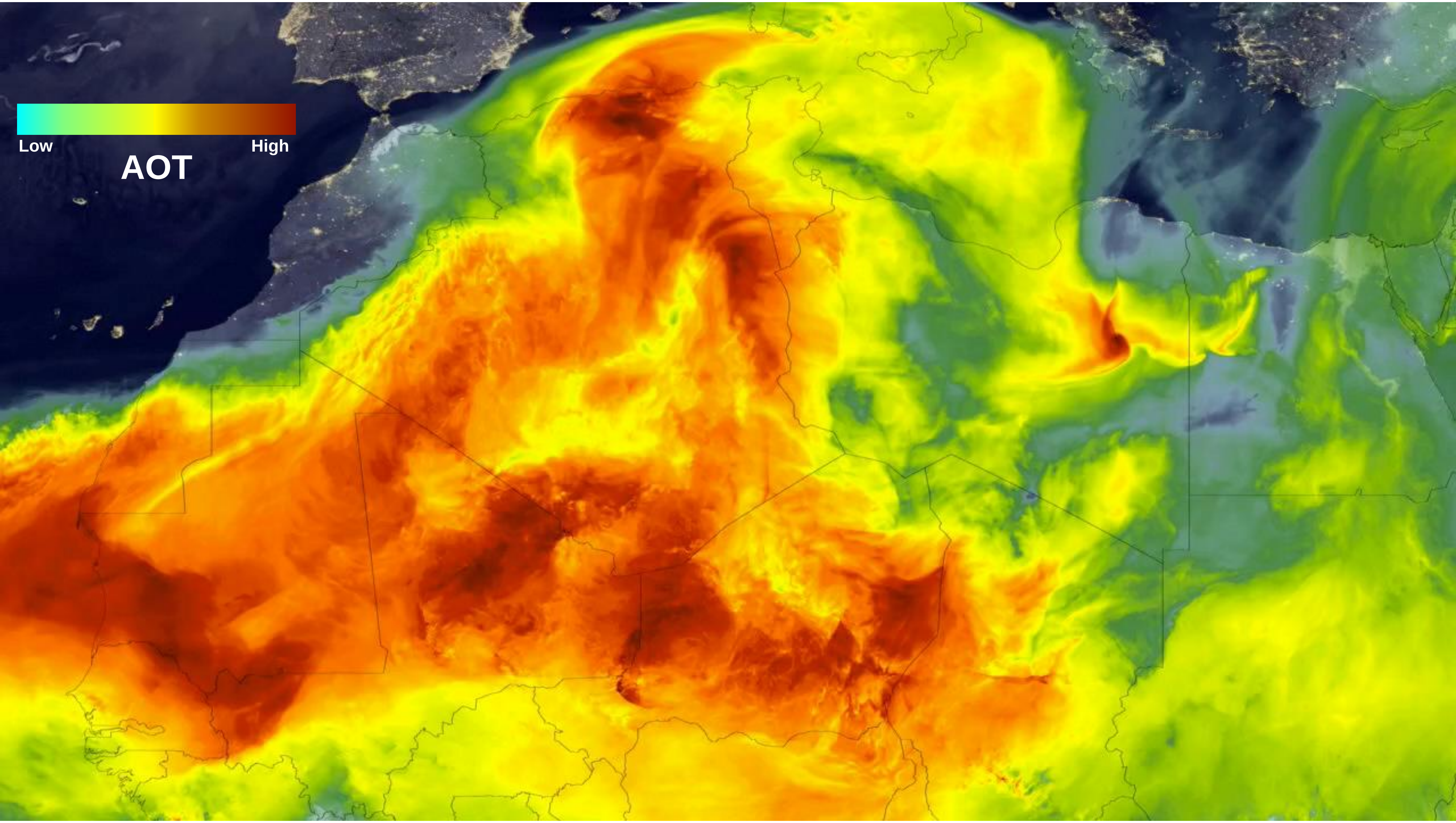
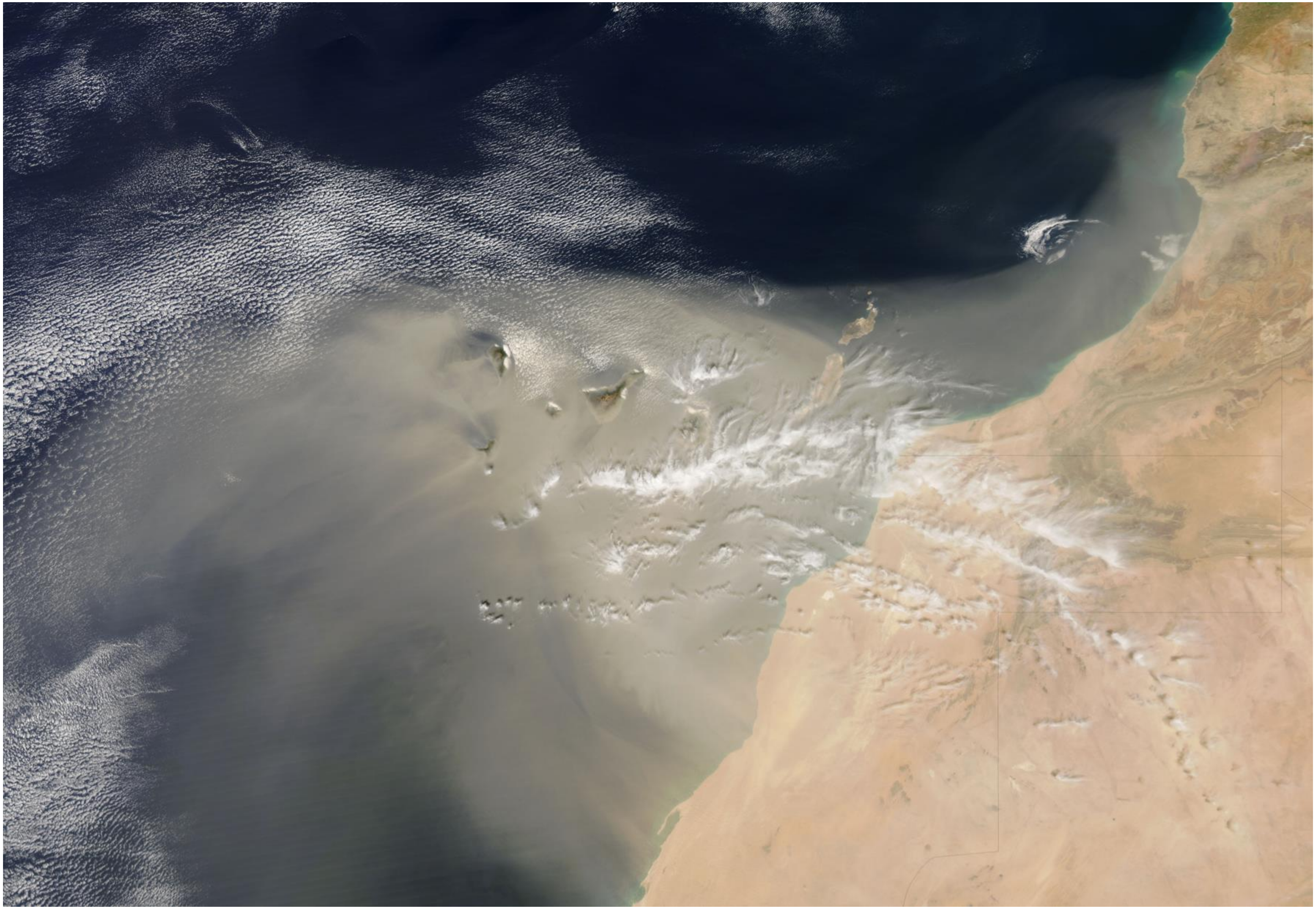
Global 1.5-km Aerosol Simulation

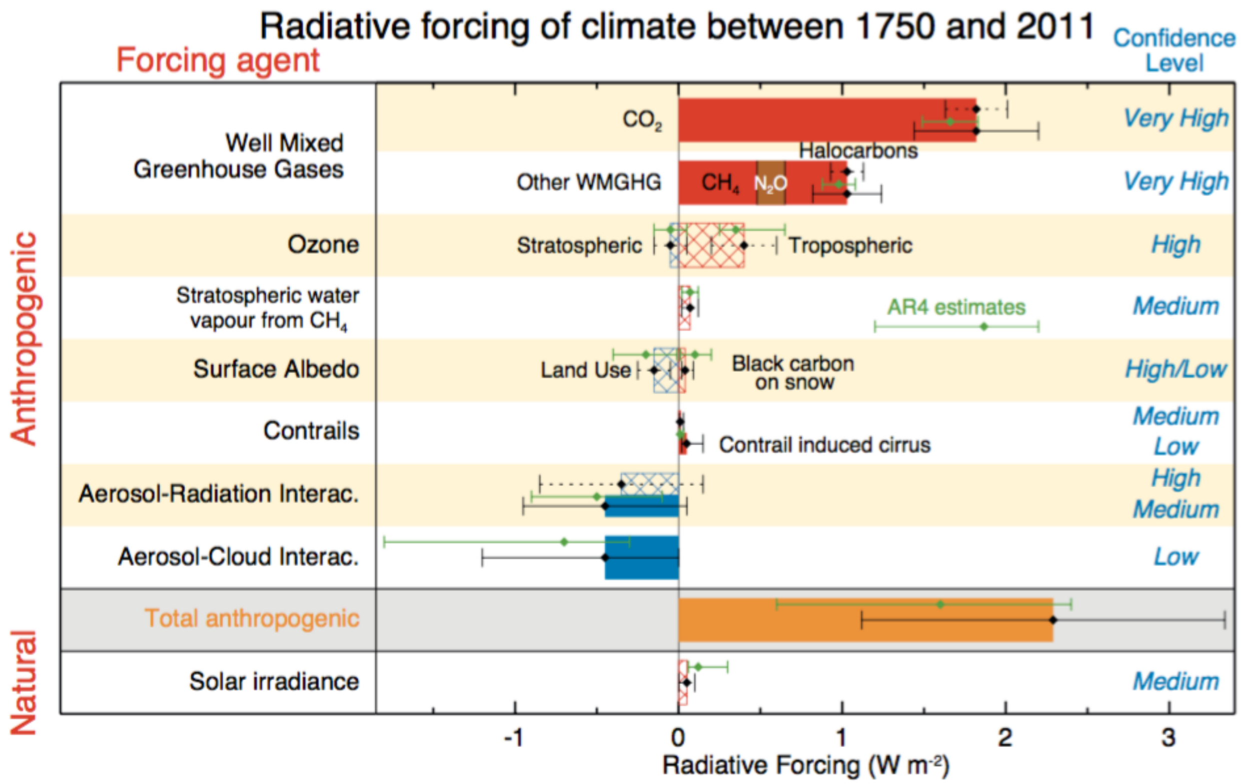


Global 1.5-km aerosol simulation produced with GEOS-5 Earth system model, focused on North African dust, running on approximately 30,000 cores at NASA GSFC NCCS, W. Putman (GMAO)

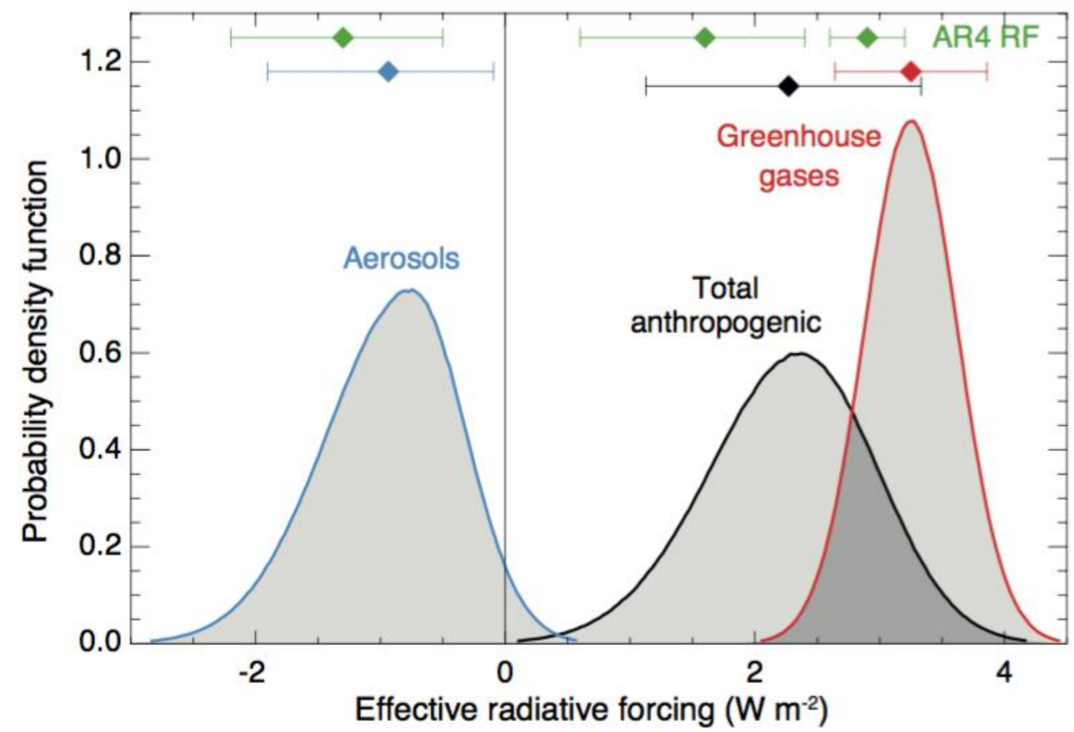
Aerosols Seen From Space



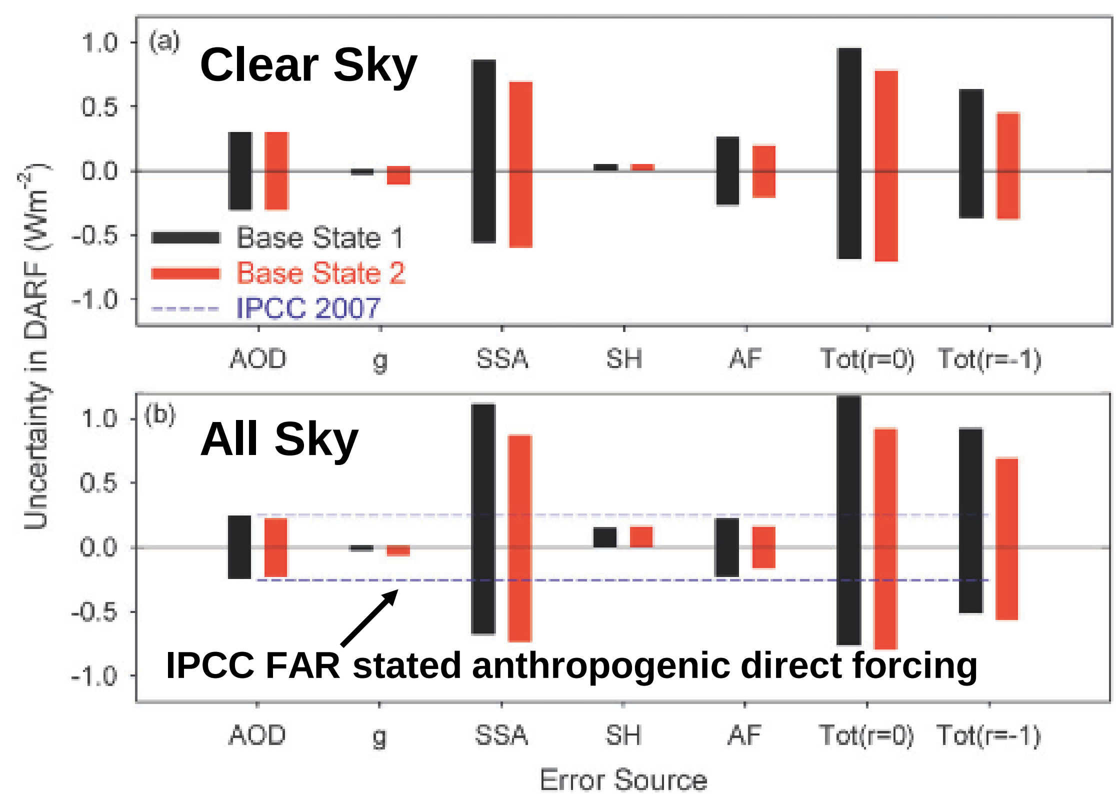
Aerosols and Climate Prediction



IPCC AR5 Technical Summary, 2013



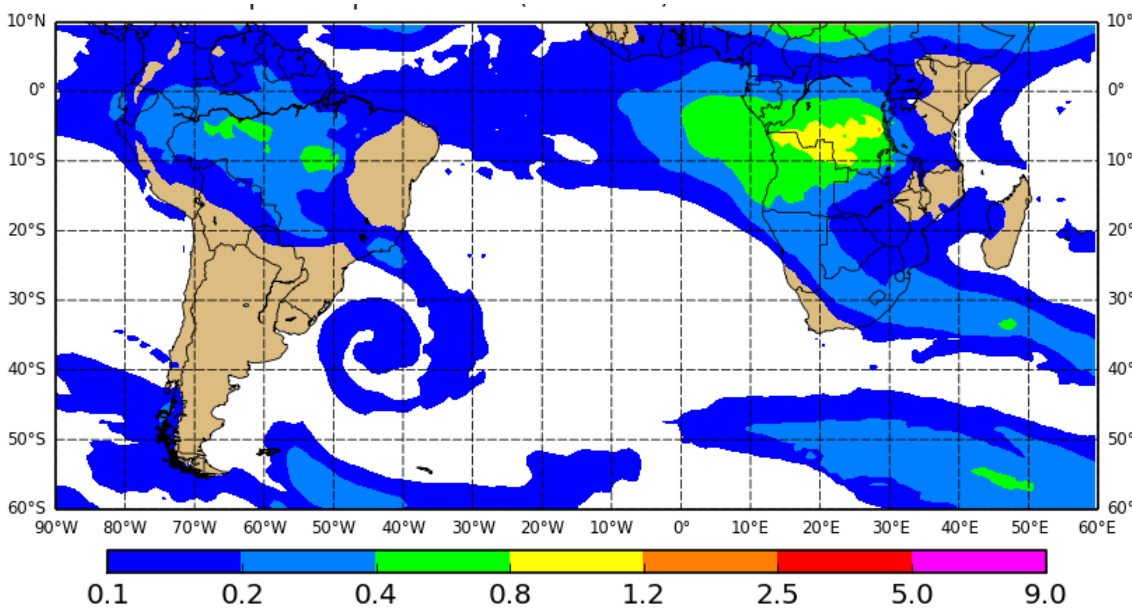
- Direct and indirect effects of anthropogenic aerosols remains the leading uncertainty in overall anthropogenic forcing of climate
- The reason is that there are fundamental uncertainties in important aerosol parameters: propagating realistic uncertainties in aerosol parameters through radiative transfer suggests IPCC estimates of uncertainty are too small
- Aerosol schemes used in near-real time forecasting models have typically come from the climate modeling community, which has different needs and has favored more complex schemes

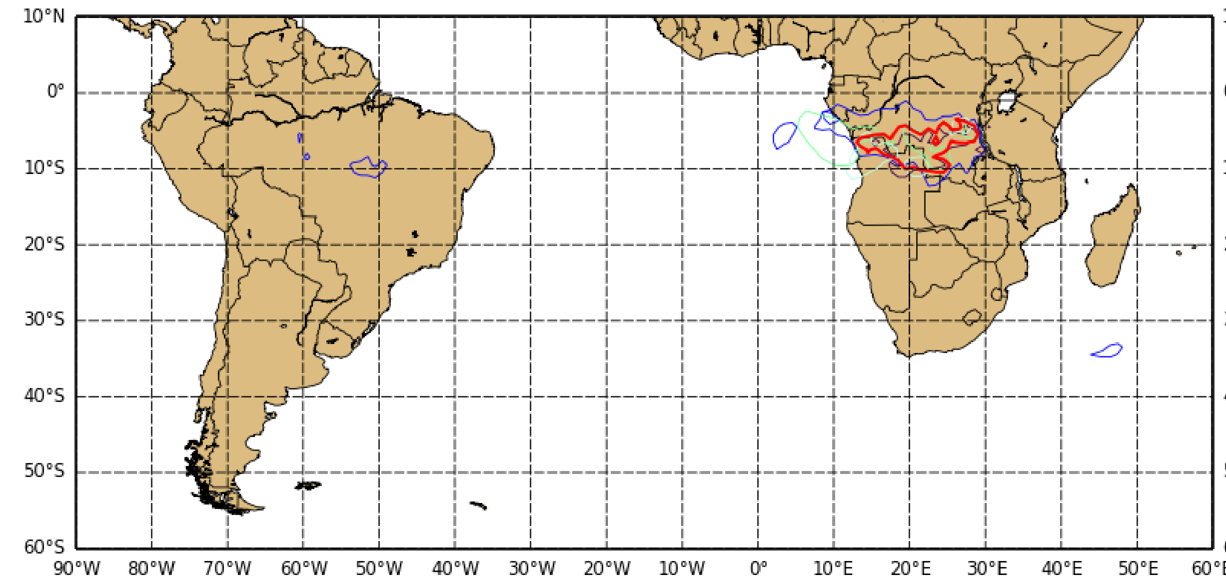


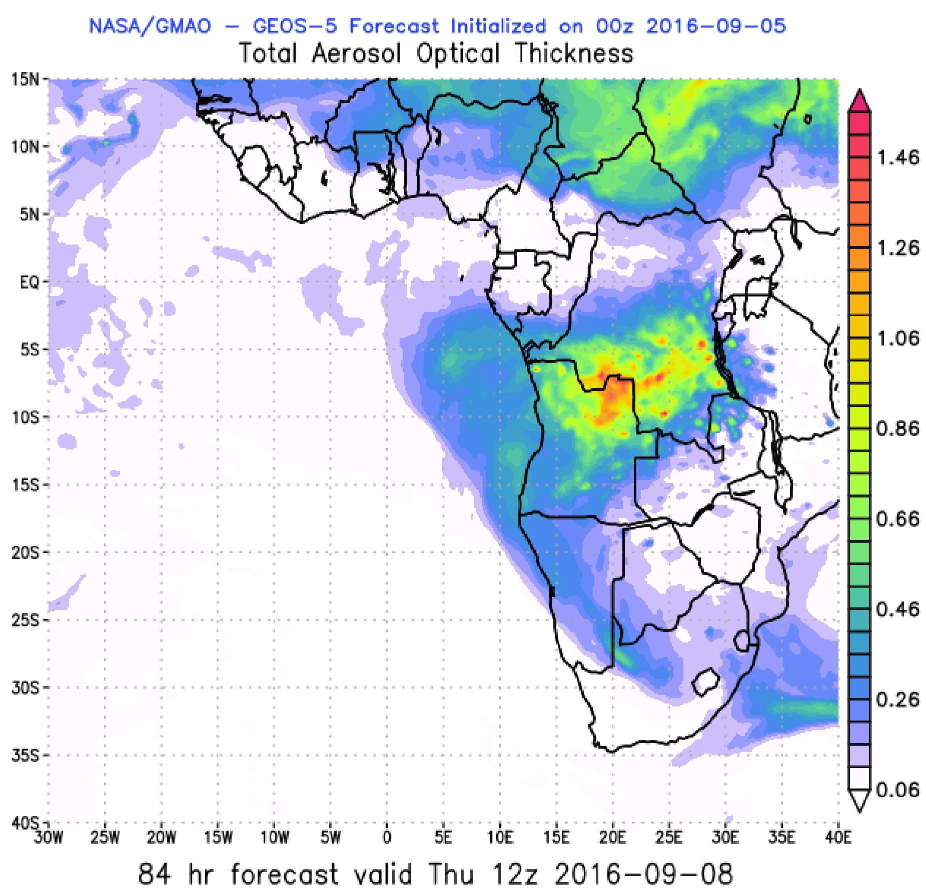
Loeb and Su, *J. Clim.*, 2010

Near-Real Time Aerosol Forecasting

ICAP Multi-Model Ensemble of AOT (left) and Individual Members AOT > 0.8 (right, n=4): valid 12z8Sept2016







- Modeling centers are increasingly recognizing the needs for near-real time aerosol prediction, with applications to: air quality, hazards, visibility, scientific mission flight planning, satellite retrieval *a prioris*, …
- ICAP is the International Cooperative for Aerosol Prediction, a grassroots group of forecasting centers and data providers communicating common issues and best practices
- The needs for aerosol prediction at NWP centers has been driven to date by practical application rather than on the NWP impacts themselves

Outline

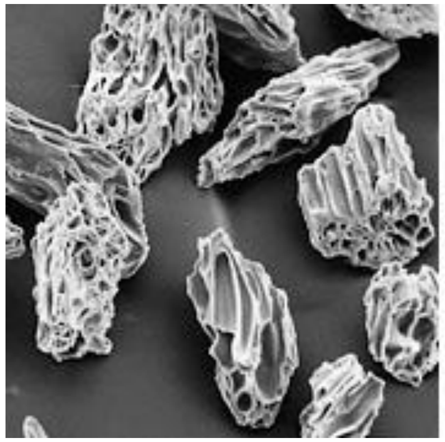
- **What are aerosols, and why are they important?**
  Aerosols are important for climate, weather prediction, and human applications, but are a very complex and under-observed system

- **How do aerosols affect weather and climate?**
  Aerosols affect weather and climate through their radiative forcing (direct effect) and their interactions with clouds (indirect effect)

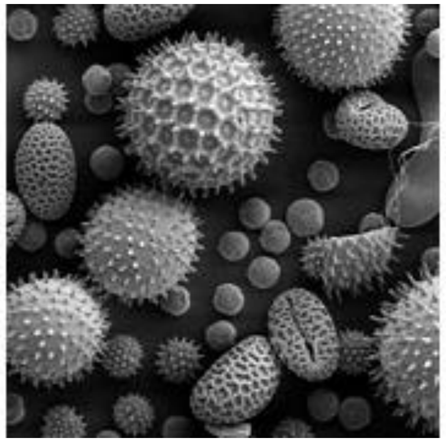
- **How do you incorporate aerosol complexity into weather and climate models?**

Complexity can mean different things: including direct and indirect effects (or not), impacts of aerosols on meteorological assimilation, more or less detailed treatments of the aerosols themselves, …

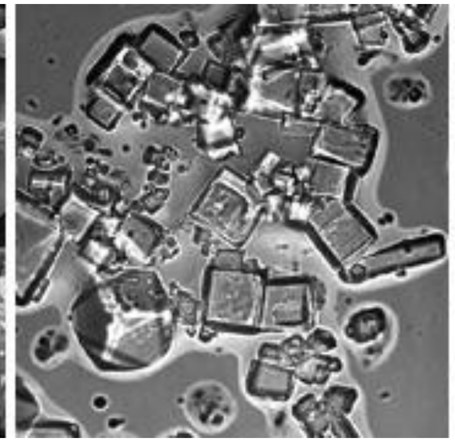
What are aerosols?



