Can Aerosol Direct Radiative Effects account for Analysis Increments of Temperature in the Tropical Atlantic?

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ABSTRACT

In the late 1990's, prior to the launch of the Terra satellite, atmospheric general circulation models (GCMs) did not include aerosol processes because aerosols were not properly monitored on a global scale and their spatial distributions were not known well enough for their incorporation in operational GCMs. At the time of the first GEOS Reanalysis (Schubert et al. 1993), long time series of analysis increments (the corrections to the atmospheric state by all available meteorological observations) became readily available, enabling detailed analysis of the GEOS-1 errors on a global scale. Such analysis revealed that temperature biases were particularly pronounced in the Tropical Atlantic region, with patterns depicting a remarkable similarity to dust plumes emanating from the African continent as evidenced by TOMS aerosol index maps. Yoram Kaufman was instrumental encouraging us to pursue this issue further, resulting in the study reported in Alpert et al. (1998) where we attempted to assess aerosol forcing by studying the errors of a the GEOS-1 GCM without aerosol physics within a data assimilation system. Based on this analysis, Alpert et al. (1998) put forward that dust aerosols are an important source of inaccuracies in numerical weather-prediction models in the Tropical Atlantic region, although a direct verification of this hypothesis was not possible back then.

Nearly 20 years later, numerical prediction models have increased in resolution and complexity of physical parameterizations, including the representation of aerosols and their interactions with the circulation. Moreover, with the advent of NASA's EOS program and subsequent satellites, atmospheric aerosols are now monitored globally on a routine basis, and their assimilation in global models are becoming well established.

In this talk we will reexamine the Alpert et al. (1998) hypothesis using the most recent version of the GEOS-5 Data Assimilation System with assimilation of aerosols. We will explicitly calculate the impact of aerosols on the temperature analysis increments in the tropical Atlantic and assess the extent to which inclusion of atmospheric aerosols have reduced these increments.

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Yoram Kaufman Memorial Symposium
NASA Goddard Space Flight Center
21 June 2016

Remembering Yoram: My Introduction to Aerosols

- Back in 1998…
  - Before MODIS
  - Before aerosols in the GEOS model
- While diagnosing temperature "errors" in the GEOS-1 Reanalysis we ran across a feature in the tropical Atlantic Ocean that appeared consistent with aerosol radiative effects.
  - Yoram's insights and enthusiasm were key
- Nearly 20 years later, latest MERRA-2…
  - Includes a coupled aerosol module
  - Assimilates MODIS, MISR and AERONET AOD data
  - More comprehensive met observing system
- In this talk we revisit our 1998 paper, and re-examine the role of aerosols in the Tropical Atlantic

Quantification of dust-forced heating of the lower troposphere

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Aerosols may affect climate through the absorption and scattering of solar radiation and, in the case of large dust particles, by interacting with thermal radiation[1–3]. But whether atmospheric temperature responds significantly to such forcing has not been determined; feedback mechanisms could increase or decrease the effects of the aerosol forcing. Here we present an indirect measure of the tropospheric temperature response by explaining the 'errors' in the NASA/Goddard model/data-assimilation system. These errors, which provide information about physical processes

NATURE | VOL 395 | 24 SEPTEMBER 1998

Outline

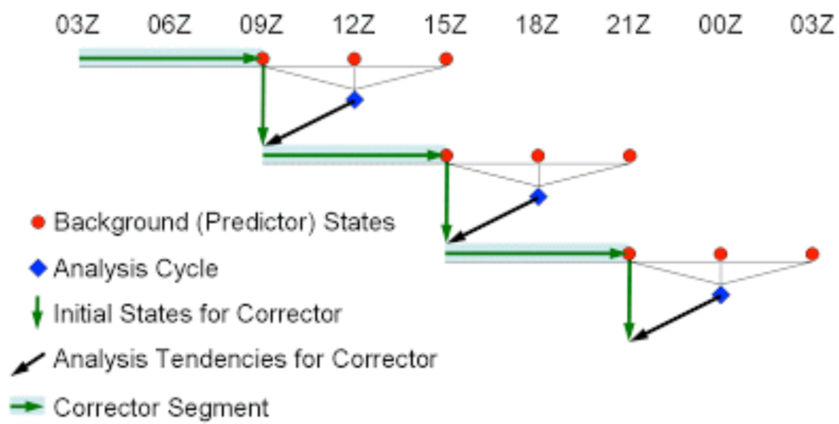
- The GEOS-1 Reanalysis and IAU
- Early GEOS-1 Results
- Dust Contamination of TOVS Retrievals?
- 20 Years Later: MERRA-2
- Impact of aerosols on analysis increments of temperature
- Impact on aerosols on met assimilation
- Concluding Remarks

GEOS-1 Reanalysis Overview

- Benchmark dataset for 1985-89
- Resolution:
  - 2 x 2.5 degrees
  - 20 σ-levels, top at 10 hPa
- DA: Optimal Interpolation
- Model: GEOS-1 GCM
  - Dynamical Core: ARIES
  - Radiation: Harshvardhan et al. (1987)
  - PBL: Helfand & Labraga (1988)
  - Convection: RAS, Moorthi & Suarez (1992)
  - No land-surface model (offline bucket)
  - No aerosols

Schubert et al. 1993

INCREMENTAL ANALYSIS UPDATES (IAU)



Bloom et al. (1996)

Role of Analysis Increments

- In a free-running model

$$\frac{\partial T}{\partial t} = \mathcal{F}_{\rm adv} + \mathcal{F}_{\rm phys}$$

- Within a data assimilation cycle an extra term accounts for the "corrections by the observations"

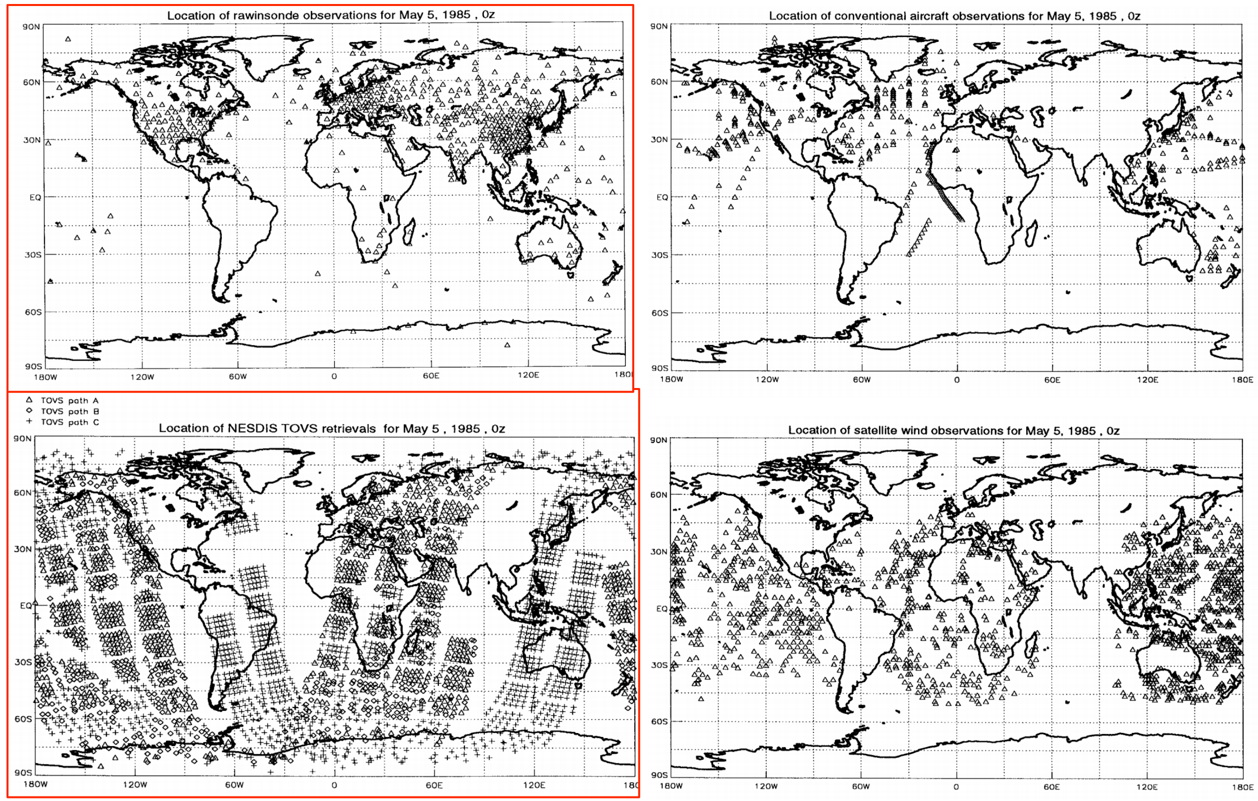
$$\frac{\partial T}{\partial t} = \mathcal{F}_{\rm adv} + \mathcal{F}_{\rm phys} + \mathcal{F}_{\rm iau}$$

