P1A.17 SPATIAL AND DIURNAL VARIABILITY IN THE SAHARAN BOUNDARY LAYER DURING GERBILS (2007): THE ATLANTIC INFLOW

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1. INTRODUCTION

The Saharan atmospheric boundary layer (SABL) is one of the deepest planetary boundary layers in the world (Gamo, 1996). The boundary layer dynamics affect dust uplift and influence the thermodynamical structure of the atmosphere within the Saharan heat low (SHL) region (Marsham et al., 2007). The low static stability in the heat low region serves to maintain the African easterly jet (AEJ), which in turn controls synoptic weather patterns propagating westwards over West Africa and the tropical Atlantic (Thorncroft and Blackburn, 1999). Recently the SHL was found to play a crucial role at the time of monsoon onset (Sultan et. al, 2006; Ramel et al., 2006; Hagos and Cook, 2007). Parker et al. (2005) highlight the important role of the diurnal cycle of the SHL within the West African Monsoon (WAM) system. Thus a correct representation of the SHL is crucial for the understanding of the WAM.

The significance of errors of the SHL thermodynamics in numerical models has been described by Haywood et al. (2005) and Tompkins et al. (2005). The GERBILS field campaign was conducted in West Africa in June 2007 to investigate errors of radiation in numerical models at the south-western edge of the SHL. We performed an operational forecast with the COSMO model of the German Weather Service (Deutscher Wetterdienst (DWD)). COSMO was validated against airborne measurements.

After the campaign we used model output to investigate the inflow from the Atlantic ocean into the south-western SHL region. The role of zonal advection from the Atlantic to maintain the balance of heat and moisture budgets was stressed by Peyrillé and Lafore (2007). Idealised numerical studies of a heat low on a landmass surrounded by sea showed the temperature gradient between land and ocean surface to produce sea breezes penetrating far inland at nighttime (Rácz and Smith, 1999; Spengler et al., 2005). Likewise experimental studies showed heat low driven sea breezes, e.g. in Spain (Kottmeier et al., 2000) or Australia (Reeder and Smith, 1999). We identified the Atlantic Inflow as a sea breeze transforming into a sea breeze front penetrating far inland and affecting the mid-troposphere through an induced gravity wave and a distinct frontal circulation. The Atlantic Inflow seems to be a characteristic meteorological feature at the Mauritanian coast, having an important impact on the regional heat and moisture budgets through low-level cooling and moistening.

In this paper we validate the representation of the Saharan Boundary Layer in COSMO based on the airborne measurements during GERBILS and discuss the Atlantic Inflow in detail. This study presents the results of a Masters thesis at the University of Karlsruhe. For further details refer to Grams (2008).

2. GERBILS CAMPAIGN

The GERBILS (Geostationary Earth Radiation Budget Experiment Intercomparison of Longwave and Shortwave radiation) field campaign, which was organised by the Met Office in June 2007, aimed to understand the differences between modelled and observed radiation over the south-western Sahara (Haywood et al., 2005).

Six scientific flights with the Facility for Airborne Atmospheric Measurements (FAAM) BAe146 aircraft took place between Niamey (Niger) and Nouakchott (Mauritania) supplemented by two scientific transit flights. The aircraft was instrumented to provide standard meteorological and air chemistry parameters. A nephelometer provides the aerosol scattering coefficient and is used to quantify atmospheric dust loadings. Furthermore dropsondes provide profiles of the meteorological parameters.

In support of the campaign, we performed an operational forecast running the COSMO (Consortium for Small-scale Modeling) model twice daily. The aims of this forecast operation were to test the accuracy of COSMO in the region where interaction between the WAM and SHL takes place, to provide a high-resolution forecast for the campaign, and to establish a framework for analysis of the weather systems observed.

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3. COSMO MODEL AND MODEL VALIDATION

The COSMO model (Doms and Schättler, 2002) is a regional numerical weather prediction model operationally used at the German Weather Service (DWD) and is also used at different institutes for scientific purposes. The non-hydrostatic thermo-hydrodynamical equations for compressible flow are formulated on a rotated geographical coordinate system, using a generalised terrain-following vertical coordinate.

