General description of IOPs

The most favorable situations for analyzing the evolution of the CBL during the afternoon transition corresponded to either anticyclonic or dry post-frontal conditions. In the first atmospheric conditions, the low troposphere was governed by the mountain-valley flows, with a northeasterly flow over the Plateau during daytime turning to south-west during nighttime. The CBL was either clear, or with few cumulus clouds. Post-frontal conditions corresponded to northwesterly winds that could be modified by the mountain-valley circulation. On these days, some cumulus clouds appeared.

During IOPs, the wind at the surface was generally weak. Surface sensible heat flux varied in relation with the surface characteristics between 100 W m^{-2} at midday over grass and moor to 400 W m^{-2} over the forest. Figure 1 shows the temporal evolution of the measured surface heat flux over different land uses during all the IOPs of the campaign. The latent heat fluxes were much more consistent between the various surfaces, reaching around 350 W m^{-2} at midday for all IOPs, which can be related with previous rainy periods in May and early June. The boundary-layer depth was usually around 1000 m, and it did not reach more than 1400 m during the campaign. The morning growth rate was quite variable from day to day.

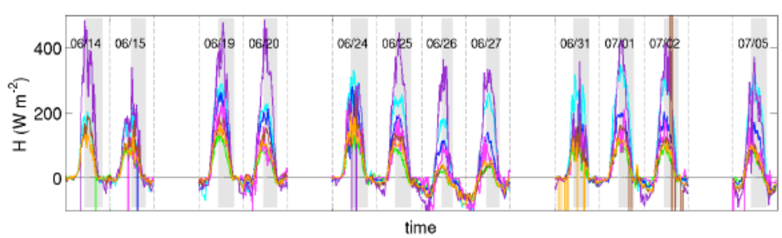

Figure 1: Temporal evolution of the surface sensible heat flux measured over different land usesduring all IOPs of the BLLAST campaign. Courtesy of Fabienne Lohou.

Analyzing the observed z_1 , we deduce three different patterns of the evolution of the boundary-layer inversion from the local maximum of the refractive index coefficient measured by the UHF wind profiler (See Fig. 2). The first z_1 evolution consisted of a smooth increase in the height of the CBL from morning until midday. In these IOPs, z_1 reach values close to 1000 m. The second type of BL development showed an abrupt increase in the boundary-layer depth during the morning, reaching higher values of z_1 up to around 1200-1400 m and becoming approximately constant the rest of the day. Finally, the last boundary-layer evolution observed consisted of a steep increase and decrease in the boundary-layer depth.

In the following subsection, we describe the meteorological characteristics of each IOP. The analysis of the local meteorological conditions is developed when-

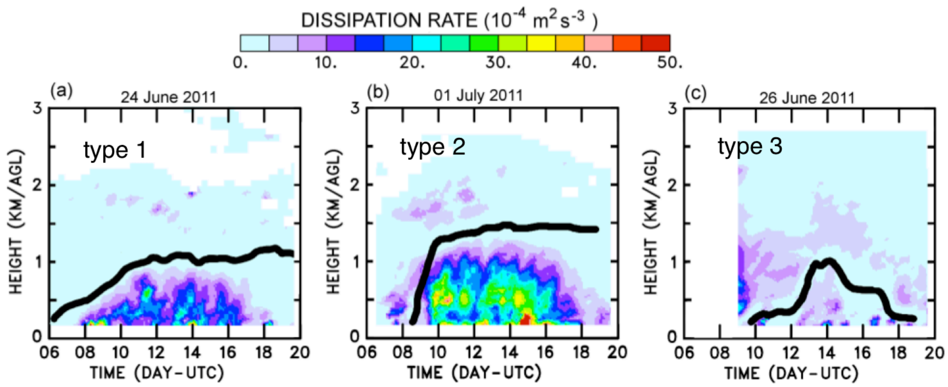

Figure 2: Three observed patterns of the evolution of the boundary-layer depth measured by UHF at Supersite 1. Courtesy of Marie Lothon.

ever possible, with the information obtained from the standard radio soundings launched from LA around 12:00, 18:00 and 00:00 UTC.

IOP 1 (15 June 2011)

During this IOP, a high-pressure system was located over the area of the campaign. However, a large low-pressure system was approaching from the north-east. This low pressure-system arrived over the Pyrenees region the following day, 16 June 2011, and meteorological conditions became unsuitable for performing an IOP (see Fig. 3a).

The evolution of the boundary-layer depth from this IOP showed an intermediate growth rate and slightly descending summit inversion during the LAT (see Fig. 3b). This can be included in type 1 shown in Fig. 2.

During this IOP, standard radio soundings were not launched during the afternoon transition; the only one was launche at 11:15 UTC. On the other hand, we used frequent radio soundings at 16:47 and 19:05 UTC to analyze the local meteorological conditions during the afternoon.

IOP 1 had clear skies with short partially clouded periods (not shown). The potential temperature was around 300 K at 11:15 UTC, with variation lower than 2 K from 16:47 to 19:05 UTC. Humidity was relatively high, 14 g kg^{-1} at 11:15 and 16:47 UTC, with a variation of 2 g kg^{-1} during the afternoon (19:05 UTC). The wind was very light close to the ground and it increased to approximately 2 m s^{-1} inside the boundary layer from the time of the first to last radio soundings being launched. In the free atmosphere, the wind speed increased to 8 m s^{-1} in all radio soundings analyzed. The wind pattern was clearly marked by the mountain-valley flow. Around 11:15 UTC, the winds came from the north-east and turned to north-west in the afternoon (19:05 UTC). All variables were constant in the free atmosphere from 11:15 to 19:05 UTC (see

Figs. 3c, d, e and f).

IOP 2 (19 June 2011)

This was the first day of an anticyclonic period caused by a high-pressure system extended from the Atlantic Ocean. Therefore, clear skies were observed during the whole day (not shown). However, a large low-pressure system was approaching from central Europe (See Fig. 4a).

The evolution of the boundary-layer depth in IOP 2 presented a rapid growth during the morning, with leveling inversion during the afternoon transition (see Fig. 4b). This can be included in type 2 shown in Fig. 2. This leveling inversion can also be observed in the analysis of radio sounding measurements (see Fig. 4c).

