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EXAMINATION OF SAHARAN BOUNDARY LAYER BY A SINGLE-COLUMN AND 3D WRF MODEL – A CASE STUDY FOR FENNEC CAMPAIGN

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ABSTRACT

Understanding of the atmospheric boundary layer (ABL) processes, as well as description of the layer characteristics and vertical structure above deserts is very important for investigation of effects of deserts on weather, climate and transport of mineral dust. According to high insolation and lack of moisture Saharan boundary layer is the one of the deepest on the Earth. The aim of our study is to examine structure of the Saharan boundary layer and temporal evolution of the ABL height employing a single-column ABL model and the 3D Weather Research and Forecasting (WRF) model. WRF runs were done using the telescopic nesting method and 4 different ABL parameterization setups. Model outputs were compared with radiosonde data obtained during Fennec campaign (2011).

Keywords: Saharan boundary layer, shallow convection, single-column ABL model, 3D WRF model, Fennec campaign

1. INTRODUCTION

Sahara, the largest hot desert on the Earth, plays a key role in regional and global climate process [1], and represents the largest source of mineral dust on the planet [2,3]. North African dust hot spots located in the Sahara and Sahel contribute to 50–70% of the global mineral dust budget [4,5]. The dust travels through the Atlantic Ocean to North and South America, but it also affects Europe's air pollution conditions. In the 40-year time period from 1979 to 2018 more than 200 North African dust events were detected in the Carpathian Basin (Central Europe) [5].

As a result of the extreme near-surface temperatures the Saharan ABL commonly reaches 5–6 km [6] making it probably the deepest on the Earth. The Saharan boundary layer is characterized with a particular structure [7]. The morning and midday, relatively shallow, convective layer is capped by a narrow (about 100 m deep) temperature inversion. The inversion layer separates convective layer from a deep near neutral residual layer formed by the previous day's completely developed convective boundary layer. The three-layered (well-mixed convective layer, weak inversion and weakly stable residual layer) potential temperature structure allows detrainment of the warmest plumes across the weak temperature inversion, which slows down the growth of the convective layer. As the boundary layer grows overshooting plumes can also entrain the free atmosphere. The convective layer often reaches its full extent only in the late afternoon. Observations show that the residual layer sometimes persist over large areas throughout the day, the boundary layer depth varies by up to 100% over horizontal distances of a few kilometers [8]. This effect can be connected with subsidence, caused by circulations induced by albedo variations [9], or by effects of orography [10].

The goal of our work is to examine vertical structure of the Saharan boundary layer and the layer's diurnal variation employing a simple single-column (1D) ABL model [11] and the 3D WRF model [12]. WRF runs were done by 4 different boundary layer parameterization setups using telescopic nesting method. Modelled vertical profiles and estimated boundary layer depths were compared with radiosonde measurement data obtained in Fennec campaign [13]. The Fennec program is a large-scale, international observational and modelling project that aimed to produce the most comprehensive dataset of the central Saharan atmosphere. The goals of the program are to derive a definitive dataset for central Sahara from ground, aircraft and satellite observations, to characterize structure of the central Sahara's atmosphere, to quantify weather prediction and climate model errors, as well as to establish mechanisms of mineral dust emissions in 2011 and 2012.

2. INVESTIGATION METHODS

2.1. Observations – The Fennec Program

Despite the Sahara's importance to Earth's climate, routine meteorological measurements are one of the sparsest of any landmass and the few data that exists is mostly from the periphery of the desert [14]. During the intensive Fennec observation periods (June 2011 and June 2012) two grounds based manned supersites and an automatic weather station network, containing eight stations across the Sahara [15], were provided the measurement data. The supersites were located at Bordj Badji Mokhtar (BBM) (in the very south of Algeria, circa 300 km northwest from the triple point of Algeria, Mali and Niger – 21.37°N 0.93°E, see Figure 1.) close to the climatological location of the Saharan heat low [7,8], as well as farther west at Zouérat (Mauritania – 22.68°N 12.47°W) [16]. Instrumentation at supersites included a flux tower, aerosol sampling equipment, 4 to 8 radiosondes daily, lidar and sodar. Radiosondes were also released at higher frequency across the Algerian network.

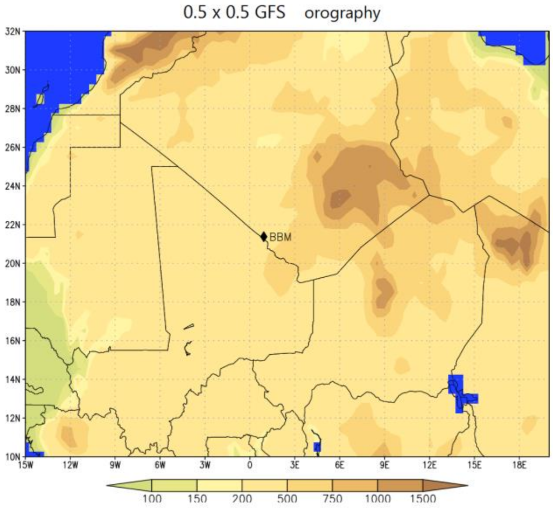

Figure 1. Location of the BBM supersite on the high resolution model orographic map.

