Anonymous Referee #3

Reviewer : *The author's have been implemented the comments resulting in a more quantitative study comparing the results of a mesoscale modelling exercise with observations of meteorological variables, boundary layer height and CO2 mixing ratios in Paris during March 2012.*
However, there are few issues that I think that should be addressed before publication:
Urban-rural differences are not properly quantified or discussed in the text. Being one of the aims of the study (number 2) I think that it would be good to include the increment on the CO2 in Paris compared to other sites as seen by observations and reproduced by the different model approaches and use the observations-model differences as a mean to quantify the performance of the model to reproduce the CO2 urban dynamics. The authors have done an attempt to quantify this with including Table 6. Calculating the differences between EIF minus GIF, EIF minus GON and EIF minus MON for the afternoon values, the CO2 urban increment is about 7-5 ppmv (observations). However, the simulated increment is 3 ppm for both REF and RUR simulations. However the authors state in Section 5.3 that "these gradients are well represented by the model with the urban scheme and a little less with the RUR simulations". It might be useful to calculate the increments for each day on the campaign and relate it to the different weather and wind patterns. An attempt has been done by the authors in the last paragraph of Section 5.3 but a better wording is needed. Note that the CO2 differences calculated between different sites in Section 5.3 are not gradients (that would be expressed in terms of ppm/m) rather than differences or increments (expressed in ppm).

Authors : All the terms "gradient" relative to differences between urban and rural CO2 concentrations have been replaced by "increment" or "difference". The increments have been calculated for each day of the campaign and are presented in the Table below. Observations show that increments between GON and GIF are positive the first 4 days and nights with the dominant NE flow and negative the last 2 days and nights with the SW flow. The spatial transitions are most of the time fairly well reproduced by REF, even if we can note some discrepancies that have been discussed in the text (for instance the overestimation by 10 ppm over MON on 25 March afternoon, discussed in 5.3). A few measurements at GIF and GON are also missing in the detailed table. Therefore, it appears that the table detailing the increments for all the days does not bring new elements and differs from the recommendation of the reviewers after the first revision to try to synthesize the CO2 results over the period, leading for instance to the new Figure 9 of the mean diurnal cycle. We could present the transects for the 2 periods (means on the first 4 days and on the last 2 days) but the missing data at GON and GIF the last 2 days prevent this. So you propose to keep the Table 6 at it was and to clarify the text.

13:00 UTC – 17:00 UTC						00:00 UTC – 06:00 UTC					
	TRN	GIF	EIF	GON	MON		TRN	GIF	EIF	GON	MON
OBS	396	402	404	398	398	OBS	408	-	395	444	404
REF	396	405	403	400	397	REF	406	430	400	434	407
RUR	396	406	404	400	397	RUR	406	429	399	435	407
OBS		399	398	396	396	OBS		433	399	423	409
REF		401	401	399	397	REF		432	401	422	408
RUR		402	401	399	397	RUR		431	400	423	408
OBS		407	408	404	403	OBS		439	419	434	428
REF		403	401	399	396	REF		427	406	423	416
RUR		405	402	399	396	RUR		431	405	424	416
OBS		402	405	401	398	OBS		436	400	430	416
REF		398	400	397	394	REF		436	402	426	409
RUR		399	401	398	394	RUR		439	401	426	409
OBS		399	414	414	404	OBS		-	400	472	407
REF		395	418	413	414	REF		478	411	464	415
RUR		398	427	426	423	RUR		473	417	465	415
OBS		394	428	-	404	OBS		417	410	-	418
REF		395	399	408	401	REF		420	406	431	411
RUR		397	400	412	404	RUR		421	410	431	412

Table : Mean CO2 mixing ratios (in ppm) for each day and for the 2 periods 13H-17H UT and 00H-06H UT, observed and predicted for the 5 sites TRN, GIF, EIF, GON and MON.

