

Anonymous Referee #1

We would like to thank you sincerely for your precious support to correct the text, and all your suggestions. Before answering to your questions, we must confess that there was an error in the coding of the deposition process : the deposition velocity was mistakenly multiplied by the volume of the grid, corresponding to a ratio of 25 for all the simulations at 5m resolution (so a deposition velocity of 50 cm/s instead of 2 cm/s was actually applied), and to a ratio of 4 for the simulation at 2m resolution (noted DX2). Consequently, the deposition effect was overestimated.

All the simulations except the one without deposition (called NDG) have been run again and most of the figures have been updated. For the REF simulation (with a deposition velocity of 2 cm/s), the discrepancies with the observed microphysical fields are a bit stronger (cloud mixing ratio and droplet concentration more overestimated), but the DE8 simulation (deposition velocity of 8 cm/s as it was requested by one of the reviewers) presents a significant improvement. The signature of the fog onset at elevated levels in the REF simulation is not so marked, and is more evident in the DE8 simulation, showing that both the tree drag effect and the deposition are necessary to reproduce the formation of fog at elevated levels. The new results do not modify the analysis of the fog event and the conclusions of the study.

The text has been also reduced to answer to the reviewers : the sensitivity test on the initial conditions has been removed, as well as the corresponding figures. The length of the text has been reduced as expected. Lastly, the text has been revised by an english native speaker.

Recommended disposition: The manuscript requires major revisions before publication in Atmospheric Chemistry and Physics.

General comments:

The manuscript presents results from various LES of a radiation fog event observed at a complex site. The simulations were aimed at identifying the main dynamical factors affecting the simulated life cycle of the fog layer, including its microstructure. The research is an original contribution toward a more complete understanding of the complex interactions shaping the evolution of a fog layer, as well as the identification of possible improvements of numerical models necessary for more accurate fog forecasts. The work is also a good example of how carefully crafted simulations can provide some insights into specific features often present in observations taken at complex sites. The discussion is comprehensive and generally well-structured, with major findings clearly emphasized. Some parts of the discussion could be shortened to further improve the clarity of the overall presentation. It is the opinion of this reviewer that major revisions are however needed before the manuscript can be accepted for publication.

More specifically:

1. First and foremost the written English is not of sufficient quality, which provides for a difficult read of the manuscript. It appears that the text was not put through a basic grammar check that most text editors have available. I highly encourage the authors to have the text revised by an English speaker to ensure appropriate terminology and sentence construction. There are also numerous opportunities to make the text more concise and clearer.

Additionally to all your suggestions, the text has been revised by a native speaker of English.

2. As this is a central aspect of this study, the parameterization of fogwater deposition on the tree canopy should be more clearly described and justified. In particular, the use of a drag term on momentum and TKE to represent the impact of a tree barrier on the flow and associated turbulence,

while the use of a parameterization of fog water deposition which is entirely independent of the flow and turbulent characteristics (i.e. constant deposition velocity) may appear as incompatible. Hence, the chosen formulation should be more clearly justified and contrasted against the work of von Glasow and Bott (1999).

You are right that the tree drag parametrization is sophisticated while the parameterization of fogwater deposition is simplistic. The tree drag parametrization has been introduced quite a long time ago in the model (Aumond et al., 2013) and validated on different cases (Bergot et al., 2015a). On the contrary, the deposition process is not taken into account in most of the models, especially NWP models. The first step here is therefore to have a first approach by examining the importance of this process, considering a simplistic formulation. As the conclusion is that this term is essential to correctly reproduce microphysical fields of the fog cycle, the next step in a further study will be to have a more sophisticated formulation as in von Glasow and Bott (1999). The text has been modified like this :

« In addition to droplet sedimentation, fog deposition is also introduced which represents direct droplet interception by the plant canopies. In the real world, it results from turbulent exchange of fog water between the air and the surface underneath, leading to collection (Lovett et al., 1997). In numerical weather prediction models (NWP), this process is most of the time not included, such as in the French NWP model AROME (Seity et al., 2011) whose physics comes from Meso-NH. As a new process to introduce, only a simple formulation of the deposition process is considered here as a first step, in order to perform a sensitivity study. The fog deposition flux F_{DEP} is predicted at the first level of the atmospheric model (50 cm height) for grassy areas, and over the 15 m height for trees, in a simplistic way following Zhang et al. (2014b): $F_{\text{DEP}} = aV_{\text{DEP}}$ with $a = r_c/N_c$ and where V_{DEP} is the deposition velocity. In a review based on measurements and parametrizations, Katata (2014) showed that V_{DEP} values ranged from 2.1 to 8.0 cm/s for short vegetation. Here V_{DEP} is assumed to be constant, equal to 2 cm/s. A test of sensitivity to this value is presented below. Water sedimentation and deposition amounts are input to the humidity storage of the surface model. A more complete approach in a further study would include a dependence of V_{DEP} on momentum transport as in von Glasow and Bott (1999) and also on LAI.»

The simplistic formulation of the deposition process and the necessity to improve it was already underlined in the conclusion : « In this study, the deposition term was introduced quite crudely and this would need some refinements in further studies. It would need to take account of the wind speed and the turbulence , and it could also consider the hygroscopic nature of canopies. By analogy with dry deposition, it would also be better to take droplet diameter into account, assuming that this field is correctly reproduced. Other studies have also shown that fog water deposition is strongly enhanced at the forest edge, becoming up to 1.5-4 times larger than that in closed forest canopies (Katata, 2014), so it could be interesting to simulate the edge effect of fog water deposition. ».

Specific comments:

1. *Throughout the text, replace “trees barrier” by “tree barrier” or by “barrier of trees”.*
OK
2. *Use of past tense to describe some aspects of the simulations throughout the paper is awkward. You may have performed the simulations in the past, but their characteristics remain true now. Please revise your use of the past tense throughout the manuscript.*
OK
3. *Throughout the manuscript, replace “ponctual” by “point”.*
OK
4. *Abstract line 2: Revise with “during the ParisFog”*
OK

5. *Abstract line 3: Please specify which aspect of “dynamics” you are referring to Boundary layer?*
Yes, it has been corrected by « the dynamics of boundary layer »
6. *Abstract line 5: deposition of what? Please specify for greater clarity.*
Yes, « deposition of droplets »
7. *Abstract line 7: We should read “as in observations” rather than “like in the observation”.*
OK
8. *Abstract last sentence: I would suggest re-wording as: : : “necessary to accurately represent the fog life cycle at very high resolution” for a clearer statement.*
Yes, thank you.
9. *Introduction line 18: How do you define “local dynamics”? and why do you not seem to include turbulence in that category?*
I mean by local dynamics local flow due to orography for instance. This has been corrected by « local flow »
10. *Introduction line 19: Please rewrite with “understanding of fog processes” rather than “fog processes understanding”.*
Yes.
11. *Introduction, line 20: Sentence is without a verb.*
OK, « can be referred » has been added.
12. *Introduction, line 22: measurements (please use plural).*
OK
13. *Introduction, line 22: “and set liquid water content”: ? I do not understand. Please revise.*
OK, set has been replaced by report.
14. *Page 2, line 5: use “as shown by Nakanishi”*
OK
15. *. Page 2, line 6: Here, need to add “to study some aspects of the characteristics of a fog layer”. Nakanishi was not the first to use LES in general, as you seem to imply.*
OK, this has been corrected by : « Many important features of fog have also been characterized using one-dimensional (1D) modelling (Bergot et al. (2007), Tardif (2007), Stolaki et al. (2015) among others). However, to study some aspects of the characteristics of a fog layer, it has become necessary to explicitly simulate turbulence motions in 3D as shown by Nakanishi (2000) who was the first to use a large-eddy simulation (LES) for fog. »
16. *Page 2, line 8: “a turbulence scheme”*
OK
17. *Page 2, line 11: Use of “stripes” is not appropriate. Maybe use “banded structures” and specify in which field(s) these structures are observed.*
OK, but « stripes » was already used by Bergot (2013). This has been corrected by : « During the formation phase, small banded structures, identified by Bergot(2013) as Kelvin-Helmoltz (KH) billows, occur in the middle of the fog layer on dynamical and thermodynamical fields. »

18. Page 2, line 14: Replace “move” by “relocate”.
OK
19. Page 2, line 18: the word “Hence” is superfluous.
OK
20. Page 2, line 26: The use of “allowing to represent” is not proper. Change to “allowing the representation of”
OK
21. Page 2, line 30: replace “it” by “values”
OK
22. Page 3, lines 3-4, sentence beginning with “Sensitivity tests will: : :”: This has been said already. Please remove sentence.
The sentence has been removed.
23. Page 3, line 5: Replace “sophisticated microphysics” by “sophisticated microphysical parameterization scheme” to be more precise.
OK
24. Page 3, line 6: Replace “taking into account” by “while accounting for”.
OK
25. Page 3, line 6: We should read “such as forests”
OK
26. Page 3, line 14: winter of
OK
27. Page 3, line 20: wind does not flow from a “side”, rather from a direction. Also, “this side” implies that information about wind direction has been provided to the reader, which wasn't. Please revise your sentence(s).
OK, this has been corrected by : : « Zaïdi et al. (2013) demonstrated the impact of the tree barrier on the observed flow when the wind was blowing from this direction, and our case study was in this configuration. »
28. Page 3, line 21: It is mentioned that the reader should refer to the study by Stolaki for a description of the instrumentation, yet the the entire next paragraph is devoted to just that. Please revise your text
The reference related to Stolaki's study for the description of instrumentation has been removed.
29. Page 3, line 23: Get rid of “At the surface”. 30m is not “at the surface” in this context.
« At the surface » has been removed.
30. Page 3, line 31: We should read “Aerosol particle measurements”, not “particles measurements”
OK
31. Page 3, line 33: What type of profiler? I suppose it is a microwave profiler. Please be more precise with your statement.

Yes, this is a RPG-HATPRO water vapour and oxygen multi-channel microwave profiler : this information has been added.

32. Page 4, line 5: 1000 UTC “on the following morning”? Please be more precise.

It has been added.

33. Page 4, line 9: I am not clear as to why fog events were not classified as stratus lowering. 150m for initial cloud formation does seem high to be a radiation fog. Please explain.

You are right that the distinction between radiative fog and cloud lowering is not easy to make. Fog classifications traditionally use the Tardif and Rasmussen (2007) method. They differentiate stratus lowering from radiative fog by the wind speed and the cloud ceiling. If the wind speed at 10m is lower than 2.5 cm/s before the formation and the cloud ceiling is less than 100m then the fog is supposed to be radiative. Our measured wind speed at 10m is under 2.5cm/s but our cloud ceiling is higher than 100m (150m). However according to Dupont et al. (2012), the lowering of a stratus is due to a cooling at its base by evaporation of sedimented droplets. Considering fall speed of 2.2 cm/s (Roach et al, 1976) it would necessitate at less 10 hours for the cloud to reach the ground. Moreover we do believe that the cloud formation at 150m is due to the modification of the flow caused by the tree barrier resulting in an important vertical mixing on a significant depth. So we conclude that this fog is a radiative one.

We propose the text :

« As underlined by Stolaki et al. (2015), this characteristic is very common at Sirta and 88% of the radiation fog events during the field experiment were also elevated. However, they were not classified as stratus lowering as they were followed rapidly by formation of fog at the surface. A delay of 30 min between the formation at 150 m height and at the ground seems too short to be a stratus lowering, which is mainly driven by the evaporation of slowly falling droplets that cool the sub-cloud layer (Dupont et al., 2012). This suggests that this type of radiation fog could be linked with, and specific to, the configuration of the Sirta site. »

34. Page 4, line 12: Replace “according to” by “following”

OK

35. Page 4, line 14: Use of “moistening” could lead to confusion. Is “moistening” referring to an increase in *relative* humidity (due to cooling) or increase in absolute humidity (water vapor content)? Please be more precise.

You are right that it was confusing. The increase in relative humidity is associated to the cooling, as we can see below on the dewpoint temperature : the difference between temperature and dewpoint temperature reduces slowly until the fog formation. « as well as a moistening » has been replaced by « inducing an increase in relative humidity ».

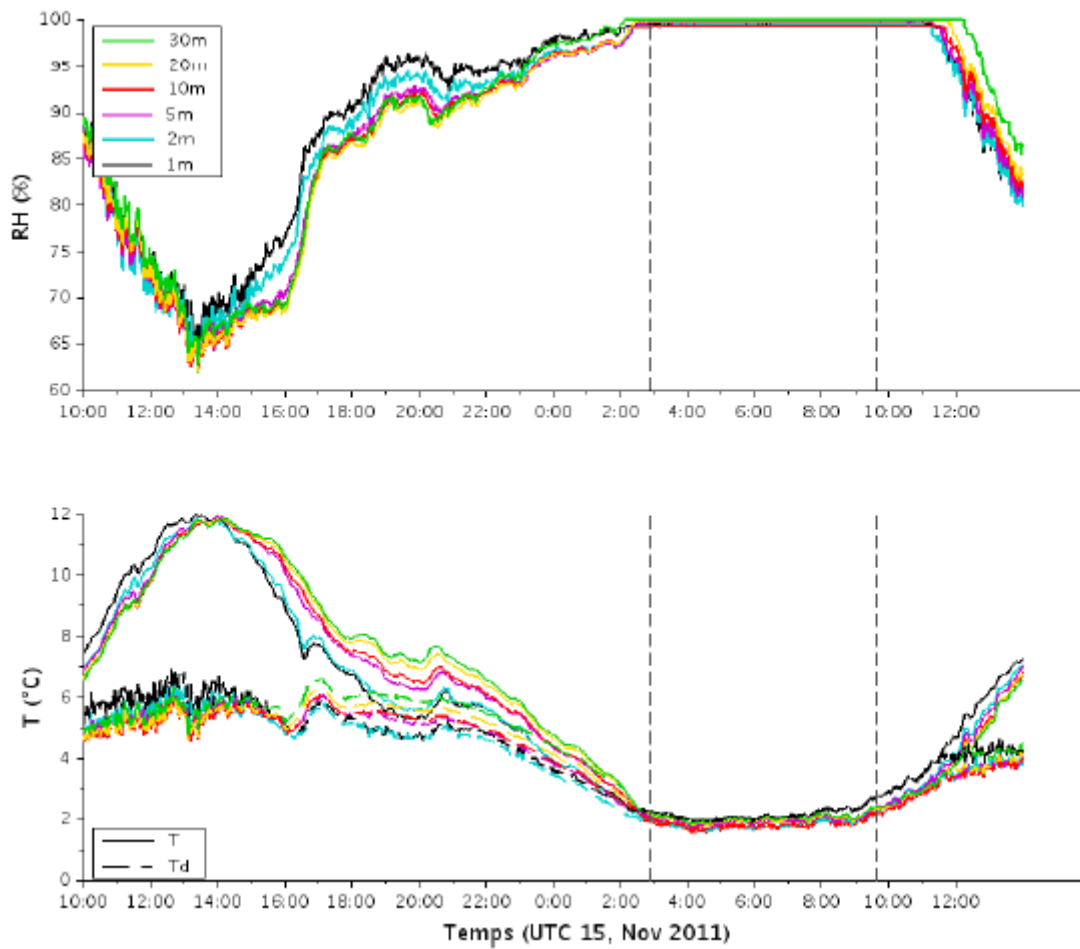


Figure : Temporal evolution of observed relative humidity (a) and temperature and dewpoint temperature (b) from 10 UTC the 14th of November to 12 UTC the 15th.

36. Page 4, line 19: Not sure I understand the meaning of “temperature convergence” in this context.

This has been corrected by : « At 0230 UTC, the apparition of fog at the ground was associated with a temperature homogenization in the first 30 metres, called temperature convergence by Price (2011) and corresponding to a neutral layer.»

37. Page 5, line 2: “fog droplet microphysics” is awkward wording in this context. Perhaps “fog microstructure” is more appropriate?

« liquid droplet » has been removed.

38. Page 5, line 5: “leaded” is not proper English.

OK, it has replaced by « brought ».

39. Page 5, line 6: LWC and N_c decreased at 3m but visibility remained constant? Please explain.

In fact, LWC and N_c decrease but visibility increases slightly. This has been corrected.

40. Page 5, line 15: Can you be more precise in your description. Not sure that “between” means in the context of a size distribution.

OK, this has been corrected by : « During the dissipation phase (in green, at 0700 UTC), the concentration of larger droplets fell but remained higher than initially. »

41. Page 5, line 29: “at the instrumental site »

OK

42. Page 6, line 1: By "It" you mean "The drag approach"? Please be more precise.

Yes : « The drag approach consists of introducing an additional term in the momentum and TKE equations »

43. Page 6, line 5: "a combination of the product" is confusing. A product already is a "combination" of terms. Simply say that it is a product of the fraction of vegetation with LAI and a weighting function. I would suggest that you show an equation for greater clarity and since it is a central aspect of your study.

The sentence has been corrected but we have not introduced an additional equation as the formulation is exactly described by the sentence : « $A_f(z)$ is the product of the fraction of vegetation in the grid cell by the leaf area index (LAI) and by a weighting function representing the shape of the trees, as presented in Aumond et al. (2013). »

44. Page 6, line 7: The vertical profile of what exactly? Please be more precise in your statement.

Yes, this has been corrected : see 43.

45. Page 6, line 7: "atlantic broad leaved trees": Where does that information included and how? Again, please be more precise in your statement. Perhaps refer to the equation that will show how A_f is expressed.

This information does not refer to the weighting function but to the vegetation cover introduced for the trees, which will be considered by the land surface scheme. This has been clarified by : « The trees introduced in the simulation domain for the land surface scheme correspond to Atlantic coast broad leaved trees » instead of « We have considered atlantic coast broad leaved trees ».

46. Page 6, line 11: Aren't "activated CCN" droplets? Please clarify the difference between N_c and N_{ccn} .

At the beginning, concentrations of activated CCN and droplets are equal but then droplet concentration is modified by several mechanisms as break-up, evaporation, autoconversion, accretion and sedimentation so concentrations of activated CCN and droplets become different. This point is presented in the 2 references relative to the microphysical scheme : Khairoutdinov and Kogan (2000) and Geoffroy et al. (2008).

Another point is that according to the Köhler theory, for a given maximum supersaturation S_{max} , aerosols activated are exactly those with a critical supersaturation lower than S_{max} . Thus, to determine the number of aerosols really activated at time t , we first compute the number of activable aerosols for S_{max} . The number of aerosols really activated is then the difference between the number of activable aerosols and the number of aerosols previously activated during the simulation. This point has been added.

47. Page 7, line 16: How is droplet concentration and cloud mixing ratio taken into account in LW and SW calculations? Just provide appropriate references.

The radiative transfer is computed with the ECMWF radiation code, using the Rapid Radiation Transfer Model (RRTM, Mlawer et al. (1997)) for longwave and Morcrette (1991) for shortwave radiation. Cloud optical properties for LW and SW radiation take account of the cloud droplet concentration in addition to the cloud mixing ratio. For SW radiation, the effective radius of cloud particle is calculated from the 2-moment microphysical scheme, the optical thickness is parametrized according to Savijärvi et al. (1997), the asymmetry factor from Fouquart et al. (1991) and the single scattering albedo from Slingo (1989). For LW radiation, cloud water optical properties refer to Savijärvi et al. (1997).

48. Page 8, line 2: I think here you rather mean that the **reduction** in visibility is

underestimated. Please revise your statements.

No, on Fig.6, the green curve is below the black one ; the parametrized visibility according to Zhang underestimates the observed visibility.

49. Page 8, lines 8 and 9: *.Variables are not transported. Perhaps simply write "momentum is advected"*

OK

50. Page 8, line 11: *Awkward use of past tense.*

The past tense throughout the manuscript has been replaced by the present tense.

