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The NEMS GFS Aerosol Component: NCEP's global aerosol forecast system

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1. Introduction

Aerosols affect the radiation budget both directly (through scattering and absorption) and indirectly (through cloud-radiation interaction). Dust-laden Saharan air layer is found to reduce occurrences of deep convection and suppress tropical cyclone activities in the North Atlantic and Caribbean (Dunion and Velden, 2004). Aerosols may be viewed in their role as air pollutants, regulated by the environmental agencies because of their adverse health effects. Long range transport of aerosol pollutants is found to impact air quality as well as visibility across international borders and across the oceans.

The Global Forecast System (GFS) is the cornerstone of the operational production suite of numerical guidance at National Centers for Environmental Prediction (NCEP). The atmospheric forecast model used in the GFS consists of a global spectral model (GSM) with a comprehensive physics suite (Moorthi et al., 2001 with recent upgrades documented at the GFS webpage at http://www.emc.ncep.noaa.gov/GFS/doc.php). The analysis system used in the GFS is a three-dimensional hybrid variational-Ensemble Kalman Filter (EnKF) system (Wang et al., 2013). The physical processes crucial for modeling the aerosol effects are, however, either poorly represented or missing in NCEP's global forecast and assimilation system. In the forecast model, the aerosol attenuation are determined from prescribed aerosol distributions based on a global climatological aerosol database (Hess et al., 1998) and the aerosol indirect effects on clouds and precipitation formation are not accounted for. Background aerosol conditions are currently assumed in the analysis system. For atmospheric conditions with anomalously high aerosol loading, bias correction and quality control procedures could be compromised due to the unaccounted effects of aerosol attenuation.

Efforts to develop a prognostic aerosol capability at NCEP have been underway within NCEP Environmental Modeling Center (EMC). Specifically, EMC has collaborated with NASA Goddard Space Flight Center (GSFC) to develop NEMS GFS Aerosol Component (NGAC) for predicting the distribution of atmospheric aerosols over a global domain. The forecast model component is the Global Forecast System (GFS) within NOAA Environmental Modeling System (NEMS) and the aerosol component is Goddard Chemistry Aerosol Radiation and Transport (GOCART) Model.

NGAC provides the first operational global aerosol forecasting capability at NOAA. The first implementation, NGAC Version 1 (NGAC V1), provides dust-only guidance since September 2012. The rational for developing global aerosol forecasting and assimilation capabilities at NCEP includes: (1) To improve weather forecasts and climate predictions by taking into account of aerosol effects on radiation and clouds; (2) To improve the handling of satellite observations by properly accounting for aerosol effects during the data assimilation procedure; (3) To provide the necessary aerosol (lateral and upper) boundary conditions for regional air quality predictions; and (4) To assess the aerosol impact on climate, human health, ecosystem, and visibility.

This document describes model configuration in section 2. The operational implementation of NGAC Version 1 is discussed in Section 3. Model evaluation and applications are presented in Section 4. Concluding Remarks are given in Section 5.

2. Model Configuration

2.1 Atmospheric Model: NEMS GFS

The efforts to develop a unified modeling framework to streamline the interaction of analysis, forecast, and post-processing systems within NCEP have been underway since late 2000 (Black et al., 2009). Specifically, NCEP EMC is developing NOAA Environment Modeling System (NEMS, http://www.emc.ncep.noaa.gov/index.php?branch=NEMS) with a component-based architecture following the Earth System Modeling Framework (ESMF) (http://www.earthsystemmodeling.org), marking the first general use of ESMF technology within NCEP. The ESMF collaboration involves many of the major climate, weather and data assimilation efforts in the U.S., including NOAA/NCEP, NASA Global Modeling and Assimilation Office (GMAO), the National Center for Atmospheric Research (NCAR), and the Naval Research Laboratory (NRL). This multi-agency effort aims to promote the exchange and reusability of earth system modeling components and to facilitate faster knowledge transfer and technology adaptation.

The general design for NEMS is depicted in Figure 1. ESMF organizes NEMS atmosphere model into collections of components with standardized interfaces, arranged in a hierarchical structure. Currently the Global Forecast System (GFS), the B-grid version of Nonhydrostatic

Multiscale Model (NMM-B), and the Flow-following finite-volume Icosahedral Model (FIM) have been placed under the NEMS framework. A unified I/O system has been developed to handle the synchronous production and writing of output, which in turn has been linked with NCEP's unified post-processing system.

The FIM atmosphere model is developed by NOAA Earth System Research Laboratory (ESRL). The NMM-B model, developed by NCEP, is the North American Model (NAM, http://www.emc.ncep.noaa.gov/index.php?branch=NAM) providing operational meso-scale weather forecasts since October 2011. The NEMS version of GFS, also developed by NCEP, consists of the same spectral dynamic core and physics parameterization as the operational GFS with the following exceptions. First, GFS atmospheric model has been restructured to include separate components for the model's dynamics and physics as well as a coupler through which information is passed between the dynamics and physics. Second, enhanced I/O and post-processing capabilities are introduced in the NEMS GFS. These include the option to output history files in native Gaussian grids instead of spectral grids and the option to run model integration in parallel to post-processing. Third, GFS physics parameterizations have been re-structured with a flexible interface, allowing it to be called by other dynamic cores. The option to assemble GFS physics as the NEMS unified physics package again reflects NCEP's modeling strategy toward a unified yet flexible modeling infrastructure. Fourth, research and development have been made to enable emerging capabilities in the NEMS GFS. The prognostic aerosol capability discussed in this paper consists of NEMS GFS with the aerosol option turned on. The Whole Atmosphere Model (WAM) developed by NCEP Space Weather Prediction Center (SWPC), spanning from the surface to the thermosphere, has been adopted into NEMS GFS via EMC-SWPC collaboration and is targeted for operational implementation in 2015. In addition, extensive work is already under way to develop a fully coupled atmosphere-land-sea ice-ocean prediction system (Climate Forecast System Version 3, CFS V3) by coupling NEMS GFS with the ocean model.

2.2 Aerosol Model: GOCART

Funded mainly by NASA Earth Science programs, the GOCART model was developed to simulate atmospheric aerosols (including sulfate, black carbon (BC), organic carbon (OC), dust, and sea-salt), CO, and sulfur gases (Chin et al., 2000, 2002, 2004, 2009; Ginoux et al., 2001, 2004; Bian et al., 2010; Kim et al., 2013). Originally GOCART was developed as an off-line Constituent Transport Model (CTM), driven by assimilated meteorological fields from the Goddard Earth Observing System Data Assimilation System (GEOS DAS). As part of the Goddard Earth Observing System Versions 5 (GEOS-5) atmospheric model development at NASA GSFC, an ESMF compliant GOCART grid component has been developed (Colarco et al. 2010). When running within GEOS-5, the GOCART component provides aerosol processes such as emissions, sedimentation, dry and wet deposition (Figure 2). Advection, turbulent and convective transport is outside the scope of the GOCART component, being instead provided by the host atmospheric model. In GEOS-5 implementation, the GOCART grid component is coupled to the radiation parameterization of the host model, providing an explicit account of aerosol direct radiative effects. In addition to the same natural and anthropogenic emissions used by the off-line GOCART model, the GOCART grid component also ingests daily biomass burning emissions from the Quick Fire Emission Dataset (QFED, Darmenov and da Silva 2013). QFED emissions are based on fire radiative power retrievals from Moderate Resolution Imaging Spectroradiometer (MODIS), on board Aqua and Terra satellites. The inclusion of daily satellite-observed smoke emissions into GOCART provides a practical tool to model the highly variable biomass burning emissions.

