Point-by-point reply to the reviewer's comments

The authors would like to thank the reviewers for the time they spend on the manuscript, and for providing helpful and constructive comments and suggestions. We have considered carefully all comments made; please find our detailed reply (italic) below.

Review #1

This article presents an analysis of the tropospheric mineral dust transport from Africa to Western Europe and during the Charmex field campaign of summer 2013. The topic is very important, mineral dust being difficult to measure and to model, but having a large impact on particulate matter concentrations in the troposphere. The use of EOF is an original way to sort multiple and complex meteorological events, combined to complex soil and surface properties, leading to huge difficulties to know where and when mineral dust emissions may occur. But several questions remains, which are listed below in the 'Major remarks'. Some other minor remarks are also proposed at the end of this review. This article may be accepted but after major revisions.

> *Many thanks for your time spend on the manuscript, your encouraging assessment and helpful comments. Please find our detailed reply below.*

Major remarks:
The main concern is the lack of originality of the paper: the use of a statistical analysis is original but the main goal of the paper is not. A lot of papers are already published about this kind of transport and over the Mediterranean. These articles are abundant in the literature (mainly ACP and JGR-atm), including the ACP/AMT Charmex special section. We recommend to the authors to better reference the recent studies and to extract a new way to introduce the results in order to be really original. A suggestion: estimate EOF for severals years over the region (using GFS or ECMWF model outputs for example) and characterize the specific year of 2013 in this ensemble. Then, using the already modeled period, conclude if 2013 led to less/more mineral dust from Africa to Europe. This suggestion requires to extend and improve the EOF part of this paper. But I think this could give a real originality of the used approach and to this study.