51. Page 8, sentence on line 17-18: *1) soil moisture not moistening*

OK

2) Used the same point measurements to initialize soil variables across the entire domain? Please justify this approach.

Soil measurements are available in one place. As we consider a flat terrain and only two cover types (grass and trees) in the simulation, it makes sense.

52. Page 8, line 30, sentence with *"good degree of confidence"*: *This is not clearly justified. Please more directly and clearly address the possible shortcomings or impact of using this on your results. You should convince the reader that this mismatch does not adversely affect your results.*

A representation of the activation is a crucial point of this study as it directly links the calculated supersaturation to activated aerosol concentration. Usually, to find the Cohard et al. (2000c) parameter values, a fit is made on the aerosol lognormal distribution. Thanks to the CCNC, we get the exact curve of the evolution of the activated aerosol concentration, but only for supersaturation above 0.1 percent. As the activation in a fog layer is supposed to be under 0.1 percent, an instrumental method has been developed by Mazoyer et al. (2016) to retrieve the activation spectrum under this value. Using the combination of both information provides the exact activation spectrum, meaning that there is no shortcoming to use this method.

We have addressed this point more directly :

« Nevertheless, considering that the activation spectrum is deduced from measurements, it includes a good degree of confidence. » has been replaced by : « Deducing the activation spectrum from measurements provides the exact solution. »

53. Page 9, lines 3-4, *"good degree of confidence"* : *Compared to surface observations? Please be more precise with your statement.*

«degree of confidence » has been replaced by « agreement with observation »

54. Page 9, statement on lines 5-6: *making some assumption of ergodicity here? Taking time averages of point observations to compare to area-averaged simulated fields? Please describe more clearly the assumptions you are making and justify.*

No, it does not correspond to some assumption of ergodicity. The horizontal variability study (Fig.9a for instance) shows that the domain near the surface can be decomposed into 4 meridional bands with similar characteristics inside each one : the first one upstream from the trees, the second one corresponding to the barrier, the third one downstream the trees and the last one far downstream the trees. The instrumented area is located inside the third one so we have averaged the simulated fields on this band to compare to the measurements.

You are right that the sentence was not clear. We propose :

« It should be emphasized that observations localized at one point will be compared to simulated fields averaged over a horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b) representative of the instrumented area. We will indeed

see that the simulation domain is divided into 4 parts with significant differences between them, but similar characteristics inside each one.»

55. Page 10, line 22: *What does “reducing the spectrum” mean? I do not know what a reduction in the spectrum mean.*

We wanted to say that the number of larger droplets has been reduced. This part has been simplified and adapted to the new results : « During the whole fog life cycle, the model overestimates droplets with a diameter larger than 4 μm and underestimates the smaller ones.»

56. Page 10, line 24: *“leaded” is not proper English*
OK.

57. Page 10, line 24: *Awkward use of “weakness”. Maybe replace by “underestimated”*
OK.

58. Page 10, line 24: *What do you mean by “surface cloud water amount by sedimentation”? Do you mean to say “amount of water deposited on the surface by sedimentation”?*

Yes. This part has been simplified and the new comment is : « The cloud water deposition rate at the ground presents a maximum of 0.36 mm/day while the maximum of droplet sedimentation rate is 0.08 mm/day, meaning that the deposition is the main contributor to the cloud water amount at the ground. »

59. Page 10, last sentence: *Maybe an important point here about usefulness of more sophisticated formulations of visibility diagnostics for models. Your simulation results indicated that a simpler formulation based solely on LMC is adequate given the difficulty in simulating N_c . Perhaps this finding could be expanded upon here.*

Thank you. It has been added : « This explains why a simpler formulation of visibility based solely on r_c is usually more adequate given the difficulty of simulating N_c for the models.»

60. Page 11, line 15: *“allows to decompose formally” is awkward. Maybe change to “serves as a basis for decomposing”*

Thank you.

61. Page 11, line 19: *“consecutively to the flow”, you rather mean “related to the flow perturbations”?*

No, we just mean that the layer of TKE deepens slowly due to the tree barrier. It has been corrected.

62. Page 12, line 10, use of “ r_c ” I believe you used “LWC” before. You should remain consistent throughout the paper.

Yes, we agree. Only cloud mixing ratio is now only used throughout the paper.

63. Page 13, line 8: *drawning? Please revise*

Yes, replaced by « bringing »

64. Page 13, sentence on lines 10-11 is unclear. Please revise.

«The fog forms at the surface upstream from the trees, and 500 m downstream, while it appears first at elevated levels between both » has been replaced by « The fog forms at the surface upstream of the trees, and 500 m far downstream, while it appears first at elevated levels over the intermediate area between the trees and far downstream (Fig. 9d).»

65. Page 13, line 31: statement with "even if measurements" is unclear. You mean "...probably overestimated, although this cannot be confirmed as measurements ..."
Yes, thank you.

66. Page 14, sentence on lines 24-25 is confusing. Please revise.
We propose : « The main differences in dynamics between NTR and REF appear first on total TKE, with ~~the absence of stronger values in the first 40 metres in NTR, as they were restricted to the immediate vicinity of the ground~~ a thinner layer of TKE values higher than $0.5 \text{ m}^2/\text{s}^2$ and smaller maxima (Fig. 8b). »

67. Page 16, line 5: "removed fully deposition" should be replaced by "removed deposition altogether" for proper wording.
Yes, thank you.

68. Page 16, line 18, LWP was largely overestimated. Where? At the surface? If so, how is LWC at surface positively correlated to the depth of the fog layer? Please provide a clearer explanation.
LWP (Liquid Water Path) corresponds to the LWC integrated on the vertical. As LWC is overestimated near the ground (Fig.13) and as the fog layer is deeper, LWP is overestimated. It has been completed by : « Due to the larger amount of cloud water near the ground, the dissipation at the ground is delayed by more than one hour . »

69. Page 16, line 21: Is DE5 based on deposition on a grassy surface only, or is deposition over the entire tree canopy considered as well? In the context of this section, this text is not clear. Please clarify.
DE5 was related to grass and tree canopy as it was like in REF. DE5 has been replaced by DE8 (deposition velocity of 8 cm/s) to answer to the new point, and the principle has been clarified.

70. Page 16, line 21: Why not use a value of 8 cm s^{-1} , the upper bound suggested by Katata?
OK, DE8 has been run and is presented instead of DE5. As explained in the introduction, the previous mistake on the deposition velocity has induced some modifications and now the DE8 simulation presents a significant improvement compared to REF.

71. Page 16, line 22: Replace "diminution" by "reduction".
OK.

72. Page 16, line 29: Replace "the remove of" by "neglecting" for proper wording.
OK.

73. Page 17, line 26: I do not think "preformation" is a word. Maybe you mean "initial formation"?
Thank you.

74. Page 17, line 27: A DSD does not "move". Maybe "characterized by higher concentrations of larger droplets"
Yes, thank you.

75. Page 17, line 30: "dilutes" is not properly used here. You rather mean "decreases" or "diminishes".
OK

76. Page 17, line 30: Also this reduced effect impacts which field(s) in particular. Please

clarify.

This has been clarified.

77. Page 17, line 32, "fog slightly deeper": Please revise as "a slightly deeper fog layer"

OK

78. Page 18, lines 26-27: I do not understand the statement "diverged on the fog life cycle in the same way". Please revise your statement.

This part has been removed as the text was too long.

79. Page 18, lines 27-28: Not a very clear statement. Please revise. And be more explicit about what you mean by "dynamical conditions".

This part has been removed as the text was too long.

80. Page 19, line 10, "as the wind overcame this obstacle": Awkward formulation. Maybe "and associated perturbed mean flow and turbulence conditions" would be a clearer statement.

OK, « overcame » has been replaced by « met »

81. Page 19, line 17: replace "meeting" with "encountering" or "reaching".

OK, "encountering".

82. Page 19, line 17: use of the expression "dynamical gradients" is not specific enough. Do you mean "wind shear" in particular?

Yes, thank you.

83. Page 19, line 18, "became well-marked": This is awkward wording. Do you mean "became prominent"?

Yes, this has been corrected.

84. Page 19, line 23, "homogeneous". Where? Throughout the fog layer? At the top of the layer? Please be more precise in your statement.

No, inside the cloud layer: «The cloud droplet concentration became quasi homogeneous in the fog layer when averaged over time but extremes of droplet concentration occurred locally near the top of the fog in the radiative cooling layer, with maxima preferentially upstream of the crests of the waves rather than downstream, in the ascent area. »

85. Page 19, line 24: "evolved" rather than "involved"?

Yes, thank you.

86. Page 19, line 29: "damaging the visibility diagnostic" is awkward wording. Maybe "worsening visibility diagnostics"?

Yes, thank you.

87. Page 19, line 31: "The removal of the deposition process" is awkward wording. Maybe replace "The removal of" by "Neglecting".

OK.

88. Page 20, line 4, "Endly": You mean "Finally" or "Lastly"?

Yes, lastly.

89. Page 20, lines 4-5: The use of "reduce much more the number concentration" is awkward.

Change to "reduce the overestimated droplet number concentration" for a more precise statement.
OK.

90. *Page 20, line 8: In what way "simulations remain very challenging"? Please explain.*
They are very challenging due to the importance to represent correctly surface heterogeneities. This has been corrected.

91. *Page 20, line 12: I suggest you replace "cannot be neglected anymore" by "should not be neglected"*
OK, thank you.

92. *Page 20, line 20: We should read "dewfall" instead of "dewfal"*
Yes, thank you.

93. *Page 20, line 23: Change "no one" to "none" for appropriate wording.*
OK

94. *Page 20, line 23: Change "to reproduce correctly" to "in correctly reproducing"*
OK.

95. *Page 39: The citation of Hammer is not accurate. That paper has now been fully published and the citation should now indicate : Atmos. Chem. Phys., 14, 10517- 10533, doi:10.5194/acp-14-10517-2014*
OK, thank you.

96. *The formatting of citations is inconsistent throughout the References section. In particular, the names of journals sometimes uses capital letters (as should be) and sometimes not. Please revise.*
Yes, it has been done.

Note: Only the most important text corrections have been suggested. A much greater number of possible corrections have been omitted due to time constraints for the reviewer. I strongly recommend that the text be reviewed by someone with a higher proficiency in English.

Large-eddy simulation of radiation fog: Part 1: Impact of dynamics on microphysics

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Abstract.

Large Eddy Simulations (LES) of a radiation fog event occurring during the ParisFog experiment have been studied with a view to analyzing the impact of the dynamics of the boundary layer on the microphysics. The LES, performed with the Meso-NH model at 5 m resolution horizontally and 1 m vertically, and with a 2-moment microphysical scheme, includes the drag effect of a trees barrier and the deposition of droplets on vegetation. The model shows a good agreement with the measurements of the near surface dynamic and thermodynamic parameters as well as the cloud water content, but overestimates the cloud droplet sizes mass and concentration. The blocking effect of the trees induced elevated fog formation, like in the actually observed, and horizontal heterogeneities, and during the formation. It also limited the cooling and the cloud water production. The deposition process was found to exert the most significant impact on the fog prediction, as it not only erodes the fog near the surface, but also modifies the fog life cycle and induces vertical heterogeneities. The comparison with the 2 m horizontal resolution simulation exhibited reveals small differences, meaning that the grid convergence was achieved. Conversely, increasing numerical diffusion through a wind advection operator of lower order led to an overestimation of the near-surface microphysical fields and had almost a very similar effect than removing the effect of the trees barrier. This study allows us to establish the major dynamical ingredients necessary needed to perform correctly accurately represent the fog life cycle prediction at very high resolution.

1 Introduction

Despite the long-standing interest in understanding fog processes, uncertainties still exist on the physical mechanisms driving fog variability. Forecasting fog remains a challenge due to because of the diversity of mechanisms involved during the fog life cycle and their interactions: local dynamics flow, turbulence, radiation, microphysics, aerosols, and surface effects. Several field experiments have been carried out since the 1970's that brought and have contributed to the important progress made in understanding fog processes understanding. Among them the noteworthy works include campaigns from Cardington in the UK (Roach et al., 1976; Price, 2011), Fog-82 in Albany, New York (Meyer et al., 1986), Lille 91 in France (Guedalia and Bergot, 1994), a campaign in the Po Valley in Italy (Fuzzi et al., 1998) and ParisFog in France (Haefelin et al., 2010). Most

of them have naturally included measurements of fog droplet spectra, and ~~seth~~ have reported liquid water contents (LWC) in the range of $0.01 - 0.4 \text{ g m}^{-3}$ and droplet number concentration (N_c) of a few tens to a hundred ~~per~~ cm^{-3} cm^3 . ~~Henee~~-Roach et al. (1976) ~~related~~ reported values of LWC between 0.05 and 0.22 g m^{-3} and N_c between 30 and 100 cm^{-3} for winter fog cases at Cardington. More recently, Mazoyer et al. (2016) reported N_c ~~for radiation fog~~ of less than 150 cm^{-3} ~~for radiation fog~~ over 3 winters during ParisFog.

Many important features of fog have also been characterized using one-dimensional (1D) modelling (Bergot et al. (2007), Tardif (2007), Stolaki et al. (2015) among others). ~~But~~ However, to study some aspects of the characteristics of a fog layer, it has become necessary to explicitly simulate turbulence motions in a 3D manner ~~has become necessary to improve our understanding of the physical mechanisms involved in a fog layer, since~~ as shown by Nakanishi (2000) who was the first to use a large-eddy simulation (LES) for fog. LES is a turbulence modelling technique in which most of the energy-containing eddies are explicitly resolved while eddies smaller than a certain cutoff ~~scale~~ size, usually taken equal to the grid spacing, are parametrized by ~~the~~ turbulence scheme. Since then, Porson et al. (2011) ~~have~~ explored the static stability in a fog layer, and Bergot (2013) ~~have~~ showed ~~n~~ the various organized structures occurring in a fog layer, which cannot be resolved in 1D. Thanks to these studies, the dynamical characteristics of ~~the~~ radiation fog are more clearly identified during the three stages of the fog life cycle defined by Nakanishi (2000): the onset, ~~the~~ development and ~~the~~ dissipation phases. During the formation phase, small ~~stripes~~ banded structures, identified by Bergot (2013) as Kelvin-Helmoltz (KH) billows, occur in the middle of the fog layer on dynamical and thermodynamical fields, ~~identified by Bergot(2013) as Kelvin-Helmoltz (KH) billows.~~ They are sometimes associated ~~to~~ with a burst of turbulent kinetic energy (TKE) (Nakanishi (2000) and Bergot (2013)) but ~~this is~~ not always ~~the case~~ (Porson et al. (2011)). During the development phase, the main dynamical processes ~~move~~ relocate to the top of the fog layer ~~and are~~ associated ~~to~~ with the maximum of TKE and horizontal rolls (Bergot, 2013). During the dissipation phase, coupled processes between the ground and the top of the fog layer explain the spatial variability of fog (Bergot (2015b)). ~~B~~ but the link between dynamics and microphysics has not been explored specifically in these LES studies.

The quality of the LES depends on the horizontal and vertical resolutions. ~~Henee~~ Beare and MacVean (2004) demonstrated that simulations in stable conditions converge at 2-m horizontal resolution. Very high vertical resolution is also essential to capture the divergence of the radiative fluxes in the first ~~few~~ metres above the surface and therefore to produce ~~athe~~ radiative cooling necessary ~~to~~ for the formation of fog (Duynderke, 1999; Tardif, 2007).

So far, most ~~of~~ fog LES studies ~~have~~ considered homogeneous canopies. Only Bergot et al. (2015a) ~~took into~~ have taken account of the effect of surface heterogeneities as buildings on radiation fog. Other studies, ~~such as those by Zaïdi et al.(2013) or Dupont and Brunet (2008),~~ have considered the impact of forests on turbulence structures, ~~like Zaïdi et al.(2013) or Dupont and Brunet (2008)~~ but not for fog situations. In this study, we will explore a LES of a fog case ~~that was~~ observed during ParisFog and strongly influenced by trees.

Also, very few fog LES studies are based on sophisticated 2-moment microphysical schemes; allowing ~~to represent~~ the impact of aerosols ~~impact~~ on the radiation fog life cycle ~~to be represented~~. Maalick et al. (2016) studied the effects of aerosols on ~~the~~ radiation fog with an LES; but in a 2D configuration that could present some limitations for the dynamical patterns of the fog layer. Additionally, most of the studies, ~~with~~ using one- or two-moment microphysical schemes, fail to reproduce realistic

liquid water contents (LWC) as they tend to overestimate it values near the ground. For instance, Zhang et al. (2014b) simulated $N_c = 800 \text{ cm}^{-3}$ and $LWC = 0.4 \text{ g m}^{-3}$ and Stolaki et al. (2015) simulated $N_c = 250 \text{ cm}^{-3}$ and $LWC = 0.34 \text{ g m}^{-3}$ near the surface, both in 1D configuration. These values that are outside of the range according to found by Mazoyer et al. (2016) considering the same site. So on the question is: is there a of a possible missing mechanism missing arises, the inclusion of which might improve the modelling of microphysical fields? Considering deposition, the interactions with the ground surface should be an important factor as already shown by Price and Clark (2014) on measurements and von Glasow and Bott (1999) or Zhang et al. (2014b) on 1D simulations.

The goal of this study is to better understand the physical processes dominating the fog life cycle on a complex site and impacting the microphysical fields. LES modelling at very high resolution (1 m vertically and 5 m horizontally) is used with surface heterogeneities (barrier of trees) and a 2-moment microphysical scheme. Sensitivity tests will help to understand the influence of some dynamical processes on the fog life cycle with a focus on microphysical properties. In order to establish the main ingredients driving the fog life cycle and the microphysical fields, and to evaluate how dynamics affects the evolution of fog, sensitivity experiments are conducted with the model considered as a laboratory. To our knowledge, this is the first time that an LES study of radiation fog has been performed at such high resolution with a sophisticated microphysical parameterization scheme taking into account while considering the effect of heterogeneities such as forests on the fog dynamics and microphysics. In a second article, the impact of aerosol activation on microphysical fields will be explored specifically, allowing to characterize the contribution of the different microphysical processes to be characterized.

Section 2 presents the measurement set-up and the observed case, and describes the numerical model. The reference simulation is analyzed in Section 3, and Section 4 is devoted to sensitivity tests. Finally, some conclusions are drawn and perspectives suggested in Section 5.

2 Experimental design and model description

2.1 Measurements set-up

The selected fog event has been observed on 15 November 2011 during the ParisFog field campaign in the winter of 2011-2012 of the ParisFog field campaign (Haefelin et al., 2010) at the Sirta (Site Instrumental de Recherche par Télédétection Atmosphérique) observatory (48.713°N and 2.208°E). The objective of the ParisFog campaign during three winters from 2010 to 2013 was to better understand the radiative, thermodynamic, dynamic and microphysical processes occurring during the fog life cycle. The site where the instrument platform was installed was a semi-urban area of a complex terrain including forest, lake, meadows and shrubs next to an urban agglomeration built up area. As shown in Figure 1a, the instrumented zone was located near a forest area. Zaïdi et al. (2013) demonstrated the impact of the trees barrier on the observed flow when the wind was blowing from this side direction, just as in our case study was in this configuration. The fog case has already been studied by Stolaki et al. (2015) in the 1D configuration, and the reader should refer to this study for the description of the instrumental set-up.

