Project Title: Upgrading a climate model to improve regional climate projections

Acronym: UpClim

Deliverable 3.9
Assessing the impact of land use forcing

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Technical References

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Department	SCHOOL OF GEOLOGY
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Terms, definitions and abbreviated terms

The following acronyms have been used across this document:

ACRONYM	FULL TERM
D3.9	Deliverable number 9 belonging to WP 3
WP	Working Package
WRF	Weather Research and Forecasting
LUC	Land Use Change
WCRP	World Climate Research Program
CORDEX	Coordinated Downscaling Experiment
FPS	Flagship Pilot Study
LUCAS	Land Use and Climate Across Scales
ERA5	ECMWF reanalysis data
CMIP6	Coupled Model Intercomparison Project (Phase 6)
ARW	Advanced Research dynamic solver
ECMWF	European Center for Medium-Range Weather Forecast
IFS	Integrated Forecasting System
C3S	Copernicus Climate Change Service
LULC	Land Use Land Cover
RCM	Regional Climate Model
LU	Land Use
NMS	National Meteorological Services

1 Introduction

Deliverable 3.9 (D3.9) is related to Task 3.3 "*Assessing the impact of land use forcing*" under WP3, "*Implementation of land use forcing*" in the framework of the UpClim project. One of the main goals of the UpClim project is to assess the impact of land use changes on regional climate over Europe. For this purpose, we employed the Weather Research and Forecasting (WRF) model and implement yearly Land Use Change (LUC) information into the model, following international coordinated protocols of the CORDEX Flagship Pilot Study (FPS) Land Use and Climate Across Scales (LUCAS) (Rechid et al., 2017). The protocol developed within LUCAS was followed in this work, to ensure the comparability and consistency of these simulations with the modeling ensemble members of the CORDEX community. To assess the impact of land use changes on regional climate two regional climate simulations were performed, one with static and one with dynamic land use changes.

2 Numerical simulations

The WRF model has been widely used as a regional climate model (Katragkou et al., 2015) and is an official model-member of the Ensemble Desing Matrix of Coupled Model Intercomparison Project (CMIP6)/EUROCORDEX (Katragkou et al., 2024). For the purposes of Task 3.3 "Assessing the impact of land use forcing", the non-hydrostatic WRF model with the Advanced Research dynamic solver (WRF-ARW, v4.5.1) has been utilized. More specifically, the selected model version is 4.5.1.4 (WRF451Q) which includes some additional modifications and improvements in NoahMP land use model (Yang et al., 2011), available from the CORDEX WRF community fork (git clone --recursesubmodules -b v4.5.1.4 https://github.com/CORDEX-WRF-community/WRF.git). Comprehensive descriptions of the WRF schemes applied are provided in the earlier deliverables D3.7 and D3.8.

The official EURO-CORDEX domain at 0.11° resolution (EUR-11) was adopted and driven by ERA5 reanalysis data (Hersbach et al., 2020). ERA5 is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) using the Integrated Forecasting System (IFS) Cy41r2, with a horizontal resolution of approximately 31 km, 137 vertical levels, and hourly output frequency. The dataset is available through the Copernicus Climate Change Service (C3S; Thepaut et al., 2018) and is provided on a regular latitude–longitude grid with a horizontal spacing of 0.25° × 0.25°.

Two simulations were performed: one with static land use change fixed to 2015 (hereafter referred to as CNTRL simulation) and a second, otherwise identical in which land use was dynamically updated each simulation year (hereafter UpClim-LUC simulation). The evolution of land use in this study follows Hoffmann et al. (2023). Details in the implementation of land use change in WRF are provided in D3.7. Both simulations covered a five-year period, from 1980 to 1984, with a spin up time of 1 year and 5 months.

3 Data and Methodology

The WRF simulations are validated using E-OBS v31.0e[1] temperature and precipitation at 0.11° resolution. The E-OBS data set is supplied by numerous National Meteorological Services (NMSs) and other providers across Europe and the Middle East, but data exchange restrictions limit station availability. As only certain agencies have increased the number of contributing stations, an increasing disparity in station density has emerged across the domain, with relatively high station densities in central Europe and Scandinavia and substantially lower densities toward the southern and eastern parts of the domain. The uncertainty quantified in the ensemble data set is strongly linked to station density and, despite being larger in data-sparse areas, likely

1 Copernicus Climate Change Service, Climate Data Store, (2020): E-OBS daily gridded meteorological data for Europe from 1950 to present derived from in-situ observations. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.151d3ec6 (Accessed on 05-12-2025)

underestimates the true uncertainty (Cornes et al., 2018).

Soil moisture is also evaluated using the European Space Agency Climate Change Initiative (ESA CCI) combined satellite soil moisture dataset at 0.25° resolution (version 5.2). The ESA Climate Office integrates both passive and active satellite observations to produce daily global soil moisture fields with near-complete spatial coverage. In datasets of this type, a standardized definition of the surface soil layer is not available; however, it is generally assumed to represent a depth of approximately 0.02–0.05 m (Ulaby et al., 1996). Accordingly, soil moisture from the first soil layer in the WRF simulations, which has a depth of 0.05 m, is used for comparison.

The ESA CCI combined soil moisture products generally show good agreement with in situ observations in temperate climates, particularly over grasslands and agricultural regions, as well as in semi-arid areas. However, they exhibit limitations in capturing temporal variability in the driest and wettest regions. Significant correlations between the ESA CCI combined soil moisture products and land surface models are typically observed in areas with a substantial fraction of bare soil (Dorigo et al., 2017). Despite its utility, the ESA CCI soil moisture dataset has limitations for climate model evaluation, including differences in surface layer thickness, spatial data gaps, and the absence of an independent reference for absolute soil moisture values. Nevertheless, it has been proposed as a reference dataset for validating land surface components in CMIP6 models (PUG, 2024; Van Den Hurk et al., 2016).

As the spatial resolutions of the E-OBS and ESA datasets differ from that of the WRF simulations, the observational data were interpolated to the model grid to ensure a consistent comparison. Bilinear interpolation was applied to temperature (°C), while first-order conservative interpolation was used for precipitation (mm) and soil moisture ($m^3\ m^{-3}$). Bilinear interpolation, which uses the four nearest grid points, provides smooth spatial transitions and is commonly applied to temperature fields. In contrast, conservative interpolation preserves the integral physical properties of the field and is therefore preferable for variables representing accumulated quantities or layer-integrated conditions, such as precipitation and soil moisture (Taylor, 2024).

4 Results

To assess the influence of land use forcing on regional climate across Europe and evaluate model performance, we compute a) the differences of the two simulations (CNTRL vs UpClim-LUC) and b) the biases of both simulations against observations: MODEL – OBS (in situ or satellite-derived). The analysis focuses on mean seasonal values over the study period (1980-1984) for three key variables: a) surface temperature, b) precipitation and c) soil moisture at the top-soil model level. In addition, histograms of mean seasonal values are also provided to illustrate variables distributions in the European region, based on the applied land mask (Figure 1). The mask was used to include only values within the EUR-11 regions of WRF simulations, while excluding values over Africa. To quantify the average difference between the model simulations and the observed values, we calculated the Root Mean Square Error (RMSE). Low RMSE values indicate more accurate model performance. The analysis is undertaken over the whole European domain and over the following subregions: Alps (AL), British Isles (BI), eastern Europe (EA), France (FR), mid-Europe (ME), Mediterranean (MD), Iberian Peninsula (IP) and Scandinavian Peninsula (SC). These subdomains are described in Christensen and Christensen (2007).

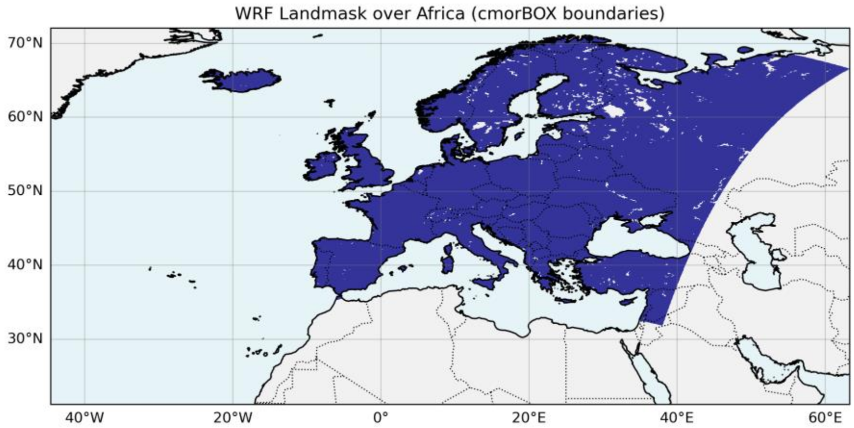

Figure 1: Tailor-made land mask excluding Africa.

