SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2020
Project Title:	Towards seamless development of land processes for Earth System prediction and projection
Computer Project Account:	spitales
Principal Investigator(s):	Andrea Alessandri
Affiliation:	ENEA Primary affiliation from 1st April 2020 is ISAC-CNR, Bologna, Italy
Name of ECMWF scientist(s) collaborating to the project (if applicable)	…………………………………………………………… ……………………………………………………………
Start date of the project:	2019
Expected end date:	2021

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	6500000	6935282	5500000	79978
Data storage capacity	(Gbytes)	15500	16000	31250	30000

Summary of project objectives (10 lines max)

The objectives of this special project are (i) to include the representation of the Earth System processes and feedbacks over land (from the latest Earth System Model developments in the frame of CMIP6 and beyond) that can suitably contribute to the the short-term climate predictions performed using EC-Earth (Hazeleger et al., 2012), (ii) to evaluate the impact of including Earth System processes over land on the skill of the retrospective seasonal forecasts, (iii) to contribute towards new frontiers in the seamless development of Earth system predictions/projections across multiple time-scales.

Summary of problems encountered (10 lines max)

The set-up and simulation of control seasonal hindcasts (SEAS-CTRL) that were planned at BSC (in the framework of APPLICATE projects) and to be expected by mid 2019 have been postponed by one year. Accordingly this delayed the commencement of the sensitivity seasonal hindcast experiment (SEAS-EXP).

The LS3MIP interface caused a slight decrease of the model computational performance with a corresponding 15% SBU increase for the sensitivity runs; this required an additional resources request of 1000000 SBU that was granted to spitales in 2019.

Summary of plans for the continuation of the project (10 lines max)

To allow us to assess the impact of the long-term mean soil moisture changes between 1982–2014 and 2071–2100 on the late 21st century climate, another set of PROJ-CTL simulations are planned by prescribing a seasonal cycle of soil moisture as transient climatology (30 year running mean) obtained from the same reference PROJ-EXP scenario.

A set of retrospective seasonal forecasts (SEAS-EXP) with improved representation of the Earth System processes over land will be performed using EC-Earth. SEAS-EXP will be compared with the control seasonal hindcasts (SEAS-CTRL) that are planned at BSC.

The analysis of climate feedbacks in the climate projections together with the verification against new-generation satellite observations of (i) historical runs and (ii) seasonal forecasts will provide knowledge to better constrain the land processes for next developments in Earth system prediction.

List of publications/reports from the project with complete references

Döscher et al, 2020: The Community Earth System Model EC-Earth for collaborative climate research. Under submission on GMD

Alessandri et al, 2020: Improving the physical parameterizations of the land-surface model in EC-Earth. In preparation.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

Climate projections and LS3MIP sensitivity experiments

A set of historical simulations and climate projections are performed with version 3.3 of EC-Earth, i.e. including all the latest Earth System Model developments over land in the frame of CMIP6. These simulations (hereinafter PROJ-EXP) constitute the first member of the EC-Earth historical and scenario (ScenarioMIP; O'Neill et al., 2016) contribution to CMIP6 (Eyiring et al., 2016). Two different scenarios are considered in this project: SSP1-2.6 and SSP5-8.5.

Following Seneviratne et al. (2013), a set of climate-sensitivity projections has been carried out disabling the land feedbacks to climate change by prescribing the soil-moisture states from a climatology derived from "present climate conditions" (1980-2014). By comparing this sensitivity-experiment with standard projections with all feedbacks in place, we aim at diagnosing the role of land-atmosphere feedback on climate change. The climate-projection sensitivity experiments follow the LS3MIP protocol (van den Hurk et al. 2016) and constitute the EC-Earth contribution to the LFMIP-pdLC experiments. The two sensitivity simulations (hereinafter PROJ-CTL) span the period 1980-2100 with SST and sea-ice conditions prescribed from PROJ-EXP and soil moisture state prescribed as the 1980-2014 seasonal-climatology obtained from the historical PROJ-EXP. PROJ-CTL simulations have been run using CMIP6 version of EC-Earth (v3.3, same used for PROJ-EXP) with modifications to include a new interface to prescribe soil moisture values, described in the following sub-section. Model resolution for the atmosphere is T255 (corresponding to approximately 80 km lat x lon) with 91 vertical levels.

