



# Évaluation de l'impact des propriétés du sol sur l'hydrologie simulée dans le modèle ORCHIDEE

Salma Tafasca

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Salma Tafasca. Évaluation de l'impact des propriétés du sol sur l'hydrologie simulée dans le modèle ORCHIDEE. Interfaces continentales, environnement. Sorbonne Université, 2020. Français. NNT : 2020SORUS117 . tel-03220775v2

**HAL Id: tel-03220775**

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# Sorbonne Université

Ecole Doctorale 398 : Géosciences, Ressources Naturelles et Environnement UMR  
METIS 7619

## Evaluation de l'impact des propriétés du sol sur l'hydrologie simulée dans le modèle ORCHIDEE

Par Salma TAFASCA

Thèse de doctorat

Soutenance le 13 Novembre 2020 devant le jury composé de :

|                         |                       |
|-------------------------|-----------------------|
| — M. Aaron BOONE        | Rapporteur            |
| — Mme Agnès DUCHARNE    | Directrice de thèse   |
| — Mme Catherine OTTLE   | Examinatrice          |
| — M. Ludovic OUDIN      | Président de jury     |
| — M. Thierry PELLARIN   | Rapporteur            |
| — M. Christian VALENTIN | Co-directeur de thèse |



## Remerciements

Tout d’abord, je remercie ma directrice de thèse Agnès Ducharne et mon co-encadrant Christian Valentin pour m’avoir confiée ce travail, et pour la confiance qu’ils m’ont accordée tout au long de cette thèse. Je les remercie pour leur patience, pour leur soutien continu et pour avoir toujours été disponibles.

Je remercie Agnès pour avoir accepté ma candidature, et pour m’avoir soutenue en fin de thèse par une prolongation de mon contrat.

Je remercie tous les membres de mon jury de thèse, et je remercie Aaron BOONE et Thierry PELLARIN pour avoir accepté d’être les rapporteurs de cette thèse.

Merci à Thomas Verbeke et Matthieu Guimberteau pour les discussions enrichissantes et pour l’aide avec le modèle ORCHIDEE.

Je remercie Sylvain Therry pour m’avoir assistée avec les problèmes techniques et personnels que j’ai rencontrés au cours de ma thèse.

Je n’oublie pas de remercier Diane, Paul et Noëlie pour leur gentillesse et leur sympathie. Merci à toute l’équipe de METIS pour m’avoir accueillie et pour toute leur aide que ce soit au niveau technique ou personnel.

Un grand merci à mon frère Samy pour son support sans pareil, que les mots ne sauront jamais décrire.

Enfin, merci à toutes les personnes qui ont contribué de loin ou de près à la réussite de cette thèse, en particulier, mes parents qui n’ont jamais cessé de m’encourager et de me motiver pour finir ma thèse.

## Résumé

Les sols jouent un rôle important dans le fonctionnement des processus hydrologiques à la surface de la Terre. La dynamique de l'eau dans le sol, l'évaporation ainsi que la transpiration des plantes sont tous des processus fortement contrôlés par les propriétés hydrauliques des sols. Ces dernières sont donc essentielles dans l'estimation des flux hydrologiques de surface. L'objectif de cette thèse est d'améliorer la représentation des propriétés hydrologiques des sols dans le modèle ORCHIDEE (ORGanizing Carbon and Hydrology in Dynamic EcosystEms), qui décrit les surfaces continentales dans le modèle de climat de l'IPSL (Institut Pierre Simon Laplace), et qui fait donc partie des modèles de surface continentales (land surface models, ou LSMs). Les propriétés du sol sont déterminées par la granulométrie de la terre fine, dite texture, et par sa structure, qui caractérise l'assemblage de ses constituants et des pores. Mais dans ORCHIDEE comme dans beaucoup des LSMs, la représentation des sols est simplifiée : les propriétés du sol sont déduites à partir d'une carte de texture par des fonctions de pedo-transfert.

La première partie de cette thèse présente l'effet de différentes cartes de textures sur les flux hydrologiques simulés, à différentes échelles, pour évaluer la réponse du modèle aux différentes textures. Cette partie démontre que, si l'influence de la texture sur les flux simulés est bien rendue par le modèle, le choix de la carte de texture joue peu sur les bilans d'eau simulés à grande échelle (Tafasca et al., 2020, HESS).

Du fait de son rôle avéré dans le fonctionnement hydrologique des sols, l'influence de la structure sur les processus hydrologiques est explorée en deuxième partie. La variabilité de la structure au sein d'une même texture de sol amène à des comportements hydrologiques différents. C'est particulièrement le cas des argiles, qui sont habituellement regroupées dans une même classe texturale, malgré une structure et des comportements hydrologiques contrastés entre les argiles gonflantes (Vertisols des zones tempérées) et non gonflantes (Oxisols des zones tropicales). Cette thèse propose ainsi une cartographie et des fonctions de pédo-transfert enrichies pour distinguer ces deux types d'argiles. Par ailleurs, un contrôle majeur de la structure est la teneur en matière organique du sol, qui influence fortement la porosité et l'ensemble des propriétés hydrauliques du sol. Plusieurs approches plus globales ont été testées pour tenir compte de cette influence dans le modèle ORCHIDEE. Une conclusion majeure de cette thèse est que la prise en compte de la structure permet une représentation plus réaliste des sols ainsi qu'une amélioration de l'évapotranspiration simulée dans le modèle ORCHIDEE.

## Abstract

Soil plays a major role in the hydrological processes at the land surface. Water movement in the soil, evaporation, and transpiration processes are all strongly controlled by soil hydraulic properties. These properties are therefore important in estimating soil water fluxes.

The objective of this thesis is to improve the representation of soil hydraulic properties in the ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms) model, which describes land surface processes in the IPSL (Institut Pierre Simon Laplace) climate model, and is therefore a land surface model (LSM).

Soil hydraulic properties are defined by both texture, which is the size-class sorting of the soil particles, and the structure, which is the arrangement of soil particles and pores. However, in ORCHIDEE, as in many other LSMs, these properties are inferred from a soil texture map, through pedotransfer functions. In the first part of this thesis, we investigate the impact of soil texture on the simulated soil water fluxes and storage at different scales, using several soil texture maps, to evaluate the model response to the different texture classes. This part shows that although the model exhibits a physically based response to soil texture, the choice of the soil texture map is not crucial in simulating water budgets at the global scale (Tafasca et al., 2020, HESS).

Due to its important role in determining soil properties, the impact of the soil structure on hydrological processes is explored. Soils of the same texture can have different structures, leading to different hydrological behaviors. This is particularly conspicuous for clay soils, which can show a large variability in structure due to swelling clays and non-swelling clays, and which are usually put together in the same soil class despite their contrasted hydrological behavior. In the second part of this thesis, we suggest a soil mapping and pedotransfer functions which differentiate these two clay types. Moreover, one of the major controls of soil structure is organic matter, which highly influences soil porosity and all the soil hydraulic properties. Different global scale approaches are tested to account for the influence of organic matter in the ORCHIDEE model. Introducing the effect of soil structure in ORCHIDEE results in a more realistic representation of soils as well as an improvement of the simulated evapotranspiration flux.

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# Chapitre 1

## Introduction

### 1.1 Les sols : élément essentiel à la modélisation hydrologique

#### 1.1.1 Le sol

Le sol est une composante essentielle du système Terre. Elle appartient à la couche fine superficielle qui recouvre les continents que l'on désigne par le terme de « zone critique ». Celle-ci comprend les organismes vivants, le sol et les nappes. Elle est considérée comme critique car sa disparition entraînerait celle de l'humanité. Le sol constitue à lui seul un système dynamique complexe indispensable à la vie sur Terre. La Soil Science Society of America (SSSA) définit le sol comme étant « La ou les couches de matières minérales et/ou organiques généralement lâches qui sont affectées par des processus physiques, chimiques et/ou biologiques à la surface terrestre ou à proximité, et contiennent généralement des liquides, des gaz et du biote et servent comme support aux plantes ». Il s'agit d'une vision plutôt agronomique puisque le sol, dans cette définition, est essentiellement, vu à travers sa fonction d'enracinement des plantes. En fait, lieu d'échanges et d'interactions entre l'atmosphère, la végétation, les nappes et les roches, il s'étend, dans sa définition internationale, depuis la surface jusqu'à la roche saine, et donc non altérée.

Le sol prend ses origines des roches, lorsque celles-ci sont altérées et décomposées sous l'action de la biosphère, de la lithosphère et de l'atmosphère. Il est composé par une fraction minérale, une fraction organique, ainsi que des êtres vivants. On y retrouve les trois phases physiques : les particules de sol, l'eau et l'air. L'ensemble de ces éléments fait du sol un milieu adapté aux besoins des animaux et végétaux ([Ruellan, 2016](#)). En fonction du climat, des reliefs et de la végétation, les sols peuvent être d'une grande diversité : des couleurs différentes, des compositions minéralogiques et/ou organiques différentes, avec

une épaisseur qui peut varier de quelques millimètres à plusieurs dizaines de mètres.

La présence humaine a toujours été étroitement liée aux sols. Henri Prat a écrit dans *l'Homme et le Sol* (Prat, 1949) la règle générale : « A sol profond et fertile, forte population. A sol rare ou pauvre, population clairsemée ». Les sols sont donc essentiels à l'Homme, ils lui servent pour se nourrir et mettent à sa disposition un accès à l'eau douce. Que ce soit pour l'agriculture (culture et élevage), la production forestière, l'industrie (coton, pâte à papier, latex...), les matériaux de construction, l'art (pigment, ocre) ou les sépultures, l'Homme continue à exploiter les sols pour subvenir à ses besoins.

De nos jours, les sols surexploités par l'Homme se dégradent sous l'effet de nombreux processus : érosion, pollution, salinisation, acidification, tassement, artificialisation. Or, cette utilisation non-réfléchie des sols engendre des dégradations considérables de la biosphère, de l'atmosphère et de l'hydrosphère (Ruellan, 2016).

En effet, les sols jouent un rôle avéré dans de nombreux écosystèmes, assurant un milieu de croissance et une réserve en eau et en nutriments aux plantes, et un habitat à la pédofaune. Leur rôle est également établi dans plusieurs cycles biogéochimiques. Un premier exemple est le cycle du carbone (Fig. 1.1). Les sols non gelés contiennent des quantités importantes de carbone, environ trois fois plus que l'atmosphère (IPCC, 2013). Des quantités équivalentes sont stockées dans le permafrost. Ce carbone dans le sol assure un équilibre dynamique entre, d'une part, l'apport en résidu de plantes et d'animaux et d'autre part, la décomposition de la matière organique en matière minérale et l'émission du gaz carbonique dans l'atmosphère.

Les sols interviennent d'une manière non moins marquée dans le cycle de l'eau. Leur importance provient de leur capacité à stocker l'eau issue des précipitations, et à la libérer par la suite dans l'atmosphère sous forme de vapeur (Fig. 1.2). En outre, ils conditionnent le partage entre infiltration et ruissellement. La part ruisselée rejoint directement le cours d'eau, une part de l'eau infiltrée retourne à l'atmosphère sous forme d'évapotranspiration, transitant par les végétaux, et l'autre part ira rejoindre un cours d'eau par les écoulements latéraux et/ou percolera vers la nappe profonde. Lors de cet acheminement de l'eau infiltrée vers la nappe, le sol joue un rôle de filtre naturel permettant la purification de l'eau souterraine. Le sol a donc un rôle régulateur des transferts entre l'eau atmosphérique, l'eau souterraine et les cours d'eau (Dörfliger and Gascuel-Odoux, 2014).

