Representation of aerosol particles and associated transport pathways in regional climate modelling in Africa

Rebecca M. Garland[1,2,*], Hannah M. Horowitz[3], Christien J. Engelbrecht[4], Zane Dedkind[1], Mary-Jane M. Bopape[5], Stuart J Piketh[2], and Francois A. Engelbrecht[1,5]

[1] *Natural Resources and the Environment Unit, CSIR, Pretoria, South Africa*
[2] *Climatology Research Group, North West University, Potchefstroom, South Africa*
[3] *Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA, USA*
[4] *Agricultural Research Council. Pretoria, South Africa*
[5] *Centre for High Performance Computing, CSIR, Pretoria, South Africa*
School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, South Africa

Aerosol particles can have large impacts on air quality and on the climate system. Regional climate models for Africa have not been well-tested and validated for their representation and simulation of aerosol particles. This study aimed to validate the current representation of aerosol particles in the Conformal Cubic Atmospheric Model (CCAM), using the CMIP5 historical emissions inventory, to monitored data over Africa. In this study, CCAM was used to produce historical regional climate model simulations at 50 km horizontal resolution, globally, through the dynamical downscaling of ERA Interim reanalysis data. CCAM has a prognostic aerosol scheme for organic carbon, black carbon, sulphate, and dust, and non-prognostic sea salt. The aerosol optical depth (AOD) at 550nm from CCAM was compared to the AOD values (observed at 440nm and adjusted to 550nm using the Ångström exponent) from AERONET stations across Africa for 1999-2012. For this validation with AERONET, sites that are strongly impacted by aerosols from natural sources were prioritized. In general, the model captures well the monthly trends of the AERONET data. In addition, a climatology of simulated aerosol transport during the southern African biomass burning season was developed using self-organizing maps. This presentation will provide, through comparisons to monitored data, a basis for understanding how well aerosol particles are represented over Africa in regional climate modelling using the emissions inventory from the latest Intergovernmental Panel on Climate Change assessment report.

***corresponding author:** RGarland@csir.co.za

Keywords: Aerosol optical depth, CMIP5 emissions, CCAM, AERONET

Introduction

Aerosol particles can impact the climate directly, through scattering and/or absorbing radiation, indirectly through modifying clouds. Currently, the largest uncertainty in climate models comes from the impacts of aerosols on the radiative balance of the Earth (Boucher et al., 2013). Africa contains the largest single sources of biomass-burning emissions and dust globally, which are large sources of aerosol particles (Crutzen and Andreae, 1990; Schütz et al., 1981). Dust aerosols, along with carbonaceous aerosols produced from biomass burning, are known to impact climate through direct scattering and absorption of radiation, and indirectly through their effects on cloud formation and properties. When considering anthropogenic emissions, black carbon is estimated to be second only to CO_2 in contributing to warming globally (Bond et al., 2013).

Meteorology plays a key role in the seasonality of emissions and transport in Africa. Changes in the large-scale circulation shift the location of maximum dust activity and transport of dust northward (~5˚N to ~20˚N) from winter through summer (e.g. Prospero et al., 2002). The seasonality of the dry season influences the seasonality of biomass burning in Africa, with the maximum biomass burning activity shifting from June-September in southern Africa, to December-February in sub-Sahelian northern Africa (e.g. Liousse et al., 2010).

Biomass burning emissions in southern Africa contribute greatly to the region's aerosol burden and in many places dominate the seasonal cycle of the column of aerosol particles in the region (e.g. Tesfaye et al., 2011; Queface et al., 2011;), which in turn can have a significant impact on the regional climate (Tummon et al., 2010).

In addition to local impacts, aerosols particles from African can be transported long distances and thus have far-reaching impacts. For example, over southern Africa, massive aerosol plumes during peak biomass burning are exported off the southeastern coast of southern Africa to the Indian Ocean (i.e. "River of Smoke"), as well as over the southwestern coast out to the Atlantic Ocean (Garstang et al., 1996; Swap et al., 2003). This latter exit pathway aligns with the stratocumulus cloud deck that forms off of the southwestern coast, and is an area of large uncertainty in modelling aerosol radiative forcing (Stier et al., 2013).

As Africa is a large source of aerosol particles, an accurate representation of African aerosols and their transport in climate models is needed to understand the regional and global radiative forcing and climate impacts of dust and biomass burning aerosols, at

present and under future climate change. However, regional climate models for Africa have not been well-tested and validated for their representation and simulation of aerosol particles (Tesfaye et al., 2013).

