7D.6 HURRICANE HELENE (2006) AND THE SAHARAN AIR LAYER

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1. INTRODUCTION

The Sahara is one of the key regions for the emission of mineral dust into the atmosphere. The dry and mineral dust particle enriched air of the Saharan boundary layer is lifted away from the surface through a variety of mechanisms (see abstract with number P1.101) and is transported over West Africa and over the Atlantic, where it forms the so called Saharan air layer (SAL). Dunion and Velden (2004) hypothesised that the SAL can affect the cyclogenesis of tropical cyclones.

It is not yet fully understood how the SAL interacts with AEWs and influences the genesis and intensity of tropical cyclones. Some studies state that the SAL has a negative effect on tropical cyclones, some say it has a positive effect. Others claim that the effect of the Saharan dust is overrated. The question as to how the SAL interacts with mesoscale convection and tropical cyclogenesis is a topic of ongoing research. Most of the previous studies are based on satellite data and only very few studies use numerical models to analyse the effect of the SAL.

Large amounts of mineral dust were emitted and transported across West Africa and the Atlantic between 9 and 15 September 2006. During this period Hurricane Helene (2006) developed. The aim of this study is to investigate the transport of the mineral dust, the impact of the dust–radiation feedback for the African Easterly Wave (AEW) out of which Hurricane Helene (2006) developed, and the radiative effect of the dust on the convective systems and their environment.

2. NUMERICAL MODEL

The model system COSMO-ART (COSMO: Consortium for Small–scale Modelling, ART: Aerosols and Reactive Trace gases) describes the emission, the transport and the deposition of gases and aerosols and their feedback onto the state of the atmosphere (Vogel et al., 2009). The model system is fully coupled online and identical numerical methods are applied to calculate the transport of all scalars. The interaction of the mineral dust particles with cloud microphysics is neglected. Mineral dust particles are represented by log normal distributions. Emission of dust particles are calculated online as functions of friction velocity, soil moisture and surface parameters (Alfaro and Gomes, 2001; Vogel et al., 2006; Stanelle et al., 2010).

The dust events between 9 and 14 September 2006 (Fig. 1) and the associated weather systems over West Africa were simulated using the model system COSMO-ART. Two model runs were conducted for this study. The first run computes the emission and transport of mineral dust aerosols, and the interaction between aerosols and radiation. Henceforth, this model run will be referred to as the RadDust run. The horizontal resolution is 28 km and the run was initialised on 9 September 2006 at 12 UTC. The convection is parametrised and the dust climatology is not applied, so that only the modelled dust concentrations impact the radiation fields. We use 6–hourly ECMWF operational analyses as initial and boundary data which contain no information about dust concentrations. For the second COSMO-ART run, the NoRadDust run, an identical model setup was used, except that the dust–radiation interaction was switched off. Thus the dust is only a tracer and no interactions involving the dust take place. Observational data was used to validate the RadDust run. The model runs are 144-h forecasts and thus too long to expect an accurate simulation of the cyclogenesis. Here we are concentrating on highlighting the mechanisms by which dust can reach a developing tropical cyclone and on the radiative impact in the model.

