BLUEGEM

Biosphere and Land Use Exchanges with Groundwater and soils in Earth system Models

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Call « Towards Sustainability of Soils and Groundwater for Society”

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The submitted proposal was comprised of separate documents that are gathered as sections in the present document, but still referred as separate PDFs in the text.

Main acronyms

AMIP: Atmospheric Model Intercomparison Project
CAP: Common Agricultural Policy (EU)
CESM: Community Earth System Model
CMIP: Coupled Model Intercomparison Project
CZ: critical zone
DIAS: Data Integration and Analysis System (Japan)
DEM: digital elevation model
ESM: Earth system model
ET: evapotranspiration
EU: European Union
FAO: Food and Agriculture Organization (U.N.)
GEWEX: Global Energy and Water cycle EXchanges
GIS: geographic information systems
GRACE: gravity recovery and climate experiment
GHG: green-house gas
GSWP3: Global soil water project Phase 3
GW: groundwater
HPC: high performance computing
IAM: integrated assessment model
IGEM: Impact of groundwater in Earth system models
IDRIS: Institut du développement et des ressources en informatique scientifique (France)
IPCC : Intergovernmental Panel on Climate Change
IPSL: Institut Pierre Simon Laplace (France)
LAI: Leaf area index
LMRB: Lower Mekong River Basin
LSM: land surface model
LUM: land use and management
MRC: Mekong River Commission
MSU: Michigan State University (USA)
NAWAPI: National Center for Water Resources Planning and Investigation (Vietnam)
NCAR: National Center for Atmospheric Research (USA) NTU : National Taiwan University (Taiwan)
OFB: French Biodiversity Agency (France)
PI: principal investigator
SDGs: Sustainable Development Goals
SIC: sea ice content
SM: soil moisture
SOC: soil organic carbon
SSP: shared socioeconomic pathway
SST: sea surface temperatures
TWS: terrestrial water storage
UNESCO: U.N. Educational, Scientific, and Cultural Organization
U-Tokyo: The University of Tokyo (Japan)
WCRP: World Climate Research Programme (U.N.)

BLUEGEM

Biosphere and Land Use Exchanges with Groundwater and soils in Earth system Models

Consortium Lead: Agnès Ducharne (IPSL, France)

Project summary

The interactions between groundwater (GW) and soil moisture (SM) exert a key role to shape the critical zone (CZ), including soils, water resources, ecosystems, near-surface climate, and social systems. In this project, we focus on several interlinked CZ processes: SM increase by capillary rise from GW that is recharged when SM is abundant; GW depletion or exhaustion by irrigation, 38% of which is GW-fed globally; SM, GW, and irrigation response to but also impact on mean climate and extreme events (droughts, heatwaves, floods), ecosystem productivity (wetlands, croplands) and soil carbon. The relative influence of these coupled processes is difficult to apprehend based on observations, as they exhibit contrasting manifestations in space and time, and are subject to increasing anthropogenic pressures. Thus, we will combine advanced numerical modelling and participatory methods to explore their long-term evolution in the Anthropocene (1900-2100), at two spatial scales: a) Global, with factorial simulations by two Earth system models to compare the influence of anthropogenic warming, land-use and irrigation management, and GW-related feedbacks, on past and future CZ pathways; b) Regional in two "focal areas", metropolitan France and the Mekong River basin, to provide contrasting examples of the studied processes and enable anchored transdisciplinary work with stakeholders, social and natural scientists. The goal is to propose tailored narratives for sustainable management, using participatory approaches to iteratively combine expert knowledge, local surveys, high-resolution Earth system simulations, and integrated assessment modelling of land-use and water management. At both scales, we will consider uncertainties to identify robust responses (likely evolutions and trade-offs, e.g. linked to GW failure to sustain irrigation and ecosystems, or climate change attenuation/amplification). Ultimately, the project will help assess the usefulness of global scenarios and projections at regional scales and frame sustainable CZ management strategies at the global scale.

BLUEGEM
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Project description

1. Background

The critical zone (CZ) and Anthropocene are linked concepts, as they both emphasize the role of humans in the environment. The CZ is defined spatially as the physical and biological compartments from the aquifer bottom to the top of the lower atmosphere within which humans live and impact their environment (Brantley 2007). The Anthropocene (Crutzen 2006) is defined over time as the period in which human activities are the main driver of global environmental changes, raising pressing questions regarding the sustainability of ecosystems and natural resources, and the diverse human groups which rely on them (Ripple 2017).

In this project, we focus on the water fluxes between groundwater (GW) and soils, which exert a significant role in shaping the CZ and climate systems, at least regionally (Taylor 2013; Seneviratne 2010). Several coupled processes are considered, both natural and human-driven, all related to the evolution of water resources and terrestrial ecosystems through the Anthropocene:

- Recharge of GW systems when/where soil moisture (SM) is abundant (Döll 2008)
- Increase of SM and evapotranspiration (ET) by capillary rise from GW, when the water table is close to the surface (Kollet 2008; *Ducharne 2020), which is crucial to sustain wetlands (Fan 2013; *Tootchi 2019)
- Relationships between SM, ecosystem productivity (wetlands, croplands) and soil organic carbon (SOC). SOC increases soil water retention (Rawls 2003) and wet conditions, in turn, favor anaerobic conditions, which prevent SOC decomposition (heterotrophic respiration) and tend to enhance carbon sequestration (*Ciais 2020), largely explaining the distribution of global peatlands (*Qiu 2019)
- The impact of SOC accumulation on climate via its influence on soil hydrological and thermal properties, and on atmospheric CO_2 and CH_4 concentrations (*McGuire 2016, *Zhu 2019)
- Increase of SM by irrigation (Ozdogan 2010; *Pokhrel 2012) to enhance and secure crop productivity, while inducing GW depletion (Famiglietti 2014; *Richey 2015; *Pokhrel 2015) since 38% of irrigation is GW-fed globally (Siebert 2010; see Fig. 1)
- Decrease of SM, streamflow, ET, and vegetation cover, partly because of GW depletion (Vicente-Serrano 2019; Condon 2019), which may either be enhanced or alleviated owing to future climate change (*Wu 2020)
- Conversely, SM, thus GW and irrigation, influence mean climate and extreme events like droughts, heatwaves, floods, with significant cooling but disputed effects on the water cycle (Seneviratne 2010; *Lo 2011, 2013; *Guimberteau 2012; *Hsu 2017, Thiery 2017, 2020; Keune 2018, *Wang 2018; *Al-Yaari 2019; Sacks 2019). Interestingly, the IGEM project (Impact of groundwater in Earth system models, coordinated by MH Lo and A Ducharne) recently showed that GW-SM interactions can significantly attenuate the intensification of droughts and hot spells with climate change in certain areas (*Ducharne 2020b). This attenuation is particularly important for human health with implications for economic activity (*Zhao 2016).
- Finally, land use and land management (crop species, farming practices, etc.) get adapted to changing conditions, either biophysical as above, but also because of economic, policy, and social conditions (Nelson 2014, *Ben Fradj 2016; Dalin 2017; *Barberis 2020).

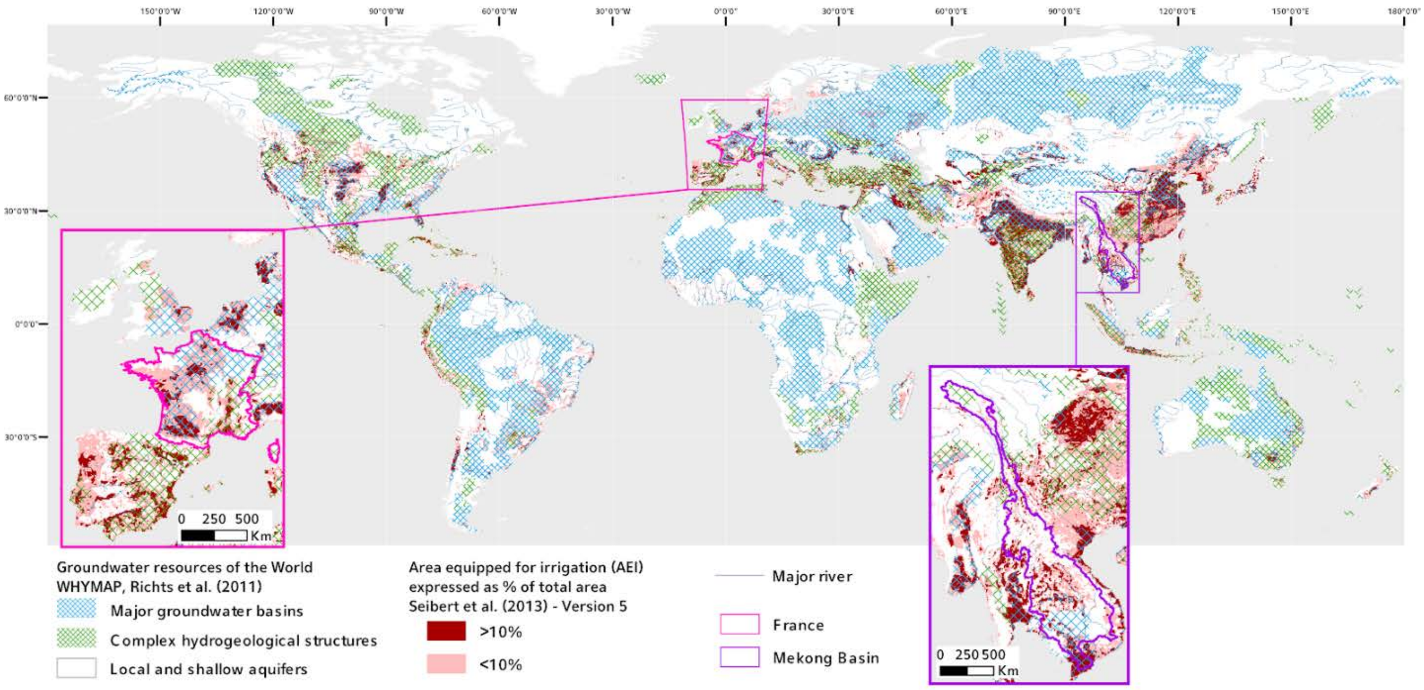

Figure 1. Global maps of groundwater systems (WHYMAP, Richts 2011) and irrigated areas in 2005 (equipped areas in fraction of 5-arcmin pixels, from Siebert 2013), with zoomed-in inlays over France and Mekong.

