Response to comments by Anonymous Referee #3

General comments:

The objective of this work is to assimilate ESA-CCI satellite-derived soil moisture estimates in CLM over Europe, from 2000 to 2006. The content of the paper is disappointing. The data assimilation experiment boils down to a sensitivity study illustrating possible model biases. Independent validation is missing. No justification is given for the choice of the 2000-2006 time period. Most recent satellites are missing in this period. It is not clear whether or not interannual variability of the vegetation is accounted for in the model. The authors do not use the scores usually used in hydrology. The improvement of the assimilation on water discharge is not convincing at all. The paper is poorly organized (no Discussion section). This work cannot be published in the present form.
Recommendation: reject.

RESPONSE: We thank the reviewer for his/her efforts. Unfortunately, some of the statements above are not correct. The DA-experiments do not boil down to a sensitivity study, there is independent validation in our opinion and we use scores which are traditionally used in land surface DA studies (it is true that we do not use scores traditionally used in conceptual rainfall-runoff modeling studies). Other issues which are highlighted above have been corrected for in the revised version of the manuscript.

The data assimilation experiment boils down to a sensitivity study illustrating possible model biases.
RESPONSE: In this study we used data assimilation approach to merge coarse resolution satellite observations with a land surface model, to generate higher resolution, downscaled estimates of the surface soil moisture profile with complete spatio-temporal coverage. The added value of our study is to apply a data assimilation modeling framework over Europe to derive a longer-term and high spatial resolution land surface data product in order to increase monitoring accuracy for land surface soil moisture and water states and fluxes.

We now discuss the added value of our data assimilation experiment in the introduction section of the revised manuscript to make our objectives clearer to the readers.

Independent validation is missing.
RESPONSE: We do not agree with this comment. Please note that we randomly selected 100 locations to assimilate the ESA CCI data into the CLM model, while the remaining data was used for independent validation. Additionally, another independent gridded observation-based runoff product was used to evaluate the performance of the soil moisture assimilation in the CLM model in improving indirectly additional hydrological variables such as runoff.

No justification is given for the choice of the 2000-2006 time period. Most recent satellites are missing in this period.

RESPONSE: In this study we used a high-resolution reanalysis system COSMO-REA6 from Hans-Ertel Centre for Weather Research (HErZ; Simmer et al., 2016) dataset, which is only now publicly available for longer time period of 1995 – 2015. However, this recent dataset was not fully publicly available at the beginning of our study. We preferred to use this data over other datasets, because of its high spatial resolution in comparison to other commonly used forcing datasets such as E-OBS and ERA-Interim at 25 and 80km resolution, respectively. In addition, the COSMO-REA6 dataset was produced through the assimilation of observational meteorological data and showed good performance particularly for precipitation when compared to observations (Wahl et al., 2017).

We agree that recent satellites such as the Soil Moisture and Ocean Salinity (SMOS) Mission, Soil Moisture Active Passive (SMAP) Mission could be another option, however, we selected the ESA CCI soil moisture product for assimilation because of its availability at longer time scales. This provides the opportunity to assess the potential impact of longer-term soil moisture observations on hydrologic simulations for climate change studies.

We clarified these points in the revised manuscript.

It is not clear whether or not interannual variability of the vegetation is accounted for in the model.

RESPONSE: In the current study we do not account for interannual variability of the vegetation. Instead we prescribed vegetation as the fractional coverage of different vegetation types according to MODIS land cover dataset for year 2001, which contains 21 land cover types defined by the International Geosphere-Biosphere Program (IGBP) (Friedl et al., 2002). This information is now added in the revised manuscript.
In the revised version of the manuscript, we will replace the CLM default PFT-specific annual LAI-cycles with prescribed LAI from MODIS to consider the inter-annual variability of the vegetation.

The authors do not use the scores usually used in hydrology.
RESPONSE: The main objective of the study is to evaluate the performance of data assimilation of remotely sensed data into a land surface model in simulating surface soil moisture. We evaluate the performance in terms of RMSE and absolute bias, which is a common practice in most land surface data assimilation studies. To address the reviewer's concern, we now evaluated the performance of the model in simulating daily soil moisture and monthly runoff for 2000 – 2006 time period over PRUDENCE regions using suggested scores as shown below in Table R1.