Implementation of the methodology for soil-moisture prescription

In collaboration with colleagues of Lund University, an interface to prescribe soil moisture values has been implemented in EC-Earth 3.3. The interface allows the prescription and relaxation of the four levels of soil moisture with the possibility to use different relaxation time scales for the different levels. The code reads soil moisture values to be prescribed every 6 hours. The setup adopted here, following the LS3MIP protocol (van den Hurk et al. 2016), is to prescribe daily soil moisture values with the same relaxation time of 24 hours for all the four soil layers in HTESSEL.

Results

In this analysis, we focus on the differences between PROJ-EXP and PROJ-CTL at the end of the 21st Century (2071–2100) in order to isolate the impact of the soil moisture changes on surface climate change. The PROJ-EXP minus PROJ-CTL differences in climatological (2071-2100) yearly-mean soil moisture are shown in Figs. 1a and 1b. Both the scenarios display drier conditions over Europe, United States, Central America, Amazon, South Africa, East China and wetter conditions over Canada and Euro-Asian boreal forests, India and Sahel. The corresponding latent and sensible heat flux changes are displayed in Figs. 1c,d and 1e,f, respectively. It is shown that all the regions with soil moisture reduction display a corresponding reduction (increase) in latent (sensible) heat fluxes, indicating a transition of the surface-energy partitioning towards drier climate conditions, in agreement with Seneviratne et al. (2013). On the other hand, the converse flux response when soil moisture increases is only found over Sahel and south India. This is consistent with the fact that indeed evapotranspiration tends to be water-limited over Sahel and India (Seneviratne et al. 2010). On the contrary, in regions such as boreal forests it is the energy availability that is mostly limiting evapotranspiration (Seneviratne et al. 2010). The land-surface feedbacks appear consistent in the two scenarios considered but become more evident in the SSP5-8.5 scenario, indicating an intensification of the land-surface feedbacks as the anthropogenic radiative-forcing increases.

