

This document is structured as follows:

1. **Replies to the referee's comments.** For this, the replies sent during the discussion phase have been attached. The referee's comment is shown in red and the reply in black. In some of them a comment has been added during the modification of the manuscript. This is shown in blue.
2. **Marked-up manuscript version.** The revised manuscript has been attached and the main modifications, as well as some related to the referee's comments, are highlighted in green.
3. **The manuscript's main modifications.** This consists of a list containing the page, line number, and an explanation of the modification.

# **1. Replies to the referee's comments**

## ***General comments to both referees***

One of the main concerns of the referees was the manuscript's structure. This was taken into account and a new one was proposed in the letters addressed to each referee. To facilitate the reading of this document and avoid repetition, this structure has been included below.

*Manuscript's structure:*

## **Abstract**

## **1 Introduction**

## **2 Data**

### **2.1 SMOS retrievals of TB**

### **2.2 Modelled TB: CMEM**

#### **2.2.1 Input data from Land Surface Models**

- Differences between LSM hydrological schemes and temperature estimation

### **2.3 Precipitation and Land Surface Temperature**

## **3 Methods**

### **3.1 Data sampling and filtering processes**

### **3.2 Comparison analysis:**

- Spatio-temporal correlation
- EOF

## **4 Results**

### **4.1 Comparison of measured and modelled brightness temperatures**

- Temporal correlation

- Spatial correlation.

## **4.2 Temporal and spatial characterization of the TB error**

### **4.2.1 TB error**

- Spatial patterns
- Expansion coefficients

### **4.2.2 LST and precipitation errors**

- Spatial patterns
- Expansion coefficients

### **4.2.3 Analysis of CMEM assumptions**

## **4.3 Annual cycle of brightness temperatures**

## **5 Discusssion**

## **6 Conclusions**

The manuscript has been modified following the structure proposed to the referees during the discussion phase. However, there are some small changes with respect to it.

- Section 2.2.1 “Input data from Land Surface Models” has been renamed to “The ORCHIDEE and H-TESSEL Land Surface Models”. We had proposed to include a sub-section named “Differences between LSM hydrological schemes and temperature estimation”. However, it has not been included, because the description itself evidences the differences between the LSM’s hydrological schemes and temperature estimation. This has been highlighted in section 2.2.1.
- Subsections without numbering were proposed in sections 3.1 (“Sampling” and “Filtering”), 3.2 (“Spatio-temporal correlation” and “Empirical Orthogonal Function”), and 4.1 (“Temporal correlation” and “Spatial correlation”). However, these have been numbered for manuscript consistency.

***Referee 1: Mr. Westerhoff***

Dear Mr. Westerhoff,

Thank you very much for taking the time to read the manuscript and commenting on parts of it. We agree with you that the presentation of this research can be clarified and below you will find the answers to the overall and minor comments you made about the manuscript titled “Comparison of measured brightness temperatures from SMOS with modelled ones from ORCHIDEE and H-TESSEL over the Iberian Peninsula” by A. Barella-Ortiz, J. Polcher, P. de Rosnay, M. Piles, and E. Gelati.

## **OVERALL COMMENTS**

The text would be somewhat clearer if input data and methodology would be separated. I now have trouble understanding what part of the input data was processed by the authors and what part of the processing was already provided with the input data set. Also, make sure you are then consistent with the past tense (e.g., we derived TB using this method). It seems like either the 2.1 and 2.2 were written by different persons, or that the authors clearly know more about the 2.2. The text does not look like a unified text. I think distinguishing between used data/models and the methodology could partly solve this. The authors are too elaborate and tend to go into ‘discussion mode’ in most parts of the paper where they shouldn’t. For example, in the data and methods section. They should be more concise and to the point. There should be a clearer explanation of why the temporal pattern seems to match, but the spatial pattern not. There must be some areas then where the temporal pattern also does not match? Please explain clearer. Please consider the topography as one of the candidate for the difference found. Please consider separating discussion and conclusion. Please explain each topic per sub-section in a discussion, which makes it clearer (and hopefully more concise). Sorry, I stopped my detailed textual comments at the EOF analyses text, since it became too unstructured for me to understand.

We propose the following structure to clarify and be more concise in the information given in each section:

See the manuscript’s structure in the “General comments to both referees”.

**Current section “Data and methods”**

Following your advice, this section will be divided into two different ones: “Data” and “Methods”.

### **Current section “Results”**

We propose to divide the current section 3.1 (Comparison of measured and modelled brightness temperatures) into two sub-sections without numbering: temporal correlation and spatial correlation.

- We believe that the good temporal correlation is due to the temperature's quick response to precipitation and to a lesser extent, to the strong annual cycle of land surface temperature (page 13030, lines 22 - 25). Contrary to the temporal correlation, the spatial one is poor. This result identifies an inconsistency between the spatial structures of measured and modelled TB. To better understand this inconsistency, we performed the EOF analysis of the TB error. In the revised version of the manuscript, we will explain in a clearer way the difference between the results of temporal and spatial correlation analyses, their meaning and the extra information the EOF analysis brings to understanding the spatial inconsistency between measured and modelled TBs. It should be noted that the EOF analysis also allowed us to confirm that the temporal correlation is driven by the TB's high frequency behaviour. Otherwise, since the dominant mode of the TB error is governed by the annual cycle of the TB signal, the values obtained for the temporal correlation would have been weaker than the ones shown in Figure 1.

- The mountainous areas are identified as areas where the temporal correlation does not match and relief effects are given as a possible explanation for this (page 13031, lines 1 – 7).

To clarify the current section 3.2 (Temporal and spatial characterization of the error), we propose the following changes:

- The EOF analysis will be explained in the new “Methods” section.
- The current sections 3.2.1 and 3.2.2 will be divided into two subsections without numbering: “Spatial patterns” and “Expansion coefficients”.

- The text explaining the reasoning behind our focus on LST and precipitation errors will be moved to the section 4.2.2 from the new structure and will also be restructured to make it more concise.
- We will move some parts of the text to the new “Discussion” section. For example, the paragraph discarding the LSMs as responsible for the spatial inconsistency between measured and observed TB (page 13037, lines 19 - 27).
- We will create a new section 4.2.3 “Analysis of CMEM assumptions”. It will include the text which is currently at the end of section 3.2.2 about the study of how may assumptions in CMEM affect modelled TBs.

The current section 3.3 (Annual cycle of brightness temperatures) will be rewritten to clarify our reasoning.

## **Current section “Discussion and conclusions”**

As you suggested, this section will be divided into “Discussion” and “Conclusions”. In the former we will discuss the similarities between the results obtained for the TB comparison and those from the SSM comparison (Polcher et al. 2015), which will no longer be in the “Results” section.

## **DETAILED COMMENTS**

### **Page 13020**

1. Abstract Just use ORCHIDEE and H-TESSEL and explain the abbreviations in the input data. I would leave out the “(CMEM)” and introduce the abbreviation in the input data section.

We agree with your proposal of not explaining the abbreviations in the abstract.

2. Line 13: “However, their spatial structures. . .”. Considering the sentence before, it is not clear what their points towards.

We propose to modify the text to: “Measured and modelled brightness temperatures show a good agreement in their temporal evolution, but are not consistent when their spatial structures are compared”.

The text has been rewritten as “Measured and modelled brightness temperatures show a good agreement in their temporal evolution, but their spatial structures are not consistent”.

**Page 13020**

3.Line 23: Replace ‘nowadays’ by ‘at present’ .

We agree with your proposal.

4. Line 25, use proper reference of WWDR

The reference will be added:

WWAP (World Water Assessment Programme). The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. Paris, UNESCO, 2012.

**Page 13021**

5. “Remotely sensed soil moisture products have brought about new ways to perform data retrieval, adding new observations to data assimilation chains. The optimal combination of these products with modelled ones is expected to provide best estimates of the true soil moisture state.” I think that ground-observed soil moisture should play a role here and should be mentioned too. Otherwise, the statement is not correct (after all, modelled ones are a guess, and remotely sensed ones are quite noisy). Or do you have a reference that claims this statement?

Ground-observed soil moisture is not included here because we cannot deal with it at the scale at which this study was carried out. However, we propose to change “the best” by “better”.

**Page 13022**

6. Line 2. Please add ‘and the relatively large radar wavelength of the L-band’ at the end of the sentence.

We do not understand your comment. We are using L-band data from a radiometer, not a radar. What we want to stress in this sentence is the sensitivity of this frequency band to the soil water content. Indeed, L-band is a relatively large wavelength (21 cm approx.), but we think this is not the point.

**Page 13023**

7. Line 20: “Furthermore, SSM is a critical variable regarding water resources especially in the Iberian Peninsula, . . .”. Why is it critical in the IP?

Surface soil moisture is a critical variable in semi-arid areas and most of the IP is semi-arid.

8. Line 21. Use ‘IP’, not ‘Iberian Peninsula’.

We agree with your proposal.

**Page 13024**

9. Line 17: “and SMOS TBs at the antenna reference plane were derived”. Did the authors derive these? If yes, this should be clear. Also, if yes, lines 17 and further should be also in past tense (e.g. line 18, “These TBs were first screened out . . .” etc )

The L1C product was provided by the Barcelona Expert Center (page 13025, lines 1 to 2) and was not part of the work done for this study.

10. Line 23: “These TBs have been first screened out for Radio-Frequency Interferences (RFIs) (strong, . . . . . from the Icosahedral Snyder Equal Area (ISEA) 4H9 grid to a 0.25 regular latitude–longitude grid, which is easier to manipulate.” Did the authors do this? If so, put it in past tense, so it is clearer whether that has been done or not. Further, is there any study known that describes the effect of the topography on incidence angle (i.e. local incidence angle)?

As in the previous comment, the L1C product was provided by the Barcelona Expert Center. The data treatment of this product has been given in this section to inform the reader about its physical characteristics. For example, the fact that TBs have been screened out for RFIs is important to know when studying the main source of the error between measured and modelled TBs. The following studies describe the effect of topography on the incidence angle of microwave radiometers: Talone et al. (2007), Pulvirenti et al. (2011), and Utku et al. (2011). To our knowledge, this effect is not corrected for in SMOS operations, they have a topography flag and do not estimate soil moisture in the locations where it is raised.

**Page 13025**

11. Line 23 - “The reason being that Wilheit (1978) was chosen in. . .” Please correct this to correct English into something like: The methodology of Wilheit (1978) to compute. . . was chosen, because. . .”. This also goes for all other times Wilheit is mentioned in the journal.

Following your advice, we will rephrase the text (see the next comment).

We do not understand what do you mean when you refer to the other times Wilheit is mentioned in the manuscript. Do you propose to replace every time we refer to Wilheit (1978) by “the methodology of Wilheit (1978)”? Should we accompany “Wilheit” by the concept “methodology”? If it is so, we believe that even if it is not written in the phrase, it is clear that



we refer to it. In fact, it is said in most of the phrases where “Wilheit” (and thus the methodology of Wilheit) appears: “Wilheit parametrization” (page 13026, line 2), “the parametrization proposed by Wilheit (1978)” (page 13038, lines 24 to 25) , “the parametrization of Wilheit (1978)” (page 13045, lines 10 to 11).

**12. Line 23: - “because it is more physically based..”. More physically based than what?**

The expression “more physically based” is used here as we believe that the methodology proposed by Wilheit (1978) is based on sounder physical grounds than the application of the Fresnel law for estimating the surface emissivity. We will modify the text as follows: “For  $TB_{HT}$  the reflectivity of the flat soil surface is computed following the Fresnel law, so it is expressed as a function of the soil dielectric constant and the observation incidence angle. This formulation considers the emission at the soil interface. As it is simple and affordable in computing time it is commonly used for microwave emission modelling and soil moisture retrieval, as well as for operational applications (e.g. Wigneron et al., 2007, de Rosnay et al., 2009). It assumes an a priori soil moisture sampling depth, which in this study corresponds to the first soil layer of the land surface model (7cm for HTESSSEL). For  $TB_{OR}$ , the multilayered soil hydrology of ORCHIDEE opens the possibility to consider the soil moisture profile and the resulting volume scattering effects on the soil emission. Therefore the reflectivity of the flat soil surface is computed using the Wilheit (1978) parameterization.”.

**13. Line 25: - Fresnel’s law. Do you have a reference? Also, this part, up to page 13026, line 18, looks somewhat like a discussion. I think this text should be in, but please be to the point and clearer. For example: “The methodology of Wilheit (1978) was used to calculate  $TB_{OR}$ . It considers the soil . . . etc . Fresnel’s Law (ref) was used to calculate  $TB_{HT}$ . The differences between the Wilheit and Fresnel’s law are: . . .”**

The following reference will be added:

“Ulaby, F. T., Moore, R. K., and Fung, A. K.: Microwave Remote Sensing (Active and Passive), vol. 2. Reading, MA: Addison-Wesley, 1986.”

The text referred to in this comment explains the choices made for the configuration of CMEM to model the smooth surface emissivity for  $TB_{OR}$  and  $TB_{HT}$ . Therefore, we believe that it should remain in this section.

**Page 13026**

14. Line 20: ‘Several differences van be identified between. . .’ You do not start an explanation of models like this. First start with the introduction of the two models, then very concise explain some differences, but refrain from stepping into the discussion mode. For example, start with line 24.

Thank you for this advice. The main objective of this section is not the description of models, but the difference in their hydrological scheme, as well as in their estimation of land surface and soil temperature. This is key because these differences allow to discard LSMs as the main cause of the spatial inconsistency between measured and modelled TBs. The title of the section may, however, not be clear enough and thus, we propose to change it to “Differences between LSM hydrological schemes and temperature estimation“. As exposed in the response to the “overall comments”, we propose to change this section to section 2.2.1 (Input data from Land Surface Models) where both LSMs will be briefly introduced. It will include a subsection without numbering (Differences between LSM hydrological schemes and temperature estimation), where the differences will be explained.

See the comment from the “General comments to both referees”.

15. Line 24: “The hydrological scheme used by ORCHIDEE is based on the model of the Centre for Water Resources Research (CWRR)” Please cite the model of the CWRR model if possible.

We propose to replace CWRR by the term “multilayer scheme”. In addition, this will also clarify the text.

## **Page 13027 and 13028**

16. The whole text is based on the difference between the two models. I think this is a wrong approach, as it makes the text very confusing. First state the two models, then concisely explain their differences. For example, for three subsections of ORCHIDEE, H-TESSSEL, and DIFFERENCES would be clearer.

Following your previous comment (number 14) the main objective of the section is to provide information about the LSMs' hydrological scheme and temperature estimation, establishing that each LSM deals with them in a different way. In our opinion, a description of the models is not necessary. As explained before, we propose to restructure this section as section 2.2.1 (Input data from Land Surface Models) with a subsection without numbering (Differences between LSM hydrological schemes and temperature estimation).

See the comment from the “General comments to both referees”.

**Page 13029**

17. Line 6-7: “Since H-TESSSEL’s surface state variables consist of a value each 6 h“ This should have been mentioned in the explanation about the models and I cannot find it.

In section 2.2.2 (Land surface models) it is said “ $TB_{HT}$  is output at 6 hourly time steps (at 0, 6, 12, and 18)” (page 13028, lines 23 to 24). We propose to rephrase the text from page 13029 to “However,  $TB_{HT}$  consists of a value each 6 hours, and an hourly sampling resulted in data being neglected because  $TB_{HT}$ ’s hours did not always correspond to those from SMOS’s observations”.

The text has been rephrased as “However,  $TB_{HT}$  consists of 6 hourly values, thus potentially resulting in a large number of neglected data because  $TB_{HT}$  and SMOS time steps did not always correspond”

**P13030**

18. 3 Results. The author step into comparison straight away. I think they could be better off and clearer if they first present the results. So the separate results of TBSM, TBOR and TBHT with some clear explanations. Then add a section 4. Analyses of the results. Starting with 4.1 Comparison of modelled and brightness temperatures, then 4.2 Temporal and spatial characterisation of the error and 4.3. Annual cycle of brightness temperatures.