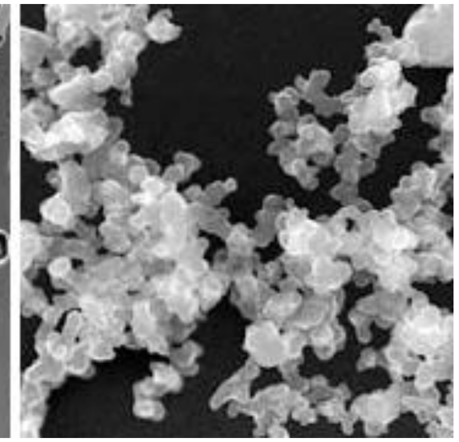
Volcanic Ash



Pollen



Sea Salt



Soot

Aerosols are solid particles or liquid droplets suspended in the atmosphere

Primary aerosol sources are dust storms, wildfires, sea spray, fossil fuel combustion. **Secondary** sources include oxidation of SO_2 from fossil fuel and volcanic sources and condensation of volatile organic gases.

Dust

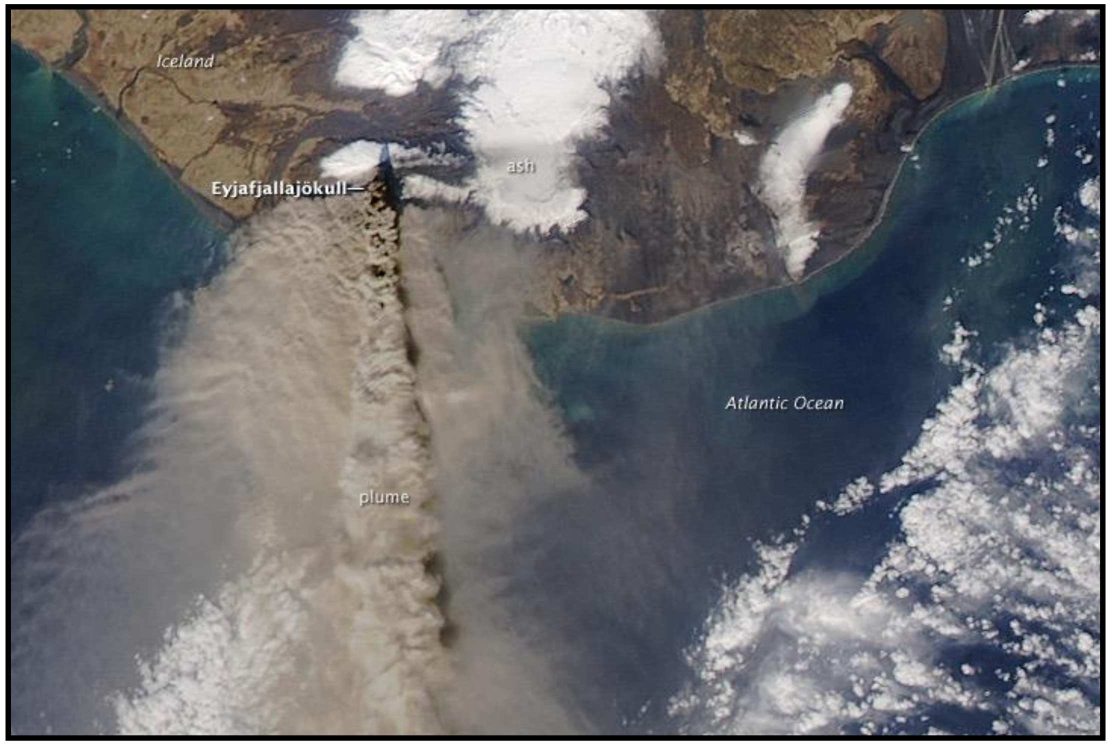
Organic Haze

Smoke

Volcanic Ash

About **90%** of aerosol emissions by mass are *natural*, mostly large dust and sea salt particles that have short atmospheric residence times. The remaining **10%** of aerosol mass is *anthropogenic* and tends to be smaller particles, *but these are almost all of the particles by number!*

Direct Human Impacts of Aerosols



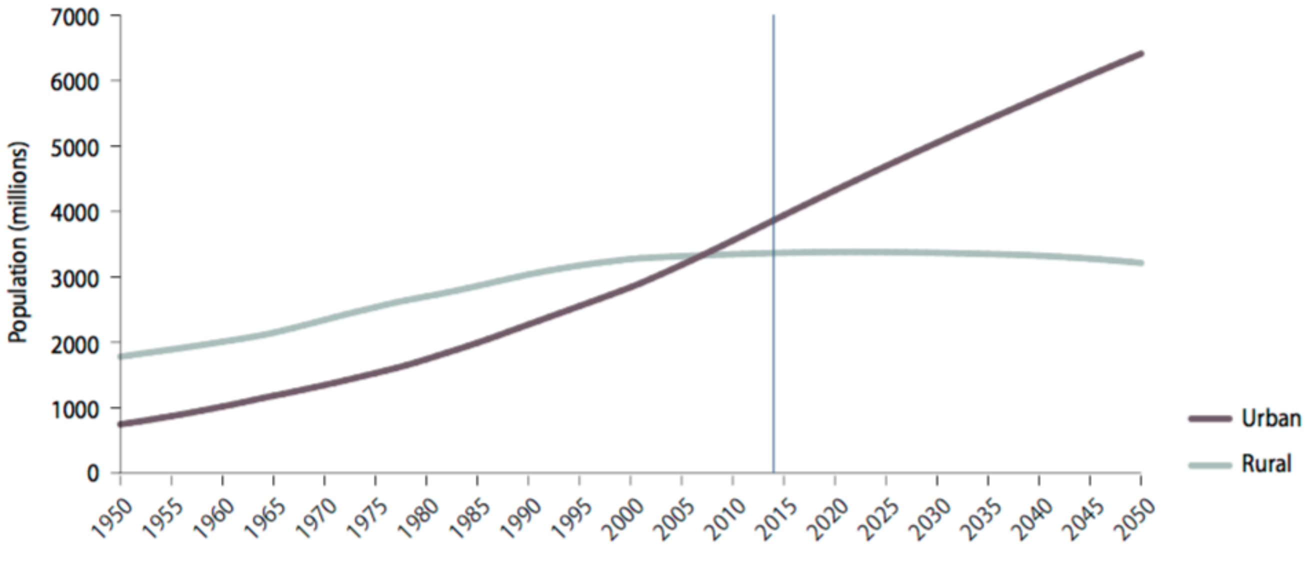
MODIS image of Eyjafjallajökull eruption, Iceland, May 2010

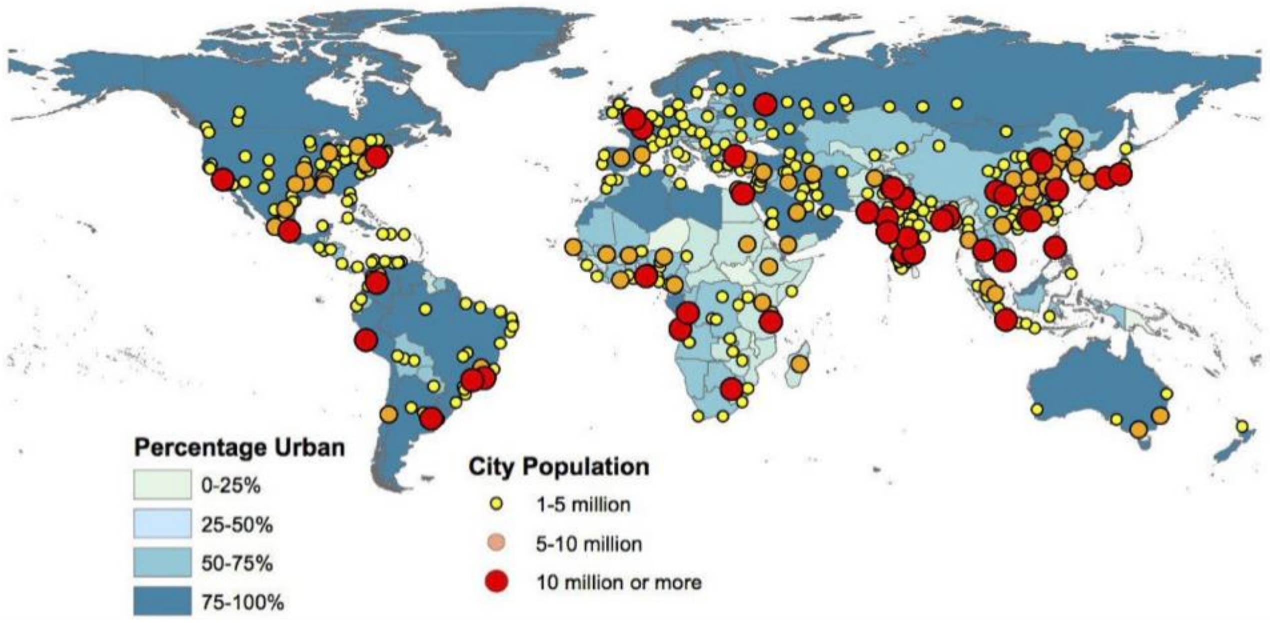
A firefighter from the Palo Alto and Santa Clarita County strike team works on the Soberanes Fire on Tuesday, July 26, 2016. From Palo Alto Fire Department.

Smog in Lianyungang, Jiangsu Province

Haboob in front of squall line, Dori, Burkina Faso, May 23, 2016

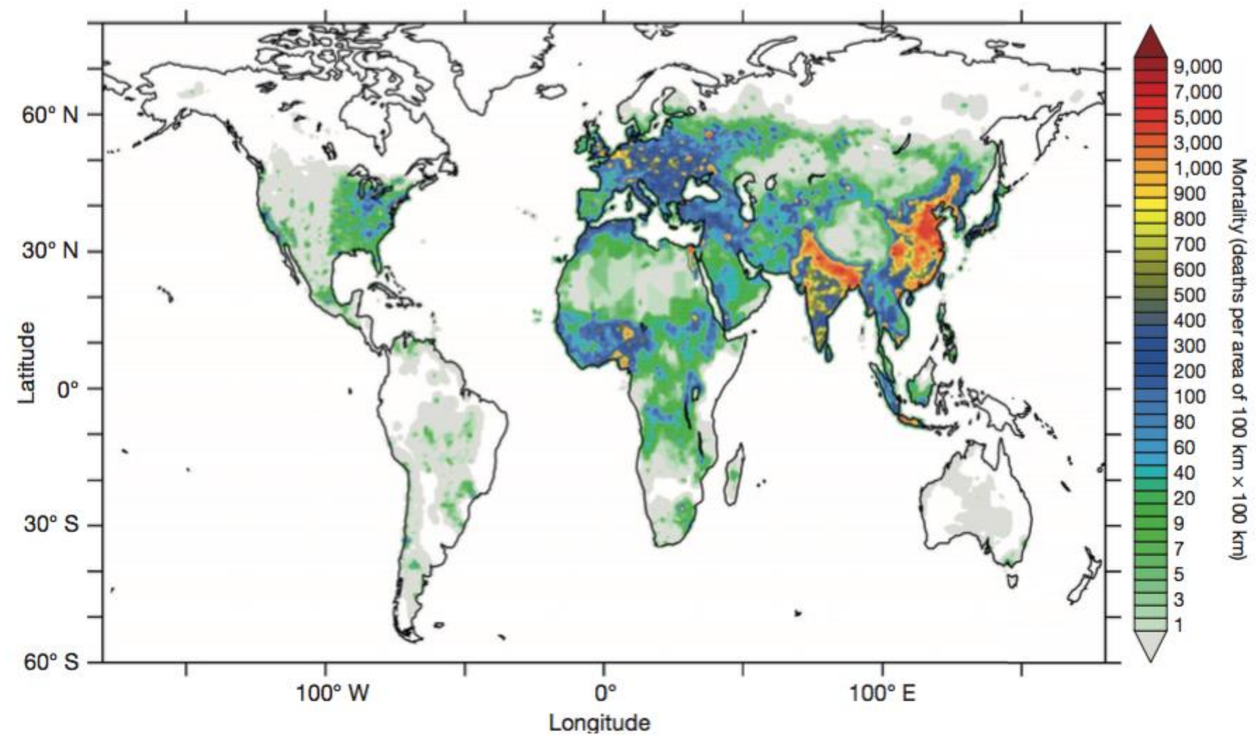
Air Quality and Human Health





UN World Urbanization Prospects Highlights (2014)

- Between 2010 and 2050 world population will increase from 7 to 9-10 billion
- All of this population growth is occurring in urban settings
- 2010: 3.3 million air quality related deaths; 2050: grows to 6.6 million
- Aerosol events implicated in vector borne diseases



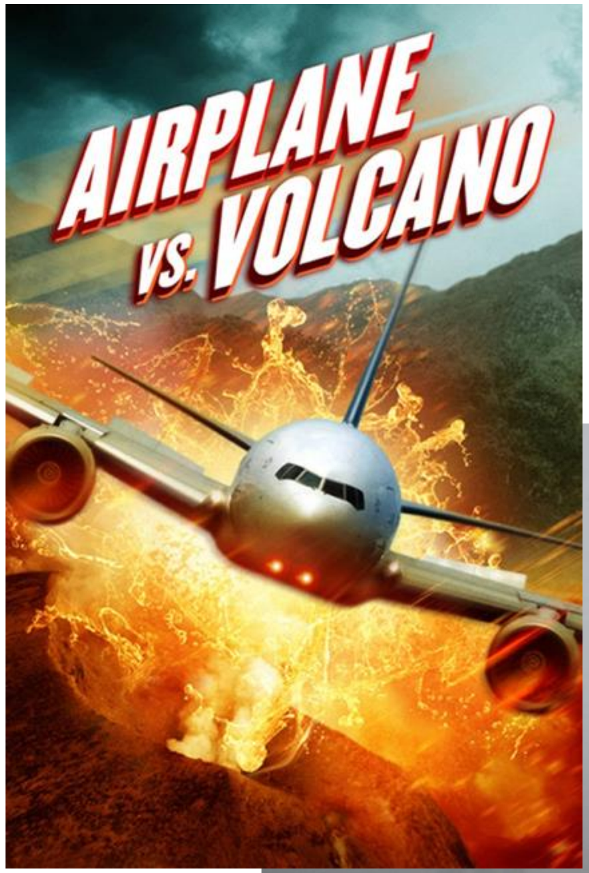
Air quality implicated premature deaths (per 10^4 km^2) in 2010 (Lelieveld et al., Nature, 2015)

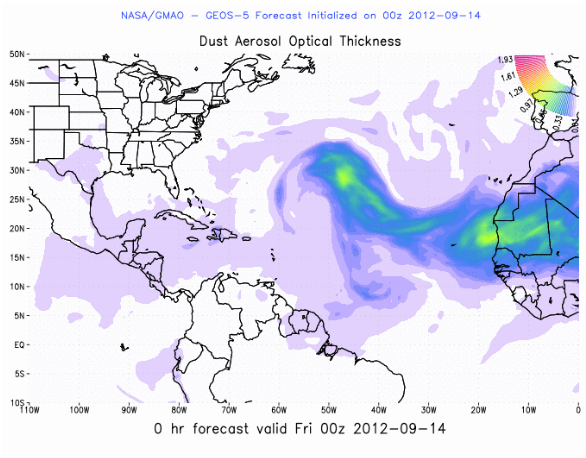
Why do we care about aerosols?

- Air quality and human health
- Aviation hazards
- Visibility

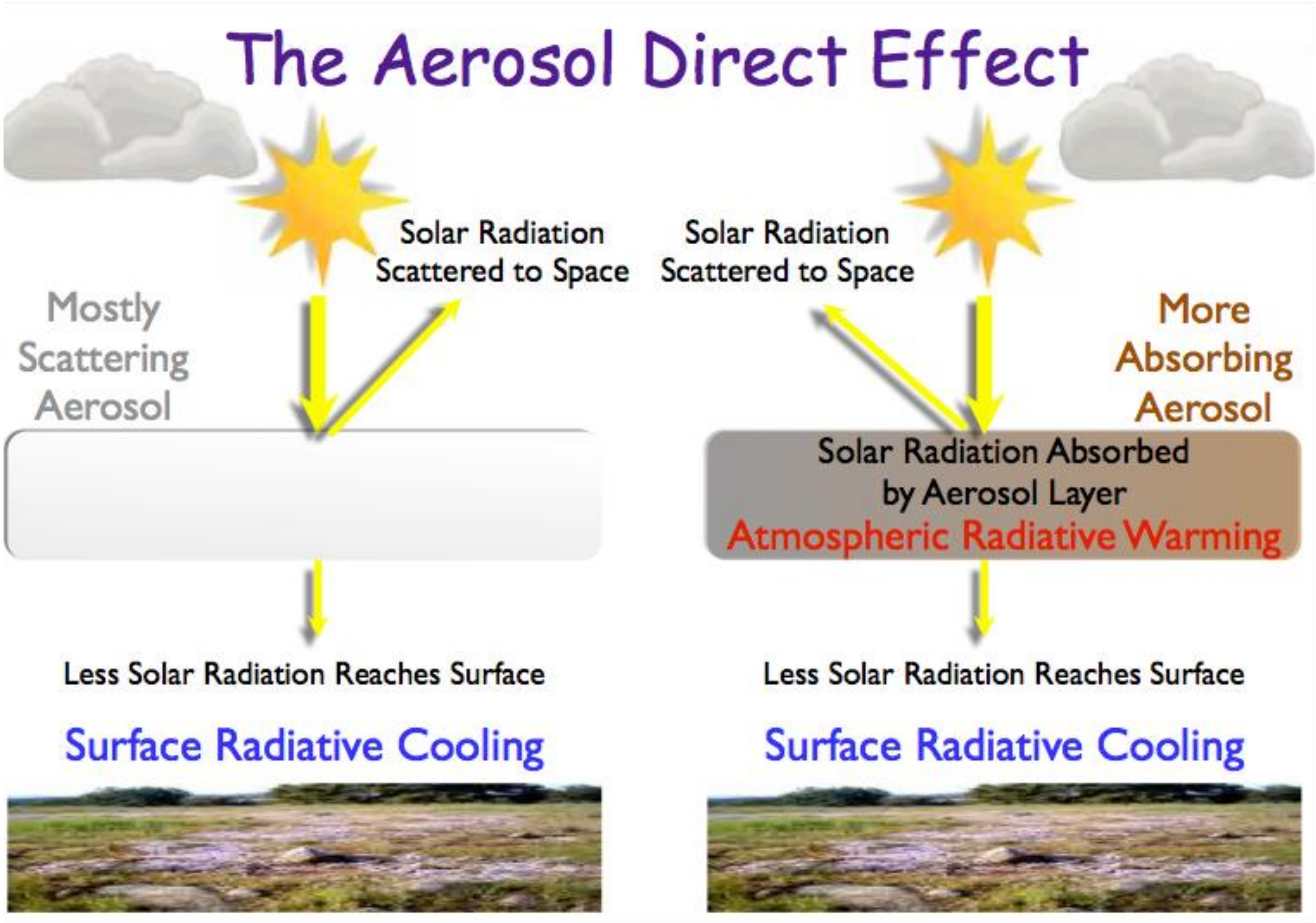
- Field campaigns
- Measurement *a priori*
- Data assimilation

- Biogeochemical cycles
- Climate
- Impact on weather and NWP

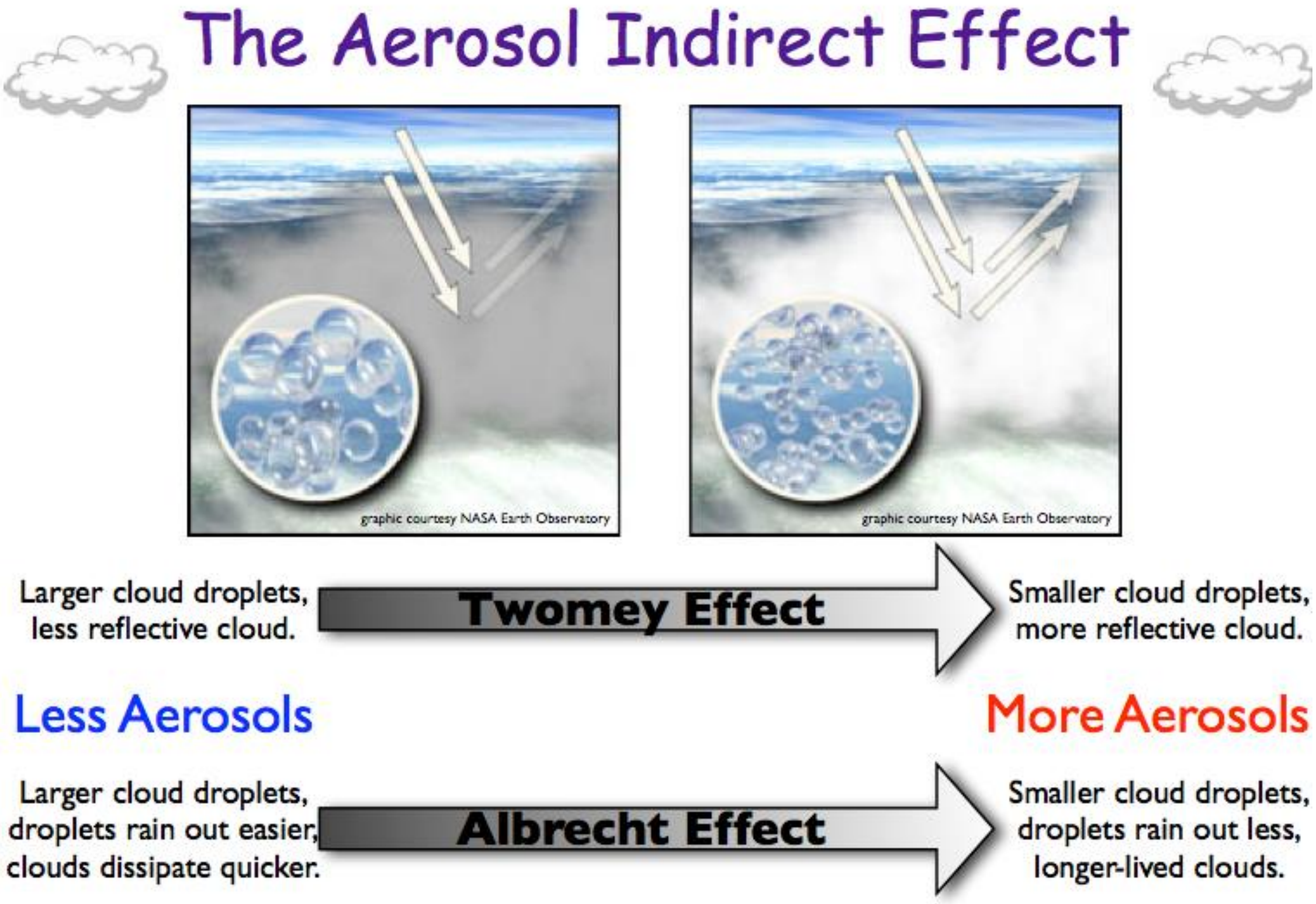




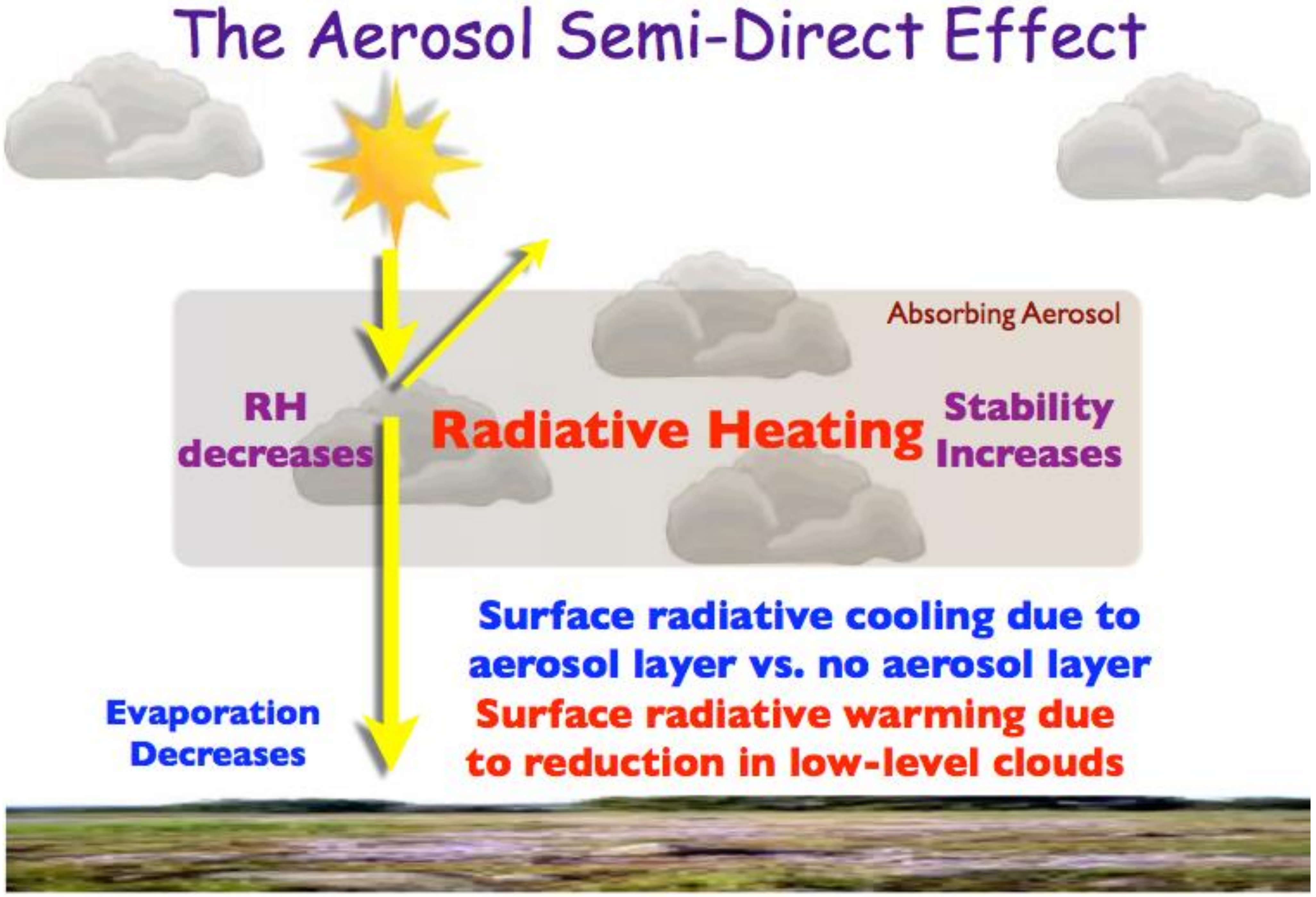
Aerosol Radiation Interaction (ARI)