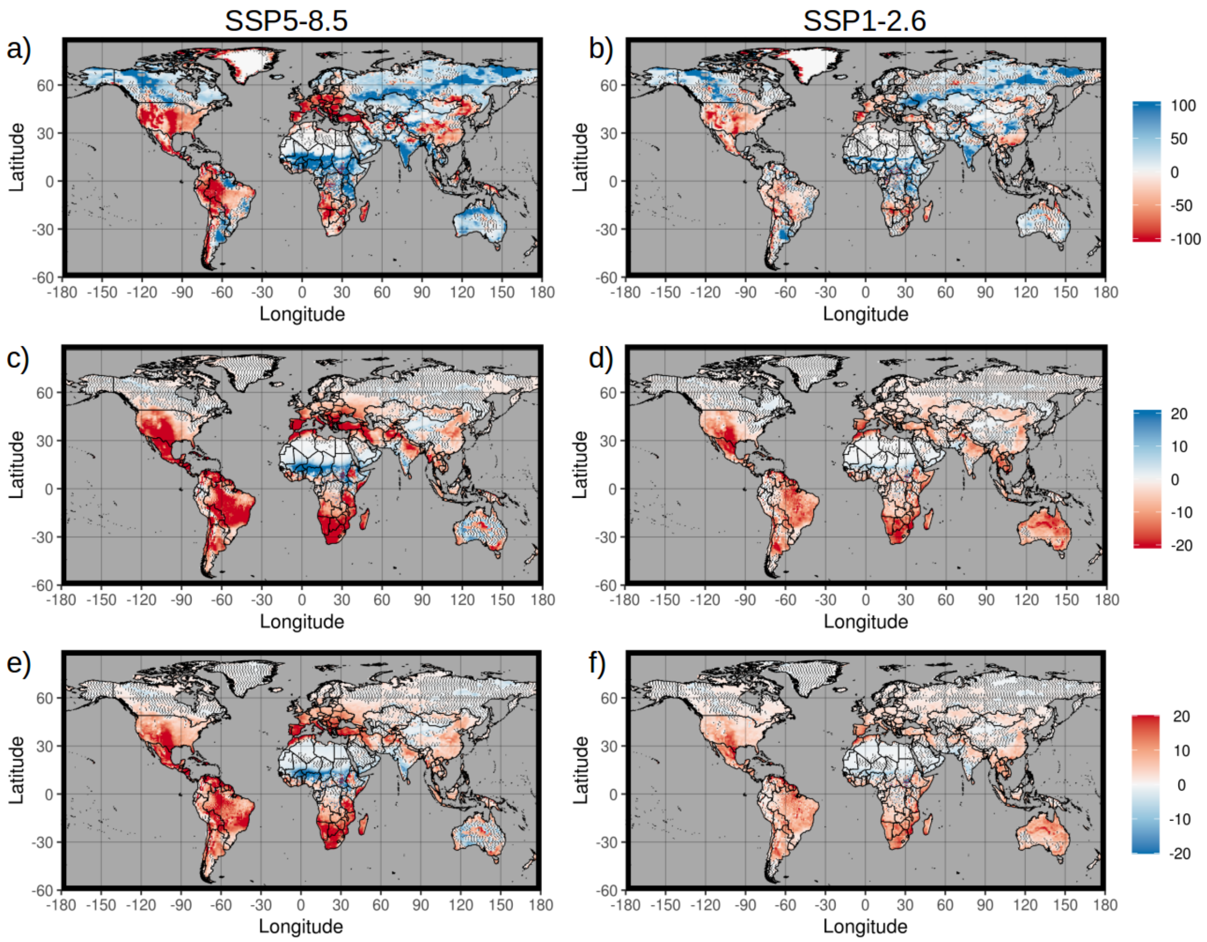

Fig. 1: PROJ-EXP minus PROJ-CTL yearly mean difference over time period 2071-2100 for the two scenarios considered: SSP1-2.6 (left column) and SSP5-8.5 (right column), (a, b) soil moisture (mm), (c, d) latent heat flux (W m-2), (e, f) sensible heat flux (W m-2). Dotted grid points did not pass a Monte Carlo bootstrap significance test at 10% level.

The (2071-2100) minus (1985-2014) difference of yearly-mean 2m-temperature for SSP5-8.5 and SSP1-2.6 are displayed in Fig. 2a and 2b, respectively. It is shown that the temperature change over the 21st century is positive everywhere over land with values ranging from 0.2 K up to more than 3 K in SSP1-2.6 and from 1 K to more than 8 K in SSP5-8.5. In both scenarios, larger temperature change is found over the Northern Hemisphere and in particular over the Great Plains of North America, boreal forests of North America and Eurasia, southern Europe, West Asia and East China. Over the regions with negative soil moisture change (Figs 1a and 1b), the 2m-temperature increases significantly (Figs 2c and 2d) but, consistently with latent and sensible heat fluxes patterns (Fig. 1c-f), the cooling signal over regions getting wetter is significant only over Sahel and South India, although slight (non-significant) cooling appear over boreal forests. Again, the sensitivity of 2m-temperature to soil moisture is much stronger in the SSP5-8.5 scenario.