We understand your concern. However, we believe that with the modifications proposed in the “overall comments” the results will be more clearly set apart, since the information will be divided into more subsections and the discussion moved to the new “Discussion” section. In our opinion with this change there is no need of making a distinction between the presentation and the analysis of the results.

**P13042.**

19. Line 5: “This study complements a previous one where modelled Surface Soil Moisture (SSM) from the ORCHIDEE Land Surface Model (LSM) was compared to retrieved SSM from SMOS (Polcher et al., 2015).“ This sentence states clearer that this work complements earlier work. Please use this clarity in a sentence in the introduction as well. I am sorry, I stopped at the EOF analyses, since it became too unstructured for me to understand. Please restructure first.

1 The “Introduction” section contains the following phrases: “The main objective of this paper  
2 is to extend the analysis of these discrepancies by comparing brightness temperatures  
3 measured by SMOS (Level 1C, L1C, product) with modelled ones obtained from the coupling  
4 of ORCHIDEE’s state variables and a RTM. In addition, a second set of modelled TBs using  
5 state variables from the Hydrology – Tiled ECMWF Scheme for Surface Exchanges over  
6 Land (HTESSEL), is included in the comparison.” They appear after the results of Polcher et  
7 al. (2015) are discussed (page 13023, lines 9 to 14). This is also reminded at the beginning of  
8 the “Results” section (page 13030, lines 8 to 12). We will rewrite this text to make it clearer.

9 The text at the beginning of the “Results” section explaining the reason why this study has  
10 been carried out, has been rewritten as “This study follows the comparison between modelled  
11 and retrieved SSM (Polcher et al., 2015) and attempts to elucidate if the difference found can  
12 be attributed either to the retrieval algorithm, which converts TBs into estimated SSM, or its  
13 modelled counterpart.”.

14 We would like to end this document by thanking you for the comments made about the  
15 manuscript. However, we are sorry that you could not provide us with your comments up to  
16 the end of the manuscript as they are pertinent and help us clarify our discourse. We hope you  
17 will see a clear improvement in the presentation of the results in the revised version of the  
18 manuscript.

19 Yours sincerely,

20 Anaïs Barella-Ortiz

21  
22 ***Referee 2: Anonymous***

23 Dear Referee,

24 Below you will find the answers to the overall and minor comments you made about the  
25 manuscript titled “Comparison of measured brightness temperatures from SMOS with  
26 modelled ones from ORCHIDEE and H-TESEL over the Iberian Peninsula” by A. Barella-  
27 Ortiz, J. Polcher, P. de Rosnay, M. Piles, and E. Gelati.

28  
29 **OVERALL COMMENTS**

1 1. The description of the methods and the results is fragmented. For example, a mixed  
2 introduction of ORCHIDEE and HTESSEL confused me on what configuration  
3 exactly used for each LSM? And the discussion of temporal and spatial correlation are  
4 not clearly separated and most of time mixed, which hinders the understanding of their  
5 studies.

- 6 • Section 2.2.2 does not aim at describing the LSMs, but at showing that each one of  
7 them deals with the hydrological scheme and surface and soil temperatures in different  
8 ways. This is key to discard the LSMs as the main source of the TB error in the  
9 discussion. The information given in this section is supported by Table 1 (page  
10 13053), which, in our opinion, clarifies the configuration of each set of modelled TBs.  
11 However, we propose to change the way this information is given to clarify our  
12 approach. In particular, we propose to divide the “Data and methods” section into two:  
13 “Data” and “Methods”. We would like to point out that we also propose to modify the  
14 structure of the other sections to clarify the way information is given in the  
15 manuscript:

16 [See the manuscript's structure in the “General comments to both referees”.](#)

- 17 • We will explain the reason why the spatial and temporal correlations appear in several  
18 sub-sections of the “Results” section.

19 First, these correlations between measured and modelled brightness temperatures are  
20 exposed in section 3.1 (page 13030). In this section, the first four paragraphs  
21 correspond to the temporal correlation and the other three to the spatial correlation.  
22 We believe that it is well structured. Nevertheless, to ease comprehension, we propose  
23 to divide this section into two sub-sections without numbering: i) temporal correlation  
24 and ii) spatial correlation.

25 Second, the results obtained for the temporal and spatial correlations are discussed  
26 after the EOF analysis of the TB error is exposed in section 3.2.1 (page 13034, lines  
27 20 to 28). This text relates the seasonality observed in the dominant mode of the TB  
28 error (EOF analysis) to the one of the spatial correlation time series (Figure 2).  
29 Therefore, it links the inconsistency found between the spatial structures of measured  
30 and modelled TBs and their annual cycle. We also highlight that while temporal  
31 correlation (Figure 1) is driven by the TB's fast varying component (its quick response

to precipitation), spatial correlation is dominated by the slow varying component (the annual cycle): this explains the apparent discrepancy between the relatively larger temporal correlation values and smaller spatial ones. The same conclusion is reached by Polcher et al. (2015) comparing remotely sensed and modelled surface soil moisture.

Third, further TB temporal and spatial correlations are computed (section 3.2.2) by varying the CMEM configuration (Table 1). The aim of this analysis is to study if the spatial inconsistency found between measured and modelled TBs could be due to assumptions made in the CMEM model. The values obtained for these correlations are compared to those obtained for the original sets of modelled TBs. To clarify the comparison, the text refers to Table 4. To improve the readability of section 3.2.2, we propose to divide it into two: i) 3.2.2 “LST and precipitation errors” and ii) 3.2.3 “Analysis of CMEM assumptions”.

Finally, the spatial correlation is also mentioned in section 3.3. It is done after identifying a systematic bias between measured and modelled data during the Winter season. This is related to the previous paragraphs, where we illustrate the spatial inconsistency between measured and modelled TBs due to their annual cycle.

We would like to note that the temporal and spatial correlation of TBs are also listed in Table 4 (page 13056).

2. The discussion on the precipitation and LST errors is wired to me. First of all, the E-OBS precipitation and LAND-SAF LST were not used in CMEM to derive TBs. However, they were used as the reference to derive the errors of precipitation and LST from ECMWF reanalysis data (e.g. forcing data for LSMs). And, then, the authors try to link such analyzed errors to the TB errors? It seems to me a major flaw in the concept of their studies on this topic.

- Brightness temperatures are defined as the product between the emissivity of the surface and its physical temperature (page 13021, lines 27 to 28). On the one hand, temperature is driven by the thermodynamics of the surface. Land Surface Temperature (LST) is an independent variable which allows us to verify if the thermodynamics of the models shows biases with spatio-temporal characteristics similar to those found for TB. On the other hand, the emissivity is driven by the

hydrological cycle at the surface. It is influenced by soil moisture, which is directly correlated with precipitation and thus, the verification of this forcing variable of the LSMs with independent data is essential.

- We do not believe that this is a flaw in the concept of the study. We have chosen to validate the two variables which are the prime driver of TB and for which independent observations exist. This allows to exclude the hypothesis that biases in the models (either originating from the forcing data or produced internally) are responsible of the errors found when comparing modelled TB with observed TB.

And i am not surprised that they cannot find the controlling factors for the TB errors over IP.

- We would like to note that the work exposed in the manuscript is not limited to studying only the forcing as the origin of this inconsistency. Certain assumptions made in the CMEM are analysed but are discarded too, as explained in page 13038. Nevertheless, we believe that further research has to be done following this line to find the main cause for the spatial differences between measured and modelled TBs. This is discussed in section 4 (from page 13044, line 17 to page 13045, line 12). LSMs are not likely to explain the TB errors found, because ORCHIDEE and H-TESSEL deal with the soil moisture and the soil temperature in different ways, but both sets of modelled TBs show a similar spatial pattern and temporal evolution of the dominant TB error mode (page 13037, lines 19 to 27). This is the reason why we highlighted the differences between the two LSMs in section 2.2.2.

I stopped further commenting this manuscript due to the perception of a wrongly conducted studies, as indicated from the above comments. Nevertheless, I do also provide the minor comments in the attached PDF

- On the one hand, we would like to thank you for providing both the overall and the minor comments. On the other hand, we hope that after the responses to the previous points you agree with our approach to discard the forcing as the main source of the inconsistency in the TB error. It should be noted that this analysis corresponds to a subsection of the “Results” section and, as explained in the previous point, other analyses were carried out. Therefore, we regret that you stopped commenting the

manuscript and would be very grateful if you could provide more insight about the other analyses presented herein.

### DETAILED COMMENTS

#### Page 13021

##### 1. Lines 11 – 18

It is not pretended to attribute the control of soil water flow to pedo-transfer functions. The text refers to them as one way in which the interaction between soil and water is approached. As for the last phrase, we refer to the soil moisture because it is the variable we are interested about in this study. In our opinion the text expresses clearly that soil moisture is interpreted in different ways depending on the hydrological scheme that a LSM considers.

#### Page 13022

##### 2. Lines 6 - 11

We propose to replace the text by the following: “ Therefore, we will refer to Surface Soil Moisture (SSM) instead of soil moisture. Some studies, like Escorihuela et al. (2010) lower the penetration depth to 1–2 cm. However, it should be highlighted that information from thicker layers can also be retrieved due to the action of roots.”

The text has been rephrased to “Therefore, we will refer to Surface Soil Moisture (SSM) instead of soil moisture. Some studies, like Escorihuela et al. (2010) lower the penetration depth to 1–2 cm.”.

#### Page 13026

##### 3. Lines 2 - 5

This corresponds to the way the CMEM model was development. We did not participate in it, but used it to model brightness temperatures. To know more details about this, we refer to literature [de Rosnay et al. (2009), Drusch et al. (2001)]. In addition, the manuscript provides the ECMWF's website about the CMEM.

##### 4. Lines 2 – 7

We would like to thank the author for providing us this reference. The modelled set TB<sub>HT</sub> was provided by the ECMWF.

##### 5. Line 10



This information is given in Table 1 (page 13053).

## 6. Line 19

A similar comment was made by the other referee. The same reply to its comment is given: The main objective of this section is not the description of models, but the difference in their hydrological scheme, as well as in their estimation of land surface and soil temperature. This is key because these differences allow to discard LSMs as the main cause of the spatial inconsistency between measured and modelled TBs. The title of the section may, however, not be clear enough and thus, we propose to change it to “Differences between LSM hydrological schemes and temperature estimation“. As exposed in the response to the other referee's “overall comments”, we propose to change this section to section 2.2.1 (Input data from Land Surface Models) where both LSMs will be briefly introduced. It will include a subsection without numbering (Differences between LSM hydrological schemes and temperature estimation), where the differences will be explained.

See the comment from the “General comments to both referees”.

## 7. Line 27

We agree with the referee's proposal.

The 11-layer depths of ORCHIDEE's hydrological scheme are given in Table 1, together to the depths of H-TESEL's hydrological scheme.

## Page 13027

## 8. Line 14

ORCHIDEE's hydrological scheme is based on the model of the Centre for Water Resources Research (CWRR). In line 14 we refer to the CWRR model, not to ORCHIDEE.

To clarify the text, “CWRR” has been replaced by the term “multilayer scheme”.

## Page 13028

## 9. Lines 4 - 6

In our opinion the layering information corresponding to ORCHIDEE's soil temperature is not relevant to the study. The reason being that ORCHIDEE's temperature profile was calculated following the same 11 layer soil discretization as the one from the soil moisture profile (page

1 13028, lines 6 to 7). However, we propose to include a reference to (Hourdin, 1992) where  
2 this information can be found.

3 The references of Hourdin (1992) and Wang et al. (2016) have been included.

4 **10. Line 26**

5 We propose to divide the “Data and Methods” section into two. The way the correlation was  
6 computed can be detailed in the new “Methods” section.

7 A sub-section 3.2.1 called “Spatio-temporal correlation” has been added. In it, the method  
8 used to perform this diagnostic is given and its computation is explained.

9 **11. Line 27**

10  $TB_{SM}$  is how measured TB from SMOS (L1C product) is referred to in the manuscript (page  
11 13025, lines 2 to 3).

12 **Page 13029**

13 **12. Line 9**

14 To sample modelled data using H-TESSEL's state variables ( $TB_{HT}$ ), TB data from i)  $TB_{SM}$   
15 and ii)  $TB_{HT}$  were averaged considering a 3 hour window. Next,  $TB_{HT}$  were sampled with  
16  $TB_{SM}$ .

17 **Page 13030**

18 **13. Lines 22 – 24**

19 In section 3.1 we perform a temporal and spatial correlation analysis to compare the temporal  
20 evolution and spatial structures of measured and modelled TBs. The text from the manuscript  
21 highlighted in your comment gives two reasons why we expected high values for the mean  
22 annual temporal correlations between these TBs: i) quick response to precipitation and, at a  
23 lesser extent, ii) strong annual cycle of surface temperature. In our opinion the text does not  
24 identify the surface temperature's annual cycle as the main controlling factor of TB  
25 calculation. In fact, further on in the same section we refer to the comparison between  
26 retrieved and modelled surface soil moisture (Polcher et al., 2015) (page 13031, lines 20 to  
27 24) that shows that temporal correlation measure between remotely sensed, in-situ, and  
28 modelled SSM, is mainly driven by the high frequency behaviour of SSM. Therefore, this  
29 diagnostic is not very sensitive to the slower variations of the field studied. We believe that

1 this is also the reason why the temporal correlation between measured and modelled TBs is  
2 high.

3 **Page 13031**

4 14. Lines 20 – 23

5 As mentioned in the previous point, Polcher et al. (2015) proves that the temporal correlation  
6 between remotely sensed, in-situ, and modelled SSM, is mainly driven by the high frequency  
7 behaviour of surface soil moisture. Therefore, this kind of analysis will not diagnose in a  
8 reliable way the soil moisture dynamics relative to the low frequency behaviour of surface  
9 soil moisture. That includes its annual cycle.

10 15. Line 24

11 This comment is analogous to number 10:

12 We propose to divide the “Data and Methods” section into two. The way the correlation was  
13 computed can be detailed in the new “Methods” section.

14 **Page 13032**

15 16. Lines 13 – 14

16 We have performed two different correlation analyses: temporal and spatial. Each one is  
17 computed in a different way and thus, a good agreement in temporal correlation does not  
18 imply that there will be a good agreement in spatial correlation.

19 On the one hand, Figure 1 shows that the mean annual temporal correlation between  
20 measured and modelled TBs is high. In our opinion this is due mainly to the measure of the  
21 correlation which is more responsive to the high frequency behaviour of temperature (quick  
22 response to precipitation) than to its low frequency behaviour (Polcher et al., 2015). On the  
23 other hand, Figure 2 shows poor spatial correlation values. So, even though there is a good  
24 agreement in the temporal evolution of measured and modelled TBs, their spatial structures  
25 are not consistent between them. Figure 2 also identifies a marked seasonality in the temporal  
26 evolution of the spatial correlation. This implies that the inconsistency in spatial structures  
27 may be related to the slow variation of TBs, and thus their annual cycle. Analysing Figures 1  
28 and 2, the temporal correlation is mainly driven by the high frequency behaviour of TBs,  
29 while the temporal evolution of the spatial correlation is more influenced by their low  
30 frequency behaviour.

**Page 13033**

**17. Line 12**

We propose to divide the “Data and Methods” section into two. The description of the EOF analysis will be moved to the new “Methods” section.

A sub-section 3.2.1 called “Empirical Orthogonal Analysis” has been added. The methodology is briefly explained and literature about it is given.

**Page 13034**

**18. Lines 14 – 15**

This comment is related to the previous one. The description of the EOF will be moved to the new “Methods” section.

**19. Lines 24 – 25**

By means of the EOF analysis of the TB error, section 3.2.1 states that the temporal evolution of its main dominant pattern evolves slowly throughout the year. This coincides with the seasonality shown in Figure 2. Therefore, the dominant mode of variability of the TB error is driven by the slow varying component of the TB signal and not its fast varying component (as the temporal correlation). We propose to change the phrase to “This is contrary to the temporal correlation analysis, which we believe is driven by their synoptic variability as occurs with surface soil moisture (Polcher et al., 2015).”