### 1.1.2 Les propriétés physiques et hydrauliques du sol

Le sol est un assemblage complexe de matière minérale, de matière organique, d'eau et de vide. Ces constituants définissent sa texture ainsi que sa structure. Ces dernières impactent l'ensemble des propriétés hydrauliques contrôlant le mouvement de l'eau dans le sol. Les propriétés hydrauliques du sol sont donc souvent déterminées à partir de la texture et de

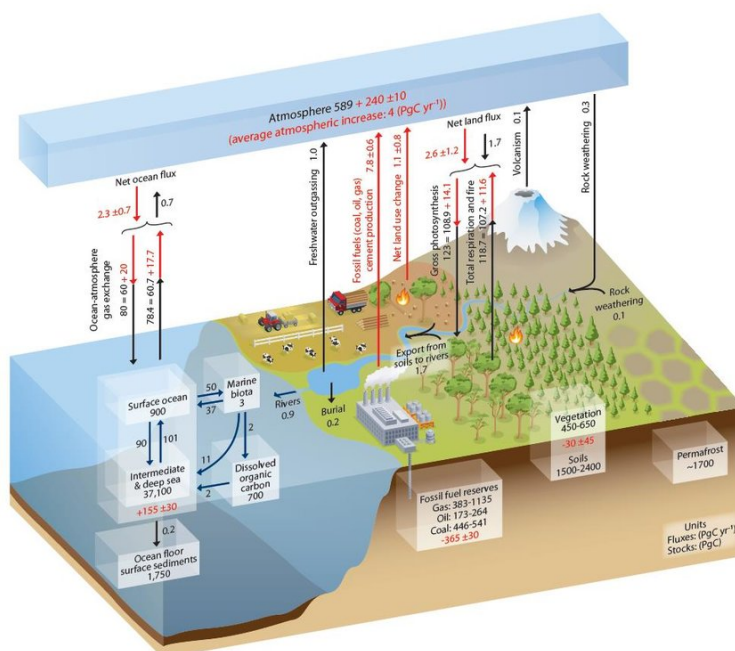


FIGURE 1.1 – Schéma simplifié du cycle de carbone (IPCC, 2013).

la structure à travers des fonctions de pédotransfert (PTF), qui constituent le lien entre les caractéristiques de constitution du sol (texture, structure) et ses propriétés hydrauliques (Saxton and Rawls, 2006).

### Les propriétés de composition du sol

La première propriété qui caractérise la composition du sol est la texture. Il s'agit d'une des principales propriétés impactant l'ensemble des fonctions et processus du sol. Les meilleurs experts peuvent évaluer la texture d'un sol à quelques pourcents près, juste en le malaxant à l'état humide avec les doigts, d'où le terme de texture. Le sable par exemple a un toucher granuleux. Il est également possible de l'entendre crisser à l'oreille, alors que l'argile est plastique et collante lorsqu'elle est humide.

Tout sol est constitué d'une matrice continue de particules minérales allant des plus fines (argiles) aux plus grossières (cailloux). C'est la distribution entre trois fractions, appelées argile, limon et sable, qui définit la texture de la terre fine (une fois tamisé les éléments grossiers  $> 2\text{mm}$ ). Pour classer les sols, les pédologues ont établi quatre classes de tailles de particules : les argiles ( $d < 2\mu\text{m}$ ), les limons ( $2\mu\text{m} < d < 50\mu\text{m}$ ), les sables ( $50\mu\text{m} < d < 2\text{mm}$ ) et les éléments grossiers ( $d > 2\text{mm}$ ) (Knight, 1938). Le diamètre seuil entre les limons et les sables est de  $50\mu\text{m}$  selon la classification de la FAO de l'USDA, et de la plupart des pays dont la France.

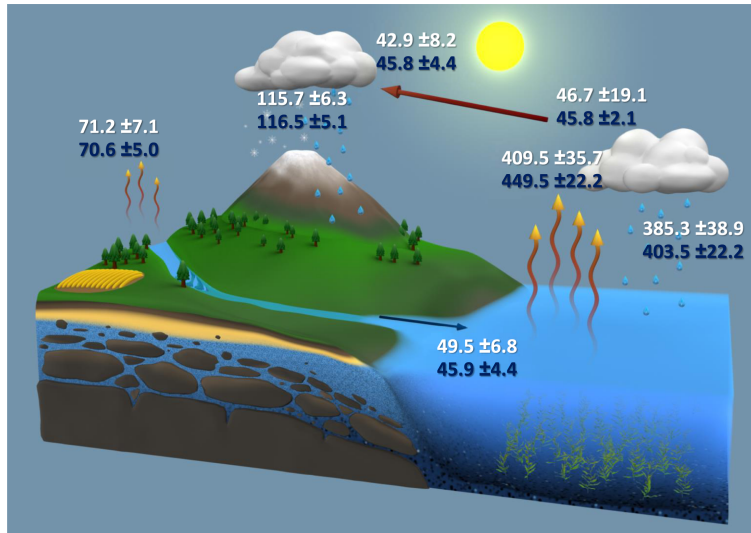


FIGURE 1.2 – Schéma et quantification des principales composantes du cycle de l'eau ( $10^3 km^3.an^{-1}$ ) (Rodell et al., 2015).

La texture du sol a été définie en fonction des fractions en masse d'argile, limon et de sable contenues dans le sol. Fondées sur les fractions de ces trois classes de tailles de particules, plusieurs classifications texturales de sol ont été proposées. Le United States Department of Agriculture (USDA) a été le premier à avoir tracé un triangle textural (Fig. 1.3a) reliant les pourcentages d'argile et de limon à des classes texturales, le pourcentage de sable pouvant être déduit des deux autres (Whitney, 1911). Davis and Bennett (1927) ont fait remarquer qu'il est important de faire figurer dans le triangle les trois compositions ensemble (argile, silt et sable), et ont proposé de modifier le diagramme de Whitney en faisant apparaître le pourcentage de sable, rendant ainsi la lecture du triangle plus complexe. En 1937, l'USDA publie le système de classification à 12 textures (Fig. 1.3b) dans son Soil Survey Manual, qui a également été adopté par la Food and Agriculture Organisation (FAO) dans la FAO and UNESCO (1971) Soil Map of the World. Cette dernière classification est communément utilisée de nos jours et a été adoptée dans cette étude.

La texture du sol est un bon indicateur des propriétés hydrauliques du sol. Les mesures expérimentales ont bien établi l'impact de la texture du sol sur l'évaporation (An et al., 2018), l'humidité du sol (Salter and Williams, 1965) et l'écoulement (Rawls et al., 1993; Osman, 2013). La texture est donc souvent utilisée comme proxy pour l'estimation des propriétés hydrauliques du sol (Saxton et al., 1986), notamment dans les modèles hydrologiques nécessitant une distribution spatiale des propriétés du sol.

La structure du sol, elle, décrit la manière dont les particules de sol sont disposées ainsi que la distribution des vides (aussi appelés pores) dans le sol (Smettem, 1987; Rahmati et al.,

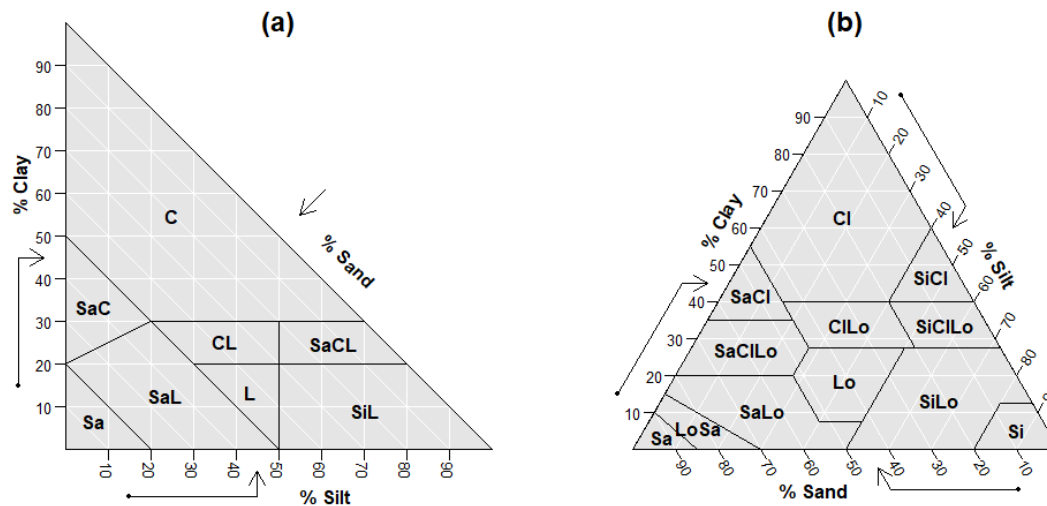


FIGURE 1.3 – Classification des sols (a) selon Whitney (1911) et (b) selon Staff and Bureau of Plant Industry (1951).

2018; Sun et al., 2018). L'espace poral (décrit ci-après) est déterminé non seulement par la texture du sol mais également par sa structure (Stengel, 1979). De nombreux processus peuvent impacter la structure du sol : la présence de racines de plantes, les verres de terre, le piétinement des pâturages, le travail du sol, la présence de matière organique, etc (Fig. 1.4). La matière organique provient de la litière, des résidus de plantes et d'animaux, et comprend également les organismes vivants dans le sol (Oades, 1988). Sa présence accroît la porosité en facilitant la construction de grumeaux, dits agrégats, par des processus de complexation entre l'humus et les argiles, chargés négativement, et les cations minéraux. Un bon indicateur de la structure du sol et de la présence de la matière organique est la densité apparente du sol ( $\rho_a$ ), qui a une forte corrélation avec la porosité et la rétention d'eau (Ruehlmann and Körschens, 2009).  $\rho_a$  est calculée comme la masse sèche du sol divisée par son volume. Elle permet d'indiquer entre autres le degré de compaction du sol. Pour une même texture de sol, une densité apparente plus élevée indique un sol plus compact, contenant moins de pores.

### Les propriétés hydrauliques du sol

**Le potentiel matriciel**  $\psi$  caractérise la force par laquelle l'eau est retenue par la matrice du sol (les particules du sol et le vide entre particules). Autrement dit, il traduit la quantité d'énergie nécessaire pour extraire l'eau du sol. Il est exprimé en unité de pression. Il est le résultat des forces capillaires et d'adsorption de l'eau sur les particules. En milieu non saturé, le potentiel matriciel prend des valeurs négatives. La teneur en eau  $\theta$ , qui est la fraction d'eau contenue dans le sol, est fortement dépendante du potentiel matriciel : plus un sol est sec, plus son potentiel est bas (forte succion).

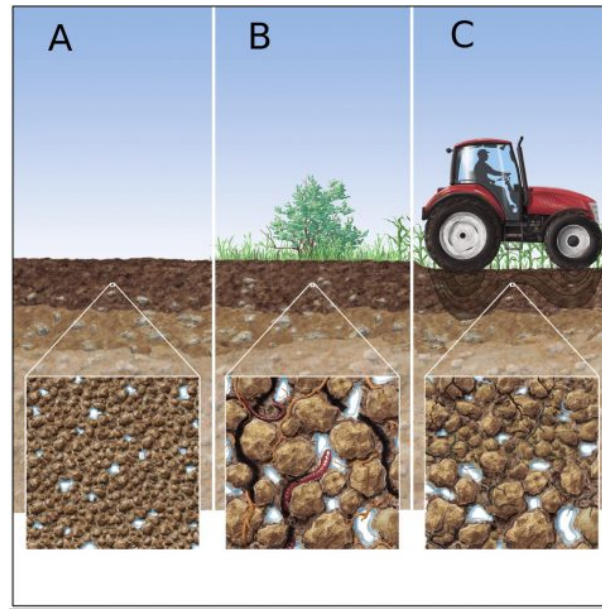


FIGURE 1.4 – Schéma de différentes structures de sol : (a) : homogène, (b) même sol avec activité biologique, (c) : sol soumis au compactage. (Figure prise de ([Romero-Ruiz et al., 2018](#)))

**La porosité** constitue le volume inter-particulaire du sol, contenant l'eau ou l'air. elle est exprimée en pourcentage du volume total du sol. Les pores déterminent le volume d'eau maximal qu'un sol peut contenir, elle traduit donc la teneur en eau à saturation d'un sol. On distingue deux types de pores dans le sol : les macropores, d'une taille généralement supérieure à  $0.08\text{mm}$ , constituent les espace inter-agrégats. Ces pores permettent le drainage de l'eau du sol par gravité, ils contrôlent donc les transferts à saturation. Les micropores sont les espaces retrouvés à l'intérieur des agrégats, leur petite taille leur permet de retenir l'eau par tension capillaire, cette porosité contrôle le potentiel matriciel du sol.