4.1 Surface Temperature

According to **Error! Reference source not found.**, for the period 1980-1984 comparison of the control simulation with no land use changes (CNTRL) with the UpClim-LUC simulation with yearly dynamical land use changes shows that **model differences in surface temperature are larger during the summer** (JJA) season (Table 4.1-c) compared to winter values (Table 4.1-a). The impact of land use changes on surface temperature in summer ranges from 1.5^{o}C in southern Europe to 0.2^{o}C in northern Europe. During wintertime the differences between the two simulations are smaller (0 to 0.5^{o}C). Comparisons with E-OBS indicate that the **CNTRL simulation has on average cold winter bias over Europe and predominantly warm bias in summer**. In the UpClim-LUC simulations the biases in summer are improved by becoming less warm or slightly cold, the changes in winter are small. The differences in surface temperature for all European subregions, each season for the two simulations are shown in Table 4.1-a. Figure 4-2 shows the seasonal RMSE for both simulations compared to E-OBS and Figure 4-2 exhibits the climatology of the CTRL simulation.

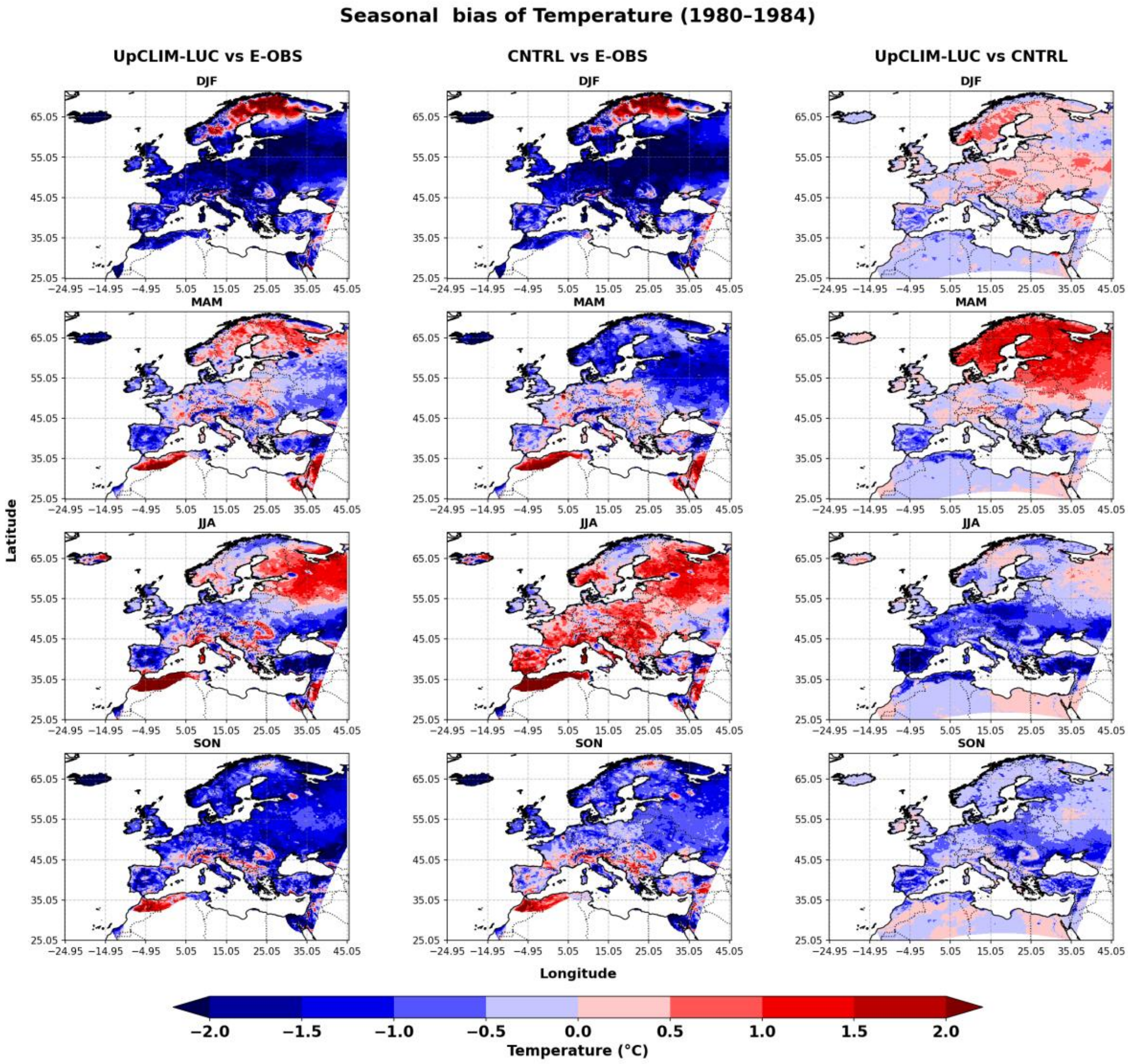

Figure 4-1: Seasonal bias of temperature (°C) for the period 1980-1984. UpClim-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use. The first column refers to the bias of UpClim-LUC (WRF minus E-OBS dataset), the second to the bias of CNTRL; the third refers to the difference between UpClim-LUC and CNTRL simulations.

Winter (DJF)									
Dataset	**AL**	**BI**	**EA**	**FR**	**IP**	**MD**	**ME**	**SC**	**GR**
UpCLIM-LUC vs E-OBS	-1.4	-1.0	-1.8	-1.5	-1.2	-1.4	-1.8	-0.4	-1.2
CNTRL vs E-OBS	-1.4	-0.9	-2.1	-1.4	-0.8	-1.1	-1.9	-0.5	-0.7
UpCLIM-LUC vs CNTRL	0.0	-0.1	0.2	-0.1	-0.4	-0.3	0.0	0.1	-0.5

Table 4.1-a: Mean seasonal bias of temperature (°C) in Europe for 1980-1984 period during winter. UpCLIM-LUC refers to driven by ERA5 reanalysis data transient LUC simulation, while the CNTRL is the control run with static LUCs. AL: Alps, BI: British Isles, EA: Eastern Europe, FR: France, IP: Iberian Peninsula, MD: Mediterranean, ME: Mid-Europe, SC: Scandinavia, GR: Greece

Spring (MAM)									
Dataset	**AL**	**BI**	**EA**	**FR**	**IP**	**MD**	**ME**	**SC**	**GR**
UpCLIM-LUC vs E-OBS	-0.3	-0.5	-0.2	-0.1	-0.8	-0.3	-0.2	0.1	-0.4
CNTRL vs E-OBS	-0.4	-0.5	-0.2	0.0	-0.3	-0.1	-0.2	-0.9	-0.1
UpCLIM-LUC vs CNTRL	0.2	0.0	0.1	-0.1	-0.5	-0.2	0.0	1.1	-0.3

Table 4.1-b: Same as in Table 4.1-a, but for spring.

Summer (JJA)									
Dataset	**AL**	**BI**	**EA**	**FR**	**IP**	**MD**	**ME**	**SC**	**GR**
UpCLIM-LUC vs E-OBS	0.2	-0.5	-0.3	-0.4	-0.7	0.0	-0.6	0.1	-0.6
CNTRL vs E-OBS	0.8	-0.3	0.7	0.5	0.8	0.6	0.3	0.3	-0.1
UpCLIM-LUC vs CNTRL	-0.6	-0.2	-1.0	-0.9	-1.5	-0.6	-0.8	-0.2	-0.6

Table 4.1-c: Same as in Table 4.1-a, but for summer.

Autumn (SON)									
Dataset	**AL**	**BI**	**EA**	**FR**	**IP**	**MD**	**ME**	**SC**	**GR**
UpCLIM-LUC vs E-OBS	-0.3	-0.9	-1.1	-0.7	-0.8	-0.5	-1.0	-1.1	-0.7
CNTRL vs E-OBS	-0.1	-0.7	-0.4	-0.2	-0.1	-0.2	-0.5	-0.7	-0.3
UpCLIM-LUC vs CNTRL	-0.2	-0.2	-0.7	-0.4	-0.6	-0.3	-0.5	-0.5	-0.4

Table 4.1-d : Same as in Table 4.1-a, but for autumn.

