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

By K. O. Lee et al.

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 #1 comments

General Comments

This piece of work investigates how the simulated accumulations, duration and extent of rainfall in an observed convective event respond to variations of the moisture content in the upstream air (in two different layers: the marine boundary layer below 1 km ASL; and the free atmosphere between 1 and 2 km ASL). The general finding is that higher moisture availability leads to increased rainfall (in terms of either duration or amount). Some subtle deviations to this general pattern are documented, but are not explained in great detail. This manuscript is written in good English and figures are very well made. The authors do a good job in justifying the design of the sensitivity study and in documenting the findings. However, they could do better in the interpretation and critical examination of the results. I have a feeling that there could be a bit more of physically- and dynamically-based reasoning in the explanation of the observed sensitivities (see for instance comment 1 below). Even if the study is well designed and there is no major flow in the arguments, I honestly have doubts about the degree of novelty and significance of the results. Here we have a sensitivity study that demonstrates that rainfall rates depend on the upstream moisture, mostly in fairly obvious ways. Is this really new enough to justify publication?
I recommend requesting major revisions before accepting the manuscript.
The authors are grateful for reviewer's interest in this study and the many helpful suggestions for improving this manuscript. Replies to each major comments and minor comments are listed below.

Major comment

1) While the sensitivity to moisture variations in the MBL seems rather obvious, that to moisture variation in the 1-2 km layer doesn't seem to be. Unfortunately, the authors don't do much to explain it. To clarify: Simulations show that moistening the 1-2 km layer enhances precipitation, in terms of duration and extent. Conversely, drying that layer reduces both precipitation duration and amount.
I found it hard to reconcile this finding with the ideas, suggested by the authors themselves, that: (1) the moisture supply for the convective system comes from the marine boundary layer, below 1 km ASL; (2) air in the cold-air-pool mostly descends from the 1-2 km layer; (3) the precipitation rate is mostly governed by the cold-air-pool dynamics.
Cold-air-pools are generated by the latent heat uptake due to evaporating precipitation in the convective downdraft. Evaporation should be enhanced if it occurs in a drier air mass, so the manuscript documents just the opposite, so this is not a good explanation. What is then the casual relationship between the moisture variations in the 1-2 km layer and the observed sensitivity? Can the authors clarify them?
Agreed. We have improved our analysis of the simulations with the moistened and dried air mass in the 1-2 km layer in the manuscript. We have done an additional analysis on rainfall intensity and cold-air pool in CNTL, FA×M and FA×P simulations (please also note that we have taken into account your suggestion to change the names of the simulations). Figure A indicates the hourly evolution of domain-averaged rainfall intensity (mm hr^{-1}) and virtual potential temperature (ϑ_v) at the first model level in a fixed area (5.5-7.5°E, 43-44.5°N) where most of precipitation

is produced. 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 Ba–c shows the reduced rainfall accumulations in FA×M compared to CNTL (blue shades) are highlighted near the Var coast.