This study aimed to validate the current representation of aerosol particles in the Conformal Cubic Atmospheric Model (CCAM) to monitored data over Africa. In addition, a climatology of simulated aerosol transport during the southern African biomass burning season was developed using self-organizing maps.

Methods

Regional Climate Modelling

CCAM (McGregor, 2005) was used to provide historical regional simulations at 50 km horizontal resolution, globally, through the dynamical downscaling of ERA Interim data reanalysis data (Dee et al., 2011). The Coupled Model Intercomparison Project Phase 5 (CMIP5) emissions inventory was used in the simulations under a scenario of RCP8.5 (Representative Concentration Pathway 8.5; i.e. low mitigation scenario) from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 report (Moss et al., 2010). CCAM modelled outputs for 1999-2012 were used in the analysis as that was the time period of the available monitored data. CCAM 6-hourly outputs were used in this analysis.

CCAM has a prognostic aerosol scheme for organic carbon, black carbon, sulphate, and dust, and non-prognostic sea salt (Rotstayn et al., 2007). In CCAM, dust is emitted into the atmosphere through mechanical action by the wind. In the CMIP5 emissions inventory each month has a constant emissions rate of the particulate organic carbon, black carbon and sulphate emissions, and these emission rates are held constant for multiple years. Thus, when using this inventory, the changes in the aerosol loading on temporal scales smaller than monthly are not due to changes in emissions, nor are some of the inter-annual variability.

In order to compare to observations, the focus of was to investigate the monthly cycle of aerosol particles from CCAM to understand if that cycle is captured correctly. Multi-year monthly averages of the CCAM modelled and the Aerosol Robotic Network (AERONET) measured aerosol optical depth (AOD) were compared.

Aerosol Optical Depth

The AOD describes the attenuation of light through the atmosphere due to aerosol particles based on the Beer-Lambert Law. The AOD is the integral of the extinction coefficient at a specific wavelength (i.e., the sum of the light at that wavelength that is scattered or absorbed by the aerosol particles) in a column of air from the surface to the top of the atmosphere (TOA). Equation (1) describes the basic equation for AOD where τ_λ is the AOD at wavelength λ, z is the height, and σ_{ext} is the aerosol extinction coefficient.

$$\tau_\lambda = \int_{z=0}^{z=TOA} \sigma_{ext}(\lambda, z)dz \qquad (1)$$

Monitored Data

The monitored data were AOD values from AERONET stations across Africa (Holben et al., 1998). For this validation, sites that are strongly impacted by natural sources (i.e. biomass burning and dust) were prioritized. As they are large sources of aerosol particles for the continent and globally, with Africa having the largest emissions in the world of dust and biomass burning aerosols (Crutzen and Andreae, 1990; Schütz et al, 1981). Thus, it is critical to understand if CCAM using the CMIP5 emissions inventory from the IPCC assessment can capture the monthly cycle of these large emission sources.

In addition, only sites that had a multi-year dataset were selected, and those sites that had continuous sampling were prioritized. Figure 1 highlights the AERONET sites that were used in this comparison. The sites are color-coded by geography and the AOD trends seen at the sites (as described in the Results and Discussion section).

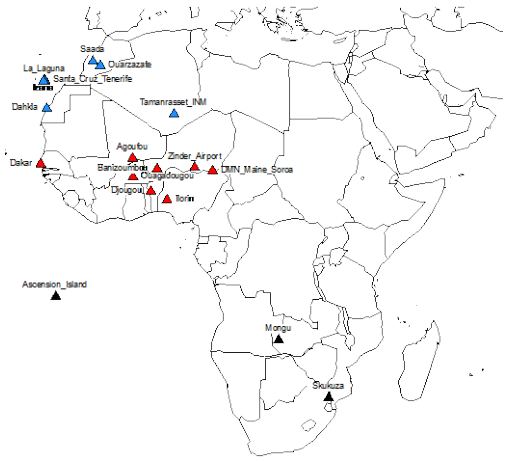

Figure 1: Map of AERONET sites used in the model-observed comparison

The modelled and monitored AOD were compared for 1999-2012. The aerosol optical depth (AOD) at 550nm from CCAM was compared to the AOD values (observed at 440nm and adjusted to 550nm using the Ångström exponent) from AERONET stations across Africa.

AERONET daily data were used, and the monthly averages were calculated using a 70% data completeness rule. In other words, if more than 30% of the daily values were missing, then a monthly average could not be calculated.

