ANR 2014 Generic Call

Societal Challenge « Efficient resource management and adaptation to climate change »

Project I-GEM

Full title: **Impact of Groundwater in Earth system Models**

Franco-Taiwanese international project

French PI: Agnès DUCHARNE (DR2 CNRS, METIS, Paris)

Taiwanese PI: Min-Hui LO (Assistant Professor, NTU, Taipei)

Duration: 48 months

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Abstract

Groundwater (GW) constitutes 30% of the fresh water resources, which are subjected to increasing withdrawals. When shallow enough, it can also sustain soil moisture, thus increase evapotranspiration, with potential impact on the climate system (in particular temperatures and precipitation). Its large residence time can also increase the Earth system's memory, with consequences on the persistence of extreme events, hydro-climatic predictability, and anthropogenic climate change, particularly the magnitude of regional warming.

Our main goal is to explore the impacts of GW on regional and global climate, and its links to water resources availability, through model analyses. To this end, our Franco-Taiwanese consortium offers a unique opportunity to compare the sensitivity of simulated climate to different GW parametrizations within 3 different climate models: the French IPSL and CNRM-GAME climate models, and the American NCAR climate model (CESM), modified and used here by the Taiwanese team.

All teams have experience in international intercomparison projects, and they have all recently emerged as important actors of the research on groundwater in climate models: the IPSL team and Min-Hui Lo have pioneered the analysis of the sensitivity of global simulated climate to GW, while the CNRM-GAME team achieved significant advances regarding the global-scale parameterization of GW and its coupling with rivers and land surfaces.

The project includes two transversal tasks: T0. Coordination; T5. International workshops; and the research program is organized into 4 successive scientific tasks:
T1**. Sensitivity to fixed water table depths** (WTD), to identify the patterns of "active WTD", below which GW do not impact regional climate
T2. **Dynamic WTD over the recent period**, to assess the potential of realistic GW parametrizations to improve the simulated climate, with a focus on land/atmosphere feedback and the persistence/memory in the Earth system
T3. **Dynamic WTD and climate change**, with two complementary questions: (*1)* What is the influence of GW on the climate change trajectory? (2) What is the impact of climate change on water resources (including GW)?
T4. **Dynamic WTD with withdrawals**, which artificially increase soil moisture via irrigation, with potential impacts on climate until water resources get exhausted.

I-GEM is also intended to consolidate the potential of France and Taiwan in the interdisciplinary research field of the global water cycle, by tightening the links between these two countries, and by federating the French community (IPSL and CNRM-GAME). We also aim at enhancing the visibility of French and Taiwanese teams, by developing closer links with European and North-American leaders in large-scale modeling of GW. To this end, we want to organize two international workshops on the role of GW in climate models, one in Taiwan and one in France, with a broad audience (T5).

Evolutions compared to the pre-proposal

This detailed proposal does not show significant evolutions compared to the pre-proposal.

Apart from detailing our work program and the required funding to achieve it, we mostly added man power to ensure the feasibility of the various tasks. The required non-permanent staff has been defined in Taiwan to a total of 9.3 years, including two PhD students (each for 32 months), and one full time research assistant for 48 months. In France, we secured the implication of permanent support staff, and we also ask for 3 years of ANR-funded post-doc, instead of 2 years in the pre-proposal. The implication of A. Ducharne (Project and METIS coordinator), and F. Chéruy (LMD coordinator), have also been raised, for them to successfully combine scientific and coordination/management work.

We also identified important work elements as new transversal tasks: T0. Coordination; T5. International workshops. For T5, we decided to duplicate the originally unique international workshop in both countries, for better equilibrium between them, and to better establish the I-GEM project as an important actor of GW/climate interaction at the international level.

Main acronyms

ANR : Agence Nationale de Recherche (F)
AMIP: Atmospheric Model Intercomparison Project
CESM: Community Earth System Model
CMIP: Coupled Model Intercomparison Project
CM: climate model
CNRM : Centre National de Recherches Météorologiques (F)
CNRS: Centre National de Recherche Scientifique (F)
ET: evapotranspiration
GCM: general circulation model
GEWEX: Global Energy and Water Cycle Experiment
GW: groundwater
IPSL: Institut Pierre Simon Laplace (F)
IDRIS : CNRS calculation centre near Paris (F)
IPCC : Intergovernmental Panel on Climate Change
LSM: land surface model
LMD: Laboratoire de Météorologie Dynamique (F)
METIS : Milieux Environnementaux; Transferts et Interactions dans les hydrosystèmes et les Sols
MoST : Ministry of Science and Technology (T)
NCAR : National Center for Atmospheric Research (USA)
NTU : National Taiwan University (T)
SM: soil moisture
WT/WTD: water table/water table depth
WCRP: World Climate Research Programme

Summary of involved people and requested funding to ANR and MoST

Table 1. Summary of involved people and requested funding (excluding management and structure fees), by country. *Persons in italic are the non-permanent staff supported by ANR/MoST funding*

Country	Partner	Last name	First name	Current position	Role and contribution to the project	Tasks	Involvement (pers.month)	Requested funding to ANR/ MoST (euros)
FRANCE							**159**	**286 800 € (ANR)**
	METIS						**93**	**186 400 €**
		Ducharne	Agnès	Senior scientist (DR2 CNRS)	National and partner coordinator; GW modeling in LMDZOR; Simulations analysis; Supervision of A. Schneider, X1, S1, S3, S4; Workshop organization	All	24	
		Jost	Anne	Associate professor (MCF UPMC)	GW modeling in LMDZOR; Simulations analysis ; Supervision of A. Schneider and S3	T2,T3,T4	6	
		Marty	Philippe	Research engineer (IR2 CNRS)	Code development and support for running the IPSL simulations	T1,T2,T4	6	
		Baro	Aurélien	Research assistant (IE1 CNRS)	Formatting GW withdrawal data	T4	4	
		Roger	Nora	Administrative technician (TCN UPMC)	Workshop organization	T5	2	
		Schneider	Ana	PhD student	GW modeling in LMDZOR; Running and analyzing IPSL simulations	T1,T2	15	
		X1		*Research scientist*	*Analyzing LMDZOR simulations; intercomparison, regarding projected climate change, its impact on water resources, and the sensitivity to water withdrawals.*	*T3,T4*	*24*	
		S1		*Student*	*Analysis of LMDZOR simulations*	*T1*	*6*	
		S3		*Student*	*Analysis of water resources changes (discharge and GW) with climate change in LMDZOR*	*T3*	*6*	
	LMD						**53**	**79 400 €**
		Chéruy	Frédérique	Senior scientist (CR1 CNRS)	Partner coordinator; simulation analysis; land/atmosphere feedbacks; Supervision of X1, X2, S1, S2	All but T5	16	
		Polcher	Jan	Senior scientist (DR2 CNRS)	Simulation analysis; GW modeling in LMDZOR; land/atmosphere feedbacks; Supervision of X2, S4	T1,T2,T4	5	
		Idelkadi	Abderrahmane	Research assistant (IE1 CNRS)	Support for running the IPSL simulations	T1,T2	5	
		Ghattas	Josefine	Research engineer (IR2 CNRS)	LMDZOR code development	T2,T4	3	
		X2		*Research scientist*	*LMDZOR simulations; comparison with NTU and CNRM-GAME simulations*	*T2*	*12*	
		Student S2		*Student*	*Impact of dynamical WTD on boundary layer structure and convection occurrence in LMDZOR*	*T2*	*6*	
		Student S4		*Student*	*Analysis of LMDZOR sensitivity to withdrawals*	*T4*	*6*	

Country	Partner	Last name	First name	Current position	Role and contribution to the project	Tasks	Involvement (pers.month)	Requested funding to ANR/ MoST (euros)
	CNRM-GAME						**13**	**21 000 €**
		Decharme	Bertrand	Senior scientist (CR1 CNRS)	Partner coordinator; GW modeling in SURFEX	All but T5	5	
		Colin	Jeanne	Research Engineer (IT MétéoFrance)	Simulation analysis; land/atmosphere feedbacks	T2,T3,T4	5	
		Tyteca	Sophie	Chief Technician (TC MeteoFrance)	Support for running the CNRM-GAME simulations	T1,T2,T3, T4	3	
TAIWAN							**151**	**230 600 € (MoST)**
	NTU						**151**	**230 600 €**
		Lo	Min-Hui	Assistant professor (NTU)	National and partner coordinator; modifying and improving GW modeling in NCAR CLM; Supervision of X3, X4, and X5; Workshop organization	All	24	
		Chou	Chia	Senior scientist (RCEC, Academia Sinica)	Simulation analysis; land/atmosphere feedbacks; discussions of experiments and results. Help supervision of X3, X4	All but T0	15	
		X3		*PhD student*	*GW modeling in CLM; Simulations analysis; Building an integrated module in CLM with irrigation and GW withdrawal processes.*	*T1,T2,T4*	*32*	
		X4		*PhD student*	*GW code development in CLM; Conduct coupled NCAR CESM simulations to assess remote impacts of GW withdrawal on the climate; Simulations analysis.*	*T2,T3,T4*	*32*	
		X5		*Research assistant*	*Support for running the NCAR CLM and CESM simulations. Model results analysis, intercomparisons (among NCAR, IPSL, and CNRM-GAME climate models)*	*T1,T2,T3, T4*	*48*	

1. Context, scientific positioning and objectives

1.1 State of the art: roles of groundwater in the Earth system

Realistic climate modeling is an important issue in climate science, as a means to ascertain poorly known processes, and to better understand and quantify the ongoing global changes. In this introduction, we intend to present the links between groundwater (GW), soil moisture (SM) and climate, which are an active research area for the Earth system modeling community. To show previous contributions of the I-GEM project's participants to advance knowledge in this area, our references are highlighted in bold.

Soil moisture (SM) is a key variable of land/atmosphere interactions, which are now recognized as a major uncertainty source in climate simulations [52][58][78][85][87][**4**][**35**]. The supply of moisture on land is limited and highly spatially variable; hence, land hydrology becomes critical in determining moisture supply to the atmosphere through the process of evapotranspiration (ET). SM exerts a positive control on ET, with usually negative feedback on air temperature [**4**][**5**], and feedback on rainfall that can either be positive (recycling) or negative, depending on boundary layer stability, convection triggering, and large-scale atmospheric circulations. Hence, positive soil moisture-rainfall has been observed in Illinois [66], in Kansas [60], and across the U.S. [77], while negative feedback have been observed in Western Africa [92], with enhanced precipitation over drier soils. Reversely, from modeling approaches coupling a land surface model (LSM) and an atmospheric model, [72] and [**31**] show that potential negative feedbacks (wetter soil inducing less precipitation) between SM and the atmosphere might exist during the dry season of Amazon, while many modelling studies show positive feedbacks in the extra-tropics or the tropics, e.g. [**3**][**4**][**18**]. These answers are often model-dependent, and the differences in convection sensitivity to ET changes can be related to convection intensity and large-scale atmospheric circulation features [**9**][**38**][85]. [76] further suggested that, during summer in mid-latitude continental areas, SM becomes more important than sea surface temperature in affecting atmospheric processes. An idealized simulation in an intermediate general-circulation model by [**6**] showed that SM variations could affect the global monsoon system.