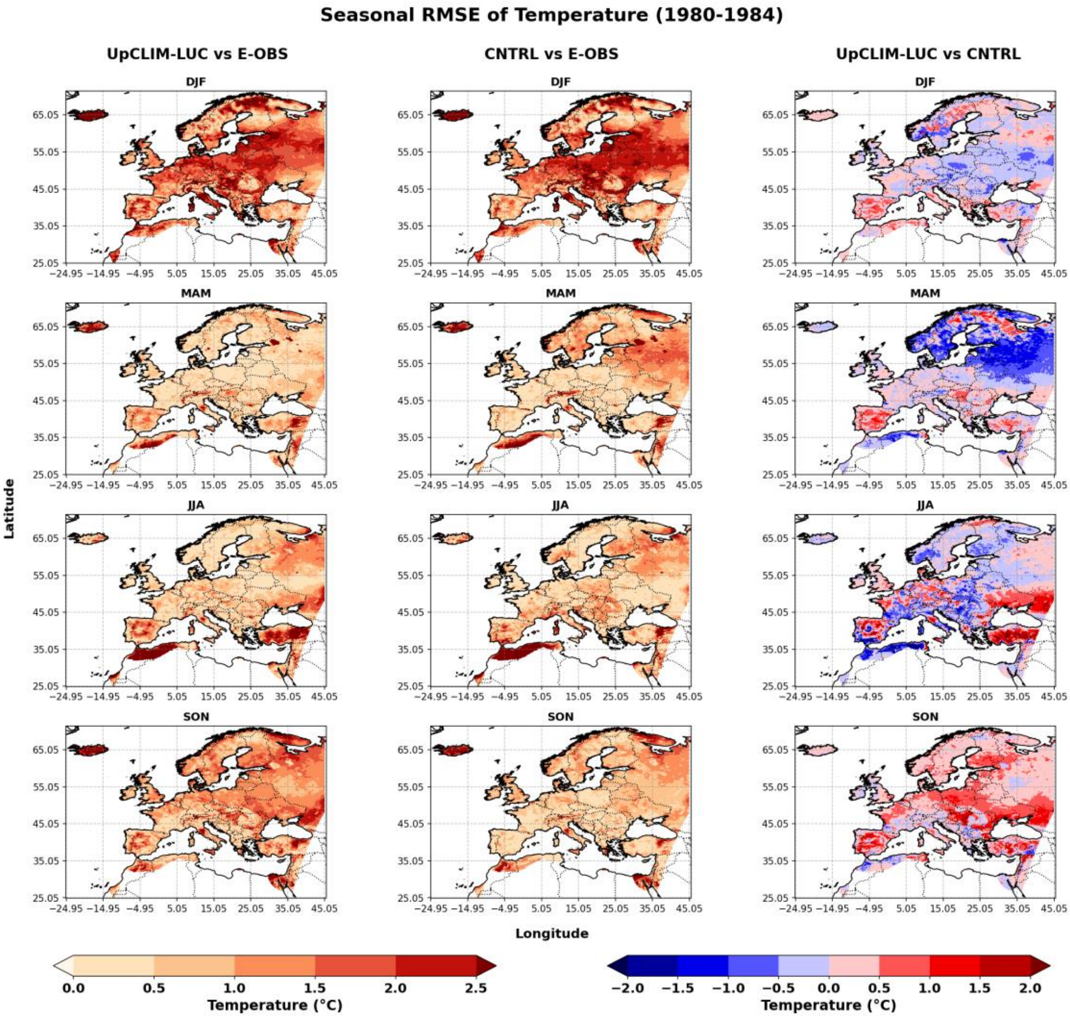

Figure 4-2: Seasonal Root Mean Square Error (RMSE) of temperature (°C) for the period 1980-1984. UpCLIM-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use. The first column refers to the RMSE of UpCLIM-LUC (relative to E-OBS dataset), the second to the RMSE of CNTRL (relative to E-OBS dataset); the third refers to the difference between the RMSE of UpCLIM-LUC and CNTRL simulations.

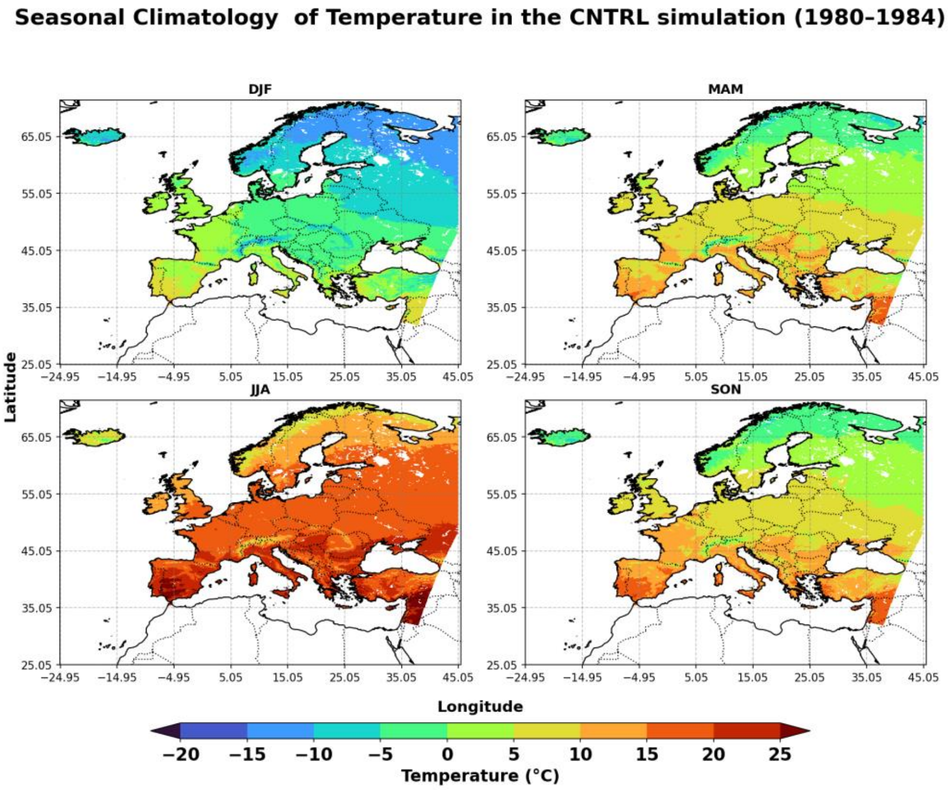

Figure 4-3: Seasonal climatology of temperature in the CNTRL simulations for the period 1980-1984.

4.2 Precipitation

According to Figure 4-4, a predominantly positive precipitation bias is observed across all seasons, indicating that the model generally overestimates precipitation over Europe. Differences in precipitation between the two simulations are small, in the range of 0.1% to 6% in winter corresponding to 0.02 mm to 0.13 mm, respectively (Table 4.2-a). In summer the differences expressed in % are larger (3 to 25%). **The effect of land use changes seems to be affecting mostly the warm season precipitation**. For all European subregions the UpClim-LUC simulations produce more precipitation than the CNTRL simulation, deteriorating thus the wet bias. Seasonal precipitation in the CNTRL simulation (Figure 4-5) is shown in Figure 4-7.

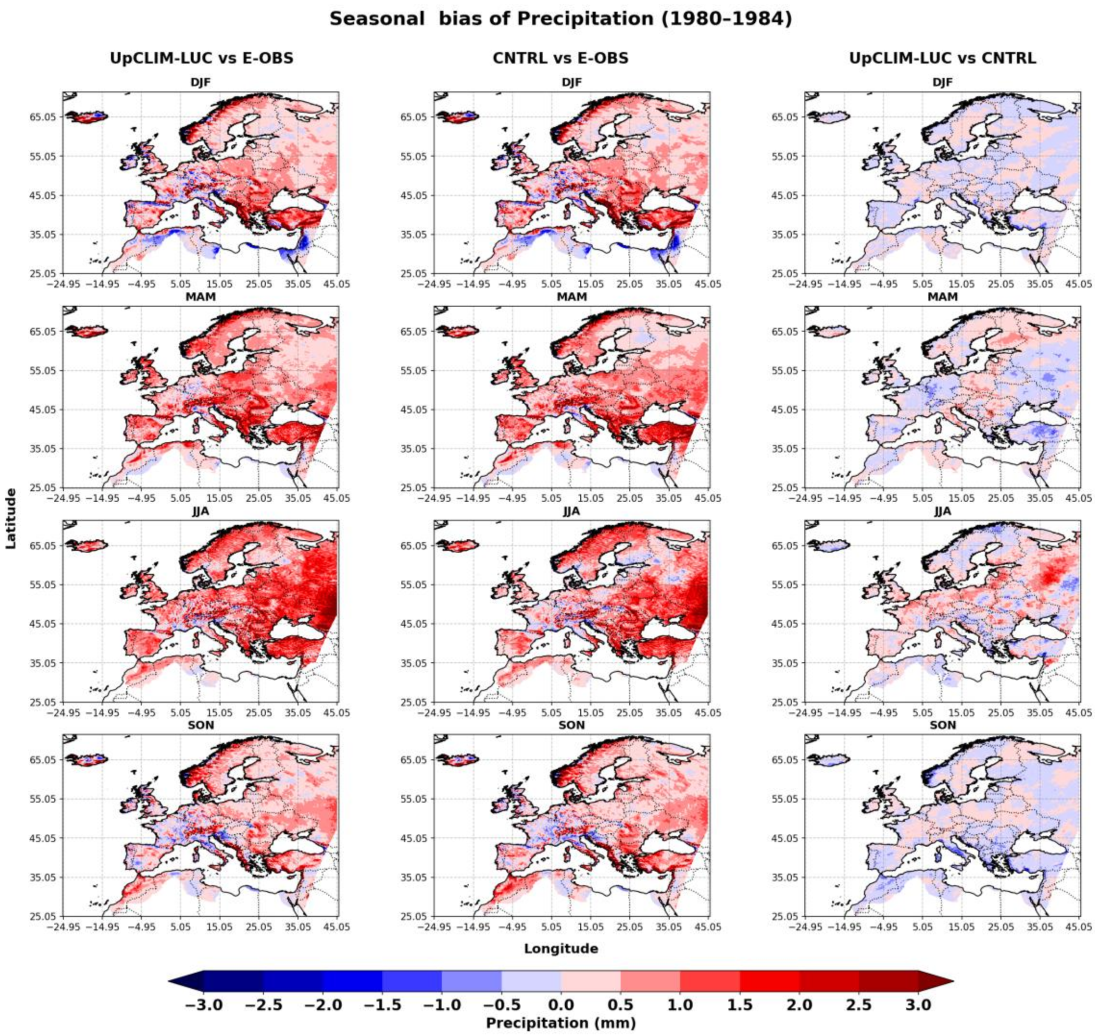

Figure 4-4: Seasonal bias of precipitation (mm) for the period 1980-1984. UpClim-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land. . The first column refers to the bias of UpClim-LUC (WRF minus E-OBS dataset), the second to the bias of CNTRL; the third refers to the difference between UpClim-LUC and CNTRL simulations.