The “Results” section has been restructured and thus, rewritten. The phrase highlighted in your comment has been deleted because it could lead to misunderstandings.

**Page 13035**

**20. Lines 4 – 5**

We are not sure of having understood your comment. ECMWF mean first guess departure is “the time averaged geographical mean of the difference between measured (SMOS) and modelled (H-TESEL and CMEM) TBs” (page 13035, lines 5 to 7). In our opinion it is relevant to include this figure because it allows us to confirm the results shown by the EOF analysis of the TB error.

**21. Lines 19 – 22**

The “Results” section (3) contains 3 subsections

3.1 The temporal and spatial correlation between measured and modelled TBs are exposed.

3.2 An EOF analysis of the TB error (the difference between modelled and measured TBs) is exposed.

3.3 The TB's annual cycle is analysed.

One of the results obtained in section 3.1 is that there is a poor spatial correlation between measured and modelled TBs. Therefore the spatial structures from these TBs are not consistent between them.

To understand why this happens, we decided to study the error between TBs using the EOF methodology. As explained in the EOF description, this methodology allows to identify the dominant spatial and temporal modes of variability of a field. In this case the field is the TB error, not the TB itself. Therefore, the results shown in this subsection are referred to the EOF analysis of the TB error. We do not deal with correlations, but with the spatial pattern of the dominant mode of variability of the TB error and with its temporal evolution (the expansion coefficients).

We have identified a dominant spatial structure of this error and we have also shown that this structure evolves during the year, being dominated by the slow varying component of the TB signal, given by its annual cycle. It should be noted that this can explain the behaviour shown in section 3.1 regarding the temporal and spatial correlation:

- The fact that the measure of the temporal correlation is driven by the TB's high frequency behaviour and does not provide reliable information of the annual cycle. Otherwise, the temporal correlation would have shown lower values than the ones observed in Figure 1.
- The marked seasonality shown in the poor spatial correlation (Figure 2).

To clarify the results presentation, we have rewritten the “Results” section. In particular, the section 4.2.1 “TB error” has been divided into two subsections: “Spatial patterns” and “Expansion coefficients”.

**Page 13036**

**22. Lines 18 – 22**

This is explained in the overall comments (point 2).

1

2 We would like to end this document by thanking you for the comments made about the  
3 manuscript.

4 Yours faithfully,

5 Anaïs Barella-Ortiz

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# Comparison of measured brightness temperatures from SMOS with modelled ones from ORCHIDEE and H-TESSEL over the Iberian Peninsula

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## Abstract

L-Band radiometry is considered to be one of the most suitable techniques to estimate Surface Soil Moisture (SSM) by means of remote sensing. Brightness temperatures are key in this process, as they are the main input in the retrieval algorithm which yields SSM estimates. The work exposed compares brightness temperatures measured by the SMOS mission to two different sets of modelled ones, over the Iberian Peninsula from 2010 to 2012. The latter were estimated using a radiative transfer model and state variables from two land surface models: i) **ORCHIDEE** and ii) **H-TESSEL**. The radiative transfer model used is the **CMEM**.

**Measured and modelled brightness temperatures show a good agreement in their temporal evolution, but their spatial structures are not consistent.** An Empirical Orthogonal Function analysis of the brightness temperature's error identifies a dominant structure over the South-West of the Iberian Peninsula which evolves during the year and is maximum in fall and winter. Hypotheses concerning forcing induced biases and assumptions made in the radiative

transfer model are analysed to explain this inconsistency, but no candidate is found to be responsible for the weak spatial correlations at the moment. Further hypotheses are proposed and will be explored in a forthcoming paper.

## **1 Introduction**

The United Nations (UN), the Food and Agriculture Organization (FAO), and the World Health Organization (WHO), have reported that water resources are not being managed in an optimum way **at present**. As a result, scarcity, hygiene and pollution issues related to improper water policies are detected. In addition, the world's population is expected to grow by 2 to 3 billion people over the next 40 years according to the UN's World Water Development Report from 2012 **(WWAP, 2012)**. This will lead to a significant increase in freshwater demand which will likely be affected by the effect of a changing climate.

To achieve a better management of water resources, it is necessary to improve our understanding of hydrological processes. In order to do this, the study of Soil Moisture (SM) is essential. It is defined as the water content in the soil and has a key role on the soil-atmosphere interface. SM determines whether evaporation over land surfaces occurs at a potential rate (controlled by atmospheric conditions) or if it is limited by the available moisture (Milly, 1992). In addition, it influences several processes, like infiltration and surface temperature, which have an important effect on plant growth and the general state of the continental surfaces. However, SM is a complex variable to model as the interactions between soils and water are not simple to represent. Its definition requires knowledge of soil hydraulic properties, which are not often available as direct measurements. Pedo-transfer functions (Marthews et al., 2014), allow to estimate hydrodynamic characteristics of the soil from available soil texture and structure information. However, the suitability of these functions is under debate (Baroni et al., 2008), as their performance depends on several factors like the climate, geology, and the measurement techniques used. Furthermore, different hydrological schemes are found in Land Surface Models (LSM), leading to various ways of understanding and formulating soil moisture.

Remotely sensed soil moisture products have brought about new ways to perform data retrieval, adding new observations to data assimilation chains. The optimal combination of these products with modelled ones is expected to provide **better** estimates of the true soil moisture state. Remote sensing allows to estimate SM by means of retrieval algorithms, like inversion algorithms (Kerr et al., 2012) or neural networks (Kolassa et al., 2013). Their main



1 input depends on the type of sensor used. This is, backscattering for an active sensor and  
2 Brightness Temperature (TB) for a passive sensor. TB corresponds to the radiance emitted by  
3 the Earth at a given wavelength and is the magnitude measured by a radiometer. It is defined  
4 as the physical temperature times the emissivity of the surface.

5 L-Band radiometry is one of the best methods to estimate soil moisture, due to the relation  
6 between SM and the soil dielectric constant ( $\epsilon$ ) in this wavelength. The latter differs  
7 significantly between a dry soil and water (4 vs. 80, respectively) and this difference is key to  
8 estimate the soil water content. It should be noted that the retrieved SM corresponds to the  
9 water contained in the first centimetres of the soil. The penetration depth in averaged  
10 conditions is about 5 cm (Kerr et al., 2010). Therefore, we will refer to Surface Soil Moisture  
11 (SSM) instead of soil moisture. Some studies, like Escorihuela et al. (2010) lower the  
12 penetration depth to 1–2 cm.

13 In the last decade, three space missions have been launched with L-Band radiometers on-  
14 board: the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2010), the  
15 Aquarius/SAC-D mission (Le Vine et al., 2010), and the Soil Moisture Active and Passive  
16 (SMAP) mission (Entekhabi et al., 2010).

17 A large number of validation studies of remotely sensed SSM products have been carried out  
18 (Albergel et al., 2011; Sánchez et al., 2012; Bircher et al., 2013). These studies are usually  
19 performed using airborne and or ground-observed data over a well equipped site. Other  
20 studies, like the one described in González-Zamora et al. (2015), validate SMOS SSM  
21 products using in situ soil moisture measurement networks, which allow to extend the study  
22 period to annual and inter-annual scales. Several studies have been performed to validate  
23 brightness temperatures too (Rüdiger et al., 2011; Montzka et al. 2013). In Bircher et al.  
24 (2013) TBs are also validated with network and airborne data over a SMOS pixel in the  
25 Skjern river Catchment (Denmark). LSMs coupled to Radiative Transfer Models (RTMs) can  
26 contribute to the analysis and validation of passive Microwave (MW) data. Models permit  
27 extending the validation to a longer period of time and perform an extensive analysis of  
28 observed and retrieved data, as shown in Schlenz et al. (2012). In this study, they compare  
29 TBs and vegetation optical depth from SMOS with modelled ones obtained from a LSM  
30 coupled to a radiative transfer model, over a period of seven months in 2011 in the Vils test  
31 site (Germany). Comparing modelled with satellite-measured brightness temperatures can  
32 help to better understand inconsistencies between retrieved and modelled data. It provides

information regarding the origin of their differences, and whether they are due to the retrieval algorithm or to issues related to the modelling process.

Polcher et al. (2015) present the first comparison of the spatial patterns of Level 2 (L2) SMOS product corresponding to retrieved SSM, with SSM modelled by the ORganising Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE) LSM (de Rosnay and Polcher, 1998; Krinner et al., 2005) over the Iberian Peninsula (IP) from 2010 to 2012. They have identified inconsistencies between the spatial structures of retrieved and modelled SSM. The main objective of the work presented herein is to extend the analysis of this inconsistency by comparing brightness temperatures measured by SMOS (Level 1C, L1C, product) with modelled ones obtained from the coupling of ORCHIDEE's state variables and a RTM. In addition, a second set of modelled TBs using state variables from the Hydrology – Tiled ECMWF Scheme for Surface Exchanges over Land (H-TESSEL), is included in the comparison. The RTM used is the Community Microwave Emission Model (CMEM) [de Rosnay et al., 2009], developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The comparison is performed over the same period and region as the study carried out by Polcher et al. (2015). The IP is an excellent test case for remote sensing of SSM, as its two characteristic climate regimes (oceanic and Mediterranean) result in a strong contrast in soil water content. Furthermore, SSM is a critical variable regarding water resources especially in the IP, which makes this study even more necessary.

The data from SMOS and the LSMs used in this paper will be presented in the next section. Next, a methodology section will follow, describing the data filtering and sampling processes carried out, together with the analysis performed to compare TBs. Afterwards, results will be presented. First, modelled and measured TBs will be compared. Secondly, their error will be characterised spatially and temporally and certain hypotheses to explain the differences found in the TB comparison will be analysed. Finally, we will study the amplitude of the annual cycle of the TB signals. The paper will end with discussion and conclusion sections.

## **2 Data**

### **2.1 SMOS retrievals of TB**

The SMOS mission is the second Earth Explorer Opportunity mission from the European Spatial Agency (ESA). The SMOS satellite was launched on November 2nd, 2009. One of its

main objectives is to provide surface soil moisture over land with a target accuracy of 0.04 m<sup>3</sup>m<sup>-3</sup>.

As previously said, TBs are the main input of SMOS's soil moisture retrieval algorithm. L-band brightness temperatures are measured by the SMOS radiometer at different incidence angles (from 0 to 65°) and polarizations (H, V, HV). The retrieval algorithm also models TBs using the state-of-the-art L-band Microwave Emission of the Biosphere (L-MEB) forward model (Wigneron et al., 2007) with some modifications. These brightness temperatures are then used to retrieve SSM using an inversion algorithm based on an iterative approach. Its objective is to minimize the sum of the squared weighted differences between measured and modelled TBs for all available incidence angles. Details about the retrieval algorithm are provided in Kerr et al. (2012).

The SMOS L1C v5.05 product over the 10W : 5W to 45N : 35N region was selected and SMOS TBs at the antenna reference plane were derived: TBs are first screened out for Radio-Frequency Interferences (RFIs) (strong, point source and tails), and also for Sun (glint area, aliases and tails), and Moon (aliases) contamination, using the corresponding flags. Ionospheric effects (geometric and Faraday rotations) are later corrected to obtain TB at the Top Of the Atmosphere (TOA). TB maps at a constant incidence angle of 42.5±5° are obtained through chi squared linear fit of all values included in the interval 42.5±5°, which is the methodology used to generate the SMOS L1C browse product (McMullan et al., 2008). Finally, these maps are resampled from the Icosahedral Snyder Equal Area (ISEA) 4H9 grid to a 0.25° regular latitude-longitude grid, to facilitate its manipulation.

The L1C product containing horizontally and vertically polarized brightness temperatures, was provided by the SMOS Barcelona Expert Center. From now on, this product will be referred to as TB<sub>SM</sub>.

## **2.2 Modelled TB: CMEM**

The Community Microwave Emission Modelling (CMEM) Platform, (<https://software.ecmwf.int/wiki/display/LDAS/CMEM>) developed at ECMWF, is a forward operator for low frequency passive MW brightness temperatures of the surface. Its physics is based on that of the L-MEB forward model and the Land Surface Microwave Emission Model (LSMEM) [Drusch et al., 2001]. CMEM is characterized by its modular structure, which allows the user to choose among different physical configurations to compute TB's key

parameters. Polarized brightness temperatures provided at TOA result from the contribution of three dielectric layers: atmosphere, soil and vegetation. Snow, also considered, is characterized as a single additional homogeneous layer.

The two sets of modelled TBs used in this study were estimated by means of the CMEM provided with state variables from i) ORCHIDEE, and ii) H-TESSEL simulations. From now on we will refer to these sets as TB<sub>OR</sub> and TB<sub>HT</sub>, respectively. TB<sub>OR</sub> was computed specifically for this study, while TB<sub>HT</sub> was provided by the ECMWF to widen the comparison between measured and modelled data. The CMEM configuration used to compute each set of TB is listed in Table 1. The table is divided into three configuration categories: physical, observing, and soil and atmospheric levels. Even though both sets have similar configurations, there are some differences which are explained below.

First, the “Physical configuration” of TB<sub>OR</sub> was selected to be as similar as possible to TB<sub>HT</sub>. However, they differ in the parameterization used to compute the smooth surface emissivity ( $\epsilon_s$ ). For TB<sub>HT</sub> the reflectivity of the flat soil surface was computed following the Fresnel law (Ulaby et al., 1986), so it is expressed as a function of the soil dielectric constant and the observation incidence angle. This formulation considers the emission at the soil interface. As it is simple and affordable in computing time it is commonly used for microwave emission modelling and soil moisture retrieval, as well as for operational applications (e.g. Wigneron et al., 2007, de Rosnay et al., 2009). It assumes an a priori soil moisture sampling depth, which in this study corresponds to the first soil layer of the land surface model (7cm for H-TESSEL). For TB<sub>OR</sub>, the multilayered soil hydrology of ORCHIDEE allows to take into account the soil moisture profile and the resulting volume scattering effects on the soil emission. Therefore the reflectivity of the flat soil surface was computed using the parameterization proposed by Wilheit (1978). The different parameterizations chosen to calculate  $\epsilon_s$  lead to another variation between the CMEM configurations. If  $\epsilon_s$  is computed using Wilheit (1978), the soil temperature profile is used to compute the Effective Temperature ( $T_{eff}$ ). On the contrary, if the Fresnel law is used, the user can choose among different parameterizations to compute  $T_{eff}$ . For TB<sub>HT</sub>, Wigneron et al. (2001) was selected.

Second, the “Observing configuration” considers different incidence angles for each set. Although the available TB<sub>HT</sub> were modelled considering an angle of 40°, 42.5° was used to model TB<sub>OR</sub>, because measured TBs were provided at this angle.

Third, a different number of soil layers was defined for the “Soil and atmospheric level configuration”: 11 ( $TB_{OR}$ ) and 3 ( $TB_{HT}$ ). ORCHIDEE's soil discretization is finer. For instance, its first layer's depth is of the order of millimetres, while H-TESSEL's is of centimetres. In order to evaluate the role of these differences in the vertical discretization and the LSMs, we performed a sensitivity analysis as detailed in the next paragraph.

In addition to the CMEM simulations performed to model  $TB_{OR}$  and  $TB_{HT}$  using the configurations indicated in Table 1, the following simulations were carried out to test if parameterization assumptions could affect the resulting TBs:

- Simulation 1:  $TB_{HT(VC)}$ , where the subscript “VC” stands for “Vegetation Cover”.

Vegetation cover is a key input. Since this parameter is directly related to land-surface emissivity, the effects of a different vegetation cover were tested on  $TB_{HT}$ . For this matter, a new set of TBs was modelled using H-TESSEL's state variables with the same configuration as detailed in Table 1, except for the vegetation cover input, where H-TESSEL's prescribed vegetation (Boussetta et al., 2013) was considered. One of the differences between this input and the ECOCLIMAP database (used in the original configuration), is that the former consists of 20 vegetation types, while the latter considers 7.