SM also influences the dynamics of these processes by buffering or memory effects, with consequences on the persistence of extreme events, climate predictability, and climate change because of increased greenhouse gas concentrations. Land surface memory can be defined as the lag response of soil moisture to precipitation [**34**][61], which can record previous atmospheric forcing anomalies, that propagates gradually to the deeper soil layers and GW with damping amplitude, and can later have impacts on the atmosphere at longer time scales (Figure 1). The variance of SM with respect to atmospheric precipitation shows a lag of 2-3 months [**30**][61][93]. This characteristic of SM persistence can prolong extreme climatic events like flooding [84] and drought [61]. Enhanced knowledge of this memory process can improve weather forecasting and climate prediction on seasonal-to-interannual time scales [57][76]. The relationship between SM and precipitation depends on both precipitation frequency and the time scale of SM retention [97], and interannual (annual) modes of climate variation impact deeper (upper) layer SM [50]. It is also recognized that under changing climatic conditions, improved understanding of the effect of land surface memory processes becomes even more important [**43**][52][58][86].

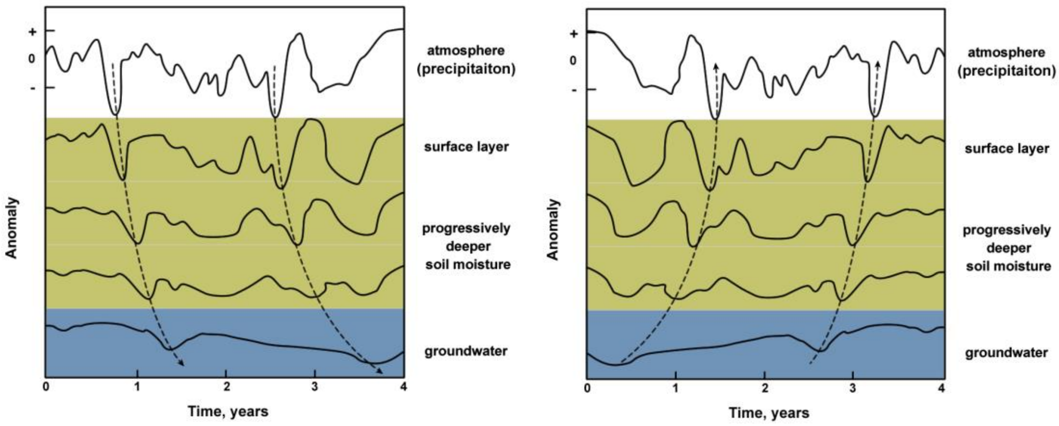

Figure 1. Schematic of propagation of precipitation anomalies in soil layers and groundwater (left), with reverse propagation the following season or year (right). After[61].

As revealed above, **GW can be stored in deeper reservoirs than soils, in particular in unconfined aquifer systems, in which the saturated part is called the water table (WT)**, characterized by slow and mostly horizontal water flows towards the river network (Figure 2), with well-known buffering effects on streamflow variability, thus hydrological regimes [**23**][75]. Starting here, we will restrict the term GW for water below the soil depth, or in the saturated part of the soil if the WT is high enough. In this framework, the vertical exchanges between GW and overlying soils consist of (i) drainage/recharge from the soil to the WT, and (ii) capillary rise from the WT if it is close enough to the ground surface, thus if WT depth (WTD) is small. This case is favorable to strong GW-atmosphere coupling, since the WT is a SM supply and can increase ET [**17**][63][100] [99], as well as the SM and climate memory, given the large residence times in WTs. [71] reported that over 30% of monthly ET comes from aquifer systems, indicating the importance of GW-atmosphere interaction. More recently, based on extensive collections of GW well data sets, [65] produced a global WTD map, and concluded that shallow GW influences approximately 25% of global land area. Besides, a recent study by [**30**] showed that in the same warm phase of ENSO, changes in the location of El Niño can cause significantly different responses in soil water storage and streamflow in the Mississippi River; however, without land subsurface hydrologic storage, the impacts of Eastern Pacific/Central Pacific El

Niño cannot persist from the winter season to the subsequent seasons. These findings indicate that including subsurface and GW hydrologic processes in future empirical or numerical modeling studies will be necessary to better explore the land-atmosphere interactions.

These analyses resulted in the inclusion of GW parameterizations in many LSMs of climate models over last decade, with various modeling approaches [**3**][**17**][**32**][**33**][**34**][**35**][**46**][64][74][79][80][82][99]. For instance, [99] showed that the partitioning of precipitation into ET and runoff can be considerably improved after incorporating WT dynamics in land surface model (LSMs) parameterization. With a 1D approach, [**34**] demonstrated that hydraulic connection between SM and GW can affect the timing of soil moisture storage, and therefore, play important roles in preserving the precipitation signals in terrestrial water (SM and GW) storage, and influencing streamflow in the subsequent months or seasons. In contrast, with a 2D approach spatialized in unit hydrologic basins, [**23**] showed the necessity to disconnect GW and SM in deep-aquifer areas, to maintain the buffering effect of GW on streamflow. This shows the difficulty to properly describe the effects of GW, including deeper layer SM, on land hydrologic processes [98], which arises in a large part from the complexity of the underground structure [91]. The work of [**46**] is pioneering in this regard, as it describes the links between SM, streamflow, and 2D flow in the saturated zone, which is separated into different aquifer systems with realistic properties.

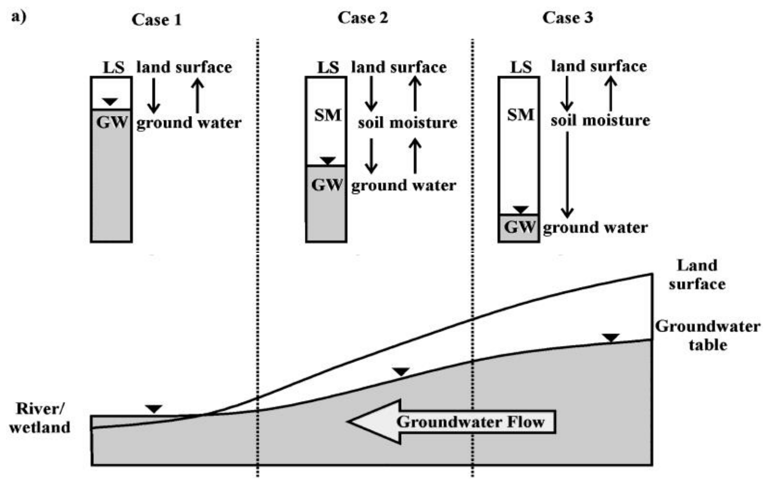

Figure 2. **Schematic interactions between groundwater (GW), soil moisture (SM) and the land surface (LS),** as a function of water table depth (WTD), which is linked to horizontal GW fluxes to the river. Case 1 is favorable to strong GW-atmosphere coupling. After [75].

However, the contributions of GW to the spatial-temporal variability of precipitation and regional/global climate have received little attention; for example, where does precipitation increase when a GW representation is included in LSMs and what mechanisms are responsible for these changes? The reason is that only few studies went to full coupling with the atmosphere, many of these few by the proposers, especially at the global scale. Recent sensitivity studies [**4**][**35**][51][73][75][101] showed that aquifers and lower soil boundary conditions can alter simulated land-atmosphere feedbacks in regional and global climate models. [**35**] reported that a groundwater representation in LSMs alters precipitation distributions through coupled GW-land-atmosphere simulations. With a simple stochastic model, [52] suggested that the long-term persistence of rainfall can be increased by GW convergence to shallow WT zones. [**34**] further indicated that GW can have nonlinear effects on the surface soil moisture persistence, depending on WT dynamics. Over the Amazon River Basin, [**31**] recently showed with coupled GW-land-atmosphere model simulations that GW can increase the latent heat fluxes and lower the surface temperature, which increases the surface pressure gradient and thus, anomalous surface divergence. Therefore, dry season convection becomes weaker when GW dynamics are included in the model. Finally, a recent study by [74] suggested that adding an aquifer to the Goddard Institute for Space Studies (GISS) ModelE general circulation model had a limited impact on mean climate, but affected seasonality and interannual persistence for the soil moisture and climate.

It has also been shown that the seasonal range of precipitation tends to increase because of **global warming**; specifically, wet seasons become wetter and dry seasons become drier [**10**][**11**]. These studies indicated that the thermodynamics component (the increase in water vapor caused by global warming [**9**]) dominates the changes in the annual precipitation range from a global point of view. However, a different mechanism (reduced convection caused by surface cooling) is responsible for the changes in precipitation over tropical rainforest areas. How the various mechanisms contribute to the changes in vertical water vapor advection is crucial to explore climate changes, and the role of GW (increase in water vapor but decrease in surface and low troposphere temperature) is unclear against the one of global warming (increase in both water vapor and temperature) [**6**][**7**][**8**][**9**][**10**][**11**].

In addition to its potential climatic role, GW also constitutes 30% of the world's fresh water resources, which particularly important for securing water access in dry areas and during dry seasons. About 2 billion people rely on GW as a primary source for domestic and agricultural usage [49]. GW also exerts a buffering influence on the seasonal variability of river flow, the other main component of water resources, so that GW is doubly important for water resources sustainability.

In many regions of the world, however, **GW resources are under stress due to GW withdrawals**, which already amount to 2% of total terrestrial runoff, and can locally be much more intense [**44**][95]. Thus, GW depletion, which occurs when withdrawal rates exceed recharge rates, concerns many regions of the world [**22**][95][96]. [**22**] used remote sensing data and some observational datasets to estimate GW depletion over California from 2003~2010 and indicated that during the drought period (after 2006) the GW depletion becomes more serious and may well be unsustainable. The recent drought (earlier 2014) in California further indicates the importance of GW in the sustainable water resources. [96] used a hydrologic model to show that nonrenewable GW abstraction contributes approximately 20% to the global gross irrigation water demand for the year 2000; in addition, this contribution more than tripled, from 75 to 234 $km^3\ yr^{-1}$, over the period 1960–2000. Combined with climate changes and population growth, the stresses on GW supplies will continue increasing in the future [**48**], but the picture would not be complete without considering the feedback of irrigation onto the climate system, e.g. [**24**][**36**].

