Author Response to Referee #1

The comments and suggestions from the referee #1 are greatly appreciated. All technical corrections have been made. The comment to provide some details on dust source function has been addressed, and the reference has been added for the CMAQ and NAM models. Please see detailed response below.

Specific Comments:

Page 2, Line 17: Change "In additional to modulate" to "In addition to modulating".

Text has been changed as suggested.

Page 2, Line 23: Change "Large amount" to "Large amounts".

Changed as suggested.

Page 7, Line 21: If DMS has not been previously defined, please define it here.

Text is changed from "DMS" to "dimethyl sulfide (DMS)".

Page 8, Line 18: What sources of data are used to determine the surface bareness and topographical features? Later on in the paragraph it is stated that a satellite observed surface vegetation cover has been developed? Was this used to determine surface bareness? Even though reference is provided, I think it would be useful to the reader to provide some details about these satellite data.

The source map used in NGAC V1 is a static map derived from AVHRR. We revise the manuscript (see below) and remove the reference to Kim et al. 2013 to avoid the confusion.

The text (P.8, Line 17) "*The dust source function regridded on the T126 GFS grid (shown in Fig. 2), representing the probability of dust uplifting, is determined from surface bareness and topographical depression features.*" is changed to "*The dust source function, representing the probability of dust uplifting, is determined from surface bareness and topographical depression features. Surface bareness is identified from the 1ºx1º vegetation data set derived from the advanced very high resolution radiometer (AVHRR) data (DeFries and*

Townshend, 1994). The static dust source function has been regridded on the GFS native T126 Gaussian grid for NGAC V1.0 (shown in Fig. 2). "

Page 10, Line 20. Suggest changing "lower spatial resolution" to "coarser spatial resolution".

Revised as suggested.

Page 12, Line 13. Change "one and a half day" to "one and a half days".

Corrected as suggested.

Page 13, Line 21: Change "captures" to "capture".

Corrected as suggested.

Page 14, Line 26: Change "also contributes the" to "also contributes to the".

Corrected.

Page 15, Line 7: Correct the spelling of independent.

Spelling has been corrected.

Page 15, Line 14: Add references for the CMAQ and NAM models

Byun and Schere (2006) is added for CMAQ. The NAM webpage is included for NAM.

List of relevant changes:

Page 2, Line 17: "In additional to modulate" changed to "In addition to modulating".

Page 2, Line 23: "Large amount" changed to "Large amounts".

Page 7, Line 21: "DMS" to "dimethyl sulfide (DMS)".

Page 8, Line 18: The text "*The dust source function regridded on the T126 GFS grid (shown in Fig. 2), representing the probability of dust uplifting, is determined from surface bareness and topographical depression features.*" is changed to "*The dust source function, representing the probability of dust uplifting, is determined from surface bareness and topographical depression features. Surface bareness is identified from the 1^ox1^o vegetation data set derived from the advanced very high resolution radiometer (AVHRR) data (DeFries and Townshend, 1994). The static dust source function has been regridded on the GFS native T126 Gaussian grid for NGAC V1.0 (shown in Fig. 2). "*

Page 8, Line 24: Remove the last sentence (on Kim et al. 2013)

Page 10, Line 20. "lower spatial resolution" changed to "coarser spatial resolution".

Page 12, Line 13. "one and a half day" changed to "one and a half days".

Page 13, Line 21: "captures" changed to "capture".

Page 14, Line 26: "also contributes the" changed to "also contributes to the".

Page 15, Line 7: "independent"

Page 15, Line 15: "CMAQ model" changed to "CMAQ model (Byun and Schere, 2006)"

Page 15, Line 16: "(NAM) model" changed to "(NAM) model (see see the NAM webpage at http://www.emc.ncep.noaa.gov/?branch=NAM)"

Page 20, Line 15: Add "Byun, D. W. and Schere, K. L.: Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system, Appl. Mech. Rev., 59, 51-77, 2006."

Page 21, Line 22: Add "DeFries, R. S., and Townshend, J. R. G.: NDVI-derived land cover classification at global scale, Int. J. Remote Sensing, 15, 3567-3586, 1994."

Page 22, Line 27: Remove Kim et al. 2013

Author Response to Referee #2

The comments and suggestions from the Referee #2 are greatly appreciated. Please see detailed response below.

Specific Comment:

The validation part is good, but I do recommend including more AERONET stations. In fact, what I wish the authors would have done is a validation effort similar in extent to what has been presented in Huneeus et al 2011. As far as I know, they even developed a tool that is straight-forwardly applicable. In doing so, the authors could test the model performance in all regions of the globe rather than at just two AERONET stations next to the main Saharan desert dust sources (which, arguably, are the most important sources). In addition, as pointed out above, they can highlight the model skill in the context of other - presumably less performant - models. In any case, I would kindly ask the authors to defend their minimalistic choice and to justify why they did not use more or omit other AERONET stations. The same is true for the choice of satellite remote sensing products. MISR, MSG Seviri or OMI are other data set available for comparison.

The Referee is correct that this manuscript only presents concise descriptions of model performance.

There are very limited, if any, peer-reviewed publications on NCEP's ongoing NEMS development and on NCEP's emerging global aerosol modeling capability. This paper, therefore, seeks to present the aerosol modeling capability in the programmatic aspects (such as the rationale, the NCEP-GSFC collaborative approach, and aerosol-related applications) rather than providing an extensive model evaluation/validation.

During the development phase, we compared NGAC V1 dust results with other models (ICAP MME and GSFC's GEOS-5), in-situ observations at multiple (> 2) AERONET sites, and aerosol retrievals from satellites (MODIS, VIIRS, and CALIPSO). This paper, however, only provides brief descriptions of NGAC V1 evaluation. Such choice, by no means, trivializes the importance of model evaluation and validation. Efforts are ongoing at NCEP to evaluate and validate parallel NGAC V2 (with dust, sea salt, OC/BC, and sulfate). The references on the approach for AeroCom and NMMB/BSC-dust model are greatly appreciated and will certainly provide valuable guidance on how to put NGAC V2 performance in better context with other aerosol models.

We have included additional sites (Sede Boker, Ilorin, Banizoumbou, and La Parguera sites) for Figure 6c-6f in Section 4.

Minor comments:

Section 2.1, p.7, line 4ff: Not sure it is relevant to mention the future development of WAM in this context. Unless it takes any bearing on the further development of the aerosol module, you may as well leave it out in order to avoid confusion.

The WAM-related discussions have been removed to avoid confusion.

Section 2.2, p.7/8: You are referring to the on-line capability of the model here. Later in section 2.3, p.9, line 19ff, you provide more details on how the on-line approach works. Are you talking about the same thing here? Please try to make the text more coherent and merge the bits that belong together.

The manuscript has been revised. The discussions on the on-line capability in p.9 line 19 have been moved to Section 1. The end of 4th paragraph in Section 1 (p.4) is changed from "The NGAC consists of two key modeling components: (1) the GFS within the NEMS architecture (NEMS GFS) and (2) the on-line aerosol module based on Goddard Chemistry Aerosol Radiation and Transport (GOCART) model" to "NGAC is the first on-line (interactive) atmospheric aerosol forecast system at NCEP. It consists of two key modeling components: (1) the GFS within the NEMS architecture (NEMS GFS) and (2) the on-line aerosol module based on Goddard Chemistry Aerosol Radiation and Transport (GOCART) model. The advantages for taking the so-called on-line approach include: (1) consistency: no spatial–temporal interpolation and the use of the same physics parameterization, (2) efficiency: lower overall CPU costs and easier data management, and (3) interaction: allows for aerosol feedback to meteorology."

Section 2.2, p.8, line 13ff: Which dust emission scheme you are using? Also, which moisture correction and surface roughness correction scheme you are using? Have you done any sensitivity experiments in order to tune the model, e.g. wrt soil moisture, or did you just tune the emission budget? As a side note: Ginoux's topographical dust source function happens to be very suitable for representing the major dust sources as they are linked to wind channelling effects due to said orography.

Ginoux's topographical dust source function is used, and the only tuning is for dust emission budget. The following is added to 2nd paragraph in section 2.3 (p.9, Line 15):

"GOCART in GEOS-4/5 has been implemented in NEMS GFS 'as is' except for emission budget. As in GEOS-4/5 (Colarco et al., 2010), the spatial distribution and intensity of dust sources in NGAC V1 follows from Ginoux et al. (2001). Owing to differences in the GEOS-4/5 meteorology and resolution relative to NEMS GFS, the global scaling constant for dust emissions (see equation (2) in Ginoux et al. (2001)) has been adjusted from C = 0.375 μg s^2 m^{-5} as in GEOS-4/5 to C = 1 μg s^2 m^{-5} in NGAC. This adjustment is determined from sensitivity experiments, allowing NGAC V2 to obtain dust emission budget comparable to GEOS-4/5."

Section 3, p.10, line 8: NCEP begins ☐NCEP has begun

The technical correction has been made.

In the next line, you mention that dust forecasts are available online. On p.11, line 3, you do actually provide an online resource which appears to be linked to these forecasts. I recommend merging the two separated statements, which presumably, refer to the same thing.