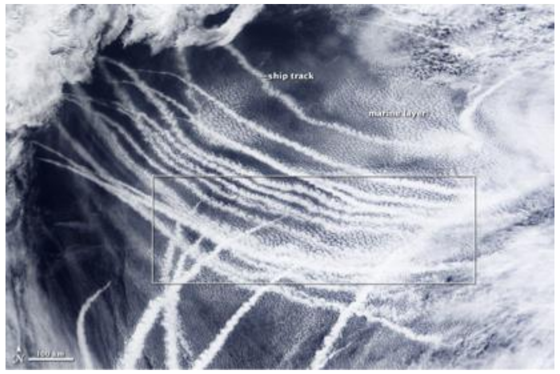
Aerosol Cloud Interaction (ACI)

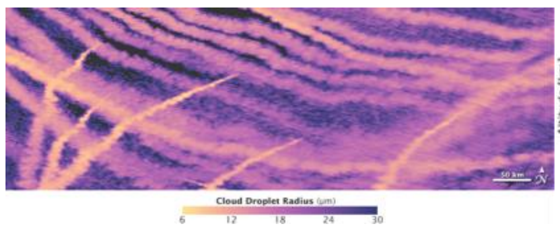


Radiation and Clouds

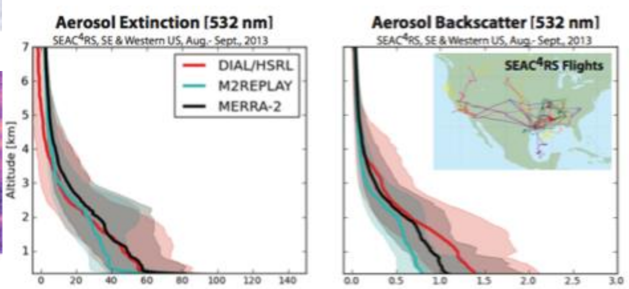


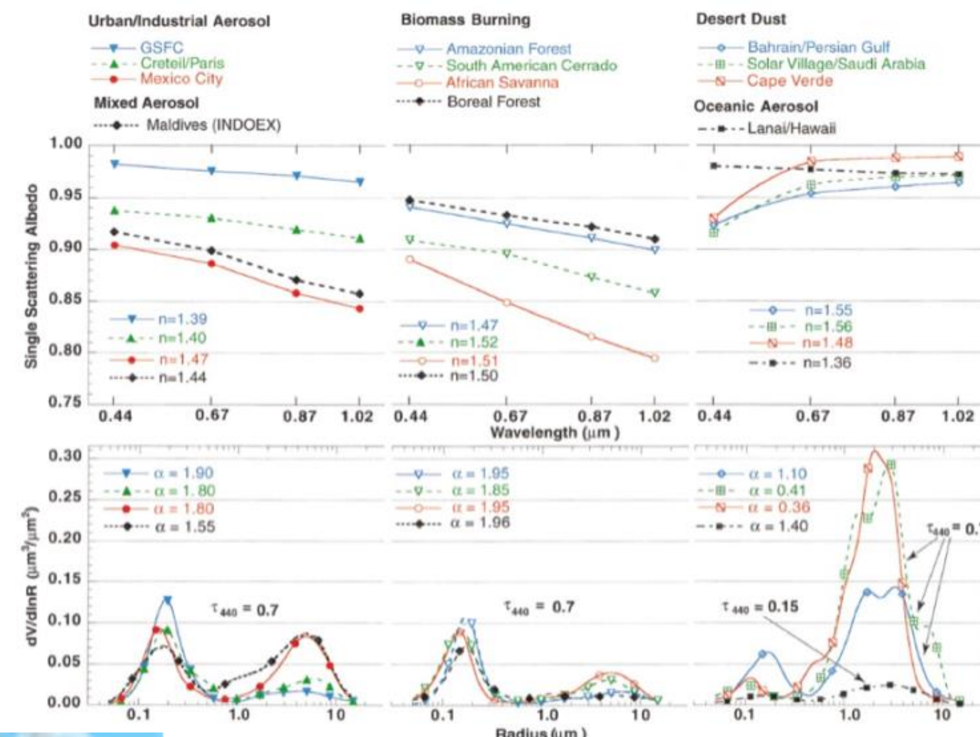
Because the Aerosol System is Complex…

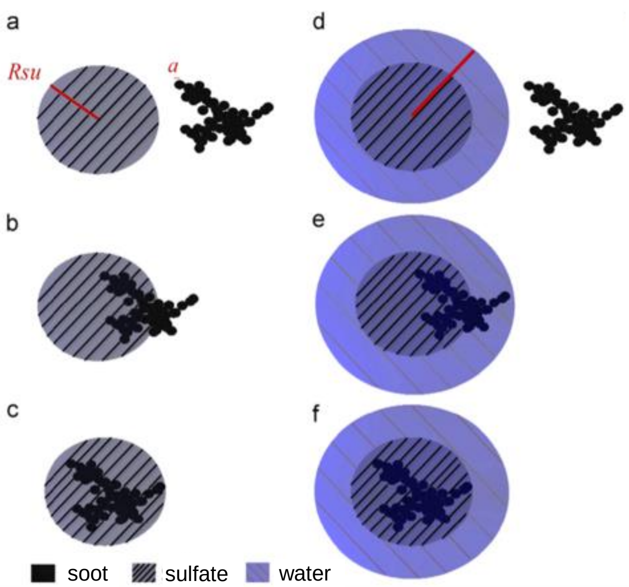


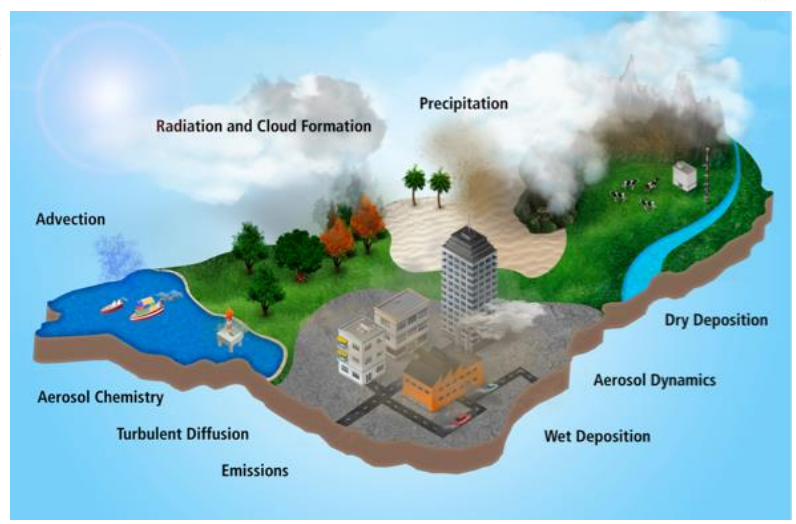


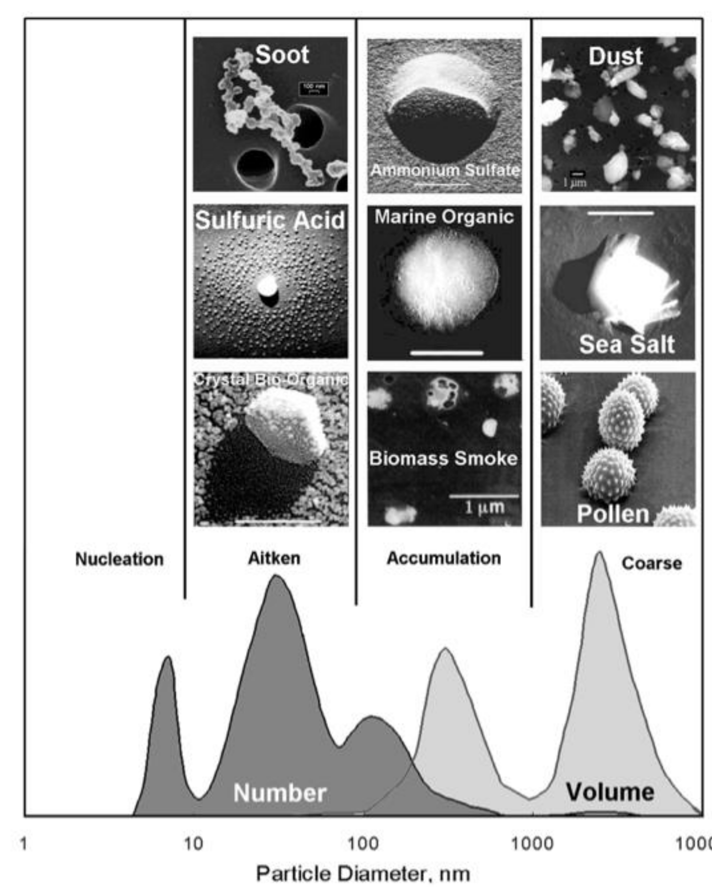
Sea Salt Dust Volcanic Ash

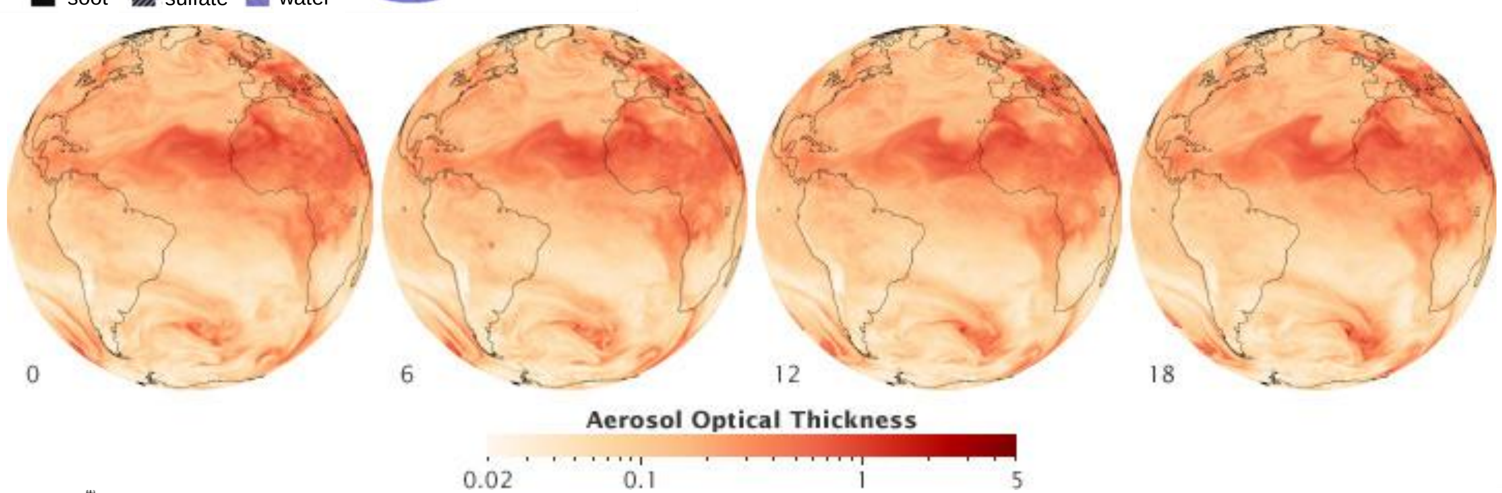




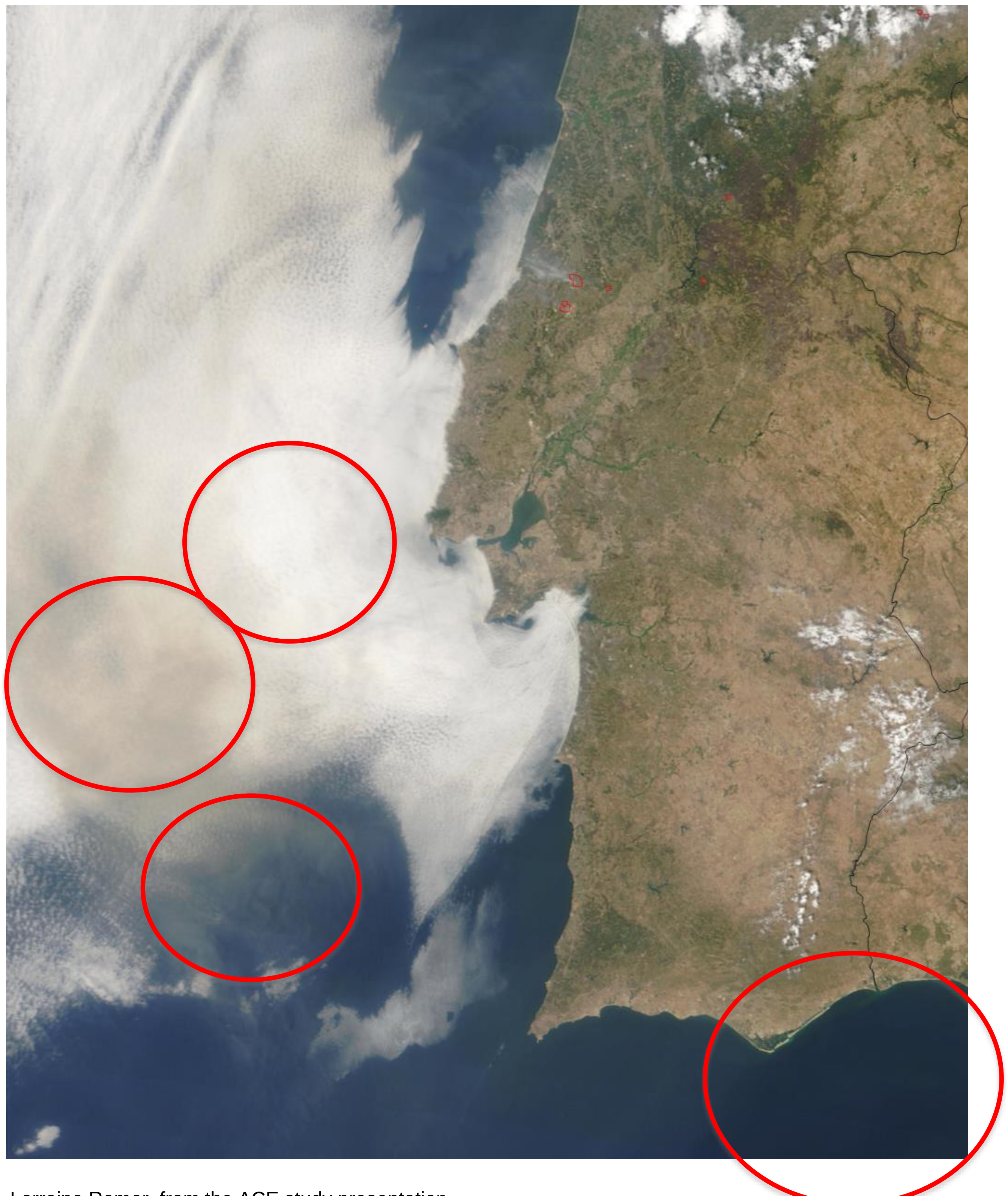








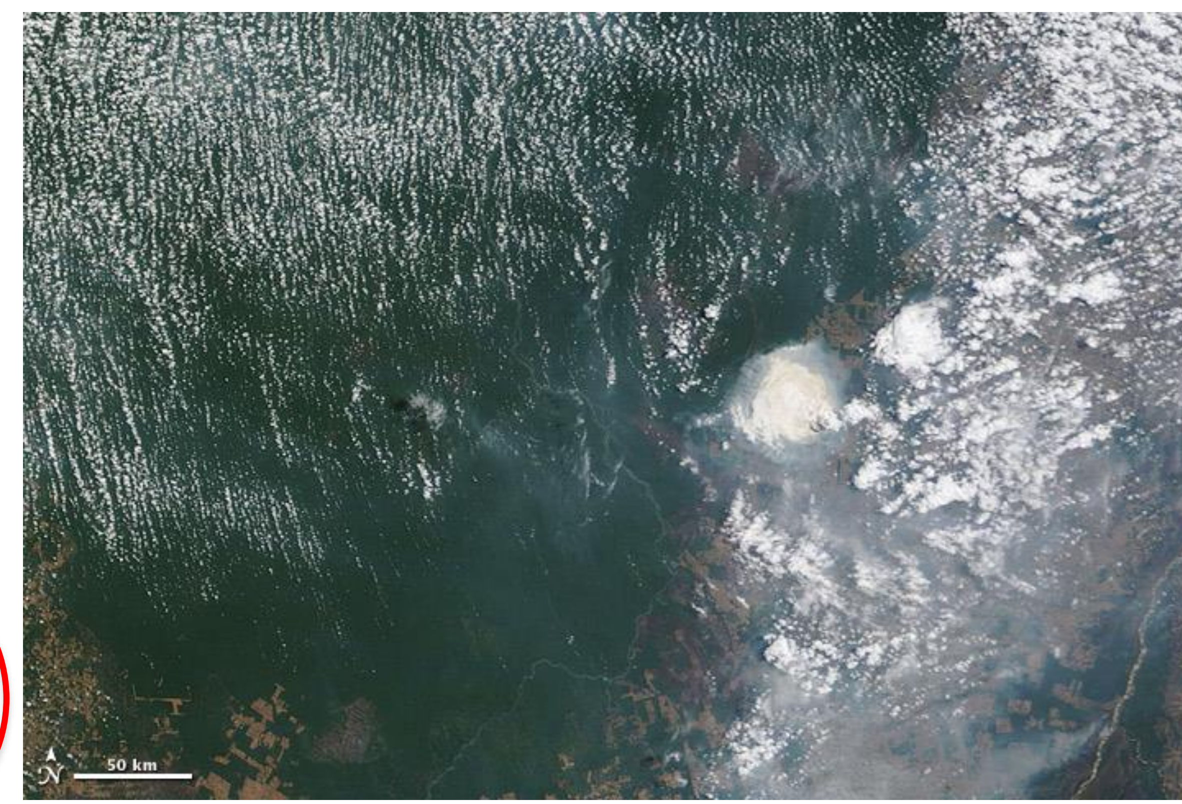
…Characterization From Space is Hard!



Lorraine Remer, from the ACE study presentation

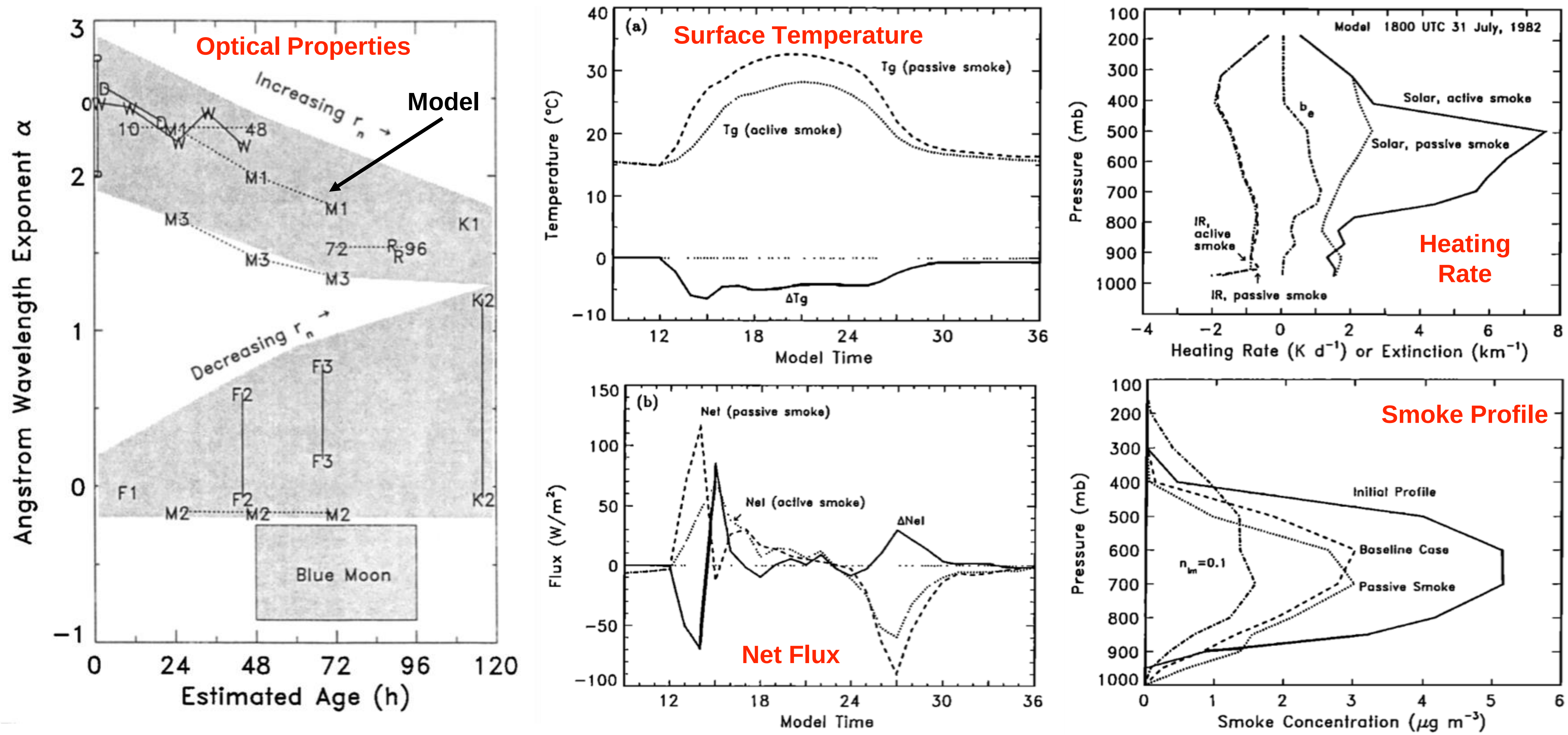
Are the aerosols:
Brightening or darkening?
Cooling or warming?
Above the cloud or below or <u>inside</u>?
Natural or anthropogenic?
How dark (absorption properties)?
Inside the clouds or not?

These questions cannot be answered today with the necessary <u>accuracy</u> or <u>coverage</u>.