3. DUST EMISSION AND TRANSPORT OVER WEST AFRICA

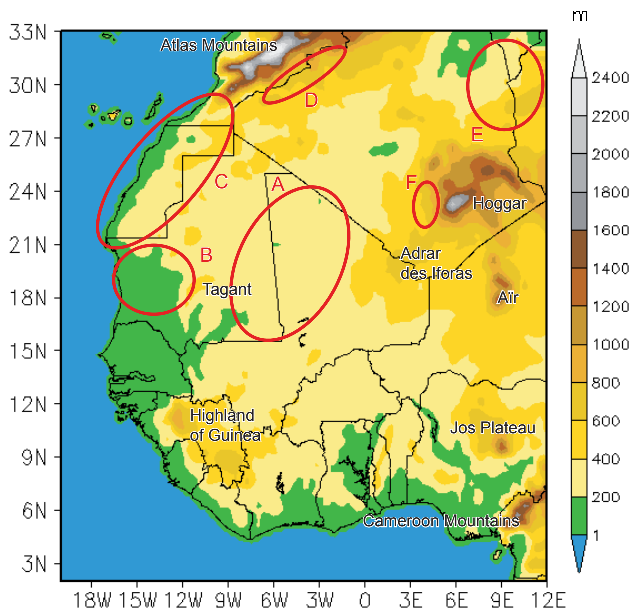

FIGURE 1: Political boundaries of the West African countries, the COSMO model orography (m above mean sea level) with a horizontal resolution of 28 km, and the main source regions of mineral dust (A to F) in the period between 9-14 September 2006.

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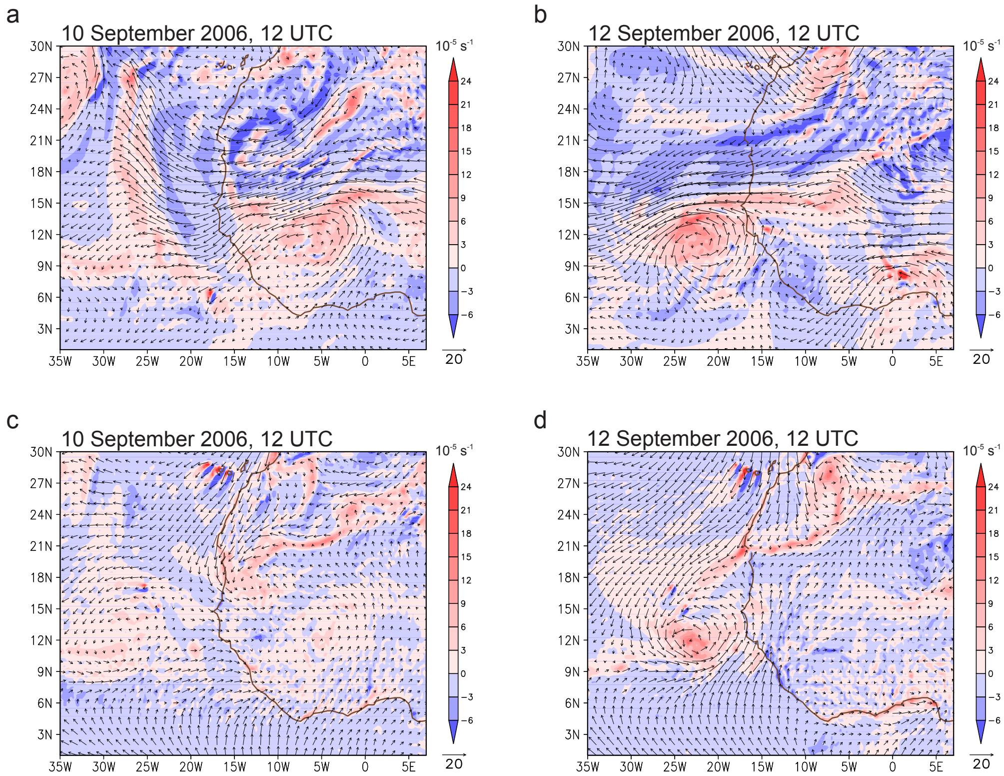

FIGURE 2: Vertical component of relative vorticity and the horizontal wind ($m\,s^{-1}$) at 700 hPa (upper row) and 1000 hPa (lower row) in the ECMWF analysis.

During this case study mineral dust was transported into the vicinity of Hurricane Helene. A number of different dynamical features contributed to this transport and dust reached the vicinity of the developing tropical cyclone via several different pathways, as described in this section.

On 9 September 2006, a low–level positive vorticity anomaly associated with the westward extension of the Saharan heat low occurred over West Africa (Fig. 2c). It moved along about 18 °N, crossed the West African coast line and then moved towards the southwest, where it merged with a positive vorticity maximum associated with the monsoon depression. When this positive vorticity anomaly was collocated with the vorticity maximum of the AEW (Fig. 2b,d), out of which Hurricane Helene (2006) developed, the development of the pre–Helene tropical depression was initiated.