- Simulation 2:  $TB_{OR(SD)}$ , where the subscript “SD” stands for “Soil Discretization”,

The impact of a coarser soil discretization on modelled TBs was tested by recomputing  $TB_{OR}$  using ORCHIDEE's state variables averaged to 3 soil layers: upper (9 cm), medium (66 cm), and lower (125 cm).

- Simulation 3:  $TB_{OR(FW)}$ , where the subscript “FW” stands for “Fresnel Wigneron”.

We tested the combined effect of using the Fresnel law to compute  $\epsilon_s$ , rather than the parameterization proposed by Wilheit (1978), and calculating  $T_{eff}$  using the methodology proposed by Wigneron (2001) instead of the soil temperature profile. For this, TBs were simulated using ORCHIDEE's state variables.

The input variables required by the CMEM to model TBs are summarized in Table 2. They are classified into dynamic and constant fields and consist of meteorological data, vegetation characteristics and soil conditions.

## 2.2.1 The ORCHIDEE and H-TESEL Land Surface Models

The ORCHIDEE LSM (de Rosnay and Polcher, 1998; Krinner et al., 2005) was developed by the Institut Pierre – Simon Laplace (IPSL). It can be run coupled with the general circulation model LMDZ, which was developed by the Laboratoire de Météorologie Dynamique (LMD), or in stand-alone mode. Uncoupled simulations were carried out for this study.

The hydrological scheme used by ORCHIDEE approaches hydrology through the resolution of a diffusive equation with a **multilayer scheme**. For this, the Fokker-Planck equation is solved over a soil 2 m deep with an 11 layer discretization. The layers' depths are informed in Table 1. The lower boundary condition is free drainage, under the hypothesis that the water content gradient between the last modelled layer and the next one (not modelled) is zero. The upper boundary condition sets the bare soil evaporation as the maximum upward hydrological flux which is permitted by diffusion if it is lower than potential evaporation

The **multilayer scheme** considers a sub-grid variability of soil moisture, which together with the fine soil discretization improves the representation of infiltration processes. The soil infiltration follows the Green-Ampt equation (Green and Ampt, 1911) to represent the evolution in time of the wetting front through the soil layers. It should be noted that partial re-infiltration occurs from surface runoff if the local slope of the grid-cell is  $\leq 0.5\%$  (D'Orgeval et al., 2008). Each grid box has a unique soil texture and structure (Post and Zobler, 2000), but three different soil columns are considered, each one with its own soil moisture discretization and root profile. These are classified as: bare soil, low and high vegetation regrouping the 13 Plant Functional Types (PFT) defined in ORCHIDEE. These PFTs contribute to the soil layers of each grouping a root density to compute extraction and soil moisture stress to the plants. The water balance is solved for each soil column resulting in three different soil moisture profiles in each grid box.

ORCHIDEE's soil temperature profile is calculated solving the heat diffusion equation. Contrary to the hydrological scheme, it considers a 7 layer discretization, where the layers' thicknesses follow a geometric series of ratio 2, and a total soil depth of 5.5 m (Hourdin, 1992; Wang et al., 2016). For this study, the first 2 m of the temperature profile were calculated following the same soil discretization as the one considered in the soil moisture calculation. The energy balance takes into account the skin temperature as presented in Schulz et al. (2001) to derive the Land Surface Temperature (LST). The soil and vegetation are considered as a single medium assigned with a surface temperature (Santaren et al., 2007).

1 The H-TESSSEL LSM (Balsamo et al., 2009), developed by the ECMWF, revises and  
2 improves certain aspects regarding the soil hydrology of the TESSEL model. Its hydrology  
3 scheme solves a diffusive equation over a multilayer scheme with a 4 layer discretization.  
4 Layer depths follow an approximate geometric relation (Table 1). In addition, the soil can be  
5 covered by a single snow layer. H-TESSSEL considers the same lower boundary condition as  
6 ORCHIDEE. However, it differs in the upper one that accounts also for infiltration. It defines  
7 a maximum infiltration rate given by the maximum downward diffusion from the saturated  
8 surface. Once this rate is exceeded by the water flux at the surface, the excess of water is  
9 derived to surface runoff.

10 The model considers six types of tiles over land: bare soil, low and high vegetation, water  
11 intercepted by leaves, as well as shaded and exposed snow. Each one of these has its own  
12 energy and water balance. However, only one soil moisture reservoir is considered. Recent  
13 improvements have replaced a globally uniform soil type (loamy) by a spatially varying one  
14 (coarse, medium, medium-fine, fine, very fine, organic). Surface runoff, based on variable  
15 infiltration capacity, was also a recent improvement.

16 H-TESSSEL's soil temperature profile is computed using the same soil discretization as the one  
17 defined in its hydrological scheme. The soil heat budget follows a Fourier diffusion law,  
18 which has been modified to consider also thermal effects caused by changes in the soil water  
19 phases (Holmes et al., 2012). To simulate the LST, a skin layer is defined representing i) the  
20 layer of vegetation, ii) the top layer of bare soil, or iii) the top layer of the snow pack. The  
21 surface energy balance equation is then linearised for each tile (Viterbo and Beljaars, 1995).

22 Both LSMs are forced with the ERA-Interim forcing (Dee et al. 2011), which is suitable for  
23 this study because it ranges from 1979 to 2012 and recent data were needed to perform the  
24 comparison with SMOS's. We are aware that biases in this kind of forcings have an effect on  
25 the LSMs simulations (Ngo-Duc et al., 2005). ORCHIDEE was configured to output hourly  
26 TB values. However,  $TB_{HT}$  is only available at 6 hourly time steps (at 00, 06, 12, and 18  
27 hours). Due to this difference, each set of modelled TBs was sampled in a different way to  
28 approximate  $TB_{SM}$  measurement times. The sampling processes will be explained in Section  
29 3.

30 The above paragraphs show that the hydrology, soil processes and land surface temperatures  
31 are approached very differently by both models. Therefore, the impact of these differences  
32 needs to be considered when comparing simulated TBs.

## **2.3 Precipitation and Land Surface Temperature**

One important common feature of the presented model simulations is the forcing data. Since biases in the imposed atmospheric conditions can affect modelled TBs, it was decided to validate two important variables for which independent observations exist. Focus was put on Precipitation (P) and the Land Surface Temperature (LST), as they are key variables for the water and radiative balances.

P is the main driver of SSM, and this directly drives the L-Band emissivity. According to Zollina et al. (2004), P generated by a reanalysis (like ERA-Interim which is used here) is highly model dependent and one of the less reliable forecast parameters since models do not represent accurately all the physical processes of the atmospheric water cycle. Therefore, the verification of this forcing variable of the LSMs with independent data is essential.

As for the radiative balance, the available energy at the surface is one of the major drivers of LST. We chose to verify this variable in this study for two reasons. First, it provides a good summary of the surface energy balance. Second, it is a key parameter in CMEM's estimation of TB. Therefore, its analysis will indicate whether the LSM thermodynamics shows biases with spatio-temporal characteristics similar to those from TBs.

The independent datasets used for validation are:

- P from the E-OBS dataset (Haylock et al., 2008),
- LST provided by the LandSAF product ([http:// landsaf.meteo.pt](http://landsaf.meteo.pt)).

## **3 Methods**

### **3.1 Data sampling and filtering processes**

To compare modelled and measured brightness temperatures,  $TB_{OR}$  and  $TB_{HT}$  were sampled with  $TB_{SM}$  and remapped to the nearest neighbour of the SMOS grid. This allows to keep the spatial structures of the coarse model resolution. Next, the three TB signals were filtered to exclude certain situations, such as frozen soils or RFIs, which are known to make SSM estimates unreliable.



### 3.1.1 Sampling

The objective of sampling the data is to use only modelled TBs corresponding to available measured values.  $TB_{OR}$  were sampled at an hourly scale. However,  $TB_{HT}$  consists of 6 hourly values, thus potentially resulting in a large number of neglected data because  $TB_{HT}$  and SMOS time steps did not always correspond. Therefore,  $TB_{HT}$  were sampled considering a 3 hour window around the observation in order to keep a larger number of modelled data for the comparison. To test the impact of this approximation, we also applied it to the  $TB_{OR}$  and compared it to the original hourly data. Differences between them were under 0.1% for the diagnostics used here, and thus, it was considered to be negligible.

### 3.1.2 Filtering

Data was filtered to discard unreasonable TB values from the comparison study. Filtering rules were devised following the ECMWF criteria used to screen  $TB_{HT}$  (Table 3). Common filters were also applied to measured and modelled TBs.

The filters applied in  $TB_{HT}$  corresponding to the water content in snow cover (snow water equivalent) and the criterion on ERA-Interim's 2 m air temperature aim to discard frozen soils, which might affect the SM retrieval (Dente et al., 2012). The same result was achieved by filtering  $TB_{OR}$  with the 2 m temperature from the forcing (as in the previous case) as well as with ORCHIDEE's average surface temperature. The first common criterion excludes TBs higher than 300 K to avoid effects of RFIs, which can result in overestimated brightness temperatures (higher than 1000K). The second common criterion aims at removing points which might be influenced by coastal or topographic effects, as does H-TESSEL's orography (slope) criterion too. The mask was built using the L2 SMOS product. Any pixel with no surface soil moisture data retrieved, together with the 24 pixels surrounding it, was excluded from the comparison.

## 3.2 Comparison analyses

### 3.2.1 Spatio-temporal correlation

The first diagnostic performed to compare measured and modelled TBs consisted in temporal and spatial correlation analyses. Our aim is to study the similarity between the spatio-temporal patterns. We used the Pearson product-moment correlation coefficient. Only values

1 statistically significant at the 95% level are considered. An averaging window of 5 days is  
2 applied for the spatial correlation analysis to ensure the highest coverage possible.

3 Even though the correlation coefficient is a widely used statistical tool, it may not be suitable  
4 when analysing certain fields. For instance, Polcher et al. (2015) showed that temporal  
5 correlation measured between remotely sensed, in-situ, and modelled SSM, is mainly driven  
6 by the high frequency behaviour of SSM. Therefore, this diagnostic is not very sensitive to  
7 the slower variations of the field studied. Performing the correlation analyses allowed us to  
8 study if this conclusion also applies to TBs.

### 9 **3.2.2 Empirical Orthogonal Function**

10 The Empirical Orthogonal Function (EOF) analysis extracts the dominant spatial and  
11 temporal modes of variability of a field. It relates the spatial patterns of each variation mode  
12 with a time series and its explained variance. We will refer to the time series of each variation  
13 mode as the Expansion Coefficients (ECs). They provide information about the spatial  
14 pattern's temporal evolution. Positive values of ECs imply that there is no sign change in the  
15 patterns. The EOF methodology is detailed in Björnsson and Venegas, (1997) for instance.

16 We apply the EOF analysis to the error between measured and modelled TBs, to characterize  
17 it spatially and temporally. Identifying the main modes of variability of an error field allows  
18 to propose and test hypotheses about its causes. We will follow this approach to analyse the  
19 impact of forcing biases on modelled TBs. Other studies have also applied this methodology  
20 to error analysis. For example, Kanamitsu et al. (2010) analyze the impact of a regional model  
21 error on the inter-annual variability of a set of analysis fields.

## 22 **4 Results**

23 The temporal evolution and spatial structures of measured and modelled TBs are analysed in  
24 this section. This study follows the comparison between modelled and retrieved SSM  
25 (Polcher et al., 2015) and attempts to elucidate if the difference found can be attributed either  
26 to the retrieval algorithm, which converts TBs into estimated SSM, or its modelled  
27 counterpart.

### 28 **4.1 Comparison of modelled and measured TBs**

29 The mean temporal and spatial correlations between measured and modelled TBs, over the IP  
30 from 2010 to 2012, are shown in Table 4. Values from the SSM comparison performed by

Polcher et al. (2015) are also included. The differences between spatial and temporal correlation are already apparent and warrant separate analyses as a first step.

#### 4.1.1 Temporal correlation

Fig. 1 shows the temporal correlation between measured and modelled daily TBs for the horizontal and vertical polarizations. Both polarizations show a good agreement between models and observations in their temporal evolution, with values above 0.7 over a large part of the IP. This can be explained by the strong annual cycle imposed by the surface temperature, but more important are the quick responses of temperature and emissivity to precipitation events, which drive TB's fast variations and correspond to the synoptic variability of the signal. The high correlations indicate that it is well captured by both models. Most of the areas with lower correlations correspond to mountain ranges. Relief effects on MW radiometry over land (Mätzler and Standley, 2000) are a difficult remote sensing problem and thus, discrepancies are expected. In fact, the lowest correlations (0.3 to 0.6) appear over some areas of the Pyrenees. Other examples are the Iberian System and the Cantabrian Mountains, located over the North-Eastern and the Northern regions of the peninsula, respectively.

There are no large differences between the temporal correlation maps of  $TB_{OR}$  and  $TB_{HT}$  with  $TB_{SM}$  (Fig. 1). Since the same forcing was used, the two LSMs share the same synoptic variability from the ERA-Interim reanalysis. However, Fig. 1 shows that the synoptic variability of H-TESSSEL leads to slightly higher correlation values than ORCHIDEE's, especially over the northern part of the IP.

#### 4.1.2 Spatial correlation

For clarity, the 5 daily spatial correlations are averaged per season and the distribution of values obtained is represented in a boxplot form in Fig. 2. In general, the correlation is poor throughout the year. Although maxima are around 0.6, the annual mean ranges between 0.2 and 0.3 (Table 4). This implies that the spatial structures from both modelled TBs are not consistent with those observed by SMOS. We would like to point out the seasonality in the correlation. The lowest correlations occur during winter, where even negative values are obtained. These improve during spring and summer, and weaken again in fall. Moreover, winter and fall generally show larger ranges of variability and thus, a wider dispersion of the data than spring and summer. Fig. 2 also shows that the vertical polarization has

systematically higher mean correlations than the horizontal one, except for the winter season. Finally, there is no significant difference in the correlation of  $TB_{SM}$  with either modelled TB as has already been noted for the temporal correlation.

## 4.2 Spatial and temporal characterization of the TB error

The spatio-temporal variability of the error between modelled and measured TBs is studied to better understand the poor consistency of their spatial structures. We want to analyse if this difference can be related to some physical process which might be incorrectly represented in both models. For this, an EOF analysis of the TB errors ( $TB_{OR} - TB_{SM}$  and  $TB_{HT} - TB_{SM}$ ) is carried out.

### 4.2.1 TB error

#### *Spatial patterns*

Fig. 3 shows the spatial patterns of the first two EOF variation modes correspondent to the TB error of ORCHIDEE ( $TB_{OR} - TB_{SM}$ ), for the horizontal and the vertical polarizations. The variance explained by each mode is also provided as a percentage in brackets. The total variance explained by the patterns of the first variation mode is above 30% in both polarizations: 36% (horizontal) and 31% (vertical). These two patterns show a similar structure characterised by high values over the South-West and a smaller area further North of the IP, which weaken as they extend through the rest of the peninsula. This similarity is confirmed by their high spatial correlation, which is 0.99 (Table 5). The second variation mode exhibits a structure that is also maximum over the South-West of the IP in both polarizations. However, the total variance explained is reduced to 6% and 7% (horizontal and vertical polarization, respectively).

Fig. 4 is equivalent to Fig. 3 but presents the TB error of H-TESSEL ( $TB_{HT} - TB_{SM}$ ). The variance fractions explained by the first EOF mode are 30% and 18% for the horizontal and vertical polarization, which are lower than those obtained for the TB error of ORCHIDEE. As in Fig. 3, the first variation modes show similar spatial structures, which are highly spatially correlated (0.86, Table 5). It is interesting to note that this structure coincides with the one identified for the TB error of ORCHIDEE (Fig. 3 a and c). This is confirmed by the high correlation obtained between the patterns of the two errors: 0.92 and 0.73 for the horizontal and vertical polarization, respectively (Table 5). The second variation mode of H-TESSEL's

TB error explains 8% (horizontal polarization) and 12% (vertical polarization). The horizontal polarization pattern shows that the error is maximum over the South-Western region of the IP, while the vertical polarization pattern does not show a clear structure. Contrary to the first variation mode, patterns from the second one show larger differences with the patterns depicted by the TB error of ORCHIDEE.