To summarize, the responses of climatic variables and patterns to GW and related feedback are still unclear, but they deserve further studies, as the above results suggest that some defects of climate models (e.g. summer warm bias in the mid-latitudes, too fast water cycle and too weak long-term memory of precipitation) could be related the absence of deep SM and GW storage, with longer time scales of persistence. Ascertaining the contribution of the various mechanisms is particularly crucial to usefully explore global changes (global warming, and land-use change including water withdrawals), and its impacts on water resources.

1.2 Research goals, novelty and potential breakthroughs

In line with the above analysis, **the main goal of this proposal is to explore the impacts of GW on regional and global climate through model analyses.** To this end, our international consortium offers a unique opportunity to compare the sensitivity of simulated climate to different GW parameterizations within three different climate models, or Earth system models: the French IPSL and CNRM-GAME climate models, and the American NCAR (National Center for Atmospheric Research) climate model (Community Earth System Model, CESM), modified and used here by the Taiwanese team. They were all used in the CMIP (Coupled Model Intercomparison Project) exercises, which feed the IPCC (Intergovernmental Panel on Climate Change) assessment reports.

As shown above, many studies established that SM increases after adding a GW component in LSMs due to the additional supply of subsurface water. However, the impact of GW on climate, including the spatial-temporal variability of precipitation and temperature, has received little attention. This proposal highlights the importance of land subsurface hydrologic processes in the climate system and its predictability, with further implications for global water cycle dynamics and water resources (defined by river discharge and GW storage/WTD).

Furthermore, most current LSMs largely ignore the effects of anthropogenic modifications such as GW withdrawals for irrigation/domestic usages. In reality, only a fraction of irrigation supply is used by plants, and evaporates into the atmosphere, thus increasing water vapor content, while the remainder can flow as runoff, or return back to the aquifer as GW recharge. In climate models, however, this partitioning cannot be well captured without a realistic GW model and representation of GW withdrawal in LSMs.

Therefore, a correct implementation of GW in climate models is an important step to turn them to real Earth system models, allowing integrated studies of global change impacts on water resources. We believe that the proposed research offers the framework to significantly advance knowledge regarding the potential improvements, or additional uncertainties, which can result from integrating GW in climate models. These improvements/uncertainties regard the simulated climate itself (historical and future trajectories, land-atmosphere feedback and its controls), and the simulated water resources.

In this framework, the novelty of our work is manifold:

- It is the first model intercomparison project (MIP) systematically including GW-LSM coupling. The interest of model intercomparison is to ascertain the conclusions regarding the studied processes, and better distinguish robust effects from model-dependent effects, which contribute to model dispersion/uncertainties.
- We expect a significant improvement of our GW-LSM models from this joint research, including the implementation of GW withdrawals for irrigation. This will contribute to improve the corresponding climate/Earth system models.
- We will also establish the sensitivity of the simulated climate (both recent and future) to GW and anthropogenic GW perturbations, including their effect on land/atmosphere feedback and Earth system memory/persistence.
- We will produce global-scale simulations of water resources and their potential changes under two anthropogenic drivers (global warming and water withdrawals), separating surface and ground water, with an attempt to assess the sustainability of recent withdrawals under climate change.

To support these ambitions, all teams have experience in international inter-comparison projects (of LSMs, e.g. PILPS, ALMIP, WATCH, or of climate models, e.g. AMIP, CMIP), and they have all recently emerged as important international actors of the research on GW in climate models: the IPSL teams and Min-Hui Lo have pioneered the analysis of the sensitivity of global simulated climate to GW, while the CNRM-GAME team achieved significant advances regarding the parameterization of GW and its coupling with rivers and land surfaces.

The I-GEM project is also intended to consolidate the potential of France and Taiwan in this interdisciplinary research field, by tightening the links between these two countries, and by federating the French community (IPSL and CNRM-GAME). We also aim at enhancing the visibility of French and Taiwanese teams, by developing closer links with European and North-American leaders in large-scale modeling of GW. To this end, we want to organize two international workshops on GW in climate models under this joint project, one in Taiwan and one in France, with a broad audience.

1.3 Project positioning

1.3.1 Relevance to the call

The I-GEM project contributes to societal challenge "Efficient resource management and adaptation to climate change" in several ways, which have in common to jointly address the climate and water fields.

We primarily aim at developing interdisciplinary knowledge about physical and dynamic processes in the Earth system, and at subsequently improving Earth system models. In this framework, our project particularly focuses on two sub-axes:

- "Functioning of climate, ocean, and major cycles", and especially the coupled functioning of the atmosphere and water cycle, with important questions about the influence of GW on climate variability
- "Functioning of the critical zone", which links soils, subsoils, and the water cycle. We precisely want to examine the influence of this component on the climate system, but also on the hydrologic regimes, and on the impact of climate change and water withdrawals on the latter.

The outcomes of our project will also be relevant to sub-axis "Change and adaptation scenario, predictability, impacts and risks", again in several ways related to interlinked environmental changes: we will examine how the slow component constituted by GW influences the long-term climate evolution, the possible interactions with GW withdrawals, and the consequences of these two types of environmental changes on water resources, which support numerous human activities. The expected results are therefore relevant to devise sound adaptation strategies regarding water resources management.

As a bilateral collaborative project, I-GEM will lead to new research capacity being built within France and Taiwan, with considerable knowledge and expertise being vested in young postgraduate and postdoctoral researchers. This joined project also fosters international collaboration, and raises the profile of France and Taiwan science and facilities by bringing together GW scientists from North American, France, Taiwan, and Asia through the international GW meetings/conferences. The national and research community benefits are: (1) to develop a long-term, high quality scientific program contributing to national objectives, including the climate related research and the water resources, (2) to develop the new scientific concepts on the interlink between climate and GW, (3) to bring together French and Taiwanese researchers in Earth System Sciences.

1.3.2 National programmatic contexts

In France, the I-GEM project (Impact of Groundwater in Earth system Models) is tightly linked to **GEM** project (Groundwater in Earth system Models), recently funded by the LEFE/INSU program until the end of 2016. It will produce the dynamic GW parametrization required for the IPSL contribution to the I-GEM project, and the GW withdrawal data required for task T4. Both projects are coordinated by A. Ducharne (METIS), with several other common participants (A. Jost, A. Baro, A. Schneider at METIS; F. Chéruy, J. Polcher, and J. Ghattas at LMD). The I-GEM is also linked to the **DEPHY2** project, also funded by the LEFE/INSU program until the end of 2016, which aims at improving the physical parametrizations of the French land-atmosphere models, and better understanding the resulting land/atmosphere interactions, in preparation for the CMIP6 exercise (with LMD, CNRM-GAME, and METIS). It also shows connection with the **REMEMBER** ANR project (2012-2016), coordinated by Ph. Drobinski at LMD, and which aims at understanding and modelling the REgional climate system ModEls in the Mediterranean for BEtter water-related Risk prevention in the context of global change, and can be seen as the French contribution and support to the HyMeX and MED-CORDEX programs (common participants: J. Polcher, LMD, and B. Decharme, CNRM-GAME). Finally, the outcomes of the I-GEM project, especially regarding climate change and GW withdrawals impacts, are relevant to the scope of the **LABEX L-IPSL**, funded by ANR in the framework of the "Investissements d'Avenir". All IPSL partners (LMD+METIS) are associated to this LABEX, and A. Ducharne is leader of the work package on climate change impacts. The I-GEM project will also have the benefit to consolidate the French collaboration in land surface modelling between IPSL and CNRM-GAME, especially regarding global scale GW modelling.

In Taiwan, the I-project will contribute to the development of climate system modeling, the Consortium for Climate Change Study (**CCliCS**) supported by the MoST.

1.3.3 International programmatic context

By its French side, the I-GEM project is related to two European projects of the FP7:
- **EMBRACE** (Earth system Model Bias Reduction and assessing Abrupt Climate change), coordinated by C. Jones (Met Office, UK) until 2015, in which F. Chéruy (LMD, IPSL referent for WP3), is involved to improve the IPSL land-atmosphere model (LMDZOR) with respect to land/atmosphere coupling;
- **eartH2Observe (**Global Earth Observation for integrated water resource assessment), coordinated by J. Schellekens (Deltares, Utrecht) until 2017, in which J. Polcher (LMD) is involved to produce a reanalysis of water resources at the global scale from observations and modelling with the IPSL's land surface model ORCHIDEE. This work will benefit from the GW developments resulting from I-GEM.

I-GEM is also relevant to the activities of the World Climate Research Programme (WCRP), and will provide a contribution to two WCRP's Grand Challenges, under the lead of Global Energy and Water Cycle Experiment (**GEWEX**):
- Water availability: How can we better understand and predict precipitation variability and changes, and how do changes in land surface and hydrology influence past and future changes in water availability and security?

- Prediction and Attribution of Extreme Events : How to better identify the factors and mechanisms that determine the location, intensity, and frequency of various climate extremes including droughts, floods, heavy precipitation events, heat waves, cold spells, tropical and extratropical storms?

The I-GEM project counts two major actors of GEWEX: Dr. Chia Chou from Academia Sinica in the Taiwanese team is currently the member of the Scientific Steering Group (SSG) of GEWEX, while Jan Polcher (LMD) is a member of the GLASS (Global Land/Atmosphere System Study) panel [**45**]. This will greatly enhance the visibility of French and Taiwanese teams of the I-GEM project. In particular, by its objective of improving the land surface description in Earth system models, I-GEM will be an active partner in GLASS, and it may also contribute to the GEWEX's regional hydrology activities, under the GHP (GEWEX Hydroclimatology Panel).

2. Scientific and technical program, project organization

2.1 Project organization and task breakdown

To address the overall question of GW and WTD influence in the Earth system over the 4 years of the proposed project, we defined 6 main tasks T0 to T5, which are detailed in section 2.3. As shown in Figure 3, they include two transversal tasks T0 and T5 related to coordination and international networking via workshops, and four scientific tasks T1 to T4.