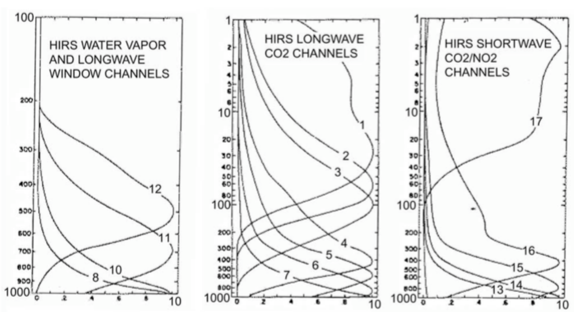
where

$$\mathcal{F}_{\rm iau} = \frac{T_a - T_f}{\tau} = \frac{T_a - T_f}{6\ \rm h}$$

GEOS-1 Upper-air Observing System

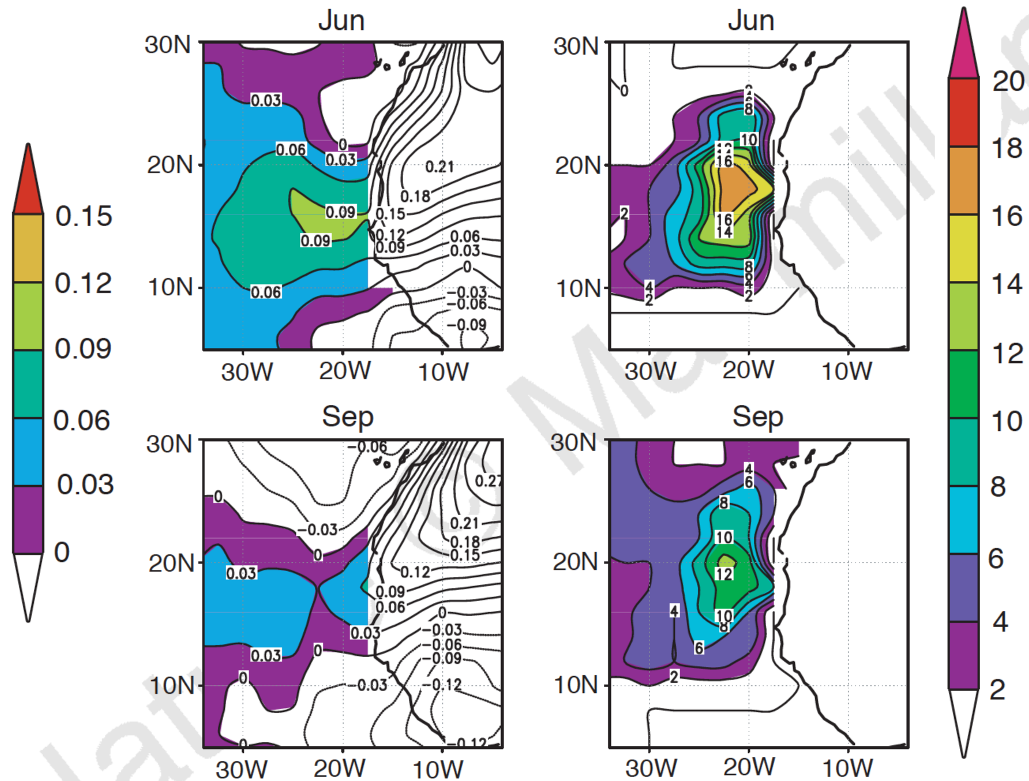
During 1985-89, NESDIS TOVS retrievals provided the bulk of the upper Temperature observations in the Tropical Atlantic Ocean.





Analysis Increments of Temperature and No. Dusty Days

- Monthly averages for 1984-88
- Number of Dust Days from early climatology by Jankoviak & Tanre (1992)
- Analysis increments of temperatures, IAU(T), averaged for the layer of 650–850 hPa.
- In GEOS-1, TOVS was the primary temperature data source over the oceans
- The maxima IAU(T) over the ocean of 0.1 K/day is close to the maxima found over the whole tropical or subtropical oceans.