For dust, a topographic source function and mobilization scheme following Ginoux et al. (2001) is used. The dust emission parameterization depends on 10-m wind, the threshold velocity of wind erosion, and dust source function. The threshold velocity of wind erosion is determined from dust density, particle diameter, and surface wetness. The dust source function (shown in Figure 3), representing the probability of dust uplifting, is determined from surface bareness and topographical depression features. A new dynamic dust source function based on the satellite observed surface vegetation change (Kim et al., 2013) has been incorporated into the off-line GOCART aerosol simulations at GSFC. The inclusion of such observation-based, time-dependent emissions is important for model to capture the large variation of aerosol sources.

2.3 Linking NEMS GFS with GOCART

The GOCART grid component originally developed for GEOS-5 is fairly independent of the host model, encapsulating the basic aerosol production and loss functionality. Consistent with standard ESMF architecture, details of the interface to NEMS are isolated into a coupler component. Figure 4 shows the integration run stream of NGAC. Couplers are built to transfer and transform the data between NEMS GFS and GOCART. For instance, the physics-to-chemistry coupler performs the following tasks: (i) vertical flip for 3-dimensional fields, as GOCART is top-down while NEMS GFS is bottom-up, (ii) unit conversion as different units are used in NEMS GFS and GOCART for some fields such as precipitation rate, and (iii) conversions and calculations for these fields needed by GOCART such as inferring relative humidity and air density from ambient temperature and moisture fields. Despite the ESMF flavor in how GOCART is implemented, GOCART is incorporated into NEMS GFS as a column process similar to how ozone physics was incorporated. It updates 3-dimensional aerosol loading after physical processes, run on the same grid as physics and dynamics, and is fully coupled with physics and dynamics at each time step.

The advantages for taking the so-called on-line approach include:

- Consistent: no spatial-temporal interpolation, and same physics parameterization
- Efficient: lower overall CPU costs and easier data management
- Interactive: allowing for aerosol feedback to meteorology

The aspect of aerosol feedback is critical since an important goal for the development of NGAC is to provide improved estimates of atmospheric aerosols for improving NCEP's medium range weather forecasts and climate prediction.

3. NGAC Operational Implementation

A phased approach is used to implement NGAC at NCEP. In the first phase, NCEP produces dust-only guidance. The second phase of NGAC implementation is to produce the full suite of aerosol forecasts (including dust, sea salt, sulfate, and carbonaceous aerosols) using satellite-based real-time biomass burning emissions. The next phase is to produce aerosol data assimilation using NGAC short term forecasts as first guess. Only first phase implementation undertaken in 4^{th} quarter of Fiscal Year 2012 (the Q4FY12 Implementation) is discussed in this document.

3.1 The Q4 FY12 Implementation

Effective on September 11, 2012, starting with the 0000 Coordinated Universal Time (UTC) cycle, NCEP began to run and disseminate dust predictions from the NGAC system. NGAC Version 1 provides 5-day dust forecasts, once per day for the 0000 UTC cycle. Dust initial conditions are taken from the 24-hours forecast from previous day while meteorological initial conditions are down-scaled from high-resolution GFS analysis (the so-called replay mode). It has the same dynamics and physics as the operational high-resolution GFS, except it uses the Relaxed Arakawa-Schubert scheme (Moorthi and Suarez, 1992, 1999) for deep convection and runs at lower spatial resolution. At present, the aerosol direct radiative effects in NGAC are determined from the same aerosol climatology data set as in the operational GFS. The specific configuration that GOCART prognostic aerosols are not interactive with the radiation scheme of NEMS GFS is chosen to facilitate more straightforward testing and fine tuning in the near term and will be changed to be radiatively interactive in later implementation.

While the ultimate goal at NCEP is a full-up earth system with the inclusion of aerosol-radiation feedback and aerosol-cloud interaction, the incorporation of prognostic aerosol modeling within the operational GFS infrastructure is not feasible at this time. Instead, the NGAC forecasts are executed at lower resolution (T126 L64, ~ 100 km) in parallel to the operational GFS (currently with T574 L64 resolution as on November 2013, ~ 27 km). NCEP is working toward having the high resolution GFS to read the low resolution NGAC aerosol fields instead of aerosol climatology in the near future. The dual resolution approach (low-resolution for aerosol forecasting and high resolution for medium range weather prediction) will likely remain unless the computation resources at NCEP are increased substantially.

3.2 NGAC Products Descriptions and Distributions

Primary NGAC output fields are global three-dimensional dust mixing ratios for five particle sizes with effective radius at 1, 1.8, 3, 6, and 10 micron. Two-dimensional aerosol products, such as dust aerosol optical depth (AOD) and surface mass concentrations, are also available.

Web-based presentation of NGAC forecasts is available at the following location:

http://www.emc.ncep.noaa.gov/gmb/sarah/NGAC/html/realtime.ngac.html

The EMC NGAC website displays dust AOD at 550nm and surface mass concentrations over global domain and several regional domains (e.g., trans-Atlantic region, Asia, and continental US (CONUS) regions).

The NGAC V1 output is available in GRIB2 format on 1x1 degree output grid, with 3-hourly output from 00 to 120 hours. Output files and their contents are listed in the Appendix. Users can access the NGAC digital products from NOAA Operational Model Archive and Distribution System (http://nomads.ncep.noaa.gov/) as well as from NCEP's ftp/http server at the following locations:

http://www.ftp.ncep.noaa.gov/pub/data/nccf/com/ngac

ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/ngac

Among these two- and three-dimensional aerosol products specified in the Appendix, dust AOD at 550 nm is the most widely used product (discussed in next section). Potential usage for NGAC V1 dust products includes, but is not limited to: dust column mass density, emission and removal fluxes for dustl budget study; dust deposition fluxes for ocean productivity; and dust surface mass concentrations for air quality. NCEP produces AOD at several spectral bands as requested by potential users and stakeholders. Specifically, AOD at 340nm, 860nm, 11.1 µm are targeted for UV index forecasts, AVHRR SST retrievals, and AIRS temperature retrievals, respectively, once the full suite of aerosols become operational in next phase implementation.

4. NGAC Evaluation and Applications

EMC Forecast Verification System (FVS) has been extended to verify NGAC dust AOD against MODIS total AOD over the Africa region where dust is the dominant aerosol type. The FVS provides quantitative measures to monitor NGAC performance routinely. The efforts to ingest near-real-time AErosol RObotic NETwork (AERONET) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) for NGAC evaluation are also in progress.

In addition, NGAC forecasts are evaluated using observed total AOD from the surface sun photometer network (AERONET) and from space-borne MODIS and also compared with dust AOD from other models. An example is give here where dust AOD at 550nm from NGAC is compared with GEOS-5 results for the June-July-August, 2013 period (Figure 5). The overall spatial pattern from NGAC is consistent with that of GEOS-5. Elevated dust loading near the source regions (e.g., Sahara desert in north Africa, the Bodele depression over Chad, the Syrian desert in mid East, the Taklimakan desert in northwest China) are clearly shown as well as long-range dust transport across the Atlantic ocean. While both GEOS-5 and NGAC use the same aerosol module (GOCART Grid Component), GEOS-5 aerosol forecast is run on higher spatial resolution (0.25 degree) with the inclusion of full aerosol sources and the assimilation of total AOD from MODIS.