The potential temperature was lower than the previous IOP. At 11:15 UTC, potential temperature was 293 K. During late the afternoon, at 17:43 UTC, it increased 4 K. During the night, a stable boundary layer was observed and the potential temperature close to the ground was 291 K. The humidity evolved from 5.5 g kg^{-1} at 11:15 UTC to 7.5 g kg^{-1} at 22:54 UTC. Wind conditions were similar to the previous IOP. Wind speed was really low inside the boundary layer, below 4 m s^{-1}, and wind speed in the free atmosphere was higher, approximately 15 m s^{-1}, producing a marked shear in the inversion zone from 11:15 to 22:54 UTC. Wind direction from 11:15 to 17:43 UTC was north-west turning to south-east at night (22:45 UTC). All variables were well-mixed in the free atmosphere from 11:15 to 22:45 UTC (see Figs. 4c, d, e and f).

IOP 3 (20 June 2011)

In general, meteorological conditions were really similar to the previous day with a high-pressure system covering the area of Lannemezan. Although the large low-pressure system over central Europe was moving away, a new one was approaching from the west the British Islands (see Fig. 5a). This low pressure system caused a three days period when the weather conditions were not suitable for the objectives of the campaign.

The evolution of z_1 on IOP 3 presented an intermediate growth rate, reaching values of around 1100 m during midday (see Fig. 5b). This can be included in type 1 shown in Fig. 2. The vertical profile of potential temperature clearly shows this continuous increase in the boundary-layer depth during the day (see Fig. 5c).

In IOP 3, potential temperature increased from 300 K at 11:01 UTC to nearly 303 K at 16:59 UTC. Moreover, during nighttime, when a stable boundary layer was observed, the potential temperature near the ground descended to 295 K at 23:04 UTC. During daytime, the humidity was more or less constant, around 8 g kg^{-1} at 11:01 and 16:59 UTC, increasing to 12 g kg^{-1} at nighttime (23:04 UTC). Wind speed at the ground was higher at 11:01 UTC (close to 5 m s^{-1}) than during the afternoon, which decreased to 3 m s^{-1} (at 16:59 UTC). As the day progressed, it decreased more to values close to 2 m s^{-1} at 23:04 UTC.

Wind direction turned from north-east to south-west from 16:59 to 23:04 UTC (see Figs. 5c, d, e and f).

IOP 4 (24 June 2011)

A large high-pressure system was covering the western part of Europe and the north of Africa (see Fig. 6a).

The evolution of the boundary-layer depth had an intermediate growth rate, reaching values of z_1 lower than the previous IOP of approximately 1000 m at midday. Moreover, the boundary-layer depth slightly decreased during the afternoon transition (see Fig. 6b). This is also shown in the vertical profile of potential temperature (see Fig. 6c). This evolution of the boundary-layer depth can be included in type 1 shown in Fig. 2.

In IOP 4, some clouds appeared during the morning, moving to the east, but the sky cleared up during the day (not shown). Potential temperature was lower from the previous IOP, evolving from 290 to 295 K from 10:52 to 16:40 UTC. At nighttime (23:12 UTC), the potential temperature near the surface descended to 288 K. What is more, the humidity was constant from 10:52 to 23:12 UTC, close to 6 g kg^{-1}, showing a deep shear in the inversion area. In relation with wind conditions, the UHF measured a very strong inversion (with a large wind-shear) at approximately 1.5 km (not shown), which can also be observed in the vertical profile of wind speed shown in Fig. 6c. As the day progressed, the wind speed increased from 2 m s^{-1} at 10:52 UTC to 3 m s^{-1} at 16:40 UTC. At nighttime (23:12 UTC), it continued increasing, but it was also light at under 4 m s^{-1}. The wind direction, as in the previous IOP, turned from east to south-west from 16:40 to 23:12 UTC (see Figs. 6c, d, e and f).

IOP 5 (25 June 2011)

The synoptical conditions were similar to the previous day, with a large high-pressure system expanding toward Eastern Europe from Western Europe and North Africa (see Fig. 7a).

The evolution of z_1 from IOP 5 was very smooth, as the growth rate was really low, creating a really thin layer which reached values of just around 600 m during midday (see Fig. 7b). Despite this, it can be included in type 1 shown in Fig. 2.

Potential temperature increased faster and to higher values than the previous day, from 298 K at 11:00 UTC to 303 K at 17:00 UTC. When the stable boundary layer was well developed at 23:00 UTC, the potential temperature decreased to 296 K. Humidity from 11:00 to 17:00 UTC was constant at 6 g kg^{-1}, but at nighttime (23:00 UTC) it increased to 9 g kg^{-1} in the stable boundary layer. Wind speed during daytime was higher than previous IOPs and it increased homogeneously from 3 m s^{-1} at 11:00 UTC to 7 m s^{-1} at 23:00 UTC. Wind direction was constant to the east inside the boundary layer and to the west in the free atmosphere from the time of the first to the last radio sounding (see Figs. 7c, d, e and f).

IOP 6 (26 June 2011)

The synoptical conditions started to change from the previous IOP; the large high-pressure system covering Europe began to be affected by a low-pressure system that was approaching from the western coast of the Iberian Peninsula (see Fig. 8a).

The evolution of the boundary-layer depth consisted of a slow growth in the boundary layer during the morning, and a collapse of the inversion during the afternoon transition, reaching maximum values of below 700 m (see Fig. 8b). This day belongs to type 3 shown in Fig. 2.

IOP 6 was not a completely clear day; there were some high level clouds until noon, and some precipitation in the mountains. Moreover, convective clouds appeared in the afternoon over the mountains (not shown). Nonetheless, IOP 6 had warmer potential temperatures, even at 11:00 UTC (307 K) or at 17:00 UTC (308 K), which, among other explanations, could be related to a shallow boundary layer. Humidity evolved from 7 g kg^{-1} at 11:00 UTC to 10 g kg^{-1} at 17:00 UTC, but it maintained the values during nighttime (23:00 UTC). In contrast, wind speed was constant from 11:00 to 17:00 UTC, at values close to 4 m s^{-1}, and it increased to 9 m s^{-1} at 23:00 UTC within the boundary layer. Wind direction evolved from east at 17:00 UTC to south at 23:00 UTC (see Figs. 8c, d, e and f).

IOP 7 (27 June 2011)

This was the last of 4 consecutive days with suitable meteorological conditions. A low-pressure system was covering the Iberian Peninsula which caused a two days period when the weather conditions were not suitable for IOPs, while a high-pressure system was moving to Central Europe (see Fig. 9a).

The evolution of z_1 from IOP 7, as in the previous IOP, was really smooth and the boundary-layer inversion collapsed from a rather shallow BL of less than 500 m at 17:00 UTC (see Fig. 9b) also shown in the vertical profile of potential temperature (see Fig. 9c). This evolution was also included in type 3 shown in Fig. 2.