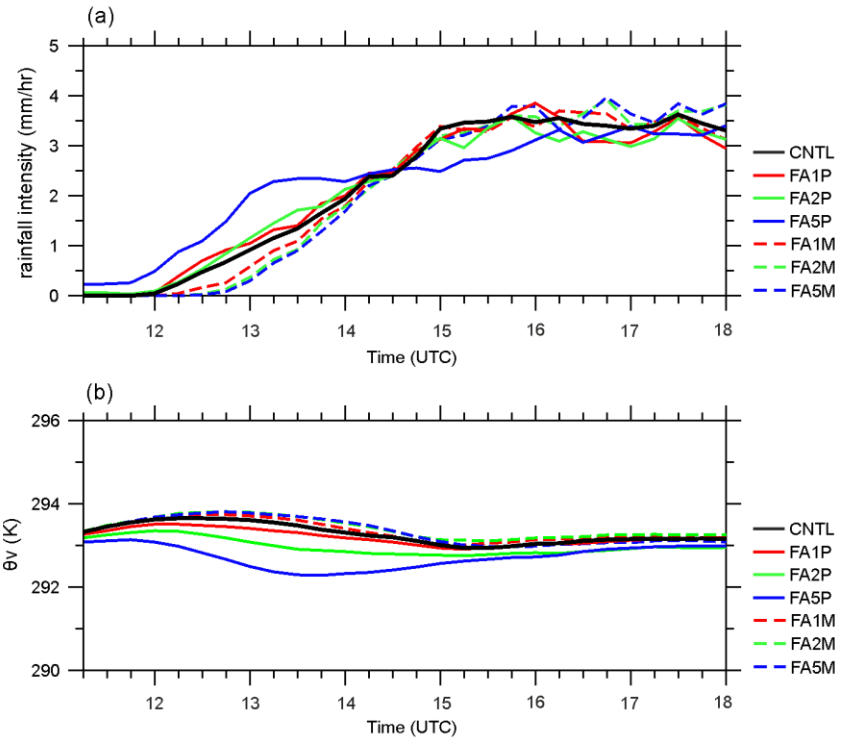

Figure A. Temporal evolution of domain-averaged rainfall intensity (mm hr^{-1}) and virtual potential temperature (ϑ_v) at the first model level in a fixed domain of 5.5−7.5°E, 43−44.5°N, simulated by CNTL (black line), FA×P (solid lines), and FA×M (dashed lines) from 1115 to 1800 UTC on 14 October 2012.

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.

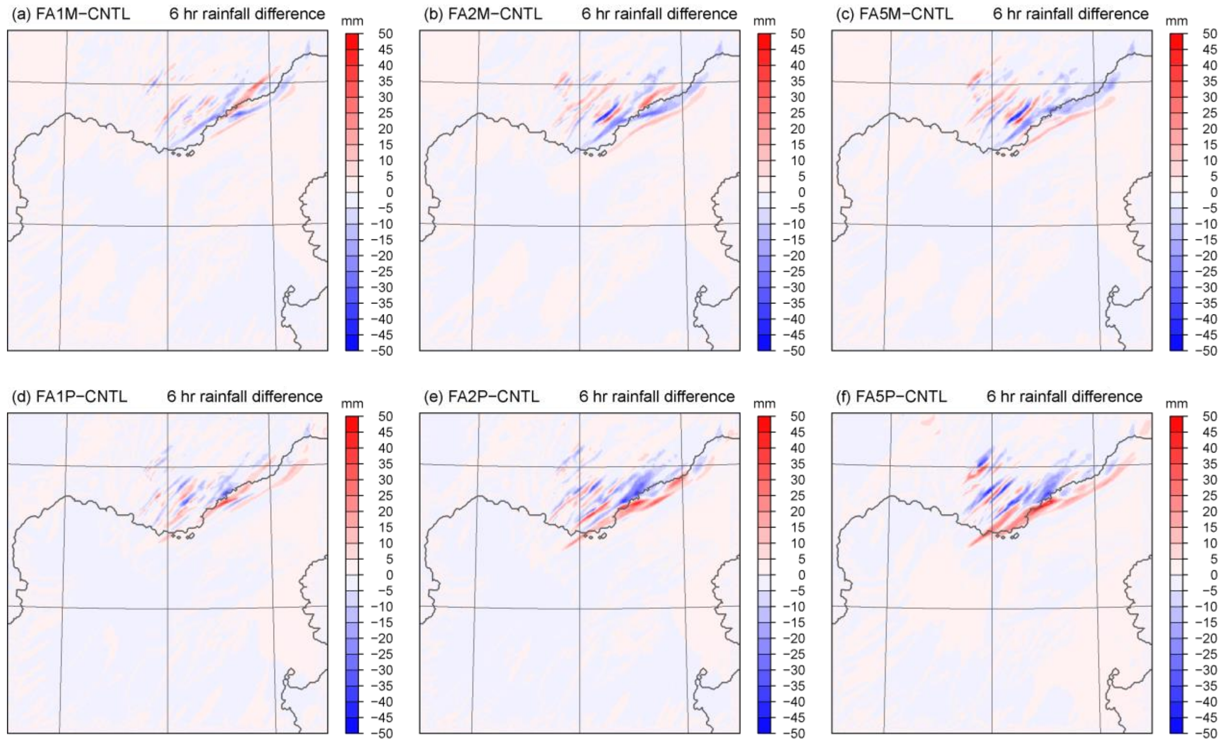

Figure B. Differences of 6 hour accumulated rainfall from 1200 to 1800 UTC on 14 October 2012 (a) FA1M minus CNTL, (b) FA2M minus CNTL, (c) FA5M minus CNTL, (d) FA1P minus CNTL, (e) FA2P minus CNTL, and (f) FA5P minus CNTL.