Table R1: Calculated hydrologic scores to evaluate model performance of daily soil moisture and monthly runoff simulated by CLM-OL and CLM-DA for PRUDENCE regions.

				Soil Moisture					
CLM-OL									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
NSE	-4.56	-0.17	-1.49	-1.52	-1.66	-1.71	-1.32	-1.81	-1.96
KGE	0.30	0.70	0.35	0.25	0.02	0.26	0.69	0.16	0.27
RMSE*	0.06	0.05	0.07	0.07	0.05	0.06	0.06	0.08	0.05
%BIAS	23.80	24.50	27.40	24.90	18.60	21.90	27.50	32.10	25.00
CLM-DA									
NSE	-0.14	0.60	0.27	0.16	-0.29	0.19	0.51	0.08	0.15
KGE	0.60	0.71	0.71	0.63	0.23	0.61	0.61	0.56	0.59
RMSE	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.04	0.03
%BIAS	5.80	-3.00	7.90	6.90	6.30	6.80	5.40	9.20	5.40
				Runoff					
CLM-OL									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
NSE	-3.7	-0.3	-9.5	-10.2	-19.3	-18.3	-9.2	-102.6	-47.4
KGE	-0.4	0.0	-1.8	-1.3	-1.9	-1.7	-1.6	-5.9	-2.9
RMSE	1.2	0.4	1.1	0.8	1.4	1.7	0.9	1.1	0.9
%BIAS	115.9	67.9	221.3	163.3	182.5	149.2	192.8	359.6	186.8
CLM-DA									
NSE	-1.46	-0.64	-0.55	-0.35	-0.65	-1.91	-0.52	-0.63	-1.66
KGE	-0.09	-0.33	-0.11	0.33	0.26	0.20	0.17	0.13	0.17
RMSE	0.85	0.41	0.42	0.29	0.40	0.66	0.34	0.14	0.20
%BIAS	-76.50	-81.10	-69.70	-51.30	-8.30	-47.90	-49.70	-12.10	-33.30

* units for RMSE are mm^3/mm^3 and mm/day for soil moisture and runoff, respectively.

While we see the value of including more scores for evaluating model performance, we note that including other scores does not change our conclusions. With respect to NSE and KGE, we clearly see a significant improvement in simulated soil moisture for CLM-DA in comparison to CLM-OL over all PRUDENCE analysis regions, except for region Scandinavia. For runoff, overall we see relatively less improvements in terms of NSE and KGE. In the land surface models such as CLM, the representation of runoff is often simplistic and conceptual and many previous studies have shown that performance of CLM model in simulating hydrological processes varies based on regions. This might be attributed to the fact that assumptions to estimate surface and subsurface runoff in the model might be valid in some regions but not in other regions (e.g. humid vs. dry regions). We also noted similar behavior of CLM in our study where the assimilation of soil moisture helps to improve runoff in some regions but degraded in other regions. Our results agree well with other data assimilation studies (e.g. Albergel et al., 2017; Parajka et al., 2006; Crow et al., 2006) which showed that assimilation is more effective in modifying the surface soil moisture but found little improvements to the discharge as a result of the remotely sensed soil moisture assimilations. This also highlights the need to jointly use soil moisture and discharge observations to improve global and continental hydrological and/or rainfall-runoff models, but this is beyond the scope of the current manuscript.

The paper is poorly organized (no Discussion section).

RESPONSE: A discussion section is added in the revised manuscript.

Specific comments:
- P. 1, L. 21 (independent CCI-SSM observations): do you mean observations independent from CCI-SM? They should be!
RESPONSE: In this study, we randomly selected 100 locations to assimilate the ESA CCI data into the CLM model, while the remaining data was used for independent validation. In the manuscript we state "The soil moisture validation of the CLM-DA and CLM-OL simulations used all the available CCI-SM data in the time period of 2000 to 2006. This approach also allowed us to independently cross-validate the SM values over grid cells that were not used in the data assimilation."

