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Spatial and temporal correlation length as a measure for the stationarity of atmospheric dust aerosol distribution

Kerstin Schepanski [a,*], Lars Klüser [b], Bernd Heinold [a], Ina Tegen [a]

[a] Leibniz Institute for Tropospheric Research, Leipzig, Germany
[b] German Aerospace Center, German Remote Sensing Datacenter, Oberpfaffenhofen, Germany

HIGHLIGHTS

- Correlation lengths (CLs) are a measure for the persistence of atmospheric dust conditions.
- CLs can be used for determining meaningful nowcasting intervals.
- Model CLs useful for assessing the impact of observation gaps on satellite CLs.

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ABSTRACT

Fields of dust aerosol optical depth (AOD) from numerical models and satellite observations are widely used data sets for evaluating the actual distribution of atmospheric dust aerosol. In this study we investigate the use of estimates of spatial and temporal correlation lengths (CLs) calculated from simulations using the regional model system COSMO-MUSCAT (COSMO: Consortium for Small-scale Modelling; MUSCAT: MUltiScale Chemistry Aerosol Transport Model) to characterize the spatial and temporal variability of atmospheric aerosol distribution, here mineral dust, and to provide an estimate on the temporal model output interval required in order to represent the local evolution of atmospheric dustiness. The CLs indicate the scales of variability for dust and thus provide an estimate for the stationarity of dust conditions in space and time. Additionally, CLs can be an estimate for the required resolution in time and space of observational systems to observe changes in atmospheric dust conditions that would be relevant for dust forecasts. Here, two years of dust simulations using COSMO-MUSCAT are analyzed. CLs for the individual years 2007 and 2008 are compared to the entire two-year period illustrating the impact of the length of time series on statistical analysis. The two years are chosen as they are contrasting with regard to mineral dust loads and thus provide additional information on the representativeness of the statistical analysis.

Results from the COSMO-MUSCAT CL analysis are compared against CL estimates from satellite observations, here dust AOD inferred from IASI (Infrared Atmospheric Sounding Interferometer), which provides bi-daily information of atmospheric dust loading over desert land and ocean. Although CLs estimated from the satellite observations are at a generally lower level of values, the results demonstrate the applicability of daily observations for assessing the atmospheric dust distribution.

Main outcomes of this study illustrate the applicability of CL for characterizing the spatio-temporal variability in atmospheric dustiness. This is in particular of interest for determining time intervals at which for example dust forecasts need to be provided. Results from this study further demonstrate that bi-daily satellite dust observations are sufficient for assessing the dust distribution over regions such as the Mediterranean region that are far from the dust sources.

1. Introduction

Mineral dust is a dominant contributor to the atmospheric aerosol burden. Suspended in the atmosphere, mineral dust particles affect the Earth energy budget directly by scattering and

* Corresponding author.
E-mail address: schepanski@tropos.de (K. Schepanski).

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absorbing radiation (Carslaw et al., 2010) and indirectly by modifying cloud properties (e.g., Tao et al., 2012). Airborne dust reduces the solar radiation reaching the Earth surface and hence affects the available irradiance that can be utilized by solar power plants. Expressed as direct normal irradiance (DNI), which is defined as the amount of solar radiation that is received by the normal plane with respect to the incoming solar rays, the surface loss of DNI can be in the order of 10% for dusty days compared to a day with low aerosol concentrations (Wittmann et al., 2008). In terms of energy production, this leads to a loss of about 25% compared to a day with low aerosol concentrations.

Atmospheric dust is observable from space by satellite instruments at different wavelengths such as terrestrial infrared (TIR), visible and ultra-violet (e.g., Banks and Brindley, 2013). Depending on orbit and repeat time, satellite observations provide only snap-shots on the spatial distribution of airborne dust, which may lead to different conclusions with regard to dust sources and transport pathways (Schepanski et al., 2007, 2009a, 2012). Complementary to instantaneous satellite observations representing individual scenes, numerical models provide information in time and space as pre-defined by the model setup considering the aim of the study design. Modells thus allow for studies examining the entire atmospheric dust cycle consisting of dust entrainment into the boundary layer and eventually into the troposphere, transport and deposition processes (Heinold et al., 2011a; Schepanski et al., 2009a, b), whereas individual satellite instruments in general allow for snap-shots of a scene determined by orbit and instrument. In the recent past, numerical simulations of the atmospheric dust cycle have contributed to the holistic analysis of field experiments such as the SAMUM-1 (SAharan Mineral dUst experiMent, http://samum.tropos.de) and SAMUM-2 experiment (Heinold et al., 2009, 2011a, 2011b) and the SOPRAN (Surface Ocean Processes in the Anthropocene, http://sopran.pangaea.de) long-term observation of dust export towards the tropical North Atlantic (Niedermeier et al., 2014).