We try to bring a better wording in Section 5.3 (new or modified elements in blue) :

"Figure 9 shows that the model reproduces well the midday lower mixing ratios at the different sites. Even if strong convective mixing in the ABL during daytime induces lower mixing ratio values, the horizontal flow can lead to significant horizontal differences on CO2 concentration. The first four days, the North-East flux induces a CO2 concentration increase from GON to GIF, as illustrated on Fig.13a, whereas it is reversed the next 2 days in the South-West flux (as illustrated on Fig.13.b). For instance, on 25 March at 15:00UT, observed horizontal CO2 increments reach up to 15ppm between GIF and GON, and this is quite well reproduced by the model (Fig.13b). The predicted mixing ratio over MON is overpredicted by 10ppm, but the station is located on the border of the predicted plume. Both the insufficient spatial accuracy of the anthropogenic emissions and errors on the horizontal transport (observed winds are in turquoise arrows) could explain it. The situation differs from the previous days when the well-established north-easterly winds dilute the pollutant, smoothing the CO2 increments and inducing the maximum mixing ratio values of the measurement stations at GIF site (Fig.13.a). During these first days, errors on the predicted winds are small as well as on CO2. Table 6 presents mean CO2 mixing ratios along a rural-urban transect during the period 13H-17H UT for the 6 days with non negligible increments. These differences are fairly well represented by the model (remove : with the urban scheme, and a little less with the RUR simulation). This demonstrates the possibility to apply inversion during daytime on urban and sub-urban area for ground and altitude stations."

Reviewer : *In a similar way, in section 4.1 authors state that the REF simulations reproduce well the urban heat island as it reproduces the increase on temperature in urban sites compared to suburban and rural sites. This is quite hard to see from Figure 4. I would suggest keeping Figure 4a but I don't think that Fig. 4b and 4c are relevant and informative for what the authors want to show. However, I would add a timeseries of the difference on temperature between the urban and suburban and between urban and rural as seen by observations and by the REF and RUR simulations. I think in that way it would be easier to see if the different model configuration reproduces the urban heat island.*

Authors : As you suggested, we have added the time series of the differences on temperature between the urban and suburban stations and between the urban and rural stations as seen by observations and by the REF and RUR simulation, but we propose to keep Fig.4 b and c, as it allows to see some characteristics of the simulation : the increasing trend of the temperature and the overestimation of the maximum temperature at the urban site. As you suggest, the urban-rural and urban-suburban contrasts are discussed with Fig.5 and not Fig.4.

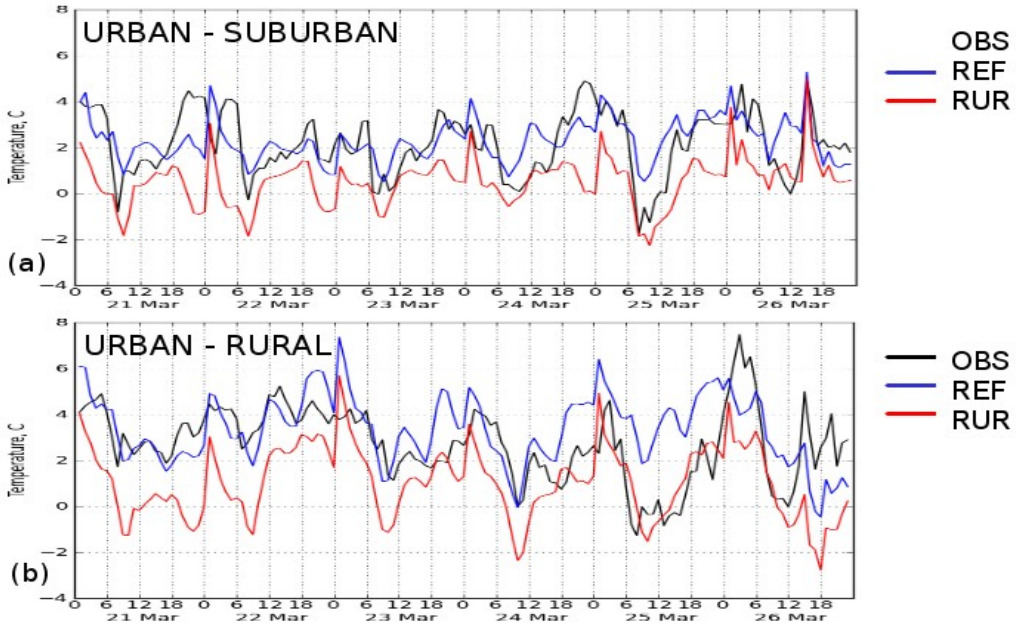


Figure 5 : Diurnal variation of hourly differences of temperature at 2m (in °C) between urban and suburban stations (a) and between urban and rural stations (b) from observations (in black), REF (in blue) and RUR (in red) simulations.