Another example is shown in Figure 6 where NGAC forecasts are evaluated with observed AOD at four AERONET sites during the September 2012-September 2013 period. The comparison is made between dust AOD at 550 nm from NGAC and total AOD at 550 nm interpolated from AOD values at 440 nm and 675 nm sampled by sun photometer. These four sites are all directly impacted by dust outbreaks. The Dakar site is located in Senegal, North Africa near the Sahara dust source region while the Capo Verde site is an ocean site at Sal Island downwind of Saharan dust sources. The Banizoumbou, Niger site is influenced by Saharan dust outbreaks and occasionally biomass burning activities (Cavalieri et al., 2010). The Solar Village, Saudi Arabia site is located in the middle of the Arabian Peninsula with significant contribution of desert dust particles. NGAC simulations are found to captures the seasonal variability in the dust loading at these sites except for Banizoumbou. Future work is needed to address the weakness found in the NGAC.

As shown in Figures 5 and 6, dust AOD at 550nm is used extensively for evaluation and verification at EMC. It is also used routinely by two international programs for model inter comparion and multi model ensemble. First, NGAC V1 is one member of the International Cooperative for Aerosol Prediction (ICAP) global multi-model ensemble. Figure 7 shows the dust AOD for 6-hour forecast initialized from 31st July 2013 00UTC from NGAC and the ICAP global multi-model ensemble. The ensemble is based on 6 members including NGAC and the models from NRL, GMAO, European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), and Barcelona Supercomputing Center (BSC). Second, dust forecasts from NGAC V1 participate in the multi-model comparison conducted by WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Regional Center for Northern Africa, Middle East, and Europe, hosted at BSC, Spain. Figure 8 shows the dust AOD valid at 2nd January 2013 12UTC from NGAC and several global and regional models. Participation in ICAP and WMO SDS-WAS provides a continuous assessment of the quality of

NGAC dust products and put them in the context of the ICAP and SDS-WAS model suite, establishing the reasonableness of NGAC relative to the community state of the art.

Trans-Atlantic dust transport is clearly shown in Figures 5 and 7. Trade winds steer African dust westward across the Atlantic ocean, covering vast areas of the North Atlantic and sometime reaching the Americas (e.g., the Caribbean, southeastern USA, Central America, and Amazon basin). This has implications for air quality, public health, climate, and biogeochemical cycle. An example on using NGAC dust information to improve regional air quality forecasts is presented here. Under a NOAA-EPA partnership, NOAA is undertaking the responsibility to develop and maintain the National Air Quality Forecasting Capability (NAQFC) (Otte et al., 2005; Davidson et al. 2008). The AQF system is based on EPA Community Multi-scale Air Quality (CMAQ) model driven by meteorological forecasts from the NCEP NAM at 12 km. Static climatological lateral boundary conditions that do not account for long-range dust transport across the boundaries are currently used.

Two CMAQ runs are conducted for the July 2010 period. The baseline run uses static boundary conditions and the experimental run uses dynamic lateral boundary conditions (LBCs) from NGAC. Figure 9 shows the observed and modeled surface particulate matter smaller than 2.5 microns (PM2.5) at two AIRNOW stations in the southeast U.S. Table 1 presents the statistic results of the CMAQ compared to the EPA AIRNOW PM2.5 observations. It is found that the incorporation of LBCs from NGAC reduces model biases and improves correlation. Clearly, the inclusion of long-range dust transport via dynamic LBCs leads to significant improvements in CMAQ forecasts during dust intrusion episodes.

5. Summary

GSFC's GOCART aerosol module has been implemented into NEMS GFS at NCEP via NOAA/NCEP-NASA/GSFC-Howard University collaborations. While NGAC (NEMS GFS coupled with GOCART) has the capability to forecast dust, sulfate, sea salt, and carbonaceous aerosols, the Q4FY12 implementation was to establish dust-only guidance.

NGAC Version 1.0 implemented in September 2012 provides the first operational global dust forecasting capability at NOAA. The NGAC dust forecasts are routinely verified against in-situ and satellite observations using EMC's verification package as well as by international programs. Qualitative evaluation and quantitative verification indicate that NGAC provides dust forecasts with reasonable quality.

While the initial NGAC implementation is limited in its scope (dust-only, without data assimilation), it has laid the groundwork for various aerosol-related applications. Future operational benefits associated with NGAC include:

- Enable future operational global short-range full-package aerosol prediction (the phase 2 implementation)
- Provide the first step toward an operational aerosol data assimilation capability at NCEP (the phase 3 implementation)
- Allow aerosol impacts on medium range weather forecasts (GFS/GSI) to be considered
- Provide global aerosol information required for various applications (e.g. satellite radiance data assimilation, satellite retrievals, SST analysis, and UV-Index forecasts)
- Allow NCEP to explore aerosol-cloud-climate interaction in the Climate Forecast System (CFS), as GFS is the atmosphere model of the CFS
- Provide lateral aerosol boundary conditions for regional aerosol forecast system

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Appendix:

Output files and their contents for NGAC V1 (Q4FY12 Implementation)

(1) ngac.t00z.a2df$HR, where HR=00, 03, ...,120:

The A2D files contain the following two-dimensional fields:

Parameter Abbrev.	Parameter	Units
AER_OPT_DEP_at550	Dust aerosol optical depth at 550nm	dimensionless
CR_AER_SFC_MASS_CON	Coarse mode surface mass concentration	kg/m3
FN_AER_SFC_MASS_CON	Fine mode surface mass concentration	kg/m3
CR_AER_COL_MASS_DEN	Coarse mode column mass density	kg/m2
FN_AER_COL_MASS_DEN	Fine mode column mass density	kg/m2
DUST_EMISSION_FLUX	Dust emission fluxes	kg/m2/sec
DUST_SEDIMENTATION_FLUX	Dust sedimentation fluxes	kg/m2/sec
DUST_DRY_DEPOSITION_FLUX	Dust dry deposition fluxes	kg/m2/sec
DUST_WET_DEPOSITION_FLUX	Dust wet deposition fluxes	kg/m2/sec

(2) ngac.t00z.a3df$HR, where HR=00, 03, ..., 120:

The A3D files contain the following three-dimensional fields at model levels:

Parameter Abbrev.	Parameters	Units
PRES	Pressure	Pa
RH	Relative humidity	%
TEMP	Temperature	K
DUST1	Mixing ratio for dust bin 1 (0.1-1.0 micron)	Kg/kg
DUST2	Mixing ratio for dust bin 2 (1.0-1.8 micron)	Kg/kg
DUST3	Mixing ratio for dust bin 3 (1.8-3.0 micron)	Kg/kg
DUST4	Mixing ratio for dust bin 4 (3-6 micron)	Kg/Kg
DUST5	Mixing ratio for dust bin 5 (6-10 micron)	Kg/Kg