The evolution of the potential temperature was similar to the previous IOP, with the high potential temperatures of close to 308 K during daytime at 11:00 and 17:00 UTC. However, at 23:00 UTC the potential temperature decreased rapidly to 300 K due to a cold front which was approaching from the British Islands. The humidity was higher than the previous day, due to a prolongated warm period. At 11:00 and 17:00 UTC, humidity was 9 g kg^{-1}, and at 23:00 UTC it increased to 14 g kg^{-1} . Wind speed increased during the day from 4 m s^{-1} at 11:00 UTC to 6 m s^{-1} at 23:00 UTC. Wind direction, as on previous days, moved from north at 11:00 UTC to east at 17:00 to west at 23:00 UTC (see Figs. 9c, d, e and f).

IOP 8 (30 June 2011)

This was the first of three consecutive IOPs. A large high-pressure system was located over the area of the campaign, which covered most of Europe and North Africa (see Fig. 10a).

The evolution of the boundary-layer depth was characterized by a large growth rate during the morning and z_1 being constant during the afternoon transition (see Fig. 10a). This kind of evolution is close to those described in type 1 (see Fig. 2).

During IOP 8, the sky was covered with low clouds, but it cleared slowly because the clouds became thinner in the afternoon (not shown). After a period with weather conditions not suitable for the objectives of the campaign, the potential temperature did not reach high values; it was around 292 K at 11:00 UTC and increased to 296 K at 17:00 UTC, then decreased to lower values at night (23:00 UTC). The humidity was constant during daytime, around 6 g kg^{-1} from 11:00 to 17:00 UTC, and it slightly increased to 8 g kg^{-1} at 23:00 UTC . Wind speed did not have large variation from 11:00 to 17:00 UTC, with low wind speed blowing within the boundary layer at 3 m s^{-1}. At 23:00 UTC, the wind speed increased slightly. There was a really marked shear with an inversion jump of approximately 6 m s^{-1} observed in all the radio soundings. Wind direction was not constant, turning and fixing from north-east at 11:00 UTC to south-west at 17:00 UTC (see Figs. 10c, d, e and f).

IOP 9 (1 July 2011)

During this IOP, a large high-pressure system was located southwest of the British Islands. The influence of this high-pressure system extended towards the east (see Fig. 11a). Higher up in the atmosphere, at 500 hPa, a strong ridge extended over Southern Europe, causing a predominantly western flow in the region.

The evolution of z_1 presented faster growth during the morning, with leveling inversion during the afternoon transition (see Fig. 11b). This sharp increase in the boundary-layer depth can be explained by assuming the merge of the boundary layer with the residual layer, as will be explained in the next chapter. The evolution of z_1 can be included in type 2 (see Fig. 2). This leveling inversion is also shown in the vertical profiles of Fig. 11c.

Potential temperature was slightly higher than the previous day; specifically, it was 296 K at 11:00 UTC and 299 K at 17:00 UTC, decreasing to 297 K at 23:00 UTC. Humidity was again constant during IOP 9, although, it was slightly lower at around 5 g kg^{-1} from 11:00 UTC to 17:00 UTC. At 23:00 UTC the vertical profile of humidity is less clear, showing a pronounced curve inside the stable boundary layer. Wind speed was light, under 3 m s^{-1} observed in all radio soundings. Wind direction was north-east until 17:00 UTC and moved to north-west at 23:00 UTC (see Figs. 11c, d, e and f).

IOP 10 (2 July 2011)

During this IOP, the synoptical conditions changed and there was a low-pressure system located over the area (see Fig. 12a).

The evolution of the boundary-layer depth was characterized by a moderate growth rate, and the height descended slightly during the afternoon transition (see Fig. 12b). Even though z_1 did not reach values as high as during the previous IOP, it reached approximately 1000 m. This evolution can be described as type 1 shown in Fig. 2.

The sky was clear, but some low stratocumulus started to appear at the end of the day (not shown).

During IOP 10, there were no standard radio soundings launched by LA at 23:00 UTC. Therefore, we show a GRAW radio sounding launched at 20:30 UTC. The potential temperature was higher than during the previous day, at 300 K at 11:00 UTC and 304 K at 17:00 UTC. The potential temperature at night descended to just 298 K at ground level. The humidity was similar to the previous day, close to 5.5 g kg^{-1} from 11:00 to 17:00 UTC, and increased to 7 g kg^{-1} at 23:00 UTC. The wind was weak in the boundary layer, around 2 m s^{-1} from 11:00 to 17:00 UTC, with a slight increase at 20:30 UTC. However, there was a really marked shear at z_1 of 10 m s^{-1} at 11:00 UTC. Wind direction was mainly from the north-east in all the radio soundings (see Figs. 12c, d, e and f).

IOP 11 (5 July 2011)

This was the last IOP of the campaign. A high-pressure system was located over the area, expanding from the Scandinavia (see Fig. 13a).

The evolution of the boundary-layer depth from IOP 11 was characterized by a slow growth of the boundary-layer depth during the morning. Moreover, it collapsed during the afternoon, giving maximum values of the boundary-layer depth less than 1000 m (see Fig. 13b). This situation is considered in type 3 (see Fig. 2).

Due to the special evolution of the boundary-layer depth, the potential temperature also evolved in a particular way. At 11:00 UTC the potential temperature was around 300 K, with a clear inversion jump; but in the following radio sounding at 17:00 UTC, the potential temperature inversion jump was nearly unappreciable and the potential temperature increased to 302 K. The humidity was higher than the previous days, being 7 g kg^{-1} near the surface during the time of the three radio soundings. Wind speed clearly increased during daytime from 1.5 m s^{-1} at 11:00 UTC to nearly 5 m s^{-1} at 17:00 UTC. At 23:00 UTC, the wind speed was slightly higher, but the increment was less marked than during daytime. Wind direction turned from east at 11:00 UTC to west at 17:00 UTC (see Figs. 13c, d, e and f). The wind became strong later in the day, starting progressively around 1800 UTC above surface according to the UHF.