At the surface, temperature and humidity sensors were located at heights between 1 and 30 m on an instrumented mast, with 0.2 K uncertainty for temperature and 2% for relative humidity. Wind speed was measured by two ultrasonic anemometers at 10 m and 30 m above ground level (agl) on the same meteorological mast. Radiative fluxes were measured on a building roof at a height of 10 m with 5 W m^{-2} and 4 W m^{-2} uncertainties for downward and upward fluxes respectively.

Two diffusometers were operated at 3 m and 18 m to provide information on the vertical visibility with an uncertainty of up to 25%. Additionally, radiosondes were launched by Météo-France twice a day from Trappes (48.7°N, 2 °E), localized 15 km to the North-West of Sirta.

The microphysical instrumentation has been presented in detail by Mazoyer et al. (2016). A Fog-Monitor 100 (FM-100) provided the size distribution for particles from $2 \mu\text{m}$ to $50 \mu\text{m}$ in diameter, while the WELAS-2000 provided particle diameter distribution was provided between $0.96 \mu\text{m}$ and $10 \mu\text{m}$ by a WELAS-2000 system. According to Mazoyer et al. (2016), aerosol particles measurements were performed by using a Scanning Mobility Particle Sizer (SMPS) measuring dry aerosol diameters between 10.6 and 496 nm every 5 min, and by a CCN chamber providing that gave the CCN number concentration at different supersaturations from 0.1 to 0.5% (Roberts and Nenes, 2005). A RPG-HATPRO water vapour and oxygen multi-channel microwave profiler was used to measure the Liquid Water Path (LWP) measurements with an error of up to 20 g m^{-2} according to Lohnert and Crewell (2003). We did not take measurements of dewfall and fog-droplet deposition.

2.2 Presentation of the observed case

2.2.1 Dynamics and thermodynamics

The radiative fog formed at 0200 UTC on 15 November 2011 and dissipated at the ground around 1000 UTC on the following morning. Conditions favouring fog were due to a ridge at 500 hPa centred over the North Sea and anticyclonic conditions near the surface. One of the features of this event is that it is an elevated fog event, formed by a cloud layer 150 m agl and followed shortly 30 min later by fog at the surface. As underlined by Stolaki et al. (2015), this characteristic is very common at Sirta since 88% of the radiation fog events formed during the field experiment were also elevated, but. However, they were not classified as stratus lowering, as they were followed rapidly by formation of fog at the surface. A delay of 30 min between the formation at 150 m height and at the ground seems too short to be a stratus lowering, which is mainly driven by the evaporation of slowly falling droplets that cool the sub-cloud layer (Dupont et al., 2012). This suggests that this property type of radiation fog could be linked with, and specific to, the configuration of the Sirta site.

The fog case is presented according to following the three phases of the fog life cycle defined by Nakanishi (2000). Before the fog onset, between 2200 and 0200 UTC, the surface boundary layer was stable and a near-surface cooling was observed, as well as a moistening inducing an increase in relative humidity (Fig. 2). Between 0000 and 0130 UTC, the relative humidity (RH) near the ground remained nearly constant around 97%. Wind speed at 10 m height was light (speed around 1.8 m s^{-1}) as well as was TKE, with small variability (Fig. 3). At 0200 UTC, the attenuated backscatter coefficient of the lidar increased significantly at 150 m agl (not shown), revealing the formation of liquid water at this height, while the RH at the surface

remained at 97%. Then the cloud base height progressively subsided during about 30 min, until it reached the ground, while the near-surface temperature continued to decrease by about 1 K. At 0230 UTC, the apparition of fog at the ground was associated with a temperature convergence/homogenization in the first 30 metres, as described/incalled temperature convergence by Price (2011), and corresponding to a neutral layer. The downwelling longwave (LWD) radiation flux increased progressively up to 325 W m⁻² during the development of the fog layer (Fig. 4).

Then, during the fog development and mature phases, between 0200 and 0700 UTC, the near-surface layer remained quasi-neutral and temperature at the different levels remained constant. The 10 m wind speed presented a higher temporal variability than previously, as well as did the TKE. Around 0400 UTC, the TKE at 10 m height increased significantly, by 0.5 m²s⁻², and remained then constant then presented some variability around this value, while maintaining a positive vertical gradient of TKE. According to Stolaki et al.(2015) and Dabas et al.(2012), t. The sodar indicated that the fog top height reached a maximum height of 300 m agl during its the mature phase (Stolaki et al.(2015), Dabas et al.(2012)).

At the beginning of the dissipation phase, from 0700 UTC, the surface temperature increased slowly (less than 0.5 K in 2 hours) and then more significantly after 0900 UTC. At 1000 UTC, the downward SW fluxes exceeded 100 W m⁻², while near-surface temperature had increased by 1 K compared to the pre-sunrise values. 30 m TKE decreased from 0800 UTC to 1000 UTC, while 10 m TKE remained approximately constant.

2.2.2 Microphysics

Measurements of liquid droplet microphysics near the surface indicated a sharp increase of LWC in cloud mixing ratio (r_c) and droplet concentration (N_c) at the fog onset just after 02030 UTC (Fig. 5 in solid lines), up to reaching $N_c = 53 \text{ cm}^{-3}$ and $LWC = 0.035 \text{ g m}^{-3}$, $r_c = 0.02 \text{ g kg}^{-1}$. This corresponded to a drop of in the near-surface visibility from 5000 m to less than 500 m (Fig. 6a in black line). The initial elevated structure of the fog led to an earlier decrease of the visibility at 18 m than at 3 m agl, with a time lag of the order of 30 min. Until 0730 UTC, LWC , r_c and N_c decreased then slowly, while inducing a small increase of the visibility at 3 m and 18 m (not shown) remained almost constant. Between 0730 and 0800 UTC, LWC , cloud mixing ratio and droplet concentration at 3 m decreased strongly, allowing an increase of the visibility at 3 m up to increase to 2000 m. At 18 m agl, the visibility remained smaller/less than 1300 m. But the fog at the surface reformed just after 0800 UTC, reaching $N_c = 30 \text{ cm}^{-3}$ and $LWC = 0.024 \text{ g m}^{-3}$, $r_c = 0.02 \text{ g kg}^{-1}$, and with a visibility of less than 500 m, before definitively dissipating at 1000 UTC. The particle size distribution (PSD) indicated that 95% of the droplets with had a diameter of less than 20 μm , meaning that there is was probably a very small impact of the coalescence process. Sampled at 3 stages of the event, the PSD evolved during the fog life cycle and appeared consistent with the classification of Wendisch et al. (1998) (Fig. 5d). The “initial phase”(in red, at 0250 UTC) was characterized by a small droplet size, but already a second mode between 8 and 12 μm was already visible, that which persisted during through the 3 stages. During the mature phase (in blue, at 0500 UTC), also called the “mass transfer stage”, larger droplets are numerous, up to 22 μm , were numerous. During the dissipation phase (in green, at 0700 UTC), the concentration of larger droplets fell but remained higher than initially the spectrum was between the two previous ones with a reduction of the largest droplets. Hence the spectral shape remained bimodal during the fog life cycle.

The maximum ~~of~~ LWP measured by the profiler was reached around 0730 UTC, at the beginning of the fog dissipation phase, with 70 g m^{-2} (Fig. 5c). The non-zero values (5 g m^{-2}) before the fog onset are ~~included in~~ within the error range of the measurement.

2.3 Model description

5 2.3.1 Presentation of the model

The non-hydrostatic anelastic research model Meso-NH (Lafore et al., 1998) (see <http://mesonh.aero.obs-mip.fr>) ~~wasis~~ was used here in a LES configuration. The LES ~~wasis~~ based on a 3D turbulent scheme with a prognostic turbulent kinetic energy (TKE) (Cuxart et al., 2000) and a Deardorff mixing length (Deardorff, 1980).

The atmospheric model ~~wasis~~ coupled with the ISBA surface scheme (Interaction between Soil Biosphere and Atmosphere, Noilhan and Planton (1989)) through the SURFEX model (Masson et al., 2013). This scheme simulates the exchanges of energy and water between the land surface (soil, vegetation and snow) and the atmosphere above it. It uses five prognostic equations for deep temperature, deep soil water content, surface temperature, surface soil water content and water interception storage by vegetation.

In order to ~~take into account~~ consider the impact of trees ~~on~~ at the instrumented site, we used the drag approach developed by Aumond et al. (2013) for a vegetation canopy. ~~Indeed, Aumond et al. (2013)~~ These authors and Zaïdi et al. (2013) have shown ~~the best results of~~ that the drag approach ~~compared to~~ gives better results than the classical roughness law ~~to~~ when reproducing the turbulence downstream of a forest area. ~~If~~ The drag approach consists of introducing an additional term into the momentum and TKE equations as follows:

$$\frac{\partial \alpha}{\partial t}_{DRAG} = -C_d A_f(z) \alpha \sqrt{u^2 + v^2} \quad (1)$$

where α represents u and v horizontal wind components and TKE , C_d is the drag coefficient, set ~~as~~ to 0.2, and $A_f(z)$ is the canopy area density, representing the surface area of the trees facing the flow per unit volume of canopy. ~~It is a combination of~~ $A_f(z)$ is the product of the fraction of vegetation in the grid cell by the leaf area index (LAI) and ~~by~~ a weighting function ~~that~~ represents the shape of the trees. ~~The vertical profile is, as~~ presented in Aumond et al. (2013). ~~The trees introduced in the simulation domain for the land surface scheme correspond to~~ We have considered a Atlantic coast broad leaved trees.

For the microphysics, the model includes a two-moment bulk warm microphysical scheme (Khairoutdinov and Kogan, 2000; Geoffroy et al., 2008), that considers droplet concentration N_c and mixing ratio r_c as prognostic variables for the fog. An additional prognostic variable N_{ccn} is used to account for already activated CCN, following the activation scheme of Cohard et al. (2000c). The aerosols are assumed to be lognormally distributed and the activation spectrum is prescribed as:

$$N_{ccn} = C S_{max}^k F(\mu, k/2, k/2 + 1, -\beta S_{max}^2) \quad (2)$$

where N_{ccn} is the concentration of activated aerosol, $F(a, b; c; x)$ is the hypergeometric function, C (m^{-3}) is the concentration of aerosols, and k, μ and β are adjustable shape parameters associated with the characteristics of the aerosol size spectrum

such as the geometric mean radius (\bar{r}) and the geometric standard deviation (σ), as well as solubility of the aerosols (ε_m) and temperature (T) (see below for the values for in our case study). S_{max} is the maximum of supersaturation, verifying $\frac{dS}{dt} = 0$. The evolution of the supersaturation S includes three terms accounting respectively the effects of a convective ascent using of vertical velocity w , the growth of droplets by condensation for the newly activated droplets, and a radiative cooling, as in Zhang et al. (2014b):

$$\frac{dS}{dt} = \phi_1 w - \phi_2 \frac{dr_c}{dt} + \phi_3 \frac{dT}{dt} |_{RAD} \quad (3)$$

where $\phi_1(T)$, $\phi_2(T, P)$ and $\phi_3(T)$ are functions of temperature and pressure. Following Pruppacher et al. (1998) and after simplification, S_{max} can be diagnosed by:

$$S_{max}^{k+2} \cdot F(\mu, k/2, k/2 + 1, -\beta S_{max}^2) = \frac{(\phi_1 w + \phi_3 \frac{dT}{dt} |_{RAD})^{3/2}}{2k c \pi \rho_w \phi_2^{3/2} B(k/2, 3/2)} \quad (4)$$

with B the Beta function and ρ_w the density of water. Thus, the aerosols activated are exactly those with a critical supersaturation lower than S_{max} . The number of aerosols really activated is then the difference between the number of activable aerosols and the number of aerosols previously activated during the simulation.

The condensation/evaporation rate is derived using the Langlois (1973) saturation adjustment scheme. The cloud droplet sedimentation, that is the gravitational settlement of droplets, is computed by considering a Stokes law for the cloud droplet sedimentation velocity and by assuming that the cloud droplet size distribution $n_c(D)$ fits a generalized Gamma law:

$$n_c(D) = N_c \frac{\alpha}{\Gamma(\nu)} \lambda^{\alpha\nu} D^{\alpha\nu-1} \exp(-(\lambda D)^\alpha) \quad (5)$$

where λ is the slope parameter, depending on the prognostic variables r_c and N_c :

$$\lambda = \left(\frac{\pi}{6} \rho_w \frac{\Gamma(\nu + 3/\alpha)}{\Gamma(\nu)} \frac{N_c}{\rho_a r_c} \right)^{1/3} \quad (6)$$

α and ν are the parameters of the Gamma law, and ρ_a is the density of dry air. They were adjusted using droplet spectra measurements from the FM-100 database of our case study and were set at $\alpha = 1$ and $\nu = 8$. These parameters are also used for the radiative transfer.

In addition to droplet sedimentation, fog deposition is also introduced which represents direct droplet interception by the plant canopies. In nature the real world, it results from turbulent exchange of fog water between the air and the surface underneath, leading to collection (Lovett et al., 1997). In numerical weather prediction models (NWP), this process is most of the time not included, such as in the French NWP model AROME (Seity et al., 2011) whose physics comes from Meso-NH. As a new process to introduce, only a simple formulation of the deposition process is considered here as a first step, in order to perform a sensitivity study. Here, the fog deposition flux F_{DEP} is predicted at the first level of the atmospheric model (50 cm height) for grassy areas, and over the 15 m height for trees, in a simplistic way following Zhang et al. (2014b):

$F_{DEP} = \rho_a \chi V_{DEP}$ with $\chi = r_c, N_c$ and where V_{DEP} is the deposition velocity. In a review based on measurements and parametrizations, Katata (2014) showed that V_{DEP} values ranged from 2.1 to 8.0 cms^{-1} for short vegetation. A more complete

approach would be to include a dependence of V_{DEP} with momentum transport and also with LAI, but we supposed here that V_{DEP} is assumed to be constant, equal to 2 cm s^{-1} . A test of sensitivity to this value will be presented below. Water sedimentation and deposition amounts are supplied input to the humidity storage of the surface model. A more complete approach in a further study would include a dependence of V_{DEP} on momentum transport as in von Glasow and Bott (1999) and also on LAI.

The radiative transfer was computed with the ECMWF radiation code, using the Rapid Radiation Transfer Model (RRTM, Mlawer et al. (1997)) for longwave and Morcrette (1991) for shortwave radiations. Cloud optical properties for LW and SW radiation took into account of the cloud droplet concentration in addition to the cloud mixing ratio. For SW radiation, the effective radius of cloud particle is calculated from the 2-moment microphysical scheme, the optical thickness is parametrized according to Savijärvi et al. (1997), the asymmetry factor from Fouquart et al. (1991) and the single scattering albedo from Slingo (1989). For LW radiation, cloud water optical properties refer to Savijärvi et al. (1997).

2.3.2 Diagnostics of visibility

Visibility can be diagnosed assuming an exponential scattering law:

$$VIS = -\frac{\ln \varepsilon}{\beta} \quad (7)$$

with β the extinction coefficient, and using a visual range defined by a liminal contrast ε of 0.02 (Koschmeider, 1924). The most common parametrizations used to diagnose the visibility with droplet properties in models with employing 1-moment microphysical schemes are expressed as:

$$VIS = \frac{a}{(\rho_a r_c)^b} \quad (8)$$

where a is 0.027 and b is 0.88 for Kunkel (1984) (units of r_c and VIS are g kg^{-1} and km respectively).

When droplet concentration N_c is taken into account with 2-moment microphysical schemes, the diagnostic becomes:

$$VIS = \frac{c}{(\rho_a r_c N_c)^d} \quad (9)$$

where c is 1.002 and d is 0.6473 for Gultepe et al. (2006) developed with eastern Canada based on observations made in eastern Canada, and c is 0.187 and d is 0.34 for Zhang et al. (2014a) from measurements made in the polluted North China Plain measurements.

Measurements of visibility can be employed to estimate the validity of the visibility diagnostics the most often used for by models. Hence, the three formulations were applied to the observed $LWC r_c$ and N_c and compared to the observed visibility in order to determine which one fitted the best the observed values best (Fig. 6a). In our case study, Zhang et al. (2014a)'s parametrization was the most adapted to the observations of our case study, as it is more sensitive to low $LWC r_c$ and N_c values, even if though it tended to underestimate slightly the observed visibility slightly. Diagnostics from Kunkel (1984), and even more so from Gultepe et al. (2006) even more, markedly underoverestimated the 3 m observed visibility in our case study.

2.3.3 Simulation set-up

For the reference simulation (noted REF), the horizontal resolution ~~wais~~ is 5 m over a domain size of 200 x 200 grid points. 126 vertical levels ~~weare~~ are used between the soil and the top of the model at 1500 m. The vertical resolution ~~wais~~ is 1 m for the first 50 m and ~~increasds-then~~ slightly above ~~this height~~. Momentum ~~variables-were-transportedis~~ ~~advected~~ with a fourth-order centred
5 scheme (noted CEN4TH), whereas scalar variables ~~weare~~ ~~transported~~~~advected~~ with the PPM (Piecewise Parabolic Method) scheme (Colella and Woodward, 1984). The time step ~~wais~~ is 0.1 s. The domain of simulation is presented ~~onin~~ in Figure 1b, with a trees barrier ~~of-15 m~~ ~~heighthigh~~ and 100 m wide perpendicular to the wind direction. The rest of the domain ~~wais~~ is composed of grass. The lateral boundary conditions ~~weare~~ cyclic. The radiation scheme ~~wais~~ is called every second.

The simulation began at 2320 UTC on 14 November 2011 before the fog formation, and covered 12 h. Temperature, humidity
10 and wind speed vertical profiles were initialized with data from the radiosonde launched ~~infrom~~ in Trappes. Meteorological conditions at Trappes can differ slightly from ~~those at~~ the Sirta site. Therefore wind, temperature and humidity were modified in the nocturnal boundary layer up to 400 m agl to ~~adjust-withfit~~ the data recorded at the 30 m meteorological mast at the Sirta site, as illustrated ~~onin~~ in Fig. A.1. The soil temperature and ~~moistenin~~~~moisture~~ ~~weare~~ given by the soil measurements, corresponding to a surface temperature of 276 K and a soil moisture of 70%. Following the profiles from soundings, a geostrophic wind of
15 8 m s^{-1} was prescribed ~~as-a-forcin~~g, without any other forcing. To generate turbulence ~~in-addition-to-the-effect-of-trees~~, a white noise of 0.5 K was applied in the first 100 m ~~in addition to the effect of trees~~.

It was also necessary to characterize the aerosol size spectrum for Eq.2. The supersaturations reached in fog were lower than 0.1% meaning that the CCNC measurements were not directly usable, as shown by Hammer et al. (2014) and Mazoyer et al. (2016). ~~But~~~~However~~, when using the Kappa-Köhler theory and the SMPS observations, the aerosols concentration at
20 supersaturations under 0.1% can be retrieved ~~knowin~~g if the aerosol hygroscopicity (κ) at these supersaturations ~~is known~~. This method, proposed by Mazoyer et al. (2016), ~~has-beenwas~~ applied to our case study ~~in~~ the hour before the fog onset. The activation spectrum was thus computed from observations above 0.1% supersaturation, and from computation ~~underbelow~~ 0.1%. ~~A-fit-of-t~~This computed activation spectrum ~~wais~~ ~~applied~~~~fitted~~ according to Eq.2 (Fig. A.2a), corresponding to the ~~size distribution of~~ aerosols particles ~~distributin~~-($C = 2017 \text{ cm}^{-3}$, $\sigma = 0.424$, $\bar{r} = 0,1, \varepsilon_m = 1$) in red ~~onin~~ in Fig. A.2b. This
25 does not match the measured distribution (in black) ~~nor~~ the lognormal fitted on the accumulation mode (in blue), ~~due-to-the~~ ~~fact-thatbecause~~ Cohard et al. (2000c) formulation ~~hw~~as not ~~been~~ developed for fog ~~with~~ low supersaturation. ~~Nevertheless,~~ ~~considering-that-the-activation-spectrum-was-deduced-from-measurements,~~ ~~it-includes-a-good-degree-of-confidence~~. ~~Deducin~~g the activation spectrum from measurements provides the exact solution.