### *Expansion coefficients*

Fig. 5 shows the ECs of the first EOF variation mode of both TB errors. Therefore, the projection of the error time series on the EOF pattern, summarizing how much the error field varies according to the pattern.

The four series show a strong annual variation which peaks in fall. High values are also observed in December 2012 and during the winter 2010 - 2011. It should be noted that the behaviour of the ECs coincides with the marked seasonality shown in Fig. 2 and thus, reinforces our observation that modelled TB patterns have their strongest disagreement with SMOS measurements in fall and winter. The ECs of the second EOF variation mode of each TB error have not been included in Fig. 5, because the spatial patterns of each error differ between them. Nevertheless, it is important to note that they show variations at higher frequency than those from the first mode.

Two conclusions can be drawn from these results:

First, the largest spatially coherent error identified in Fig. 3 and 4 (a and c) is dominated by the slow varying component of the TB signals, which is driven by the annual cycle. At first sight, this might seem to contradict the temporal correlation analysis (Fig. 1). However, it evidences that the slow (annual cycle) and fast (synoptic variability) components of TBs show different behaviours. In addition, it confirms our hypothesis that the temporal correlation of TB is driven by its synoptic variability, as demonstrated in the SSM comparison performed by Polcher et al. (2015).

Second, modelled TBs are warmer than measured ones over South-Western IP during fall and winter, as revealed by the first EOF patterns and their oscillations (Fig. 3 to 5). To further analyze this result, we looked at ECMWF's mean first guess departure from the months of November 2010 to 2012. This diagnostic consists of the time averaged geographical mean of the difference between SMOS measured TBs and modelled ones using the CMEM and H-TESSEL's surface state variables (Fig. 6). For all three years we see a contrast between the

error over the North-Western region of the IP (in an orange colour) and over the South-Western region and a smaller area further North (in a blue colour). According to this, measured TBs are warmer than modelled ones over the North-West of the IP during these three periods, while modelled TBs are warmer than SMOS's over the South-West of the IP. This is in good agreement with the behaviour described by the first EOF variation mode of both TB errors (Fig. 3 and 4, a and c). It should be noted that the mean first guess departure shows a global bias between the spatial patterns of measured and modelled TBs. However, only the IP is represented in this figure to show clearly the spatial structures.

To sum up, the EOF analyses of the two TB errors identified a common dominant structure, which is maximum in the fall and winter seasons, over the South-West of the IP and a smaller area further North. It represents between 18% and 36% of the error depending on the modelled TB set considered and its polarization. Moreover, it corresponds well with the ECMWF mean first guess departure for the 2010-2012 November months.

#### 4.2.2 LST and Precipitation errors

Precipitation and LST data are used to explore possible causes for the difference between measured and modelled TBs. Errors are calculated with respect to independent datasets. The dominant error pattern of each variable is computed via EOF analysis and compared with the dominant pattern of the two TB errors. If similarities can be identified, then possible causal links between these variables and the TB error can be explored.

The precipitation error was calculated as the difference between the P provided by the ERA-Interim forcing and the E-OBS independent dataset. The LST errors were computed as the difference between modelled LST (from ORCHIDEE or H-TESSSEL) and the EUMETSAT LandSAF product (<http://landsaf.meteo.pt>).

#### *Spatial patterns*

The first EOF patterns of P and LST errors are represented in Fig. 7, together with their explained variance. The precipitation error is common to both models as it originates in the selected forcing. The dominant spatial structure of this error, which represents only 15% of the total variance, has its maximum in the South-East of the IP and is different from the one found for TB. The error patterns from LST differ remarkably between the two models and do not seem related to the TB error. On the one hand, a North-South gradient is observed in ORCHIDEE's LST error (Fig. 7 a), which is most likely explained by forcing induced biases

1 due to available energy affecting the LSM simulation. On the other hand, H-TESSEL's LST  
2 error pattern (Fig. 7 c) shows a gradient from East to West.

### 3 **Expansion coefficients**

4 The ECs correspondent to each of these patterns are presented in Fig. 8. Those for the  
5 precipitation error show a higher frequency variation than those of the LST and TB errors.  
6 ORCHIDEE's LST error behaves as expected from land-surface physics, with a maximum in  
7 summer when the largest amount of energy is absorbed by the surface and thus, small errors  
8 in the energy balance translate into large temperature differences. This is not the case for H-  
9 TESSEL's LST error, whose ECs show higher frequency variation with maxima in the fall  
10 season and at the end of the winter in 2011 and 2012.

11 The dominant modes of variability of P and LST errors show different spatial and temporal  
12 characteristics than the TB error dominant pattern. Neither the spatial structures coincide, nor  
13 their temporal evolution over the 2010 to 2012 period. The TB errors show a strong annual  
14 variation which peaks in fall and winter. The ECs of ORCHIDEE's LST error show a  
15 maximum in summer, while those for H-TESSEL's LST and P errors are characterized by  
16 higher frequency variations.

17 Therefore, this analysis excludes the hypothesis that biases in precipitation driving the models  
18 or errors in their surface temperature are the direct cause of the inconsistency in TB's spatial  
19 structures. The strong similarities of the TB errors in two quite different LSMs further  
20 strengthens the rejection of this hypothesis.

### 21 **4.2.3 Analysis of CMEM assumptions**

22 The CMEM is another candidate to explain the TB error since it is also a common element  
23 from both sets of modelled TBs. In fact, modelled TBs have been shown to be more sensitive  
24 to the configuration of the microwave model than to the LSM used (de Rosnay et al., 2009).

25 As explained in section 2, we performed a sensitivity analysis to test if certain CMEM  
26 parameterizations could explain the differences between measured and modelled TBs. As a  
27 result, three new sets of modelled TBs were estimated:  $TB_{HT(VC)}$ ,  $TB_{OR(SD)}$ , and  $TB_{OR(FW)}$  to  
28 evaluate the role of vegetation, vertical discretization, and the emissivity parameterization  
29 respectively.

1 In the first place,  $TB_{HT(VC)}$  shows similar mean spatial correlations with  $TB_{SM}$  as the ones for  
2  $TB_{HT}$  and  $TB_{SM}$  (Table 4). In addition, an EOF analysis of the difference between this new  
3 estimate and observed TBs (figure not included) shows similar spatial patterns as the ones  
4 identified in Fig. 4 (a and c), as well as a good agreement between their ECs.

5 In the second place, no significant differences were observed between  $TB_{OR(SD)}$  and  $TB_{OR}$   
6 when compared to  $TB_{SM}$ . For instance, mean spatial correlations computed using  $TB_{OR(SD)}$   
7 and  $TB_{SM}$  are 0.22 and 0.33 for the horizontal and vertical polarization, which are similar to  
8 the values obtained for  $TB_{OR}$  and  $TB_{SM}$  (Table 4).

9 In the third place, an EOF analysis of the TB error computed using the  $TB_{OR(FW)}$  and the  $TB_{SM}$   
10 sets (figure not included), shows a similar dominant structure both in space and time to the  
11 one observed in Fig. 3 (a and c). In addition, similar spatial correlations between  $TB_{OR(FW)}$   
12 and the  $TB_{SM}$  to those from  $TB_{OR}$  and  $TB_{SM}$  are also found (Table 4).

13 As synthesized in Table 4, in the current state of CMEM the vegetation cover, the number of  
14 soil layers, and the  $\epsilon_s$  and  $T_{eff}$  parameterizations can be discarded as the dominant factors  
15 responsible for the poor spatial correlation between modelled and SMOS TBs.

### 16 **4.3 Annual cycle of TBs**

17 The slow varying component of the TB signals is analysed pixel by pixel, because it has been  
18 identified as the driver of the largest spatially coherent error structure between measured and  
19 modelled TBs (Fig. 5). For this matter, the mean annual cycle of each TB signal was  
20 computed for each pixel and then smoothed using a spline filter to remove sub-monthly  
21 fluctuations. The period of study is too short to ensure that a simple annual mean cycle filters  
22 out high frequency variations. In Fig. 9 the normalized amplitudes of the annual TB cycle are  
23 displayed.

24 The spatial structures shown in SMOS's maps (Fig. 9, c and f) exhibit strong resemblances to  
25 those observed in the first EOF patterns of the TB error (Fig. 3 and 4, a and c). However, this  
26 structure is not found in the maps corresponding to  $TB_{OR}$  and  $TB_{HT}$ , where there is less  
27 contrast in the spatial distribution of the relative amplitude of the annual cycle. This indicates  
28 that the LSMs combined with CMEM do not reproduce the annual cycle amplitude of TBs  
29 observed by SMOS.



1 To further analyse this result, two study areas are defined (Fig.10). The first one is over the  
2 South-Western IP (7.5W : 4W, 40N : 38N) and corresponds to part of the area where the  
3 largest differences in TB's normalized amplitudes are identified. The second one is the North-  
4 Western region (8.25W : 6W, 43N : 41.75N) of the IP and is chosen because it shows similar  
5 annual cycle amplitudes of TB in the two models and SMOS. In addition, the EOF analysis of  
6 the TB error showed opposite behaviours in these areas.

7 Fig. 10 shows the smoothed annual cycle of the horizontal and vertical polarizations of the TB  
8 signals from both regions. The LST from the LandSAF product as well as those modelled by  
9 ORCHIDEE and H-TESSSEL are also displayed because of their direct relation to TBs. The  
10 plots show that the TB's annual cycle behaviour differs between the two regions. Therefore,  
11 the processes responsible for the TB error are probably different in each one of them.

12 The following results can be extracted from the plot corresponding to the South-Western area  
13 (Fig. 10 a):

14 In winter the difference between models is small compared to their relative warm bias when  
15 compared to SMOS. In summer the agreement is relatively good with observations laying  
16 within the spread of the models. This explains the result presented above, namely that the  
17 amplitude of the simulated annual cycle is smaller than for the remotely sensed TB.  
18 Examining the LST one can note that the biases are relatively small and ORCHIDEE  
19 generally matches better the LandSAF product, but H-TESSSEL shows a larger and more  
20 correct amplitude of the annual cycle. This might explain why this model has the largest  
21 amplitude of TB in both polarisations, indicating that a large fraction of the error on the  
22 annual cycle of TB is caused by the emissivity simulated by CMEM given the surface states  
23 of both LSMs.

24 Over the North-Western IP SMOS observations are mostly within the uncertainty spanned by  
25 the two models. One notable exception is the summer period for the horizontal polarization  
26 where both models are cooler. Also in this region the amplitude of TB in both polarizations is  
27 larger in H-TESSSEL than ORCHIDEE and closer to that measured by SMOS. Again, this can  
28 be related to LST. Although ORCHIDEE has smaller biases, the H-TESSSEL amplitude of the  
29 annual cycle is larger and closer to the observed one.

30 The strong difference in behaviour between the two selected regions in winter explains the  
31 resemblance of the dominant EOF mode in TB errors of both models with the regions of  
32 maximum amplitude of the annual cycle of observed TBs. For both regions, the LST biases of

the LSMs do not show a clear relation to the simulated TBs. H-TESSEL has the warmest surface temperatures but the lowest TBs, indicating that its state variables produce a lower emissivity than ORCHIDEE when processed by CMEM. On the other hand the differences in annual amplitudes of LST could contribute to those seen for the TB. This is also supported by the fact that the dominant variation modes of LST errors are not related to those of TBs. This would indicate that the major contribution to the TB errors found for the models does not originate in their forcing or their ability to simulate the land surface energy balance and temperature, but rather in the way CMEM simulates L-band emissivity based on their description of the surface state.

## **5 Discussion**

This work complements with an analysis of TBs the study by Polcher et al. (2015), which compared the SSM product of SMOS with ORCHIDEE's modelled SSM. Both studies present a spatio-temporal correlation analysis and obtain similar results: a good agreement in temporal evolutions and a large mismatch between the spatial structures of measured and modelled SSM and TB.

The temporal correlation between  $TB_{OR}$  and  $TB_{SM}$  is very similar to that between retrieved (SMOS) and modelled (ORCHIDEE) SSM (Table 4). In addition, both variables show lower correlations over mountain ranges. As noted for SSM, the temporal correlation is mainly driven by its fast varying component and is not very sensitive to the annual cycle (Polcher et al., 2015).

Spatial correlations are low for both variables, indicating an inconsistency between the spatial structures of measured and modelled data. Polcher et al. (2015) showed that the spatial correlation between retrieved and modelled SSM is worse for the SSM's slow varying component than for its fast varying component. This can be due to the fact that the largest spatially coherent error between measured and modelled TBs is dominated by their slow varying component, as shown in this paper.

The EOF analysis presented here identified a dominant structure over the South-Western IP using both sets of modelled TBs, which explains a large fraction of the TB error. This structure differs from the error characterization of the SSM comparison, which showed the largest discrepancies between modelled and retrieved SSM over the North-Western IP. In fact, only weak differences were found for SSM over the South-Western region (Polcher et al., 2015). These results indicate that the transfer functions used by SMOS to derive SSM

1 from observed TBs or CMEM, which estimates TBs from modelled SSM (together with other  
2 state variables), play an important role and have to be better understood in order to explain the  
3 differences between the SMOS observations and the simulated surface states.

4 None of the hypotheses tested to identify a methodological weakness in the forcing of both  
5 LSMs or the configuration of CMEM, which would explain this common error, was  
6 conclusive. The differences in TB between the LSMs and SMOS are noteworthy and we  
7 believe that understanding them should be a priority for the community to achieve a better  
8 usage of these observations. As the LSMs used here are very different in their conception, it is  
9 unlikely that they produce the same systematic SSM bias which would explain the large  
10 discrepancy in the South-West of the IP during winter. On the other hand, processes which  
11 are not represented with enough detail in both schemes could explain the error and need to be  
12 analysed as to their potential to explain the discrepancies.

- 13 • In the first place, it is interesting to study the Leaf Area Index (LAI), because it is  
14 linked to the seasonal cycle of vegetation. It may, therefore, reveal some  
15 underestimated effects of vegetation dynamics on modelled TBs, which could be  
16 related, to a certain extent, to the seasonality identified in the dominant structure of the  
17 TB error. In addition, the LAI is a key component in the CMEM parameterization of  
18  $\tau_{\text{veg}}$ . However, the areas of the IP where the TB error is the largest are those of least  
19 vegetation. Therefore, in our opinion, modelled LAI is not likely to be the main cause  
20 of the differences in TB's spatial structures.
- 21 • In second place, assumptions made in the modelling of rainfall interception may also  
22 explain some differences between modelled and measured TBs. In particular, those  
23 shown in Fig. 10 (b) over the North-Western region of the IP. This region is  
24 characterized by an oceanic climate and thus, wet winters and mild summers, with a  
25 high precipitation, and often rainfall occurring as drizzle. Contrary to the Southern  
26 region, there is more vegetation and thus, rainfall interception plays a key role over  
27 this area and may be of interest to revise how this process is modelled. However, the  
28 IP region with strong interception is not the one with the largest TB error. The error  
29 over the South-Western region is larger than over the North-Western region, as shown  
30 by the EOF analysis.
- 31 • In third place, the attenuation effect of litter on the soil and its interception of water  
32 could also explain differences obtained between modelled and measured TBs, since it

is not taken into account by models, but is part of satellite observations. However, we believe that probably it would not cause an impact structured as the one observed over the South-Western area of the IP without affecting other regions. Indeed this process would be strongest in regions with dense vegetation.

