# Integrated analyses and near-real time forecasts of atmospheric composition with focus on aerosol

**Angela Benedetti**
**ECMWF**

**In collaboration with:**
**Jean-Jacques Morcrette, Johannes Kaiser, Luke Jones, Carole Peubey, Olaf Stiller, Marta Janiskova', Johannes Flemming, Antje Dethof, and Richard Engelen**

# Outline

- General introduction
- Special topic: Eyjafjallajokull eruption
- Brief technical overview of the aerosol modelling and analysis system
- Results from retrospective reanalysis (2003-2009)
- Near-real time aerosol forecasts
- Dust warning system
- Work in progress and future developments

# GMES Atmosphere Component Service

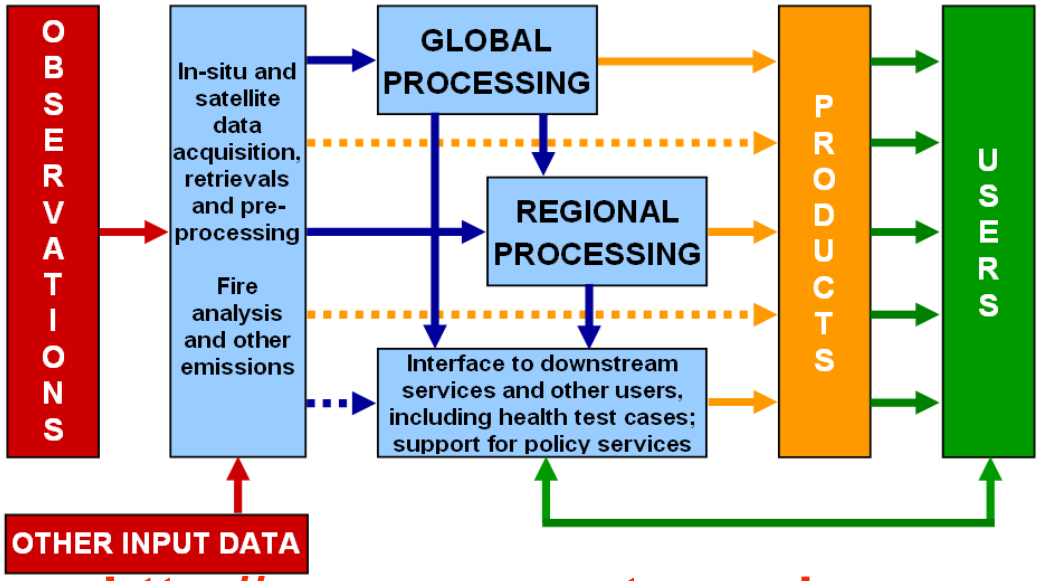
- **Part of Europe's Global Monitoring for Environment and Security initiative**
  - **development of operational space-based observation**
  - **strengthening of complementary in-situ observing systems**
  - **development and operation of services, based on core integrated assimilation and forecasting**
  - **three environmental services for Land, Ocean and Atmosphere**

- **A 32-partner EC project called GEMS (Global and regional Earth-system Monitoring using Satellite and in-situ data)**
  - **developed systems for the core GMES atmospheric service**
  - **May 2005-May 2009, status completed**

- **A 48-partner EC-funded project called MACC:**
  - **provides pilot GMES Atmosphere Component Service**
  - **succeeds earlier projects GEMS and PROMOTE**
  - **coordinated by ECMWF**
  - **started in June 2009, scheduled to end October 2011**

# MACC – Monitoring Atmospheric Composition and Climate

- Integrates space-based and in-situ observations of atmospheric composition with state-of-the art atmospheric modelling
- Provides monitoring and forecasting services
- Helps Europe to respond to climate change and poor air quality

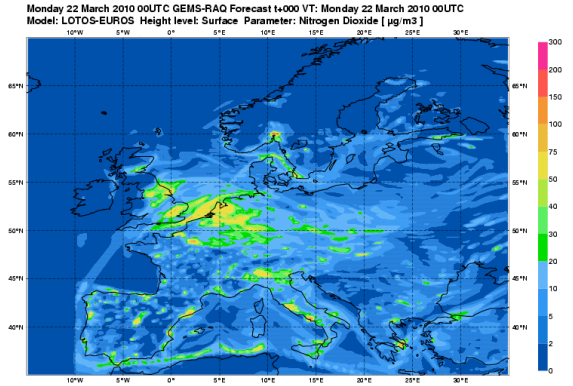



http://www.gmes-atmosphere.eu

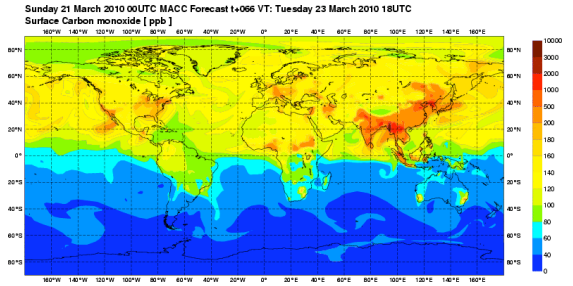
# MACC Daily Service Provision

http://www.gmes-atmosphere.eu


Air quality

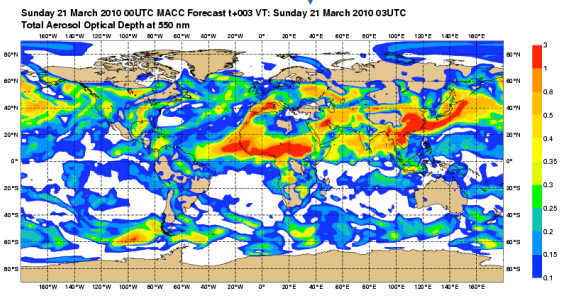



Global Pollution

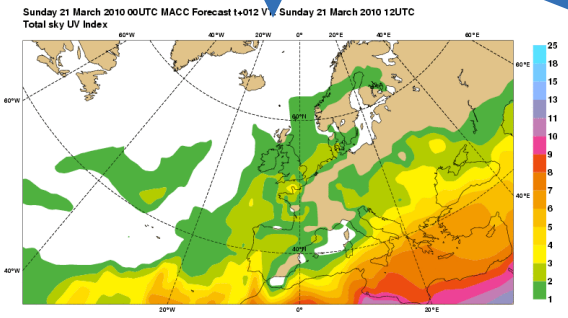


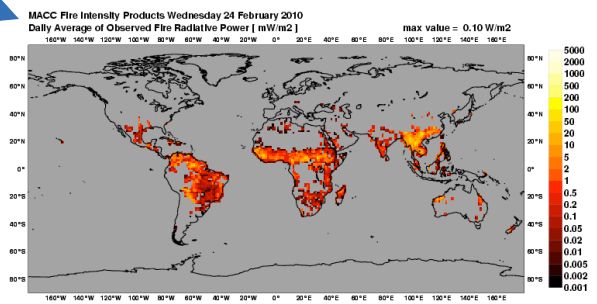

Biomass burning

Aerosol




UV index

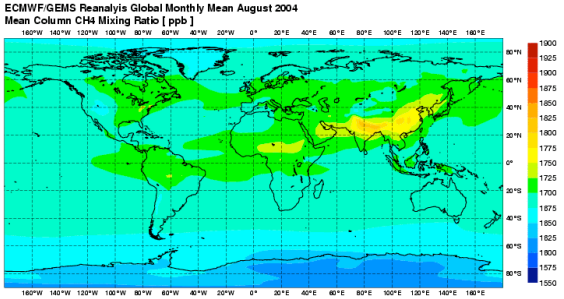


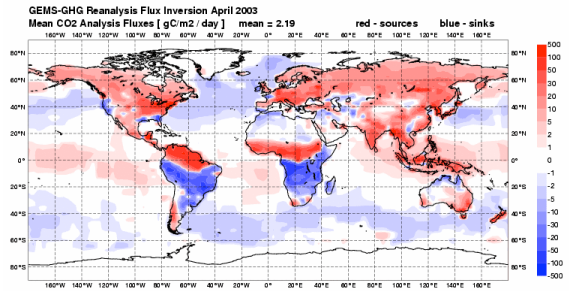
# MACC Service Provision

## http://www.gmes-atmosphere.eu

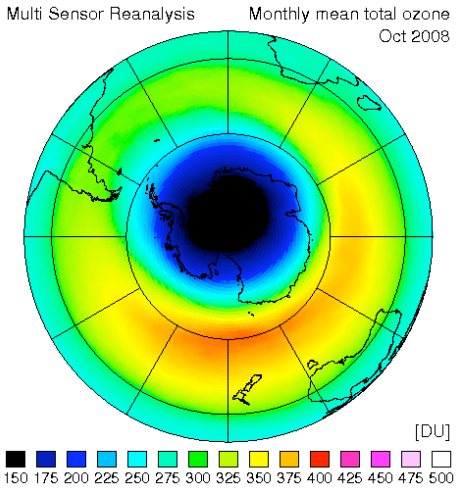

Reanalysis




Flux Inversions




Ozone records



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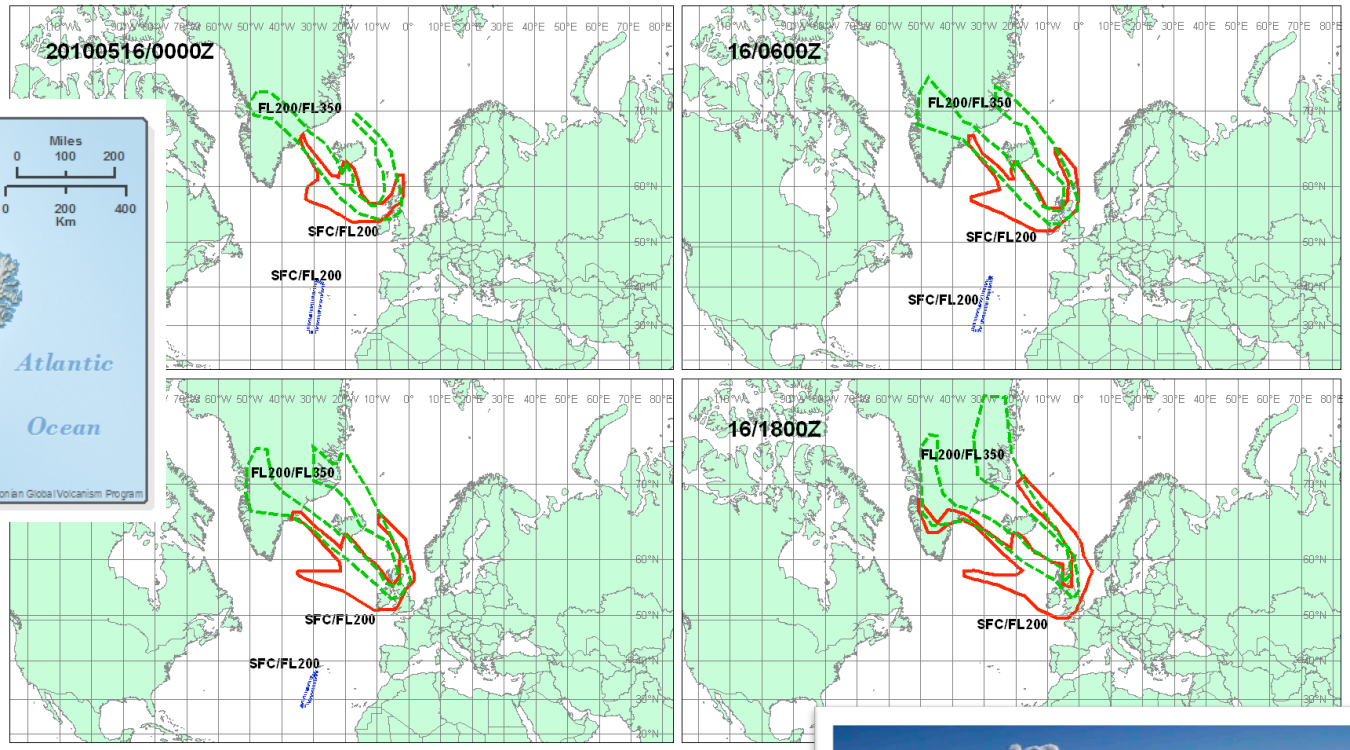
# Eyjafjallajökull eruption

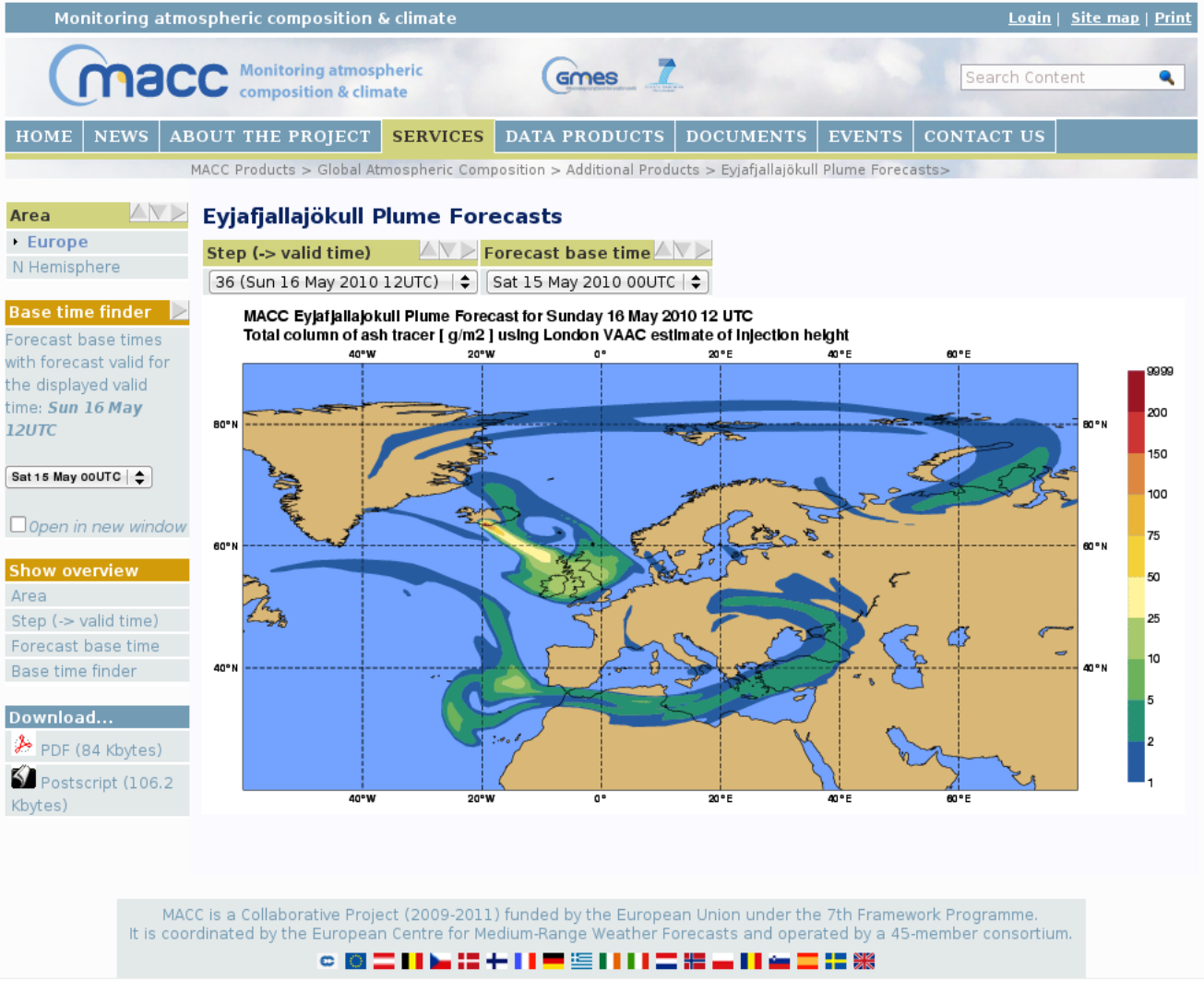

VA ADVISORY
DTG: 20100516/0000Z
VAAC: LONDON
VOLCANO:
EYJAFJALLAJOKULL 1702-02
PSN: N6338 W01937
AREA: ICELAND

SUMMIT ELEV: 1666M
ADVISORY NR: 2010/122
INFO SOURCE: ICELAND MET OFFICE
AVIATION COLOUR CODE: RED
ERUPTION DETAILS: ERUPTION CONTINUES WITH ESTIMATED PLUME TOPS BETWEEN FL190 AND FL230.

