Impact of upstream moisture structure on a back-building convective precipitation system in south-eastern France during HyMeX IOP13

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Reply to the referees' comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #2 comments

General Comments

The sensitivity of HyMeX SOP1-IOP13 to low level moisture content is analyzed in a series of sensitivity experiments. The two layers 0-1 km and 1-2 km are analyzed separately in order to test whether an increase or decrease in moisture content would affect the rainfall location, amount, and duration. The main conclusion is that the moisture structure in the lower troposphere is a key for accurate prediction at short-term range of precipitation in the coastal mountainous region in southern France. Results are presented clearly and comprehensively, although some deepen investigation is suggested.

We appreciate the time and effort you put in this review as well your mindful comments on our paper. We have worked hard to comply with all of them. Replies to each major comment and minor comment are listed below.

Major comment

The reasons why an increase of humidity in the 1-2 km layer would increase the cold pool are not clear and should be investigated better. My interpretation is that a higher humidity content produces earlier precipitation (as discussed in Page 13, line 27-28), thus producing anticipated and stronger cold pool than in control run. I suppose the cold pool is mainly generated by the mid-level air, thus it is not affected directly by the changes of vapour content in the low troposphere. Anyway, this or any other justifications you have should be properly supported.

Agreed. When a low-level cold pool forms under a meso-scale convective system (MCS), and it can lift the ambient low-level flow at its leading edge (Ducrocq et al., 2008) or modify the low-level circulation locally and enhance convergence areas (Duffourg, et al., 2016). In this study, the origin of air parcel in the low-level cold pool that developed under a convective system is retrieved using a 3-D backward trajectory analysis. We found the air parcel feeding the cold pool development was relatively dry, with water vapour mixing ratios less than 6 g kg^{-1} in the 1-2 km ASL layer. We have done an additional analysis on rainfall intensity and cold-air pool in CNTL, FA×M and FA×P. The discussion of simulations with the moistened and dried air mass in the 1-2 km ASL layer are improved in the manuscript.

Figure Aa shows that the rainfall intensity in FA×M simulation (dashed lines) is reduced by about 0.1−0.5 mm hr^{-1} compared to CNTL (black line) between 1200 and 1430 UTC, and the rainfall intensity ≥ 0.1 mm hr^{-1} starts about 45 min later (1300 UTC, dashed line) than in CNTL (1215 UTC, black line). Under the weakened precipitation, evaporation rate is reduced. The corresponding values of ϑ_v in the FA×M simulations are increased by about 0.2−0.5 K with respect to CNTL (dashed line, Fig. Ab). While the dried air mass in the 1-2 km layer is advected toward upstream the convection, it mixes with the moist air below, reducing the total moisture below 2 km. With the reduced moisture in the lower troposphere, the triggered convection near the Var coast produces less intensive rainfall and the weakened cold pool.

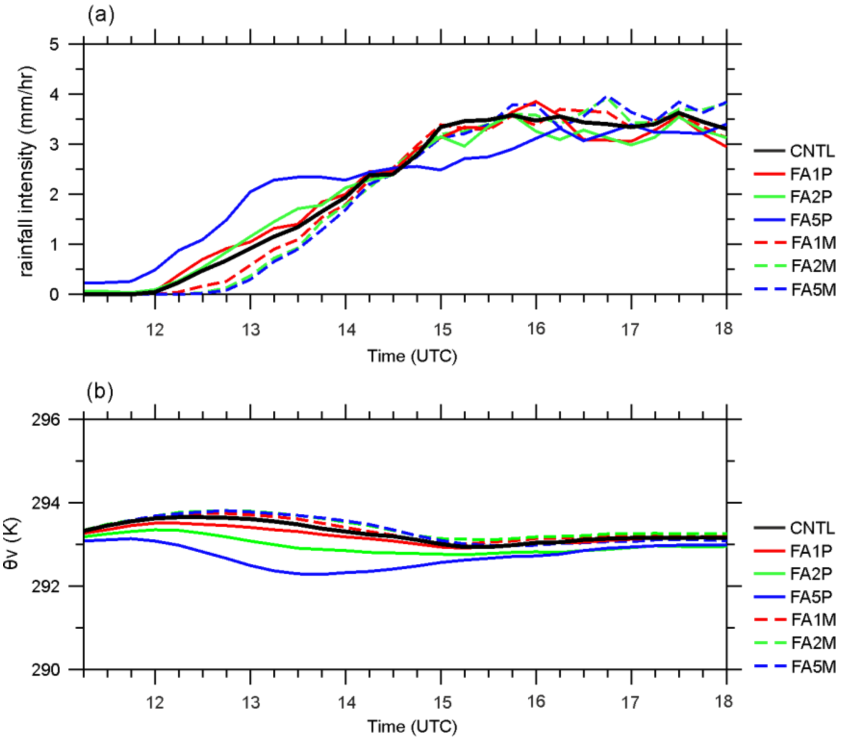

Figure A. Temporal evolution of domain-averaged rainfall intensity (mm hr^{-1}) and virtual potential temperature (ϑ_v) at the first model level in a fixed domain of 5.5−7.5°E, 43−44.5°N, simulated by CNTL (black line), FA×P (solid lines), and FA×M (dashed lines) from 1115 to 1800 UTC on 14 October 2012.

