

**Rebuttal for manuscript:**

Fiedler et al (2013) How important are cyclones for mineral dust emission in North Africa?, Atmos. Chem. Phys. Discuss., 13, 32483-32528, 2013, doi:10.5194/acpd-13-32483-2013

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We would like to thank both reviewers and the editor Heini Wernli for their feedback, which helped to improve our manuscript. Please find our response to each point below the reviewers' comments (bold).

**Reviewer 1**

**My main concern is the too simple attribution of the dust emissions to a depression or cyclone without deeper analysis of the intensity of these components. In this study the authors consider the simultaneous presence of dust emissions and synoptic component as a causal relationship. AEWs and HL present a large temporal variability of intensity that could influence differently the 10m wind field and so the dust emissions.**

The coincidence of depressions with dust emission suggests some level of causal relationship but this is not always clear-cut, as embedded mechanisms like NLLJs can play a role. We have expanded the discussion of this aspect in the manuscript and changed wording throughout the manuscript to make the distinction between causality and coincidences clearer.

We added a paragraph to Section 3.4: "Estimating the dust emission amount associated with the heat low likely involves a number of mechanisms. Emissions can be directly caused by the horizontal pressure gradient around the heat low, but this alone may not always be sufficient to cause substantial dust mobilization. Often mid-morning winds are enhanced through the NLLJ mechanism (Fiedler et al., 2013), which depends on the horizontal pressure gradient around the heat low, but also on the diurnal evolution of the boundary layer. Using the NLLJ identification method from Fiedler et al. (2013) to estimate the amount of dust emission associated to NLLJs within depressions results in an annual and spatial average of 12%. Between March and October 12–16% of the dust emission is associated with both phenomena, while values are below 10 % during the rest of the year (not shown). This result is in agreement with Fiedler et al. (2013) who show a frequent NLLJ formation along the margins of the Saharan heat low. Another process potentially embedded in depressions is dust emission associated with haboobs, which are presumably not well represented in ERA-Interim data due to the use of convective parameterisation. Both NLLJs and haboobs will be discussed in more detail along with mobile and long-lived depressions. These are termed cyclones in the following and will be investigated next. "

The intensity of the dust emission flux from cyclones is analyzed in Section 3.5.1. In addition we now show the anomaly factor of depressions.

**Also, the contribution of the convection is not enough taken into account. The large scale components (and more specifically the cyclones) could be decomposed in two different classes following if they are associated or not with convection and with cold pools. The authors should also present the contribution and mechanisms involved with dust emissions not associated with depression or cyclone.**

We agree that the contribution from cold pools over a climatological time period would be an interesting analysis. ERA-Interim does, however, not resolve or parameterize cold pools in agreement with the reviewer's point of view. The implication of the missing representation of cold pools for the results in this manuscript is discussed in Section 3.6.2 and in the conclusions. We discuss the relevance of other processes in the introduction, and analyse NLLJs as dust-emitting mechanism within atmospheric depressions in Section 3.5 and migrating, long-lived cyclones in Sections 3.6.2 and 3.6.3 (see also the previous point).

**Also, before to analyze the contribution of each component on dust emissions, the authors should discussed the impacts of these components on the 10m wind speed distribution.**

We discuss the near-surface wind associated with cyclones in Section 3.6.3.

**Finally, reanalysis are less good to represent fine scale processes, especially cold pool, this tends to promote large scale origins of dust emissions. This also should be discussed.**

Cold pools are currently not parameterized. Evidence exists that their missing ventilation of the summertime heat low in a 40-day convection permitting simulation may lead to a stronger heat low during summer (Marsham et al., 2011, 2013). The net effect on the dust emission amount is uncertain due to the nonlinear dependency of dust emission on wind speed. We comment on the missing representation of cold pools in Sections 3.5, 3.6.2 and in the conclusions.

**Detailed comments:**

**p32488 I9: I am not sure that the reference (Todd et al) is well adapted here.**

The time period investigated in this study is relatively short, but is based on unique observations from the central Sahara during the Fennec project. We have added Lavaysse et al. (2009) as reference to include a climatological analysis of the heat low too.

**P32488 I29: Please add this reference about the origins of AEWs: Leroux, Stephanie, Nicholas M. J. Hall, George N. Kiladis, 2011: Intermittent African Easterly Wave Activity in a Dry Atmospheric Model: Influence of the Extratropics. J. Climate, 24, 5378–5396.**

Thanks, we added the following to Section 1: "More recent work suggests deep convection (Mekonnen et al., 2006, Thorncroft et al. 2008) and extra-tropical influence (Leroux et al., 2011) as trigger of AEWs."

**p32491 I23: About the point 3. I am not convince by the method to exclude heat lows. A decreasing core pressure could be also associated with heat low.**

We use all three criteria (decreasing core pressure, horizontal displacement and lifetime) simultaneously to identify cyclones. We added this to Section 2: "... identified by the following filter criteria that have to be fulfilled simultaneously"

**P32494 I4: In figure 2 and in the text '... with 40-100 events in the 20-yr period ...', the authors should present the results in term of occurrence probability instead of number. That takes into account the duration of the events and will be more useful when the impacts of these events on dust emissions will be discussed.**

Changed as suggested.

**P32495 I10: How do the authors explain the presence of depression in the Senegal coast?**

We added the following to Section 3.1: " Particularly the atmospheric depressions close and offshore of the West African coast point to the presence of AEW signatures."

**P32498 I10: The authors should show the occurrence probability of the depression over the Sahara during the year and for each season. The heat low is always detected over Sahara in summer. That means that the authors consider all dust emissions are associated with the heat low during this summer period? The authors should use the intensity of the depression and analyze the influence of the hl activity on the 10 m wind field then the contribution on dust emissions.**

The results suggest that the majority of summertime dust emission is associated with the Saharan heat low, but embedded mechanism may play a role. This aspect is now discussed in more detail (please refer to responses above).

**p32499 The section on seasonal climatology is too descriptive. Please reduce this subsection and clarify the most important results.**

We have shortened this part.

**P32501 I29: 'This results gives evidence ...' Please compare these results with the occurrence probability of each component. The heat low is present all year long. It is statistically evident to find a contribution larger than an another rarer component. The comparison between the ratio of dust emission contribution vs. the occurrence probability should be done.**

We have extended the comparison of the dust emission fraction with the occurrence frequency of depressions.

**P32503 I5: Could the authors clarify the method to distinguish each quadrant. Maybe these quadrants should be relative to the cyclone displacement instead of East/West.**

The direction of the cyclone displacement is discussed in the context of the dust emission per quadrant. We have chosen a geographical position of the cyclone quadrants. Added: " Here, dust emission is analyzed in four quadrants the position of which follow their geographical orientation depicted in Figure 13."

**P32505 I7: 'The diurnal ...' it is difficult to interpret this figure since these emissions occurred at different places following the season.**

The diurnal cycle is shown for different months. Most cyclones and the dust emission associated with them occur during winter and spring in the north. Changed to: "These diurnal differences for late winter and spring in the north can be explained by the development of the boundary layer."

**P32506 I21: Where does the soil moisture data come from?**

The soil moisture is from ERA-Interim (Section 2): "The dust model is driven by three-hourly 10m-wind speeds and soil moisture of the uppermost soil layer from ERA-Interim forecasts (Dee et al. 2011)."

**P32506 I26: This paragraph is not clear. Could the authors clarified the method used to assess the soil moisture impacts?**

Changed to: "The magnitude of the effect is studied with two dust emission calculations with and without accounting for soil moisture, respectively (Section 2). "

**Figure 5: Please simplify the orography.**

Done.

**Figure 7: Please add the annual occurrence probability of depressions (and its radius of influence).**

We now show the occurrence frequency in this and the following figures. The radius of influence is set to 10 degree, which is now added to the figure captions: "Dust emission within a radius of 10 degrees from the depression/cyclone centre is considered (Section 2). "

**Figure 8: As previously, the occurrence probability of depressions should be added.**

Done

**Figure 10 and 11, same as previously. Ratio of dust emissions should be compared with the occurrence probability.**

Done

**Figure 14: The authors should compare these distribution with dust emissions that occurred without cyclone. Without this kind of comparison, I am not sure to understand the interest of this figure.**

The fraction of dust emission associated with cyclones is shown in Figures 10 and 11. The dust emission not associated with cyclones must by definition be associated with other processes. The original Figure 14 addressed the distribution of dust emission associated with cyclones on sub-daily scales at the top and the effect of soil moisture on dust emission in the annual cycle at the bottom. We now use two separate figures to explain the quantities shown more clearly.

**Reviewer 2:**

**- Validity of the approach:**

**The study has a major problem regarding the approach used to evaluate the dust emission associated with depressions. The authors gave conclusions based on the coincidence in time and space between the presence of depressions and dust emission. But this doesn't mean that one is caused by the other. Add to this that most of the time depressions are present together with other mechanisms involved in dust emission in North Africa. I'm not sure the amount of dust emission you attribute to depressions in the paper is actually exclusively due to depressions. The majority of the results and conclusions related to the depressions part of the paper are based on this method and I have a great doubt on their representativeness and validity. The method, results and conclusions regarding this part should be revisited or you can shorten the paper to the cyclone part which is more convincing.**

We agree that the dust emission associated to depressions must not entirely be related to the depression itself but may involve other mechanisms like the NLLJ, which we discuss in Section 3.5 and the conclusions. We also changed formulations throughout the manuscript to make the distinction between both clearer. See also our reply to reviewer #1.

**- Validation of some results against observations:**

**What one would expect from this study is to see some use of the available observations on dust emission over North Africa to validate some of the results that are driven exclusively from models and reanalyses. There is for example a great opportunity to consider the SEVIRI observations that are now available for many years and in high temporal and spatial resolution to validate the results on the climatology of the cyclones for example, but also to validate the model regarding dust emissions and many other possibilities that will give highest impact to the results described here.**

We now include a presentation and discussion of the validation of the dust source activation frequency of our dust model calculation against SEVIRI in a new Section 3.4.

**- The link between wind and dust emission:**

**There is big assumption made here; the authors calculate the dust flux based on wind reanalyses and soil humidity, but there is a lot more that is crucial for dust emission. One of these factors for example is the availability of materials at the surface to be emitted by strong winds. How this factor is taken into account? Is the model used for dust emission was tested and validated against observations.**

We use the same approach for calculating dust emission as in Fiedler et al. (2013). Potential dust sources are defined as grid boxes where at least two dust emission events have been observed based on the dust source activation frequency from Schepanski et al. (2007, 2009, 2012). The dust

emission model used here is tested and validated against observations (Tegen et al., 2002) and widely used, e.g. the dust emission scheme is implemented in different research models including the global aerosol-climate model ECHAM-HAM (e.g. Zhang et al., 2012) and the regional climate model COSMO-MUSCAT (e.g. Heinold et al., 2011). In addition, we have now included a validation of the dust emission calculation against satellite observations. We added the following to Section 2: "This dust emission scheme is validated by Tegen et al. (2002) and used in both global and regional climate models (Heinold et al. 2011, Zhang et al. 2012). Here, the dust model is driven by..."

**- Missing important mechanisms for dust lofting**

**Many of the well-known mechanisms for dust emissions over North Africa are missing in this study (for example dust emission by the monsoon front in the intertropical discontinuity region e.g. Bou Karam et al 2008, dust emission by dry cyclones in the same region e.g. Bou Karam et al., 2009, dust emission by density currents from cold pools that migrate over the Sahara e.g. Flamant et al., 2007; Bou Karam et al., 2014, etc.). Consider mentioning them when you make the overview on the mechanisms for dust lofting in the introduction. Also, these mechanisms are present generally during summer i.e at the same time as the Heat low and associated depressions. Moreover they are often present in the same area. How the authors can be sure that the dust flux they calculated is related to one mechanism (here depressions) and not to the others?? Again the approach used here is light and not convincing (see my first comment).**

We agree that other mechanisms can be embedded in the identified atmospheric depressions, particularly the summertime heat low, as we discuss in Section 3.5 and now more clearly in the conclusions. Studies by Diana Bou Karam are reviewed in Knippertz and Todd (2012) and also cited here. We have changed the following to make the distinction between case studies mentioned above and studies addressing the relative importance for dust emission on longer time scales in Section 1: "Knippertz and Todd (2012) review the literature on relevant meteorological processes for dust emission. Recently a number of studies have addressed the relative importance of meteorological processes for dust emission focusing on the meso-scale." and added "Bou Karam et al. (2008) suggest that the ITD plays a role for emitting dust aerosol and uplifting of aged dust plumes."

**- Estimation of the error associated with the numbers you give:**

**The results are based on model calculations, what is the error associated with the numbers you give? How confident one should be in reading them? Is the model used was able to produce realistically dust emission associated with cyclone (validation via a case study)? Does it over or under estimate dust emission (both its localization and amount)?**

**Consider adding a paragraph on the estimate of the error associated with your results, it is very important for the reader to know how close to the reality are the numbers you give both on the climatology and on the dust emission mass especially that these results are based on models and it is well known how it is difficult for the current models to simulate dust emission over North Africa (e.g. the introduction of this paper).**

We now more clearly evaluate our results in Sections 3.5, 3.6.2 and the conclusions (please refer to responses to reviewer #1). We also include a validation and discussion of the dust emission activation frequency with satellite data in a new Section 3.4.

**- Appropriateness of abstract, introduction and conclusions**

**Since the results after revisions based on the above comments may be quite different from the current ones these parts of the manuscript need to be revisited after revisions especially the conclusions on dust emission related to depressions.**

We changed these sections accordingly.

**Specific Comments:**

**- The title doesn't say anything about depressions although great part of the paper is on this, why?**  
The focus was set on cyclones initially. Identifying depressions was an intermediate step towards addressing the question asked. We now changed the title to "How important are atmospheric depressions and mobile cyclones for emitting mineral dust aerosol in North Africa?"