We performed an operational forecast on a domain covering the major parts of the planned flight track along 18°N during GERBILS running COSMO (version LM3.19) on a HP XC6000 super computer at the Scientific Super Computing Center[*] at the University of Karlsruhe. The horizontal resolution was 0.0625° (7km) and 35 levels in the vertical were used. Initial conditions were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis. Lateral boundary conditions were taken 3 hourly from the ECMWF operational forecast.

During the analysis of the meteorological conditions the model was rerun on a domain shifted 5° westwards and with adapted model code to provide the individual tendency terms of the temperature and specific humidity tendencies. This COSMO_budget run enabled a deeper insight into the physical processes governing the Atlantic Inflow. The model domains are shown in Figure 1 (black outline), including the model orography in the COSMO forecast domain.

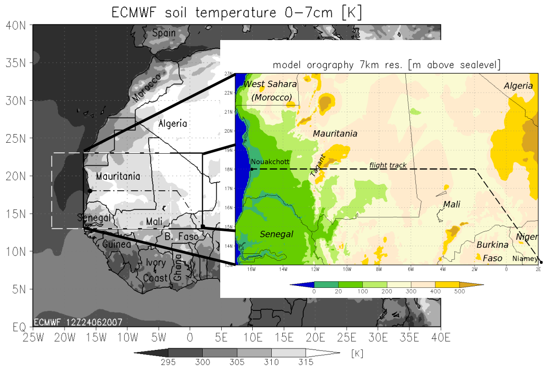

Figure 1. Surface temperature from ECMWF analysis 12Z24062007. COSMO forecast domain (black solid), domain shifted westwards for COSMO_budget run (white dashed), and COSMO forecast domain with orograhy.

The comparison of aircraft and dropsonde profiles of virtual potential temperature and specific humidity with model profiles at the corresponding grid points showed, that COSMO captures the main features of the SABL very well. As an example a profile at the eastern edge of the SHL at 18°N is shown (Figure 2). The height of the boundaries between the convective internal boundary layer (CBL) and Saharan Air Layer (SAL)/Saharan

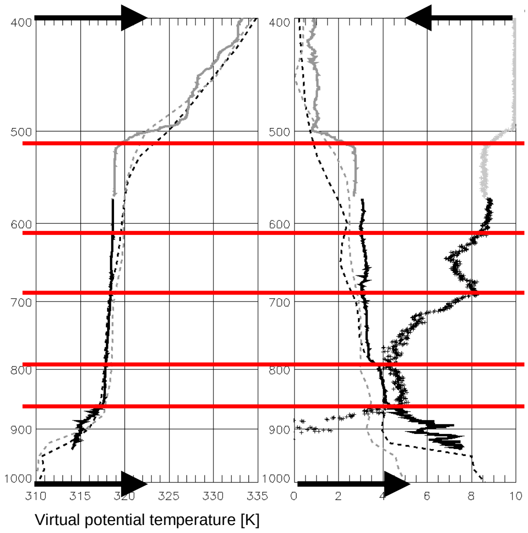

Figure 2. Aircraft profiles 18°N, 3.5°W, 24/06/2007 , 11:30 UTC, virt. pot. temp. (solid, left), specific humidity (solid, right), aerosol (+,right). COSMO at starting (end) point of profile (black (grey) dashed), boundaries of layers (solid, red).

residual layer (SRL) and between SAL/SRL and free atmosphere are correctly modelled to within 10 hPa. Also, the absolute values of model virtual potential temperature in the CLB and in the lower SAL/SRL agree with the measurements. In the upper part of the SAL/SRL and in the free atmosphere the model overestimates the virtual potential temperature by around 1-2K. Specific humidity is highly correlated with the aerosol content, resulting in a distinct fine layering of the humidity profile. As actual dust is not modelled in COSMO the absolute values and the fine structure of the model specific humidity profile differs from the measurements. However the main features (CBL, SAL/SRL) are qualitatively well captured in the model.