The regions where significant emission of mineral dust occurred during this case study are illustrated in Fig. 1. The secondary heat low circulation over West Africa led to strong wind speeds near the surface and, thus, to the emission of significant amounts of mineral dust (Fig. 1 region A). Dust was emitted by the gust fronts of the convective systems over land, and due to orographical effects at the Algerian Mountains (Fig. 1 region C), the Atlas Mountains (Fig. 1 region D), and north and west of the Hoggar (Fig. 1 regions E and F). The mineral dust was transported over the Atlantic in the SAL. Relatively high values of aerosol optical thickness (AOT) (not shown) occurred north and northeast of the convective systems that developed into a tropical depression, and were present in the vicinity of the storm during the whole genesis period of Hurricane Helene. The AOT has only moderate intensity compared to other dust events that occurred in March, June and July of 2006, during which the AOTs reached values in the order of 3.

As the low–level positive relative vorticity anomaly moves across the West African coast line, large amounts of dust are transported over the Atlantic. A strong temperature gradient occurs near the surface from about 15 °N and 20 °N along the West African coast, between the coastal zone and the desertic inland, separating cold stably–stratified maritime air in the west from hot neutrally–stratified air over land. This low–level front remains stationary during the day (Fig. 3a) and moves eastwards in the late afternoon and evening hours (Fig. 3b). The most favourable location for frontal propagation is between 17 °N and 19 °N. This inland propagating front is part of the Atlantic inflow (Grams et al., 2010). Mineral dust glides up along the isentropes of the baroclinic zone of the Atlantic inflow. As the front moves inland, increased mineral dust concentration can be found in the same region. This could be observed almost every day. It was modified, however, by the low–level circulation moving westwards across the West African coastline in the late evening hours on 10 September 2006, and by the mon-

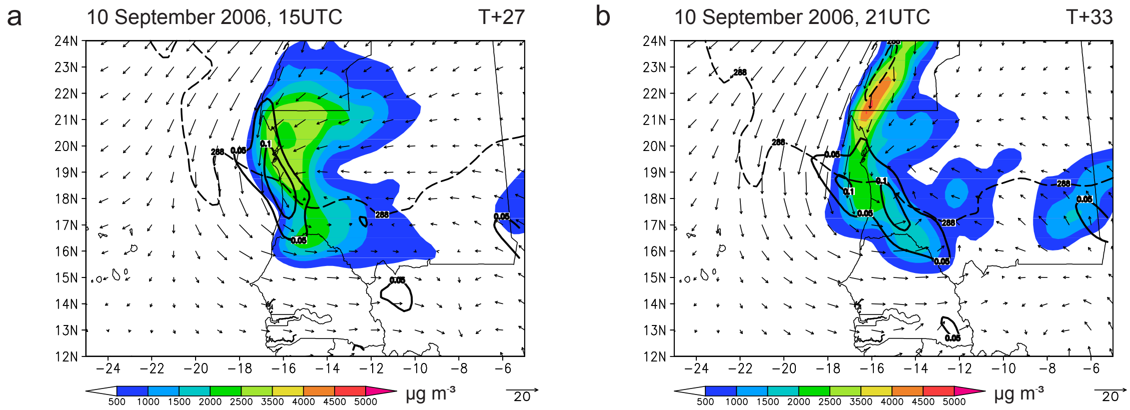

FIGURE 3: The aerosol mass concentration (shaded, μg m-3), the temperature gradient (solid black line displaying the 0.05 and 0.1 K km^{-1} contour), the 288 K dewpoint temperature (dashed line) indicating the position of the ITD, and the horizontal wind speed (arrows, m s^{-1}) at 975 hPa on 10 September 2006 at 15 UTC (a), and at 21 UTC (b). Based on the model run initialised on 9 September 2006, 12 UTC including the dust–radiation interaction (RadDust).

soon flow that reaches far north on 11 and 12 September as the monsoon trough over the Atlantic moves westward. The position of the low–level circulation over the eastern Atlantic leads to a second maximum in the temperature gradient just off shore. The emission of mineral dust by the Atlantic inflow in this model run is mainly restricted to region B in Fig. 1.