**- P32484 'In summer, depressions, particularly Saharan heat lows, coincide with up to 90% of the seasonal total dust emission over wide areas of North Africa'. Coincide doesn't mean they are caused by. It is well known that dust emission is highest during summer because of many other factors than the heat low. See my main comment number 1.**

This word choice was intended as we agree that coinciding does not imply a causal relationship. We discuss NLLJs as an embedded mechanism (please see also responses above).

**- P32486 Harmattan Surge: I'm not convinced what you call Harmattan surge is a separate feature than cyclone. Although they occur a bit far from the visible cold front and cloud band of the cyclone these winds are linked to the cyclone and stop when the cyclone stops. The cyclone is mostly visible due to the cloud band which is over a much localized area, but it affects a larger area than the visible one (e.g. Bou karam et al., 2010). The paper you cited to justify this use (Knippertz and Fink, 2006) doesn't deal actually with cyclone but with an extratropical front dust emission during which Harmattan surge occurred. Consider rectification.**

We extended the introduction by an explanation of the distinction between the Harmattan surge and the cyclone: "Both the cyclone and the Harmattan surge are usually caused by a wave at upper-tropospheric levels. While the trough is typically associated with the cyclone, the ridge to the west of it can cause the strengthening of anticyclonic conditions over wide areas of North Africa, which increases the northeasterly Harmattan winds. Harmattan surges may reach almost continental scale and cause dust emission – typically involving the NLLJ mechanism – as far south as the Bodélé Depression and the West African Sahel (Knippertz and Todd, 2010)."

**- P32491 You describe the method by from Schepanski and Knippertz (2011) and then you say 'The criteria from Schepanski and Knippertz (2011) used to filter tracks of Sudano-Saharan depressions are not applied here', it is confusing, describe directly what is used in the present study.**

Changed to: "The investigation of depressions and migrating cyclones over North Africa presented here is broader than that by Schepanski and Knippertz (2011). Here, depressions are all..."

**- P32493 The way you define the cyclone-affected area in my opinion is not enough to cover all the area affected by the cyclone (see also my comment regarding Harmattan surges) although the horizontal extend of the Saharan cyclones is about 10° it doesn't mean that the wind fields beyond this area are not affected. This will lead to an underestimation of the dust emission associated with the cyclone.**

We tested the sensitivity of the cyclone-affected area. Increasing the radius from 10 to 20 degrees had an overall small effect on the spatial pattern of dust emission associated with the dust emission amount (Section 2.2). This shows that the 10-degree radius usually captures the centre of action.

**- Pages 32496 and 32497 consider citing Bou Karam et al., 2009 that deals with cyclones connected to AEWs.**

Thanks, it is now cited.

**- P32499 Paragraph 3.5.1 is too descriptive, can be more concise.**

We have shortened this passage.

**- P32502 Paragraph 3.5.2 Consider my comment on the definition of cyclone-affected area**

**above.**

Please refer to our response above.

**- P32505 Line 7 to 26 too long and repetitive, consider simplifying.**

Changed to: "These diurnal differences for late winter and spring in the north can be explained by the development of the boundary layer in the context of the synoptic-scale conditions. Dust emission occurs when the momentum transport to the surface is sufficiently large to exceed the threshold for emission onset. Reduced stability during the day enables downward turbulent momentum transport, which increases the near-surface wind speed. This effect is expected to be largest, when the daytime boundary layer is sufficiently deep for reaching layers of high wind speed in the free troposphere. Strong winds prevail relatively close to the surface during cyclone passage in winter and spring. These cyclones form in a baroclinic zone between the warm (deep) North African air mass compared to the cold (shallow) air polewards. The contrast between the air masses causes a particularly strong thermal wind, i.e. an increase of the geostrophic wind with height in the lower troposphere. Along with typically deep daytime boundary layers over North Africa momentum from the free troposphere is efficiently transported towards the surface. In the Sahara, the boundary layer reaches a sufficiently large depth at or closely after mid-day (Culf, 1992), which coincides well with the mid-day peak of dust emission found here. The time of maximum dust emission is in agreement with the observation of suspended dust in cyclones shown in Fig.1."

**- P32506 Line 21. Or the difference can be due to the fact that with depressions you have the dust emission of all the other mechanisms. See my major comments number 1 and 4.**

We discuss the dust emission associated with cyclones in this section. The relevance of embedded NLLJs in depressions is discussed in Sections 3.5 and for cyclones in Section 3.6.3

**- P32507 line 7 to 9, sentence not clear.**

Changed.

#### **Figures**

**- Figure 6: Consider improving the font size, it is very small and hard to read.**

Done.

**- Figure 14a: The colors used are hard to distinguish.**

Done.

# How important are atmospheric depressions and mobile cyclones for emitting mineral dust aerosol in North Africa?

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**Abstract.** This study presents the first quantitative estimate of the mineral dust emission associated to with atmospheric depressions and migrating, long-lived cyclones in North Africa. Results from a tracking algorithm are combined with dust emission flux calculations. Atmospheric depressions are automatically tracked at 925 hPa based on ERA-Interim data from the European Centre for Medium-Range Weather Forecasts for 1989–2008. The results highlight that depressions are abundant and associated with 55% of the dust emission amount annually and spatially averaged over North African dust sources. Even larger contributions to dust emission from depressions are found south of the Atlas Mountains during spring with regionally up to 90%. It is spring when the largest monthly totals. A set of filter criteria is applied to identify migrating, long-lived cyclones. Dust emission is calculated with a dust emission model driven by 10m-winds and soil moisture from ERA-Interim. Emission peaks during winter and spring with spatial averages of 250–380 gm<sup>-2</sup> of dust emission occur in per month. Comparison of the dust source activation frequency from the model against SEVIRI satellite observation shows a good agreement in the Bodélé Depression but differences in the north and west of North Africa. The remaining months have a total dust emission smaller than 80%. In summer, depressions, particularly Saharan heat lows, coincide with up. Depressions are abundant, particularly in summer when the Saharan heat low is situated over West Africa and during spring in the lee of the Atlas Mountains. Up to 90% of the seasonal total dust emission over wide areas of North Africa.

In contrast to depressions, migrating cyclones that live for more than two days are rare and are associated to 4.55% of the annual and spatial dust emission average. Migrating cyclones over North Africa occur primarily in spring

annually and spatially averaged) of dust emission occurs within 10 degrees of these depressions, with embedded mechanisms such as nocturnal low-level jets playing a role. Cyclones are rarer and occur primarily north of 20°N with eastwards trajectories and typical life times of three to seven days. Regionally larger seasonal totals of dust emission are associated to cyclones with up to 25% over Libya. In summer, N in spring in agreement with previous studies and over summertime West Africa consistent with near-surface signatures of African Easterly Waves (AEWs) emit regionally up to 15% of the total emission. The diurnal cycle of dust emission underlines that emission associated to cyclones at mid-day is substantially larger than at night by a factor of three to five. Soil moisture weakens dust emission during cyclone passage by. Dust emission within 10 degrees of cyclones peaks over Libya with up to 25% in spring. Despite the overall small contribution of migrating cyclones to dust emission 4% annually and spatially averaged, cyclones coincide with particularly intense dust emission events exceeding the climatological mean flux by a factor of four to eight. This implies, that both depressions and migrating, long-lived cyclones are important for dust emission in North Africa. Soil moisture weakens dust emission during cyclone passage by about 10%.

## 1 Introduction

The accurate simulation of mineral dust aerosol in the Earth system is one of the great challenges of current atmospheric research. Dust aerosol is important due to its proposed but uncertain effects on the radiation transfer in the atmosphere with implications for the water and energy cycle, as well as



65 effects on eco-systems and humans (Carslaw et al., 2010; 120  
 Shao et al., 2011; Knippertz and Todd, 2012, and references  
 therein). Despite these impacts of dust aerosol, estimates of  
 the annual total of dust emission from state-of-the-art climate  
 models vary from 400 to 2200 Tg for North Africa (Huneeus  
 70 et al., 2011), the largest dust source on Earth. Further reduc-  
 tion of this ~~modelling~~-modeling uncertainty depends on im-  
 proving the representation of dust emission. Both the realis-  
 tic description of soil properties and meteorological mech-  
 anisms for peak wind generation are important. The wind  
 75 speed near the surface is particularly crucial as it controls the  
 onset of dust emission, and the magnitude of the flux non-  
 linearly (e.g. Kok et al., 2012; Marticorena and Bergametti,  
 1995; Tegen et al., 2002).

A systematic analysis of mechanisms generating peak  
 80 winds strong enough for mobilizing dust provides the ba-  
 sis for evaluating dust emission from atmospheric models.  
 Knippertz and Todd (2012) review the literature on relevant  
 meteorological processes for dust emission. Recently a num-  
 ber of studies have addressed the relative importance of me-  
 85 teorological processes for dust emission ~~with a clear focus~~  
focusing on the meso-scale. Cold pool outflows from convective  
 downdrafts (haboobs) are suggested as an important dust  
 storm type in summertime West Africa (e.g. Marsham et al.,  
 2011; Heinold et al., 2013). A 40-day horizontally high-  
 90 resolved simulation suggests that haboobs generate about  
 half of the dust aerosol amount in this region, but a physical  
 parameterization for atmospheric models with coarse spatial  
 resolution is currently missing (Heinold et al., 2013). An-  
 other important process for dust emission is the nocturnal  
 95 low-level jet (NLLJ), which frequently forms in North Africa  
 (Schepanski et al., 2009; Fiedler et al., 2013). Based on a 32-  
 year climatology, up to 60 % of the dust emission is associ-  
 ated ~~to~~-with NLLJs in specific regions and seasons (Fiedler  
 et al., 2013).

100 The main meteorological driver for the largest dust emis-  
 sion amount of the continent that occurs north of 20° N be-  
 tween December and May (Fiedler et al., 2013), however, is  
 not well quantified. ~~It is~~ During this time of year ~~when~~-  
 cyclones affect the region (e.g. Alpert and Ziv, 1989; Winstan-  
 105 ley, 1972; Hannachi et al., 2011). The core of these cyclones  
 can either lie over the continent itself or further north in the  
 Mediterranean region (e.g. Maheras et al., 2001; Schepanski  
 and Knippertz, 2011). Several studies suggest that cyclones  
 can cause dust storms (Bou Karam et al., 2010; Hannachi  
 110 et al., 2011; Schepanski et al., 2009; Schepanski and Knip-  
 pertz, 2011), although a case study by Knippertz and Fink  
 (2006) for the exceptionally strong and continental-scale dust  
 storm in March 2004 gives evidence that a cyclone only  
 produces one part of the associated dust emission. The re-  
 115 maining dust mobilization is linked to strong northeasterly  
 Harmattan winds. These Harmattan surges manifest them-  
 selves by an increased horizontal pressure gradient between  
 the post cold frontal ridge and the prevailing low pressure  
 over the continent. ~~Harmattan surges can lead to continental~~

~~scale dust outbreaks with subsequent transport towards the  
 Sahel.~~ Both the cyclone and the Harmattan surge are usually  
 caused by a wave at upper-tropospheric levels. While the  
 trough is typically associated with the cyclone, the ridge to  
 the west of it can cause the strengthening of anticyclonic  
 conditions over wide areas of North Africa, which increases  
 the northeasterly Harmattan winds. Harmattan surges may  
 reach almost continental scale and cause dust emission –  
 typically involving the NLLJ mechanism – as far south as the  
 Bodélé Depression and the West African Sahel (Knippertz  
 and Todd, 2010). The dust may than be transported towards  
 the Atlantic Ocean and beyond. Klose et al. (2010) show that  
 about half of dust suspended over the Sahel may be linked to  
 a pressure pattern typical of Harmattan surges: a low over the  
 Arabian Peninsula and the Azores High expanding eastwards  
 into the continent. The mass of dust emission associated ~~to~~  
 120 with cyclones has not been estimated before. The aim of the  
 present study is to reveal how much dust emission is linked  
 to migrating cyclones affecting North Africa.

Previous work on cyclones influencing North Africa focus  
 on the meteorological analysis in the Mediterranean basin.  
 Alpert et al. (1990) use five years of analysis data from  
 the European Centre for Medium-Range Weather Forecasts  
 (ECMWF) for ~~analysing~~-analyzing Mediterranean cyclones  
 statistically. A longer time period of 18 years of ECMWF re-  
 analysis is exploited by Trigo et al. (1999) for cyclone track-  
 ing. The contributing factors of cyclogenesis in the Mediter-  
 125 ranean region is investigated later by Trigo et al. (2002).  
 Maheras et al. (2001) present a 40-year climatology of sur-  
 face cyclones based on re-analysis from the National Cen-  
 ters for Environmental Prediction (NCEP) and underline the  
 variability of both the position and the core pressure of cy-  
 clones with the time of day. Since the method does not have  
 a criterion for cyclone migration, the climatology by Ma-  
 heras et al. (2001) includes heat lows and orographic depres-  
 sions. NCEP data is also used for a springtime climatology  
 of cyclones north of 20° N for 1958–2006 (Hannachi et al.,  
 2011). Hodges et al. (2011) compares cyclone climatolo-  
 gies derived from state-of-the-art re-analysis showing spa-  
 tial differences of track densities and cyclone intensity. All  
 of these studies highlight distinct regions that are prone to  
 frequent cyclogenesis. These are over ~~sea~~-the Aegean Sea,  
 the Gulf of Genoa and the Black Sea (Trigo et al., 2002).  
 Regions of frequent cyclogenesis in northern Africa lie to  
 the south of the Atlas Mountains, and east of the Hoggar  
 Mountains (Alpert and Ziv, 1989; Trigo et al., 1999; Maheras  
 et al., 2001; Schepanski and Knippertz, 2011; Winstanley,  
 1972). Cyclones may further form or intensify over Libya,  
 also termed Sharav or Khamsin cyclones (Alpert and Ziv,  
 1989, e.g.) which are thought to be the main driver for dust  
 transport towards the ~~Eastern~~-eastern Mediterranean (Moulin  
 et al., 1998; Winstanley, 1972). Classically the term “Sharav”  
 is used for heat waves in Israel, for which cyclones from  
 Africa are one of the meteorological conditions (Winstanley,  
 1972). Most of the cyclones in the Mediterranean basin form

175 between December and May, when the temperature contrast 230  
between land and sea is largest.