The section along the flight track at 18°N of virtual potential temperature from the 12 hour COSMO forecast of 00UTC 24/06/2007 showed a baroclinic zone separating the deep well-mixed SABL east of 8°W and the rather stably stratified Atlantic influenced atmosphere in the west (Figure 7). The SABL is evident from 8°W to 3°W with a shallow CBL separated from the SAL aloft by a strongly stable layer. The SAL extends up to 500hPa at 6°W. East of 3°W the monsoon flow is evident with the monsoon layer extending up to 800hPa at 2°E and the SAL aloft extending up to 600hPa. The transition to the moderately stable stratified atmosphere over the Atlantic and the coastal plain in western Mauritania is marked by a baroclinic zone between 8°W to 11°W. On 24 June 2007 flight B299 took place along 18°N from 11:00UTC to 14:30UTC. The aircraft and dropsonde data was interpolated to produce a section of virtual potential temperature and specific humidity (Figure 7). Despite the coarse resolution of available measured data this section proofs the existence of the baroclinic zone at 18°N and the distinction of an

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[*] http://www.rz.uni-karlsruhe.de/ssck/3429.php

Atlantic influenced atmosphere east of 8°W, the SABL from 8°W to 3°W and the monsoon layer east of 3°W.

The sections of humidity mixing ratio at 18°N show a moist layer extending up to 700 hPa east of the Tagant mountains (12°W) (Figure 7). This is a remnant moist layer from a northward monsoon penetration the day before. Near the coast (16°W) a dryer layer (from around 980 hPa to 900 hPa) intrudes into the moist layer in model data. The SHL region is evident from around 8°W to 4°W with low values of humidity mixing ratio. East of 3°W higher values of mixing ratio mark the monsoon layer. Again the measurements proof the modelled section along 18°N. As a result of the good representation of the SABL in COSMO, mid-level clouds (e.g. altocumulus at the top of the SAL) were well predicted during GERBILS.

A low-level flight at 18°N on 28 June 2007 showed an albedo anomaly at 8°W having an effect on potential temperature and humidity mixing ratio. This feature was only weakly represented in the model. However the model captured the strong increase of potential temperature when entering the SHL region at 12°W and due to the Tagant as an elevated heat surface.

4. THE ATLANTIC INFLOW

The analysis of the temporal and spatial evolution of the baroclinic zone in the west of the Saharan heat low using COSMO data, showed a complex mesoscale meteorological system with a distinct diurnal cycle at the Mauritanian coast, which we call the “Atlantic Inflow”. This system consists of the sea breeze at the western Atlantic coast of West Africa, the baroclinic zone marking the transition towards the SABL/monsoon layer, and the perturbation of the mid-level troposphere through an induced gravity wave and a distinct frontal circulation. Through its advection of cool and moist maritime air the Atlantic Inflow has an important impact on the regional heat and moisture budgets.

Three modes of the Atlantic Inflow can be distinguished depending on the synoptic situation at 18°N. In the ‘standard’ mode (e.g. 24 June 2007) the SHL is located east of the Tagant (12°W). In the west of the SHL the mid- and high-level troposphere is stably stratified, while a CBL extending up to 800 hPa is evident at daytime due to the surface heating. The Atlantic Inflow penetrates into the lower-level CBL and the stably stratified atmosphere above. The ‘heat low’ mode is marked by a westward shift of the SHL to the Atlantic coast and the Atlantic Inflow intrudes into the deep well-mixed SABL. In the ‘monsoon’ mode the Inter Tropical Discontinuity (ITD), separating the south-westerly cool and moist monsoon flow from the north-easterly hot dry and dusty Harmattan flow, is located north of 18°N. Thus the Atlantic Inflow penetrates into the monsoon layer and the SAL above.