An NWP Example

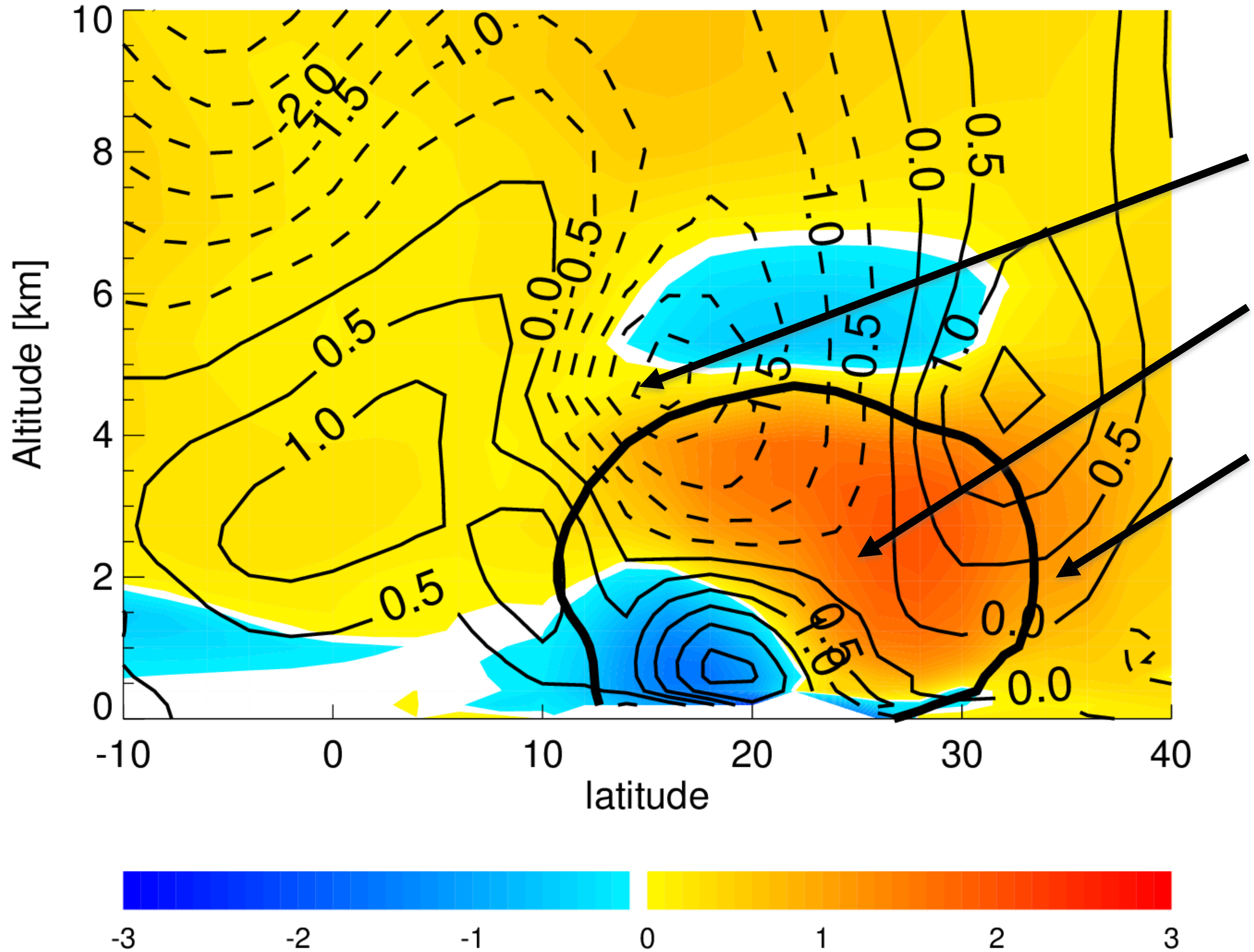
on of Canadian smoke plumes with radiatively interactive sectiona



Westphal and Toon, *JGR*, 1991

Impact of Dust Radiative Forcing

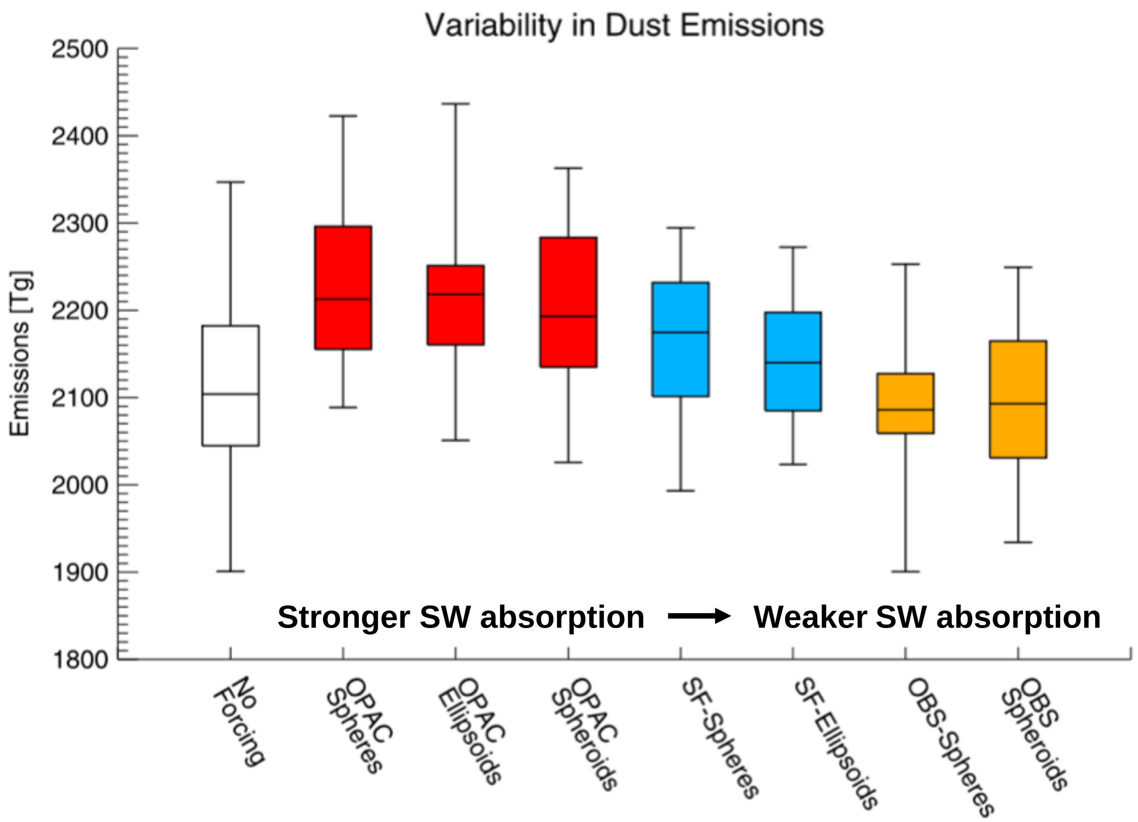
Airborne Saharan dust particles absorb solar and infrared radiation, affecting weather and climate. Difference of simulations ARI - no-ARI.

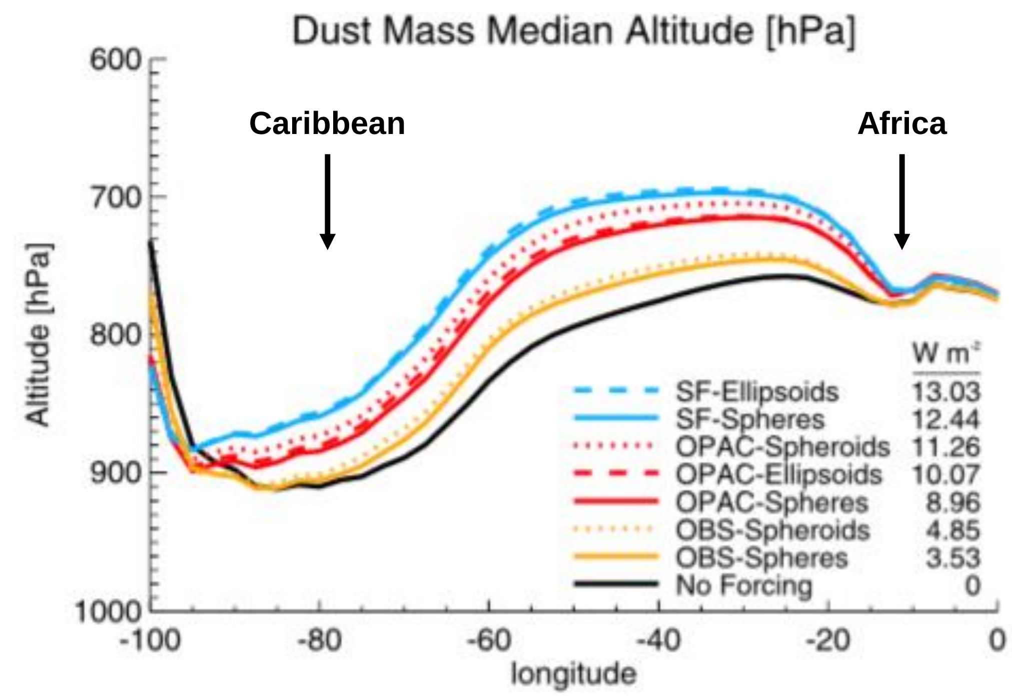


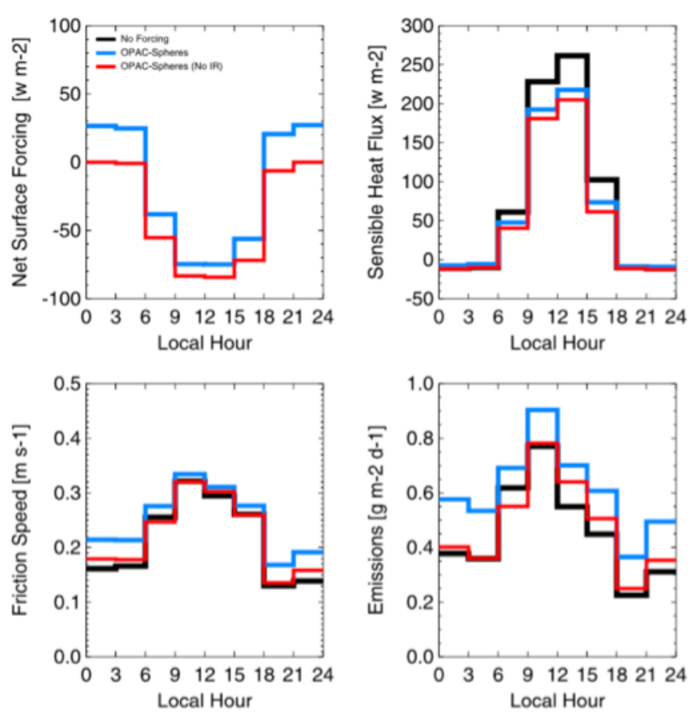
A North-South vertical slice through the summertime western Saharan atmosphere, where a dust plume is centered at about 20°N (thick, solid line).

Colarco et al. *JGR* 2014

Impact of Dust Radiative Forcing



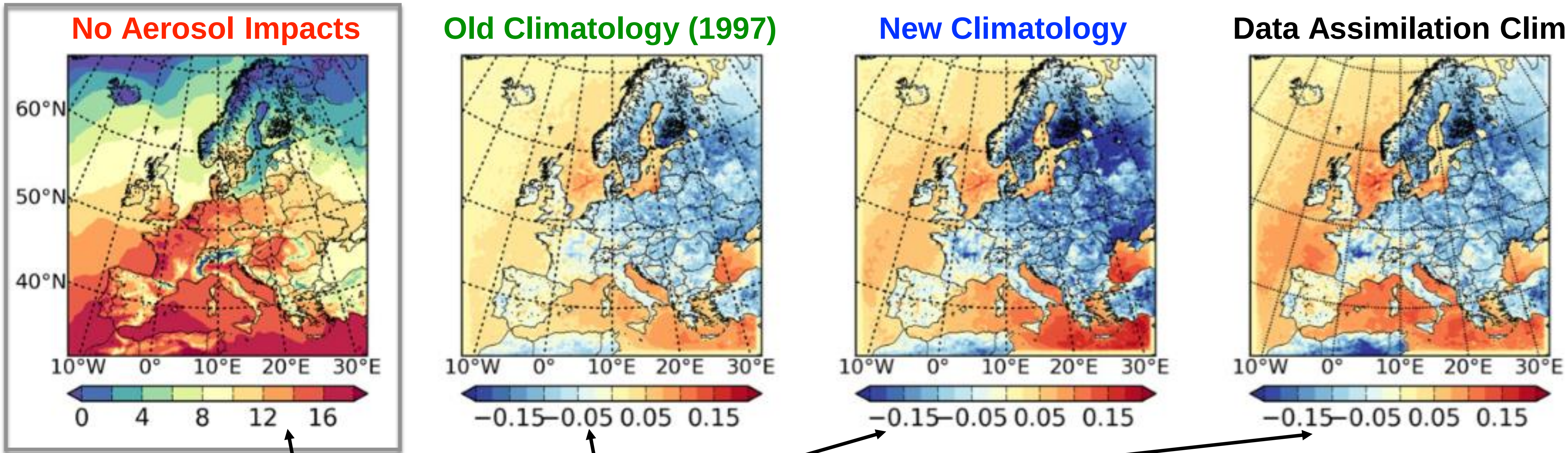




Colarco et al. *JGR* 2014

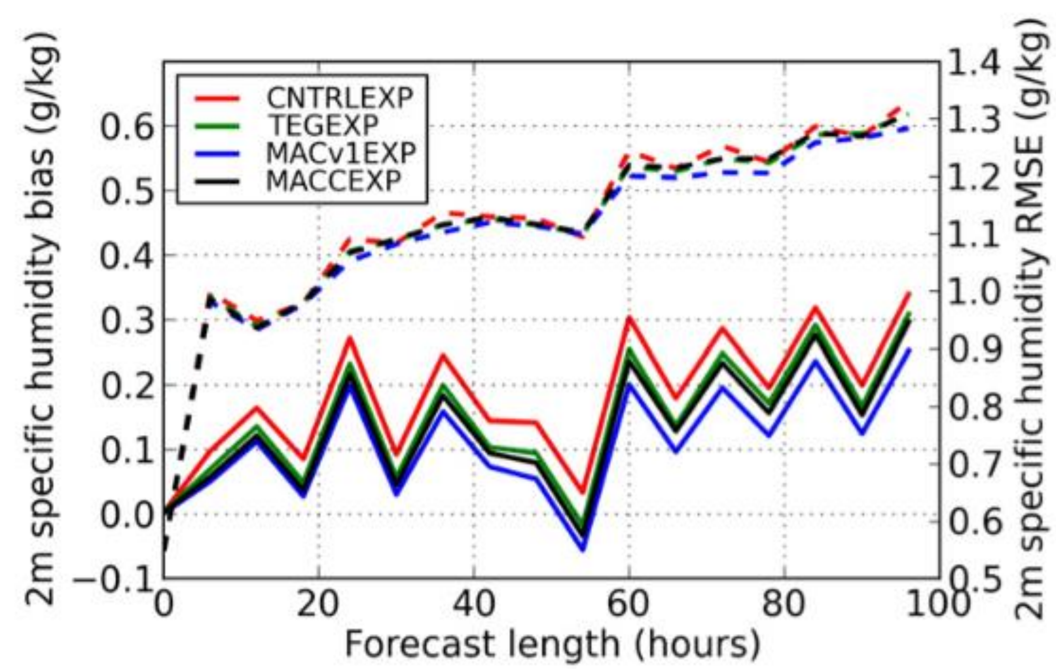
- Strong SW absorption in our model leads to enhanced dust emissions, contrasts with Miller et al. (2004), Perez et al (2006)
- Stronger SW absorption also associated with higher altitude of Saharan dust transport
- LW effects more pronounced in our model (larger particles) and were important to controlling diurnal cycle

Climatological Aerosol Forcing



Baseline and **relative difference** in T_{2m} for European limited area ALADIN-HIRLAM weather model due to aerosol climatologies used

- Aerosol direct effects included by imposed (but simple) climatologies from external sources
- Clear reduction in meteorological surface parameter biases by including aerosol impacts
- Not obvious however that forecast skill is improved by choice of climatology (or that bias/rmse dramatically better for more sophisticated climatology)



Toll et al., *Atmos. Res.*, 2016

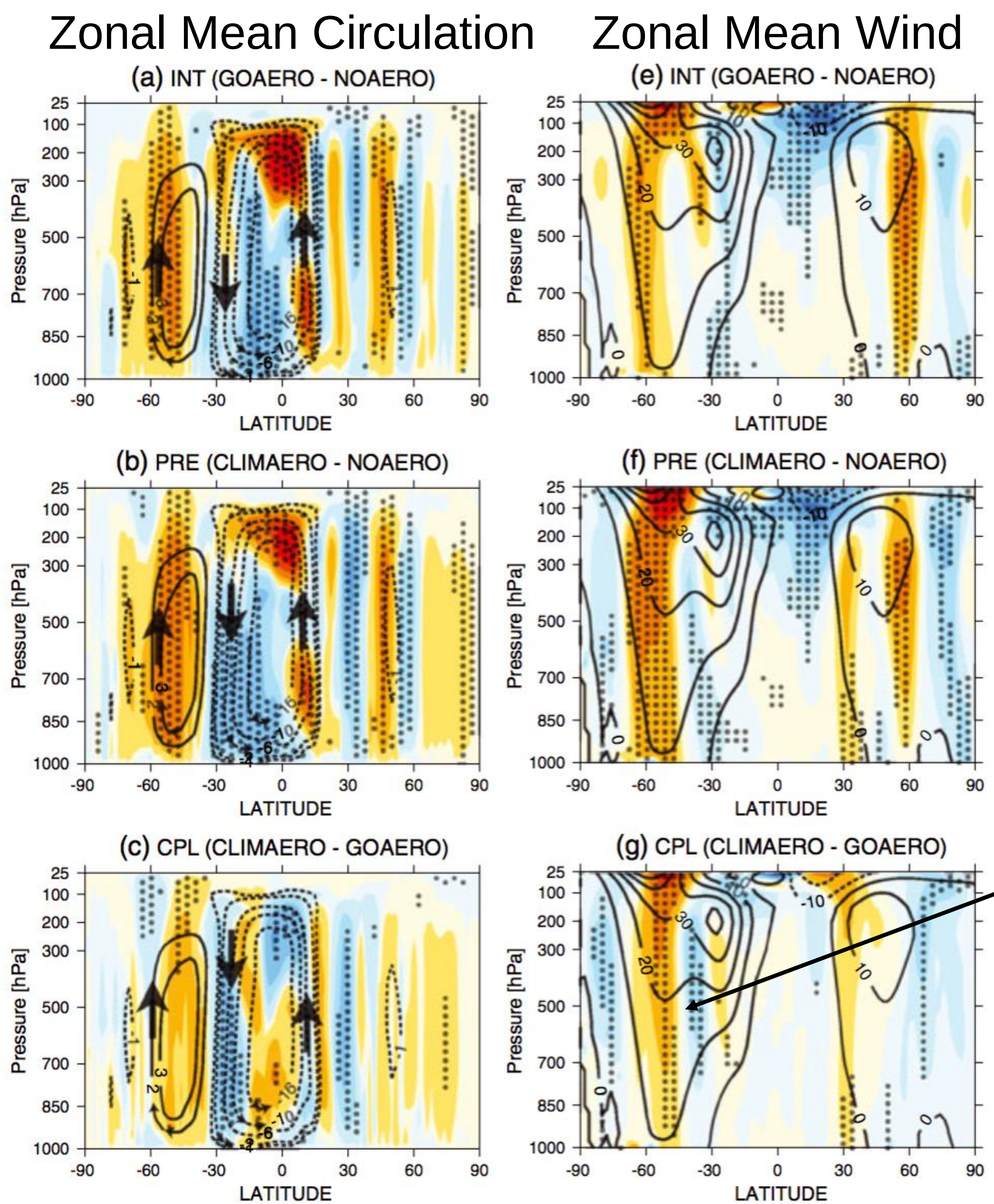
Increasing Complexity in Model

JJA

Interactive Aerosols

Climatological Aerosols

Difference of Climatological - Interactive Aerosols

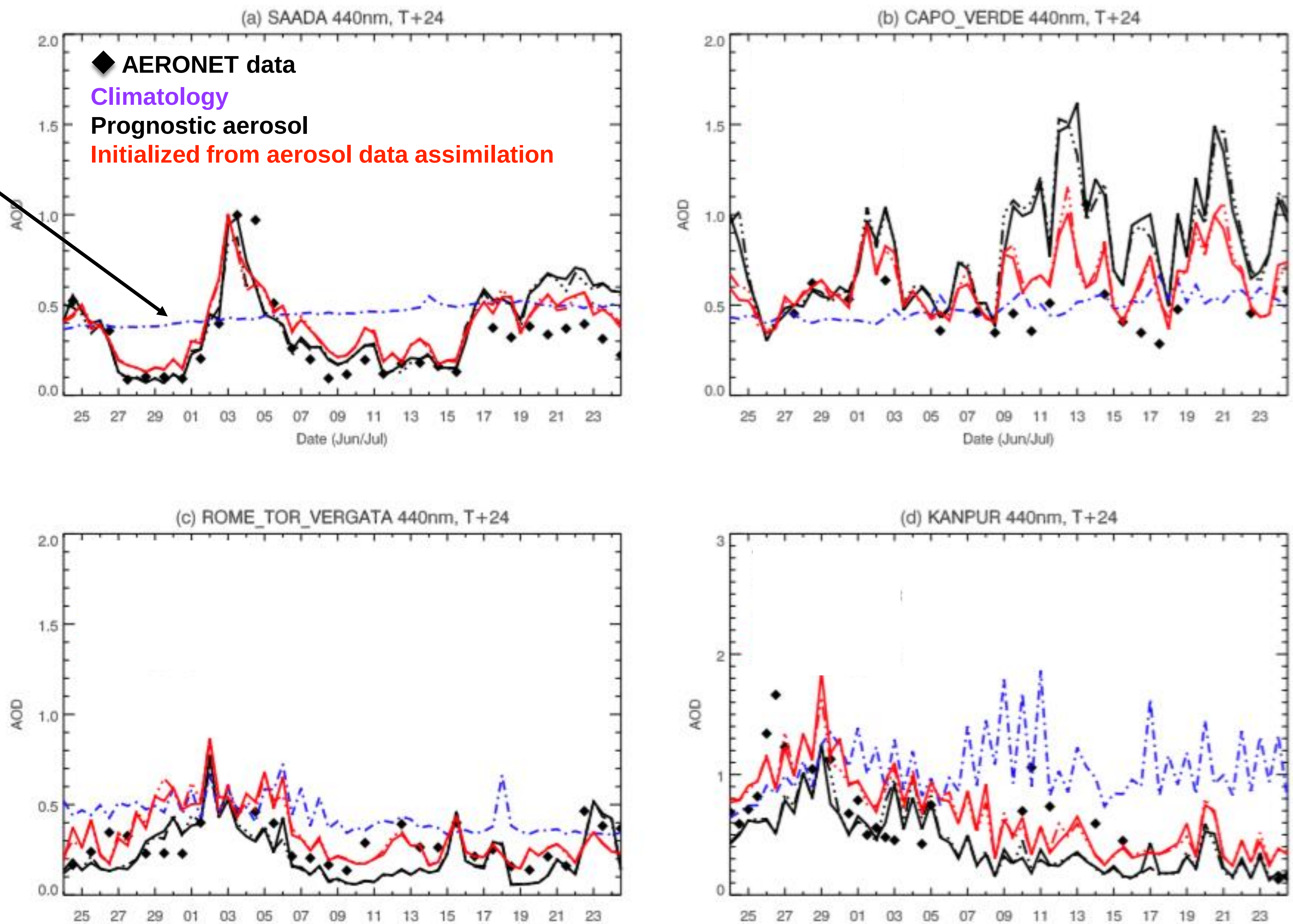


Most of these differences are related to natural aerosols, which have higher time variability