> *Many thanks for this comment! We have followed the reviewers (and editors) suggestion and extended the EOF part of this manuscript. We have calculated the EOF from ERA-Interim geopotential fields for 1979-2015. Comparing the EOF calculated from this 37-year period to those calculated from the 2013, the same patterns occur as shown on the figure below. To assure comparability between the analysis of the meso-scale model COSMO-MUSCAT and the global-scale ERA-Interim reanalysis, the EOF analysis is done for the June-July 2013 period as well as for the June-July 1979-2015 period.*
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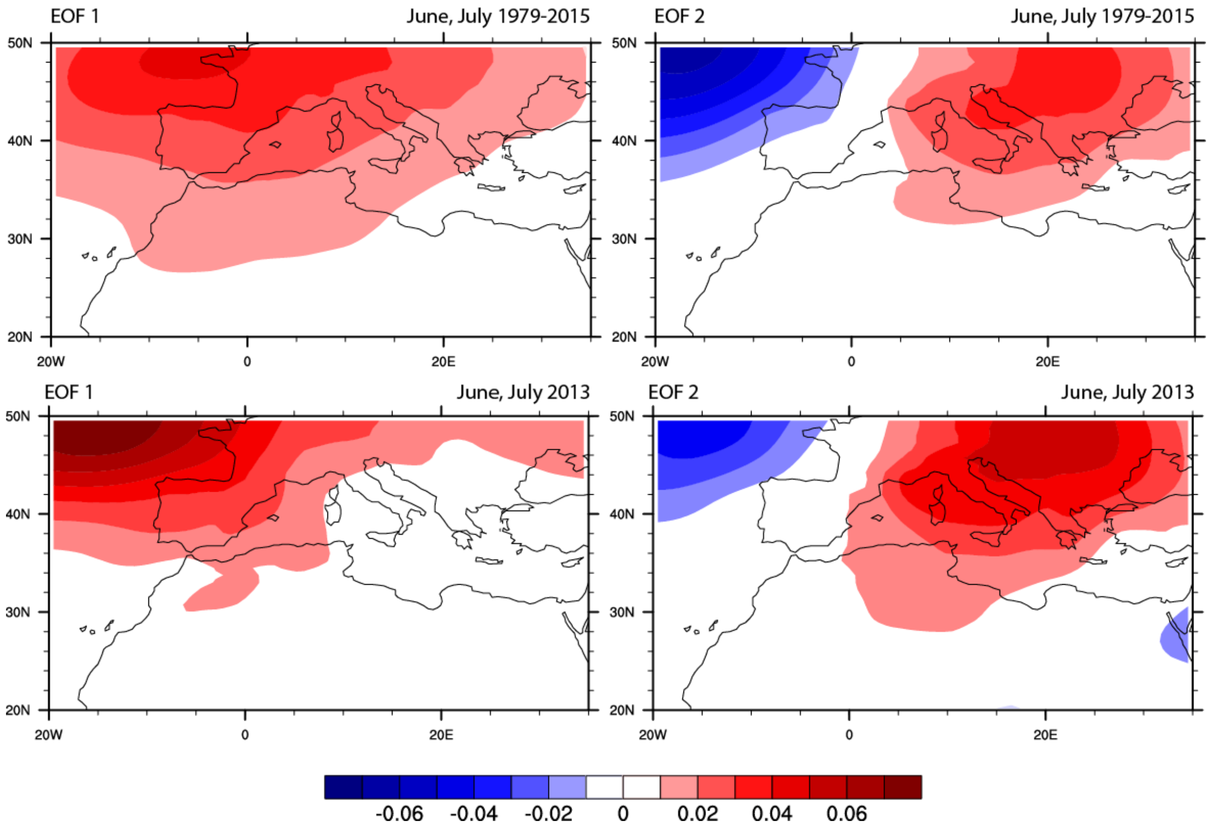
> *Based on the extended EOF analysis, the 2013 results are placed in the context of the results from the 1979-2015 EOF analysis: "Same EOF analyses are performed using the ERA-Interim 850hPa geopotential as input fields. The compiled EOFs are based on a 37-year (1979-2015) June-July time period and thus provide a reference for climatological time scales. In order to assure comparability between the EOF analysis done for the ERA-Interim fields and the analysis using COSMO-MUSCAT geopotential fields, results for the June-July 2013 period were compared first. EOFs for both data sets illustrate similar patterns as described above. Composite plots based on the calculated PC reveal matching patterns, too, however, the subtropical ridge entering the Mediterranean basin extends further to the east in COSMO-MUSCAT simulations as well as the SHL is deeper (not shown). 850hPa geopotential composites calculated for the 1979-2015 June-July period illustrate patterns similar to the 2013 composites. The characteristics of June-July's atmospheric circulation can be described by the predominance of the respective EOF phase as both negative and positive phase represent a particular atmospheric circulation pattern (cf. Fig. 5). Figure 6 summarizes the predominance of the two EOF phases for the individual years of 1979-2015 (June-July only).*