To allow for an as accurate as possible estimate on the effects of the atmospheric dust burden on surface solar irradiation, observations and nowcasting capabilities have to be available on a sufficiently high temporal and spatial resolution. The studies by Wittmann et al. (2008) and Schroedter-Homscheidt et al. (2013) illustrate the monetary benefit of short-term (24–48 h) numerical forecasts of DNI that consider the actual atmospheric aerosol load. Estimates on the required spatial and temporal resolution at which information on the distribution of the column atmospheric dust loading, for example expressed by the Aerosol Optical Depth (AOD), can be provided by statistical analysis of the dust variability such as estimating correlation lengths (CLs). Eventually, this allows for an accurate assessment of the local stationarity of the dust distribution for example during the following 24 h. In case of the solar energy sector this allows for accurately predicting the solar irradiation reduction by dust and thus the electricity productivity of individual solar power plants.

This study further aims at understanding the characteristic lengths for dust presence, in space and time, in order to examine the representativeness of daily or sub-daily information on the atmospheric dust loading retrieved from e.g. forecast models or satellite observations. The Mediterranean region is chosen as focus for this study as it is characterized by regular dust plumes originating from the North African deserts and thus spatio-temporally changing atmospheric dust concentrations (e.g., Salvador et al., 2014). Furthermore, solar power plants are deployed in this region and energy production is affected by passing dust plumes.

In order to assess the impact of temporal resolution on estimates of CLs, we perform a model exercise allowing for testing different commonly applied model output time intervals. Here, CLs are calculated from dust AOD time series simulated by the atmosphere-dust model system COSMO-MUSCAT (COSMO: Consortium for Small-scale Modelling; MUSCAT: MUltiScale Chemistry Aerosol Transport Model). In contrast to the satellite observations available on a specific orbit and sensitive to the cloudiness, numerical model output provides a homogeneous field in the sense, that an AOD value can be calculated for each grid box. Thus model output fields can be taken as “best available” approach without data gaps due to cloud cover or limited spatial cover due to orbit geometrics and providing continuous data sets in space and time. Here, a two-year period covering the years 2007 and 2008 is statistically analyzed and compared with regard to their variability in space and time. Moreover, we compare the COSMO-MUSCAT results to CLs calculated from satellite dust observations, here from IASI (Infrared Atmospheric Sounding Interferometer) flying on the MetOp satellite.

The manuscript is structured as following: In Section 2 an overview of the data used in this study is given including a brief description of the meso-scale COSMO-MUSCAT model system used to perform the 2-year model run and an outline of the satellite dust observations from IASI. Section 3 presents the methods applied for calculating spatial and temporal correlation length followed by Section 4 discussing the spatial and temporal correlation length calculated from COSMO-MUSCAT model simulations and from satellite observations (Section 5). The outcomes of this study are discussed and concluded in Section 6.

2. Model and observations

2.1. COSMO-MUSCAT atmosphere-dust model system

The meso-scale atmosphere-dust model system COSMO-MUSCAT consists of the non-hydrostatic atmosphere model COSMO that is on-line coupled to the 3-D chemistry tracer transport model MUSCAT including a dust emission (Tegen et al., 2002) and deposition scheme (Zhang et al., 2001; Berge, 1997; Jakobson et al., 1997). The atmospheric dust cycle consisting of emission, transport and deposition is simulated within MUSCAT but on-line driven by meteorological and hydrological fields calculated by COSMO. A detailed description of the on-line coupled atmosphere-dust model system is given by Heinold et al. (2011a). COSMO-MUSCAT has recently been used to study the atmospheric dust cycle and related processes such as meteorological drivers for dust emission (Schepanski et al., 2009a, b; Tegen et al., 2013) and dust radiative effects (Heinold et al., 2011b). Here, model simulations are performed at 28 km (approximately 0.25°) horizontal grid spacing for a domain covering Africa north of the Equator to 60° N and from 30° W to 35° E. An extensive validation on the accuracy of the model simulation in terms of capturing atmospheric circulation, dust fluxes and atmospheric dust loading is published in Tegen et al. (2013).

COSMO-MUSCAT model output is provided at 3-hourly (00 UTC, 03 UTC, 06 UTC, 09 UTC, 12 UTC, 15 UTC, 18 UTC and 21 UTC) temporal resolution. For time series analyses at 6-hourly, 12-hourly and 24-hourly resolution respectively used in this study the sampling interval at which the output fields are considered is reduced stepwise. Thereby, the first time step is always the 00 UTC COSMO-MUSCAT output.

The purpose of analyzing COSMO-MUSCAT dust fields in this study is to demonstrate the applicability of simulated dust AOD fields for the evaluation of the present atmospheric dust loading and its evolution or persistence during the following 24 h with regard to different temporal sampling intervals or model output intervals respectively. As the atmospheric dust distribution is driven by atmospheric circulation, which undergoes an interannual