The reference simulation will ~~be~~-now ~~be~~ presented.

30 3 The reference simulation

The performance of the REF simulation ~~iswill be~~ first examined, based on a comparison with observed values of thermohygro-metric, dynamic, radiative and microphysical parameters near the ground. Considering that the REF simulation reacheds ~~a-good~~ ~~degree-of-confidene~~agreement with observation, ~~the~~ vertical evolution and horizontal variability of the simulated fog ~~arewill~~

be then characterized during the different phases of the fog life cycle. It should be emphasized that observations localized at one point ~~were~~ will be compared to ~~averaged~~-simulated fields ~~averaged~~ over an horizontal area located downstream of the trees barrier (blue contour area of Fig. 1b) representative of the instrumented area, ~~as w~~. We will indeed see that ~~there were significant horizontal heterogeneities over this area~~ the simulation domain is divided into 4 parts with significant differences between them, but similar characteristics inside each one.

3.1 Parameters near the surface

3.1.1 Dynamics and thermodynamics

Figure 2 shows the time series of near-surface observed and simulated temperature and RH. At the initialization of the simulation, near-surface temperatures ~~were~~ are in agreement with the observations while RH ~~were~~ is very slightly underestimated. During the cooling before the fog onset, the model developed a ~~too stable~~-layer that is too stable, especially in the first 5 metres between 0000 and 0100 UTC. The convergence of temperature ~~was~~ simulated with 30-40 minutes of delay compared to the observations

Considering RH near the surface (and the microphysical fields below), the fog started to appear around 0230 UTC. Between 0430 and 0830 UTC, simulated and observed temperature ~~were~~ are in fairly good agreement, with a quasi-neutral near-surface layer. The fog started to dissipate from the ground at 0830 UTC, with approximately one hour and a half ahead of the local observation. This time lag discrepancy induced a slight overestimation of near-surface temperature, increasing up to which is less than 0.5 K at 1100 UTC. But Nevertheless, the negative temperature gradient near the surface representative of the development of the convective boundary layer ~~was~~ quite well reproduced after the beginning of the dissipation.

Dynamical fields at 10 m and 30 m ~~were~~ are fairly well reproduced by the model (Fig. 3 in red): the 10 m wind speed (Fig. 3a) ~~was~~ in good agreement with the observation during all throughout the simulation. Until 0300 UTC, a quasi linear increase of TKE ~~was~~ produced by the model with a higher TKE at 10 m agl higher than at 30 m contrary to the observations (Fig. 3b). Around 0300 UTC, a more sudden increase of TKE occurred like, as in the observations but 30 min before and with a lower magnitude, even if it was underestimated. Then the simulated TKE remained quasi almost constant around $0.7 \text{ m}^2 \text{ s}^{-2}$ from 0400 UTC onwards around $0.7 \text{ m}^2 \text{ s}^{-2}$, with a slightly higher variability than before. The model developed similar TKE values at 10 m and 30 m, while ~~30 m~~-observed values ~~were~~ are higher at 30 m.

Considering the radiative fluxes (Fig. 4), the increase of the LWD flux associated with fog onset ~~was~~ simulated with a delay of 30-40 minutes, meaning that there ~~was~~ is a delay in the simulated formation of fog at elevated levels. After that, the LWD flux of 325 W m^{-2} ~~was~~ correctly reproduced, indicating that the temperature and the optical thickness of the fog ~~were~~ are fairly well simulated. Observations developed a difference of 8 W m^{-2} between LWU and LWD during the fog life cycle, but the model failed to reproduce this difference, leading to a slight underestimation of LWU. If the measurements ~~did~~ do not encounter an contain any errors, this probably means that the radiative properties of the simulated surface ~~were~~ are not perfectly represented. A test on the emissivity of the surface (1 instead of 0.96) had no impact on the radiative fluxes, suggesting that the soil temperature was probably underestimated. After sunrise (0659 UTC), the downward and upward SW fluxes ~~were~~ is

gradually overestimated by up to 15 W m^{-2} , and LWD were slightly underestimated in a similar way due to the advanced dissipation time.

3.1.2 Microphysics

Considering the microphysical fields at 3 m agl, the onset of $LWC r_c$ higher than $0.001 \text{ g m}^{-3} \text{ g kg}^{-1}$ was in agreement with the observations presents 30 min of advance (Fig. 5ba). Cloud droplets appear more than one hour before the observation but correspond to very low concentration (less than 10 per cm^3) and negligible cloud mixing ratio. The delay identified on LWD flux increase and on the temperature convergence is not reproduced on $LWC r_c$, meaning that the time of formation of fog at the ground was quite correctly reproduced (even with a small advance of 30 min) but the previous formation at elevated levels was underestimated. This is corroborated by the LWP evolution (Fig. 5c), also characterized by a 430 min delay compared to the Sirta point observation, in agreement with LWD fluxes.

The increase of $LWC r_c$ during the development phase was in agreement with the observed one but this phase was too long is too strong leading to an overestimation, with a maximum value of 0.07 g m^{-3} instead of 0.035 g m^{-3} 0.2 g kg^{-1} instead of the 0.03 g kg^{-1} observed. Then, during the mature phase, the slow decrease of $LWC r_c$ was reproduced, up until 08300900 where both observed and simulated values became less than 0.001 g m^{-3} . But as we have seen before, in reality, this first event of fog dissipation only concerned the levels very near close to the surface levels, as and observed visibility at 18 m remained less than 1300 m. On the contrary In contrast, the fog did not reformed near the surface in the simulation, which induces an advance of almost one hour on the dissipation time. The discrepancies between simulation and observation was higher are greater on cloud droplet concentration than on LWC cloud mixing ratio during all throughout the fog life cycle, as the model strongly overestimated N_c , up to by a factor of that may be as high as 714 (maximum values of 350700 cm^{-3} simulated against 53 cm^{-3} observed, Fig. 5ab). Maxima of N_c and $LWC r_c$ occurred are reached at the same time, around 0300 UTC, then both r_c decreased while N_c remains constant. But N_c increased again during the dissipation phase, before dropping sharply at the end of the fog.

The droplet size distribution (DSD) in the model is described by the normalized form of the generalized gamma distribution which gives a monomodal form (Fig. 5d). During the formation phase (red lines) whole fog life cycle, the model overestimated smalls droplets with a diameter between $2.5 \mu\text{m}$ and $7.5 \mu\text{m}$ larger than $4 \mu\text{m}$ and underestimates the smaller ones and did not produce droplets of diameter larger than $9 \mu\text{m}$. This trend continued during the fog life cycle (blue and then green line) even if it was less marked than at the initial stage. The model produced the largest droplets at the mature stage like in the observations, before reducing the spectrum during the dissipation. The simulated modes corresponded to $4 \mu\text{m}$, $7.5 \mu\text{m}$ and $6 \mu\text{m}$ of diameters at the 3 stages. The overestimation of small droplets and the underestimation of larger ones led to the weakness of droplet sedimentation. Indeed, the surface cloud water amount by sedimentation is negligible after 12 hours of simulation (around 10^{-4} mm), while it reached 0.0674 mm by deposition. The cloud water deposition rate at the ground presents a maximum of $0.36 \text{ mm} \cdot \text{day}^{-1}$ while the maximum of droplet sedimentation rate is $0.08 \text{ mm} \cdot \text{day}^{-1}$, meaning that the deposition is the main contributor to the cloud water amount at the ground.

The weakness of droplet sedimentation could partly explain the overestimation of N_c during all the whole fog life cycle, as well as the LWC , as it kept too much water in the fog layer.

But another reason that could explain the overestimation of droplet concentration and that will be developed in the Part 2 of this study, is that the equation (3) allowing, which allows to compute the supersaturation peak value to be computed, does not take into account the sink term due to pre-existing LWC into account, as explained in by Thouron et al. (2012). Due to the overestimation of simulated droplet concentrations mass and number, the Zhang all the diagnostics of visibility applied to simulated microphysical fields underestimated the observed visibility at 3 m and 18 m, especially the Zhang's formulation (Fig. 6). The Gultepe formulation is better adapted to our simulation, reproducing correctly the visibility drop at the onset of the fog, while the visibility remained slightly underestimated during the fog life cycle. As LWC values are better reproduced r_c is less underestimated than N_c , the Kunkel formulation provides the least bad matched for the observations the best. This explains why a simpler formulation of visibility based solely on r_c is usually more adequate given the difficulty of simulating N_c for the models.

The comparison between the REF simulation and observation for the set of parameters shows a fairly good agreement, even if there are some discrepancies. The main discrepancies were, concerning the fog life cycle, are an underestimation of the effect of elevated fog formation and, inducing an advance of 1.5 h on 30 min in the onset time near the ground and an advance of 1 h in the dissipation time. These elements are probably partly due to the semi-idealized representation of the Sirta surface in the simulation, and also to the comparisons with punctual observations, knowing given the horizontal variability as that we will see further below. Considering the microphysical fields, the main discrepancy was an overestimation of the concentration of small droplets concentration near the ground, and, to a less degree, of LWC the cloud mixing ratio. They are felt to be acceptable and we can therefore consider that the REF simulation can be used to explore the processes driving the fog life cycle and to conduct sensitivity tests to try to reduce these discrepancies.

3.2 Vertical evolution

First the fog vertical evolution of the fog is analyzed. Figure 7 represents the time evolutions variations of vertical profiles of r_c and N_c , the radiative cooling rate and the vertical velocity in the updrafts, while parts a, c and d of Figure 8 and represents the same time evolution variation for total turbulent kinetic energy (resolved plus subgrid, noted TKE), and dynamical and thermal production of TKE for the REF simulation, all averaged over the horizontal area downstream the trees barrier. As a preliminary comment, a first noteworthy feature is that subgrid kinetic energy is one order less lower than resolved kinetic energy (not shown), meaning that the 5 m horizontal resolution allows an LES approach as most of the eddies are resolved.

The evolution of r_c allows to decompose formally serves as a basis for decomposing the fog life cycle into the three phases: the formation, between 0200 and 0320 UTC, until the fog became optically thick; the development, between 0320 and 0720 UTC, until r_c at upper levels of the fog layer begins to decrease, and the dissipation from 0720 UTC (Fig. 7a).

Before the fog onset and during the formation phase, the TKE was small and spread over a 30 m layer that deepened slowly, consecutively to the flow induced by due to the trees barrier (Fig. 8a). TKE was mainly produced occurs by dynamical production, which presents maxima at two levels: near the surface and at 15 m height due to the trees (Fig. 8c). Thermal

production ~~wais~~ negative due to the thermal stratification (Fig. 8d). The radiative cooling near the ground (Fig. 7c) and the mixing by the tree drag effect ~~we~~are the ingredients ~~allowing the apparition of that allow fog to appear at elevated level~~the same time over a 30 m deep layer (Fig. 7a). Then the mixing by the trees barrier caused ~~a subsiding effect of the fog layer down to the ground and a vertical development above to develop vertically at greater heights~~ (Fig. 7a). Hence, the effect of elevated formation ~~wais~~ reproduced, even if the height of fog onset ~~wais~~ underestimated (150 m given by the ceilometer and 30 m in the simulation). ~~T~~, and the period ~~of subsiding effect of during which the fog subsides to reach the ground wais therefore shorter and equal to 20 min~~almost instantly. During this first phase, mean updraft vertical velocities ~~we~~are small, up to 0.15 m s^{-1} (~~not shown~~)(Fig. 7d), in agreement with Ye et al. (2015), who observed a vertical velocity of $0.1 - 0.2 \text{ m s}^{-1}$ in a fog layer between 40 m and 220 m ~~depth~~deep in China. Considering Eq.3 for supersaturation evolution with the two source terms ~~function of depending on~~ vertical velocity and radiative cooling, the activation of fog droplets ~~was~~ during the fog formation ~~fog is~~ mainly produced by radiative cooling at the top of the fog layer (Fig. 7b and c).

At the beginning of the development phase (around 0320 UTC), when the fog ~~depth~~ reached ~~s~~ approximately 80 m, it ~~became~~omes optically thick to longwave radiation. ~~E~~At exactly ~~at~~ that time, TKE increased ~~s~~ significantly by dynamical production (Fig. 8a and c), in agreement with Nakanishi (2000), ~~meaning's findings, which indicates~~ a dynamical change. The optical thickness of the fog layer caused ~~d~~as strong radiative cooling at the top of the fog layer, ~~higher~~greater than 5.5 K h^{-1} (in absolute value, Fig. 7dc), and ~~LWC~~ r_c values ~~beca~~ome stronger in the upper part of the fog layer. Hence, the fog top ~~beca~~omes the location of the dominant processes with radiative cooling. It induced ~~s~~ small downdrafts and buoyancy reversal. ~~Additionally~~In addition to the vertical velocity of the updrafts now higher than 0.2 m s^{-1} ~~in all~~throughout the fog layer, a second maximum of droplet concentration of ~~1000~~1100 cm^{-3} occurs ~~s~~ in the upper part of the fog layer around 0320 UTC. The sudden optical thickening corresponded ~~s~~ to the increase of surface LWD ~~up~~to 320 W m^{-2} (Fig. 4) and to ~~the~~ maximum of cooling at the ground (Fig. 2a). ~~In~~At the same time, temperatures converged ~~between~~in the vertical levels near the ground (Fig. 2a and b), showing the effect of fog on the stability profile as analyzed by Price (2011).

Then, during the development phase, the top of the fog layer ~~wais~~ characterized by vertical wind shear inducing a ~~positive~~ dynamical production of TKE, while small values of positive thermal production appeared ~~ed~~ at the top due to buoyancy reversal. Inside the fog layer, in the ~~40~~lowest 40 metres, the drag effect of the trees induced ~~d~~highers values of kinetic energy higher than $0.6 \text{ m}^2 \text{ s}^2$. The maximum of r_c continued ~~s~~ to increase in the upper part of the fog layer up to 0500 UTC, reaching 0.357 g kg^{-1} at 120 m (Fig. 7a). ~~In~~At the same time, LWD surface fluxes remained ~~ed~~ constant while the fog layer continued ~~s~~ to deepen and the LWP ~~continues~~ to increase ~~up to~~until 0500 UTC (Fig. 5c).

Around 0430-0500 UTC, a change occur ~~s~~ed ~~o~~in the development of the fog layer: it continued ~~s~~ to thicken, but at a ~~smaller~~lower rate, while the LWP began ~~s~~ to decrease in the simulation. This change of growth at the top of the fog layer ~~wais~~ associated ~~to~~with a warming in the fog layer (not shown) and a decrease of the maximum radiative cooling near the top ~~that~~which spreads over a ~~broader~~greater depth (Fig. 7c). This ~~also~~ corresponded ~~also~~ to an increased number of resolved updrafts and downdrafts near the top (Fig. 7d). ~~The~~ variability of the fog depth ~~also~~ became ~~omes~~ also stronger, ~~linked to in connection with~~ fog-top waves as we will see ~~further~~below. This change of growth seems to be linked to the fact that the fog layer reached ~~s~~ the top of the nocturnal boundary layer, meeting stronger temperature, humidity and wind gradients. This increased ~~s~~ the top

entrainment process, limiting the deepening of the fog layer. With the decrease of the top radiative cooling, cloud droplet concentration becomes ~~quasi~~more homogeneous in the fog layer, except near the ground where it decreases by deposition. In the same way, the cloud mixing ratio also begins to decrease ~~also~~ near the ground (Fig. 7b).

The beginning of the dissipation phase ~~in the simulation~~ (around 0720 UTC) ~~can be identified~~ is preceded by the beginning of solar radiation, and divergence between surface LWU, which starts to increase, and surface LWD, starting decreasing ~~in the simulation~~ (Fig. 4). The dissipation of the fog begins at the surface, and the fog lifted into a stratus layer. The radiative heating of the surface ~~increased~~ induces the convective structure of the fog as vertical velocity in the updrafts increases (Fig. 7b and d) and thermal production of TKE becomes significantly positive (Fig. 8d). Additionally, after sunset, downdrafts at the top of the fog layer increased the amount of solar radiation reaching the ground and feeding the heating at the base of the fog layer. Hence, near the ground, both thermal and dynamical effects contributed to the production of TKE, and to a deepening of the TKE layer up to 60 m. The height of the fog top continues to increase as it is driven by radiative and evaporative cooling inducing vertical motions and top entrainment. ~~If~~ Although mixing ratio decreases at all levels, droplet concentration increases sharply when the fog layer lifted from the surface (Fig. 7b). As the cloud evolves into a stratus layer, droplet activation is no longer induced by radiative cooling at the top of the fog layer but by updraft vertical velocity ~~in all that~~ all cloud depths, and especially near the stratus base. The stronger vertical velocity (Fig. 7d) allowed to activate more droplets for the same water content amount. Droplets become smaller and more numerous, preventing the droplet sedimentation process and limiting the decrease of LWP, ~~while~~. Moreover, the deposition process is not longer active any more ~~without~~ as there are no cloud droplets at the surface. We will now consider the horizontal heterogeneity of the fog layer.

3.3 Horizontal variability

To better characterize turbulent structures and the impact of trees on the fog layer, the horizontal variability of the fog layer is examined. Figure 9 presents horizontal and vertical cross-sections of wind speed, cloud mixing ratio, potential temperature and TKE at 0240 UTC during the formation phase. The trees barrier induces a blocking effect of the flow upstream, and enhances the turbulence by wind shear downstream, accelerating the flow near the ground and creating longitudinal structures in the direction of the wind. Ascents occurred upstream and small subsidence downstream, up to 2 cm s^{-1} (not shown), drawing brings warmer and dryer air from above to the ground. Therefore structures of stronger wind near the ground downstream coincided with structures of warmer ~~and~~, clear air as they delayed the fog formation. The fog formed at the surface upstream ~~from~~ of the trees, and 500 m far downstream, while it appeared first at elevated levels ~~between both~~ over the intermediate area between the trees and far downstream (Fig. 9d). The fog took about 1 hour to cover the entire domain at ground level. Thus, heterogeneity of the surface vegetation explains heterogeneities in fog onset over the Sirta site, as well as the fog property of developing fog first at elevated levels. After the formation phase, the base of the fog layer stands at the ground over the whole domain. These results are in agreement with the effects of building effects on fog studied by Bergot (2015b) who found a 1.5 hour period of heterogeneity of fog formation over the airport area.

During the development phase, as shown on the vertical cross-sections of Fig. 10 at 0620 UTC, horizontal rolls appeared at the top of the fog layer and are associated with dynamical production of TKE by shear. They are aligned almost per-

pendicularly to the mean wind direction (not shown). These structures correspond to Kelvin-Helmoltz (KH) instability, already observed by Uematsu et al. (2005) and modelled by Nakanishi (2000) and Bergot (2013). They had a depth corresponding to about one third of the fog layer height, h_{keas} in Bergot (2013), and a horizontal wavelength of the order of 500 m. These horizontal rolls explain the oscillations at the top of the fog layer visible in Fig. 7 and Fig. 8. They became well marked from 04300500 UTC when the depth of the fog layer began to increase more slowly, as the fog layer reached the top of the nocturnal boundary layer, meeting stronger wind gradients (not shown). They induced strong horizontal variability of cloud mixing ratio near the top of the fog, with larger values in the ridges of the fog-top rolls, and smaller ones in the troughs (Fig. 10a). Local updraughts occurred upstream of the crest of the wave, and downdraughts downstream, both up to 1.2 ms^{-1} (Fig. 10d). Maximum of droplet concentration occurs near the top of the fog layer (Fig. 10b) in the radiative cooling layer (Fig. 10c), and preferentially upstream the crest of the wave rather than downstream, in the ascent area, where they were preferentially activated and transported. These extrema of droplet concentration do not appear in Fig. 7 as they are hidden by the spatio-temporal average.