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

♣ Page 13, from 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 2-4

"[…] 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."

2) The initialization of the sensitivity runs with dry or moist bubbles, and the related consequences, could be described better. Even if they can be guessed by the reader, several aspects are not thoroughly explained. (A) How far do the bubbles travel, between the model initialization and the initiation of convection? (B) How is their shape deformed? (c) Most importantly, do bubbles follow exactly the same trajectories for all sensitivity runs? How much do the trajectories differ between runs? (D) Most of the initial profiles in Figure 5 differ by constant amounts in either the lower or upper layers, but this is not always the case. For instance, the *5P profiles deviate from this pattern. Why?

Agreed. The details regarding the initialization and evolution of the sensitivity bubbles and its deviation among the experiments have been revised in sections 2.2, 3 and 4, as discussed below (newly added part is marked in red).

We have added this bit of information in results as:

♣ Page 5, line 17-23

"[…] Then the convection (highlighted by reflectivity values exceeding 45 dBZ, Lee et al., 2012) initiates upstream (yellow star, Fig. 2b), about 25 km further south than observed at 1200 UTC and maximum 15-minute precipitation over 5 mm is simulated approximately 93 km from the initiation at 1230 UTC (Fig. 2b). It develops preferably towards Marseille, then around the Argens valley region and the east coastal Var region (Figs. 2b and 3a−b), similarly as observed. The intense precipitation (≥ 15 mm per 15 min, red circle in Fig. 2b) is first simulated at 1400 UTC north of Marseille (5.6°E, 43.5°N) in a location distant of about 95 km from the bubble initiation."

♣ Page 10, line 3-5

"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."

♣ Page 10, line 10-13

"[…] The intense precipitation (≥ 15 mm per 15 min) starts 3 hour later in MBL5M than in CNTL, MBL1M, and

MBL2M. The convection at 1800 UTC is located at the eastern coast of Var, as in CNTL (square in Fig. 2b) and MBL×M (square in Fig. 8a–c), and then stays 2–3 additional hours in this region."

♣ Page 12, line 2-6

"[...] In MBL×P experiments (Fig. 8d–f), precipitation is initiated over the sea at 1200 UTC, and then the bubbles travel along similar pathways over the sea as in CNTL. However the inland precipitation starts later (e.g. 15, 45, and 90 min later in MBL1P, MBL2P, and MBL5P, respectively) than in CNTL. This late onset of inland precipitation is also consistent with more widespread precipitation over the sea in MBL2P and MBL5P (Fig. 7e, f)."

♣ Page 13, line 17-20

"[...] The sensitivity bubbles of FA experiments travel north-eastward over the sea as similar as seen in CNTL and MBL, but the horizontal extent is slightly reduced by mixing with the ambient air mass during the travel. The convection initiates about 20 km offshore of the Var coast (yellow star, Fig. 14a–c)."

♣ Page 15, line 9-12

"[...] The convection initiates near the Var coast, as in CNTL, however the horizontal extent of the convective region (reflectivity ≥ 45 dBZ) is relatively large compared to CNTL. The precipitation starts at 1200 UTC about 50 km offshore the southern Var coast, when the bubble reaches this region ~140 km distant from the location of initiation [...]"

3) Naming the two experiment series MST* and DRY* is confusing, because runs 1-2-5M are dry in both series, while 1-2-5P are moist in both series. I suggest renaming to MBL*) for "marine boundary layer"; e.g. MBL5M) and FA* (for "free atmosphere" – or something similar).