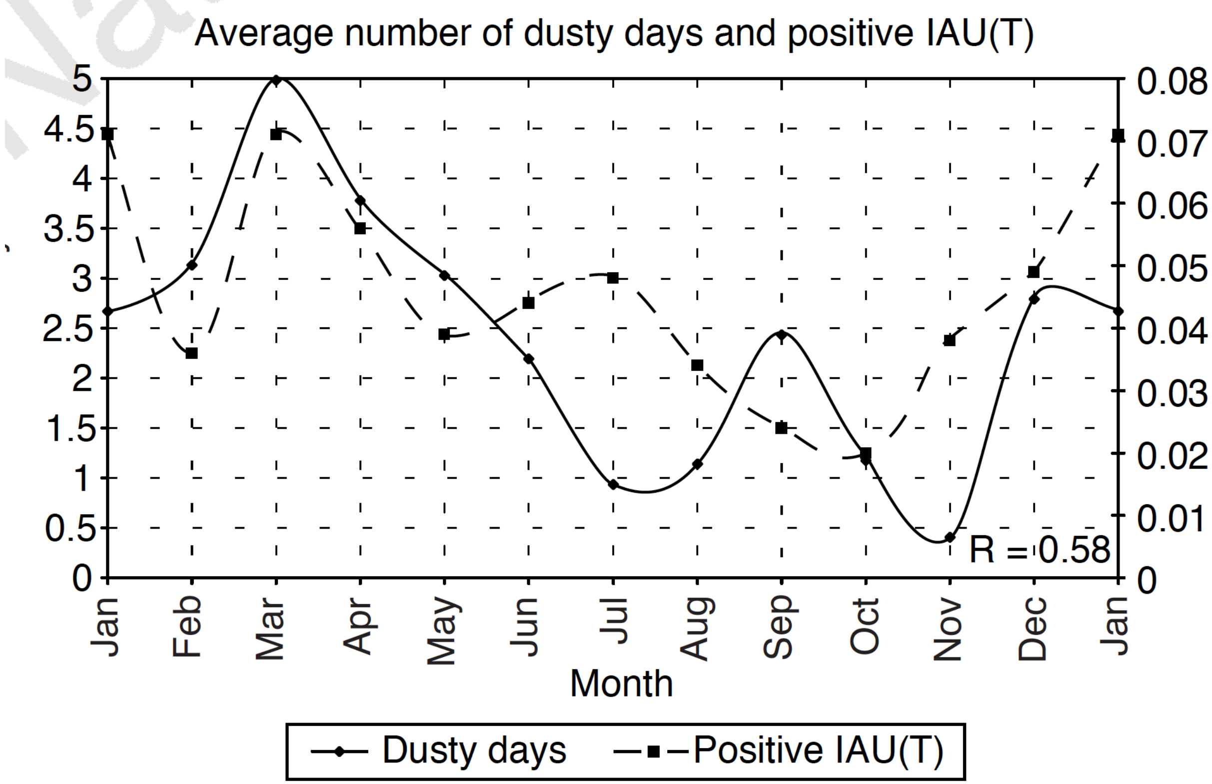


IAU(T), K/day

No. Dusty Days

Analysis Increments of Temperature and Aerosols

- The monthly heating rate in degrees Kelvin per day, as deduced from IAU(T) and the average number of dusty days
- The unexplained heating of 0.027 Kd-1 may be due to other deficiencies such as the model's inability to simulate fully the warmth of the Saharan Air Layer.
- Most of the SAL heating effect on the IAU, however, is below the dust layer.



$$IAU(T) = 0.027+7.1\ 10^{-3}\ N_{dust}$$

Caveat

Dust Contamination of TOVS Temperature Retrievals

Weaver *et al.* (2003) suggested that the TOVS retrievals used by the GEOS-1 Reanalysis might have been contaminated by dust.

"Accounting for dust absorption in the retrieval system yields warmer surface temperatures (0.4 K) and warmer lower tropospheric temperatures in regions of moderate dust loading over the tropical Atlantic."

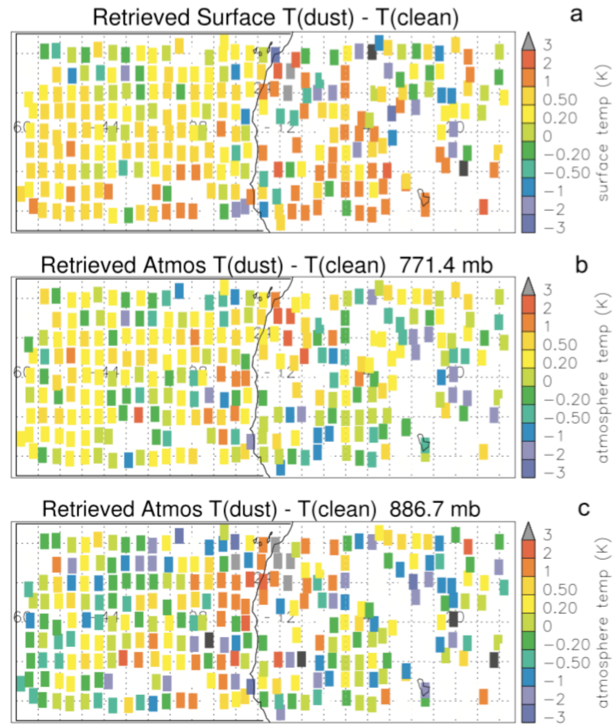


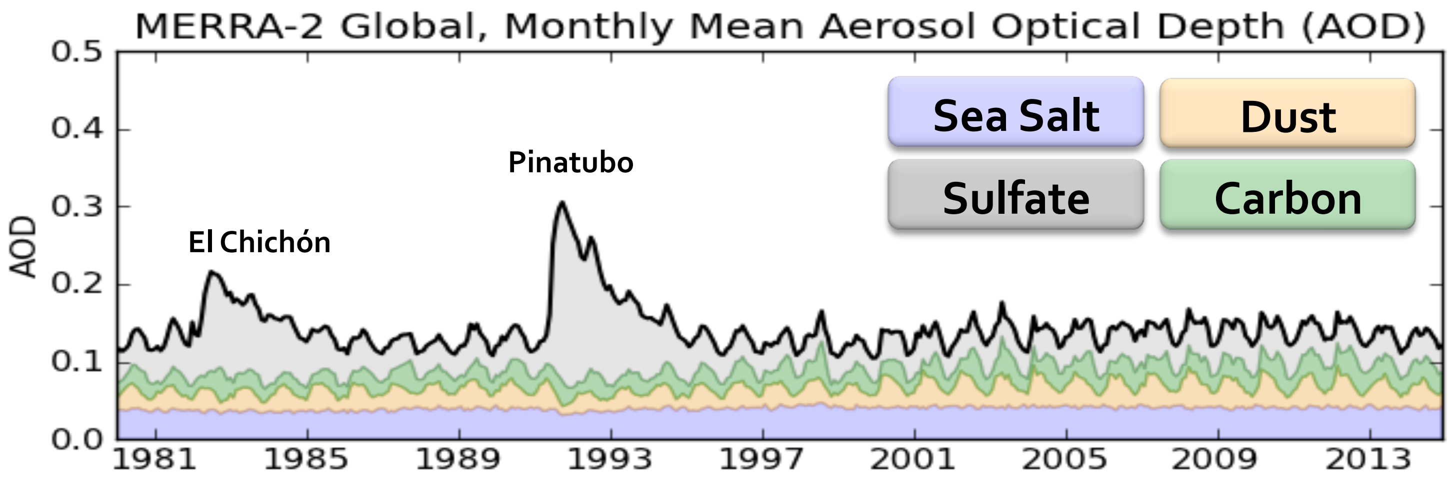
Figure 10. Difference between retrieved temperature from an fvDAS assimilation that accounts for dust minus retrieved temperature from standard assimilation that does not account for dust at (a) surface, (b) 886 hPa, and (c) 771 hPa. Each box represents a time average of temperature retrievals from NOAA-14 sounded from 2–10 June 2001 at 3am local time.

