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MODELING THE TRANS-ATLANTIC TRANSPORTATION OF SAHARAN DUST

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Abstract

In the present study we are simulating the trans-Atlantic transport of dust from Sahara to the South-Central America, using the regional climate model RegCM4 and its online dust scheme, for the year 2007. The simulated horizontal and vertical distributions of the mineral dust optical properties were evaluated against the LIVAS CALIPSO satellite dust product. The Trans-Atlantic dust transport is simulated adequately with RegCM4, but there are some spatial discrepancies. Dust optical thickness is overestimated in the eastern Sahara throughout the year by 0.1-0.2, while near the gulf of Guinea is underestimated during winter and spring. Although RegCM4 dust plume is located southern on winter and spring, it doesn't spatially match the dust optical thickness of LIVAS. In summer and autumn the vertical distribution of dust between 3-4km during the Trans-Atlantic transport is simulated by the model adequately up to 30ºW-40ºW longitude. However, during winter-spring RegCM4 misplaces dust loading into higher altitude. Finally, we discuss some possible reasons and mechanisms that might be responsible for the differences between the model and the observations.
Keywords: *RegCM4, LIVAS, Aerosol.*

Περίληψη

Στην παρούσα μελέτη προσομοιώνουμε την μεταφορά σκόνης από την Σαχάρα προς τον Ατλαντικό ωκεανό και την Νότια-Κεντρική Αμερική, χρησιμοποιώντας το περιοχικό κλιματικό μοντέλο RegCM4 για το έτος 2007. Εκμεταλλευόμενοι τις οπτικές ιδιότητες της σκόνης, αξιολογούμε την οριζόντια και κατακόρυφη κατανομή της με το δορυφορικό προϊόν LIVAS. Η μεταφορά της σκόνης πάνω από τον Ατλαντικό προσομοιώνεται επαρκώς από το RegCM4, πάραυτα εντοπίζουμε ορισμένες χωρικές διαφοροποιήσεις σε σχέση με τις παρατηρήσεις. Το οπτικό βάθος της σκόνης υπερεκτιμάται στην ανατολική Σαχάρα σε όλες τις εποχές του χρόνου κατά 0.1-0.2. Αντίθετα, κοντά στην κόλπο της Γουινέας το μοντέλο υποεκτιμά το οπτικό βάθος τον

χειμώνα και την άνοιξη. Η μεταφορά σκόνης πάνω από τον Ατλαντικό πραγματοποιείται πιο Νότια τον χειμώνα και την άνοιξη από το μοντέλο, όμως η αλλαγή αυτή δεν επαρκεί για να ταυτιστεί η χωρική κατανομή της σκόνης του μοντέλου και του LIVAS. Το καλοκαίρι και το φθινόπωρο η κατακόρυφη κατανομή της σκόνης στο ύψος 3-4km προσομοιώνεται επιτυχώς από το RegCM4, όμως τον χειμώνα και την άνοιξη το μοντέλο τοποθετεί μεγάλη ποσότητα σκόνης σε μεγαλύτερο υψόμετρο. Επίσης, προτείνουμε ενδεχόμενους μηχανισμούς που μπορεί να ευθύνονται για την διαφοροποίηση μεταξύ του μοντέλου και των παρατηρήσεων.
Λέξεις κλειδιά: *RegCM4, LIVAS, Αιωρούμενα σωματίδια.*

1. Introduction

Mineral dust is the most abundant atmospheric aerosol in the atmosphere. Natural dust is emitted in episodic events over arid and semi-areas that are concentrated between 15º-30º latitude in both hemispheres. The largest source of mineral dust is the Sahara desert (Huneeus *et al.*, 2011), a vast arid region in the Northern Africa that receives less than 200 mm year-1 of precipitation (Engelstaedter *et al.*, 2006). Between the zone 40ºN-10ºS latitude, dust is transported by the easterly trade winds though the Atlantic ocean to the American continent affecting the radiation budget of the planet with numerous direct (Tegen, 2003) and indirect mechanisms (Bangert *et al.*, 2012). Dust that is deposited in the Atlantic and to Amazon forest provides crucial nutrients that are essential for the marine (Mahowald *et al.*, 2005) and forest ecosystems (Bristow *et al.*, 2010). Dust may also affect the growth and intensity of strong weather convective system near the equator, that eventually may evolve into tropical cyclones, known as easterly waves (Zipser *et al.*, 2009).