Cyclogenesis in Northwest Africa occurs east of an upper level trough where positive vorticity advection supports the formation of a depression near the surface. These troughs  
180 advect cool air masses at their western side towards the Sa- 235  
hara and transport Saharan air northwards at their eastern side (e.g. Maheras et al., 2001; Knippertz and Fink, 2006). The interaction with orography can lead to cyclogenesis at the lee side of mountain ranges. In North Africa, the position  
185 of lee cyclogenesis is typically the southern side of the Atlas Mountains (e.g. Schepanski and Knippertz, 2011; Trigo et al., 2002). Migrating lee cyclones usually follow east- to  
190 northeastward trajectories with propagation speeds around  $10 \text{ ms}^{-1}$  (e.g. Alpert and Ziv, 1989; Alpert et al., 1990; Bou Karam et al., 2010; Hannachi et al., 2011). They can advect 245  
hot, dry and dusty air towards the ~~Eastern-eastern~~ Mediterranean, but may also bring rainfall (Winstanley, 1972) with flood risk in Israel (Kahana et al., 2002). Unusually deep cyclones over the ~~Western-western~~ Mediterranean that move  
195 from Algeria northwards are documented for winter that can cause high impact weather (Homar et al., 2002; Homar and Stensrud, 2004; Homar et al., 2007).

In contrast to cyclones at the northern fringes of the continent, low latitudes are characterized by shallow depressions. Horizontal pressure gradients during the presence of depressions can be large enough for generating dust storms (Winstanley, 1972; Hannachi et al., 2011). Depressions in form of heat lows build in response to strong solar irradiation, the location of which changes in the course of year.  
200 In North Africa the heat low moves from positions near 260  
the equator in the east between November and March towards West Africa between April and October (Lavaysse et al., 2009). The Saharan heat low during summer is typically quasi-stationary over several days to weeks (Lavaysse et al., 2009; Todd et al., 2013) and coincides with high concentrations of dust aerosol (e.g. Knippertz and Todd, 2010). The heat low strongly affects the positions of the intertropical discontinuity (ITD), where the northeasterly Harmattan winds and the southeasterly monsoon winds converge. Bou Karam et al. (2009) suggest that the ITD plays a role for emitting dust aerosol and uplifting of aged dust plumes.  
215

A migrating depression type originating in low-latitudes is the Sudano-Saharan depression the concept of which is described in classical literature and has recently been revised (Schepanski and Knippertz, 2011, and references therein).  
220 These depressions form in the central Sahara, usually south-west of the Tibesti Mountain. They initially migrate westwards before turning anticyclonically over West Africa to track eastwards over northern parts of the continent. Analysis of  
225 20 years of ECMWF ERA-Interim re-analysis suggests that Sudano-Saharan depressions are rare and too shallow ~~for causing-to cause~~ sufficiently high wind speeds for significant amounts of dust uplift emission (Schepanski and Knippertz, 2011).

~~Another-Other~~ migrating depressions at low latitudes are surface signatures of African Easterly Waves (~~AEWAEWs~~). Based on upper-air soundings, Burpee (1972) shows that AEWs form south of the African Easterly Jet (AEJ) at 700 hPa along  $10^\circ \text{ N}$ . The AEJ results from the horizontal temperature contrast between the hot Saharan air poleward and the cooler air masses equatorward of the AEJ. Burpee (1972) suggests that the wind shear at the AEJ is the origin of wave-like disturbances. More recent ~~works suggest deep convection as a work suggests deep convection~~ (e.g. Mekonnen et al., 2006; Thorncroft et al., 2008) and extra-tropical influence (Leroux et al., 2011) as trigger of AEWs. The main genesis region of AEWs remains controversial and ranges from  $10^\circ \text{ E}$  to  $40^\circ \text{ E}$  (Burpee, 1972; Mekonnen et al., 2006; Thorncroft and Hodges, 2000; Thorncroft et al., 2008, and references therein) from where they propagate westwards with the mean flow. AEWs occur about every three to five days between June and September with a peak activity at the beginning of August (Burpee, 1972; Jones et al., 2003). At 850 hPa, AEW signatures occur both north and south of the AEJ axis at  $10^\circ \text{ N}$  and  $20^\circ \text{ N}$  (Mekonnen et al., 2006). AEW signatures at 850 hPa ~~They~~ are most frequently found in West Africa with up to six events between May and October around  $20^\circ \text{ N}$  and  $10^\circ \text{ W}$  (Thorncroft and Hodges, 2000). AEWs are linked to variability of dust mobilization and concentration over West Africa although the diurnal cycle seems similarly important (Luo et al., 2004). Knippertz and Todd (2010) argue that dust emission associated ~~to-with~~ AEWs is driven by embedded haboobs and NLLJs. Predominant emission in the late afternoon and evening is an indication for haboobs (Marshall et al., 2011; Heinold et al., 2013) while morning emissions can be linked to the breakdown of NLLJs (Schepanski et al., 2009; Fiedler et al., 2013). AEWs are also important for atmospheric transport of dust aerosol (Jones et al., 2003) and are linked to tropical cyclone formation (e.g. Hopsch et al., 2007).

~~Horizontal pressure gradients during the presence of depressions can be large enough for generating dust storms~~. ~~In addition to wind speed, the~~ The presence of soil moisture can have important implications for dust emission (Fecan et al., 1999). An increase of soil moisture strengthens the bonding forces between soil particles constraining higher wind speeds for dust emission (Cornelis and Gabriels, 2003; Fecan et al., 1999). While precipitation amounts and therefore soil moisture are generally small in ~~wide areas across large areas of~~ the Sahara, cyclones are an important source for rainfall in North Africa (Hannachi et al., 2011) and may be able to moisten the soil sufficiently for increasing the threshold of dust emission onset. This soil moisture effect is predominantly expected for cyclones along the North African coast between December and May, and near-surface signatures of AEWs at the southern fringes of the Sahara desert between May and September. The magnitude of the soil moisture effect during cyclone passage is, however, not well quantified.

The present study is the first climatological estimate of the mass of emitted dust aerosol associated ~~to~~ with depressions and migrating, long-lived cyclones in North Africa. The latter are herein a sub-class of atmospheric depressions. Depressions are defined as minima in the geopotential height at 925 hPa that are identified and tracked with an automatic algorithm. Minima in the field of geopotential height are termed cyclones if they migrate, live for more than two days, and have a decreasing core pressure at the beginning of their life cycle. The depression and cyclone tracks are combined with dust emission calculations driven by ECMWF ERA-Interim data. Details of the method are explained in Section 2. Section 3 presents the results for the climatology of depressions and cyclones for dust emission. Conclusions are drawn in Section 4.

## 2 Method

### 2.1 Depression and cyclone identification

The present study uses the depression tracks over North Africa for 1989–2008 retrieved by Schepanski and Knippertz (2011). Schepanski and Knippertz (2011) investigate Sudano-Saharan depressions by using the tracking algorithm from Wernli and Schwiertz (2006) with modifications for low latitudes. Threshold values are adapted and the original input fields of mean sea level pressure are replaced by the geopotential height at 925 hPa that represent North African conditions better. The automated algorithm determines minima relative to the adjacent grid cells and is applied to the ERA-Interim re-analysis with a horizontal resolution of  $1^\circ$  (Dee et al., 2011). Even though the input data set is six-hourly, minima are identified daily at 00 UTC in order to avoid miss-tracking erroneous tracking caused by the large diurnal cycle of the geopotential height at low levels over North Africa (Schepanski and Knippertz, 2011). The influence of the time of day on a depression identification is shown by Maheras et al. (2001).

Once a minimum is identified, the corresponding area of the depression is determined by the closed contour that lies furthest away from the centre. The value of the contour interval is 4 gpm corresponding to about 0.5 hPa (Schepanski and Knippertz, 2011). Depressions are connected to a track if two consecutive positions lie within 1000 km. This criterion allows for a maximum speed of  $11.6 \text{ ms}^{-1}$  that is sufficient for the majority of systems in North Africa (Schepanski and Knippertz, 2011).

The criteria from used to filter tracks of Sudano-Saharan depressions are not applied here. Instead, a broader investigation of depressions and migrating cyclones over North Africa is intended. Depressions presented here is broader than that by Schepanski and Knippertz (2011). Here, depressions are all identified minima in the geopotential height at 925 hPa without a geographical restriction. The selection of migrat-

ing cyclones from the original set of all identified depressions requires generalized criteria applicable for the entire domain and time period. Note that migrating cyclones include both near-surface signatures of AEWs and cyclones. Both are termed cyclones in this paper and identified by the following filter criteria that have to be fulfilled simultaneously:

1. Cyclones have to be identified in at least three consecutive nights reflecting a life time of 48 hours as the minimum time period for a complete life cycle of a cyclone. This assumption complies with life times given in the literature (Hannachi et al., 2011; Bou Karam et al., 2010).
2. Each cyclone has to propagate over a pre-defined horizontal distance between genesis and lysis. The mean propagation speed is defined as the maximum displacement during the life time of the system calculated from the range of longitudes and latitudes of centre positions. The threshold for the propagation speed is  $5^\circ$  per day corresponding to a mean cyclone speed of  $5\text{--}6 \text{ ms}^{-1}$ . This generous criterion is well below migration speeds reported for cyclones over North Africa (Alpert and Ziv, 1989; Bou Karam et al., 2010; Knippertz and Todd, 2010; Schepanski and Knippertz, 2011).
3. The propagation speed alone does not successfully exclude all identified cases of the Saharan heat low, the mean position of which migrates over time. In order to exclude most heat lows, the identified cyclones have to have a decreasing core pressure between the first and second night. This criterion reflects cyclogenesis and successfully reduces the number of identified cyclones in summertime West Africa. Tracks of filling cyclones in the Mediterranean region are also excluded by this criterion, particularly frequent in the east during spring. Sensitivity tests show that reducing the number of cyclones in the Mediterranean basin has a negligible effect on the contribution to dust emission dust emission coinciding with cyclones (Section 3.6). This suggests that filling cyclones with centres away from dust sources do not generate wind speeds sufficiently large for mobilizing dust.

### 2.2 Dust emission

Mineral dust emission is calculated for 1989–2008 with the dust emission model by Tegen et al. (2002) following the experiment setup in Fiedler et al. (2013). The This dust emission scheme is validated by Tegen et al. (2002) and used in both global and regional climate models (Heinold et al., 2011; Zhang, 2012). Here, the dust model is driven by three-hourly 10m-wind speeds speed and soil moisture of the uppermost soil layer from ERA-Interim forecasts (Dee et al., 2011). These forecasts are for 12 hours and are initialized at 00 and 12 UTC, and interpolated onto a horizontal grid of

1°. ERA-Interim re-analysis produces the best diurnal cycle of wind speed amongst state-of-the-art re-analysis projects compared to flux tower observations over land (Decker et al., 2012). Choosing ERA-Interim short-term forecasts is motivated by the higher temporal resolution compared to the six-hourly re-analysis product that is not sufficient for resolving all wind speed maxima during the day (Fiedler et al., 2013). Statistics of the near-surface wind speed from these short-term forecasts are found to be close to the six-hourly re-analysis of ERA-Interim (Fiedler et al., 2013).

Preferential dust sources are prescribed using the dust source activation frequency (DSAF) map derived from satellite observations (Schepanski et al., 2007, 2009). A source is defined as a region where at least two dust emission events are detected between March 2006 and February 2008 as in Fiedler et al. (2013). Depending on surface properties like vegetation fraction, soil moisture, and roughness length, dust emission occurs in these sources when the particle-size dependent threshold of the 10m-wind speed is exceeded (for details see Marticorena and Bergametti, 1995; Tegen et al., 2002). Soil moisture has to be below  $0.28 \text{ m}^3 \text{ m}^{-3}$ , the field capacity assumed for silt and clay soil types. An experiment without soil moisture is run for estimating the effect of water in the topsoil on dust emission.

Calculating the contribution of dust emission associated with depressions and cyclones to dust emission requires the definition of an area affected by associated peak winds. The tracking algorithm determines an area for the grid boxes lying within the outermost closed contour of the geopotential height at 925 hPa at mid-night. This centre area is used for analysing the track density per season (Section 3.1 and 3.2). Dust emission, however, may occur in an area larger than the centre, e.g. near the cold front fronts. In order to include these dust emissions in the climatology, a cyclone-affected area is approximated by a circle around the identified minimum in the geopotential height. This area is calculated at mid-night and used for selecting the three-hourly dust emission associated to with the depression or cyclone between 15 UTC of the previous day and 12 UTC of the same day (Section 3.5 and 3.6). The radius of this circle is set to  $10^\circ$ , a value corresponding to a latitudinal distance of 964 km at  $30^\circ \text{ N}$ . The choice of  $10^\circ$  is justified motivated by previous studies (e.g. Bou Karam et al., 2010) and tested by sensitivity experiments. These show that even when the radius of the circle is doubled, the spatial pattern of the fraction of dust emission associated to with cyclones shown in Section 3.6 is robust.

Figure 1 shows the cyclone-affected area and false colour images derived from thermal and infrared radiation measurements from the “Spinning Enhanced Visible and Infrared Imager” (SEVIRI) of the geostationary Meteosat Second Generation (MSG) satellite (e.g. Schepanski et al., 2007, 2009). The DSAF of this satellite product for March 2006 to February 2010 (Schepanski et al., 2007, 2009; Schepanski et al., 2012) is used for validating the dust emission calculation. The typical horizontal extent of these cyclones, visible by the

curling cloud band (red) and indicated by a circle around the cyclone centre, is on the order of  $10^\circ$ . Dust aerosol is visible near the cloud band, but parts of it is likely obscured by clouds. At 9 March 2013, dust emission also occurs over southern West Africa (Figure 1b), highlighted by an ellipse. These emissions are not directly related to the cyclone but likely caused driven by a Harmattan surge associated with the post frontal ridge (e.g. Knippertz and Fink, 2006; Knippertz and Todd, 2012, and references therein).