Recent GEOS-5 Reanalysis Activities

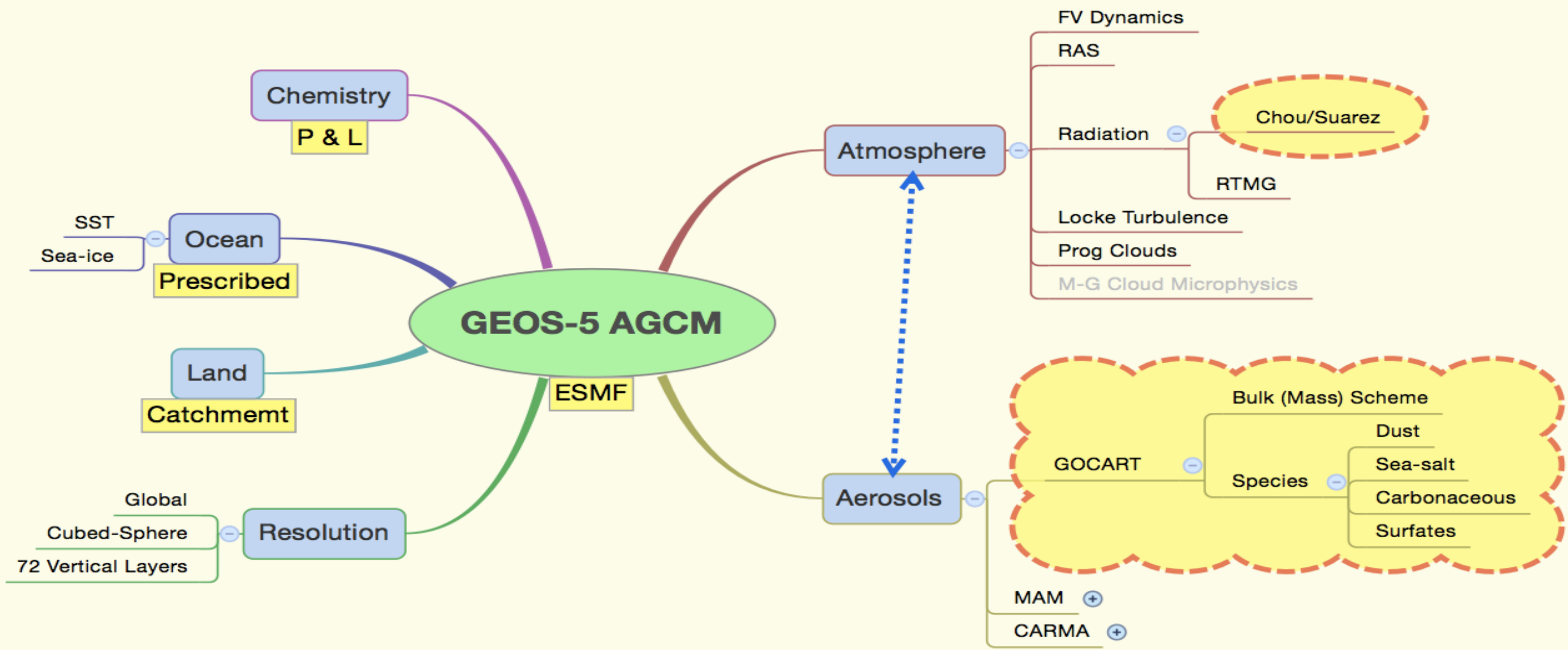
Name	Nominal Resolution	Period	Aerosol Data	Available
MERRA	50 km	1979-2016	NONE	Now
MERRAero	50 km	2002-2015	MODIS C5	Now
FP for Inst. Teams	50 km	1997-	MODIS C5	In progress
MERRA-2	50 km	1980-present	AVHRR, MODIS C5, MISR, AERONET	Now
MERRA-2 Dynamical Downscaling	12.5 km	2000-2015	AVHRR, MODIS C5, MISR, AERONET	Q1 2016

MERRA-2 Global Mean AOD Analysis: 1980 - Onward

- Unique amongst its peers, the MERRA-2 reanalysis now includes an aerosol reanalysis for the modern satellite era (1980 – onward).
- Aerosols are ***coupled*** to the meteorological reanalysis (both radiatively and through emissions/loss processes).

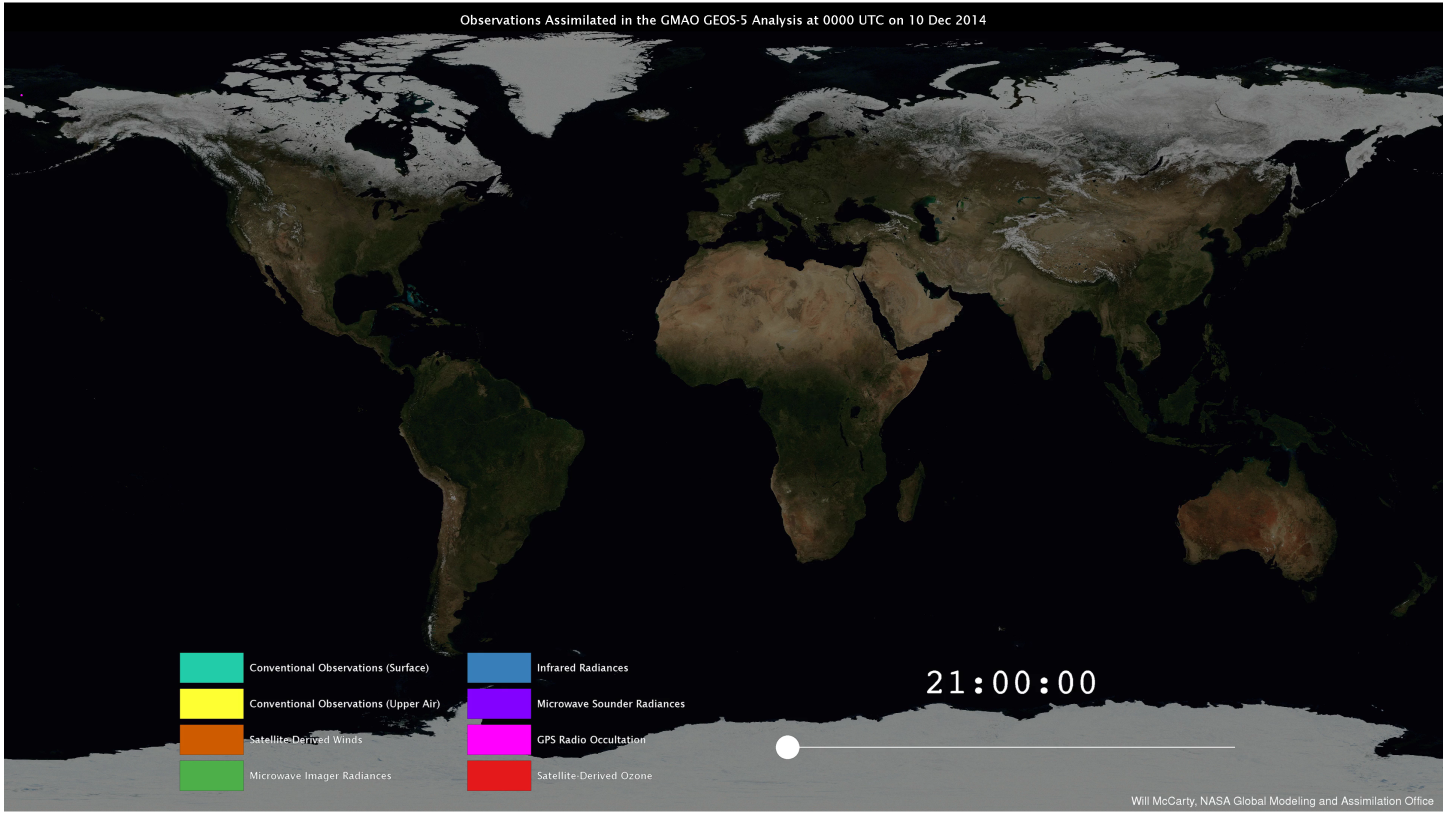


GEOS-5 Model Configuration for MERRA-2



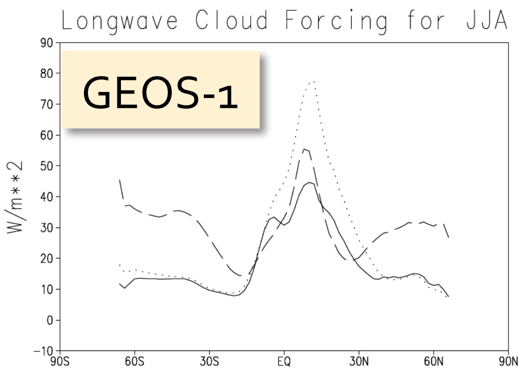
Global, 50 km, 72 Levels, top at 0.01 hPa

