Investigation of aerosol effects on weather forecasts using NCEP global models

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Lessons learned from developing NCEP's global aerosol forecasting and assimilation system

With acknowledgments to colleagues and collaborators

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Outline of the presentation

- Introduction
- Dual-resolution weather-aerosol system
  - Aerosol-radiation-cloud interaction
  - Impact of aerosols on brightness temperature calculations
  - Aerosol spatial-temporal distributions
- Closing remarks

Why include aerosols in the predictive systems

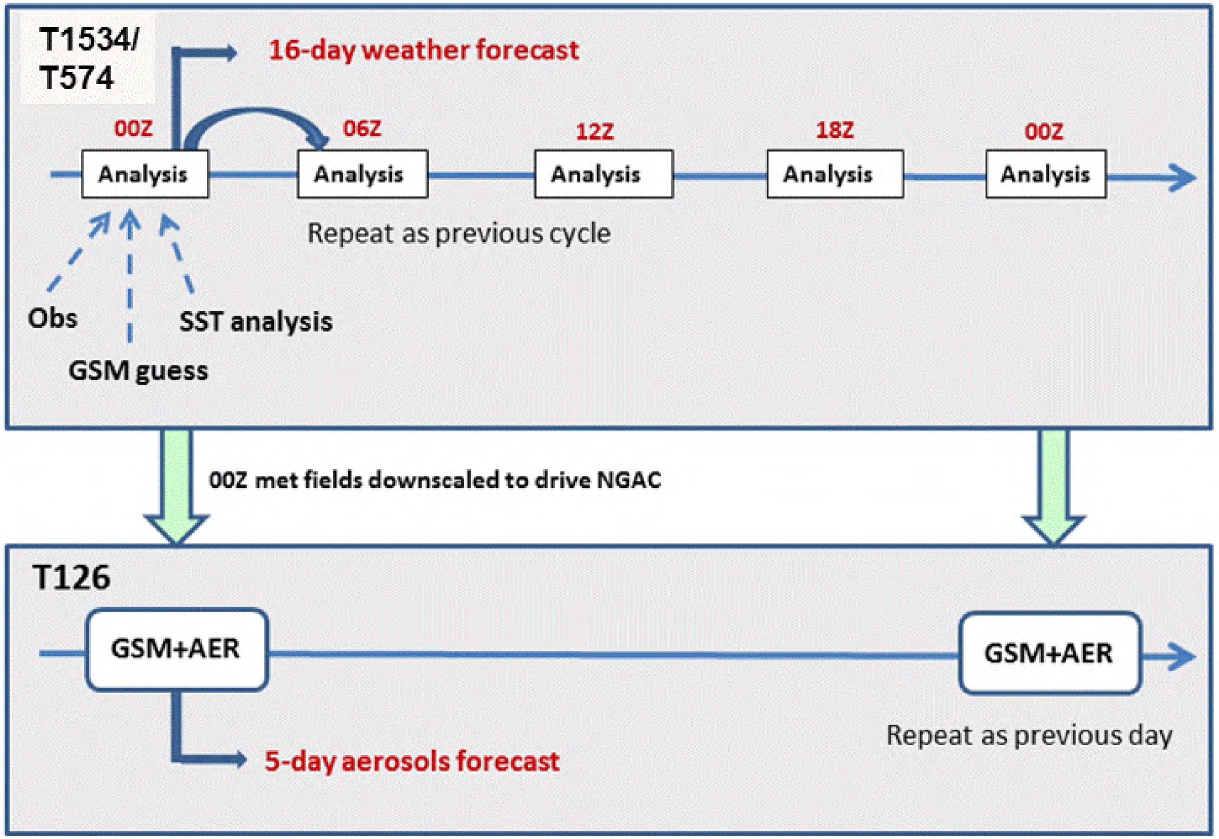
- Improve weather forecasts and climate predictions by taking into account of aerosol effects on radiation and clouds
- Improve the handling of satellite observations by properly accounting for aerosol effects during the data assimilation
- Provide aerosol (lateral and upper) boundary conditions for regional air quality predictions
- Produce quality aerosol information that address societal needs and stakeholder requirements, e.g., air quality, health professionals, policy makers, climate scientists, and solar energy plant managers

Global aerosol forecasting

- Aerosol modeling, traditionally serving regional air quality and climate communities, has seen rapid development at several operational NWP centers over the last few years
- Aerosol prediction systems are built upon modeling/assimilation developments already in place for the meteorological systems. Examples include:
  - NRL: NAAPS, driven by NOGAPS (Zhang et al., 2008; Westphal et al., 2009)
  - ECMWF: IFS coupled with LMD (Benedetti et al., 2009; Morcrette et al., 2009)
  - GMAO: GEOS-5 coupled with GOCART (Colarco et al., 2009)
  - NCEP: NEMS GFS coupled with GOCART (Lu et al., 2016. Wang et al., 2018)
- Development of near-real-time aerosol forecasting systems and aerosol data assimilation methodologies leverage the expertise in the NWP community particularly in the areas of observability, data assimilation, verification, and ensemble.

Dual resolution weather-aerosol system at NCEP

Operational: One-way coupling



GFS for weather

GFS: Only consider aerosol-radiation feedback

GSI: Background aerosols

RTG_SST#: No aerosol correction

NGAC* for aerosols

Initial conditions:

ATM: downscaled from GDAS

AER: cycled from NGA runs

#: Real-time Global Sea Surface Temperature

*: NGAC is one version of GSM (in NEMS framework; with the prognostic aerosol option)

Dual resolution weather-aerosol system at NCEP

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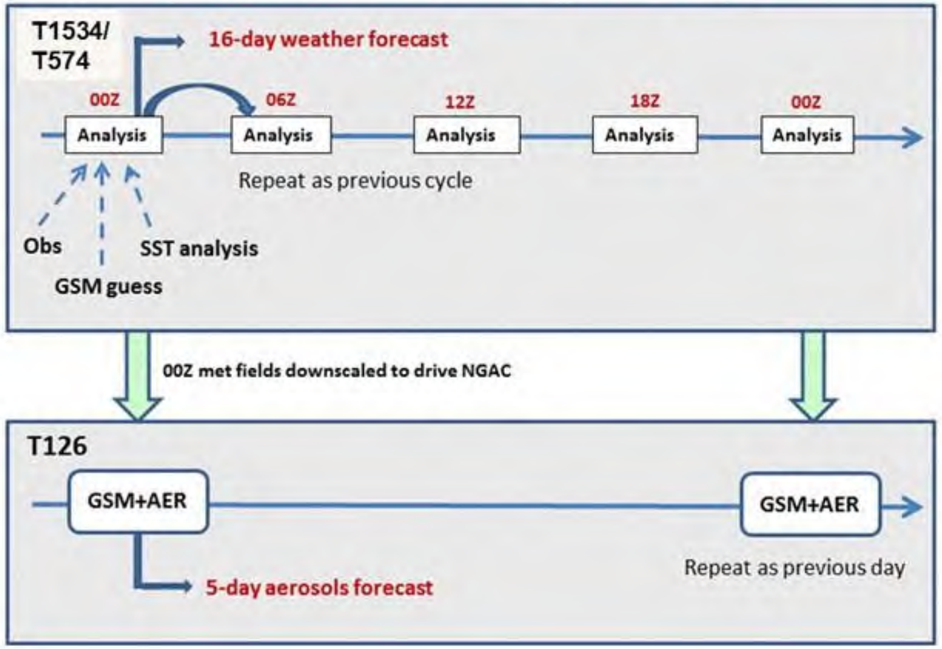

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Model Physics

NGAC* for aerosols

Initial conditions:

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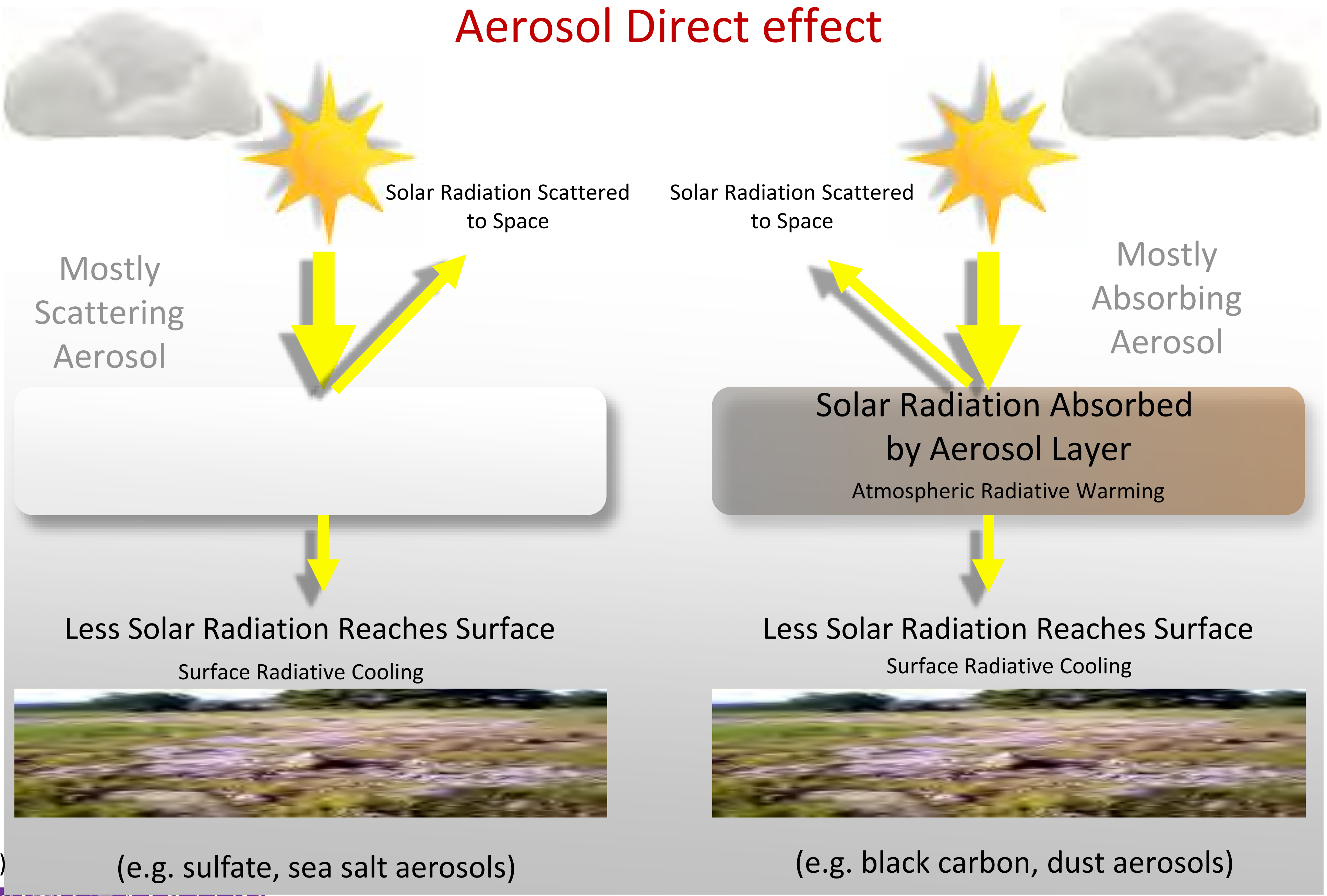
Operation configuration: In GFS physics, aerosol attenuation is determined from the OPAC climatology and aerosol indirect effect is not considered

Aerosol Direct effect

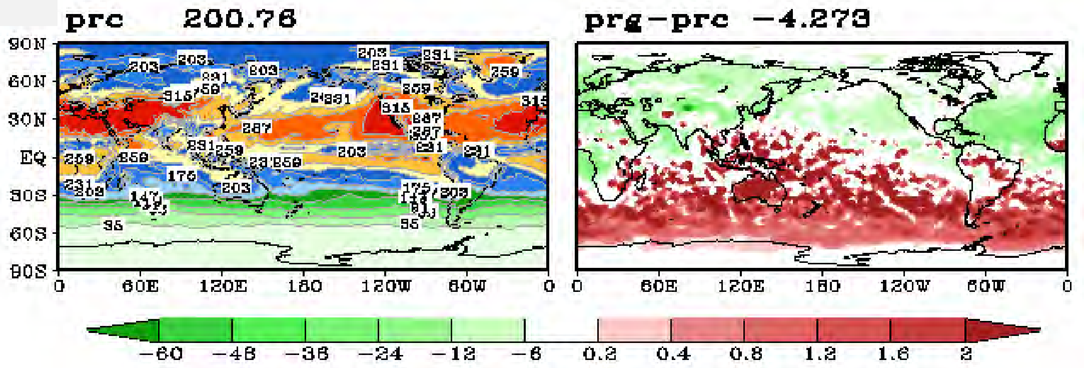


C. A. Randles (GSFC)

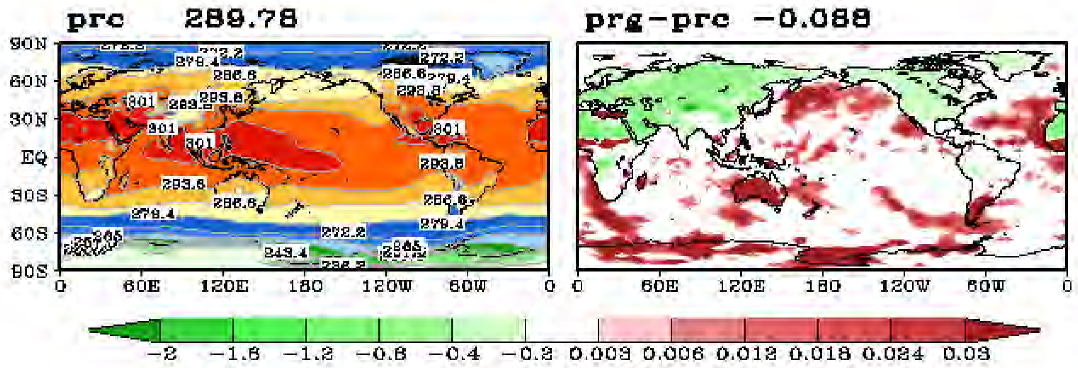
Aerosol-Radiation Feedback

- T126 L64 GFS/GSI[#] experiments for the 2006 summer period
- PRC uses the OPAC climatology (as in the operational applications)
- PRG uses the in-line GEOS4-GOCART[%] dataset (updated every 6 hr)

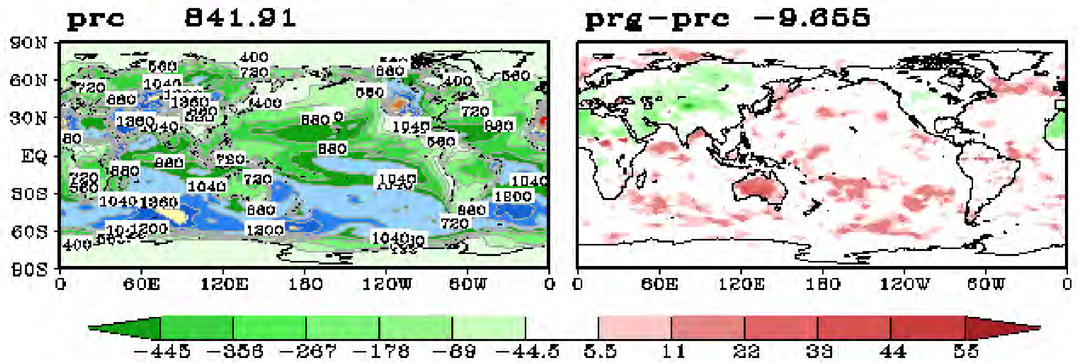
Surface downward SW fluxes are reduced



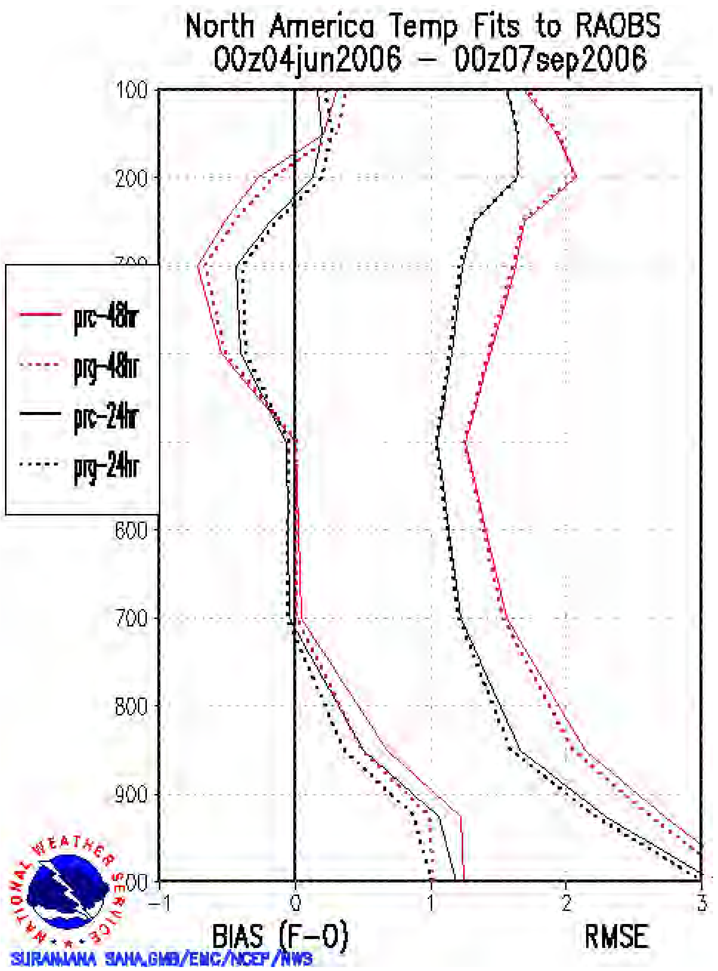
Cooler near surface tempeature

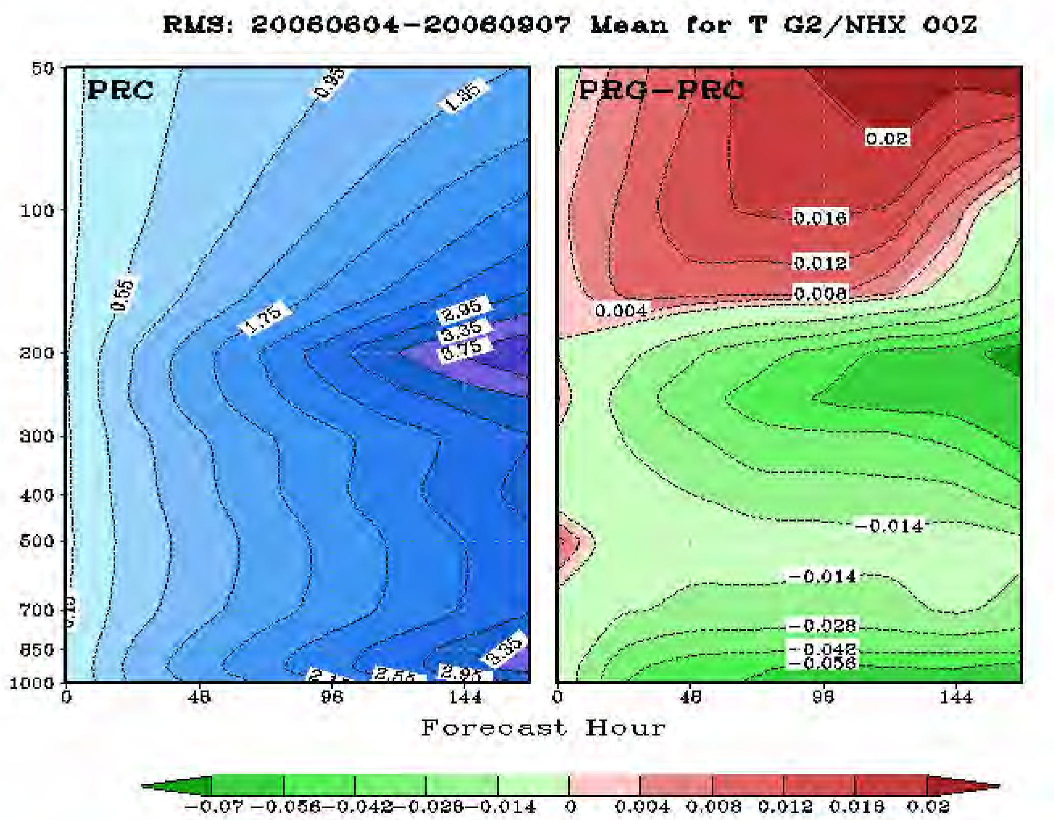


Suppressed PBL depth



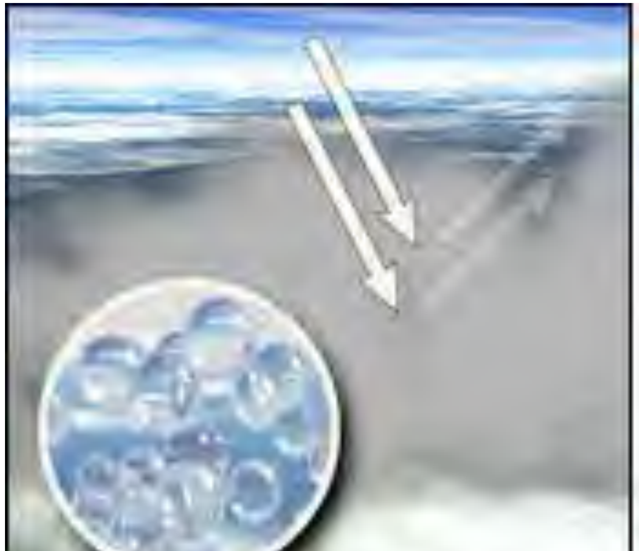
Aerosol-Radiation Feedback

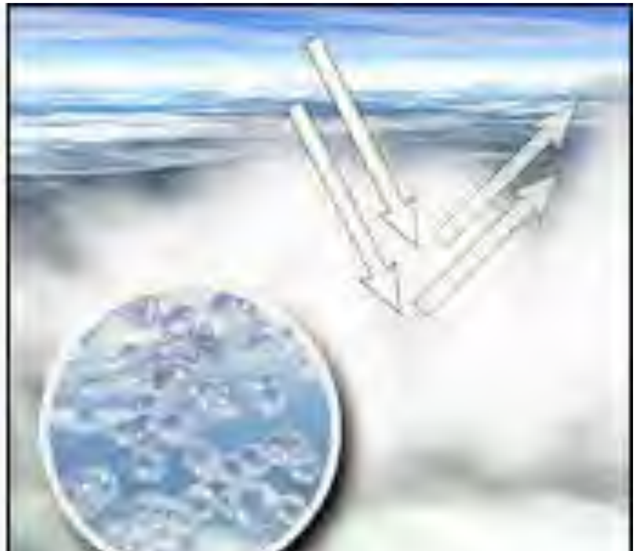




Verification against analyses and observations indicates a positive impact in temperature forecasts due to realistic time-varying treatment of aerosols.