The enhanced rainfall intensities (about 0.2−2.5 mm hr^{-1}) are seen in FA×P simulations (colored solid lines, Fig. Aa) compared to CNTL (black line) between 1200 and 1430 UTC, especially FA5P produces the precipitation about 45 min earlier in time. Under the intensifying precipitation, the values of ϑ_v in FA×P simulations are about 0.2−1.7 K reduced, indicating the intensified cold pool formed by evaporative cooling than in CNTL (Fig. Ab). As the moistened air mass in the 1-2 km layer mixed with the moist air below during its advection towards the region of upstream convection, the total moisture below 2 km ASL increased. Thanks to the moistened lower troposphere, the convection triggered near the Var coast produces more intensive rainfall (red shades, Figure Bd–f) and correspondingly more intense cold pool. Also the moistened air masses in the lower troposphere initiate precipitation earlier while the precipitating area, particularly over the sea, is enlarged.

We have add Figure A (as Figure 16) and clarify the mechanism in the manuscript as:

♣ From Page 13, line 29

"Figure 16 shows that the rainfall intensity in FA×M simulation (dashed lines) is reduced by about 0.1−0.5 mm hr^{-1} compared to CNTL (black line) between 1200 and 1430 UTC, and the rainfall intensity ≥ 0.1 mm hr^{-1} starts about 45 min later (1300 UTC, dashed line) than in CNTL (1215 UTC, black line). Under the weakened precipitation, evaporation rate is reduced. The corresponding values of ϑ_v in the FA×M simulations are increased by about 0.2−0.5 K with respect to CNTL (dashed line, Fig. 16b). While the dried air mass in the 1-2 km layer is advected toward upstream the convection, it mixes with the moist air below, reducing the total moisture below 2 km. With the reduced moisture in the lower troposphere, the triggered convection near the Var coast produces less intensive rainfall and the weakened cold pool."

♣ Page 14, line 12-18

"In summary, decreasing the moisture content in the dry layer between 1 and 2 km ASL reduces the total amount of precipitation as well as the area affected by the precipitation and the duration of the precipitating episode. As the MABL is nearly saturated, the convection triggers easily along the coast but develops less intensively. The maximum of precipitation located along the eastern Var coast is reduced, corresponding to a weakened cold pool and weakened ascents at its southern boundary. This shows that around the coast, the dryness in the 1−2 km ASL layer is not a major ingredient for the convection development and the cold pool generation when the lowermost layer is nearly saturated."

♣ Page 15, line 15-24

"[…] Figure 16a shows the enhanced rainfall intensities (about 0.2−2.5 mm hr^{-1}) in FA×P simulations (colored solid lines) compared to CNTL (black line) between 1200 and 1430 UTC, especially FA5P produces the precipitation about 45 min earlier in time. Under the intensifying precipitation, the values of ϑ_v in FA×P simulations are about 0.2−1.7 K reduced, indicating the intensified cold pool formed by evaporative cooling than in CNTL (Fig. 16b). As the moistened air mass in the 1-2 km layer mixed with the moist air below during its advection towards the region of upstream convection, the total moisture below 2 km ASL increased. Thanks to the moistened lower troposphere, the convection triggered near the Var coast produces more intensive rainfall and correspondingly more intense cold pool. Also the moistened air masses in the lower troposphere initiate precipitation earlier while the precipitating area, particularly over the sea, is enlarged."

♣ Page 16, line 1-3

"[…] In the environment with similar instability but with further moistened conditions in the lower troposphere, the triggered convection further intensifies with enlarged horizontal extent of cold pool and strengthened ascents at its southern boundary."

♣ From Page 16, line 29

"Similarly, moistening the layer at 1−2 km ASL (see Fig. 17c), just above the MABL, increases the humidity in the lowermost 2 km ASL by mixing in the environment with a similar instability as in CNTL. With more moisture in lower troposphere, the triggered convection further intensifies which produces an enlargement of the horizontal extent of cold pools (dark blue area). […]"

♣ Page 17, line 14-16

"[…] The dryness in the 1−2 km ASL layer is not a major ingredient for the convection development and the cold pool generation when the lowermost layer is nearly saturated."