Agreed. The name of the two experiments series has been changed from MST and DRY to MBL and FA, respectively, in the text and in the related tables and figures (1, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16), as suggested.

Minor comments

4) Page 1, line 14: "intensive observation period". Please introduce the acronym IOP here.

The acronym IOP has been introduced (Page 1, line 14).

5) Page 1, lines 18-21: Sentence unclear. The response of what to what?

Corrected (Page 1, line 18-19) as:

"The sensitivity experiments are designed to investigate the response of the HPE to the variability of the water vapour content upstream [...]"

6) Page 1, line 27-28: A lifetime can be "shortened", but the amount is "reduced".

Corrected (Page 1, line 27).

7) Page 2, line 3: "At the same time". At the same time of which event?

Deleted for the sake of clarity.

8) Page 2, line 6: "in lower troposphere" → "in the lower troposphere"

Corrected (Page 2, line 5).

9) Page 3, line 12-13: Please split this sentence. "...over the sea. These are difficult..."

Corrected (Page 3, line 15).

10) Page 3, line 21: "disturbances" → "disturbance".
Corrected (Page 3, line 23).

11) Page 4, line 1: "moist structure" → "moisture structure"
Corrected (Page 4, line 4).

12) Page 4, line 18: In a bulk one-moment microphysical scheme, the number concentration of cloud concentration nuclei is prescribed. What value was used? Is it appropriate for maritime convection?
There is no prescribed concentration of cloud condensation nuclei in the ICE3 scheme (Caniaux et al., 1994; Pinty and Jabouille, 1998) used by Meso-NH: condensation of cloud water is the result of a saturation adjustment procedure while the conversion of cloud droplets into raindrops is based on a threshold of cloud water content.

13) Page 6, line 12: "French coasts" → "French coast".
Corrected (Page 6, line 18).

14) Page 7, line 6: The meaning of "WVMR" can be easily guessed, but it is better to expand the acronym on its first occurrence.
The acronym of WVMR is stated in page 6, line 23.

15) Page 8, line 3-10: This is a very long sentence. Consider reformulating: "To investigate the WVMR impact on the location, intensity and duration of precipitation, we consider several indicators…"
Corrected as suggested in Page 8, line 18-19 as:

"To investigate the WVMR impact on the location, intensity and duration of precipitation, we consider several indicators, […]"

16) Page 8, line 10-19: Traditionally, figures are numbered in the same sequence as they are cited. Here, the order of citation is awkward: 6-10-7-13-8-14-9. Please fix.
As suggested, the order of citation has been revised. However for the sake of readability, we introduce Figures 6 and 12 in a same sentence (from Page 8, line 24).

17) Page 9, line 20: "in the mountainous region of close to Marseille". Confusing. Consider deleting. "West of 6°E" is easier to understand.
Corrected (Page 10, line 10) as:

"[…] rainfall accumulations stay longer west of 6°E than in CNTL […]"

18) Page 9, line 22, Figure 9: How are the CAPE values computed? Are they spatially averaged? What is the initial height of the rising parcels?
The CAPE values are averaged within a "sensitivity bubble" every 15 min. The initial height of the rising parcels is around 20 m. The relevant explanation is added in manuscript in Page 10, line 15-16 as:

"[…] Figure 9 shows the domain-averaged CAPE values (using a rising air parcel having its initial height about 20 m) within the sensitivity bubble upstream […]"

19) Page 10, line 3: Does an air mass "weaken"? What you referring to, exactly? Virtual potential temperature? Extent of the cold-air pool?

Corrected (Page 10, line 25-27) as:

"[…] The extent of cold air mass (ϑ_v < 291 K at the first model level) formed along the foothill of the mountain by evaporation of the intense precipitation is also reduced in MBL×M (Figure 11a–c). […]"

20) Page 10, line 5: "This combination of decreased CAPE and weakened cold pool can explain the weakened precipitation." The casual link is unclear. Does the cold pool become weaker because of the weaker precipitation, or vice versa?