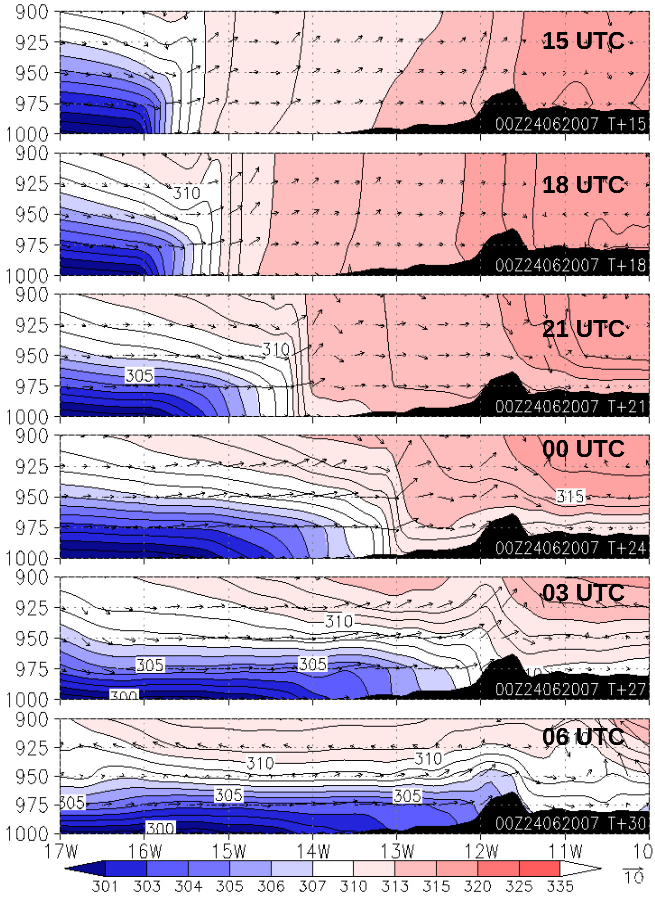

Figure 3. Sequence of longitudinal-vertical sections of virtual potential temperature at 18°N (shaded, and black contours, with a 1K contour interval) and wind vectors in plane of section. Orography is black shaded.

The inland penetrating sea breeze front and the advection of cool, maritime air with stable stratification become evident in longitudinal-vertical sections at 18°N (Figure 3). At 15 UTC a stationary front becomes established at the coast. At 18 UTC the front starts moving inland in the low levels and reaches the Tagant mountains at around 2 UTC. Cold stably stratified air is advected behind the front. In the next morning cool air covers the entire coastal plain.

The magnitude of the virtual potential temperature gradient $|\nabla \Theta_v|$ is suitable to investigate the horizontal extent of the Atlantic Inflow front. The front becomes evident by $|\nabla \Theta_v|>0.04$ Kkm^{-1} and an increase of wind speed combined with a change in wind direction to (north) westerlies behind the front (Figure 4). The Atlantic Inflow shows deepest inland penetration south of 20°N and north of the ITD.

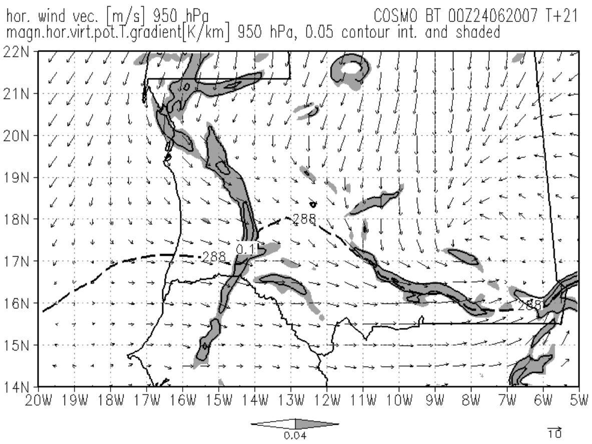

Figure 4. Magnitude of virtual potential temperature gradient (shaded and black contours, with a contour interval of 0.05 K km^{-1}), horizontal wind vectors (black arrows, m s^{-1}), and the 288 K dewpoint temperature isotherm at 950 hPa, 21 UTC 24 June 2007.

The terrain in western Mauritania is favourable for the inland penetration (Figure 1). South of 20°N a wide coastal plain extends from the coast at 16°W to the foot of the Tagant mountains at 12°W, which form the first orographic barrier east of the coast and reaches 400-600 m above mean sea level.