Aerosol INDirect effect


graphic courtesy NASA Earth Observatory

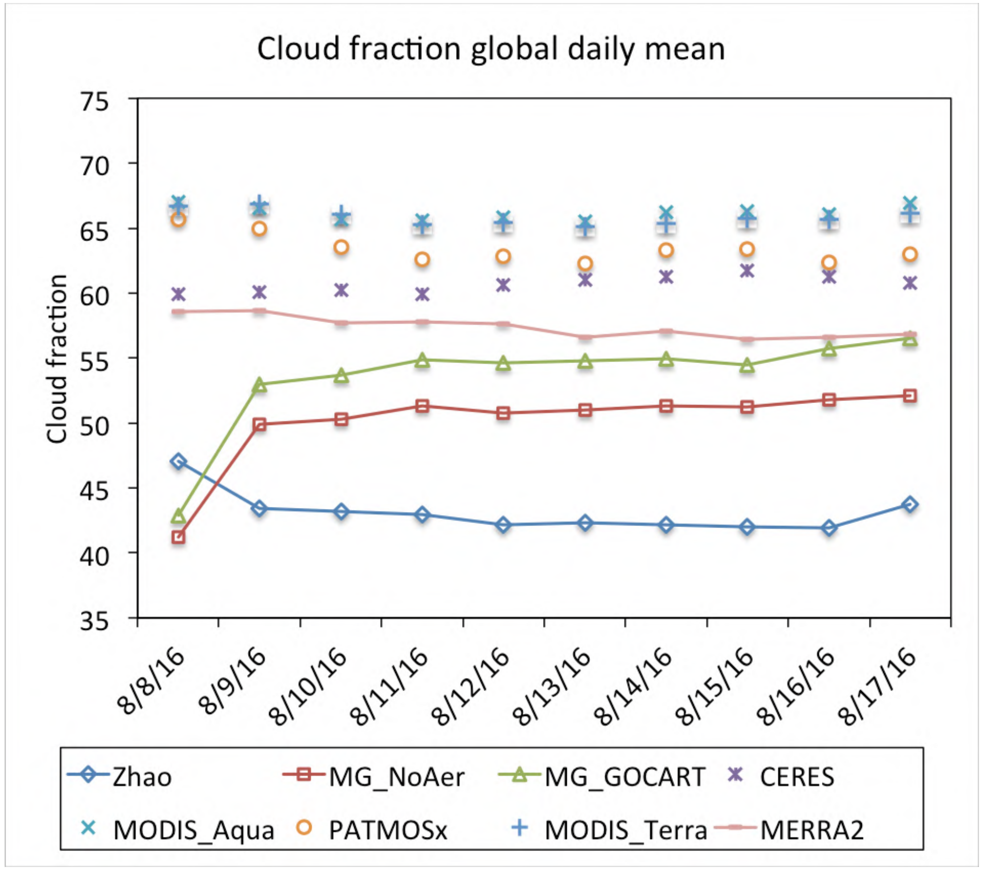

graphic courtesy NASA Earth Observatory

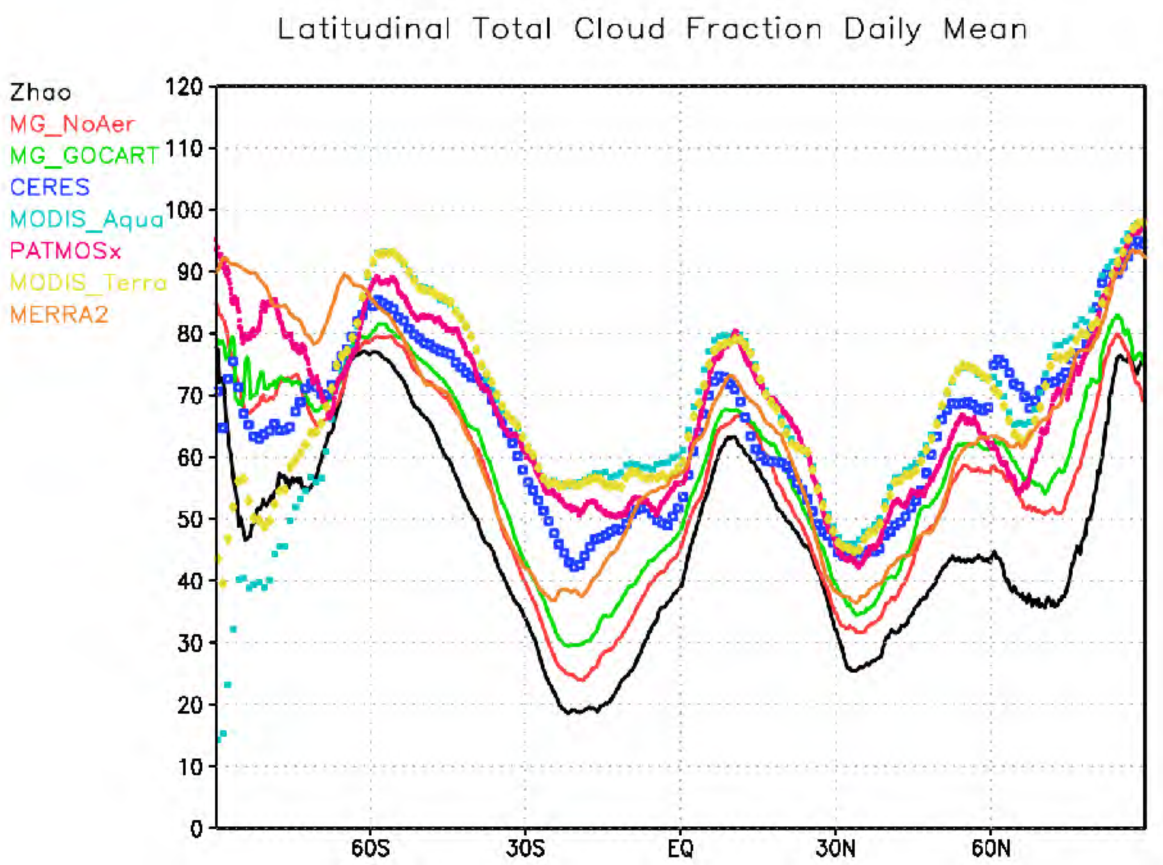
Larger cloud droplets, less reflective cloud. → **Twomey Effect** → Smaller cloud droplets, more reflective cloud.

Less Aerosols | Increased Cooling by Clouds | More Aerosols

Larger cloud droplets, droplets rain out easier, clouds dissipate quicker. → **Albrecht Effect** → Smaller cloud droplets, droplets rain out less, longer-lived clouds.

Cloud properties – global cloud fraction daily mean

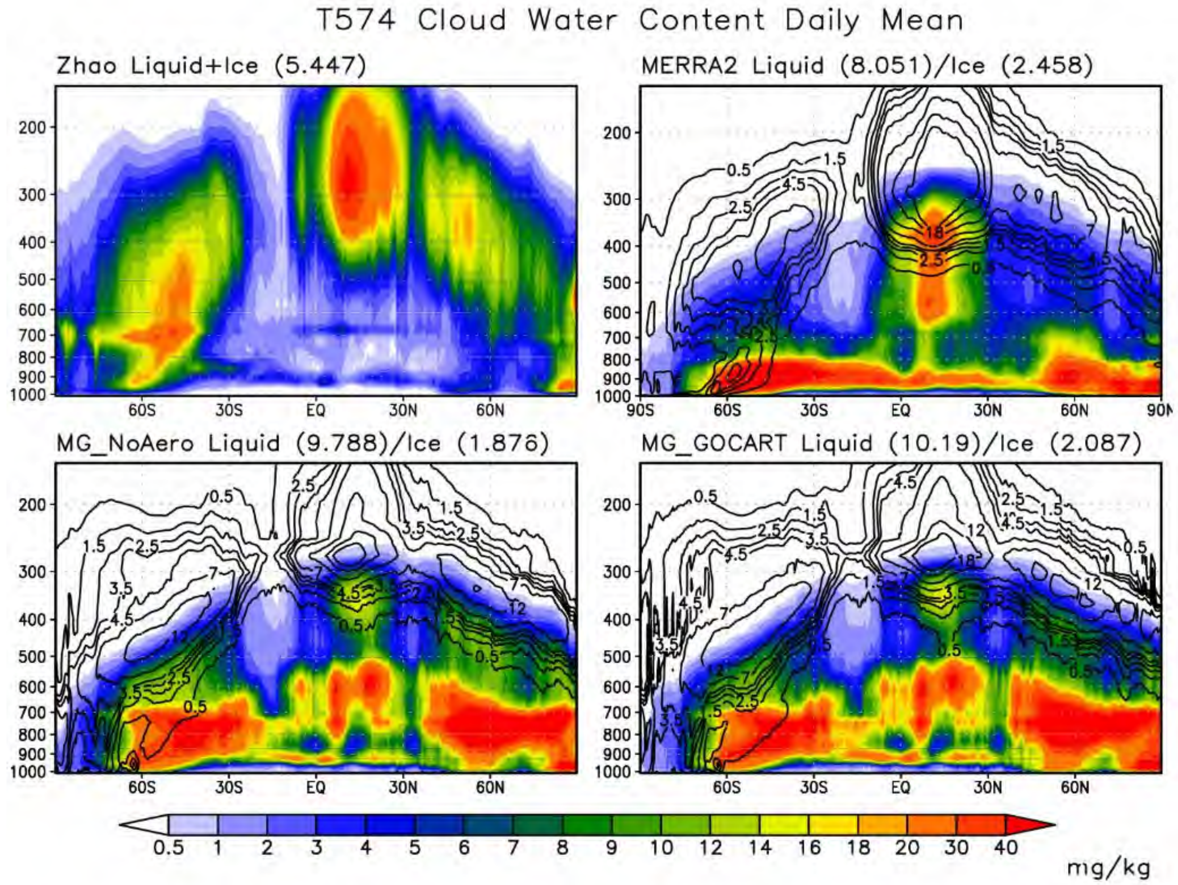


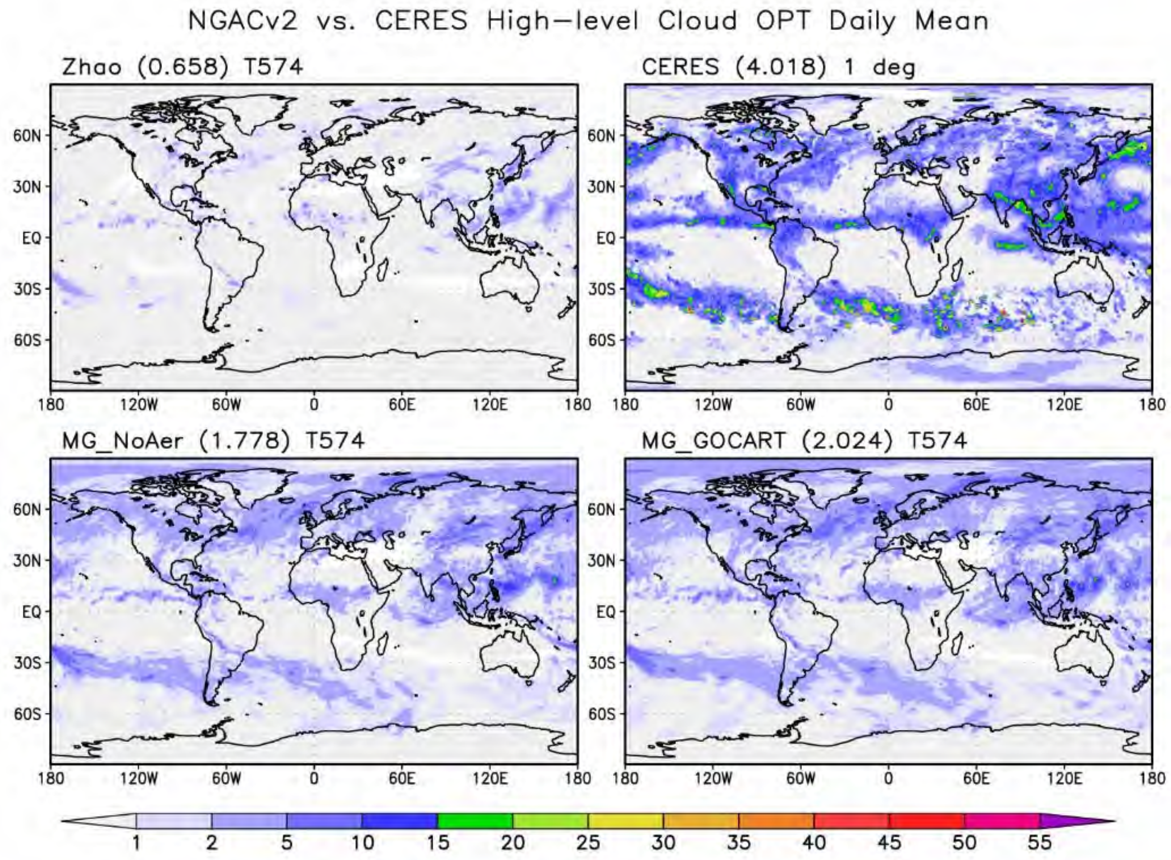


Data sources

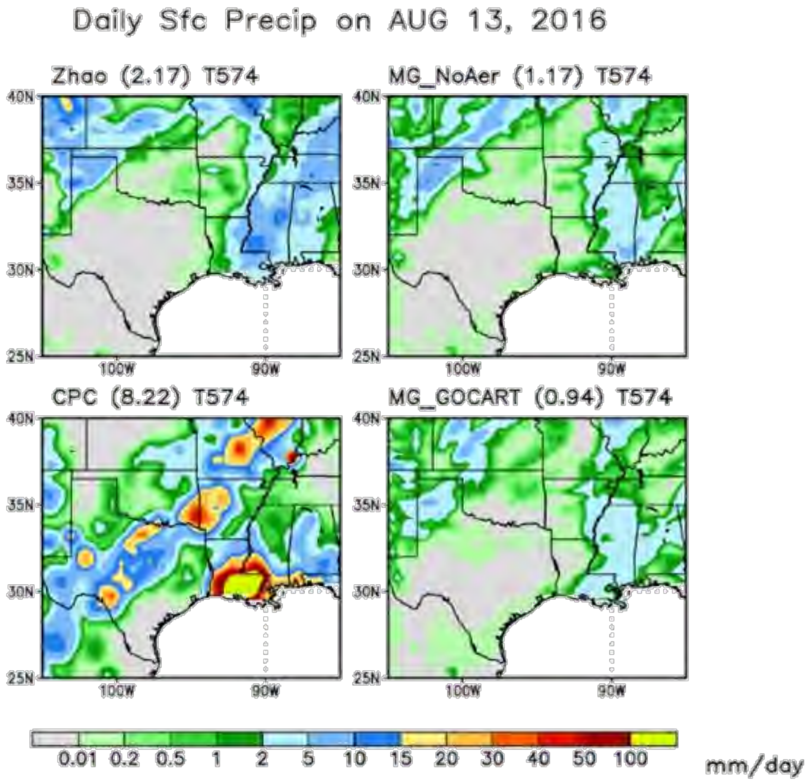
- MODIS: Aqua and Terra Dark Target Deep Blue combined
- CERES: SYN1deg MODIS-derived and 3-hourly geostationary satellite cloud properties
- PATMOSx: AVHRR-derived daily cloud fraction (CALVR-x algorithm)
- MERRA2: cloud properties from GMAO reanalysis

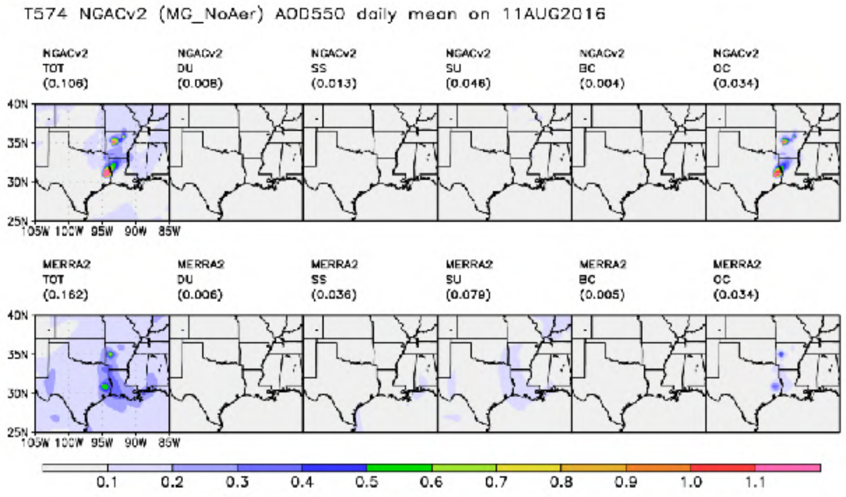
Cloud water content and cloud optical depth

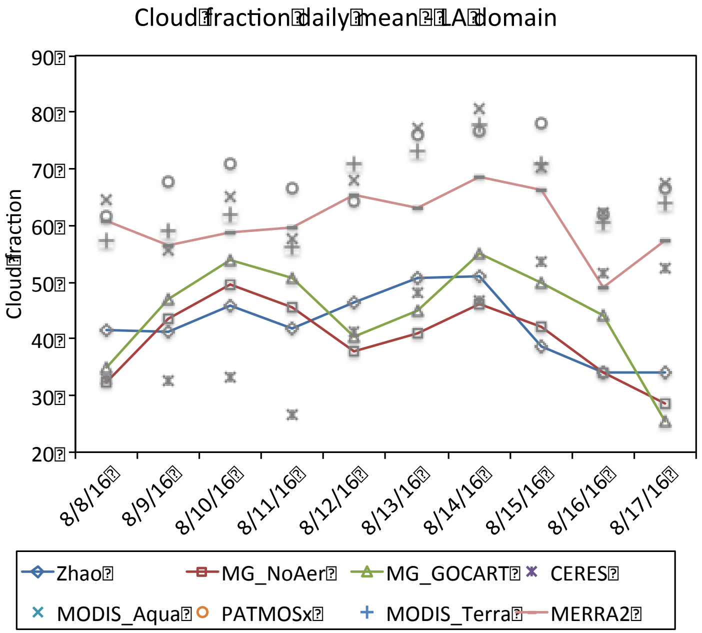




Regional Impact: Louisiana flooding event



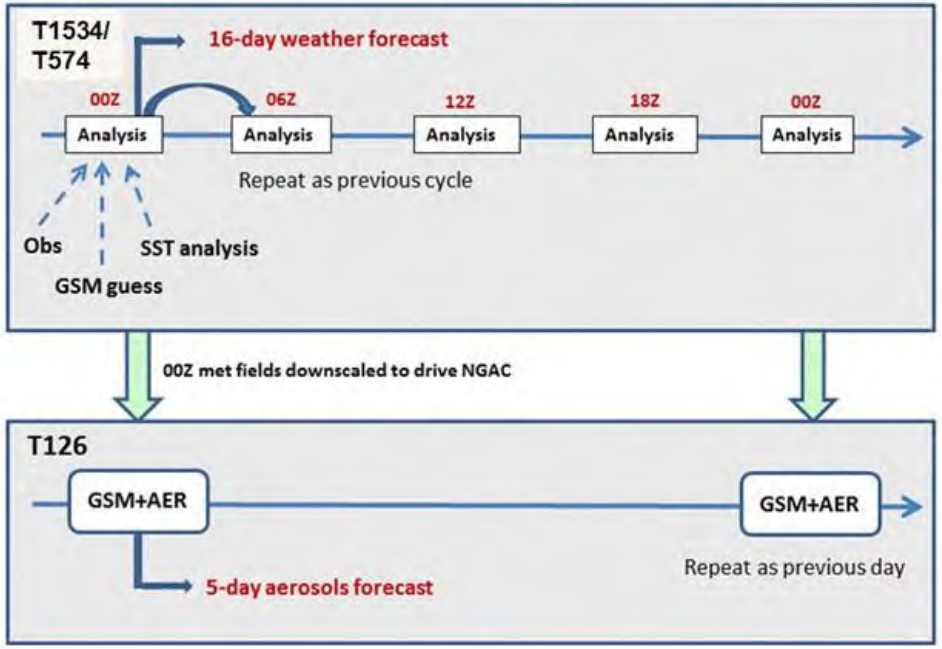




Despite the improvement in cloud properties by adopting the MG scheme, the impact of physics upgrade on precipitation is insignificant for this case.