RMK:
NXT ADVIS

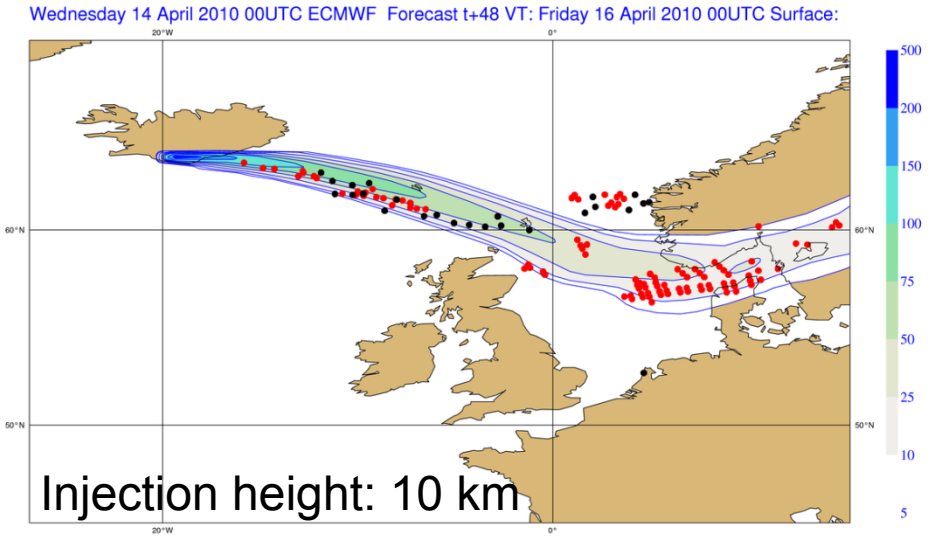
**London VAAC provided official plume forecasts using the NAME model verified with available observations.**

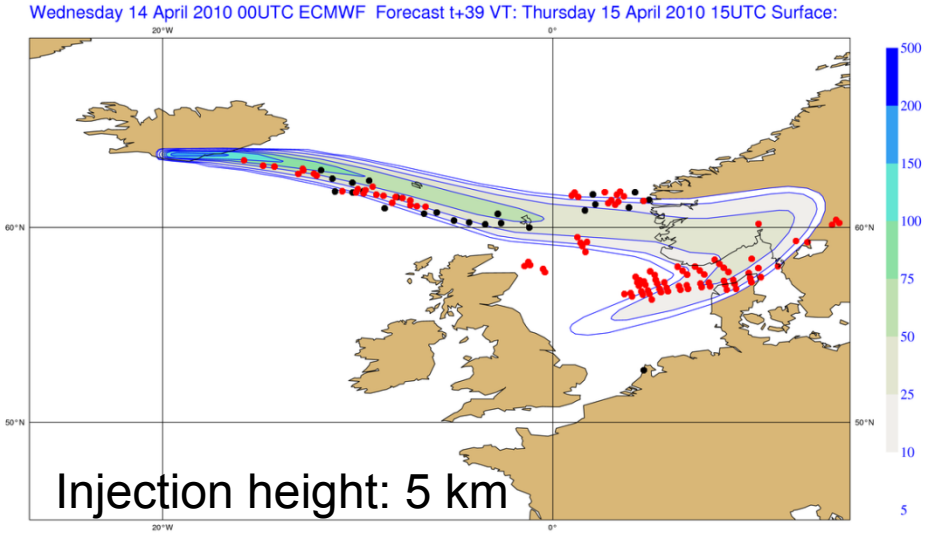
# Daily MACC forecasts



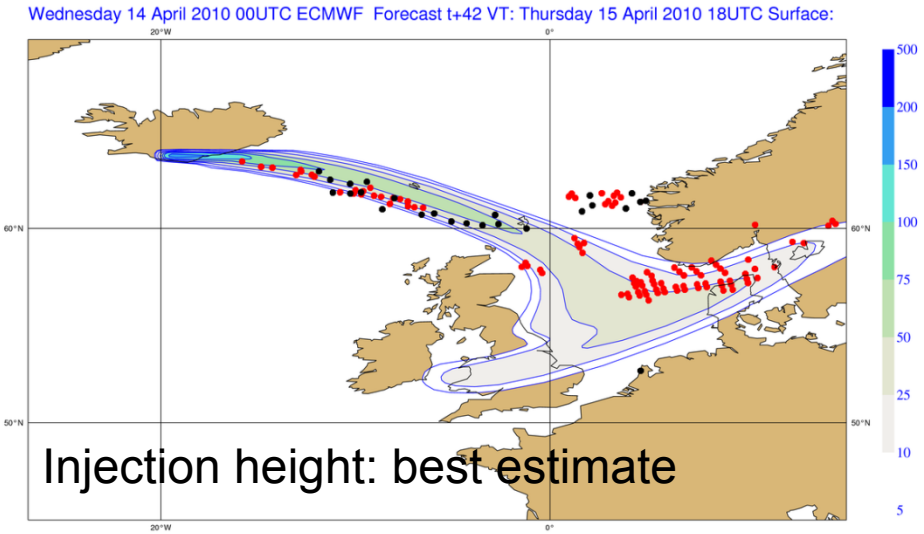

The global MACC system at ECMWF provided daily 4-day forecasts of the plume **shape** based on basic assumptions for the injection height and mass.

# Comparison with observations




ECMWF **AIRS** and **IASI** aerosol detection.

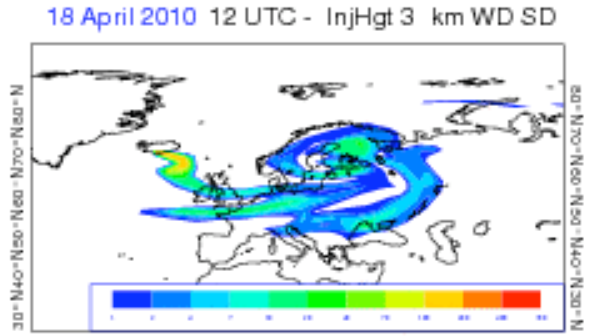



Various observations can be used to verify the plume forecasts and their assumptions

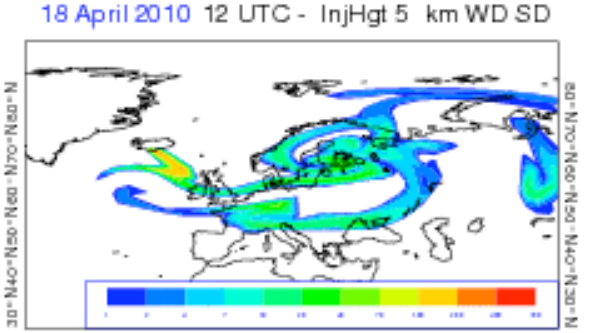
Courtesy of Reima Eresmaa and Tony McNally

# Effect of injection height

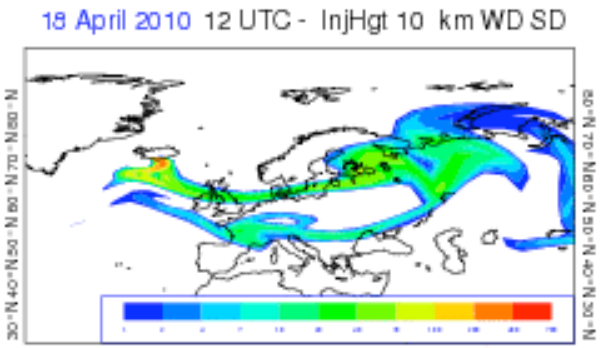
3 km




5 km




10 km

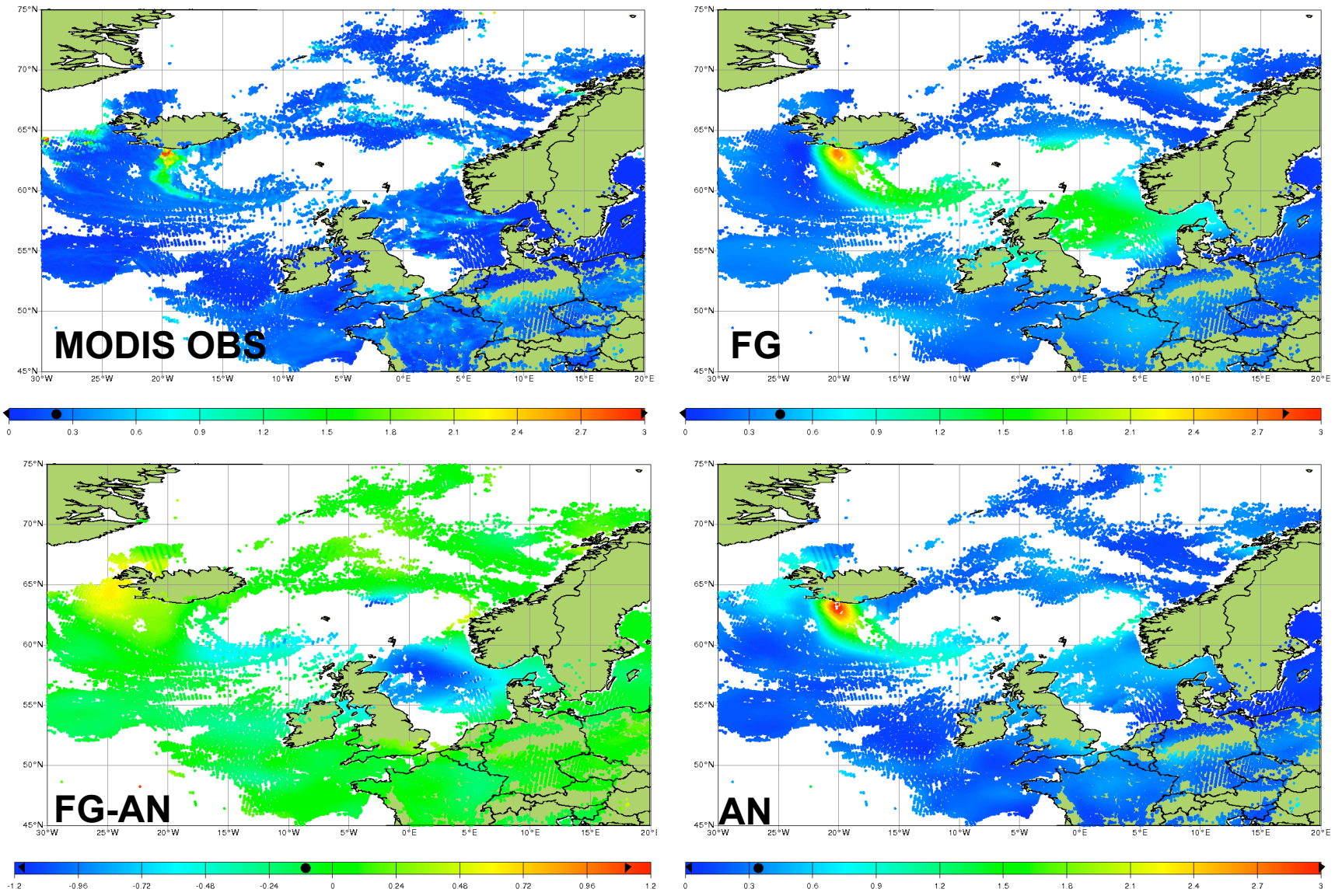



Most of the uncertainty in the plume forecasts is caused by the assumptions about the injection height.

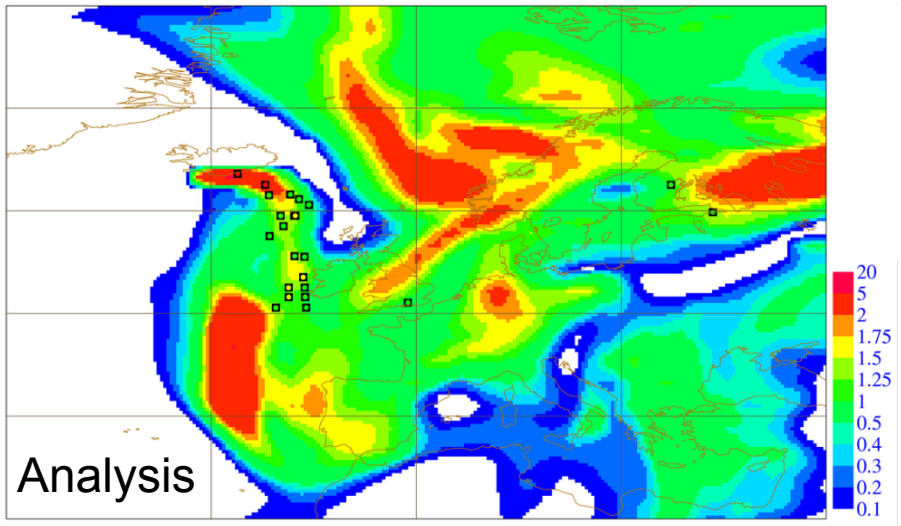
Assumptions about deposition processes have less of an impact.

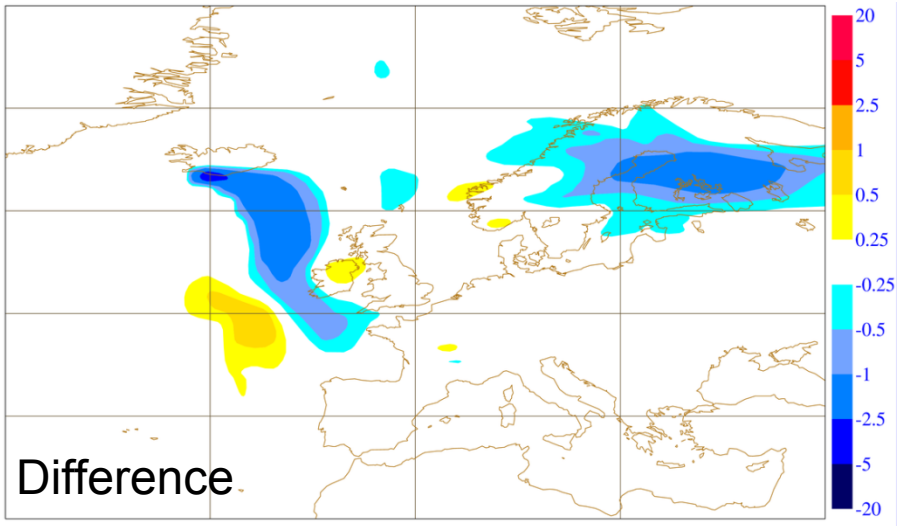
ECMWF will work with other modelling groups to improve plume modelling.

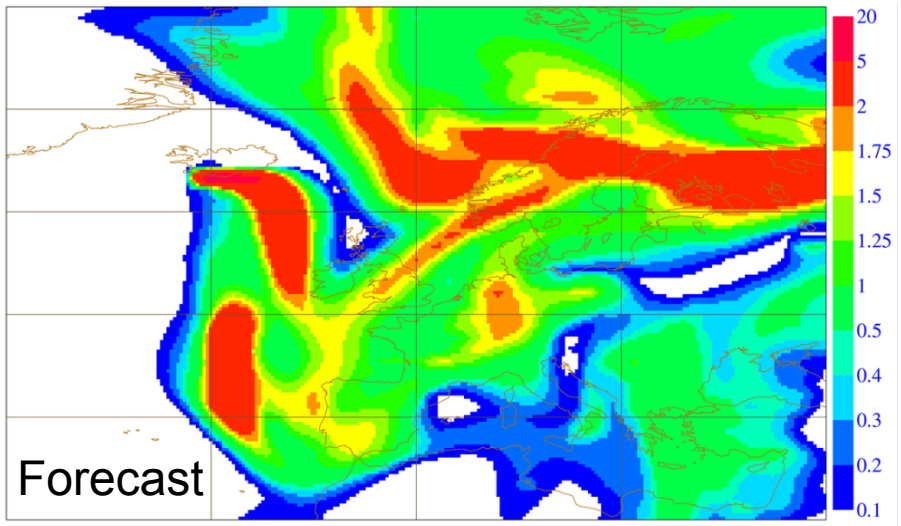
# Aerosol Assimilation



# $SO_2$ Assimilation




Assimilation of OMI data can potentially help to improve $SO_2$ plume forecasts, but is difficult because of small amount of observations and high noise levels.

Courtesy of Antje Inness

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# The ECMWF aerosol model

12 additional aerosol-related prognostic variables:
* 3 bins of sea-salt (0.03 – 0.5 – 0.9 – 20 $\mu$m)
* 3 bins of dust (0.03 – 0.55 – 0.9 – 20 $\mu$m)
* Black carbon (hydrophilic and –phobic)
* Organic carbon (hydrophilic and –phobic)
* $SO_2$ -> $SO_4$

Processes included are: emission sources from “standard” emission inventories (SPEW, EDGAR, etc.), horizontal and vertical advection by dynamics, vertical advection by vertical diffusion and convection, dry deposition, sedimentation, wet deposition by large-scale and convective precipitation, hygroscopicity (SS, OM, BC, SU)

*** Forward modelling: Morcrette et al.,2009, JGR**
*** Analysis including assimilation of MODIS tau550: Benedetti et al., 2009, JGR**

# 4D-var assimilation system for aerosols

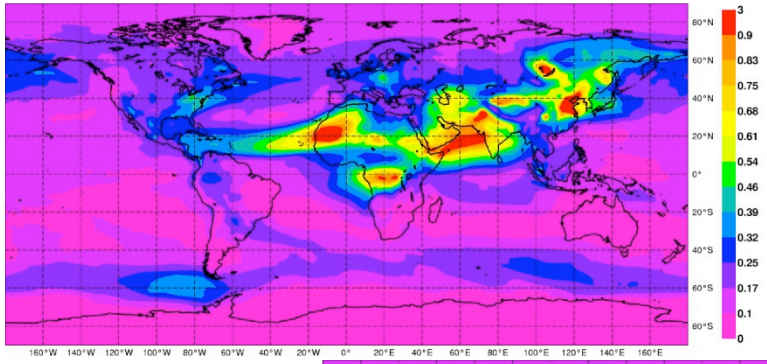
- The control variable is formulated in terms of the total aerosol mixing ratio. An additional control variable (fine mode mixing ratio) is under testing.

- Background error statistics have been computed using the NMC method.

- Assimilated observations: MODIS Aerosol Optical Depths (AODs) at 550 nm over land and ocean. Observation errors were initially prescribed as a percentage of the observed optical depth value (now changed to fixed value as a result of investigation on bias correction).

