Characteristics of the Boundary Layer Structure Under Extreme Surface Conditions at Cordoba, Argentina

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Key Points:

* Extreme hot and dry (precipitation) conditions showed higher (lower) boundary layer height compare to the average conditions.
* Boundary layer height changes under extreme conditions can be attributed to the changes in the surface sensible heat fluxes.
* Extreme dry conditions can initiate extreme hot conditions by increasing heat entrainment and storing the heat within the residual layer over the night.

Abstract

The structure of boundary layer is largely determined by surface properties. In this study, we investigate how different is the boundary layer under three kinds of extreme surface conditions. Sounding measurements of extreme dry, hot, and precipitation conditions at the Cordoba site of the RELAMPAGO field campaign are used. Under 3-hourly extreme dry and hot conditions, nearly doubled height of boundary layer is observed, while it was halfened under extreme precipitation condition. These changes in boundary layer height was associated with vertical temperature gradient near surface and changes in surface sensible heat flux. When there were consecutive extreme dry days, heat entrainment from the top gradually increased and heat was stored within the nocturnal boundary layer and resulted in extreme hot surface temperatures. Thus, extreme dry conditions can work as a springboard to extreme hot conditions.

1. Introduction

The atmospheric boundary layer is the atmospheric layer that is closely related to our daily life due to its proximity. For example, the concentration of pollutants can be modulated by vertical mixing of the air within the layer (Liu and Chan, 2002; Kim and Kim, 2020), and surface temperatures can be changed by the heat stored within the layer (Miralles et al., 2014).

Not only boundary layer affects the properties on the surface, but also it is largely affected by surface conditions (Garrat, 1992). Surface winds, humidity, and temperature gradients can affect surface fluxes that determine the structure of the boundary layer. Land-use and soil type can also change boundary layer processes. Then, one could ask a question what would happen if there exist extreme conditions over the surface. How different would boundary layer look like under extreme surface conditions?

This study utilizes profound measurements done within the RELAMPAGO (Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations) field program to answer the question. In addition to figuring out different structures of the vertical profiles, we tried to investigate what makes the boundary layer different from average conditions. On top of that, we also take a closer look at the evolution of boundary layer when there were consecutive extreme dry and hot conditions over the surface to check the potential relationship between two kind of extremes.

2. Data and Methods

The RELAMPAGO field program offers rich and intense atmospheric and hydrologic data measured during the operation period over Argentia. We selected one radiosonde, two flux tower, and three meteorological station near Cordoba region (Fig. 1). Tower and station data are used to determine extreme conditions, and sounding measurement is used to investigate corresponding vertical structure of boundary layer. In this study, only measurements from 2018 October 15th between 2019 April 30th are used, the period when soundings were available.

We used three different kind of extreme conditions. Extreme dryness, temperature, and precipitation periods are defined as the 3-hourly interval that 3-hour average value of each variable exceeds 5th percentile end of relative humidity, temperature, and precipitation, respectively. 3-hour average is used to match with sounding measurement term, so that we can easily select corresponding soundings. In order to get robust extreme conditions over the area, we further filtered out periods when all available tower or station data agree as extreme period.

Boundary layer height is calculated following Seidel et al., 2012, the altitude where Bulk Richardson number exceeds 0.25. Surface sensible and latent heat flux are derived from the covariance of vertical wind with temperature and water vapor that were measured from flux tower at Berrotaran.

A picture containing map

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**Figure 1**. Location of measurements used in this study. Radiosonde (red), flux tower (yellow), and meteorological station (black) measurements from RELAMPAGO field program are used.

**3. Extreme conditions and their vertical structure**

Most of the extreme conditions are observed during 09-15 local time when boundary layers grow, not during the evening and night when the layer tend to collapse (Fig 2b). The most notable change in the boundary layer under the extreme conditions is the height of the layer (Fig. 2a). Compare to the height of average conditions, dry and hot extreme soundings show higher layer heights and precipitation extreme soundings show lower heights. They are well above 75th (below 25th) quartile range. Note that while total averaged height of the layer was 912m, it was 1778m, 1966m, and 444m for dry, hot, and precipitation extremes, respectively. Interestingly, dry and hot extremes showed about two fold of the height, while precipitation extreme showed about a half.

Chart, box and whisker chart

Description automatically generated**Figure 2**. (a) The average diurnal cycle of boundary layer height with averaged layer heights during the extreme conditions. (b) The number of soundings observed during the extreme at each 3-hourly local time.

Averaged vertical profiles of each extreme hour and daytime are shown in Fig. 3. For extreme precipitation cases, exceptionally low temperature is observed over the surface with steep increase in temperature with height. Also, there’s a steep increase in virtual potential temperature (, blue curve in Fig 3b). As a result, only shallow unstable layer is formed. On the other hand, dry and hot extreme profiles show smaller lapse rate and there are also huge gradient in temperature within the surface layer. This, in turn, forms deeper and well mixed boundary layer compare to the average condition. The specific humidity profile of extreme hot conditions showed the most humid air at low level atmosphere. Interestingly, the low level humidity of extreme precipitation condition was smaller than the average, while it showed nearly constant specific humidity upto 2500m.