Dual resolution weather-aerosol system at NCEP

Operational: One-way coupling



GFS for weather

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RTG_SST#: No aerosol correction

Data Assimilation

NGAC* for aerosols

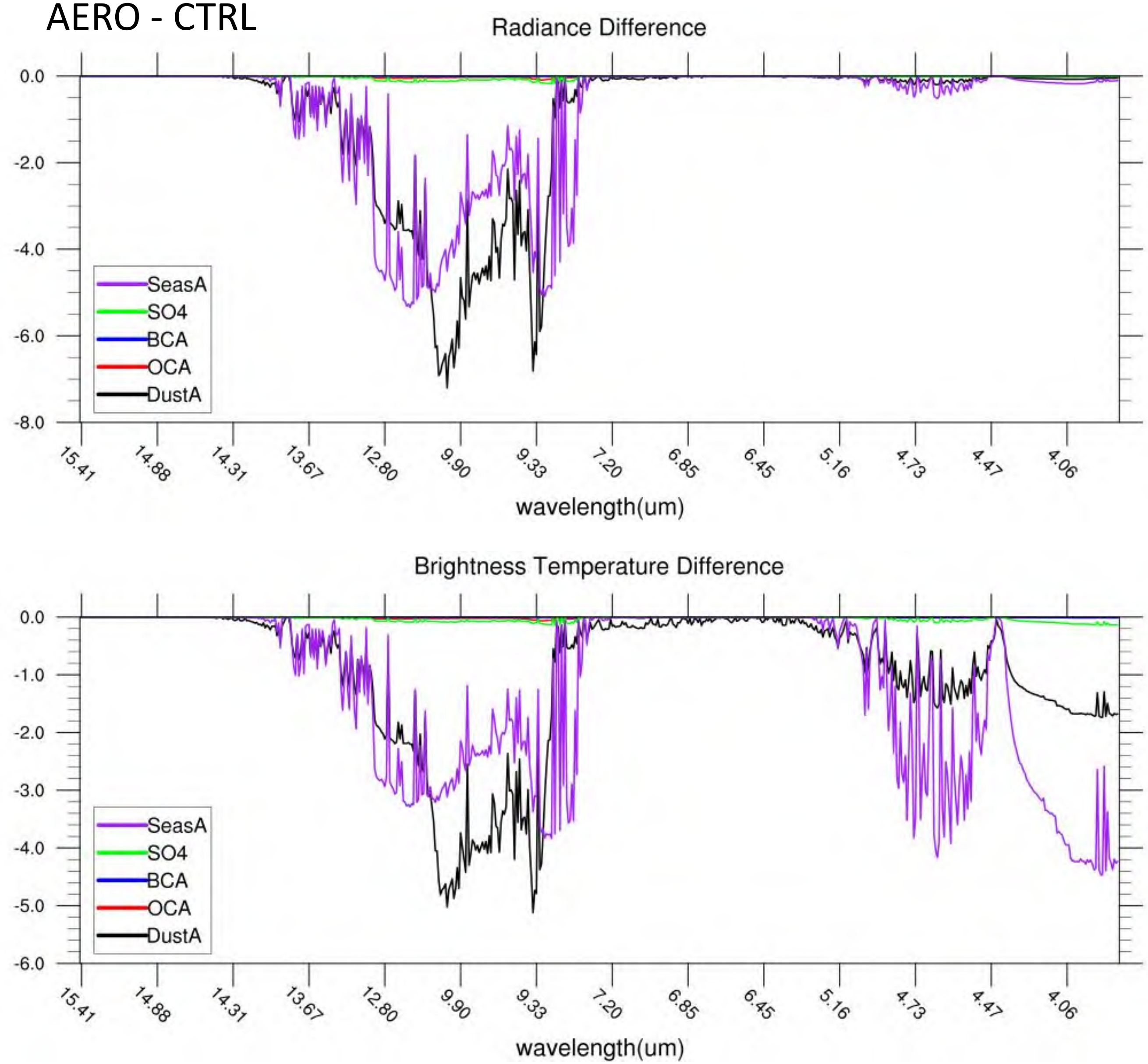
Initial conditions:

ATM: downscaled from GDAS

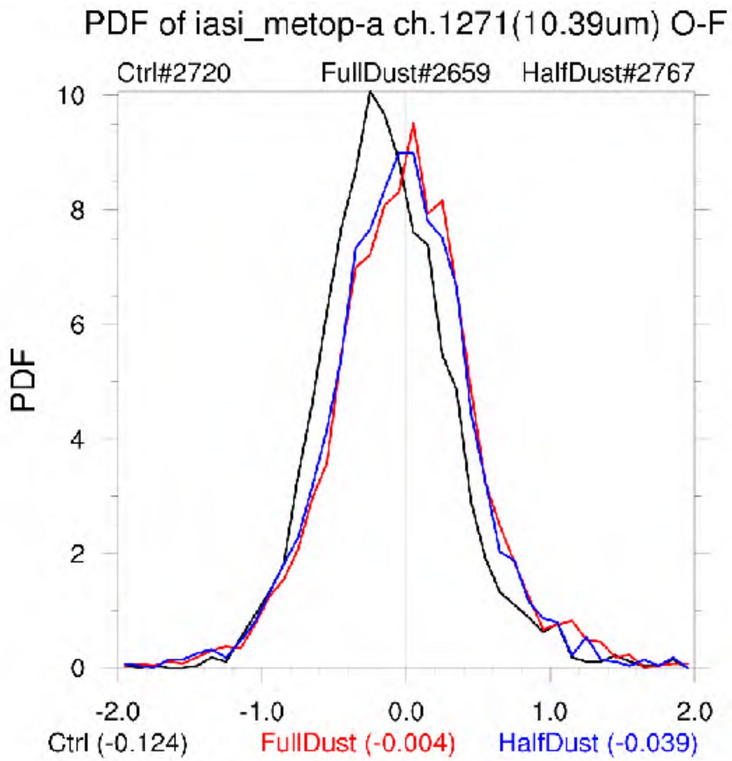
AER: cycled from NGA runs

Stand-alone CRTM experiments (IASI/Metop-a)

AERO - CTRL



Dust and sea salt aerosols have considerable impact on radiance and BT at the window channels. Taking aerosols into account in the BT calculation reduces biases in OMF.

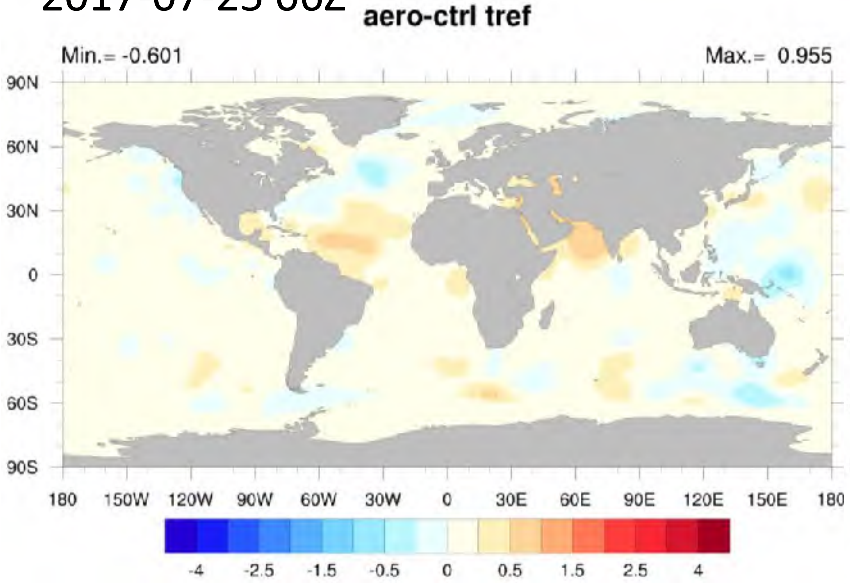


Fully cycled GDAS experiments

Aerosol-affected radiances is enabled in the GDAS analysis step.
Cooling effect obtained with aerosol-affected BT leads to warmer analyzed surface temperature

Foundation temperature differences (Aer – Ctl)

2017-07-25 06Z



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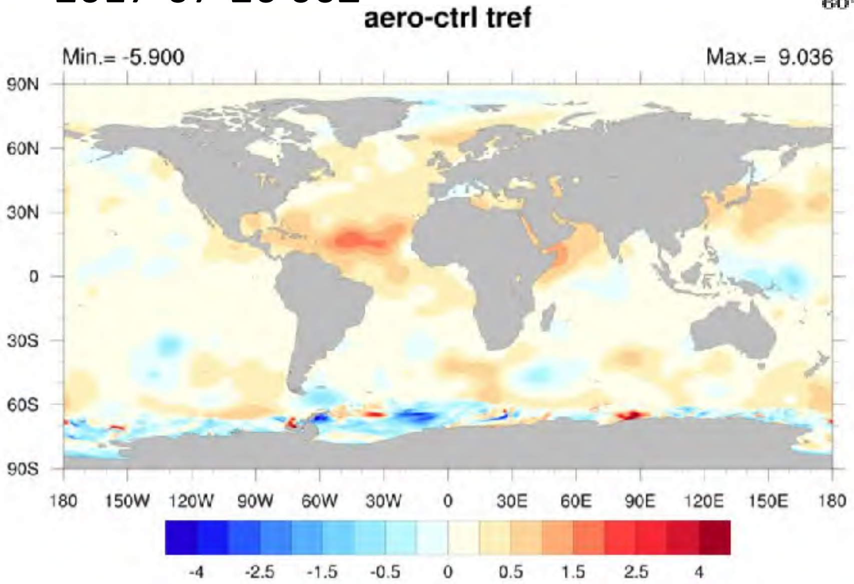


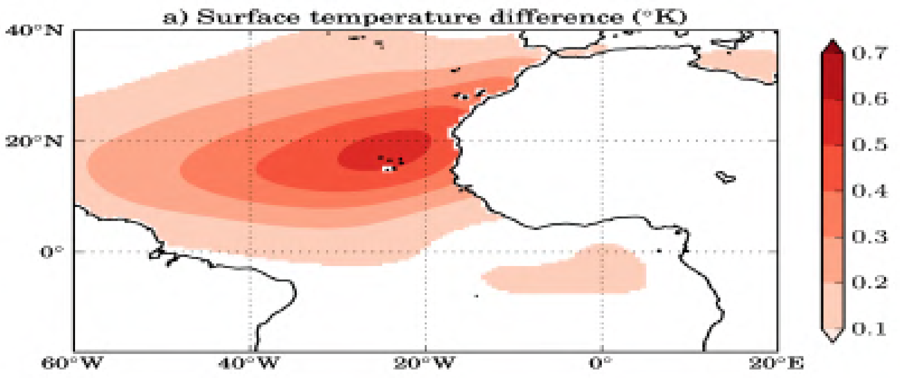
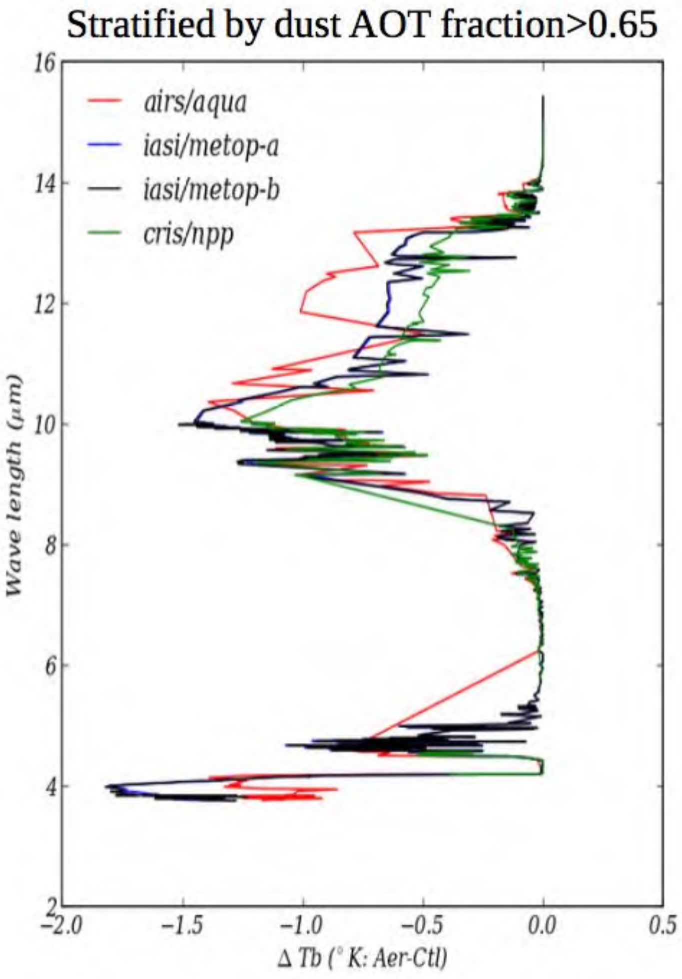


Figure 17a from Kim et al (2018) Monthly mean analysis temp difference (AER-CTR) during Aug 2017



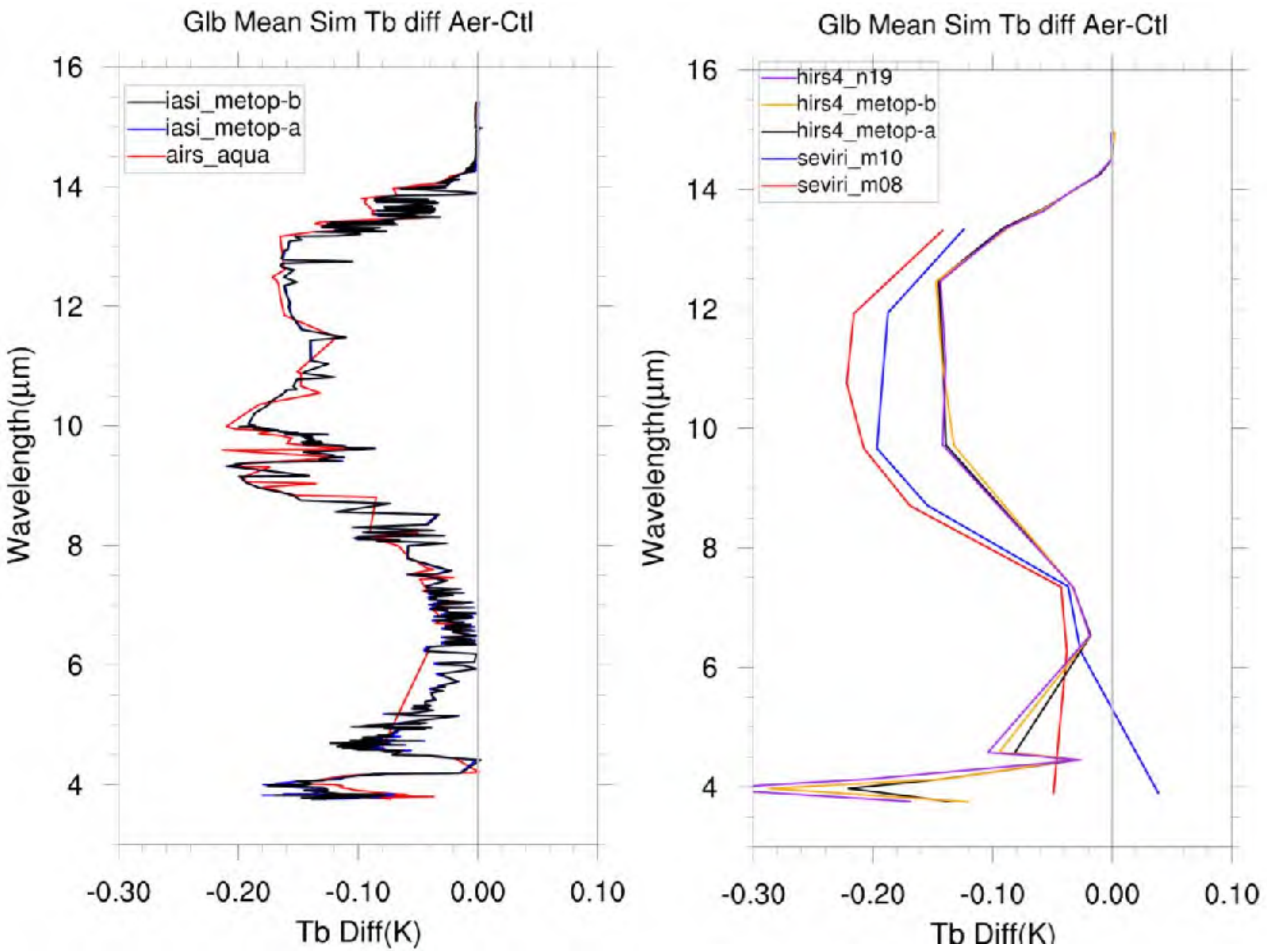
Jong Kim, poster at JCSDA workshop, 2017

Kim et al (2018).: Preliminary evaluation of influence of aerosols on the simulation of brightness temperature in the NASA's Goddard Earth Observing System Atmospheric. NASA/TM-2018-104606/Vol. 49

The control experiment (CTL) runs the default GSI configuration, for which GSI is aerosol-blind. This fully cycled experiment is used as a baseline for comparison as well as for storage of meteorology and aerosol background fields that are used in an offline set of GSI analysis experiments. In these offline experiments, referred to as AER, GOCART aerosols are made available to the observation operator and are used in the calculation of BTs through CRTM. In this framework, where the AER offline analyses do not feed back to the cycling ADAS, it can be safely assumed that differences between the AER analyses and the CTL analyses are solely due to the CRTM aerosol-related calculations.

Spectrum difference of Tb

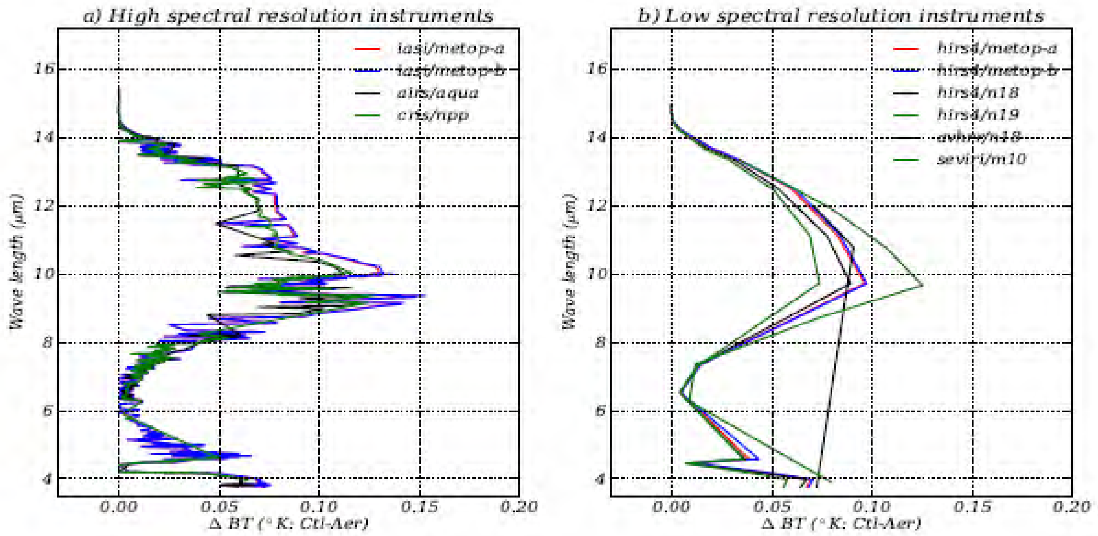
Average from 20170728 00z to 20170827 18z, over dust dominated areas (dust AOD fraction > 0.65 and total AOD > 0.3)



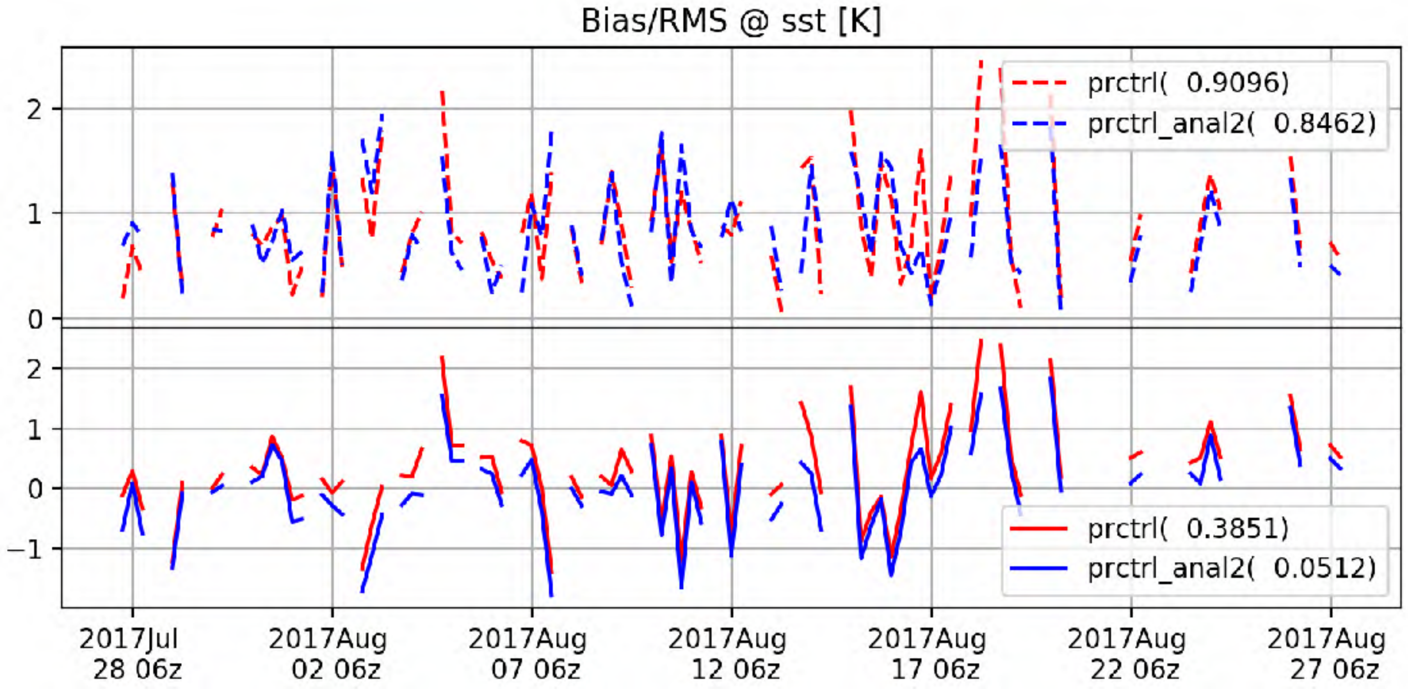
Following Kim's experiment, e.g., fully cycle control run provides the aer/met to off-line aerosol-aware run.