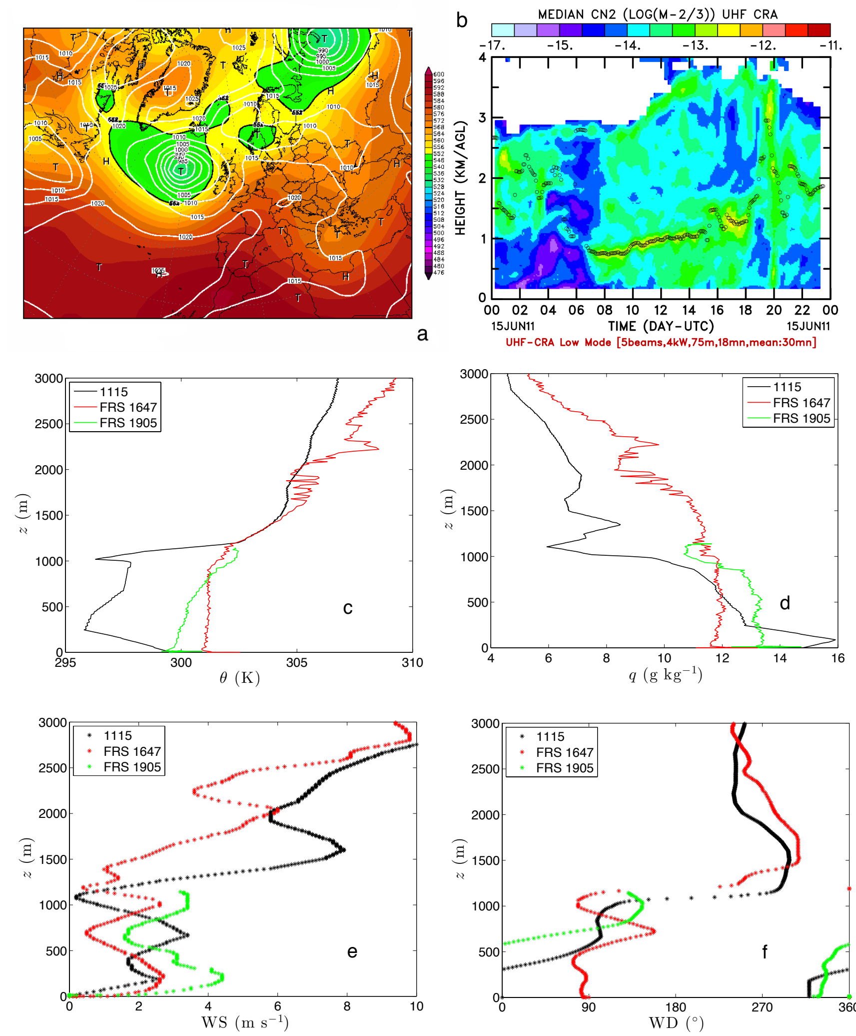

Figure 3: (a) 500hPa geopotential height (color contours) and surface pressure (white contours) obtained by NCEP Reanalysis, (b) temporal evolution of the boundary-layer depth measured by UHF located at Supersite 1 and vertical profiles of (c) potential temperature, (d) humidity, (e) wind speed and (f) wind direction measured by radio soundings during 15 June 2011.

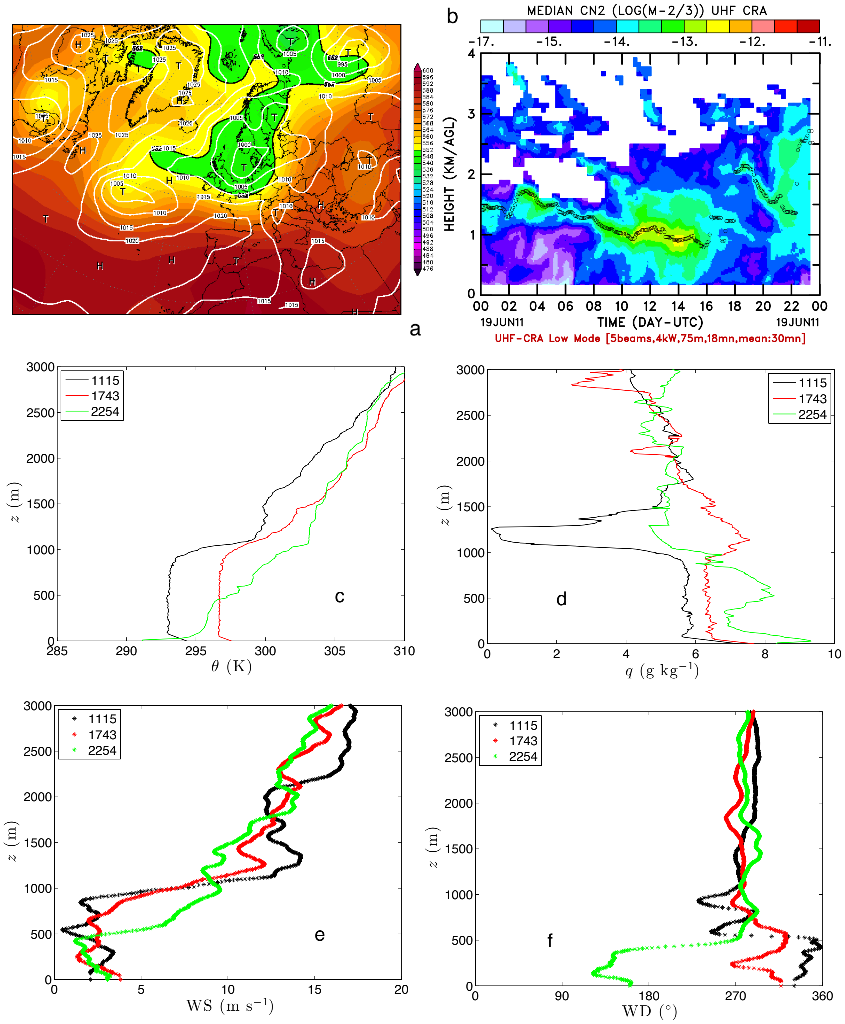

Figure 4: Same as Fig. 3 for 19 June 2011.