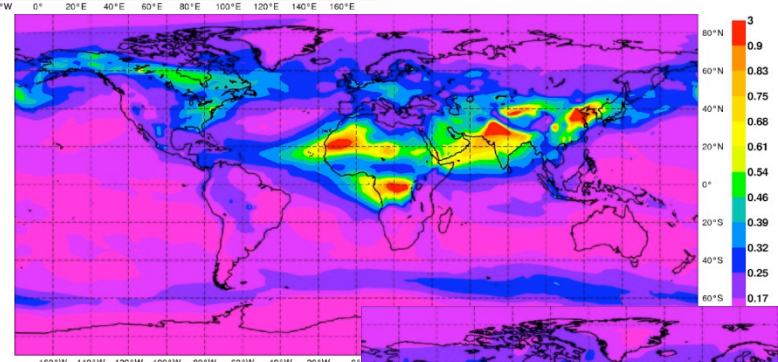
- Validation datasets: optical depths from the AErosol Robotic NETwork (AERONET) and aerosol backscattering from CALIPSO

# Total aerosol optical depth (from GEMS reanalysis)

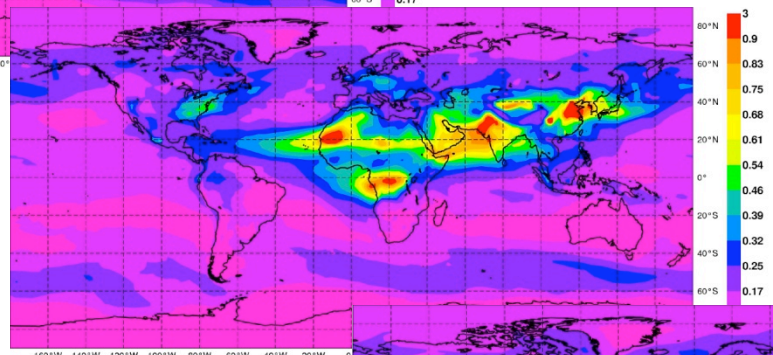



- **July 2003: AOD maxima over Siberia associated with wild fires.**
- **July 2004: presence of a large aerosol load in the North-West of America connected with pollution transport from East Asia.**

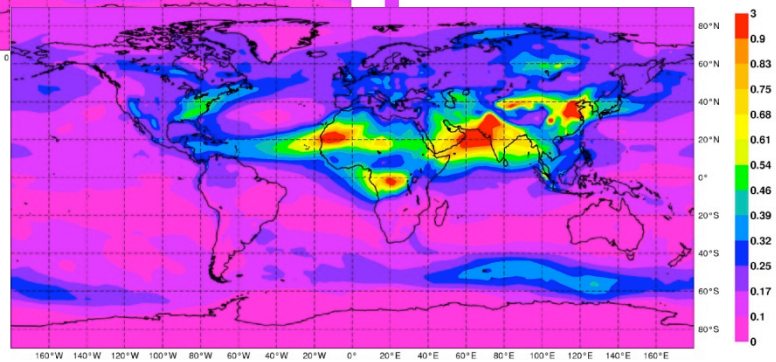
**July 2003**



**2004**



**2005**

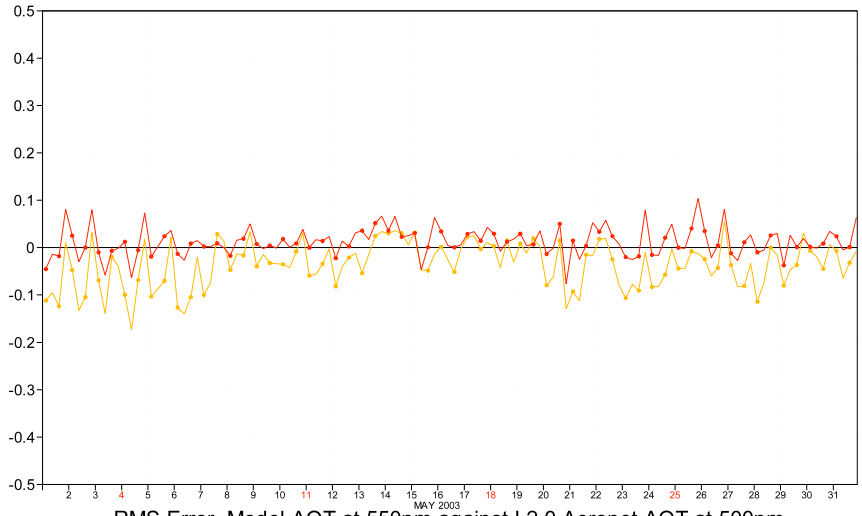


**2006**

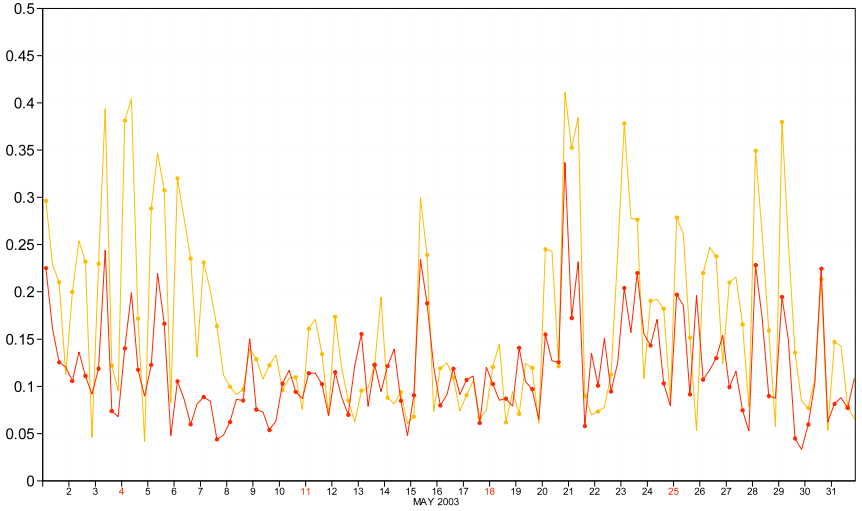
- **Biomass burning over West Africa and desert dust emissions from the Sahara are the main "constant" features**
- **Aerosol load in the Indian Ocean associated to strength of the monsoon**
- **The winter hemisphere usually presents larger values of AOD over the oceans connected to more intense circulation and increased production of maritime aerosols with inter-annual variability dependent on that of wind intensity at the ocean surface.**

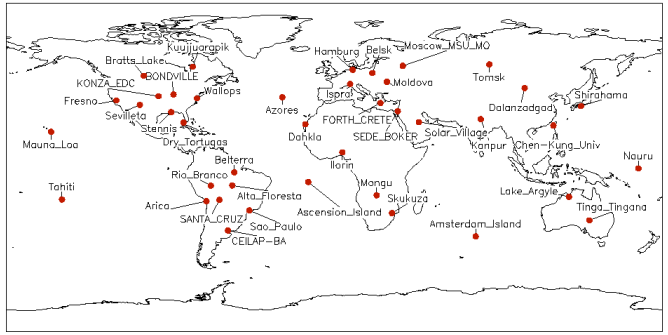
# Global comparisons with AERONET (May 2003)

FC-OBS Bias. Model AOT at 550nm against L2.0 Aeronet AOT at 500nm.
Meaned over 41 sites globally. Period=1-31 May 2003. FC start hrs=00,12Z.




RMS Error. Model AOT at 550nm against L2.0 Aeronet AOT at 500nm.
Meaned over 41 sites globally. Period=1-31 May 2003. FC start hrs=00,12Z.




**Analysis (red) shows lower bias and lower RMS wrt AERONET optical depths than free-running model**
**(dark yellow)**

**<u>Average bias (over 41 stations)</u>:**
**0.012 (ASSIM) vs -0.036 (FCST)**

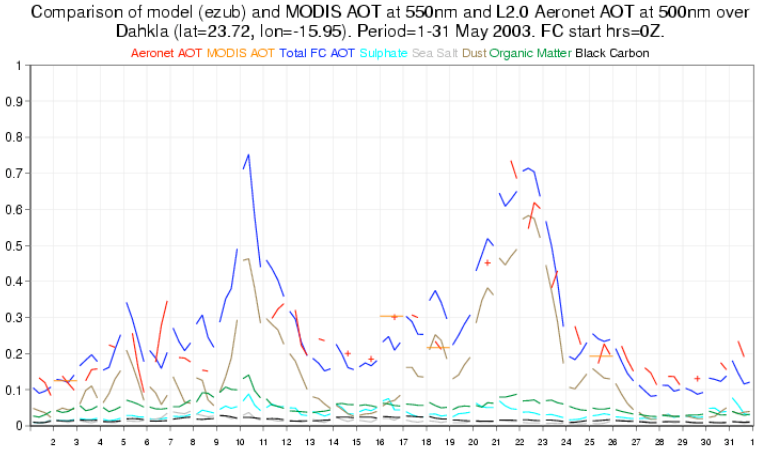
**<u>RMS</u>:**
**0.117 (ASSIM) vs 0.164 (FCST)**

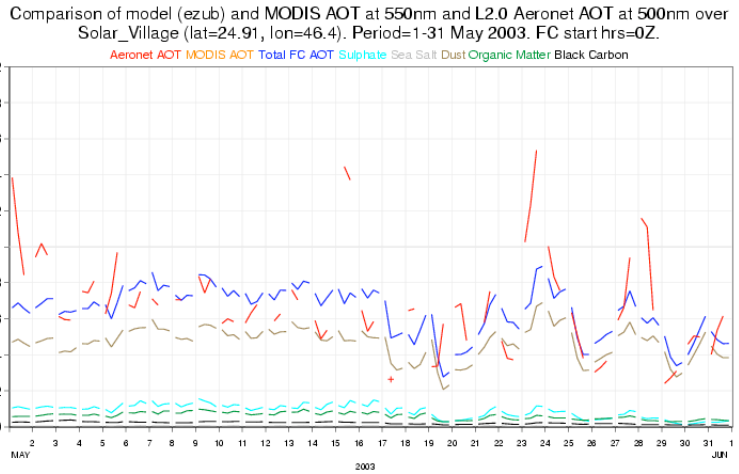
**Analysis**

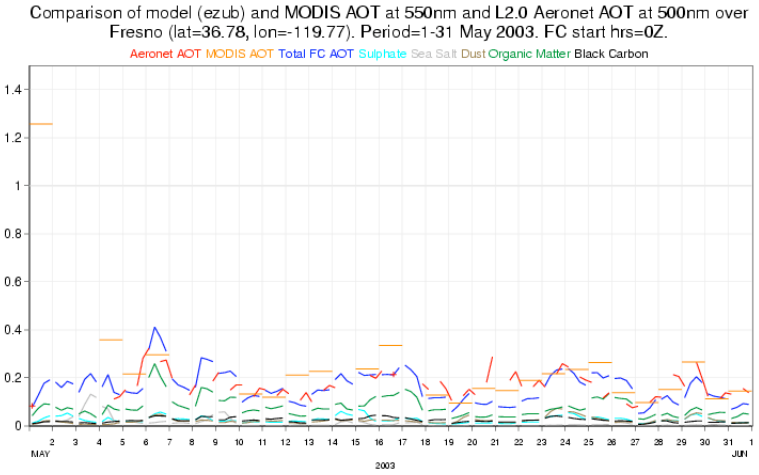
**Free-running forecast**

# AERONET site comparisons (May 2003)

- **Dust-dominated sites (Dakla and Solar Village) show good agreement between the analysis and AERONET despite the lack of MODIS data over these sites**



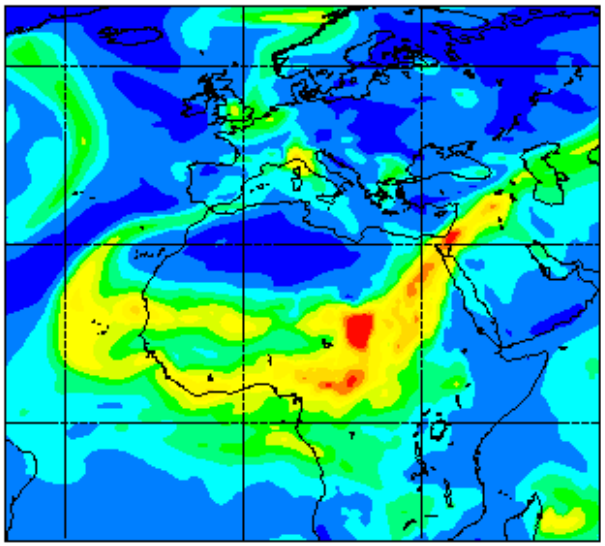

- **AERONET data for Fresno (CA) also confirm a good performance of the analysis**

**AERONET**
**MODIS AOD**
**MODEL AOD**

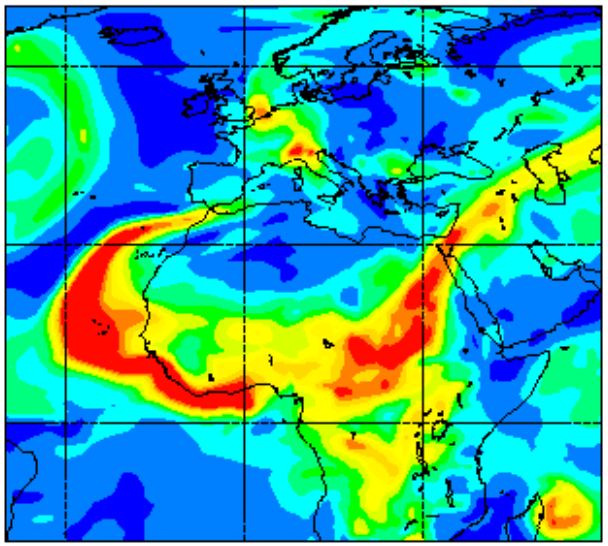
**Sulphate**
**Sea-salt**
**Dust**
**Organic Matter**
**Black carbon**

# Saharan dust outbreak: 6 March 2006

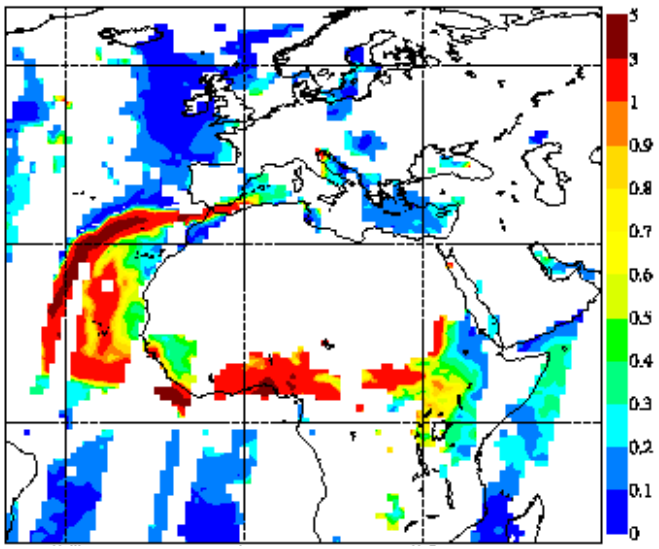
**Model simulation**



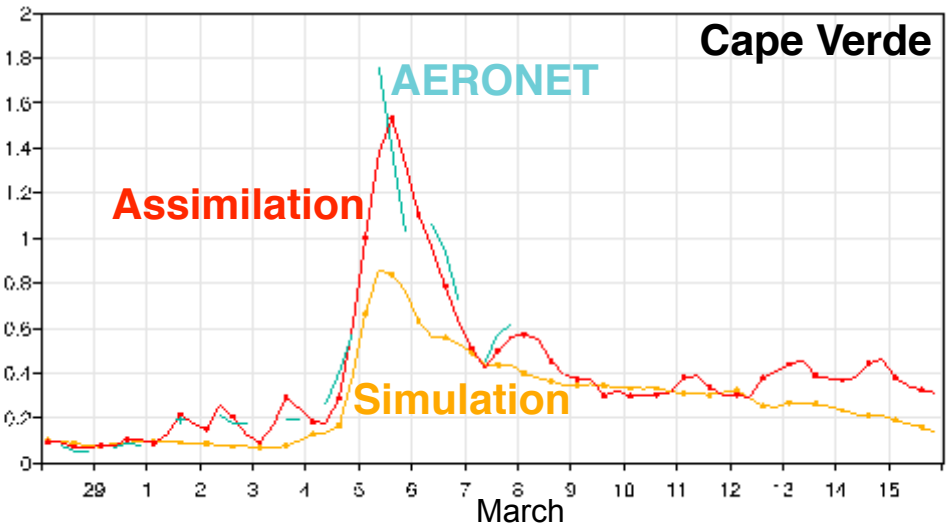
**Assimilation**

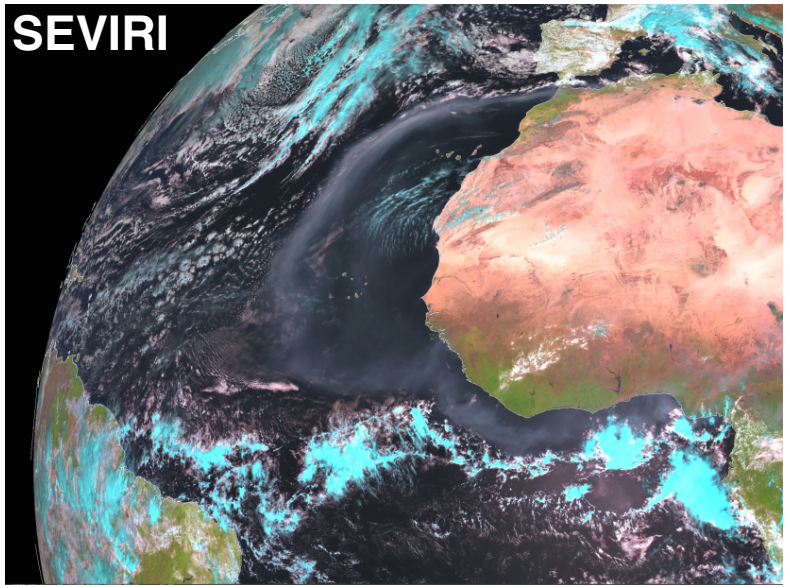


**MODIS**




**Aerosol optical depth at 550nm**



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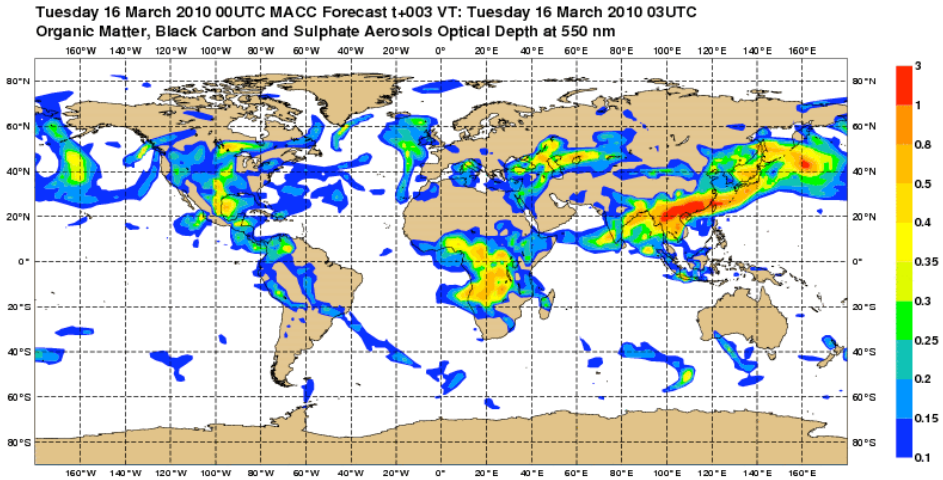
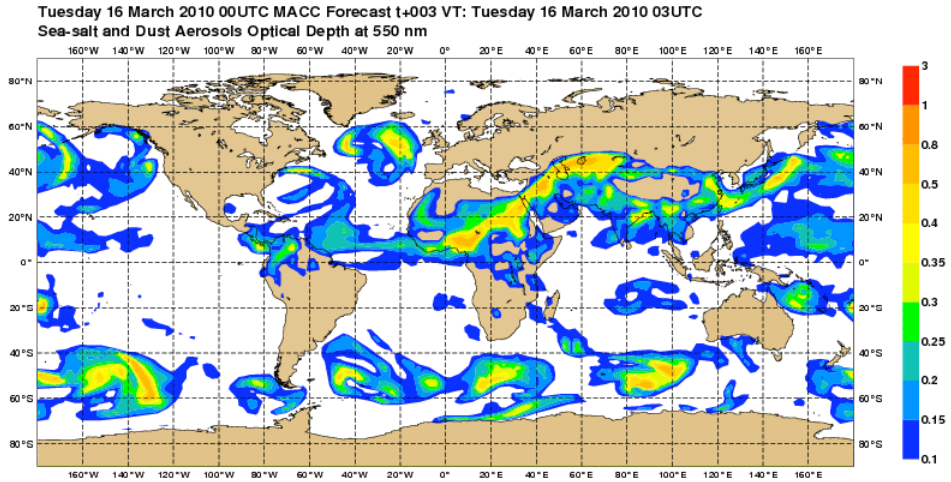
# Real time forecasts of atmospheric aerosol