Dust particles size in the atmosphere ranges from 0.01μm to 100μm (Knippertz and Stuut, 2014). The atmospheric lifetime of dust particles controls the evolution of dust size distribution as they move downwind (Mahowald *et al.*, 2014). Large particles, due to their size and weight, are concentrated close to the ground and they are quickly removed from the atmosphere through dry deposition processes. Since they have such a short atmospheric life, they are located mainly close to the source regions. On the other hand, small particles, usually smaller than 2.5μm, can be uplifted and remain on the mid-troposphere while they are being transported for thousands kilometers away from their source regions. Although size and density of dust particles are the key factors that force sedimentation, particle shape can have a big impact both on their deposition velocity and optical properties (Formenti *et al.*, 2011).

Previous researches have highlighted the almost constant dust plume that begins on the western coast of Sahara and floats over the North Atlantic ocean reaching the South-Central America (Chin *et al.*, 2014; Kim *et al.*, 2014; Yu *et al.*, 2015). Although the dust plume covers the largest part of the North Atlantic ocean all year long, it has some spatial-seasonal characteristics. Backscattering measurements of dust from the satellite instrument CALIOP showed that the dust transport peaks at summer and weakens in autumn. In both of these seasons dust concentration reach its highest point between 10ºN-20ºN latitude. Contrary in winter and spring dust transport shifts southward close to the equator between 0º to 10ºN latitude. These seasonally differences extend also on the vertical distributions of dust that looms over the North Atlantic (Yu *et al.*, 2015).

During the trans-Atlantic dust transfer Million tons (Tg) of dust emitted by Sahara are deposited over the North Atlantic and the South and Central America every year. Though the exact number of the deposited dust for these regions it is still debated (Kaufman, 2005; Koren *et al.*, 2006; Ridley *et al.*, 2012), partly because satellite products do not measure directly deposition fluxes and the ground-based station network that actually measure dust deposition fluxes is spatially sparse, especially over the ocean. Moreover, the emitted dust from Sahara greatly differs between models by a factor of five (from 422 to 2025 Tg year-1) when average for the same region (Kim *et al.*, 2014). Thus, deposition and transportation of simulated dust may not be representative.

2. Data

2.1. RegCM4

The Regional Climate Model (RegCM) is a space limited numerical model which was developed at the National Center of Atmospheric Research (NCAR) and the Abdus Salam International Center for Theoretical Physics (ICTP). In the present study we are using the 4th version of the model, RegCM4 (Giorgi *et al.*, 2012). Land-Atmosphere interactions are analyzed with the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson *et al.*, 1993), while there is a recently implemented alternative option to use the Community Land Model (CLM4.5) (Oleson *et al.*, 2013). The radiation transfer scheme used on RegCM4 is based on the NCAR Community Climate Model version 3 (CCM3) (Kiehl *et al.*, 1996) as introduced by (Giorgi *et al.*, 1999). Recently the correlated-k Rapid Radiation Transfer Model (RRTM) was implemented (Mlawer and Clough, 1997; Mlawer *et al.*, 1997).

The online dust emission scheme (Marticorena and Bergametti, 1995; Alfaro *et al.*, 1997; Gong, 2003; Zakey *et al.*, 2006) depends on the simulated surface wind shear and surface attributes. Dust ascends from the ground when the surface wind velocity exceeds a specified wind speed threshold known as threshold friction velocity. Surface roughness and soil moisture, which are essential for the calculation of threshold friction velocity, are provided by the surface scheme BATS (Zakey *et al.*, 2006). Following the calculation of the dust mass emission fluxes, the tracer transport equation is applied for each transported bin (Solmon *et al.*, 2006). Removal processes through dry deposition and wet deposition (washout) are included in the model (Zakey *et al.*, 2006). The optical properties of dust are calculated for every size bin and each spectral band of the radiation scheme in use (CCSM or RRTM) using Mie theory. The spectral band closer to 550nm (350-640nm in CCM3) is used for evaluation against most satellite derived aerosol optical depth and extinction products.