### 3 Results

#### 3.1 Climatology of depressions

Figure 2 shows the seasonal mean track density seasonally averaged occurrence frequency of depressions identified by the algorithm. During In winter, depressions are found over the Mediterranean basin with 40–100 events in the 20-year period during 4 % of the time (Figure 2a) , i.e. 2–5 cyclones corresponding to up to five depressions per winter. Hot spots Maxima of similarly large track densities depression occurrence frequencies lie to the south of the High Atlas and to the west of the Ethiopian Highlands (refer to Figure 5 for geographical terms). The origin of these depressions may be partly related to lee troughs that are associated with closed contours in the geopotential height at 925 hPa. In the case of the Ethiopian Highlands, the heat low that is located here during winter (Lavaysse et al., 2009) may explain another large portion of identified depressions. The general location of depressions over the Mediterranean Sea and the lee hot spot maximum of the Atlas Mountains are in agreement with previous studies (Trigo et al., 1999; Maheras et al., 2001). The exact number and location of hot spots, however, depend on the underlying data set and identification technique (e.g. Maheras et al., 2001; Hannachi et al., 2011; Hodges et al., 2011, and references therein).

Depressions over the continent in spring are generally more frequent than in winter with 10–100 depressions over most areas (Figure 2b). The hot spot maximum south of the High Atlas dominates the climatology in the north with depression numbers around 200, i.e. occurrence frequencies of up to 30 % corresponding to ten depressions per season spring. A secondary maximum can be identified at the northern side of the Hoggar Mountains with up to 100 depressions an occurrence frequency of up to 8 %. These two hot spots maxima agree with the formation of springtime cyclones from the literature, although the exact locations and frequencies differ (Maheras et al., 2001; Hannachi et al., 2011). Other studies for springtime North Africa find a single hot spot maximum for depressions (Trigo et al., 1999). Reasons for these differences are the choice of a different data basis, time period, identification method, as well as the time of day due to the influence of daytime heating the diurnal cycle of the net radiation budget on heat lows

(Maheras et al., 2001). Further ~~hot-spots-maxima~~ that can be related to lee troughs are found southwest of all mountains in the central Sahara due to the prevailing northeasterly Harmattan winds during this season. ~~Maxima of the occurrence frequency~~ in the vicinity of the Ethiopian Highlands and the Ennedi Mountains ~~reach around 100 depressions. Wide areas in the centre of North Africa have track densities are, herein, particularly large with~~ around 20 ~~depressions. The similarity to the location of the heat low climatology by suggests that these depressions are heat lows~~ %.

Between June and August, ~~West Africa has track densities of 40–200 depressions occurrence frequencies of up to 20 % are found over West Africa~~ (Figure 2c). Here, the Saharan heat low dominates the climatology while AEWs regularly influence the meteorological conditions (Lavaysse et al., 2009; Thorncroft and Hodges, 2000; Luo et al., 2004). ~~Particularly the atmospheric depressions close and offshore of the West African coast point to the presence of AEWs.~~ Similar track densities are found in the vicinity of mountains where the Saharan heat low influences the occurrence of depressions, predominantly at the Hoggar Massif (Lavaysse et al., 2009).

The heat low over West Africa and the ~~hot-spots-maxima~~ near mountains in the central Sahara are ~~present in summer and also present in~~ autumn but the relative importance changes (Figure 2d). In autumn, the ~~track density frequency of depressions~~ west of the Ethiopian Highlands is larger with ~~values around 200 depressions up to 30 %~~, while the ~~track densities values~~ over West Africa decrease to less than ~~100 depressions~~ 6 %. This pattern is coherent with the shift of the heat low from West Africa towards the southeast near the equator (Lavaysse et al., 2009). Heat lows and depressions in the vicinity of mountains seem to dominate the climatology of depressions throughout the year. Migrating cyclones and surface signatures of AEWs are ~~separately~~ investigated in the ~~following next~~ section.

### 3.2 Climatology of cyclones

Migrating cyclones and surface signatures of AEWs are filtered as described in Section 2.1. The term cyclone is used for both types in the following. Cyclones regularly form over North Africa and the Mediterranean region, but the number of events is substantially smaller than the number of depressions. In the annual mean, ten cyclones occur in the sub-domain investigated, namely 0° to 40° N and 20° W to 45° E. Figure 3a shows the seasonal fraction of the total number of 196 cyclones that pass the filter. The analysis reveals that most of the cyclones form between March and May with 37 %. The remaining seasons have fewer events with roughly 20 % each.

The time series of the total number of cyclones per year is shown in Figure 3b. The year-to-year variability of cyclone activity is relatively large with a factor three to four. The years with most identified events are 2003 with 19 cyclones,

followed by 2002 with 16, 1996 and 1999 with 14 events each. The most inactive years are 1998, 2000, 2001 and 2007 with five to seven cyclones each. Most of this variability can be explained by the cyclone activity during spring. The year-to-year variability for this season is particularly large. Years with a large event number experience 6–12 cyclones, while years with low activity have one to three events between March and May.

Figure 4 shows the seasonal distribution of cyclone ~~centres occurrence frequency~~ in the 20-year period. The dominant cyclone track between December and February stretches from the Aegean Sea to Cyprus (Figure 4a). Some areas in this track ~~count at least ten cyclones in the period, i.e. have occurrence frequencies of up to 0.8 % corresponding to~~ one cyclone every second year. Including filling cyclones doubles the number of cyclones passing the eastern Mediterranean (~~not shown~~). Few cyclones are situated over the African continent during winter. ~~Maxima around six cyclones are~~ ~~A maximum cyclone frequency of 0.4 % is~~ limited to areas along the northern coast between Tunis, Tunisia, and Tobruk, Libya. ~~Similarly large Similar~~ values are found north of the Great Eastern Erg ~~and~~, the south-eastern side of the Tell Atlas, Algeria and Tunisia. ~~Up to six cyclones track~~, north of the Hoggar Mountains, Algeria, ~~and~~ south of the High Atlas Range, Morocco, ~~and south of Tripoli, Libya~~.

Between March and May, cyclones occur most frequently over North Africa (Figure 4b). Cyclones at the southern side of the High Atlas are identified ~~up to eight times in up to 0.5 % of the time~~ between 1989 and 2008. ~~Up to ten cyclones track~~ Cyclones over areas of the Great Eastern Erg between the Tell Atlas Mountains and the Hoggar Massif, Tunisia and Algeria ~~occur in up to 0.8 % of the time~~. This cyclone frequency is comparable to the cyclone track in the wintertime Mediterranean Sea (Figure 4a–b). The eastern side of the Al-Hamra Plateau, Libya, also shows ~~around ten cyclones a frequency around 0.8 %~~, which is consistent with the reported ideal conditions in this region (Alpert et al., 1990; Pedgley, 1972).

The peak cyclone activity north of 25° N in winter and spring rapidly decreases as the year progresses. ~~Cyclones are rare in summer with maxima of two cyclones~~ (Figure 4c). Maxima of the track density are shifted ~~southward from the north~~ to West Africa ~~with six to ten events along where cyclones occur in up to 0.6 % of the time. These occur primarily over Mali and Mauritania around 20° N, a region known for frequent occurrence of AEW signatures at higher altitudes~~ (Thorncroft and Hodges, 2000; Mekonnen et al., 2006). Here, the cyclones are connected to AEWs that are strong enough to form a signature near the surface. Agustí-Panareda et al. (2010) ~~suggest that AEWs are too weak in the ECMWF model over the eastern North Atlantic. This would imply that fewer AEWs are strong enough to be detected with the tracking algorithm used here.~~ It is interesting that the track density peaks in the lee of mountains similar to the springtime maximum in the north. These ~~hot-spots-maxima~~

are situated at the western sides of the ~~mountains~~ Tibesti, Air, and Adrar des Iforas. ~~The peak at the Tibesti is particularly strong with 8–10 cyclones~~ mountains. The location suggests that the interaction of the flow with mountains aid the deepening and formation of closed contours in the geopotential height at 925 hPa. ~~A much larger area of maximum track densities of 5–10 is found over Mali and Mauritania centred around 20~~ This result is in agreement with Bou Karam et al. (2009) who show that vortices form in the lee of mountain barriers during summer. Autumn shows the smallest cyclone activity with occurrence frequencies below 0.3 N, a region known for frequent occurrence of AEW signatures at higher altitudes. The spatial pattern of cyclone tracks is similar in autumn, but the absolute number is smallest % (Figure 4d).  
 The regions of most frequent cyclone occurrence are summarized in Figure 5. These are the northern fringes of North Africa between December and May and West Africa from June to August. The characteristics of the cyclones are investigated in the following.

### 3.3 Characteristics of cyclones

Figure 6 shows the life time and zonal displacement of the identified cyclones for areas north and south of 20° N over the continent. In the north, cyclogenesis occurs 56 times during the 20-year period, more than half of which form between March and May (32 cyclones). Most of these cyclones have their origin in the vicinity of the Atlas Mountains with 26 cyclones between 15° W and 10° E. Cyclones in the north frequently live for three days in spring (Figure 6a). Life times between five and seven days are similarly common for the season. Springtime cyclones predominantly follow eastward tracks in the north (Figure 6c). The migration distance is most often 30° to the east, closely followed by 20° and 10°. Some cyclones with eastward trajectories also form south of 20° N during spring (Figure 6d). Wintertime cyclones have a similar distribution of the migration direction. The prevailing eastward migration in the north is in agreement with previous studies (e.g. Alpert et al., 1990; Hannachi et al., 2011).

South of 20° N, the seasonality of cyclogenesis is different. Out of 50 cyclones forming here in total, 36 % occur between June and August followed by 26 % and 28 % in autumn and spring, respectively. Figure 6b shows the cyclone life time for the south. Here, the majority of cyclones are identified over three to four days. Summertime cyclones also live frequently for six days. The prevailing migration direction during summer and autumn is westwards by mostly 20–30° (Figure 6d) that is consistent with the propagation of AEWs (Burpee, 1972; Thorncroft and Hodges, 2000).

### 3.4 ~~Dust Climatology of dust emission associated to~~ depressions

Before combining the atmospheric depressions and cyclones with dust emission, the latter is validated against a satellite

product. Unfortunately a quantitative estimate for the emitted mass is currently unavailable from long-term observations over North Africa. As an alternative, the DSAF from satellite observations (Schepanski et al., 2007, 2009; Schepanski et al., 2012) is used for a qualitative comparison of the number of dust emission events from the dust emission calculation for the period March 2006 to February 2010. Simulated dust emission events with fluxes exceeding  $10^{-5} \text{ g m}^{-2} \text{ s}^{-1}$  are taken into account only, as small amounts are unlikely to be detected by the instrument (Laurent et al., 2010).

Figure 7 shows the annual mean DSAF from the dust emission calculation forced with meteorological fields from ERA-Interim. The DSAF below 5 % compare well against the model simulation over large areas in the central Sahara. Maxima between the Hoggar and the Tibesti Mountains as well as over the Bodélé Depression with up to 35 % activation frequency are also well represented. Comparison to ground based measurements in the Bodélé Depression has also shown a good agreement of the time and intensity of dust emission from this area (Fiedler et al., 2013). However, the high DSAFs from the model at the western coast of the continent are not seen in the satellite product (Figure 7). During spring and summer, the western coast may be influenced by moist air advected from the Atlantic, which can prevent dust detection in the satellite product (Brindley et al., 2012), although the visual identification by Schepanski et al. (2012) might be less influenced by moisture than an automatic algorithm (Ashpole and Washington, 2013). Also the tendency to larger DSAF over the north compared to the south in the model simulation is not in agreement with the satellite DSAF. In winter and spring clouds associated with cyclones may obscure parts of the dust emission in observations along the northern margins of the desert (Figure 1), previously indicated by Schepanski et al. (2009). It is important to highlight that these differences of DSAF do not allow a conclusion on the quality of the dust emission amount. The model can have higher DSAFs, but these events could be weaker than the detected source activations, and vice versa (Tegen et al., 2013). From the perspective of dust modelling, quantitative estimates of the emission amount from observation would be useful. The dust emission amount is used in the following sections to estimate the relative importance of atmospheric depressions and cyclones for North African emission.

### 3.5 Dust emission associated with depressions

Annually and spatially averaged across dust sources of North Africa, 55 % of the dust emission is associated ~~to~~ with atmospheric depressions. Regionally ~~even~~ larger fractions of dust emission coincide with depressions ~~that are shown~~ shown along with the occurrence frequency of depressions in Figure 8. ~~Areas Particularly areas~~ in northern and western Africa have dust emission associated to ~~with~~ depressions of up to 80 %. Since the influence of depressions

on dust emission is limited to a radius of  $10^\circ$  (Section 2), nearby maxima of the depression occurrence frequency can be associated with them. For instance, the large dust emission amounts associated with depressions in the north and also close to the Ethiopian Highlands are associated with maxima in occurrence frequency. In contrast, dust emission in the northeast and west coincide with few depressions suggesting that these events are particularly intense.