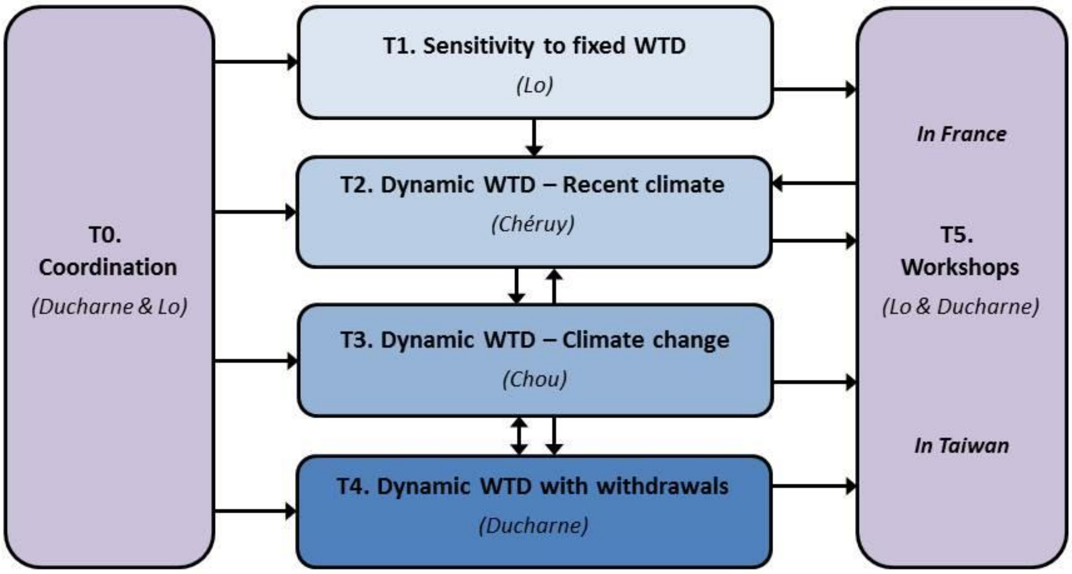

Figure 3. Articulations between the six tasks composing the I-GEM project.

As detailed in the timetable of section 2.3 (Table 3), these scientific tasks (T1 to T4) proceed in chronological order, for both scientific and technical reasons. All teams are presently ready for the simplified simulations of T1 with fixed WTD, which will allow us to test our protocol for comparable simulations. The subsequent intercomparison, apart from its scientific interest, can also be seen as a collaborative training, and the results will be particularly useful for later inter-comparing the simulations with dynamic WTD (T2, T3, T4), in which the discrepancies in GW parametrization will introduce further spread in the atmospheric response. These tasks T2 to T4, with dynamic WTD in the climate models, correspond to three levels of increasing complexity: in T2, we test the impact of introducing a dynamic WT in the recent context, with an interesting validation work; in T3, we complement the recent simulations by future climate simulations; in T4, we further add the effect of anthropogenic water withdrawals, in both recent and future simulations.

Note also that, unless otherwise mentioned, most actions contributing to the scientific tasks (T1 to T4) will be duplicated by the three modeling teams (IPSL, CNRM-GAME, Taiwan). In particular, the required simulations will be performed by each team, which will also perform specific analyses on their own, and contribute to the inter-comparison analysis.

2.2 Modeling framework

In the rest of this proposal, we will distinguish (i) online simulations, in which a LSM is respectively coupled to an atmospheric model, (ii) offline simulations, where the atmospheric model is replaced by an atmospheric forcing, (iii) coupled simulations, with coupled land, atmosphere, and ocean models. Our goal is to compare three climate models, IPSL-CM [**21**], CNRM-CM [**47**], and CESM [68], and given our focus on land-atmosphere interactions, we will mostly perform online simulations, combining their atmospheric model (respectively LMDZ; ARPEGE-Climat; Community Atmospheric Model, CAM) and their LSM (ORCHIDEE [**26**]; SURFEX-TRIP [**14**]; Community Land Model CLM [**83**]).

In all cases, soil water fluxes are described by a 1D vertical diffusive equation, amenable to describe both saturated and unsaturated cases, solved over a multi-layer discretization. The standard versions describe a free drainage at the soil bottom, leading to an unsaturated soil, but it is also possible to force saturation in the soil column at any prescribed depth in all models (T1).

The GW parameterization to describe a dynamic WTD, however, is quite different in the three cases:

- **in CLM-GW (NTU)**, it is a simple extension of the above 1D diffusion equation, with full hydraulic connection between the saturated and unsaturated zone, but no horizontal GW flux between neighboring grid-cells [82]. The GW parameters come from GRACE-based look-up table to realistically simulate the water exchange between the GW and SM in the CLM [**33**]. In the standard version of CLM, there are 10 soil hydrologic active layers with increasing thickness from 0 to 3.43 m below the surface. Below 3.43 meters, there is an unconfined GW aquifer, and the depth to the bedrock is 25 meters (or maximum GW aquifer storage of 5000 mm with specific yield of 0.2).
- **in SURFEX-TRIP (CNRM-GAME)**, a physically-based GW scheme was implemented to describe the horizontal water flows in the saturated zone, in areas where important aquifer systems are known to exist [**46**]. It is coupled to the river routing model TRIP, and the hydraulic connection with the surface results from aquifer-river exchanges, and from upward capillary fluxes to the soil moisture where the WT elevation is higher than river stage.
- **in ORCHIDEE (IPSL)**, the effect of GW on river discharge is also described within the river routing model, using a linear reservoir model to represent GW storage and delay, with no horizontal GW fluxes between grid-cells [**19**][**37**]. This GW parametrization is currently being improved, to account for the effects of hydrogeological properties on GW dynamics, and to introduce water fluxes between WT and SM, in a subgrid fraction, as a function of topography and hydrogeologic data. This work builds upon recent developments to permit saturation into the soil column [**3**], and will be performed by Ana Schneider, under the supervision of A. Ducharne and A. Jost, within the companion GEM project (see section 2.5.5). The resulting version of ORCHIDEE with a realistic GW description should be available for the beginning of T2, i.e. Dec 2015.

Table 2. Main features of the 11 mandatory simulations to be produced by each team.

Task	Deliverable	Description	Period	Nb.
T1	D1.1	Reference with free drainage and no WTD/GW parametrization	Recent	1
		With fixed WTD (at 1, 2, 3, 5, 8 m)	Recent	5
T2	D2.1	With dynamic WTD, no withdrawals	Recent	1
T3	D3.1	Reference with free drainage and no WTD/GW parametrization	Future	1
		With dynamic WTD, no withdrawals	Future	1
T4	D4.2	With dynamic WTD + withdrawals	Recent	1
		With dynamic WTD + withdrawals	Future	1

We identified 11 mandatory simulations, summarized in Table 2, to be run by all three teams for intercomparison. To this end, we need to minimize the sources of differences, and we will use the AMIP (Atmospheric Model Intercomparison Project) protocol [67], so the three models will use the same prescribed sea surface temperatures (SSTs), sea ice, land use, atmospheric composition and solar forcing. These "time-slice" simulations will cover a 30-year period, excluding spin-up, which can be long with GW

(> 10 years), because of its long residence time. For the simulations covering the recent period, the AMIP forcing will be used. For future climate "time-slices" (T3 and T4), we will use identical radiative forcing scenarios in the three models (RCP or $2CO_2$), and the above prescribed SSTs and sea-ice, modified to account for ocean warming, between the central time of the two time-slices, in a transient simulation by a fully coupled ocean-atmosphere climate model using the selected radiative forcing scenario.

We now briefly describe the atmospheric/land surface models. They will not be used with the same resolution (because of different compromises in the three teams between calculation needs, code stability, and innovation), and for easier comparison, their results will interpolated to a common resolution;

- **NTU**: the atmospheric model of CESM (Community Atmosphere Model, CAM), and its land component (Community Land Model, CLM), will both be run at 1.9°x2.5° global resolution, with 30 vertical layers for the CAM. Soil depth is 3.4 meters with 10 soil hydrologic active layers uniformly globally. For sub-task T2.5, NTU will also run fully coupled simulations with the ocean component of CESM, the Parallel Ocean Program version 2 (POP2), including many physical and software developments incorporated by the members of the Ocean Model Working Group at NCAR. When activating the ocean dynamics in CESM, the POP2 will be run at 1°x1° resolution and 30 vertical levels.
- **CNRM-GAME**: for ARPEGE and its land surface component SURFEX, the horizontal resolution should be T127 (~1.5°) with 91 vertical levels. Soil depth depends on land use, between 20 cm for bare rocks, to 8 m for tropical forests and 12 m over permafrost area, but any soil depth can be uniformly imposed (for T1). SURFEX is coupled via the OASIS coupler to the TRIP routing scheme in which the GW parametrization is implemented, and which works at the 0.5° resolution, to simulate WT and river flow at 0.5°.
- **IPSL**: the model resulting the coupling of LMDZ and ORCHIDEE is often called LMDZOR. It will be run by the IPSL team, which gathers LMD and METIS. We will use the standard atmospheric physics (LMDZ5A), at the low standard resolution (96x95 horizontally, ~3.7°x1.9°; 39 vertical levels). In ORCHIDEE, soil depth is 2 m by default, but the number of soil layers to solve water diffusion is rather flexible [**3**], and soil depths as large as 50 m have been numerically tested with success. Following [**4**], IPSL will also run some zoomed and nudged simulations over Europe, to regionally achieve a higher resolution and a more realistic climate, and examine in closer details the possible feedback of GW on boundary layer structure and convection triggering (T2.3). We will use the new version of atmospheric physics (LMDZ6), with a profound recast of the parameterizations of boundary layer, turbulence, shallow and deep convection [**28**].

For T2 and T4, each group will also run complementary off-line simulations of the LSM+GW models, *i.e.* using historical meteorological forcing (*e.g.* WATCH, WFDEI, forcing from Princeton, NCAR, NASA), as an important validation step, and to better distinguish, in the response differences, what comes from the atmospheric models and what comes from the LSMs.

All teams have access to high-level calculation facilities. The IPSL team relies on the IDRIS facilities, and according to the ANR guidelines, we submitted a DARI proposal (N° a2014010013) for the required calculation hours and storage (73,300 hours and 26 To, for the 4 years of the I-GEM project).

2.3 Description of the tasks and deliverables

In this section, we detail how each task is broken down into subtasks (Tx.y), which all correspond to a deliverable (Dx.y). For scientific tasks T1-T4, these deliverables are either:

- "cognitive", in which case we will deliver a report or paper draft, depending on the eventual interest of the results of the subtask,
- "technical", when we will deliver improved code, formatted withdrawals data, or simulation output. The 11 simulations to be delivered by each team are described in Table 2.