Inside the fog layer, the radiative cooling was negligible while vertical velocity presented strong spatial heterogeneities. Maxima of supersaturation appeared to be strongly correlated with vertical velocity (Fig. 10e), with values up to 0.275% which were probably overestimated even if, although this cannot be confirmed as measurements of supersaturation peaks were not available beyond the surface. But however droplet concentration was quasi-homogeneous over the horizontal domain variations are smooth, and it does not show a strong correlation with the maximum supersaturation, due to the pre-existing droplets.

Near the ground, maximum simulated values of supersaturation lay around 0.1% while Hammer et al. (2014) and Mazoyer et al. (2016) reported observed supersaturation peaks lower than 0.1%. The presence of trees and the deposition process induced smaller droplet mixing ratio and concentration near the surface.

During the dissipation phase, heterogeneities remain at the top of the fog layer, but the signature of KH waves disappeared (not shown). The dissipation of fog at ground level took about 20 minutes, and, as noted in Bergot et al. (2015a), it does not reveal a clear effect of surface heterogeneity, as well as in Bergot et al. (2015a).

Having characterized vertical and horizontal heterogeneities of the fog during its life cycle, sensitivity tests are now presented to identify the sources of variability and their impact on the microphysical fields.

4 Sensitivity study

In order to better characterize the physical processes dominating the fog life cycle and driving the microphysical properties, sensitivity tests were conducted in a second step. The resulting simulations are summarized in Tab.1, considering their difference with the REF simulation.

4.1 Impact of trees

To evaluate the impact of trees on the dynamics and on the microphysics of the fog, a simulation called NTR has been run, where the barrier of trees was replaced by grass. Hence, deposition on the grass

was considered over the whole domain. Fig. 3a shows that, without trees, the 10 m wind speed was overestimated over the instrumented area (Fig. 3a). As in REF but 30 min earlier, the model developed a sudden increase of TKE at 0300 around 0230 UTC at the beginning of the development phase, meaning that this change was linked to the increase of the optical thickness, and not to the turbulence induced by trees (Fig. 3b and Fig. 8b). But after this period, TKE was underestimated and remained stronger at 10 m height than at 30 m, contrary to observation, which means that the drag effect of trees was responsible for the observed stronger TKE at 30 m height. The fact that the REF simulation developed quasi-very similar TKE at 10 m and 30 m agl probably means that the representation of surface heterogeneities was still underestimated, which can be explained by the broad range of surface covers present in reality, in addition to the trees (lake, small buildings, etc.); but not included in the simulation.

The main differences in dynamics between NTR and REF appeared first on total TKE, with the absence of stronger values in the first 40 metres in NTR, as they were restricted to the immediate vicinity of the ground a thinner layer of TKE values higher than $0.5 \text{ m}^2 \text{ s}^{-2}$ and smaller maxima (Fig. 8b). Before the fog formation, the too-thin layer of turbulence near the ground in NTR limited the supply of warmer air from above, inducing an overestimation of the vertical temperature gradient before the fog, and emphasizing the cooling in the low levels, with 2 K less than in REF (Fig. 2c). Figure 11a presents the temporal evolution of cloud mixing ratio vertical profiles during the NTR simulation, to be compared to Fig. 7a and b for REF, and Figure 12a and b exhibited instantaneous vertical cross sections of potential temperature at the fog formation with REF and NTR. The stronger cooling with NTR homogenized the fog formation at the ground and prevented elevated fog formation. The consequence is that the onset of fog with NTR occurred almost 2 hours before the earlier than actually observed and than in the REF simulation (Fig. 2d). Fig. 13 summarizes the impact of sensitivity tests on the microphysical fields and NTR (purple lines) can be compared to REF (red lines) in Fig. 13a, b and c. During the formation and the development phases, the depth of the fog layer was thinner in NTR than in REF, because of the formation at the ground and the absence of mixing without trees, thus limiting the vertical development. The maximum of cloud mixing ratio with NTR was increased compared to REF, due to the absence of warming by entrainment, leading and leads to a cooling largely overestimated cooling near the ground when compared in comparison to observations (Fig. 13a). Therefore the Kunkel diagnostic underestimated the visibility much more than REF, as well as do the other diagnostics (Fig. 6d). Inside the fog layer, despite the increase of r_c , the positive temporal evolution of N_c , called the production of N_c , was not higher than in REF (Fig. 11b), as smaller vertical velocities and higher cloud mixing ratio production compensated for the stronger cooling in the activation process.

Additionally, near the ground, droplet concentration was even smaller than in REF, as deposition effect, acting only at the first vertical level in NTR, was active since from the onset of the fog, due to the absence of elevated formation and to the thinner fog layer. Consequently, the DSD at 3 m shifted towards larger droplets in NTR (Fig. 13c), consistently with the reduction of droplet concentration.

Also, during the development phase, 500 m wavelengths of KH waves were more smooth and regular without trees (Fig. ??) and this has been noted during all the whole phase. This can be shown on kinetic energy spectra applied onto vertical velocity over the whole fog depth, computed according to Ricard et al. (2013) and presented in Fig. 14. The spectra of REF and NTR presented two main differences: firstly the TKE variance was smaller with NTR at wavelengths finer shorter than

200 m, meaning that the flow presented ~~less fewer~~ fine scale structures without the tree drag effect. ~~S~~ and, secondly, the peak of variance at 500 m wavelength, corresponding to the KH waves, ~~was~~ more pronounced ~~within~~ NTR.

~~The regular KH waves with NTR induced a regular wave pattern of the radiative cooling layer at the top of the fog layer (Fig. ??e). Therefore, higher droplet concentrations were spread over a deeper layer at the top of the fog with NTR than with REF (Fig. ??b). This is also emphasized by the fact that the pre-existing cloud water content, higher with NTR than with REF, is not taken into account in the diagnostic of maximum supersaturation as it should be. Comparing Fig. ?? to Fig. 10, it also appears that vertical velocity associated to KH waves at the top of the fog were smaller with NTR than with REF, but this was not systematic during the period. However, the intensity of vertical velocity at the top of the fog layer seems to be correlated to with the depth of the KH waves. Hence, it appears that surface heterogeneities relative to the trees introduced small perturbations up to the top of the fog layer on this case, that modified the regular wave pattern but that did not remove the KH waves.~~

~~During the dissipation phase, KH waves at the top of the fog layer remained longer in NTR as the dissipation time was delayed (not shown). This time lag was in better agreement with the observations, unlike the rest of the fog life cycle.~~

To summarize, the absence of trees barrier produced ~~s~~ an unrealistic simulation, as it ~~induced~~ ~~causes~~ the fog onset to occur too early ~~onset of fog~~ (almost 2 hours ~~of~~ ~~in~~ advance), ~~a too strong~~. It also induces cooling that is too strong in the low levels, and a large overestimation of the near surface LWC ~~cloud mixing ratio during all~~ throughout the fog life cycle, damaging the visibility. On the other ~~side~~ hand, droplet activation ~~was~~ reduced near the ground due to smaller vertical velocities and to a stronger impact of surface deposition, shifting the DSD to larger droplets. ~~If~~ ~~The absence of trees~~ also modified ~~s~~ the signature of the KH waves at the top of the fog layer, with a more regular pattern and ~~less fewer small scale~~ heterogeneities ~~on the microphysical fields near the top of the fog layer~~. The impact of the deposition process will now be examined more precisely.

4.2 Impact of deposition

~~Two~~ ~~Three~~ simulations ~~have been~~ ~~were~~ carried out to better characterize the role of the deposition process, both keeping the trees barrier. The first one, called NDT, removed only deposition over trees compared to REF, considering that trees acted as grass for deposition. This was done by activating deposition only at the first level of the model. The second one, called NDG, removed ~~s~~ fully deposition altogether. The third one, noted DE58, considered a deposition velocity V_{DEP} of 58 cm s^{-1} over grass and trees, which is the upper bound given by Katata (2014) instead of 2 cm s^{-1} ~~like~~ as in REF. Figure 13a ~~b~~ ~~e~~ ~~a~~, b and c compares ~~near surface~~ 3 m microphysical fields, and Figure 15a the LWP.

NDT ~~very slightly~~ increased ~~s~~ ~~slightly~~ droplet mass and number downstream of the trees barrier, ~~as well as~~ and the LWP during the fog life cycle (Fig. 15). ~~But~~ ~~Conversely~~, removing deposition everywhere with NDG had ~~s~~ a considerable impact as it increased ~~s~~ ~~by a ratio of 8~~ the cloud mixing ratio and the concentration near the surface ~~by a factor between 2 and 3~~. With NDG, the onset of fog occurred ~~s~~ at the surface and not ~~at elevated level~~ on a 30 m deep layer, almost 2 hours ~~before~~ ~~earlier~~ than in observations and in the REF simulation (Fig. 11c). During the development phase, ~~there is no longer~~ a vertical gradient of r_c and N_c ~~has disappeared~~ (Fig. 11c and d), ~~even if radiative cooling at the top was stronger with higher cloud mixing ratio (with maxima of cooling more than -8 K h^{-1})~~. The temporal evolution of cloud droplet concentration in the fog layer

shows constant vertical profiles, without maxima during the formation and the dissipation phases like, as in REF. Hence, cloud droplet concentration was constant during the fog life cycle near the ground, while observations reported a decrease during the development phase (Fig. 13ab). NDG also developed also a broader DSD, with more numerous large droplets with a diameter larger than $4 \mu\text{m}$. Therefore, droplet sedimentation was significantly increased as NDG reported a mean cumulated cloud water amount of 0.053 mm reaching the surface during the 12 hours by sedimentation, while the REF simulation produced 0.067 mm of cloud water at the surface after 12 hours, the sedimented water being negligible. The fog layer was also deeper during all throughout the life cycle, and therefore the LWP was largely overestimated with a maximum between 0500 and 0600 UTC, of about twice the observed value (Fig. 15). Due to the larger amount of cloud water near the ground, the dissipation at the ground was delayed by more than one hour. Moreover, NDG reports a maximum cumulated cloud water amount reaching the ground of 0.053 mm after the 12 hours by sedimentation, while the REF simulation produces a maximum of 0.074 mm by deposition and sedimentation. Even if NDG produces higher LWP over a longer period and higher concentration of large droplets than REF, the cloud water amount reaching the ground is lower, meaning that a deposition velocity of 2 cm s^{-1} is more efficient than the sedimentation process to collect cloud water at the ground.

Another test, noted DE5, considered a deposition velocity V_{DEP} of 5 cm s^{-1} instead of 2 cm s^{-1} like in REF (Fig. 13abe and Fig. 15a). In contrast, DE8 induced a slight diminution significant reduction of the near surface LWC , N_c and the LWP, but the fog life cycle, the droplet concentration and the LWP remained almost unchanged and the onset of fog near the ground coincides relatively well with the observation. The formation of fog at elevated levels is more pronounced, and r_c over the whole fog depth is reduced during the development phase compared to REF (Fig. 11d and e). With DE8, the cloud water deposition rate at the ground presents a maximum of $0.48 \text{ mm} \cdot \text{day}^{-1}$ during the period while the maximum of droplet sedimentation rate is $0.02 \text{ mm} \cdot \text{day}^{-1}$. Among the different simulations conducted in this study, the performance of DE8 to reproduce the microphysical fields is the best. This means meaning that the deposition process is not too highly sensitive to the deposition velocity.

Zhang et al. (2014b) hadve already shown that taking into account including a deposition term in simulations seemed to have some effect on the droplet concentration in the layer near the ground and consequently on visibility. B but their effect was less pronounced than here. A possible explanation is that both u_* , the friction velocity, and the mean volumetric diameter of droplets, taken into account used in their parametrization, were underestimated. In our case, the deposition process, even with a simple parametrization, appeared to be essential to correctly simulate the fog life cycle and to be closer to approach the observed microphysical values near the ground more closely. It impacted significantly the microphysical fields significantly. Hence, the remove of neglecting this process induced increases droplet sedimentation, but in insufficient quantity to avoid unrealistic droplet concentration and cloud mixing ratio in the fog layer and near the surface. It also modified the fog life cycle in terms of onset and dissipation times, LWP and microphysical characteristics inside the fog layer. The, and prevented elevated fog formation, which was a climatological characteristic of the Sirta site, is the result of the tree drag effect, which mixes the lowest levels, and the deposition process, which erodes the near-surface water content. We will now examine the impact of the horizontal resolution on the simulated fog life cycle.

4.3 Sensitivity to effective resolution

In order to assess the impact of spatial resolution on the fog life cycle, a 2 m horizontal resolution (called DX2) was carried out using the same momentum advection scheme ~~than~~ as in REF (CEN4TH). According to Skamarock (2004), kinetic energy (KE) spectra deduced from simulations allow ~~to set up~~ the effective resolution ~~to be set up~~ as the scale ~~from~~ at which the model ~~starts~~ to depart from the theoretical slope, which is -3 for vertical velocity spectra applied to stable turbulence. Mean KE spectra applied to ~~the~~ vertical wind component revealed effective resolution of the order of $4 - 5 \Delta x$ for simulations with CEN4TH (DX2 and REF), in agreement with Ricard et al. (2013), namely 8 m and 20 m respectively (Fig. 14).

With DX2, top entrainment ~~was~~ more active as updrafts and downdrafts ~~were~~ represented at finer resolution, limiting the cooling near the surface (Fig. 12d) and the vertical development of the fog. ~~The cloud mixing ratio near the ground is slightly reduced, but the droplet concentration is almost unchanged, inducing a shift of the mode of the DSD to $7 \mu\text{m}$ instead of $8 \mu\text{m}$ (Fig. 13d, e and f). Only small droplets were more numerous, increasing slightly droplet concentration during all the fog life cycle (Fig. 13d and f). The fog onset and dissipation times and the LWC were almost unchanged~~ time is set a bit later and the dissipation time a bit sooner (Fig. 13e), and the LWP ~~was~~ slightly reduced compared to REF (Fig. 15b) ~~but~~. ~~The close results~~ But the differences between DX2 and REF ~~are~~ remain quite small in agreement with the convergence ~~in stable conditions~~ around 2 m resolution ~~in stable conditions~~ already shown by Beare and MacVean (2004).

~~Then~~ In two other tests ~~have been held performed~~ on the wind transport scheme, keeping the 5 m horizontal resolution ~~at~~, the CEN4TH scheme ~~has been~~ was replaced by the WENO (Weighted Non-Oscillatory, Shu (1998)) scheme at 3rd order (called WE3) or 5th order (called WE5). These spatial schemes, associated ~~to~~ with an Explicit Runge-Kutta temporal scheme, allow time steps 10 times larger than CEN4TH associated ~~to~~ with a Leap-Frog temporal scheme, but they were run here with the same small time step (0.1 s) for ~~the~~ comparison. Due to the upstream spatial discretization, WENO schemes ~~were~~ implicitly diffusive and ~~were~~ therefore characterized by a coarser effective resolution, especially WENO3 due to its lower order ~~at~~. Fig. 14 shows that the effective resolutions ~~were~~ 35 m (i.e. $7 \Delta x$) and 70 m (i.e. $14 \Delta x$) for WE5 and WE3 respectively (Fig. 14).

WE3 ~~significantly~~ reduces ~~significantly~~ the top entrainment and the supply of warmer ~~and~~, dryer air from above ~~at~~. This emphasizes the cooling near the surface (Fig. 12c). ~~Indeed, as~~ the diffusive contribution of the advection operator dissipates small updrafts and suppressed ~~as~~ part of the resolved kinetic energy variance, in particular ~~the one~~ that present at the top of the fog layer. This induces an overestimation of the thermal gradient near the surface before the fog, and ~~a too strong~~ leads to cooling that is too strong by 1 K during the fog (not shown). The consequences of the ~~enhanced~~ increased cooling ~~were~~ that the onset of fog at the surface ~~happened~~ occurs 1.5 h ~~before~~ earlier than actually observed ~~(with an initial formation at elevated levels that is not shown)~~, the LWC_{rc} during all the fog life cycle ~~was~~ largely overestimated throughout the fog life cycle, and the dissipation ~~time~~ ~~was~~ delayed (Fig. 13e). The DSD ~~moved towards~~ is characterized by higher concentrations of larger droplets (Fig. 13.f). ~~It increased the droplet sedimentation as the mean cloud water content reaching the surface by sedimentation was $4 \cdot 10^{-4}$ mm after 12 hours of simulations, that is 4 times more than in REF, compared to 0.1 mm by deposition for WE3.~~ Considering the microphysical fields, WE3 tends to be closer to NTR simulation, meaning that a diffusive transport scheme ~~dilutes~~ significantly ~~significantly~~ diminishes the tree drag effect.

~~On the contrary~~In contrast, the differences ~~were very small~~ between WE5 and REF are very small: only the LWP ~~was a bit~~ higher with WE5 during the dissipation phase due to a ~~fog slightly deeper~~lightly deeper fog layer. This underlines the less diffusive behaviour of WENO5 and its higher accuracy compared to WENO3.

Thus the jump ~~in~~ the effective resolution with the diffusive WENO3 scheme affected~~s significantly~~ the fog life cycle ~~significantly~~, while the smaller deviation with WENO5 had~~s~~ almost no impact. Increasing numerical implicit diffusion seem~~ed~~s to have almost ~~similar than~~the same effect as removing the drag effect of trees. This ~~has~~ also underlined~~s~~ the importance of the numerical schemes ~~in order to~~for correctly handling of the cloud edge problem (Baba and Takahashi, 2013). ~~As well a 2 m horizontal resolution instead of 5 m did not bring important changes. Finally, sensitivity tests on initial fields are presented.~~

4.4 Sensitivity to initial conditions

10 This test was designed to see whether the initial humidity field could reduce the bias on microphysical fields. Two simulations were considered. In the first, called HM2, the relative humidity of the initial profile in the boundary layer was reduced by 2%, and, in the second, called HP3, the relative humidity of the initial profile was increased by 3% over the same depth. In Fig. 13g, h and i, it appears that the fog life cycle is significantly modified, with a fog onset time deviating from the observations : it ~~occurs around 2 hours earlier with HP3 and 2 hours later with HM2. However 3 m r_c is almost the same during the development~~ and mature phases. Also neither of the simulations changes the DSD or the droplet concentration extrema. The LWPs of REF, HM2 and HP3 are superimposed (Fig. 15c) during the mature phase, so the dissipation time is unchanged.

It appears that taking away some humidity in the initial state does not reduce the droplet concentration, and the overestimation of the droplet concentration cannot be explained by an inadequate initial humidity profile.

20 Sensitivity tests were also conducted for surface temperature (+—2 K) and humidity (+—10%), but had very small effects on the fog life cycle and on the microphysical fields (not shown).

The last test involved an increase (VP3) or a decrease (VM3) of the wind speed in the free atmosphere in the initial and forcing conditions. In Fig. 13g, h and i, it can be seen that the lower the wind, the earlier the formation time, the higher the r_c and the later the dissipation time, as the mixing with higher dry, warm air is reduced. In contrast, a stronger wind drastically reduces the duration of the fog life cycle and the surface r_c . VM3 succeeds in broadening the droplet spectrum, but the extrema ~~of the droplet concentration do not change significantly.~~

Thus, all the tests presented in Figures 13 and 15 fail to reduce the droplet concentration compared to REF. Only the NTR simulation reduces it somewhat, due to a broader droplet spectrum, but it overestimates the r_c and advances the fog onset. This probably means that modifying the dynamical conditions is not a way to improve the droplet concentration prediction further, considering the improvement brought by the deposition process.