Figure 5 is referenced and discussed 3 times :

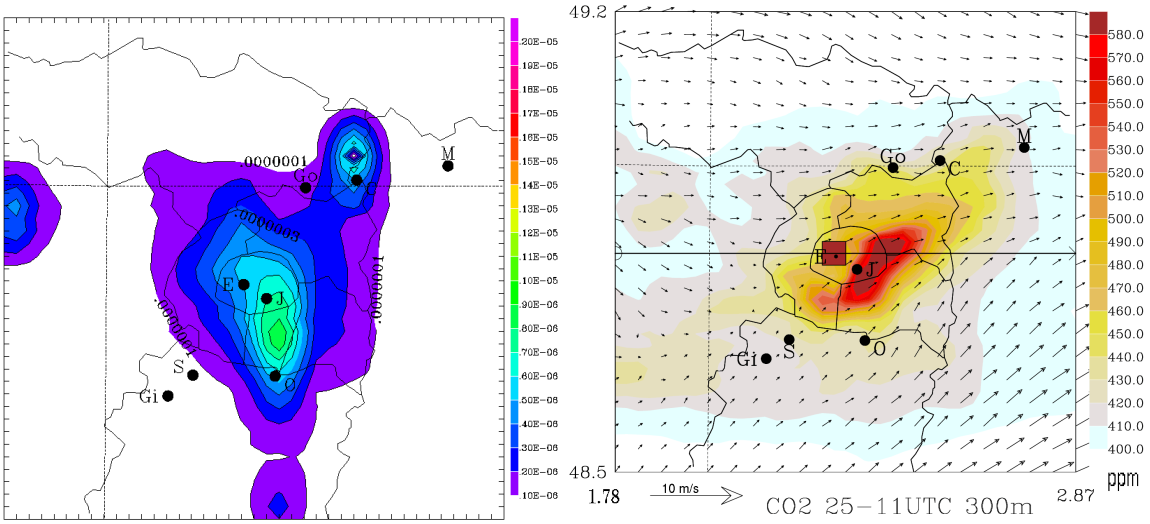
- In 4.1 for the observations : "The observed differences of temperature between the urban site on one side, and the sub-urban and rural sites on the other side, representative of the UHI, are presented on Fig.5. They were most of the time positive and can reach 5°C and 7°C respectively. They were stronger at night than during day, and mostly, the contrast between the three sites was negligible during sunrise. The highest nocturnal UHI between urban and rural sites occurred on 26 March with a difference of 7°C, whereas the difference was slightly negative 12 hours before, during 25 March afternoon, due to the absence of wind inducing a generalized strong heating over all the domain. Also, the dry conditions that prevailed the previous days

reduced the soil moisture at the rural site and evapotranspiration by the vegetation became therefore small during daytime."

- In 4.1 for the REF simulation : "The UHI intensity is fairly well represented by the REF simulation (Fig.5), with a good range of values, and maxima during the nights and minima during the days. The main discrepancy concerns the absence of urban-rural contrast observed during the day of 25 March, that is not captured by the model, and the maximum observed UHI during the following night that is underestimated (5°C instead of 7°C)."
- In 4.3 for the RUR simulation : "On Fig.4c, the RUR simulation underestimates systematically the urban temperature (Table 3 with a negative bias of –3°C, and the corrections by the analysis at 00:00UT are important) and removes the UHI (Fig.5 in red line). However some contrasts between the three sites remain that are only linked to the orography effect of the Paris basin and to the cooling associated to the evapotranspiration for the rural site compared to the rock replacing the urban area in the RUR simulation."

Reviewer : *Given the data shown, I am not sure how the authors conclude that "apply inversion during daytime on urban and sub-urban area not only the afternoon but including the morning, and not only for tower sites but also for ground stations".*
There are still quite a few subjective assessments in the text when comparing observed and modelled variables. For example, in page 16 the author's state that "... there are small biases on CO2 mixing ratios that could be partly linked to the misrepresentation of the anthropogenic emissions and to horizontal transport errors" and the report the CO2 fields on 25 March at 11:00 when there is a discrepancy of more than 100 ppm between observations and model. I would suggest the authors to review the text and remove subjective assessments and just state the quantitative scores.