The majority of climate models use a log-normal fitting to represent the particle size distribution of the transported dust bins. Though, it is favourable to use physical based characteristics to define the size groups of dust bins to improve the evaluation against observational data (Formenti *et al.*, 2011). A physical based iso-gradient method was developed by (Foret *et al.*, 2006) which aggregates dust size groups according to their deposition velocity. This iso-gradient method was implemented into RegCM4 that now simulates 12 transport dust bins.

3. LIVAS

LIVAS, which stands for "LIdar climatology of Vertical Aerosol Structure for space-based lidar simulation studies" (Amiridis *et al.*, 2015), is an effort to derive a 3-dimentional global climatic dataset utilizing the CALIPSO measurements, funded by the European Space Agency (ESA). CALIPSO is capable to obtain high resolution profiles of the attenuated backscatter of aerosols and clouds at 532nm and 1064nm. It can retrieve aerosol optical properties below optically thin clouds, in clear skies and above clouds while it cannot detect aerosol layers below optically thick low-level clouds (Winker *et al.*, 2009). The LIVAS database is available globally, in a mean monthly basis, over 1ºx1º horizontal resolution. The vertical resolution is the same as CALIPSO L2 vertical resolution and varies from 60m between -0.5km and 21km to 180m above 21km (Amiridis *et al.*, 2015). In this work we use the specialized LIVAS pure dust product, which includes the extinction coefficient of pure dust, calculated from the dust percentage of "dust" and "polluted dust" aerosol subcategories of CALIPSO (Amiridis *et al.*, 2013).

The LIVAS extinction dust product is corrected for the Lidar Ratio (LR) based on multi-year measurements performed by the ground-based lidar stations of the EARLINET lidar network. The LR value may vary a lot even for aerosols of the same group-type. The LR of dust particles depends on their refractive index. The refractive index values rely upon the composition of dust and most importantly on the relative proportion of clay-sized mineral illite in dust (Schuster *et al.*, 2012). Thus, regions with different physiochemical dust characteristics lead to different LR values. The 0.3.1

version of LIVAS separates the globe into three regions depending on the LR assumption they use. The regions specified usually receive dust loading from known dust sources with specific physiochemical composition, hence similar LR value.

4. Results

Dust Optical Depth (DOD) and Dust EXtinction coefficient (DEX) for each layer of RegCM4 was assessed using the LIVAS dust product. Since those two datasets were produced based in different spatiotemporal considerations, some necessary pre-processing steps were required before the evaluation. The simulated spatial fields were firstly interpolated into the 1ºx1º grid of LIVAS in order to calculate directly the differences between the two datasets. Furthermore, since LIVAS was produced using the attenuated backscatter measurements of the CALIOP instrument upon the non-geostationary satellite CALIPSO, the spatial-temporal fields are not consecutive. Dust optical measurements were available only when the satellite orbit and the cloud vertical distribution in the atmosphere were favourable. Thus, a spatiotemporal mask was produced using the exact UTC time and grid cell location specified in LIVAS. The UTC times specified in the metadata of LIVAS were interpolated to the closest timestep of the model. The spatial-temporal mask of LIVAS was applied in the 6-hourly RegCM4 data and thereafter we have calculated the monthly, seasonal and yearly means.

Figure 1 depicts the yearly DOD mean for 2007 as it was processed for LIVAS, simulated by RegCM4 and their difference. The model clearly exhibits some spatial discrepancies compared to LIVAS. It overestimates the DOD over the Eastern Sahara by 0.1-0.2 and underestimates it over the Northern Africa land mass located just above of the gulf of Guinea. On the other hand it simulates fairly well the dust plume extending from the western coast of Northern Africa towards Atlantic.

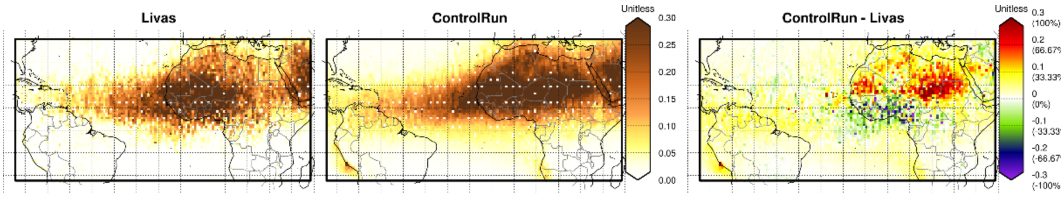

Figure 1 - Dust optical depth for Livas at 532nm and RegCM4 at 550nm for the year 2007.