The relative influence of these coupled processes is difficult to apprehend, as they exhibit contrasting manifestations in space and time. Uncertainties are even larger regarding future transitions, as the choices of human societies are fundamentally uncertain. This is particularly true when dealing with water resources, which are a limiting factor for many societies (agriculture, energy production, drinking water, tourism; but also preservation of water-related ecosystems in rivers, wetlands, or forests), and are likely to cause conflict if water becomes scarce (Flörke 2018).

Water conflicts already exist in severely water stressed regions, and are anticipated to develop in many areas of the world (*Kim 2019), including most of Southern Europe (*Padron 2020) as climate change follows an overall "dry gets drier - wet gets wetter" pattern (Chou 2013; *Lan 2019). The "wet gets wetter" trend found in all monsoon areas but South-America (Chen 2020) raises serious concerns about enhanced river flooding, in conjunction with sea level rise in coastal areas, but it does not prevent from seasonal drought during the growing season, which drives irrigation increase in many countries (Siebert 2015; Puy 2018), including most of South-east Asia (Erban 2016; *Pokhrel 2018a). Hopefully, the resulting water availability decreases (including severe GW depletion as already said) can be counteracted by water use regulations, which have recently led to a deceleration of irrigation in China (*Zhou 2020).

In this context, modelling is very useful in understanding past trends (*Piao 2007, *Sterling 2013, *Xi 2018; Vicente-Serrano 2019) and exploring future pathways. Earth system models (ESMs, Heavens 2013) have evolved from "simple" climate models by adding increasingly complex descriptions of the biosphere and biogeochemical cycles, largely owing to improved land surface models (LSMs). Land hydrology has also been refined, and some LSMs include descriptions of GW-SM interactions (*Koster 2000; *Lo 2010; *Koirala 2019; *Rashid *2019*; *Tootchi 2019b), and water management including various types of irrigation (*Pokhrel 2016, *Xi 2018).

These improved LSMs, however, are typically used in land-only mode (not coupled to an ESM) for impact assessment (*Pokhrel 2012, 2015, *Habets 2013, *Schewe 2014, *Reinecke 2020), and are overlooked in most climate projections including those performed recently for CMIP6 (the latest phase of the Coupled Model Intercomparison Project, Eyring 2016, Lawrence 2016, *van den Hurk 2016), presently analyzed for the forthcoming IPCC assessment reports. Furthermore, these ESM projections describe global land use and management (LUM) changes according to prescribed scenarios (Hurtt 2020), which do not respond dynamically to simulated climate change, although they are derived to be compatible with the assumptions framing how global society, demographics and economics might change over the next century for CMIP6 projections.

These assumptions are known as the shared socioeconomic pathways (SSPs, Riahi 2017) and result from narratives and storylines, commonly used to explore plausible futures when scientific uncertainty great, as is often the case when addressing human societies (*Ducharne 2007; Alcamo 2008; Trutnevyte 2014, Shepherd 2018). Narratives and storylines are also potent tools for the communication of ESM results, which is a challenge owing to great uncertainty and the immense societal and political stakes (Funtowicz 1993).

2. Research plan

2.1 Objectives, novelty, and potential breakthrough

The overarching goal of the BLUEGEM project is to explore the evolutions of GW, irrigation, and climate in the Anthropocene (1900-2100), to better understand their coupling, foresee their potential changes, and identify possible social consequences, which are of paramount importance to assess in order to identify sustainable pathways with respect to water resources, food security, biodiversity, and human well-being and socio-economic activities.

To this end, we will combine advanced numerical modelling of biophysical and social systems, as well as participatory methods with stakeholders, to address 3 innovative objectives:
Objective 1. Establish the fingerprint of GW-SM interactions and irrigation on global and regional climate, water resources, biosphere, and soil carbon pools.
Objective 2. Provide improved projections of global and regional climate, water resources, biosphere and soil carbon pools, fully taking into account the influence of GW irrigation and GW-SM interactions.
Objective 3. Integrate local and regional knowledge and expertise as well as socio-economic data to refine the land use and irrigation scenarios used in state-of-the-art climate projections (CMIP6) and to explore pathways for sustainable CZ management.

The BLUEGEM project, however, will not focus on the following topics, although they present obvious links with our processes of interest: GW influence on rooting depth (Fan 2017), artificial reservoirs (Habets 2018), methane emissions (Zhang 2017), saltwater intrusion due to GW depletion in coastal areas (Erban 2016; *Pokhrel 2018a).

2.2 Studied domains

The BLUEGEM project addresses two spatial scales:
a) Global, using simulations by two ESMs to compare the influence of anthropogenic warming, land-use and irrigation management, and GW-related feedbacks, on past and future CZ pathways. At the global scale, only 2% of land was equipped for irrigation in 2005 (Siebert 2013), corresponding to but 12% of the pixels in Fig. 1. Half of them fall in major GW systems (sedimentary basins, covering only 1/3 of terrestrial areas), and it is estimated that 38% of irrigation is GW-fed globally (Siebert 2010), as these aquifers usually constitute a reliable water resource (from both quantity and quality point of views).
b) Regional in two "focal areas", metropolitan France and the Lower Mekong River basin (LMRB), to provide contrasting examples of the studied processes and enable anchored transdisciplinary work with local stakeholders and social scientists.

The LMRB (630,000 km^2; the Upper Mekong in China will be excluded in our analyses) is undergoing unprecedented hydrological, ecological, and socio-economic transformation due to climate change and growing human land-water management (*Pokhrel 2018a; *Shin 2020). The changes in monsoon patterns have altered the flood pulse, reducing dry-season flows (Delgado 2010) and increasing GW use (*Pokhrel 2018a). Flow regulation by upstream dams (*Pokhrel 2018b) have further modified surface water dynamics, making dry-season flows highly unpredictable (Li 2017; Nguyen 2020). This has further increased the need for GW irrigation. Vietnam currently irrigates ~60% of rice, and relies on GW for drinking water as surface water during dry season is saline (IUCN 2011). GW-irrigation in Cambodia is currently ~10%, but is increasing at >10% per year (Erban 2016). Therefore, it is feared that the LMRB might be facing severe challenges (e.g., sharp water table decline) in sustainably managing GW even in the near future, but very little is known about how soils and GW in the LMRB are responding to climate change and growing human influences, because most previous studies have focused on surface water (*Pokhrel 2018b).

France (500,000 km² excluding overseas) is characterized by large extents of major aquifers (50%), and if only 5% of land is equipped for irrigation, it touches 55% of the pixels in Fig. 1. As a result, 45% of irrigation in France is withdrawn from GW (Siebert 2010), explaining why this area undergoes decreases of GW level that are observable by spatial gravimetry (*Rodell 2018). Of course, climate change also contributes to these trends because of increasing droughts and heat waves (Vicente-Serrano 2019, *Yiou 2020), and decreases in mountain snowpack (*Magand 2015). In August 2020, about half of French departments (over 96) have banned total water use with exceptions for drinking and civil security (Propluvia). Future climate change is projected to enhance summer drought over the entire country (*Habets 2013; Dayon 2018), and all stakeholders (public agencies, farmers, industries) see it as a major threat to the sustainability of water resources including irrigation (*Sauquet 2016, Lhuissier 2016, *Barberis 2020).

2.3 Main methods

BLUEGEM heavily relies on models of biophysical and socio-economic CZ processes to quantitatively assess past and future trends. We will use two state-of-the-art ESMs, both used in CMIP6: IPSL-CM6 (*Boucher 2020, *Cheruy 2020), and CESM2 (Danabasoglu 2020), with a horizontal resolution of 2.5°x1.25° and 1.25°x0.9° respectively. The corresponding LSMs, namely ORCHIDEE and CLM5, describe the dynamics of the biosphere and soil carbon (*Krinner 2005; *Zhu 2019, Lawrence 2019), for specified land use and soil properties. Photosynthesis and carbon assimilation are coupled to transpiration, and drive the evolution of biomass, LAI (leaf area index), and litter accumulation; the latter is processed in the soil, the balance of mineralization (leading to CO_2 emissions) and storage depending on temperature and SM. These processes are thus strongly coupled to the water and energy budget of the land surface.

Both LSMs also represent GW-SM interactions and irrigation. Irrigation is simulated by prescribing irrigated areas (using the data of Siebert, or better information at regional scale) and calculating the irrigation amount to alleviate water stress for crops and approach potential ET (*Xi 2018, *Felfelani 2018). Both models represent GW storage in each grid-cell based on linear reservoir, providing base flow to the streams, but they differ in the way they describe vertical SM-GW interactions:

- In ORCHIDEE, they only occur in a subgrid fraction of each grid-cell, physically corresponding to lowland areas and prescribed from a dedicated global wetland map (*Tootchi 2019, 2019b). GW convergence from upland areas increases SM in the lowland fraction, so the water table can rise, and feed base flow to the river, as well as enhanced ET compared to the upland fraction.
- In CLM5, capillary rise is simulated on a sub-grid level considering different land use type fractions, and depending on the hydraulic gradient between the soil bottom and the water table, the depth of which depends on GW storage and aquifer properties.