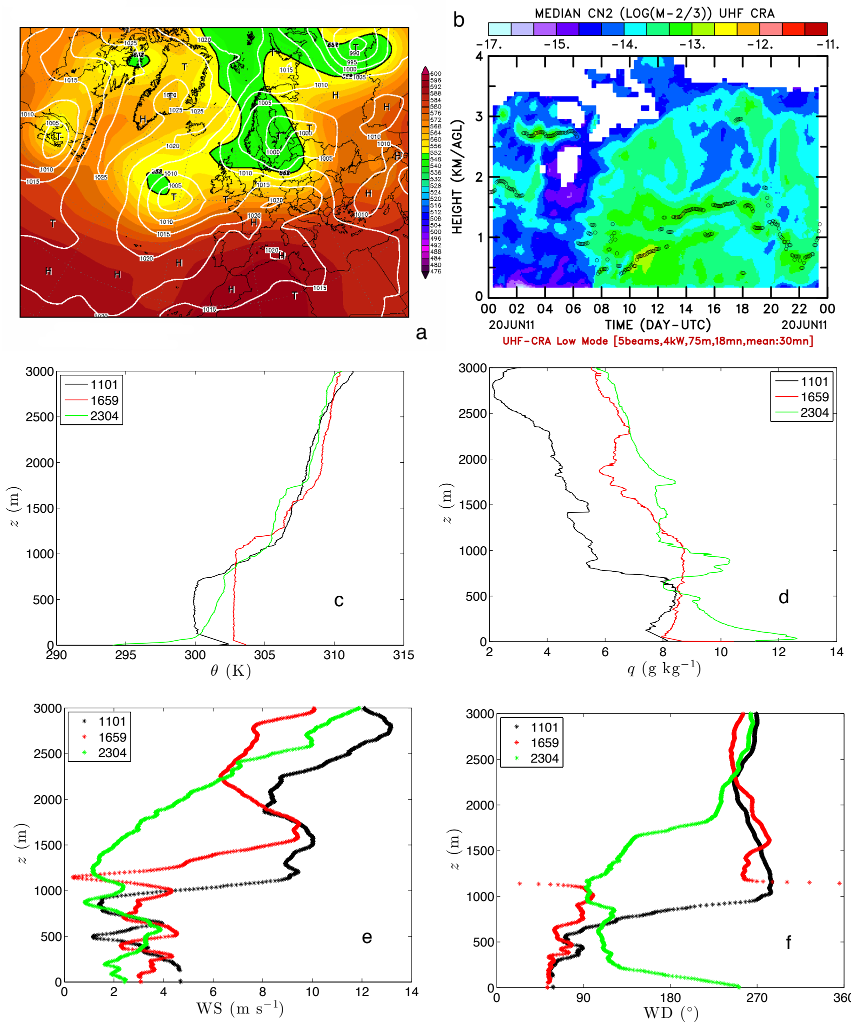

Figure 5: Same as Fig. 3 for 20 June 2011.

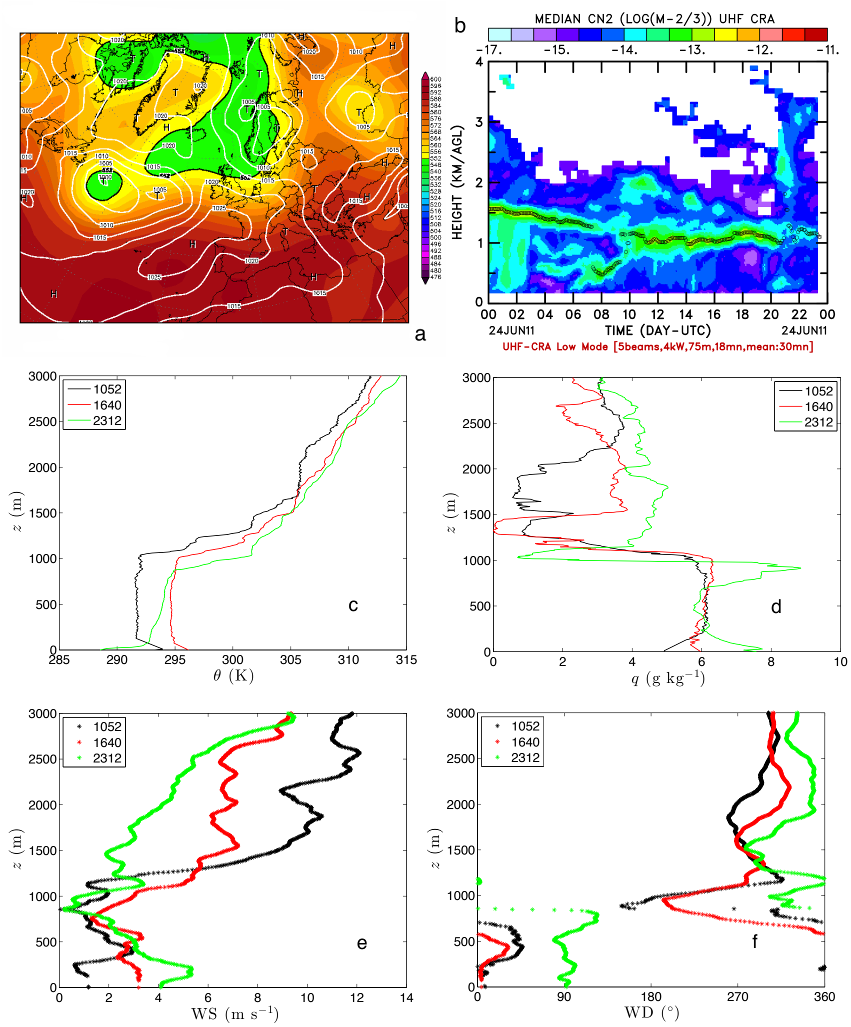

Figure 6: Same as Fig. 3 for 24 June 2011.