As it was highlighted previously, the Atlantic dust plume is driven by some strong seasonal characteristics. Therefore, in Figure 2 we are exploring the seasonal DOD over our domain. The distinct underestimation close to gulf of Guinea highlighted in Figure 1 prevail over winter and spring while DOD is overestimated over Eastern Sahara all year long. During winter and especially spring, the Atlantic dust plume moves southward (Yu *et al.*, 2015) closer to the equator, but most of the global/regional climate models cannot accurately simulate that change (Prospero *et al.*, 2014). Although RegCM4 shows a slight southward transfer in winter-spring across the Atlantic compare to summer-autumn, it is not enough to accurately simulate the observed spatial pattern of LIVAS. Like most of the models, RegCM4 simulates the trans-Atlantic transport better during summer than in winter (Huneeus *et al.*, 2011).

In order to understand and evaluate the vertical distribution of dust during the Trans-Atlantic transport, we have calculated the mean vertical profiles over 10º longitude zones starting from 10º to 70º west as shows in Figure 3. These zones were limited between the latitude 10ºS and 35ºN, since most of the transported dust is located within this range. The analysis was concentrated over the different vertical patterns emerge between winter-spring and summer-autumn.

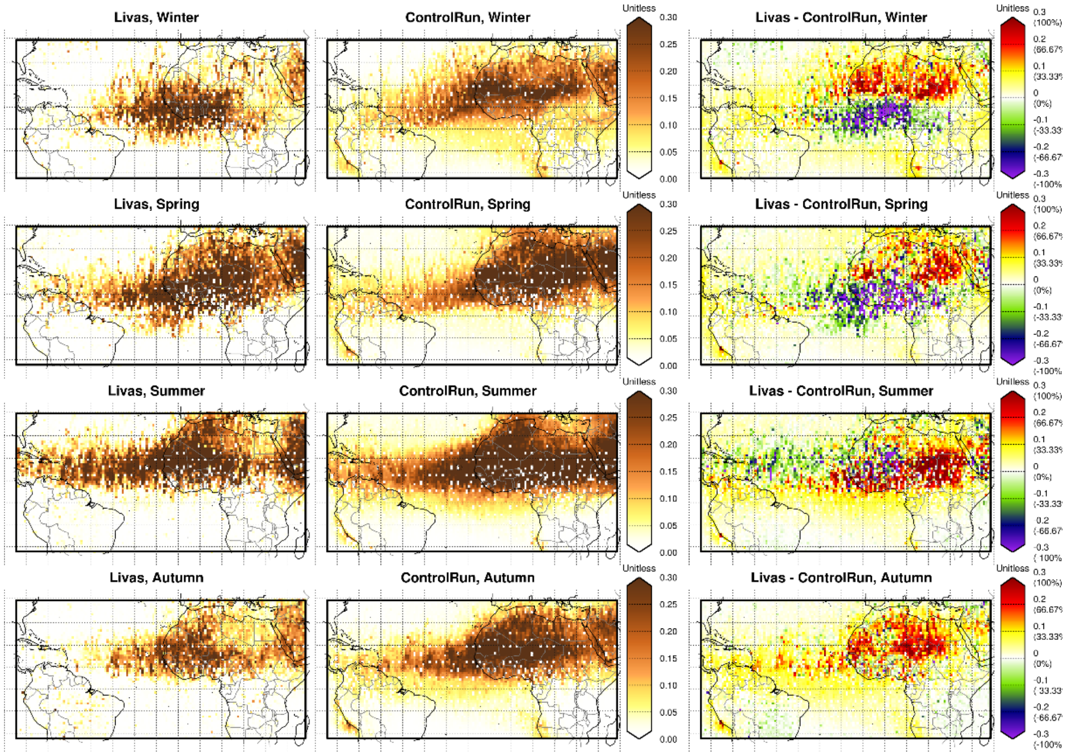

Figure 2 - Dust optical depth for Livas at 532nm and RegCM4 at 550nm for the year 2007. Top to end row winter, spring, summer, autumn are displayed respectively.