A cross section through the region of largest dust concentrations on 11 September (Fig. 4) shows that the dust is lifted upwards in the region with the strongest potential temperature gradient due to the warm air of the Saharan heat low to the northeast and the colder air of the maritime region in the southwest. The dust is transported up to 600 hPa (Fig. 4b). Isentropic upgliding in the baroclinic zone between the maritime and the Saharan air is indicated at 1300-1400 km. Mineral dust is also transported upwards by the strong turbulent mixing over the SHL during the day. This effect weakens during the evening hours. The isentropic upgliding occurs in this baroclinic zone which transports the mineral dust up to a height of about 500 hPa, where it descends slightly. At 700 hPa, significant amounts of dust are transported across the Atlantic.

In the afternoon hours on 11 September 2006 another significant dust event occurs in Mauritania (Fig. 5c) due to the enhanced monsoon flow that reaches far north. The mineral dust is lifted up at about 12 °W and 16-18 °N. A maximum in dust concentration can also be seen at 800 hPa (Fig. 5b) and 700 hPa (Fig. 5a). Another maximum in dust concentration occurs along the West African coastline north of 22 °N in association with a strong Harmattan (Fig. 5c). A band of dust enriched air is located north–northeast of the low–level circulation.

During the following hours, the mineral dust concentrations further increase due to new dust emissions. Moreover, the dust is advected westwards by the AEW at 700 hPa (Fig. 5d), and northwestwards at 800 (Fig. 5e) and 950 hPa (Fig. 5f) by the monsoon flow. Additionally, on 12 September at 00 UTC considerable ascent occurs between about 14-20 °N along the West African coast. In this region dust is lifted up into the AEW trough, where mineral dust concentration in the order of 300-900 μg m^{-3} can be found (Fig. 5d). The dust from the northern dust event is advected towards the south and the dust is lifted up along a northeast–southwest orientated band which collocates with the position of the ITD.

On 12 September 2006 at 04 UTC, the mineral dust from the southern region of high dust concentration at 950 hPa reaches roughly 21 °N (Fig. 5i). This region is characterised by the convergence between the Harmattan and the monsoon flow. The mineral dust advected by the Harmattan flow and the dust transported by the monsoon flow is partly lifted up in here. The other part rotates cyclonically around the low–level circulation. At 800 hPa, the mineral dust concentration shows a distinct maximum offshore between 16 and 18 °N (Fig. 5h). At 700 hPa, instead, maximum dust concentrations can not be seen in this region but south of it (Fig. 5g).

All the previous dust events occurred north of the AEJ at the time of their emission and during the transport across West Africa. The dust from this event, however, is transported along about 15 °N over the Atlantic within the AEW out of which Hurricane Helene developed.

The convective systems over the Atlantic are embedded within a mesoscale mid– and low–level circulation. The low–level circulation was found to be warmer than its environment. The strong Harmattan deflected the mineral dust transport towards the southwest. The strong northwesterly monsoon flow, enhanced the low–level circulation and the dust spirals around the low–level circulation centre until the low–level and the mid–level circulation centres are collocated (in the late evening hours on 12 September; not shown). From this time on, relatively high AOTs can be found within the centre of the developing tropical depression. During the tropical cyclogenesis, bands of dry and dusty air spiral towards the storm centre.