Randles et al. *JGR* 2013

Increasing Complexity in Model

Clearly climatology cannot represent specific events



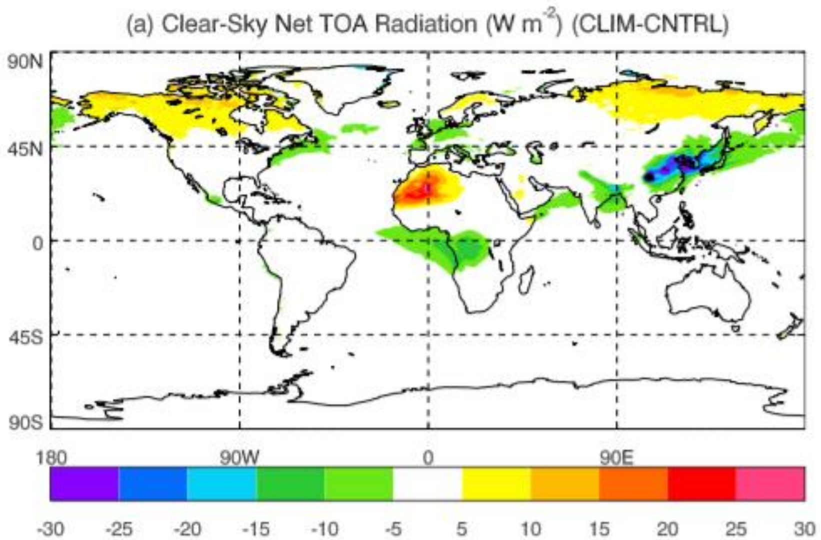
Mulcahey et al. *ACP* 2014

UKMO MetUM Forecasts

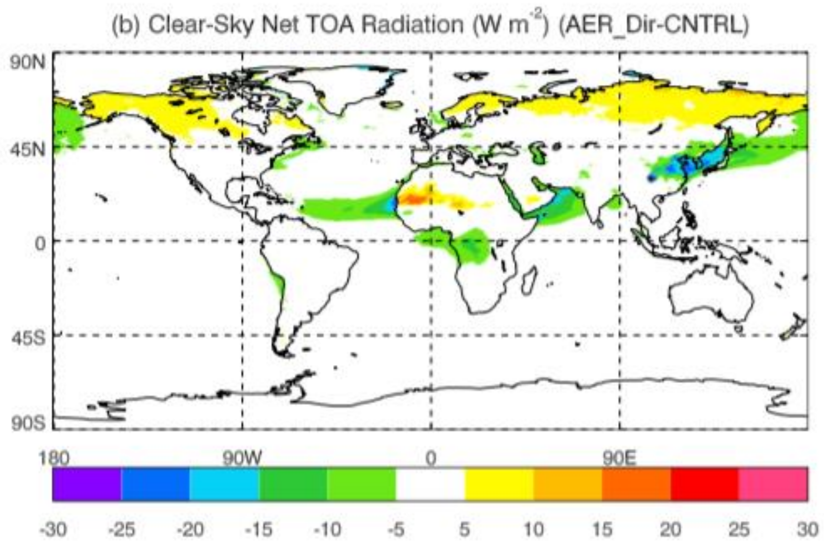
Increasing Complexity in Model

Differences in clear-sky net TOA forcing from model with static climatological aerosols

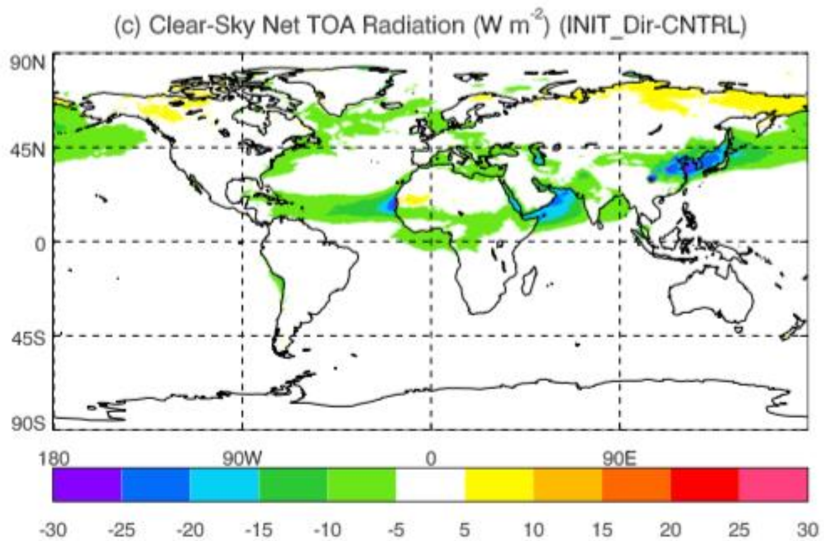
Monthly varying climatology



Prognostic aerosol with ARI



Data assimilation initialized with ARI



Mulcahey et al. *ACP* 2014

Increasing Complexity in Model

Potential cloud droplet # concentration [cm^{-3}]

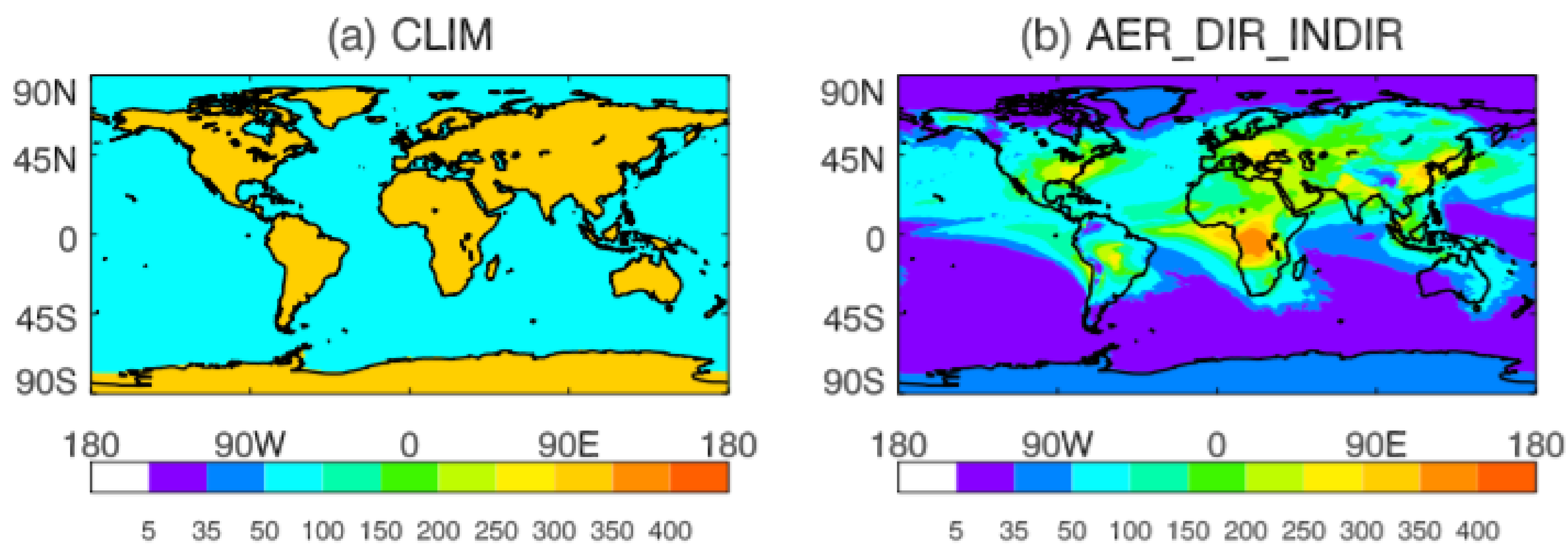
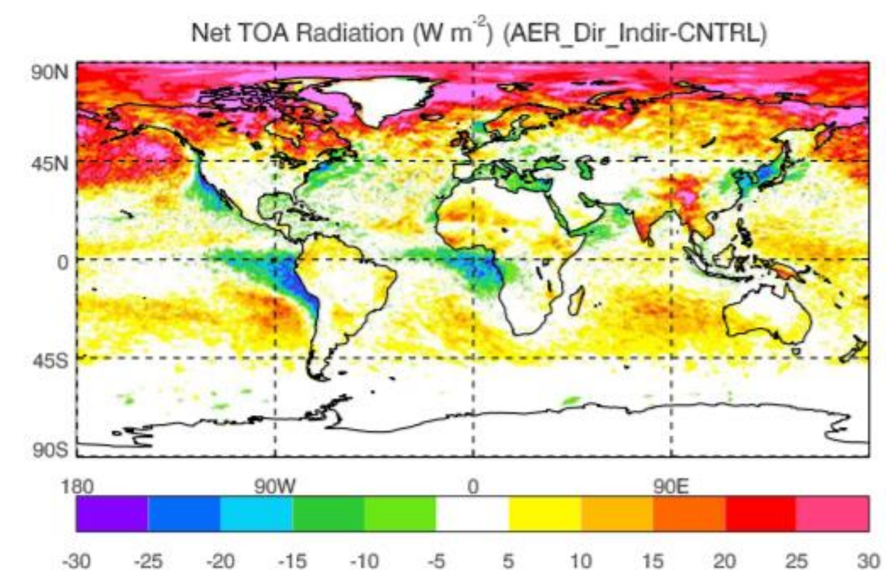


Table 2. The global mean day 5 all-sky net radiative forcings ($W m^{-2}$) from the different aerosol representations.

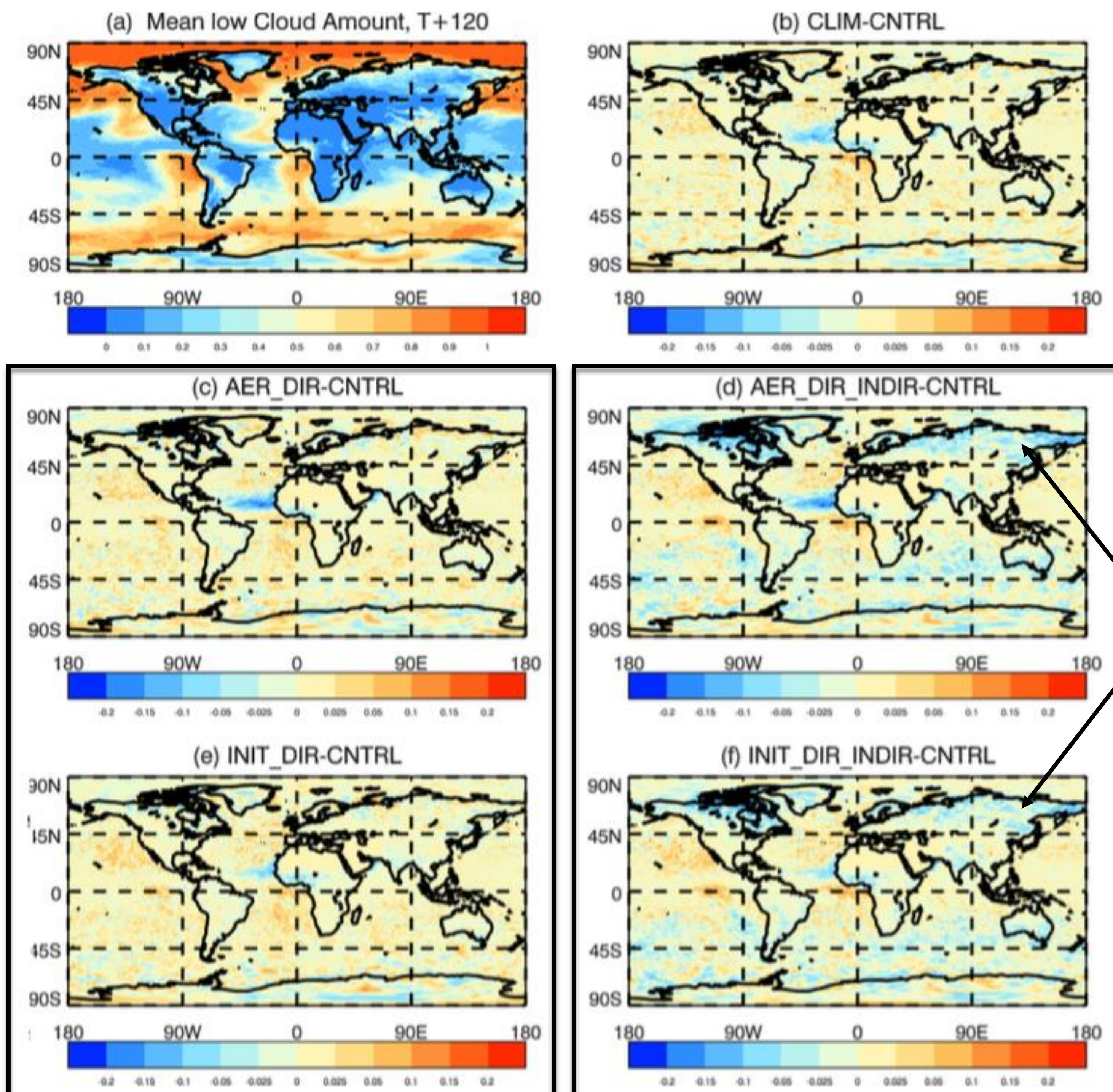
	TOA	ATM	SFC
CLIM	−0.30	−1.72	1.42
AER_DIR	−0.87	−2.91	2.04
AER_DIR_INDIR	4.18	−2.62	6.80
INIT_DIR	−1.48	−2.29	0.89
INIT_DIR_INDIR	2.26	−1.81	4.07

Mulcahey et al. *ACP* 2014



Increasing Complexity in Model

Aerosol impacts on low cloud amounts



Direct Effects

Indirect Effects

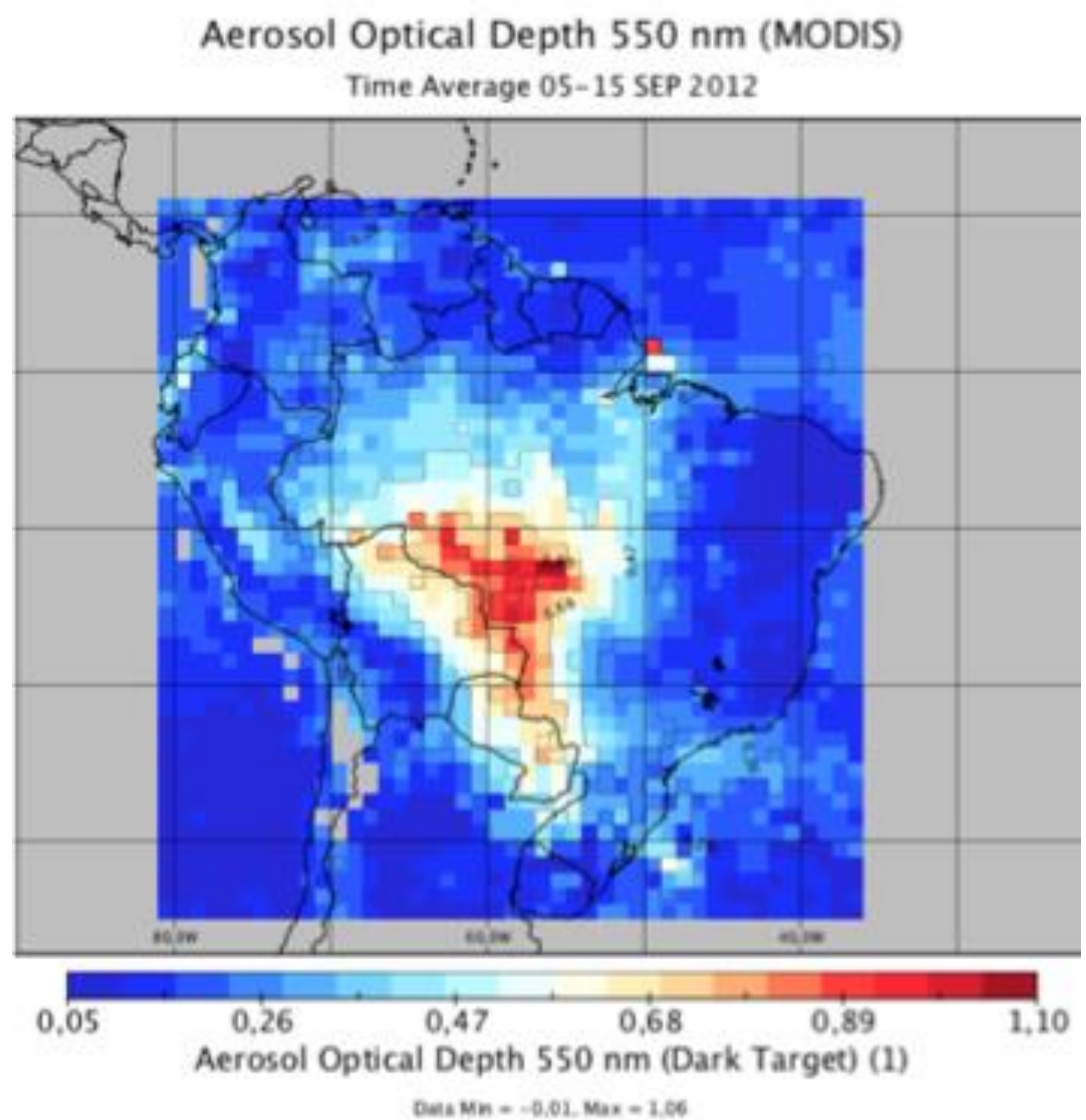
positive impact on model temperature and radiation biases

Mulcahey et al. *ACP* 2014

Interactive Aerosol Forcing

WGNE Exercise
Evaluating Aerosols Impacts on Numerical Weather Prediction

- WGNE (WMO) exercise:
  - How important are aerosols for predicting the physical system (NWP, seasonal, climate) as distinct from predicting the aerosols themselves?
  - How important is atmospheric model quality for air quality forecasting?
  - What are the current capabilities of NWP models to simulate aerosol impacts on weather prediction?
- Series of models run same aerosol conditions in series of forecast experiments; e.g., SAMBBA case of S. American Aerosols
- All models run with and without **aerosol radiative interaction**; JMA additionally includes **aerosol cloud interaction**



Saulo Freitas

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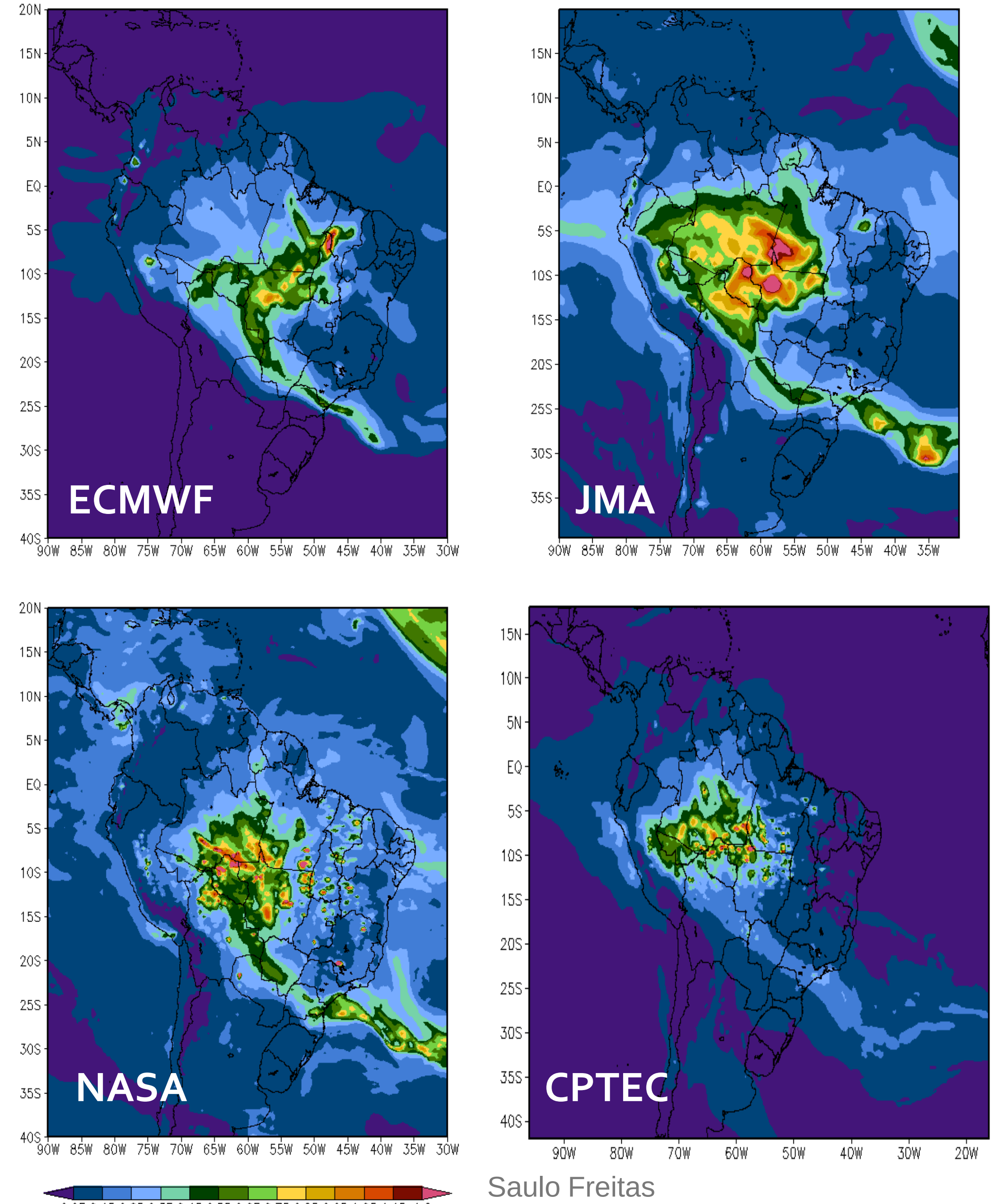
AOD at 550 nm
Forecast for 18UTC11SEP Init.: 00UTC10SEP



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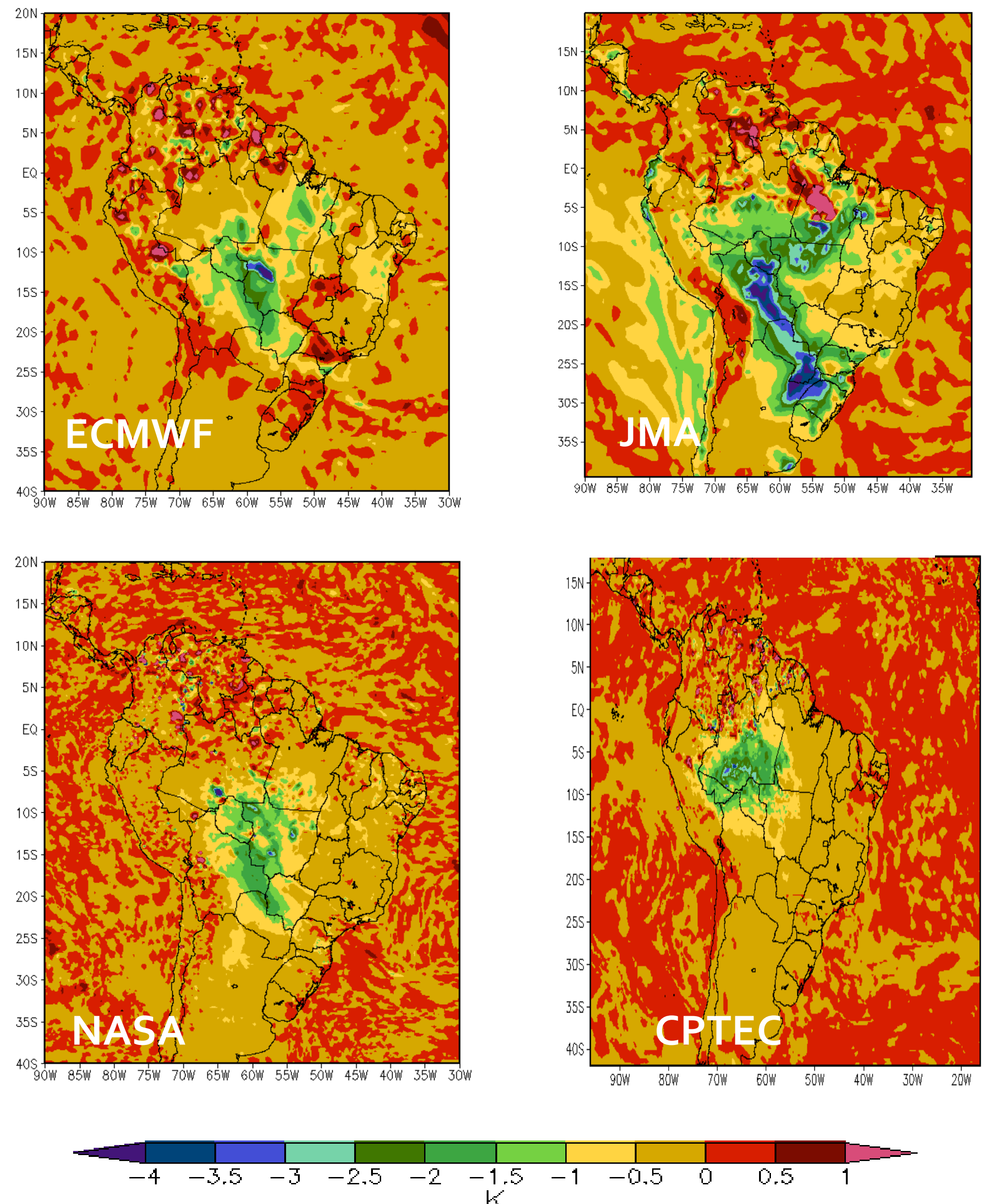
2-m Temperature Difference (AER-NOAER)
Forecast for 15UTC11SEP Init.:00UTC10SEP