Winter (DJF)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs E-OBS	0.40 (17.2%)	0.16 (13.4%)	0.68 (59.1%)	0.34 (14.6%)	0.43 (41.9%)	1.17 (55.8%)	0.30 (22.6%)	0.43 (34.6%)	1.63 (63.9%)
CNTRL vs E-OBS	0.43 (20.3%)	0.24 (15.3%)	0.71 (61.5%)	0.28 (12.7%)	0.56 (50.1%)	1.23 (57.1%)	0.33 (24.1%)	0.46 (35.5%)	1.71 (63.6%)
UpCLIM-LUC vs CNTRL	-0.03 (-2.5%)	-0.09 (-1.7%)	-0.03 (-1.1%)	0.05 (1.8%)	-0.13 (-5.8%)	-0.06 (-0.7%)	-0.02 (-0.9%)	-0.02 (-0.1%)	-0.08 (0.1%)

Table 4.2-a: Mean seasonal bias of precipitation (mm) and relative bias (% in brackets) in Europe for 1980-1984 period during winter. UpClim-LUC refers to driven by ERA5 reanalysis data transient LUC simulation, while the CNTRL is the control run with static LUCs. AL: Alps, BI: British Isles, EA: Eastern Europe, FR: France, IP: Iberian Peninsula, MD: Mediterranean, ME: Mid-Europe, SC: Scandinavia, GR: Greece

Spring (MAM)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs E-OBS	1.02 (38.5%)	0.79 (38.8%)	0.97 (67.4%)	0.50 (21.1%)	0.80 (47.3%)	1.20 (80.4%)	0.40 (23.9%)	0.68 (59.2%)	1.05 (67.6%)
CNTRL vs E-OBS	1.00 (37.3%)	0.78 (38.7%)	0.82 (57.6%)	0.54 (22.8%)	0.83 (49.1%)	1.05 (72.0%)	0.58 (31.7%)	0.53 (44.9%)	1.14 (72.4%)
UpCLIM-LUC vs CNTRL	0.01 (1.9%)	0.01 (0.1%)	0.15 (6.7%)	-0.04 (-1.2%)	-0.03 (-0.9%)	0.14 (6.0%)	-0.18 (-6.1%)	0.15 (12.3%)	-0.08 (-3.2%)

Table 4.2-b: Same as inTable 4.2-a, for spring.

Summer (JJA)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs E-OBS	0.56 (18.6%)	0.65 (34.8%)	1.10 (51.7%)	0.51 (28.4%)	0.76 (183.6%)	0.84 (341.5%)	0.78 (36.9%)	0.74 (35.0%)	1.20 (584.9%)
CNTRL vs E-OBS	0.46 (16.5%)	0.37 (19.6%)	0.92 (43.5%)	0.23 (12.9%)	0.56 (130.5%)	0.81 (315.8%)	0.40 (18.7%)	0.63 (30.3%)	1.19 (404.2%)
UpCLIM-LUC vs CNTRL	0.10 (3.2%)	0.28 (13.2%)	0.19 (6.8%)	0.28 (14.5%)	0.19 (25.5%)	0.03 (12.7%)	0.39 (15.8%)	0.11 (5.6%)	0.01 (22.2%)

Table 4.2-c: Same as in Table 4.2-a, for summer.

Autumn (SON)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs E-OBS	0.31 (10.6%)	0.18 (7.2%)	0.38 (30.8%)	-0.01 (-0.2%)	0.21 (16.8%)	0.54 (29.8%)	0.30 (18.6%)	0.51 (23.5%)	1.05 (71.4%)
CNTRL vs E-OBS	0.22 (7.2%)	0.11 (5.5%)	0.38 (30.7%)	-0.05 (-1.8%)	0.31 (24.3%)	0.87 (49.1%)	0.24 (15.7%)	0.56 (24.8%)	1.37 (94.2%)
UpCLIM-LUC vs CNTRL	0.09 (3.2%)	0.07 (1.8%)	0.00 (0.6%)	0.04 (2.0%)	-0.10 (-5.1%)	-0.33 (-12.2%)	0.05 (2.6%)	-0.06 (-0.7%)	-0.32 (-11.7%)

Table 4.2-d: Same as in Table 4.2-a, for autumn.

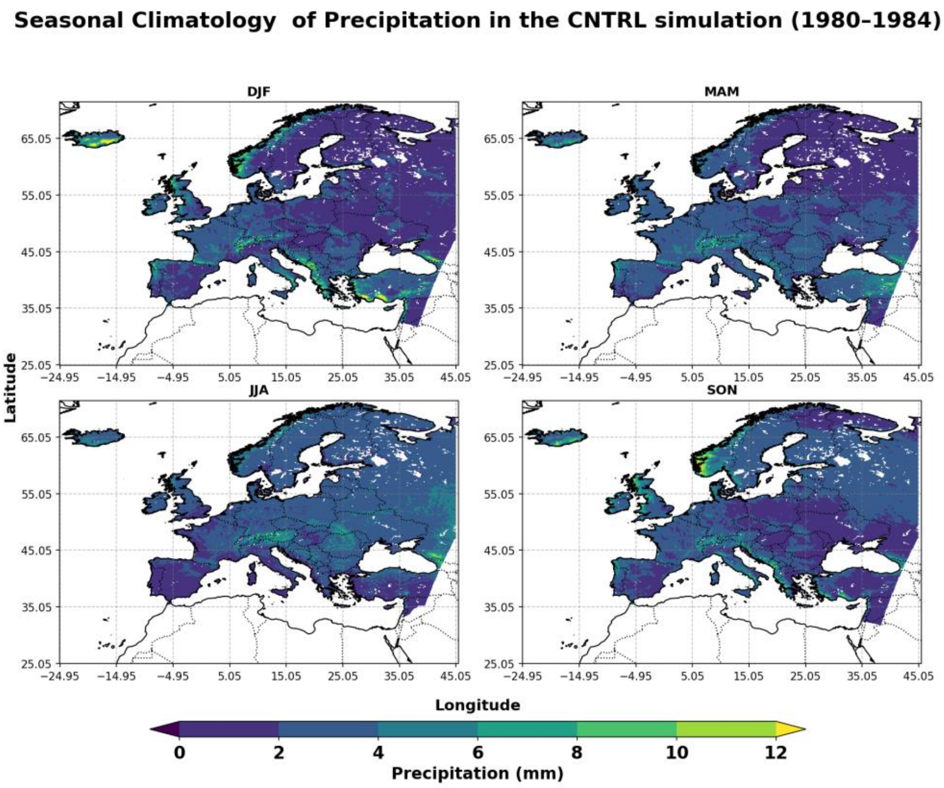

Figure 4-5 Seasonal climatology of precipitation in the CNTRL simulations for the period 1980-1984. Climatology is calculated for areas where E-OBS data are available for comparison.