(3) ngac.t00z.aod_$NM, where NM=11p1um, 1p63um, 340nm, 440nm, 550nm, 660nm, 860nm:

Aerosol optical depth (dimensionless) at specified wavelengths (11.1, 1.63, 0.34, 0.44, 0.55, 0.66, and 0.86 micron)

Note NGAC products are encoded in GRIB2 using a relatively-new GRIB2 template. Users should download the latest versions of wgrib2 and the other NCEP GRIB2 utilities to use the NGAC output products. Many of these utilities were updated on July 17, 2012 and can be assessed from this URL: http://www.nco.ncep.noaa.gov/pmb/codes/nwprod/util/exec

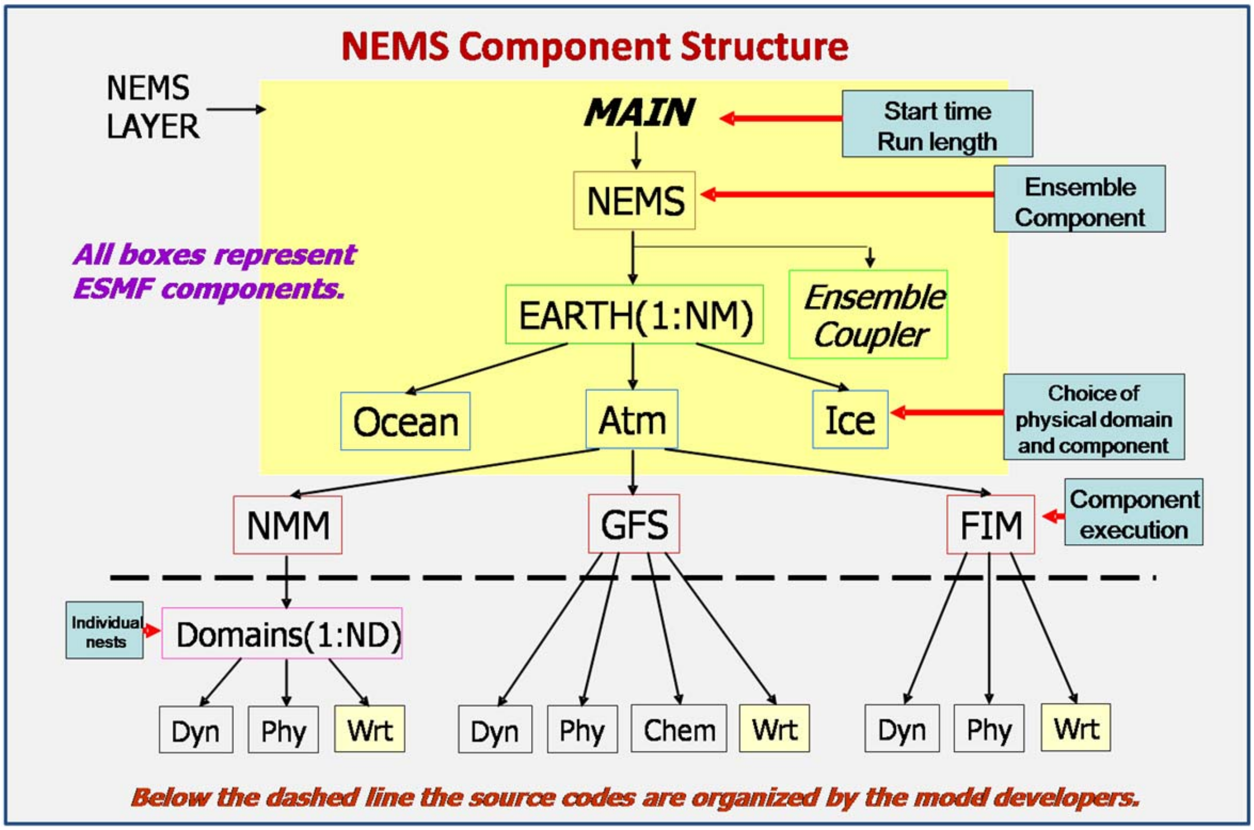


Figure 1. Schematic of the NEMS Component Structure.

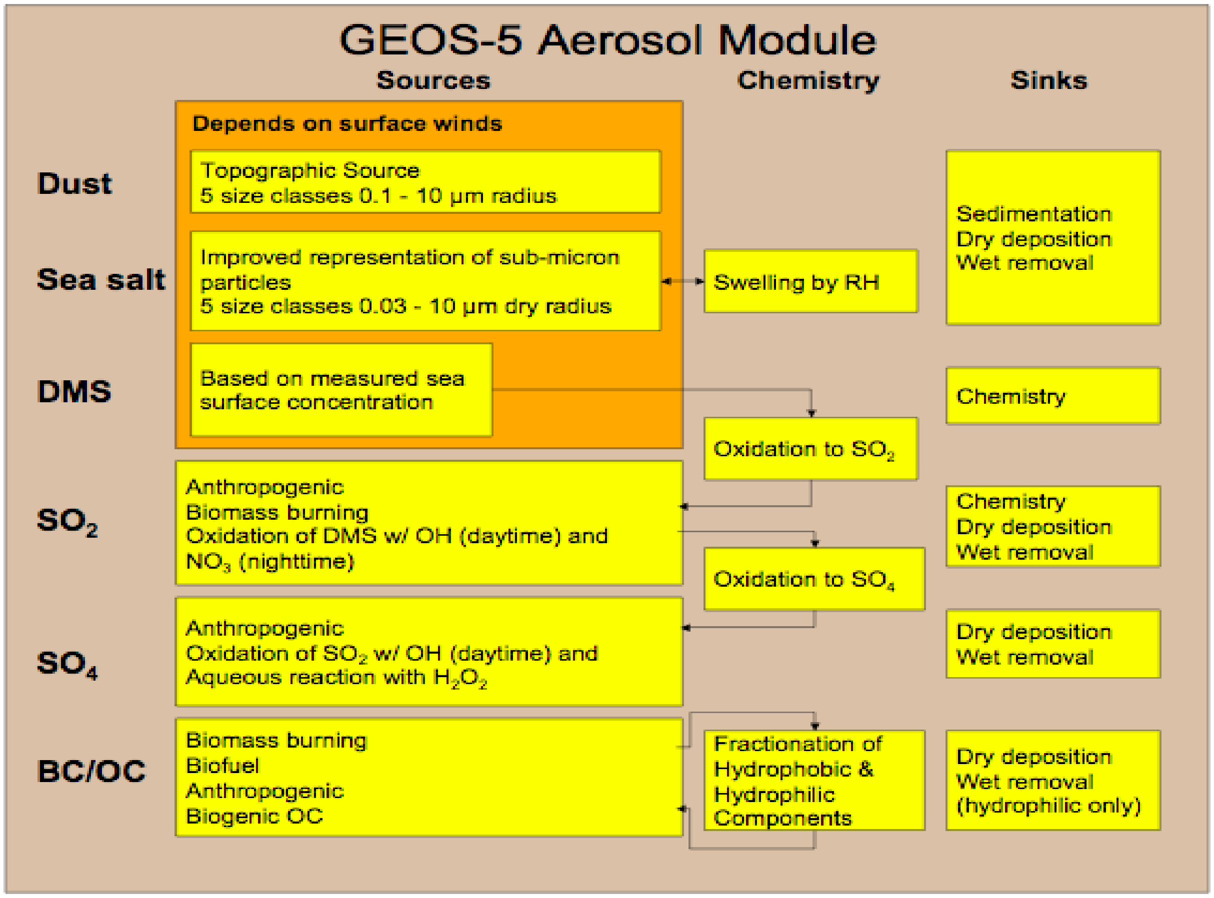


Figure 2. Schematic summary of the GOCART aerosol modules as adapted and being implemented in GEOS-5 and NEMS. Aerosol sources and inventories are similar to Ginoux et al. (2001) and Chin et al. (2002, 2003).