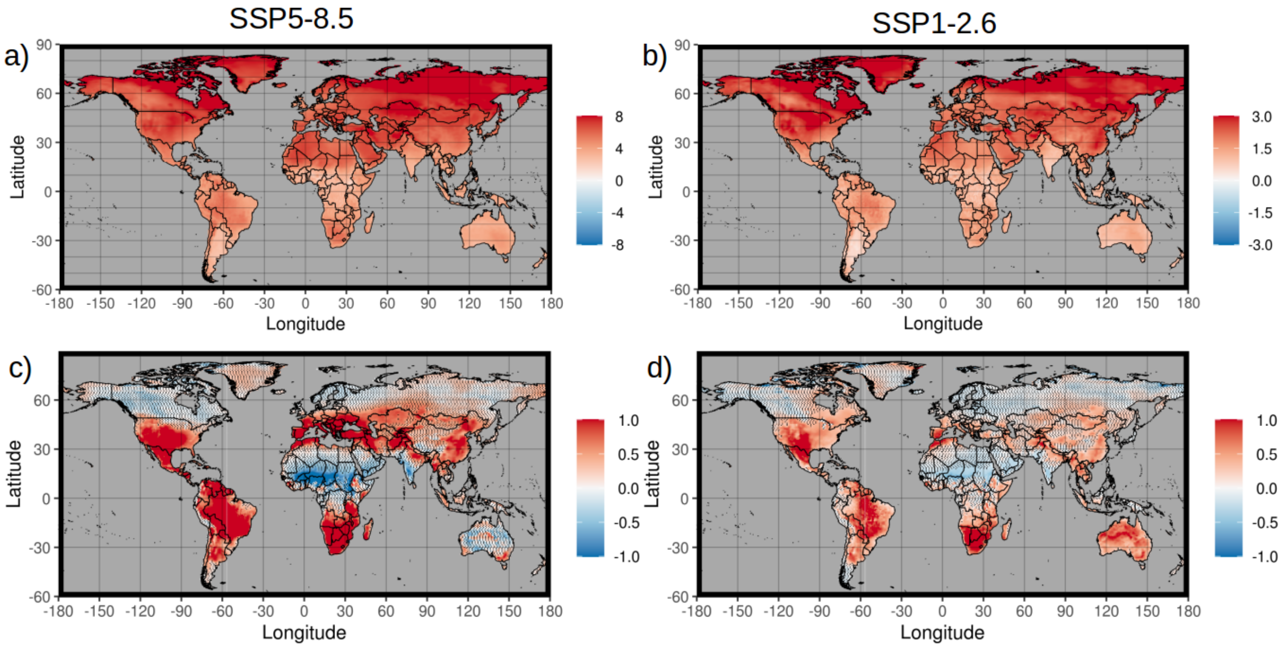

Fig. 2: Sensitivity of 2m-temperature to soil moisture changes for the two scenarios considered: SSP1-2.6 (left column) and SSP5-8.5 (right column); (a, b) yearly mean difference of 2m-temperature over time period 2071-2100 with respect to present day conditions (1985-2014); (c, d) PROJ-EXP minus PROJ-CTL yearly mean difference over time period 2071-2100. Values in K. Dotted grid points did not pass a Monte Carlo bootstrap significance test at 10% level.

The climate change signal of precipitation (Fig. 3 a, b) displays a clear intensification of the hydrological cycle in the Northern Hemisphere, especially in SSP5-8.5 scenario. The larger effects on precipitation due to soil moisture forcing occur over the Great Plains of North America, Brazil, La Plata Basin, Sahel, Europe and Central Asia, in agreement with observational analysis by Catalano et al. (2016). Most of these regions correspond to transition zones between dry and wet climates, where evaporation is highly sensitive to soil moisture (Koster et al. 2000). Precipitation tends to be reduced in PROJ-EXP with respect to PROJ-CTL, apart from the Indian monsoon region and a narrow band in Sahel. As expected, precipitation reduction is associated to drying soil moisture conditions almost everywhere; the only exception is the African area north of the Gulf of Guinea where precipitation reduces but soil moisture increases. This may be related to the change in the dynamics of the West African monsoon that may be partially related to the modified land-sea contrast in PROJ-CTL compared to PROJ-EXP (Fig 2c). This is consistent with Cherchi et al. (2011) where it has been shown that the West African monsoon can have a different behaviour compared to other monsoon systems because of a non-linear dynamical response to anthropogenic forcing that could lead to negative precipitation changes.