The two statements (in 2nd and 5th paragraphs, respectively) have been merged.   The 2nd paragraph now mentions the link for EMC NGAC webpage.   The discussions on how NGAC is initialized has been moved from 2nd paragraph to the end of section 3.

Section 3, p.10, line 27: I don't quite understand this sentence: "This aerosol-radiation decoupled configuration that GOCART aerosols are not radiatively coupled to the AGCM is intended […]". Please rephrase!

The text has been modified (P10)"Note the interaction of GOCART aerosol fields and GFS's radiation package has been disabled in NGAC V1.0.   This configuration that aerosols are not radiatively coupled to AGCM is intended to facilitate aerosol modeling development in the near term. Once the prognostic aerosol capability reaches desired maturity level, this aerosol-radiation decoupled configuration will be changed allowing the aerosol direct and semidirect radiative effects to be accounted for."

Section 4.2, p.12, line 16ff: Why did you only compare with MODIS? What about OMI, MISR, MSG Seviri? In Fig 5: Why only monthly AOD means rather than seasonal means? At least it has to be consistent! Text and Figure capture say different things.

This manuscript aims to provide a high-level description of NGAC from the programmatic aspects, so does not cover detailed model evaluation/validation.

For Fig.5, the text in Page 12 Line 16 has been revised from "Figure 5 shows seasonal dust distributions over the subtropical Atlantic region." to "Figure 5 shows monthly-mean dust distributions over the subtropical Atlantic region at different seasons."

Section 4.2, p.13, line 9ff: As highlighted in the specific comment, I would kindly ask you to either justify the choice of only two AERONET stations for comparison, or provide a more comprehensive analysis. While the performance at the two stations shown in Fig 6 is really good, it may well just be by chance. I'd rather know the model performing not so well in some regions as opposed to not knowing at all. Also, what about Lidar observations? How do you know the model is able to represent the vertical structure of the dust plume away from sources? EARLINET and CALIOP are the tools to go with. Again, please justify why you didn't use either of those.

Four additional sites are added. The discussions in section 4.2 (p.13) are modified to "Among the six stations included in the comparison, three sites are located in dust-prone Sahara-Sahel region (Dakar, Ilorin, and Banizoumbou), one site is located in dust-prone Middle East area (Sede Boker), and two sites are located in tropical Atlantic Ocean region (Cape Verde and La Parguera). The Dakar site is located in Senegal, North Africa near the dust source region. The Ilorin site, located in Guinea Savanna zone, experiences dust and episodic smoke aerosols. The Banizoumhou site, located in the Sahel region, is influenced predominantly by dust transport from the Sahara. For the two ocean sites, Cape Verde is influenced by dust outflow from Saharan sources while La Parguera is influenced by long-range transport of Saharan dust. The Middle East site, Sede Boker, is located in the Negev desert of Israel and experiences mainly dust and urban aerosols. At these sites except for Ilorin, NGAC V1.0 simulations are found to capture the seasonal variability in the dust loading. Overall, NGAC V1.0 shows similar seasonal variability to and is well correlated with the AERONET observations."

To justify why only concise model evaluation is presented, the last paragraph in Section 4.2 (p.13) is moved to Section 4 (p.11).

In the original manuscript, the last paragraph in Section 4.2 (Page 13):
"NCEP is currently working toward the phase-two NGAC implementation (i.e., full-suite of aerosols including dust, sea salt, sulfate, and carbonaceous aerosols using near-real-time smoke emissions from satellite fire products). The planned NGAC upgrade will produce total AOD,

allowing us to evaluate NGAC results beyond dust- dominated regions."

In the revised version, the 1st paragraph in Section 4 (Page 11) becomes:
"In this section, the results of operational NGAC V1.0 forecasts are presented. NCEP is currently working toward the phase-two NGAC implementation (Lu et al., 2016). The NGAC V2 includes full-suite of aerosols using near-real-time smoke emissions from satellite fire products. The NGAC upgrade will produce total AOD, allowing us to evaluate NGAC results beyond dust-dominated regions. Efforts are underway to evaluate experimental NGAC V2 with other models (ICAP MME and GSFC's GEOS-5), in-situ observations at AERONET sites throughout the globe, and aerosol retrievals from multiple satellites, including MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). In this paper, only concise model results are presented as the paper mainly provides the programmatic aspects of NGAC development and implementation."

Section 5.1, p.15, line 2ff: Fig 8 does not seem to add any extra value. Unless you compare NGAS with ICAP directly, rather than showing the average of all ICAP models (MME), I don't see any benefit of putting the Figure and suggest to take it out.

Figure 8, showing the dust AOD regional ensemble products from the WMO SDS-WAS regional center at BSC, has been removed. The text has been revised accordingly: (1) 2nd paragraph in Section 5.1 is shorten as the reference to Figure 8 (WMO SDS-WAS regional MME) is removed, (2) 2nd and 3rd paragraphs are merged into one paragraphs, and (3) CMAQ results (previously Figure 9) is now Figure 8.

List of relevant changes:

Page 4, Line 2: Change "The NGAC consists" to "NGAC is the first on-line (interactive) atmospheric aerosol forecast system at NCEP.   It consists of"

Page 4, Line 5: Add the following at the end of this paragraph: "The advantages for taking the so-called on-line approach include: (1) consistency: no spatial -temporal interpolation and the use of the same physics parameterization, (2) efficiency: lower overall CPU costs and easier data management, and (3) interaction: allows for aerosol feedback to meteorology."

Page 7, Line 6: Remove the WAM-related sentence

Page 9, Line 15: Add the following at the beginning of 2nd paragraph: "GOCART in GEOS-4/5 has been implemented in NEMS GFS 'as is' except for emission budget. As in GEOS-4/5 (Colarco et al., 2010), the spatial distribution and intensity of dust sources in NGAC V1 follows from Ginoux et al. (2001). Owing to differences in the GEOS-4/5 meteorology and resolution relative to NEMS GFS, the global scaling constant for dust emissions (see equation (2) in Ginoux et al. (2001)) has been adjusted from C = 0.375 µg s^2 m^{-5} as in GEOS-4/5 to C = 1 µg s^2 m^{-5} in NGAC. This adjustment is determined from sensitivity experiments, allowing NGAC V2 to obtain dust emission budget comparable to GEOS-4/5"

Page 9, Line 19: The text is removed

Page 10, Line 8: "begins" changed to "has begun"

Page 10, Line 10: Insert "Information on accessing NGAC model output is provided in the Appendix. Daily web-based presentation of NGAC V1.0 forecasts is available at the EMC NGAC webpage: http://www.emc.ncep.noaa.gov/gmb/NGAC/html/realtime.ngac.html.   The website displays Aerosol Optical Depth (AOD) at 550 nm and surface mass concentrations over global domain and several regional domains (e.g., trans-Atlantic region, Asia, and Continental US (CONUS) regions)."

Page 10, Line 10: Remove "Dust initial conditions are taken from the 24 h NGAC V1.0 forecast from previous day while meteorological initial conditions are down-scaled from high-resolution Global Data Assimilation System (GDAS) analysis."

Page 10, Line 26: This paragraph has been revised to "Dust initial conditions are taken from the 24 h NGAC V1.0 forecast from previous day while meteorological initial conditions are

down-scaled from high-resolution Global Data Assimilation System (GDAS) analysis.   Note the interaction of GOCART aerosol fields and GFS's radiation package has been disabled in NGAC V1.0.   This configuration that aerosols are not radiatively coupled to AGCM is intended to facilitate aerosol modeling development in the near term.   Once the prognostic aerosol capability reaches desired maturity level, this aerosol-radiation decoupled configuration will be changed allowing the aerosol direct and semidirect radiative effects to be accounted for."

Page 11, Line 3-7: The text is removed

Page 11, Line 9: Add the following: "NCEP is currently working toward the phase-two NGAC implementation (Lu et al., 2016). The NGAC V2 includes full-suite of aerosols using near-real-time smoke emissions from satellite fire products. The NGAC upgrade will produce total AOD, allowing us to evaluate NGAC results beyond dust-dominated regions.   Efforts are underway to evaluate experimental NGAC V2 with other models (ICAP MME and GSFC's GEOS-5), in-situ observations at AERONET sites throughout the globe, and aerosol retrievals from multiple satellites, including MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP).   In this paper, only concise model results are presented as the paper mainly provides the programmatic aspects of NGAC development and implementation."

Page 12, Line 19: "Figure 5 shows seasonal dust distributions over the subtropical Atlantic region." Is changed to "Figure 5 shows monthly-mean dust distributions over the subtropical Atlantic region at different seasons."