Figure 4 and Figure 5 illustrate the vertical DEX distribution and its evolution across the Trans-Atlantic dust transport in summer-autumn and winter-spring, respectively. Note that the upper row (first 3 plots) depicts the zones closer to the emission sources that bear higher DEX values, since dry deposition which is the dominant removal process for large particles didn't have the time to remove dust from the Atmosphere. The second row, depicts the zones closer to the central and south America, where most of the larger dust particles have been deposited into the Atlantic ocean, reducing therefore the DEX values.

During summer-autumn, RegCM4 simulates remarkably well the vertical distribution of dust on the eastern Atlantic zones. If we exclude the values close to the surface, both the model and the observation show a maximum between 3-4km. The simulated DEX shows a slower decrease with height after the peak value, while LIVAS DEX rapidly declines to almost zero after 5-6km. Consequently, RegCM4 overestimates DEX above 5km, especially in the zones located in the western Atlantic ocean. The displacement of the simulated dust high in the mid-Troposphere may affect greatly the dry and wet deposition processes in the model as well as the trans-Atlantic transfer. In winter-spring the transport takes place in a lower altitude and DEX swiftly reduces from the ground up almost linearly till 5km. The slower decrease of DEX with height after 5km is taking place also winter-spring. According to LIVAS, more than 96% and 99% of DEX is found between 200m-5000m in summer-autumn and winter-spring respectively.

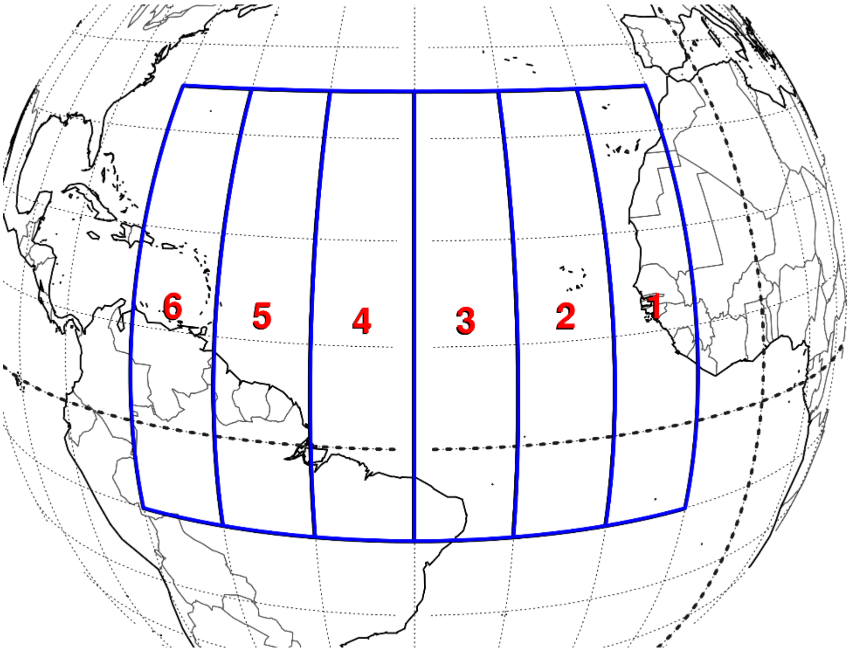

Figure 3 - Subregions where the averaged DEX profiles have been calculated.