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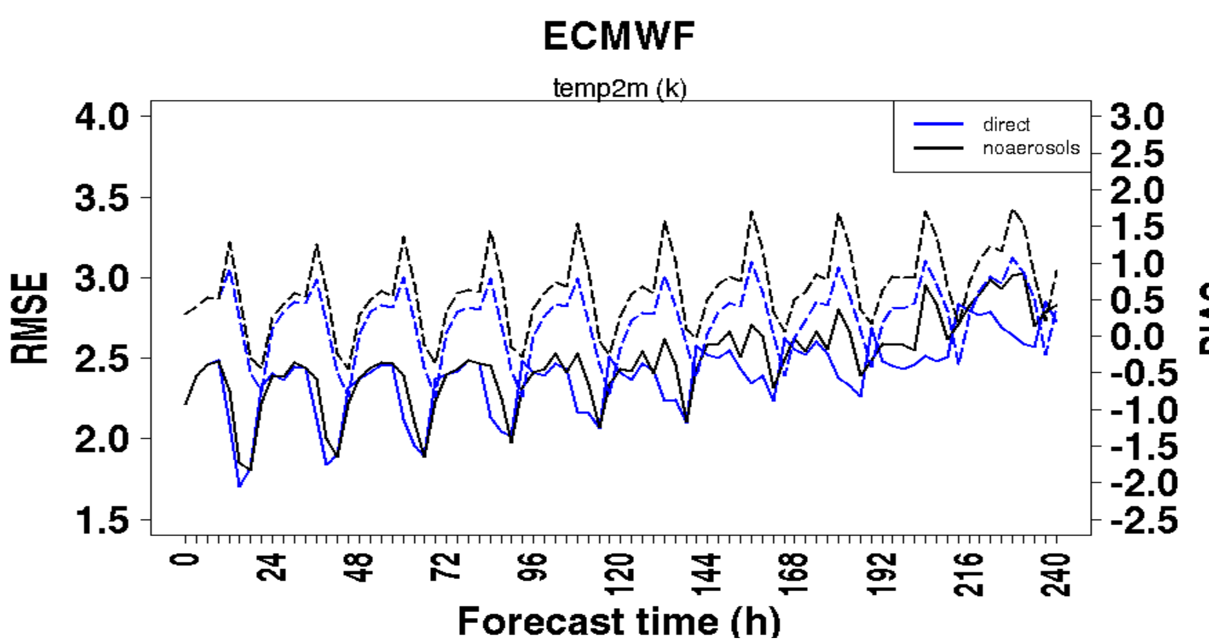
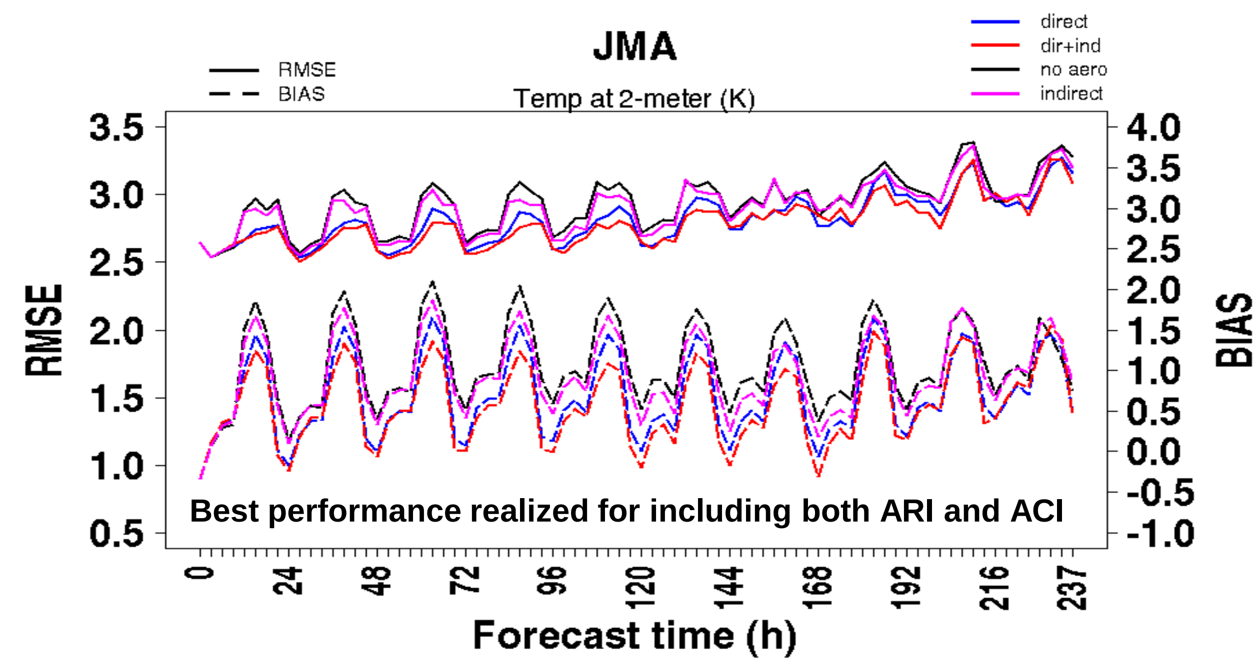
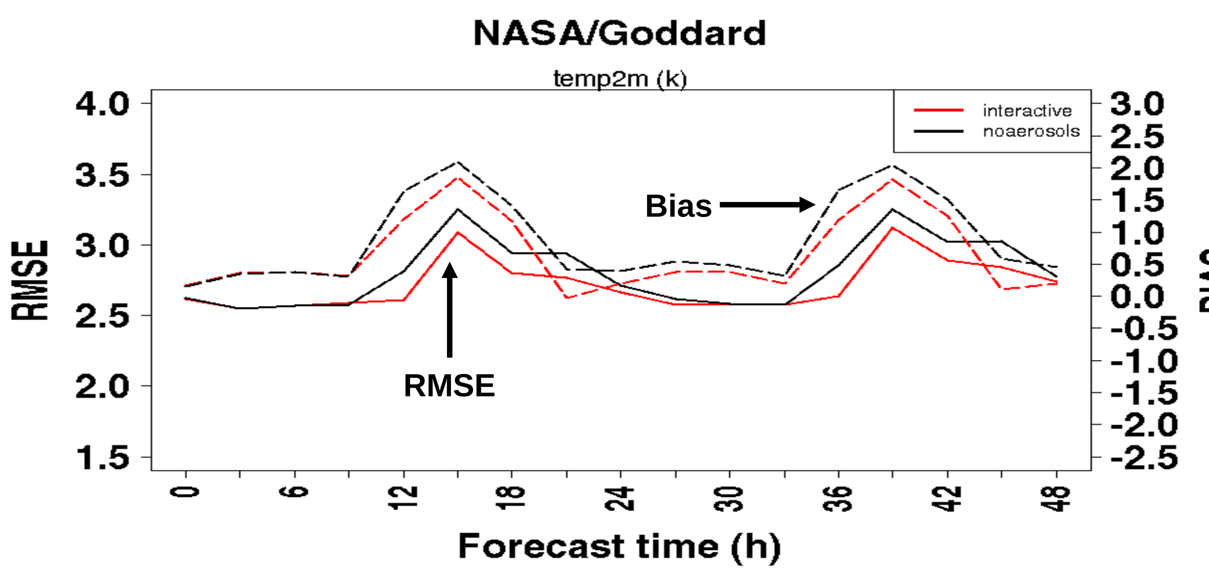
Interactive Aerosol Forcing

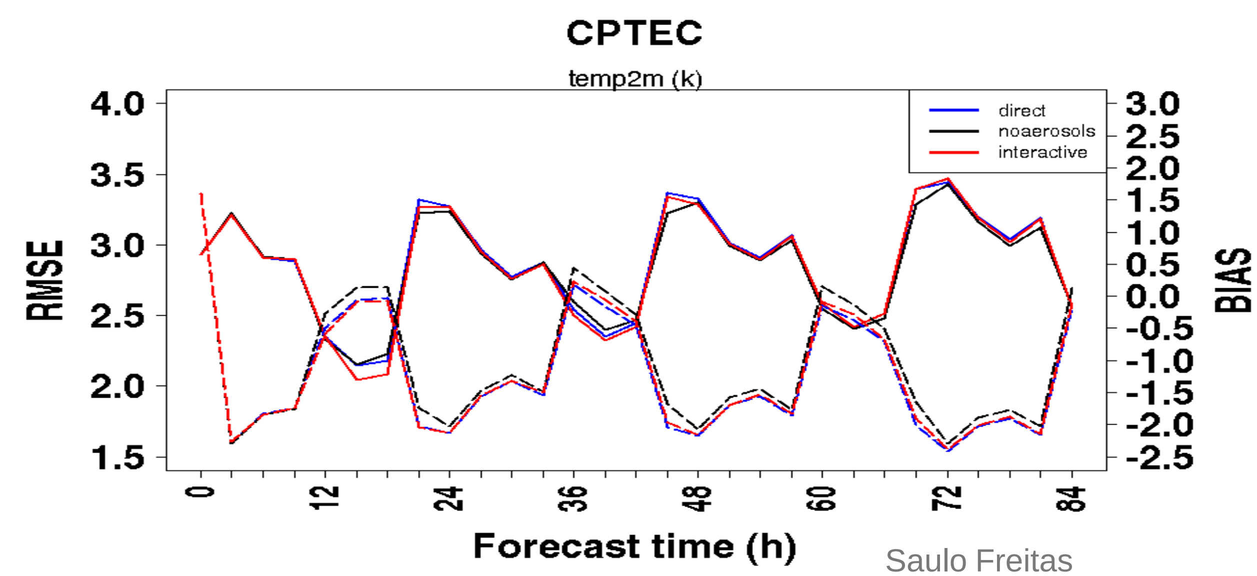
WGNE Exercise
Evaluating Aerosols Impacts on Numerical Weather Prediction

RMSE/BIAS: 2-m Temperature (K)





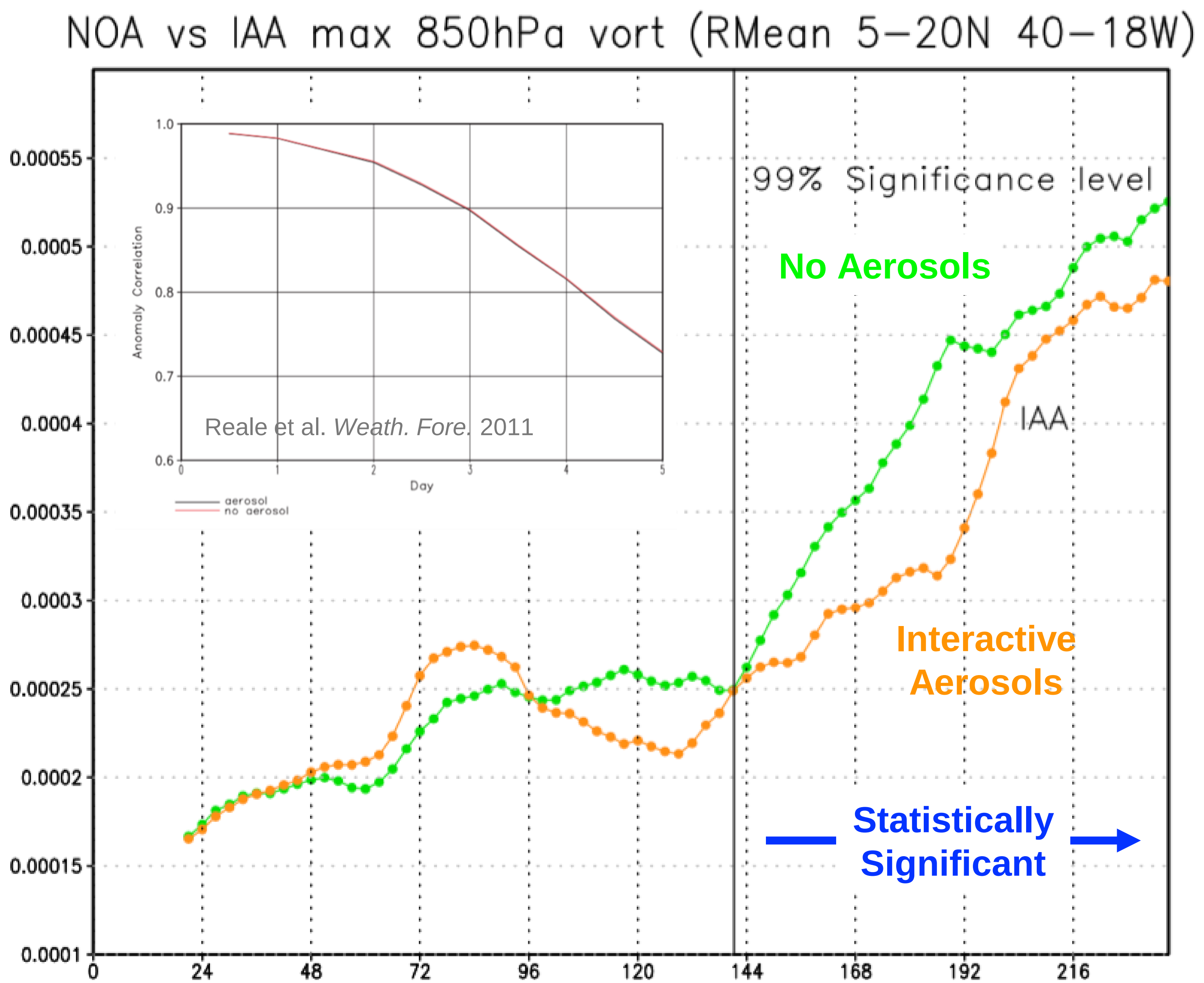




Saulo Freitas

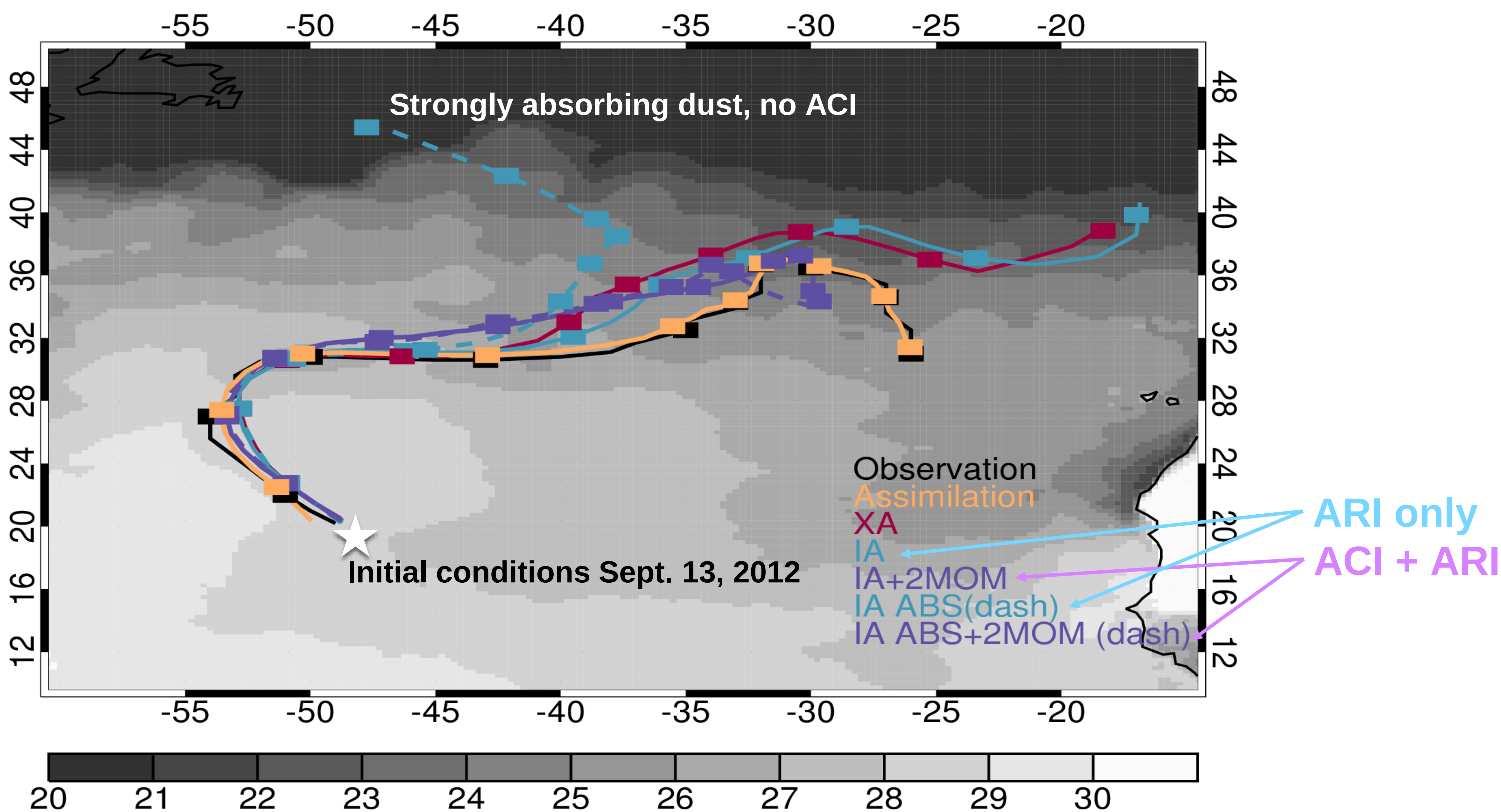
Dust Impacts on Tropical Cyclones

- Inclusion of interactive aerosols in GEOS-5 model in NWP configuration has no impact on anomaly height correlation (inset)
- Statistically significant changes in forecast vorticity at 5 - 6 day range



Reale et al. *GRL* 2014

Dust Impacts on Tropical Cyclones



Development of Hurricane Nadine, September 13 - 23, 2012

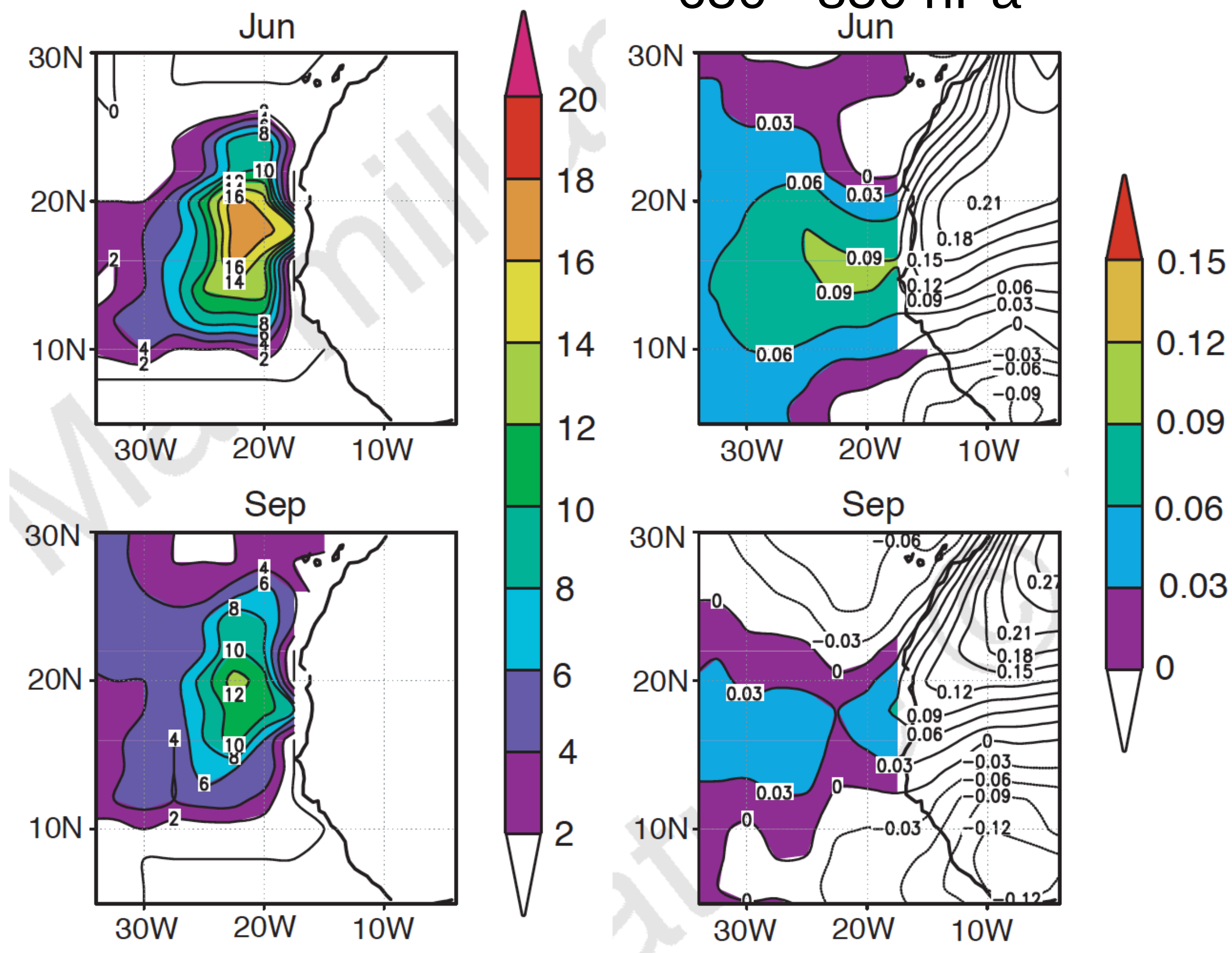
Nowottnick et al., in preparation, 2016

Aerosol Impacts on Analyses

- Almost 20 years ago it was recognized that there was a correlation between Saharan dust presence and analysis increments in the GEOS-1 reanalysis
- It was hypothesized at the time that the IAU could be at least particle explained by missing model physics; i.e., the radiative effects of aerosols

\# of dusty days

IAU Temperature Increment [K day^{-1}] 650 - 850 hPa



Alpert et al. *Nature* 1998

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AOD

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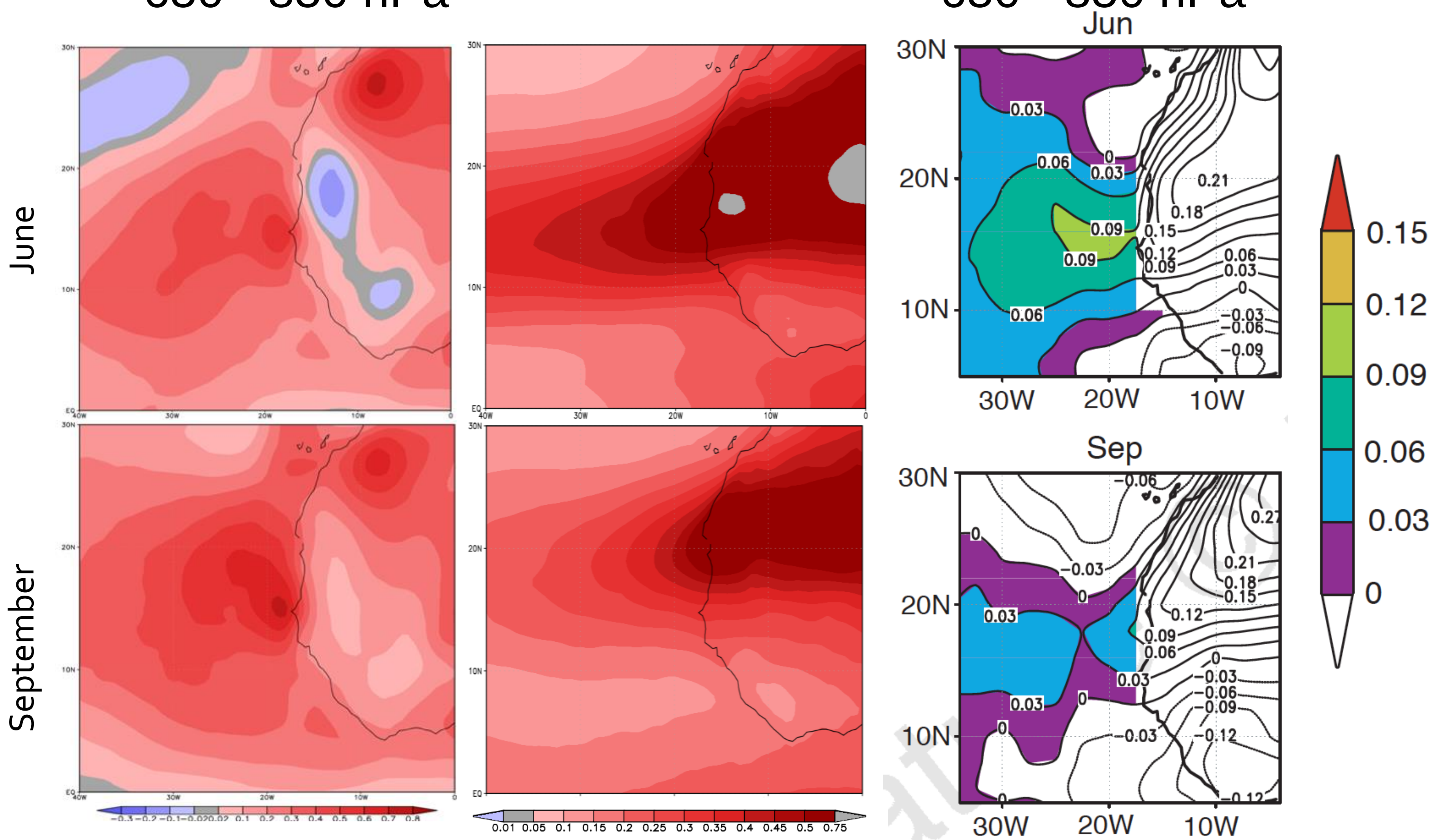

Monthly means (2000-2015)