Page 13, Line 10: "two dust-prone stations" changed to "six stations"

Page 13, Line 18: The text is replaced by "Among the six stations included in the comparison, three sites are located in dust-prone Sahara-Sahel region (Dakar, Ilorin, and Banizoumbou), one site is located in dust-prone Middle East area (Sede Boker), and two sites are located in tropical Atlantic Ocean region (Cape Verde and La Parguera). The Dakar site is located in Senegal, North Africa near the dust source region. The Ilorin site, located in Guinea Savanna zone, experiences dust and episodic smoke aerosols. The Banizoumhou site, located in the Sahel region, is influenced predominantly by dust transport from the Sahara. For the two ocean sites, Cape

Verde is influenced by dust outflow from Saharan sources while La Parguera is influenced by long-range transport of Saharan dust. The Middle East site, Sede Boker, is located in the Negev desert of Israel and experiences mainly dust and urban aerosols. At these sites except for Ilorin,"

Page 13, Line 24: The text is removed

Page 15, Line 2: The reference to Figure 8 is removed

Page 15, Line 6: Merge this paragraph with previous paragraph

Page 15, Line 19: "Figure 9" changed to "Figure 8"

Page 23: add "Lu, S., Wang, J., Bhattacharjee, P., Zhang, X., Kondragunta, S., da Silva, A., McQueen, J., Moorthi, S., Hou, Y., and Tallapragada, V.: The implementation of NEMS GFS Aerosol Component (NGAC) version 2: Global aerosol forecasting at NCEP using satellite-based smoke emissions, 5-8, Joint Center for Satellite Data Assimilation Quarterly, 53, available at: http://www.jcsda.noaa.gov/news.php (last access: 24 April 2016), doi;10.7289/V50C4SS7, 2016.

Page 34: Add Figures 6c-6f

Page 36: Remove Figure 8

Page 37: Figure 9 is now Figure 8

Geosci. Model Dev. Discuss., 9, 1–37, 2016
www.geosci-model-dev-discuss.net/9/1/2016/
doi:10.5194/gmdd-9-1-2016

This discussion paper is/has been under review for the journal Geoscientific Model Development (GMD). Please refer to the corresponding final paper in GMD if available.

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0 for global dust forecasting at NOAA/NCEP

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Received: 23 October 2015 – Accepted: 27 November 2015 – Published:

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Abstract

The NOAA National Centers for Environmental Prediction (NCEP) implemented NEMS GFS Aerosol Component (NGAC) for global dust forecasting in collaboration with NASA Goddard Space Flight Center (GSFC). NGAC Version 1.0 has been providing 5 day dust forecasts at 1° × 1° resolution on a global scale, once per day at 00:00 Coordinated Universal Time (UTC), since September 2012. This is the first global system capable of interactive atmosphere aerosol forecasting at NCEP. The implementation of NGAC V1.0 reflects an effective and efficient transitioning of NASA research advances to NCEP operations, paving the way for NCEP to provide global aerosol products serving a wide range of stakeholders as well as to allow the effects of aerosols on weather forecasts and climate prediction to be considered.

1 Introduction

Aerosols affect the energy balance of Earth's atmosphere through the absorption and scattering of solar and thermal radiation (Mitchell, 1971). Aerosols also affect Earth's climate through their effects on cloud microphysics, reflectance, and precipitation (Twomey, 1974; Albrecht, 1989; Jones et al., 1994; Lohmann et al., 2000). In ad­ditional to modulate Earth's climate and hydrological cycle (Ramanathan et al., 2001), aerosols are important for atmospheric chemistry, the biosphere, and public health. Aerosols can be viewed in their role as air pollutants because of their adverse health effects (Pöschl, 2005). Long range transport of aerosols can affect the air quality and visibility far from the source regions (Prospero, 1999; Jaffe et al., 2003; Colarco et al., 2004). In addition, aerosols may play a significant role in atmospheric oxidation processes (Andreae and Crutzen, 1997; Dickerson et al., 1997). Large amount of mineral dust are deposited to the oceans (Duce et al., 1991; Prospero et al., 1996) and the atmospheric input is found to be important for marine productivity (Chen et al., 2007).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Line17: changed to "addition to modulating"

Line 23: changed to "amounts"

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While the importance of aerosols on climate has long been established, it is only recently that the aerosol effects are being increasingly recognized as important for weather predictions (Perez et al., 2006; Mulcahy et al., 2014). Haywood et al. (2005) shows that the neglect of the radiative effects of mineral dust leads to systematic biases in the top-of-the-atmosphere radiative budget in the UK Met Office (UKMO) numerical weather prediction (NWP) model. By prescribing updated aerosol climatology in the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP model, a shift in the African Easterly Jet (AEJ) in better agreement with observations is demonstrated in Tompkins et al. (2005) and improvements in local medium-range forecast skills and global seasonal-mean are shown in Rodwell and Jung (2008). A number of studies have suggested that aerosols can significantly impact severe weather, such as intensifying Pacific storm track (Zhang et al., 2007; Wang et al., 2014), modifying hurricane and tropical cyclones (Rosenfeld et al., 2012; Herbener et al., 2014), affecting deep convective storms and tornado intensity in the US (Wang et al., 2009; Saide et al., 2015), and enhancing catastrophic floods in Southwest China (Fan et al., 2015).

Despite recent progress in atmospheric aerosol modeling, the physical processes crucial for modeling aerosol effects are either poorly represented or outright missing in National Centers for Environmental Prediction (NCEP) global models. The NCEP's Global Forecast System (GFS) is the cornerstone of NCEP's operational production suite of numerical guidance. The atmospheric forecast model used in the GFS is global spectrum model (GSM) with a comprehensive physics suite (see the GFS webpage at http://www.emc.ncep.noaa.gov/GFS/doc.php). Until now, the model only considers aerosol radiative effects and the aerosol distributions are prescribed based on a global climatological aerosol database (Hess et al., 1998).

Efforts to develop prognostic aerosol capability in NCEP global models have been underway in the last few years, which in turn is part of NCEP's modeling development efforts toward a unified modeling framework. Specifically, NCEP is developing NOAA Environmental Modeling System (NEMS) as its next-generation operational system (Black et al., 2007, 2009) and has collaborated with NASA/Goddard Space Flight Cen-

[GMDD](...)

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

ter (GSFC) to develop NEMS GFS Aerosol Component (NGAC) for predicting the dis-
tribution of atmospheric aerosols (Lu et al., 2010, 2013). ~~The NGAC consists of~~
key modeling components: (1) the GFS within the NEMS architecture (NEMS GFS)
and (2) the on-line aerosol module based on Goddard Chemistry Aerosol Radiation
and Transport (GOCART) model.

NGAC Version 1.0 (NGAC V1.0) has
at NCEP since September 2012. It pro
of dust aerosols with global coverage.
system in turn provides a first step tow
NCEP. The rationale for developing the g
capabilities at NCEP includes: (1) to imp
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
assimilation procedure, (3) to provide aerosol (lateral and upper) boundary conditions
for regional air quality predictions; and (4) to provide global aerosol products to meet
the stakeholder needs such as air quality, UV index, visibility, ocean productivity, solar
energy production, and sea surface temperature (SST) retrievals.

Aerosol modeling, traditionally serving regional air quality and climate communities,
has seen rapid development at several operational and research NWP centers in the
last few years (Reid et al., 2011; Benedetti et al., 2011, 2014). This includes NCEP (dis-
cussed in this paper), ECMWF (Benedetti et al., 2009; Morcrette et al., 2009), UKMO
(Woodward, 2001, 2011), Naval Research Laboratory (NRL, Zhang et al., 2008; West-
phal et al., 2009), NASA Global Modeling and Assimilation Office (GMAO, Colarco
et al., 2010), Japan Meteorological Agency (JMA, Tanaka et al., 2003), and Barcelona
Supercomputing Centre (BSC, Perez et al., 2011; Basart et al., 2012). In addition, the
efforts to develop regional and global multi-model ensemble for aerosol prediction are
underway (Sessions et al., 2015), offering aerosol products for research applications
and eventually operational use. The implementation of NGAC V1.0 at NCEP not only

> **Line 2, Insert one sentence** "NGAC is the first on-line (interactive) atmospheric [...]

> **Line 5, add one sentence at the end of this paragraph:** The advantages for taking the so-called on-line approach include: (1) consistency: no spatial -temporal interpolation and the use of the same physics parameterization, (2) efficiency: lower overall CPU costs and easier data management, and (3) interaction: allows for aerosol feedback to meteorology

contributes to the NCEP production suite but also to the international efforts for multi-model ensembles.

In this paper, we describe the development and implementation of NGAC V1.0 at NCEP. In Sect. 2, we describe the model configuration. In Sect. 3, we present the operational implementation of NGAC V1.0. In Sect. 4, we present the results of NGAC V1.0 forecasts and the comparisons to other global aerosol models and observations. In Sect. 5, we demonstrate two examples of NGAC V1.0 applications. Section 6 provides concluding remarks.

2 Model configuration

2.1 Atmospheric model: NEMS GFS

The efforts to develop a unified modeling framework to streamline the interaction of forecast, analysis, and post-processing systems within NCEP have been under-way since late 2000 (Black et al., 2007, 2009). Specifically, NCEP is developing NEMS (http://www.emc.ncep.noaa.gov/index.php?branch=NEMS) with a component-based architecture following the Earth System Modeling Framework (ESMF, see http://www.earthsystemmodeling.org). The ESMF is a community effort to promote the exchange and reusability of earth system modeling components and to facilitate faster knowledge transfer and technology adaptation. The ESMF collaboration involves many of the major climate, weather and data assimilation efforts in the United States, including NOAA/NCEP, NASA/GMAO, NRL, NOAA Geophysical Fluid Dynamics Laboratory (GFDL), and the National Center for Atmospheric Research (NCAR).