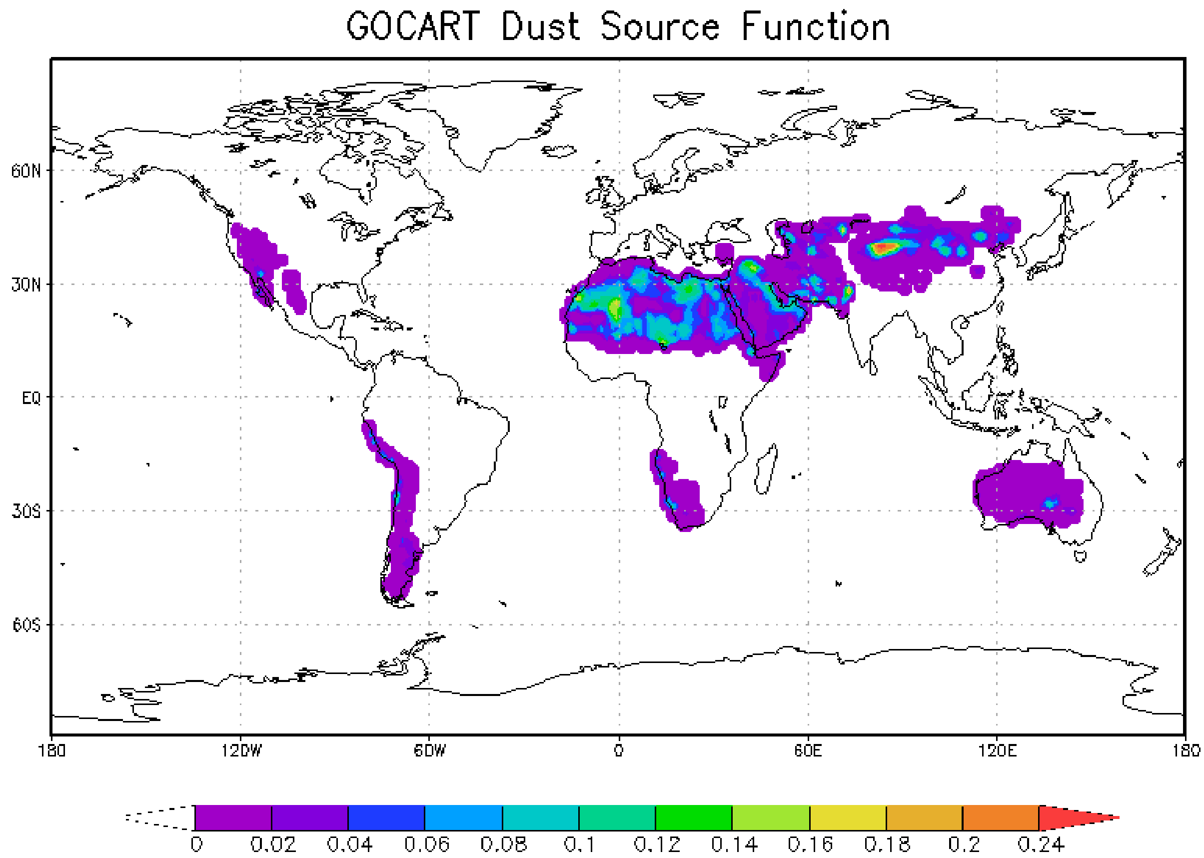


Figure 3. GOCART dust source function, mapped to T126 resolution.

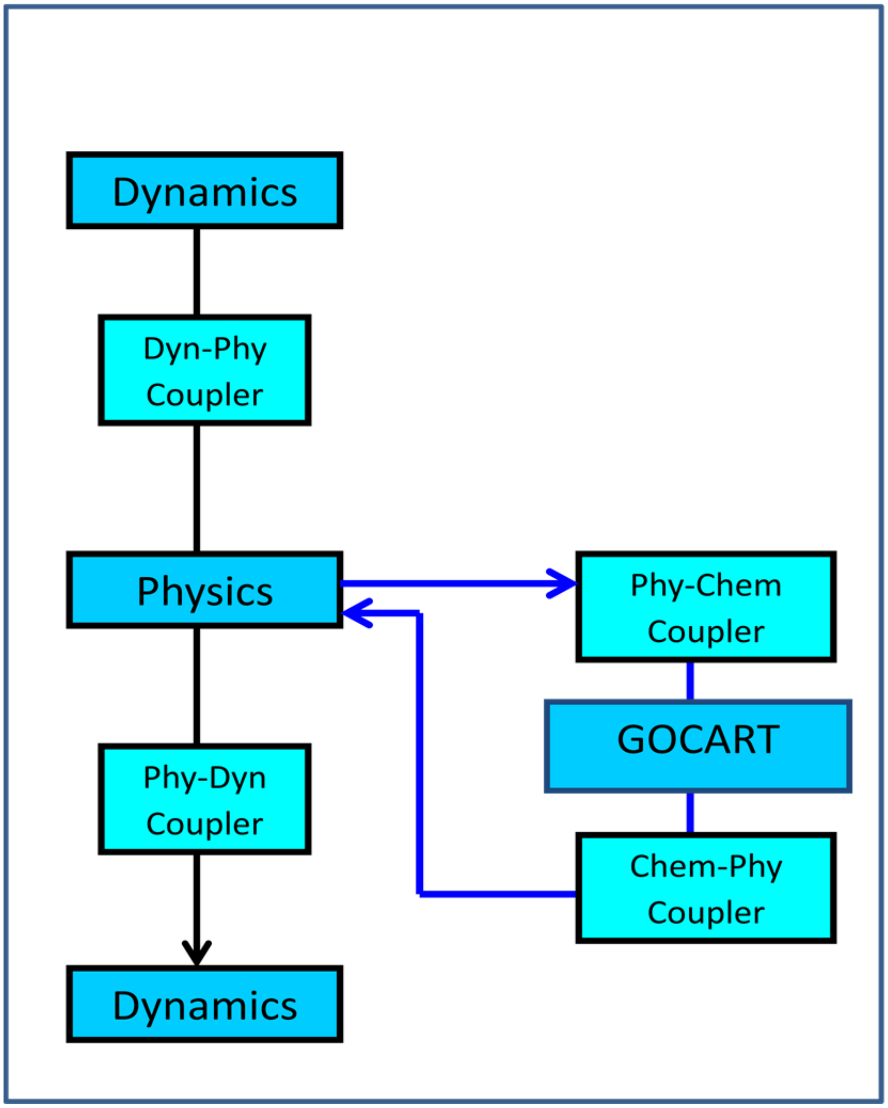


Figure 4. Primary integration runstream of NGAC.