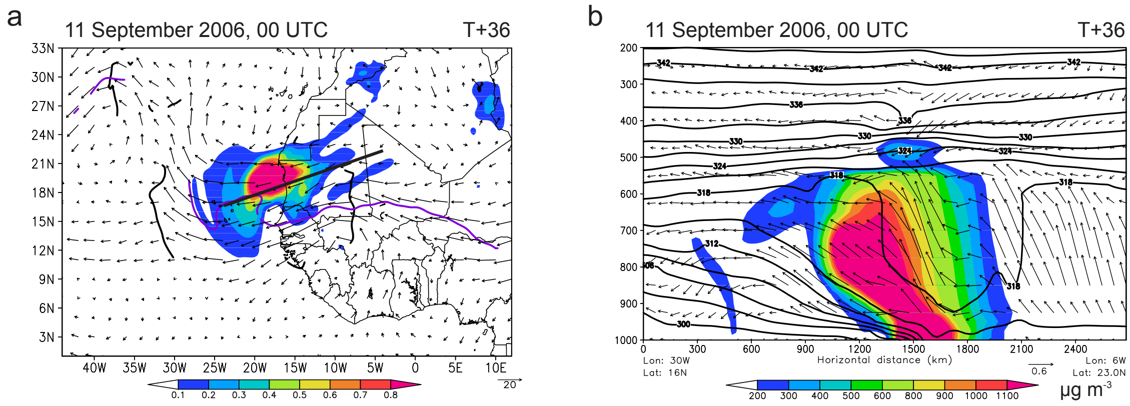

FIGURE 4: (a) The horizontal wind speed (arrows, m s^{-1}) at 700 hPa, the aerosol optical thickness (shaded), the AEW trough (black curvy line) and AEJ axes (purple line) on 11 September 2006, 00 UTC (T+36). The black solid line displays the position of the cross section depicting the mineral dust mass concentration in μg m^{-3} in (b) at the same time. Pressure in the vertical component. Based on the model run initialised on 9 September 2006, 12 UTC including the dust–radiation interaction (RadDust).

4. THE IMPACT OF THE DUST–RADIATION FEEDBACK

To assess the effect of mineral dust in the atmosphere during the cyclogenesis of Hurricane Helene, we compare the simulation in which the dust interacts with the radiation scheme (RadDust) with the simulation in which dust acts as a passive tracer (NoRadDust).

Several differences occur in the potential temperature, zonal and meridional wind fields during the simulated period. The most marked, however, is the intensification of the monsoon trough on 12 September 2006. The potential temperature at 950 hPa north of the low–level circulation centre is about 4 K higher in the RadDust run than in the NoRadDust run (Fig. 6d). High dust concentrations can be found n this region, so the potential temperature increase can be attributed to the absorption of incoming shortwave radiation by the dust particles (Fig. 6b). A broad region with enhanced dust concentration west of the circulation centre is also characterised by an increase in low–level potential temperature. A marked temperature decrease up to 4 K occurs over land north of about 18 °N. It can partly be attributed to an elevated dust layer that is located at around 900 hPa in this region. The mineral dust absorbs the incoming shortwave radiation and the temperatures in this dust layer increase (not shown). Below, the temperatures decrease as the the shortwave radiation is reduced. Associated with these potential temperature differences we see an increase in the easterlies and northerlies north of the low–level circulation, and an increase in the westerlies and southerlies south of the low–level circulation (Fig. 6f) in the RadDust run. This is an indication that the monsoon trough has intensified and the low–level vorticity has increased.

Although some of the thermodynamical changes are clearly associated with the direct interaction between dust and radiation at the time in question, others cannot be directly connected, indicating that changes in the circulation have occurred due to the dust–radiation interaction at previous times.

The differences between the RadDust and the NoRadDust runs become more distinct with time. On 15 September 2006 at 06 UTC, dust concentrations can be found in the storm's centre in the RadDust run and even higher values in a narrow band southwest of it (Fig. 7a). The centre of tropical storm Helene had a lower geopotential height in the RadDust run than in the NoRadDust run (Fig. 7b) indicating that the tropical storm develops faster in the RadDust run. The system had a warmer core in the RadDust run (not shown). The storm's centre in both runs is displaced by about 2 ° (Fig. 7b).