The development of NEMS aims to develop a common superstructure for NCEP production suite. Other motivations include: (1) to reduce overhead costs and provide a flexible infrastructure in the operational environment, (2) to modularize large pieces of the systems with ESMF components and interfaces, and (3) to enable NOAA con-

[GMDD](#)

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

tribution to the National Unified Operational Prediction Capability (NUOPC) with Navy and Air Force.

The NEMS is organized into collections of components with standardized interfaces, arranged in a hierarchical structure. Currently the GFS, the B-grid version of the Non-hydrostatic Multi-scale Model (NMM-B), and the Flow-following finite-volume Icosahedral Model (FIM) have been placed under the NEMS-atmosphere framework. A unified parallelized I/O package is developed to handle the synchronous production and writing of history files, 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) for global weather prediction research. The NMM-B model, developed by NCEP, is the forecast model for the North American Meso-scale Forecast System (NAM) providing operational meso-scale weather forecasts since October 2011. The NEMS version of GFS (referred to as NEMS GFS in this paper) consists of the same spectral dynamic core and physics parameterizations 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. Despite extensive use of ESMF superstructure, infrastructure and utilities in NEMS, the underlying science code, however, remains the same as the operational GFS. Second, enhanced I/O and post-processing capabilities are introduced in the NEMS GFS. These include an option to output history files in native Gaussian grids instead of spectral grids and an 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. This option to assemble GFS physics as the NEMS unified physics package again reflects NCEP's modeling strategy toward a unified and yet flexible modeling infrastructure.

The NEMS has been under active development. Efforts to incorporate non-atmospheric components, e.g., ocean, wave, and sea ice models, are underway. The coupling infrastructure is based on the ESMF and NUOPC Layer code and conven-

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

[GMDD](javascript:void(0))

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

tions. Development is also made to enable emerging environmental prediction capabilities. The aerosol forecasting capability, NGAC, discussed in this paper is virtually NEMS GFS with the prognostic aerosol option turned on. Parallel efforts are underway to extend NEMS GFS to 600 km to model dynamical, physical, and chemical interactions between the lower atmosphere and the upper atmosphere. ~~The development of Whole Atmosphere Model (WAM), spanning from the surface to the thermosphere, aims to forecast solar and geophysical events that affect satellites, power grids, communication, and navigation.~~

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), and sulfur gases (Chin et al., 2000, 2002, 2003, 2004, 2007, 2009; Ginoux et al., 2001, 2004; Bian et al., 2010; Colarco 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, e.g., Chin et al., 2002). As part of the GEOS Version 4 (GEOS-4) atmospheric model development at NASA GMAO, an ESMF compliant GOCART grid component has been developed (Colarco et al., 2010). When running within versions 4 and 5 of GEOS (GEOS-4/5), the GOCART component provides aerosol processes such as emissions, sedimentation, dry and wet deposition (Fig. 1). Dynamic sources (wind-speed dependent) are considered for DMS, dust and sea salt. Emissions for SO_2 and carbonaceous aerosols arise from nature and anthropogenic sources, including biogenic, biofuel, anthropogenic, and biomass burning emissions. Aerosol chemistry currently uses prescribed OH, H_2O_2, and NO_3 fields for DMS and SO_2 oxidations. Aerosol sinks include wet removal (scavenging and rainout) and dry deposition (gravitational sedimentation and surface uptake). Advection, turbulent and convective transport is outside the scope of the GOCART component, being instead provided by the host atmospheric model. Unlike off-line CTM, this on-line

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Line 21: dimethyl sulfide (DMS)

aerosol module accurately utilizes winds, convective mass flux, and eddy diffusivity valid at each time step, without the need for temporal or spatial interpolation of any kind.

Research and development efforts have further enhanced GOCART modeling capabilities. The transition from off-line to on-line coupling approach mentioned above is an example. In addition, the GOCART grid component now has the option to ingest daily biomass burning emissions from the Quick Fire Emission Dataset (QFED, Darmenov and da Silva, 2015). QFED emissions are based on fire radiative power retrievals from MODIS (Moderate Resolution Imaging Spectroradiometer, on board Aqua and Terra satellites). The inclusion of such observation-based, time-dependent emissions is important for the model to capture the large temporal-spatial variation of 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 su̶r̶f̶a̶c̶e̶ ness. ~~The dust source function regridded on the T126 GFS grid (shown representing the probability of dust uplifting, is determined from surface topographical depression features.~~ The maxima of dust source function with the climatologically active dust sources or so-called dust hot spots. dent examples are the Sahara desert in north Africa, the Bodele depression over Chad, the Syrian desert in mid-East, the Taklimakan desert in northwest China, the Lake Eyre basin in Australia, the Sonoran desert in southwest California, the Namibian sources in southwest Africa, and Patagonian desert and Andean Plateau in the Andes. ~~A new dynamic dust source function based on the satellite observed surface vegetation cover has been developed and incorporated into the off-line GOCART aerosol simulations at GSFC (Kim et al., 2013).~~

L18: this sentence is replaced by "The dust source function, representing the probability of dust uplifting, is determined from surface bareness and topographical depression features. Surface bareness is

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

2.3 Coupling NEMS GFS with GOCART

The GOCART grid component originally developed for GEOS-4/5 is fairly independent of the host atmospheric model, encapsulating the basic aerosol production and loss functionality. Consistent with standard ESMF architecture, the interfaces linking GO-CART and NEMS GFS have been isolated into coupler components. Figure 3 shows the integration run stream of NGAC. Coupler components are built to transfer and transform the data between NEMS GFS and GOCART. The physics-to-chemistry coupler performs several tasks including: (i) the vertical flip for 3-dimensional fields, as GO-CART 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) the calculations for these fields needed by GOCART such as inferring relative humidity and air density from ambient temperature and moisture fields. After running GOCART, the chemistry-to-physics coupler transfers updated 3-dimensional aerosol fields and 2-dimensional aerosol diagnosis fields from GOCA

Despite the ESMF flavor in how GOCART is imp into NEMS GFS as a column process similar to ho It updates 3-dimensional aerosol loading after phys as physics and dynamics, and is fully coupled with step. ~~The advantages for taking the so-called on-lin~~ ~~no spatial–temporal interpolation and the use of the~~ ~~efficiency: lower overall CPU costs and easier dat~~ ~~allows for aerosol feedback to meteorology. The a~~ ~~since the ultimate goal for the development of NG~~ ~~of atmospheric aerosols for improving NCEP's m~~ ~~seasonal climate prediction.~~

> Line 15, Add the following at the beginning of this paragraph:
> GOCART in GEOS-4/5 has been implemented in NEMS GFS `as is' except for emission budget. As in GEOS-4/5 (Colarco et al., 2010), the spatial distribution and intensity of dust sources in NGAC V1 follows from Ginoux et al. (2001). Owing to differences in the GEOS-4/5 meteorology and resolution relative to NEMS GFS, the global scaling constant for dust emissions (see equation (2) in Ginoux et al. (2001)) has been adjusted from $C = 0.375\ \mu g\ s^2\ m^{-5}$ as in GEOS-4/5 to $C = 1\ \mu g\ s^2\ m^{-5}$ in NGAC. This adjustment is determined from sensitivity experiments, allowing NGAC V2 to obtain dust emission budget comparable to GEOS-4/5.

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Title Page

Interactive Discussion

Discussion Paper | Discussion Paper | Discussion Paper

GMDD

9, 1–37, 2016

The implementation ... GFS ... mponent (NGAC) version 1.0

3 NGAC V1.0 operational implementation

A phased approach is used to manage the operational implementation of NGAC at NCEP. The first phase is to produce dust-only guidance, the second phase is to produce the full suite of aerosol forecasts (including dust, sea salt, sulfate, and carbonaceous aerosols), and the third phase is to produce aerosol analysis using NGAC forecasts as first guess. Only the initial deployment undertaken in 2012 is discussed in this paper.

Effective on 11 September 2012, starting with the 00:00 UTC cycle, NCEP ~~begins to~~ run and disseminate data from the NGAC V1.0 system at T126 L64 resolution. It pro- vides 5 day dust forecasts, once per day for the 00:00 UTC cycle. ~~Dust initial cond are taken from the 24 h NGAC V1.0 forecast from previous day while meteorologic tial conditions are down-scaled from high-resolution Global Data Assimilation Sy (GDAS) analysis.~~

Model configurations in NGAC V1.0 are same as those specified in operational resolution GFS runs with the following exceptions. First, NGAC uses Relaxed Araka Schubert scheme (the RAS scheme, Moorthi and Suarez, 1992, 1999) while GFS Simplified Arakawa–Schubert scheme (the SAS scheme, Han and Pan, 2011) hanced tracer treatment (e.g., convective t... incorporated into the RAS scheme, providin... eling. Second, NGAC V1.0 is run at ~~lower~~ s... GFS. In February 2015, GFS was upgrad... Lagrangian T1534 (~ 13 km). NGAC V1.0,... tober 2015. Third, NGAC V1.0 produces his... currently while GFS produces post-process... out.