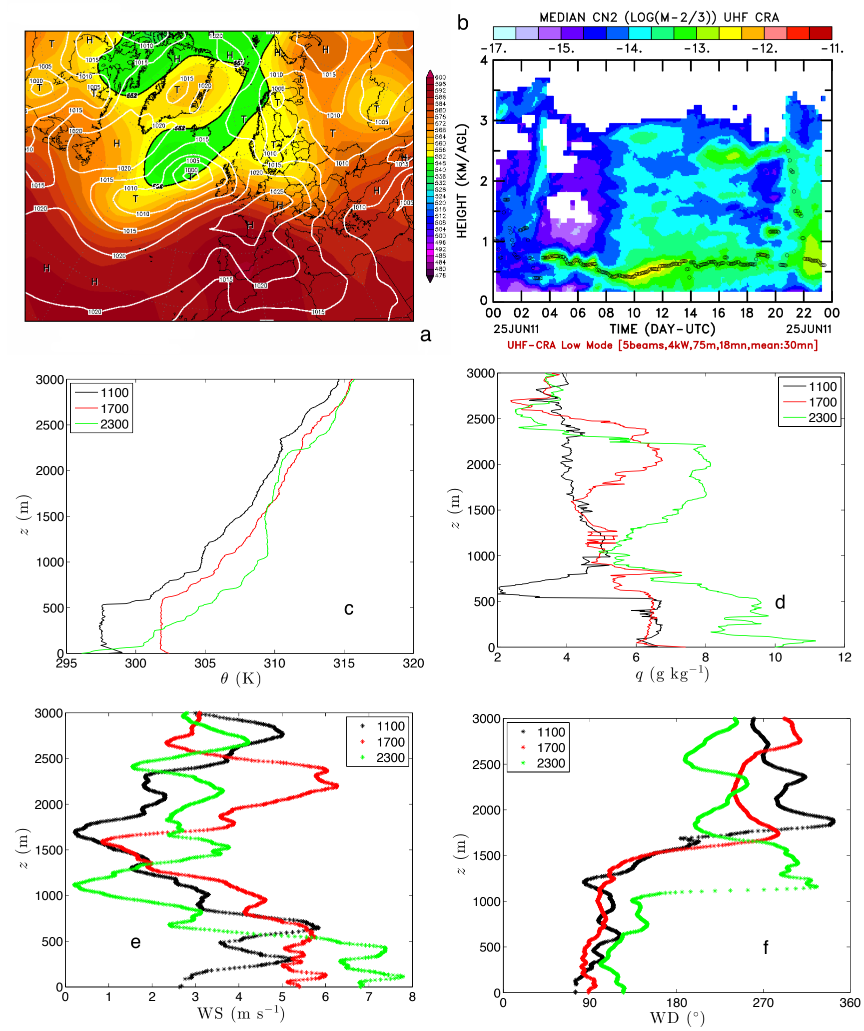

Figure 7: Same as Fig. 3 for 25 June 2011.

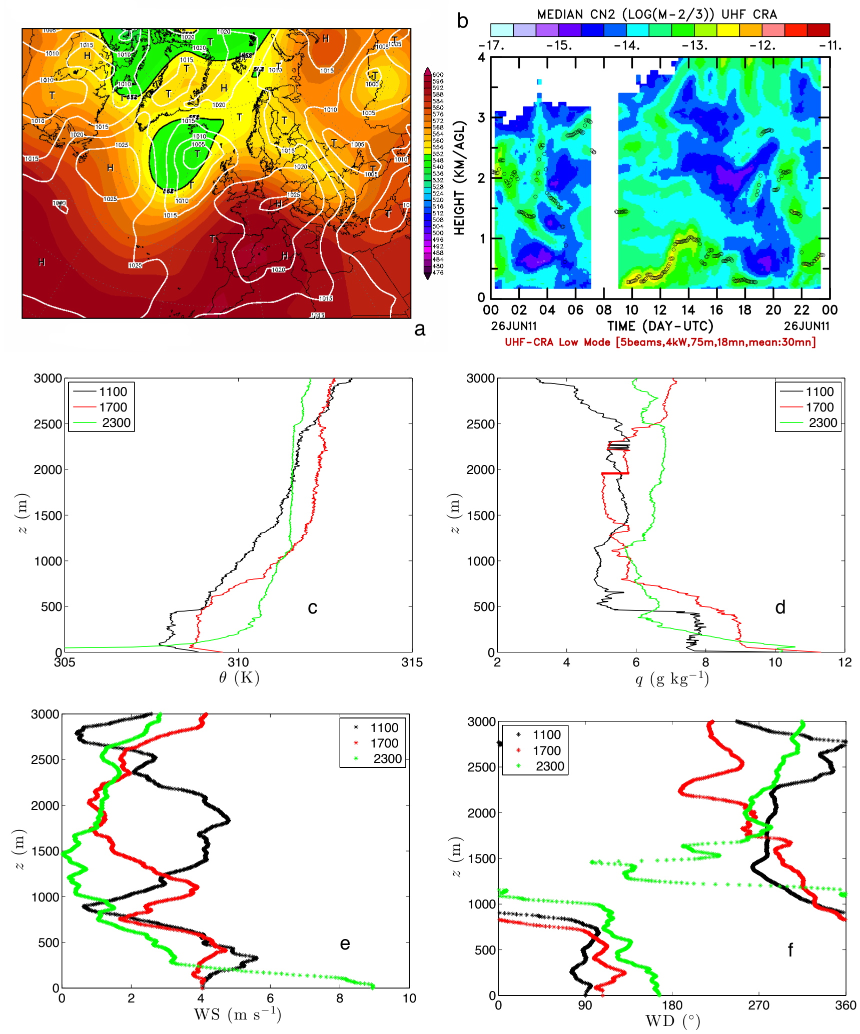

Figure 8: Same as Fig. 3 for 26 June 2011.