Aussi appelée perméabilité, **la conductivité hydraulique** ( $K$ ) quantifie la capacité d'un milieu poreux à laisser passer l'eau. Elle est exprimée en unité de vitesse. Lors de l'écoulement de l'eau dans le sol, l'écoulement s'effectue préférentiellement au niveau des pores saturés. Plus il y a d'eau dans le sol, plus il y a de pores saturés assurant l'écoulement de l'eau. Ainsi, la conductivité hydraulique varie en fonction de la teneur en eau dans le sol. Dans un milieu saturé, la conductivité hydraulique est maximale (conductivité hydraulique à saturation ;  $K_s$ ).  $K_s$  est étroitement liée à la taille et à la distribution des pores, plus un sol est poreux, plus l'infiltration sera rapide. Ainsi, les sols sableux ayant des pores grossiers auront une plus forte perméabilité que les sols argileux dont la taille des pores est inférieure.

En anglais dit *permanent wilting point*, **le point de flétrissement**  $\theta_w$  est la teneur en

eau minimale dans le sol au-delà de laquelle les plantes flétrissent. A cette teneur en eau, il y a besoin d'une tension de  $-1500\text{ kPa}$  pour soutirer l'eau du sol. A cet état, les plantes ne peuvent plus absorber l'eau. Le point de flétrissement varie avec la texture du sol, les textures sableuses retiennent moins l'eau que les textures argileuses, et donc ont un point de flétrissement inférieur.

**La capacité au champ**  $\theta_{fc}$  est définie empiriquement comme la teneur en eau qui demeure dans le sol après 48 heures de drainage gravitaire, à la suite d'un état de saturation. Cette teneur en eau correspond à des tensions variant de  $-10\text{ kPa}$  à  $-33\text{ kPa}$  selon la texture. En déduisant le point de flétrissement à la capacité au champ, on obtient la réserve utile du sol, qui constitue la fraction maximale d'eau que le sol peut stocker et fournir aux plantes.

### 1.1.3 La modélisation hydrologique

En recherche scientifique, un modèle numérique est une représentation mathématique simplifiée d'un système réel [Moradkhani and Sorooshian \(2008\)](#). Cette représentation mathématique est traduite numériquement pour permettre une résolution par des calculateurs. A travers des modèles, on espère étudier, comprendre et prédire des phénomènes réels.

Les modèles hydrologiques permettent de décrire et d'anticiper la distribution, la circulation ainsi que le stockage de l'eau dans les sols et les bassins versants. Ils traitent également les interactions de l'eau avec l'environnement, y compris avec la biosphère, tout cela dans un contexte simplifié et idéalisé par rapport au système réel complexe.

L'unité géographique en hydrologie est souvent le bassin versant. Les modèles hydrologiques sont donc une représentation de la réponse des bassins versants vis-à-vis des forçages climatiques. Les entrées des modèles hydrologiques consistent généralement en des données climatiques (précipitation, température de l'air, etc.), des propriétés du sol, de topographie, végétation et d'autres paramètres physiques, et leurs sorties sont les flux hydriques résultants. Il est également nécessaire de spécifier un état initial au modèle pour pouvoir modéliser une évolution dans le temps.

Il existe plusieurs classifications de modèles hydrologiques :

- Selon la nature des relations entre les variables : on peut distinguer par exemple les modèles déterministiques, où les sorties sont entièrement déterminées par les paramètres du modèle et les conditions initiales ([Dassargues, 1990](#)), des modèles stochastiques, qui eux possèdent un caractère aléatoire pouvant conduire, pour un même jeu de paramètres, à des résultats différents.

- Selon la nature des processus utilisés : On peut distinguer les modèles à base physique des modèles paramétriques. Alors que les premiers sont basés sur des principes et des équations physiques, les seconds consistent en des relations entrées-sorties incluant des paramètres dont la valeur est déterminée par calage. Les modèles paramétriques peuvent être soit conceptuels ou empiriques. Les premiers recourent à une simplification des concepts physiques, comme par exemple de représenter le fonctionnement hydrologique des sols par celui d'un réservoir ; les deuxièmes sont souvent dits boîtes noires, ils ne permettent aucune représentation physique des processus hydrologiques, et font essentiellement usage de l'intelligence artificielle ([French et al., 1992](#); [Minns and Hall, 1996](#)).
- Selon la représentation de l'espace : on peut distinguer les modèles globaux, où les bassins versants constituent une unique unité spatiale homogène, des modèles semi-distribués ou distribués, où il y a prise en compte de la variabilité spatiale ([Refsgaard and Knudsen, 1996](#); [Beven, 2001](#)).
- Selon la représentation temporelle : on peut distinguer des modèles hydrologiques continus qui simulent sur des échelles temporelles continues et longues ou événementiel qui s'intéressent à l'étude de l'événement pluvieux.

De nombreux modèles hydrologiques sont conçus à la base de différentes catégories de modèles. Le choix du type du modèle hydrologique adéquat dépend des objectifs de la modélisation en question : la prévision des crues, la prévision d'étiage, le dimensionnement d'ouvrages, l'étude d'impact du changement climatique et des propriétés du sol sur le comportement hydrologique des bassins, la gestion des ressources en eau et l'évaluation des bilans d'eau (ce qu'on appelle le bilan hydrologique et qui correspond à la répartition des apports d'eau entre les différents flux hydrologiques le stockage d'eau dans un bassin versant). De par leur conception, certains modèles seront destinés pour des applications particulières s'ils permettent une bonne représentation des processus impliqués. De tels modèles sont de nos jours indispensables pour la gestion des défis actuels et à venir dans le domaine de l'eau ([Devia et al., 2015](#)).

## 1.2 La modélisation hydrologique des surfaces continentales

Les modèles de surface continentale (Land Surface Models en anglais, abrégés par LSMs) sont des outils de représentation des flux d'eau, d'énergie et de carbone à la surface de la Terre (Fig. 1.5). Ces modèles ont fait leur première apparition pour être couplés à des modèles de climats, mais peuvent aussi être utilisés seuls, pour étudier les bilans hydrique et énergétique terrestres, et prédire les changements futurs. Dans ce cas, le LSM est forcé par des informations atmosphériques, souvent issues d'observations et d'assimilations de

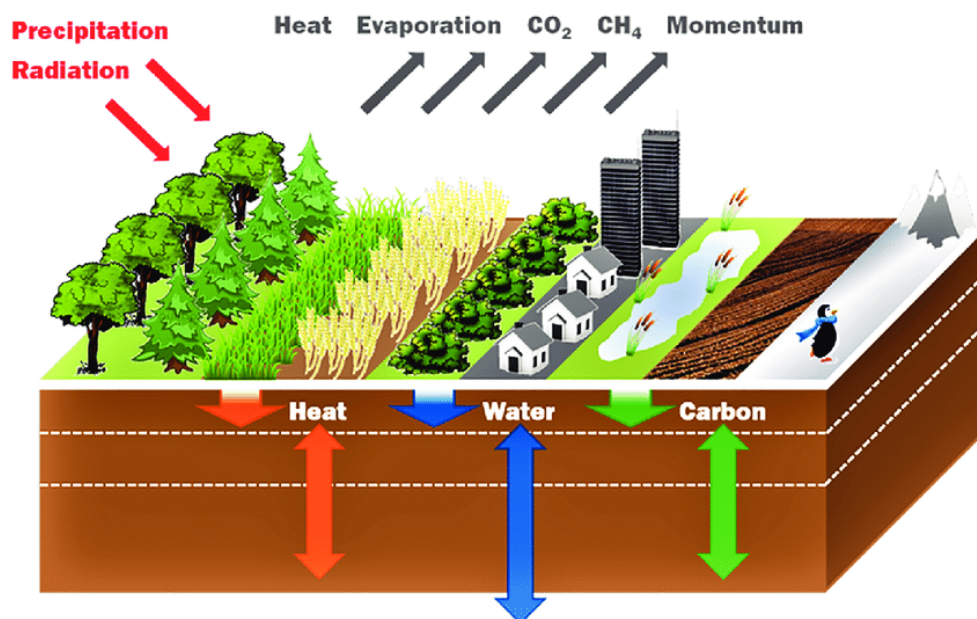


FIGURE 1.5 – Schéma des processus représentés dans un LSM (Figure prise de [Brown et al. \(2017\)](#) )

données. Du fait de leur complexité et de leur échelle globale, les LSM nécessitent une puissance numérique et un temps de calcul considérables. Le choix des résolutions spatiale et temporelle doit être fait de manière à optimiser le temps de calcul, tout en ayant des précisions suffisantes des processus modélisés.

Les premiers LSM consistaient en une représentation simplifiée de la surface terrestre avec un modèle simple, dit modèle réservoir ou Bucket model ([Manabe, 1969](#)). Dans ce modèle, seul le premier mètre de la colonne du sol est fonctionnel, ce dernier est représenté par une couche unique, ou un réservoir. Il prend en entrée les précipitations, et génère du ruissellement lorsque le réservoir est plein. L'évaporation est limitée par la teneur en eau dans le sol, elle est égale à la demande atmosphérique lorsque la teneur en eau est supérieure à la capacité au champ. Par la suite, et en vue de l'impact avéré de l'hydrologie terrestre sur le climat, des modèles plus complexes se sont développés, permettant la représentation d'un élément essentiel, qu'est la végétation. Plusieurs LSM se sont également tournés vers une représentation plus réaliste de la diffusion de l'eau dans le sol en optant pour une description multicouches de type Richards, qui décrit les transferts d'eau en milieux poreux non saturé.

### 1.3 Problématique de la thèse

La dynamique de l'eau dans le sol, l'évaporation ainsi que la transpiration des plantes sont tous des processus fortement contrôlés par les propriétés hydrauliques du sol. Les modèles hydrologiques à base physique expriment la variation de la teneur en eau dans le sol et de la conductivité hydraulique en fonction de ces paramètres du sol.

Souvent dans les LSM, ces paramètres sont déduits d'une carte de texture à travers des fonctions de pédotransfert (PTF) (Pachepsky and van Genuchten, 2011). En effet, la mesure directe des propriétés hydrauliques du sol étant couteuse en temps et en argent, les PTF constituent une alternative pour estimer les propriétés hydrauliques des sols à partir d'autres propriétés déjà disponibles, comme la texture du sol (Cosby et al., 1984; Carsel and Parrish, 1988; Saxton and Rawls, 2006). Dans les LSM, les PTF communément utilisées sont des simples tables qui donnent les paramètres hydrauliques du sol en fonction de sa classe de texture. Cette représentation simplifiée des sols dans les LSM nous amène à nous poser plusieurs questions que nous explorons au cours de cette thèse, à l'aide du modèle ORCHIDEE, décrit en **chapitre 2**.

Plusieurs efforts de cartographie globale de la texture existent dans la littérature, ce qui nous confronte à un choix de la « bonne » carte de texture. Dans le **chapitre 3** de ce manuscrit, on s'intéresse à l'impact de différentes cartes de texture sur les flux hydrologiques simulés par le modèle ORCHIDEE, à différentes échelles, afin d'essayer d'identifier laquelle de ces cartes serait la « meilleure ». Ce travail a donné lieu à une publication dans *Hydrology and Earth System Sciences* (HESS) (Tafasca et al., 2020).

Cette étude s'intègre dans le projet Soil Parameter Model Intercomparison Project (SP-MIP) (Gundmundsson and Cuntz, 2017), qui a pour objectif de quantifier l'influence des paramètres du sol sur la dispersion des résultats des différents LSMs. Certaines des simulations menées dans le cadre de ce projet ont été utilisées dans ce chapitre. L'exercice SP-MIP (décrit en Annexe A) a constitué une partie importante de cette thèse, qui a nécessité un travail sur le code et un formatage des données atmosphériques (décrit dans l'Annexe B).