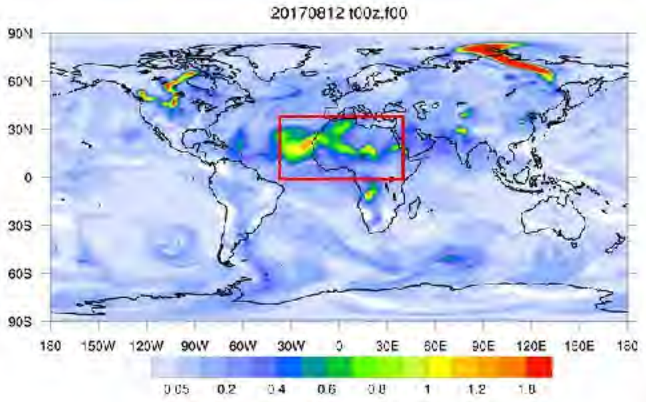
Avg ove Aug 2016

Figure 3 from Kim et al (2018)



Bias/RMS Timeseries (SST)





*Red: Control, Blue: Aerosol, Upper: RMS, lower: Bias

SST Bias and RMS, averaged over the period, are reduced in the aerosol-aware experiment

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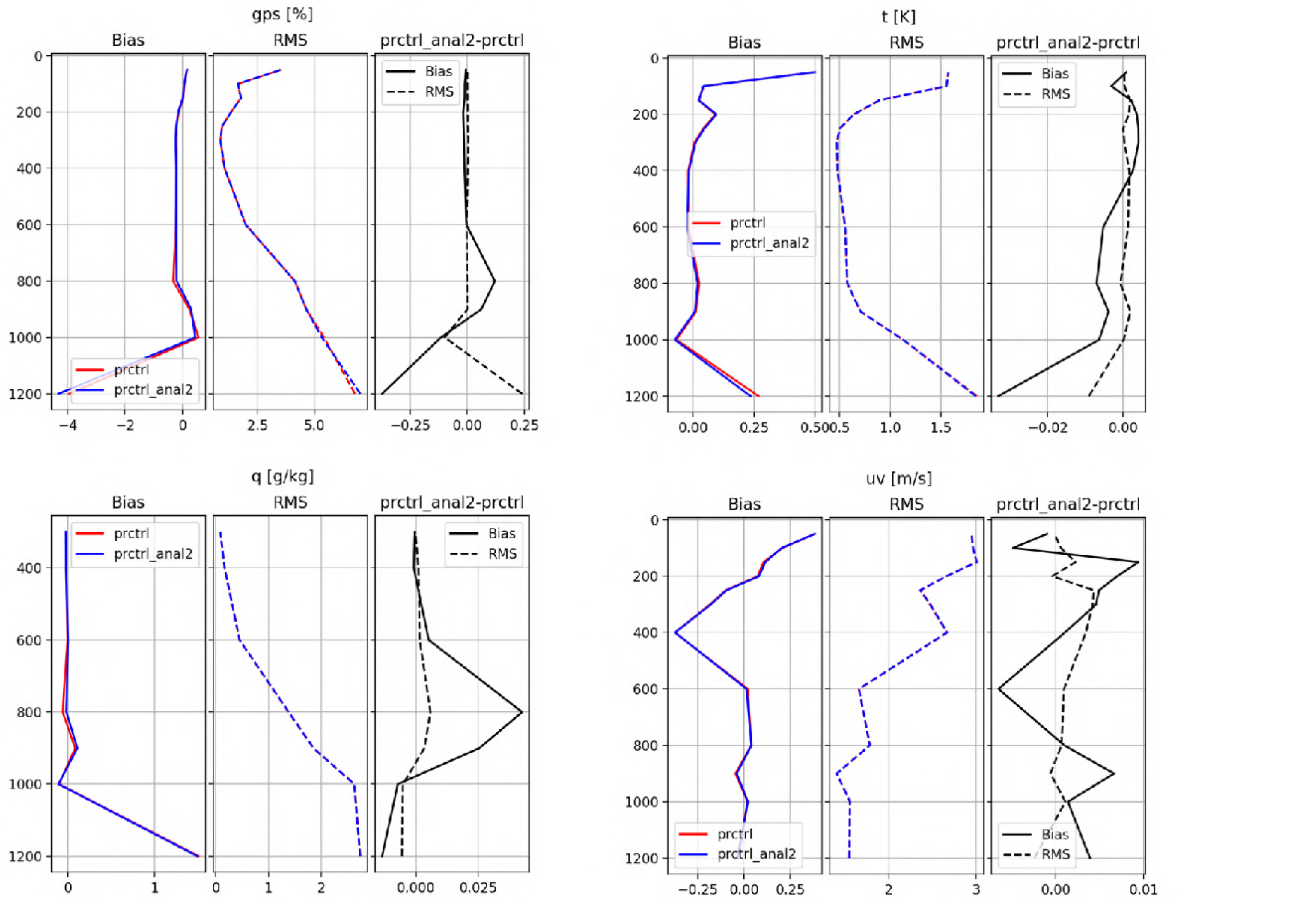
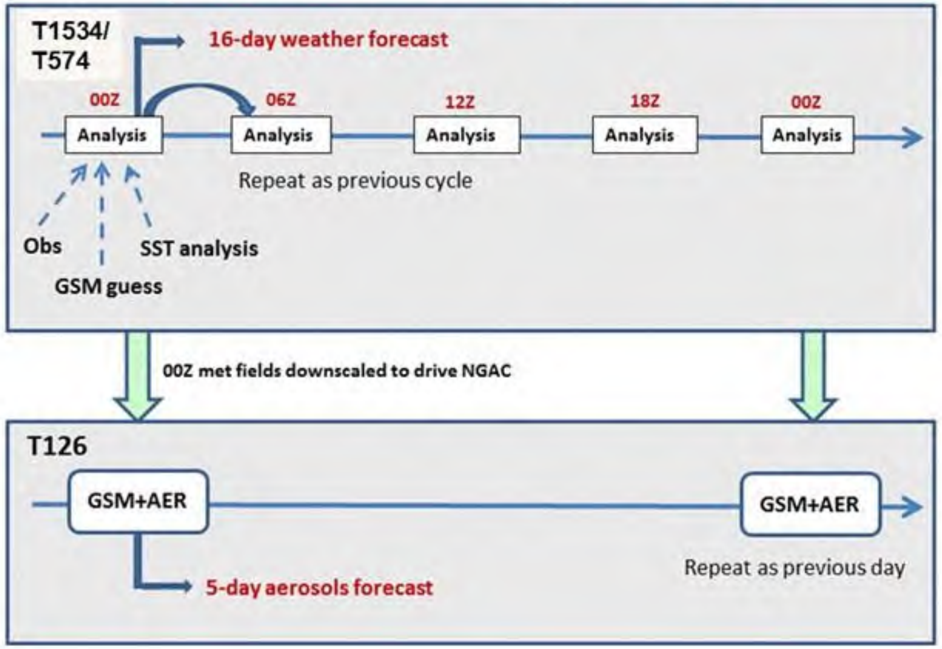
Bias/RMS for GPS, T, Q, Wind



Dual resolution weather-aerosol system at NCEP

Operational: One-way coupling



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NGAC* for aerosols

Prognostic aerosols

Initial conditions:
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AER: cycled from NGA runs

What is Chemical Weather

Local, regional, and global distributions of important trace gases and aerosols, and their variability on time scales of minutes to hours to days, particularly in light of their various impacts, such as human health, ecosystems, the meteorological weather and climate.

Lawrence et al. *Environ. Chem.*, 2, 6-8, 2005

Short-term (less than two weeks) variability of the atmospheric chemical composition.

Kukkonen et al., *ACP*, 12, 1-87, 2012

Aerosol processes in AGCMs

- Bulk mass model. Mass-based aerosol models are used in 1st generation climate models.
- Modal aerosol model. Being added to new generation of climate models due to established recognition that model need to represent evolution of size distribution.
- Process-based sectional model. With high complexity (100+ tracers), it is not affordable in in-line mode. Future (3rd generation) GCMs.

NASA/GSFC GOCART Module

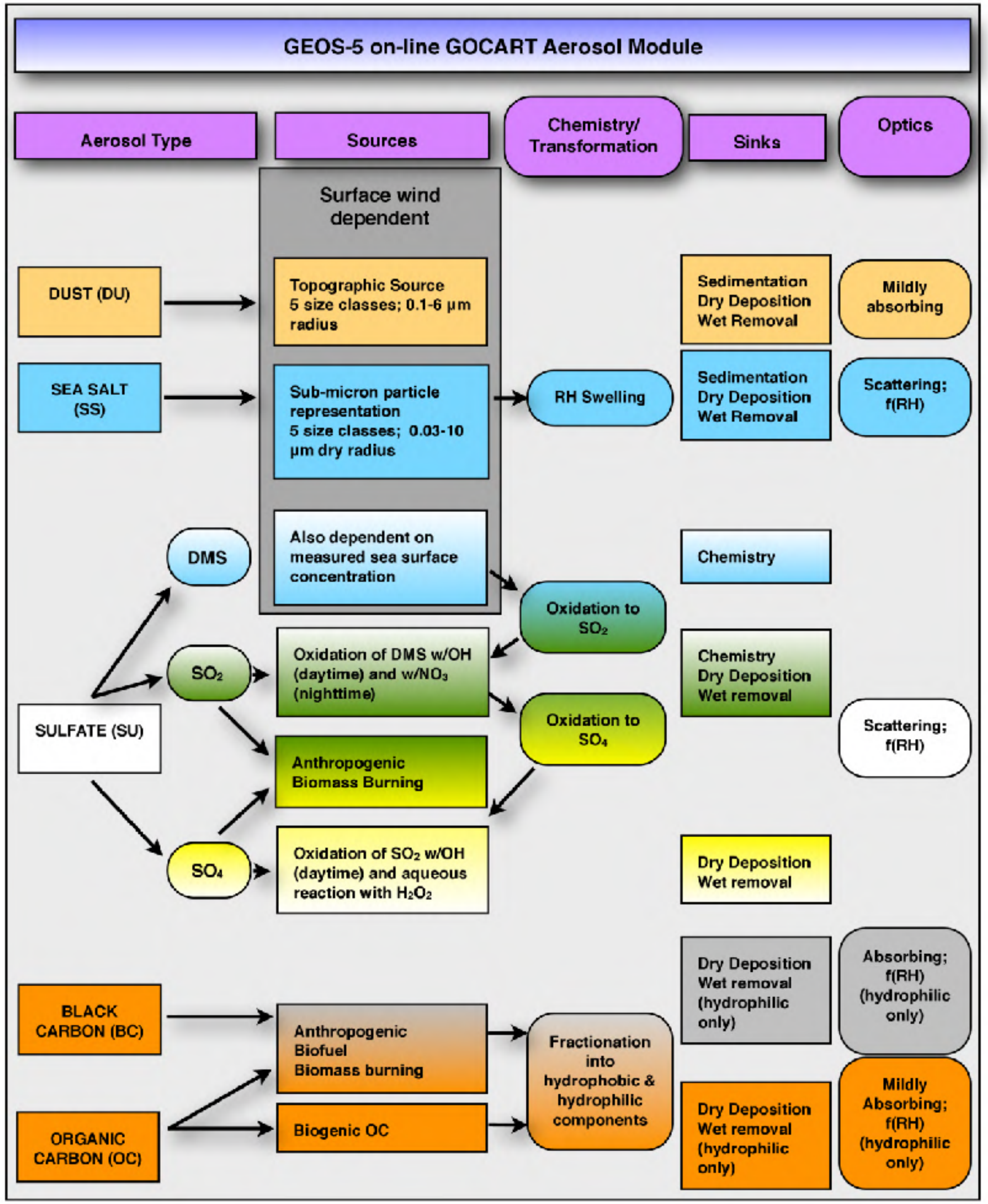
In-line chemistry advantage

- Consistency: no spatial-temporal interpolation and same physics parameterization
- Efficiency: lower overall CPU costs and easier data management
- Interaction: Allows for feedback to meteorology

Used operationally at GMAO for field campaign support, near-real-time global aerosol forecast (GEOS-5) and aerosol reanalysis (MERRAero and MERRA2)

Implemented into NCEP's NEMS GSM for global aerosol forecasts since 2012.

NCEP's unified modeling: Efforts under way at ESRL & NCEP to develop/implement GOCART coupled FV3-GFS

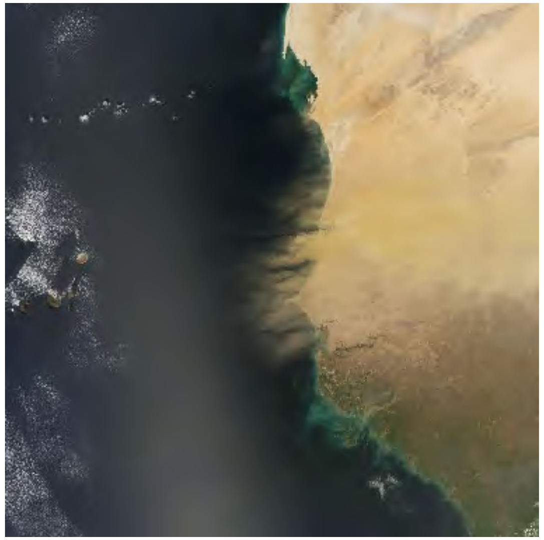


Using satellite data to improve aerosol forecasting

Satellite observations have been used to improve aerosol products

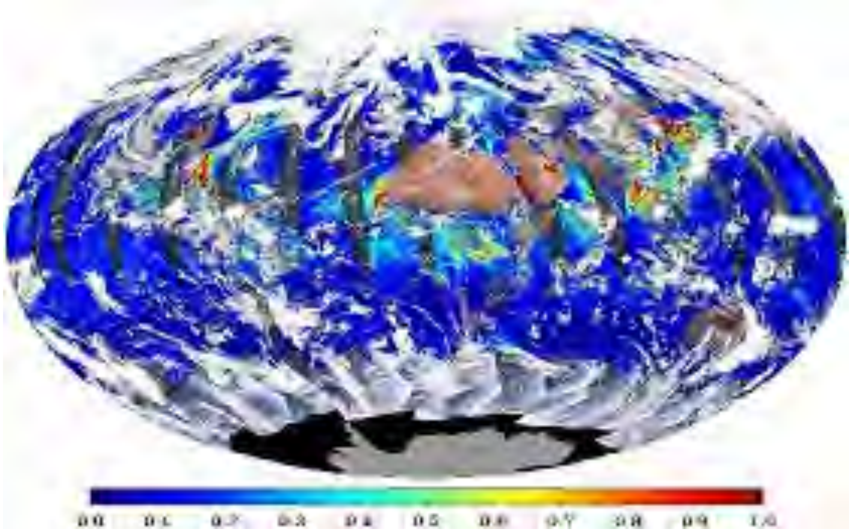
- Routine monitoring of model performance
- Near-real-time biomass burning emissions from satellite observations
- Data assimilation of satellite aerosol observations

Dust off Africa, observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA’s Aqua satellite



https://earthobservatory.nasa.gov

Aerosol optical depth (AOD) from Visible Infrared Imaging Radiometer Suite (VIIRS) sensor onboard the Suomi National Polar Orbiting (SNPP) satellite

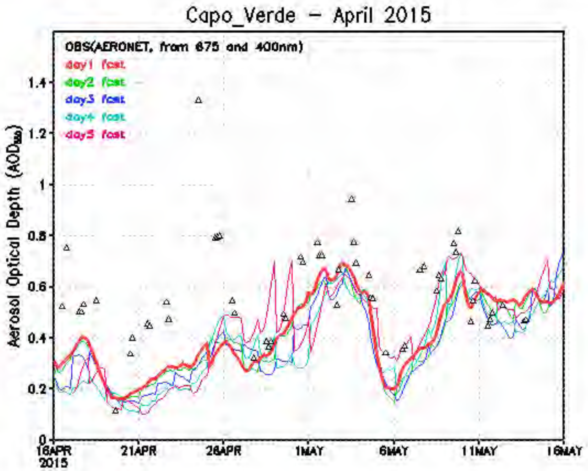


https://www.star.nesdis.noaa.gov

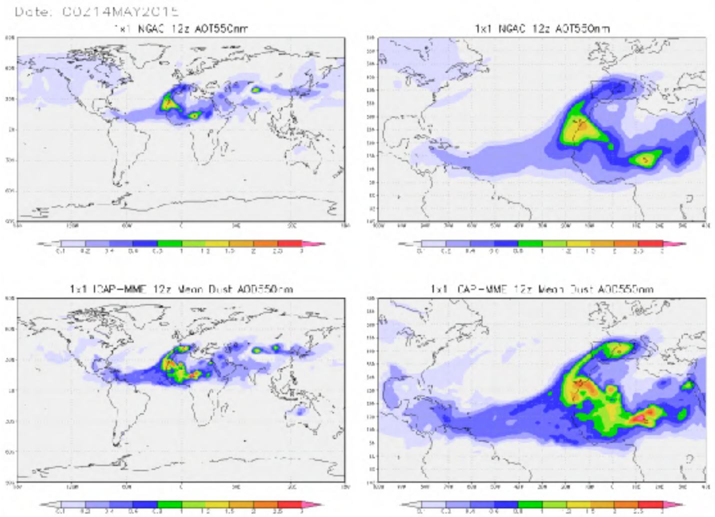
NGACv1 evaluation and verification

Daily verification:

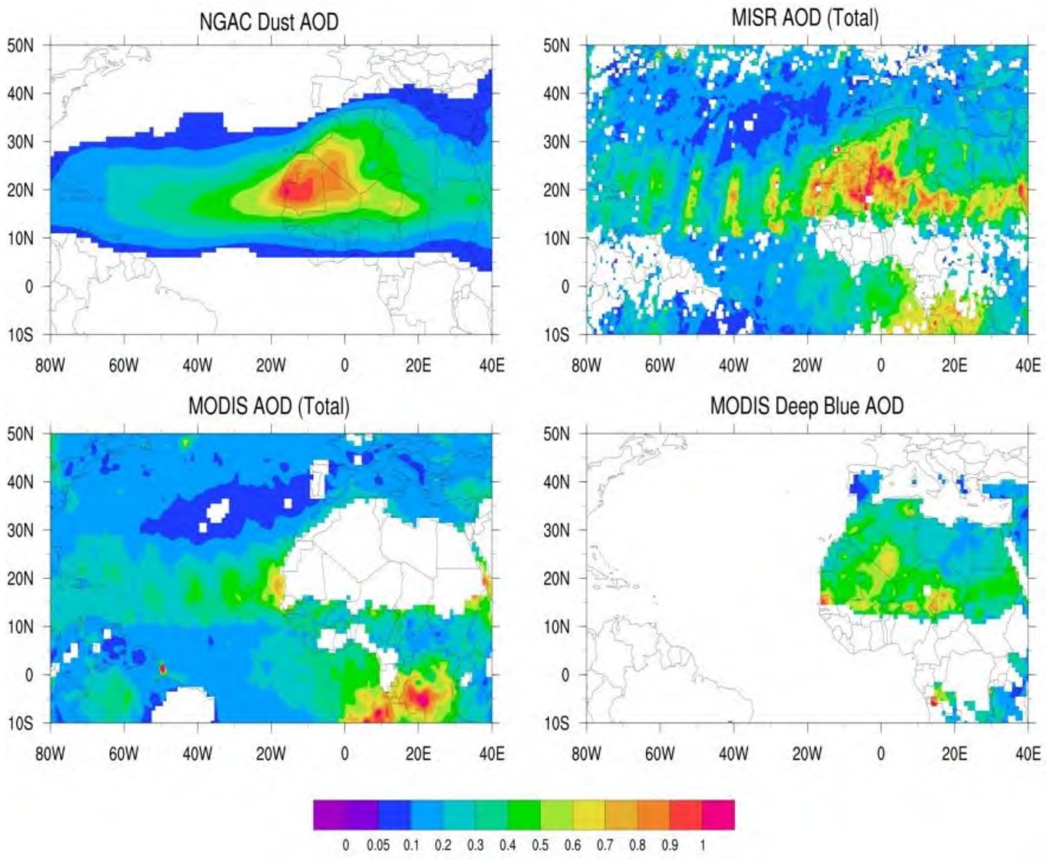
NGAC vs AERONET



NGAC vs ICAP-MME



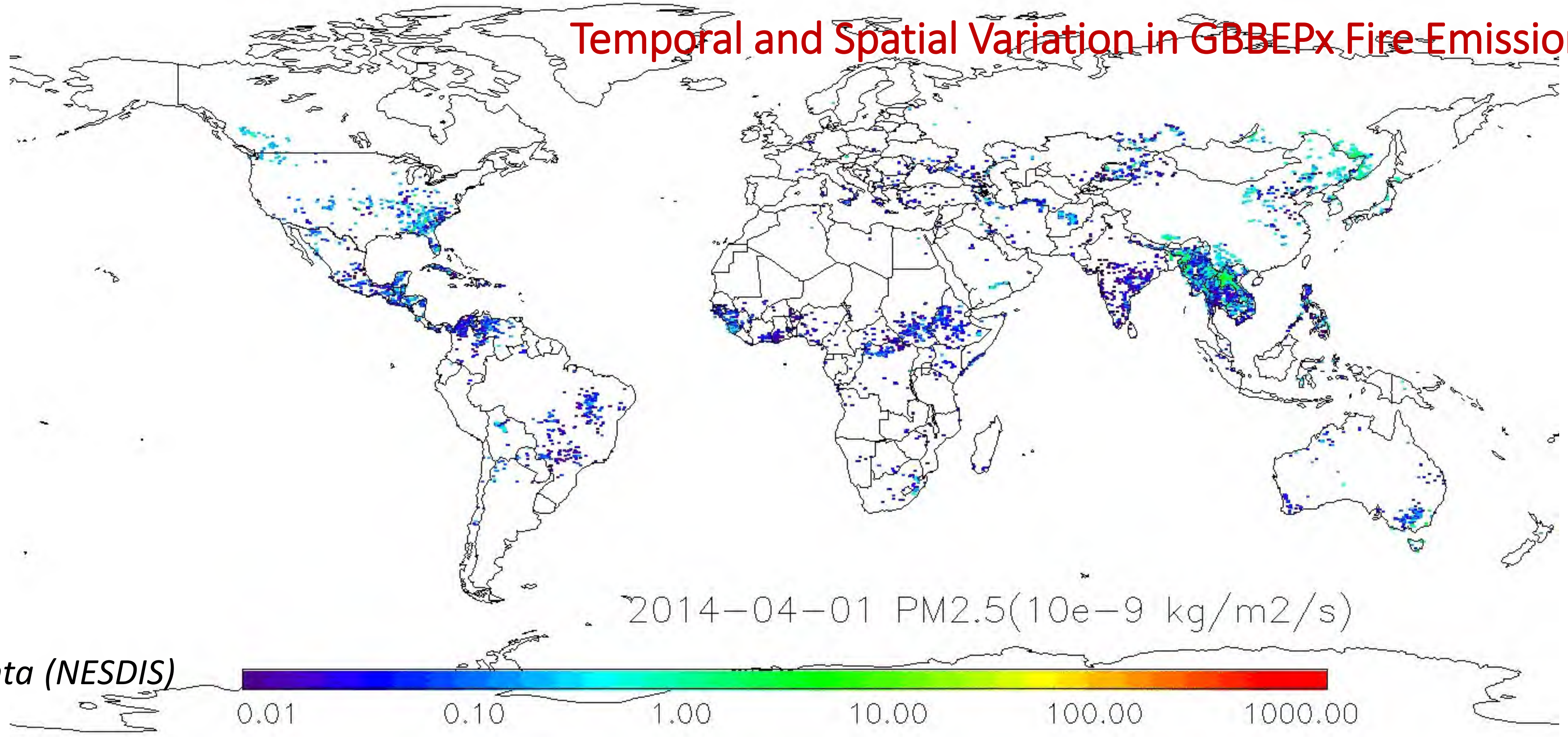
Monthly comparison between NGAC and satellites



Near-real-time fire emissions from satellites

NRL:	FLAMBE (Fire Locating and Modeling of Burning Emissions), fire counts from MODIS/GOES
ECMWF:	GFAS (Global Fire Assimilation System), FRP from MODIS
GMAO:	GFED2 (Quick Fire Emission Dataset Version 2), FRP from MODIS
NCEP:	GBBEPx (Blended Global Biomass Burning Emissions Product – eXtended), FRP from MODIS and multiple geostationary satellites

Temporal and Spatial Variation in GBBEPx Fire Emissions



Shobha Kondragunta (NESDIS)

Assimilating satellite aerosol retrievals

With GSI, NCAR and ESRL assimilates MODIS AOD using WRF-CHEM as first guess.
The GSI option is extended to assimilate VIIRS AOD using NGAC as first guess.

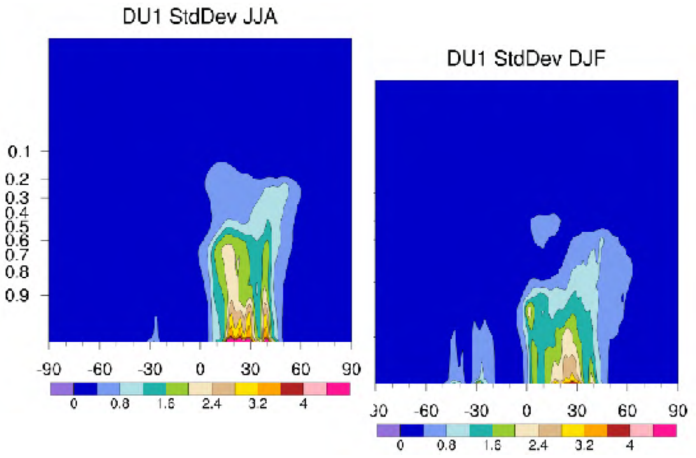
AOD DA (GSI)

Observation operator: CRTM v2.2.3

Background Errors

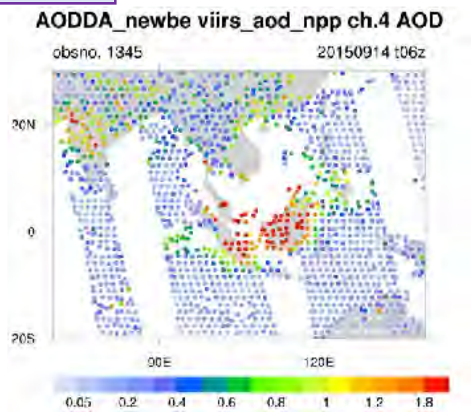
First guess (NGACv2)

Observation Inputs (VIIRS AOD)



NMC method is used to determine BE from 12-month NGAC runs

- First global in-line aerosol forecast system at NCEP
- Multi-species forecasts (dust, sulfate, sea salt, and carbonaceous aerosols) at T126 L64



- Data screening and thinning, considering offset from analysis time, distance from the grid, and retrieval quality
- Observation errors are determined from VIIRS versus AERONET comparisons

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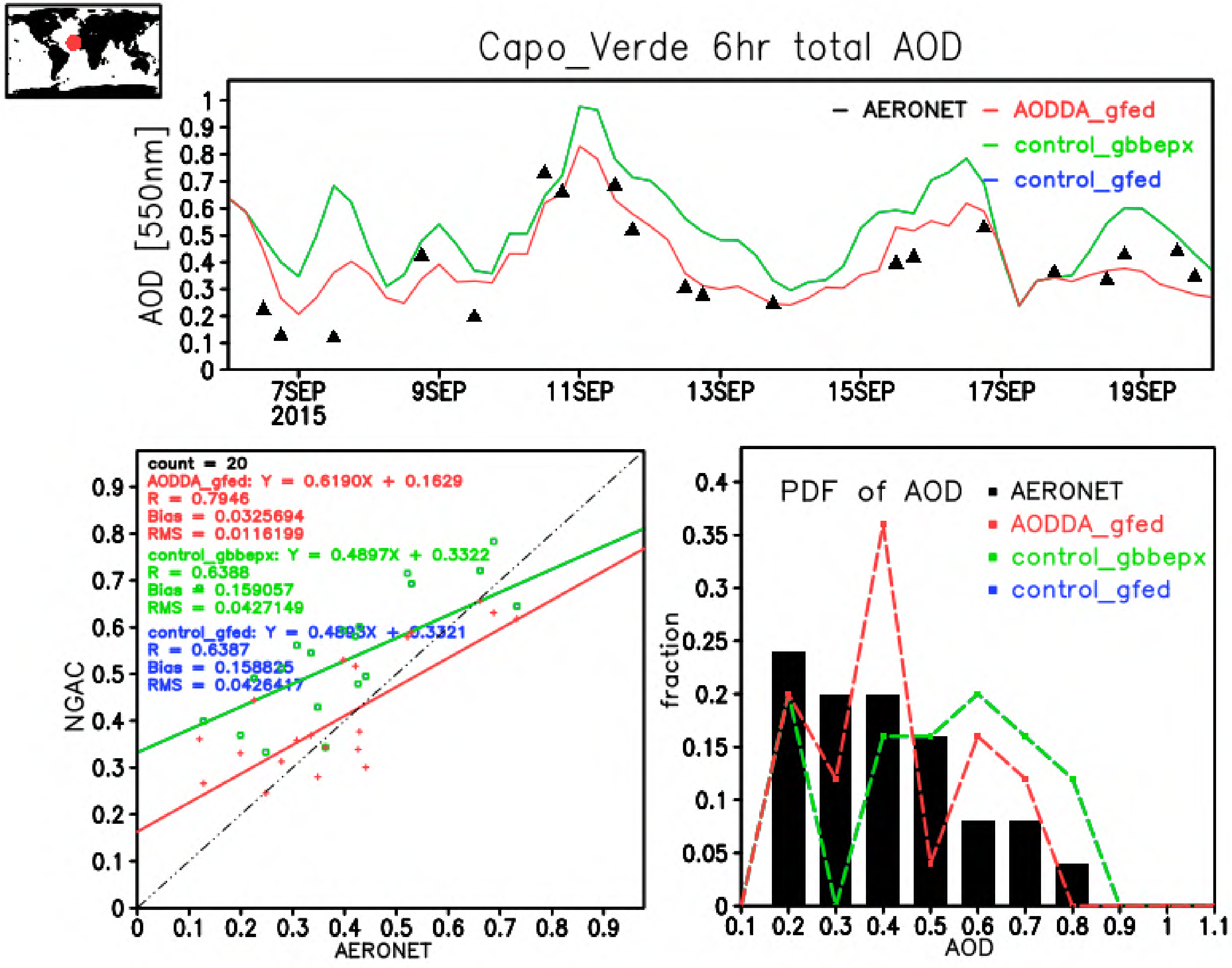
Central Weather Bureau, Taiwan, 28 Aug 2018

NGACv2 Experiments

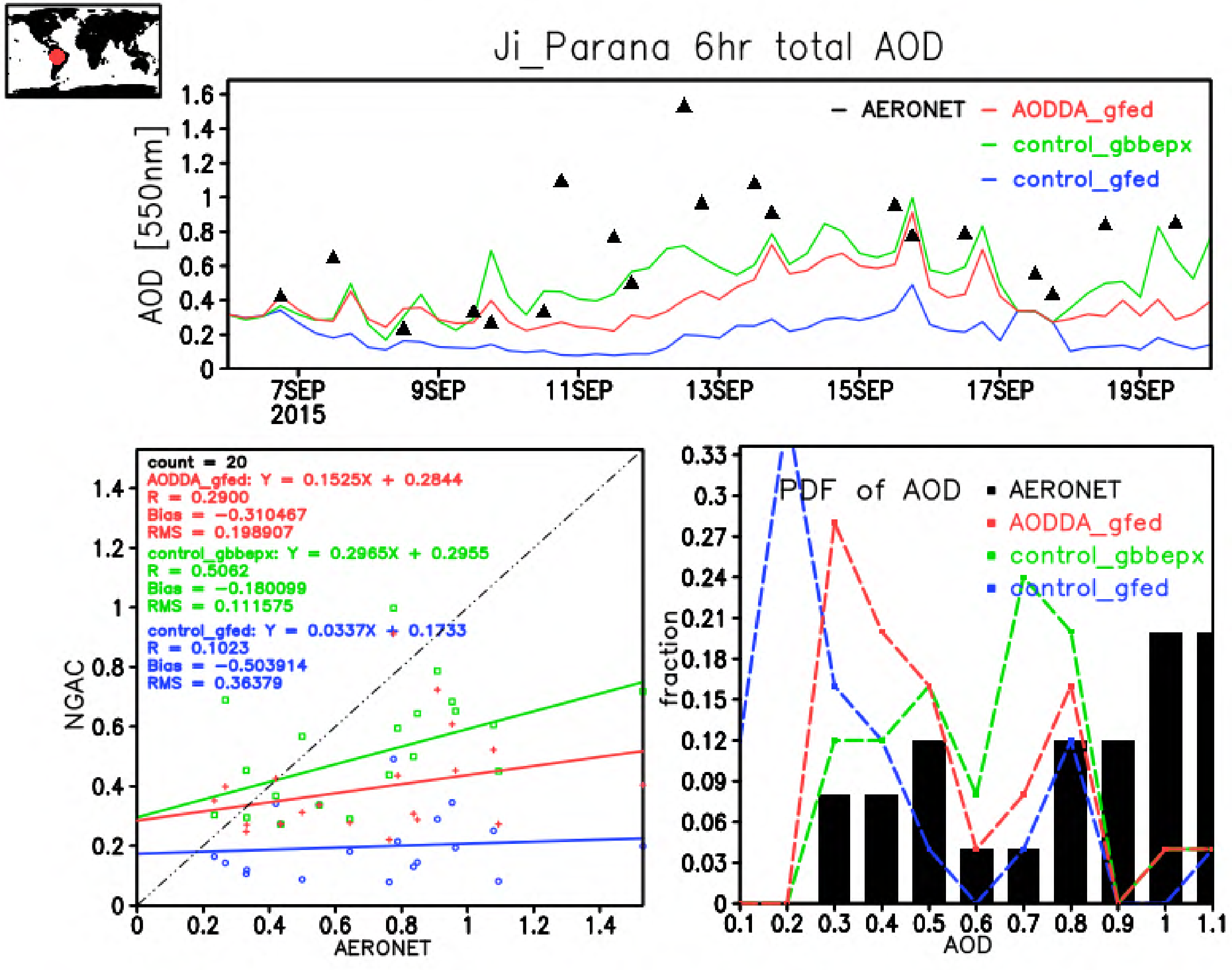
Objective: To investigate the effects of aerosol DA on improving aerosol forecasts as well as to assess the performance gain resulted from the use of satellite emission information.

- T126 L64 NGACv2 experiments are conducted using different configuration:
  - GBBEPx (NRT smoke emissions), the operational NGACv2 configuration
  - GFED (climatological smoke emissions)
  - GFED + VIIRS AOD DA
- The experiments cover Sept 6-20, 2015
- The initial condition are taken from EMC's NGACv2 parallel run



GFED vs GFED+DA: the inclusion of VIIRS obs
GFED vs GBBEPx: the use of NRT smoke emissions

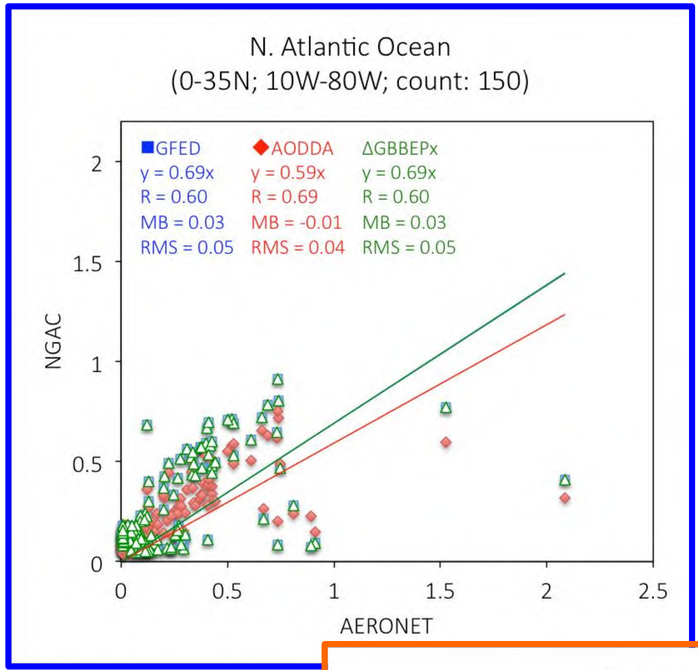
Positive impact from assimilating AOD. With the assimilation of VIIRS aerosol retrievals, NGACv2 AOD agree well with AERONET AOD.

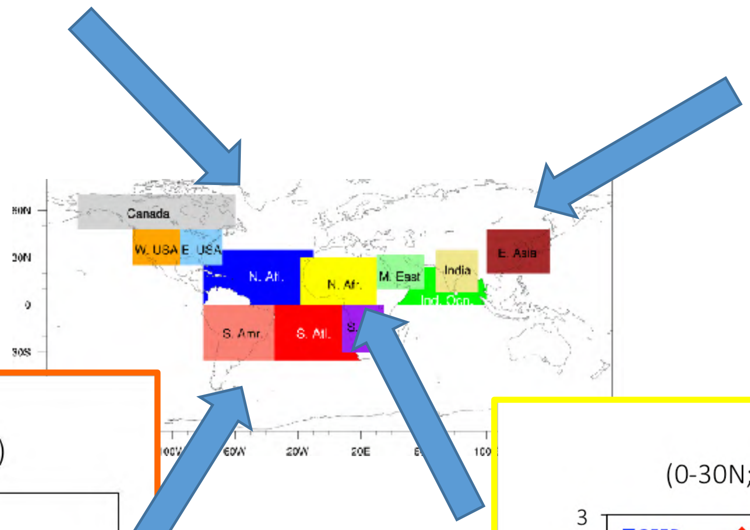


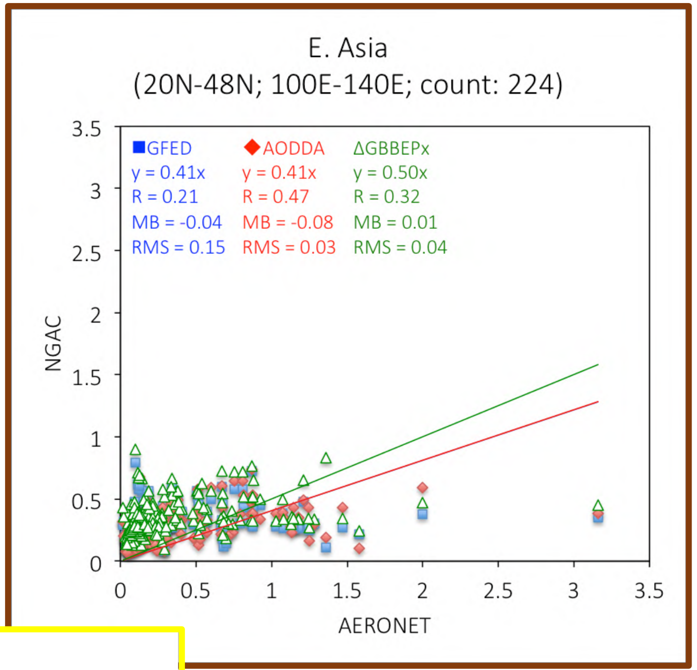
GFED vs **GFED+DA**: the inclusion of VIIRS obs
GFED vs **GBBEPx**: the use of NRT smoke emissions

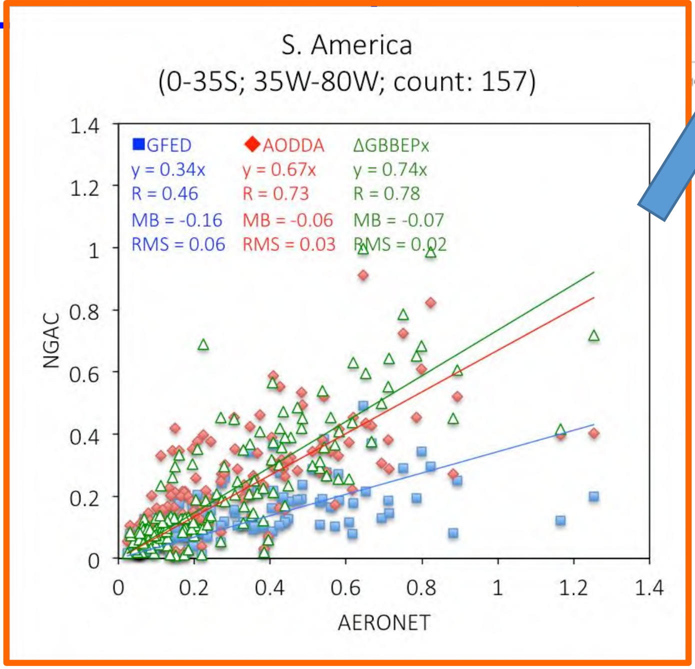
Positive impact from using NRT fire emissions.
For the areas affected by biomass burning, the use of NRT fire emissions reduces the errors in NGACv2 AOD.

