Study of Heat Island Effects at Cape Verde during SAMUM−2 with Doppler Lidar and LES

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1. Introduction

During January/February and May/June 2008 we operated a 2-µm Doppler lidar at Santiago, the main island of the Republic of Cape Verde, in the framework of the second Saharan Mineral Dust Campaign (SAMUM−2). We observed the effects of differential heating of the island and the surrounding ocean on the development of the island boundary layer. Depending on the actual wind direction, the air masses were transported over the island's surface from 2 to more than 20 km, before they reached the field site. As a consequence, either low boundary layer (BL) heights of 600-700 m height were observed or convective mixing of diabatically heated air occurred and we observed BL extends of up to 1300 m height (see Figure 1).

2. Field site and instruments

The archipelago is situated approximately 700 km from the West African coast of Senegal and consists of 10 islands. The observation site was located at the south eastern point of Santiago island close to the capital city of Praia (see red circle in Figure 3). In the main direction of the north easterly trade-wind flow only hills of 100 m height were found. However, a mountain with almost 1400 m height is located at the centre of the Santiago. About 30 km northeast of the site (upstream of the typical trade-wind flow), the small island of Maio is situated. Both islands surfaces are characteristic for subtropical scrublands. Heating of air masses over the island and the development of convection strongly depends on the surface heat flux and the residence times over the land surface. Strong gradients of maximum soil temperatures of 43-48 °C during daytime and surface air temperatures of about 24-26 °C were observed.
Several lidar and in-situ instruments were deployed at the Praia Airport (14.94° N, 23.48° W, 75 m asl) within 2 km distance of the coastline in order to study the optical and microphysical properties of Saharan dust and Central African biomass-burning smoke particles [1]. In this contribution we focus on the accompanying measurements of our wind lidar (WILI) [2].

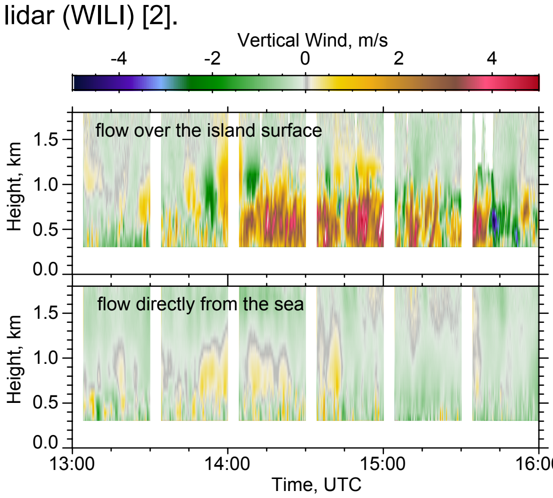

Figure 1: Vertical wind within the BL at the field site during northwesterly (top) and northeasterly air mass advection, respectively, on 23 and on 25 February 2008.

This pulsed coherent Doppler lidar system operates at 2 µm wavelength. The pulsed Tm:LuAG laser delivers pulse energies of 2 mJ at a repetition frequency of 750 Hz. The spatial and temporal resolutions of the system are 75 m and 1-5 s, respectively. By use of a beam-steering unit we were able to measure horizontal and vertical wind speeds.
Our scan strategy focused on observations of vertical winds in the dust and smoke layers and of particle terminal velocities in altocumulus clouds. Hence, we only performed PPI scans every 30 min in order to measure the horizontal wind components. We also conducted RS-92 rawinsoundings once per day and thus we were able to perform comparisons of the derived horizontal wind vectors. Figure 2 shows a single comparison of horizontal wind for the noon soundings on 23 and 25 January 2008. Very good agreement was found. A comparison for all wind profiles within the boundary layer from January/February 2008 determined from wind lidar and RS-92 showed standard deviations of the order of 1 m/s for the wind speed and 20° for the wind direction, respectively.