Les PTF communément utilisés dans les LSM sont des tables construites autour d'un nombre limité de classes de texture. Or, les propriétés du sol peuvent avoir une grande variabilité au sein d'une même classe texturale, qui peut même excéder la variabilité inter-classes (Loosvelt et al., 2011). La classe texturale Argile est particulièrement caractérisée par une large variabilité des propriétés selon sa composition minéralogique. Tandis que les Vertisols (argiles gonflantes), riches en smectites, présentent des caractéristiques hydrauliques propres aux sols fins, les Oxisols (argiles non-gonflantes), principalement constituées de kaolinite, ont un comportement proche des sables, avec une perméabilité beaucoup plus élevée que celle des Vertisols. Les cartes de texture basées sur la classification USDA ne permettent pas de distinguer ces deux types d'argiles différents, et la plupart des PTF

basées sur la classification USDA considèrent les deux comme argiles de type Vertisols, ce qui engendre d’importants biais négatifs dans l’évapotranspiration simulée. Dans le **chapitre 4**, on introduit une nouvelle classe de texture de sol, correspondant aux argiles non-gonflantes de type Oxisols, ce qui permettra de distinguer entre les deux types d’argile au comportements différents. Des simulations sont conduites afin d’évaluer l’impact de cette nouvelle classe de sol par rapport à des données d’évapotranspiration et de débits.

Par ailleurs, de plus en plus de LSM tiennent compte de la structure du sol (De Lannoy et al., 2014; Loosvelt et al., 2011), en plus de la texture, pour déterminer ses propriétés. Pour une même texture, une structure de sol différente peut amener à des propriétés hydrauliques différentes. La structure étant en grande partie contrôlée par la teneur du sol en matière organique, sa prise en compte est d’autant importante dans les tourbières, retrouvées principalement dans les zones de haute latitude et altitude, où les basses températures empêchent la décomposition de la matière organique qui s’accumule, ainsi que dans les sols tropicaux saturés. Dans ORCHIDEE, la distribution spatiale des biais d’évapotranspiration suit les mêmes patterns que ceux de la distribution de la matière organique, quel que soit le forçage climatique utilisé. Ceci suggère que ces biais seraient dus à la non-représentation de la forte capacité de rétention d’eau dans ces sols riches en matière organique. Dans le **chapitre 5**, on introduit l’effet de la matière organique sur les propriétés hydrauliques du sol, et on évalue son impact sur les flux hydrologiques simulés.

Afin de pousser plus loin l’étude sur le lien entre les sols et les processus hydriques de surface, on s’intéresse dans le **chapitre 6** à une modélisation locale de petite échelle. En effet, la faible résolution à laquelle opèrent les LSMs, y compris ORCHIDEE, ne permet pas de bien représenter les hétérogénéités du paysage. Plusieurs simulations locales avec des configurations de sol différentes sont menées sur deux sites de l’Afrique de l’Ouest, caractérisés par des processus hydriques de surface complexes, et une hétérogénéité importante du paysage, afin de tester la sensibilité du modèle à plusieurs paramètres contrôlant l’hydrologie du sol.

Les chapitres 3 à 5 sont rédigés en anglais sous forme d’articles, précédés par une introduction en français. Le chapitre 3 est déjà publié dans HESS, les chapitres 4 et 5 sont destinés à être soumis prochainement.



# Chapitre 2

## La représentation des sols dans le modèle ORCHIDEE

### 2.1 Présentation générale du modèle ORCHIDEE

ORganizing Carbon and Hydrology In Dynamics EcosystEms (ORCHIDEE) est le modèle de surface continentale développé par l’Institut Pierre Simon Laplace (IPSL), il constitue la composante ”surface continentale” du modèle de climat de l’IPSL, mais peut également être utilisé seul, forcé par des données atmosphériques. Les premières versions d’ORCHIDEE ont été développées par le Laboratoire de Météorologie Dynamique (LMD) pour calculer les bilans d’eau et d’énergie à la surface de la Terre ([Laval et al., 1981](#)). Par la suite, une composante principale, qu’est la végétation, a été introduite au modèle, à travers des classes de végétation ou *plant Functional Types* (PFTs), qui permettent de décrire les différentes occupations du sol dans chaque maille ([Krinner et al., 2005](#)). Chaque PFT est représentative d’un groupe d’espèces de végétation aux propriétés similaires. ORCHIDEE distingue 15 PFT dont une réservée au sol nu, deux aux cultures, quatre aux prairies, et le reste pour les forêts. La liste de ces PFT ainsi que leurs paramètres correspondants sont fournis dans la Table 2.1. Ainsi, ORCHIDEE permet également la simulation de la dynamique de la végétation et du carbone ([Krinner et al., 2005](#)).

ORCHIDEE est composé de plusieurs modules :

**SECHIBA** (Schématisation des ECangess Hydriques à l’Interface entre la Biosphère et l’Atmosphère) est le module qui simule les bilans d’eau et d’énergie à la surface des continents ([Ducoudré et al., 1993](#)). Il décrit les échanges hydrologiques entre le système sol-végétation-atmosphère, ainsi que le partitionnement de l’énergie entre les flux de chaleur latente et sensible. Ce module simule également les mécanismes d’évolution du permafrost

| Numéro | Type                       | h   | c   | $r_s$ | LAI <sub>min</sub> | LAI <sub>max</sub> | Soil Tile |
|--------|----------------------------|-----|-----|-------|--------------------|--------------------|-----------|
| 1      | Sol nu                     | 0   | 5.0 | 0     | 0.0                | 0.0                | 1         |
| 2      | Arbres feuillus persistant | 30  | 0.8 | 25    | 8.0                | 8.0                | 2         |
| 3      | Arbres feuillus caduque    | 30  | 0.8 | 25    | 0.0                | 8.0                | 2         |
| 4      | Arbres résineux persistant | 20  | 1.0 | 25    | 4.0                | 4.0                | 2         |
| 5      | Arbres feuillus persistant | 20  | 0.8 | 25    | 4.5                | 4.5                | 2         |
| 6      | Arbres feuillus caduque    | 20  | 0.8 | 25    | 0.0                | 4.5                | 2         |
| 7      | Arbres résineux persistant | 15  | 1.0 | 25    | 4.0                | 4.0                | 2         |
| 8      | Arbres feuillus caduque    | 15  | 1.0 | 25    | 0.0                | 4.5                | 2         |
| 9      | Arbres résineux caduque    | 15  | 0.8 | 25    | 0.0                | 4.0                | 2         |
| 10     | Prairies C3 caduque        | 0.5 | 4.0 | 2.5   | 0.0                | 2.5                | 3         |
| 11     | Prairies C4 caduque        | 0.6 | 4.0 | 2.0   | 0.0                | 2.0                | 3         |
| 12     | Cultures C3 caduque        | 1   | 4.0 | 2.0   | 0.0                | 2.0                | 3         |
| 13     | Cultures C4 caduque        | 1   | 4.0 | 2.0   | 0.0                | 2.0                | 3         |
| 14     | Prairies C3 tropicales     | 0.5 | 4.0 | 2.5   | 0.0                | 2.5                | 3         |
| 15     | Prairies C4 boréales       | 0.5 | 4.0 | 2.5   | 0.0                | 2.0                | 3         |

TABLE 2.1 – Liste des différentes PFT et leur caractéristiques.  $h(m)$  : hauteur moyenne de la végétation ;  $c(m^{-1})$  : coefficient de décroissance exponentielle du profil racinaire ;  $r_s(s.m^{-1})$  : résistance structurale ; LAI : l’indice foliaire.

et les processus liés à la neige (Wang et al., 2013), et opère à un pas de temps de 30 minutes (Fig. 2.1).

**STOMATE** (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems) est le module qui décrit les processus liés à la végétation dans ORCHIDEE. Ce module calcule la photosynthèse, le carbone du sol, la biomasse et d’autres processus biochimiques. Il permet donc de simuler l’évolution de la fraction effective des PFTs dans chaque maille, ainsi que l’indice foliaire *Leaf Area Index* (LAI), à un pas de temps journalier (Viovy, 1996).

**DGVM** (Dynamic Global Vegetation Model) est le module qui décrit la distribution de la végétation en étant couplé à SECHIBA, STOMATE et le module LPJ (Lund–Potsdam–Jena Dynamic Global Vegetation Model) qui modélise l’évolution de la végétation avec le climat (Sitch et al., 2003). DGVM simule la croissance, la compétition et la mortalité de la végétation, et ce à un pas de temps annuel.

Pour les travaux de cette thèse, le module STOMATE est activé et le module DGVM désactivé. Des cartes d’occupation du sol sont utilisées en entrées du modèle (section 2.3). La version 2.0 d’ORCHIDEE, utilisée dans CMIP6 (Boucher et al., 2020; Cheruy et al., 2020), est utilisée dans les chapitres 3 et 6, et la version 2.2 est utilisée dans les chapitres 4 et 5. Cette dernière version qui apporte des changements principalement liés

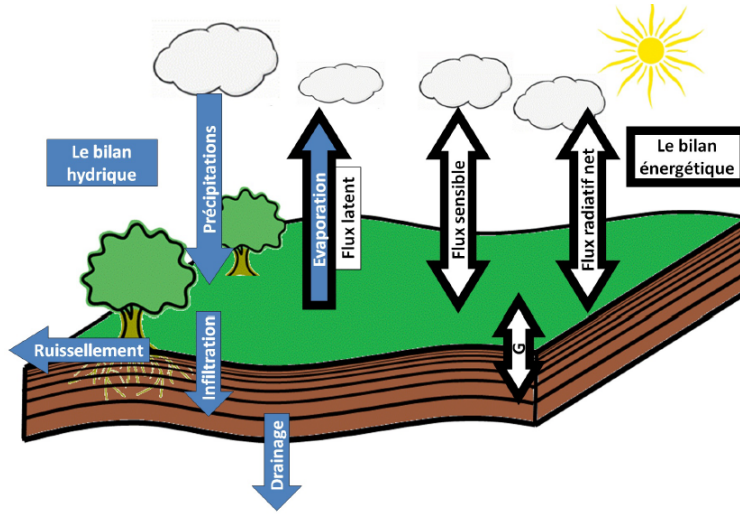


FIGURE 2.1 – Schéma des principaux flux hydriques et énergétiques simulés dans SECHIBA ( $G$  représente la diffusion dans le sol) (Campoy, 2013).

à la nouvelle machine de calcul, avec quelques corrections de bugs. Les deux versions sont donc équivalentes de point de vue fonctionnement hydrologique.

### Les différentes paramétrisations hydrologiques

Dans chaque maille, le bilan d'eau, qui décrit le partitionnement des précipitations en différents flux hydrologiques, est calculé dans trois réservoirs différents : le réservoir de l'eau interceptée par la canopée, le réservoir de la neige et le réservoir du sol. Le bilan d'eau s'écrit :

$$P = R_{\text{tot}} + ET + \frac{\partial W}{\partial t} \quad (2.1)$$

où  $P$  sont les précipitations (pluie et neige),  $ET$  l'évapotranspiration,  $R_{\text{tot}}$  l'écoulement qui est égal au ruissellement plus le drainage, et  $W$  est le stock d'eau dans les différents réservoirs.

Ces réservoirs sont alimentés par les précipitations. Le premier réservoir à se remplir est celui de la canopée, ensuite, l'eau des précipitations qui atteint la surface du sol en plus de la neige fondue sont redistribuées en plusieurs flux d'évaporation, de ruissellement, d'infiltration et de drainage.

Chaque maille dans ORCHIDEE est subdivisée en trois colonnes du sol, appelées "*soil tiles*". Chaque *soil tile* est réservée pour un type d'occupation du sol : la première regroupe les forêts, la deuxième regroupe les prairies et cultures et la troisième est pour le sol nu.

### Infiltration, ruissellement et drainage

En surface, l'eau des précipitations non interceptée par la canopée et la fonte de la neige alimentent les flux d'évaporation, de ruissellement et d'infiltration :

$$P_g + N_g = E_g + I + R_s \quad (2.2)$$

où  $P_g$  sont les précipitations qui atteignent le sol,  $N_g$  la fonte de la neige (si elle a lieu) ,  $E_g$  l'évaporation du sol,  $I$  l'infiltration,  $R_s$  le ruissellement et  $W_s$  l'humidité du sol ou le stock d'eau dans le sol. Lorsque l'eau disponible à l'infiltration excède la capacité du sol à infiltrer, l'excédent part en ruissellement. L'eau infiltrée est à son tour redistribuée dans le sol, où une part est puisée par les plantes pour leur transpiration, alors que la part qui atteint le fond de la colonne du sol constitue le drainage.