Arlindo da Silva

Alpert et al. *Nature* 1998

Aerosol Impacts on Analyses

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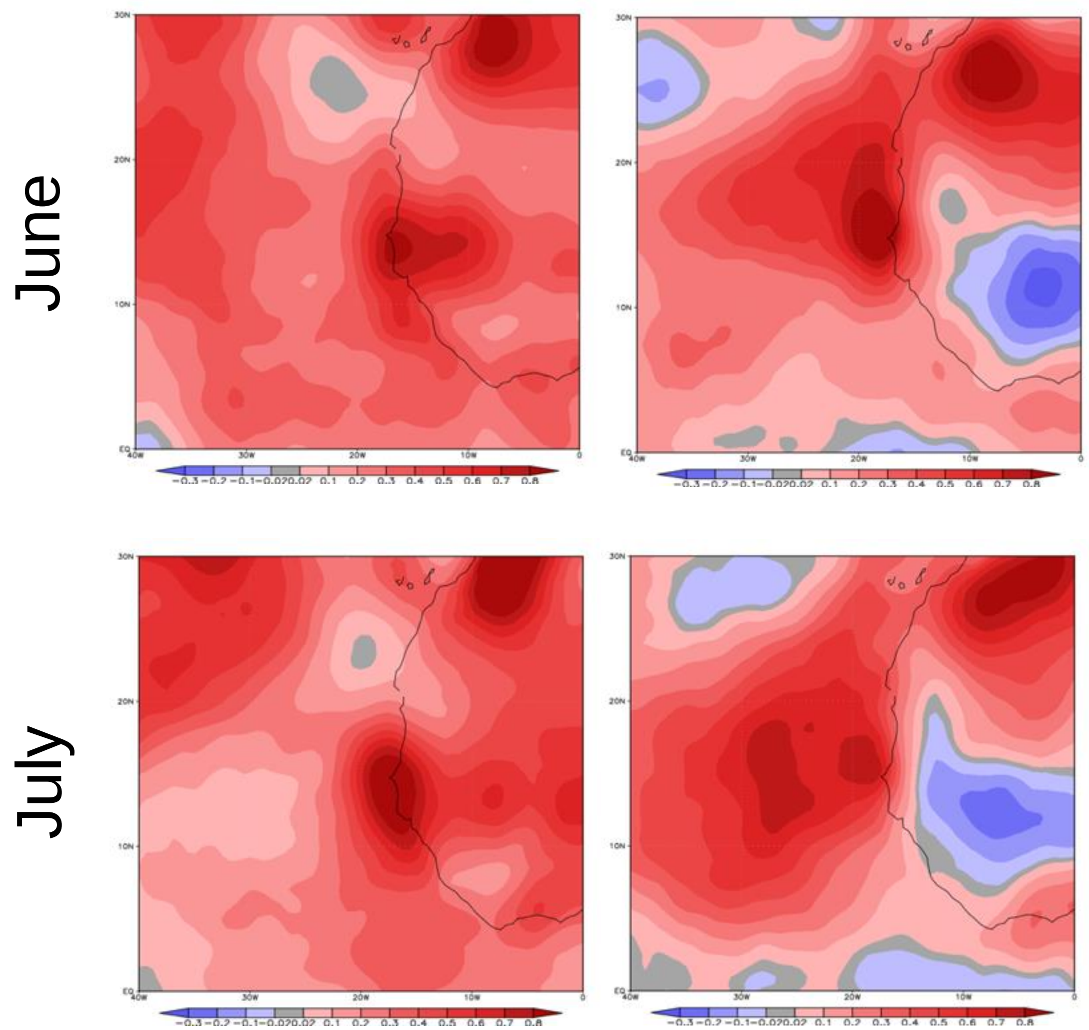
- It was hypothesized at the time that the IAU could be at least particle explained by missing model physics; i.e., the radiative effects of aerosols
- Revisiting this with the modern MERRA-2 reanalysis (includes aerosol radiative effects)
- IAU definitely different (smaller?) with aerosol effects included

IAU Temperature Increment [K day^{-1}] 650 - 850 hPa

With aerosols | Without aerosols



2008

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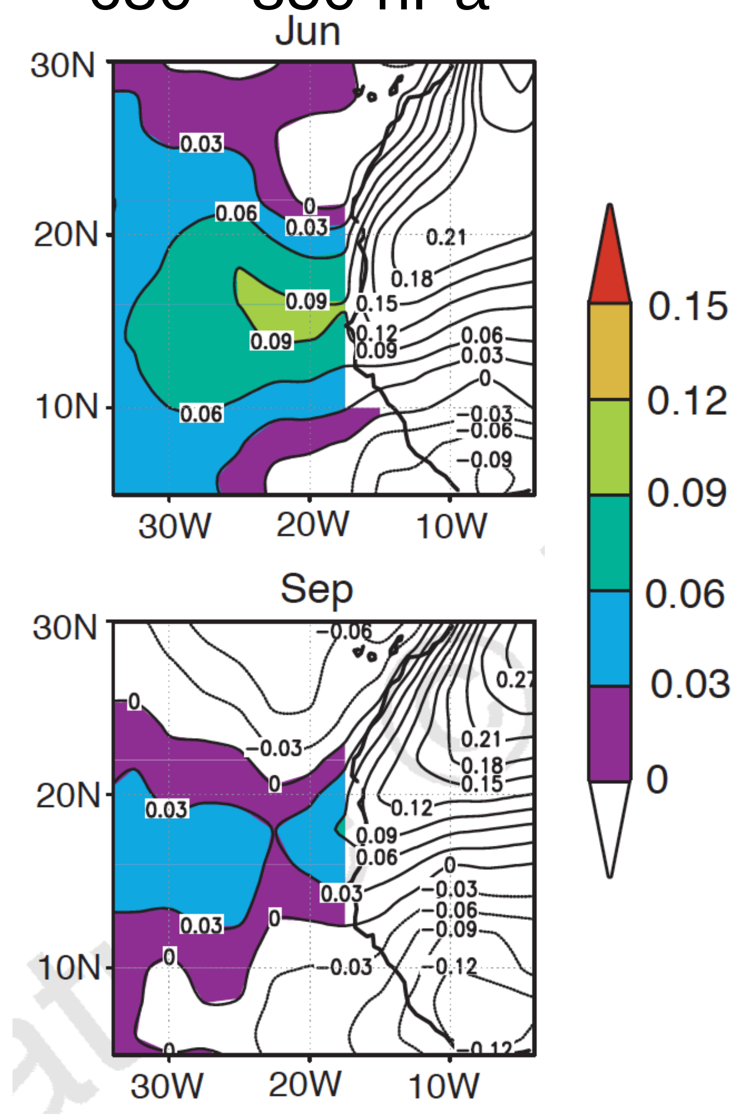
IAU Temperature Increment [K day^{-1}] 650 - 850 hPa

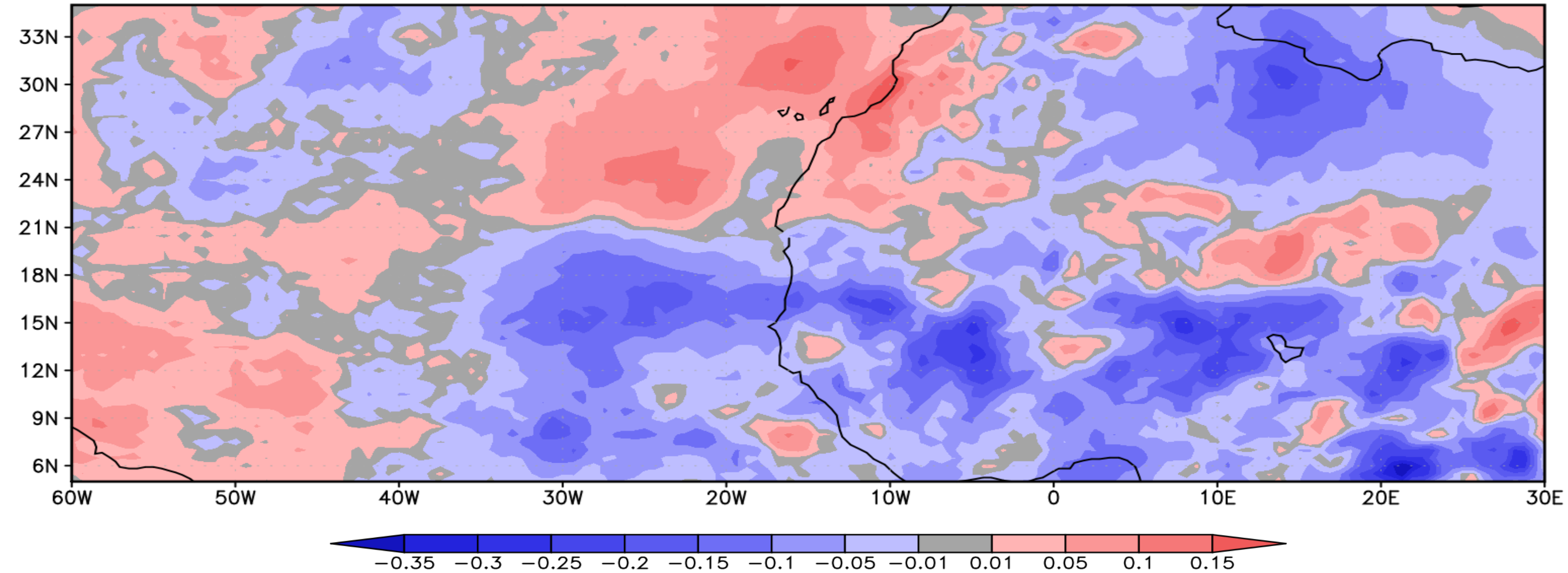


Alpert et al. *Nature* 1998

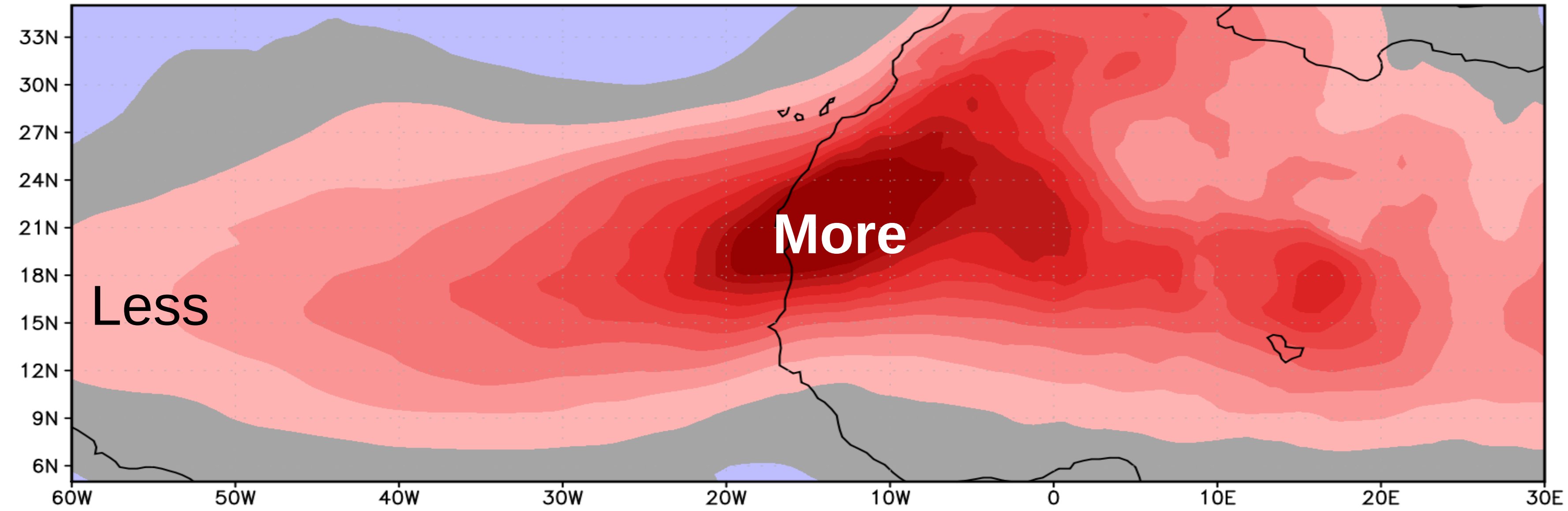
Aerosol Impacts on Analyses

- Finally, what are the prospects and potentials of including aerosols in the meteorological assimilation operator itself?
- Example is two GEOS-5 model runs, both with radiatively interactive aerosols
- In one the aerosols are also included in the meteorological (GSI) operator; i.e., affect model radiance calculation en route to met DA

$\Delta T_{analysis}$ [K] 650 - 850 hPa, with-without aerosols in GSI, July 2008



Dust Mass Loading (approx 650 - 850 hPa, July 2008)



Arlindo da Silva

Aerosol Impacts on Analyses

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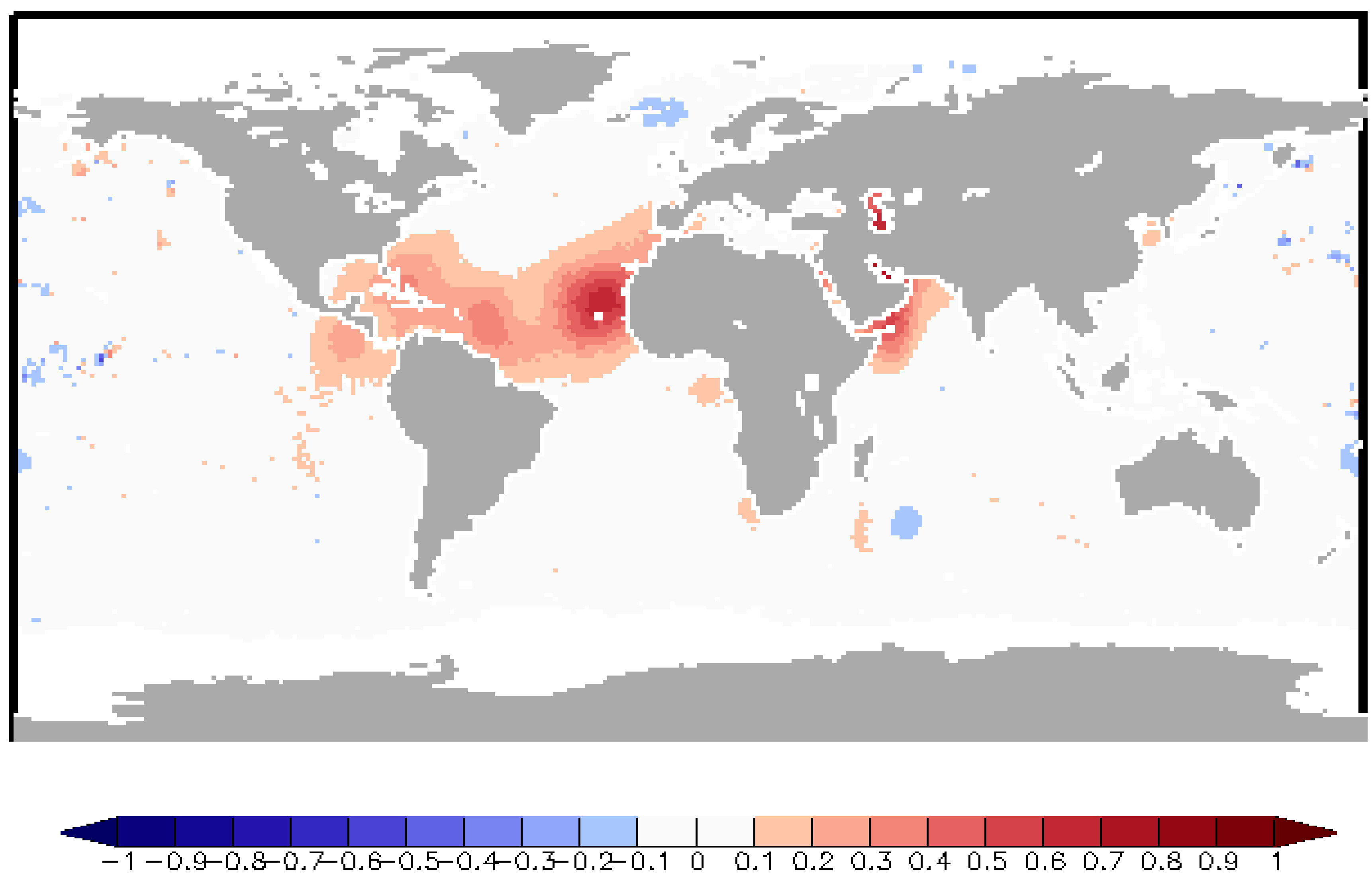
- Example is two GEOS-5 model runs, both with radiatively interactive aerosols
- In one the aerosols are also included in the meteorological (GSI) operator; i.e., affect model radiance calculation en route to met DA
- This then too has an impact on the analyzed SST

$\Delta T_{SST,analysis}$ [K], with-without aerosols in GSI, July 1, 2015

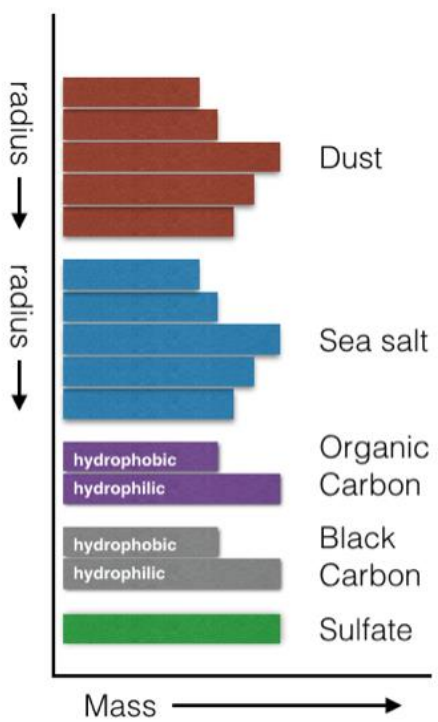


Arlindo da Silva, Jong Kim

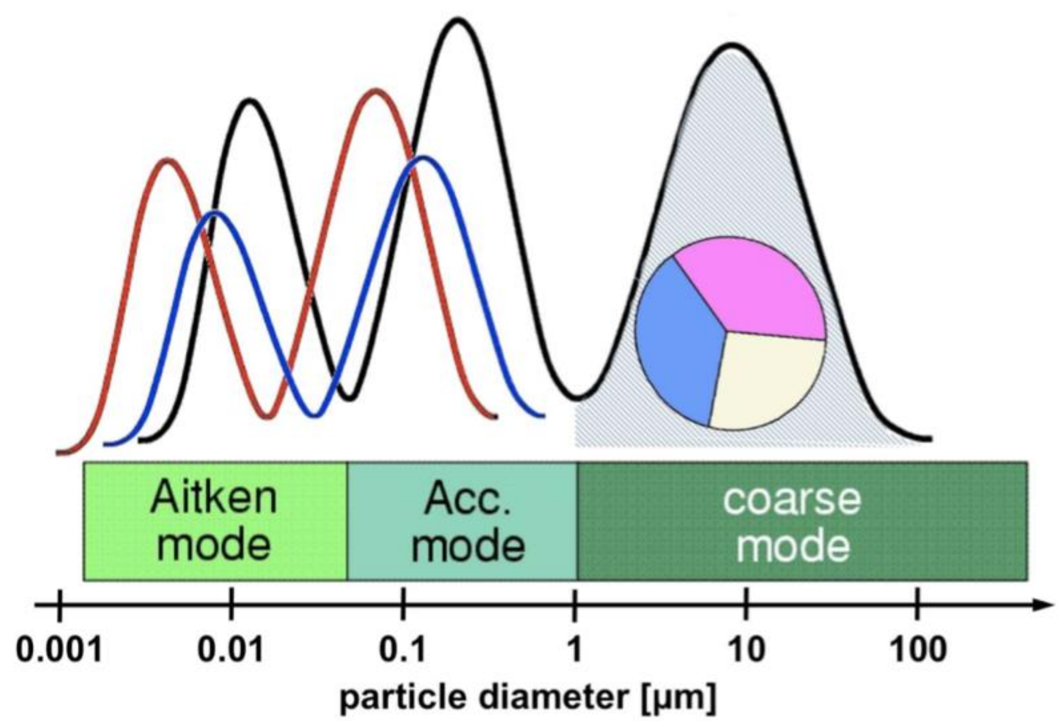
Aerosol Module Complexity

Interactive models tend to come in three flavors that have to do with how size and mixing state is represented (or hybrids of these)

- **bulk models:** speciated mass, external mixing, particle size specified (i.e., no microphysics)
- **modal/moments models:** mass and number, internal mixing, particle size spread into (usually) series of lognormal modes
- **sectional models:** mass and/or number, internal mixing, particle size discretized into series of size bins

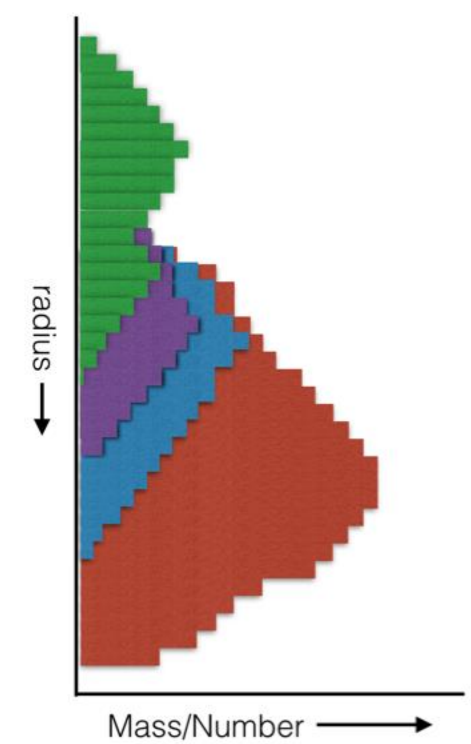


bulk (~10 tracers)



Aquila et al., *GMD*, 2011

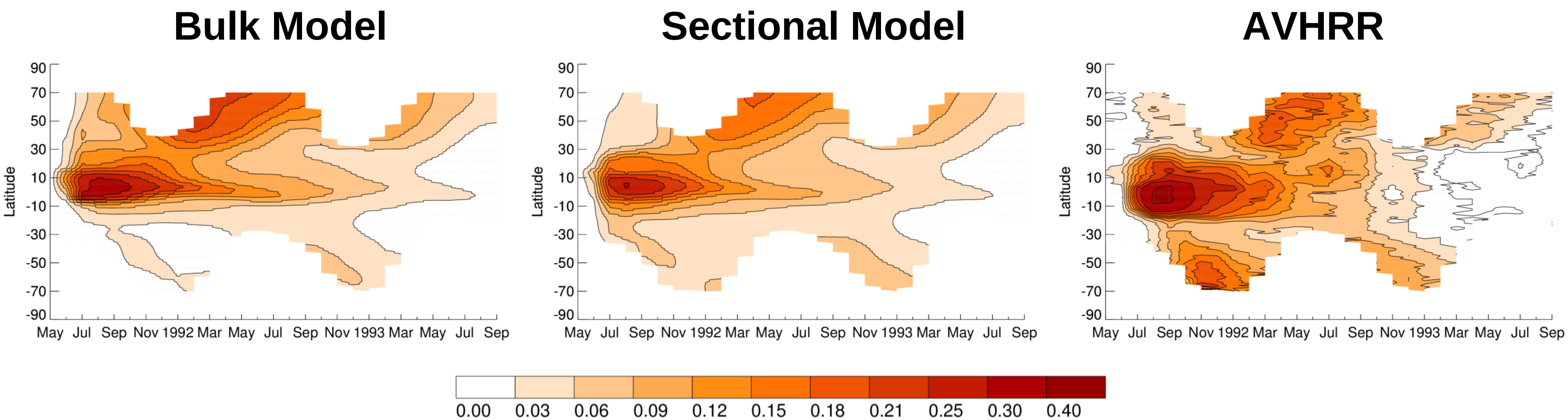
modal (~40 tracers)