The seasonal distribution of ~~these fractions~~ the dust emission fraction associated with atmospheric depressions is shown in Figure 9. ~~Contributions from depressions to dust emission during winter have values below~~ Depressions coincide with 50 % ~~in~~ of the dust emission in winter over most of North Africa (Figure 9a). Larger fractions are associated ~~to depressions in West Sahara, with depressions in~~ Libya, Tunisia, and Sudan with values of up to 80 %. These ~~hot spots~~ maxima coincide with the frequent formation of depressions ~~in the north of the continent over the Mediterranean region~~ and in the lee of the Ethiopian Highlands. The frequent formation close to the High Atlas is not associated with a dust emission maximum suggesting weak winds over the potential dust sources. The large fractions of dust emission in West Sahara occur away from a location with frequent depression formation pointing to rare but strong depressions. Spring shows even larger ~~contributions to dust emission from~~ dust emission associated with depressions in wide areas to the north of  $25^\circ$  N and west of  $10^\circ$  E with up to 90 % (Figure 9b). ~~These areas lie within or close to regions where depressions frequently form.~~

Depressions in summer are ~~linked to~~ associated with up to 90 % of the ~~regional~~ dust emission across most of North Africa (Figure 9c). ~~Depressions are abundant in this season. Most of them, particularly over West Africa, are likely Saharan heat lows given the spatio-temporal agreement with the climatology by~~ Lavaysse et al. (2009). Areas of ~~their frequent formation enclose most of the dust emission coinciding with them.~~ In autumn, similarly large values ~~for dust emission associated to depressions~~ are found along the northern and western margins of the continent, west of the Hoggar Massif and west of the Ethiopian Highlands (Figure 9d). The ~~frequent formation of depressions within a radius of~~  $10^\circ$  coincides with these maxima. This large and widespread ~~contributions from~~ agreement between dust emission and depressions in summer is surprising as other dust-emitting processes have been ~~discussed~~ suggested in the literature (e.g. Fiedler et al., 2013; Heinold et al., 2013). ~~An important mechanism for dust emission in summertime West Africa is the downward mixing of momentum from NLLJs. NLLJs are frequently embedded along the margins of the West African heat low and shall be briefly discussed here.~~

Estimating the dust emission amount associated with the heat low likely involves a number of mechanisms. Emissions can be directly caused by the horizontal pressure gradient around the heat low but this alone may not always be sufficient to cause substantial dust mobilization.

Mid-morning winds can be enhanced through the NLLJ mechanism (Fiedler et al., 2013). ~~Estimating the contribution to dust emission from~~, which depends on the horizontal pressure gradient around the heat low ~~includes the emissions associated to NLLJs and possibly other processes occurring within the assumed radius of~~  $10^\circ$ . The example of the embedded NLLJ illustrates that the results for, but also on the diurnal evolution of the boundary layer. Using the NLLJ identification method from Fiedler et al. (2013) to estimate the amount of dust emission associated with NLLJs within depressions results in an annual and spatial average of 12%. Between March and October 12–16% of the dust emission associated to depressions are not necessarily excluding other processes. ~~These contributions to dust emission are expected to change if only migrating is associated with both phenomena, while values are below 10% during the rest of the year (not shown). This result is in agreement with Fiedler et al. (2013) who show a frequent NLLJ formation along the margins of the Saharan heat low. Another process potentially embedded in depressions are haboobs, which are presumably not well represented in ERA-Interim data due to the physical parameterisation of moist convection. Dust emission coinciding with NLLJs and haboobs may also occur along with mobile and long-lived depressions~~ are taken into account. ~~These systems,~~ These are termed cyclones in the following ~~, are~~ and will be investigated next.

### 3.6 Dust emission associated ~~to~~ with cyclones

#### 3.6.1 Seasonal climatology

The ~~climatology is shown as absolute emissions associated to migrating cyclones~~ absolute emission amount associated with migrating cyclones is shown first followed by the presentation of the ~~relative contribution to dust emission fraction of the total dust emission associated with cyclones.~~ Figure 10 shows the seasonal total of dust emission and the number of intense emission events associated ~~to~~ with cyclones averaged over the 20-year period. Intense emission is defined for fluxes greater than  $10^{-5} \text{ g m}^{-2} \text{ s}^{-1}$  following Laurent et al. (2010). Across the continent and throughout the year, the seasonal total of dust emission within the cyclone-affected area (Section 2.2) is most frequently less than  $1 \text{ g m}^{-2}$ . Single regions and seasons, however, show distinct maxima of dust emission of up to  $10 \text{ g m}^{-2}$  that lie north of  $20^\circ$  N. Between December and February, peak emissions ~~in the vicinity of~~ near the Atlas and Hoggar Mountains as well as in Libya are  $2\text{--}4 \text{ g m}^{-2}$  (Figure 10a). ~~The areas where at least~~ Areas with more than three intense emission events per season ~~occur~~ lie mostly away from ~~the areas with the largest total emission dust emission maxima.~~ This points ~~at~~ to moderate but frequent dust emissions in winter ~~hot spots~~ maxima, while rather small total emissions in some regions are generated by a few intense events.

Spring shows larger Springtime dust emission of 4–10 gm<sup>-2</sup> associated to cyclones with cyclones occur over a wider area (Figure 10b). It is this season when the The overall largest dust emission associated to cyclones occur with cyclones are found in this season. Cyclones are particularly frequent then due to the large temperature contrast between land and sea which favours their development. Peak emissions by coinciding with cyclones are found south of the foothills of the Atlas Mountains, and as far east as the western fringes west of the Libyan desert. Spring has more More than three intense emission events occur over most of the region north of 20° N. Areas with seasonal emission maxima have even larger numbers of intense emission events of Maxima of the emission amount coincide with more than six, partly more than nine in some areas even nine, intense emission events. This suggests that intense events substantially contribute to the largest emission amounts associated to with springtime cyclones. It is spring when the temperature contrast between land and sea is largest which favours the development of cyclones with high wind speeds.

The findings change dramatically in summer when maxima of the seasonal total dust emission associated to maximum emissions associated with cyclones are situated over West Sahara and western parts of Mauritania Africa with up to 6 gm<sup>-2</sup> (Figure 10c). More coinciding with more than six intense emission events are limited to the West African coast and coincide well with the largest seasonally total of dust emission. Here, surface signatures of AEWs may be deepest and cause the highest wind speeds (e.g. Thornicroft and Hodges, 2000). The coastal effect may be a contributing factor for strong winds in this region. In autumn, the number of intense emissions is here in the west is smaller with three events (Figure 10d). It is this season when the seasonal total of and the total dust emission associated to with cyclones is smallest over most of North Africa with with typically less than 1 gm<sup>-2</sup> (Figure 10d). This is in agreement with few cyclones identified for this season.

The fraction of the dust emission associated to with migrating and long-lived cyclones relative to the total amount emitted per year is 4% annually and spatially averaged over dust sources. Figure 11 shows the distribution of the fractional contributions these fractions and the occurrence frequency of cyclones annually averaged. Single regions in the northeast of Africa have contributions to dust emission by have dust emission associated with cyclones exceeding 10%. The seasonal mean fraction of dust emission associated to cyclones is regionally larger These regions are close to areas where cyclones occur most frequently.

The dust emission fraction is larger regionally in single seasons which are shown in Figure 12. From December to February, substantial dust emission fractions associated to with cyclones occur in areas north of 20° N only (Figure 12a), because of the limitation of cyclone tracks to northern locations (Figure 412a). Here, the The largest dust emission

amounts associated to cyclones reach typical with cyclones reach values of 5–15 % and lie between 15° W and 15° E. The dominant cyclone track Cyclones tracking over the eastern Mediterranean Sea in winter does not cause the majority of dust emissions in North Africa are not associated with large amounts of North African dust emission indicated by dust emission fractions below 5 % in regions east of 15° E. In spring, however, larger dust emissions of 10–25 % are associated to with cyclones in this region (Figure 12b) when the main cyclone track shifts southwards onto the continent (Figure 4b). This is the overall largest area and magnitude of cyclone contribution to dust emission dust emission coinciding with cyclones in North Africa. Smaller areas with similar springtime fractions of dust emission associated to migrating cyclones in spring lie to the south of the Atlas Mountains, to the northeast of the Hoggar Massif and in the Tibesti Mountains. These are within a distance of 10° from the areas of most frequent cyclone presence.

The dust emission associated to cyclones between Between June and August is shown in Figure 12c. Contributions from dust emission fractions in regions north of 20° N drop to values below 5 % while cyclones in isolated areas in Mali and Mauritania have contributions of are associated with 5–15 % Typical contributions of cyclones to dust emission of the dust emission amount (Figure 12c). Over West Africa, surface signatures of AEWs occur along 20° N and enclose these maxima of the dust emission fraction. Dust emission associated with cyclones remain similar in autumn but the spatial pattern of hot spots location of maxima changes (Figure 12d). Higher The highest values of around 15 %, now, occur in the centre of the Sahara, in the Western Great Erg and in the Libyan Desert (Figure 12c–d). These occur away from areas of frequent cyclone passage suggesting that rare events are associated with relatively strong emission. It is, however, important to underline that the dust emission flux connected to cyclones in the south is relatively small with seasonal in autumn with typical totals below 1 gm<sup>-2</sup>. This implies that, even though the relative contribution importance is comparable to the north in winter and spring, the importance in terms of total dust mass is smaller (Figure 10d).

In light of the large fractional contribution from depressions to relative importance of depressions for dust emission (Section 3.5), the overall fractional contribution of fraction associated with migrating cyclones is surprisingly small. Springtime contributions of depressions of depressions are associated with up to 90 % of dust emission in the lee of the High Atlas change to contributions below but considering migrating cyclones as a sub-class of depressions changes the fraction of dust emission to less than 15 % when migrating cyclones are taken into account only (compare Figure 9b and 12b). Over Libya, contributions from springtime dust emission associated with depressions are with values around 50 % also larger than the contribution from ones with cyclones with



maxima around 25 % ~~during spring. Although a reduction is expected from the climatology with depressions to the one with cyclones~~, the magnitude of it is rather large particularly in the lee of the Atlas Mountains with a factor of six. Particularly in the lee of the Atlas Mountains the dust emission associated with cyclones is six times smaller than the amount associated with depressions. A reduction of dust emission is expected in the climatology with cyclones as a sub-class of depression. The High Atlas is the region where ~~the presence of lee troughs in the climatology of depressions is expected. These results~~ lee depressions may lead to cyclogenesis. The present results, however, indicate that only a few of these lee ~~troughs develop to dust-emitting cyclones.~~ Large depressions develop into migrating and long-lived cyclones. There are also no large and widespread dust emission associated ~~to with~~ surface signatures of AEWs during summer ~~do not occur as seen in the climatology of depressions.~~ This result gives evidence that most of the dust emitted ~~during the presence of in summertime~~ depressions is due to ~~the Saharan heat low or other mechanisms embedded like NLLJs (Section 3.5)~~ their frequent occurrence over West Africa.

Despite their ~~small contributions to the coincidence with a small~~ total dust emission amount in the north, intense emission fluxes are regularly associated ~~to with~~ migrating cyclones in spring (Figure 12b). This aspect is analyzed further by defining a dust emission anomaly as the quotient of the dust emission associated ~~to with~~ cyclones and the 20-year mean of the dust emission flux in the same month. Figure 13 shows this anomaly factor for both depressions and cyclones along with the dust emission flux spatially averaged across dust-emitting grid boxes. The largest dust emission fluxes occur between February and May with values larger than  $1.5 \cdot 10^{-6} \text{ g m}^{-2} \text{ s}^{-1}$ . ~~It is During~~ this time of year ~~when~~ the largest total dust emission occur over the north (Fiedler et al., 2013). The anomaly factor ~~during this season of cyclones during these months~~ has values between four and eight, i.e. the dust emission associated ~~to with~~ springtime cyclones is four to eight times larger than the long-term mean of the dust emission flux.

From March to May, the anomaly factor of cyclones exceeds the values for depressions pointing to mobile cyclones as an important source for intense emission in spring. The dust emission is generally smaller during summer with fluxes of  $0.7\text{--}1.3 \cdot 10^{-6} \text{ g m}^{-2} \text{ s}^{-1}$  while the anomaly factors of cyclones increases to values of five to nine. During July the anomaly factor of cyclones is, herein, larger than the one of depressions. Even larger anomaly factors of cyclones exceeding the values for depressions are found between September and November with up to 20, but both the dust emission flux and the number of cyclones is then smallest. This result underlines. These results underline that even though the total emission associated ~~to with~~ migrating cyclones is rather small compared to the absolute emission in the north, the emission events during cyclone pas-

sage are particularly intense. For depressions, the emission intensity is more moderate throughout the year, but still clearly above the climatological level.

### 3.6.2 Dependency on cyclone quadrant

The areas of largest dust emission amounts associated ~~to with~~ cyclones reside close to ~~hot-spots maxima~~ of cyclone tracks (Section 3.2). However, ~~hot-spots for maxima of~~ cyclones and dust emission (Figure 4 and 12) do not match perfectly due to two factors. On the one hand the location of peak winds within the cyclone-affected area is often away from the actual centre. On the other hand the parameterization of dust sources restricts the region of active emission within the cyclone-affected area. The map of potential dust sources enables dust emission in most areas of North Africa so that the location of peak winds is expected to be the dominant factor. The spatial distribution of the dust emission within the cyclone-affected area is investigated in the following. Since the emitted mass associated ~~to with~~ cyclones is relatively small south of  $20^\circ \text{ N}$  in general (Section 3.6.1), only the northern sub-domain is taken into account. Here, dust emission is analyzed in four quadrants the position of which follow their geographical orientation depicted in Figure 14.

Figure 14 shows the annual cycle of the fraction of dust emission per quadrant of the cyclones north of  $20^\circ \text{ N}$  spatially averaged. The results highlight that most dust is emitted in the northern quadrants with typical mean values of 30–55 % between November and March. In April, dust emission prevails in the northeast and southeast with about 30 % contribution each. Dust emission associated ~~to with~~ cyclones in May is roughly equal equally distributed across the quadrants. June to September have clear maxima of dust emission in the southwest with 60–80 %. The total mass emitted between June and September, however, is smaller than at the beginning of the year (Figure 10). Cyclones in October have most dust emission in the southeast, but the integrated mass of dust emission is smallest during autumn (Figure 10d).