L'infiltration est limitée par la conductivité hydraulique en surface, elle est décrite par une approche de sous-pas de temps pour le calcul de la propagation du front d'infiltration, inspirée du modèle de [Green and Ampt \(1911\)](#).

Afin de représenter l'infiltration des systèmes de mares dans le modèle, une part  $\gamma$  de l'eau ruisselée  $R_s$  est soumise à un processus de réinfiltration dans les mailles à faible pente ([D'Orgeval et al., 2008](#)) :

$$\gamma = 1 - \min(1, S/S_{\max}) \quad (2.3)$$

où  $S$  est la pente de la maille et  $S_{\max}$  la pente seuil = 0.5%.

### Les flux évaporatifs

L'évapotranspiration  $ET$  est une composante essentielle du bilan d'eau. Elle constitue le flux de chaleur latente dans le bilan énergétique. Elle est composée de l'évaporation du sol  $E_g$ , la transpiration des plantes  $E_t$ , la sublimation de la neige  $E_s$  et l'évaporation de l'eau interceptée par le feuillage  $E_i$  :

$$ET = E_g + E_t + E_s + E_i \quad (2.4)$$

L'évapotranspiration est calculée à partir de l'évapotranspiration potentielle :

$$E_{\text{pot}} = \frac{\rho}{r_a} (q_{\text{sat}}(T_s) - q_{\text{air}}), \quad (2.5)$$

où  $\rho$  est la densité de l'air,  $r_a$  est la résistance aérodynamique,  $q_{\text{sat}}(T_s)$  est l'humidité spécifique de l'air saturé à la température  $T_s$ , et  $q_a$  est l'humidité spécifique de l'air.

L'évapotranspiration est restreinte par un stress hydrique  $\beta$  qui lie  $ET$  à  $E_{\text{pot}}$  :

$$ET = \beta E_{\text{pot}} \quad (2.6)$$

Cette fonction de stress  $\beta$  comprends les stress hydriques de chaque sub-flux évaporatif, et les fractions de maille dont ils sont issus.

L'évaporation du sol provient de la *soil tile* sol nu, et des fractions non-couvertes par le feuillage des autres *soil tiles*. Elle est calculée en supposant un taux d'évaporation potentiel, sauf si l'eau devient limitante, et que la diffusion ascendante à la couche superficielle ne permet pas de satisfaire l'évaporation potentielle. Dans ce cas, la diffusion est recalculée en supposant une évaporation inférieure (Ducharne et al., 2020).

La transpiration dépend du profil d'humidité du sol et du profil de densité racinaire (De Rosnay and Polcher, 1998), elle est limitée par la conductance stomatique des plantes. La sublimation de la neige ainsi que l'évaporation de l'eau interceptée par la canopée, elles, ne sont soumises à aucun stress hydrique, et donc se produisent au taux potentiel.

### Le module de routage

Les écoulements sortants d'une maille (ruissellement et drainage) sont transformés en débits dans les cours d'eau par un module de routage, développé en 2003 par (Polcher, 2003). Ce module, prend en entrée un réseau hydrographique qui sera couplé au maillage d'ORCHIDEE. Il est basé sur des modèles existants de routage (Miller et al., 1994; Hagemann and Dümenil, 1997; Ducharne et al., 2003).

L'écoulement est transporté horizontalement par un système de réservoirs linéaires, avec dans chaque maille trois réservoirs. Le réservoir profond, aussi appelé réservoir lent, représente l'eau souterraine, il est alimenté par le drainage, et se caractérise par un temps de résidence lent. Le deuxième réservoir est celui de subsurface, il est alimenté par le ruissellement, et permet la prise en compte du décalage temporel entre la génération du ruissellement et son arrivée au cours d'eau. Enfin, le troisième réservoir est celui du cours d'eau, il est alimenté par les deux réservoirs précédents, et le débit des mailles amont, ce qui permet le transport horizontal de maille à maille jusqu'à l'exutoire, alors que les deux

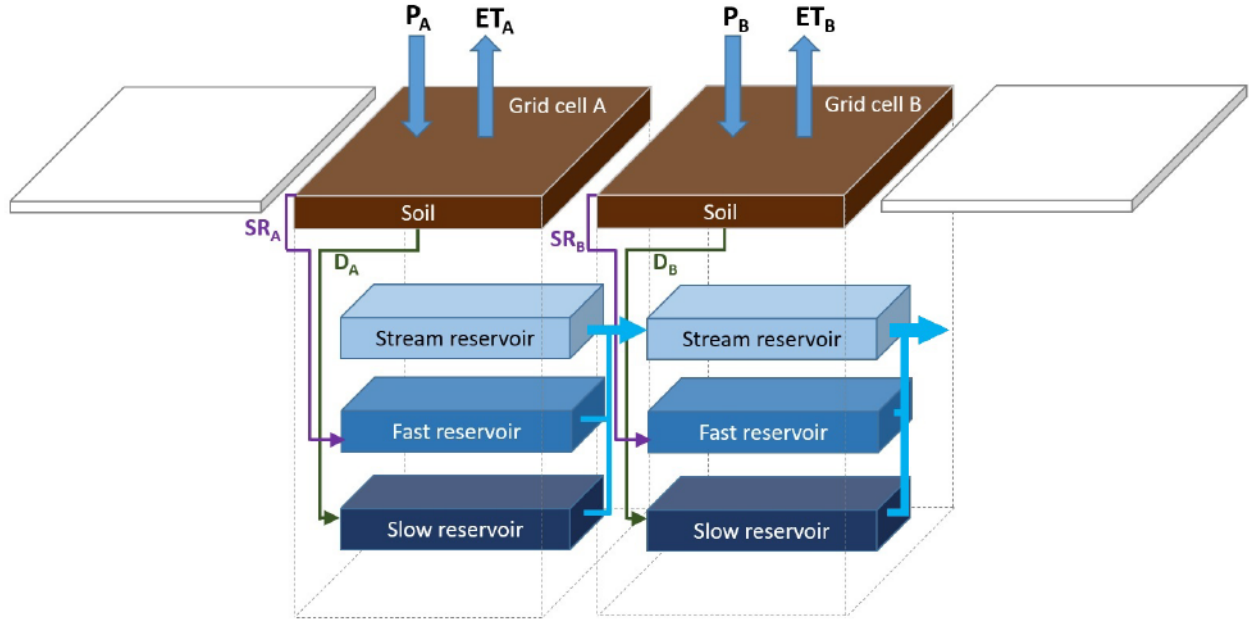


FIGURE 2.2 – Schéma du système de réservoirs dans le module de routage.  $P$  représente les précipitations,  $ET$  l'évapotranspiration,  $SR$  le ruissellement et  $D$  le drainage. (Khalaf, 2017).

premiers réservoirs n'agissent que localement au sein de chaque maille (Fig. 2.2). Dans chacun de ces réservoirs  $i$ , la variation du volume d'eau est décrite par :

$$\frac{dV_i}{dt} = Q_i^{\text{in}} - Q_i^{\text{out}} \quad (2.7)$$

où  $V_i$  représente le stock d'eau dans le réservoir  $i$ , et  $Q$  est le flux d'eau entrant ou sortant du réservoir. Le débit d'eau sortant du réservoir  $i$  est exprimé :

$$Q_i^{\text{out}} = \frac{V_i}{\tau_i} \quad (2.8)$$

où  $\tau_i$  est le temps de résidence dans le réservoir  $i$ . Il est calculé à partir d'un indice topographique  $k$  (Ducharne et al., 2003), qui est proportionnel à la longueur de la maille et inversement proportionnel à sa pente ; et d'une constante  $g$  qui prend une valeur différente pour chaque réservoir.

$$\tau_i = k.g_i \quad (2.9)$$

### La neige et le permafrost

La neige est décrite par un schéma à trois couches, où la densité de la neige contrôle l'albedo et les propriétés isolantes de la neige (Wang et al., 2013). Le gel du sol est optionnel dans ORCHIDEE, lorsqu'il est activé, une part de l'humidité du sol peut geler en fonction de la température (Gouttevin et al., 2012). Les processus de diffusion de chaleur dans le sol sont calculés sur une profondeur de 90 m, lorsque le gel du sol est activé, et sur 10 m lorsqu'il ne l'est pas. Le calcul de la diffusion de l'eau dans le sol, lui, se fait sur une colonne de sol de 2 m. La teneur en eau de la dernière couche hydrologique du sol est extrapolée entre 2 et 10 ou 90 m. Les paramètres thermiques qui contrôlent la diffusion de la chaleur dans le sol sont déterminés par la texture (Wang et al., 2016), tout comme les paramètres hydrauliques. Les processus thermiques ne seront cependant pas abordés dans cette thèse.

## 2.2 L'hydrologie du sol

L'hydrologie du sol dans ORCHIDEE est basée sur une description physique multi-couche du sol, aussi appelée CWRR (Center for Water Resources and Research) (De Rosnay et al., 2002; D'Orgeval et al., 2008; Campoy et al., 2013). Chaque colonne de sol est discrétisée en onze couches, avec des épaisseurs croissantes avec la profondeur, et s'étend sur une profondeur de deux mètres. La distribution de l'eau dans le sol est calculée en résolvant l'équation de Richards à une dimension, avec l'hypothèse d'un drainage libre au fond, i.e. un drainage égal à la conductivité hydraulique de la dernière couche de la colonne du sol. Puisque la dimension horizontale des mailles dans ORCHIDEE est assez grande, les flux d'eau latéraux entre mailles adjacentes sont négligés.

L'équation de Richards s'écrit :

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K(\theta) \left( \frac{\partial h}{\partial z} - 1 \right) \right) \quad (2.10)$$

où  $\theta$  désigne la teneur en eau volumétrique du sol,  $h$  le potentiel hydraulique et  $K(\theta)$  la conductivité hydraulique à la teneur en eau  $\theta$ . L'introduction de la diffusivité du sol  $D(\theta)$  par Childs et al. (1950) :

$$D(\theta) = K(\theta) \frac{\partial h}{\partial \theta} \quad (2.11)$$

permet d'écrire l'équation 2.10 sous la forme :

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D(\theta) \frac{\partial \theta}{\partial z} - K(\theta) \right) \quad (2.12)$$

L'équation 2.12 permet de décrire le mouvement vertical de l'eau dans un sol non saturé, homogène et isotrope, en fonction de la teneur en eau  $\theta$ .

### Le modèle de Mualem - Van Genuchten

$K(\theta)$  et  $D(\theta)$  sont donnés par le modèle de Mualem (1976)- Van Genuchten (1980) :

$$K(\theta) = K_s \sqrt{\theta_f} \left(1 - \left(1 - \theta_f^{1/m}\right)^m\right)^2, \quad (2.13)$$

$$D(\theta) = \frac{(1-m)K(\theta)}{\alpha m} \frac{1}{\theta - \theta_r} \theta_f^{-1/m} \cdot \left(\theta_f^{-1/m} - 1\right)^{-m}, \quad (2.14)$$

où  $K_s$  est la conductivité hydraulique à saturation, ( $\text{m.s}^{-1}$ ),  $\alpha$  ( $\text{m}^{-1}$ ) est un paramètre correspondant à l'inverse de la valeur de la charge hydraulique critique,  $m$  et  $n$  des paramètres du modèle Van Genuchten liés par :

$$m = 1 - 1/n. \quad (2.15)$$

$\theta_f$  est la teneur en eau relative :

$$\theta_f = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (2.16)$$

$\theta_r$  et  $\theta_s$  sont respectivement la teneur en eau résiduelle et celle à saturation.  $\theta$  est toujours comprise entre  $\theta_r$  et  $\theta_s$ .