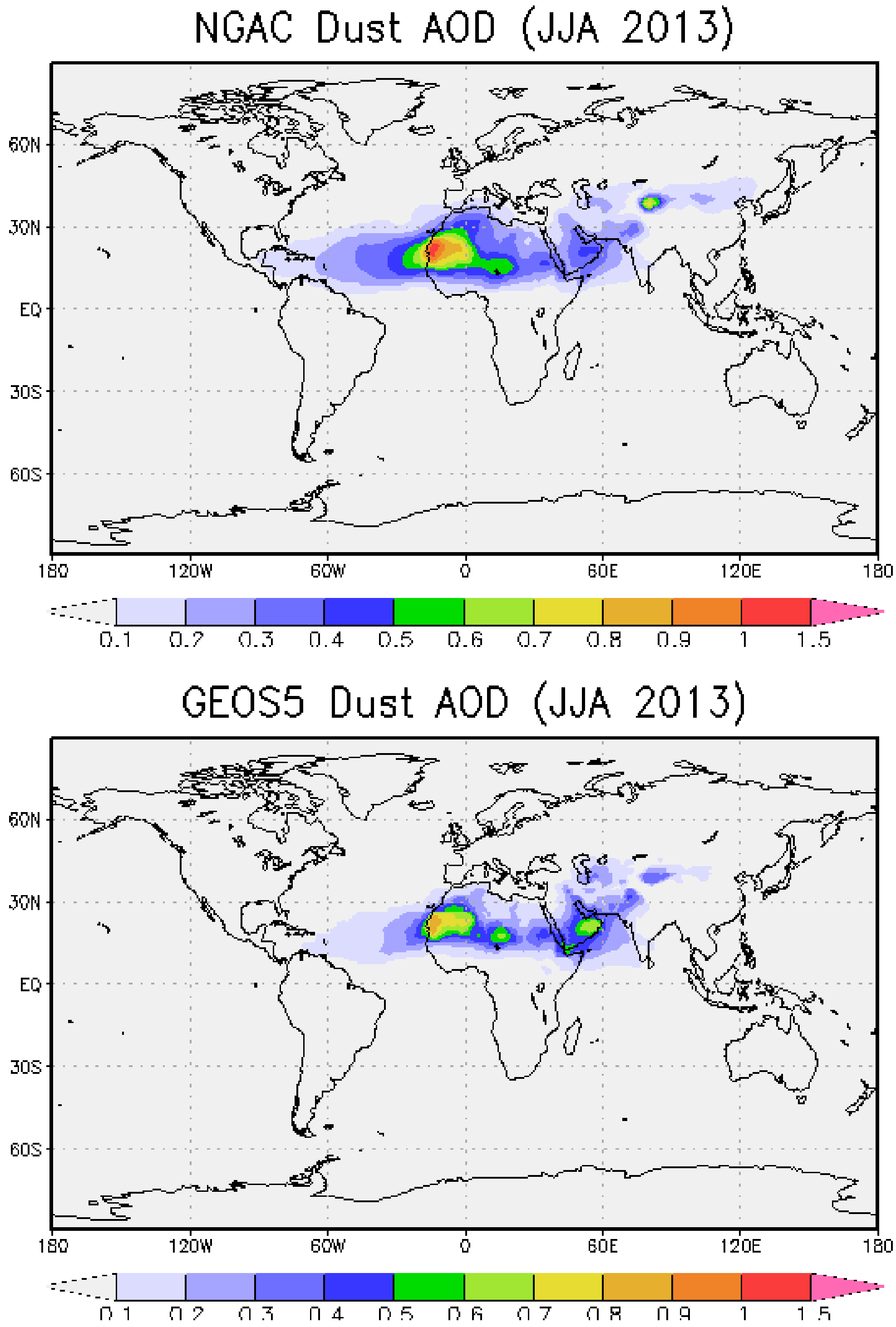
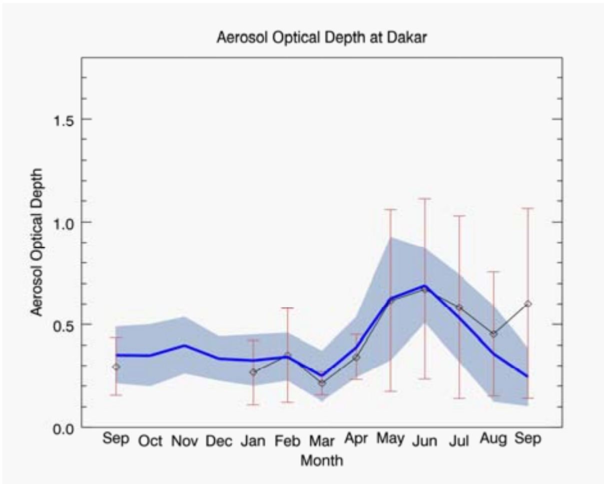
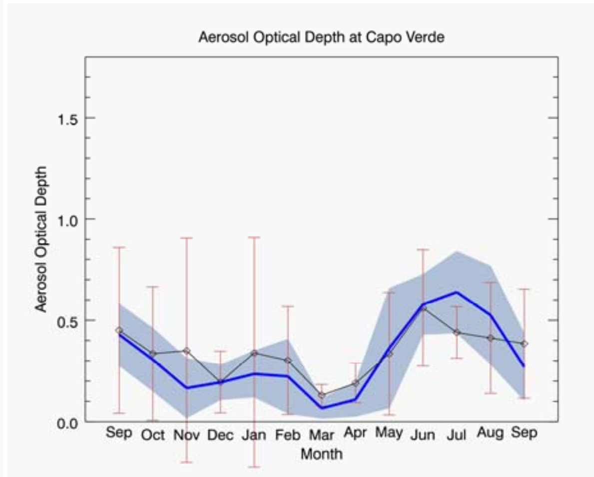


Figure 5. Three-month-averaged dust AOD comparison between NGAC (top panel) and GEOS-5 (bottom panel) for the June-July-August 2013.