The ground based campaign was complemented by several aircraft campaigns. The instrumented UK FAAM BAe-146 aircraft flew into the central Sahara from Morocco in April 2011 and from the Fuerteventura base in June 2011 and June 2012. The June 2011 campaign also included the instrumented French Falcon F20. Over all campaigns, more than 200 hours of science flights were conducted, included the first-ever flights to sample vertical structure of the Saharan ABL using an extensive suite of onboard instrumentation. Approximately 300 dropsondes were also released [7, 13].

2.2. The Single-Column Model

Single-column models (SCM) are very useful tools in ABL investigation. Such models are comprehensive enough to illustrate basic ABL characteristics, describe vertical structure and model turbulent boundary layer processes. The used single-column model [11, 17] employs a first order turbulence closure and a combined (local and nonlocal) mixing scheme [18]. In stable and neutral static conditions, turbulent mixing is simulated as a subgrid (local) process. During unstable conditions, depending on the calculated ratio between local and nonlocal mixing of heat, the model simulates turbulent mixing of sensible heat, moisture, and momentum as a split between small scale and large scale processes. The height of the ABL, one of the mean characteristics of the boundary layer, shows a strong diurnal variation. The model determines the ABL height by specifying a critical value of the bulk Richardson number. The model was verified by controlled offline numerical experiments and the Wangara database [19]. Employing the single-column model vertical potential temperature profiles were calculated and the height of the Saharan boundary layer was estimated.

2.3. The 3D WRF Model

The WRF model [12] developed by UCAR (University Corporation for Atmospheric Research) is a well-established, tested, and documented, non-hydrostatic, mesoscale meteorological model, applicable for both atmospheric research and weather forecasting purposes ranging from micro to global scales. Its modularity and flexibility together with its detailed documentation, as well as a possibility to compare different parameterization processes suited well for the needs of our purposes.

Advanced Research WRF (ARW) core, versions 3.5 (release April 18, 2013), later version 3.9 have been applied to generate numerical input for our NWP system. Input geographical dataset have been generated from USGS (United States Geological Survey) dataset originally used by WRF in 0.5º × 0.5º resolution (see Figure 1.). According to our previous WRF investigations [20] three level telescopic nesting was applied ranging from 27 km in the coarsest domain (d01) through 9 km in the intermediate domain (d02) to 3 km horizontal resolution in the high resolution lowest nested domain (d03) that is located in BBM. The aim behind the nesting is to increase spatial resolution just in the central model domain with the idea to optimise computing time. Telescopic nesting is shown in Figure 2. The number of vertical levels was 30, the top level was on 50 hPa. GFS data with

0.25º × 0.25º resolution was applied as initial and boundary conditions for the limited area integration of the outermost domain in every 3 hours, with no additional data assimilation. Using the same physical parameterizations and four different ABL parameterizations vertical potential temperature profiles and diurnal variation of the ABL height were obtained and examined.

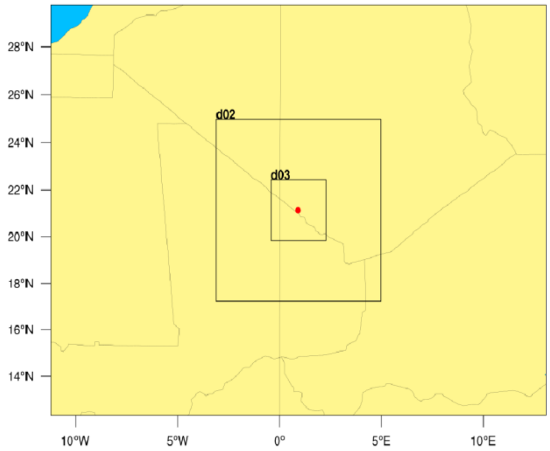

Figure 2. The telescopic three level nested model domains.

3. RESULTS

The SCM was initialized with a 0.5 Hz radiosonde data (potential temperature, water vapor mixing ratio and horizontal wind components) obtained at 0900 UTC 20 June 2011 from the BBM supersite using Vaisala RS92 sonde. This day was chosen because the midday temperature profile was representative of a typical Saharan ABL and the height of the boundary layer exceeds 5000 m by the end of the day, with little influence from synoptic processes [7]. The time variation of the observed quantities at the lowest model level was set explicitly as a lower boundary condition in the model.