- Finally, issues related to the fundamental simplification of subgrid processes in LSMs may also contribute to the inconsistency between the spatial structures of modelled and measured TBs. For instance, LSMs do not represent small scale features as open water in lakes and rivers, swamps, irrigated areas or other water ponded on the surface and could contribute strongly to L-band emissivity of the surface. Assumptions made by LSMs could neglect key issues from the small scale which could be carried over to the large scale of TBs. For the moment, we do not see why these simplifications of LSMs would have the strongest impact in the South-West of the IP.

Instrumental issues from SMOS could also explain the differences in TB spatial structures, in case these are not of climatological or geophysical nature. For example, one of the most important causes of noise in SMOS surface soil moisture is Radio-Frequency Interferences (RFIs). Daganzo-Eusebio et al. (2013) describe their effect on SMOS data. Some of them are difficult to detect and thus, RFIs may not be properly filtered out. For instance, Dente et al. (2012) identified an irregular angular pattern in the TBs affecting data from the L1C product used to retrieve soil moisture. In their opinion, this was caused by weak RFIs which were not correctly filtered. Another explanation could be antenna pattern errors, as SMOS TBs seasonal and latitudinal drifts detailed in Oliva et al. (2013). However, RFIs are not likely to be the main cause of the differences between measured and modelled TBs, because the main spatial structure identified in both TB errors is found to be dominated by the brightness temperature's annual cycle. This suggests that it contains a geophysical signal.

In our opinion, further analyses should be carried out regarding the CMEM assumptions concerning emissivity. According to Jones et al. (2004), the soil moisture and vegetation water content have a significant effect on the sensitivity of TB at the top of the atmosphere. However, they impact microwave emission in different ways. On the one hand, an increase in soil moisture results in a higher soil dielectric constant ( $\epsilon$ ) and thus, on lower emissivities. On the other hand, an increase in the vegetation water content rises the scatter and the absorption, increasing the emission. The  $\epsilon$  is key in the computation of emissivity, while the vegetation optical depth ( $\tau_{veg}$ ) is closely related to the vegetation water content. Both variables are

modelled in CMEM and the same parameterization has been used to estimate the two sets of modelled TBs: Wang and Schmugge (1980) for  $\epsilon$  and Wigneron et al. (2007) for  $\tau_{veg}$ . Furthermore, the same parameterization has been used to model the rough surface emissivity ( $\epsilon_r$ ) in both cases: Wigneron et al., 2001. Considering that similar spatial patterns were obtained for the TB error using two different LSMs, focus should be put on the above mentioned variables ( $\epsilon$ ,  $\tau_{veg}$ , and  $\epsilon_r$ ) in CMEM. We suggest to prioritize the analysis of the relation between the vegetation water content and TB because of the role the vegetation opacity model plays in CMEM's configuration, as shown in de Rosnay et al. (2009). In addition, no significant differences were observed between modelled and retrieved SSM over South-Western IP (Polcher et al. 2015), where the maximum TB error was identified. This reassures our suggestion of prioritizing  $\tau_{veg}$  with respect to  $\epsilon$ , since the latter is directly related to SSM.

## 6 Conclusions

TBs of SMOS Level 1C product were compared to two sets of modelled TBs. The latter were obtained using simulated state variables (from the ORCHIDEE and H-TESSEL LSMs) and a radiative transfer model, CMEM. The study was carried out over the Iberian Peninsula (IP) for the period 2010 to 2012.

On the one hand, a temporal correlation analysis between measured and modelled data shows that there is a good agreement in their temporal evolution. However, this diagnostic is mainly driven by the TB's signal synoptic variability, as occurs with SSM (Polcher et al., 2015). On the other hand, a spatial correlation analysis detected a large mismatch between the TB spatial structures provided by models and observations.

An EOF analysis of the error between modelled and measured TBs suggests that the inconsistency is not limited to a particular LSM. It is dominated by the TB slow varying component, peaking in fall and winter. In addition, modelled TBs are larger than SMOS measurements during these seasons over the dominant error structure detected. This structure explains between 18% and 36% of the TB error variance, depending on the LSM and polarization. Therefore, there is a high percentage of the error (between 82% and 64%) that shows structures which have to be analysed and explained. Since these are not present in both LSMs, they are of lower priority and have not been approached in this study.

Forcing induced biases are discarded as the main cause of the spatial inconsistency in TBs after computing the dominant error structures of precipitation and Land Surface Temperature

(LST). Nevertheless, the degree of accuracy of the forcing cannot be fully established because of scale issues and the lack of sufficient independent measurements. The difference in TBs' spatial structures could also be thought of a combination of non linear relations between errors in precipitation and LST, but this is beyond the scope of this paper.

Assumptions made in certain CMEM parameterizations are also discarded as the main source of the spatial inconsistency between measured and modelled TBs: the vegetation cover input; the number of soil layers defined; and some parameterizations to compute the smooth surface emissivity (Fresnel law and Wilheit (1978)) and the effective temperature (Wigneron et al. (2001) and the temperature profile).

Previous studies found differences between the spatial structures of modelled and retrieved SSM (Parrens et al., 2012; Polcher et al., 2015). This paper shows that these structures are not consistent also when comparing modelled and observed TBs. In addition, this issue is amplified for the TBs compared to SSM, because the latter are bounded by zero and saturation. This could explain the generally better spatial correlation for SSM in winter, when it reaches saturation in large parts of the IP. Although this study is limited to the IP, differences in spatial structures occur at a global scale. We would like to draw the reader's attention to the fact that TBs are not only the main input of SMOS soil moisture retrieval algorithm, but that they are used to retrieve other variables, like vegetation optical depth or salinity. We believe that analysing the spatial inconsistencies between modelled and measured TBs is important, as these can affect the estimation of geophysical variables, TB assimilation in operational models, as well as result in misleading validation studies. Therefore, obtaining the spatial contrast of measured TBs in models is a challenge which, in our opinion, deserves a higher priority in the community.

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25

1 Table 1. CMEM configuration for the two sets of modelled TBs.

	Configuration	Parameterization	
		ORCHIDEE	H-TESSSEL
Physical configuration	Soil dielectric constant	Wang and Schmugge (1980)	
	Effective temperature	Soil temperature profile	Wigneron et al. (2001)
	Smooth surface emissivity	Wilheit (1978)	Fresnel law
	Rough surface emissivity	Wigneron et al. (2001)	
	Vegetation optical depth	Wigneron et al. (2007)	
	Atmospheric optical depth	Pellarin et al. (2003)	
	Temperature of vegetation	Surface soil temperature	
	Vegetation cover input data	Ecoclimap	
Observing configuration	Microwave frequency	1.4Ghz	
	Incidence angle	42.5°	40°
Soil and atmospheric level configuration	Number of soil layers*	11	3
	<i>(number of layers in the top 5 cm)</i>	<i>(5)</i>	<i>(1)</i>

2 \*Layer depths of ORCHIDEE's hydrological scheme [cm]: 0.099, 0.391, 0.978, 2.151, 4.497,  
3 9.189, 18.570, 37.340, 74.880, 150, and 200

4 \*Layer depths of H-TESSSEL's hydrological scheme [cm]: 7, 21, 72, and 189

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Table 2: Input variables for the CMEM to compute TBs at TOA.

Soil conditions	Constant fields	Soil texture fraction [%]
		Orography [km]
Vegetation	Constant fields	High and low vegetation types
		High and low vegetation fractions
		Water fraction
	Dynamic fields	Low vegetation LAI
Meteorology	Dynamic fields	Soil moisture profile [ $\text{m}^3 \text{m}^{-3}$ ]
		Soil temperature profile [K]
		Skin temperature [K]
		Snow depth [m]
		Snow density [ $\text{kgm}^{-3}$ ]
		2 m temperature [K]

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Table 3: TB filtering criteria to keep data, applied to the TB signals.

TB <sub>OR</sub>	TB <sub>HT</sub>	All TB signals
ORCHIDEE's daily average surface temperature > 275 K	Snow water equivalent < 0.01 m	Daily TB < 300 K
ERA-Interim's daily average 2 m air temperature > 273 K	ERA-Interim's daily average 2 m air temperature > 273.5K Orography (slope) < 0.04	Mask (from SMOS's L2 product)

Table 4: Mean temporal and spatial correlations for SSM (Polcher et al., accepted) and the horizontal and vertical polarization of TBs over the Iberian Peninsula from 2010 to 2012.

	Temporal		Spatial	
	Horizontal	Vertical	Horizontal	Vertical
TB <sub>OR</sub> vs. TB <sub>SM</sub>	0.75	0.76	0.20	0.30
TB <sub>HT</sub> vs. TB <sub>SM</sub>	0.82	0.82	0.24	0.29
TB <sub>HT(VC)</sub> vs. TB <sub>SM</sub>	-	-	0.17	0.36
TB <sub>OR(SD)</sub> vs. TB <sub>SM</sub>	-	-	0.22	0.33
TB <sub>OR(FW)</sub> vs. TB <sub>SM</sub>	-	-	0.20	0.30
SSM <sub>OR</sub> vs. SSM <sub>SM</sub>	0.81		0.28	



Table 5: Spatial correlation for the first and second variation modes of the EOF analyses performed for the difference between modelled and measured TBs. TBH and TBV correspond to the horizontal and vertical polarizations, respectively.

	Mode 1	Mode 2
$TB_{OR} - TB_{SM} \text{ (TBH) vs. } TB_{OR} - TB_{SM} \text{ (TBV)}$	0.99	0.97
$TB_{HT} - TB_{SM} \text{ (TBH) vs. } TB_{HT} - TB_{SM} \text{ (TBV)}$	0.86	0.75
$TB_{OR} - TB_{SM} \text{ (TBH) vs. } TB_{HT} - TB_{SM} \text{ (TBH)}$	0.92	0.69
$TB_{OR} - TB_{SM} \text{ (TBV) vs. } TB_{HT} - TB_{SM} \text{ (TBV)}$	0.73	0.48

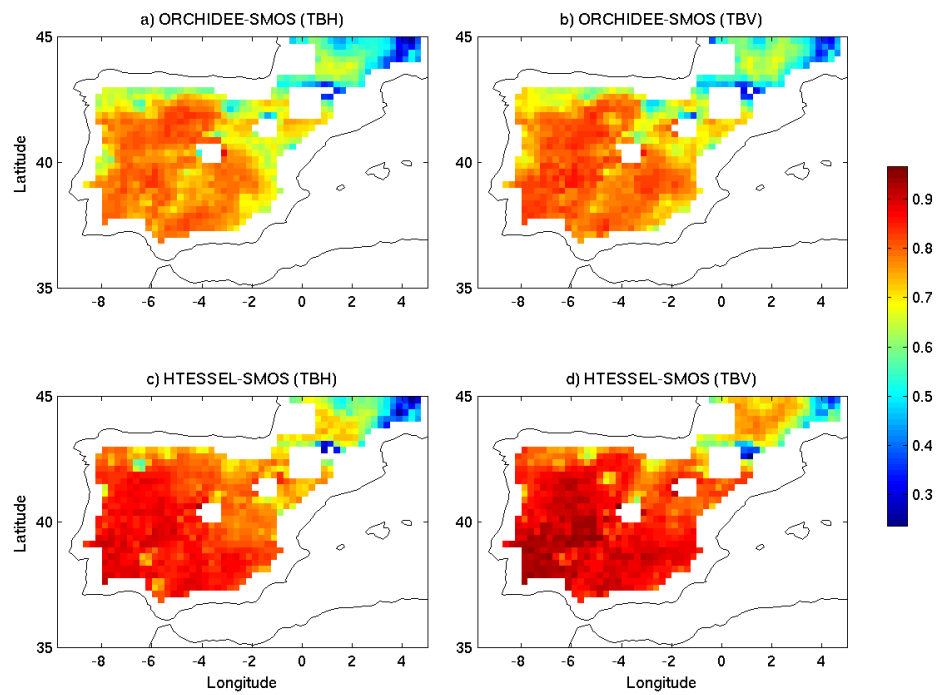


Figure 1: Temporal correlation between modelled and measured TBs from 2010 to 2012. TBH and TBV correspond to the horizontal and vertical polarizations, respectively.

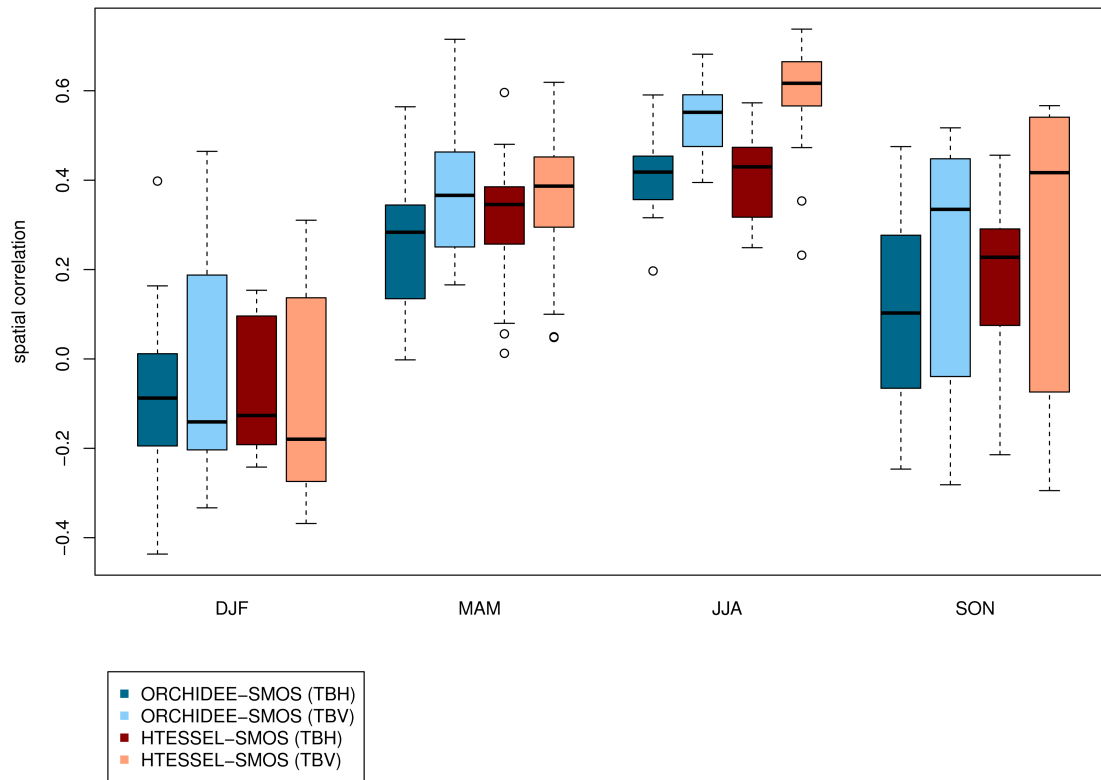


Figure 2: Boxplot showing the annual cycle of the spatial correlation between modelled and measured TBs, over the Iberian Peninsula from 2010 to 2012. TBH and TBV correspond to the horizontal and vertical polarizations, respectively. Values have been grouped per seasons: winter (DJF), spring (MAM), summer (JJA), and fall (SON).