30 5 Conclusion

Large eddy simulations of a radiation fog event observed during the ParisFog campaign were performed, with the aim of studying the impact of dynamics on microphysics. In order to study the local structures of the fog depth, simulations were

performed at 5 m resolution on the horizontal scale and 1 m on the vertical scale near the ground, and included a trees barrier present near the instrumented site, taken into account in the model withby means of a drag approach. The model included a 2-moment microphysical scheme, and a deposition term was added to the droplet sedimentation, representing the droplets interception of droplets by the plant canopies and acting only at the first vertical level above grass, and everabove the height of the trees.

The performance of the reference simulation was satisfactory as there was a fairly good agreement with the classical near-surface measurements. The main discrepancies were an overestimation of the concentration of small droplets concentration near the ground, to a less degree of liquid water content, and an advance on the dissipation time of little more than one hour. This good performance allowed to explore the processes driving the fog life cycle to be explored.

The formation of the fog at elevated levels and the rapid subsiding effect of the fog layer down to the ground just after, that is fact that it subsided to the ground in a very short time, a frequently observed characteristic of radiation fog events at the Sirta site, has been elucidated as a consequence of the tree drag effect as when the wind overcame this obstacle and the deposition effect which reduces the formation of droplets near the surface. In contrast, the fog formed at the surface first upstream from the trees and 500 m downstream of the trees, leading to a duration of about one hour of duration for the fog formation at the surface over the whole domain.

At the beginning of the development phase, the fog became optically thick to longwave radiation, inducing a significant increase of kinetic energy by dynamical production, and that which was also associated to with temperature convergence at low levels. The radiative cooling near the top of the fog layer was the main source of droplet activation so that the droplet concentration was maximum in the upper levels of the cloud.

During the development phase, a slower growth of the fog layer depth occurred grew more slowly when the fog layer reached the top of the nocturnal boundary layer, meeting encountering stronger thermodynamical and dynamical gradients and wind shear. Horizontal rolls at the top of the fog layer, associated to with Kelvin-Helmoltz instabilities, became well-marked prominent. The cloud droplet concentration became quasi homogeneous in the fog layer on time when averaged over time b. But locally, extremes of droplet concentration occurred locally near the top of the fog in the radiative cooling layer, with maxima preferentially upstream of the crests of the waves rather than downstream, in the ascent area, meaning that mainly. This indicates that vertical velocity and secondly makes the main contribution to droplet activation at the top of the fog layer, followed by the contribution of radiative cooling contribute to droplet activation at the top of the fog layer. Inside the cloud layer, maxima of supersaturation were directly linked to the local updrafts, while variations of the droplet concentration remained almost homogeneous were smoother.

During the dissipation phase, as the fog involved into a stratus layer, the cloud mixing ratio decreased at all levels but. However, a sharp increase of in the droplet concentration occurred over the whole depth of the cloud as because droplets were now only activated by the convective ascents at the base of the stratus.

Then different Various sensitivity tests provide a better understanding of the physical processes involved during the fog life cycle allowed to identify the main processes affecting the evolution of fog. The tree drag effect and the deposition process were considered as essential to correctly reproduce the main characteristics of the fog. The absence of the trees barrier produced an

unrealistic fog simulation, with a too early an onset, a too excessively strong cooling and a large overestimation of the near-surface $LWC r_c$, damaging the visibility diagnostic worsening visibility diagnosis. It also modified the signature of the KH waves at the top of the fog layer, with a more regular pattern shown on energy spectra.

5 The removal of Neglecting the deposition process over all the whole vegetation canopy exerted the most significant impact on the fog prediction, as it produced more unrealistic water content near the surface, prevented elevated fog formation, but and also modified the fog life cycle and suppressed vertical and temporal heterogeneities of the microphysical fields. Conversely, increasing the droplet deposition velocity from 2 cm s^{-1} to 8 cm s^{-1} reduced significantly the cloud mixing ratio near the surface and the droplet concentration.

10 Increasing the horizontal resolution up to 2 m did not change significantly the fog prediction significantly, meaning which means that a grid convergence seems to be achieved at these resolutions. Conversely, increasing the numerical diffusion with a momentum transport scheme of lower order, which involves involving a coarser effective resolution, limited drastically limited the top entrainment, and tended almost to strongly towards the solution where the tree drag effect was ignored, underlying the importance of the properties of numerical schemes in LES, in particular at cloud edges.

15 Lastly Other tests, not presented here, modifying the initial conditions in terms of humidity or wind profiles, impacted the fog life cycle but failed to reduce much more the overestimated droplet number concentration. This means that taking away some humidity in the initial state did not reduce the droplet concentration, and the overestimation of the droplet concentration could not be explained by an inadequate initial humidity profile.

This study demonstrates the feasibility and the interest of LES including surface heterogeneities to improve our understanding of the fog processes. At these fine resolutions, surface heterogeneities have a strong impact which, explains a part of the variability in the fog layer. F and making these simulations remain very challenging. Therefore, horizontal and vertical variabilities of the fog layer also need also to be much more thoroughly explored in future field experiments. The horizontal variability especially at the onset of the fog also underlines that a point observation may not be very representative for what happens in over a coarser grid box of a numerical weather prediction model for instance.

25 One of the main points of this study is that fog water deposition cannot should not be neglected anymore in 3D fog forecast models, as still often occurs. It not only influences not only microphysical fields near the ground but also the whole fog life cycle. It seemed to be more important than droplet sedimentation in our case, keeping bearing in mind that the concentration of small droplets was overestimated this observed case was characterized by small droplet concentrations and cloud mixing ratio. In this study, the deposition term has been was introduced quite crudely and this would need some refinements in further studies. It would need to be proportional to take account of the wind speed and the turbulence, and it could also consider the 30 hygroscopic nature of canopies. By analogy with dry deposition, it would also be better to take into account droplet diameter into account, supposing assuming that this field is correctly reproduced. Other studies have also shown that fog water deposition was strongly enhanced at the forest edge, becoming up to 1.5-4 times larger than that in closed forest canopies (Katata, 2014), so it could be interesting to simulate the edge effect of fog water deposition. It is also crucial to perform measurements of fog water deposition and dewfall during field experiments (Price and Clark, 2014).

This study has shown the ~~strong~~great importance of some dynamical effects ~~which operate~~ing at a first order ~~to predict~~ ~~correctly~~for correct predictions of the fog life cycle. ~~But among all~~Despite the number of tests carried out, no ~~one~~ has succeeded ~~to reproduce correctly~~in correctly reproducing the droplet concentration, ~~which is~~ always overestimated. Now that the fog life cycle ~~is~~has been correctly reproduced on this case, trying to correct this defect appears ~~as~~to be the ~~main~~ priority. Thouron et al. (2012) have developed a new scheme based on a supersaturation prognostic variable to avoid excessive droplet concentration in 2-moment microphysical schemes, as they ~~have~~ demonstrated that some assumptions of the adjustment process are not ~~longer~~ valid ~~anymore~~ with LES. One of the main points is ~~to take into account~~that the pre-existing cloud water ~~should be taken into account~~ as a sink of supersaturation, in order to limit the activation of cloud droplets. The relevance of this scheme, applied in Thouron et al. (2012) to cumulus and stratocumulus clouds, needs to be demonstrated for fog clouds, and this will be the subject of the second part of this study.

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Name of the simulation	Difference of configuration with REF
NTR	No TRee: homogeneous surface
NDT	No Deposition on Trees
NDG	No Deposition (on Grass and/or trees)
DE58	Deposition velocity equal to 58 cm s^{-1}
DX2	Horizontal resolution = 2m
WE3	3rd order WENO advection for momentum
WE5	5th order WENO advection for momentum
HM2	Initial RH minus 2%
HP3	Initial RH plus 3%
VM3	Geostrophic wind minus 3 m s^{-1}
VP3	Geostrophic wind plus 3 m s^{-1}

Table 1. Simulation configurations for sensitivity tests

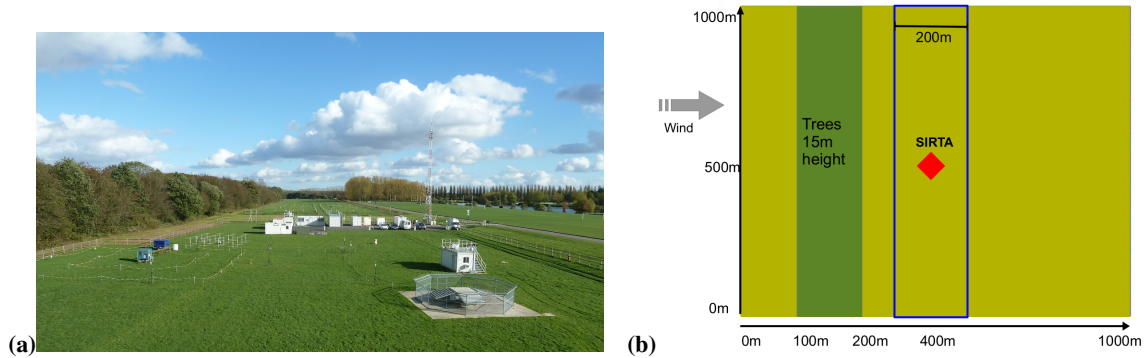


Figure 1. View of the measurement site (a) and modelling domain (b) with the trees barrier. All the simulated averaged results are presented in the blue contour area.

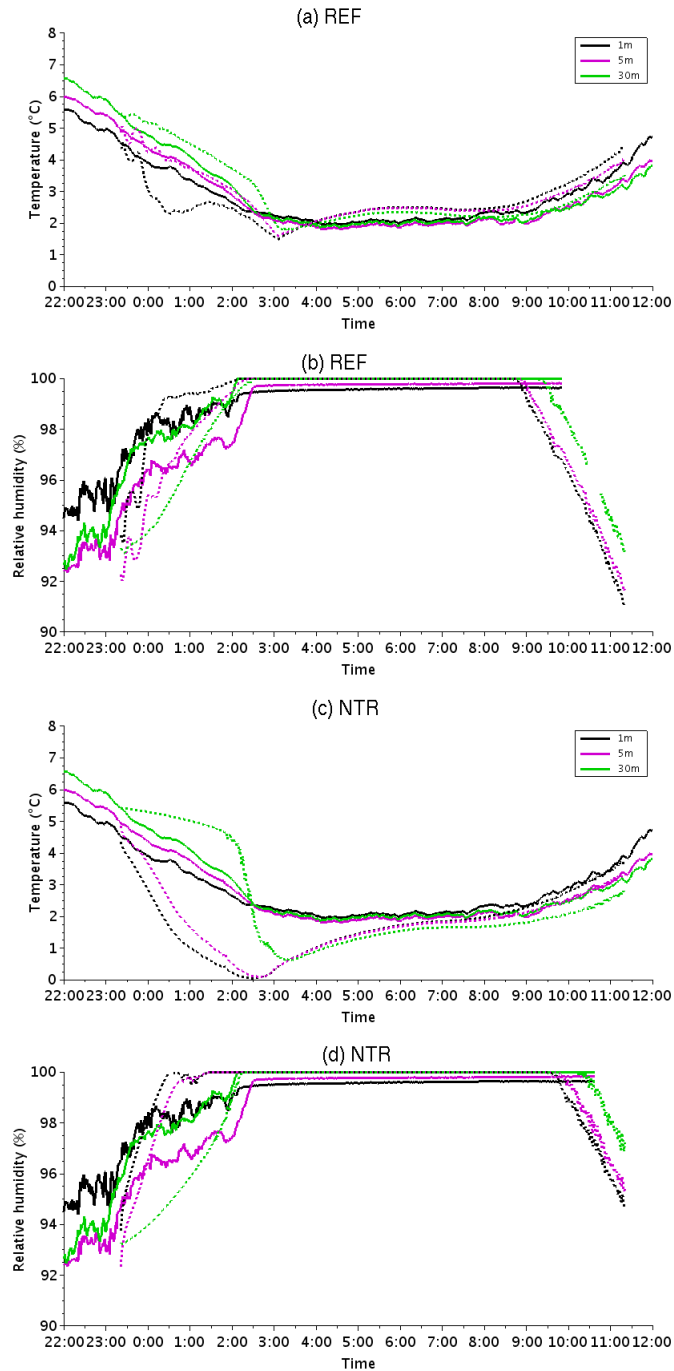


Figure 2. Observed (solid lines) and simulated (dashed lines) temporal evolution of temperature (a and c) and relative humidity (b and d) at 1m, 2m, 5m, 10m, 20m and 30m for the REF (a and b) and the NTR (without trees) (c and d) simulations. Simulated fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

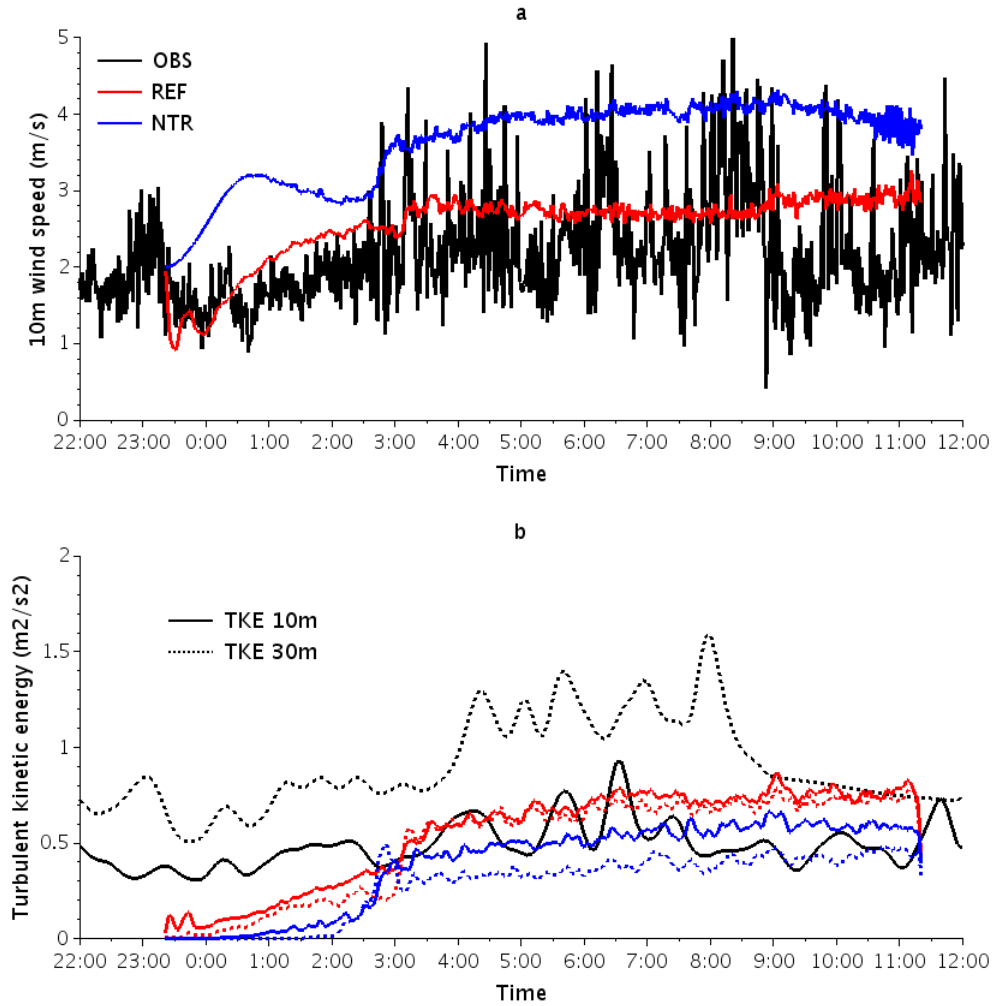


Figure 3. Observed (black lines) and simulated (coloured lines) temporal evolution of 10m wind speed (a) and 10m (solid line) and 30m (dotted line) TKE (b) for the REF (red line) and the NTR (without trees) (blue line) simulations. Simulated fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

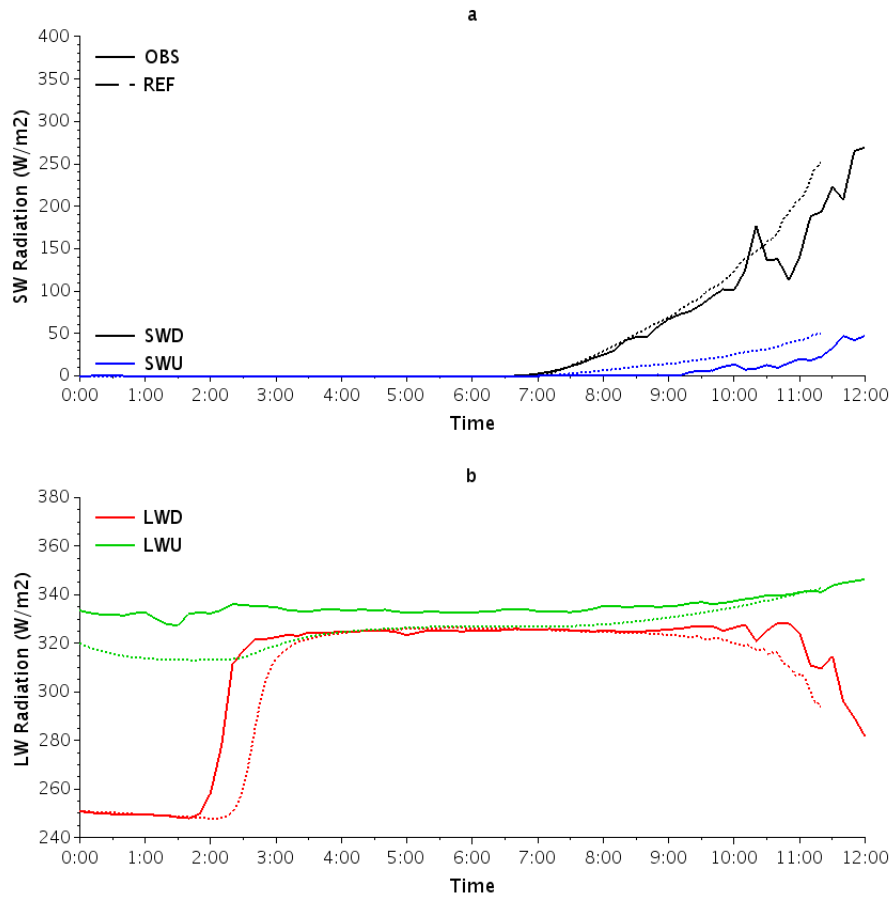


Figure 4. Observed (solid lines) and simulated (dotted lines, with the REF simulation) temporal evolution of downward and upward (at 1m) shortwave (a) and longwave (b) radiation fluxes (in W/m^2). Simulated fields are averaged over the horizontal area located downstream the tree barrier (blue contour area of Fig. 1b).