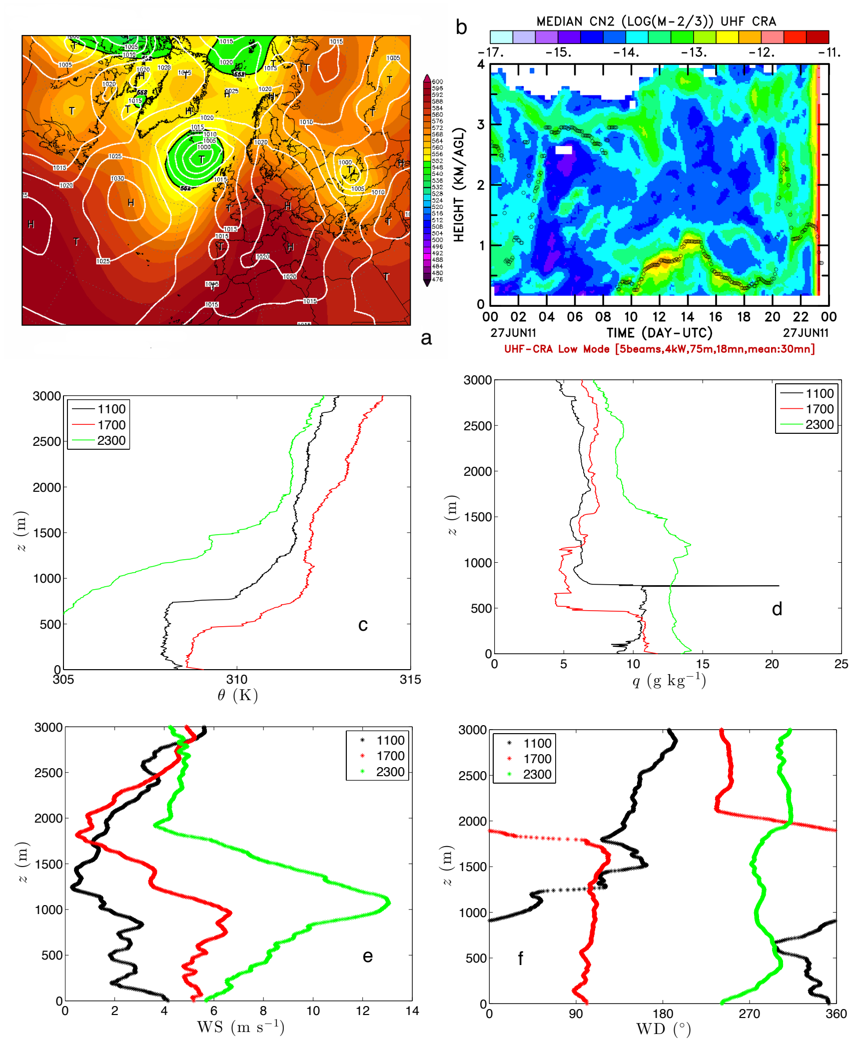

Figure 9: Same as Fig. 3 for 27 June 2011.

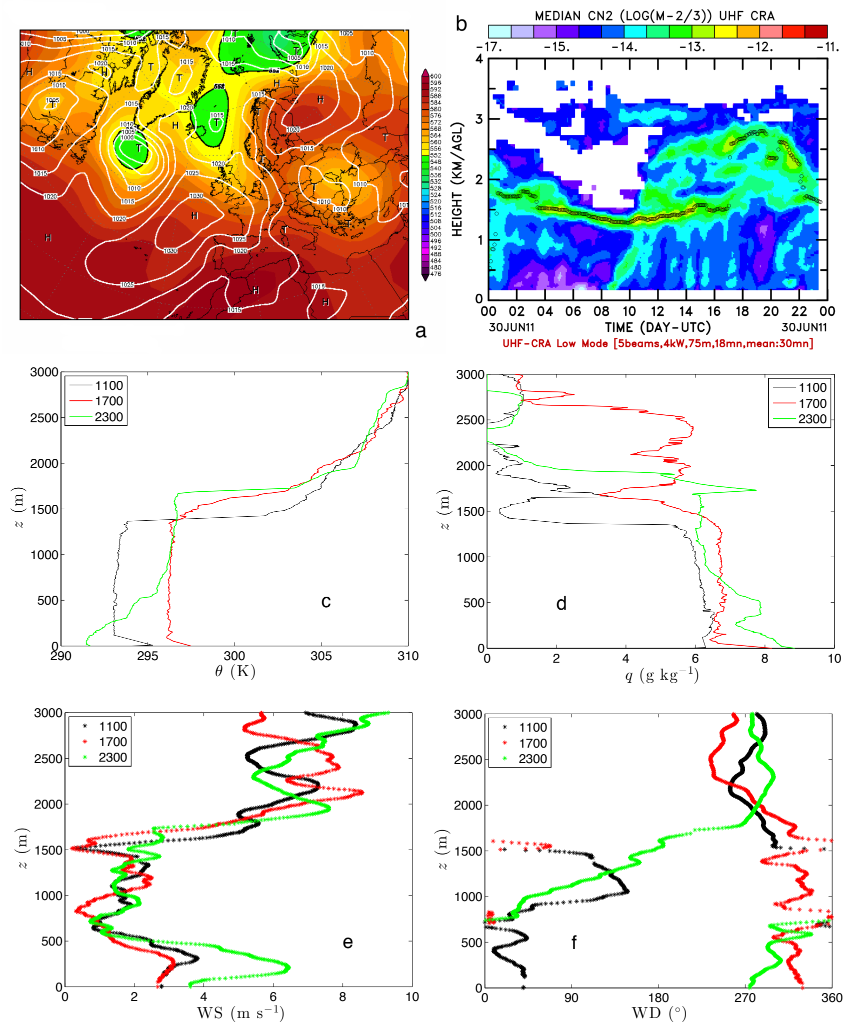

Figure 10: Same as Fig. 3 for 30 June 2011.

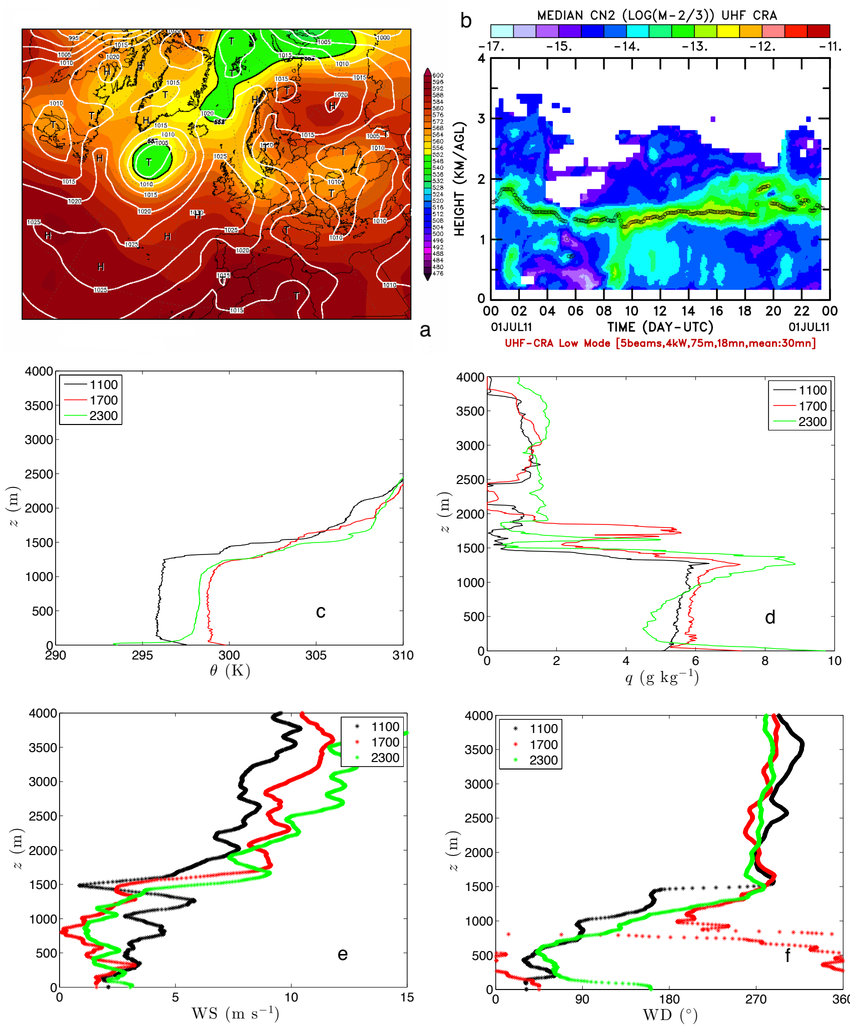

Figure 11: Same as Fig. 3 for 1 July 2011.