These ~~result results~~ can be linked with the position of the highest wind speeds. In the case of a well-defined extra-tropical cyclone, the ~~cool cold~~ front typically lies to the west of the cyclone centre initially and moves towards the south and east thereafter. Peak winds, and therefore dust emission, are most likely at and behind the cool front as well as close to the cyclone centre due to the increased horizontal gradient of the geopotential height in these areas. Dust emission would primarily occur in the southwest initially, followed by prevailing emission in the southeast. At a later life stage, an extra-tropical cyclone typically forms an occlusion causing peak winds near the cyclone core. Dust emission may then form in all quadrants similarly. Integrated over the entire life time, most dust emission may be expected in southern quadrants if the cyclone has an extra-tropical character. While this is not found for the spatial average, examination

of the spatial distribution of dust emission per quadrant (not shown) reveals that areas south of the Atlas Mountains show indeed more than 50 % of the dust emission in the southwest or southeast quadrants between February and May. This distribution complies with the expectation for extra-tropical cyclones. However, the lack of a southern maximum in the spatial mean in winter and spring suggests that cyclones do not show typical characteristics of extra-tropical cyclones everywhere. Evaluating the spatial distribution of the dust emission per quadrant shows that dust emission in northern quadrants primarily occur in the central Sahara during spring. Here, the heat low lies typically to the south and relatively higher pressure northwards. This implies that instead of a classical frontal structure, a large horizontal gradient in the geopotential height occurs at the northern side of a fraction of cyclones.

Summertime dust emission is mainly situated in the southwest of the cyclone centre in the spatial mean. Over West Africa, even larger emission fractions of up to 90 % occur in the southwest (not shown). The majority of cyclones during this season live particularly long and migrate westwards (Figure 6a,c) pointing at surface signatures of AEWs. The dominant quadrant during this time of year is well in agreement with the position of emission ahead of AEWs where NLLJs are expected (Knippertz and Todd, 2010). The automated detection algorithm from Fiedler et al. (2013) is used for estimating the mean fraction of dust emission within the cyclone-affected area that coincide with the occurrence of NLLJs. The result suggests peak contributions from NLLJs to the dust emission associated to cyclones of 10–30 % over parts in West Africa (not shown). Another important driver for dust emission in association with AEWs are haboobs typically developing to the east of an AEW (Knippertz and Todd, 2010). The missing physical parameterization of these cold pools, as an important mechanism for dust emission during this time of the year and region, may cause an underestimation of the dust emission to the east of AEWs. The diurnal cycle of dust emission indicates driving mechanisms on a sub-daily scale that is analyzed next.

### 3.6.3 Differences per time of day Diurnal cycle

Figure 15a-b shows the annual cycle of the total dust emission per time of day within the cyclone-affected area north of 20° N. Cyclones are associated with a substantial amount of mineral dust in late winter and spring. Maxima occur during mid-day with peaks of 90–110 gm<sup>-2</sup> in March, and 70–90 gm<sup>-2</sup> in May in contrast to values below 20 gm<sup>-2</sup> between June and January (Figure 15ab). The dust emission during the influence of cyclones has a diurnal cycle with a distinct maximum during the daytime. Emission at night has typical values around 10 gm<sup>-2</sup> and never exceeds 30 gm<sup>-2</sup> during spring (Figure 15ab). At 09 UTC dust emission is often twice as large with

maximum values of 60 gm<sup>-2</sup> in May. Emissions at 12 and 15 UTC are even larger by a factor of two to four.

~~The diurnal differences. These diurnal differences for late winter and spring in the north can be explained by the development of the boundary layer in the context of the synoptic-scale conditions. Dust emission occurs when the momentum transport to the surface is sufficiently large to exceed the threshold for emission onset. The stabilizing effect of surface cooling at night leads to a decrease of vertical momentum transfer to the surface. In contrast to the night, reduced stability during the day enables a larger transport of momentum to the Earth surface. It is this momentum transport that increases the near-surface wind speed and mobilizes dust particles. The downward mixing of momentum downward turbulent momentum transport, which increases the near-surface wind speed. This effect is expected to be largest, when the daytime boundary layer is sufficiently deep for reaching a layer where layers of high wind speed prevails, typically in the free troposphere. Winter and spring is characterized by a relatively strong baroclinic zone at which the cyclone forms. The thermal wind describing the change of geostrophic wind over height is stronger the deeper (shallower). Strong winds prevail relatively close to the surface during cyclone passage in winter and spring. These cyclones form in a baroclinic zone between the warm (cool) air mass. The deep North African air mass is particularly deep compared to the air polewards due to the strong heating of the continent. The thermal wind is thus relatively large implying a strong cold (shallow) air polewards. The contrast between the air masses causes a particularly strong thermal wind, i.e. an increase of the geostrophic wind with height in the lower troposphere. Along with typically deep daytime boundary layers over North Africa momentum from the free troposphere is efficiently transported towards the surface. In the Sahara, the boundary layer reaches its largest a sufficiently large depth at or closely after mid-day (Culf, 1992), that which coincides well with the mid-day peak of dust emissions shown emission found here. The time of maximum dust emission is in agreement with the observation of suspended dust in cyclones shown in Figure 1.~~

The emission flux at 09 UTC in May, however, is almost as large as the mid-day values pointing at embedded NLLJs as a driving mechanism. The top of Figure 15a shows the fraction of dust emission within the cyclone-affected area that is associated to NLLJs. The latter are defined and automatically identified as in Fiedler et al. (2013). Based on these results, dust-emitting NLLJs are not frequently embedded in the cyclone-affected area with less than 10% in winter and spring. This finding is well in agreement with the generally small dust emission amount associated to NLLJs during winter and spring in the north (Fiedler et al., 2013). The larger dust emission flux from cyclones at 09 UTC in May is, therefore, not predominantly linked to NLLJs. It seems most plausible that the momentum from the free troposphere is more efficiently mixed downwards in May than

earlier in spring and winter. This is likely caused by a larger ~~and earlier onset of the solar irradiation~~ solar irradiation and longer days in late spring, aiding the development of the day-<sup>185</sup> time boundary layer.

NLLJs that can be embedded in AEWs are linked to 20 % of the dust emission in the cyclone-affected area in June and around 10 % in July and August. ~~However, the total dust emission of summer is relatively small compared to spring. Haboobs may be the key driver in West Africa during summer. AEWs are typically accompanied by deep moist convection the cold downdrafts of which may form an haboob. Haboobs are poorly represented in the 10m-wind field of ERA-Interim. Another reason for overall small dust emissions from AEWs may be the soil moisture effect that is discussed in the following section.~~<sup>190</sup>

### 3.6.4 Impact of soil moisture

The dust emission amount associated to cyclones is smaller ~~than the contribution estimated for depressions by one order of magnitude. One reason may be the weakening or suppressing effect of soil moisture on dust emission.~~<sup>1205</sup> While arid conditions prevail in North Africa, cyclones can produce rainfall that feeds soil moisture. The presence of soil moisture may weaken or suppress dust emission. The magnitude of ~~the this~~ effect is studied with ~~a dust emission calculation~~ two dust emission calculations with and without accounting for moisture soil moisture, respectively (Section 2.2).<sup>1210</sup>

~~Figure 15b~~ Figure 16 shows the annual cycle of the fraction of dust emission suppressed by the presence of soil moisture along with the total dust emission when moisture is taken into account as a benchmark. During late winter and spring, the time when dust emission associated ~~to with~~ cyclones,<sup>1220</sup> show a clear maximum of 250–380 gm<sup>-2</sup>, soil moisture suppresses roughly 10 % of the dust emission spatially averaged across the north. Other months show values ranging from 5 % to 20 %, but the total dust emission is smaller than 100 gm<sup>-2</sup> in July and smaller than 80 gm<sup>-2</sup> during the rest of the year,<sup>1225</sup> It is interesting that the value for the emission reduction by soil moisture during cyclone passage for the 20-year period is of the same order of magnitude as the soil moisture effect for haboobs in a 40-day convection-permitting regional simulation for August 2006 (Heinold et al., 2013) ~~–The spatial distribution of the fraction of dust emission associated to cyclones from Section 3.6.1 is robust against excluding the soil moisture in the dust emission calculation despite the underestimation of precipitation and soil moisture over West Africa in August 2006 by the ECMWF model~~ (Agusti-Panareda et al., 2010, and references therein).<sup>1230</sup>

## 4 Conclusions

The present work provides the first climatological estimate of the amount of dust emission associated ~~to depressions and with atmospheric depressions and mobile, long-lived~~ depressions and mobile, long-lived cyclones over North Africa for 1989–2008. ~~Dust emission simulations with the model by driven by ERA-Interim forecasts show large dust emissions north of 20N for December to May.~~ Atmospheric depressions are tracked following the method from Schepanski and Knipertz (2011) ~~for estimating the amount of dust emission associated to both depressions and migrating, long-lived cyclones.~~ While these depressions may be stationary or mobile with varying lifetimes, a sub-class called cyclones is defined which has to fulfill a set of filter criteria, namely a horizontal displacement, a lifetime longer than 48 hours and a decreasing core pressure during the first day. The key findings from the depression and cyclone climatologies are:<sup>1200</sup>

1. Depressions are abundant over North Africa due to the frequent formation of lee troughs in spring and heat lows ~~with maxima in the track density of up to 100 events. Cyclones migrating and living longer than 48 hours, however, are less frequent with a total of 196 cyclones across North Africa. The cyclone track density compared to depressions in summer with a maximum occurrence frequency of 40 %, while the occurrence frequency of cyclones is smaller by a factor ten. The smaller number of cyclones of ten. This~~ suggests that only few depressions ~~, e.g. in the lee of the Atlas Mountains during spring,~~ become migrating and long-lived cyclones.
2. The cyclone climatology highlights that 37 % of cyclones affecting North Africa occur in spring. Their centres most frequently lie north of 20° N with a clear cyclone track stretching from south of the Atlas Mountains towards the ~~Eastern Mediterranean.~~ Eastern Mediterranean in agreement with previous studies (Alpert et al., 1990; Hannachi et al., 2011; Thorncroft and Hodges, 2000; Trigo et al., 1999; Maheras et al., 2001). Springtime cyclones predominantly migrate eastwards, and live for three to seven days. ~~The Their~~ year-to-year variability ~~of cyclones~~ is largest during this season.

~~The depression and cyclone tracks are applied to the dust emissions for 1989–2008 in order to estimate their relative contribution to the dust emission amount. The results highlight that depressions coincide with~~ Dust emission is simulated with the model by Tegen et al. (2002) driven by ERA-Interim forecasts which show large values north of 20° of the dust emission while migrating and long-lived cyclones N for December to May (Fiedler et al., 2013). The comparison of the modelled DSAF against the satellite product from Schepanski et al. (2012) shows good agreement

in the Bodélé Depression as a key region for dust emission, but differences in the north and west of North Africa. These may be partly due to missed dust detection in the satellite product due to the presence of clouds and atmospheric moisture (Schepanski et al., 2009; Brindley et al., 2012), or limitations of the representation of dust emission and winds in the model setup used.

Dust emission amounts are associated with 4 depressions and cyclones when they occur within a radius of 10 degrees from the centres. The highlights of the results are:

1. Depressions coincide with 55 % of the dust emission annually and spatially averaged for over North African dust sources. Regionally larger contributions from both depressions and cyclones are found that vary with the season. The largest contributions from cyclones to dust emission are found during spring over wide areas in Libya with typically 15–25 and seasonally up to 90 % of the dust emission amount is associated with them. Embedded mechanisms such as the NLLJ, defined as in Fiedler et al. (2013), coincide with 12 % of the dust emission associated to cyclones is, here, amongst the largest with regionally 4–10. This dust emission amount associated to cyclones is up to one order of magnitude smaller than the seasonal mean dust emission for spring of regionally 10–50 over Libya. Similar dust emission amounts associated to cyclones and fractional contributions to the seasonal total emission are found in isolated areas south of the Atlas Mountains, associated with depressions annually and spatially averaged. This result is in agreement with Fiedler et al. (2013) who show that NLLJs form frequently along the margins of the Saharan heat low.
2. In contrast to cyclones, depressions show here contributions to dust emission with up to 90 of the seasonal emission. These results suggest that the few depressions, migrating and long-lived cyclones do not emit the majority of dust aerosol in the north. However, the analysis of the emission flux magnitude reveals that emission events associated to cyclones are particularly intense. The dust emission flux during cyclone passage is larger than the climatological mean by a factor of four to eight. Another interesting aspect is that the dust emission associated to springtime cyclones is substantially larger during mid-day than at night by a factor of three to five. This result suggests that the growth of the boundary layer into the baroclinic zone of the cyclone is important for generating peak winds that are strong enough for mobilizing mineral dust. The effect of soil moisture on dust emission within the cyclone-affected area is a weakening on the order of 40 are rarer and associated with only 4 % of the dust emission annually and spatially averaged. The largest emission coinciding with cyclones is found during

spring over wide areas in Libya and small areas south of the Atlas mountains with 15–25 %.

3. In summer, AEWs play a role for dust emission in are associated with 5–15 % of the dust emission amount in isolated areas over West Africa. It has been suggested that AEWs amplify here. Here, AEWs amplify sufficiently for forming a signature close to the surface (Thorncroft and Hodges, 2000). The results of the present study indicate that maximum contributions of AEWs to dust emission are 5–15 but these are limited to isolated areas. The majority of the emissions within the cyclone-affected area is found in the southwestern quadrant of the AEW signature, i.e. the sector ahead of AEWs with northerly winds and potential NLLJ formation (Knippertz and Todd, 2010). NLLJs, defined as in, coincide with 10–20 % of the monthly emissions associated to cyclones during summer while there are less than 10 % coincide with NLLJs and cyclones during the rest of the year. Larger dust emissions at the eastern side of AEWs are expected when haboobs are represented that are currently not parameterized but relevant for dust emission applications. Contrary to AEWs, summertime depressions, like the Saharan heat low, coincide with up to 90 of would be expected, if haboobs were represented more realistically. Their missing parameterization and the underestimated strength of AEWs in the ECMWF model (Agusti-Panareda et al., 2010) probably lead to an underestimation of associated winds and dust emission.
4. Despite the small total emission amount associated with cyclones, their emission flux magnitude is particularly intense. The dust emission flux during cyclone passage is larger than the climatological mean by a factor of four to eight and is often larger than for depressions.
5. Another interesting aspect is that the dust emission across wide areas of North Africa. NLLJs form along the margins of the Saharan heat low that are at least in parts included in the summertime dust emission associated to depressions, associated with springtime cyclones is substantially larger during mid-day than at night by a factor of three to five. This result suggests that the growth of the boundary layer into the baroclinic zone of the cyclone is important for generating near-surface winds that are strong enough for mobilizing mineral dust.
6. The reduction of dust emission through soil moisture is rather small with values on the order of 10 %.