Note both GFS and NGAC use climatolog... age. This aerosol-radiation decoupled confi... diatively coupled to the AGCM is intended...

Annotations:

Line 8: changed to "has begun"

Line 10, insert the following:: "Information on accessing NGAC model output is provided in the Appendix. Daily web-based presentation of NGAC V1.0 forecasts is available at the EMC NGAC webpage: http://www.emc.ncep.noaa.gov/gmb/NGAC/html/realtime.ngac.html. The website ...ical Depth (AOD) at ...mass ...global domain and ...ains (e.g., trans-... and Continental

L26: This paragraph has been revised:: "Dust initial conditions are taken from the 24 h NGAC V1.0 forecast from previous day while meteorological initial conditions are down-scaled from high-resolution Global Data Assimilation System (GDAS) analysis. Note the interaction of GOCART aerosol fields and GFS's radiation package has been disabled in NGAC V1.0. This configuration that aerosols are not radiatively coupled to AGCM is intended to facilitate aerosol modeling development in the near term. Once the prognostic aerosol capability reaches desired maturity level, this aerosol-radiation decoupled configuration will be changed allowing the aerosol direct and semidirect radiative effects to be accounted for

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

==in the near term and will be changed once the prognostic aerosol capability reaches desired maturity level.==

~~Daily web-based presentation of NGAC V1.0 forecasts is available at the following location: http://www.emc.ncep.noaa.gov/gmb/NGAC/html/realtime.ngac.html~~

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

4 NGAC results

In this section, the results of operational NGAC V1.0 forecasts are ==prese==

10 ### 4.1 Dust emissions and budget

Figure 4 shows the annual dust emissions calculated from the first yea[ ]production (the September 2012–September 2013 period). The similarit[ ]annual dust emissions and the dust source function (shown in Fig. 2) [ ]the source function is of central importance in determining dust uplift[ ]
15 other parameters. In the Ginoux et al. (2001) dust emission scheme, a [ ]factor (C, equal to $1\,\mu g\,s^2\,m^{-5}$) is used to scale total dust flux to yield a [ ]about 1800–$2000\,Tg\,yr^{-1}$. This factor is adjusted to $0.375\,\mu g\,s^2\,m^{-5}$ in GE[ ]to differences in the GEOS-4 meteorology relative to previous version [ ]assimilated meteorology. As we adopted the on-line version of GOCART[ ]
20 4/5 into NEMS GFS, the scaling factor is reverted back to $1\,\mu g\,s^2\,m^{-5}$ [ ]the differences in AGCM and resolution (i.e., $0.25°$ resolution for GEO[ ]resolution for NEMS GFS).

Table 1 provides a summary of NGAC V1.0 calculated annual emissio[ ]lifetime (or atmospheric residence time) relative to other similar global ae[ ]
25 including three versions of GOCART results and the models participating[ ]

Line 9: add the following: "NCEP is currently working toward the phase-two NGAC implementation (Lu et al., 2016). The NGAC V2 includes full-suite of aerosols using near-real-time smoke emissions from satellite fire products. The NGAC upgrade will produce total AOD, allowing us to evaluate NGAC results beyond dust-dominated regions. Efforts are underway to evaluate experimental NGAC V2 with other models (ICAP MME and GSFC's GEOS-5), in-situ observations at AERONET sites throughout the globe, and aerosol retrievals from multiple satellites, including MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). In this paper, only concise model results are presented as the paper mainly provides the programmatic aspects of NGAC development and implementation."

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9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C. H. Lu et al.

Comparisons between Observations and Models (AeroCom) model intercomparison studies (http://aerocom.met.no/aerocomhome.html). The three GOCART results are from on-line GEOS4-GOCART (Colarco et al., 2010) and off-line GOCART CTM driven by two versions of GEOS DAS meteorological analyses (Chin et al., 2009; Ginoux et al., 2001).

Large difference (diversity) are found in emissions, burdens, and lifetimes within the AeroCom models, which is primarily related to the differences in the emission parameterizations, the particles sizes, the meteorological fields and model configuration used in the individual models (Textor et al., 2006). The simulated total dust emissions, annual burden, and lifetime in NGAC V1.0 are within the range of the AeroCom models. The annual emissions are similar in NGAC V1.0 and on-line GEOS4-GOCART (1980 vs. 1970 $Tg\,yr^{-1}$). In NGAC V1.0, the lifetime is about one and a half day shorter than in on-line GEOS4-GOCART (4.3 days vs. 5.85 days) and the annual burden is about 30 % lower (21.9 vs. 31.6 Tg). The results suggest more efficient removal processes in NGAC V1.0 than in GEOS4.

4.2 Aerosol optical depth

In this section we present the results of NGAC V1.0 dust distributions. We first compare NGAC dust AOD to dust AOD from GEOS-5 and total AOD from MODIS onboard Terra. Figure 5 shows ~~seasonal~~ dust distributions over the subtropical Atlantic region. The source regions over the Sahara and Sahel are clearly shown as well as the patterns of long-range dust transport. Trade winds steer African dust westward across the Atlantic ocean, covering vast areas of the North Atlantic and sometime reach the Americas (e.g., the Caribbean, southeastern United States, Central America, and Amazon basin). This has implications for air quality, public health, climate, and biogeochemical cycle. For instance, about half of the annual dust supply to the Amazon basin is emitted from a single source in the Sahara, the Bodele depression (Koren et al., 2006).

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

While elevated dust off the western Africa coast is persistent through the seasons, the models and satellite observations show a clear latitudinal shift of the dust plume over the tropical Atlantic from winter to summer. This seasonal shift has been attributed to the movements of the Inter Tropical Convergence Zone (ITCZ) which occupies its southernmost location in winter and northernmost location in summer (Huser et al., 1997; Ginoux et al., 2001). The results are consistent with the seasonal cycle discussed in Knippertz and Todd (2012) in which detailed descriptions of meteorological processes controlling the emissions and transport of African dust are provided.

The comparison of model forecasts to L1.5 AErosol RObotic NETwork (AERONET) AOD at 550 nm for 2013–2014 period at ~~two dust-prone~~ stations. AERONET AOD at 550 nm is computed using logarithmic interpolation values at 440 and 675 nm. We bin the AERONET observations within one-hour time window centered at NGAC synoptic output times of 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00, and 24:00 UTC. The calculation of monthly mean requires a minimum of 5 days with valid values. We show the comparison of the model AOD to AERONET observations, including the time series, a scatter plot, a fractional distribution histogram (PDF) of the model and observed AOD, and some statistics including mean bias, root-mean-square errors, linear fit parameters, and correlation coefficients. ~~The~~ ~~site is located in Senegal, North Africa near the dust source region. The Cap~~ ~~site is an ocean site influenced by transport of dust from Saharan sources.~~ ~~sites,~~ NGAC V1.0 simulations are found to captures the seasonal variability in loading. Overall, NGAC V1.0 shows similar seasonal variability to and is well correlated with the AERONET observations.

~~NCEP is currently working toward the phase two NGAC implementation (i.e., full~~ ~~suite of aerosols including dust, sea salt, sulfate, and carbonaceous aerosols us-~~ ~~ing near-real-time smoke emissions from satellite fire products). The planned NGAC~~ ~~upgrade will produce total AOD, allowing us to evaluate NGAC results beyond dust-~~ ~~dominated regions.~~

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Pa

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

5 NGAC applications

NGAC V1.0 provides 2- and 3-dimensional aerosol products at 1° × 1° resolution on a global scale. Potential usage for these aerosol products includes, but is not limited to: AOD at 340 nm for UV index forecasts; AOD at 550 nm for multi-model ensemble and aerosol data assimilation; AOD at 860 nm for Advanced Very High Resolution Radiometer (AVHRR) SST retrievals; AOD at 11.1 µm for the Atmospheric Infrared Sounder (AIRS) temperature retrievals; three dimensional dust mixing ratios for atmospheric correction; dust column mass density, emission and removal fluxes for aerosol budget study; dust deposition fluxes for ocean productivity and dust surface mass concentrations for air quality. Here we present two examples of NGAC product applications.

5.1 Multi-model ensemble

The International Cooperative for Aerosol Prediction (ICAP), consisting of forecasting center model developers and remote sensing data providers, began meeting in April 2010 to discuss issues relevant to the operational aerosol forecasting (Benedetti, 2011; Reid et al., 2011). ICAP members created a developmental global multiple-model ensemble (MME) to explore probabilistic aerosol prediction and assess relative differences among models (Sessions et al., 2015). Consensus ICAP forecasting began in early 2011 and the experimental ICAP-MME became quasi-operational for public release in 2015. Current ICAP MME products include total AOD ensemble from four complete aerosol forecast models from NRL, ECMWF, JMA, and GMAO and three dust-only models from NCEP, UKMO, and BSC. Figure 7 shows the dust AOD from ICAP-MME (with 7 members) and NGAC V1.0, valid at 12:00 UTC 4 July 2015. Spatial pattern of dust loading from NGAC V1.0 is consistent with the ICAP-MME, with elevated dust AOD located in the Sahara, the Arabian Peninsula, and Asia as well as evident long range trans-Atlantic transport of Saharan dust reaching southeastern United States.