## Anthropogenic aerosols



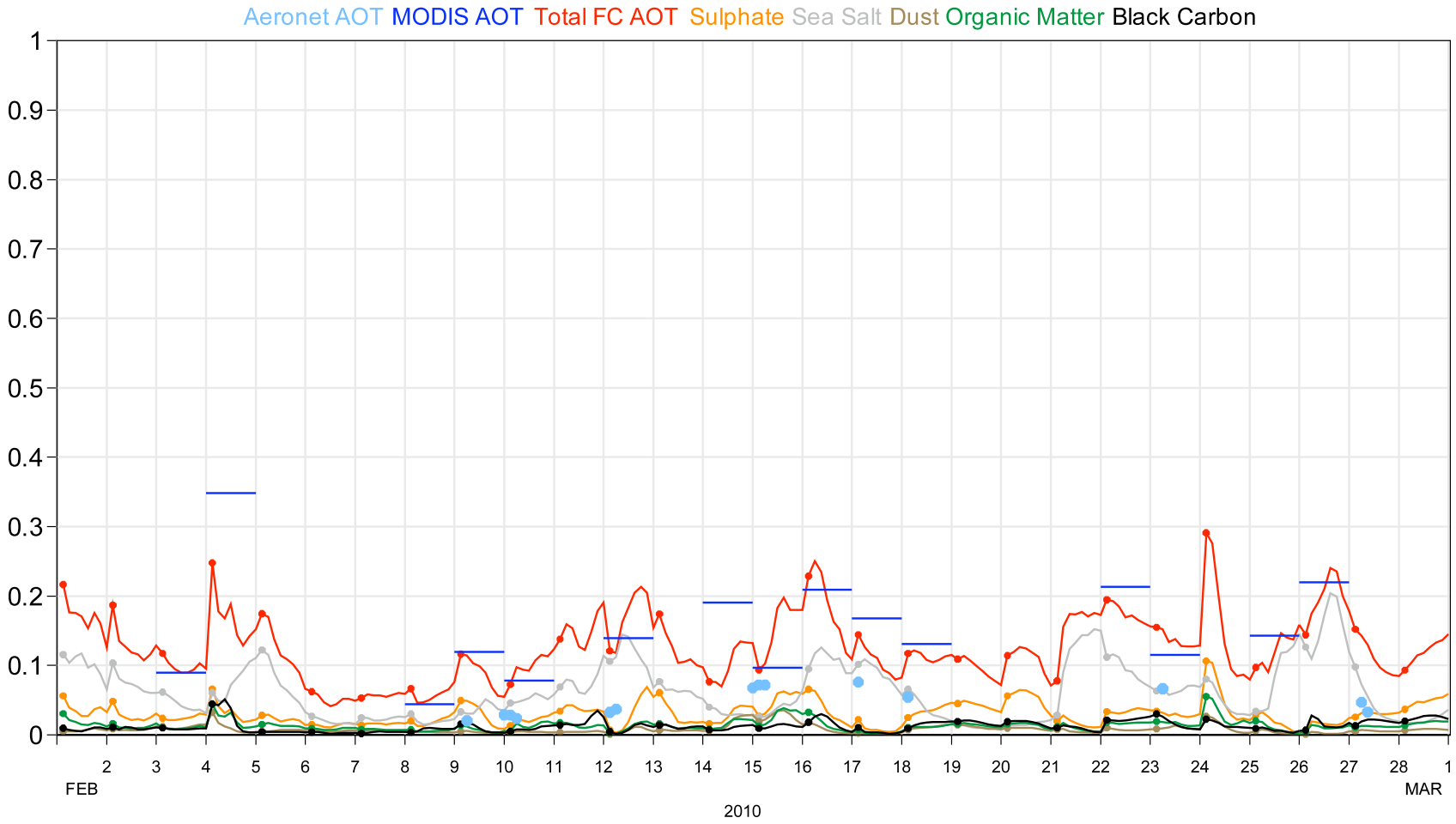

## Natural aerosols




**The same system developed for the multi-year reanalysis was used for the near-real time forecasts (with and without assimilation). The aerosol forecasts with assimilation of MODIS data have been running daily since July 2008.**

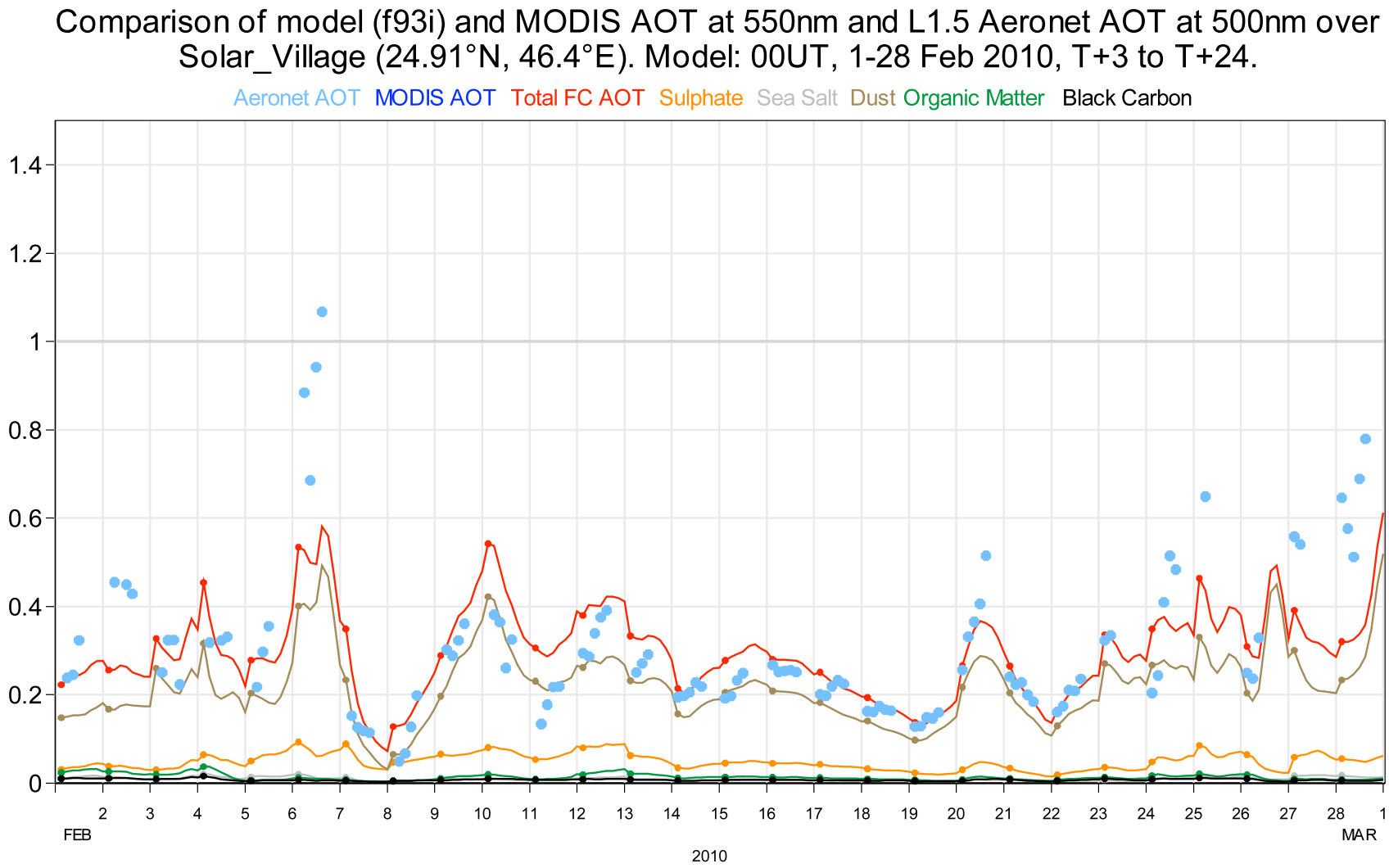
# AERONET site comparisons (February 2010)

Comparison of model (f93i) and MODIS AOT at 550nm and L1.5 Aeronet AOT at 500nm over Amsterdam_Island (37.81°S, 77.57°E). Model: 00UT, 1-28 Feb 2010, T+3 to T+24.



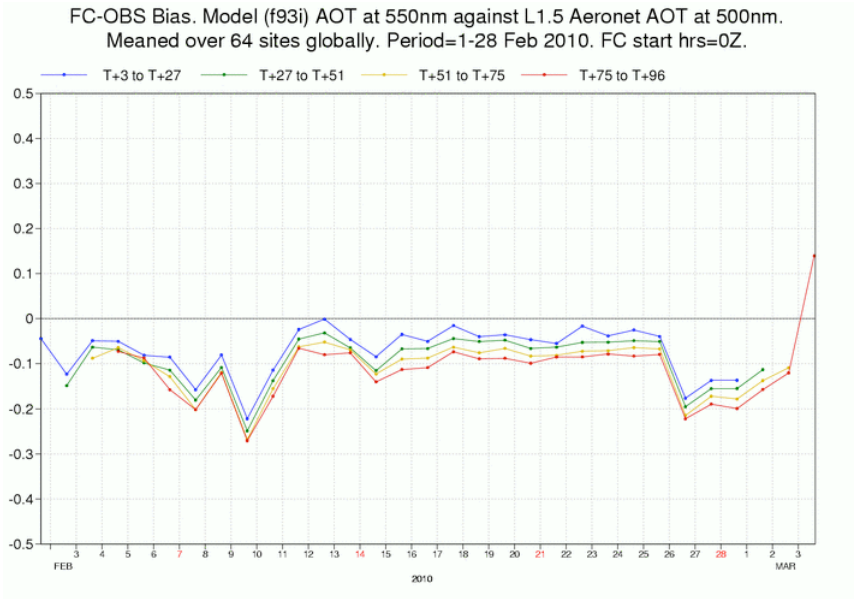

- **AERONET data for Amsterdam Island show that the analysis is driven by the MODIS observations and that the latter are biased with respect to AERONET.**

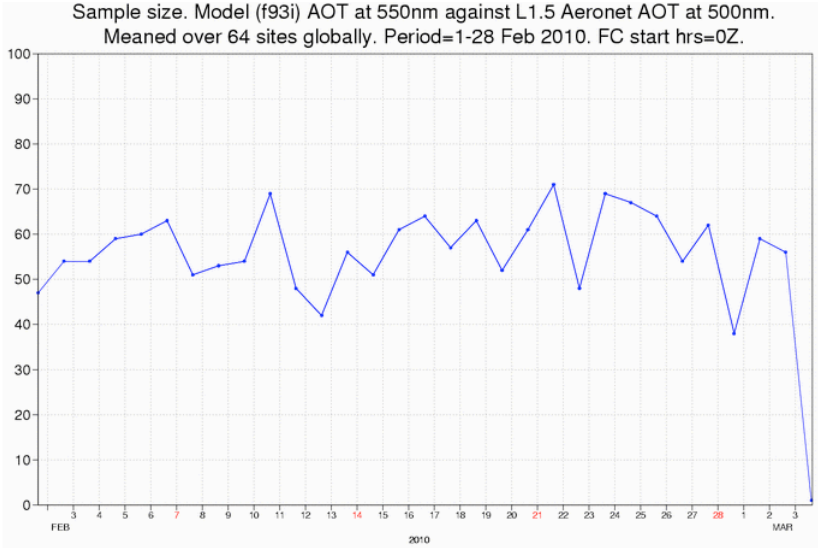
# AERONET site comparisons (February 2010)

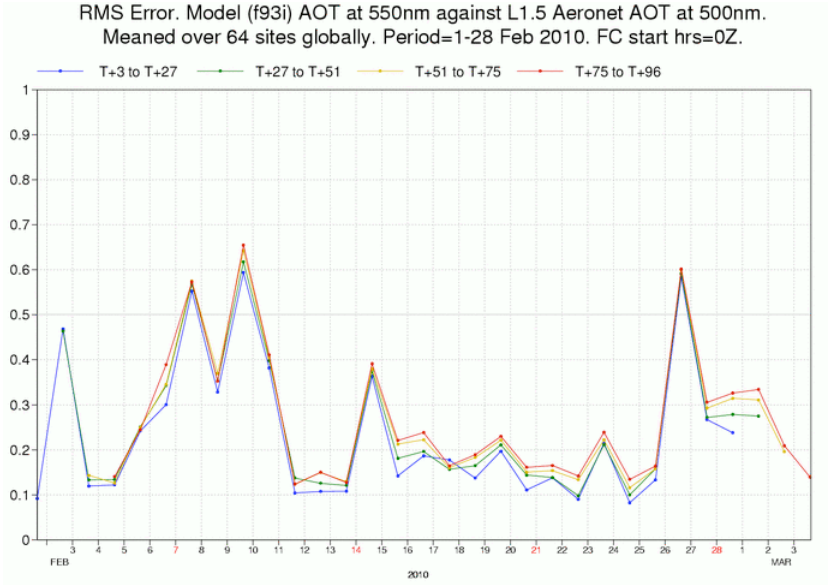



- **Dust-dominated site (Solar Village) show good agreement between the analysis and AERONET despite the lack of MODIS data over this type of sites**

# Forecast range verification (24h means, Feb 2010)



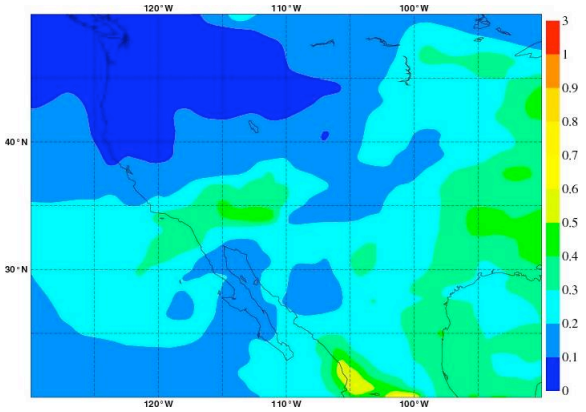




- **Bias increases with forecast range**
- **Less noticeable on the RMS**

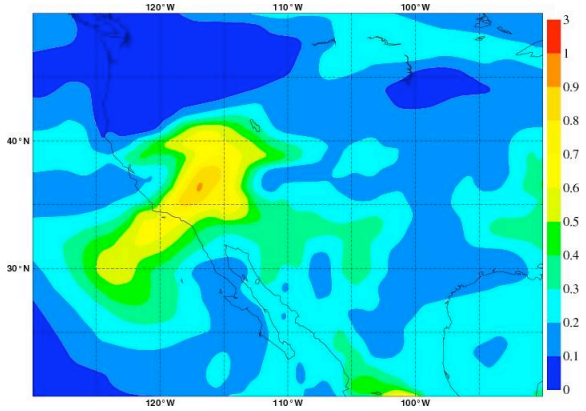
**Day 1**
**Day 2**
**Day 3**
**Day 4**

# California fires of July 2008 from the near real-time forecast

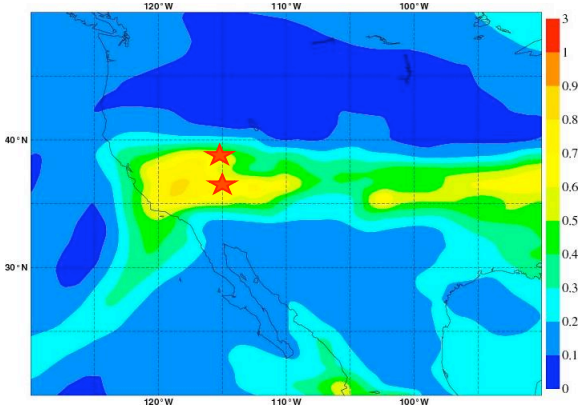
**Free running forecast for July 11, 06UTC**



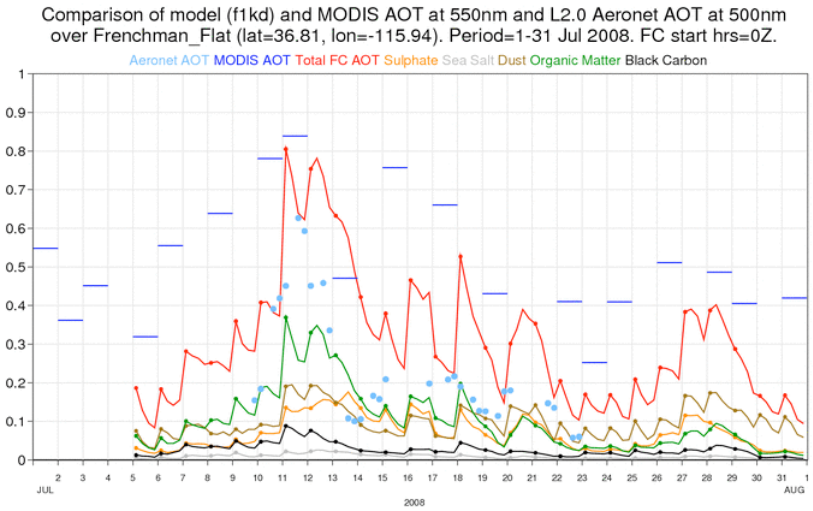

**Forecast from AN for July 11, 06UTC**

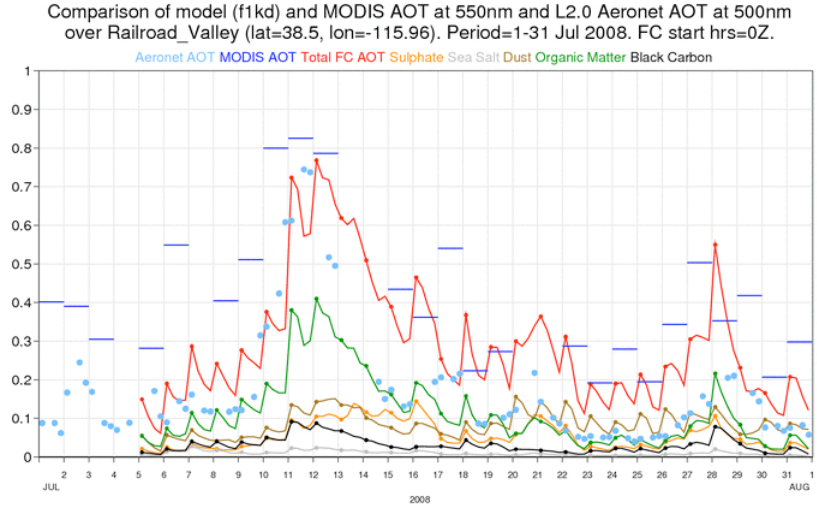



**Forecast from AN for July 14, 00UTC**




**Verification using downwind AERONET stations ★**



# Sydney dust storm, 23-09-09

BBC Low graphics | Help

NEWS LIVE BBC NEWS CHANNEL

News Front Page

Page last updated at 10:42 GMT, Wednesday, 23 September

## Desert dust storm chokes Sydney


Sydney's red dust has been blown from the outback

**A large stretch of Australia's east coast, including the largest city Sydney, has been shrouded in red dust blown in from the desert outback.**

Visibility in Sydney was so bad that flights were diverted and harbour ferry traffic disrupted.