Out of the 61 days of the two-month period June to July 30 days are associated with atmospheric circulation pattern classified by the negative EOF, and 31 days are assigned to the pos. EOF phase. However, the total range between the number of days classified as negative respectively positive EOF is 49 in 1980 versus 53 in 2006 illustrating a strong interannual variability. In this context, June-July 2013's atmospheric circulation over the North African - Mediterranean sector characterized by 26 days of negative EOF and 35 days of positive EOF is slightly dominated by the pattern classified as positive EOF with a predominating subtropical ridge entering the Mediterranean basin (cf. Fig. 5a). Please note that the statistic does not provide any information on the strength of the pressure differences between the centers of action identified by the EOF analysis (here: subtropical anticyclone and heat trough). The number of days assigned to the respective EOF phase may differ between the COSMO-MUSCAT and ERA-Interim simulation due to the different scales and physics parameterization of the numerical core. " (page 10 and 11)



We further discuss the EOF analysis of the climatological time period during the Discussion section: "EOF analysis of long-term reanalysis fields such as from the ERA-Interim product reveal an interannual variability of the predominance of the negative respective positive EOF phase and consequently of the related atmospheric circulation pattern (Fig. 6). Composites from the atmosphere-dust model system COSMO-MUSCAT illustrate a link between phase of the EOF - classifying the related atmospheric circulation - and different elements of the atmospheric dust life-cycle. As dust emission and transport is a direct function of the wind, which is determined by pressure gradients that result from the atmospheric circulation, this link is also suggested by the physical understanding of the atmospheric dust life-cycle. In the frame of this study, the predominance of atmospheric circulation pattern determining dust export toward the Mediterranean basin and southern Europe is in focus. Hence, the number of days that can be classified as either negative or positive EOF are relevant. The variability in northward dust export due to the atmospheric circulation is elaborated in detail exemplarily for June-July 2013 by choosing the meso-scale model COSMO-MUSCAT which simulates the atmosphere and the dust life-cycle as simultaneously as possible. This way the distribution of *dust in the atmosphere is consistent with the simulated state of the atmosphere. Although the EOF analysis from 37-years of ERA-Interim reanalysis fields as presented in section 3 provides first insights into the interannual variability that contribute to the variability in atmospheric dust emission conditions and transport capacities, simulations from climate models with on-line coupled dust modules such as ECHAM6-HAM2 (Heinold et al., 2016) are required to fully investigate the links between the predominance of atmospheric circulation pattern and dust export fluxes."*

The second lack is the validation of the modeled meteorology and the mineral dust production model used. It is clear that mineral dust emissions are a combination of 'favorable' meteorology (surface wind speed) and 'favorable' soils and surface (including roughness length, soil humidity, vegetation, topography). The accuracy of the result will be the multiplication of these two large uncertainties. But the modeled wind speed is not validated and the mineral dust production model is an old one, with a large set of uncertainties: the vertical dust flux is tabulated with a constant, the number of bins are low. In addition, the model is regional and applied to a period corresponding to an intensive field campaign: numerous papers are on the ACP/AMT section. Why are they not used?

Regarding the general model accuracy and uncertainty, the model has been extensively tested in the past with observations from several field studies and available station observations and remote sensing data (Heinold et al., 2009, 2011, Schepanski et al., 2009, 2015, Tegen et al., 2013, Niedermeier et al., 2014). In the frame of ChArMEx, COSMO-MUSCAT model simulations were validated in contribution to two publications: Mallet et al. (2016) and Granados et al. (2016). As the present study aims for elaborating the variability of dust export toward the Mediterranean, which somehow affects the examination of results from the ChArMEx project, we decided to not examine individual case studies for the sake of a clear manuscript agenda.

The third lack is the differences between the used tools and the goal of the paper. The use of EOF and meteorology at 850hPa is a climatological approach. This provides informations on long-range transport only (and certainly not on surface wind speed, the main engine for mineral dust production). On the other hand, the simulation is carried on for two months only: perhaps a specific case, not representative of general circulations, this has to be evaluated and discussed. This remark may be smoothed by extending the paper as suggested in remark #1.

Please see our reply above. We have extended the "climatological approach" and discuss the summer 2013 (June-July) with regard to the summers 1979-2015.

Minor remarks:

- The abstract is too long. New results must be better highlighted. This sentence shows the confusion about the meteorological scales in the study: 'The study elaborates the question on the variability of dust transport toward the Mediterranean and Europe in dependence on the atmospheric circulation as a driver for dust emission and a determinant for dust transport routes...'. The atmospheric circulation is not the driver of emissions. It is only a driver for transport, once dust are emitted.

Many thanks for your comment. We have shortened and revised the abstract.

We agree, dust emission is determined (and limited) by both, soil conditions and atmospheric conditions. In meteorological terminology, however, 'atmospheric circulation' (see e.g. AMS glossary) refers to the large-scale synoptic features and their interplay, i.e., pressure and wind systems. Therefore, the atmospheric circulation does drive the (surface) winds that can mobilize and transport mineral dust. In order to clarify, we restate the sentence as follows:

"'The study elaborates the question on the variability of dust transport toward the Mediterranean and Europe with regard to the atmospheric circulation conditions controlling emission and transport routes of Saharan dust […]"

- Introduction: A key point is the well-cited publication of (Shao, 2011). This shows this kind of study was already done. Perhaps the authors may extend the presentation of this publication to better place their own findings. Same remark for the studies of (Moulin et al.): the influence of NAO was deeply studied in these papers and their results could be better presented.