Aerosol Particle Transport

An aerosol climatology and associated transport patterns were analysed through Self Organizing Maps (SOMs) (Hewitson and Crane, 2012). CCAM simulated AOD and the geopotential heights of 700-850 hPa were extracted for July to October for 1979-2012. It was observed in the SAFARI campaign that during the biomass burning period, aerosol particles are transported aloft (peaks between ~600-800 hPa) (Haywood et al., 2004). The SOM analysis for geopotential height was performed for 35 nodes, and the AOD associated with each synoptic type were mapped onto the nodes. This analysis focused on southern Africa (20°W – 35°E, 40°S-0°S) during the biomass burning period to understand the simulated aerosol climatology and transport patterns.

Results

Figure 2 displays the multi-year monthly mean for the studied sites for both the observed data (in pink) and the CCAM data (in blue). The dark blue line in Figure 2 are when all CCAM data are used, the light blue line are when the CCAM data from only those months where there was monitoring data are used. The shaded region is one standard deviation of the dark blue line, and is shown to highlight the spread of the monthly means from CCAM.

The panels in the figure are ordered with the northern Africa sites first, then the western Africa sites, and then the southern.

The northern Africa sites have generally low AOD values Africa sites. Note that the scales are not the same in all the panels to aid in viewing of the trends. (<~0.5), with peaks in June-August. The western sites (red in Figure 1) are strongly influenced by dust and have highest AOD values of the African sites studied. At these sites, the AOD peaks generally around March and/or June, though there is variety in the timing of peak across the sites. The southern-most western Africa sites (i.e. Djougou and Ilorin) have an earlier peak in January and February. The southern African sites have peaks during the biomass burning period in the austral late winter and spring, generally peaking in September.

Figure 2 highlights that the monthly trends in the CCAM data, and the comparison of the modelled and monitored data, are similar using either all the CCAM data or only those that align to the available monitoring data. The differences in only including those CCAM outputs where AERONET data were available that are seen are within one standard deviation of the monthly averages for the dark blue line (i.e. all CCAM data) for all sites except Ouarzazate.

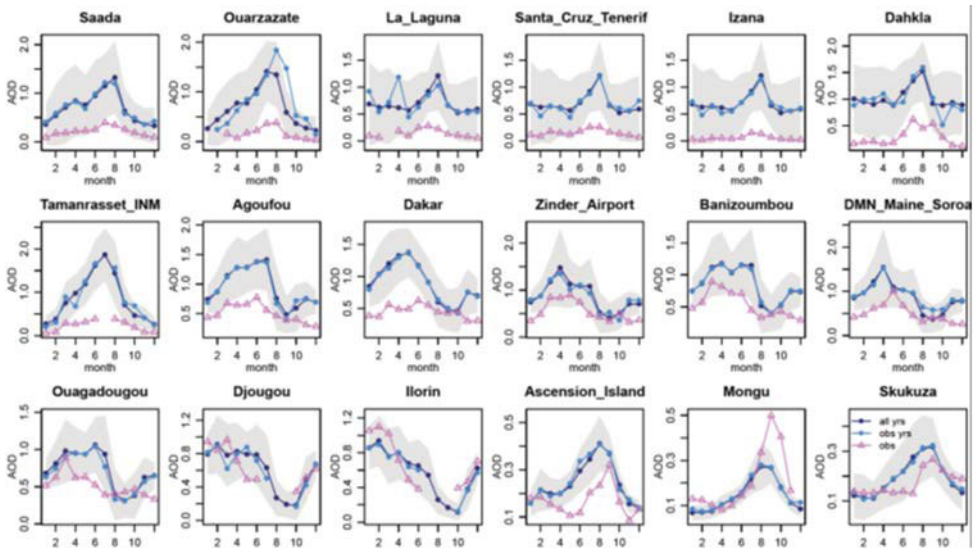

Figure 2: AOD at 550nm for observed (pink) and modelled with all CCAM outputs (dark blue) and only those months with AERONET data (light blue). The shaded areas is one standard deviation from the monthly averages of the dark blue line

For most sites, the monthly cycle (i.e. timing of peak and minimum AOD values) is well-captured by CCAM using CMIP5 emissions. Additionally, the magnitude of multi-year monthly average of the observed AOD are within one standard deviation of the model for at least half of the observed monthly averages for all sites, with the except seven sites (Ascension Island, Mongu, Dakar, Agoufou, Tamanrasset_INM, Ourzazate, Dahkla). The reasons for these differences are currently under investigation; it is interesting to note that these sites are not in only one region, but are from all three regions studied (i.e. western, northern and southern Africa).