In addition to global ESMs simulations, used to assess the influence of irrigation and GW-SM interactions on the simulated climate and CZ processes, we will also run high-resolution land-only simulations in the two focal areas, in which ORCHIDEE and CLM5 will be informed by detailed input datasets and calibrated, and more realistically reproduce the water fluxes and storages than global simulations, to be used in the tasks of the social dimension. Climate forcing required for these simulations will be deduced from the global ESM simulations based on multiple statistical downscaling techniques.

In France, we will also carry out integrated assessment modeling (IAM) on the GW-LU-irrigation nexus under climate change, owing to the AROPAj agro-economic model of European agricultural supply (*Jayet 2013, *Leclère 2013, *Barberis 2020), using input data from the selected SSPs and ESM projections.

It must be noted that we will not aim at finely quantifying the uncertainties of our projections, although we know they are numerous. With only two ESMs and LSMs, it is not possible to fully address model uncertainty. Instead, we will compare them to the larger sample of CMIP6 models (task T2.3a), and focus on the identification of (a) effective feedbacks (thus important to take into account in the next generation of ESMs and IAMs), and (b) plausible future pathways, important for devising transition strategies (hoping sustainable solutions are indeed plausible).

BLUEGEM also strongly relies on participatory research methods, to engage local communities in the design and implementation of the project's research activities, and also as an effective vehicle to disseminate research results. Three participatory research methods will be used: participatory GIS, participatory cultural mapping, and storylines. Participatory GIS asks community members to respond to maps derived from the project and to complement this information with their own spatially important information that would otherwise be inaccessible using remote imaging technologies. Similarly, participatory cultural mapping trains community members to generate their own maps reflecting their cultural heritage. Finally, storylines will help engage local communities and bridge the gap between scientific and local epistemologies.

Type of activity	Global [MHL]	France [AD]	Mekong [YP]
T1 Coordination	**T1** - Project coordination between disciplins & domains **[AD]**		
T2.1 ESS Model developments	**T2.1Ga** - ORC: soil carbon **[BG]** **T2.1Gb** - CLM5: water management **[MHL,YP]**	**T2.1F*** - ORC-HR: calibration **[AD,PP]**	**T2.1M** - CLM5-HR: calibration **[YP]**
T2.2 ESS Simulations & Downscaling	**T2.2G** - Factorial ESM simulations over 1900-2100 **[MHL]**	**T2.2FM** - Downscaling over France & Mekong **[HK]**	
		T2.2Fa - HR ORC simulations **[AD,JP]**	**T2.2M** - HR CLM5 simulations **[YP]**
		T2.2Fb - Run-time bias-corrected simulations **[FC]**	
T2.3 ESS Analyses	**T2.3a** - Model benchmarking **[HK,MHL]**		
	T2.3b - Trend attribution, influence of land-atmosphere feedbacks **[MHL,FC,HK]**		
	T2.3c - Impact assessment (water resources, soil carbon, biosphere) **[YP, BG,HK]**		
T3 HSS work		**T3F** - Agro-economic scenarios of LU & irrigation evolutions **[PAJ,AD]**	**T3Ma** - Hot spots and bright spots of farmer behaviors **[DK]**
			T3Mb - Farming futures and social-ecological feedbacks **[DK, SYK]**
T4 Transdisciplinary work	**T4G** - Participatory workshop on GW-irrigation management options **[AD, AJ]**	**T4F** - Plausible storylines for LU and GW management with stakeholders **[AJ,CM]**	**T4M** - Participatory GIS and participatory cultural mapping **[DK,YP, SYK]**
		T4FM - Comparison of the focus areas **[AD,YP]**	
T5 Dissemination & data management	**T5a** - Preparation of selected variables and indicators **[HK,PP]**		
	T5b - Data storage and exchanges among project partners **[HK,MHL]**		

Figure 2. Overall organization of the BLUEGEM tasks.

2.4 Tasks

The workload is divided into several tasks, each with one lead person (and co-lead for big or interdisciplinary tasks). As shown in Figure 2, the tasks are organized following two entries: geographic domain (global, France, and Mekong: G, F, and M respectively), vs. disciplinary work (Earth system science (ESS) in blue; Human and social science (HSS) in red; transdisciplinary work in purple; transversal activities in green). The task leaders are identified by their initials, given in Table 2 of the Management plan.

T1. Coordination: see "Management plan".

T2.1Ga - ORCHIDEE Development: soil carbon and soil hydrology

The empirical functions used to describe the influence of SM on heterotrophic respiration are diverse, and induce great uncertainty in the soil carbon budget, ranging from a net sink to a net source (Falloon 2011). Moyano (2012) showed that the effect of SM on SOC dynamics depends on several soil characteristics (SOC content, bulk density, texture, etc.) which they integrated in a more complex function, according to which heterotrophic respiration is not continuously increased with SM, but displays an optimum after which carbon can effectively accumulate, as expected in very wet conditions. Here, we will incorporate this function (Moyano 2012) in ORCHIDEE to better address the effect of GW-SM interaction on heterotrophic respiration, SOC stocks, and related processes. This parametrization will be used for global ESM simulations, with the developments consolidated in T2.1F for land hydrology.

T2.1Gb - CLM5 Development: water management

A new version of CLM5 will be developed for CESM2 with full integration of GW, irrigation, and human water use. We will build on the version recently advanced at MSU, with improved irrigation amount and timing owing to a spatially-explicit irrigation threshold (*Felfelani 2018). The GW scheme has also been improved, by incorporating capabilities to simulate lateral flow and aquifer pumping using well hydraulics formulations (*Felfelani 2019; *Felfelani 2020).

T2.1F - ORC-HR: calibration

This task aims at merging several recent developments related to water resources and water management in ORCHIDEE, presently in different model versions (GW-SM interactions, irrigation, high resolution routing, flooding). The resulting version, also including SOC developments from T2.1Ga**,** will be calibrated for high-resolution off-line simulations over France (8 km), using tailored climate and land use input data covering the last decades. This work will benefit from IPSL funding for an 18-month postdoc expected to start in early 2021 (see support letter and job offer).

T2.1M - CLM5-HR: calibration

A high-resolution (0.05°) version of CLM5 will be set up for the LMRB. We will calibrate the model using GW data (e.g., hydraulic conductivity, depth to bedrock) from the MRC and NAWAPI (National Center for Water Resources Planning and Investigation, Vietnam). Results will be validated with the observations of hydrologic fluxes and storages: river discharge with the data from MRC, terrestrial water storage (TWS) with the data from the gravity recovery and climate experiment (GRACE) satellites (Scanlon 2016) and related historical reconstructions (Humphrey 2019; Humphrey 2017), water table depth with well observations in Vietnam obtained from regional collaborators and the global equilibrium water table depth (Fan 2013).

T2.2G - Factorial ESM simulations over 1900-2100

To reduce the uncertainty and calculation cost of ESM simulations, we will not simulate the ocean compartment and use land-atmosphere simulations with prescribed sea surface temperatures (SST) and sea ice cover (SIC). For the historical period (1900-2015), both ESMs will use observation-based forcing data for SST, SIC, LU, and radiative forcing, as distributed for CMIP6. For the future period, we will also use identical forcing datasets for both models, from two different SSPs, which all include projections of irrigated areas (Hurtt 2020): SSP5-8.5 gives the largest global warming and is useful to obtain statistically significant changes; another SSP will be selected at the beginning of the project with the social scientists and stake-holders to match their regional questions. The corresponding SST and SIC will be based on bias-corrected existing CMIP6 ocean-atmosphere projections. For each ESM, we plan 6 simulations combining 2 SSPs and 3 LSM configurations with and without irrigation and capillary rise from GW (noGWcap_noIRR, GWcap_noIRR, GWcap_IRR). This protocol generalizes the one of the IGEM project by adding a second SSP and including irrigation. If required to amplify the statistical significance of the GW and irrigation effects (which tend to be weak in front of climate change response, *Ducharne 2020b), we will run 5 members of each simulation.

T2.2FM - Downscaling over France & Mekong

Surface meteorological variables (precipitation, solar radiation, air temperature, humidity, pressure, and wind speed) from T2.2G will be downscaled into 0.05 degree grids over France and Mekong to force high-resolution regional simulations. Overall, the bias correction sequence will follow the generation of GSWP3 forcing data (trend preserving quantile mapping, *Kim 2017), used for water budget reconstructions over the 20th century in many international projects including CMIP6, and we will fully exploit locally available in-situ data. Spatial disaggregation will account for topographic effects using a recent very high resolution DEM (*Yamazaki 2017).

T2.2M - HR CLM5 simulations

Using the above meteorological forcing, we will conduct historical simulations with CLM5 over the LMRB for 1979-2020 period to examine the historical changes in soils and GW caused by climate variability and change, land use/land cover change, irrigation, and GW use. We will compare two simulations: one with and the other without anthropogenic activities. Data collected from various sources including census data on agriculture and irrigated extents will be used as model input. Future simulations will be conducted for 2020-2100 period to examine the changes in soils and GW for the early (2021-2040), mid (2041-2070), and late (2071-2100) 21st century. Following the simulation protocols for global runs, we will run a series of simulations to examine the impacts of climate change on soils and GW, and the potential role of GW in achieving GW sustainability in the region.

T2.2Fa - HR ORC simulations

The same set of simulations as in LMRB will be run with the version of ORCHIDEE calibrated for France in T2.1F, and analyzed similarly, in collaboration between IPSL and OFB. Specific simulations will also be performed, to assess the effectiveness of managed aquifer recharge (simplified via increased soil hydraulic conductivity), or of potential GW use regulations, and of the LU and irrigation evolutions projected in T3F.