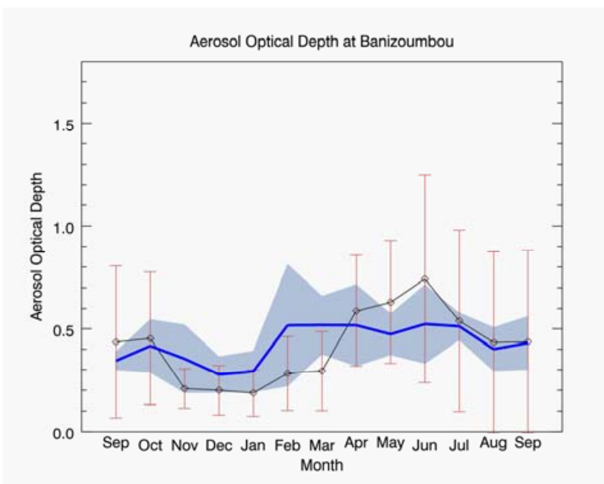
A



C



B



D

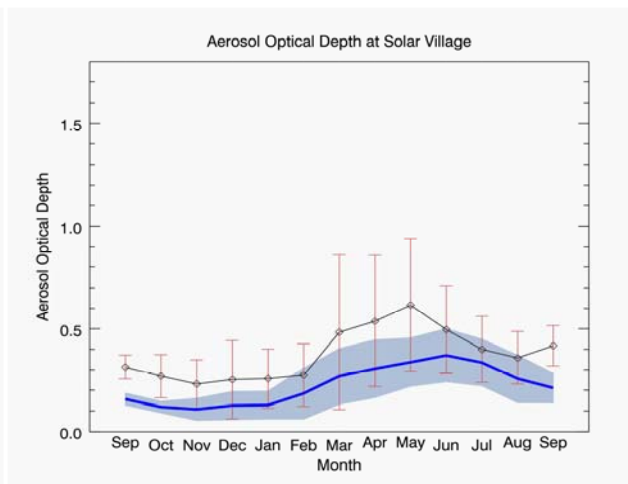
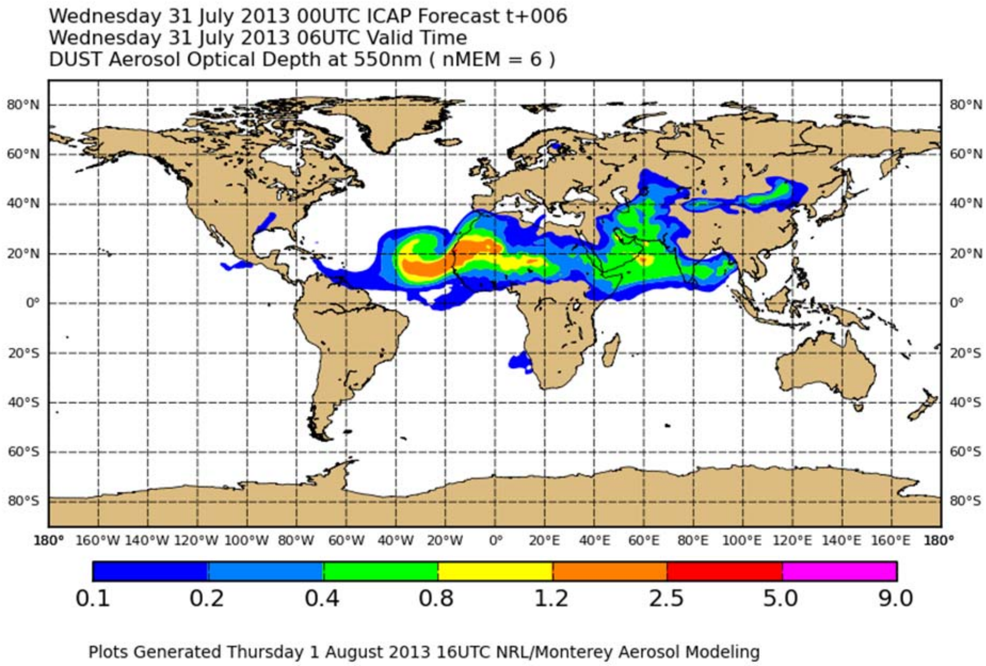


Figure 6. Model versus AERONET 550-nm AOD comparisons at (A) Dakar, (B) Capo Verde (C) Banizoumbou, and (D) Solar Village for the 2012/09-2013/09 period. The model monthly means and standard deviation about the mean are shown in the blue line and grey shading. The AERONET monthly means and standard deviation about the mean are shown in the black line and red bars. We thank Didier Tanre for the efforts in establishing and maintaining Capo Verde Banizoumbou, and Dakar sites as well as Brent Holben for the Solar Village site.



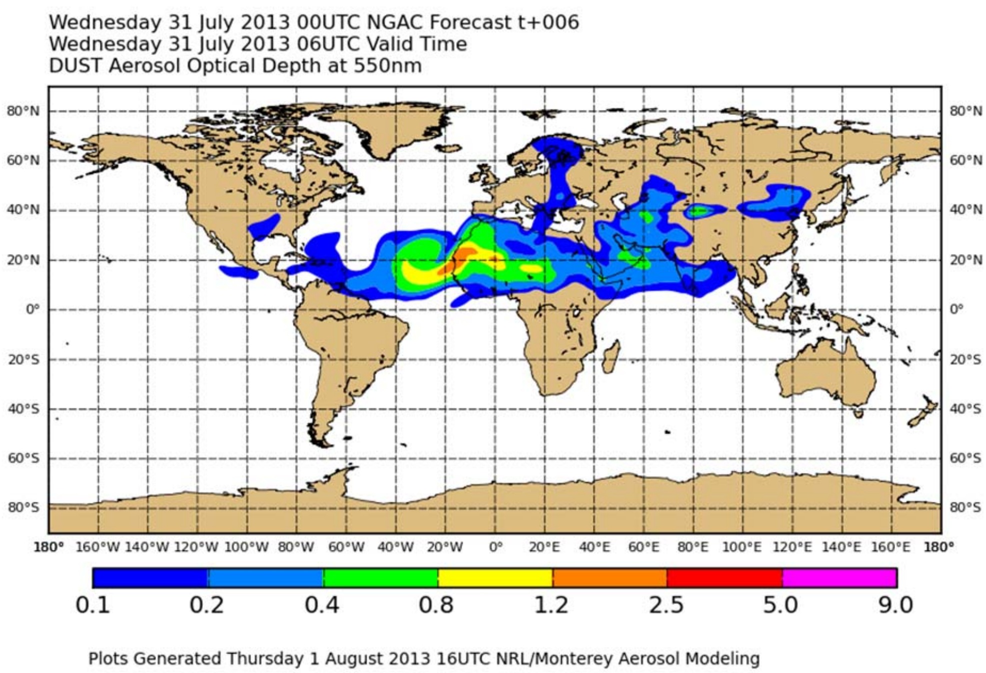


Figure 7. Dust AOD for 6-hour forecast, initialized from 31st July 2013 00UTC for NGAC (top panel), and the ICAP multi-model ensemble (bottom panel). These figures are taken from the ICAP website, managed by NRL aerosol group.