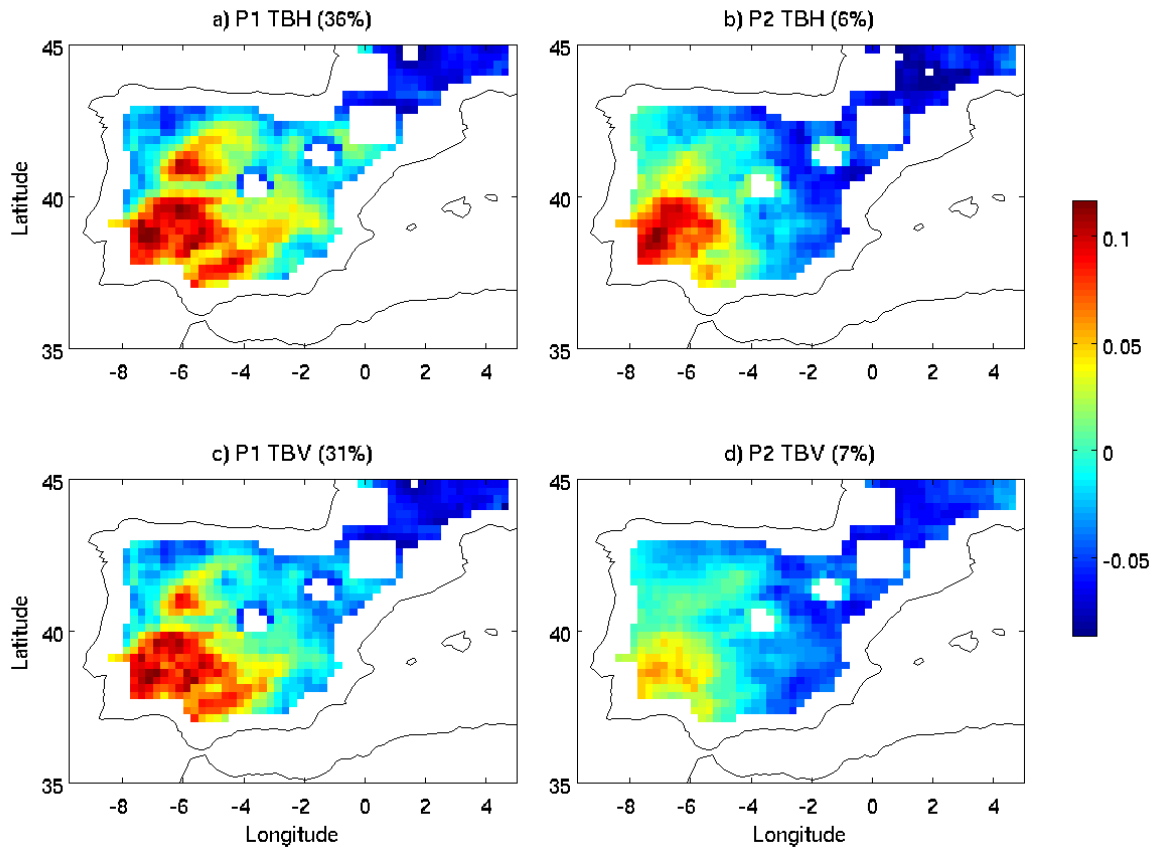


Figure 3: Spatial patterns associated with the first two EOF variation modes (P1 and P2) of the difference between modelled TB (ORCHIDEE) and measured TB (SMOS). TBH and TBV correspond to the horizontal and vertical polarizations, respectively. The percentage of variance explained by each mode is included in brackets.

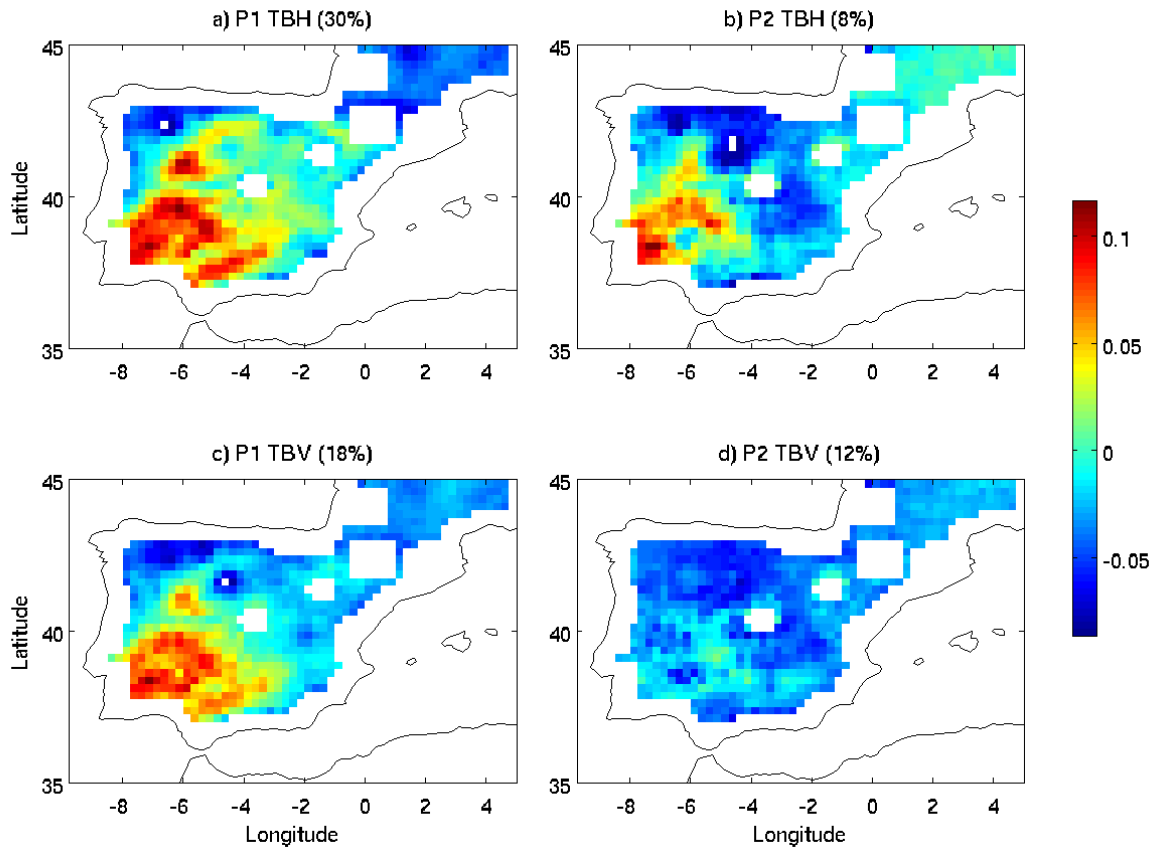


Figure 4: Spatial patterns associated with the first two EOF variation modes (P1 and P2) of the difference between modelled TB (H-TESSEL) and measured TB (SMOS). TBH and TBV correspond to the horizontal and vertical polarizations, respectively. The percentage of variance explained by each mode is included in brackets.

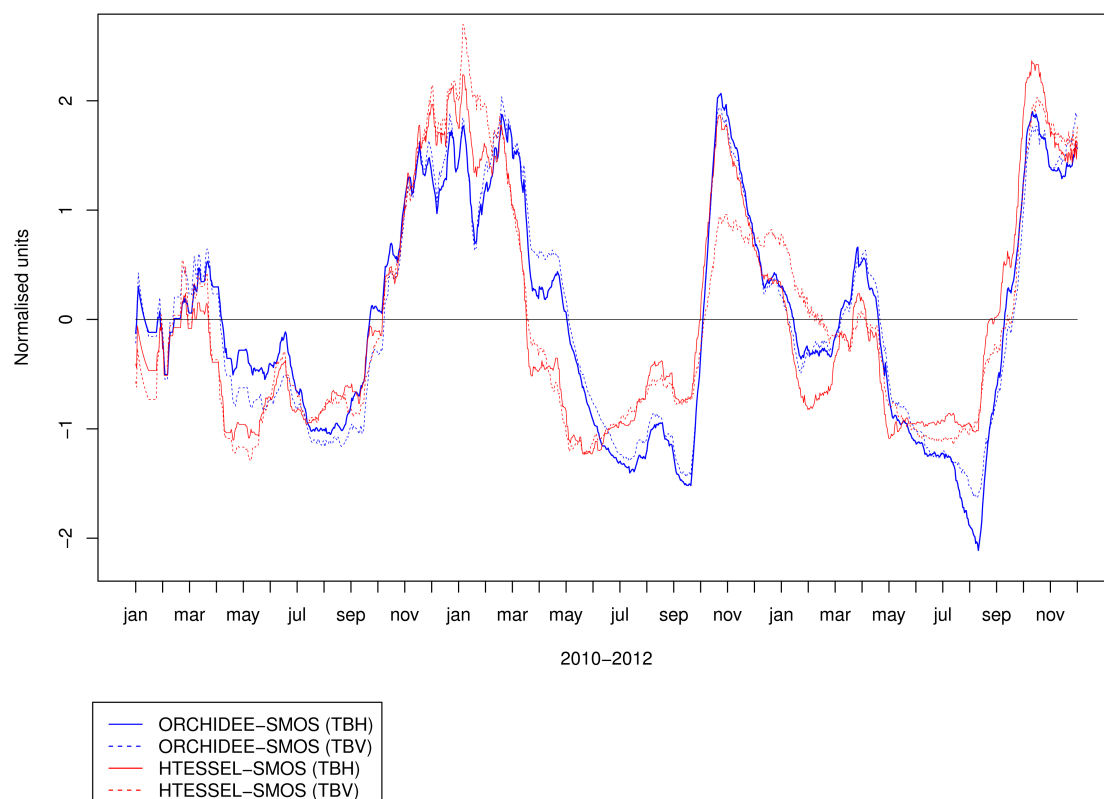


Figure 5: Temporal evolution of the expansion coefficients correspondent to the first EOF variation mode of the TB errors (ORCHIDEE versus SMOS and H-TESSSEL versus SMOS) over the Iberian Peninsula. Values have been normalised using the standardization method. TBH and TBV correspond to the horizontal and vertical polarizations, respectively.

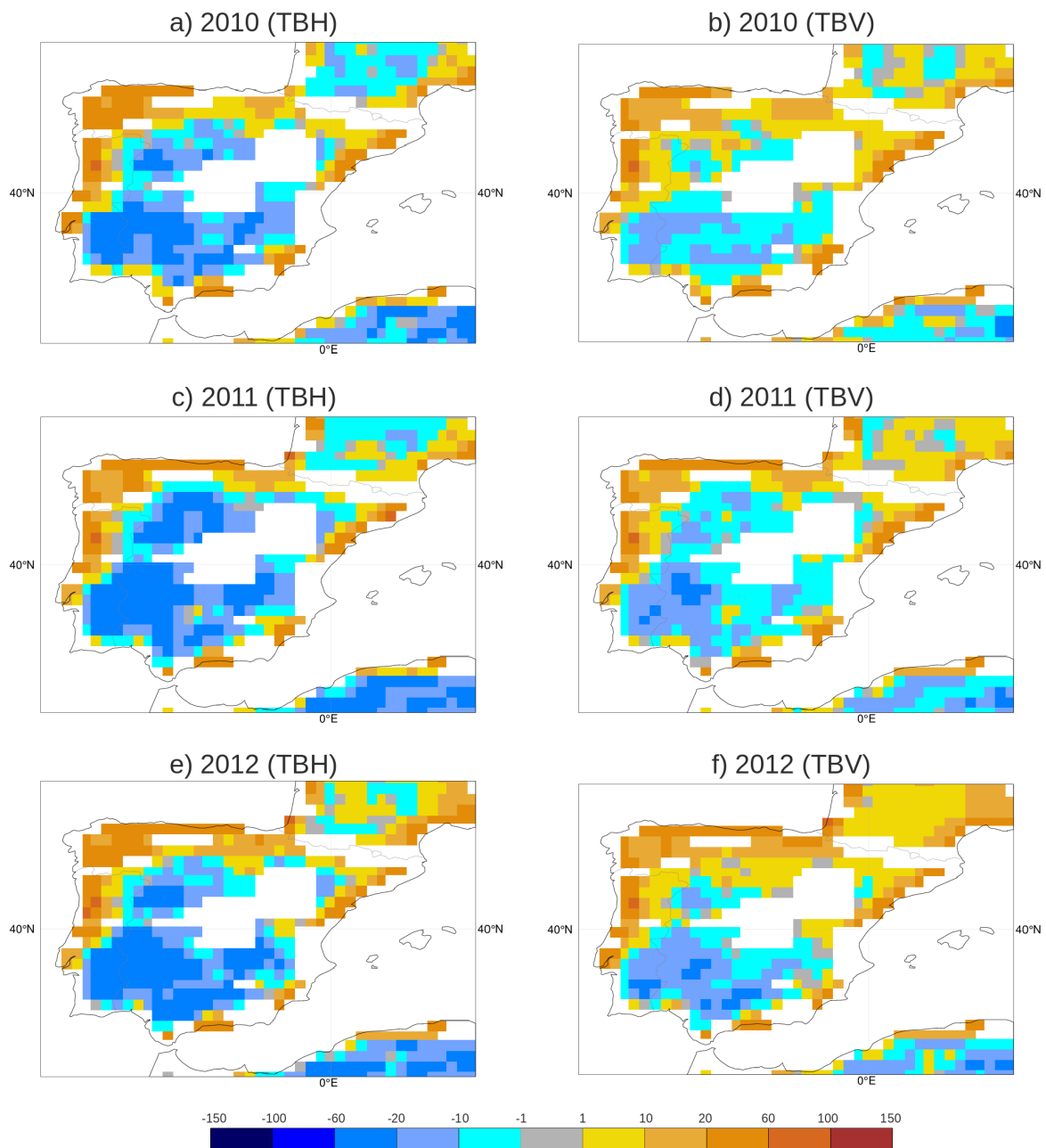


Figure 6: ECMWF's mean first guess departure (observation-model [K]) from the months of November 2010 to 2012. TBH and TBV correspond to the horizontal and vertical polarizations, respectively.

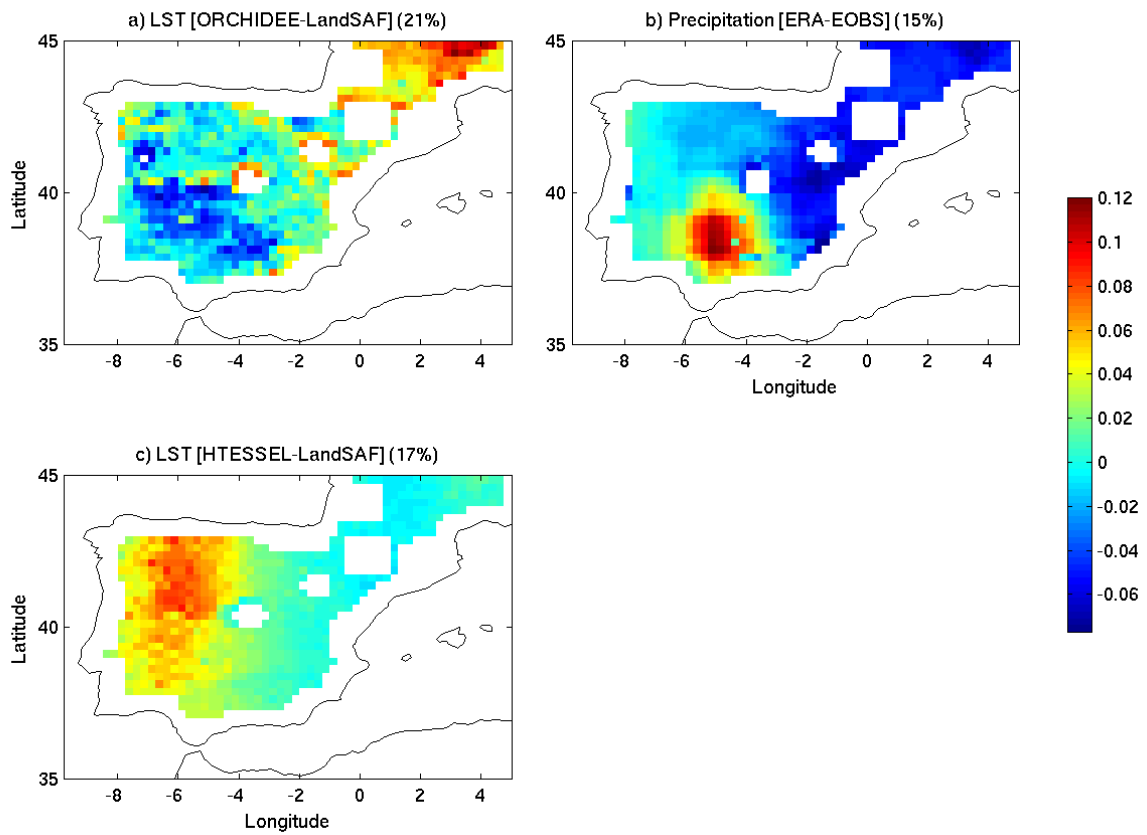


Figure 7: Spatial patterns from the first EOF variation mode of the LST and the precipitation errors. The percentage of variance explained by each mode is included in brackets.