Le modèle de Van Genuchten fournit également l'équation du potentiel matriciel en fonction de la teneur en eau dans le sol :

$$\psi(\theta) = -\frac{1}{\alpha} (\theta_f^{-1/m} - 1)^{1/n}, \quad (2.17)$$

Les paramètres utilisés dans le modèle Van-Genuchten peuvent prendre différentes valeurs en fonctions de la texture du sol. Dans ORCHIDEE, les paramètres de Carsel and Parrish (1988) sont utilisés (Table 2.2). Les courbes de rétention d'eau résultantes de ces paramètres sont illustrées dans la figure 2.3

### La texture du sol dans ORCHIDEE

ORCHIDEE lit une carte de distribution spatiale de texture de sol, et calcule les paramètres correspondant à l'aide de la look-up table de Carsel and Parrish (1988). Deux cartes de texture de sol peuvent être utilisées par défaut dans ORCHIDEE, elle sont

| -               | $K_s$       | n    | $\alpha$  | $\theta_s$   | $\theta_{fc}$ | $\theta_w$   | $\theta_r$   |
|-----------------|-------------|------|-----------|--------------|---------------|--------------|--------------|
| -               | $mm.d^{-1}$ | -    | $mm^{-1}$ | $m^3.m^{-3}$ | $m^3.m^{-3}$  | $m^3.m^{-3}$ | $m^3.m^{-3}$ |
| Sand            | 7128.0      | 2.68 | 0.0145    | 0.43         | 0.0493        | 0.0450       | 0.045        |
| Loamy Sand      | 3501.6      | 2.28 | 0.0124    | 0.41         | 0.0710        | 0.0570       | 0.057        |
| Sandy Loam      | 1060.8      | 1.89 | 0.0075    | 0.41         | 0.1218        | 0.0657       | 0.065        |
| Silt Loam       | 108.0       | 1.41 | 0.0020    | 0.45         | 0.2402        | 0.1039       | 0.067        |
| Silt            | 60.0        | 1.37 | 0.0016    | 0.46         | 0.2582        | 0.0901       | 0.034        |
| Loam            | 249.6       | 1.56 | 0.0036    | 0.43         | 0.1654        | 0.0884       | 0.078        |
| Sandy Clay Loam | 314.4       | 1.48 | 0.0059    | 0.39         | 0.1695        | 0.1112       | 0.100        |
| Silty Clay Loam | 16.8        | 1.23 | 0.0010    | 0.43         | 0.3383        | 0.1967       | 0.089        |
| Clay Loam       | 62.4        | 1.31 | 0.0019    | 0.41         | 0.2697        | 0.1496       | 0.095        |
| Sandy Clay      | 28.8        | 1.23 | 0.0027    | 0.38         | 0.2672        | 0.1704       | 0.100        |
| Silty Clay      | 4.8         | 1.09 | 0.0005    | 0.36         | 0.3370        | 0.2665       | 0.070        |
| Clay            | 48.0        | 1.09 | 0.0008    | 0.38         | 0.3469        | 0.2707       | 0.068        |

TABLE 2.2 – Les 12 classes de textures USDA et leurs paramètres de Van Genuchten correspondants fournis par [Carsel and Parrish \(1988\)](#)

toutes deux basées sur la FAO/UNESCO Soil Map of the World ([FAO and UNESCO, 1971](#)). Cette dernière est construite à partir de 1700 échantillons de sol, en plus de cartes auxiliaires de topographie, géologie, climat et végétation pour la prédiction des textures en zones non documentées, elle est fournie à une résolution de 1/5000000. La première carte de texture est celle de [Zobler \(1986\)](#), elle est définie à une résolution de 1°, et est composée de 5 classes texturales : Grossières, Moyennes à Grossières, Moyennes, Fines à Moyennes et Fines. La deuxième est celle fournie par [Reynolds et al. \(2000\)](#), définie à une résolution de 5', elle fournit la texture à une profondeur de [0, 30cm] et à [30cm, 100cm]. Elle est composée de onze classes texturales parmi les douze classes définies par l'USDA ([Staff and Bureau of Plant Industry, 1951](#)) (Fig. 2.4). Ces deux cartes sont illustrées dans la figure 2.5.

Pour déterminer les paramètres de Van-Genuchten à partir de la texture, le modèle utilise la look-up table de [Carsel and Parrish \(1988\)](#). Celle ci fait correspondre à chaque classe texturale de l'USDA les paramètres correspondants. Dans le cas de la carte Zobler, le modèle simplifie la representation des texture en les réduisant à trois textures uniquement, correspondant aux classes Sandy Loam, Loam et Clay loam de la classification USDA. C'est cette dernière carte qui a été utilisée dans les simulations CMIP6. La Table 2.2 regroupe l'ensemble des 12 classes de texture USDA et leurs paramètres correspondants. Dans ORCHIDEE.

La texture, ainsi que l'ensemble des paramètres du sol sont homogènes sur toute la maille, et sur le long de la profondeur du sol, à l'exception de la conductivité hydraulique à saturation  $K_s$ .

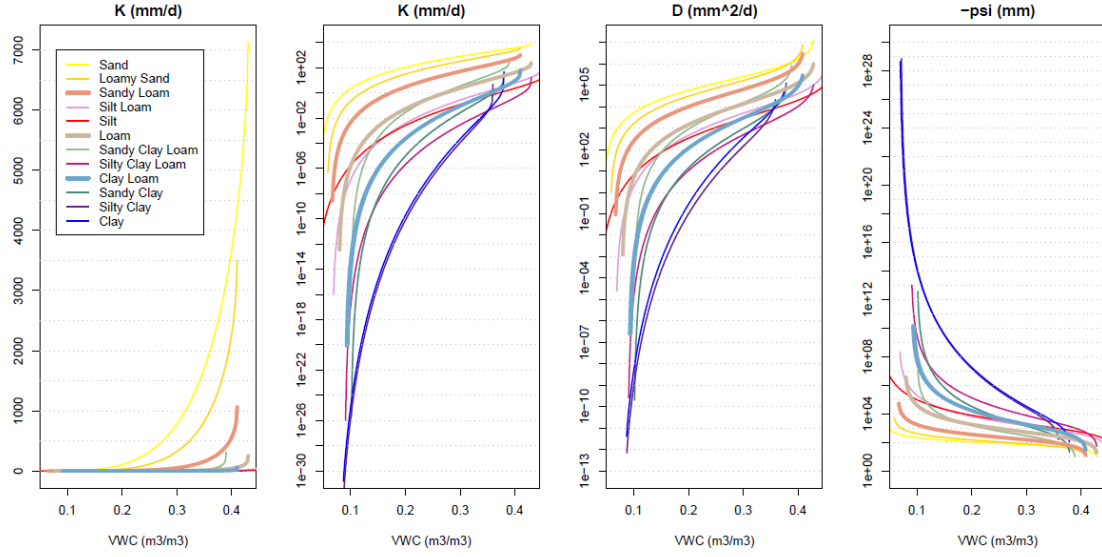


FIGURE 2.3 – Relations de Van Genuchten de  $K(\theta)$ ,  $D(\theta)$  et  $\psi(\theta)$ , pour les 12 classes de textures USDA. La différence entre les deux premières fenêtres est que la deuxième utilise un axe logarithmique pour  $K(\theta)$  (Ducharme et al., 2020).

### Les variabilités verticale et horizontale de $K_s$

Pour tenir compte de la compression du sol en profondeur,  $K_s$  décroît exponentiellement au delà de 30 cm de profondeur :

$$K_s(z) = F_K K_s^{\text{ref}}, \quad (2.18)$$

$$F_K = \min(\max(\exp(-f(z - z_{\text{lim}})), 1/F_K^{\text{max}}), 1). \quad (2.19)$$

Où  $z$  est la profondeur,  $K_s^{\text{ref}}$  est la conductivité hydraulique à saturation de référence dérivée de la texture,  $z_{\text{lim}}$  la profondeur à partir de laquelle  $K_s$  commence à décroître, elle est par défaut égale à 30 cm,  $f$  le taux de décroissance, par défaut égale à  $2m^{-1}$  et  $\frac{1}{F_K^{\text{max}}}$  est un paramètre toujours inférieur à  $F_K$ , par défaut égal à 0.1.

En présence de racines, la valeur de  $K_s$  augmente en surface, pour permettre la prise en compte de l'effet de la végétation sur la structure du sol dans la zone racinaire, qui devient plus perméable. Pour chaque *soil tile*  $c$ , un coefficient racinaire est calculé :

$$F_{K_{\text{root}}}(c) = \prod_{j \in c} \max \left( 1, \left( \frac{K_s^{\text{max}}}{K_s^{\text{ref}}} \right)^{f^j (1 - c_j z)/4} \right) \quad (2.20)$$

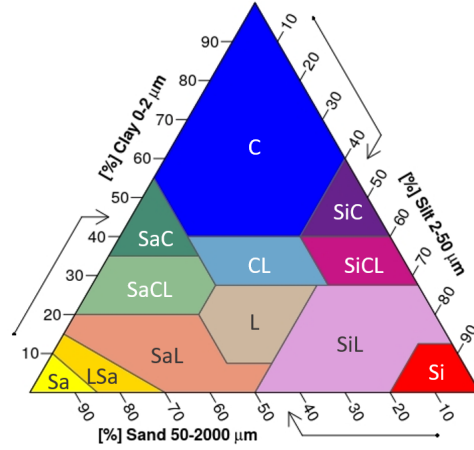


FIGURE 2.4 – Les 12 classes texturales de l'USDA

où  $j$  désigne les PTF contenues dans la tile  $c$ ,  $f^j$  est la fraction de la PTF  $j$  contenue dans  $c$ ,  $K_s^{\max}$  est la valeur maximale de  $K_s^{\text{ref}}$ , donc celle du sable.

Ce coefficient prend en compte l'ensemble des PTF contenues dans la *soil tile*. La conductivité hydraulique à saturation à la profondeur  $z$  et pour la tile  $c$  devient donc :

$$K_s^*(z, c) = K_s(z) F_{K_{\text{root}}}(c), \quad (2.21)$$

Où  $K_s(z)$  est donnée par l'équation 2.18.

En plus de varier avec la profondeur du sol,  $K_s$  varie horizontalement suivant une distribution exponentielle, cette distribution horizontale de  $K_s$  est utilisée uniquement dans le calcul de l'infiltration. Au niveau de chaque couche de sol  $i$ , le taux d'infiltration  $I$  est exprimé par :

$$I = K_i(1 - \exp(-I_{\text{pot}}/K_i)) \quad (2.22)$$

où  $K_i$  est la perméabilité à l'interface entre la couche  $i$  et  $i-1$ ,  $I_{\text{pot}}$  est le taux d'infiltration potentiel correspondant à l'eau disponible à l'infiltration. Cela revient à une conductivité effective de :

$$K_{i,\text{eff}} = K_i(1 - \exp(-I_{\text{pot}}/K_i)) \quad (2.23)$$

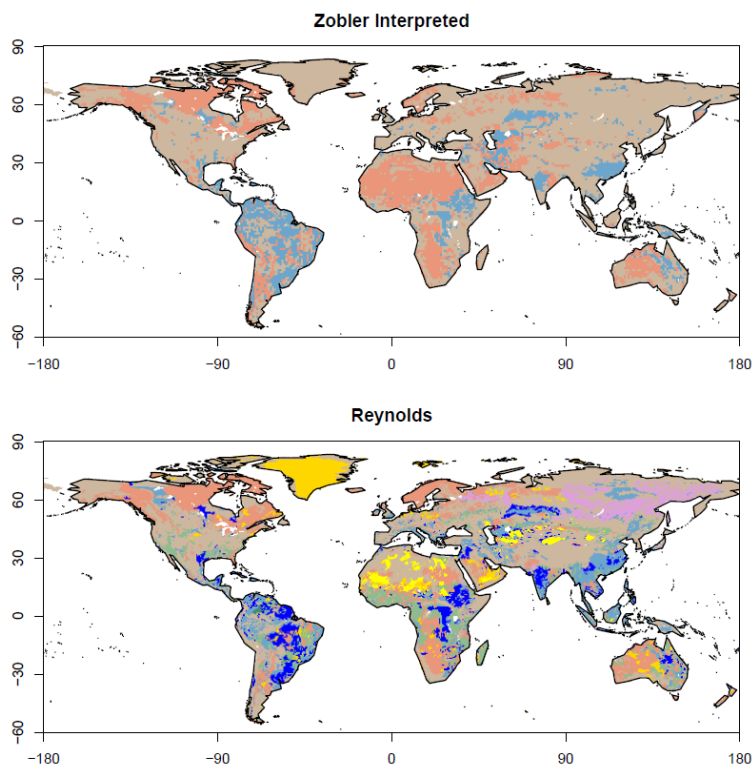


FIGURE 2.5 – Les cartes de texture du sol utilisées dans ORCHIDEE

## 2.3 Les principaux forçages du modèle

### Les forçages atmosphériques

ORCHIDEE reçoit en entrée les données atmosphériques de précipitations, rayonnements descendants, vitesse du vent, humidité, température et pression atmosphérique (Table 2.3). Dans le cas où ORCHIDEE n'est pas couplé à un modèle atmosphérique, ces entrées sont fournies par des données issues d'observations combinées à des modèles. Ces dernières sont généralement fournies à des pas de temps grossiers (3 à 6h), ils sont désagrégés par ORCHIDEE au pas de temps demi horaire pour correspondre au pas de calcul dans SECHIBA. Dans cette thèse, deux forçages atmosphériques sont utilisés : le GSWP3-v1 (Kim, 2017) et le CRUN-NCEP (Compo et al., 2011). Ces deux forçages sont décrits dans la section 3.2.2.