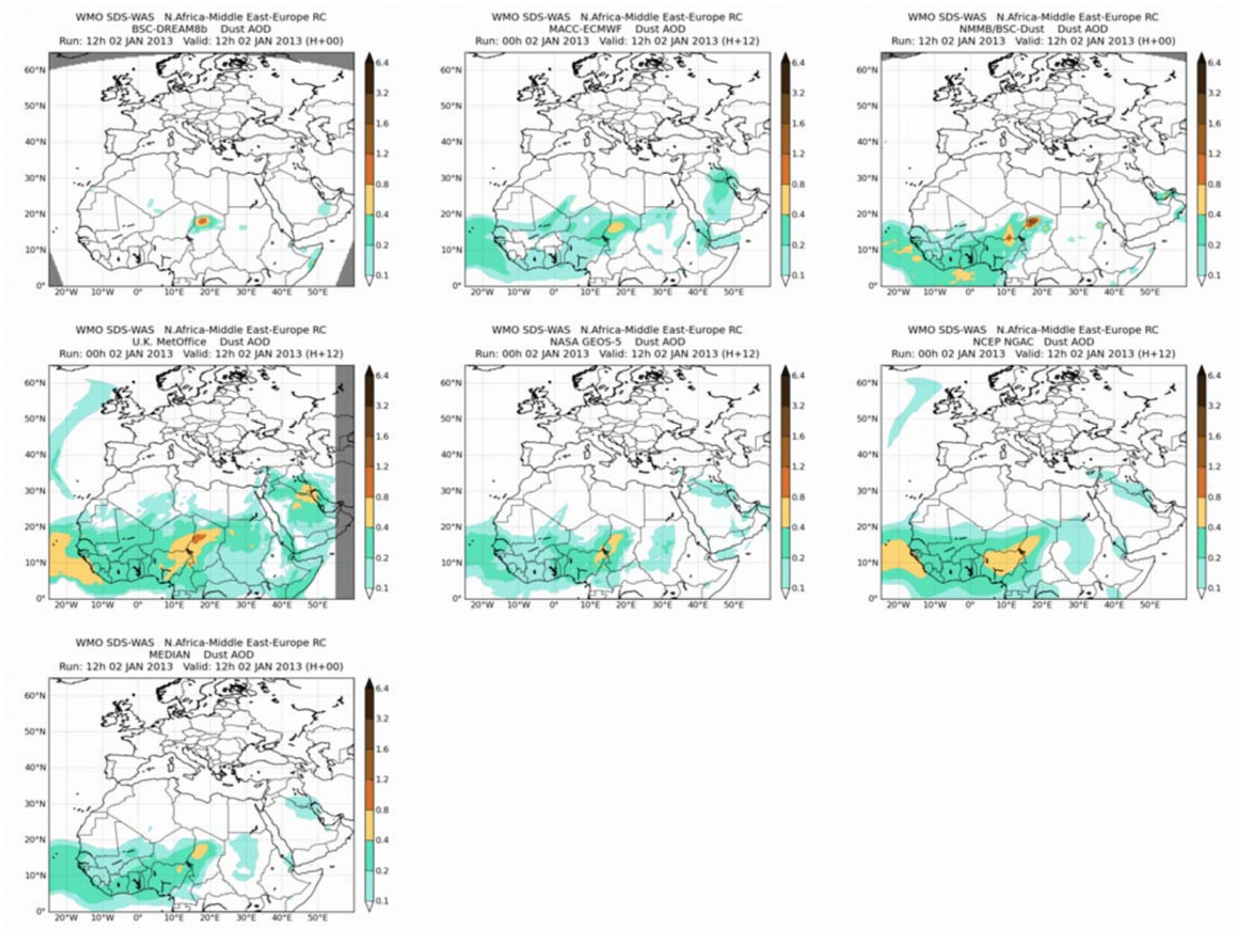


Figure 8. Dust AOD valid at 12UTC 2nd January 2013 for BSC-DREAM (top row-left panel), ECMWF (top row-middle panel), BSC-NMMB (top row-right panel), UKMO (middle row-left panel), GSFC (middle row-middle panel), NCEP (middle row-right panel), and the multi-model median (bottom row) This figure is taken from the WMO SDS-WAS Africa node website, managed by BSC.

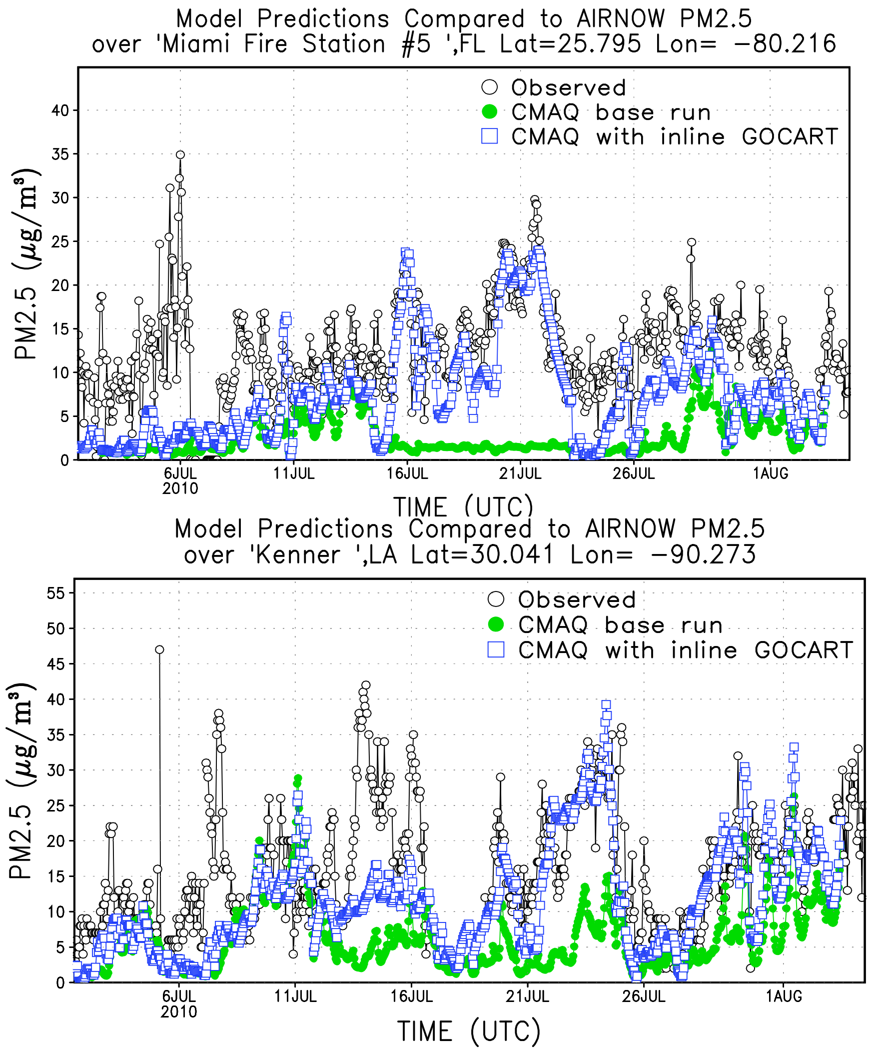


Figure 9. Time series of PM2.5 from EPA AIRNOW observations (black dot), CMAQ baseline run using static LBCs (green dot) and CMAQ experimental run using NGAC LBCs (blue square) at Miami, FL (top panel) and Kenner, LA (bottom panel).

Table 1. Statistic results comparing CMAQ model results with EPA AIRNOW PM2.5. The baseline run uses static LBCs and the experimental run uses NGAC LBCs. The mean bias (MB) and correlation (R) are calculated for the entire CONUS domain (1^{st} and 3^{rd} rows) and the sub-domain south of 38°N and east of 105°W (2^{nd} and 4^{th} rows) during the 07/01-08/03 2010 period (1^{st} and 2^{nd} rows) and a shorter time period covering 07/18-07/30 (3^{rd} and 4^{th} rows).

	CMAQ Baseline	CMAQ Experimental
Whole domain July 1 – Aug 3	MB= -2.82 R=0.42	MB= -0.88 R=0.44
South of 38°N, East of -105°W July 1 – Aug 3	MB= -4.54 R=0.37	MB= -1.76 R=0.41
Whole domain July 18– July 30	MB= -2.79 R=0.31	MB= -0.33 R=0.37
South of 38°N, East of -105°W July 18– July 30	MB= -4.79 R=0.27	MB= -0.46 R=0.41