The sea breeze front is a result of the strong temperature gradient between the ocean and land surface (Figure 1). The cold Canary current and upwelling deep waters lead to a cold ocean surface (22°C) and a rather cool air layer at the Mauritanian coast. In contrast the strong daytime insolation heats the land surface to more than 45°C. Thus a strong temperature and density gradient is evident along the Mauritanian coast. However, during the day turbulent mixing due to dry convection over land hinders the inland movement of the cooler air. The cooling due to horizontal advection is balanced by warming due to turbulent diffusion (Figure 6). At around 17 UTC horizontal advection dominates and the low-level front starts moving inland, reaching the Tagant at around 2 UTC the next day.

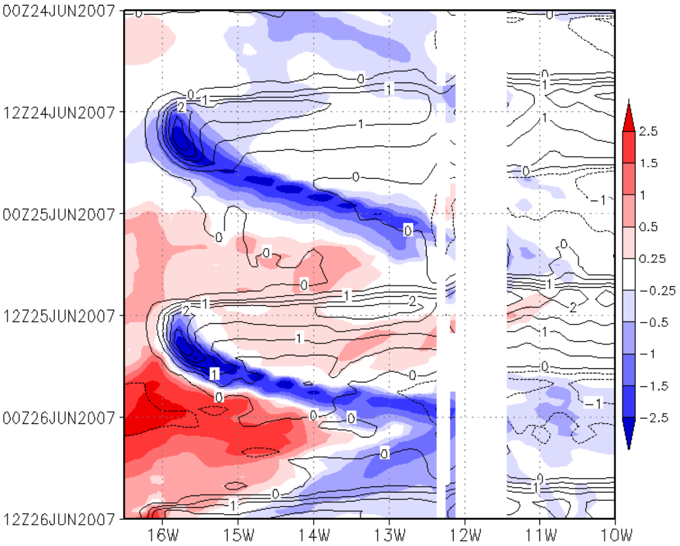

Figure 6. Hovmöller plot of virtual potential temperature tendencies in K h^{-1} due to horizontal advection (shaded) and turbulent diffusion (black contours, with a 0.5 K h^{-1} contour interval), averaged from 17°N to 19°N, and at 975 hPa.

At a specific location the passage of the Atlantic Inflow front can be detected as a sharp decrease of potential temperature of -2.5 Kh^{-1} to -5.0 Kh^{-1} from the surface up to around 925 hPa and a sudden increase of the zonal wind component of around 5 m s^{-1} to values higher than 10 m s^{-1}. Depending on the synoptic situation the passage is also evident by an increase in specific humidity. In the wake of the front the cool and moist air is advected from the Atlantic. The inland penetrating coastal front has characteristics of a density current (Linden and Reible, 1986; Smith, 1988) and the calculated densimetric speed of 10 m s^{-1} is the same as the propagation speed estimated from Figure 3 or Figure 6.

The density current in the low levels affects the mid- and high-level troposphere through a gravity wave and a distinct frontal circulation which are induced at its head. The intruding denser air lifts the isentropes at its front. As a result a gravity wave is evident in the mid levels (Figure 5), which propagates eastwards with the low-level front and against the mean flow (which is from the east in the mid levels). The phase lines are slightly tilted eastwards. A frontal circulation, with ascent at low levels (950-700 hPa) ahead of the low-level front, descent in the mid levels above the Atlantic Inflow front and a further updraft in the higher levels behind the front is combined with the gravity wave. The vertical structure of the Atlantic Inflow is modified by the synoptic conditions. When intruding into the SABL (heat low mode) the prefrontal updraft is much more pronounced and extends from the surface up to the top of the SAL at around 500 hPa. Nevertheless a gravity wave is induced in the stably stratified atmosphere above the SAL. In the monsoon mode the frontal circulation is similar to the standard mode but weaker. Also the induced gravity wave is less pronounced. Remarkably, the mid-level gravity wave and frontal circulation decouples from the low-level front when reaching the Tagant and propagates further eastwards, while the low-level front can not overstep the orographic barrier.