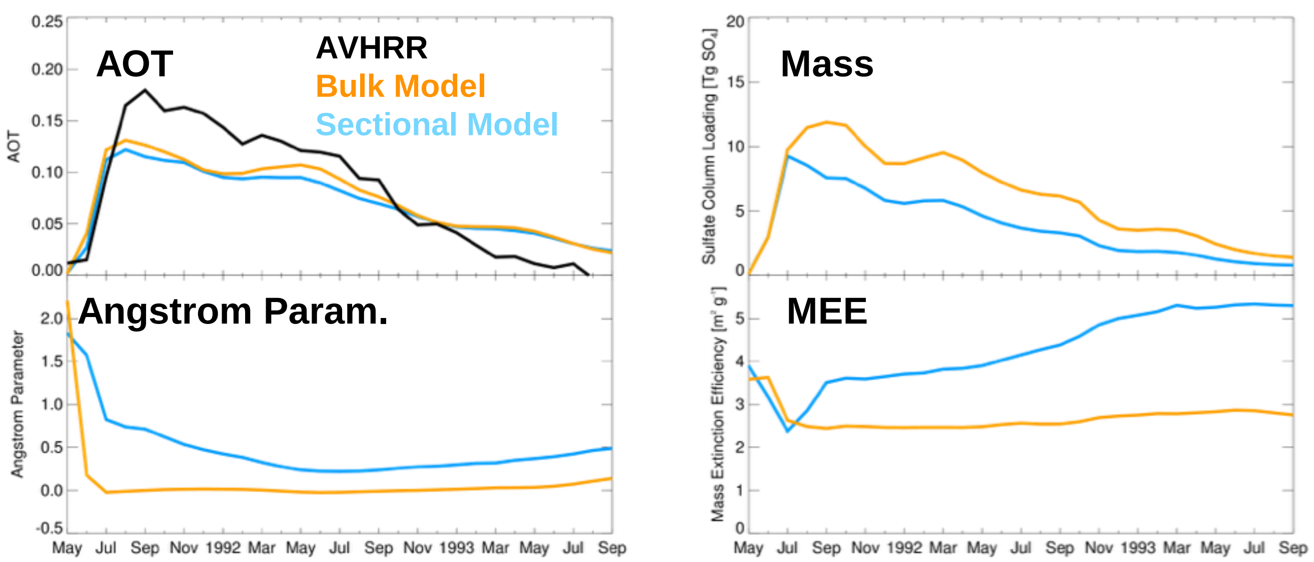
sectional (~100 tracers)

cost/complexity ⟶

Major Volcanic Eruption

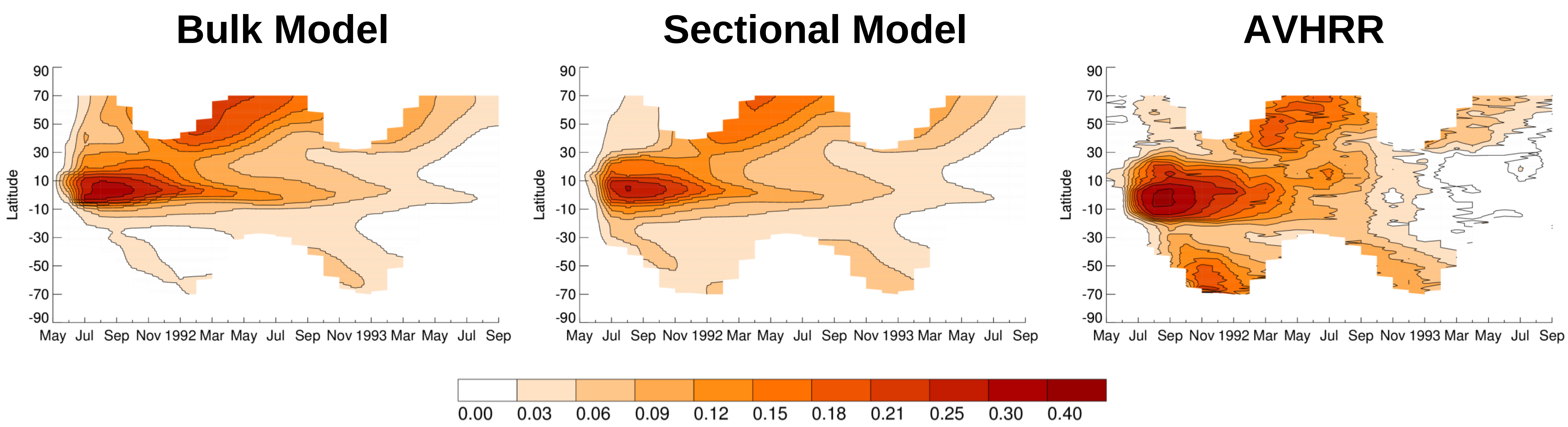


Mass and Optical Properties

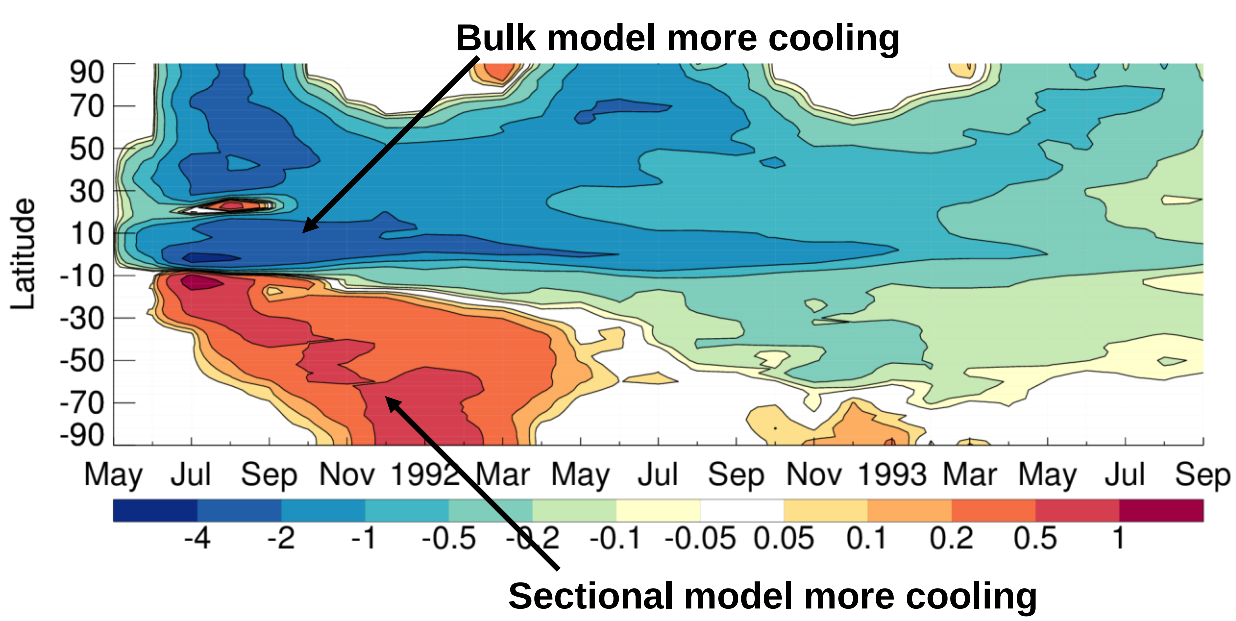


- Simulation of the June 1991 Mt. Pinatubo volcanic eruption with GEOS-5 model with both bulk (GOCART) and sectional (CARMA) microphysics for sulfates
- Different optical properties evolve depending on aerosol scheme complexity

Major Volcanic Eruption

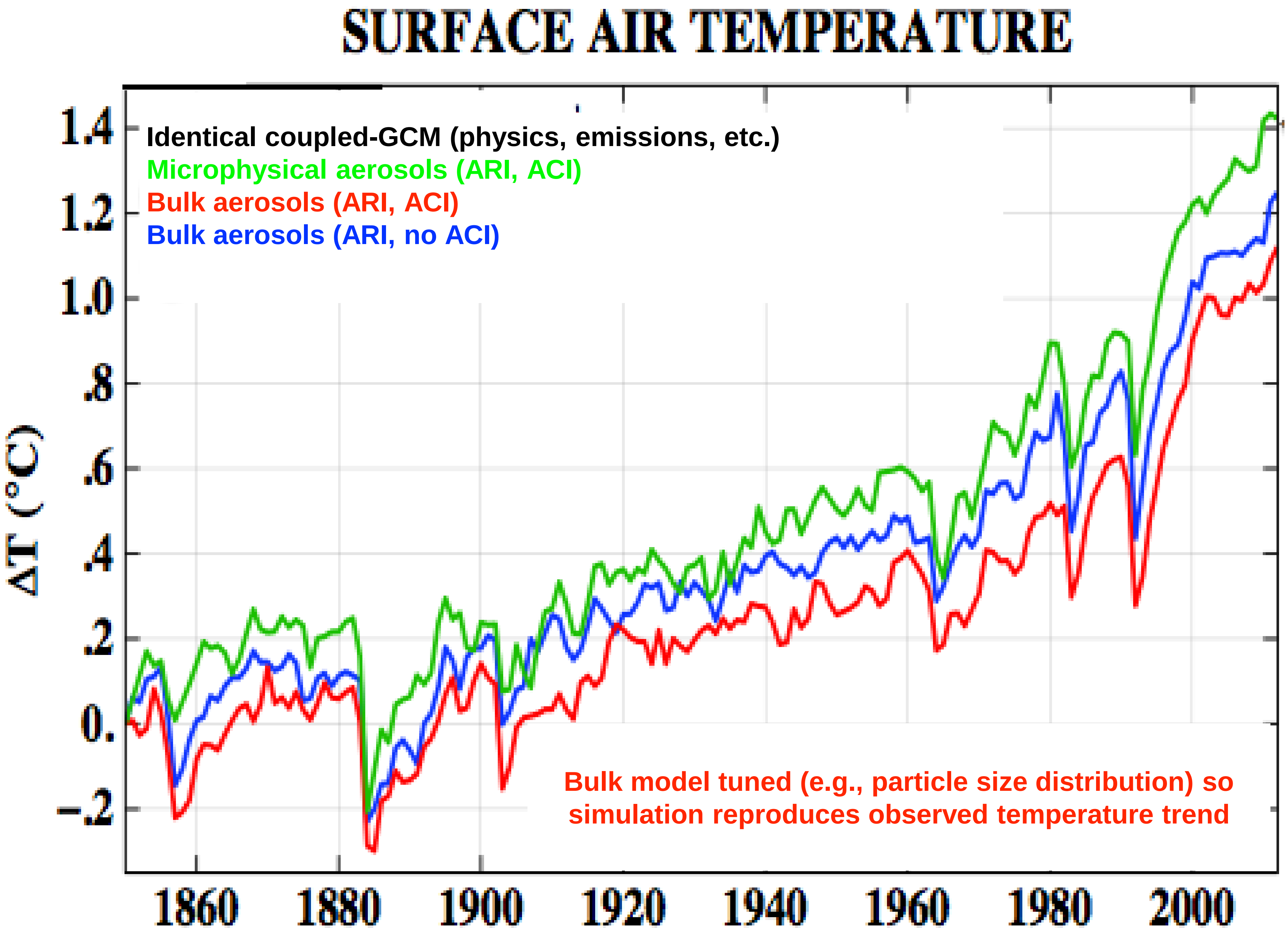


ΔSW_{TOA} Bulk - Sectional Model [W m^{-2}]



- Simulation of the June 1991 Mt. Pinatubo volcanic eruption with GEOS-5 model with both bulk (GOCART) and sectional (CARMA) microphysics for sulfates
- Different optical properties evolve depending on aerosol scheme complexity
- These are manifest in different aerosol radiative forcing

Impact of Aerosol Microphysics



Susa Bauer, GISS/Columbia

Diversity of Microphysical Simulations

AeroCom suite of simulations

Model	Scheme type	Classes	Multi-dist	Tracers	Host model	Resolution	Reference
CAM5-MAM3	modal (2 m)	3	N	15	GCM (free)	$1.9° \times 2.5° \times$ L30	Liu et al. (2012)
HadGEM3-UKCA	modal (2 m)	5	Y	20	GCM (nudg)	$1.3° \times 1.9° \times$ L63	Mann et al. (2014)
TM5	modal (2 m)	7	Y	25	CTM	$2.0° \times 3.0° \times$ L34	Aan de Brugh et al. (2011)
GLOMAP-mode	modal (2 m)	7	Y	26	CTM	$2.8° \times 2.8° \times$ L31	Mann et al. (2012)
EMAC	modal (2 m)	7	Y	41	GCM (nudg)	$2.8° \times 2.8° \times$ L19	Pringle et al. (2010)
ECHAM5-HAM2	modal (2 m)	7	Y	29(a)	GCM (nudg)	$1.9° \times 1.9° \times$ L31	Zhang et al. (2012)
GISS-MATRIX	modal[b] (2 m)	16	Y	60	GCM (nudg)	$2.0° \times 2.5° \times$ L40	Bauer et al. (2008)
CanAM4-PAM	pcwise-lgnrml (2 m)	7	N	20	GCM (free)	$3.7° \times 3.7° \times$ L35	von Salzen (2006)
GEOS-Chem-APM	mode & sect. (1 m)	100	Y	100	CTM	$2.0° \times 2.5° \times$ L47	Yu and Luo (2009)
ECHAM5-SALSA	sectional (2 m)	20	Y	65	GCM (nudg)	$1.9° \times 1.9° \times$ L31	Bergman et al. (2012)
GISS-TOMAS	sectional (2 m)	12	N	72	GCM (free)	$4.0° \times 5.0° \times$ L09	Lee and Adams (2010)
GLOMAP-bin	sectional (2 m)	40	Y	160	CTM	$2.8° \times 2.8° \times$ L31	Spracklen et al. (2005a, 2011)

[a] Although treatment of SOA in ECHAM5-HAM2 involves 20 SOA species, only four additional advected aerosol tracers are required in addition to the 25 for ECHAM5-HAM. Another four species are required for the condensable organic gases.
[b] Note that GISS-MATRIX scheme follows the quadrature method of moments.

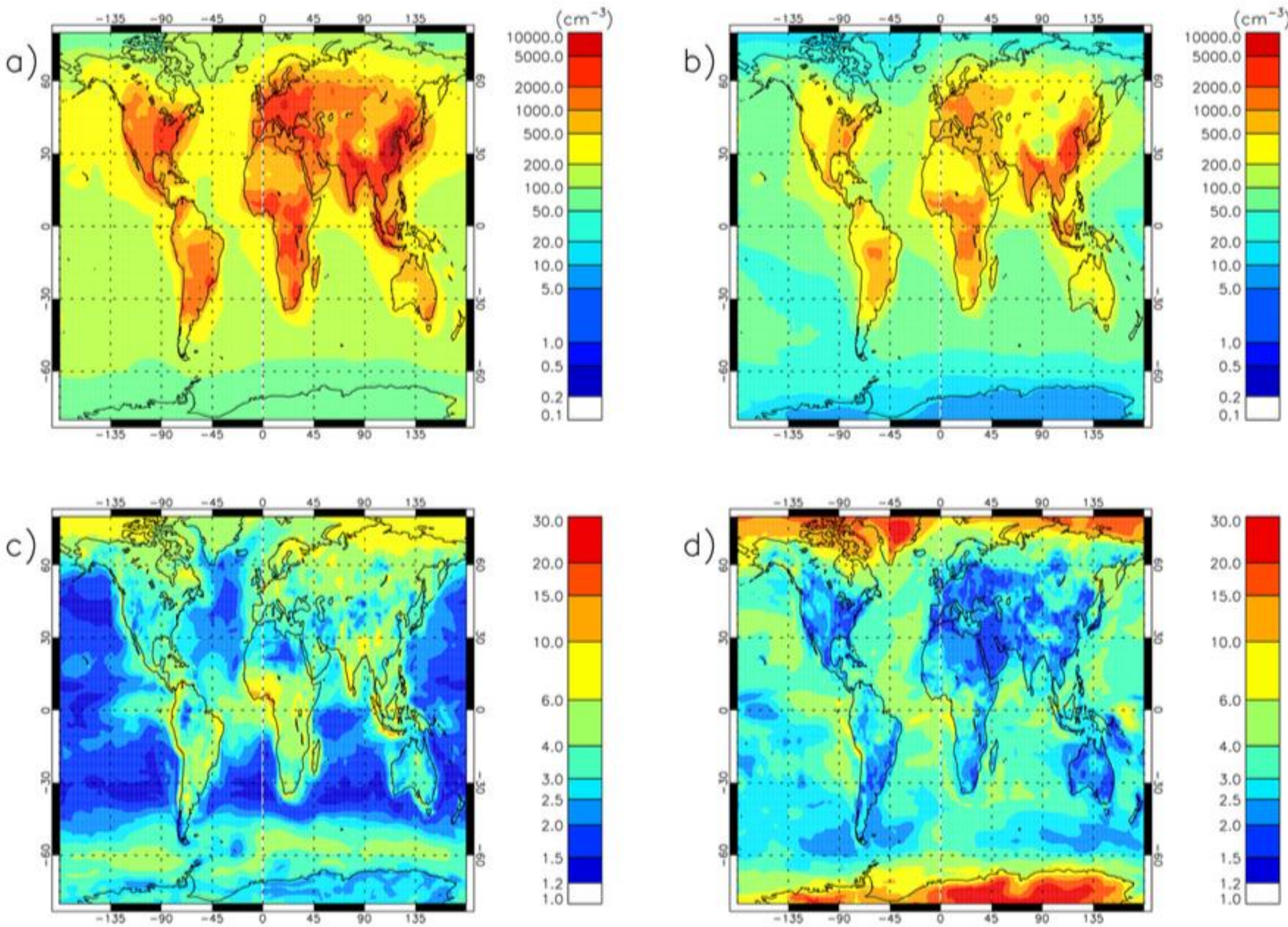
Mann et al. *ACP* 2014

Diversity of Microphysical Simulations

Diversity in simulation of fine particle concentrations

Mean Surface Level N_{30nm}

Mean Surface Level N_{100nm}



Diversity (ratio max/min) N_{30nm}

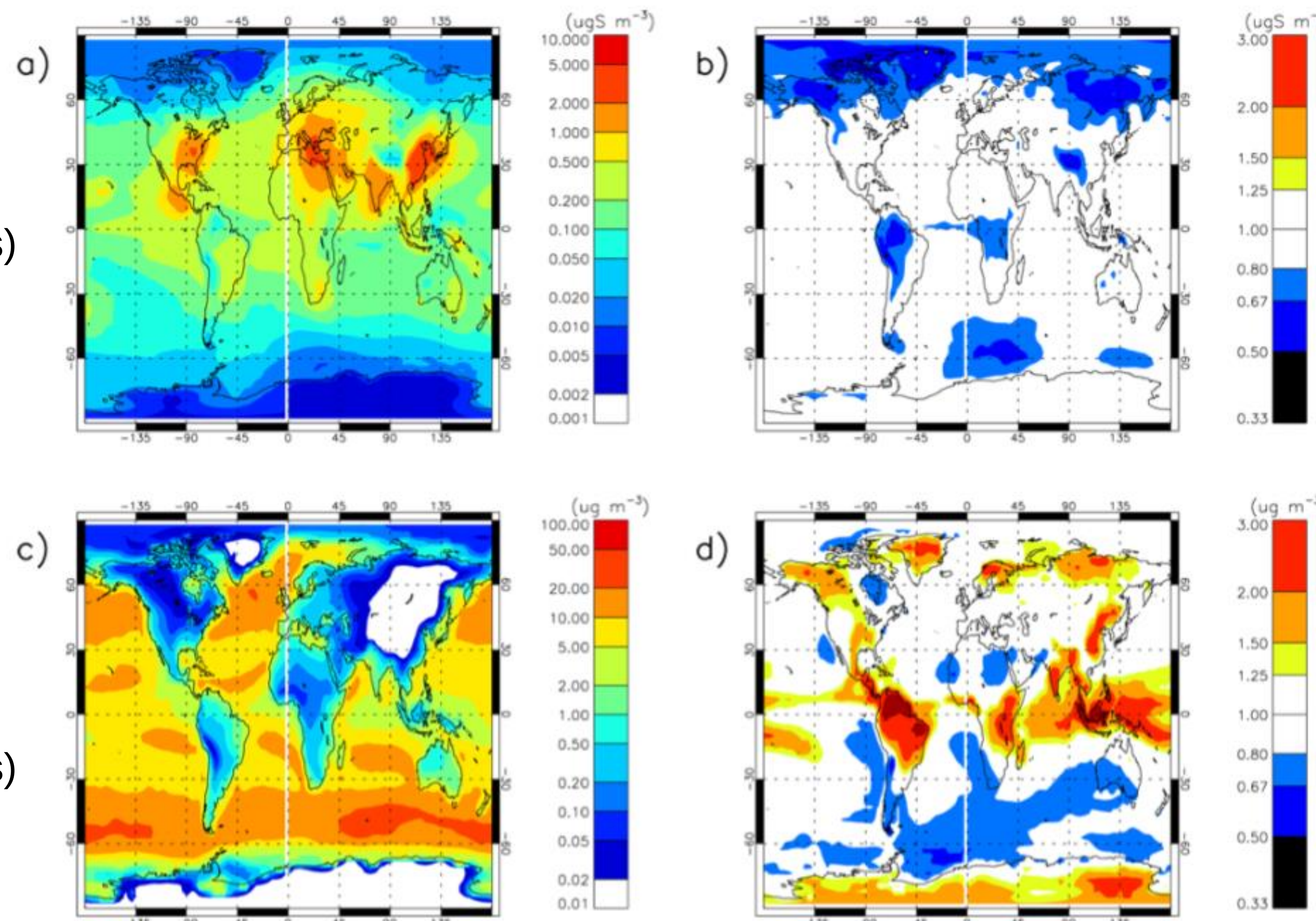
Diversity (ratio max/min) N_{100nm}

Mann et al. *ACP* 2014

Comparison of Sectional to Modal Scheme

Sulfate Surface Mass GLOMAP-Mode (26 tracers)

Ratio of Mode/Bin (160 tracers)



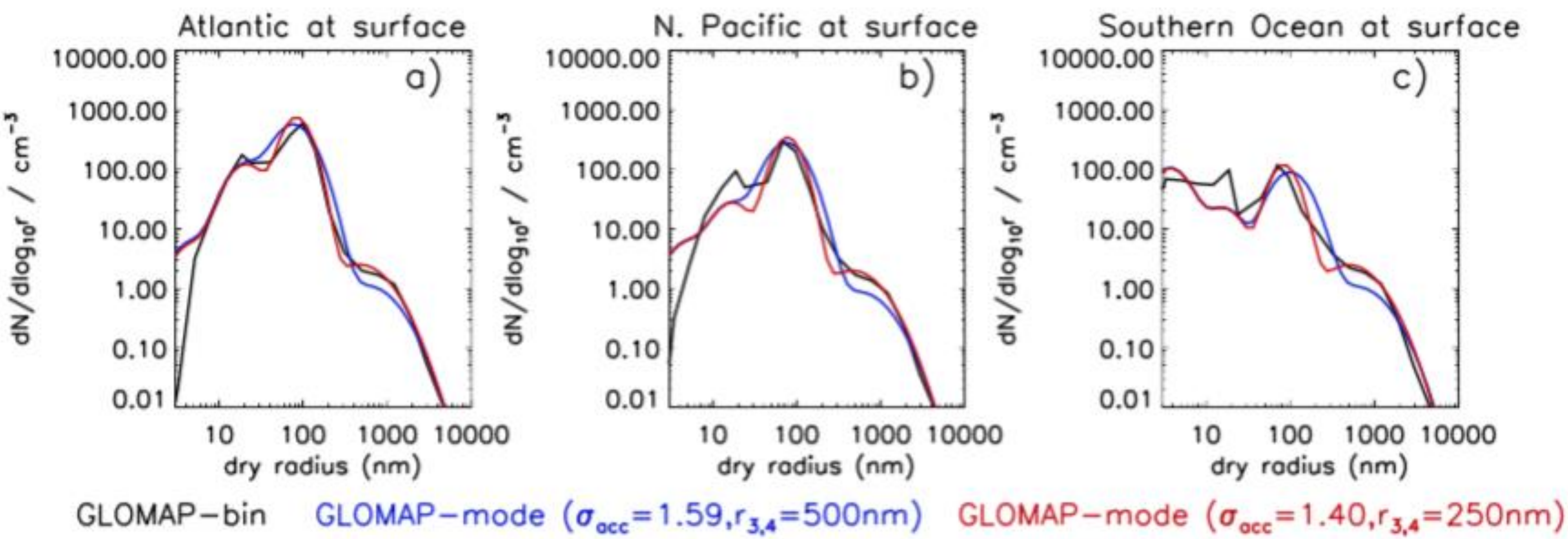
Sea Salt Surface Mass GLOMAP-Mode (26 tracers)

Ratio of Mode/Bin (160 tracers)

Mann et al. *ACP* 2012

Comparison of Sectional to Modal Scheme

led (but expensive) sectional scheme to “tune” size distributions



Mann et al. *ACP* 2012

Reduced Complexity of Modal Schemes

MAM7 (31 tracers) uses 7 modes to represent aerosols
MAM3 (15 tracers) uses 3 modes, lumping coarse modes
and omitting primary carbon mode at a savings of 40% from MAM7

	MAM3	MAM7
Direct	−0.02 ± 0.01	−0.00 ± 0.01
SW indirect	−2.05 ± 0.09	−1.99 ± 0.04
SW semidirect	0.06 ± 0.13	−0.01 ± 0.03
SW indirect + semidirect	−1.99	−2.00
LW indirect	0.52 ± 0.05	0.54 ± 0.05
LW semidirect	0.02 ± 0.12	−0.08 ± 0.07
LW indirect + semidirect	0.54	0.46
Total	−1.47 ± 0.11	−1.54 ± 0.06

Take Home Messages

- **There are clear NWP and climate impacts from including aerosol radiative and cloud interactions**
  - Changes in dynamics and cloud fields affect aerosol lifecycle, plume height, long-range transport, overall forcing of the climate system, etc.
  - Inclusion of aerosols in NWP systems has benefit to surface field biases (e.g., T_{2m}, U_{10m})
  - Including aerosol affects has impact on analysis increments and can have statistically significant impacts on, e.g., tropical cyclogenesis
  - Above points are made especially with respect to aerosol radiative interactions, but aerosol-cloud interaction is a bigger signal on the global system

- **Many of these impacts are realized even in models with relatively simple (bulk) aerosol schemes (~10 - 20 tracers)**
  - Simple schemes though imply simple representation of aerosol absorption and—importantly for aerosol-cloud interaction—particle size distribution
  - Even so, more complex schemes exhibit a lot of diversity between different models, with issues such as size selection both for emitted particles and for modes
  - Prospects for complex sectional schemes to tune modal (and even bulk) schemes toward better selection of size representation

- **I think this is a ripe topic for more research**
  - Systematic documentation of benefits of no vs. climatological vs. interactive (direct and then direct+indirect) aerosols
  - Document aerosol impact on analysis increments, inclusion in NWP data assimilation operator
  - Further refinement of baseline assumptions in model design (e.g., absorption, particle size distribution)
  - Did not get into model resolution and interplay of other physical processes with aerosols (e.g., moist physics, obviously important), chemistry