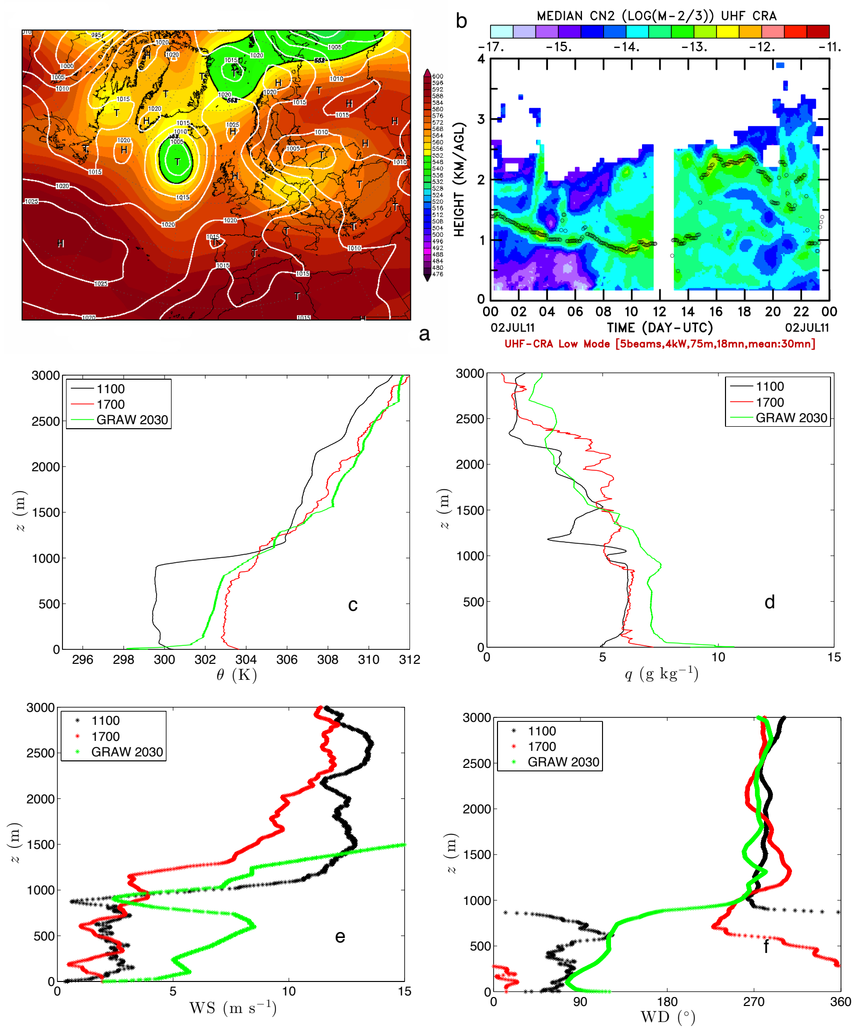

Figure 12: Same as Fig. 3 for 2 July 2011.

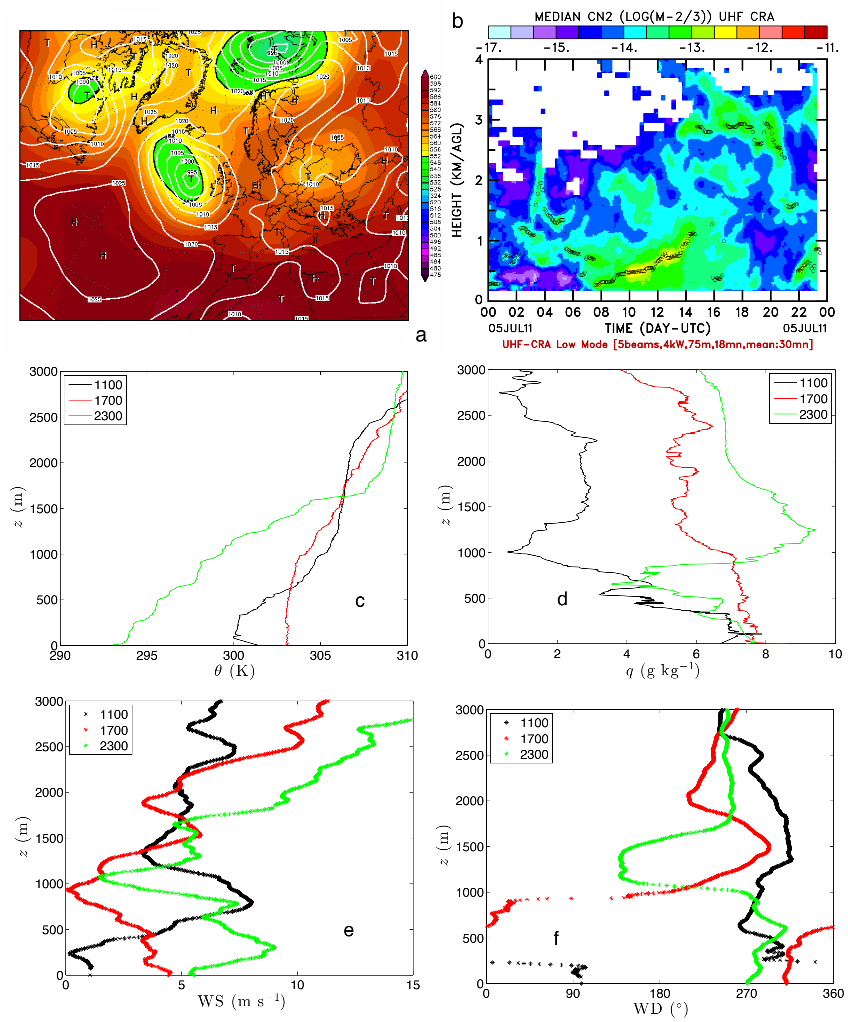

Figure 13: Same as Fig. 3 for 5 July 2011.