Dust forecasts from NGAC V1.0 also contributes the regional multi-model ensemble produced 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 (http://sds-was.aemet.es). ~~Figure 8 shows the dust AOD regional ensemble products valid at 12:00 UTC 4 July 2015. The multi-model products describing centrality (multi-model median and mean) and spread (standard deviation and coefficient of variation) are generated from multiple global and regional forecast models e~~ Participation in ICAP-MME and WMO SDS-WAS multi-model ensemble provides a continuous and indenpent assessment of the quality of NCEP global dust products. Overall, NGAC V1.0 forecasts are found to be comparable to that produced by other domestic and international modeling centers.

5.2 Dynamic lateral boundary conditions for regional models

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 (AQF) system (Davidson et al., 2004). The AQF system is based on EPA Community Multi-scale Air Quality (CMAQ) model driven by meteorological forecasts from NCEP North American Meso (NAM) Model. Static lateral boundary conditions (LBCs) assuming no dust at the model boundary are currently used.

Two CMAQ runs are conducted for the July 2010 period. The baseline run uses static LBCs and the experimental run uses dynamic LBCs from NGAC V1.0. Figure 9 shows the observed and modeled surface Particulate Matter smaller than 2.5 micron (PM at two AIRNOW stations in the southeast region. Table 2 presents the statistic results of the CMAQ compared to the EPA AIRNOW PM$_{2.5}$. It is found that the incorporation of dynamic LBCs from NGAC V1.0 reduces model biases and improves correlation. Clearly, the inclusion of long-range dust transport through dynamic LBCs leads to significant improvements in CMAQ forecasts during dust intrusion episodes.

Line 6: merge the this and previous paragraphs into one

Line 7: correction "independent"

Line 15: (CMAQ) model (Byun and Schere, 2006)

Line 16: NAM model (see the NAM webpage at http://

Line 19: Figure 9 changed to Figure 3

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

[GMDD](#)

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

6   Conclusions

NASA/GMAO's GOCART aerosol module has been implemented into NEMS GFS at NCEP through NOAA/NCEP-NASA/GSFC collaborations. While NGAC has the capability to forecast dust, sulfate, sea salt, and carbonaceous aerosols, the initial phase-
⁵ one implementation is to establish dust-only numerical guidance. NGAC Version 1.0, implemented in September 2012, provides the first operational global dust forecasting capability at NOAA. Its AOD product has been incorporated into global and regional multi-model ensemble products (ICAP and WMO SDS-WAS, respectively) in quasi-operational mode.
¹⁰ The NGAC V1.0 dust forecasts are routinely verified using AOD observations from space-borne MODIS and ground-based AERONET. NGAC V1.0 results are also compared with those from other similar aerosol models. It is shown that the NGAC V1.0 simulated spatial distributions and seasonal variations are consistent with the observations. In addition, the emissions, burdens, and lifetime of dust aerosols in NGAC V1.0
¹⁵ are within the range of similar aerosol models.

While the initial NGAC implementation is limited in its scope (a dust-only system without aerosol data assimilation), it laid the ground work for various aerosol-related applications. Future operational benefits associated with the global aerosol forecasting system at NOAA includes:

²⁰ – Enable operational global short-range multi-species aerosol prediction.

– Provide the first step toward an operational aerosol data assimilation capability at NCEP.

– Allow aerosol impacts on medium range weather forecasts to be considered.

– Provide global aerosol information for various applications, including satellite radi-
²⁵ ance 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.

Appendix A: NGAC output

Output files and their contents for NGAC V1.0 (Q4FY12 Implementation)

(1) ngac.t00z.a2df$HR, where HR = 00, 03, ..., 120:
2-D products including
AER_OPT_DEP_at550: dust aerosol optical depth at 550 nm (dimensionless)
CR_AER_SFC_MASS_CON: coarse mode surface mass concentration ($kg\,m^{-3}$)
FN_AER_SFC_MASS_CON: fine mode surface mass concentration ($kg\,m^{-3}$)
CR_AER_COL_MASS_DEN: coarse mode column mass density ($kg\,m^{-2}$)
FN_AER_COL_MASS_DEN: fine mode column mass density ($kg\,m^{-2}$)
DUST_EMISSION_FLUX: dust emission fluxes ($kg\,m^{-2}\,s^{-1}$)
DUST_SEDIMENTATION_FLUX: dust sedimentation fluxes ($kg\,m^{-2}\,s^{-1}$)
DUST_DRY_DEPOSITION_FLUX: dust dry deposition fluxes ($kg\,m^{-2}\,s^{-1}$)
DUST_WET_DEPOSITION_FLUX: dust wet deposition fluxes ($kg\,m^{-2}\,s^{-1}$)

(2) ngac.t00z.a3df$HR, where HR = 00, 03, ..., 120:
3-D products at model levels including
PRES: pressure (Pa)
RH: relative humidity (%)
TEMP: temperature (K)
DUST1: dust bin1 (0.1–1 micron) mixing ratio ($kg\,kg^{-1}$)
DUST2: dust bin2 (1–1.8 micron) mixing ratio ($kg\,kg^{-1}$)
DUST3: dust bin3 (1.8–3 micron) mixing ratio ($kg\,kg^{-1}$)

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

[GMDD](#)

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

DUST4: dust bin4 (3–6 micron) mixing ratio (kg kg^{-1})
DUST5: dust bin5 (6–10 micron) mixing ratio (kg kg^{-1})

(3) ngac.t00z.aod_$NM, where NM = 11p1um, 1p63um, 340, 440, 550, 660, 860 nm:
Aerosol optical depth (dimensionless) at specified wavelengths (11.1, 1.63, 0.34, 0.44, 0.55, 0.66, and 0.86 micron)

Data and code availability

Products from the NCEP operational production suite are distributed and accessible to general users, free of charge, in real-time (typically no later than 3 h after the data are created) at NOAA Operational Model Archive and Distribution System (NOMADS). Source code as well as relevant run scripts, parameters, and fixed field files can be obtained from NCEP Central Operations (NCO) ftp site at the following location: http://www.nco.ncep.noaa.gov/pmb/codes/nwprod/ngac.v1.0.0.

The NGAC V1.0 output is available in GRIdded Binary Version 2 (GRIB2) format on 1° × 1° degree grid, with 3 hourly output out to 120 h. Users can access the NGAC V1.0 digital products from NOMADS at the following location: http://nomads.ncep.noaa.gov/pub/data/nccf/com/ngac.

NGAC V1.0 output instantaneous values of 3-dimensional dust mixing ratios for five particle sizes with effective radius at 1, 1.8, 3, 6, and 10 micron. The model also output time-averaged 2-dimensional diagnostics fields relevant to aerosol budget, such as emission fluxes. These aerosol fields are written out at GFS native Gaussian grid, and post-processed to GRIB2 format and regular 1° × 1° degree grid. Dust AOD at 550 nm and other selected spectral is calculated from instantaneous dust distributions with aerosol optical properties based on Chin et al. (2002). NGAC V1.0 GRIB2 output files and their contents are listed in the Appendix.

Acknowledgements. The NGAC project has been supported by NASA Applied Science Program and NOAA-NASA-DOD Joint Center for Satellite Data Assimilation. The authors thank

[GMDD](#)

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Didier Tanre for the efforts in establishing and maintaining Cape Verde and Dakar sites. Brent Holben leads the AERONET program and provided access to near-real-time L1.5 data set. The authors also appreciate the multi-model ensemble work done by the NRL (for ICAP) and BSC (for WMO SDS-WAS NA-ME-E Regional Center). The lead author C.-H. Lu is grateful for technical help and/or scientific input from her NCEP EMC colleagues, Wei-Yu Yang, Perry Shafran, and Ho-Chun Huang, and Yuqiu Zhu. She also thanks her NCEP NCO colleagues for transitioning pre-operational NGAC V1.0 system into NCEP production, including Simon Hsiao, Xiaoxue Wang, Christine Caruso Magee, Jeff Ator, Boi Vuong, Rebecca Cosgrove and Daniel Starosta. The pre-implementation evaluation by Walter Sessions, Nick Nalli, Andy Harris, Craig Long, Gary Votaw, and Jeral Estupinan is also greatly appreciated.

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The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Table 1. Global annual emissions, annual burden and lifetime for dust aerosols[*].

	Emissions (Tg yr^{-1})	Burden (Tg)	Lifetime (day)
NGAC V1.0	1980	21.9	4.3
On-line GEOS4	1970	31.6	5.85
Off-line GEOS4	3242	38.4	4.33
Off-line GEOS	1604–1956	31–40	6.6–7.3
AeroCom	1123 [514–4313]	15.8 [6.8–29.5]	4.6 [1.6–7.1]

[*] Note: the top number is the NGAC V1.0 results from September 2012–September 2013, the second number is the results of on-line GEOS4-GOCART simulations (Table 1 in Colarco et al., 2010), the third number is the results of off-line GEOS4-GOCART model (Table 1 in Colarco et al., 2010 which in turn is provided by Mian Chin using the off-line GEOS4-GOCART model described in Chin et al., 2009), the fourth number is the results of off-line GEOS-GOCART model (Table 2 in Ginoux et al., 2001), and the fifth number is the average of the AeroCom models with the range of the models in parentheses (Table 3 in Huneeus et al., 2011).