We have clarify 'low-level cold pool' in the Introduction (Page 3, line 3-5), as:

"[…] Furthermore, a low-level cold pool forming under a MCS can also lift the impinging ambient low-level flow at its leading edge (Durocq et al., 2008) or modify the low-level circulation locally and enhance convergence areas (Duffourg et al., 2016)."

Minor comments

Page 1, line 19: …the response to the variability…

Corrected (Page 1, line 19).

Page 2, lines 27: A simplified theory for the interaction of the low-level jet with a mountain range is provided in Miglietta, M. M., and Rotunno, R.: Numerical simulations of sheared conditionally unstable flows over a mountain ridge, J. Atmos. Sci., 71, 1747-1762, 2014

The reference paper has been cited (Page 3, line 3).

Page 3, line 6: … with respect to …
Corrected (Page 3, line 8).

Page 4, line 4: grid spacing is more appropriate than horizontal resolution.
Corrected (Page 4, line 20).

Section 2.2: Since the title of the section includes "validation", you should include an image of observations, e.g. the observed 6-h accumulated rainfall, for sake of comparison.
The objective of this section is to describe the results of the control simulation in order to compare them with the results of sensitivity simulations in the next sections. Thus, the title of section 2.2 has been modified to "Control simulation" (Page 5, line 9).

Page 5, line 14: "maximum 15-minute" instead of "6-hour"
Corrected (Page 5, line 18-19).

Page 5, line 16: … similarly as observed…
Corrected (Page 5, line 21).

Page 6, line 20: where are SSM/I data retrieved? in the same window considered for the analysis data?
Yes, SSM/I data over the north-western Mediterranean region was used, and this information is described in manuscript (Page 6, line 27-28) as:

"SSM/I over the north-western Mediterranean are in broad agreement, […]"

Page 6, line 25: since most of the IWV concentrates below 1 km ASL, one would expect that humidity is due to evaporation more than to advection: did you try any sensitivity experiment to test how the results change in the absence of surface fluxes?
By comparing control and sensitivity experiments, we investigate the impact of the advected air mass below 1 km ASL. We agree that the humidity can be increased by local evaporation over the sea. Indeed, additional sensitivity experiment would be needed to understand the impact of evaporation over the sea, hence we have not looked into this. However, the first author is currently leading a study based on stable water isotopologue data to see the influence of local surface flux and advected moisture on convection development on the same case study.

We have added the sentence from Page 17, line 29 as:
"[…] Another approach is to use stable water isotopologue data to disentangle the various moisture sources, i.e. evaporation over the sea, advected moisture upstream of the HPEs in the Mediterranean (Sodemann et al., 2017)."

Page 7, line 14: It is not clear how you impose under-saturation in case of increased moisture (MST5P experiment)
The relevant explanation has been improved. The expression "keeping the air under-saturated" has been changed for "up to the saturation limit"

We have added the sentence in Page 7, line 20-21 as:
"In other words, the water vapour value at saturation with respect to liquid water was calculated at each altitude and used as an upper threshold of the modified WVMR."

Page 9, line 20: stay instead of stays

Corrected (Page 10, line 10).

Page 10, line 21: rephrase as "instead of 435 min in CNTL"

Corrected (Page 11, line 18) as:

"instead of 435 min in CNTL, […]"

Page 12, line 23-24: which are the implications of the improved location of the simulated rainfall? Does it mean that the reference analysis is not accurate in the 1-2 km layer?

It is true that drying air mass even by 1 g kg^{-1} in the 1−2 km ASL layer leads to an onset of the precipitation at a more realistic location, about 25 km closer to Marseille. This evidences the importance of having precise observation-based water vapour profiles over the sea to improve the analysis and in turn the rainfall forecast in terms of location. This finding has been added in the conclusion.

Figure 6 caption: is the duration of precipitation above a threshold calculated in a fixed point and does it refer to any point in the domain?

Yes, a fixed point in the domain (north of 40.5°N, east of 3.5°E, i.e. to the northeast of the initiated bubbles) is used to calculate the duration of precipitation. The sentence has been corrected as suggested.

Figure 7 caption: what do the ellipses represent?

The meaning of the ellipses is given in the caption, as:

"Figure 7. […] Ellipsoid in (a)−(c) indicates the area with less precipitation than CNTL, while the ellipsoid in (d)−(e) shows the shifted precipitation area to the offshore region."

Figure 10 caption: how is the "sensitivity bubble" shown in this figure related to that shown in Fig. 1?

The CAPE values in both CNTL and FA×M (previously named DRY×M but modified to comply with Referee's #1 comments) slightly increased over time in the location of the sensitivity area as it mixed with the adjacent moister air.

We have added this information in manuscript in Page 10, line 3-5 as:

"The sensitivity bubbles of MBL experiments travels north-eastwards over the sea as in CNTL, and it keeps its ellipse shape but with a slightly reduced horizontal size due to lateral mixing with the ambient air mass during its advection."