The timetable below (Table 3) shows how we organized these tasks and their deliverables over the 4 years of the project, assuming it can start in December 2014. It also shows the timing of the staff involvement, and we took care to correctly overlap the student's presence to their assigned tasks, especially for Ana Schneider, who will finish her PhD in September 2016, and the French Master students, with training between February and July. Permanent researchers (listed in Table 4) do not appear in the Table 3, but they will contribute all along the project, by their particular expertise on their assigned tasks, and with an emphasis on coordination, supervision, and the elaboration of scientific syntheses (communications, report/paper writing).

Note, also, that we only displayed contribution to T5 for the workshop organization. The attendance is not displayed, but most researchers (permanent or non-permanent) will attend at least one of them.

Table 3. Timetable of the tasks, subtasks, deliverables of the project, and of the staff involvement. Each year is subdivided into 4 trimesters. The asterisk ∗ indicates when each of the three modeling teams is responsible of the task for its own team, under the supervision of the task leader. Green coloring shows the “technical” tasks. The deliverables’ due time is displayed with an arrow (➤), pointing to the end of the due month.

Tasks and sub-tasks	Leader	Year 1				Year 2				Year 3				Year 4			
T0. Coordination	**Ducharne, Lo**																
T0.1 Web site	Ducharne	➤															
T0.2 Annual meetings	Ducharne, Lo				➤				➤				➤				➤
T0.3 ANR/MoST reporting	Ducharne, Lo		➤						➤								➤
T1. Sensitivity to fixed WTD	**Lo**																
T1.1 Simulations	∗		➤														
T1.2 Analysis & intercomparison	Lo, Ducharne				➤												
T2. Dynamic WTD – Recent period	**Chéruy**																
T2.1 Simulations	∗						➤										
T2.2 Validation	Chéruy, Polcher							➤									
T2.3 Influence on climate, L/A feedback	Chéruy, Lo									➤							
T2.4 GW vs ocean memory	Lo												➤				
T3. Dynamic WTD – Climate change	**Chou**																
T3.1 Simulations	∗								➤								
T3.2 Influence on climate change trajectory	Chou, Chéruy												➤				
T3.3 Climate change impact	Ducharne														➤		
T4. Dynamic WTD with withdrawals	**Ducharne**																
T4.1 Formatting the withdrawals	Marty										➤						
T4.2 Simulations	∗											➤					
T4.3 Historical influence and validation	Polcher														➤		
T4.4 Future climate vs withdrawals	Ducharne, Lo																➤
T5. International workshops	**Lo, Ducharne**																
T5.1 In France	Ducharne								➤								
T5.2 In Taiwan	Lo																➤

Staff involvement	Tasks	Year 1				Year 2				Year 3				Year 4			
Permanent support																	
P. Marty, METIS, 6 mo	T1.1, T2.1, T4.1, T4.2																
J. Ghattas, LMD/IPSL, 3 mo	T2.1, T4.2																
A. Idelkadi, LMD, 5 mo	T1.1, T2.1, T3.1, T4.2																
S. Tyteca, CNRM-GAME, 3 mo	T1.1, T2.1, T3.1, T4.2																
J. Colin, CNRM-GAME, 5 mo	T2.2, T2.3, T3.1, T4.2																
A. Baro, METIS, 4 mo	T4.1																
N. Roger, METIS, 2 mo	T5.1																
Non permanent																	
A. Schneider (PhD), METIS, 15 mo	T1,T2																
Res. scientist X2, LMD, 12 mo	T2																
Res. scientist X1, METIS, 24 mo	T3,T4																
Master student S1, METIS, 6 mo	T1																
Master student S2, LMD, 6 mo	T2																
Master student S3, METIS, 6 mo	T3																
Master student S4, LMD, 6 mo	T4																
PhD Student X3, NTU, 32 mo	T1,T2,T4																
PhD Student X4, NTU, 32 mo	T2,T3,T4																
Research Assistant X5, NTU, 48 mo	T1,T2,T3,T4																

T0. Coordination

Leaders: A. Ducharne (METIS) & M.-H. Lo (NTU)

The leaders of this task are the two PIs of the I-GEM project. They are responsible of the delivery of the deliverables, and will ensure the scientific animation via regular project meetings. Since it is a challenge to physically gather participants from France and Taiwan, this will be limited to 4 annual meetings, alternatively in each country (**T0.2**). A preliminary meeting will be organized in France before the project official start, when Min-Hui Lo is invited professor at UPMC in September 2015. Other meetings will be organized at a higher frequency owing to videoconferencing, between the PIs and the tasks coordinators (~every 3 months), and with the involved participants when required on technical or scientific issues, for intercomparison in particular (task meetings).

Another tool for communication will be the project website (**T0.1**), which will be created by A. Ducharne, to gather important information: (i) explaining the project and its major outcomes (meetings' minutes, reports, accepted papers, list of conferences) to other scientists, in open access; (ii) diagnostics on the simulations and their intercomparison (graphics, summary data) to be shared among the project's participants, and filtered by a password. This website will explicitly mention the ANR and MoST support.

The two PIs are also in charge of the international visibility of the project and the dissemination of the scientific results (participation to international conferences, coordination of the publication strategy, and organization of the international workshops, separated in T5). A. Ducharne and M.-H. Lo will satisfy to the requirements of ANR and MoST, respectively, in terms of reporting, restitution meetings, etc. (**T0.3**). The due dates of the project's reports in Table 3 are arbitrary, and will be corrected when the information is known.

In addition, each task has one leader, which is responsible of the respect of the task deliverables with the project's PIs, of the scientific animation of the task, including the organization of task meetings when required. The tasks leaders also help the two PI's in the project reporting, by providing the elements for these reports. One or two leaders are also identified for each subtask (see Table 3) to assist the task's leaders owing to their specific expertise. This is not the case, however, for the subtasks aiming at producing the mandatory simulations in the three teams, for which the partner coordinators will be responsible of the proper delivery.

Deliverables:
D0.1. Project web site
D0.2 Minutes of the annual meetings
D0.3 ANR/MoST requirements, including summary description of the joint project, progress and final reports, restitution meetings

T1. Sensitivity to fixed WTD

Leader: M.-H. Lo (NTU)

The goal of this idealized experience is to compare the responses of the 3 atmospheric models to WT inclusion, in a way that minimizes the differences coming from the LSMs. To this end, we build upon the pioneering work of [89], who tested the climate sensitivity to different ratios of ET to potential ET. In **T1.1**, we will follow [**3**], and run simulations with forced saturation below different prescribed depths (thus corresponding to different prescribed WTD, possibly around 1, 2, 3, 5, and 8 m). In doing so, water conservation is violated and the simulated climate gets all the wetter as the prescribed WTD is shallower, which brings the system closer to an aqua-planet. In **T1.2**, we want to compare the sensitivity of the three atmospheric models to the resulting ET increases, in terms of regional changes in precipitation, circulation, temperature, and land-atmosphere feed-backs. We also want to identify/compare the patterns of "active WTD", defined for this project as the deepest one to achieve a significant change in ET and/or climate variables such as air temperature or precipitations. A fundamental question is whether active WTD has distinct features in so-called transitions zones with strong land-atmosphere coupling, and how its patterns intersects with WTD and hydrogeological maps [65][69][91]. The answers should constitute important guidelines to devise a sensible GW parameterization in Earth system models (see T2.2).

The ones at CNRM and IPSL only describe capillary rise in a subgrid fraction of the LSMs grid cells, close to the rivers, where WTD is supposed to be small enough. Therefore, complementary experiments will consist in prescribing a WTD in a restricted fraction of each land grid-cell (for instance 25% [65], with WTD around 0.5, 1, and 2 m), to assess how this influences the sensitivity of active WTD and climate compared to the mandatory experience with full WT coverage.

Deliverables:
D1.1. Results of 6x3 mandatory simulations with prescribed WTD or free drainage, and preliminary comparison
D1.2. Report or paper draft, regarding the identification of the "active WTD", its comparison between models, and how the differences can be related to the land and atmospheric components.

T2. Dynamic WTD over the recent period

Leader: F. Chéruy (LMD)

The second step of the project will be to compare the response of the our land-atmosphere models when coupled to dynamic GW parametrizations, i.e. with GW storage and WTD that vary over time as a result of vertical water exchanges with overlying soil, and GW flow to the river network. The overall goal of this comparison is to ascertain the potential of realistic GW to improve the simulated climate, and to identify the most interesting features of the three GW parametrizations in this regard.

The goal of **T2.1** is to produce the online mandatory simulations with dynamic WTD under recent climate, while **T2.2** focuses on the compared validation of these simulations with respect to observational data. The evaluation will focus on climatological means and mean seasonal cycles, and address climate data (GPCC for precipitation; CERES-EBAF for radiation; CRU and reanalyses for various atmospheric variables; e.g. [**4**][**5**][**18**][**24**][**35**]) and "land-surface" data (river discharge and hydrologic regimes, terrestrial water storage changes from the GRACE spatial gravimetry mission, WTD measurements, ET and soil moisture products, wetlands and open water extents; e.g. [**2**][**15**][**16**][**19**][**23**][**26**][**32**][**33**]**[37][46]**). For the latter, we will also consider offline simulations with the tested models, because they remove biases coming from the atmospheric models. In all cases, we will distinguish areas where important aquifer systems are known exist, and areas where the dynamic WTD is lower than the active WTD identified in T1.2, in an attempt to link good/bad performances to GW features. Finally, despite their interest for climate change, Arctic river basins will be overlooked here, because of the lack of well-established permafrost parameterization in the three LSMs.

T2.1 and T2.2 are tightly coupled as the goal of model evaluation is to improve the models if deficiencies are revealed, which is usually the case, and if a solution for model improvement is found, which is harder. To respect the project's work flow, an important milestone is to deliver the reference version of the land-atmosphere models with dynamic WTD, and the corresponding mandatory simulation under recent climate, at Month 18 (D0.1). This is crucial to work efficiently on the intercomparison of T2, T3, and T4, without redoing the analysis because one team has changed its mind. It is also important to keep the same version for the results of T2, T3, and T4 to be consistent with each other. Therefore, we allotted one full year to task T2.1.