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GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

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9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

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Table 2. Statistic results comparing CMAQ model results with EPA AIRNOW PM$_{2.5}$. The mean bias (MB) and correlation (R) are calculated for the baseline run using static LBCs and the experimental run using NGAC LBCs.

Domain/Period	CMAQ Baseline	CMAQ Experimental
Whole domain, 1 Jul–3 Aug	MB = −2.82, R = 0.42	MB = −0.88, R = 0.44
South of 38° N, East of 105° W 1 Jul–3 Aug	MB = −4.54, R = 0.37	MB = −1.76, R = 0.41
Whole domain, 18–30 Jul	MB = −2.79, R = 0.31	MB = −0.33, R = 0.37
South of 38° N, East of 105° W 18–30 Jul	MB = 4.79, R = 0.27	MB = −0.46, R = 0.41
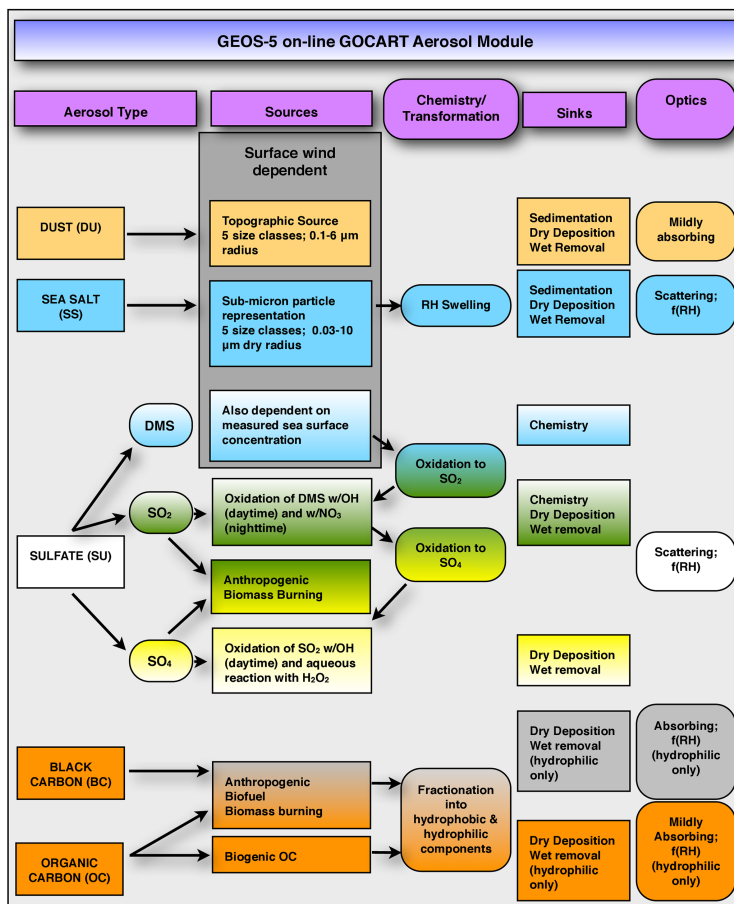
Figure 1. Schematic summary of the GOCART aerosol module as adapted and being implemented in GEOS-4/5 at GMAO and NEMS GFS at NCEP.

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

GOCART Dust Source Function
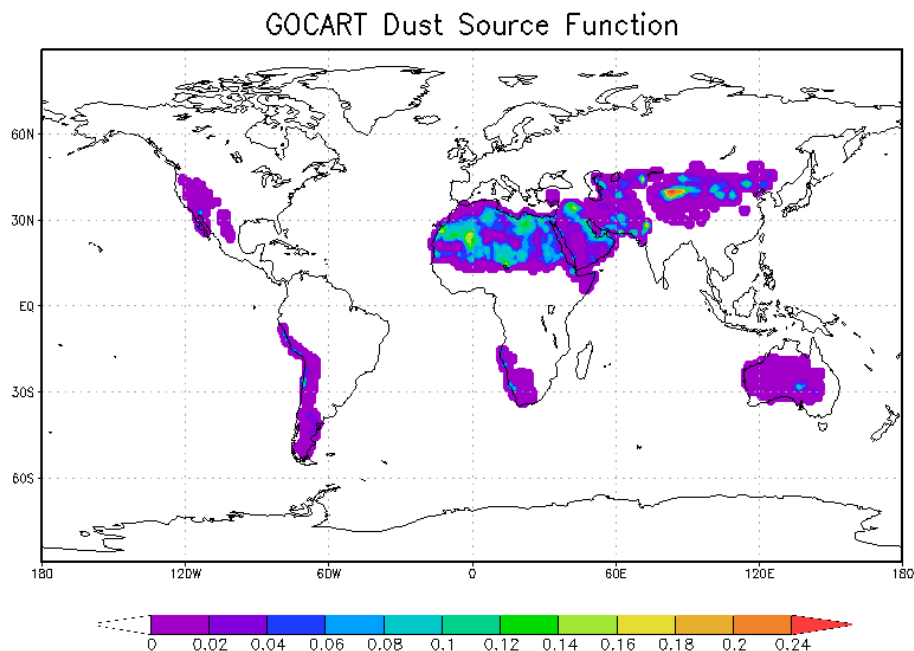
Figure 2. The dust source function or probability of dust uplifting, mapped to GFS T126 resolution, used in NGAC V1.0.

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GMDD

9, 1–37, 2016

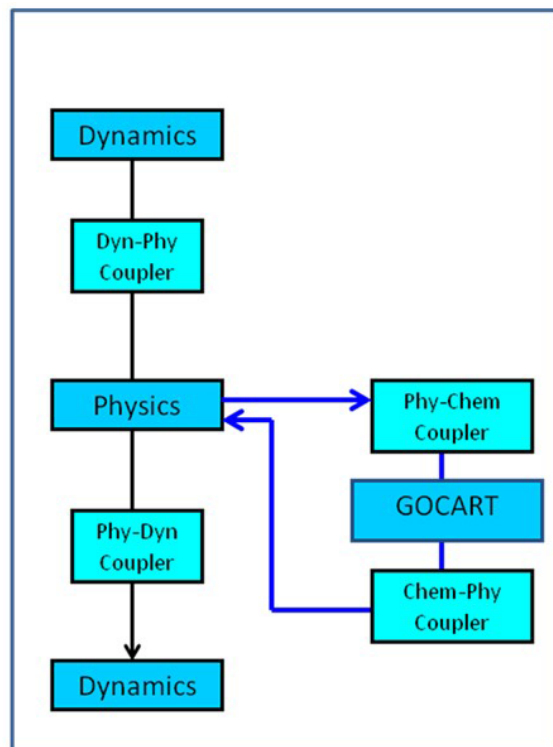
The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Figure 3. Primary integration runstream of NGAC.

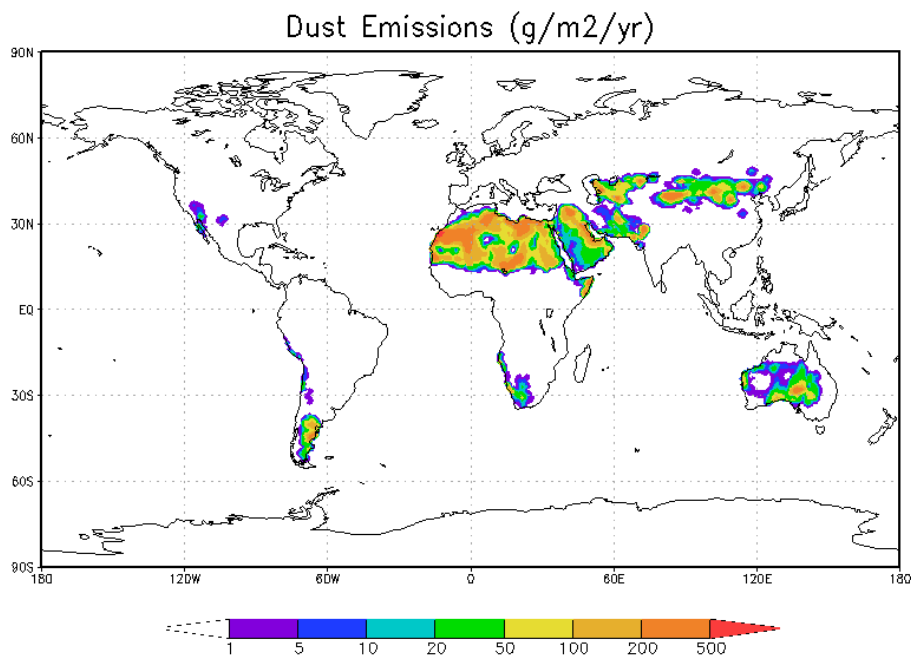



Figure 4. Annual dust emissions (in $\mathrm{g\,m^{-2}\,yr^{-1}}$) over the September 2012–September 2013 period.