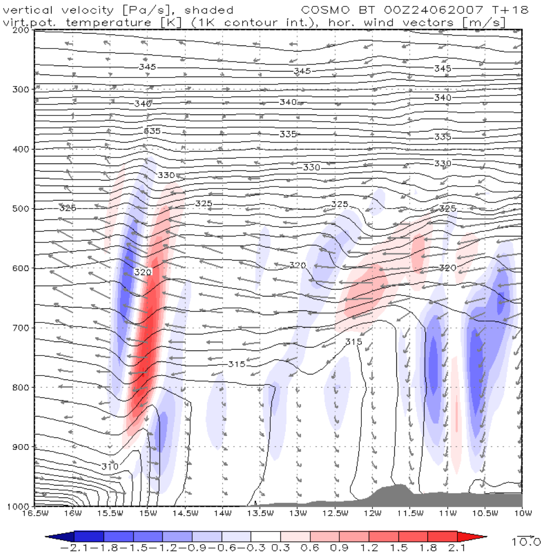

Figure 5. Longitudinal-vertical section at 18°N and at 18 UTC 24 June 2007: vertical velocity (shaded, with a 0.3 Pa/s contour interval), virtual potential temperature (black contours, with a 1 K contour interval), and **horizontal** wind vectors (grey arrows). Grey shading indicates orography.

5. HEAT AND MOISTURE BUGETS

Finally, the COSMO_budget run is used to investigate the impact of the Atlantic Inflow on the regional heat and moisture budgets. An area average of the individual tendency terms (horizontal and vertical advection, radiation (only Θ), turbulent diffusion, sub-grid and grid scale moist convection and computational effects) is calculated at each level over a box in the Atlantic Inflow region. Time-averages, are computed over a 48 hour period and over the time when the Atlantic Inflow front passed the box (forecast hours 18 to 22). In the two day average cooling through horizontal advection was almost balanced by warming due to turbulent diffusion, which confirms the balance between horizontal advection and turbulent diffusion being the steering mechanism for frontal propagation.

However, at the time of the occurrence of the Atlantic Inflow turbulent diffusion was negligible and cooling due to horizontal advection of more than -1 Kh^{-1} was dominant in the low levels. The profiles of specific humidity tendency terms showed moistening of 0.2 gkg^{-1} in the low levels due to horizontal advection at the time of the Atlantic Inflow.

6. SUMMARY AND CONCLUSION

In this study we applied the COSMO model to investigate the spatial and diurnal variability in the Saharan Atmospheric Boundary Layer at the south-western edge of the Saharan heat low. The validation of model data against airborne measurements showed that COSMO captures the monsoon layer, the CBL, and the SAL/SRL rather well. As a result COSMO predicts the mid-level clouds at the top of the SAL very well.

The Atlantic Inflow was found to be an important meteorological feature at the western Atlantic coast of West Africa in the COSMO forecasts during GERBILS. Every day a stationary front became established at the coast penetrating up to 400 km inland at nighttime having gravity current character and affecting the mid-level troposphere through an induced gravity wave and its frontal circulation. Recently density currents in West Africa were found to produce important dust uplifts (Bou Karam et al., 2007; Knippertz et al., 2007; Marsham et al., 2008). Thus we assume the strong updraft at the head of the Atlantic Inflow density current to produce dust uplift. A first run with COSMO-ART (Vogel, 2007), a COSMO version including actual dust, confirms this assumption.

Furthermore, the Atlantic Inflow directly affects the regional heat and moisture budgets through advection of cool moist air into western Mauritania.

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REFERENCES

Bou Karam, D. et al., 2008: Dust emissions over the Sahel associated with the West African Monsoon inter-tropical discontinuity region: a representative case study. *draft for Q. J. R. Meteorol. Soc.*

Doms, G. and Schättler, U., 2002: A description of the nonhydrostatic Regional Model LM. Part I: Dynamics and Numerics. *Consortium for Small-Scale Modelling, available at http://www.cosmo-model.org* .