5. SUMMARY

The AEW out of which Hurricane Helene (2006) developed, the associated weather systems and mineral dust sources, as well as the dust transport were simulated using the model system COSMO-ART. The RadDust run was compared to satellite images observational data from the AMMA campaign. The agreement between the observations and the model results at the beginning of the simulation period was found to be reasonably good, but the model runs were too long to accurately simulate the whole tropical cyclogenesis.

Large amounts of mineral dust occurred north of the AEJ axis. On 11 September 2006 in the afternoon hours, a dust event was initiated east of Dakar within the trough of the AEW out of which Hurricane Helene developed. This mineral dust was transported along two pathways. One the one hand, the dust was lifted up over Mauritania close to the region where it was emitted, and predominantly between about Dakar and Cap Blanc along the West African coast line. It reached heights of about 600 hPa and was advected westwards by the AEW. On the other hand, the dust is transported northwestwards by the low–level monsoon flow. The Harmattan and the monsoon flow converged along a northeast–southwest orientated band. In this region the dust is partly lifted and the

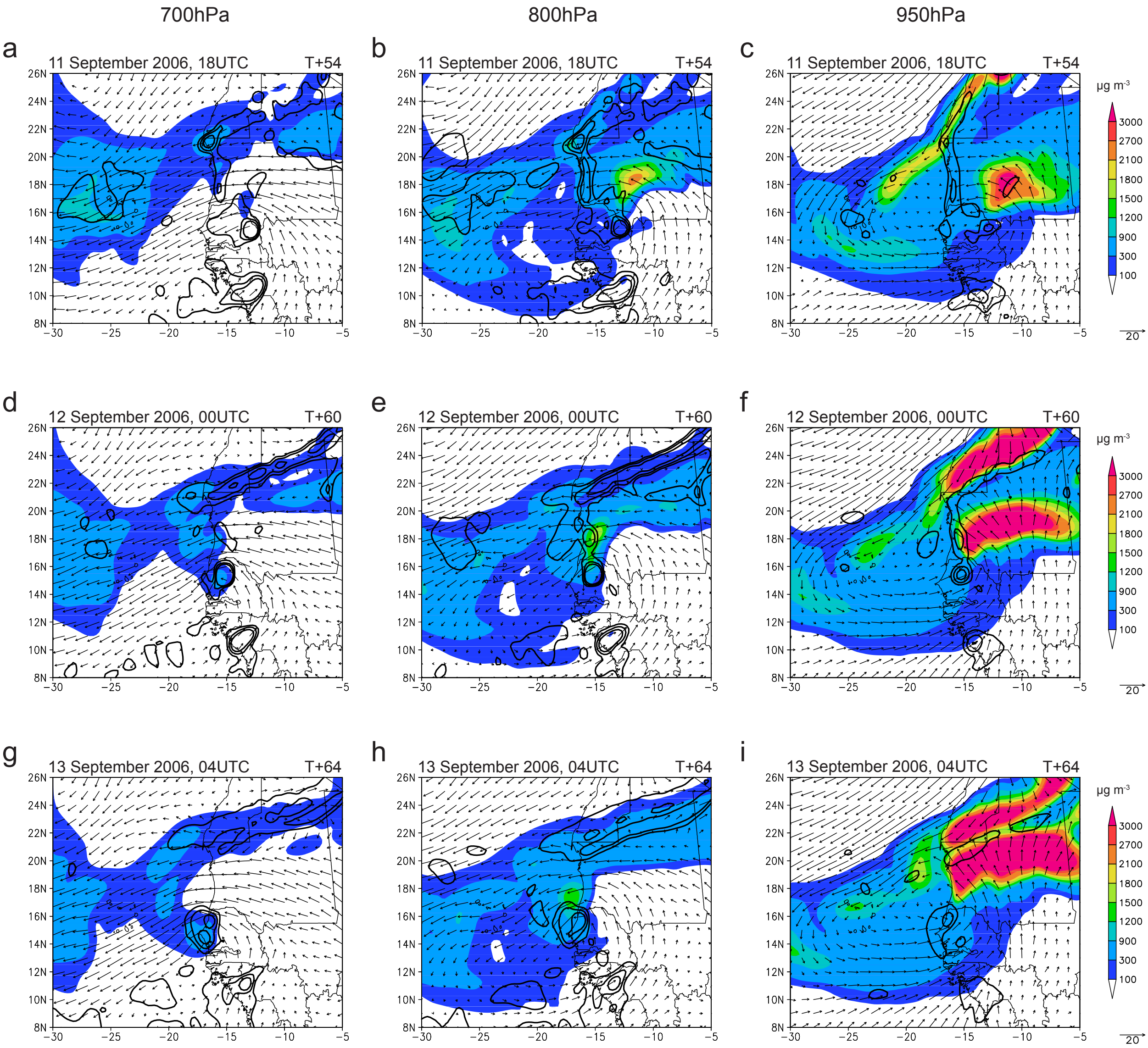

FIGURE 5: Horizontal wind speed (arrows, $\mathrm{m\,s^{-1}}$), mineral dust mass concentration (shaded, $\mu\mathrm{g\,m^{-3}}$), and vertical velocity (-1.2 $\mathrm{Pa\,s^{-1}}$, -0.6 $\mathrm{Pa\,s^{-1}}$, -0.2 $\mathrm{Pa\,s^{-1}}$ contours, i.e. regions of ascent) at 700 hPa (left), 800 hPa (middle), and 950 hPa (right) on 11 September 2006, 18 UTC and 12 September at 00 UTC and 04 UTC. Based on the model run initialised on 9 September 2006, 12 UTC including the dust–radiation interaction (RadDust).

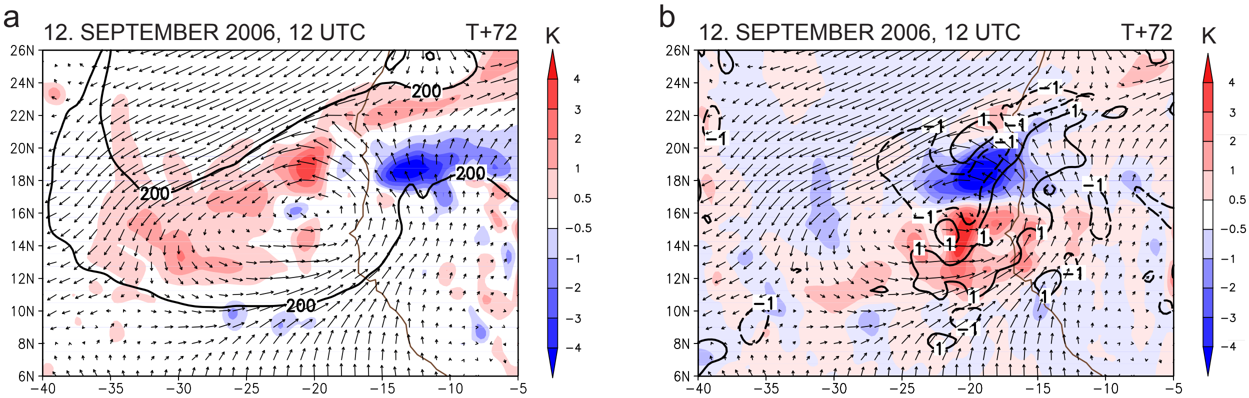

FIGURE 6: (a) Differences between the RadDust and NoRadDust model runs in potential temperature (shaded, K) at 950 hPa, and the 200 μg m^{-3} mass concentration contour. (b) Differences between the RadDust and NoRadDust model runs in in zonal wind (m s^{-1}, shaded) and meridional wind (2 m s^{-1} contour interval) at 950 hPa. The dotted line denotes the zero line. The horizontal wind speed (arrows in m s^{-1}) from the RadDust run is shown on 12 September 2006 at 12 UTC (T+72).