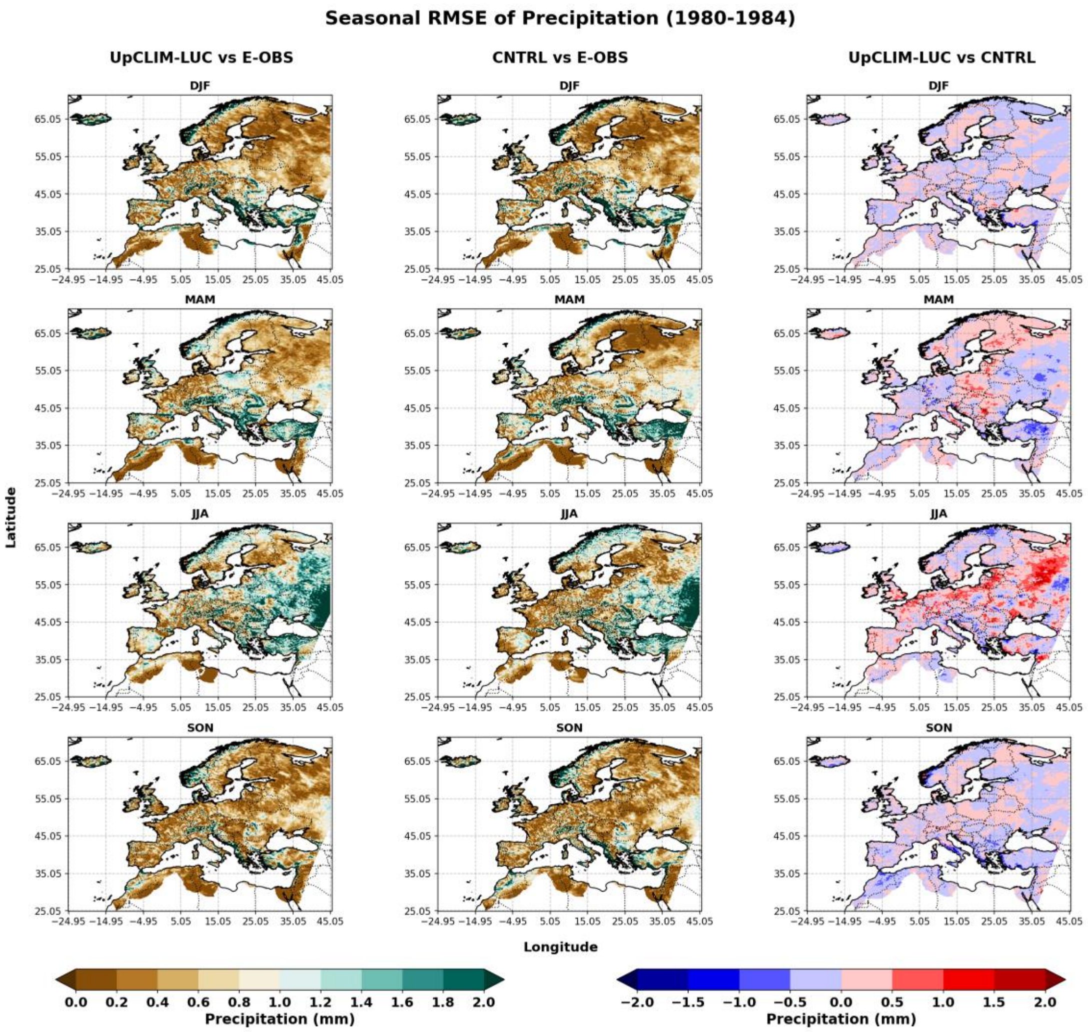

Figure 4-6: Seasonal Root Mean Square Error (RMSE) of precipitation (mm) for the period 1980-1984. UpClim-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use. The first column refers to the RMSE of UpClim-LUC (relative to E-OBS dataset), the second to the RMSE of CNTRL (relative to E-OBS dataset), the third refers to the difference between the RMSE of the UpClim-LUC and CNTRL simulations.

According to Figure 4-6, the highest RMSE values appear during summer over Eastern Europe –an area that simultaneously exhibits the strongest positive seasonal precipitation bias. The precipitation distribution in E-OBS is unimodal (Figure 4-7), as in the case of both simulations. Figure 4-7 exhibit the seasonal histograms of precipitation for Europe. The agreement between the observed (E-OBS) data and the modeled values are better in winter (DJF). Larger discrepancies are seen in summer (JJA): **observed summer precipitation has higher frequency in lower precipitation size bins (<2 mm) and much lower frequency in higher precipitation size bins (<3 mm)),** explaining the wet precipitation biases of the simulations.

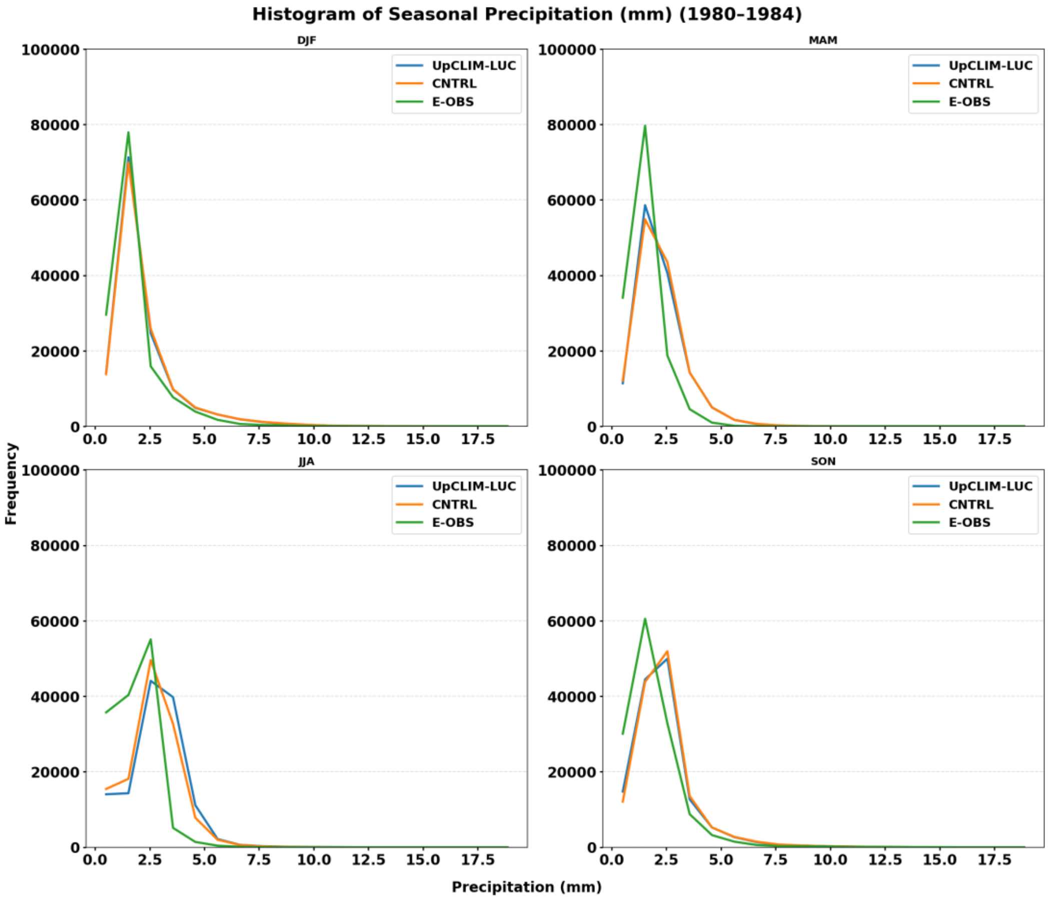

Figure 4-7: Histogram of mean seasonal precipitation (mm) for the period 1980-1984. UpClim-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use.

4.3 Soil moisture

As shown in Figure 4-8, the differences in soil moisture between the two simulations are small for all seasons. **Both simulations exhibit wet soil moisture bias**, with respect to the ESA-CCI soil moisture product. The wet soil bias is higher in winter compared to the summer values, ranging from 112% (AL) to 240% (SC) over the different European subregions in the CNTRL run. RMSE values for both simulations compared to ESA CCI soil moisture are shown in Figure 4-9.