T2.2Fb - Run-time bias-corrected IPSL-CM simulations

Land-atmosphere feedbacks exert a significant influence on climate change pathways (*Cheruy 2014,*Berg 2016,*Ducharne 2020b) but they can be distorted by ESM biases, and are absent from land-only simulations. We will thus test the interest of an innovative method for bias-correcting climate projections during run time (by “nudging” selected atmospheric variables based on observations during the historical period cf. Cheruy 2013, and based on historical trends over the future period, cf. Krinner 2019). This approach will be used with IPSL-CM6 only, with a zoom over France (30-km grid cells), and the factorial design of T2.2G.

T2.3a - Model benchmarking

To assure the quality of simulations comprehensively, process-wise model verification will be carried out. The International Land Model Benchmarking (ILAMB; Collier 2018) provides a tool for model-data intercomparison and integration, designed to investigate the performance of land models. The system employs a suite of in situ, remote sensing, and reanalysis datasets. Based on these generalized evaluation metrics, we will assess the predictability of the global and regional historical energy and water cycle variables (e.g., temperature, precipitation, soil-moisture) simulated by LSMs and GCMs in T2.2G, T2.2Fa, T2.2M, and T2.2Fb.

T2.3b - Trend attribution, influence of land-atmosphere feedbacks

Besides standard assessment criteria which mostly ignore that "stationarity is dead" (Milly 2008), we will also assess how our simulations (land-only and coupled) capture past trends, which is important to support their use for future impact assessment (T2.3c). The factorial simulations will allow us to quantify the contribution of the different drivers and processes to the overall trend, focusing on TWS (Scanlon 2018), ET (*Jung 2010), SM, river discharge, GPP, LAI and irrigation (*Xi 2018, Vicente-Serrano 2019). GW fluxes and irrigation are expected to respectively increase and decrease SM variability and memory (because of the high residence time of GW and the strong response of irrigation to weather conditions, Russo 2017) and we will assess their impact on the persistence of extreme events (heatwaves, drought, convective showers) and climate change trajectory. In doing so, we will highlight regions/periods over which GW and irrigation can either attenuate or amplify the manifestations of climate change, compared to CMIP6 projections which ignore them.

T2.3c - Impact assessment (water resources, soil C, biosphere)

Here, we will reverse to a more classical perspective and map the worldwide impacts of climate change, LU and irrigation on natural and cultivated biosphere, soil carbon content and fluxes, and water resources. For the latter, we will distinguish SM, streamflow, and GW (novel using direct ESM results), and assess the changes in extreme conditions (low/high flows and GW levels). The end goal is to identify projections/regions in which GW resources deplete severely with negative impacts on the sustainability of biosphere, irrigation hence socio-economic systems (tipping points), thus calling for adapted LU and GW management strategies, in contrast to projections/regions where sustainable trade-offs can be achieved under the selected SSPs assumptions. In the two focal areas, we will also use the calibrated land-only simulations for more realistic assessments, in preparation for the transdisciplinary analyses of task T4.

T3F - Agro-economic scenarios of land-use & irrigation evolutions

This task has two main goals:

1. Integrate the impacts of farmers' decisions on the physical variables and processes simulated or taken into account by LSMs (land allocation, carbon storage and GHG emissions, water resources for irrigation especially by GW)
2. Analyze the coordination and effectiveness of economic instruments and public decisions in the economic regulation of the agriculture-environment system under multiple objectives (the Common Agricultural Policy at European level, now favoring crop diversification; long-term GHG mitigation & adaptation; food security; bioenergy production; fighting GW depletion).

The AROPAj model aims at optimizing land allocation at the scale of "farm types" (FT) statistically representative of a set of real farms surveyed by the Farm Accountancy Information Network, defining 1900 FT for the EU, including 160 for France. AROPAj is a supply-side economic model, in the economic sense that prices are exogenous (and therefore parameterized). For instance, the introduction of a tax on GHG emissions/GW withdrawals can be assimilated to CO_2/water pricing imposed on players emitting GHGs/withdrawing GW. AROPAj can be used to test LU or policy scenarios, or projected to the future, if the changes in all input parameters are known (Humblot 2017), which is now possible owing to the agronomic model STICS (Brisson 2003, Rosenzweig 2014), sometimes complemented by a GW model to address GW quality issues (*Bourgeois 2016). Such model association is common in agro-economic analysis (Nelson 2014).

A question will be to replace the crop model STICS by ORCHIDEE (IPSL LSM) to benefit from its description of GW-SM-biosphere interactions, if the simulated crop biomass can be used as a correct proxy to crop yield. Another major input to AROPAj consists of economic policy objectives likely to be assigned to farmers to meet environmental criteria, and they will be chosen in association with the OFB. Eventually, this task will propose LU and irrigation scenarios for the future that will be discussed with stakeholders in T4F and tested as input to ORCHIDEE in T2.2Fa, then in T2.2Fb to examine the consequence on regional climate if the land surface response in large enough in T2.2Fa.

T3Ma - Hot spots and bright spots of farmer behaviors

Changes in the CZ related to GW, SM, soil carbon, and climate profoundly affect the livelihoods and well-being of millions of people dependent on CZ ecosystem services in the Mekong region and elsewhere (Kramer et al. 2017). We will overlay maps of biophysical changes simulated with the project's ESMs with farmer behavioral changes from the Cambodian Agricultural Survey (2013 & 2018) to understand, utilizing hierarchical spatially explicit modelling, how temporal and spatial biophysical changes manifest themselves in agricultural settings including choices related to farm area, crop and livestock holdings, irrigation use, and farm inputs. Less direct impacts on land tenure, crop commercialization, market engagement, labor allocation, credit use, and livelihood diversification will also be evaluated. By doing so, we hope to identify both hotspots and bright spots of farmer behavior as they relate to CZ processes. Hotspots are those areas where farmer behaviors exacerbate the unstainable loss of CZ ecosystem services. Bright spots, on the other hand, are identified as statistical outliers, farmer behaviors that foster sustainability contrary to general practices (Bennett 2016, Cinner 2016).

T3Mb - Farming futures and social-ecological feedbacks

We will use household surveys and key informant interviews to collect local perceptions and understanding of and adaptations to temporal and spatial biophysical changes to the CZ. Our results not only will help us understand how local people respond sustainably to biophysical changes in the CZ but also help us identify and model the effects of these behaviors on CZ processes. For example, one widespread adaptation to changes in GW and irrigation may be double cropping of paddy rice. Such behaviors, however, if adopted broadly, can further stress water resources through unsustainable water withdrawals. The MRC (stakeholder agency) will actively engage in this task.

T4F - Elaboration of storylines for LU-GW with stakeholders

When presenting projections with a range of uncertainties, like in the IPCC reports, climate and biophysical changes tend to appear as a global problem expressed through statistics rather than useful information for local people. Storylines, however, allow both decision makers and the general public to relate the projections to their own experiences and facilitate appropriation of scientific information (Shepherd 2019).

For this approach to be practically relevant for management while reflecting the current state of knowledge, it is essential to take the time to understand stakeholders and to make scientific concerns understandable to them (Porter 2016). The task will thus start with semi-structured interviews (Longhurst 2003) and a first workshop led by the OFB with regional water agencies and other selected local stakeholders to map their concerns regarding water management and irrigation in a changing climate. We will then prepare a set of relevant storylines, which will eventually be presented and discussed in a workshop with the participating stakeholders. The main goal is to understand whether BLUEGEM's results have an influence on the way stakeholders perceive future water management policies, then leading to revisit them for better adaptation strategies. A secondary goal is to evaluate the potential of storylines to facilitate creative and explorative thinking (Malekpour 2016).

T4M - Participatory GIS and participatory cultural mapping

Utilizing participatory GIS (geographic information systems) and cultural mapping, we will provide understanding and analysis of farmer bright spots in order to identify sustainable agricultural practices that may be adopted more broadly. Participatory GIS asks local stakeholders to engage with high resolution maps, generated from model outputs, to provide greater contextual understanding of and responses to biophysical change. Similarly, participatory cultural mapping is an innovative method of training local communities to generate spatial and conceptual maps that draw on oral traditions (e.g. songs, stories, rituals) and other forms of intangible and tangible heritage to illustrate the cultural significance of water, land, and other natural resources (Crawhall 2009) and in turn, providing greater understanding of behavioral adaptations to biophysical change.

T4FM - Comparison of the focus areas from natural and social points of view

This task aims at comparing the context and CZ changes in France and Mekong in simple terms, with indicators (biophysical & societal) selected for efficient dissemination/outreach (tested and improved owing to workshops with stakeholders in T4F and T4M). In particular, we will try to conceive robust sustainability indicators for GW, by comparing the interest of referring to assess sustainability with respect to recharge, recharge and baseflow, or volume/GW level.

T4G - Participatory workshop for storylines on GW-irrigation

This part, aiming at upscaling plausible options for GW and irrigation management across the globe under climate change, is proposed via the "Coordination Grant" (see corresponding PDF).

T5a - Preparation of selected variables and indicators

This task proposes to calculate and map globally the simple indicators selected by T4FM, and to make them available online. Regional and/or specific indicators will also be prepared via the "Coordination Grant, in collaboration with other projects of this Belmont CRA, as explained in the corresponding PDF (Action 1).

T5b - Data storage and exchanges among project partners

See "Data Management Plan".