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GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

GMDD

9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

C.-H. Lu et al.
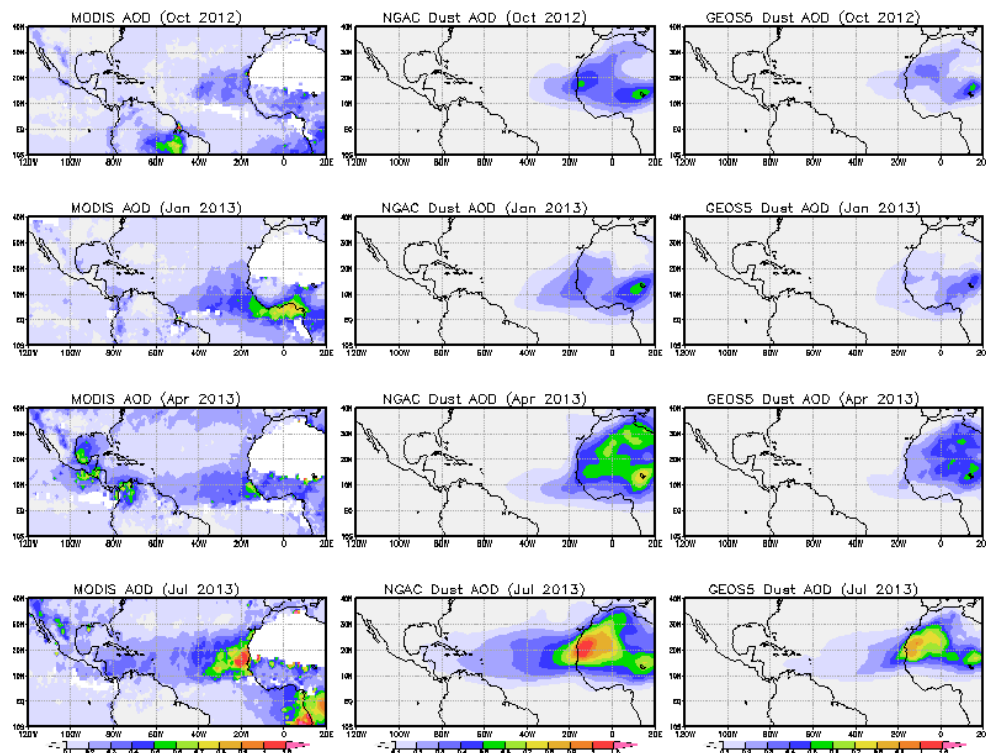
Figure 5. Comparisons of monthly-mean MODIS total AOD (left), NGAC V1.0 dust AOD (middle), and GEOS5 dust AOD (right) at 550 nm for October 2012, January 2013, February 2013, and July 2013 periods.

Figure 6. (a) NGAC V1.0 vs. L1.5 AERONET 550-nm AOD comparisons at Cape Verde for the 2013–2014 period: a time series, scatterplot, and fractional distribution histogram. In the time series, the model monthly means and standard deviation about the mean are shown in the black symbols and lines. The AERONET monthly means and standard deviation about the mean are shown in the red shading and orange bars. In the PDF plot, the model is indicated by the black symbols and line, and the AERONET observations are indicated by orange bars. We thank Didier Tanre for the efforts in establishing and maintaining Cape Verde and Dakar sites. **(b)** NGAC V1.0 vs. AERONET [...] 3–2014 period: a time series, scatterplot, and [...]

Insert Fig 6c, 6d, 6d, and 6f.
Figure captions: **(c)** NGAC V1.0 vs. AERONET 550 nm AOD comparisons at Banizoumbou for the 2013 -2014 period: a time series, scatterplot, and fractional distribution histogram.
(d) NGAC V1.0 vs. AERONET 550 nm AOD

Interactive Discussion

Figure 7. Dust AOD valid at 12:00 UTC 4 July 2015 for ICAP multi-model ensemble (top) and NGAC V1.0 (bottom). The ensemble is based on 7 members, including the models from NCEP (NGAC V1.0), GMAO, ECMWF, NRL, JMA, UKMO, and BSC. These figures are produced by the Naval Research Laboratory.

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9, 1–37, 2016

The implementation of NEMS GFS Aerosol Component (NGAC) Version 1.0

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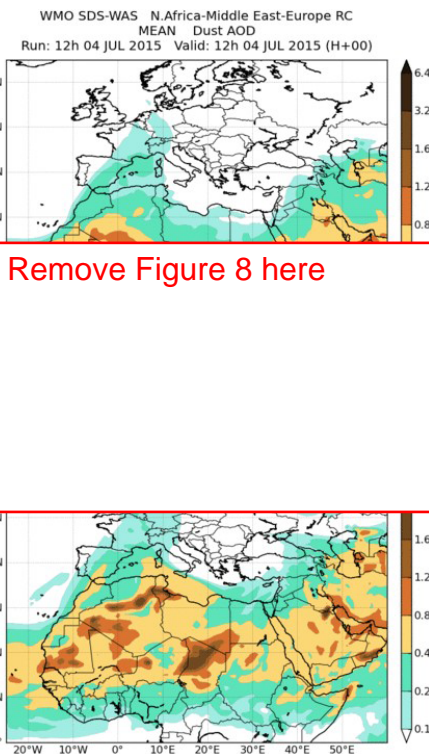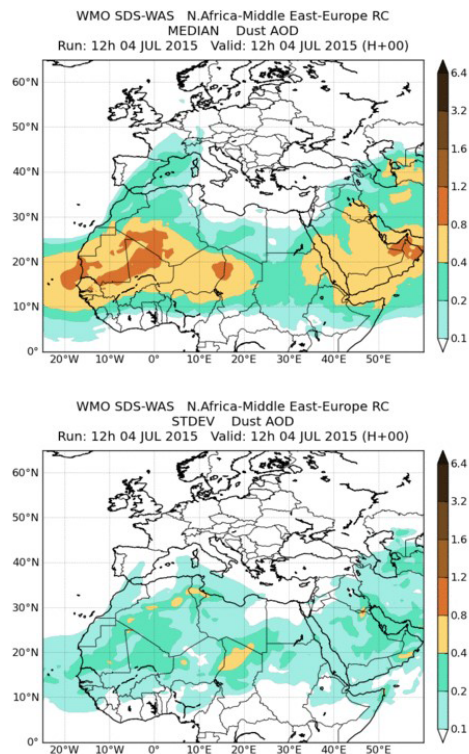
Figure 8. Dust AOD regional ensemble products valid at 12:00 UTC 4 July 2015. The multi-model products describing centrality (multi-model median and mean) and spread (standard deviation and range of variation) are generated from multiple global and regional forecast models, including NGAC V1.0. This figure is produced by the Regional Center for Northern Africa, Middle East and Europe of the WMO SDS-WAS program.
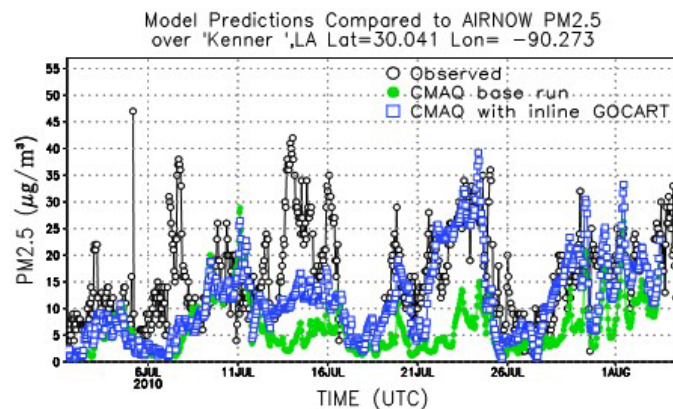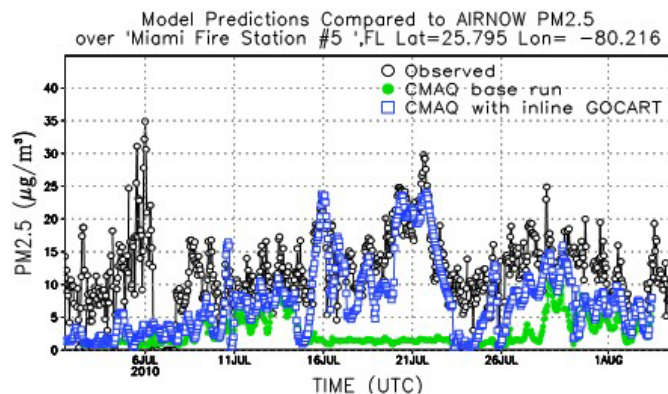
Figure 9. Time series of PM$_{2.5}$ from EPA AIRNOW observations (black dot), CMAQ base run using static LBCs (green dot) and CMAQ experimental run using NGAC LBCs (blue square) at Miami, FL (top panel) and Kenner, LA (bottom panel).

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