One interesting thing that we can notice is the difference in the surface layers where huge temperature gradient () is observed for dry and hot extremes which is nearly the twice of average conditions (). This indicates that the fluxes originate from the surface might be the driver of different vertical structure of boundary layers under extremes.

**Chart, radar chart

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**Figure 3**. Averaged vertical profile (bold) of different extreme surface conditions is depicted with the spread of one standard deviation above and below mean (dashed). Numbers of extreme events used to calculate average profile is denoted within the bracket in the legend. Averaged day (15-18 LST) profile is also shown as a reference. (a) Virtual potential temperature, (b) specific humidity, and (c) potential temperature are shown.

Changes in surface energy balance suggests that the surface heat flux changes drive the vertical structure of boundary layer. The averaged daily profile of net radiation observed from tower and station show that there were additional net radiations during extreme dry and hot days (Fig. 4a), about . Interestingly, increased amount of sensible heat flux at Berrotaran is about the same amount that was increase in net radiation (Fig. 4b), while the changes in latent heat flux was insignificant (Fig. 4c). This increase in surface sensible heat flux is in line with huge temperature gradients in surface layers. Huge decrease in sensible heat flux during extreme precipitation is also responsible for the decrease in the layer height. In sum, boundary layer height changes under extreme conditions can be attribute to the changes in the surface sensible heat flux.

**Chart, histogram

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**Figure 4**. The net radiation from all five sites and calculated surface sensible and latent heat flux at Berrotaran (s14). Note heat flux measurement was only available at the Berrotaran. Individual daily profiles of net radiation and heat fluxes are also depicted with lighter color. Note that there were lots of missing observations of net radiation under extreme precipitation.

**4. Consecutive extreme**

It is notable that there are a lot of similarities between extreme dry and hot conditions. Their vercial temperature profiles are almost parallel (Fig. 3a and c), and the changes in surface energy balance are quite similar (Fig. 4). Regarding the similarity of the two extremes, it is tempting to check whether there is any connection between them. And there was a perfect period to investigate this when dry and hot extreme conditions appear throughout four consecutive days.

Graphical user interface

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**Figure 5**. Evolution of afternoon (15 LST) profiles of (a) virtual potential temperature and (b) specific humidity between November 16th and 22nd. Soundings of the bottom 500m at the nighttime (c and d) during extreme conditions. November 18th and 19th were extreme dry days, and November 20th and 21st were extreme hot days. White crosses denote the boundary layer height and red arrow shows rough increasing trend. Black arrow illustrates increasing heat entrainment from the top.

At the Cordoba site, extreme dry conditions were observed on November 18th and 19th, then extreme hot conditions followed on 20th and 21st. Throughout the period, boundary layer height increases, especially during the extreme condition days (Fig. 5a and b, red arrow). During the extreme dry days, heat from the top of the boundary layer starts to penetrate into the increased mixed layer. This is reflected as the downward propagation of high virtual potential temperatures at the afternoon (Fig 5a, black arrow). Then, surface temperature and humidity gradually increases, reaching the maximum surface on November 21st. It is notable that the strong surface inversion layer is observed during the nighttime (Fig. 5c), which means that heat is stored up within the residual layer over night. This could have helped higher surface temperature to be observed on the following day (Miralles et al., 2014). Also, specific humidity increases following the temperature (Fig. 5d), but there was larger increase near the surface compare to upper levels, which is analogous to the averaged profiles of two extremes (Fig. 3b).

This result is similar to the discussion from Miralles et al., 2014, where they investigated the development of mega-heatwave. Although this period is not the ‘mega-heatwave’ case, increase in the sensible heat flux with drying of surface preceding the extreme hot surface temperature is fairly comparable.

5 Conclusions and Discussion

We could investigate how extreme surface conditions change vertical structure of boundary layer thanks to RELAMPAGO field program measurements. By filtering out dry, hot, and precipitation extreme hours around Cordoba region, we found that there were notable differences in the structure of boundary layer. In general, dry and hot extreme conditions had deep and well mixed boundary layer with about a two fold height of average conditions. And under extreme precipitation, mixing of the layer was suppressed with shallow unstable layer. All of the height changes could be attributed to the changes in the surface sensible heat flux. On top of that, we also found that prolonged dry extremes can initiate extreme surface temperature conditions. This could be done by the increase in heat entrainment from the top and accumulation of heat within the residual layer over night.

Further studies could tackle the problem of how and why the specific humidity increases during this extreme heat condition (Fig. 5d). This might require us to look at spatial patterns associated with the extreme events, such as changes in the low level jet or moisture advection. In addition, there are more interesting topics to study in terms of land-atmosphere interaction. Although it was not clearly seen from our analysis, investigating the relationship between dry and hot extreme with precipitation could be an example.

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