In conclusion, the influence of depressions is important for dust emission across in North Africa throughout the year. Migrating cyclones with life times of more than two days although their influence on dust

emission may be indirect through processes acting on smaller scales. Cyclones are comparably rare and do not substantially contribute to the total dust emission mass are not associated with a substantial dust emission amount in most regions. However, cyclones generate intense dust emission fluxes making them nevertheless important for dust emission modelling exceeding the intensity associated with depressions in most months. Large parts of the climatological dust emission maximum between November and May north of 20° N shown in Fiedler et al. (2013) are not associated with depressions and cyclones investigated here. Harmattan surges developing in consequence of post cold frontal ridging are proposed as another mechanism capable of emitting large amounts of dust aerosol. This dust storm type will be subject of future work.

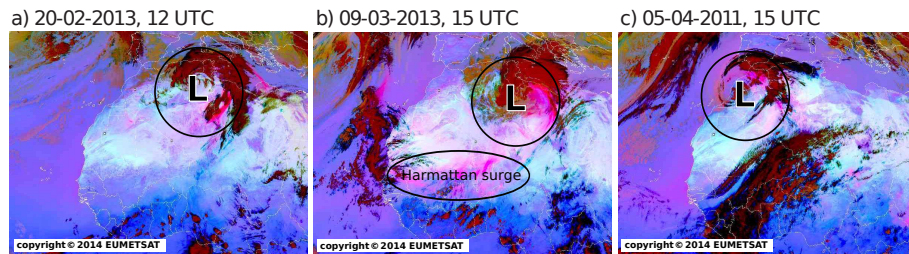
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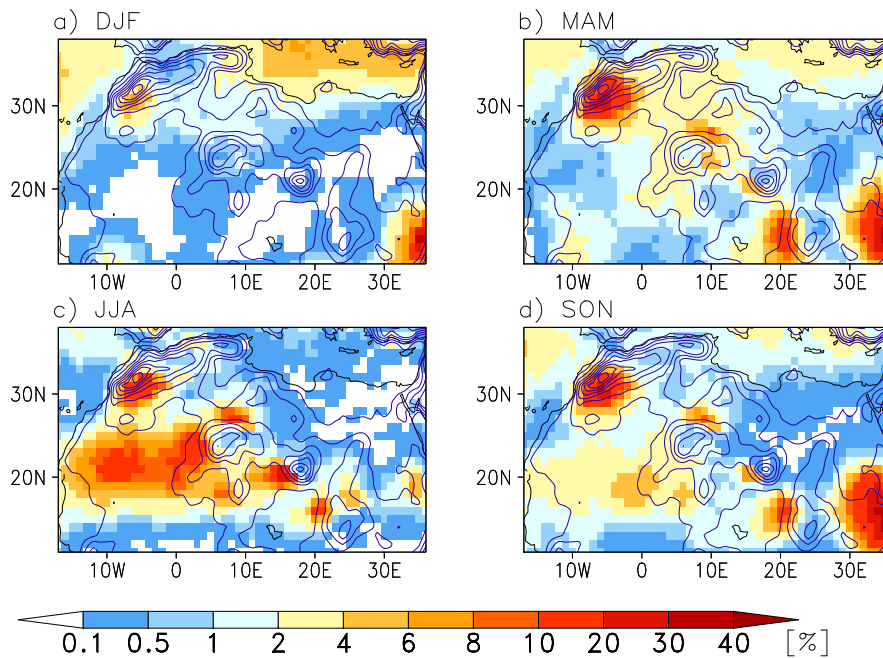
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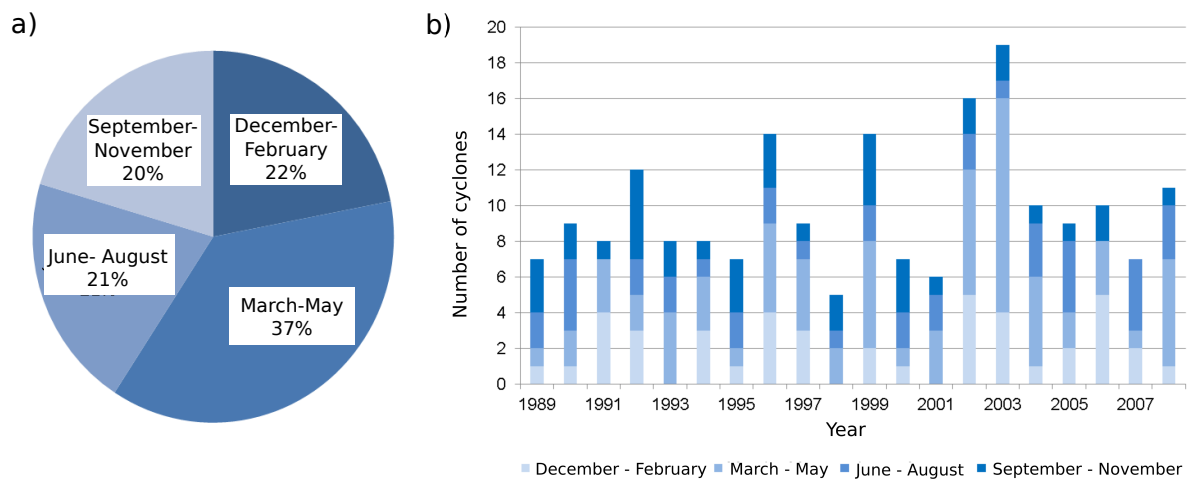


**Fig. 1.** Observations of cyclones and associated dust aerosol over North Africa. Shown here are false-colour images from MSG-SEVIRI (e.g. Schepanski et al., 2007) indicating mineral dust aerosol (pink) and clouds (red and black). Circles and ellipse mark the cyclone-affected area with a radius of  $10^\circ$  and dust emission associated ~~to~~ with a Harmattan surge, respectively.

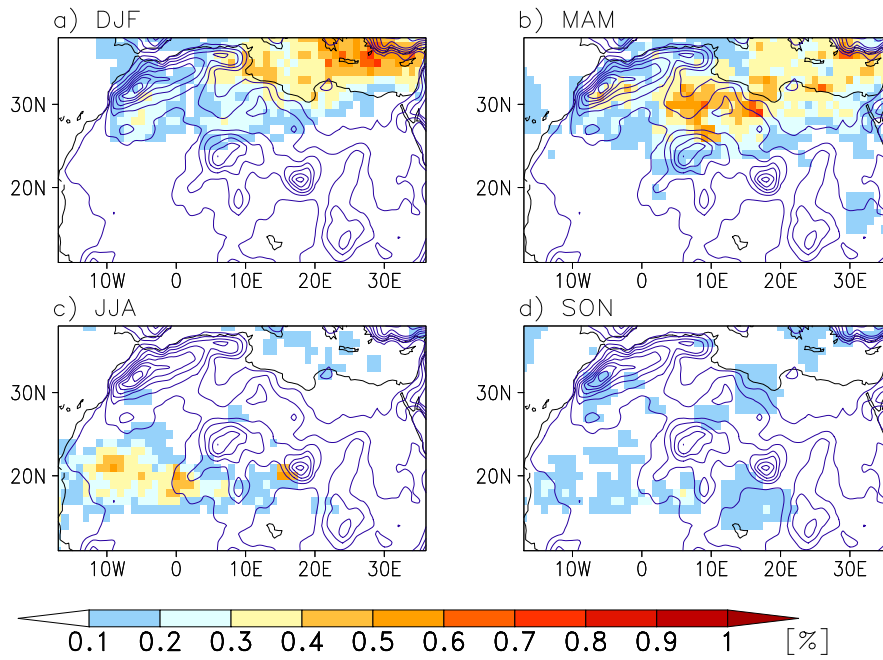


**Fig. 2.** Track density of all identified depressions. Climatology of ~~total depression number~~ the occurrence frequency of depressions for (a) December– February, (b) March–May, (c) June–August, and (d) September–November for 1989–2008 based on the depression centre defined by the outermost closed contour in the geopotential height at 925 hPa from the tracking algorithm (Section 2.1). Contours show orography in steps of 200 m.

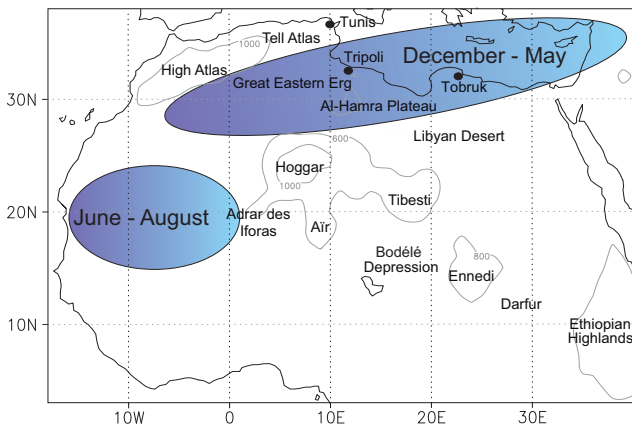




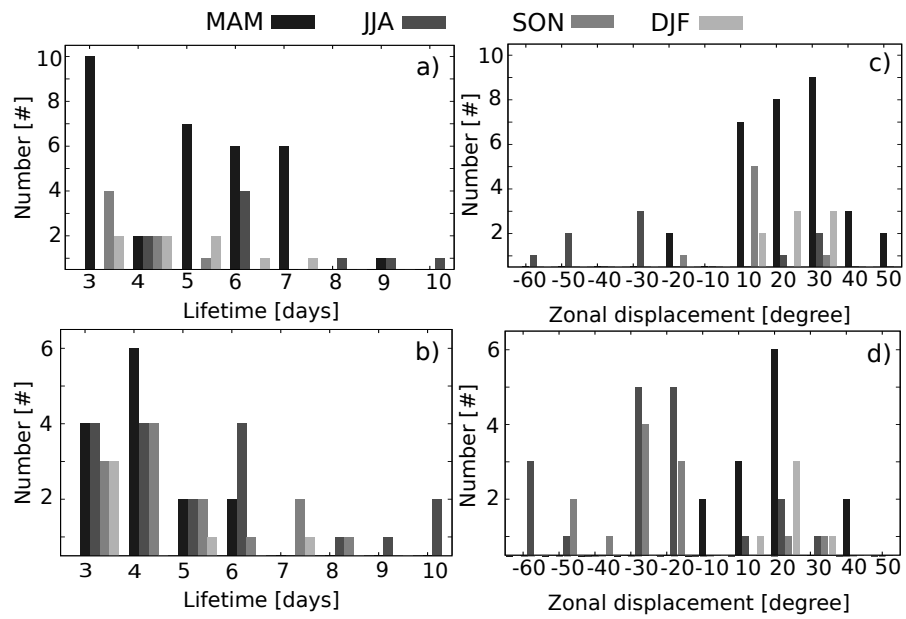
**Fig. 3.** Seasonal and interannual variations of long-lived and migrating cyclones. (a) Seasonal distribution of cyclones and (b) time series of cyclones in the sub-domain  $0^{\circ}$ – $40^{\circ}$  N and  $20^{\circ}$  W– $45^{\circ}$  E for 1989–2008.



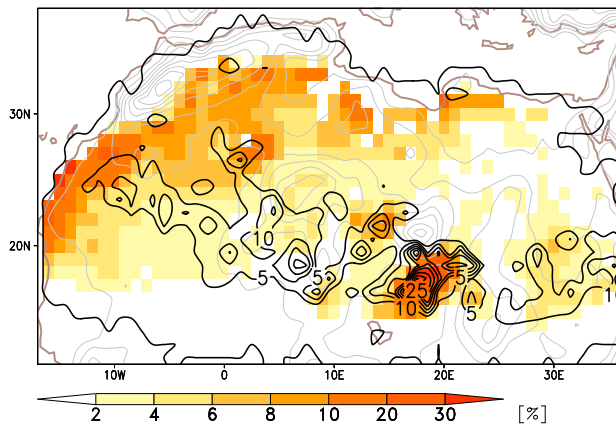
**Fig. 4.** Track density of long-lived and migrating cyclones. Climatology of ~~total cyclone number~~ the occurrence frequency of cyclones for (a) December–February, (b) March–May, (c) June–August, and (d) September–November for 1989–2008 based on the cyclone centre defined by the outermost closed contour in the geopotential height at 925 hPa from the tracking algorithm (Section 2.1). Contours show orography in steps of 200 m.



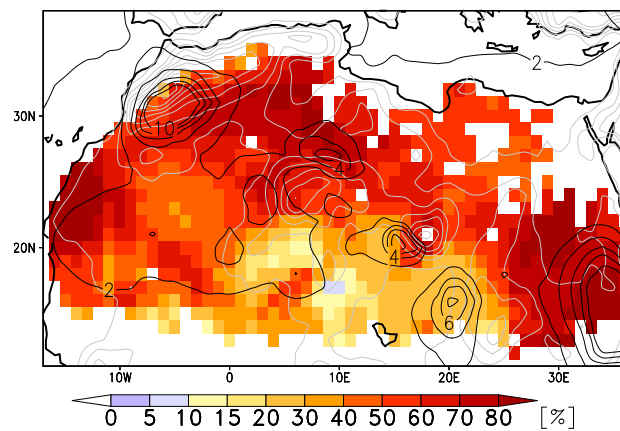
**Fig. 5.** Schematic overview on regions of most frequent cyclone occurrence. Contours show orography in steps of 200 m based on ERA-Interim. Geographical terms used in the text are indicated.