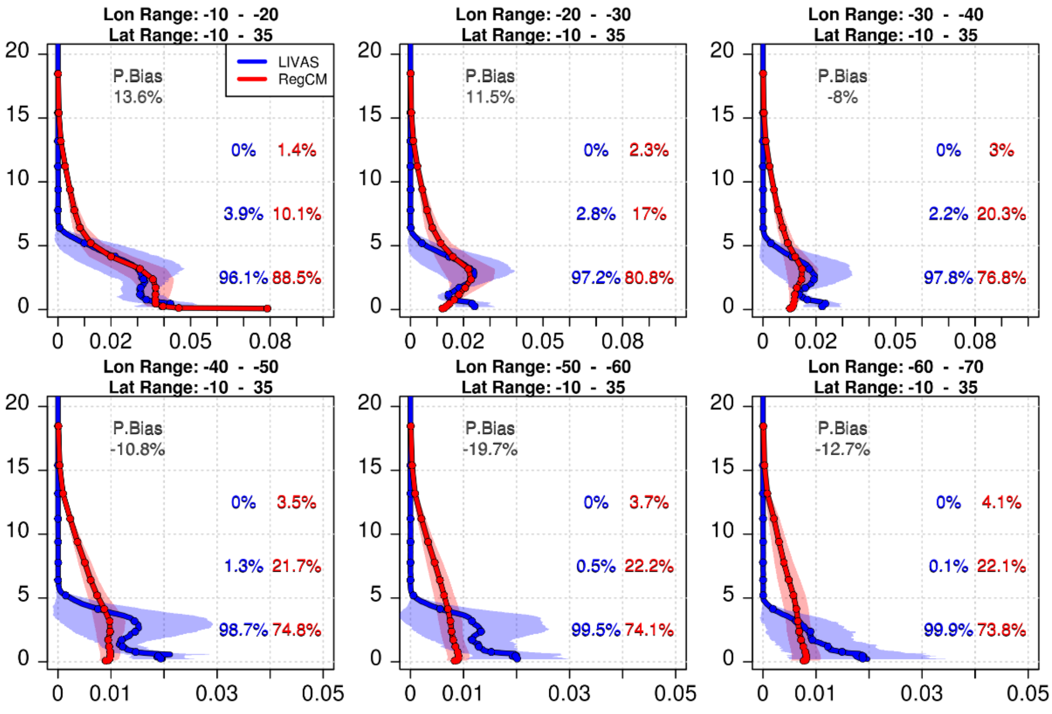

Figure 4 - Summer-autumn vertical column profiles of Dust EXtrinction (DEX) coefficient for averaged regions over the Atlantic. Blue line depicts LIVAS and red RegCM4. The colored percentage numbers present the amount of DEX located between 0-5km, 5-10km and 10-20km respectively. The percentage bias (P. Bias) is also illustrated on the plot.

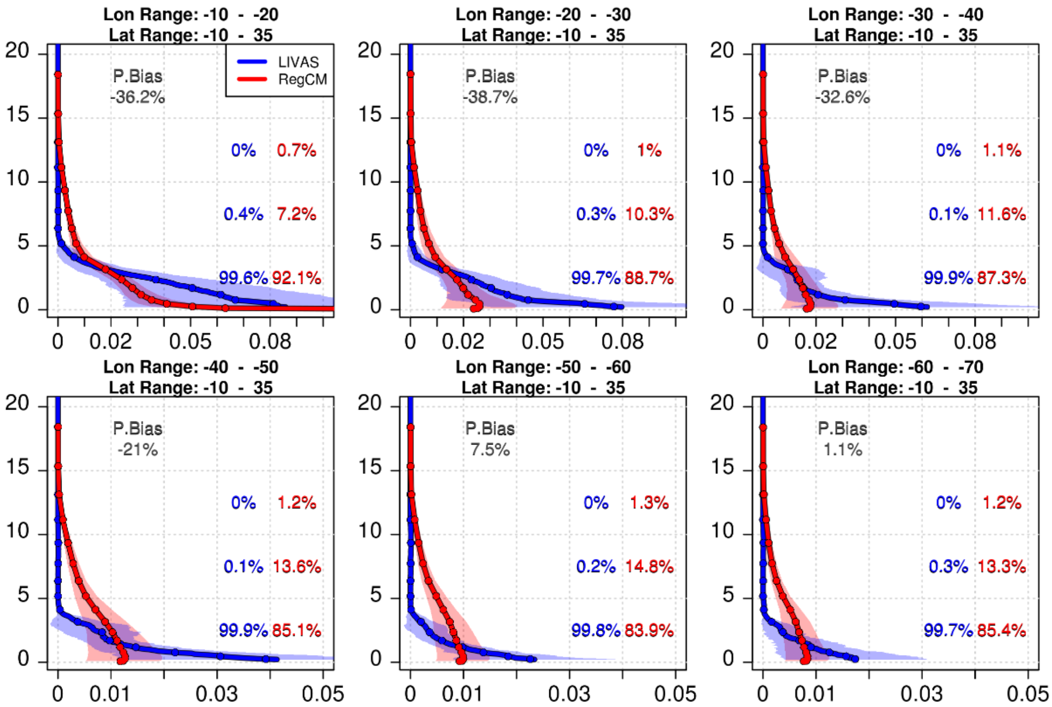

Figure 5 - Winter-spring vertical column profiles of Dust EXtrinction (DEX) coefficient for averaged regions over the Atlantic. Blue line depicts LIVAS and red RegCM4. The colored percentage numbers present the amount of DEX located between 0-5km, 5-10km and 10-20km respectively. The percentage bias (P. Bias) is also illustrated on the plot.