### Autres forçages

En plus des données atmosphériques, ORCHIDEE prend en entrée d'autres cartes de description globale des surfaces continentales :

| Variable | Description                             | Unité              |
|----------|-----------------------------------------|--------------------|
| Ta       | Température de l'air à 2 mètres         | K                  |
| Qa       | Humidité spécifique de l'air à 2 mètres | $kg.kg^{-1}$       |
| W        | Vitesse du vent à 10 mètres             | $m.s^{-1}$         |
| Psurf    | Pression de surface                     | Pa                 |
| Swdown   | Rayonnement solaire incident            | $W.m^{-2}$         |
| Lwdown   | Rayonnement infrarouge incident         | $W.m^{-2}$         |
| Pr       | Pluie                                   | $kg.m^{-2}.s^{-1}$ |
| Ps       | Neige                                   | $kg.m^{-2}.s^{-1}$ |

TABLE 2.3 – Liste des différentes variables atmosphériques utilisées en entrée dans ORCHIDEE

- Une carte de pente pour le calcul de la fraction de réinfiltration. La carte ETOPO fournissant la pente moyenne de chaque maille à une résolution de 15' a été introduite dans ORCHIDEE par [Orgeval \(2006\)](#).
- Les cartes des bassins versants et des directions d'écoulement pour le module de routage.
- Les cartes annuelles de végétation (distribution spatiale des PFTs) lorsque le module DVGM n'est pas activé. La carte utilisée dans cette thèse est celle utilisée pour les simulations CMIP6 ([Boucher et al., 2020](#); [Cheruy et al., 2020](#))
- Les cartes de LAI lorsque le module STOMATE n'est pas activé.
- Une carte de texture pour le calcul des paramètres du sol.



# Chapitre 3

## Sensibilité d'ORCHIDEE aux cartes de texture du sol

Dans ce chapitre, on s'intéresse à l'étude de l'impact de la texture du sol sur les différents flux hydriques simulés par ORCHIDEE, de l'échelle de la maille à l'échelle globale. Pour cela, on a testé plusieurs cartes de texture de sol communément utilisées dans les LSM, en plus de cartes uniformes. On est parti du besoin d'identifier la "meilleure" carte de texture, vu que dans la littérature, il n'existe aucune étude qui identifie cette meilleure carte. Les résultats obtenus n'ont pas permis d'identifier une carte meilleure que les autres, ce qui nous a permis de conclure que le choix de la carte de texture du sol n'est pas crucial dans la modélisation des surfaces continentales. Cette étude a fait l'objet d'un article publié dans *Hydrology and Earth System Sciences* (HESS) : Tafasca, S., Ducharne, A., and Valentin, C. (2020). Weak sensitivity of the terrestrial water budget to global soil texture maps in the ORCHIDEE land surface model. *Hydrology and Earth System Sciences*, 24(7) :3753–3774. Publisher : Copernicus GmbH.

Cette étude est basée en grande partie sur les simulations qu'on a effectuées dans le cadre du projet Soil Parameter Model Intercomparison Project (SP-MIP), auxquelles on a rajouté deux simulations supplémentaires pour compléter l'étude. Le but du projet SP-MIP est de quantifier à quel point les écarts entre modèles sont dus aux paramètres hydrauliques du sol.

### Abstract

Soil physical properties play an important role for estimating soil water and energy fluxes. Many hydrological and land surface models (LSMs) use soil texture maps to infer these properties. Here, we investigate the impact of soil texture on soil water fluxes and storage at different scales using the ORCHIDEE LSM, forced by several complex or globally-uniform

soil texture maps. At point scale, the model shows a realistic sensitivity of runoff processes and soil moisture to soil texture, and reveals that loamy textures give the highest evapotranspiration and lowest total runoff rates. The three tested complex soil texture maps result in similar water budgets at all scales, compared to the uncertainties of observation-based products and meteorological forcing datasets, although important differences can be found at the regional scale, particularly in areas where the different maps disagree on the prevalence of clay soils. The three tested soil texture maps are also found to be similar by construction, with a shared prevalence of loamy textures, and have a spatial overlap over 40% between each pair of maps, which explains the overall weak impact of soil texture map change. A useful outcome is that the choice of the input soil texture map is not crucial for large-scale modelling but the added-value of more detailed soil information (horizontal and vertical resolution, soil composition) deserves further studies.

### 3.1 Introduction

Land surface models (LSMs) simulate water and energy fluxes at the interface between the land surface and the atmosphere. They were developed for continental to global scales to provide realistic land boundary conditions to climate models [Remaud et al. \(2018\)](#), and to investigate the water, energy and carbon cycles at the Earth surface, and the related natural resources and risks ([Guimberteau et al., 2017](#); [Haddeland et al., 2011](#); [Sterling et al., 2013](#); [Zhao et al., 2017](#)). By lack of sufficient spatial coverage for detailed soil properties, LSMs, like many physically-based hydrological models, rely on pedotransfer functions (PTF), which relate available soil information to the required soil properties ([Looy et al., 2017](#); [De Lannoy et al., 2014](#)). The simplest approach, still used by most LSMs, relies on soil texture, as classified by the US Department of Agriculture (USDA) into 12 soil classes based on the percent of sand, silt and clay particles ([Staff and Bureau of Plant Industry, 1951](#)). Look-up tables relate these broad texture classes to multiple soil properties, usually with one single central value for each class and property, as found in [Cosby et al. \(1984\)](#) and [Carsel and Parrish \(1988\)](#) for the [Clapp and Hornberger \(1978\)](#) and [Van Genuchten \(1980\)](#) soil water models, respectively.

In this framework, several global soil texture maps are used by LSMs, with different resolutions and soil texture distributions based on the 1 :5,000,000 FAO/UNESCO Soil Map of the World ([FAO and UNESCO, 1971](#)), itself based on soil surveys defining 106 soil units, [Zobler \(1986\)](#) and [Reynolds et al. \(2000\)](#) provided soil texture maps at a resolution of 1° and 5 arc-min respectively, for depths of 30 and 100 cm for [Reynolds et al. \(2000\)](#), and 30 cm for [Zobler \(1986\)](#); the FAO/UNESCO Soil Map of the World was updated as the Harmonized World Soil Database (HSWD), produced at 30 arc-sec by including new regional and national soil information ([Nachtergaele et al., 2010](#); [Batjes, 2016](#)); the soil texture map of the 1-km SoilGrids database ([Hengl et al., 2014](#)), recently updated at 250

m (Hengl et al., 2017), is not independent from the above FAO/UNESCO global soil maps, but also relies on large number of national and international soil profile databases, combined with automated spatial prediction models. Both HSWD and SoilGrids soil texture maps are available at seven depths ranging from 0 cm to 2 m.

Most studies concluding that soil texture exerts an important impact on soil hydrology were conducted at small to medium scales, either through site measurements (e.g. An et al. (2018); Song et al. (2010)), or regional-scale and multi-site data analysis (Lehmann et al., 2018; Wang et al., 2009) and model sensitivity analyses. Using a mesoscale hydrologic model over the Mississippi river basin, Livneh et al. (2015) compared two different soil texture maps, and the more spatially detailed one better reproduced hydrologic variability and extreme events. With the Noah LSM over China, Zhang et al. (2016) found that the sensitivity of the simulated water budget to soil texture was dependent on climate, soil moisture being less sensitive to soil texture in arid areas, while evapotranspiration and runoff showed the highest sensitivity in the transitional zones. Li et al. (2018) confirmed these results over the Tibetan Plateau but showed additional influence of the vegetation cover on the sensitivity to soil texture, as also found over the US (Xia et al., 2015). At a global scale, De Lannoy et al. (2014) developed an improved soil texture map for the Catchment LSM, by merging several texture and organic material maps. Combined with updated PTF, this new map offered modest yet significant improvements of the simulated hydrology compared to various point-scale measurements. Related studies revealed a strong impact of soil water-holding capacity and its spatial patterns using the first generations of LSMs, but with bucket-type soil hydrology instead of Richards equation (Milly and Dunne, 1994; Ducharne and Laval, 2000).

Here, we aim at exploring more systematically the impact of soil texture on the water budget from point to global scale, using a state-of-the-art LSM with physically-based soil hydrology, and multiple input soil texture maps. After presenting the model and soil texture maps used in this work, the results are presented as follows. We first provide an analysis of the similarities and differences between the different soil maps, then, we evaluate the point-scale response of the model to different soil textures to make sure it displays a reliable behaviour. This point-scale response is then analysed from a geographic point of view, with a comparison to a distributed observation-based evapotranspiration product, and a focus is made on areas with a large sensitivity to the soil texture maps. We finally explore how the magnitude and significance of the simulated evapotranspiration response changes with the scale of analysis up to the land scale, defining the terrestrial water budget. The closing section summarizes the main conclusions of the study, and discusses its limitations and perspectives.

## 3.2 Materials and methods

### 3.2.1 Soil texture in the ORCHIDEE LSM

ORCHIDEE (ORganizing Carbon and Hydrology in Dynamic EcosystEms) is the land component of the IPSL (Institut Pierre-Simon Laplace) climate model, and describes the complex links between vegetation phenology and the water, energy and carbon exchanges at the land surface (Krinner et al., 2005). We use here the version of ORCHIDEE developed for CMIP6 (Eyring et al., 2016) and detailed in forthcoming papers (Boucher et al., 2020; Cheruy et al., 2020; Ducharne et al., 2020) .

The physically-based soil hydrology scheme solves the vertical soil moisture redistribution based on a multi-layer solution of the saturation-based Richards equation, using a 2-m soil discretized into 11 soil layers of increasing thickness with depth (De Rosnay et al., 2002). Infiltration is processed before soil moisture redistribution, owing to a time-splitting procedure inspired by the model of Green and Ampt (1911), with a sharp wetting front propagating like a piston (D’Orgeval et al., 2008; Vereecken et al., 2019). The unsaturated values of hydraulic conductivity and diffusivity are given by the model of Mualem (1976) - Van Genuchten (1980).

In each grid cell, the corresponding parameters (saturated hydraulic conductivity  $K_s$ , inverse of air entry suction  $\alpha$ , shape parameter  $m$ , porosity, and residual moisture) are taken from Carsel and Parrish (1988), as a function of the dominant USDA soil texture class, itself derived from an input soil texture map. The tabulated values of the different soil parameters are displayed in Figure 3.12 for each USDA class. Soil texture is assumed to be uniform over the soil column in ORCHIDEE, which does not permit to distinguish several soil horizons. However,  $K_s$  decreases exponentially with depth, to account for the effects of soil compaction and bioturbation, as introduced by D’Orgeval et al. (2008) following Beven and Kirkby (1979). It must also be noted that the horizontal variations of  $K_s$  are taken into account by an exponential probability distribution, but only for calculating infiltration and surface runoff (Entekhabi and Eagleson, 1989; Vereecken et al., 2019). The soil texture also influences heat capacity and conductivity, and heat diffusion is calculated with the same vertical discretization as water diffusion in the top 2m, but extended to 10 m (Wang et al., 2016).