These results suggest that the model is overestimating the AOD for the northern-most sites due to an overestimation of dust. Preliminary analysis of the southern Africa aerosol climatology and associated transport patterns through SOMs, suggest that CCAM does represent the two major pathways of biomass burning aerosol exit off of the continent.

Conclusions

In general, CCAM captures well the monthly trends of the AERONET data across the continent. Additionally, the magnitude of the multi-year monthly averages of the observed AOD are within one standard deviation of the model for at least half of the observed monthly averages for 11 of the 18 studied sites. These are important first findings of the use of CCAM with the CMIP5 emissions inventory for simulating aerosol particles over Africa, as the CMIP5 emissions inventory is currently the inventory widely used globally to project climate futures. In addition, preliminary analyses indicate that the model does capture the spatial trends in the transport of aerosol particles from southern Africa during the biomass burning season.

This study is the first step in validating the aerosol output from CCAM over Africa. Future work will focus on understanding the causes for the discrepancies between the modelled and monitored values, including additional African AERONET sites, as possible, and understanding the sensitivity of the southern African climate (e.g. surface temperature) to the presence and characterization of aerosol particles.

Acknowledgments

This work was supported by NRF CSUR Grant Number 9157 and a CSIR PG Grant. HH was funded through the NSF GROW with USAID RI Fellowship. We thank the PIs and their staff for establishing and maintaining the 18 AERONET sites used in this study.

References

Bo-nd T et al., 2013, 'Bounding the role of black carbon in the climate system: A scientific assessment', *J. Geophys. Res*, 118.

Boucher O et al., 2013, 'Clouds and aerosols' IPCC AR5.

Crutzen, PJ and Andreae, MO. 1990, 'Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles' *Science,* 250:1669-1678.

Dee, DP et al. 2011, 'The ERA-Interim reanalysis: Configuration and performance of the data assimilation system' *Quart. J. R. Meteorol. Soc.*, 137**:**553-597.

Garstang et al. 1996 'Horizontal and vertical transport of air over southern Africa', *J. Geophys. Res,* 101:23721-23736.

Haywood JM, Osborne SR and Anel SJ. 2004. 'The effect of overlaying absorbomg aerposol layers on remoste sensing retrievals of cloud effective radius and cloud optical depth' *Q.J.R. Meteorol. Soc*, 130:779-800

Hewitson BC and Crane RG, 2002, 'Self-organizing maps: applications to synoptic climatology,' *Clim Res*, 22:13-26.

Holben BN.et al., 1998, 'AERONET - A federated instrument network and data archive for aerosol characterization', *Rem. Sens. Environ.,* 66:1-16.

Liousse C et al. 2010, 'Updated African biomass burning emission inventories in the framework AMM-IDAF program, with an evaluation of combustion aerosols, *ACP*, 10.

McGregor JL. 2005, CSIRO Atmospheric Research Tech. Paper, No 70, 43 pp.

Moss, RH et al. 2010. 'The next generation of scenarios for climate change research and assessment,' *Nature*, 463.

Prospero JM et al., 2002 'Environmental characterization of global sources of atmospheric soil dust identified with NIMBUS 7 TOMS absorbing aerosol product,' *Reviews of Geophysics.*

Rotstayn, LD *et al.* 2007*,* 'Have Australian rainfall and cloudiness increased due to the remote effects of Asian anthropogenic aerosols?' J. Geophys. Res.*,* 112.

Schütz L. et al, 1981, 'Saharan dust transport over the North Atlantic Ocean', Spec. Pap. Geol. Soc. Am., 186:87–100.

Stier P. et al, 2013, 'Host model uncertainties in aerosol radiative forcing estimates: results from the AeroCom Prescribed intercomparison study,' *ACP, 13.*

Swap R et al. 2003 'Africa burning: A thematic analysis of Southern African Regional Science Initiative (SAFARI 2000),' *J. Geophys. Res*, 108.
Tesfaye M et al. 2011, 'Aerosol climatology over South Africa based on 10 years of MISR data,' *J. Geophys. Res*, 116.

Tesfaye M et al. 2013, 'Evaluation of regional climate model simulated aerosol optical properties over South Africa using ground-based and satellite observations.' *ISRN Atmospheric Science,* 2013.

Tummon F et al., 2010, 'Simulation of the direct and semidirect aerosol effects on the southern African regional climate during the biomass burning season, *J. Geophys. Res*, 115

Queface AJ et al., 2011, 'Climatology of aerosol optical properties in Southern Africa,' *Atmos Env.*, *45.*