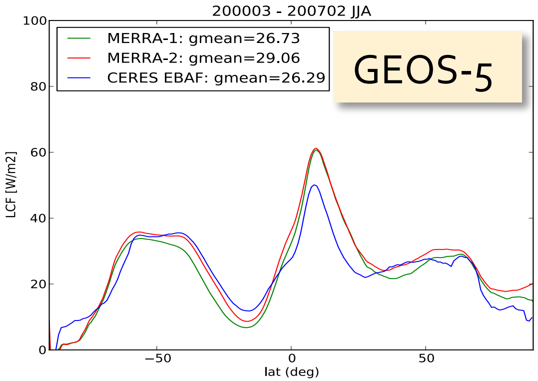
Current Observing System

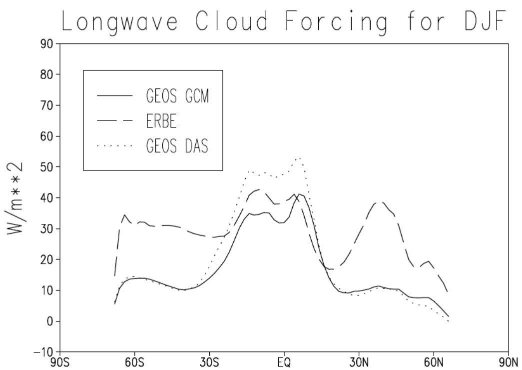


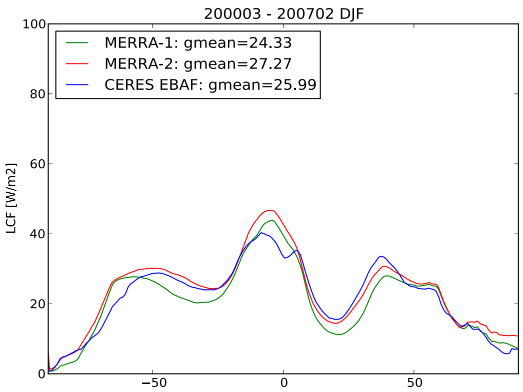
Courtesy Will McCarty

From GEOS-1 to GEOS-5





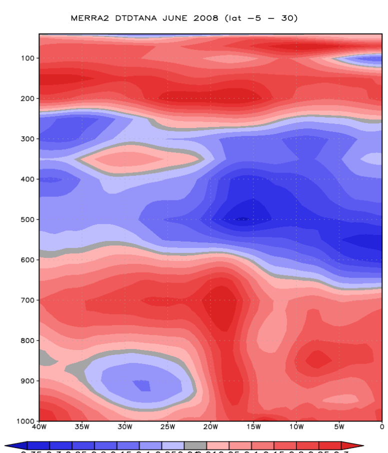




MERRA-2 Reanalysis

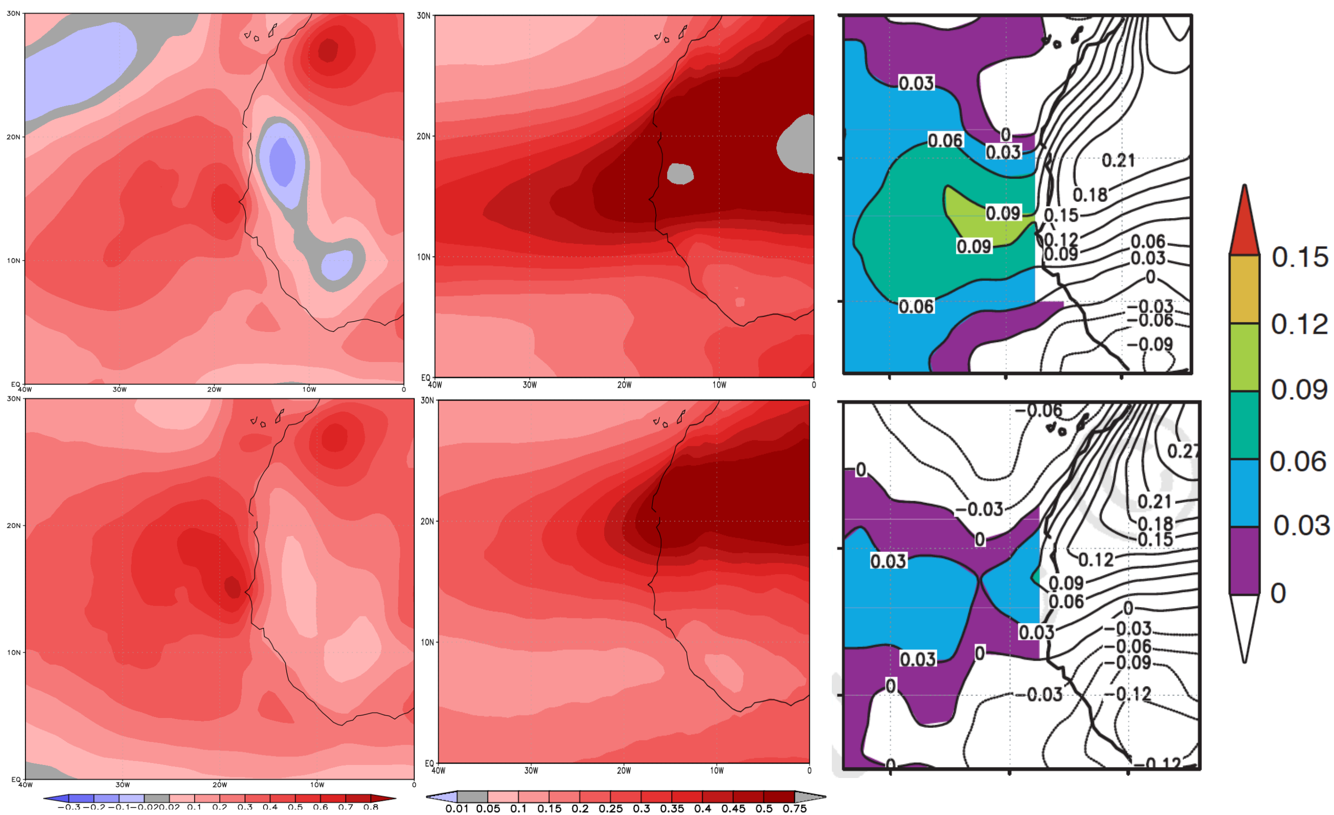
Analysis Increments of Temperature and Aerosol Optical Depth Analysis

- Monthly averages for 2000-2015
- Analysis increments of temperatures, IAU(T), averaged for the layer of 650–850 hPa.



June

September

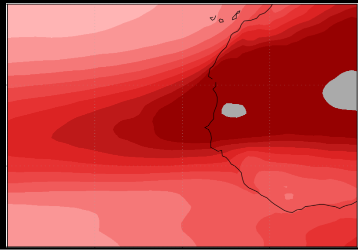


IAU(T), K/day

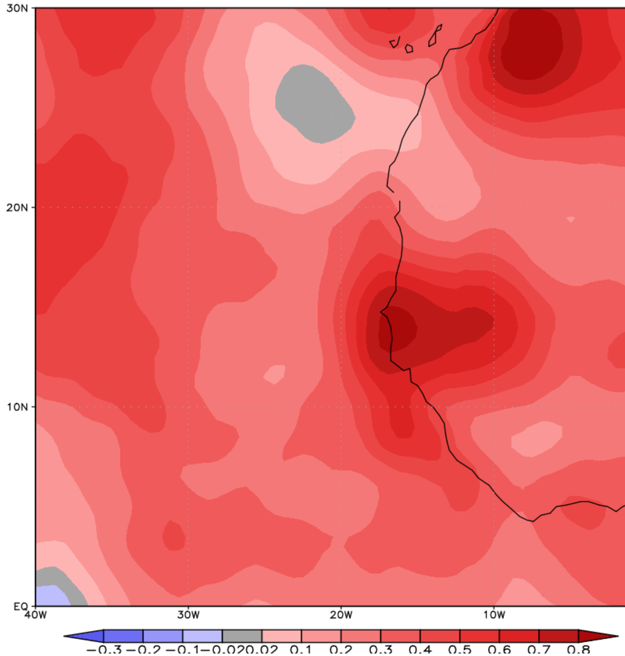
AOD (all species)