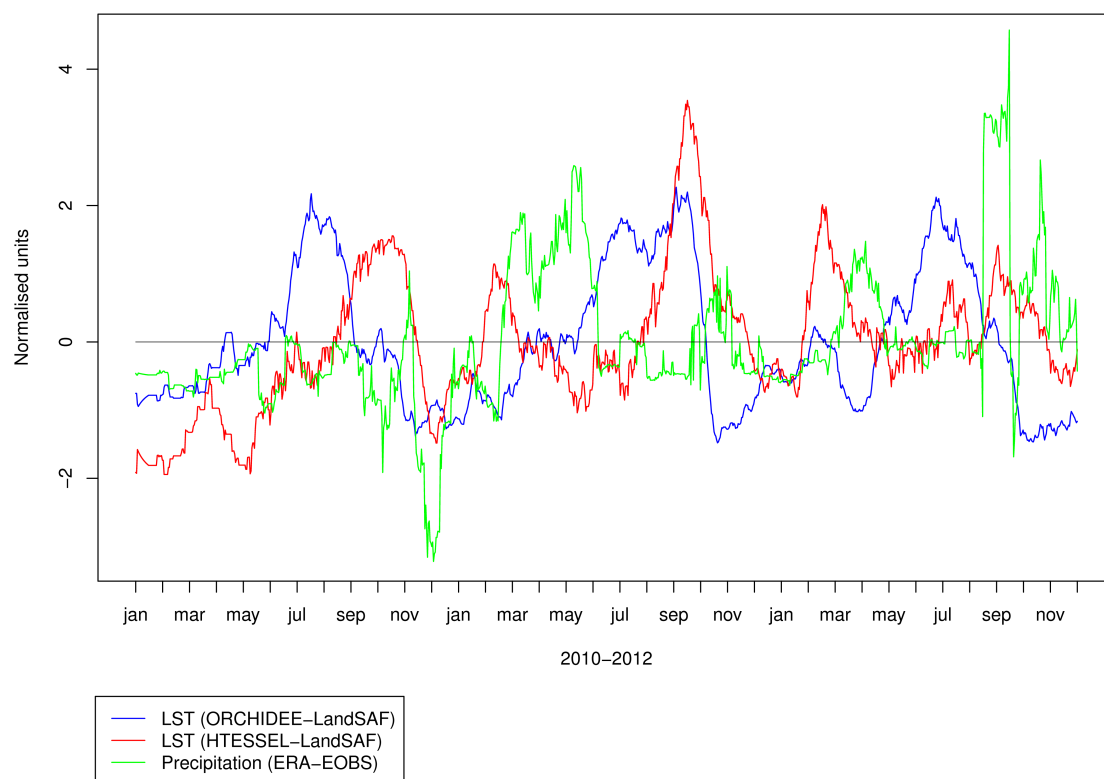


Figure 8: Temporal evolution of the expansion coefficients correspondent to the first EOF variation mode of the LST and the precipitation errors. As in Fig. 5, values have been normalised using the standardization method.

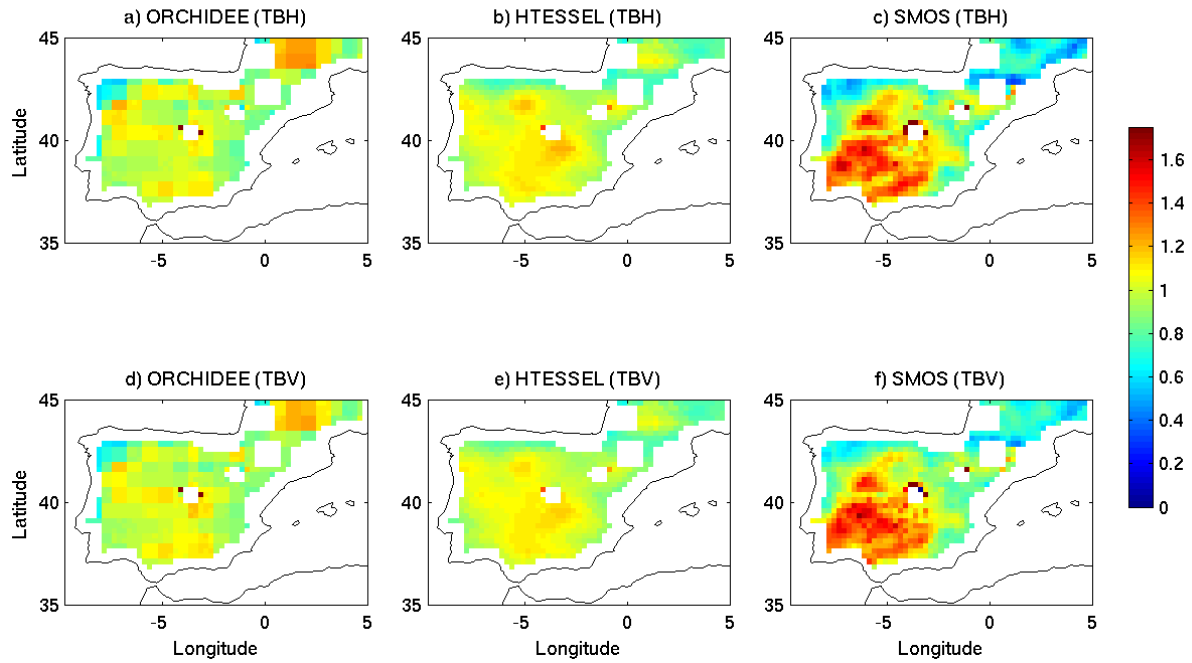


Figure 9: Normalised amplitude of the smoothed annual cycle of modelled and measured TBs:  $\frac{\text{amplitude(TB)}}{\overline{\text{TB}}}$ . TBH and TBV correspond to the horizontal and vertical polarizations, respectively.

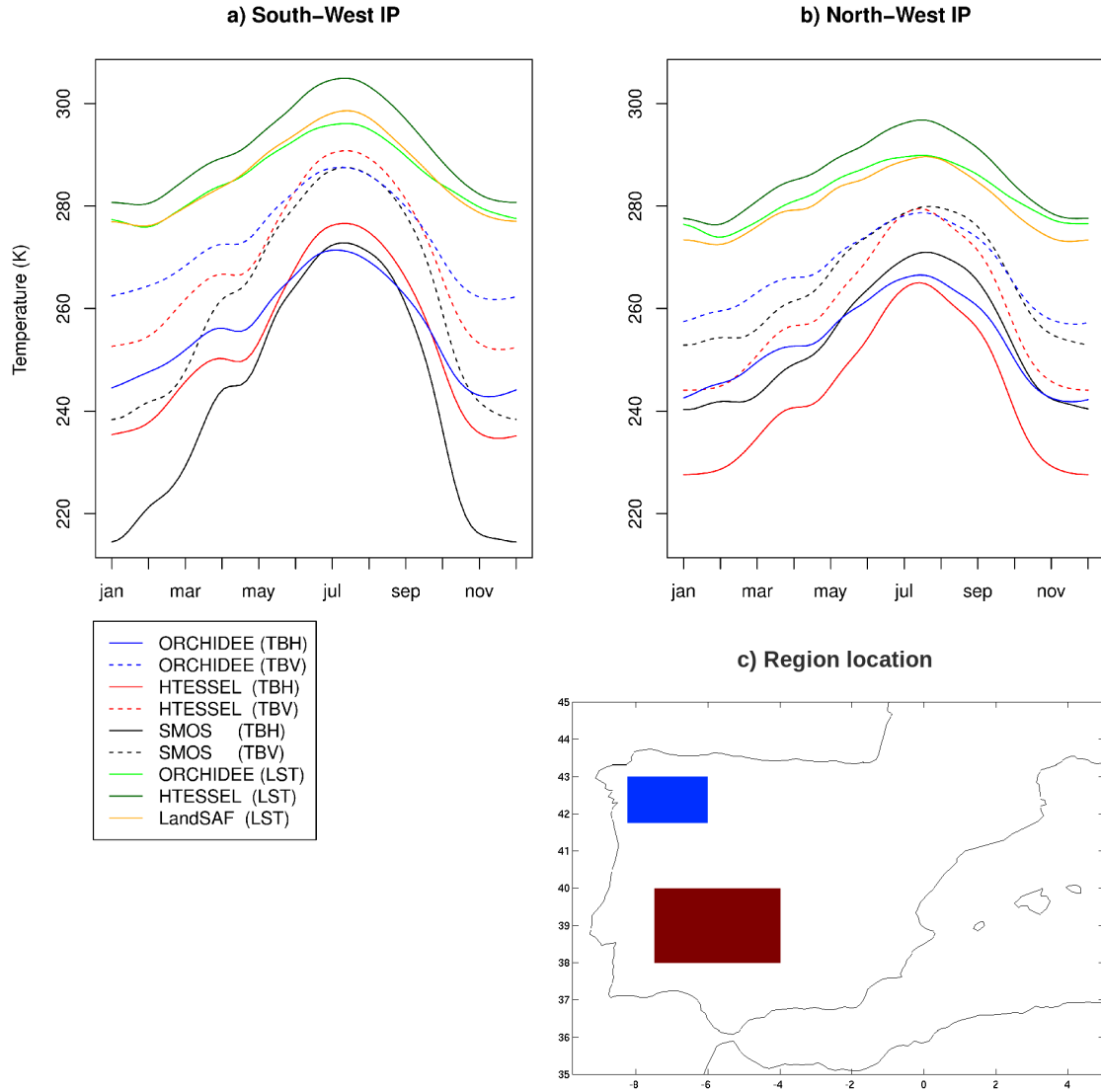


Figure 10: Smoothed annual cycle of  $TB_{SM}$ ,  $TB_{OR}$ , and  $TB_{HT}$ , as well as of the LST signals from ORCHIDEE, H-TESSEL, and LandSAF over a South-Western (a) and North-Western (b) region of the Iberian Peninsula, from 2010 to 2012. The TBH and TBV correspond to the horizontal and vertical polarizations, respectively. The regions' location is shown in figure c: South-West (red) and North-West (blue).

### 3. The manuscript's main modifications

This section identifies the main modifications performed in the manuscript. These will be identified by the page and line numbers of the version included in the previous section.

The manuscript's main change is that its structure has been modified. As a result, the text has varied considerably. To identify these changes the sections and subsections affected have been highlighted. In addition, modifications related to some of the referee's detailed comments have also been included.

**Page 23, line 23:** Modification relative to referee's 1 detailed comment number 1.

**Page 23, lines 24 to 25:** Modification relative to referee's 1 detailed comment number 2.

**Page 24, line 7:** Modification relative to referee's 1 detailed comment number 3.

**Page 24, line 10:** Modification relative to referee's 1 detailed comment number 4.

**Page 24, line 30:** Modification relative to referee's 1 detailed comment number 5.

**Page 25, lines 10 to 12:** Modification relative to referee's 2 detailed comment number 2.

**Page 26, line 19:** Modification relative to referee's 1 detailed comment number 8.

**Page 26, line 27:** The content of section 2 has varied from "Data and methods" to "Data".

**Page 26, line 28:** The name of section 2.1 has varied from "SMOS data" to "SMOS retrievals of TB".

**Page 27, line 25:** The content of section 2.2 has varied from "Radiative transfer model and land surface models" to "Modelled TB: CMEM".

**Page 28, lines 14 to 24:** Modification relative to referee's 1 detailed comments number 11 and 12.

**Page 28, line 15:** Modification relative to referee's 1 detailed comment number 13.

1 **Page 30, line 1:** The content of section 2.2.1 has varied from “CMEM” to “The  
2 ORCHIDEE and H-TESSEL Land Surface Models”.

3 **Page 30, lines 7 and 13:** Modification relative to referee’s 1 detailed comment  
4 number 15, and referee’s 2 detailed comments number 8.

5 **Page 30, lines 27 to 28:** Modification relative to referee’s 2 detailed comment  
6 number 9.

7 **Page 32, line 1:** The content of section 2.3 has varied from “Brightness temperature  
8 comparison” to “Precipitation and Land Surface Temperature”.

9 **Page 32, line 21:** The content of section 3 has varied from “Results” to “Methods”.

10 **Page 32, line 22:** The content of section 3.1 has varied from “Comparison of  
11 modelled and measured brightness temperatures” to “Data sampling and filtering  
12 processes”.

13 **Page 33, line 1:** A new section 3.1.1 named “Sampling” has been included.

14 **Page 33, lines 3 to 5:** Modification relative to referee’s 1 detailed comment number  
15 17.

16 **Page 33, line 10:** A new section 3.1.2 named “Filtering” has been included.

17 **Page 33, line 25:** The content of section 3.2 has varied from “Temporal and spatial  
18 characterization of the error” to “Comparison analyses”.

19 **Page 33, line 26:** The content of section 3.2.1 has varied from “TB error” to “Spatio-  
20 temporal correlation”.

21 **Page 34, line 9:** The content of section 3.2.2 has varied from “LST and precipitation  
22 errors” to “Empirical Orthogonal Function”.

23 **Page 34, line 22:** The content of section 4 has varied from “Discussion and  
24 conclusions” to “Results”.

25 **Page 34, lines 24 to 27:** Modification relative to referee’s 1 detailed comment  
26 number 19.

27 **Page 34, line 28:** A new section 4.1 named “Comparison of modelled and measured  
28 TBs” has been included.

1 **Page 35, line 3:** A new section 4.1.1 named “Temporal correlation” has been  
2 included.

3 **Page 35, line 22:** A new section 4.1.2 named “Spatial correlation” has been included.

4 **Page 36, line 4:** A new section 4.2 named “Spatial and temporal characterization of  
5 the TB error” has been included.

6 **Page 36, line 10:** A new section 4.2.1 named “TB error” has been included.

7 **Page 36, line 11:** A new sub-section of section 4.2.1 named “Spatial patterns” has  
8 been included.

9 **Page 37, line 6:** A new sub-section of section 4.2.1 named “Expansion coefficients”  
10 has been included.

11 **Page 38, line 14:** A new section 4.2.2 named “LST and Precipitation errors” has  
12 been included.

13 **Page 38, line 24:** A new sub-section of section 4.2.2 named “Spatial patterns” has  
14 been included.

15 **Page 39, line 3:** A new sub-section of section 4.2.2 named “Expansion coefficients”  
16 has been included.

17 **Page 39, line 21:** A new section 4.2.3 named “Analysis of CMEM assumptions” has  
18 been included.

19 **Page 40, line 16:** A new section 4.3 named “Annual cycle of TBs” has been included.

20 **Page 42, line 10:** A new section 5 named “Discussion” has been included.

21 **Page 45, line 13:** A new section 6 named “Conclusions” has been included.

22 **Page 49, lines 14 to 15:** Modification relative to referee’s 2 detailed comment  
23 number 9.

24 **Page 52, lines 1 to 2:** Modification relative to referee’s 1 detailed comment number  
25 13.

26 **Page 52, lines 5 to 7:** Modification relative to referee’s 2 detailed comment number  
27 9.

- 1 **Page 52, lines 20 to 21:** Modification relative to referee's 1 detailed comment  
2 number 4.
- 3 **Page 53, lines 2 to 4:** Modification relative to referee's 2 detailed comment number  
4 7.
- 5 **Page 56, Table 4:** Mean spatial correlation of  $TB_{HT(VC)}$ ,  $TB_{OR(SD)}$ , and  $TB_{OR(FW)}$  with  
6  $TB_{SM}$  have been included in Table 4.