Corrected (Page 10, line 29) as:

"[…] of decreased CAPE and weakened cold pool which are induced by the weakened precipitation […]"

21) Page 10, line 21: "instead of CNTL of 435 min" → "instead of 435 min in CNTL"

Corrected (Page 11, line 18).

22) Page 11, line 1: "in the MST1P" → "in MST1P"

Corrected (Page 11, line 26).

23) Page 11, lines 24-25: "CAPE favours triggering". CAPE doesn't favour triggering. Roughly speaking, CAPE quantifies the "degree of instability". You can have high values of CAPE and no way to overcome convective inhibition. Conditional instability (steep mid-level lapse rate) is on ingredient of deep moist convection; triggering (uplift) is another one.

The interpretation about the high values of CAPE has been modified in Page 12, line 24-25 as:

"[…] (Figure 11f). CAPE values higher than 1500 J kg^{-1} lead to an increase of the degree of instability in the upstream environment […]"

24) Page 12, line 13: "the duration are" → "the duration is"

Corrected (Page 13, line 10-11).

25) Page 13, line 4: "increased over the time" → "increased over time"

Corrected (Page 14, line 10).

26) Page 13, line 12: "in lower troposphere" → "in the lower troposphere"

Corrected (Page 15, line 23).

27) Page 13, line 15-19: "However, the duration of precipitation over land (Dland) and the duration of more intense precipitation (DRR15, ≥ 15 mm in 15 min) are shortened (from 315 min in CNTL to 270 min, 240 min, and 240 min in DRY1P, DRY2P, and DRY5P, respectively for Dland, and from 120 min in CNTL to 105 min, 60 min and 30 min, in DRY1P, DRY2P, and DRY5P respectively for DRR15)". Such lengthy sequences of acronyms and numbers are hard to read and not very informative. What really matters is the sign of the deviation from CNTL – there is probably no need to mention more than that. If you want to include numerical values, you can put them in a table. There are other similar sentences in the manuscript. Removing them would make the paper much better readable.

As suggested, the relevant sentences have been shortened without numerical values (from Page 14, line 24 and from Page 9, line 11).

28) Page 14, lines 6-8: “and less stationary system” → “and a less stationary system”
For the sake of readability, we modify the sentence as:

♣ Page 15, line 25-26
“[…] It also appears that the precipitation is less stationary.”

29) Page 14, line 15: “topped by dry air mass” → “topped by a dry air mass”.
Corrected (Page 16, line 10).

30) Page 14, line 27-28: “A small increase of moisture content favours convection triggering”. If the authors are alluding to the effect of moisture in increasing CAPE, then this has nothing to do with triggering (see a previous comments). Incidentally, moisture can also make (orographic) triggering easier by reducing the static stability (buoyancy frequency) of the atmosphere. But I think this is not what authors mean here.
Agreed. The relevant interpretation to CAPE has been modified (Page 16, line 22-23) as:

“[…] A small increase of moisture content in the warm and moist MABL increases the degree of instability.”

31) Figure 2, caption: There’s an ellipsoid in panel a. Please explain what it is. Also, please make thicker, so as to make it visible.
The ellipsoid in panel (a) has been removed for the sake of clarity.

32) Figure 6: I am confused by the units of RR_{acc} and RR_{sum}. I am fine with RR_{acc} being in m^2, but, if RR_{sum} is a domain wide sum, shouldn’t it be expressed in liters? 1 mm = 1 liter/m^2. Sum up over all grid points accounting for the mesh size should give liters of water.
RR_{acc} is a maximum value of 6-hours accumulated precipitation amount, and it has been renamed by RR_{max} for better understanding. For better comparison among experiments, RR_{sum} is recalculated to domain-averaged total sum of the 6-hours accumulated precipitation amount for a fixed area bounded by 40.5−45°N and 3.5−9°E where the sensitivity bubble passed through. Now RR_{sum} has a unit of mm. Figures 6 and 12, and the relevant text have been modified.

33) Figure 7: Same as above. Please explain the meaning of the ellipsoids, and make them thicker.
Corrected.

34) Figure 9: Label and units are missing on the y axis.
Corrected.

35) Figure 10: Same as above. Please make the ellipsoids thicker.
Corrected.