IAU(T), K/day (GEOS-1)

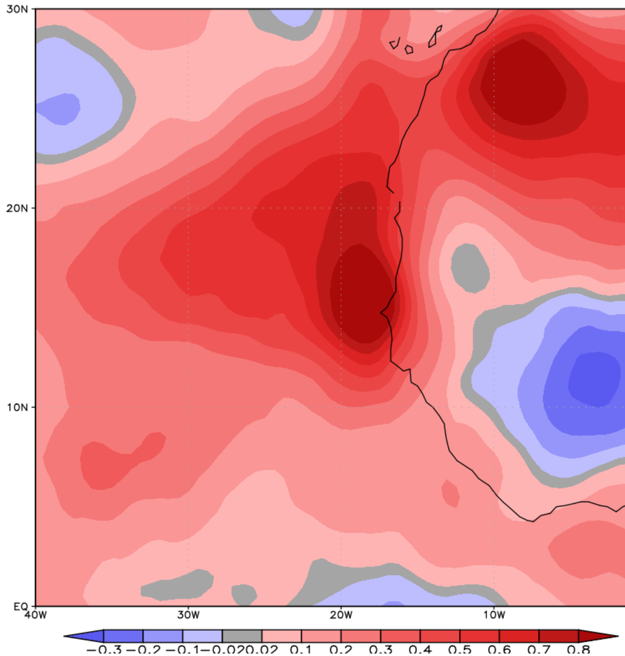
IAU(T) for June 2008



MERRA-2 WITH AEROSOLS

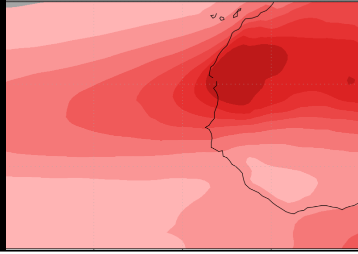


MERRA-2 W/O AEROSOLS

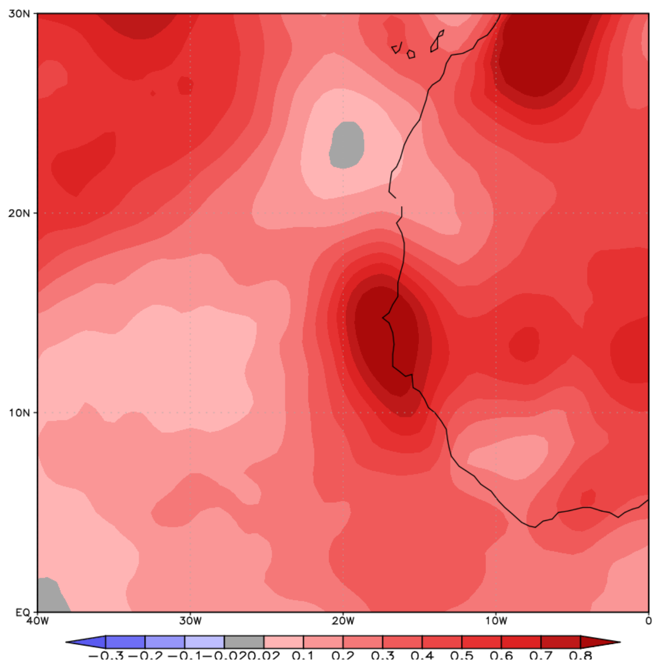


650-850 hPa Layer

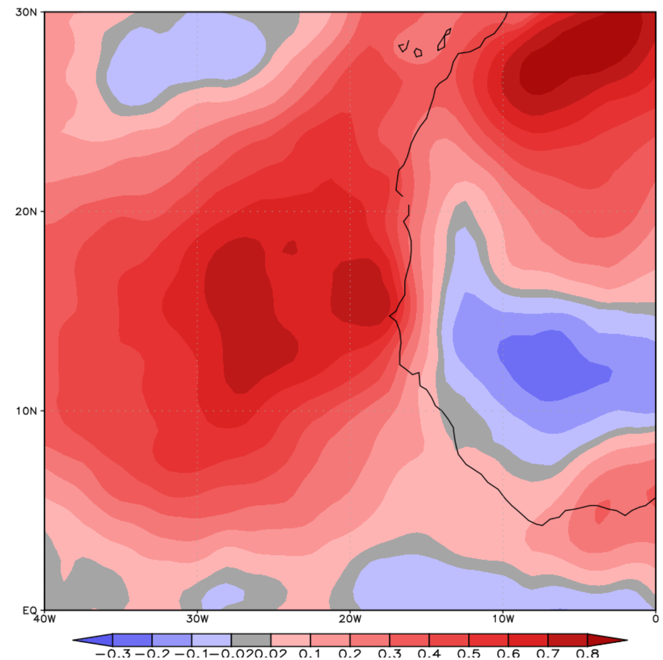
IAU(T) for July 2008



MERRA-2 WITH AEROSOLS

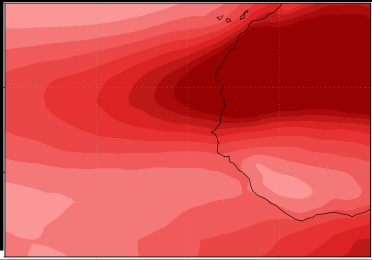


MERRA-2 W/O AEROSOLS

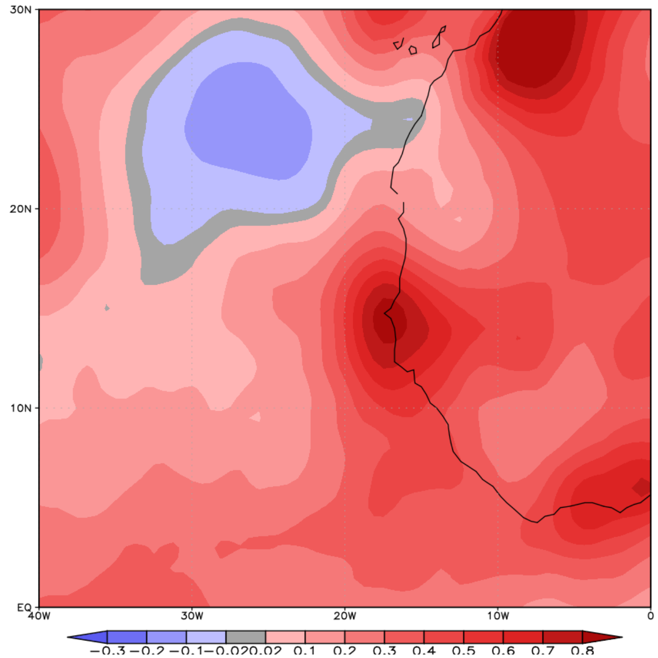


650-850 hPa Layer

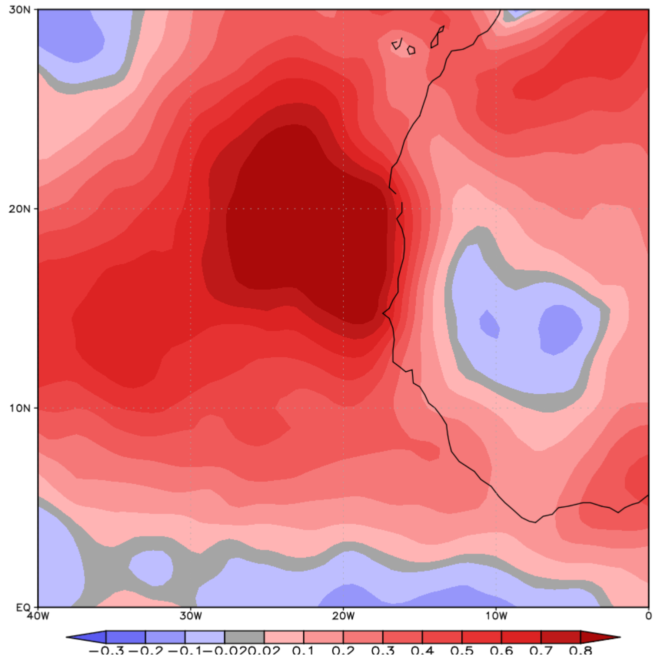
IAU(T) for August 2008



MERRA-2 WITH AEROSOLS



MERRA-2 W/O AEROSOLS



650-850 hPa Layer

Assessing Dust Contamination: Aerosols in GSI

- CRTM allows for the inclusion of (GOCART) aerosols
- The GEOS-5 GOCART aerosol species have been introduced as *state variables* in GSI
  - No aerosol increments for now