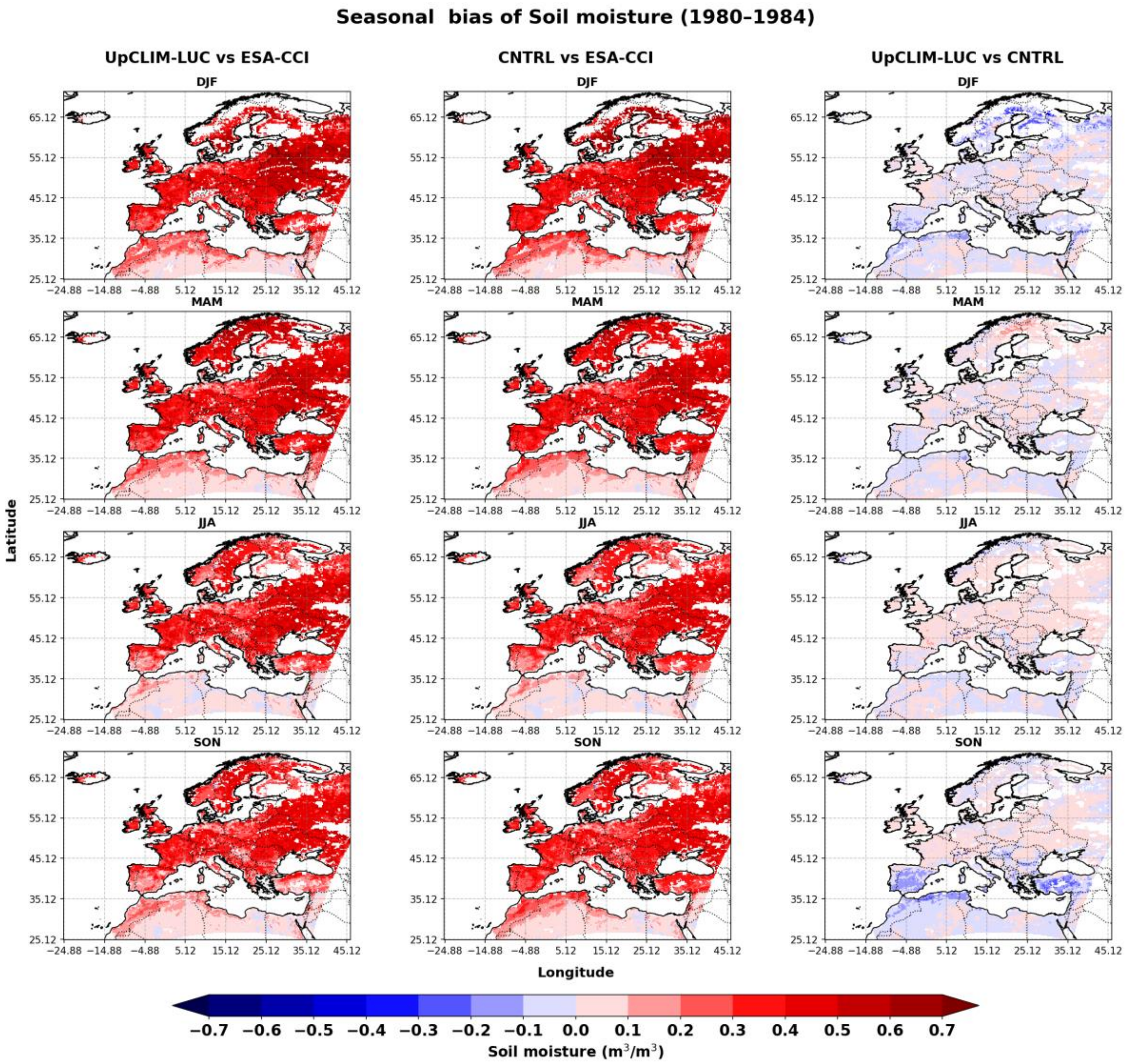

Figure 4-8: Seasonal bias of soil moisture (m^3/m^3) for the period 1980-1984. UpCLIM-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use. . The first column refers to the bias of UpClim-LUC (WRF minus ESA-CCI dataset), the second to the bias of CNTRL; the third refers to the difference between UpClim-LUC and CNTRL simulations.

Winter (DJF)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs ESA-CCI	0.35 (112.9%)	0.38 (128.5%)	0.45 (179.0%)	0.39 (145.5%)	0.32 (139.8%)	0.36 (137.1%)	0.36 (132.4%)	0.47 (204.9%)	0.36 (140.1%)
CNTRL vs ESA-CCI	0.34 (112.1%)	0.38 (128.1%)	0.45 (176.9%)	0.38 (144.1%)	0.37 (161.4%)	0.38 (144.8%)	0.37 (135.1%)	0.54 (240.8%)	0.38 (147.4%)
UpCLIM-LUC vs CNTRL	0.00 (0.7%)	0.00 (0.2%)	0.01 (0.8%)	0.00 (0.5%)	-0.05 (-8.4%)	-0.02 (-3.1%)	-0.01 (-1.2%)	-0.08 (-9.6%)	-0.02 (-3.0%)

Table 4.3-a Mean seasonal bias of soil moisture (m^3/m^3) and relative bias (% in brackets) in Europe for 1980-1984 period during winter. UpClim-LUC refers to driven by ERA5 reanalysis data transient LUC simulation, while the CNTRL is the control run with static LUCs. AL: Alps, BI: British Isles, EA: Eastern Europe, FR: France, IP: Iberian Peninsula, MD: Mediterranean, ME: Mid-Europe, SC: Scandinavia, GR: Greece

Spring (MAM)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs ESA-CCI	0.38 (127.6%)	0.36 (122.7%)	0.40 (161.0%)	0.39 (154.3%)	0.34 (150.2%)	0.36 (141.3%)	0.34 (123.5%)	0.46 (200.1%)	0.37 (154.3%)
CNTRL vs ESA-CCI	0.37 (126.2%)	0.36 (121.9%)	0.39 (158.4%)	0.39 (152.2%)	0.36 (158.8%)	0.36 (141.6%)	0.34 (122.6%)	0.44 (188.6%)	0.37 (155.4%)
UpCLIM-LUC vs CNTRL	0.00 (1.0%)	0.00 (0.3%)	0.01 (0.9%)	0.01 (0.8%)	-0.02 (-3.6%)	-0.00 (-0.2%)	0.00 (0.4%)	0.03 (4.1%)	-0.00 (-0.5%)

Table 4.3-b: Same as in Table 4.3-a, for spring.

Summer (JJA)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs ESA-CCI	0.33 (118.3%)	0.33 (115.6%)	0.37 (164.1%)	0.36 (167.3%)	0.24 (131.0%)	0.26 (127.9%)	0.32 (122.5%)	0.32 (125.5%)	0.27 (144.3%)
CNTRL vs ESA-CCI	0.32 (114.1%)	0.32 (110.1%)	0.35 (155.8%)	0.33 (153.3%)	0.23 (129.4%)	0.26 (130.0%)	0.30 (116.6%)	0.32 (122.9%)	0.27 (149.6%)
UpCLIM-LUC vs CNTRL	0.01 (3.3%)	0.02 (2.6%)	0.02 (3.1%)	0.03 (5.5%)	0.01 (0.1%)	-0.00 (-1.6%)	0.01 (2.6%)	0.01 (1.6%)	-0.01 (-2.1%)

Table 4.3-c: Same as in Table 4.3-a, for summer.

Autumn (SON)									
Dataset	AL	BI	EA	FR	IP	MD	ME	SC	GR
UpCLIM-LUC vs ESA-CCI	0.32 (110.1%)	0.36 (122.6%)	0.34 (137.2%)	0.35 (140.8%)	0.23 (111.4%)	0.24 (102.8%)	0.31 (117.3%)	0.34 (129.0%)	0.20 (98.0%)
CNTRL vs ESA-CCI	0.31 (107.2%)	0.34 (117.2%)	0.34 (137.4%)	0.33 (134.9%)	0.30 (153.0%)	0.29 (126.9%)	0.30 (114.1%)	0.34 (129.6%)	0.28 (135.8%)
UpCLIM-LUC vs CNTRL	0.01 (2.4%)	0.02 (2.5%)	-0.00 (-0.5%)	0.01 (2.5%)	-0.08 (-16.3%)	-0.05 (-10.3%)	0.01 (1.2%)	-0.00 (-0.1%)	-0.07 (-15.4%)

Table 4.3-d: Same as in Table 4.3-a, for autumn.