3. Relevance to the call

By bringing together a wide panel of natural scientists, social scientists, and stakeholders all involved to design the proposed research, BLUEGEM contributes in several ways to the Collaborative Research Action (CRA) "Towards Sustainability of Soils & Groundwater for Society":

- Topic 1: we propose novel research to assess "climate change impacts on soil and GW resources in a long-time perspective", and also the reverse influence of GW, SM and socio-economic decisions on the future climate;
- Topic 2: the socio-economic decisions we focus on are the ones controlling LU and irrigation changes, thus happening in "highly anthropized ecosystems";
- Our project will lead to "improved predictive capacity" of important CZ processes linked to GW, soils and irrigation, by improved articulation of their human and natural dimensions, both in models and their input socio-ecological scenarios;
- We put a strong emphasis on transdisciplinary work and dissemination to a broad audience of local actors of LU, soils and water management owing to the engagement of influential stakeholders in France and LMRB, and a rich array of participatory methods.

Owing to advanced disciplinary and transdisciplinary methods, we believe the BLUEGEM project will produce useful outcomes to expand CZ knowledge and models, and inform salient decision-making regarding the sustainability of the soil-GW-irrigation system under anthropogenic pressures.

Management plan

1. Consortium description

1.1 Expertise and complementarities

The proposed project was jointly elaborated by five complementary research teams in natural and social sciences and two stakeholder organizations, encompassing a total of 8 countries over 3 continents:

- **IPSL** (France) federates 8 research units with a mission to foster and coordinate research on climate and environment changes. The IPSL climate model has been involved in all the CMIP phases since 1995. The PI for IPSL and BLUEGEM lead, A. Ducharne, conducts research on the links between land surface hydrology and the climate system, with a major focus on GW and anthropogenic pressures. She belongs to the group developing the ORCHIDEE land surface model, like the other IPSL task leaders: F. Cheruy (land-atmosphere coupling, atmospheric parametrizations); B. Guenet (soil carbon); A. Jezequel (extreme events; science-society relationships); P. Peylin (carbon cycle, data assimilation); J. Polcher (water cycle, human influences, co-chair of the GEWEX Scientific Steering Group). The IPSL group also includes P. Ciais, among the top-cited researchers in Geosciences and Environment, and co-chair of Global Carbon Project.
- **INRAE** (France) is involving its laboratory of Public Economy. The PI is P.A. Jayet, economist, focusing on the relationships between agriculture and the physical environment and their economic regulation, in the framework of climate change.
- at **U-Tokyo** (Japan), the PI is H. Kim, with an overall research goal to understand how water, climate and society are interconnected within the Earth System, and a recognized expertise in bias-correction and downscaling methods. He has been actively involved in CMIP6 coordination.
- at **NTU** (Taiwan), the PI is M.H. Lo (Department of Atmospheric Sciences), who combines climate modelling (with CESM) and satellite data to explore how land surface process and land use changes impact regional and global climate. He developed the GW parameterization in CLM/CESM. Dr. S.Y. Kuo (affiliated to Academica Sinica) works on sociological and political dimensions of environmental and sustainability problems, such as climate change and natural disasters, and will co-lead social and transdisciplinary tasks.
- **MSU** (USA) is represented by two PIs: Y. Pokhrel (Department of Civil and Environmental Engineering) focuses on how the water cycle responds to the combined effects of climate change and human activities, and he pioneered the representation of these human factors, including irrigation and GW pumping, into global/regional hydrologic models; D. Kramer (James Madison College - public affairs and public policy) focuses on how local communities respond and adapt to infrastructure development and how these changes affect human/environment interactions. This research involves analyzing the integration of natural and human systems.

The stakeholders organizations bring authorized knowledge regarding CZ sustainability issues in the two focal regions of the project:

- **OFB** (French Biodiversity Agency, France, PI: C. Magand) is a national public agency under the Ministry of Environment. Its missions include to implement a sustainable management of water resources under global change, and to support related research.

- **MRC** (Mekong River Commission, Laos, PI: L. Thym) is an inter-governmental organization that works directly with the governments of Cambodia, Laos, Thailand, and Vietnam to jointly manage the shared water resources and the sustainable development of the Mekong River. It has signed a "memorandum of understanding" with MSU to jointly work on issues related to climate change and socio-economic development in the LMRB.

This broad transdisciplinary consortium has a rich history of mutual collaborations, which will help the BLUEGEM project being more effective, from both human and scientific points of views. The previous projects of particular relevance include:

- The bi-lateral project IGEM (Impact of groundwater in Earth system models, PIs: Lo and Ducharne) prefigured BLUEGEM in several ways: it permitted to develop the GW parametrization of ORCHIDEE; it showed the potential of GW-SM for the attenuation of climate change manifestations (e.g., droughts, hot spells); BLUEGEM's ESM simulation protocol expands IGEM's one, owing to a yes/no option on irrigation, a second SSP, and multi-member simulations to amplify statistical significance.
- LS3MIP (Land Surface, Snow and Soil moisture Model Intercomparison Project, PI: Kim, with Cheruy and Ducharne) is the first CMIP activity with LSM simulations, and the applied benchmarking and bias-correction/nudging methods will benefit BLUEGEM.
- The bi-lateral project "Using climate models to explore the impact of land-use change on extreme climate" (PIs: Lo and Kim, ending late 2020) relies on CESM to study the impacts of land-use changes on droughts and precipitation extremes over the Maritime Continent.
- In the Mekong region, BLUEGEM complements four other ongoing projects on which both Drs. Pokhrel and Kramer participate with MRC: NASA IDS, NASA LCLUC, NSF Career Grant (Pokhrel), and the Henry Luce Foundation's Initiative of SE Asia. The proposed BLUEGEM activities will be conducted synergistically with those prior projects. In terms of high-resolution hydrological modeling over the Mekong region, we will build methodologically on extensive modeling works conducted under the NASA and NSF-funded projects which considered the impacts of dams on surface water dynamics and also included irrigation and GW components. In terms of social science, the NASA- and Luce-funded projects support household surveys in the Tonle Sap region of Cambodia which query local residents on livelihoods, ecosystem services, and adaptation strategies to climate change and dam impacts. These data will compliment data and analyses done under BLUEGEM. The Luce-funded project supports participatory GIS and cultural mapping in the same communities and households, and these data will also be used in BLUEGEM, which adds a much broader spatial extent by utilizing data from the Cambodian Agricultural Census.
- France has a long history of applied research for river basin adaptation to climate change under the auspices of Ministry of Environment, often steered by the OFB or prefiguring agencies. A. Ducharne was PI or participant of several such climate change impacts projects, all with public stakeholders and/or private partners. One of them funded the Ph.D thesis of C. Magand (OFB PI) on climate change impacts in the heavily human-influenced Durance watershed (Mediterranean area), under the supervision of A. Ducharne.

1.2 Contributions and roles

The consortium is detailed at individual level in Table 1. It involves a total of 34 persons, 10 of which will be hired for the project at graduate or post-doctoral level. The permanent staff includes 13 task leaders, mostly senior scientists with a strong history of mutual collaborations, along with two early-career scientists (A. Jezequel at IPSL, S.Y. Kuo at NTU), driven by a strong commitment to bridge the gap between science and society. They will benefit from the rich BLUEGEM environment to develop their research within the transdisciplinary tasks. The senior scientists will actively support their integration to the project, and the one of PhD students, research assistants, and post-docs, who will benefit from a high-level training environment.

Table 1. Contributions of all involved persons in the BLUEGEM project. The contributed tasks appear in boldface if the person is leading it. Blue color indicates that the persons will hired, paid or subcontracted (shown by an) with BLUEGEM funds. The time contribution is given in person.month except for the mean % time.*