  - Aerosol effects included in the observation operators for AIRS, HIRS, IASI, etc
- Once aerosol assimilation becomes operational at NCEP this feature could be exercised there as well.

Aerosol Contamination of GSI IR Radiances – Early Results

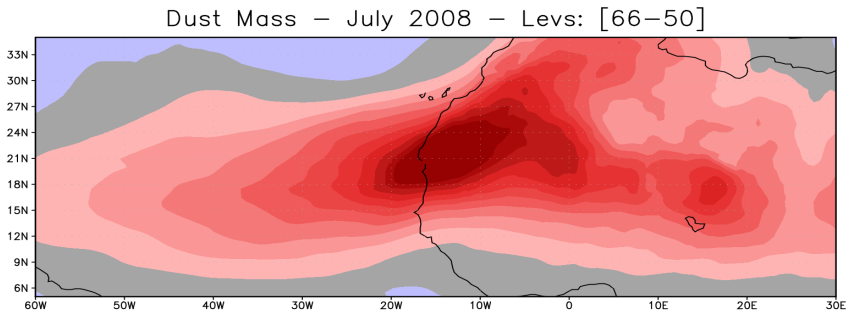
CONTROL EXPERIMENT

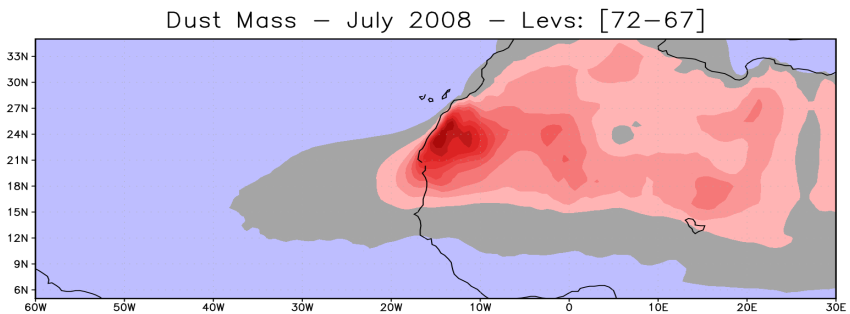
- Aerosols fully interactive in GEOS-5
  - No AOD assimilation
- Standard GSI global analysis
- ARCTAS Period
  - Summer 2008
- Resolution:
  - ½ degree

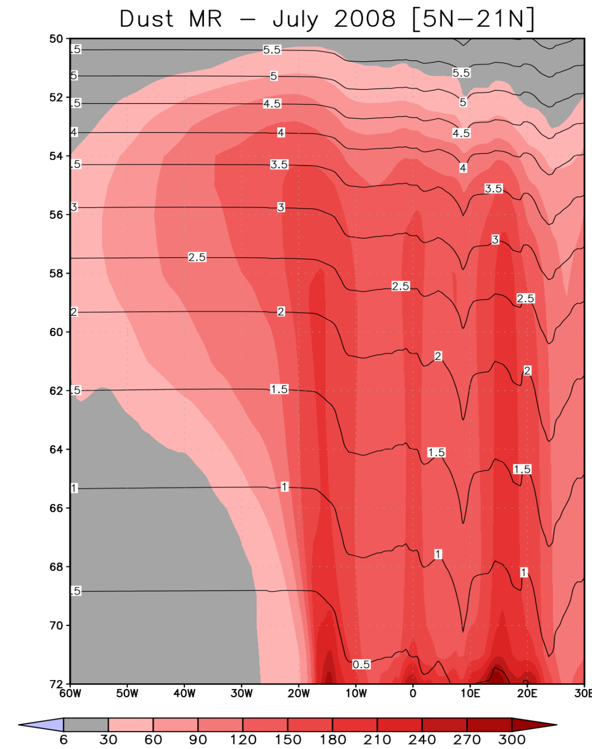
AEROSOL EXPERIMENT

- Aerosols fully interactive in GEOS-5
  - No AOD assimilation
- GSI observation operators:
  - 15 GOCART species
    - Concentration
    - Effective radius
  - Optical parameters internally determined by CRTM