Due to the available Fennec data the model was run from 0900 to 1800 UTC. According to previous single-column model investigations [7] calculations were done by a 50 m vertical model resolution and 1 minute time step. ABL depth was calculated every 10 minutes. The model determines the ABL height by specifying a critical value of the bulk Richardson number which was set to 0.25.

Figure 3. compares measured and modelled virtual potential temperature profiles. As it was expected [7] the simple SCM predicts more slowly grow of the ABL in the morning period from 0900 to 1200 UTC. Very rapid growth of the ABL is obtained from 1200 to 1400 UTC. The convective boundary layer reaches maximum height about 1500 UTC and shows no significant structural changes before the evening collapse.

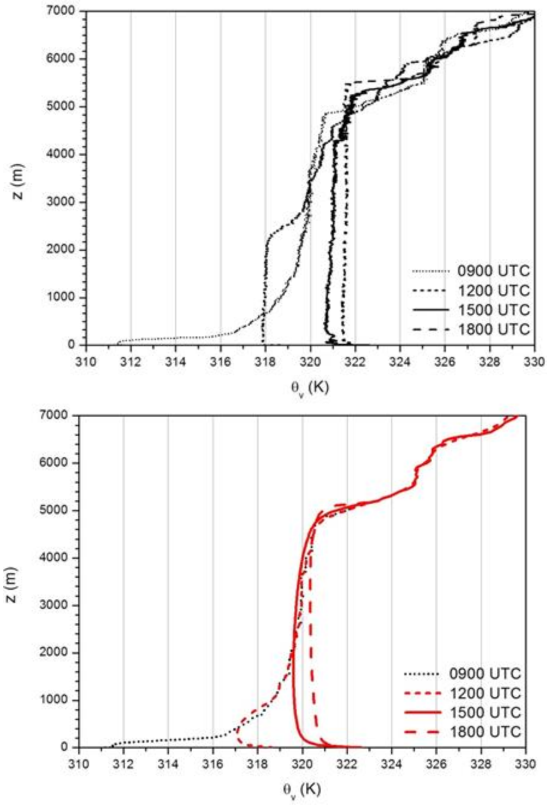

Figure 3. Radiosonde (above) and SCM (below) virtual potential temperature (θ_v) profiles.

Figure 4. represents ABL heights estimated using radiosonde data and calculated by SCM. Due to slowly morning growth of the convective layer our model failed to reproduce the fine vertical structure of the particular boundary layer and underestimates ABL height in the morning period. In the afternoon when the deep Saharan boundary layer was formed the SCM slightly underestimates ABL height.

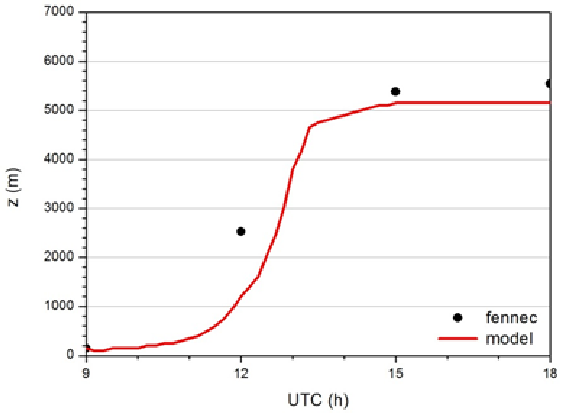

Figure 4. Temporal evolution of the estimated (radiosonde) and predicted (SCM) height of the ABL.

3D WRF runs were performed using the following settings [12]: WRF single–moment 3–class and 5–class schemes for microphysics (option 4), RRTMG shortwave and longwave schemes (option 4), Unified Noah land surface model (option 2), Kain–Fritsch scheme for cumulus parameterization (option 1) expect the high resolution telescopic domain (d03) where the cumulus parameterization was turned off (option 0). We used 4 different boundary layer schemes with the idea to compare potential temperature profiles obtained by different types of description of the mixing processes in the boundary layer. Model runs were done by the following schemes: Yonsei University Scheme (option 1, T1), Mellor-Yamada-Janjic scheme (option 2, T2), Mellor-Yamada Nakanishi Niino level 2.5 scheme (option 5, T3) and asymmetric convection model 2 (option 7, T4).