In **T2.3**, we will lead the analysis further regarding the influence of GW on the simulated climate. Given the role of GW as a long-term memory component, we will focus on climate and hydrological variability, including the persistence of extreme events (e.g. hot, dry, or wet spells) at seasonal to inter-annual timescales. We will also try to find explanations to systematic performance differences (between models, seasons, and regions), related to the GW parametrizations, the atmospheric general circulation, or land/atmosphere feedback. In particular, we would like to assess if the inclusion of GW can help reducing the spread between climate models, which is the signature of poorly simulated processes or interactions between them, and which is particularly large in transition zones with strong land/atmosphere coupling [**5**]. To this end, IPSL will carry out a complementary regional scale study over Europe (with two zoomed and nudged simulations, cf. section 2.2), to examine the impact of dynamical GW on the surface energy budget diurnal cycle, the structure of the boundary layer, and convection triggering, in summer.

In **T2.4**, the Taiwanese team will also explore the relative contribution of GW and ocean in the long-term variability of the climate system. Ocean is the major memory component for the global water cycle. To examine if there is a "memory exchange" between GW and ocean, the long-term variability of GW storage and precipitation will be compared, with and without coupling the ocean model of the NCAR climate model, to examine if the ocean feedback intensifies or damps the GW's impacts. We will examine impacts of the individual effects (GW and ocean) on the air-sea/air-land coupling and focus on how the temporal and spatial variability of the precipitation is influenced by ocean and GW dynamics, separately. To this end, we will activate the ocean model (POP2) in the NCAR CESM to conduct two more simulations (1. with both GW dynamics and POP2; 2. without GW dynamics, but with POP2). With the two extra simulations, we can identify the relative contribution of ocean and GW memory to the interannual variability of several climatic variables (such as precipitation, temperature, and water vapor), boundary layer properties, and the global water cycle.

Deliverables:

D2.1. Reference versions of the land-atmosphere models with dynamic WTD, results of 1x3 mandatory simulations performed with these versions under recent climate, and preliminary comparison

D2.2 Report or paper draft, on compared validation of the three reference models with dynamic WTD, including performance criteria (e.g. bias, RMSE, correlation, Nash efficiency, etc.)

D2.3 Report or paper draft, on intercomparison, exploring the impacts of GW on the climate (How do the different models respond to GW dynamics in the GCMs?)

D2.4 Report or paper draft, on memory exchanges between GW and ocean (Does ocean play a significant role in affecting the results we find in the prescribed sea surface temperature simulations?)

T3. Dynamic WTD and climate change

Leader: C. Chou (NTU/Academia Sinica)

A further objective is to understand the roles of GW in the framework of future anthropogenic climate change. To this end, we first need to perform two future climate simulations with each model, with and without dynamic WTD (**T3.1**). Combined with the recent simulations with and without dynamic WTD (performed in T2.1 and T1.1 respectively, see Table 2), we can thus compare the changes in various climatic and hydrologic variables, with and without GW. The analysis will address two complementary questions.

In **T3.2,** given that GW can modulate the magnitude and variability of ET, thus of surface and air temperature, and precipitation, we will study the influence of GW on climate change itself. We will compare the changes in temperature between future and recent simulations (related to climate sensitivity), and how regional warming compares to global-scale warming [**5**][**43**][52]. This comparison will also be performed on precipitation, not forgetting its links with the general circulation, in tropical and extra-tropical zones [**7**][**8**][**9**][**10**][**12**], and with soil moisture / atmosphere interactions, especially in transition zones [**43**]. In doing so, a special attention will be devoted to the low frequency modes, since GW can induce inter-annual persistence; and monthly to higher frequency modes, related to extreme events (wet, dry, hot spells), which are of uttermost importance for climate change impacts on ecosystems and societies (see below).

In **T3.3**, we will reverse perspective, and examine the impact of climate change on water resources. We won't perform here a full climate change impact analysis with downscaling and uncertainty analysis [**20**][**27**], but we want to examine, directly in the coupled land-atmosphere models, how the changes in water resources between recent and future climates can be modified if one accounts for GW. We will also explicitly quantify the changes in GW availability, which is novel in online climate change simulations. We will compare these modifications in the three modeling frameworks in an attempt to identify where/when the different GW parametrization induce robust/uncertain responses, especially regarding the variability of high and low river flows (both influenced by GW flow), as they are related to floods and droughts, which are key variables to the vulnerability to climate change [**25**][**41**].

For both subtasks T3.2 and T3.3, we will simplify the future scenario by neglecting land use change in the future: we will keep the historical land use for both time-slices, and their only differences will be SSTs, sea-ice, and atmospheric radiative forcing (section 2.2). The only land-use change we will consider in the project is the one of water withdrawals and irrigation, in Task 4.

Deliverables:

D3.1. Results of 2x3 mandatory simulations under future climate, with dynamic WTD or free drainage, and preliminary comparison.

D3.2. Report or paper draft, focusing on how GW and global warming contribute to the changes in global circulation and climate variables.

D3.2. Report or paper draft, comparing how GW affects the changes in water resources (GW and river discharge) accompanying global warming.

T4. Dynamic WTD with withdrawals

Leader: A. Ducharne (METIS)

Another major anthropogenic change affecting terrestrial hydrology is the redistribution of water withdrawn in rivers and aquifers (GW) onto soils for irrigation [**44**], to secure and enhance crop production. The sensitivity of climate to irrigation has already been largely studied [**24**][**36**], but often without distinguishing between surface and GW sources, since the latter are not yet a standard component of climate models. This prevents from fully integrated analysis regarding the links between climate and water resources availability, which is our intention in this task.

To this end, we will use the distributed global-scale database of water withdrawals (both in GW and rivers) proposed in the companion project GEM recently funded by the LEFE/INSU program. The construction of this database is just starting (main contributor: A. Baro, METIS), based on existing information on recent withdrawals [**44**][69][75][88][90][95]. We expect it to be ready by the end of 2016, and **T4.1** will be devoted to the proper formatting of the data for the land-atmosphere models.

In **T4.2**, we will first adapt the models to reduce GW volumes from these withdrawals (river abstraction is already described), and to redistribute them over cultivated soils (following irrigation from riverine water) or back to rivers (when the purpose is drinking water or industrial use), using off-line and on-line test simulations. We will then produce the mandatory T4 online simulations, with dynamic WTD and withdrawals, under both recent and future climate.

In **T4.3**, we will compare the recent simulations of T2 and T4, with and without withdrawals, to assess if the latter permit a better fit to observed data (climate and land surface data). As in T2.2, we will pay a special attention to the geographic patterns of the studied sensitivity, with respect to the intensity of the withdrawals, the nature of the aquifers, the “active WTD”, and the climate and hydrological regimes. In particular, it is possible that GW withdrawals can exert a significant impact on SM and the atmosphere in areas where GW do not, because they are too deep or confined (e.g. Saharan and Nubian Aquifer Systems, Great Artesian Basin). Offline simulations will also be used, as in T2.2, but also to attempt an attribution of long-term runoff changes between historical climate change and withdrawals [**1**][**44**].

In **T4.4**, finally, we want to address the role of GW withdrawals in the context of climate change. Like in T3, the question is twofold. Firstly, we will examine if/how future climate is sensitive to the sustained increase of SM related to irrigation, since our models will not include any evolution of irrigation demand and withdrawals with climate change, such as available outside from climate models [52][59]. This assumption is of course unrealistic, and a second step will be to study the sustainability of these withdrawals (based on recent databases) under climate change. It is difficult to define a clear methodology three years ahead, but an interesting starting point could be to define threshold values in WTD and/or baseflow (GW return flow to the river system), below which withdrawals would be canceled. We could then compute and compare “failure indicators”, such as the number of days when withdrawals cannot be fulfilled, or the missing volume, which would be interesting vulnerability indicators regarding water resources and their usage.

These threshold values and failure indicators will likely be very model-dependent, because of differences in climate and aquifer properties (efficient thickness and porosity). We hope we may learn a lot on desirable values of the aquifer properties from the comparison of the above indicators, starting under recent climate.

Deliverables:
D4.1. Formatted water withdrawals for use in T4.2
D4.2. Results of 2x3 mandatory simulations with dynamic WTD and withdrawals, under recent and future climate, and preliminary comparison
D4.3 Report of paper draft, on the comparison of the three recent climate simulations and their validation (How/where does withdrawals improve the model performances against observations?)
D4.4 Report of paper draft, on the compared sensitivity of climate and water resources to anthropogenic emissions and water withdrawals

T5. International workshops

Leaders: M.-H. Lo (NTU) & A. Ducharne (METIS)

We also aim at developing and tightening our links with international leaders in large-scale GW modeling, mostly in North-America (*e.g.* Drs. Famiglietti, UC Irvine; Fan, Rutgers; Maxwell, Colorado School of Mines; Krakauer, CUNY; Gleeson, McGill; Thérien, U. Laval), but also in Europe (*e.g.* Drs. Miguez-Macho, U. Santiago de Compostella; Döll, U. Frankfurt; Bierkens, Utrecht). To this end, we want to organize two international workshops on GW in climate models, one in France (**T5.1**) and one in Taiwan (**T5.2**), in the first and last half of the project respectively. These workshops will gather the I-GEM participants, and we will send broad announcements to all interested scientists in the world, with invitations to prominent senior scientists and selected PhD students. We target 5-day workshops with an audience of around 30 persons to leave plenty of time for both detailed scientific talks, and round-table discussion. These workshops will also serve the communication of our results, in addition to classical international conferences.

Regarding the links with the project coordination, the two workshops will be phased with two annual project meetings, which will take place just before or after the workshops, to limit travel. We also chose to organize the first workshop in France (T5.1), and the second in Taiwan (T5.2), so that leading work on science and workshop organization does not fall at the same time for A. Ducharne and M.H. Lo.

Deliverables:
D5.1 and D5.2 will consist of online booklets, one for each workshop, posted on the I-GEM project web site (see T/D0.1). These online booklets will include the list of participants and program, the abstracts and pdfs of oral presentations and posters (upon agreement of the authors), and a synthesis of the round tables.

2.4 Presentation of the consortium

The strength of the proposed project is that it gathers four complementary research teams, with a strong expertise in the modeling of groundwater and/or land-atmosphere coupling in climate models, and a real experience of interdisciplinary research, and model intercomparison projects. In addition to the permanent research scientists listed in Table 4 (for a total of 95 pers.month), all teams secured the implication of technical support staff, mostly for code management, and performing the simulations and related data processing (26 pers.month of permanent staff in France; 48 pers.month for a non-permanent research assistant in Taiwan, cf. Tables 1 and 3). Note finally that if METIS and LMD are considered as separate partners in the project, they will work together to perform and analyze the IPSL simulations.