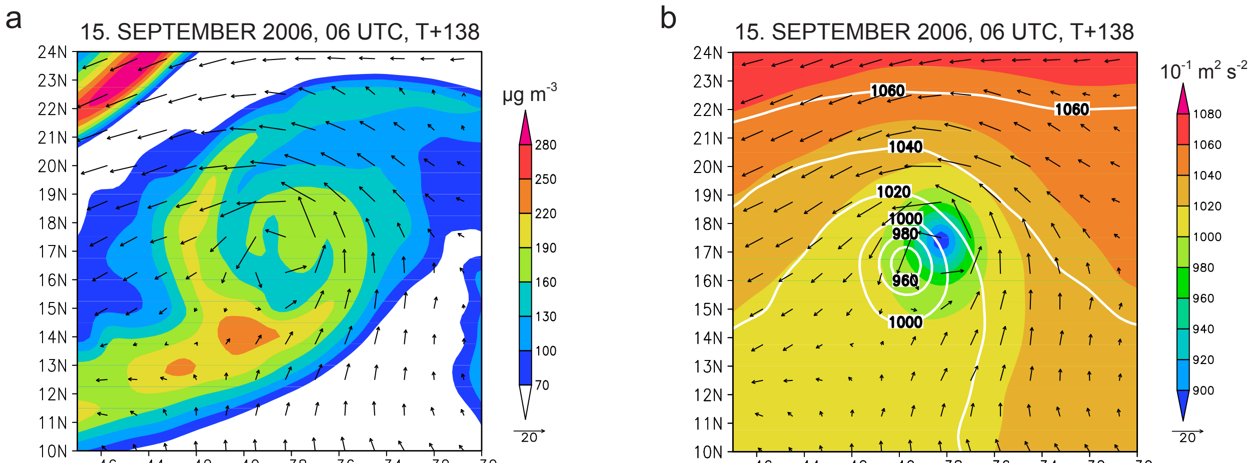

FIGURE 7: (a) The mineral dust concentration (μg m^{-3}) at 850 hPa in the RadDust run, and (b) the geopotential (10^{-1} m^2 s^{-2}) at 900 hPa, for the RadDust run (shaded) and the NoRadDust run (contours). Additionally, the horizontal wind field in the RadDust run is shown on 15 September 2006 at 06 UTC (T+138).

other part rotated cyclonically around the low–level circulation. Thus the mineral dust is both lifted up into the AEW trough, and advected at lower levels by the monsoon flow into the centre of the low–level monsoon circulation.

When the low–level and the mid–level relative vorticity anomaly related to the AEW are collocated on 12 September 2006 in the late afternoon hours, dust can be seen in the centre of the developing tropical depression. The dust concentration in the storm's centre decreases with time due to wet and dry deposition, but relatively high AOTs can be observed in the centre when Helene reached hurricane intensity. During the development from a tropical depression to a mature hurricane, bands of dry air spiralled towards the storm centre and a dry intrusion occurs west and southeast of the storm, close to the centre.

The comparison between the RadDust and NoRadDust model runs showed that the potential temperature increased in the near–surface and uplifted mineral dust regions due to the absorption of radiation by aerosol particles. In the regions below the elevated dust layer, cooling occurs due to the reduction of incoming shortwave radiation. The monsoon trough was stronger in the RadDust run than in the NoRadDust run.

The effect of dust on the tropical cyclogenesis is assumed to depend on the intensity of the dust event, i.e. the mineral dust mass concentrations. The dust concentrations or the AOTs for the Helene case were relatively low compared to other mineral dust events in West Africa. The temperature increase due to the absorption of radiation by the dust particles in the present case led to warming in the TC core, which in turn enhanced the system. This may not be the case for more intense dust outbreaks. The main difference to previous studies is that the dust in the present study occurs partly in regions that are relatively moist, especially in the vicinity of the storm's centre. If the air is dry and dust enriched then it is likely to suppress convection as pointed out by several other studies.

Further analyses of this case is needed to quantify how the interaction between radiation and dynamics influences the tropical cyclogenesis and their evolution. The analysis of potential temperature and potential vorticity budgets, as used in Schwendike and Jones (2010), can be applied.

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