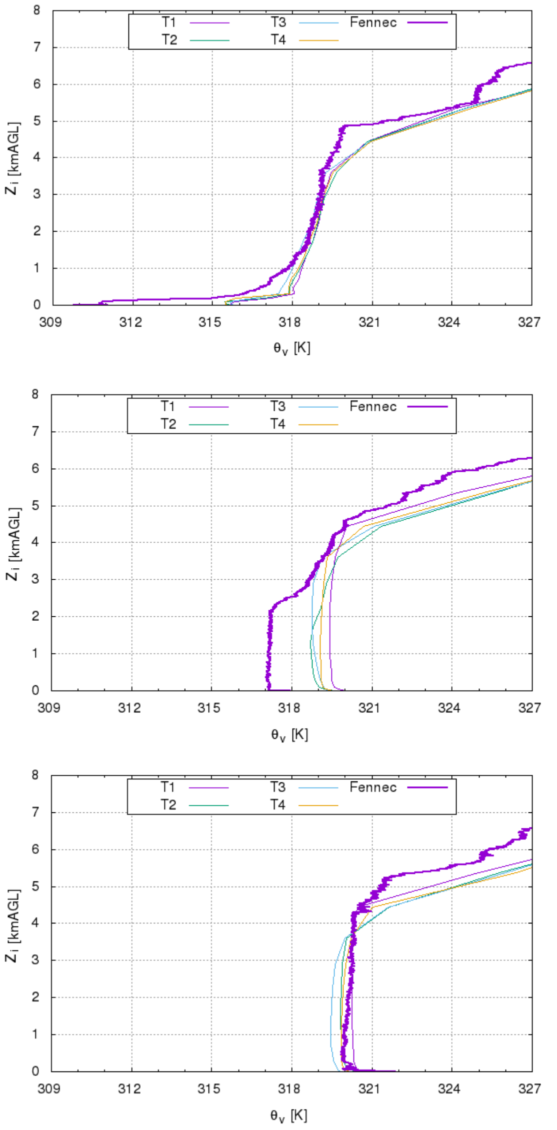

Figure 5. Modelled (3D WRF for BBM) and measured (radiosonde) potential temperature (θ_v) profiles for 0900 UTC (above), 1200 UTC (in the middle) and 1500 UTC (below).

Figure 5. presents comparison between potential temperature profiles for BBM simulated by WRF model using different mixing schemes and measured radiosonde data. Due to higher near surface temperatures at 0900 UTC modelled profiles show earlier formation of the convective layer and overestimate ABL height at 1200 UTC. Furthermore, predicted profiles for 1500 UTC are very close to observations, but underestimate the ABL height.

Figure 6. shows diurnal course of the modelled WRF ABL heights from 0600 to 2100 UTC, and compares model results with radiosonde data estimations. Using all the ABL mixing schemes WRF runs predict rapid formation of the convective ABL from 0900 to 1100 UTC, the layer reaches its full extent to 1200 UTC. Period from 1200 to 1700 UTC is characterized by minor changes in ABL height estimation. Collapse of the boundary layer is predicted around 1800 UTC by all the used schemes. Comparing to observational radiosonde data the model runs predict earlier timing of formation of the convective layer and collapse of the Saharan boundary layer, as well as underestimate maximum ABL height.

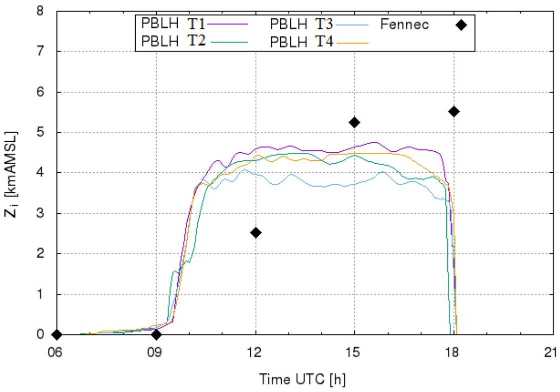

Figure 6. Courses of the estimated (radiosonde) and modelled (3D WRF for BBM) ABL heights.

5. SUMMARY AND CONCLUSIONS

Sahara desert plays crucial role in our climate system. Description of Saharan ABL and simulation of boundary layer processes is very important for weather prediction and environmental modelling. We examined one of the deepest ABL on the Earth employing SCM and 3D WRF model (by telescopic nesting and 4 different mixing schemes). Modelled virtual potential temperature profiles were compared to radiosonde data obtained in Fennec campaign (20 June 2011).

During the formation of the convective layer (from 0900 to 1200 UTC) our SCM failed to reproduce rapid grow and the fine vertical structure of the particular Saharan ABL, as well as underestimates ABL height. In the afternoon when the convective ABL was formed compared to radiosnde measurements underestimation of ABL height is negligible.

3D WRF model runs predict very early grow of the convective ABL and overestimate ABL height in the morning period. During the afternoon model predictions underestimate ABL heights and show early collapse of the boundary layer. Our plan is to perform further WRF simulations with different model setups for the defined Sahara region.

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