Gamo, M., 1996: Thickness of the dry convection and large-scale subsidence above deserts. Bound.-Lay. Meteorol., 79, 265-278.

Grams, C.M., 2008: The Atlantic Inflow: atmosphere-land-ocean interaction at the south-western edge of the Saharan heat low. *Diploma thesis available at http://www.imk.uni-karlsruhe.de/english/3841.php* .

Hagos, S.M. and Cook, K.H., 2007: Dynamics of the West African Monsoon Jump. *J. Climate*, 20, 5264-5284

Haywood, J.M. et al., 2005: Can desert dust explain the outgoing longwave radiation anomaly over the Sahara during July 2003? *J. Geophys. Res.-Atmos.*, 110 (D9), 5105-+, doi:10.1029/2004JD005232.

Knippertz, P. et al., 2007: Dust mobilization due to density currents in the Atlas region: Observations from the Saharan Mineral Dust Experiment 2006 field campaign. *J. Geophys. Res.-Atmos.*, 112 (D11), 21109-+,

Kottmeier, C. et al., 2000: Sea breezes and coastal jets in south-eastern Spain. *Int. J. Climatol.*, 20, 1791-1808.

Linden, P.F. and Simpson, J.E., 1986: Gravity-driven flows in a turbulent fluid. *J. Fluid. Mech.*, 172, pp. 481-497.

Marsham, J.H. et al., 2007: Observations of mesoscale and boundary-layer circulations affecting dust uplift and transport in the Saharan boundary layer. *Submitted to Atmos. Chem. Phys.*

Marsham, J.H. et al., 2008: Uplift of Saharan Dust at the inter-tropical discontinuity (ITD). *Submitted to J. Geophys. Res.-Atmos.*

Parker, D.J. et al, 2005: The diurnal cycle of the West African monsoon circulation. *Q. J. R. Meteorol. Soc.*, 131, 2839-2860.

Peyrillé, P. and Lafore, J.P., 2007: An Idealized Two-Dimensional Framework for the Study of the West African Monsoon. Part II: Large-Scale Advection and the Diurnal Cycle. *J. Atmos. Sci.*, 64, 2783-2803, doi: 10.1175/JAS4052.1.

Rácz and Smith, 1999: The dynamics of heat lows. *Q. J. R. Meteorol. Soc.*, 125, 225-252.

Ramel, R. et al., 2006: On the northward shift of the West African monsoon. *Clim. Dynam.*, 26, 429-440.

Reeder, M.J. and Smith, R.K., 1999: Meteorology of the Southern hemisphere. *Meteorological Monographs*, 27(49), 211-223.

Smith R.K. and Reeder, M.J, 1988: On the Movement and Low-Level Structure of Cold Fronts. *Mon. Weather Rev.*, 116, 1927-1944.

Spengler, T., 2005: The dynamics of heat lows in simple background flows. *Q. J. R. Meteorol. Soc.*, 131, 3147-3165, doi:10.1256/qj.04.177.

Sultan, B., 2006: Characterization of the Diurnal Cycle of the West African Monsoon around the Monsoon Onset-*J. Climate*, 20, 4014-4032.

Thorncroft, C.D. and Blackburn, M., 1999: Maintenance of the African easterly jet. *Q. J. R. Meteorol. Soc.*, 125, 763-786.

Vogel, B., 2007: A new Online Coupled Regional Scale Model System to treat the Dispersion of Aerosols and Reactive Trace Gases. *Available at http://www.imk.uni-karlsruhe.de/3613.php* .

Tompkins A.M., et al., 2005: The African easterly jet in the ECMWF Integrated Forecast System: 4D-Var analysis. *Q. J. R. Meteorol. Soc.*, 131, 2861-2885.