Table 4. Involved permanent researchers, with their expertise fields and project contribution. The following acronyms are used: HY: Hydrology; GW: Groundwater/Hydrogeology; LSP: land surface processes; LAC: land/atmosphere coupling; AS: Atmospheric Sciences; BL: Boundary Layer meteorology; CM: Climate Modeling; CC: Climate Change.

Name	Affiliation	Expertise	Implication	Tasks
A. Ducharne	METIS/IPSL, Paris	LSP, HY, GW, LAC, CC, CM	24 pers.mo	All (French PI)
M.H. Lo	Atmospheric Sciences, NTU, Taipei	GW, HY, LSP, CM, LAC	24 pers.mo	All (Taiwanese PI)
F. Chéruy	LMD/IPSL, Paris	BL, AS, CM, CC, LAC	16 pers.mo	All but T5
C. Chou	RCEC, Academia Sinica, Taipei	AS, CM, CC, BL, LAC	15 pers.mo	All but T0
B. Decharme	CNRM-GAME, Toulouse	LSP, HY, GW, CM, CC, LAC	5 pers.mo	All but T5
A. Jost	METIS/IPSL, Paris	GW, HY, LSP, CC	6 pers.mo	T2,T3,T4 (WTD)
J. Polcher	LMD/IPSL, Paris	LSP, LAC, HY, BL, CM, CC	5 pers.mo	T2,T4 (Historical)

The presentation below is to be complemented by a selection of the participants' publications, in section 4.1.

2.4.1 METIS is a joint laboratory of CNRS, UPMC and EPHE (UMR 7619), which recently joined the IPSL. Formerly known as Sisyphe, it is specialized in water sciences (hydrology, hydrogeology, applied geophysics, water quality), with a strong expertise in numerical modeling of the relevant processes from plot to river basin scales. In particular, METIS has been involved in the development of hydrological and groundwater parametrizations in both the IPSL and CNRM-GAME climate models. **Agnès DUCHARNE**, the project's French PI, is senior research scientist at the CNRS, with a recognized experience in the modeling of hydrological processes in LSMs (IPSL's ORCHIDEE, NASA's Catchment LSM), and the use of LSMs to understand global changes and its impacts. She has been working on the links between GW and surface water and energy budgets for more than 10 years. She also has a strong experience in student and young scientists supervision, and she has already managed 8 research projects (see online CV at http://www.sisyphe.upmc.fr/~ducharne/). **Anne JOST** is associate professor at UPMC in hydrogeology, with complementary expertise in pergelisols and paleoclimate. Both of them co-supervise **Ana SCHNEIDER**'s PhD, which aims at developing a realistic GW parametrization in ORCHIDEE, in the framework of the GEM project funded by LEFE/INSU until the end of 2016.

2.4.2 LMD is a joint laboratory of CNRS, UPMC, Ecole Polytechnique, and ENS (UMR 8539), and a founding member of IPSL. It focuses on atmospheric sciences (climate, air quality, and planetary atmospheres) and develops the atmospheric model LMDZ of the IPSL climate model, which participated to all CMIP exercises. **Frédérique CHÉRUY** is specialized in boundary layer meteorology and has recently focused on land-atmosphere coupling. She co-supervised with A. Ducharne the PhD of Aurélien Campoy, who first introduced a constant WTD in ORCHIDEE. **Jan POLCHER** is one of the world's leaders in LSMs. He has been one the core developers of ORCHIDEE since its creation, and the founder of the GLASS panel in the GEWEX international program.

2.4.3 CNRM-GAME is a joint laboratory of CNRS and Météo-France (UMR 3589), which hosts all meteorological and climate research performed by Météo-France. In particular, it develops the CNRM-GAME climate model. **Bertrand DECHARME** belongs to the GMGEC group (Groupe de Météorologie de Grande Echelle et Climat, GMGEC) and is specialized in the interactions between hydrological processes and climate. He is in charge of land surface developments for the Climate model. He recently supervised the PhD of JP Vergnes, who developed a physically-based ground-water model for the global scale into the SURFEX surface model. **Jeanne COLIN** belongs to the GMGEC group and is specialized in the interactions between the surface (land or sea) and the atmosphere. She is in charge of the coupling between SURFEX and ARPEGE-Climat.

2.4.4 NTU consists of two researchers from different institutes. **Min-Hui LO**, the project's Taiwanese PI, is expert in land surface and climate modeling and land-atmosphere interactions, using the NCAR Community Land Model (CLM) and its coupling to the NCAR atmospheric model. He obtained his PhD at UC-Irvine in 2010, and is now assistant professor at National Taiwan University (the best university in Taiwan), while acting as topical editor for the GMD journal (see online CV at http://homepage.ntu.edu.tw/~minhuilo/). **Chia CHOU**'s expertise is in climate dynamics and climate change. He obtained his PhD at UCLA in 1997, and is a senior researcher at Academia Sinica (the best research institute in Taiwan), at the Research Center for Environmental Changes (RCEC). He is currently member of the GEWEX Scientific Steering Group, and served as the panel committee chair for the Atmospheric Science Division of the MoST, Taiwan, in the past three years.

2.4.5 Experts The project will also benefit from interactions between the involved scientists and colleagues in their home institutions, who agreed to be solicited as **experts**, but will not directly contribute to any specific task:

- METIS: G. de Marsily (hydrogeologist; emeritus professor, French Academy of Sciences), M. Meybeck (large scale hydrology and geochemistry; emeritus CNRS researcher), F. Habets (mesoscale groundwater and hydrometeorological modeling; CNRS senior scientist);
- LMD: J.-L. Dufresne, F. Hourdin (climate modeling and climate change Centre; both CNRS senior scientists); J.-L. Dufresne is currently head of the IPSL Climate Modeling Centre (http://icmc.ipsl.fr/), and lead author of IPCC's AR5 Chapter 12 on "Long-term climate change";

- CNRM-GAME: H. Douville (climate modeling; CNRM senior scientist, member of WRCP working group on seasonal to interannual prediction)
- NTU: Huang-Hsiung Hsu (climatologist at Academia Sinica); Chien-Ming Wu (cloud resolving modeler, Assistant Professor at NTU); Wei-Ting Chen (climate modeling, Assistant professor at NTU); Yen-Ting Hwang (climate modeling, new faculty at NTU).

2.5 Requested funding

In both countries, the requested funding **between 200-299 k€** mostly regards non-permanent staff and travel, including the organization of an international workshop in each country (T5). As summarized in Table 5, the requested resources are well balanced between the French and Taiwanese partners, especially if one considers the large differences in contractual salaries between the two countries. The French and Taiwanese partners also contribute in a quite well balanced way to the project in terms of personnel involvement, for both scientific and coordination work.

Table 5. Summary of the French/Taiwanese contributions and funding requests for the project.

	Type of expense	Unit	France (ANR)	Taiwan (MoST)
	Total staff	**pers.month**	**167**	**144.6**
Contribution to project	Permanent staff	pers.month	92	39
	Non-permanent staff	pers.month	15	0
Requested funding	Non-permanent staff	pers.month	60	105.6
		€	155 800	115 200
	Equipment	€	15 500	36 000
	Travel	€	92 500	65 000
	Other expenses	€	23 000	14 400
	Total (excluding management fees)	**€**	**286 800**	**230 600**

We detail and justify below the requested funding, partner by partner, for each major expense item. For all French teams, we budgeted the same travel costs: return flights to Taiwan = 1000 €; per diem in Taiwan = 150 €; 1 mission in France = 500 € for 1-2 days; 1 international conference including registration fees = 3000 €. The monthly gratification for Master's students is 450 € (exonerated from social charges). We also budgeted publications fees to 2000 €/article, which is quite standard in EGU and the best American journals, and can otherwise serve to buy public access in journals without publication fees (Climate Dynamics, Climatic Change, Journal of Hydrology, etc.). We finally need some hardware elements: PCs for the non-permanent scientists (2000€/ each), local storage capacities for analyses and intercomparison (in addition to full storage of the simulations at the calculation centers), and multi-point videoconferencing to ensure regular advancement and coordination meetings.

2.5.1 METIS, with a total funding request of **186 400 €** to ANR (excluding management fees)

POST-DOC X1	At METIS, supervised by A. Ducharne and F. Chéruy	**100 000 €**
24 months	M25-M48	
Tasks	T3,T4: Analysis of LMDZOR simulations and intercomparison with the ones of CNRM-GAME and NTU, regarding projected climate change, its impact on water resources, and the sensitivity to water withdrawals.	
Profile	The postdoc will have a PhD thesis in atmospheric or water sciences and speak English. We expect a good experience in numerical modeling of the Earth climate system.	

Based on UPMC cost for 2-4 years of experience after the PhD, which leads to a net salary of 2200 €/month

Master student S1	At METIS, supervised by A. Ducharne and F. Chéruy	**2 700 €**
6 months	M4-M9	
Tasks	T1: Analysis of LMDZOR simulations with fixed WTD	
Profile	M2 student in atmospheric or water sciences.	

Master student S3	At METIS, supervised by A. Ducharne and A. Jost	**2 700 €**
6 months	M28-M33	
Tasks	T3: Analysis of water resources changes (discharge and GW) with climate change in LMDZOR.	
Profile	M2 student in atmospheric or water sciences.	

TRAVEL		**67 000 €**
T5 workshop (France)	Invitations and organization	35 000 €
T5 workshop (Taiwan)	3 x 10 days (5 for workshop, 3 for project coordination, 2 for travel)	9 000 €
Other travel to Taiwan	2 x 7 days	5 000 €
National travel	12 x 1-2 days, for project coordination and communication	6 000 €
International conference	4 participations	12 000 €

The international workshop in France (T5b) is planned for 5 days, and budgeted as following:

- Full invitation of 5 senior scientist : 2500 € for travel, and 1000 € for accommodation/meals (200 € per diem)
- Partial invitation of 5 young scientist : 1500 € grant for travel
- Organization : 10 000 €, for rooms, social diner, breaks, if in Paris; and/or travel/accommodation of the METIS participants if not in Paris

OTHER EXPENSES		**14 000 €**
Publication fees	2 papers	4 000 €
Storage	1 rackable bay + 24 To	5 000 €
Videoconference	Integrated system + Polycom license	3 000 €
Computer	1 PC for the non-permanent staff (X1)	2 000 €

2.5.2 LMD, with a total funding request of **79 400 €** to ANR (excluding management fees)

POST-DOC X2	At LMD, supervised by F. Chéruy and J. Polcher	**45 000 €**
12 months	M13-M24	
Tasks	T2: produce and evaluate the LMDZOR simulations; contribute to intercomparison with NTU and CNRM-GAME simulations, with particular attention on land/atmosphere feedback in the transition zones.	
Profile	The postdoc will have a PhD thesis in atmospheric or water sciences and speak English. We expect a good experience in numerical modeling of the Earth climate system.	