ABC News — NewsRadio — Now playing — Video

News Home | Just In | Australia | World | Business | Entertainment | Weather

DUST STORM Video, your pics and comments

Print Email Share Add to My Stories

## Dept admits error in air quality forecast

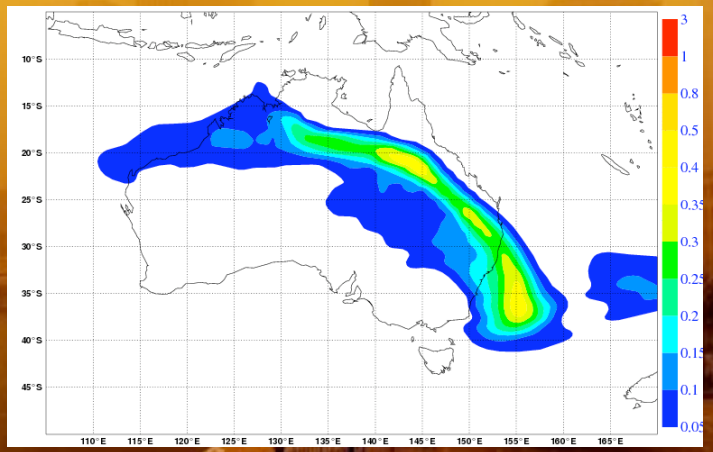
Posted 11 hours 54 minutes ago
Updated 11 hours 51 minutes ago

**The New South Wales Environment Department has admitted its forecast for air quality in Sydney today was wildly wrong after a dust storm prompted hundreds of emergency calls due to breathing difficulties.**

**Audio:** Respiratory expert Dr Christine Jenkins speaks to ABC Local Radio (ABC News)

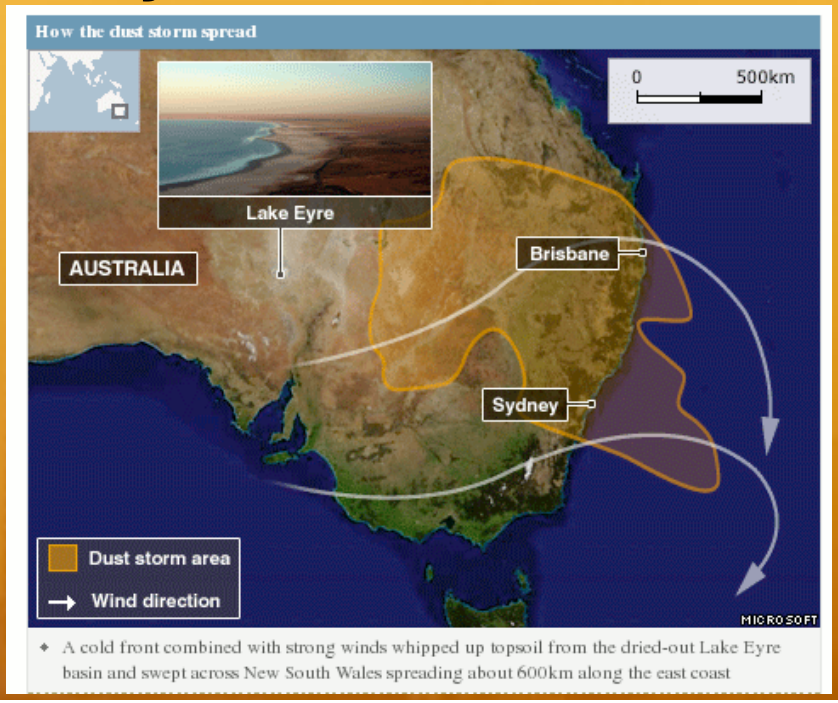
Until this morning, the department's website was forecasting conditions would be good.

**24h forecast for Wednesday 23, September, 00UTC**



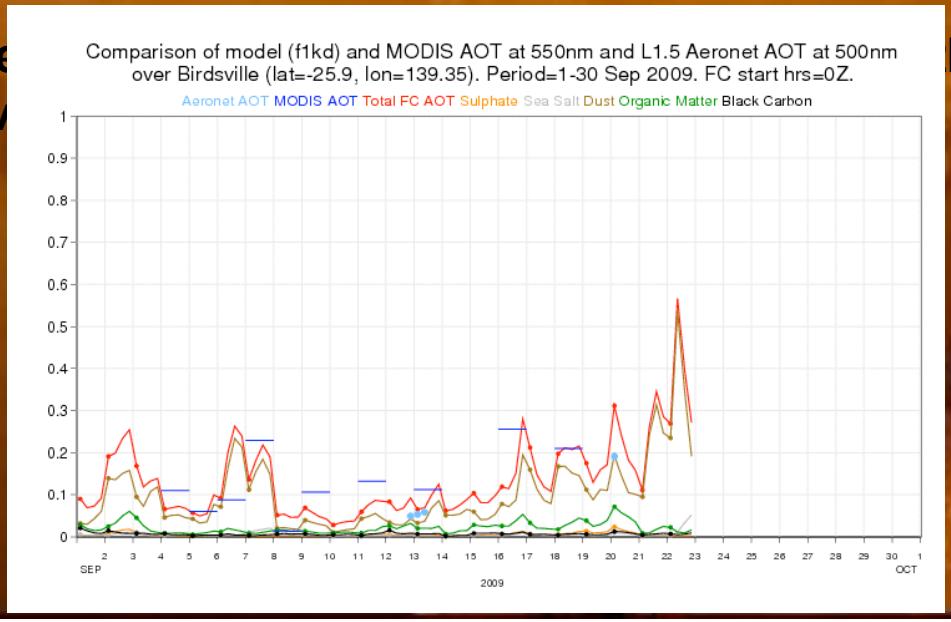

AFP

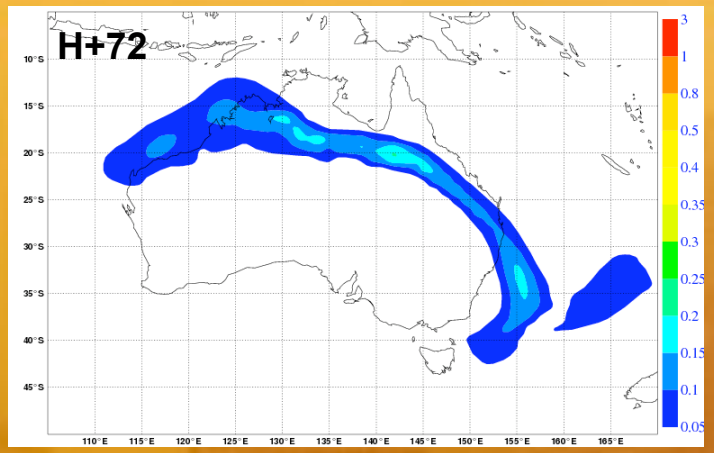
# Sydney dust storm, 23-09-09

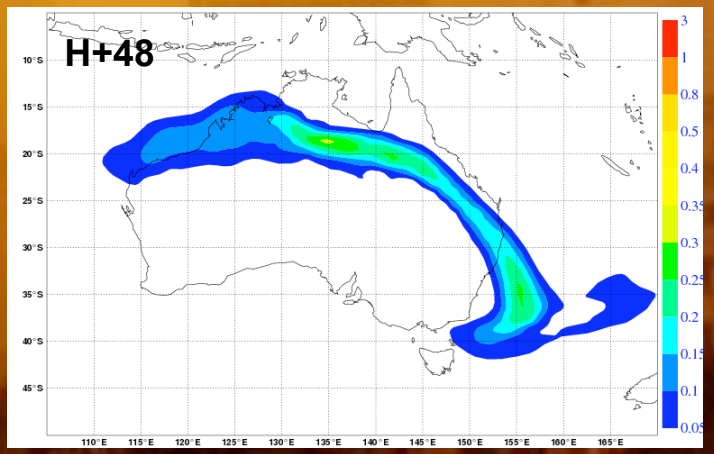


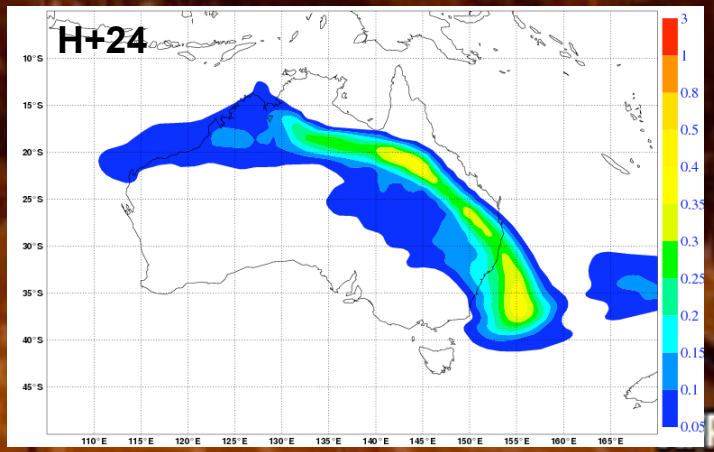

- A cold front combined with strong winds whipped up topsoil from the dried-out Lake Eyre basin and swept across New South Wales spreading about 600km along the east coast

Ae hly
av



# Dust warning system

## Huge sandstorm covers Beijing, turns sky orange

Associated Press

Buzz up! 76 votes | Send | Share | Print

By CARA ANNA, Associated Press Writer – Sat Mar 20, 12:38 pm ET

Reuters – Tourists wearing face masks stand amid a sandstorm on Tiananmen Square in Beijing March 20, 2010. REUTERS/Grace ...

Slideshow: **China Sandstorms**

BEIJING – Tons of sand turned Beijing's sky orange as the strongest sandstorm this year hit northern China, a gritty reminder that the country's expanding deserts have led to a sharp increase in the storms.

The sky glowed Saturday and a thin dusting of sand covered Beijing, causing workers and tourists to muffle their faces in vast Tiananmen Square. The city's weather bureau gave air quality a rare hazardous ranking.

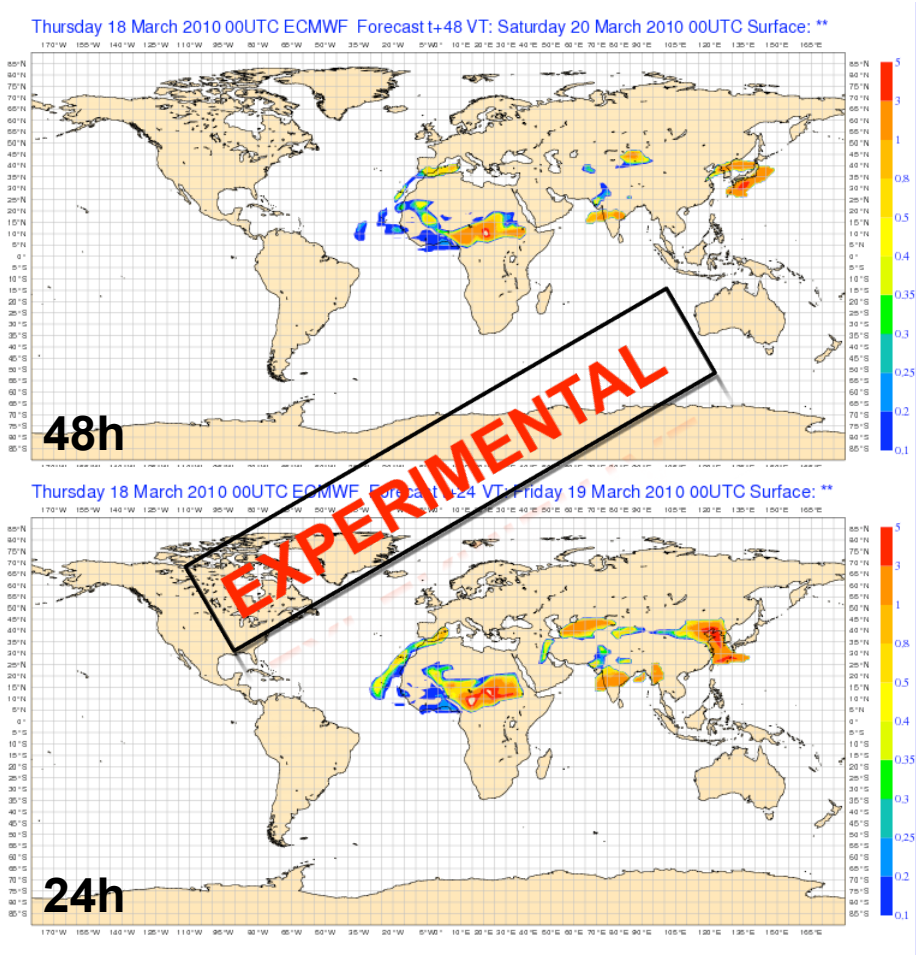
Air quality is "very bad for the health," China's national weather bureau warned. It said people should cover their mouths when outside and keep doors and windows closed.

China's expanding deserts now cover one-third of the country because of overgrazing, deforestation, urban sprawl and drought. The shifting sands have led to a sharp increase in sandstorms — the grit from which can travel as far as the western United States.

The Chinese Academy of Sciences has estimated that the number of sandstorms has jumped six-fold in the past 50 years to two dozen a year.

Beijing's Tiananmen Square was shrouded in orange dust

## Dust Index




**Index = absolute( (forecast AOD - mean AOD)/(std. dev. AOD)) * (forecast AOD)**

Standard deviation and mean AOD are calculated for every month of the years 2008 and 2009 which are used as reference.

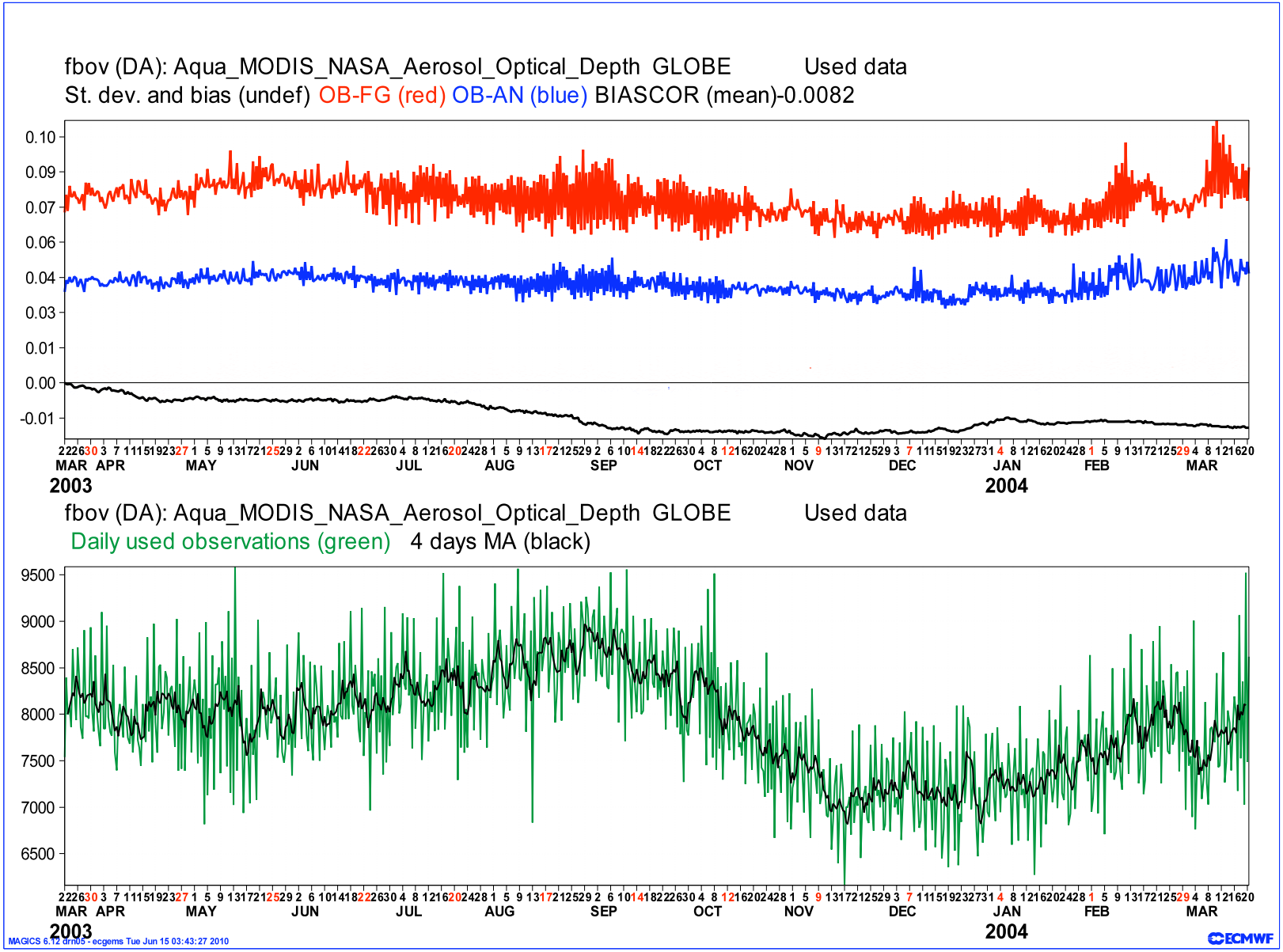
# Outline

- General introduction
- Special topic: Eyjafjallajokull eruption
- Brief technical overview of the aerosol modelling and analysis system
- Results from retrospective reanalysis (2003-2009)
- Near-real time aerosol forecasts
- Dust warning system
- Work in progress and future developments