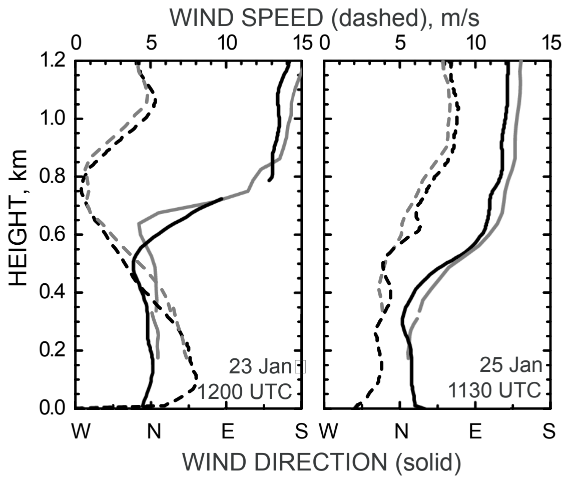

Figure 2: Comparison of wind speed and direction within the boundary layer determined from Doppler lidar (grey) and RS-92 (black) at Cape Verde.

It was found that typically (like on 25 January) the northeasterly trade winds were predominant only up to a few hundred meters of height. Above, the wind direction turned rapidly towards southerly or southwesterly directions.

In addition to the Doppler lidar, a High-Spectral-Resolution Lidar [3] on board the German research aircraft FALCON of the DLR allowed us to observe the maritime and island boundary layer on two-dimensional cut planes.

3. Doppler lidar measurements

On 23 January, north to north westerly surface layer air flow was present. Air masses travelled for more than 20 km distance over the island and thus were heated for about 45 min before we observed them. As seen from Figure 1 (top) a well defined convective boundary layer developed over the island and was measured at the lidar site. Between 1400 and 1500 UTC convective plumes with vertical velocities of >4 m/s were detected up to 1300 m height. Above the mixing layer, very often isolated waves were present (e.g. 1000-1500 m height at 1400 UTC) because of the stable stratification at the top of the BL and the stimulation from convective plumes below. In the vicinity of the lidar site we also observed several dust devils bye eye on that day.

On 25 January, surface winds from north-easterly direction were present. Hence, the air masses were only in contact with the island's surface for very short time (<5 min) before they reached the measurement site. As a consequence, Figure 1 (bottom) shows almost no convective plumes. Only minor up- and downdrafts were observed up to 500 m height. Above, coherent structures of subsiding or uplifted air occurred and prevailed for more than 30 min. These structures were probably connected to sea breeze circulation patterns.

4. Large Eddy Simulations

To further understand our measurements at Cape Verde, we operated a newly developed atmospheric Large-Eddy-Simulation model which runs on graphical processor units (GPU). This new model is based on IfTs All-Scale Atmospheric Model [4]. But in contrast to the original model it allows us to perform LES on a 256x256x64 grid about 80 times faster in approximately real time. We performed the simulations on a domain of 92x92x3.7 km³.

In order to include a well developed maritime BL as boundary condition, we performed a second simulation of an "island free" periodic domain on a second GPU and used these results as nesting boundary input for the original Cape Verde domain. Further details of the model can be found at http://asamwiki.tropos.de. Only by use of this model we can broaden the ground based measurements close to the islands coast into greater time and spatial scales. However, in this first step we did not include the orography of the island in the LES.

Figure 3 shows the LES model output for the vertical-velocity field at 200 m height for 1530 UTC on 25 January 2008. The only input parameters for the LES model were the locally measured atmospheric profiles from radiosondes and the surface fluxes, which we approximated from the GDAS1 model dataset (http://ready.arl.noaa.gov/).

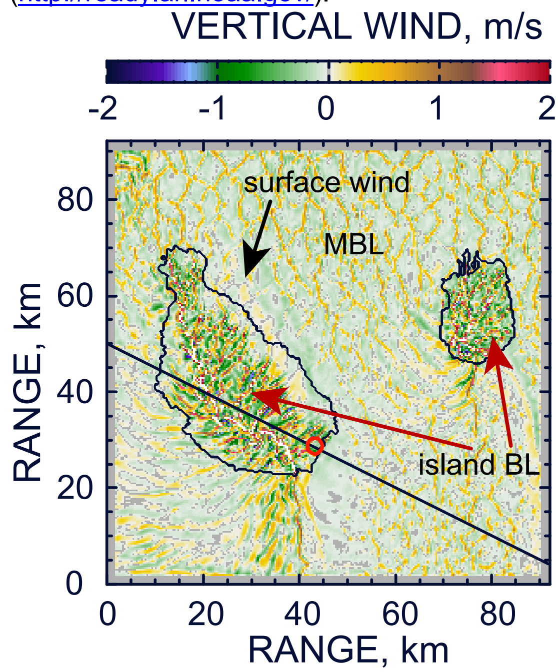

Figure 3: LES model of vertical velocities at 200 m height for the Cape Verde region on 25 January 2008. The red circle marks the lidar site at Santiago Island. The smaller island of Maio lies in close distance.