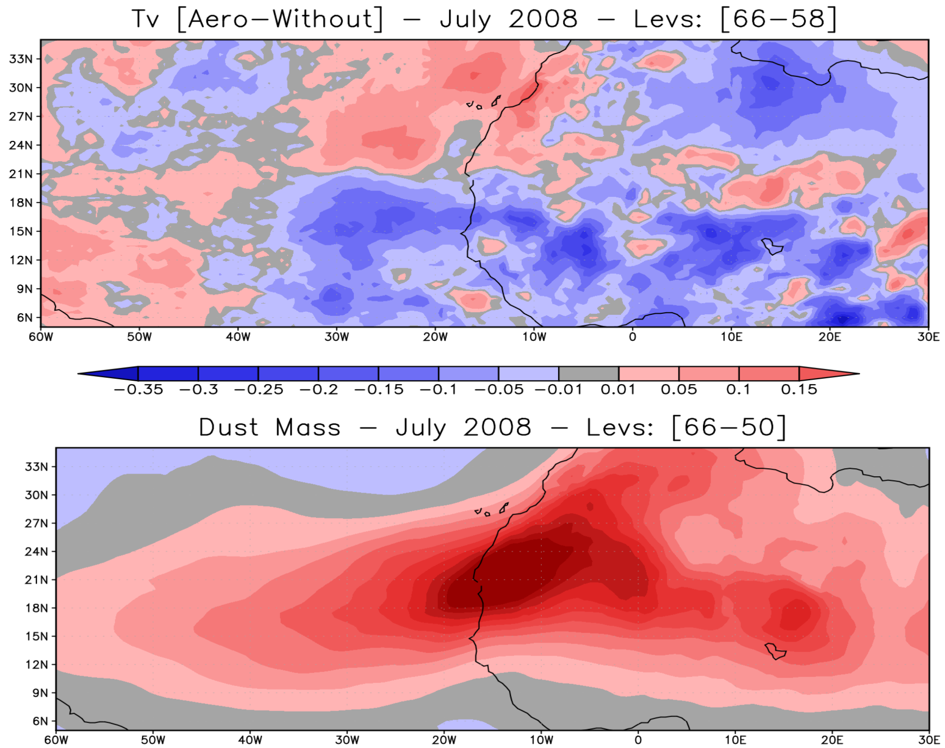
Dust Distribution



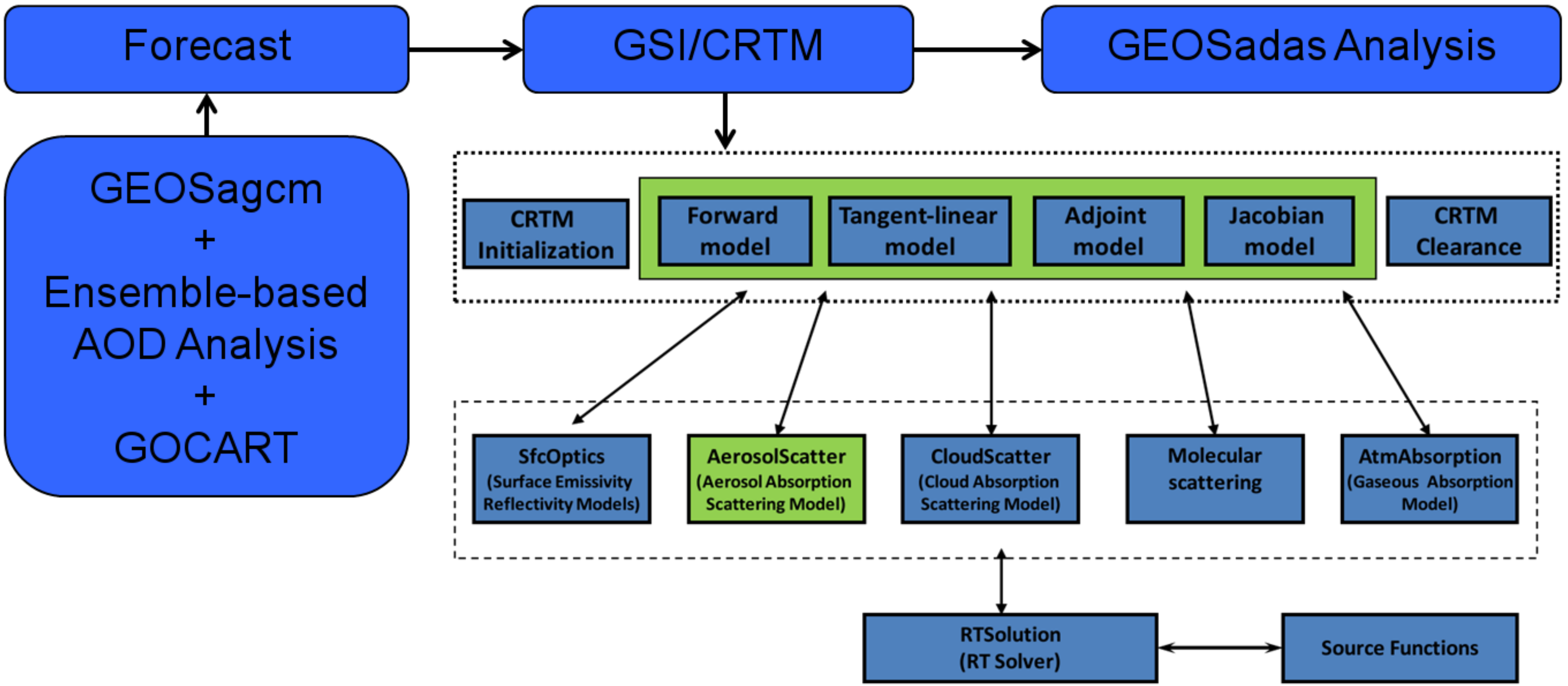




Temperature Analysis
$\Delta T = T_{aero} - T_{control}$

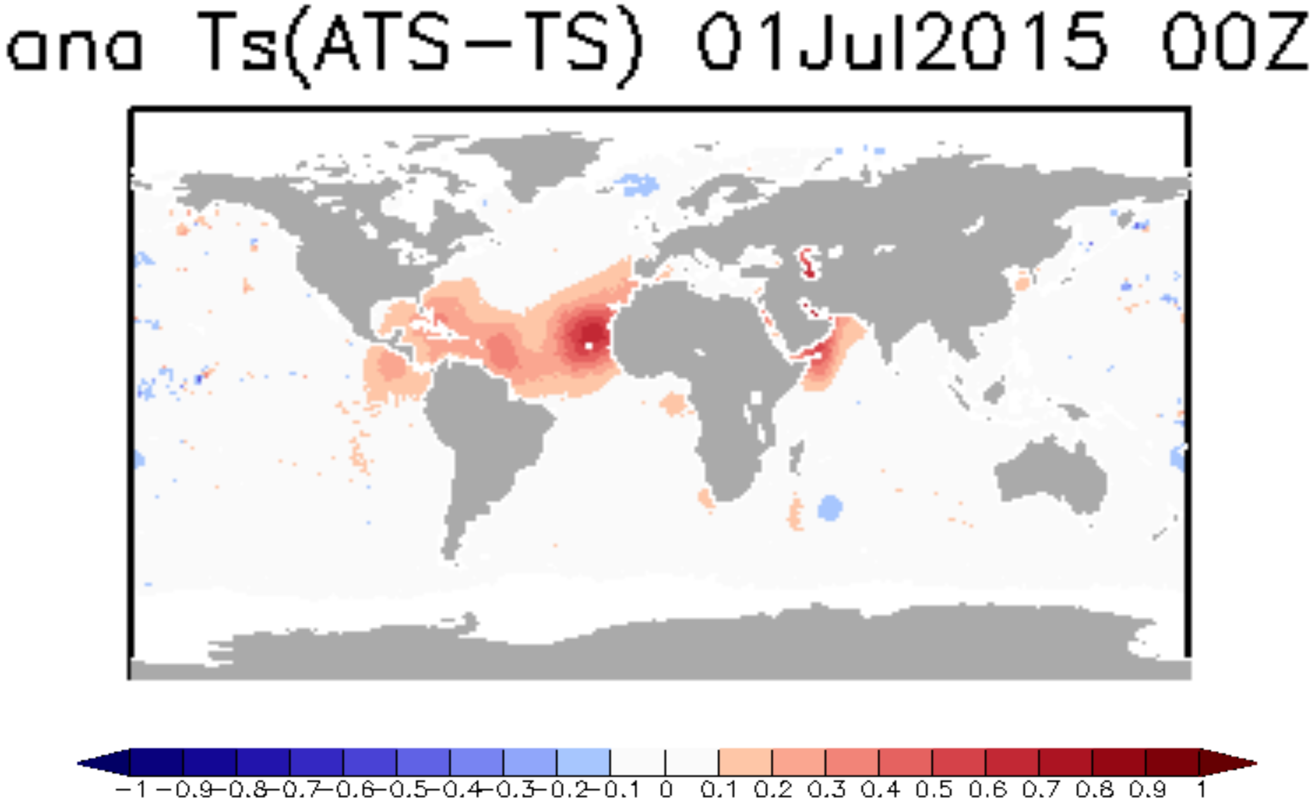


Aerosols in Current GEOS-5 DAS



Courtesy Jong Kim

Impact on SST Analysis



Courtesy Jong Kim

Summary

- In nearly 20 years, the evolution from GEOS-1 to GEOS-5 Data Assimilation System has brought about several advances:
  - Increase in resolution and new parameterizations
  - A modern data assimilation system with a robust observing system (assimilation of radiances, etc.)
  - Aerosol coupling to radiation and AOD assimilation
- It is now possible to demonstrate that the inclusion of aerosols in GEOS-5 does in fact reduce the analysis increments of temperature in the tropical as postulated by Alpert et al. (1998), although precise magnitude still up to debate
- Dust contamination of the meteorological observing system is real
  - an active topic of development.