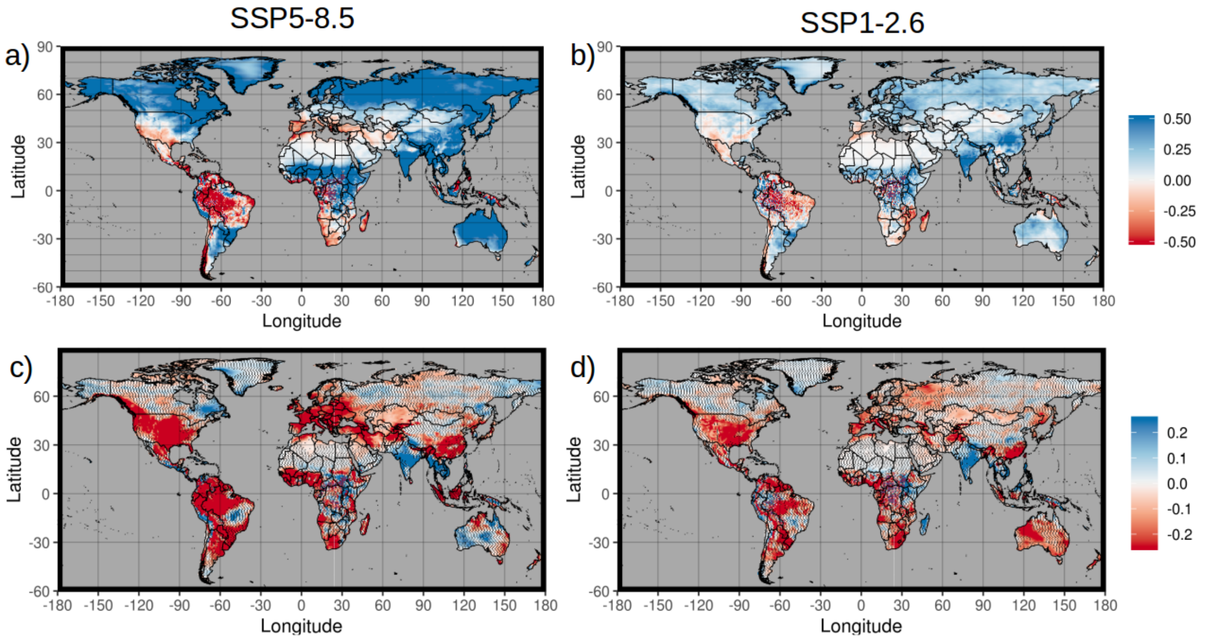

Fig. 3: As Fig. 2 but for precipitation.

Hydrological processes in HTESSEL: off-line evaluation of rootzone storage capacity

The root zone storage capacity represents the total volume of water that is accessible to roots and defines how long vegetation is able to maintain transpiration into the dry season. In this study catchment root zone storage capacities are estimated from observations based on climate records with the mass balance approach, which has proven good results in hydrological modelling (Gao 2014; de Boer-Euser 2016; Nijzink 2016; Wang-Erlandsson 2016).

We evaluate the performance of the off-line HTESSEL model in reproducing observed river discharge and the relation of the performance to the model parameterisation of root zone storage capacity. River discharge observations of fifteen Australian river catchments, clustered in tropical, temperate and Mediterranean regions, are compared to off-line runoff simulations by HTESSEL in the corresponding grid cells. Table 1 presents the long-term mean discharges from observations compared to the HTESSEL model simulations and Kling Gupta Efficiencies (KGE) based on monthly modelled river discharge. The KGE describes the combined performance of the model to bias of flows, variability of flows and correlation between modelled and observed discharge and is maximised by a value of 1, which indicates a perfect model fit (Gupta 2009). It is observed that HTESSEL underestimates discharge fluxes in the tropical and temperate regions, and thereby overestimates mean evaporation fluxes following the water balance (Not shown). The results are the opposite in the Mediterranean regions. The KGE values presented in Table 1 indicate that HTESSEL has limitations in reproducing observed monthly discharge in the study regions; the lowest performance is in the Mediterranean regions where the negative KGE indicate that here the simulation of river discharge is far from observations.

Table 1. Average observed and modelled long term mean river discharge in the catchments clustered in three climate regions with the relative difference between model and observations in brackets. The Kling Gupta Efficiency (KGE) is based on monthly modelled river discharge with a value of 1 indicating a perfect model (Gupta, 2009).

Climate region	$\bar{Q}_{\mathbf{observed}}$ **(mm year^{-1})**	$\bar{Q}_{\mathbf{modelled}}$ **(mm year^{-1})**	**KGE (-)**
Tropical	302	208 *(-31%)*	0.33
Temperate	57	37 *(-35%)*	0.37
Mediterranean	53	150 *(+185%)*	-1.14

Whereas there is general consensus that climate is the main driver of root development, HTESSEL describes the root zone storage capacity as a function of model soil depth and soil type, disregarding vegetation dynamics (Kleidon 2004; Collins 2007; Guswa 2008). Root zone storage capacities in HTESSEL strongly exceed the climate based estimates (HTESSEL: 597 mm, Mass Balance: 317 mm), which would indicate an overestimation of evaporation fluxes by the model, possibly causing the underestimation in simulated river flows presented in Table 1 over Tropical and Temperate domains. On the other hand, over Mediterranean regions the overestimation of river flow is probably related to deficiencies in the parameterization of subsurface runoff.

It is planned to likely extend this analysis in the future to enable a global-scale evaluation of the hydrological performance of HTESSEL in relation to the representation of the root zone storage capacities. This could allow the effective implementation of a solution to replace the current parameterisation of root zone storage capacity by the more realistic climate-based estimates based on the mass balance approach.

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