# Recent developments

- **Model improvements contributed greatly to improving the analysis**
- **Modifications in observation errors also contributed to a better analysis performance. In general, specification of observation errors proved to be FUNDAMENTAL (example from the assimilation of SEVIRI AOD data in collaboration with Carole Peubey).**
- **Aerosol assimilation system has been shown to be flexible in regards to the inclusion of AOD observations at 550nm from different sensors (AATSR, SEVIRI, ground-based AERONET observations).**
- **Assimilation of AOD from sensors other than MODIS has emphasized the need for a bias correction. This has been recently implemented using the same approach which is adopted for radiance and ozone data (variational estimation of bias parameters). Work on the bias correction has shown weaknesses in the error assumptions both on background and observations.**
- **Dual control variable is being put in place to benefit from assimilation of fine mode aerosol optical depth.**
- **Quantitative use of CALIPSO data for verification.**
- **Lidar assimilation of aerosol backscatter is being developed in the context of the ESA project QuARL (1D-Var to be extended to full 4D-Var system in the next years).**

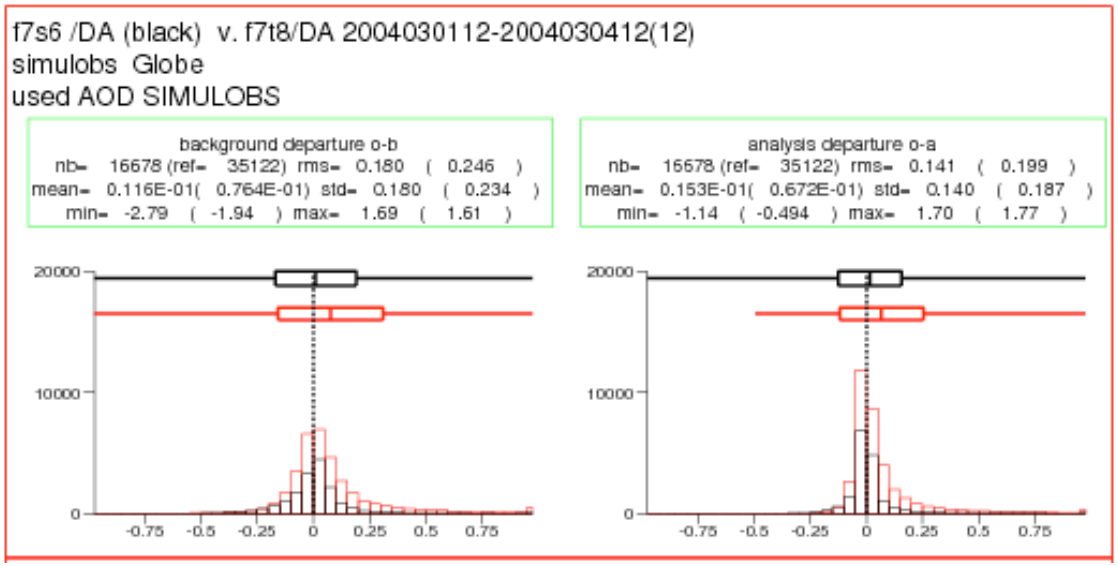
# Monitoring First Guess /Analysis departures and bias



# Assimilation of SEVIRI optical depths:

## Importance of the observation errors and quality control

**observation errors fixed at 30% (red) of the AOD vs errors provided with retrieved AOD (black)**



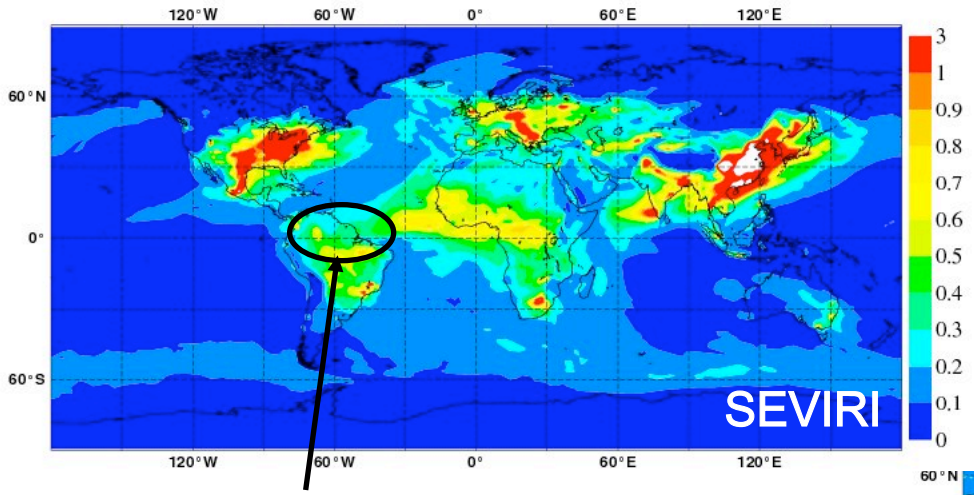

**Obs-first-guess** **Obs-analysis**

**→ more desirable first-guess and analysis departure distributions with the retrieval errors: smaller bias and more Gaussian shape compared to using the errors of 30 %.**

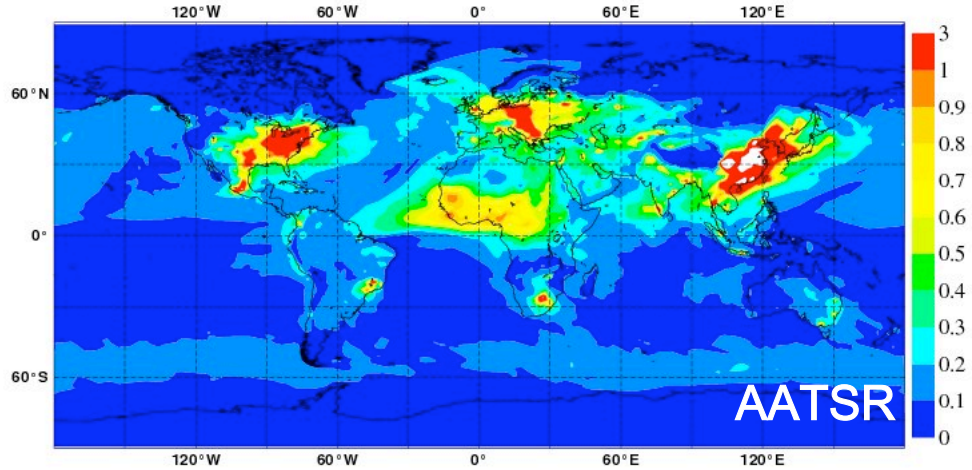
**→ the number of assimilated data in the retrieval error case is half that of the 30% error case.**

Work by: Carole Peubey

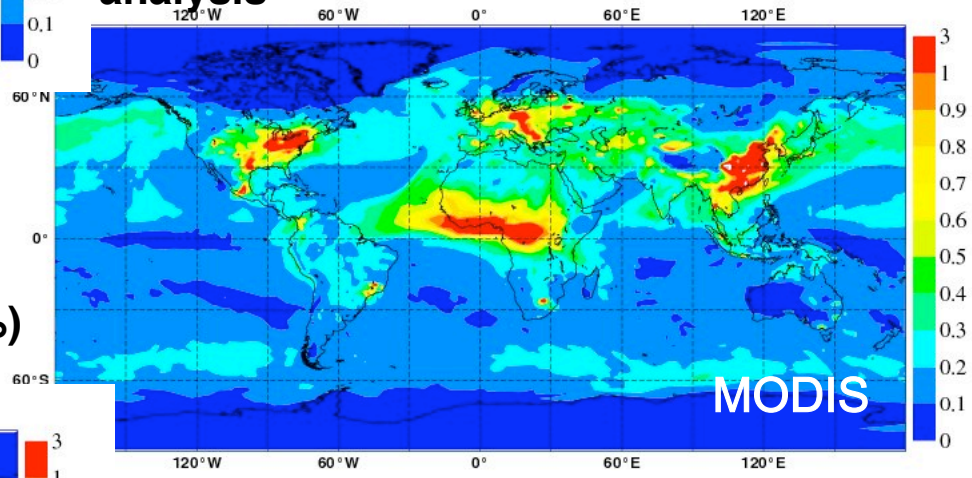
# Assimilation of SEVIRI and AATSR AOD (March 2-15, 2004)




- Spurious values over the Amazon in the SEVIRI dataset
- AODs capped to 2
- Same prescribed observation error (30%)




- Large discrepancies over equatorial West-Africa where MODIS AOD are higher
- Generally higher background aerosol load over the ocean in MODIS - could be related to coverage
- Lower AOD values over CHINA in MODIS analysis




- Technical feasibility was demonstrated
- More scientific investigation is needed
- Runs will be repeated with upgraded model version with a bugfix for sulphate description.

# Dual aerosol control variable

- Additional control variable in the control vector (fine mode aerosol mixing ratio defined as the sum of the first bin of sea-salt, first bin of desert dust, black carbon, organic matter, and SO4).

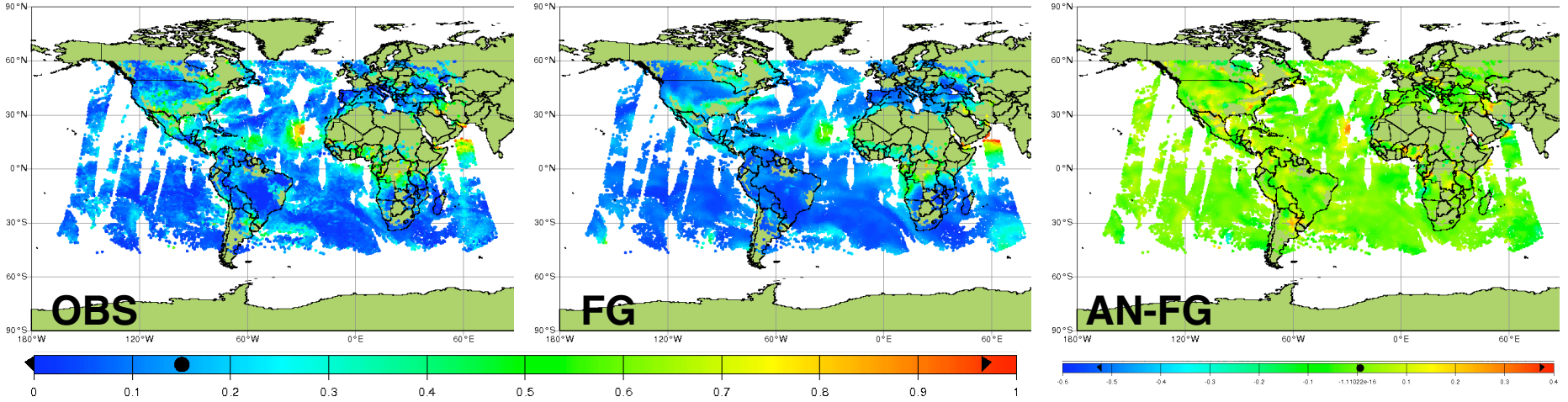
- MODIS observations of fine AOD are only used over ocean

- Total AOD is also used to constrain the total aerosol mixing ratio. Same error as for fine AOD (0.05).

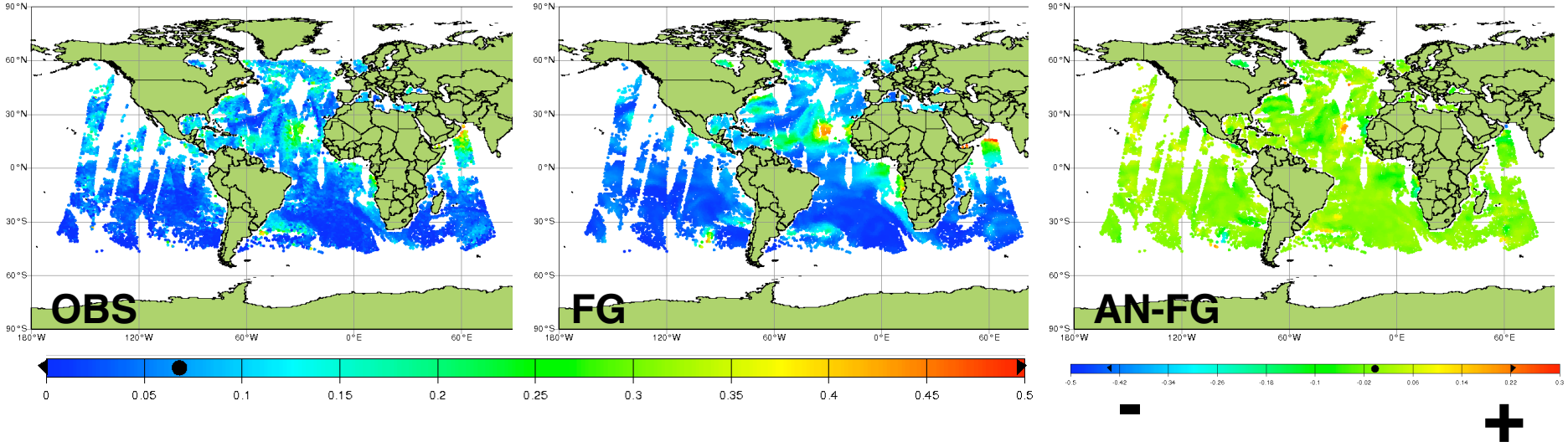
- Correlations between the two control variables are not accounted for – work in progress, plans to put a “balance” operator for aerosol mixing ratio.