						Dedicated time (in pers.mo but mean % time)					
Org.	Last name	First name	Initials	Gen.	Position	Y1	Y2	Y3	Total	%	Tasks (in bold if coordination)
IPSL	**12 pers (91.5 pers.mo)** + 2 pers requested (30 pers.mo)					55,5	37,5	28,5	121,5	24	
	Ducharne	Agnes	**AD**	F	Senior scientist	6	6	6	18	50	**Project, France, T1, T2.1F**, T2.2G, **T2.2Fa**, T2.3ab, T2.3c, **T3F, T4G**, T4F, **T4FM**, T5a
	Cheruy	Frederique	**FC**	F	Senior scientist	2	2	2	6	17	**T2.2Fb**, T2.2G, **T2.3b**, other T2.3
	Guenet	Bertrand	**BG**	M	Senior scientist	2	2	2	6	17	**T2.1Ga**, T2.3ab, **T2.3c**, T4F, T4FM
	Jezequel	Aglae	**AJ**	F	Junior scientist	2	2	2	6	17	**T4F, T4G**, T4FM
	Peylin	Philippe	**PP**	M	Senior scientist	1	1	1	3	8	**T2.1F**, T2.2Fa, T2.3, T4FM, **T5a**
	Polcher	Jan	**JP**	M	Senior scientist	1	1	1	3	8	T2.1F, T2.2Fa, T2.3, T4G
	Ciais	Philippe	PC	M	Senior scientist	0,5	0,5	0,5	1,5	4	T2.1Ga, T2.1F*, T2.3
	Ghattas	Josefine	JG	F	Research engineer	1	1	1	3	8	T2.1Ga, T2.1F*, T2.2G, T2.2Fb, T5b
	Baro	Aurelien	AB	M	GIS engineer	1	1	1	3	8	T2.1F, T2.3
	Arboleda	Pedro	PA	M	PhD student	12			12	33	T2.2G, T2.3
	Coulon	Maelle	MC	F	PhD student	6	6		12	33	T2.2Fb, T2.3ab
	X1				IPSL Post-doc	12	6		18	50	T2.1F, T2.2Fa, T2.3
	X2				Post-doc	9			9	25	T2.1Ga, T2.3
	X3				Post-doc		9	12	21	58	T2.2G, T2.2Fab, T2.3, T4FM
OFB	**2 pers (7.5 pers.mo)**					2,5	2,5	2,5	7,5	10	
	Magand	Claire	**CM**	F	Scientific officer	2	2	2	6	17	T3F, **T4F**, T4FM
	Augeard	Benedicte	AB	F	Scientific manager	0,5	0,5	0,5	1,5	4	T4F, T4G
INRAE	**2 pers (13 pers.mo)** + 2 pers requested (39 pers.mo)					18	18	16	52	36	
	Jayet	Pierre-Alain	**PAJ**	M	Senior scientist	3	3	3	9	25	**T3F**, T4F, T4FM
	Ollier	Maxime	MO	M	PhD student	2	2		4	11	T3F
	Humblot	Pierre	PH	M	Research engineer*	1	1	1	3	8	T3F
	X4				PhD student	12	12	12	36	100	T3F, T4F, T4FM
U-Tokyo	**2 pers (21 pers.mo)** + 2 pers requested (39 pers.mo)					20	20	20	60	42	
	Kim	Hyunjun	**HK**	M	Assoc. Professor	6	6	6	18	50	T2.2G, **T2.2FM**, T2.3a, **T2.3b**, T2.3c, **T5a, T5b, Data Management**
	Yamazaki	Dai	DY	M	Assoc. Professor	1	1	1	3	8	T2.2FM, T2.3c
	Tokuda	Daisuke	DT	M	Project scientist	12	12	12	36	100	T2.2G, T2.2FM, T2.3a, T2.3b, T2.3c
	Eiji	Ikoma	EI	M	Assoc. Professor	1	1	1	3	8	T5a, T5b
NTU	**3 pers (84 pers.mo)** + 2 pers requested (72 pers.mo)					34	34	34	102		
	Lo	Min-Hui	**MHL**	M	Assoc. Professor	6	6	6	18	50	**Global, T2.1Gb, T2.2G, T2.3ab**, T2.3c, **T4G, T5b**
	Kuo	Shih-Yun	**SYK**	F	Junior Researcher	2	2	2	6	17	**T3Mb, T4M**
	Chen	Yi-Ying	YYC	M	Assist. Researcher	2	2	2	6	17	T2.2G, T2.3b
	X5				Research assistant	12	12	12	36	100	T2.3abc, T5b
	X6				Research assistant	12	12	12	36	100	T2.1Gb, T2.2G, T2.3b
MSU	**2 pers (17 pers.mo** incl. 3.75 requested) + 2 pers requested (22 pers.mo)										
	Pokhrel	Yadu	**YP**	M	Assoc. Professor	3,5	3,5	3,5	10,5	30	**Mekong, T2.1M, T2.1Gb, T2.2M**, T2.3ab, **T2.3c, T4M, T4FM**
	Kramer	Dan	**DK**	M	Professor	2,2	2,2	2,2	6,6	18	**T3Ma, T3Mb, T4M**, T5a
	X7				PhD Student	4,5	4,5	4,5	14	38	T2.1M, T2.1Gb, T2.2M, T2.3abc, T4M,
	X8				PhD Student	2,8	2,8	2,8	8	23	T3Ma, T3Mb, T4M
MRC	**1 pers (3 pers.mo)**										
	Thim	Ly	LT	M	Research Scientist	1	1	1	3	8	T2.1M, T2.2M, T4M

Despite a higher involvement from French partners (due to higher funding by the ANR), we underline the **balanced collaboration between countries**, with PIs from the four countries sharing responsibilities for all main coordination activities (Coordination and France led by A. Ducharne, France; Mekong led by Y. Pokhrel, USA; Global led by M.H. Lo, Taiwan; Data management and dissemination led by H. Kim, Japan). We also have a correct gender balance with women in leading positions (5/13 task leaders and overall project).

A major strength of the BLUEGEM project is the strong involvement of stakeholders, who actively contributed to the project's orientations so they match the various concerns they are mandated to address at the scale of France and the LMRB. Although it does not stand out in the "Project description" by lack of space, they have been particularly attentive to the regional significance of the GW, LU and irrigation management strategies that will be examined by the project via modelling and participatory work, and they will continue, should the project be funded. To this end, they will bring their network of more local stakeholders to the proposed transdisciplinary work in the two regions (T4F and T4M). They also engaged to participate to the comparison of the two regions (T4FM) to better highlight situations leading to either degradation or recovery of CZ ecosystem services, and to generalize this comparaison at a broader scale and propose plausible options for sustainable GW and irrigation management across the globe under climate change (task T4M relying on an international participatory workshop proposed under the Coordination grant).

Finally, **the BLUEGEM project will also benefit substantially from in-kind collaborators**, who have expressed major interest in the project in their support letters: Dr. Bui (NAWAPI, Vietnam) and Dr. Ngo Duc (University of Science and Technology of Hanoi, Vietnam) in the LMRB; the 30-yr old interdisciplinary research programme PIREN-Seine in France; and Drs. Scanlon and Famiglietti for global scale studies. They all share a long track record of transdisciplinary research, with the project PIs on the one hand, and with MRC and OFB for the first three collaborators, and north-american and international stakeholders for the last two.

2. Project coordination

Table 2 displays how the different tasks will be articulated together and scheduled along the 3 years of the project. **Important milestones come from the meetings organized by the Belmont Forum for the CRA** (kick-off: mid 2021; mid-term: late 2022; end-of-term: mid 2024), and the project organization has been prepared so that we can benefit from these opportunities for discussion and further elaboration of our results with the other funded projects, via the activities proposed under the Coordination grant.

Each task will be performed under the responsibility of 1 to 3 task leaders, depending on the volume of work planned and its inter/trans-disciplinary nature. It will be the responsibility of the project and domain leaders to ensure that responsibility is not diluted when having several task leaders. **The standard deliverable of each task is a report or paper**, complemented by the project website (T1); new code versions (T2.1, T3F); downscaling, simulation, and participatory GIS outputs (T2.2, T3F, T3Ma, T5a) as described in the Data Management Plan.

A specific task is planned to ensure that work progress effectively and in a timely manner (task T1, led by A. Ducharne, Lead PI). This coordination task will rely on regular project meetings (at least every 3 months via videoconference) set up by the project lead with all PIs and leaders of active tasks. Because of the international dimension of the project, these meetings will be scheduled at the time found effective for proposal preparation (8 am at MSU, 2 pm in France, 8 and 9 pm in Taiwan and Japan respectively). The project meetings will be the place to coordinate activities, track progress, and discuss latest outcomes, dissemination strategy (publications, conferences, data access), and reporting duties (yearly reporting of project accomplishments due each year to the Belmont Forum on June 15th). More specific meetings may also be organized by task/domain/project leaders, especially if needed to raise the schedule constraint mentioned above, or for any particular requirement. The CRA meetings will finally offer us the opportunity to gather several PIs in person.

We have also established an international advisory board to support the scientific coordination of the project. It is composed of five recognized science and policy experts: Stefan Siebert (Georg August Universität Göttingen, Germany), specialist of global irrigation for the FAO; Jay Famiglietti (U. Saskatoon, Canada) and Bridget Scalon (UT Austin, USA), both specialists of global GW issues; Brian Eyler (Stimson Center Director for Southeast Asia, Washington DC, USA), and Alice Aureli (head of the UNESCO Groundwater Systems and Settlements Section, Paris, France). They agreed to join us three times (by videoconference), in close link with the CRA meetings, to provide guidance and identify additional resources (material and otherwise) for developing and sharing our research.

Table 2. Gantt chart of the BLUEGEM project, where the 3-yr duration is divided in 12 trimesters, from t1 (supposed to start in April 2021) to t12 (supposed to end in March 2024). Belmont meetings are expected around t1, t6, and t12 (vertical bars). The initials of the task leaders are defined in Table 1. The last column shows the connections between the different tasks, in terms of data fluxes.

Tasks	Domain	Leaders	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	Gets info from
T1 - Project coordination	All	AD													T4F,T4M
T2.1Ga - ORC Development: soil carbon	Global	BG													
T2.1Gb - CLM5 Development: water management	Global	MHL,YP													
T2.1F - ORC-HR: calibration	France	AD,PP													
T2.1M - CLM5-HR: calibration	Mekong	YP													
T2.2G - Factorial ESM simulations over 1900-2100	Global	MHL													T1
T2.2FM - Downscaling over France & Mekong	F&M	HK													T2.2G
T2.2Fa - HR ORC simulations	France	AD,JP													T2.1M,T2.2FM,T3F,T4F
T2.2M - HR CLM5 simulations	Mekong	YP													T2.1F*,T2.2FM,T4M
T2.2Fb - Run-time bias-corrected simulations	France	FC													T1,T2.2FM
T2.3a - Model benchmarking	All	HK,MHL													T2
T2.3b - Trend attribution, land-atmosphere feedbacks	All	MHL,FC,HK													T2
T2.3c - Impact assessment (water, soil C, biosphere)	All	YP,BG,HK													T2
T3F - Agro-economic scenarios of LU & irrigation	France	PAJ,AD													T1,T4F,T2.2G,T2.2.Fa,T5a
T3Ma - Hotspots and bright spots of farmer behavior	Mekong	DK													T2.2M,T2.3c,Other Project
T3Mb - Farming futures and social-ecological	Mekong	DK,SYK													T2.2M, T2.3c
T4G - Workshop on GW-irrigation management	Global	AD,AJ													T2.3,T5a,T4FM
T4F - Plausible storylines of LU-GW management	France	AJ,CM													T2.3,T3Fb,T5a
T4M - Participatory GIS and cultural mapping	Mekong	DK,YP,SYK													T2.2M,T2.3c,Other Project
T4FM - Comparison of the two focus areas	F&M	AD,YP													T2.2, T2.3, T3, T4F,T4M,
T5a - Preparation of selected variables and indicators	All	HK,PP													T2.2,T3F
T5b - Data storage and exchanges within project	All	HK,MHL													T1,T2.2, T2.3, T3,T4,T5a

Another important coordination tool is the project website that will be created to centralize all information related to BLUEGEM, for both internal communication between project members (meeting dates and minutes, simulation protocols, deadlines, etc.), and for external communication, as detailed in the Dissemination plan.