The simulations are consistent with our measurements and may explain that − although strong convective plumes developed over the central island on 25 January, too − we could not observe these plumes at the measurement site. Moreover, because of the central island heat effect a subsidence region formed at the east coast region, where our wind lidar was located (compare slight green coloured band at the east coast of Santiago in Figure 3 and persistent downwinds in Figure 1).

5. Observations from the airborne lidar

The black line in Figure 3 indicates the flight track of the DLR FALCON. Figure 4 (bottom) shows the aerosol scattering ratio (total/Rayleigh backscattering) at 532 nm wavelength obtained from the airborne HSRL measurements.

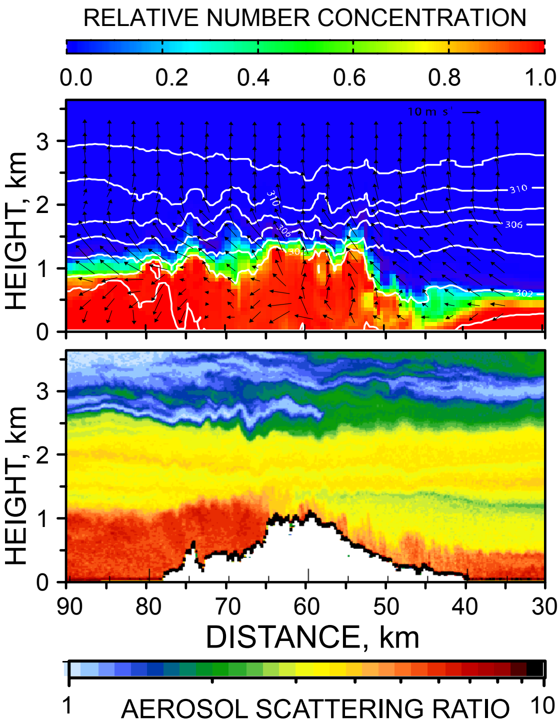

Figure 4: Bottom: aerosol scattering ratio measured with HSRL at 532 nm wavelength onboard the FALCON on 25 January 2008. Top: LES model output for the same plane as the flight track. The colours represent a passive aerosol tracer which has been released from 0-700 m height in the undisturbed MBL. Isentropic levels and horizontal wind speeds are shown in addition. The lidar site was located at 45 km distance in the plot.

On the southeastern side of the island (at 30-45 km distance), the undisturbed MBL with a height of about 600-700 m was observed. In contrast, on the northwest side of the island (70-90 km distance) a mixing layer height of 1100-1200 m height was present. It should be noted that the wind direction in the boundary layer was perpendicular to the cut plane in this figure, i.e., the air masses did not overpass the mountain area (see Figure 3) but moreover were in contact with the island for longer times. In addition, Figure 4 (top) shows the LES output for the same cut plane of Figure 3. For the simulation we released a passive aerosol tracer in the undisturbed MBL, which then was nested into the model regime with the islands. Again, on the east side of the main island, a “clear slot” formed, because of subsidence at the islands coasts and uplift above the centre of the island. The heated island surface, enables convective plumes to form and a mixed island BL to grow. In the model, these plumes transport surface aerosol upwards and reach heights of 1000-1400 m over the island, which is in good correspondence to the FALCON measurements. Also, the waves visible on the isentropic levels at even higher altitudes are consistent with the observed waves at 2-3 km altitudes.

6. Conclusion

During SAMUM−2 we observed complex layers of maritime aerosol and Saharan dust (both within the MBL) and biomass-burning smoke (above the MBL) in the vicinity of Cape Verde. This study shows that the small islands in the Atlantic Ocean can have a strong influence on vertical mixing of these aerosol layers. The heat island effect can enable the formation of lofted dust layers by uplift of dust at the centre of the islands and further by advection of the dust out on the sea and over the MBL, caused by the trade wind counter flow from the southwest at these altitudes. In the same way, also smoke particles from lofted layers could be washed downward to the surface.
LES modelling was applied to better interpret the observations. These simplified simulations, without considering the island’s orography yet, were already very consistent with the observations. However, for further studies we will implement the terrain of the islands into our model.
A detailed analysis of this first study has already been submitted for publication [5].

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8. References

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