Authors : Considering the coarse 10km resolution of the anthropogenic emissions, it seems inevitable to get locally some misrepresentations of the emissions. On 25 March at 11:00, ground emissions are presented on the figure below, as well as the predicted CO2 mixing ratios. Surface emissions are concentrated on the eastern part of the city. Therefore, the SW wind tilts the plume along an axis SW-NE, and the Eiffel Tower is away from this area. The wind predicted at Eiffel Tower is correct (250° and 2m/s observed at 300m), so it can reasonably be assumed that the too coarse resolution of the anthropogenic emissions leads to a lack of concentration over Eiffel tower.
However, we have not insisted on this point, so we have removed the sentence : "there are some biases on CO2 mixing ratios, that could be partly linked to the misrepresentation of the anthropogenic emissions and to horizontal transport errors."
But we have maintained : "It is therefore likely that the underestimation at EIF is partly due to the too coarse anthropogenic emissions, as the correct mixing ratios have been produced on another part of Paris, and partly to horizontal transport errors, frequent with weak winds."



a. b.

Figure : a. Ground CO2 emission flux (in ppp.m/s) at 11 UT . b. Ground predicted CO2 mixing ratio (in ppm) on 25 March at 11 UT with observation in coloured squares.

Reviewer : *CO2 measurements from different sites appear to have different time resolution as pointed by the authors in this revised manuscript: 1h for GIF and TRN and 5 min for EIF, GON and MON. Which is the temporal resolution of the simulations? Looking at the new Figure 10, it would be good to compare the CO2 simulated concentration to CO2 observations for all sites using 1 h means? It might smooth out some of the observed variability and it would homogenize the number of points for the different sites.*

Authors : The temporal resolution of the simulations is 1 min. Figure 10 concerns only Eiffel site. Following your suggestion, CO2 simulated and observed concentrations have been averaged over 1h to smooth out the observed variability and this improves the clarity of the results. It doesn't induce some modification in the text.