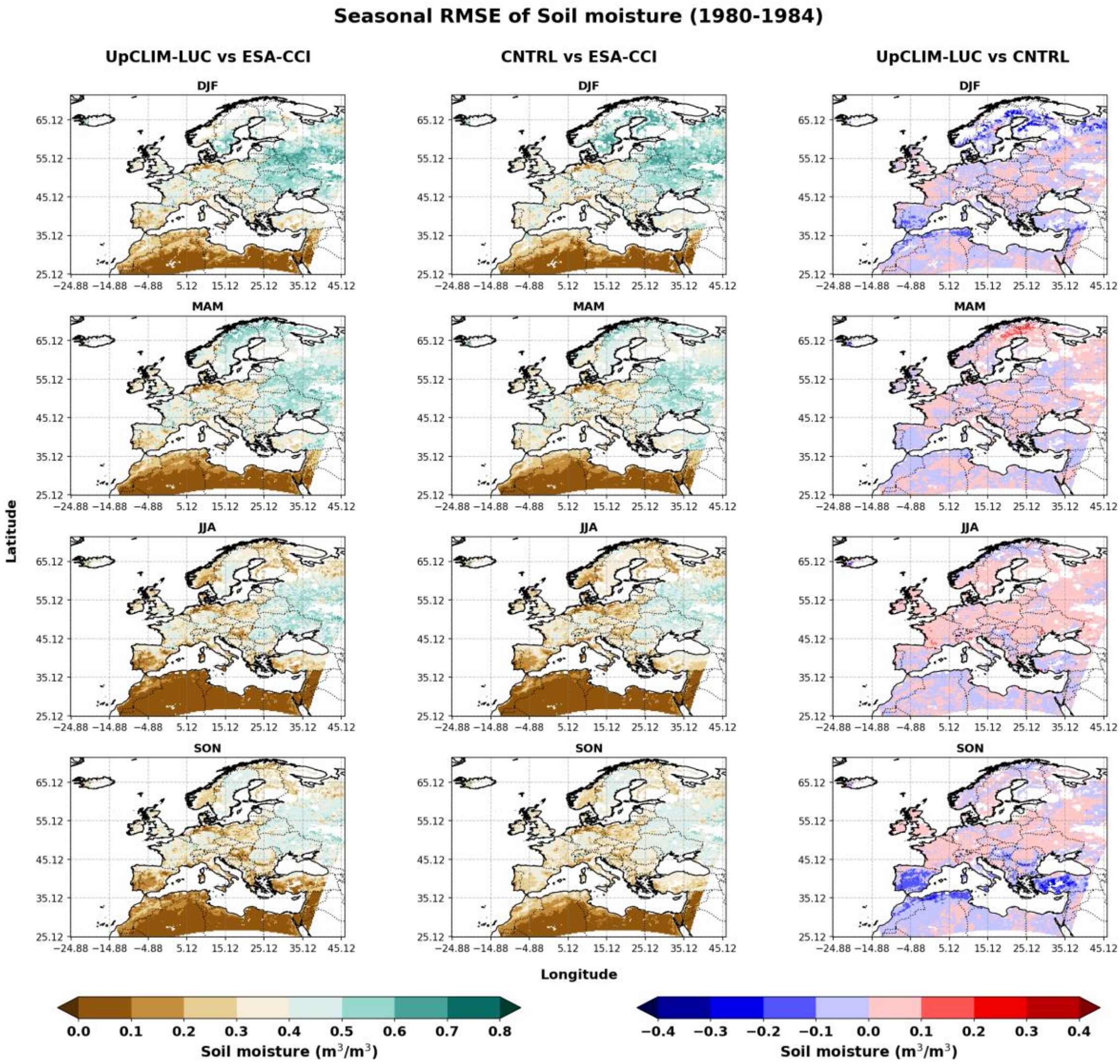

Figure 4-9: Seasonal Root Mean Square Error (RMSE) of soil moisture (m^3/m^3) for the period 1980-1984. UpClim-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use. The first column refers to the RMSE of UpClim-LUC (relative to ESA-CCI dataset), the second to the RMSE of CNTRL (relative to ESA-CCI dataset), the third refers to the difference between the RMSE of the UpClim-LUC and CNTRL simulations.

Soi moisture values in the CNTRL simulation are higher over Eastern Europe throughout all seasons, particularly during winter (Figure 4-12, left panel). In the rest of EUR-11 regions, soil moisture ranges from 0.3 to 0.8 m^3/m^3 across all seasons. Over the Iberian Peninsula, soil moisture values are lower (~0.1 or 0.2 m^3/m^3) during summer.

To investigate the soil moisture of WRF with other reanalysis products we compare with soil moisture of ERA-5 and ERA5-Land (Figure 4-12) and identify that WRF has considerably higher soil moisture than both reanalysis products. The reanalysis dataset (ERA5 and ERA5-Land) exhibit a common soil moisture pattern (**Error! Reference source not found.** (middle and right panels), with high values (~0.6 to 0.7 m^3/m^3) over northern Europe throughout all seasons. In the remaining regions, soil moisture is lower and particularly during summer, soil moisture over the Iberian Peninsula is close to 0.2 m^3/m^3.

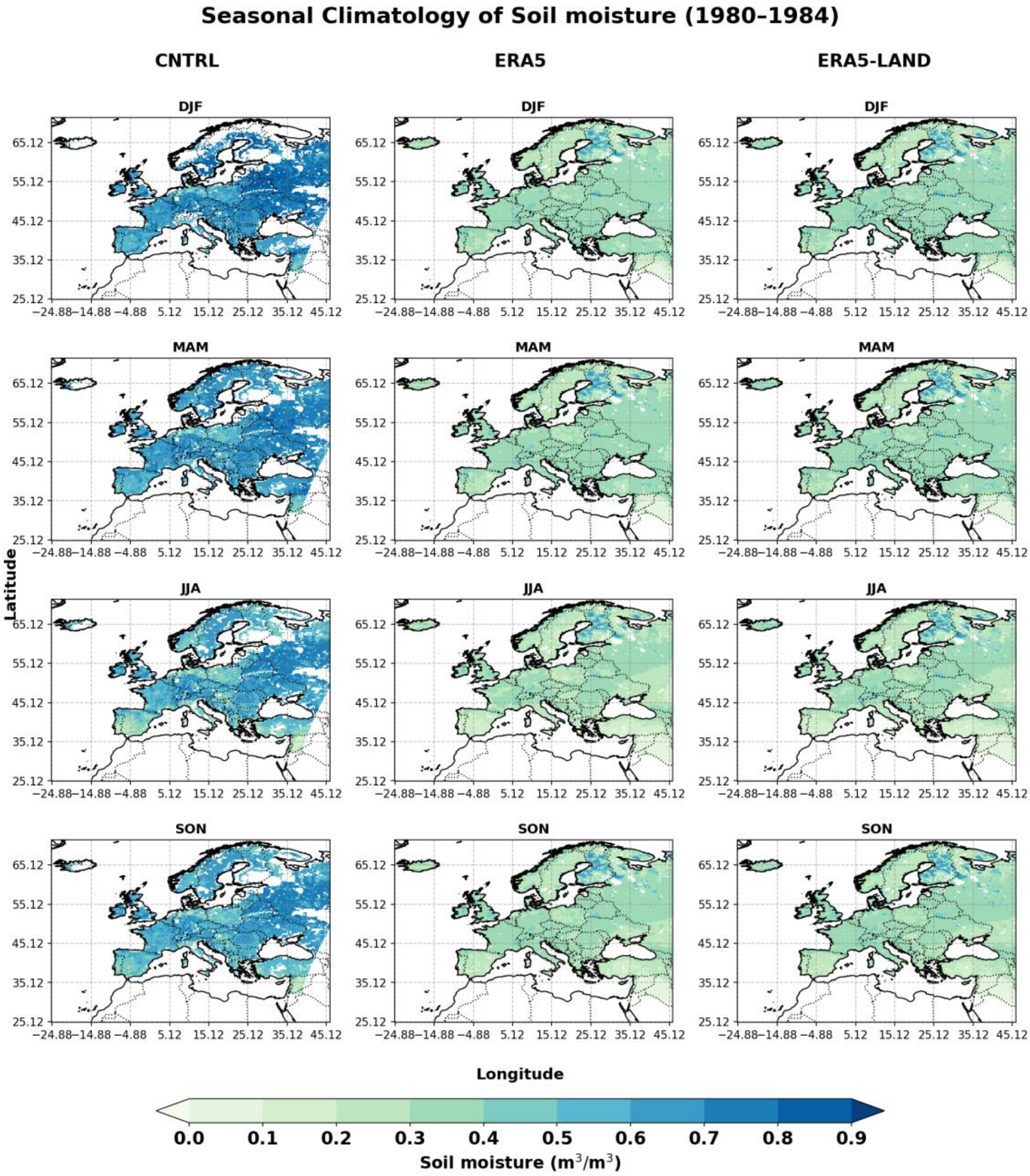

Figure 4-10: Seasonal climatology of soil moisture in the CNTRL ERA5 and ERA5-land reanalysis simulation for the period 1980-1984. Climatology is calculated for areas where ESA-CCI data are available for comparison.

As shown in Figure 4-7, the distribution of soil-moisture values in the ESA-CCI dataset differs substantially from that of the WRF simulations. The ESA distribution extends up to 0.5 m^3/m^3 across all seasons and is unimodal, with the highest frequency occurring close to 0.25 m^3/m^3. In contrast, both the CNTRL and UpClim-LUC simulations exhibit a bimodal distribution, with values ranging from 0.1 m^3/m^3 to approximately 1.0 m^3/m^3. In both simulations, the soil moisture value of about 0.70 m^3/m^3 corresponds to the highest frequency. This feature is in accordance with the considerably higher soil moisture of the simulations compared to the observations depicted in Figure 4-8.