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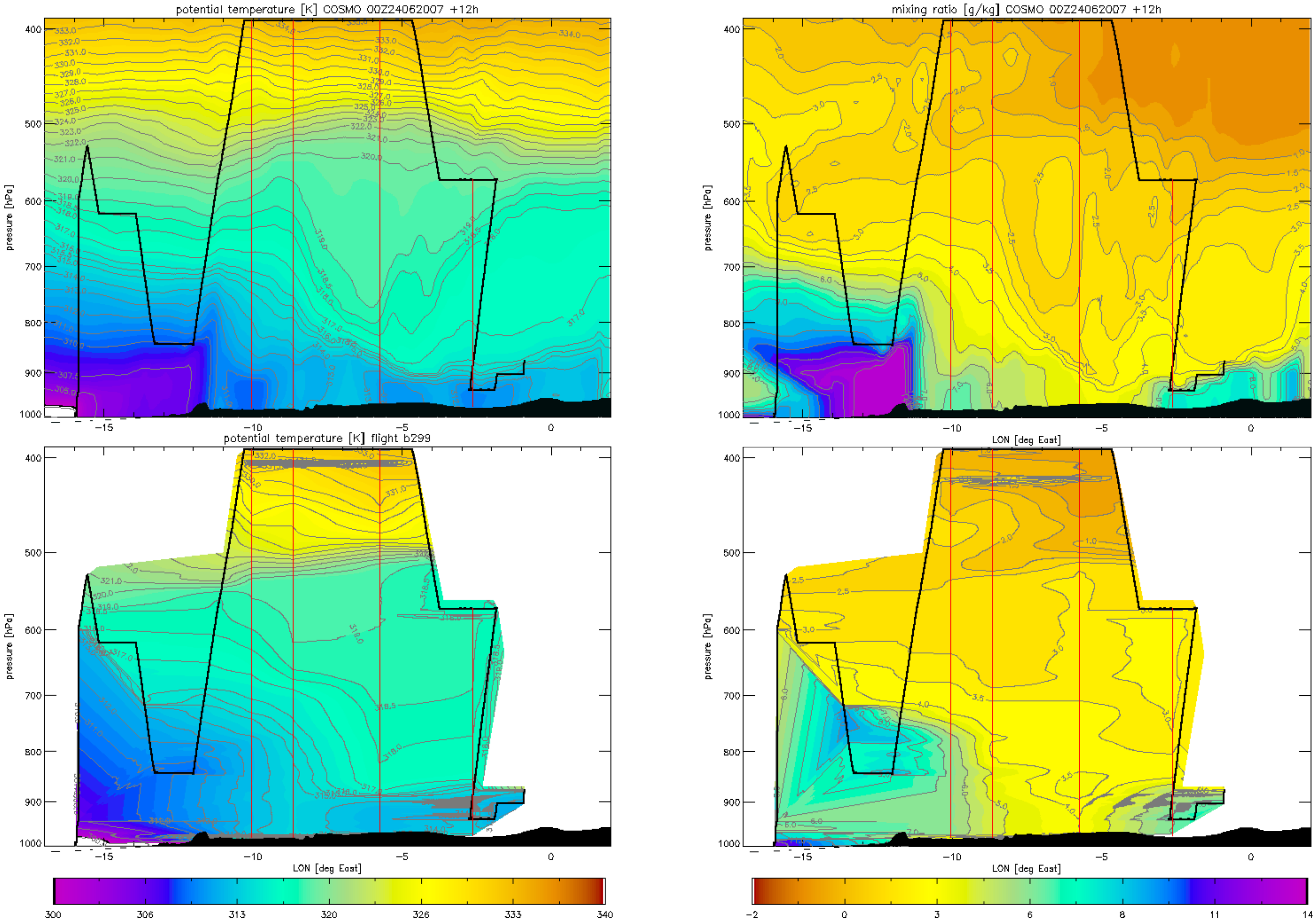

Figure 7. Longitude-height cross section of potential temperature in K (left) and humidity mixing ratio in g kg^{-1} (left) along 18°N. The plots at the top show COSMO model data at 12 UTC 24 June 2007 based on a 00Z forecast the same day. The plots at the bottom show sections interpolated from aircraft and dropsonde data. The flight track is indicated as black line, drop sonde locations are indicated as red lines. Black shading indicates the terrain.