Many thanks for your comment; we have added a paragraph describing the results of Moulin et al., in particular the influence of the NAO on dust emission over North Africa:
"Moulin et al. (1997) propose a link between the spatial distribution and the phase of the North Atlantic Oscillation, which is described by an index reflecting the pressure difference between Icelandic low and Azores high. The authors conclude, that the seasonal variations in pressure difference over the North Atlantic, in particular the modulation of the atmospheric circulation over the North Atlantic - European sector, impacts on the North African atmospheric dust life-cycle. Consequently, a high positive NAO index, characterized by a deepening of the Icelandic low and a strong Azores high, fosters drier conditions over North Africa and thus enhances the chances for dust mobilization."

2 Data and methods:

- Definition of wind shear stress could be deleted, being well known. For the model introduction, please add more details on the uncertainties.

The definition of the wind shear stress is removed. For model uncertainties we refer to previous studies using the dust model version of COSMO-MUSCAT. The model has been extensively tested with observations from several field studies and available station and remote sensing data (Heinold et al., 2009, 2011; Schepanski et al., 2009; Tegen et al., 2013; Niedermeier et al., 2014).

- p5.l.5: The alpha constant is not defined. But this could clearly be a very important parameter.

The sandblasting efficiency alpha was introduced earlier (page 4, line 21), however, it is defined here again.

- p5.l.20: If the model is on-line, the shape of the dust (and the related constants) may have an effect on AOD but also on direct and indirect effects. Please clarify.

Dust-radiation interactions are computed online at solar and thermal wavelength bands and account for variations in the simulated size-bin resolved aerosol concentrations (Helmert et al., 2007). It can impact on the meteorology and consequently implicitly feed back on dust emission and dust transport (Heinold et al., 2008). As we already describe in detail on page 5, the dust optical properties are computed using Mie theory, which requires assuming spherically shaped particles. Although this assumption usually does not hold for mineral dust, the errors in radiative flux computation are small when integrating over hemispheres (Mishchenko et al., 1995; Seinfeld and Pandis, 1998). Otto et al. (2009) showed that AOD, single scattering albedo, and asymmetry parameter were in error by 3.5%, 1%, and 4% respectively if spherical instead of non-spherical particles were assumed. Based on this, the shape effect on dust AOD is negligible relative to the other uncertainties in an atmospheric model.

2.2 Validation of simulations using only AOD is frequent for global models. But may appear too simple for regional models. The paper could be improve using more and finest data, especially because the study is linked to an intensive filed campaign.

We do not see what is wrong about using AOD sun photometer measurements, which are very robust and accurate. Together with in-situ concentration measurements they belong to the highest quality data available. However, ground based in-situ observations may not be representative for dust transport within the atmospheric column. For a better spatial evaluation of our model results, we have added a comparison with MODIS collection 6 AOD products.

2.3 Indeed the EOF are designed for long-time period. Please discuss the fact this tool is only used for a short period. What is the representativity of the results in this case. Or think to the suggestion #1 of this review.

We have seized your suggestion #1 and brought the results from the EOF analysis for the June-July 2013 period in the context of a 37-year period (1979-2015).

3. This section is interesting, a good bibliography but very long and a mixture of several topics. The first part is close to the introduction (some references are the same) and the second part presents applications of EOF: the topic of section 2. Please simplify and merge these three sections. Results for EOF could be in a new section 3: 'Meteorological validation against measurements and EOF results'.

We followed the reviewer's suggestion and have thematically reordered the bespoken sections. The overview on dust transport pathways (formerly first part of section 3) now follows the Introduction. The EOF analysis builds a new section on its own, section 4.

4.

p.9, l.9: 'Dust source activation...' the concept for dust emissions (meteorology and soil/surface) was already described and cited several times before. The authors may be more synthetic and directly goes to the new results.

Many thanks for spotting this! We have cleaned the respective paragraph and results are presented more directly.

5.4 Dust deposition. This is an interesting section, but a validation to existing data is necessary before to conclude with the model only. In particular, the wet scavenging is often roughly designed in the models and the uncertainty is important.

We agree that large uncertainties in modelling mineral dust are related to the representation of dry and wet deposition processes. Niedermeier et al. (2014) showed that COSMO-MUSCAT in general does a good job in terms of sedimentation and dry deposition. Wet deposition is difficult to measure, and to our knowledge no data are available here.

Conclusion: The end of the conclusion is more related to a bibliography. Please focus on your results only.

We have revised the conclusion section and focus on our results only.