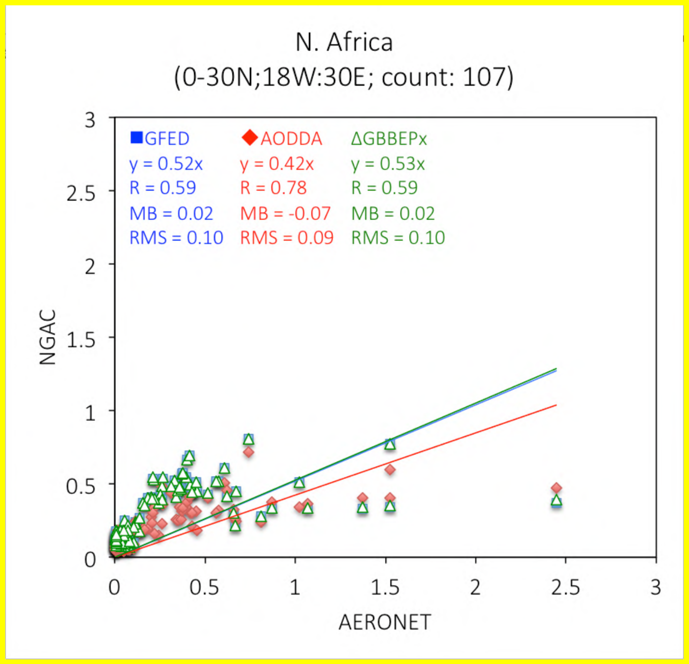
NGACv2 versus AERONET comparisons











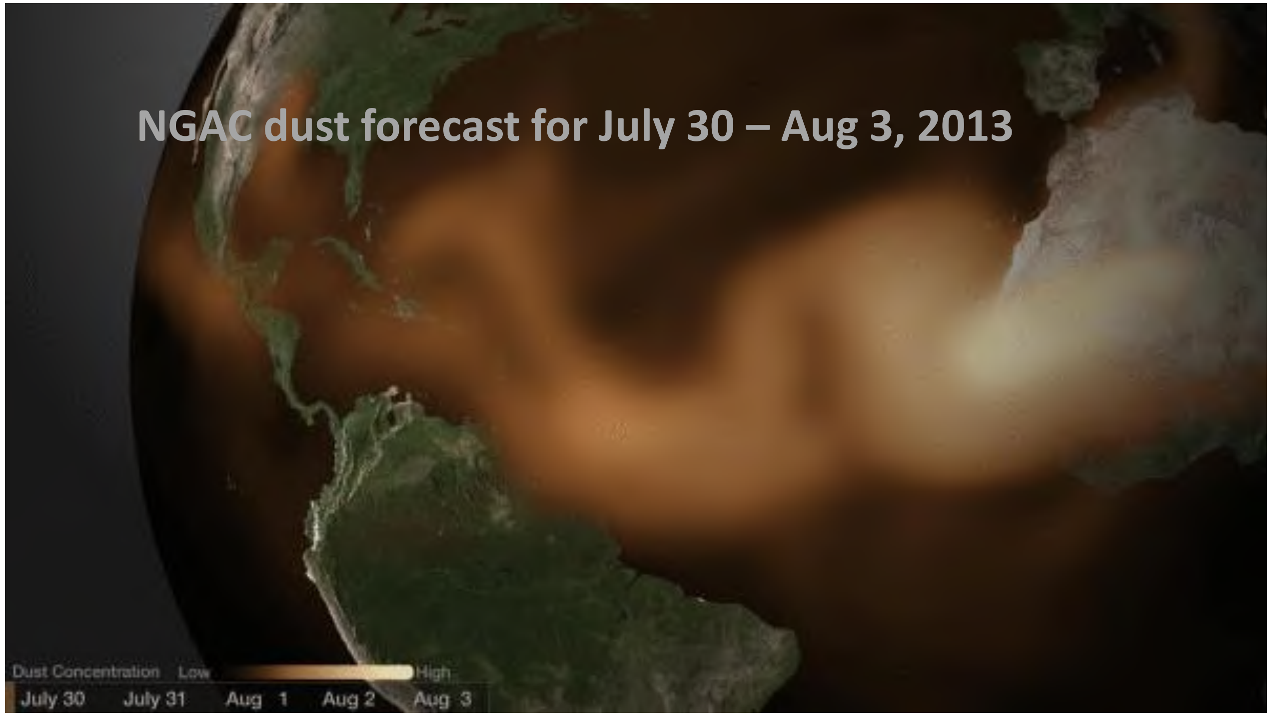
Long range aerosol transport

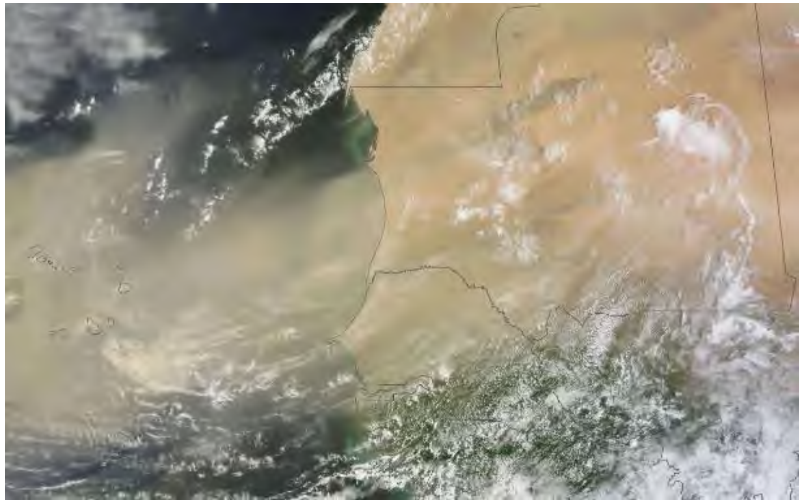
Trans-Atlantic Sahara dust

[Nightly News](#) | July 31, 2013

Massive dust storm sweeps over Atlantic

The Saharan Air Layer, a burst of dust, could possibly suppress this year's hurricane season. NBC's Brian Williams reports.

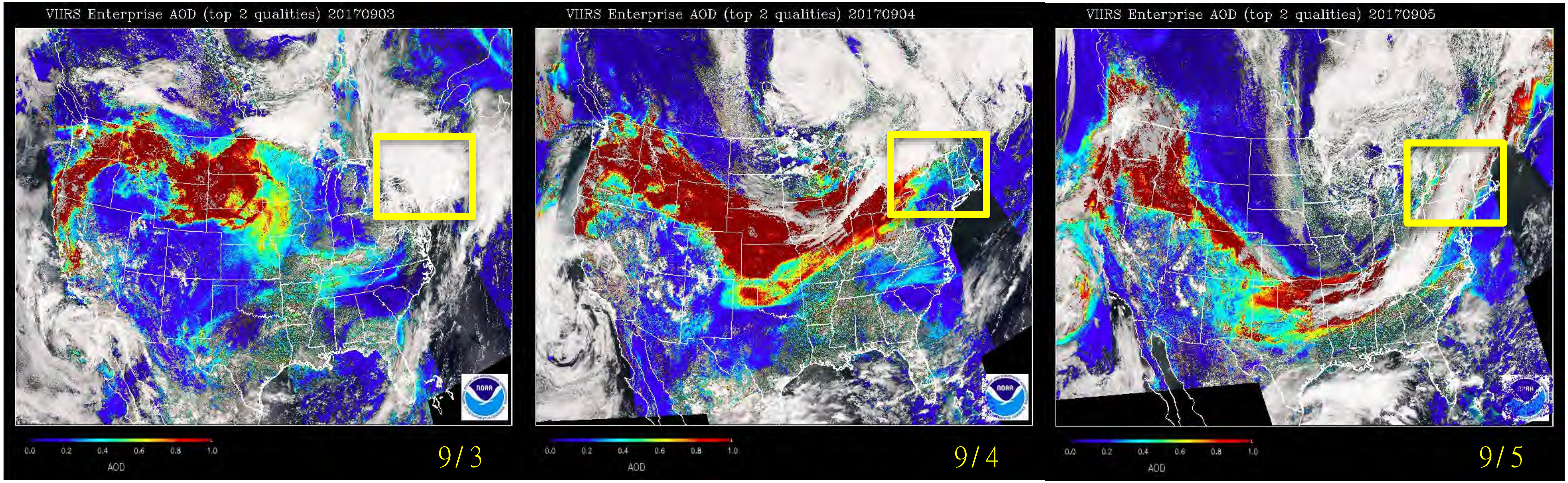




Saharan dust cloud captured by Aqua MODIS satellite on July 30, 2013 (LANCE Rapid Response. MODIS/Worldview)

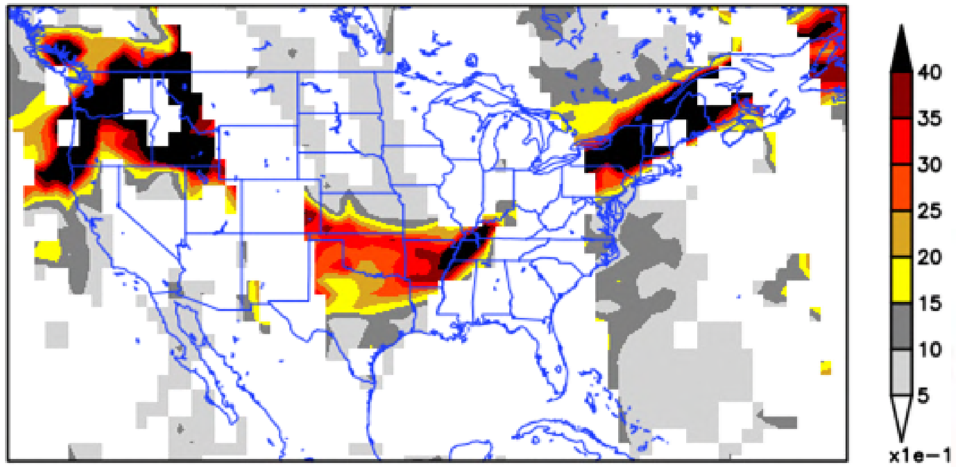
Long-range aerosol transport

VIIRS Aerosol Optical Depth (AOD) for 2017-09-03 to 2017-09-05



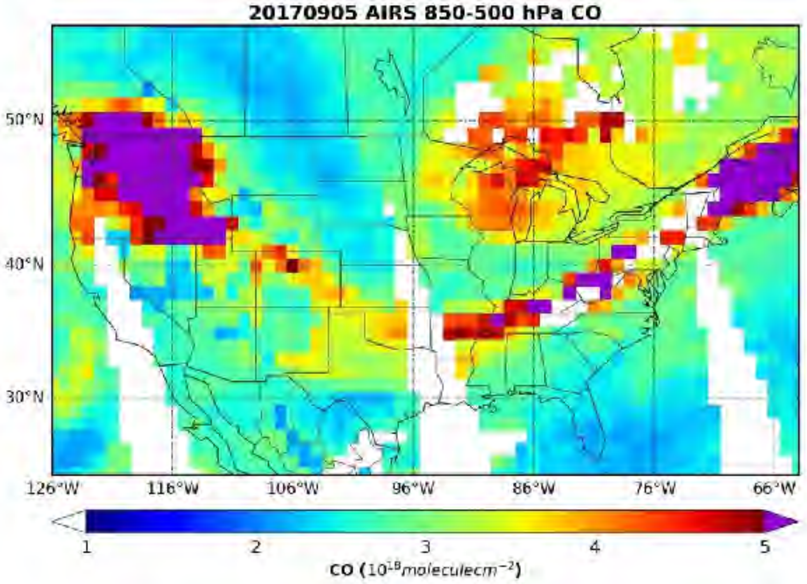
- While AOD is widely used in aerosol modeling community, it lacks sufficient information content in chemical composition and vertical structure
- AOD observations are used in conjunction with aerosol model/reanalysis, surface network, and other satellite retrievals

OMI UV Aerosol Index (2017-09-05)

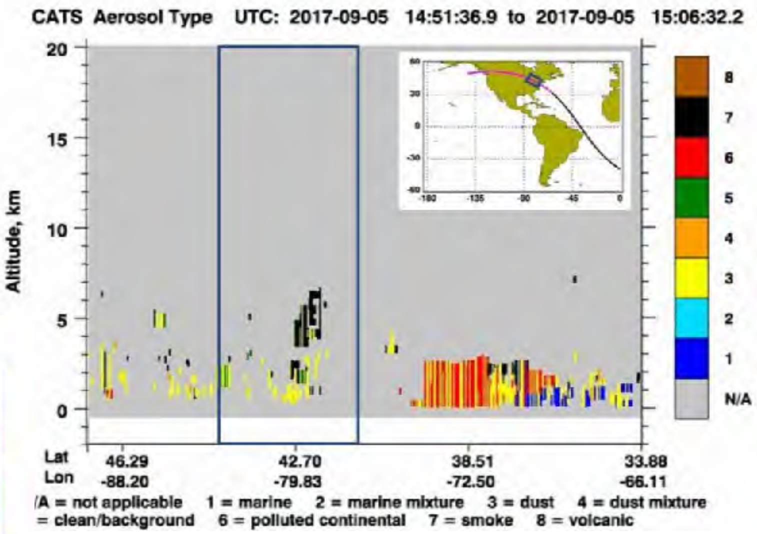


Ratio of measured backscattered UV radiation versus calculated Rayleigh scattering

AIRS CO (850-500 mb)

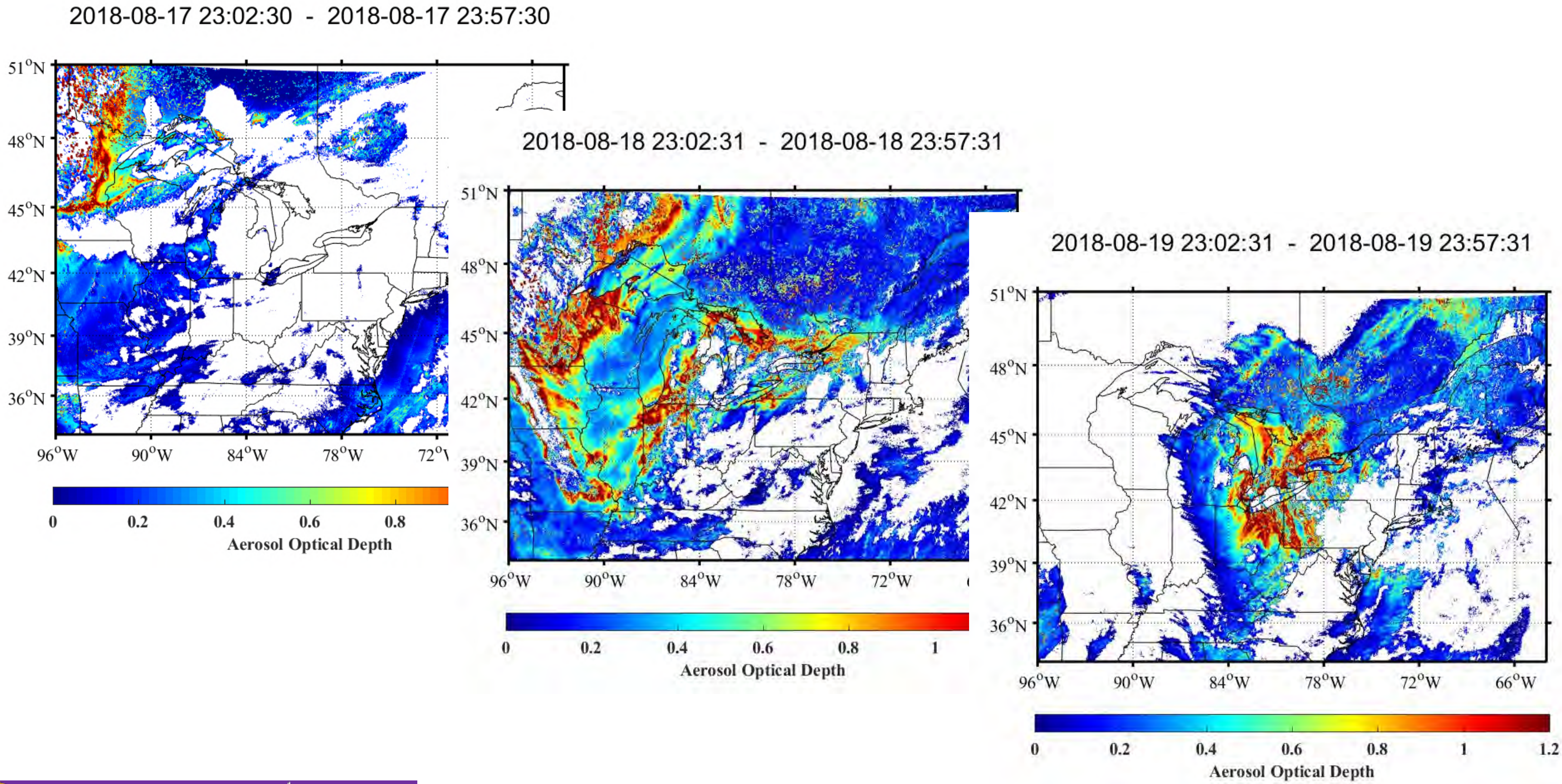


CATS aerosol subtype



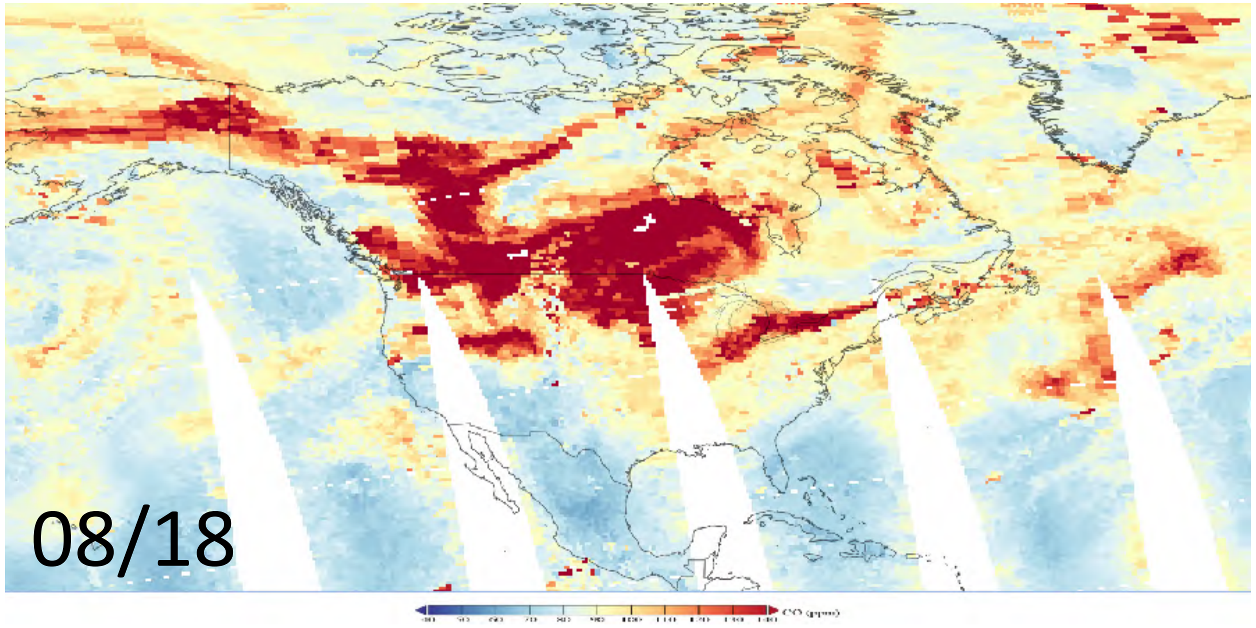
Space-borne aerosol lidar measuring backscatter