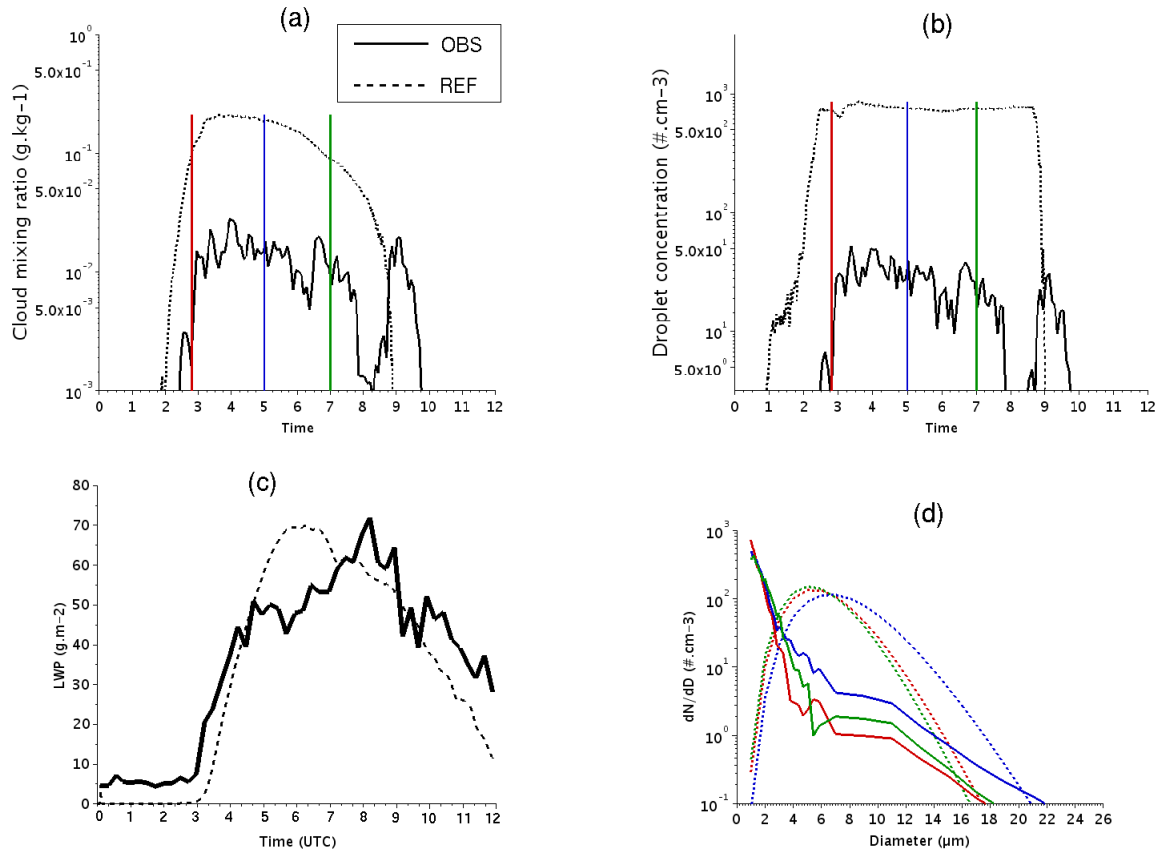


Figure 5. Time series of droplet concentration (a, in cm^{-3}), liquid-water content cloud mixing ratio (ba, in $\text{g m}^{-3} \text{g}^{-1}$), droplet concentration (b, in cm^{-3}), and LWP (c, in g m^{-2}), and particle size distribution (d, in cm^{-3}) at 0250 UTC (in red), 0500 UTC (in blue) and 0700 UTC (in green) at 3 m agl observed (— solid line), and simulated by REF (--- dotted line). Simulated fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

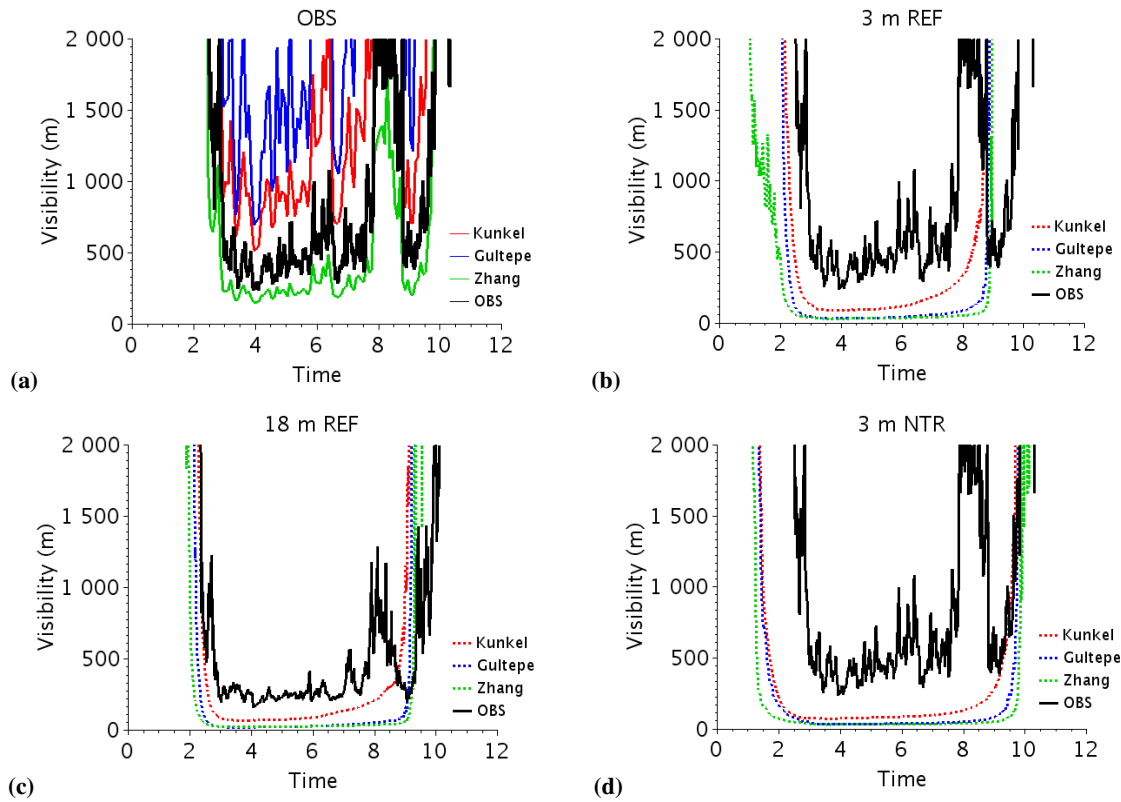


Figure 6. (a) 3 m observed (in black) and diagnosed (in colour) visibility with the observed microphysical fields according to Kunkel (1984), Gultepe et al. (2006) and Zhang et al. (2014a) (in m). (b) and (c) 3 m and 18 m visibility diagnosed with the microphysical fields from the REF simulation. (d) 3 m visibility diagnosed with the microphysical fields from the NTR simulation (in m). **Diagnosed visibility from simulations uses averaged microphysical fields over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).**

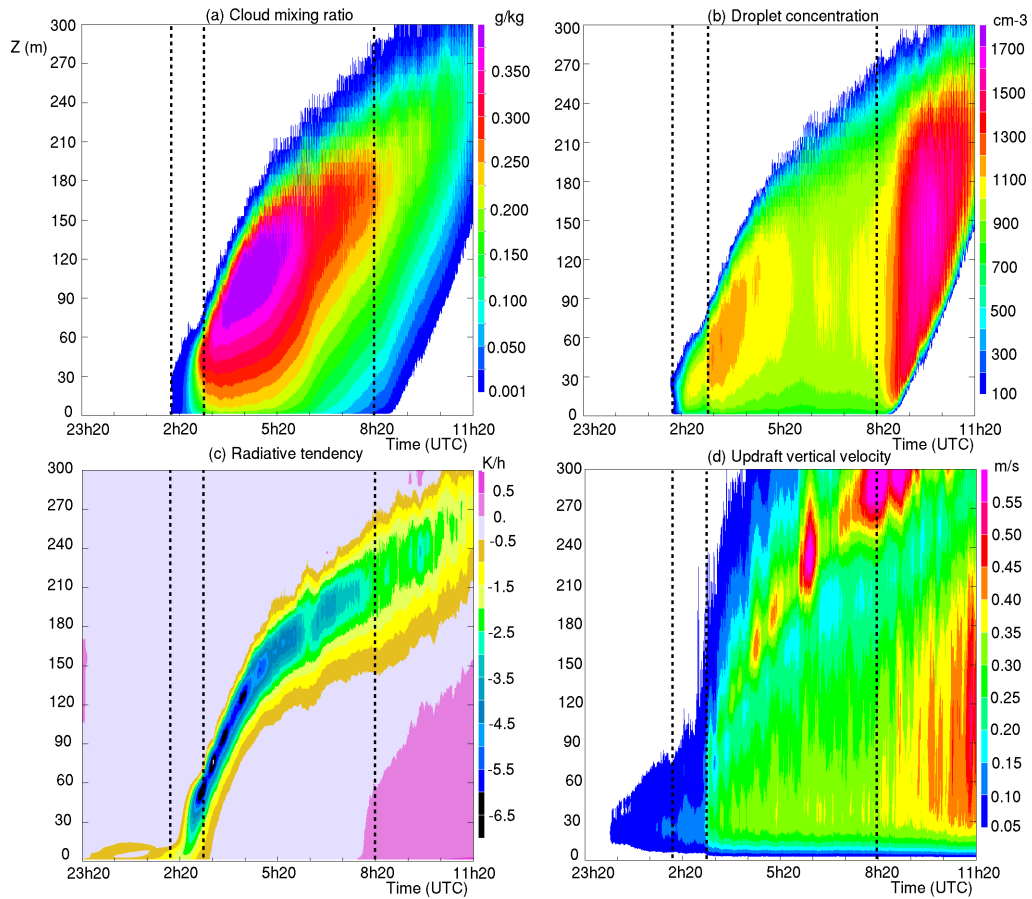


Figure 7. Temporal evolution of simulated vertical profiles of cloud mixing ratio (a, in g kg^{-1}), droplet concentration (b, in cm^{-3}), radiative tendency (c, in K/h) and updraft vertical velocity (d, in m s^{-1}) for the REF simulation. Fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b). The three phases of the fog life cycle are delimited by dotted lines.

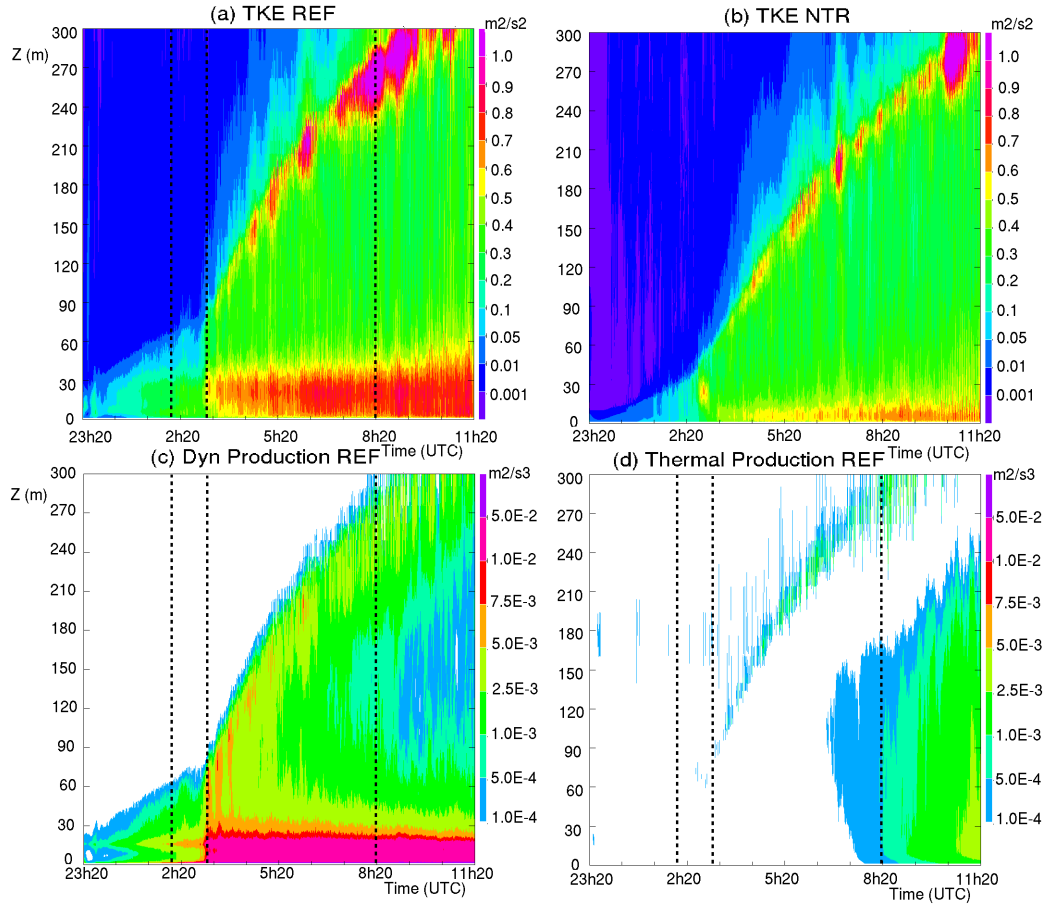


Figure 8. Temporal evolution of mean vertical profiles of total (resolved+subgrid) turbulent kinetic energy (in $m^2 s^{-2}$) for REF (a) and NTR (b) simulations, and dynamical (c) and thermal (d) production of total turbulent kinetic energy (in $m^2 \cdot s^{-3}$) for the REF simulation. Fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b). The three phases of the fog life cycle are delimited by dotted lines.

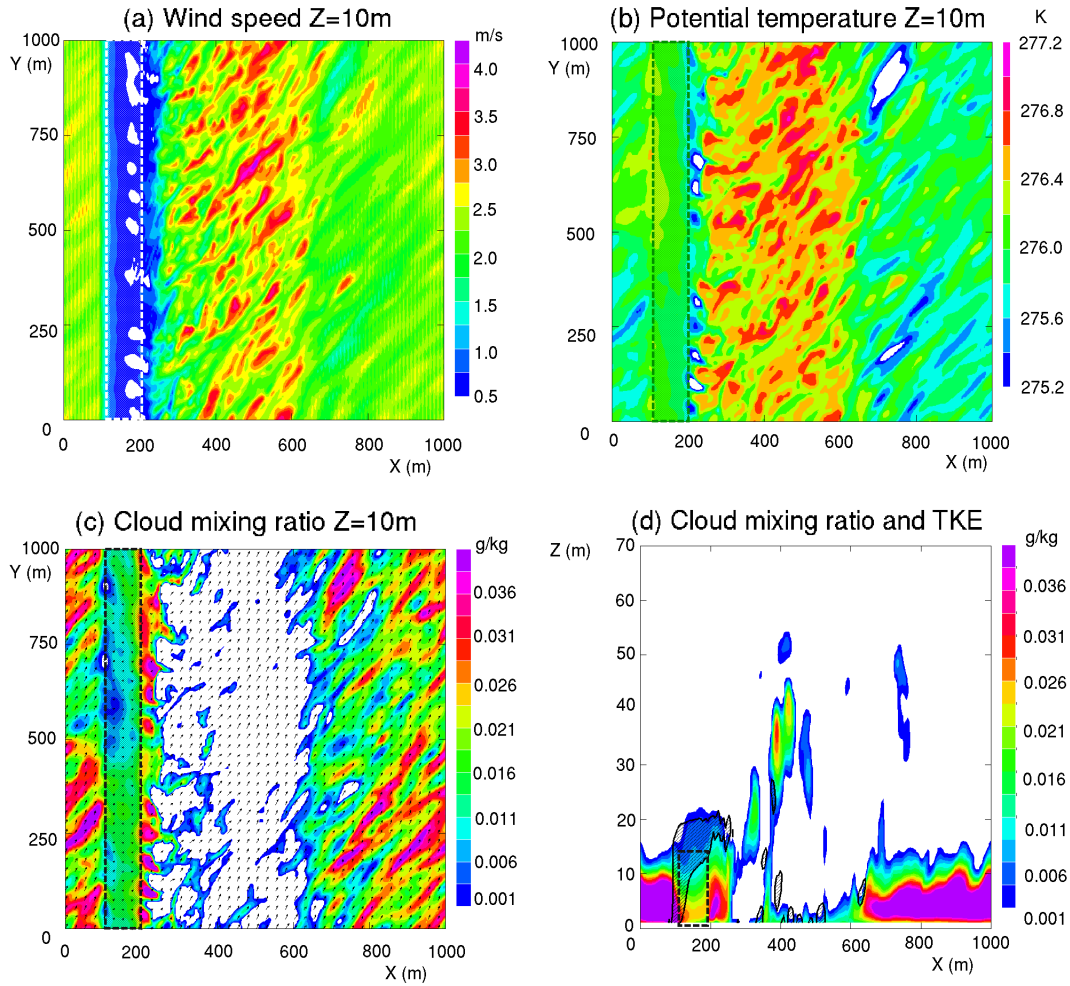


Figure 9. REF simulation at 0240 UTC: (a), (b) and (c): Horizontal cross-section at 10 m height of wind speed (a, in m s^{-1}), potential temperature (b, in K) and cloud mixing ratio (c, in g kg^{-1}). (d): Vertical cross-section at $Y=500\text{m}$ of cloud mixing ratio (in g kg^{-1}) with area of TKE higher than $0.1 \text{ m}^2 \text{ s}^{-2}$ shaded. The barrier of tree is marked with a rectangle.

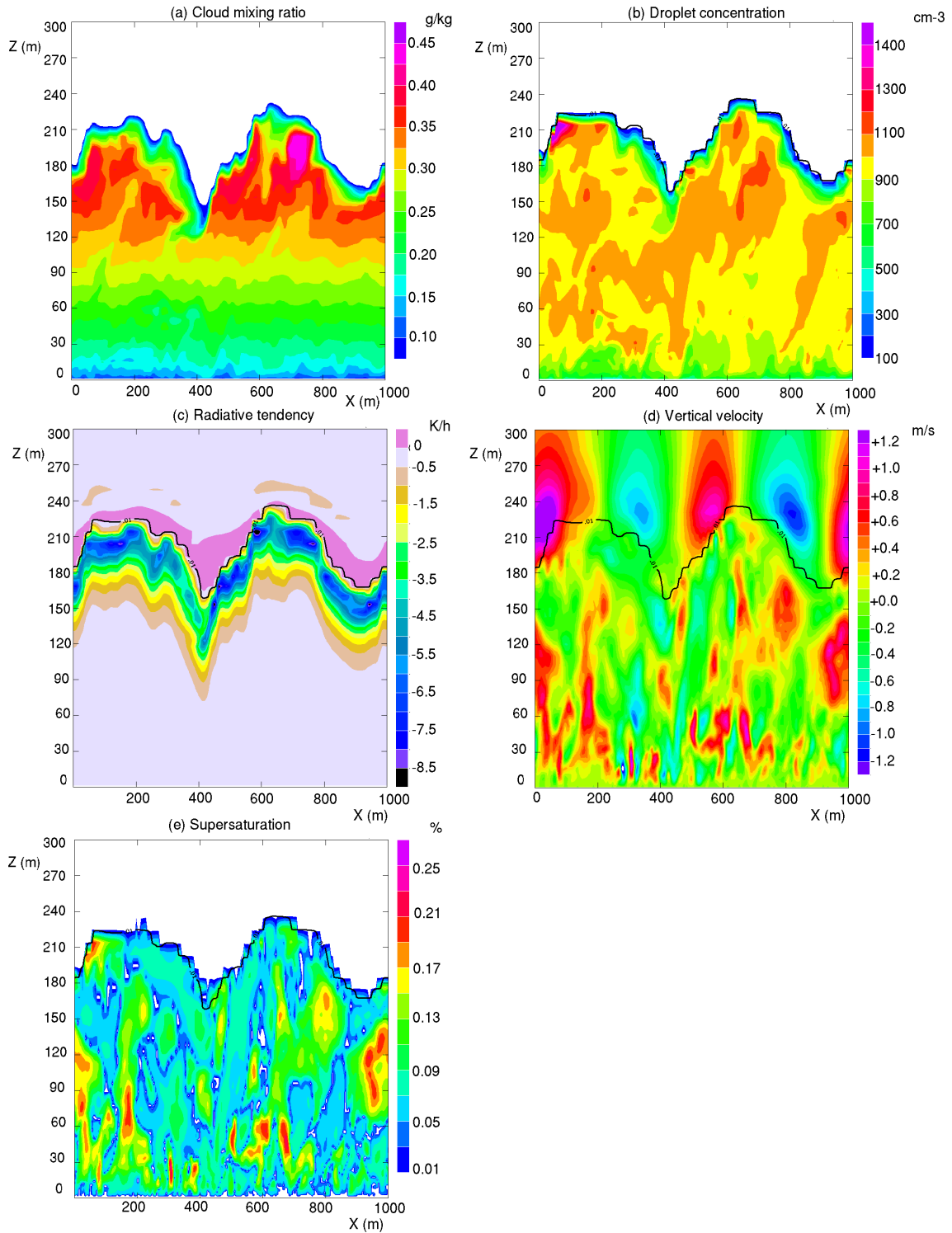


Figure 10. Vertical cross-section at $Y=500\text{m}$ at 0620 UTC for the REF simulation: (a) cloud mixing ratio (in g kg^{-1}), (b) droplet concentration (in cm^{-3}), (c) radiative tendency (in K/h), (d) vertical velocity (in m s^{-1}) and (e) maximum of supersaturation (in %) with the isoline of $r_c = 0.01 \text{ g kg}^{-1}$ superimposed.