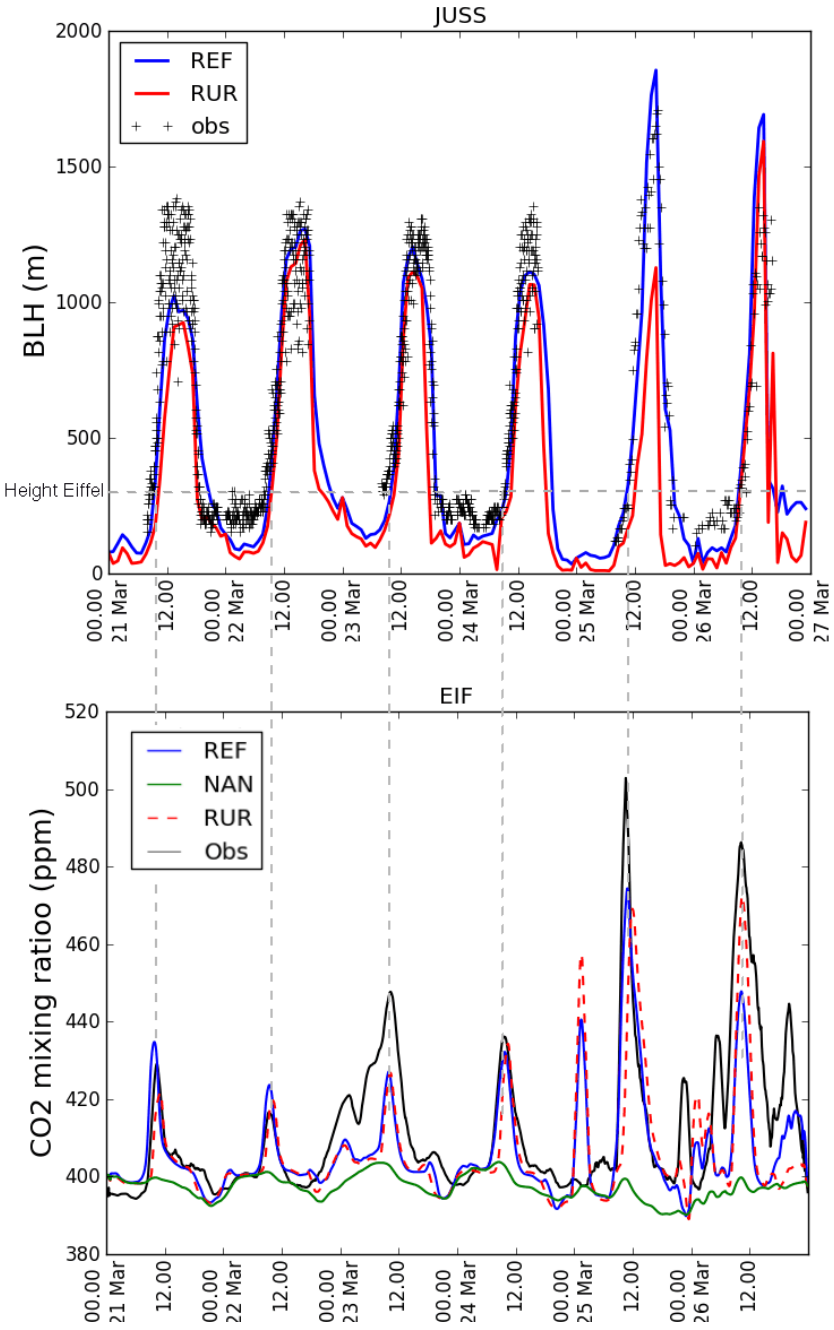


Figure : Time series of BLH predictions and observations at JUSS (in m a.g.l., AGL) for REF (blue) and RUR (red) simulations. (b) Time series of CO2 observations and predictions (in ppm) at EIF for REF (blue), RUR (red) and NAN (green) simulations, hourly averaged. The vertical dashed lines correspond to the time in the morning at which observed BLHs reach 310m (Eiffel measurement height).

Reviewer : *Specific/technical comments:*
- The authors use quite a few times in the text the concept "urban-rural contrast". They should be more specific to what they refer: differences in temperature, CO2 mixing ratio, boundary layer height, etc.

Authors : Yes, this has been corrected :

- in the abstract, “urban-rural contrasts on temperature”
- 4.1 p.12, twice: “urban-rural contrasts on temperature”
- 4.2 p13 : “The highest contrast on BLH “
- 4.3 p14 : “the absence of urban-rural contrasts on temperature reduces the wind.”
- 5.3 p18 : “urban-rural contrasts on BLH can lead to significant horizontal increments”
- 6 p20 : “Also, at the ground stations, minimum predicted and measured mixing ratios are in agreement, with significant horizontal increments linked to urban-rural contrasts on BLH. “
- 6 p20 : “The urban parameterisation scheme TEB proved crucial to reproduce the UHI, the urban-rural contrasts on BLH”

Reviewer : *- Abstract: “Statistical scores show a good representation of the UHI and urban-rural contrasts” : too qualitative and not discussed in the main text*

Authors : This has been completed in the abstract : “Statistical scores show a good representation of the Urban Heat Island (UHI) with stronger urban-rural contrasts on temperature at night than during the day up to 7°C” and this has been discussed in the main text with the new Fig.5 you have proposed to include.

Reviewer : *- Abstract: gradients are not calculated and either reported in the text. A gradient would be expressed in C/m (temperature gradient); ppm/m (mixing ratio gradient), etc.*

Authors : You are right, the gradient term has been replaced by “increment” or “difference”.

Reviewer : *- Abstract: How much is the CO2 underestimated at sub-urban sites due to the negative bias on the modelled BL? How much is the CO2 overestimation at night when the urban parameterization is removed?*

Authors : This has been added :
- “The main discrepancy is a small negative bias over urban and sub-urban sites during nighttime (respectively –45m and –5m), leading to a few overestimations of nocturnal CO2 mixing ratios at sub-urban sites and a bias of +5ppm. “
- “ A sensitivity test without urban parameterisation removes UHI and underpredicts nighttime BLH over urban and sub-urban sites, leading to large overestimation of nocturnal CO2 mixing ratio at the sub-urban sites (bias of +17ppm).”