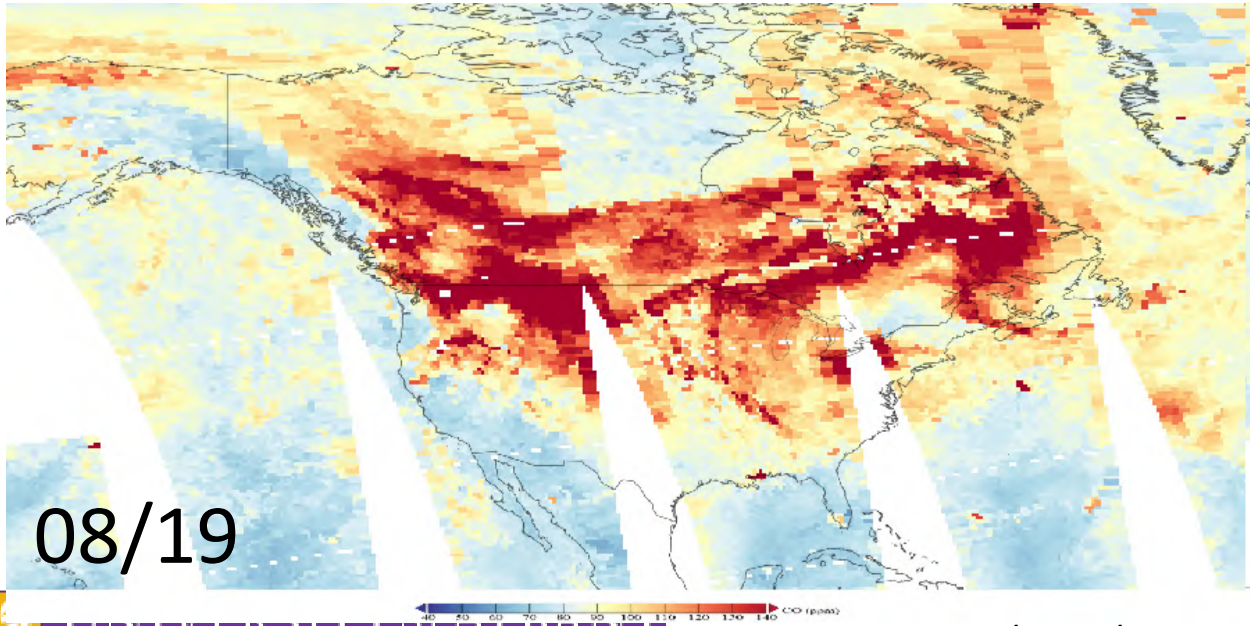
AOD from GEOS-16

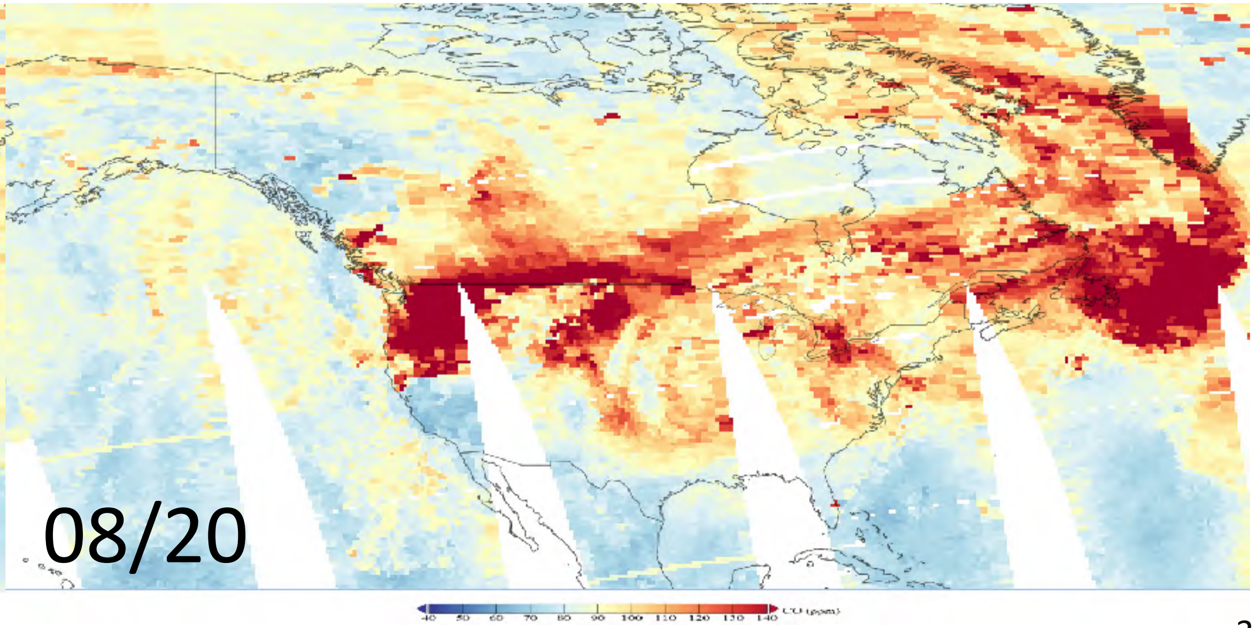


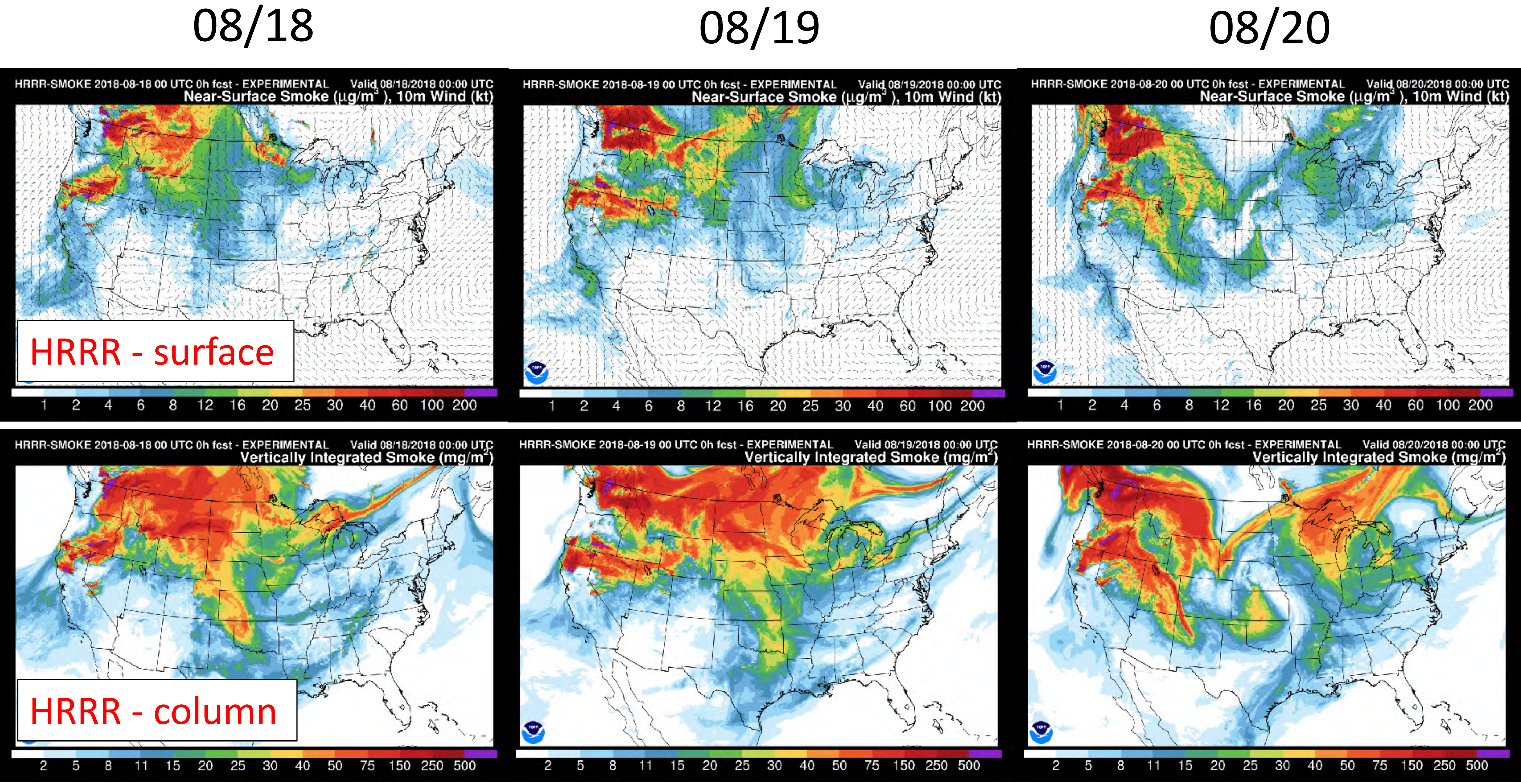
AIRS - Total column CO (ascending/daytime)

From AIRS Near Real-Time Data Portal:
https://disc1.gesdisc.eosdis.nasa.gov/airsnrtClient/index.htm









08/18
08/19
08/20
HRRR-SMOKE 2018-08-18 00 UTC 0h fcst - EXPERIMENTAL Valid 08/18/2018 00:00 UTC
Near-Surface Smoke (μg/m³), 10m Wind (kt)
HRRR-SMOKE 2018-08-19 00 UTC 0h fcst - EXPERIMENTAL Valid 08/19/2018 00:00 UTC
Near-Surface Smoke (μg/m³), 10m Wind (kt)
HRRR-SMOKE 2018-08-20 00 UTC 0h fcst - EXPERIMENTAL Valid 08/20/2018 00:00 UTC
Near-Surface Smoke (μg/m³), 10m Wind (kt)
HRRR - surface
1 2 4 6 8 12 16 20 25 30 40 60 100 200
HRRR-SMOKE 2018-08-18 00 UTC 0h fcst - EXPERIMENTAL Valid 08/18/2018 00:00 UTC
Vertically Integrated Smoke (mg/m²)
HRRR-SMOKE 2018-08-19 00 UTC 0h fcst - EXPERIMENTAL Valid 08/19/2018 00:00 UTC
Vertically Integrated Smoke (mg/m²)
HRRR-SMOKE 2018-08-20 00 UTC 0h fcst - EXPERIMENTAL Valid 08/20/2018 00:00 UTC
Vertically Integrated Smoke (mg/m²)
HRRR - column
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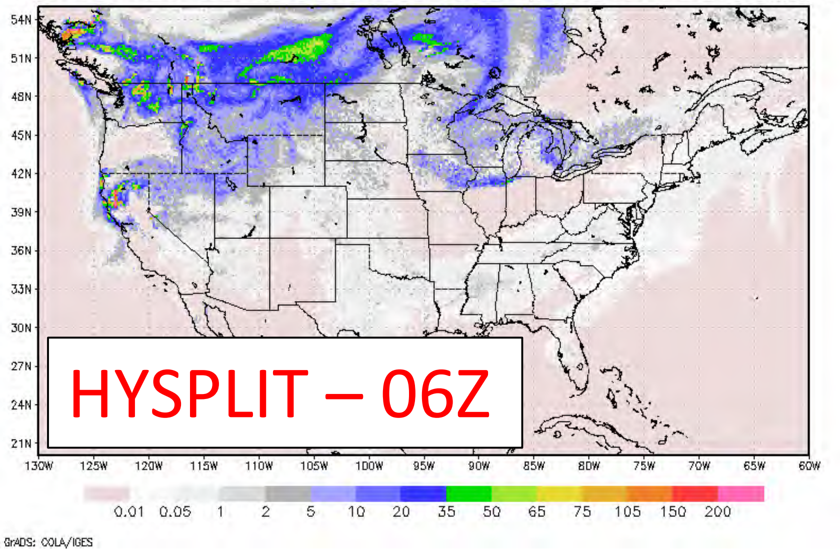
08/18

HYSPLIT PROD t06z pbl smoke 20180818/1800V012 conc ug/m3



08/19

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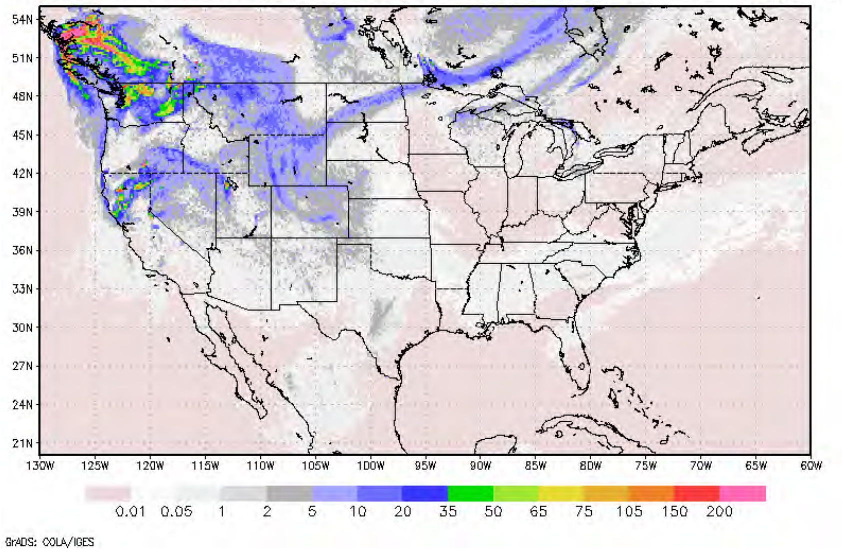

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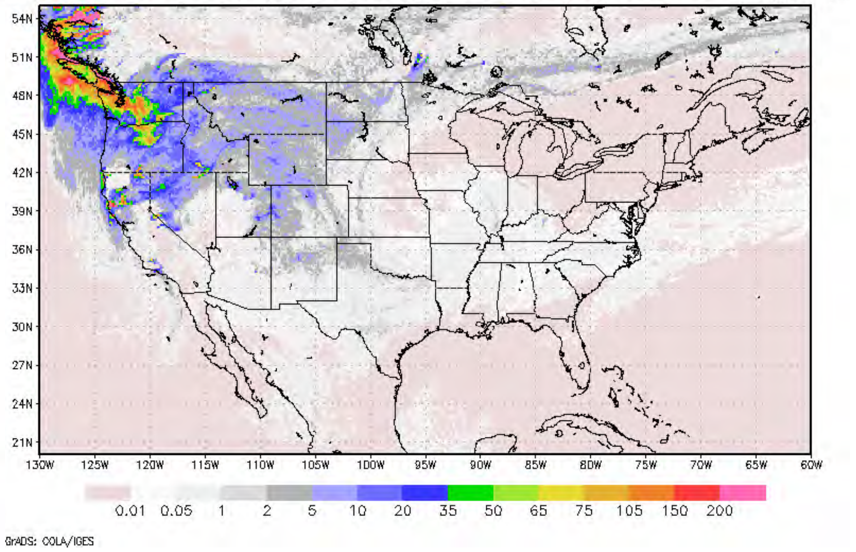
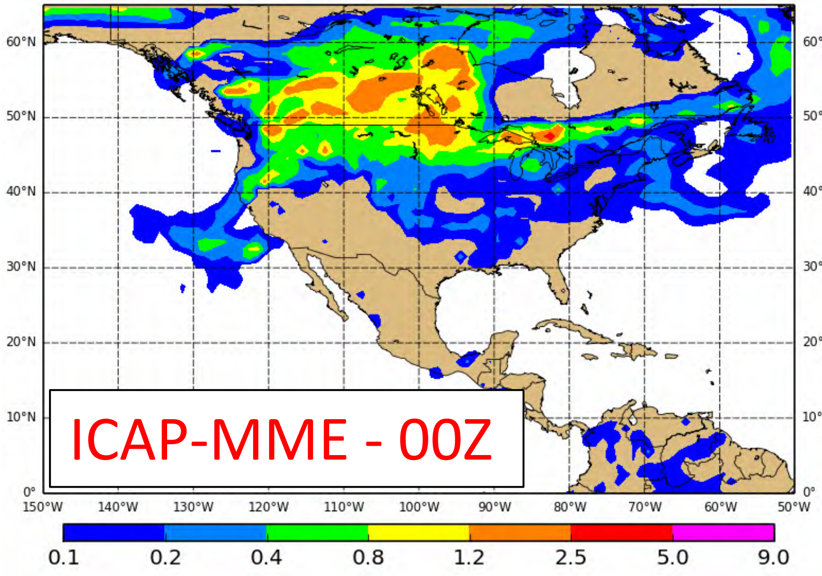
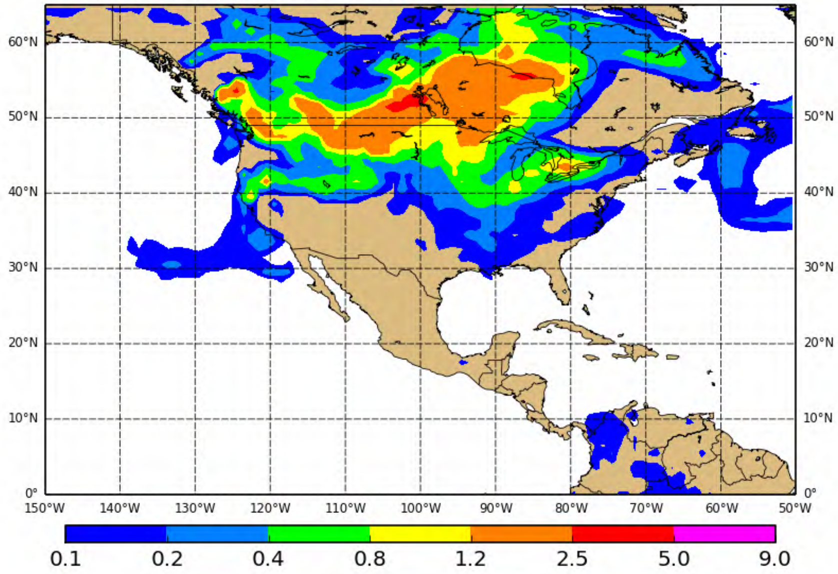


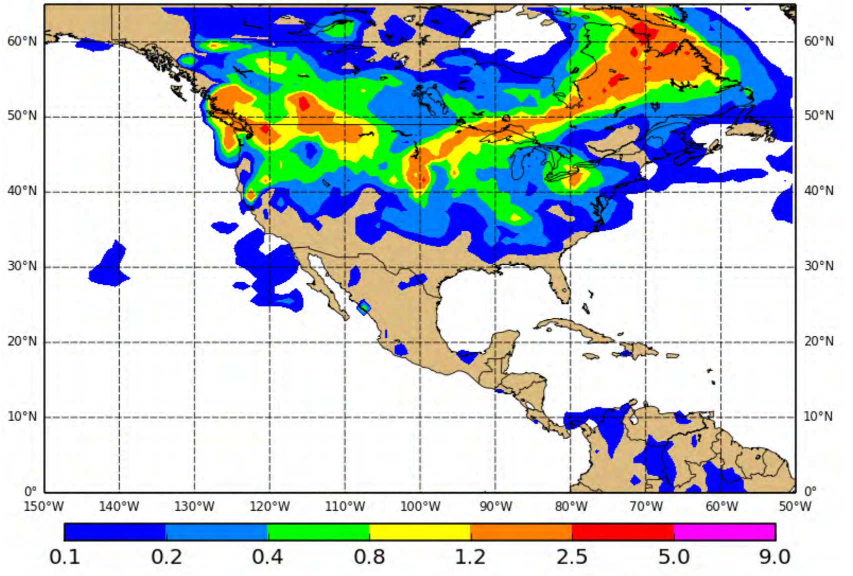
Saturday 18 August 2018 00UTC ICAP Forecast t+000
Saturday 18 August 2018 00UTC Valid Time
SMOKE Aerosol Optical Depth at 550nm (nMEM = 2)



Sunday 19 August 2018 00UTC ICAP Forecast t+000
Sunday 19 August 2018 00UTC Valid Time
SMOKE Aerosol Optical Depth at 550nm (nMEM = 3)

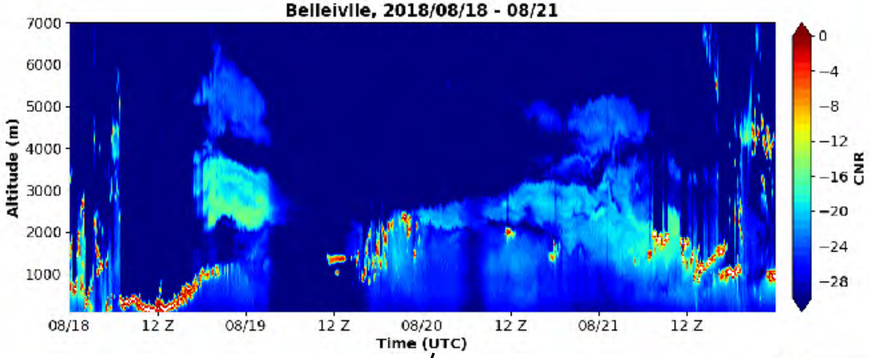


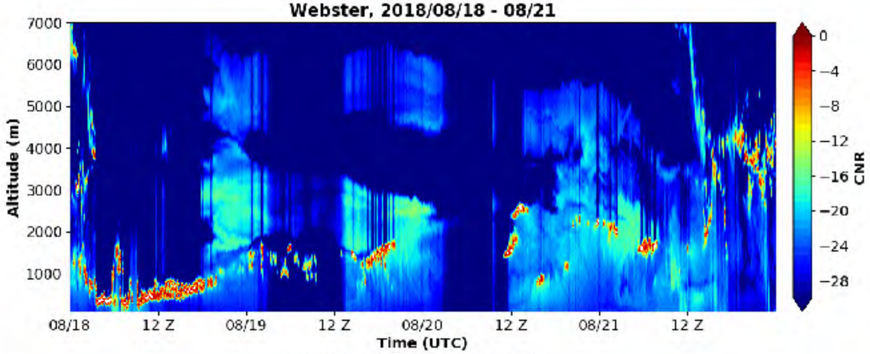
Monday 20 August 2018 00UTC ICAP Forecast t+000
Monday 20 August 2018 00UTC Valid Time
SMOKE Aerosol Optical Depth at 550nm (nMEM = 2)