# Assimilation of MODIS fine mode aerosol optical depth (July 2007)

## TOTAL

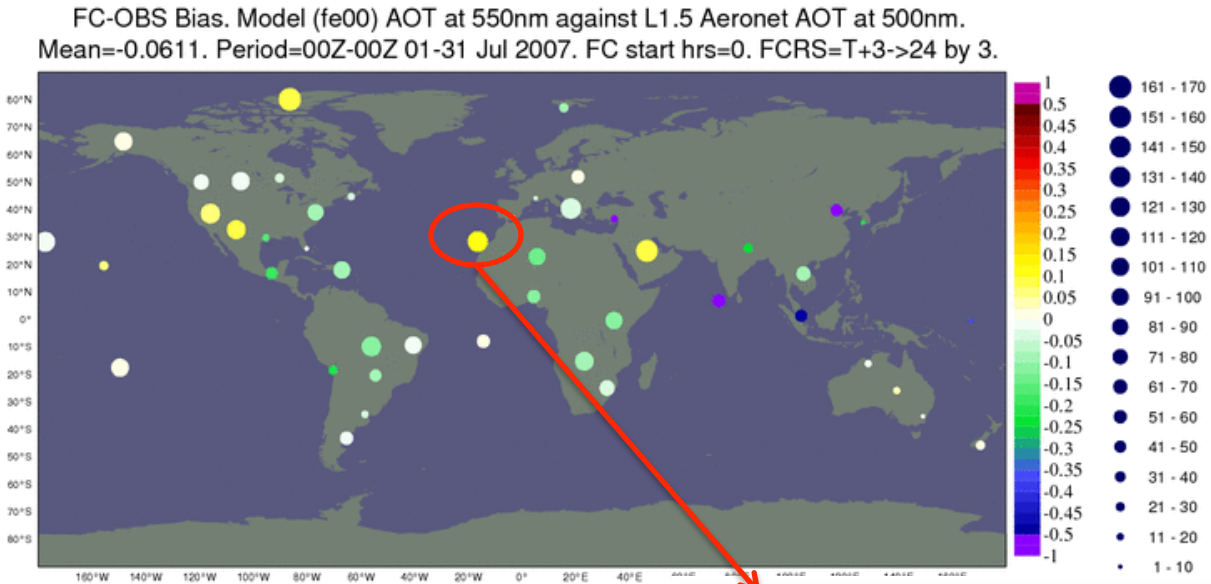



## FINE MODE



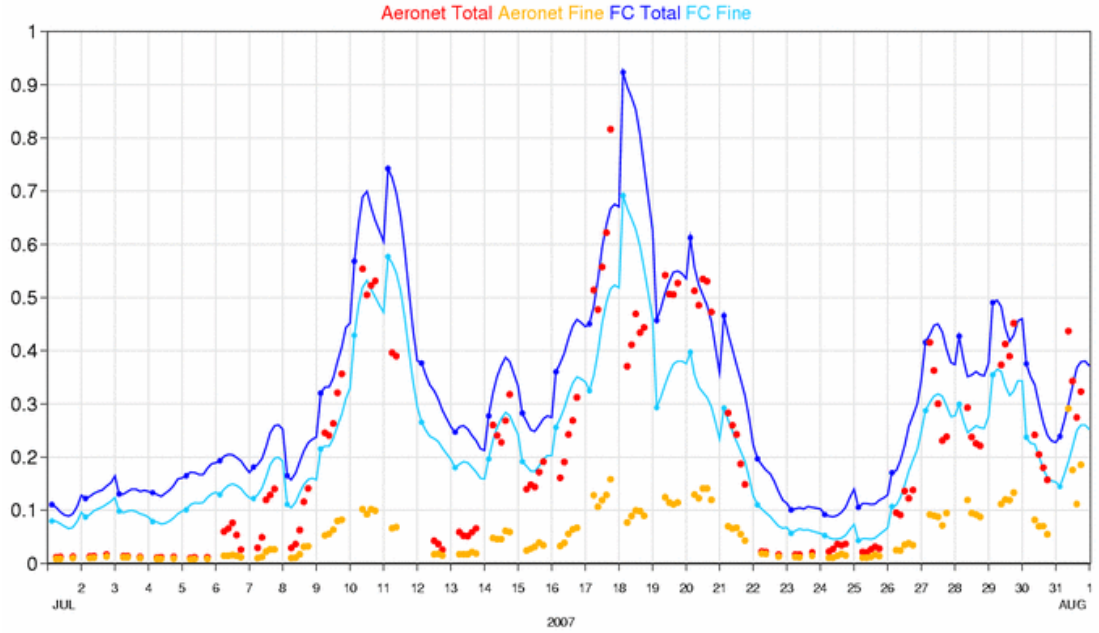

**Analysis is not able to correct in the right direction both fine and total AOD in certain areas.**

# Verification of fine mode aerosol optical depth (AERONET)



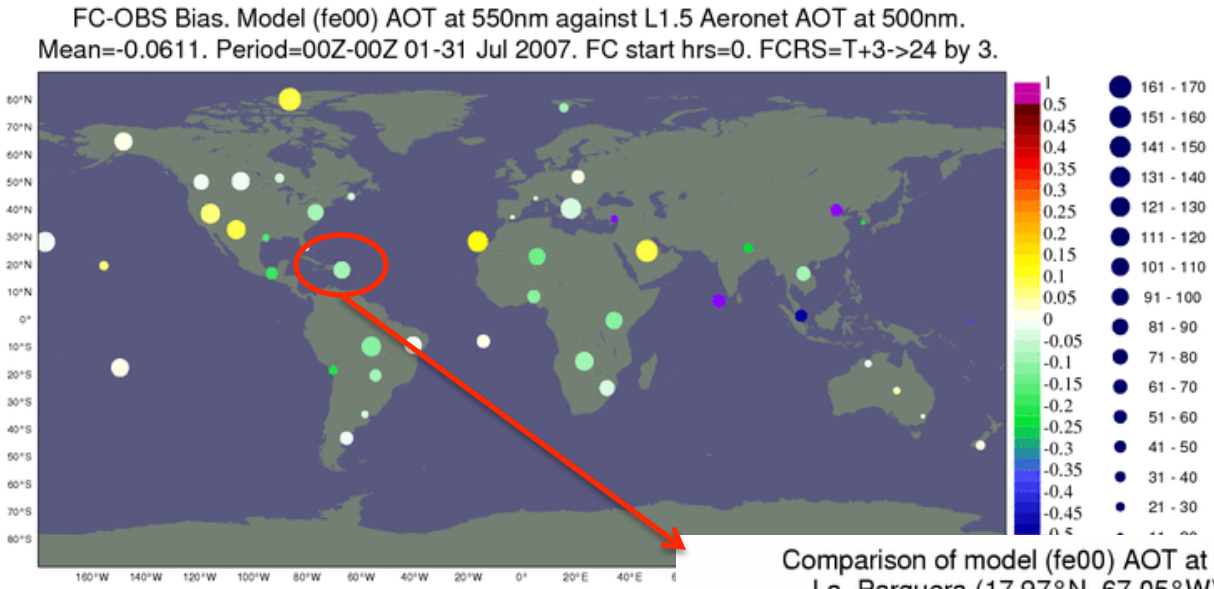

RMS Error. Model (fe00) AOT at 550nm against L1.5
Mean=0.318. Period=00Z-00Z 01-31 Jul 2007. FC start

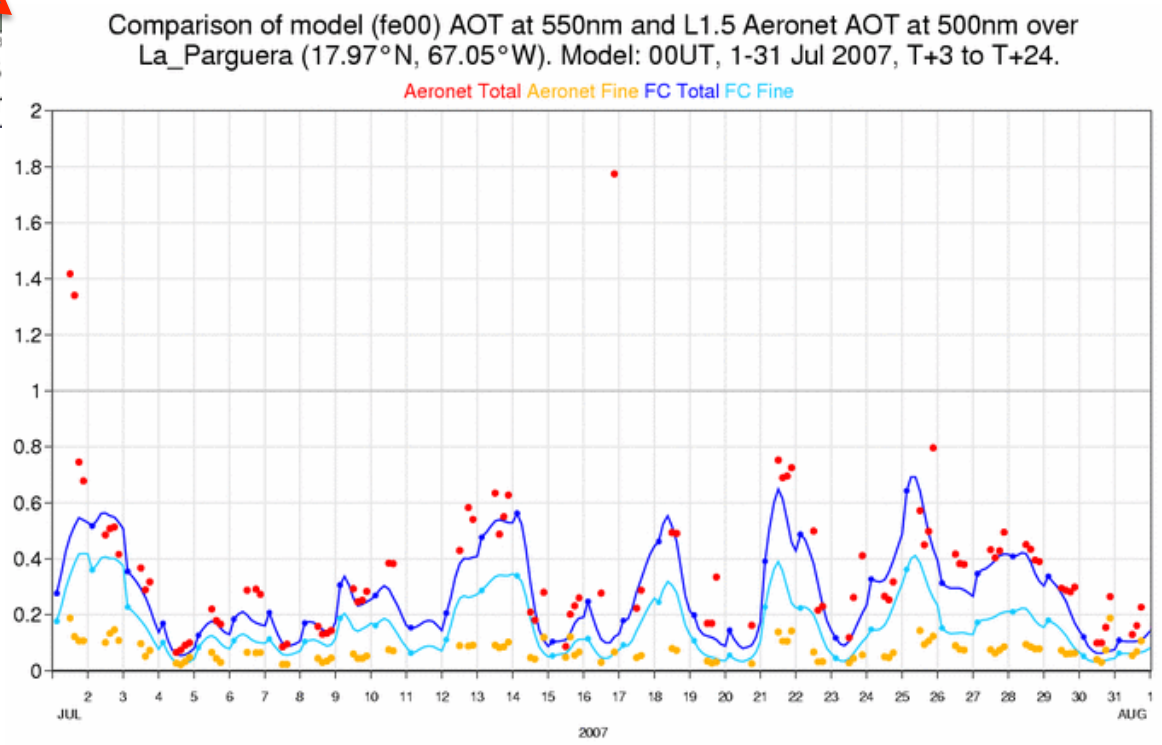
Comparison of model (fe00) AOT at 550nm and L1.5 Aeronet AOT at 500nm over Izana (28.31°N, 16.5°W). Model: 00UT, 1-31 Jul 2007, T+3 to T+24.




**Thanks to Luke Jones**

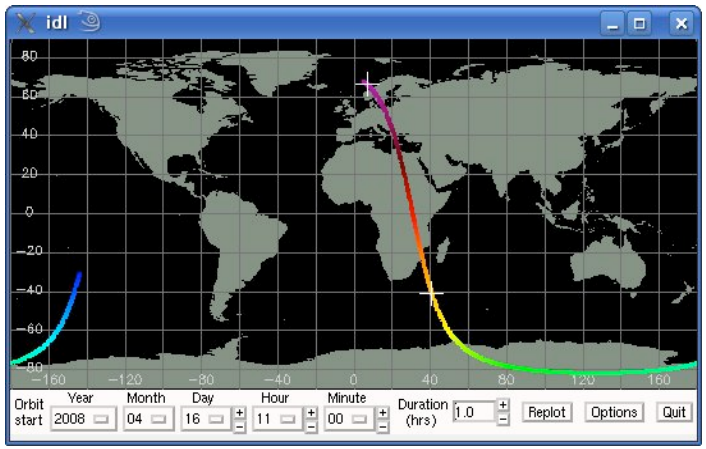
# Verification of fine mode aerosol optical depth

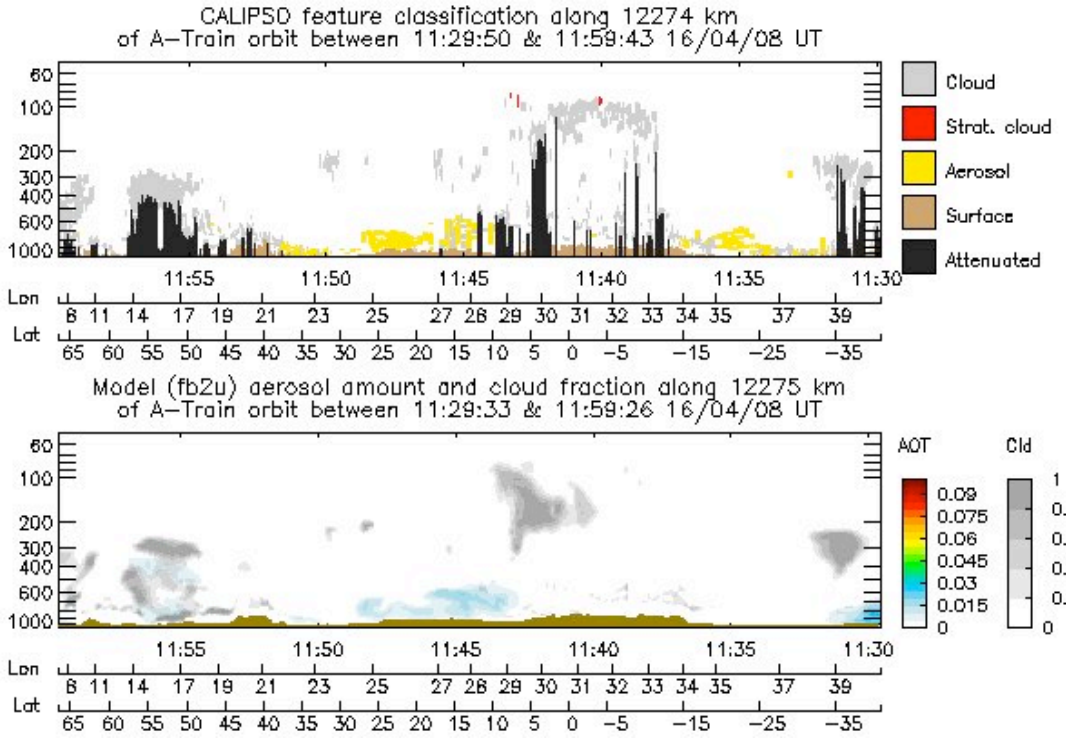



**Thanks to Luke Jones**

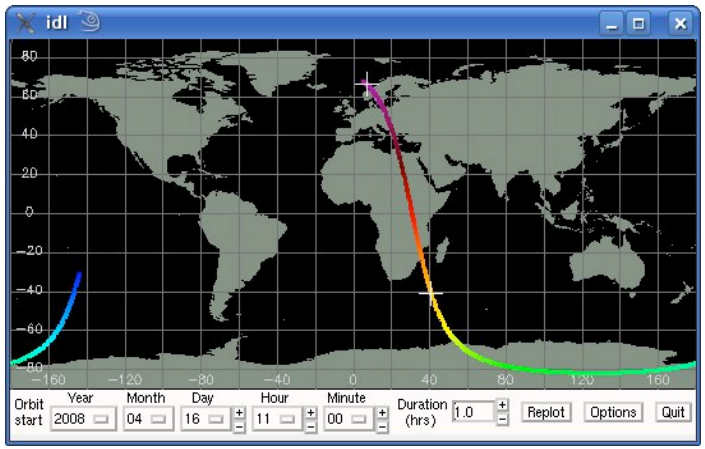
# Comparison with CALIPSO aerosol mask

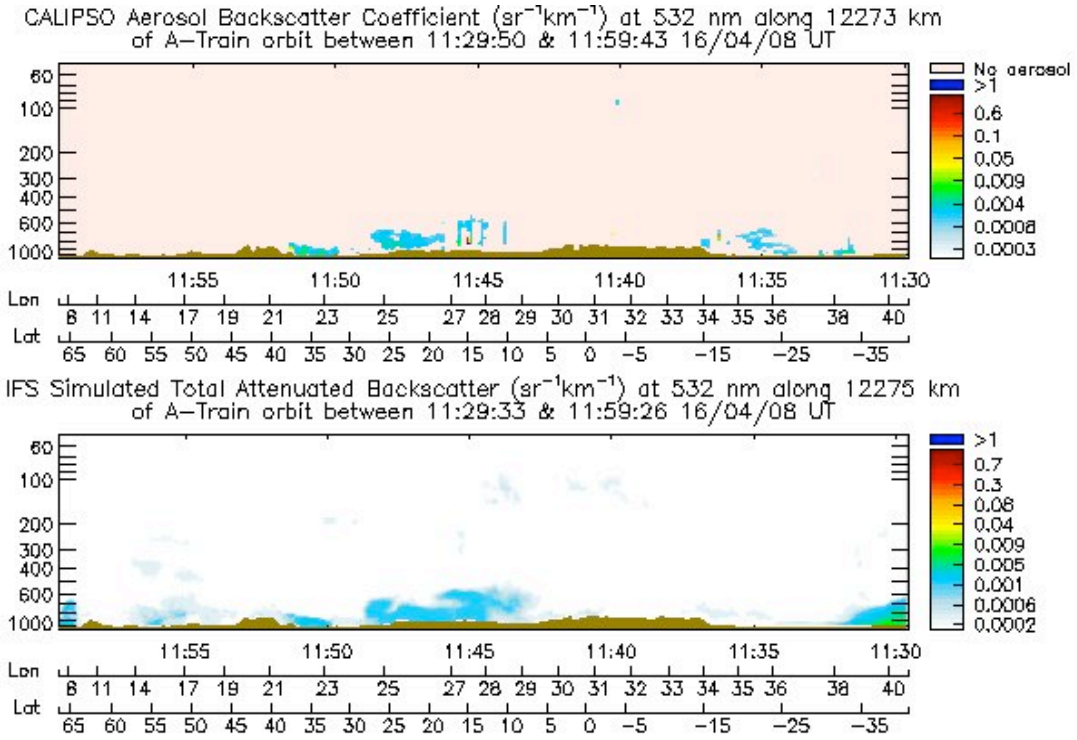



- General good agreement in the vertical but no major differences with or without assimilation
- For some convective situations, too much aerosol is present in the upper troposphere in the model and analysis (likely to depend on interaction between convection/vertical diffusion and aerosol transport)
- Assimilation of optical depth obs do not constrain the vertical profile (only operate a total aerosol mass adjustment)

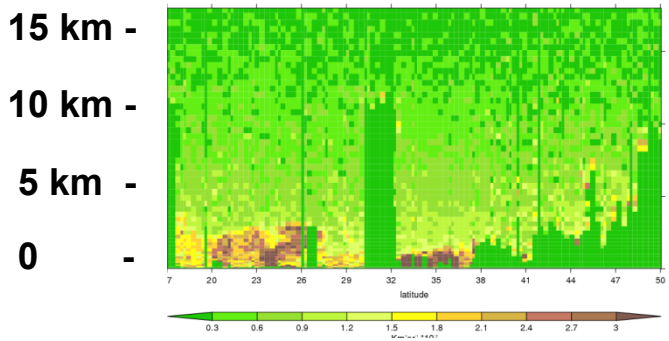
# Comparison with CALIPSO aerosol backscatter



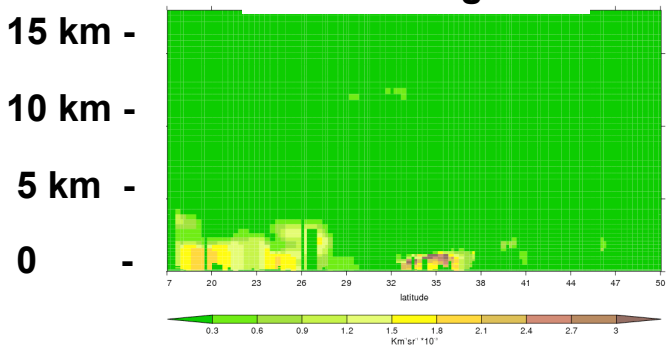



# 1D-Var experiments with CALIPSO data

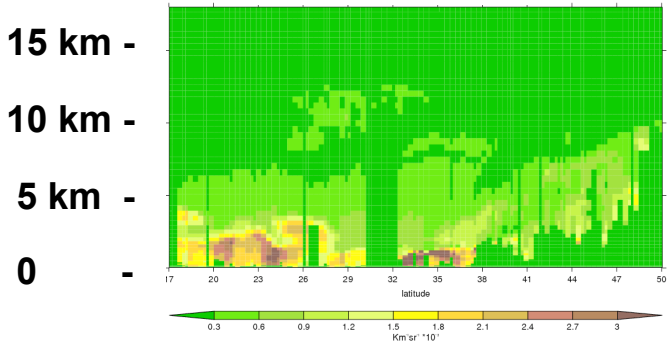
**Observed lidar backscatter**

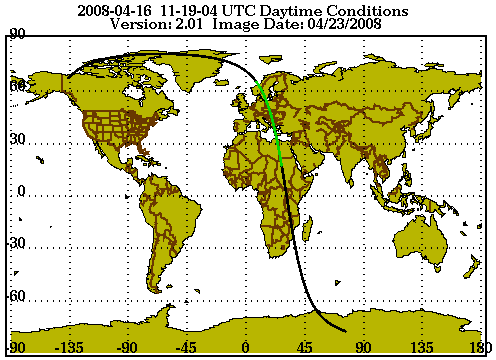



**Model first guess**




**Model analysis**




- Optical properties derived using Mie theory for the 11 aerosol species

- CALIPSO backscatter data at 532 nm pre-processed with cloud screening using level 2, 5 km cloud top height product (no data used below highest cloud top)

- Observed lidar backscatter averaged to model grid box

- Observation error set to 25% of observation value (acceptable for feasibility study)

- First guess of aerosol backscatter of good enough quality to allow assimilation

**Work by: Olaf Stiller, Jean-Jacques Morcrette, and Marta Janiskova'**

# Summary and future plans

- The assimilation of MODIS aerosol optical depths has proven successful in improving the forecast of aerosol with the GEMS/MACC ECMWF aerosol model. Inclusion of Aerosol Optical Depth data from different sensors (SEVIRI, AATSR) is promising but biases in products have to be identified and corrected.

- A variational bias correction for AOD observations has been implemented and is included in the new MACC reanalysis which was started in March 2010.

- Aerosol will be run interactively with radiation and cloud microphysics

- Further improvements to the analysis include the development of a dual control variable (fine mode mixing ratio and total aerosol mixing ratio) - ongoing.