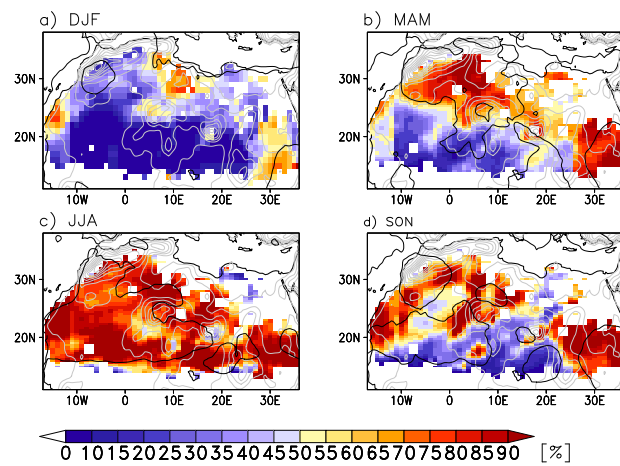
**Fig. 6.** Histograms of characteristics from long-lived and migrating cyclones. Cyclone life times for 1989–2008 forming (a) in the north (15° W–35° E, 20° N–32° N), and (b) in the south (15° W–35° E, 0° N–20° N); and zonal displacement of cyclone centres during their life time forming (c) in the north, and (d) in the south.



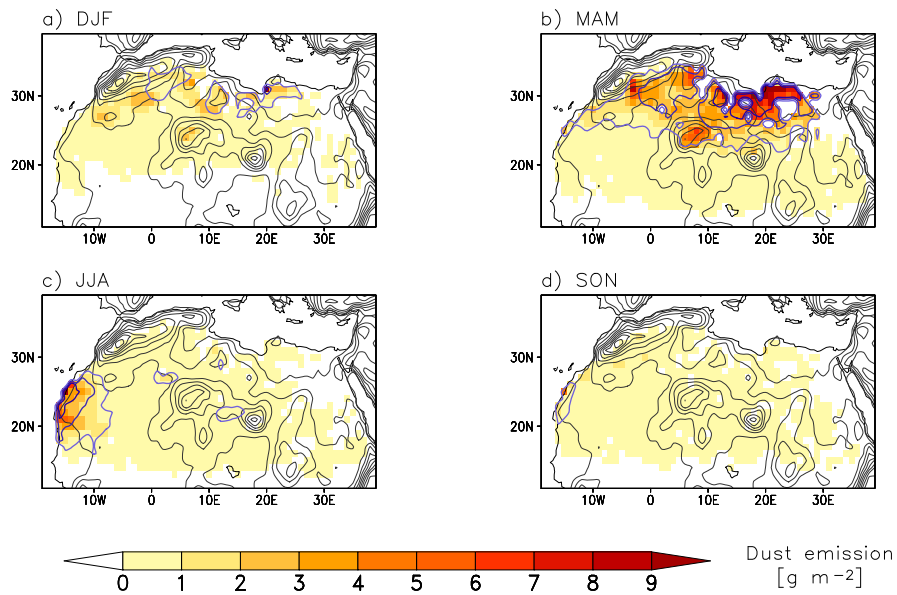
**Fig. 7.** Dust source activation frequency based on satellite observations and ERA-Interim data. Annual mean dust source activation frequency (DSAF) based on the dust emission model by Tegen et al. (2002) driven by the near surface wind speed and soil moisture from three-hourly ERA-Interim forecasts (shaded). Dust emission events larger than  $10^{-5} \text{ g m}^{-2} \text{ s}^{-1}$  are considered only, as smaller dust amounts are unlikely to be detected in the satellite product (Laurent et al., 2010). Black contours show the annually averaged DSAF derived from SEVIRI satellite observation by Schepanski et al. (2007); Schepanski et al. (2012) in steps of 5%. The time period considered is March 2006 to February 2010 following the satellite observation. Grey contours show orography in steps of 200 m.



**Fig. 8.** Annual fraction of dust emission amount associated to with depressions. Shown is the contribution to the fraction of total dust emission associated with depressions in percent averaged for 1989–2008. Contours (shaded). Dust emission within a radius of  $10^\circ$  from the depression centre is considered (Section 2). Black contours show the annually averaged occurrence frequency of depressions in steps of 2%. Grey contours show orography in steps of 200 m.

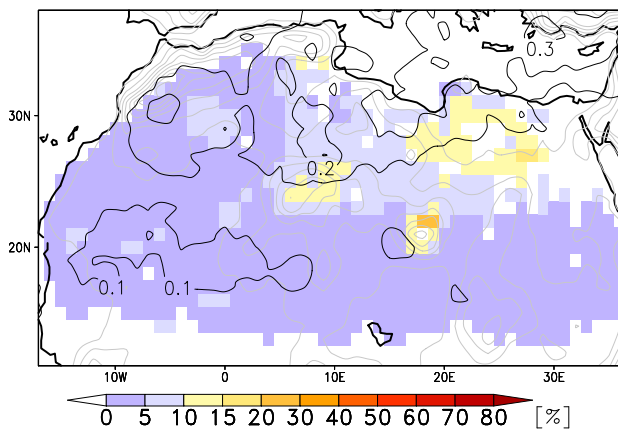


**Fig. 9.** Seasonal fraction of dust emission amount associated ~~to~~ with depressions. Shown are ~~contributions~~ fractions of total dust emission associated with depressions in percent for (a) December–February, (b) March–May, (c) June–August, and (d) September–November averaged for 1989–~~2008~~. ~~Contours~~ 2008 (shaded). Dust emission within a radius of  $10^\circ$  from the depression centre is considered (Section 2). Areas within the black contour have an occurrence frequency of depression of more than 2% (Figure 2). Grey contours show orography in steps of 200 m.

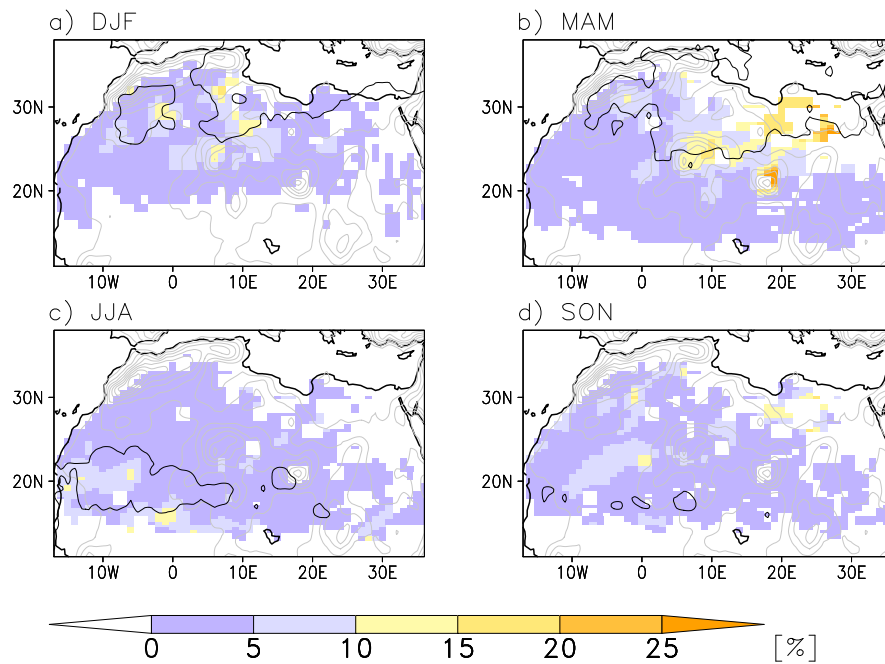


**Fig. 10.** Seasonal dust emission associated ~~to~~<sup>with</sup> long-lived and migrating cyclones. Shown are mean emissions (shaded) for (a) December–February, (b) March–May, (c) June–August, and (d) September–November averaged for 1989–2008. Black contours show orographic height in steps of 200 m. Blue contours show the number of intense dust emission events, defined by a flux larger than  $10^{-5} \text{ g m}^{-2} \text{ s}^{-1}$  following Laurent et al. (2010), in steps of three events.

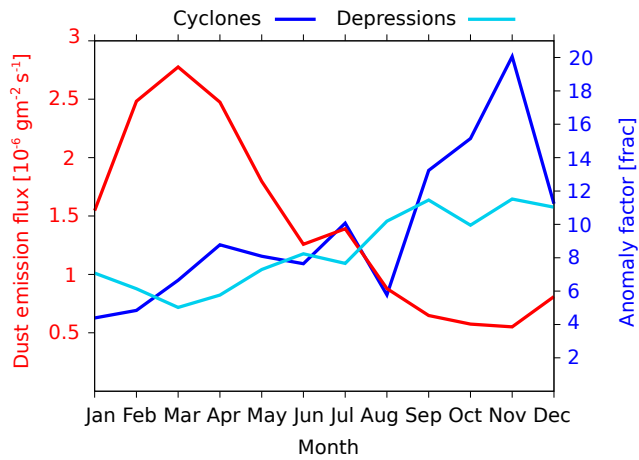




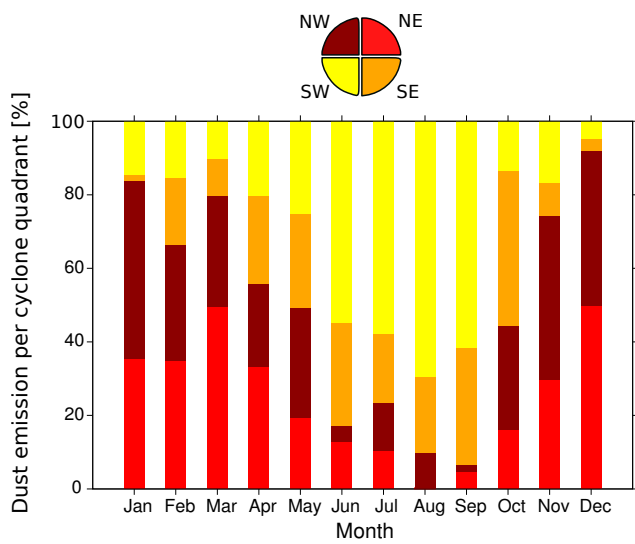
**Fig. 11.** Annual fraction of dust emission amount associated to with long-lived and migrating cyclones. Shown is the contribution to the fraction of total dust emission associated with cyclones in percent averaged for 1989–2008. Contours 2008 (shaded). Dust emission within a radius of  $10^\circ$  from the cyclone centre is considered (see Section 2). Black contours show the annually averaged occurrence frequency of cyclones in steps of 0.1 percent. Grey contours show orography in steps of 200 m.



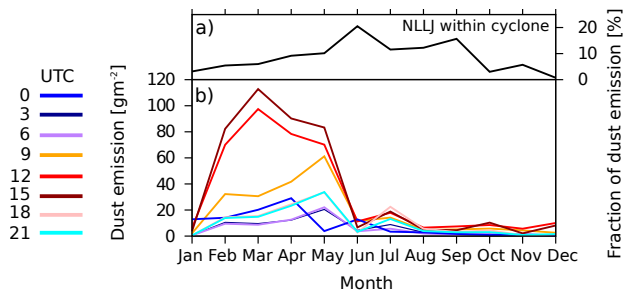
**Fig. 12.** Seasonal fraction of dust emission amount associated to-with long-lived and migrating cyclones. Shown is the contribution to the are fractions of total dust emission associated with depressions in percent for (a) December–February, (b) March–May, (c) June–August, and (d) September–November averaged for 1989–2008. Contours-2008 (shaded). Dust emission within a radius of  $10^\circ$  from the cyclone centre is considered (Section 2). Areas within the black contour have an occurrence frequency of depression of more than 0.2% (Figure 2). Grey contours show orography in steps of 200 m.



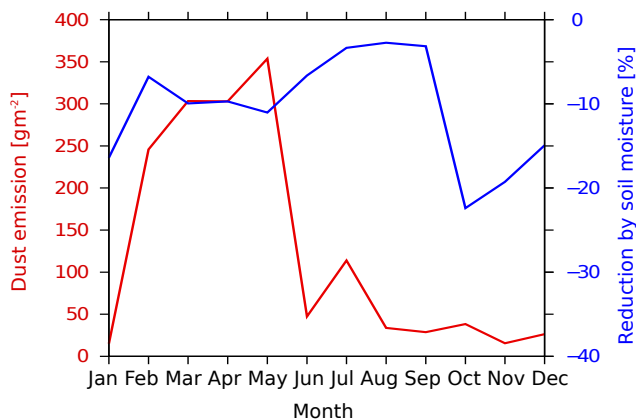
**Fig. 13.** Intensity of dust emission fluxes associated ~~to~~ with long-lived ~~and~~ migrating cyclones ~~and~~ atmospheric depressions. Annual cycle of the dust emission flux ~~associated with cyclones~~ (red) and the ~~intensity of the dust emission associated to cyclones shown as~~ anomaly factor ~~of cyclones~~ (blue) ~~and depressions~~ (cyan) averaged over dust-emitting grid boxes for 1989–2008. The anomaly factor is ~~a measure of emission intensity and~~ defined as the quotient of the dust emission flux associated ~~to~~ with the cyclone/~~depression~~ and the 20-year mean of the dust emission flux of the same month.



**Fig. 14.** Monthly fraction of dust emission from the four quadrants of long-lived and migrating cyclones averaged for the northern sub-domain ( $15^{\circ}$  W– $40^{\circ}$  E and  $20^{\circ}$  N– $40^{\circ}$  N) and for 1989–2008.



**Fig. 15.** Total dust emission amount associated to ~~with~~ long-lived and migrating cyclones. Annual cycle (a) of ~~dust emission for different times of the day (colours)~~ and of the fraction of dust emission associated with cyclones ~~coinciding with NLLJ events; and NLLJs and~~ (b) of the total dust emission ~~and associated with cyclones at different times of the~~ ~~fraction of dust emission suppressed by soil moisture~~ day (colours). Values are spatially integrated over the northern sub-domain (15° W–40° E and 20° N–40° N) and monthly averaged over 1989–2008. NLLJ events are identified as in Fiedler et al. (2013).



**Fig. 16.** Dust emission amount associated with long-lived and migrating cyclones but weakened by soil moisture. Annual cycle of the total dust emission (red) and the fraction of dust emission suppressed by soil moisture (blue). Values are spatially integrated over the northern sub-domain (15° W–40° E and 20° N–40° N) and monthly averaged over 1989–2008.