Based on CNRS cost for 0-2 years of experience after the PhD, which leads to a net salary of 2000 €/month

Master student S2	At LMD , supervised by F. Chéruy	**2 700 €**
6 months	Mx-Mx+30/36	
Tasks	T2: impact of dynamical WTD on boundary layer structure and convection occurrence in LMDZOR, with nudged and zoomed simulations.	
Profile	M2 student in atmospheric sciences.	

Master student S4	At METIS, supervised by J. Polcher and A. Ducharne	**2 700 €**
6 months	M40-M45	
Tasks	T4: Analysis of LMDZOR sensitivity to withdrawals with a focus over Europe	
Profile	M2 student in atmospheric or water sciences.	

TRAVEL		**19 000 €**
T5 workshop (Taiwan)	2 x 10 days (5 for workshop, 3 for project coordination, 2 for travel)	6 000 €
Other travel to Taiwan	1 x 7 days	2 500 €
T5 workshop (France)	1 x 1500 € if not in Paris	1 500 €
Other national travel	6 x 1-2 days, for project coordination and communication	3 000 €
International conference	2 participations	6 000 €

OTHER EXPENSES		7 000 €
Publication fees	1 paper	2 000 €
Videoconference	Integrated system + Polycom license	3 000 €
Computer	1 PC for the non-permanent staff (X2)	2 000 €

2.5.3 CNRM-GAME, with a total funding request of **21 000 €** to ANR (excluding management fees)

EQUIPMENT		15 500 €
Storage	Bay with 26 To	8 500 €
CPU	1 server + 1 computation node	7 000 €

TRAVEL		3 500 €
National travel	4 x 1-2 days, for project coordination and communication	2 000 €
T5 workshop (France)	1 x 1500 €	1 500 €

OTHER EXPENSES		2 000 €
Publication fees	1 paper	2 000 €

2.5.4 NTU, with a total funding request of **230 600 €** to MoST (excluding management fees)

PhD Student X3	At NTU, supervised by M.-H. Lo and C. Chou	33 600 €
32 months	M1-M32	
Tasks	T1,T2,T4: GW modeling in CLM; Simulations analysis; Building an integrated module in CLM with irrigation and groundwater withdrawal processes.	
Profile	PhD student in atmospheric sciences	

PhD Student X4	At NTU, supervised by M.-H. Lo and C. Chou	33 600 €
32 months	M17-M48	
Tasks	T2,T3,T4: GW code development in CLM. Conduct coupled NCAR CESM climate model simulations for remote impacts of GW withdrawal on the climate. Simulations analysis.	
Profile	PhD student in atmospheric sciences	

Research Assistant X5	At NTU, supervised by M.-H. Lo and C. Chou	36 000 €
48 months	M1-M48	
Tasks	T1-T4: Support for running the NCAR CLM and CESM simulations. Model results analysis, intercomparisons (among CESM, IPSL and CNRM-GAME climate models).	
Profile	Master student in atmospheric sciences	

EQUIPMENT		36 000 €
Storage	4 disk arrays, for a total of 200 To storage space	36 000 €

TRAVEL		65 000 €
T5 workshop (Taiwan)	Invitations and organization	25 500 €
T5 workshop (France)	3 x 10 days (5 for workshop, 3 for project coordination, 2 for travel)	9 000 €
Other travel to France	5 x 7 days	12 500 €
International conference	6 participations	18 000 €

The international workshop in Taiwan (T5a) is planned for 5 days, and budgeted as following:

- Full invitation of 5 senior scientist : 2500 € for travel, and 1000 € for accommodation/meals (200 € per diem)
- Meeting cost : 8 000 €

OTHER EXPENSES		14 400 €
Publication fees	3 papers	6 000 €
Computers	3 PCs for the non-permanent staff (X3-X5)	6 000 €
Matlab license	3 x 800 €	2 400 €

2.5.5 Additional funding

The I-GEM project is co-funded by the European Union via the Climate-KIC (Knowledge and Innovation Community), which supports the PhD grant of A. Schneider (METIS, supervised by Ducharne and Jost, and contributing 15 pers.month to the I-GEM project).

As recommended by the ANR “Guide des Déposants”, the calculation hours required at the IDRIS calculation center for the IPSL simulations are requested via the joint submission of a DARI proposal to GENCI (N° a2014010013, for 73,300 calculation hours and 26 To storage space over 4 years).

The project will also benefits from companion research projects:

- The companion project GEM has received 36 k€ by the LEFE/INSU program for 3 years (2014-2016), and will contribute to the I-GEM project by (i) developing a GW parametrization for ORCHIDEE/LMDZ, which will be used in T2, T3, T4; (ii) creating a global database of anthropogenic water withdrawals (in both surface and ground water), distributed to the I-GEM partners for T4.
- One of the MoST projects at Academia Sinica, called Consortium for Climate Change Study (CCliCS), co-funds 33% of the two Taiwanese PhD students, for the complementary project of using GRACE data for parameter estimations in CLM-GW.

We also obtained 1 month of invited professor at UPMC for Min-Hui Lo in September 2014, thus before the provisional start of the project if it gets funded. This month in Paris will then serve to launch the project, and to precisely establish the protocol of Task T1.

Finally, in case needed, we could look for additional funding, especially for the French workshop: CNRS support for the French participants via the “thematic schools” funding; Labex L-IPSL for additional invitations.

2.6 Risk analysis

No major risk is foreseen at the consortium scale, because it remains small and includes scientists that are complementary, with a solid experience in project management and young scientist supervision, and a successful history of collaboration (several projects between the French partners, ALMIP2 project between all four partners). We are also highly motivated by the research question underlying this project, as shown by our efforts to aggregate various sources of funding (see above), and the opening to a wider community via the two international workshops (T5) is a further motivation to the successfully achieve the project.

From a computational point of view, all teams have access to high-level calculation and storage means. The task schedule leaves some room for possible evolutions of the super-calculators. The IPSL and CNRM-GAME teams will be involved in the CMIP6 simulations during the project, but this shouldn’t be a conflict, given the small size of our simulations compared to the long-term fully coupled CMIP6 simulations (with ocean and carbon cycle). The NTU team has the accesses to the supercomputers at both Academia Sinica and the National Center for High-performance Computing (NCHC). We have been building a close relationship with them in the past two years. The data storage capacity could be an issue so that we propose to purchase the disk arrays to store those global model simulations.

At NTU, the foreseen risks could be on conducting the coupled ocean simulations, which require more computational power. The proposed simulations may not be finished on time (end of 3rd year), but we should be able to finish the simulations before the end of this project, and this does impact the other teams anyway.

At IPSL (METIS+LMD), the major risk for the project is if the GW parametrization for ORCHIDEE is not ready for the beginning of Task T2 (M13, i.e. Dec 2015), despite the efforts around Ana Schneider’s PhD, within the GEM project funded by LEFE/INSU. At the first sights of any such delay, A. Ducharne and A. Jost (supervisors of Ana Schneider at METIS) will increase their help to get the parametrization as early as possible. They may also be helped by research scientist X2 at LMD if the delay becomes too long and Ana Schneider needs to shift to writing her PhD manuscript. In such a case, task T2 would start based on CNRM-GAME and NTU simulations, given that one year and a half have been allotted to perform the required simulations (T2.2), perform individual analyses and validation (T2.3) and intercompare the results of the three teams (T2.4). The IPSL simulations would then start after the other ones, and research scientist X1 at METIS may be involved in their analysis, after X2.

At CNRM-GAME, the risk comes from the small man power that could be assigned to the project. This is sufficient, however, for performing the 11 mandatory simulations (Table 2) and related sanity checks, but their in-depth analysis will largely rely on the rest of the project's staff, in the framework of each task's intercomparison.

Finally, there are no ethical issues with this proposal.

3. Scientific communication and valorization

I-GEM is a fundamental research project, and our main communication target is our scientific colleagues. The dissemination of our results will thus classically rely on national and international conferences (e.g. EGU, AGU, AMS, GEWEX, IAHS, AOGS; Ateliers de Modélisation de l'Atmosphère and ANR meetings in France; MoST meetings for the Atmospheric Science Division in Taiwan), and publications in top-ranking scientific journals. It should also strongly benefit from the two international workshops we want to organize. All documents related to these conferences, papers, and workshops, will be posted on the project's web site (D0.1), as well as the reports that will be part of our "cognitive" deliverables.

In addition, our simulation results (D1.1, D2.1, D3.1, and D4.2) may be diffused to interested scientists, for public research only, upon demand to the project's coordinators, and upon agreement from the partners having performed the simulations. These conditions will be mentioned on the project's web site.

Apart from knowledge progress, the most certain scientific spin-off of the project is the tightening of franco-taiwanese links in the field of climate and environment. It could also be the first step of a larger international project, for instance in the framework of GEWEX (see section 1.3.3), which would greatly enhance the visibility of the I-GEM project, and this may be discussed during our international workshops. Our offline simulations could also be defined to join the ISI-MIP project [94], aiming at intercomparing "impact" models, among which hydrological models [56]. From a more technical point of view, our work is expected to improve three Earth system models to be used in CMIP6.

The project will also have a significant contribution to higher education, by the training of three PhD students (two in Taiwan, and Ana Schneider in France), and four French Master students. These students and the postdoctoral researchers will also benefit from interactions with top international scientists. A potential spin-off of the project could be the elaboration of a convention for student exchange between UPMC and NTU, in the field of atmospheric and water sciences.

We do not expect direct outcome in the economic sphere (industrial innovation and employment), apart from what our scientific results could bring to the field of climate change mitigation and adaptation. In particular, we will try in T4 to devise indicators of GW failure to sustain water withdrawals, which could be very useful for elaborating adaptation strategies. To further develop these ideas, we want to initiate contact with major international actors of climate change adaptation and mitigation, such as the World Bank and UNESCO, for instance by inviting S. Hallegate and A. Aureli, respectively, to our I-GEM workshops.

Finally, a broader diffusion of our results climate to change impact modelers, impact and adaptation consultants, as well as other experts using climate change data, may be achieved owing to the IS-ENES2 European project (Infrastructure for the European Network of Earth System Modelling Phase 2), which supports meetings (in which we could present our results), and a web portal to access climate change data. IPSL is the coordinator of this large project, and contacts will be taken with S. Joussaume, the IS-ENES2 PI, to discuss this possibility.

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