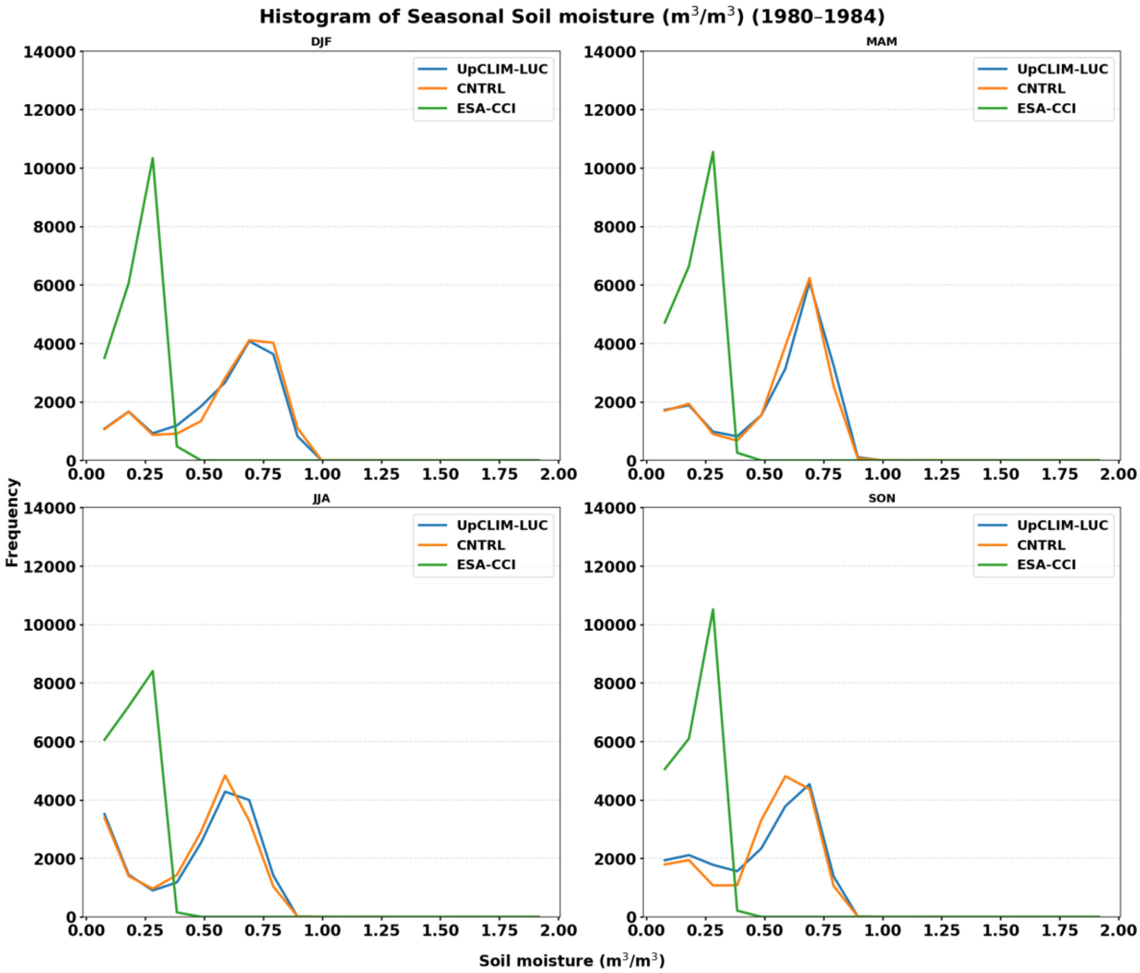

Figure 4-13: Histogram of mean seasonal soil moisture (m³/m³) for the period 1980-1984. UpCLIM-LUC refers to driven by ERA5 reanalysis data transient LULC simulation, while the CNTRL is the control run with static land use.

5 Conclusions

The findings below concern the analysis of two 5-year long simulations (1980-1984) performed in the framework of the UpClim project. We compare the CNTRL simulation with static land use and UpClim-LUC, which incorporates transient land-use changes to identify regional differences in key climatic variables. We also compare with observational data, E-OBS for temperature and precipitation and ESA-CCI for soil moisture, to identify seasonal biases.

2 m temperature: the impact of land use changes is mostly identified during summer months (JJA) compared to winter months and mostly in southern (1.5°C) than in northern Europe (0.2°C). WRF exhibits an average cold bias over Europe in winter and predominantly warm bias in summer (CNTRL simulation). The incorporation of land use changes alleviates the summer warm bias or even contributes towards small cold biases.

Precipitation: The effect of land use change seems to be affecting mostly the warm season precipitation. Both simulations suffer from wet biases (13-64% in winter and higher in summer) and the incorporation of land use change deteriorates the wet bias. The simulated precipitation has higher frequencies for higher precipitation size bins (>3 mm) compared to the observed values.

Soil moisture: The effect of land use on soil moisture is small in this set of 5 yearlong simulations. WRF simulations have considerable higher soil moisture than the observational dataset.

It should be noted that the results of the current analysis should be considered indicative only, as a robust climatological assessment would ideally require a 30-year simulation period. Nevertheless, these initial results from the evaluation-type simulations driven by reanalysis data are encouraging, as the climatologies of three key variables are appropriately reproduced. The soil moisture overestimation, needs further investigation. Additionally, clear and robust differences in key climatic variables are identified between simulations with and without land-use change. This provides strong motivation to invest further resources in conducting historical and future projection simulations that explicitly include and exclude land-use change, to better elucidate the role of land-use change in shaping future regional climate. The issue of observational uncertainty also requires further attention, as several regions in Europe—particularly southeastern Europe—are affected by relatively large uncertainties in in-situ–based observational products. These uncertainties reduce confidence in the corresponding model validation results.

6 References

Christensen, J. H. and Christensen, O. B.: A summary of the PRUDENCE model projections of changes in European climate by the end of this century, Clim. Change, 81, 7–30, doi:10.1007/s10584-006-9210-7, 2007

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of Geophysical Research: Atmospheres*, *123*(17), 9391–9409. https://doi.org/10.1029/2017JD028200;

Dorigo, W., Wagner, W., Albergel, C., Albrecht, F., Balsamo, G., Brocca, L., Chung, D., Ertl, M., Forkel, M., Gruber, A., Haas, E., Hamer, P. D., Hirschi, M., Ikonen, J., de Jeu, R., Kidd, R., Lahoz, W., Liu, Y. Y., Miralles, D., … Lecomte, P. (2017). ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions. *Remote Sensing of Environment*, *203*, 185–215. https://doi.org/10.1016/J.RSE.2017.07.001

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J. N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/QJ.3803

Hoffmann, P., Reinhart, V., Rechid, D., De Noblet-Ducoudré, N., Davin, E. L., Asmus, C., Bechtel, B., Böhner, J., Katragkou, E., & Luyssaert, S. (2023). High-resolution land use and land cover dataset for regional climate modelling: Historical and future changes in Europe. *Earth System Science Data*, *15*(8), 3819–3852. https://doi.org/10.5194/ESSD-15-3819-2023

Katragkou, E., Garciá-Diéz, M., Vautard, R., Sobolowski, S., Zanis, P., Alexandri, G., Cardoso, R. M., Colette, A., Fernandez, J., Gobiet, A., Goergen, K., Karacostas, T., Knist, S., Mayer, S., Soares, P. M. M., Pytharoulis, I., Tegoulias, I., Tsikerdekis, A., & Jacob, D. (2015). Regional climate hindcast simulations within EURO-CORDEX: Evaluation of a WRF multi-physics ensemble. *Geoscientific Model Development*, *8*(3), 603–618. https://doi.org/10.5194/GMD-8-603-2015,

Katragkou, E., Sobolowski, S. P., Teichmann, C., Solmon, F., Pavlidis, V., Rechid, D., Hoffmann, P., Fernandez, J., Nikulin, G., & Jacob, D. (2024). Delivering an Improved Framework for the New Generation of CMIP6-Driven EURO-CORDEX Regional Climate Simulations. *Bulletin of the American Meteorological Society*, *105*(6), E962–E974. https://doi.org/10.1175/BAMS-D-23-0131.1

Rechid D., Davin E., de Noblet-Ducoudre N., Katragkou El., and LUCAS team, CORDEX FPS LUCAS- Land Use and Climate Across Scales – a new initiative on coordinated regional land use change and climate experiments for Euroep, 19th EGU General Assembly, EGU2017, Conference Proceedings, 23-28 April, 2017, Vienna, Austria p 13172, Vol 19, 13172.

PUG, P. U. G. (2024). *ESA Climate Change Initiative Plus Soil Moisture*. https://climate.esa.int/en/projects/soil-moisture/soil-moisture-key-documents/

Taylor, K. E. (2024). Truly conserving with conservative remapping methods. *Geoscientific Model Development*, *17*(1), 415–430. https://doi.org/10.5194/GMD-17-415-2024

Thepaut, J.-N., Pinty, B., Dee, D., Thepaut, J.-N., Pinty, B., & Dee, D. (2018). The Copernicus Programme and its Climate Change Service (C3S): A European Response to Climate Change. *Cosp*, *42*, A0.4-15-18. https://ui.adsabs.harvard.edu/abs/2018cosp...42E3368T/abstract

Ulaby, F. T., Dubois, P. C., & Van Zyl, J. (1996). Radar mapping of surface soil moisture. *Journal of Hydrology*, *184*(1–2), 57–84. https://doi.org/10.1016/0022-1694(95)02968-0

Van Den Hurk, B., Kim, H., Krinner, G., Seneviratne, S. I., Derksen, C., Oki, T., Douville, H., Colin, J., Ducharne, A., Cheruy, F., Viovy, N., Puma, M. J., Wada, Y., Li, W., Jia, B., Alessandri, A., Lawrence, D. M., Weedon, G. P., Ellis, R., … Sheffield, J. (2016). LS3MIP (v1.0) contribution to CMIP6: The Land Surface, Snow and Soil moisture Model Intercomparison Project - Aims, setup and expected outcome. *Geoscientific Model Development*, *9*(8), 2809–2832. https://doi.org/10.5194/GMD-9-2809-2016

Yang, Z. L., Niu, G. Y., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., Longuevergne, L., Manning, K., Niyogi, D., Tewari, M., & Xia, Y. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 2. Evaluation over global river basins. *Journal of Geophysical Research: Atmospheres*, *116*(D12), 12110. https://doi.org/10.1029/2010JD015140