Reviewer : *- Introduction: the reference to previous studies studying CO2 in urban areas is not related to previous inverse modelling studies using rural observatories. Furthermore, the studies have different aims. Kort et al. (2012) quantified the urban CO2 dome in LA and Mumbai using satellite data while Gurney and Strong (2012) quantified urban emissions. A better contextualization of these studies is needed.*

Authors : The sentence “Urban CO2 studies have been recently pursued with different methods on different cities (Indianapolis: Gurney et al. 2012, Salt Lake City: Strong et al. 2011, Los Angeles: Kort et al. 2012)” has been modified like this :
“Recent urban CO2 studies have been pursued with different objectives : for instance, Kort et al. (2012) quantified the urban CO2 dome over Los Angeles and Mumbai using satellite data, Gurney et al. (2012) aimed the quantification of CO2 emissions at Indianapolis, and Strong et al.(2011) studied urban CO2 cycles within the Salt Lake Valley.”

Reviewer : *- Introduction. Add to the Arellano et al. Reference "specially in the morning hours during the rapid growth of the ABL in a rural site in the Netherlands"*

Authors : OK

Reviewer : *- End of first paragraph page 5: Still unclear. Do the authors mean "that urban areas are challenging to represent in inversion studies because the CO2 field (and other pollutants) are heterogeneous due to the presence of point sources. However, the CO2 field is homogenous during night time thanks to a decrease on the emissions intensity and thanks to a well mixed Nocturnal Boundary Layer" ?*

Authors : The text has been clarified :

"In this context, urban areas are challenging to represent for CO2 inversion studies: first emissions are very heterogeneous, and second, BLH is also spatially variable. Angevine et al. (2003) pointed out the important implications of urban-rural contrasts for air quality. However, the Nocturnal Boundary Layer (NBL) is mixed compared to the rural one. If the urban effects are well represented, this can limit the errors of the model generally associated to the stable conditions."

Reviewer : *- Aim (2) in page 5: What does it mean the effect on urban-rural contrasts on the atmospheric CO2 field? Does it relate to changes on the emissions intensity? Or weather conditions? Or the interaction both of them?*

Authors : The aim (2) is only relative to the dynamical impact of urban-rural contrasts on CO2 dispersion.
We propose to add the term "dynamical" : "(2) to evaluate the dynamical effect of urban-rural contrasts on the atmospheric CO2 field"

Reviewer : *- Page 9. Need a reference or explanation of what MACC analysis is.*

Authors : The 2 references have been added :

Engelen, R. J., S. Serrar and F. Chevallier, 2009: Four-dimensional data assimilation of atmospheric CO2 using AIRS observations, J. Geophys. Res., doi:10.1029/2008JD010739.

http://www.gmes-atmosphere.eu/about/project_structure/global/g_ghg/

Reviewer : *- Last sentence page 14: "At the rural sites, curves are combined". Needs clarification.*

Authors : Yes, you are right, the term is not appropriate, "combined" has been replaced by "superimposed".

Reviewer : *- Page 16. With the data given it is quite difficult to state that " the underestimation at EIF ids partly due to the too coarse anthropogenic emissions, as the correct mixing ratios have been produce on another part of Paris ... and transport errors". Have the measured winds in surface stations compared with Meso-NH wind fields? That might be an indication of the transport errors.*

Authors : On 25 March at 11 UT, predicted winds are in agreement with observation, at 10 m height (2 stations in Paris center) and at 300m (250° and 2m/s observed at Eiffel Tower).

This has been added in the text :
"The model underpredicts the maximum over Eiffel Tower, even if predicted winds are in agreement with observations at the ground and at 300m height (Eiffel station), but reproduces CO2 mixing ratio magnitudes at $300m$ comparable to the measurements magnitude over the eastern part of Paris town (Fig.12.f with measurement in coloured square)."

But more generally, predicted winds are frequent with weak winds, as shown on Fig.13.b and Fig.14.b, where observed winds have been added in colour arrows (only 2 measurement stations). That's why we wrote :
"It is therefore likely that the underestimation at EIF is partly due to the too coarse anthropogenic emissions, as the correct mixing ratios have been produced on another part of Paris, and partly to horizontal transport errors, frequent with weak winds."