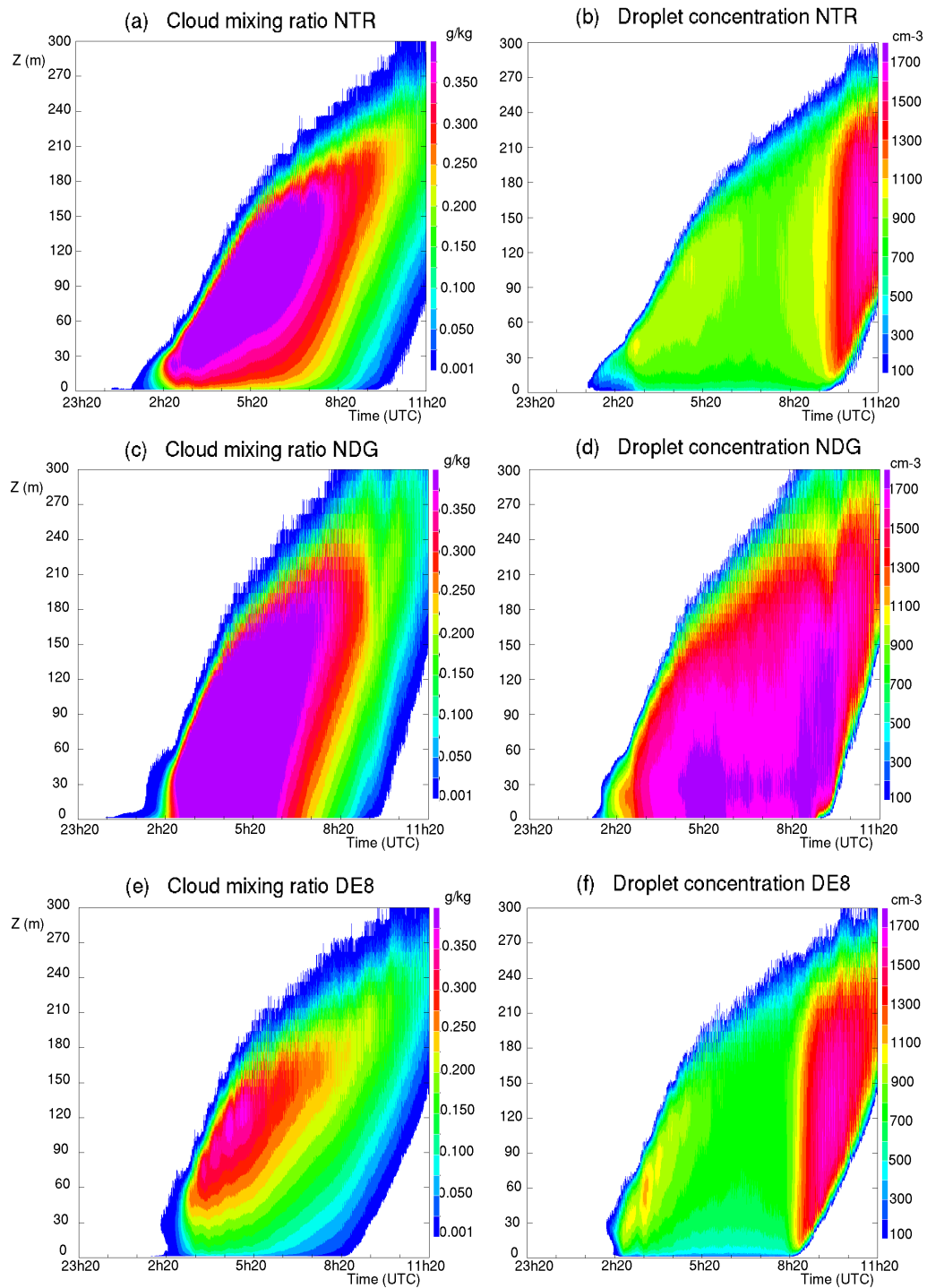


Figure 11. Temporal evolution of simulated vertical profiles of cloud mixing ratio (a, and c and e, in g kg^{-1}) and droplet concentration (b, and d and f, in cm^{-3}) for NTR and NDG and DE8 simulations. Fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

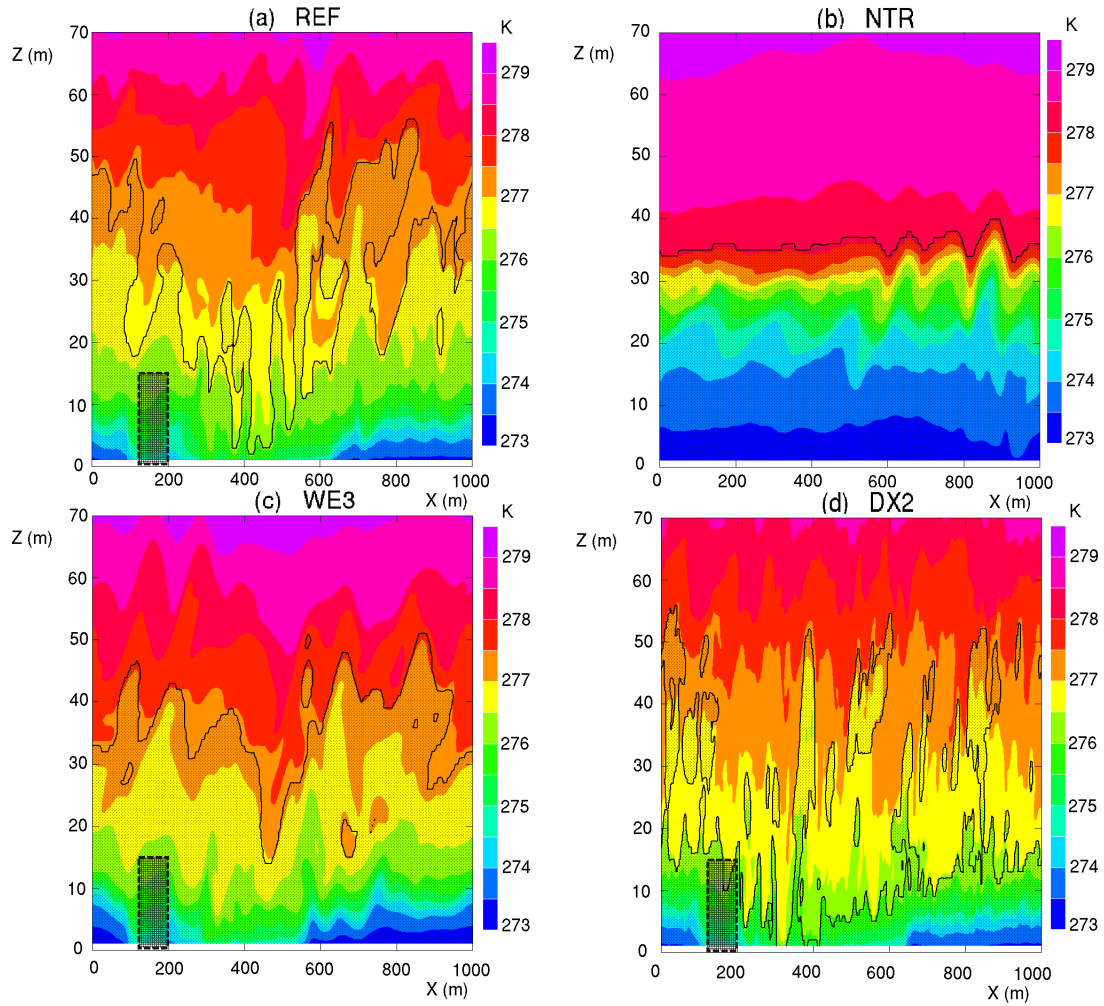
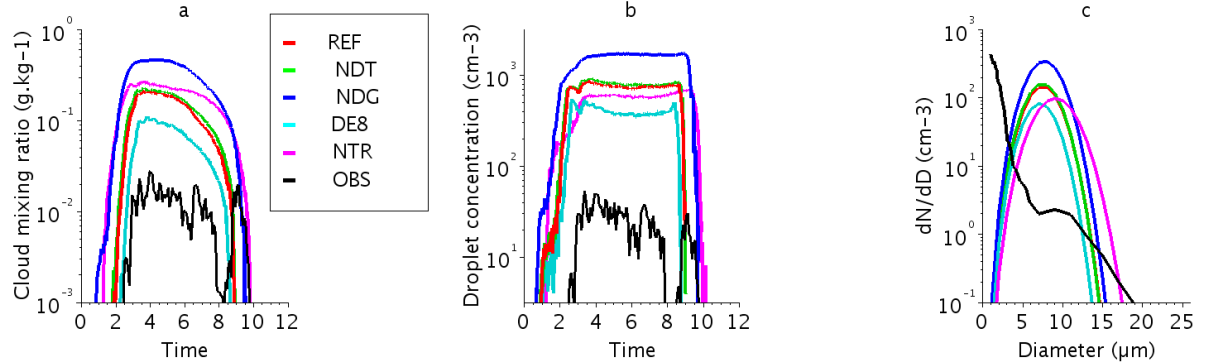


Figure 12. Vertical cross-sections at $Y=500\text{m}$ and 0220 UTC of potential temperature (in K) for the REF (a), NTR (b), WE3 (c) and DX2 (d) simulations, with area of cloud mixing ratio higher than 0.1g kg^{-1} superimposed with dots and the barrier of tree marked with a rectangle..

Impact of trees and deposition



Impact of resolution and advection scheme

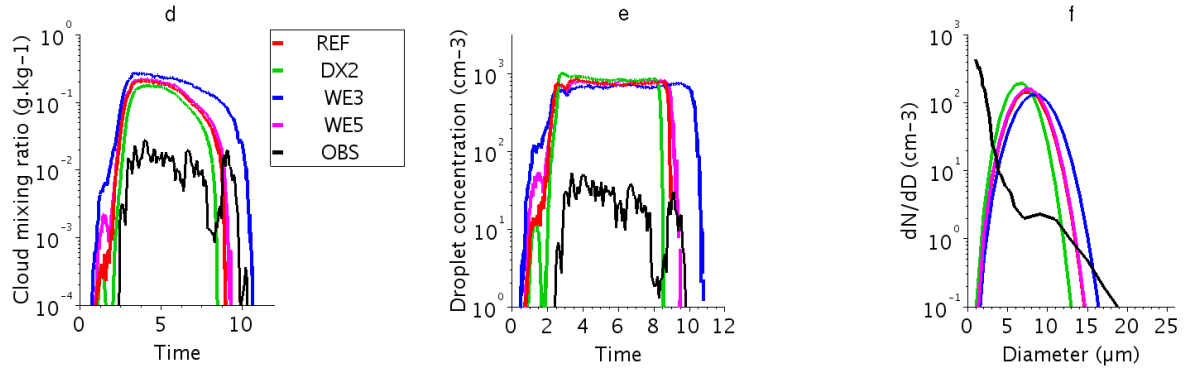


Figure 13. Time series of droplet concentration (a, d and g, in cm^{-3}), liquid water content/cloud mixing ratio (b, e and h and d, in $\text{g}\cdot\text{m}^{-3}\cdot\text{g}\cdot\text{kg}^{-1}$), droplet concentration (b and e, in cm^{-3}), and droplet size distribution (e, f and i and f, in cm^{-3}) at 0520 UTC and 3 m agl observed (in black), and simulated (in colour). Simulated fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

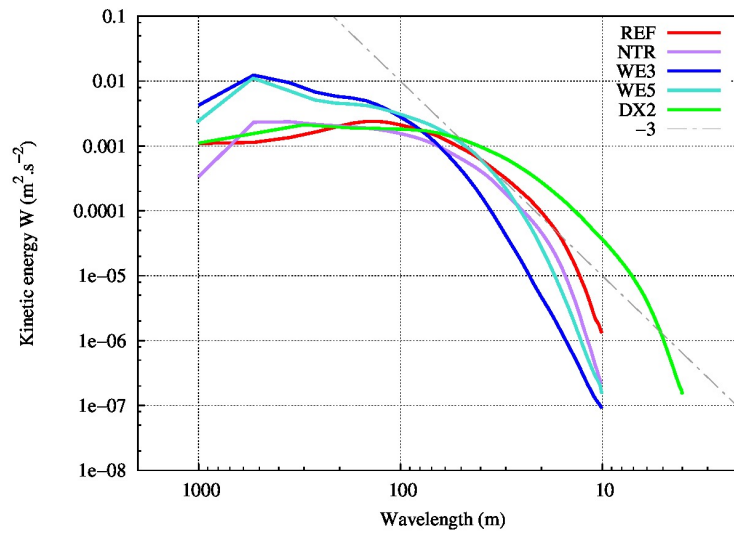


Figure 14. Mean kinetic energy spectra for vertical wind computed over the whole fog layer and horizontal domain at 0620 UTC for the REF, WE3, WE5, DX2 and NTR simulations.

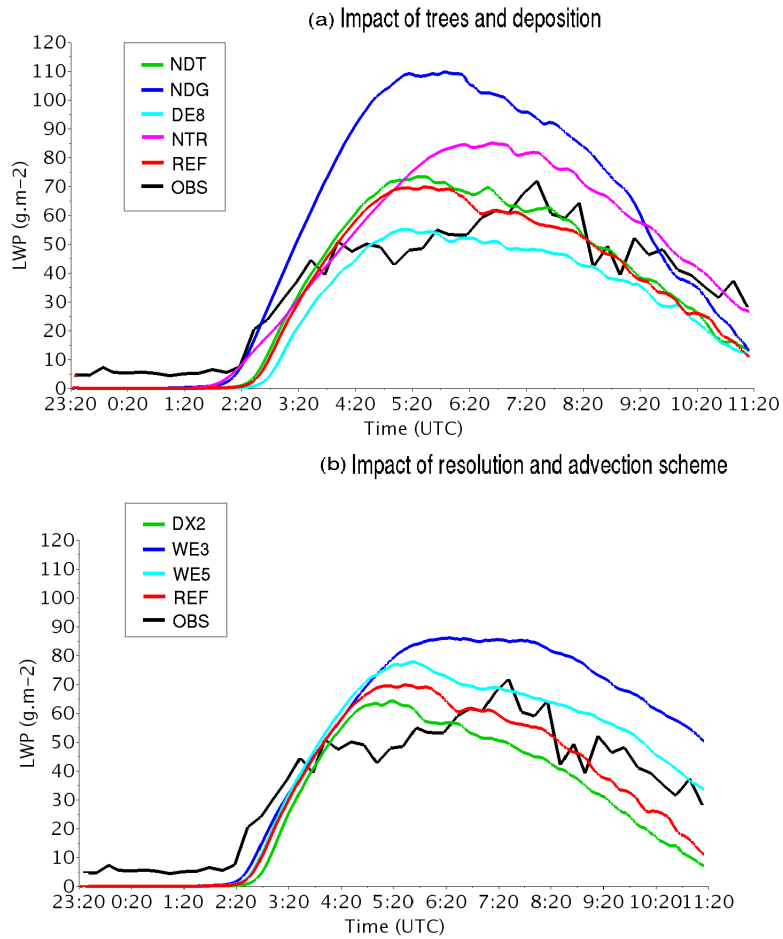


Figure 15. Time series of LWP (in $\text{g}\cdot\text{m}^{-2}$) observed (in black), and simulated (in colour) for the different simulations. Simulated fields are averaged over the horizontal area located downstream of the tree barrier (blue contour area of Fig. 1b).

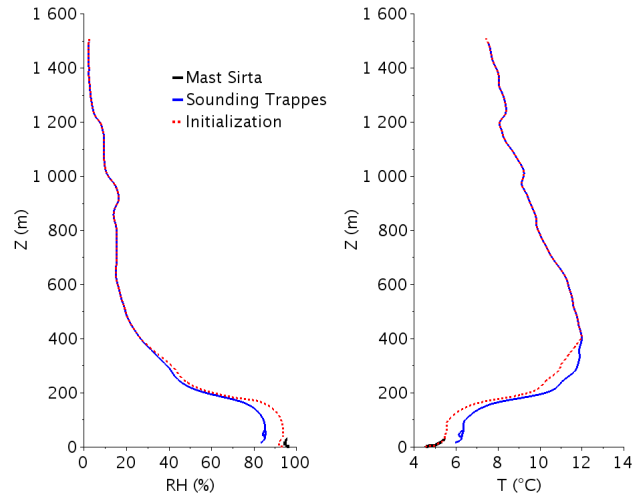


Figure A.1. Relative humidity (in %) and temperature (in C) vertical profiles at 2320 UTC on 14 November 2011 observed at the Sirta mast (in black); and by the Trappes radiosounding (in blue) and used for the REF initialization.

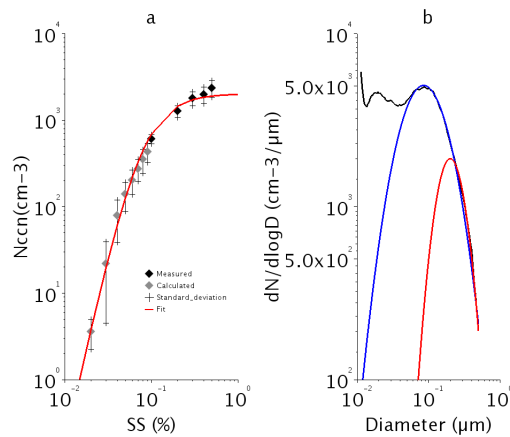


Figure A.2. (a) Activation spectrum: from CCNC measurement before the fog onset (between 0130 and 0230 UTC) for supersaturations higher than 0.1% in black dots, from calculation for supersaturations lower than 0.1% in grey dots, and fitted from the using Cohard et al. (2000c)'s parametrization in red. (b) Particle size distribution from the aerosol measurements (in black), the lognormal distribution fitted to the accumulation mode (in blue) and according to Cohard et al. (2000c) (in red).

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