- Work will continue on the assimilation of aerosol observations from passive and active sensors.

**Thanks for your attention!**

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- Inness, A., J.Flemming, M.Suttie, and L.Jones, 2009: GEMS data assimilation system for chemically active reactive gases. Technical Memorandum 587, ECMWF, 26 pp.

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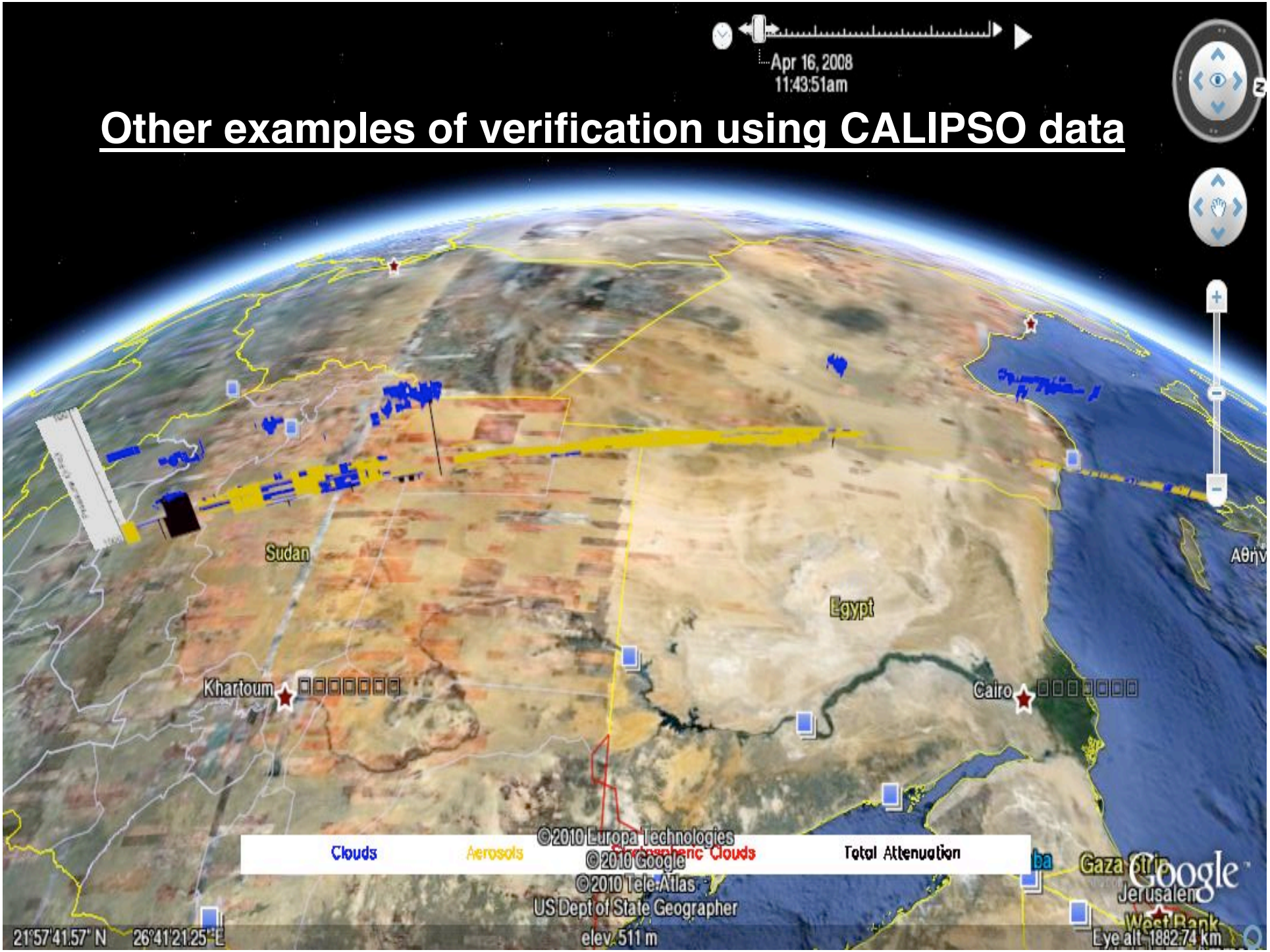
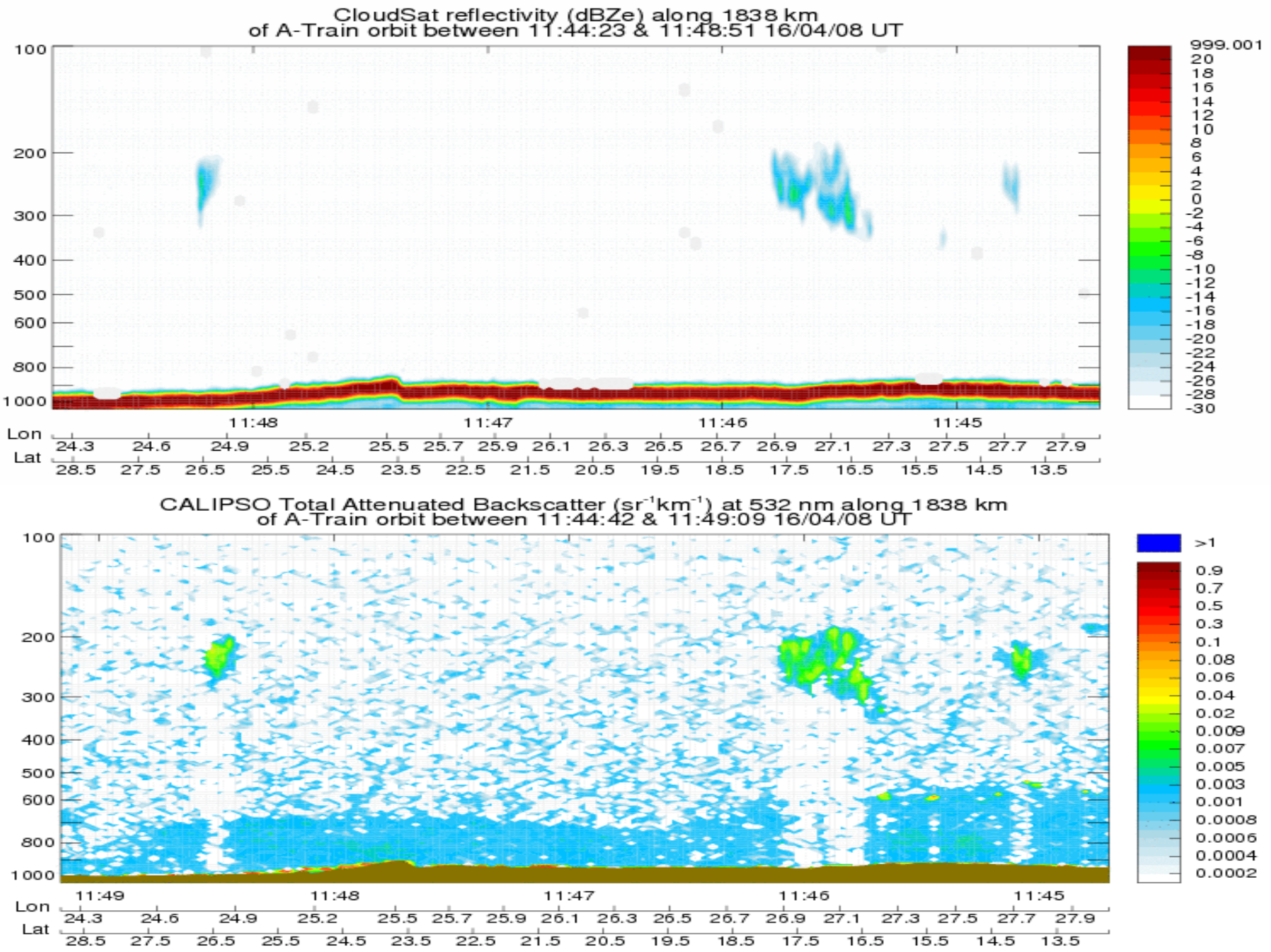
# Other examples of verification using CALIPSO data




CloudSat reflectivity (dBZe) along 1838 km
of A-Train orbit between 11:44:23 & 11:48:51 16/04/08 UT
100
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500
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800
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10
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2
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-24
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28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5
CALIPSO Total Attenuated Backscatter (sr-1km-1) at 532 nm along 1838 km
of A-Train orbit between 11:44:42 & 11:49:09 16/04/08 UT
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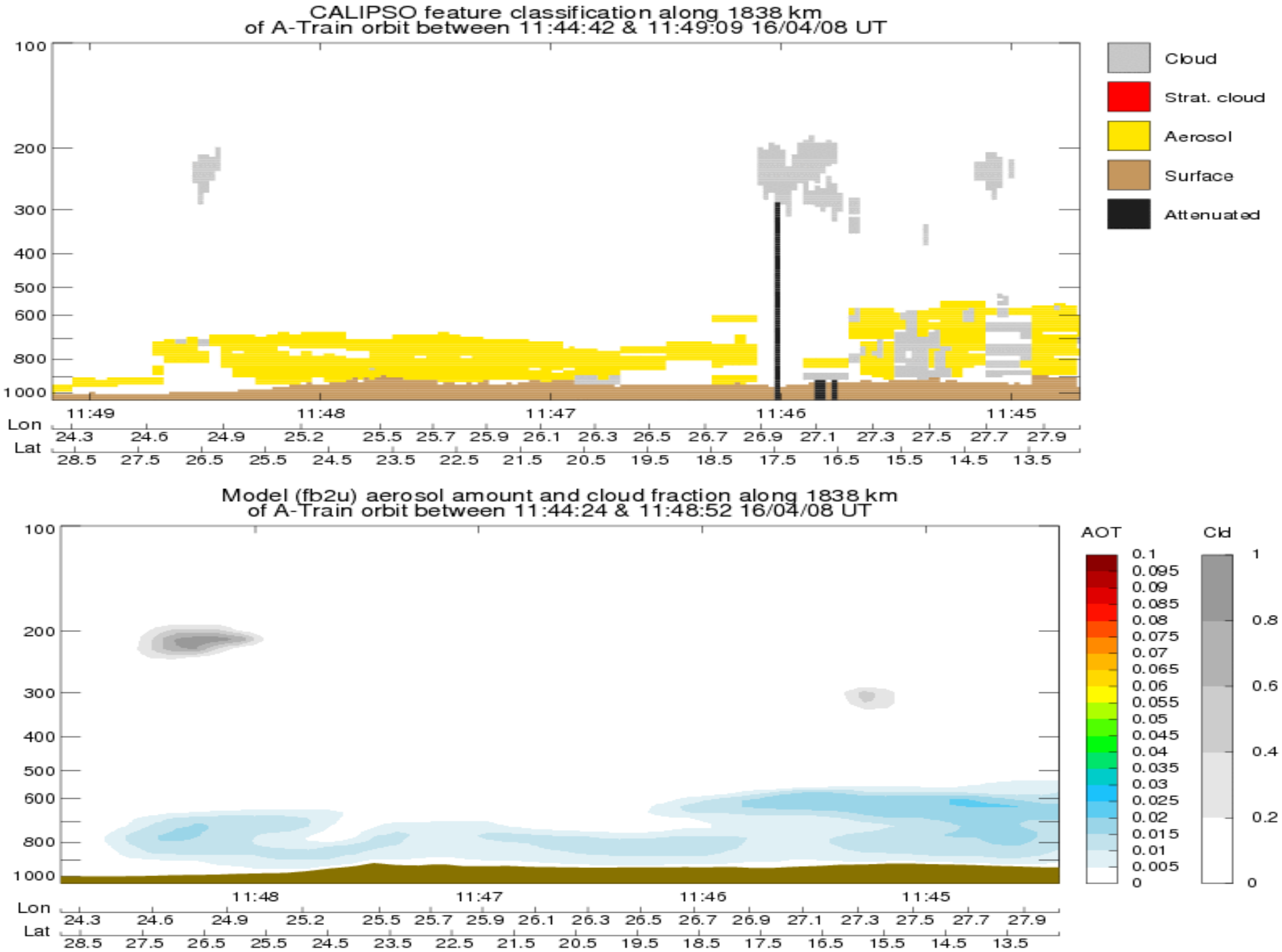
28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5


CALIPSO feature classification along 1838 km
of A-Train orbit between 11:44:42 & 11:49:09 16/04/08 UT
Cloud
Strat. cloud
Aerosol
Surface
Attenuated
100
200
300
400
500
600
800
1000
11:49
11:48
11:47
11:46
11:45
Lon
Lat
24.3 24.6 24.9 25.2 25.5 25.7 25.9 26.1 26.3 26.5 26.7 26.9 27.1 27.3 27.5 27.7 27.9
28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5
Model (fb2u) aerosol amount and cloud fraction along 1838 km
of A-Train orbit between 11:44:24 & 11:48:52 16/04/08 UT
AOT
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0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
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Cld
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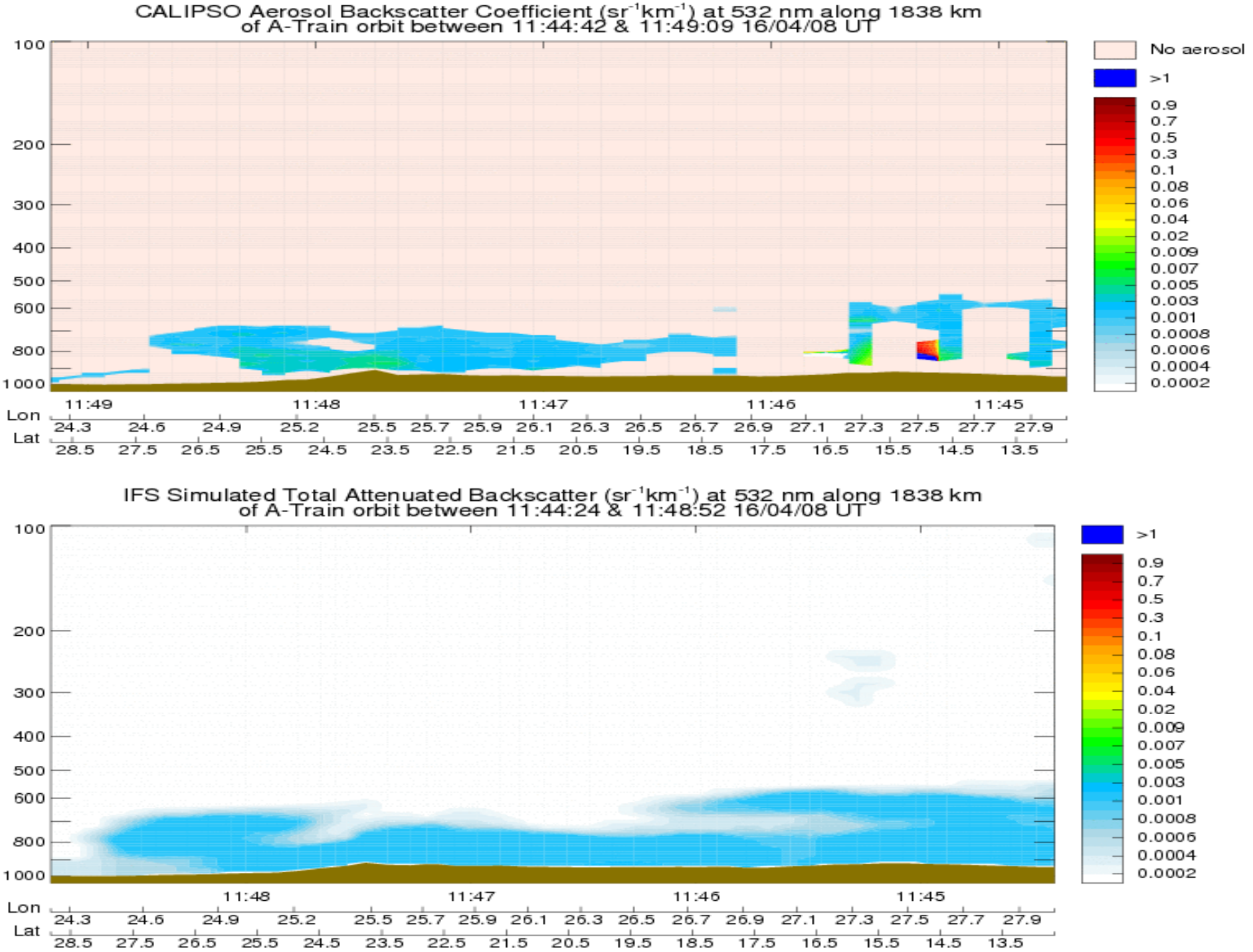
24.3 24.6 24.9 25.2 25.5 25.7 25.9 26.1 26.3 26.5 26.7 26.9 27.1 27.3 27.5 27.7 27.9
28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5


CALIPSO Aerosol Backscatter Coefficient (sr⁻¹km⁻¹) at 532 nm along 1838 km
of A-Train orbit between 11:44:42 & 11:49:09 16/04/08 UT
100
200
300
400
500
600
800
1000
No aerosol
>1
0.9
0.7
0.5
0.3
0.1
0.08
0.06
0.04
0.02
0.009
0.007
0.005
0.003
0.001
0.0008
0.0006
0.0004
0.0002
11:49
11:48
11:47
11:46
11:45
Lon
Lat
24.3 24.6 24.9 25.2 25.5 25.7 25.9 26.1 26.3 26.5 26.7 26.9 27.1 27.3 27.5 27.7 27.9
28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5
IFS Simulated Total Attenuated Backscatter (sr⁻¹km⁻¹) at 532 nm along 1838 km
of A-Train orbit between 11:44:24 & 11:48:52 16/04/08 UT
100
200
300
400
500
600
800
1000
>1
0.9
0.7
0.5
0.3
0.1
0.08
0.06
0.04
0.02
0.009
0.007
0.005
0.003
0.001
0.0008
0.0006
0.0004
0.0002
11:48
11:47
11:46
11:45
Lon
Lat
24.3 24.6 24.9 25.2 25.5 25.7 25.9 26.1 26.3 26.5 26.7 26.9 27.1 27.3 27.5 27.7 27.9
28.5 27.5 26.5 25.5 24.5 23.5 22.5 21.5 20.5 19.5 18.5 17.5 16.5 15.5 14.5 13.5