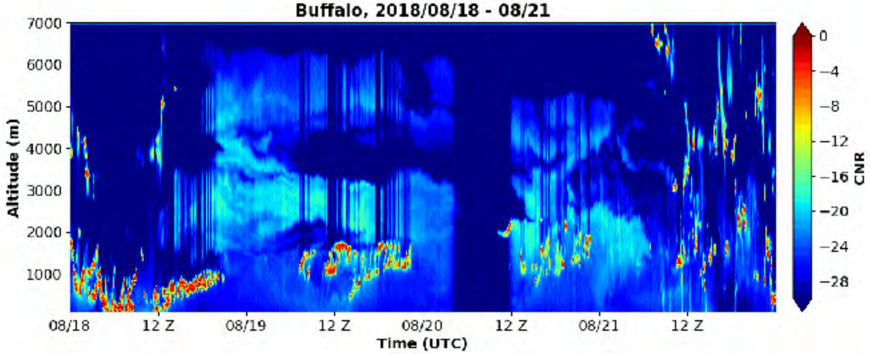


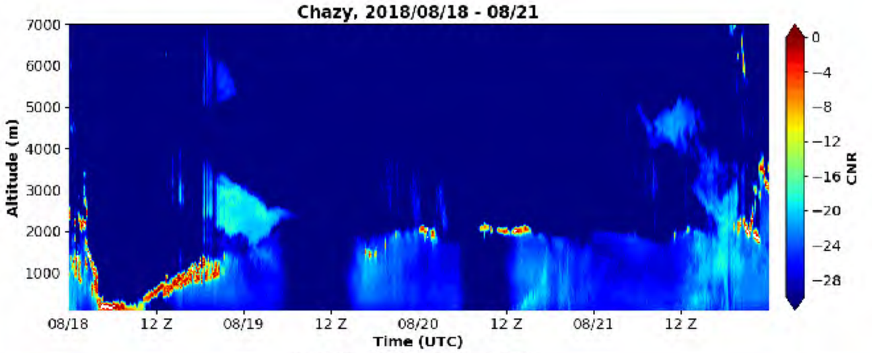
NYS Mesone
Profiler observations

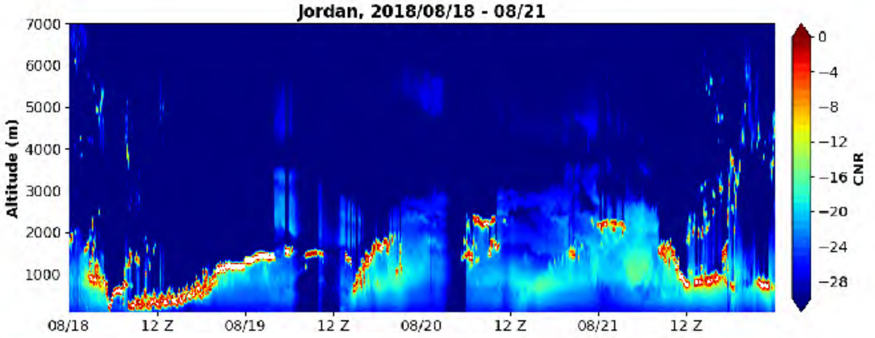
2018 08/18-08/20

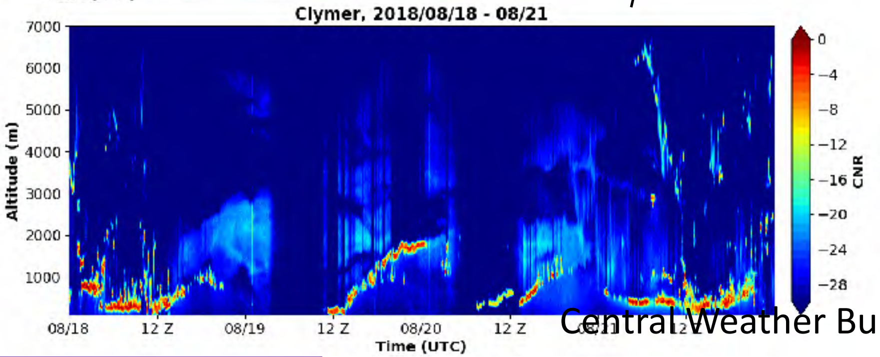


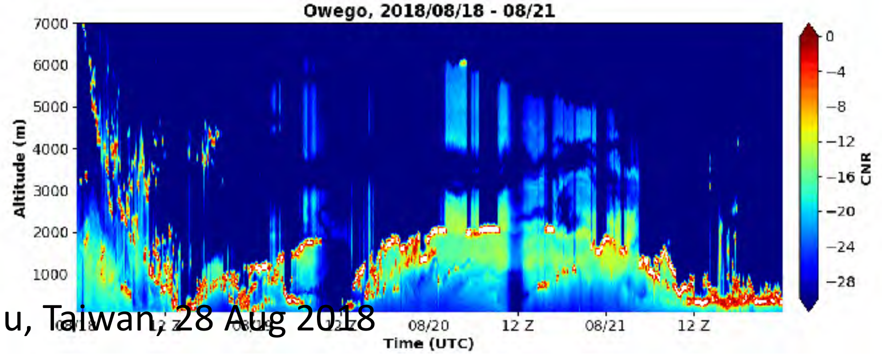












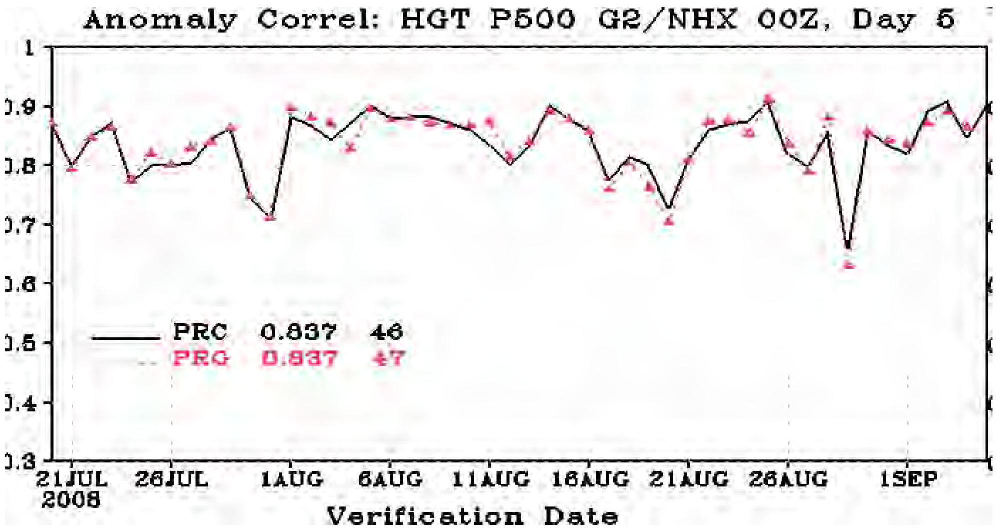
Looking Forward ….

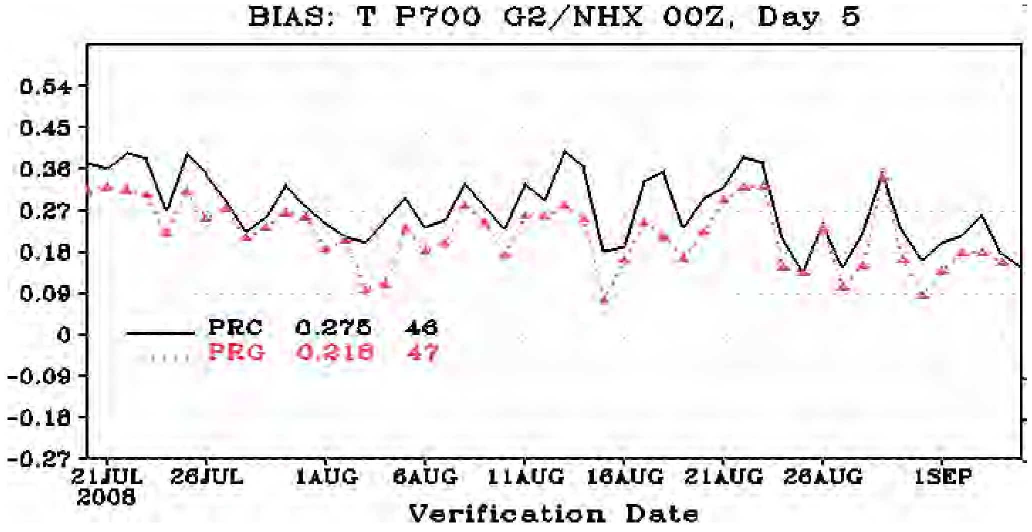
How much complexity is needed to accurately represent the aerosol processes and effectively account for aerosol effects?

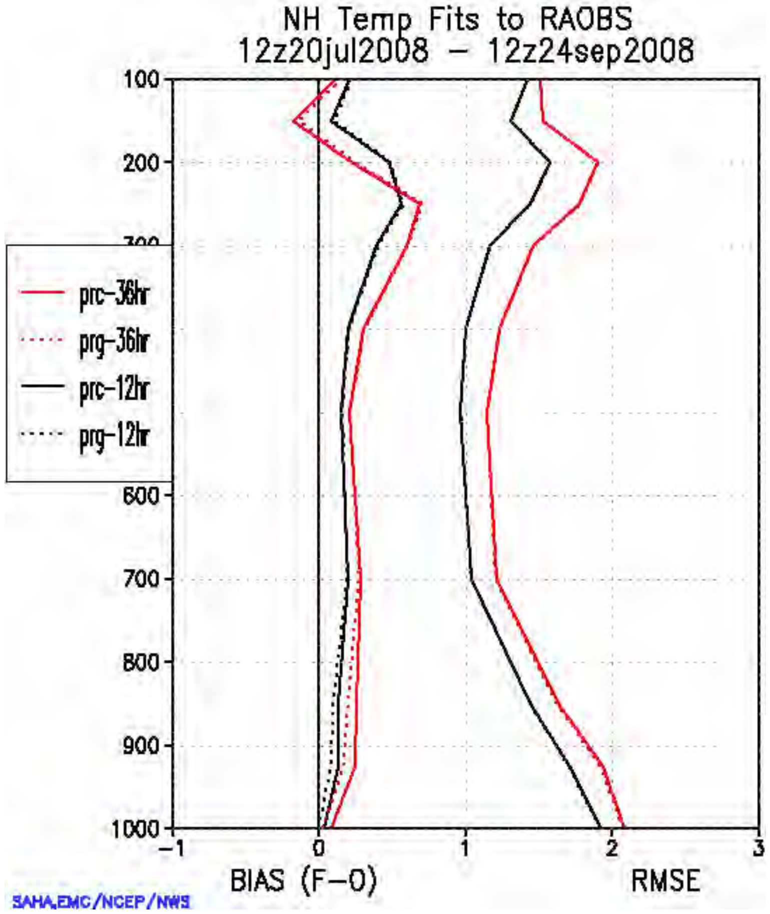
- Likely depend on applications
- Constrained by the resources

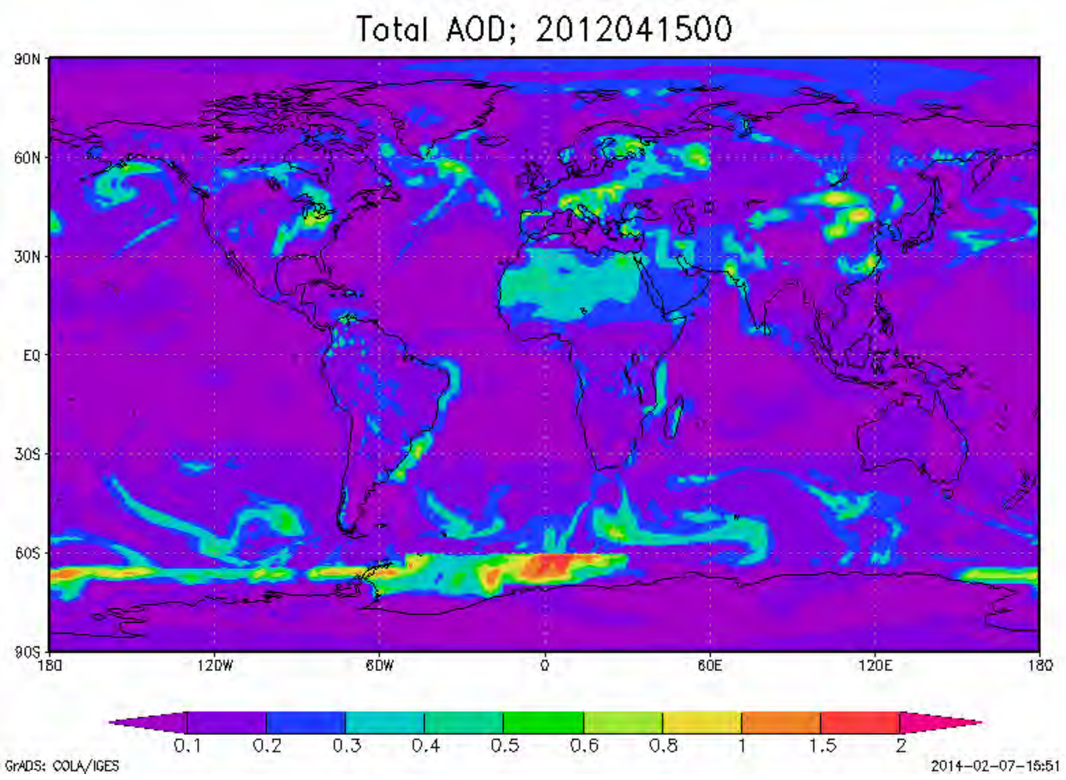
Aerosol-Radiation Feedback: Positive Impact on Weather Forecasts

- T382 L64 GFS/GSI# experiments for the 2008 summer period
- PRC uses the OPAC climatology (as in the operational applications)
- PRG uses the off-line GEOS4-GOCART% monthly dataset



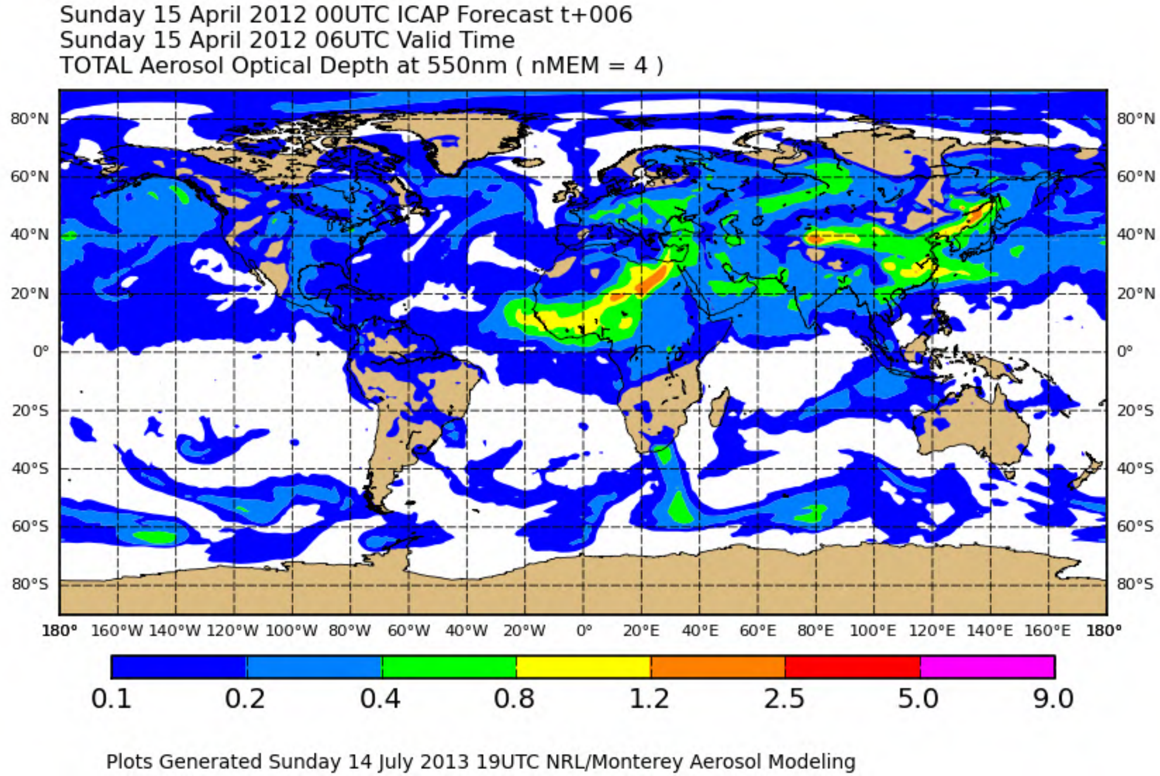




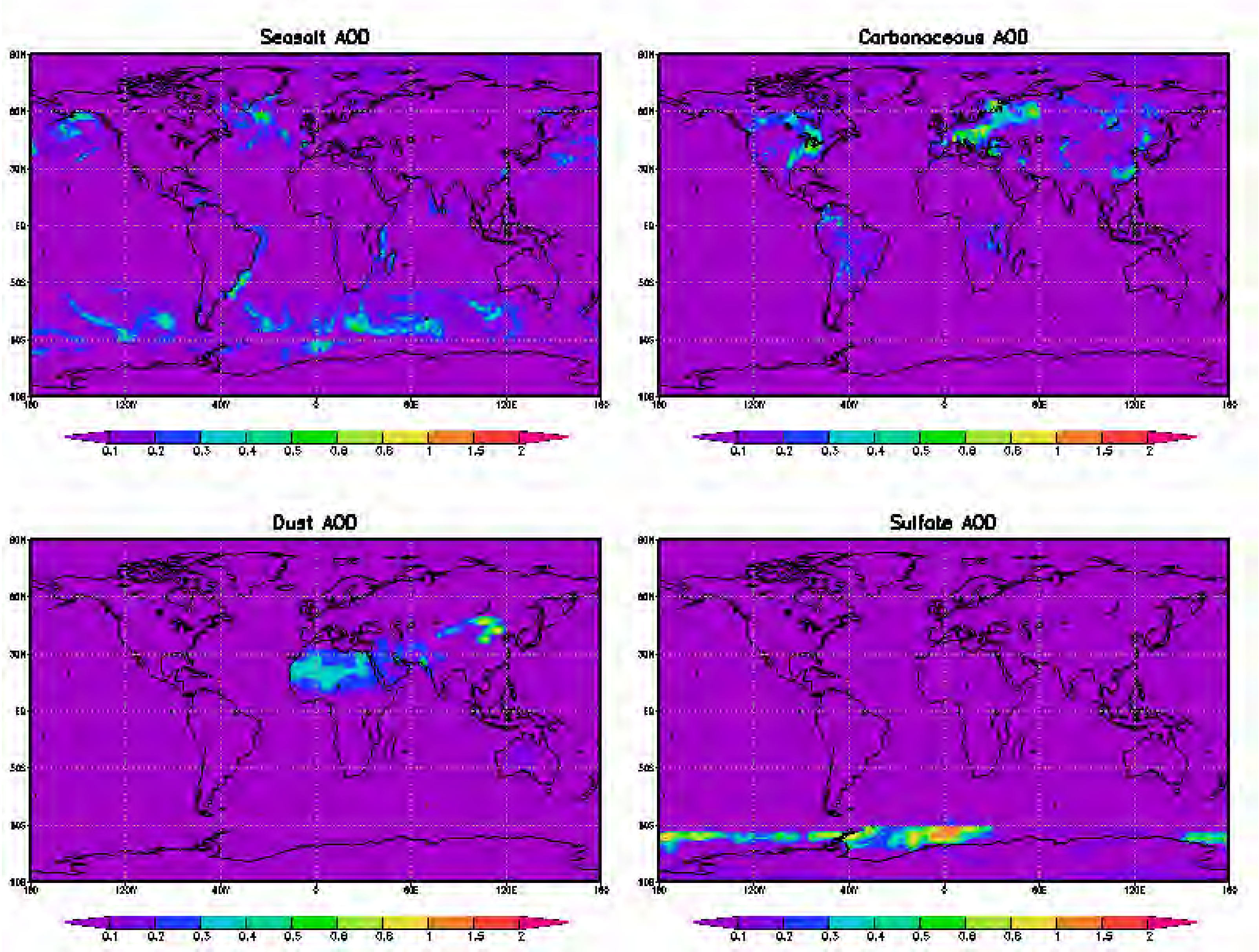


OPAC Climatology in GFS
5° x 5° monthly data set

ICAP-MME, from NRL, GMAO, ECMWF, JMA



AOD from individual aerosol species (sea salt, OC/BC, dust, sulfate)



Global Aerosol Data Set (Hess et al., 1997): SUSO is used to describe stratospheric aerosols based on Shaw (1979)

Lessons learned from GFS and NGAC aerosol-related work

- Aerosol aware physics parameterizations
  - Aerosol direct effect: Positive impact on NWP using realistic (improved) aerosol distributions
  - Aerosol indirect effect: Neutral to positive impact; more development and testing needed
- Aerosol aware data assimilation
  - CRTM experiments: dust & sea salt affect radiance/BT
  - GDAS experiments: neutral to positive impact from aerosols
- Aerosol forecasting
  - Spatial and temporal distributions with reasonable accuracy
  - Utilization of satellite observations (data assimilation, real-time emission estimations, verification/evaluation)

Closing Remarks

- At NWP centers, aerosol prediction systems are built upon modeling/assimilation methodologies already in place for the meteorological systems.
- How much complexity is needed to accurately represent the aerosol processes and its effects?
  - Operational efficiency constraint vs complexity for research applications
  - Institutional mission and user needs
- At NCEP, NGGPS-AAC (aerosol and atmospheric composition) priorities include
  - Improve aerosol forecast capability
  - Impacts of aerosols on radiation and microphysical processes
  - Data assimilation of aerosol observations

Thanks.

Questions or comments?