Reviewer : *- Page 17: (R2 is equal to 0.23 and bias to +17). The bias is lacking of unities.*

Authors : Yes, "ppm" has been added.

Reviewer : *- Page 18-19. Add the relevant Fig number to "Fig. ??".*

Authors : This has been corrected.

Reviewer : *- Page 19 (last sentence paragraph 5.3). "It underlines the possibility to apply inversion also in the nocturnal UBL". Needs more explanation and evidence.*

Authors : This has been modified and completed like this :
"The complex wind circulation on 26 March at 03:00UT, corresponding to the maximum UHI of the period (Fig.5), involves a stronger variability on CO2. It is mostly represented by the model, but the complex mesoscale circulation associated to the UHI is a source of transport errors, as illustrated by the observed wind arrows. Applying inversion in the nocturnal UBL is more appropriate on urban than rural sites due to the vertical mixing, caught by the urban parameterisation, but it must rely on a significant period of well-established flux, to limit horizontal transport errors.

Reviewer : *- Page 20, first paragraph. In inversion models the CO2 concentration measured in the afternoon at altitude sites is also used because they are representative of regional fluxes.*

Authors : Yes, this has been added : "For rural stations, it is well-known that only afternoon values of CO2 mixing ratio are well appropriate for estimating carbon sources/sinks on land, and preferentially for data sampled several hundred meters above ground, as they are representative of regional fluxes, and as they can be represented substantially more robustly in atmospheric models (Geels et al., 2007)."

Reviewer : *- Table 1. The precision figures should have the same number of significant digits*

Authors : OK

Reviewer : *- Table 5 (and text referring to it). The labels for 12 UT and 00 UT for both observations and simulations should be consistent (not 00 UT and 24 UT).*

Authors : 12 UT is associated to 12h forecast, and 00 UT is associated to 24h forecasts and not 00h forecasts meaning that it does not correspond to initial fields corresponding to analysis (with soundings assimilation).

Reviewer : *- Figure 7. I'd be clearer to add the standard deviation as +/- error bars or shaded area*

Authors : It has been modified like this.

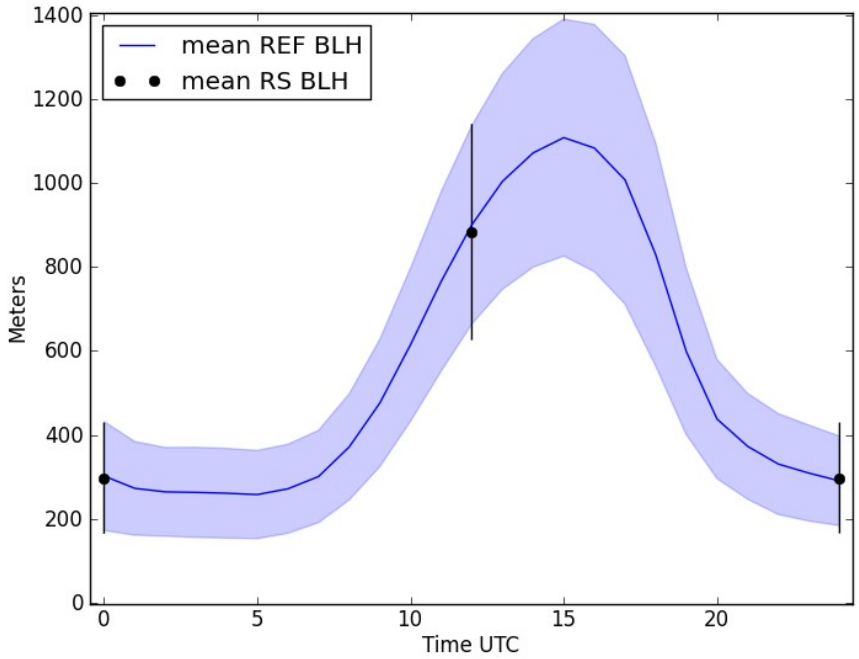


Figure : Diurnal cycle over the year of the BLH at Trappes predicted by REF (blue line for the Mean and blue area for the standard deviation) with the observed values marked by dots for the mean and by bars for the standard deviation.