- P. 3, L. 3: 10**0km?
RESPONSE: 10^0km

- P. 4, L. 3 (CLM): how is vegetation represented in this version of the model?
RESPONSE: We prescribed vegetation as the fractional coverage of different vegetation types according to MODIS land cover dataset for year 2001, which contains 21 land cover types defined by the International Geosphere-Biosphere Program (IGBP) (Friedl et al., 2002). For each land cover, average monthly leaf and stem area index (LAI and SAI) values are based on the global CLM3.5 surface dataset, which was created using the multiyear MODIS land surface data products (Oleson et al., 2008). This is now explained in the revised manuscript.

- P. 5, L. 5 (LAI): does this mean that LAI for a given month is the same from one year to another? Given the marked impact of LAI on evapotranspiration, this might introduce marked soil moisture biases.
RESPONSE: As mentioned in the previous comment, in the current modeling setup we prescribed static vegetation cover as the fractional coverage of different land cover type and for each type, we specify the average monthly LAI values based on global CLM 3.5 surface dataset (Oleson et al., 2008). In the revised manuscript, we will replace the CLM default PFT-specific annual LAI-cycles with prescribed LAI from MODIS to account for the inter-annual variability of the vegetation.

- P. 5, L. 20 (6 km): it is written in the Abstract and in Section 2.3.2 that the assimilation was made at a spatial resolution of 3 km. Why such a mismatch with the spatial resolution of atmospheric forcing?
RESPONSE: In our study, we used the high-resolution reanalysis system COSMO-REA6 from Hans-Ertel Centre for Weather Research (HErZ; Simmer et al., 2016) dataset, which is available at 6km resolution. However, we performed model simulations over the EURO-CORDEX domain at 3km resolution, which is inscribed into the official EUR-11 grid at 0.11° spatial resolution. To match the model resolution, the 6km COSMO-REA6 was interpolated to 3km resolution.

- P. 7, L. 4: E-OBS was not defined before.
RESPONSE: Thanks you for pointing this out. We have now defined the E-OBS.

- P. 11, L. 13 (this study demonstrates): I am not convinced, there is no demonstration.

RESPONSE: The original statement has been revised for clarity.

- P. 11, L. 32 (soil texture): Absolute CCI-SM values depend on pedotransfer functions and texture of the NOAH model. They are not "observed" and they should not be taken for granted. This is not a good way of doing data assimilation.

RESPONSE: We can't completely agree with this comment. According to Dorigo et al., 2017, "the European Space Agency CCI soil moisture product is the first multi-decadal, global satellite-observed soil moisture (SM) dataset as part of its Climate Change Initiative (CCI) program. This product, named ESA CCI SM, combines various single-sensor active and passive microwave soil moisture products into three harmonised products: a merged ACTIVE, a merged PASSIVE, and a COMBINED active + passive microwave product." It is true that the soil moisture values in the passive microwave product is not entirely model-independent, for the combined product (i.e. active + passive microwave product), the systematic differences between ACTIVE and PASSIVE are corrected by matching the CDF of each pixel against long-term LSM-based soil moisture, which is provided by GLDAS-Noah.
Several authors (e.g. Albergel et al., 2013, 2017; Dorigo et al., 2017; McNally et al., 2016; Wagner et al., 2012) have highlighted the quality and stability of the product. For example Albergel et al., 2017 assimilated the CCI soil moisture data into the land surface model over the Euro-Mediterranean region for the time period of 2000 – 2012.
In addition, in this study we use an observation uncertainty during assimilation, as stated already in the manuscript: "In this study, we assumed a spatially uniform observational error for CCI-SM (i.e. 0.02 mm3/mm3) in the CLM-PDAF setup." Therefore, the experimental design follows a usual and adequate way of doing data assimilation.

- P. 22, Table 1: what about other key hydrological scores such as KGE or NSC? Given what can be seen in Fig. 10, I doubt these scores are improved by the assimilation.

RESPONSE: See our previous response and Table R1 above to the comment on hydrological scores.

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