Finally, within task T1, the Lead PI will be the contact point for any solicitation by the Belmont Forum or other interested person or organization. She will also ensure that a Consortium Agreement (including Intellectual Property Rights) is signed among the partners of the research consortium prior to the start of the project, as requested by the Belmont Forum.

3. Risk analysis

We believe there is no risk that the BLUEGEM cannot deliver the intended outcome, since it relies on solid bases: strong commitment by all partners, with balanced expertise and responsibilities; successful antecedent collaborations; and pre-existing modelling tools and data.

An important challenge will be to deliver ESM results for the mid-term Belmont Forum reporting and meeting (and the Coordination Action n°2 with other funded projects at mid-term, see Coordination grant), given that some developments are needed, but we are confident that the IPSL and CESM simulations will be produced with preliminary analyses in due time:

- LSM developments is the technical core of many participants, and will benefit from important resources, including external funding by IPSL, and a PhD student for the articulation between ORCHIDEE and the agro-economic model, jointly supervised by P.A. Jayet and A. Ducharne ;
- We rely on state-of-the-art ESMs, benchmarked in many international MIPs (model intercomparison projects), which also provide established modelling frameworks. Task T2.2Fb

comes with some risks, as it focuses on innovative run-time bias correction of climate projections, but it is not necessary to achieve the overall project goals;

- Computing resources will be secured in the HPC centers routinely used to run IPSL-CM and CESM2. This requires writing a proposal, but they are usually accepted, and the fact that CMIP6 simulations are coming to their end should free computing resources.

Note also that we have not included simulations by the Japanese MIROC ESM in T2.2G, although this model has participated in the CMIP6 exercise, and its land surface model MATSIRO is able to simulate GW influence on soil moisture and irrigation. The reason is a forthcoming migration to a new HPC environment, so there is a significant risk that MIROC simulations cannot be achieved in due time (estimated to 50%, thus leaving 50% chances that our multi-model sample is richer for uncertainty analyses).

Finally, the global COVID-19 pandemic needs to be considered: not only does it place questions of societal resilience and sustainability in stark relief, but it also has the potential to complicate the realization of an international project like BLUEGEM. As mentioned above, the project coordination will strongly rely on videoconferencing, which can also be adopted for transdisciplinary work in France (workshops and interviews) although real meetings are preferable. The input and validation data supporting modelling activities over France (T2.1F, T2.2F, T3F) are all existing data and require no field work. In the Mekong region, because social science data collection for the Mekong is funded under existing, complimentary projects, we have had the time to develop various contingency plans for travel to and the social science field-work. First, our rich network of local and regional academic partners are prepared to assume a much larger role in data collection and training (i.e. household surveys, participatory GIS, and cultural mapping). We have great confidence in their capacity to do so. Second, we have created a robust, virtual communication platform to share methodologies and survey instruments as well as to interact in regular project meetings for social science and transdisciplinary work (T3M and T4M).

Dissemination plan, engagement, and impact

1. Dissemination activities

1.1 BLUEGEM

We will create a website to centralize all information related to the project BLUEGEM that serves both coordination (see Management plan) and dissemination purposes. To the latter end, it will:

- explain the project to a broad audience (academic and non-academic) and its ongoing activities (e.g. transdisciplinary workshops, attended conferences, accepted papers)
- provide direct access to its major outcomes (e.g. conference presentations or reports about the BLUEGEM projections, their analyses, and the proposed narratives for sustainable GW and LU management at the end of the project)
- offer a catalog of the project data that we will publicly share (simulations results, indicators), with metadata and links to the places where data are accessible: primarily the long-term data repository hosted by DIAS in Japan (details below in section 1.4 and the Data Management Plan), the multimedia platform recently sponsored by Mekong Culture: Water, Ecologies, Land, and Livelihoods (details in section 1.5), and the GitHub repository planned in our Data Management Plan for sharing our modelling codes.

The BLUEGEM website will explicitly mention the support of the Belmont Forum and the funding agencies, and it will be maintained after the project duration. Some elements may be password protected (e.g. non validated preliminary results). The website of the IGEM project will serve as a template (https://www.metis.upmc.fr/~ducharne/gem/anr.php).

1.2 Scholarly reports, papers, and conferences

As in any research project, the project members will disseminate project results through peer-reviewed publications in discipline-based journals as well as high-profile interdisciplinary journals. Project members will make extra efforts to publish in broadly disseminated, open-access journals.

Project results will also be actively disseminated at the diverse set of international conferences which project members in natural and social sciences regularly attend. They include those sponsored by the American and European Geophysical Unions (at which we may host a dedicated session, like session H41S - Water and Society: Groundwater in a Changing Climate, co-convened in Fall 2019 by M.H. Lo), GEWEX, the American Association of Geographers, the American Academy for the Advancement of Science, or the Resilience Conference sponsored by the Resilience Alliance and the Stockholm Resilience Centre (e.g. http://resilience2017.org/)

We will also target forthcoming conferences focused on the sustainability of soils, groundwater, and the water-food nexus, as the ones proposed in 2021 to be coupled to the kick-off meeting of the present Belmont call (UNESCO/IAH-CFH/IHP International Conference on "Groundwater, key to the Sustainable Development Goals"; HESSS5: 5th International Conference on Hydrology and Earth System Science for Society), or other conferences on Sustainable Development Goals (SDGs).

1.3 Dissemination and impact to broader audiences

We summarize here the ways we intend to share our results beyond the academic sphere to advance transdisciplinary knowledge at different scales.

Regional conferences and workshops

In addition to the above international conferences, project members, along with regional partners, will present BLUEGEM results at regional conferences and workshops, often organized around specific topics like water, soils, and climate change, with a mixed audience comprising academic institutions, non-governmental organizations, policymakers, the private sector, and "local" and international development agencies. For example, the "Greater Mekong Forum on Water, Land, and Ecology"is an annual knowledge sharing event under the auspices of the CGIAR international development agency, while the European Climate Research Alliance organizes regular meetings to disseminate and expand knowledge for climate action. In France, where water management is strongly structured at the sub-national scale within the main river basins, we will participate in the annual meetings of the PIREN-Seine research program which is co-funding the project, and propose communications to various regional institutions, often associations, prompting the diffusion of scientific knowledge for climate change adaptation and attenuation (e.g. Acclimaterra, presided by H. Le Treut, French Academy of Sciences, former director of IPSL, in South-West France where irrigation is a recurring concern).

Belmont Forum activities

Of course, the Belmont Forum itself is an efficient vehicle to disseminate and enrich the funded projects results. To fully benefit from this framework, we are applying for a coordination grant consisting of two actions: 1) sharing project results with other CRA project participants; and 2) assembling other CRA project participants to discuss plausible options for the sustainable management of groundwater and irrigation under climate change across the globe, with a panel of elicited experts (some of them among the project's advisory board). This coordination grant provides the benefits of leveraging broad expertise on groundwater and irrigation sustainability and to consider multiple regions of the world, transferring scientific knowledge from BLUEGEM to other CRA projects, and promoting new international scientific and non-scientific collaborations.

Advisory Board

The project's Advisory Board is composed of several esteemed science and policy experts with significant influence and reach within their respective domains. We will engage the advisory board at critical times over the course of the project to seek advice, identify additional resources (material and otherwise), and to share and promulgate results. We expect the dissemination of project results to be greatly facilitated, especially at continental to global scales, via the rich networks of Advisory Board members including but not limited to UNESCO and the Stimson Center (https://www.stimson.org/).

1.4 Data sharing

As per our Data Management Plan, which complies with the Belmont Forum Open Data Policy and Principles as well as FAIR principles, we will publicly share the data produced by the BLUEGEM project, with few exceptions. In order to provide post-project accessibility and to facilitate the efficient handling of a big data products (anticipated approximately 50TB), the collection, storage, and distribution of data will be centralized through a long-term data repository hosted by Data Integration and Analysis System (DIAS; https://www.diasjp.net/en) in Japan. DIAS complies with FAIR principles and is not only re3data.org registered but is also recognized as an exemplary case in comprehensively reviewing e-Infrastructure for interdisciplinary and super interdisciplinary collaboration within the Belmont Forum (https://diasjp.net/en/about/.

1.5 Multimedia platform (Mekong)

BLUEGEM is complementary to several ongoing research activities of the project PIs that may provide additional venues for dissemination of regional results in the LMRB. One such project is the recently sponsored Mekong Culture: Water, Ecologies, Land, and Livelihoods (WELL) endeavor sponsored by the Henry Luce Foundation's Iniative for Southeast Asia (PIs Kramer and Pokhrel). The programmatic anchor of Mekong Culture WELL is a publicly-accessible, web-based multimedia platform (MP) in three languages designed to engage a range of publics on the cultural, political, and ecological dimensions of WELL in SEA by spotlighting interdisciplinary research synergies on these issues, energizing local collaborations, and highlighting the contributions of local, regional and global communities, artists, and activists. For example, we have recently collaborated with internationally renowned video and photography documentarians to provide compelling and accessible vignettes highlighting project results. Because of the significant substantive overlap between Mekong Culture WELL and BLUEGEM, we will utilize this existing multimedia platform to share and diversify project outcomes for the Mekong.