5. Discussion

Our experiment with RegCM4 can simulate the Trans-Atlantic seasonal transport of dust fairly accurate but it differentiates from LIVAS on some key spatial features especially in winter and spring. The spring southward shift observed in satellite measurements emerges from various independent factors (Prospero *et al.*, 2014). One of these factors is the seasonal changes of the active dust sources in Sahara. Based on a simulation of an offline dust model that uses the re-analysis database ERA-40 and ground-based measurements for several soil characteristics in Sahara, we know that emitted fluxes follow a marked seasonal cycle that peaks in spring over the eastern part of the desert and in summer on the western (Laurent *et al.*, 2008). Eastern dust sources therefore play a major role over the Trans-Atlantic transportation, since most of the dust is produced on that side of the desert. According to DOD, RegCM4 dust production correlates with that spatial-temporal pattern, where western Sahara DOD peaks at summer and eastern at spring. More importantly during spring, the model is over-productive in the eastern Sahara, since it overestimates DOD when compared to LIVAS. Thus, the simulated seasonality of the dust sources in the Eastern Sahara are not responsible for the underestimation of the southward Trans-Atlantic transportation during spring. Nevertheless, this conclusion needs further investigation since it is based on DOD and not in actual emitting fluxes and the seasonality of the active dust sources varies from year to year (Prospero *et al.*, 2002).

A more probable cause for the underestimation of the southern Trans-Atlantic transport during spring-winter from RegCM4 might be the location of the Inter-Tropical Convergence Zone (ITCZ) that correlates with the western Africa monsoon in this area. The ITCZ controls the seasonal precipitation rates over the semi-arid Sahel area and more importantly the changes in large-scale wind patterns. Both of these factors affect dust productivity and transport (Engelstaedter *et al.*, 2006; Engelstaedter and Washington, 2007; Williams, 2008).

According to CALIPSO measurements most of the global models underestimate DEX in lower levels close to the sources and overestimates it on higher altitudes above Atlantic (Koffi *et al.*, 2012). Our simulation demonstrates the same behaviour. The vertical uplift of dust is forced by three processes in RegCM4, turbulence, wet convection and general dry advection of the atmosphere. The long-range Trans-Atlantic transport is affected mostly by the last two mechanisms. The Emmanuel convective scheme (Emanuel, 1991) used over ocean in our simulation accounts for vertical transport of aerosol tracers into a cumulus convection. Therefore, if we overestimate cumulus convection over the Atlantic, we might as well overestimate the dust vertical distribution especially in altitudes greater than 5km. Further research and extended cloud evaluation is necessary to answer this question.

The continuation of this research can be summarized in four steps. (1) Confirm the seasonality of the emitted fluxes from the Sahara desert with the observational data, (2) evaluate the large scale wind and precipitation patterns on our domain (3) investigate the role of in cloud convective uplift on the vertical distribution of dust during transport and (4) calculate the dust loss frequency of the model, which is defined by the ratio of total removal rate to dust load, and compare it with previous studies (Kim *et al.*, 2014).

6. Conclusion

RegCM4 is capable of capturing the Trans-Atlantic transport of dust from Sahara towards the South-Central America. The model was evaluated with the pure dust satellite product LIVAS. Some localized discrepancies have been found. RegCM4 overestimates the DOD over the eastern Sahara in all seasons, while it underestimates over the gulf of Guinea during winter-spring. A misrepresentation of western Africa monsoon that controls the spatial-temporal evolution of ITCZ as well as the precipitation and the large scale wind patterns might be responsible for these biases. We found that RegCM4 overestimates DEX in altitudes greater than 5km in all seasons. On summer-autumn the vertical distribution of dust between 3-4km during the Trans-Atlantic transportations is simulated by the model adequately till 30ºW-40ºW longitude. However, during winter-spring RegCM4 misplaces dust loading into higher altitude.

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