2. Engagement of local and regional stakeholders

The project's participatory research methods serve two joint purposes: engaging local communities in the design and implementation of the project's research activities, and facilitating the appropriation of the results by potential users. We use three participatory research methods in this project - participatory GIS, participatory cultural mapping, and storylines.

Participatory GIS aims to promote community empowerment, innovation, and change through the use of collaborative mapping exercises. Using maps generated by the project's model outputs on climate, groundwater, irrigation, and land use, community members are asked to communicate individually or in small groups significant spatial information which can then be used in conjunction with other remotely sensed or spatialized data. Furthermore, participatory mapping can be used to facilitate plausible response scenarios to changing biophysical conditions.

Similarly, participatory cultural mapping (PCM) is an innovative method of training local communities to generate themselves spatial and conceptual maps that draw on oral traditions (e.g. songs, stories, rituals) and other forms of intangible and tangible heritage to illustrate the cultural significance of water, land, and other natural resources for local livelihoods, identities, and community relationships (Crawhall 2009). The lack of understanding of the cultural importance of natural resources is often an insurmountable barrier to finding sustainable pathways. PCM can reduce these barriers.

Storylines are a tool used by researchers to translate scientific knowledge and results into narrative elements aimed at lay audiences. The essential elements of storylines are primary actors, a sequence of events, the physical setting, a problem to be solved, barriers to reaching solutions, and take-home messages. We will craft storylines aimed at engaging local communities in order to span the gaps between Western scientific and local epistemologies, creating opportunities for local empowerment and improvement.

These three kinds of methods will be implemented via workshops, interviews, and focus groups with key local or regional stakeholders, who will be invited to a series of sessions throughout the entire course of the project for them to understand the objectives of the project, provide opinions to the project (i.e., to co-design the project, to provide storylines), receive the results of the project, and make informed decisions based on the scientific evidence.

3. Impact and expected outcomes

BLUEGEM will firstly expand knowledge and new concepts on the evolving CZ processes during the Anthropocene and the influence of human activities on the sustainability of GW resources, agriculture, and land use. It will also offer a new perspective on the uncertainties of "classical" climate change projections, which overlook the interactions between GW, irrigation, and the climate system, as regretted in the Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2).

Secondly, BLUEGEM results will contribute to environmental policies at several scales. They will be shared with key local and regional policy communities (i.e. policy-makers and policy professionals). For example, our partner in Mekong region, the Mekong River Commission (MRC), is the primary intergovernmental organization to share information and recommendations related to sustainable development in the region among Thailand, Lao PDR, Cambodia, and Viet Nam. The MRC provides several accessible and well-known platforms (e.g. conferences, workshops, data portal, multimedia, reports) to share project analyses and recommendations to a broad community of policy-makers in the region. Furthermore, in our attached support letter from Vietnam's National Center for Water Resources Planning and Investigation (NAWAPI), Dr. Bui states their willingness to translate project results into ministerial policy. In France, the OFB partner will help translate project results into adaptation policies at national scales, which is its mission, and at the scale of the major river basins with the corresponding water agencies. The OFB is also involved in various networks providing guidance for European policy making regarding environmental issues for which the results of the BLUEGEM will be of interest, especially for those pertaining to possible evolution of the Common Agricultural Policy (CAP, cf task T3F). We hope that the involvement of experts from influential international organizations (e.g., UNESCO, World Bank, Stimson Center) may help us propose broadly applicable GW and irrigation management strategies that can be usefully discussed in international policy forums to develop Sustainable Development Goals (SDGs).

Finally, BLUEGEM will increase scientific synergies between teams and partner organizations in the eight involved countries. It will lead to new transdisciplinary research capacity being built, with considerable knowledge and expertise being vested by graduate students and early career scientists. This joint project shall also increase the visibility of France, Taiwan, Japan and USA transdisciplinary science, owing to our commitment for academic dissemination and outreach, within the Belmont Forum and beyond. As a perspective, we believe our results and strategy may promote enhanced collaborations with colleagues from plenty of regions where GW and irrigation are active drivers of CZ evolutions (e.g. Western Africa, USA, South America, and China), and be of interest to several international research programs placing an increasing emphasis towards science for and with society (e.g. the WCRP Grand Challenge on "Water for the Food Baskets of the World").

Coordination grant

In the name of the BLUEGEM project, the CNRS-IPSL partner (led by A. Ducharne) is applying for an additional "coordination grant" (as possible for ANR funded organizations), to develop collaboration and synergies between the individual projects that will be funded by the present Collaborative Research Action (CRA) on soils and groundwater (GW) sustainability.

Two actions are proposed in this framework, for a funding request of 50 kE (14 kE for Action 1, 32 kE for Action 2, 4kE as overheads). As detailed below, the added-value of the two proposed coordination actions is three-fold:

1. Benefit from the expertise gathered within the other CRA projects, and supplemented by invited international experts, to propose anchored solutions for the sustainable adaptation of GW and irrigation management in a larger number of regions;
2. Transfer BLUEGEM knowledge to the other CRA projects: direct data transfer via Action 1; training to up-to-date global climate and CZ trends and concerns, during the workshops of Action 2;
3. Promote new international collaborations between the workshops attendants, whether scientists or stakeholders.

Coordination Action 1. Share BLUEGEM's global simulation results to the other CRA projects.

We will share a list of our global simulations and main variables (on the BLUEGEM web page, planned under task T1), and upon request by the PIs of the other projects, we will extract the requested data for their regions of interest (in netcdf format). The results of the high-resolution simulations over France and Mekong may also be distributed if necessary, but in a more limited way, since the high resolution drastically increases the data file's size (for both storage and transfer).

For easier appropriation, we also propose to plot maps and time series for selected variables, to be discussed with the projects' PIs. Indicators based on simple combinations or the simulated variables may also be produced, if simple enough and upon discussion.

The results of data processing will be made available online to the general public, in a FAIR way (Findable, Accessible, Interoperable, Reusable), unless they involve non-open input data (which will not be the case for our simulation results). This action will therefore contribute to task T5a of the project, aiming at disseminating the BLUEGEM results.

Involved BLUEGEM scientists *at IPSL: A. Ducharne, P. Peylin (leaders), A. Baro (GIS engineer), V. Bastrikov (subcontractor)*

Coordination Action 2. Gather interested scientists and stakeholders from the other CRA projects to discuss plausible options for GW and irrigation management across the globe under climate change.

This action corresponds to task T4G of the BLUEGEM project, which will only be undertaken if the coordination grant is obtained.

The approach is to use participatory methods to combine the results from the BLUEGEM project (global scale simulations, social science and transdisciplinary work at regional scale in two contrasted regions), with the expertise of other CRA projects and invited international experts, gathered at workshops organized alongside the CRA meetings, to discuss plausible options for GW and irrigation management across the globe under climate change.

The other CRA projects will be involved at each of the three Belmont CRA meetings:

- information on BLUEGEM, and Actions 1 and 2 at the kick-off meeting for identification of interested projects
- the mid-term meeting (half-day) will permit informal exchanges between BLUEGEM scientists and interested PIs and project members on (i) BLUEGEM results and participatory work methods, (ii) the natural and social issues related to GW-irrigation-climate change in the areas addressed by the other CRA projects.
- the main workshop of Action 2 (1 or 2 days depending on the number of participants) will take place alongside the end-of-term CRA meeting, for interactive discussion regarding plausible solutions for sustainable GW and irrigation management, and how they relate to regional features. Following task T4F, the expected outcomes should take the form of storylines, which are efficient to convene information in a decision-making perspective (Malekpour 2017). We will highlight if general solutions can be proposed (trans-regional), and also regions where consensual tradeoffs seem difficult to achieve.

The international experts (maximum 5 to keep the discussion tractable and open, and prevent experts from dominating the discussion) will be selected for their broad vision of the GW and irrigation problems and their interactions with climate and societal changes. They will be invited to the final workshop and will be informed about the first two stages. We count on many of our international advisory board members to accept our invitation to this workshop: Stefan Siebert, world expert on global irrigation (SIebert 2010, 2013, 2015); Bridget Scanlon and Jay Famiglietti, world experts on GW sustainability issues (Scanlon 2012, Taylor 2013, Famiglietti 2014, Siebert 2015); Alice Aureli, head of the UNESCO Groundwater Systems and Settlements Section. We will also solicit Stéphane Hallegate, economist at the World Bank, strongly involved in climate change adaptation and SSPs (Rozenberg 2014).

It must be underlined that the first two phases of the proposed action (at kick-off and mid-term CRA meetings) can be organized as videoconferences if needed if the COVID-19 pandemic was to prevent travel on the long-term. It would be much more difficult for the third phase, but we hope the sanitary crisis will have found a solution by mid 2024.

This ambitious coordination action will benefit from several BLUEGEM outcomes: (i) the experience of participatory research undertaken in tasks T4F (led by A. Jezequel) and T4M, (ii) the results of task T4FM aiming at providing a straightforward comparison of the main trends, issues and possible solutions in the two focal regions, (iii) Coordination action 1, which is expected to raise interest from several other CRA projects. It will also benefit from the experience of A. Ducharne to organize this kind of workshops during the recent IGEM (Impact of groundwater in Earth system models) project jointly coordinated with M.H. Lo. The two international workshops they organized in this framework gathered many GW scientists from around the world (about 30 senior scientists and 20 early career ones), contributing to one submitted paper (*Gleeson 2020), and motivating several of them to prepare the BLUEGEM project.

Involved BLUEGEM scientists *at IPSL: A. Ducharne (leader), A. Jezequel, J. Polcher; and at NTU: M. Lo.*

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