Evapotranspiration is described by a classical bulk aerodynamic approach, distinguishing four sub-fluxes : sublimation, interception loss, soil evaporation, and transpiration. The latter two are directly coupled to soil water redistribution, and depend on soil moisture and properties, which control how the corresponding rates are reduced compared to the potential rate : transpiration is limited by a stomatal resistance, increasing when soil moisture drops from field capacity to wilting point (which both depend on soil texture as detailed in Supplementary section 3.5) ; soil evaporation is not limited by a resistance, but

only by upward capillary fluxes, which control the soil propensity to meet the evaporation demand (D’Orgeval et al., 2008; Campoy et al., 2013). Evapotranspiration also depends on the vegetation of each grid-cell, described here as a mosaic of up to 15 plant functional types (PFTs), based on the global land cover map used in the IPSL simulations for CMIP6 (Boucher et al., 2020). In each PFT, root density is assumed to decrease exponentially with depth, with a PFT-dependent decay factor. The resulting root density profile is combined to the soil moisture profile and a water stress function depending of field capacity and wilting point to define the integrated water stress factor of each PFT on transpiration.

This flux is also coupled to photosynthesis, which depends on soil moisture, light availability, CO<sub>2</sub> concentration, and air temperature, following Farquhar et al. (1980) and Collatz et al. (1992) for C3 and C4 plants, respectively. The resulting carbon assimilation is allocated to several vegetation pools, including leaf mass thus leaf area index (LAI), owing to a dynamic phenology module called STOMATE (Krinner et al., 2005). It must be underlined that LAI has an important influence on the partition between soil evaporation and transpiration, via the fraction that is effectively covered by foliage, which increases exponentially with LAI with a coefficient of 0.5, also controlling light extinction through the canopy (Krinner et al., 2005). This fraction contributes to transpiration and interception loss, while the complementary fraction is assumed to be bare of vegetation, and only contributes to soil evaporation.

### 3.2.2 Simulation protocol

We performed nine global-scale simulations with ORCHIDEE (tag 2.0), using different soil texture maps and climatic forcing datasets (Table 4.1).

The analysed period is 1980-2010, following a 20-year spin-up since 1960 to provide accurate initial conditions. Atmospheric forcing datasets being known to exert a first-order influence on LSM results (Guo et al., 2006; Yin et al., 2018), we used two different datasets to drive our simulations, to compare the related uncertainties to the ones coming from the different soil texture maps. Both datasets were constructed at a 0.5° resolution by downscaling and bias-correcting an atmospheric reanalysis. All simulations but one use the GSWP3-v1 meteorological dataset (Kim, 2017), with a 3-hourly time step, and based on the 20th Century Reanalysis (Compo et al., 2011). In contrast, simulation EXP1 uses the 6-hourly CRU-NCEP-v7 meteorological dataset (Wei et al., 2014a), based on the NCEP/NCAR reanalysis (Kalnay et al., 1996), and extended beyond 1957-1996 in near real-time. Both meteorological datasets were selected for the off-line CMIP6 simulations (Van den Hurk et al., 2016).

The three simulations EXP2 to EXP4 rely on complex soil texture maps to define the dominant texture class of each 0.5° grid cell (Fig. 3.1) : the 1° map of Zabler (1986) originally contains 5 soil textural classes, but is simplified by ORCHIDEE into three USDA texture

| Experiment | Soil map   | Climate forcing | PTF                       | Text. distrib                                                                       |
|------------|------------|-----------------|---------------------------|-------------------------------------------------------------------------------------|
| EXP1       | Reynolds   | CRU-NCEP        | Carsel and Parrish (1988) |  |
| EXP2       | Reynolds   | GSWP3           | Carsel and Parrish (1988) |  |
| EXP3*      | Zobler     | GSWP3           | Carsel and Parrish (1988) |  |
| EXP4*      | SP-MIP     | GSWP3           | Carsel and Parrish (1988) |  |
| EXP5*      | SP-MIP     | GSWP3           | Schaap et al. (2001)      |  |
| EXP6*      | Loam       | GSWP3           | Schaap et al. (2001)      |  |
| EXP7*      | Silt       | GSWP3           | Schaap et al. (2001)      |  |
| EXP8*      | Loamy Sand | GSWP3           | Schaap et al. (2001)      |  |
| EXP9*      | Clay       | GSWP3           | Schaap et al. (2001)      |  |

\* Indicates the experiments used in the SP-MIP. See Fig. 1 for colour codes.

TABLE 3.1 – Summary of the experiments used in this study. Texture distribution displays the percentage of each soil texture in the used soil map

classes (Sandy Loam, Loam, and Clay Loam); the 5-arc-min map of Reynolds et al. (2000) uses the USDA classification and we used directly the 30-cm map; the third map was upscaled from the 1km SoilGrids map at the 0 cm depth (Hengl et al., 2014) by selecting the dominant soil texture in every  $0.5^\circ$  pixel.

This map was provided at a  $0.5^\circ$  resolution by the Soil Parameter Model Intercomparison Project (Gundmundsson and Cuntz, 2017), which aims at quantifying to which degree the differences between LSMs result from soil parameter specification, and will thus be referred to as the SP-MIP map in the following.

In addition, we tested four spatially uniform texture maps, corresponding to the Loam, Loamy Sand, Silt, and Clay classes (EXP6 to EXP9), to analyse the importance of the spatial variability of soil texture on the terrestrial water budget. These simulations were defined by SP-MIP, and rely on hydraulic parameter values given by Schaap et al. (2001) for each USDA class. We ran an additional simulation (EXP 5) with the SP-MIP map and the soil parameters of Schaap et al. (2001) to quantify the difference induced by this PTF compared to the default PTF of ORCHIDEE (Carsel and Parrish, 1988) used with the SP-MIP map in EXP4. It must be noted that the five simulations based on the soil parameters of Schaap et al. (2001) also differ from the four others (EXP1 to EXP4) because the decrease of  $K_s$  with depth is relaxed, to comply with the SP-MIP protocol.

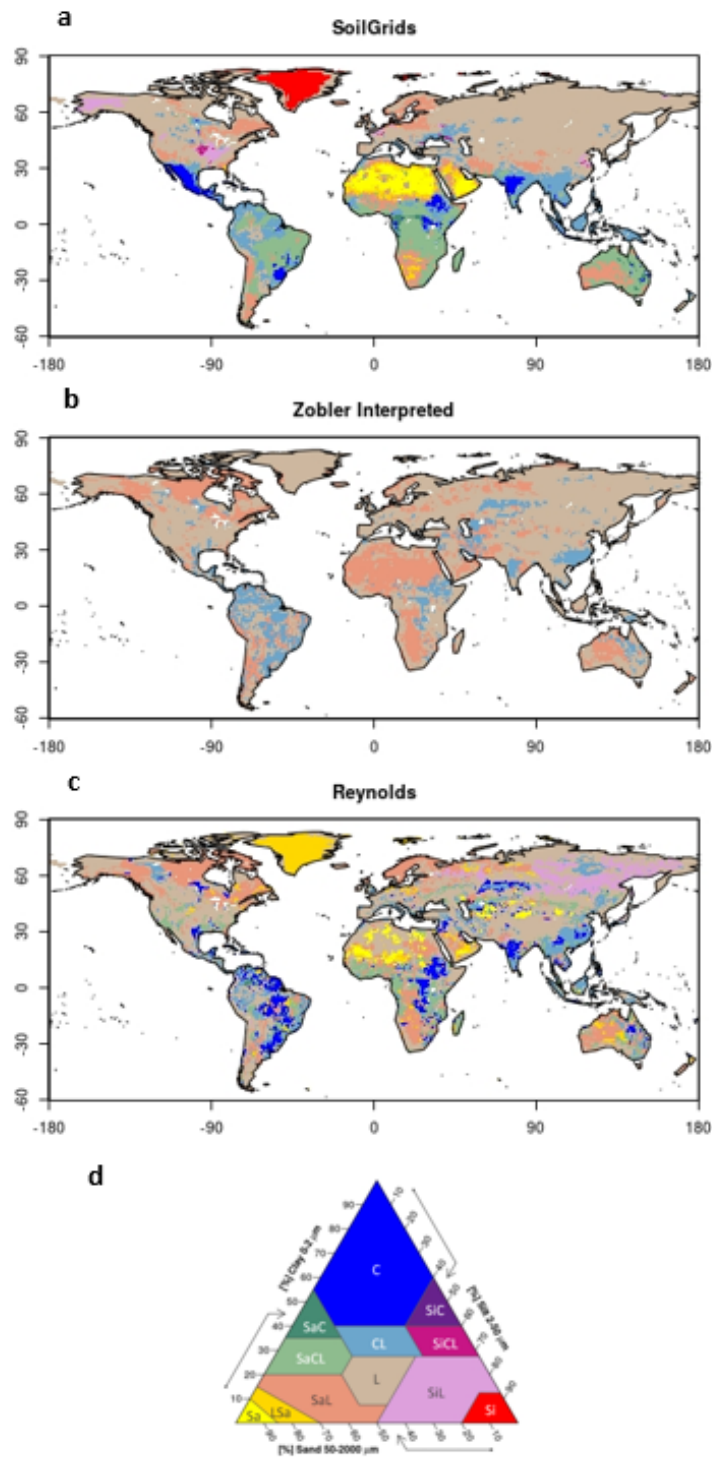


FIGURE 3.1 – (a-c) Global maps of soil texture classes used in this study. (d) Soil texture triangle of the 12 textural classes as defined by the USDA. For texture labels see (Table 4.2).

| Texture class   | Label | % Clay | % Silt | % Sand | dm ( $\mu\text{m}$ ) |
|-----------------|-------|--------|--------|--------|----------------------|
| Clay            | C     | 62.9   | 17.5   | 19.5   | 1.6                  |
| Silty Clay      | SiC   | 46.7   | 46.7   | 6.7    | 5.4                  |
| Silty Clay Loam | SiCL  | 33.8   | 56.3   | 10.0   | 15.9                 |
| Clay Loam       | CL    | 33.8   | 33.8   | 32.5   | 25.1                 |
| Silt            | Si    | 5.3    | 87.3   | 7.3    | 26.6                 |
| Silt Loam       | SiL   | 13.4   | 65.2   | 21.4   | 29.0                 |
| Loam            | L     | 18.7   | 40.2   | 41.0   | 39.3                 |
| Sandy Clay      | SaC   | 41.7   | 6.7    | 51.7   | 112.9                |
| Sandy Clay Loam | SaCL  | 27.1   | 12.9   | 59.9   | 373.3                |
| Sandy Loam      | SaL   | 10.4   | 25.1   | 64.6   | 490.7                |
| Loamy Sand      | LSa   | 5.8    | 12.5   | 81.7   | 806.1                |
| Sand            | Sa    | 3.3    | 5.0    | 91.7   | 936.4                |

TABLE 3.2 – Percent sand, silt and clay contents of the geometric centroids of the 12 USDA soil texture classes.  $d_m$  : the computed median diameter.

### 3.2.3 Calculation of median diameter dm for each of the 12 USDA soil texture classes

Every texture class is represented by a polygon in the USDA textural triangle (3.1d). For each texture class, we located the centroid of the corresponding polygon to obtain a central value of the composition in clay, silt and sand particles (Table 3.2). These clay, silt and sand particles have various diameters, respectively ranging in  $[0, 2\mu\text{m}]$ ,  $[2\mu\text{m}, 50\mu\text{m}]$  and  $[50\mu\text{m}, 2000\mu\text{m}]$  (Staff and Bureau of Plant Industry, 1951). To construct the particle-size distribution curve of each texture class (Fig. 3.2), we further assumed that clay, silt and sand particle diameters are uniformly distributed in the latter intervals. The median diameter of each texture class is then obtained by intersecting the corresponding curve with a cumulative value of 50%, such that half of soil particles reside above this point, and half reside below this point. The resulting median diameters are listed in Table 3.2.

Carsel and Parrish (1988) provide the mean content of sand, silt and clay for each soil texture, but their estimations are based on American soil surveys, which might not be representative of the whole globe, so we preferred to use the composition of the of the polygon centroids. Note that using the mean composition of by Carsel and Parrish (1988) leads to very similar results.

### 3.2.4 Evaluation datasets

To assess the realism of our simulations, we use three different datasets. Jung et al. (2010) constructed a series of global 1° evapotranspiration maps at the monthly time step from 1982 to 2008, by interpolating in situ eddy-covariance measurements from the FLUXNET network using machine learning algorithms and ancillary geospatial information (land sur-

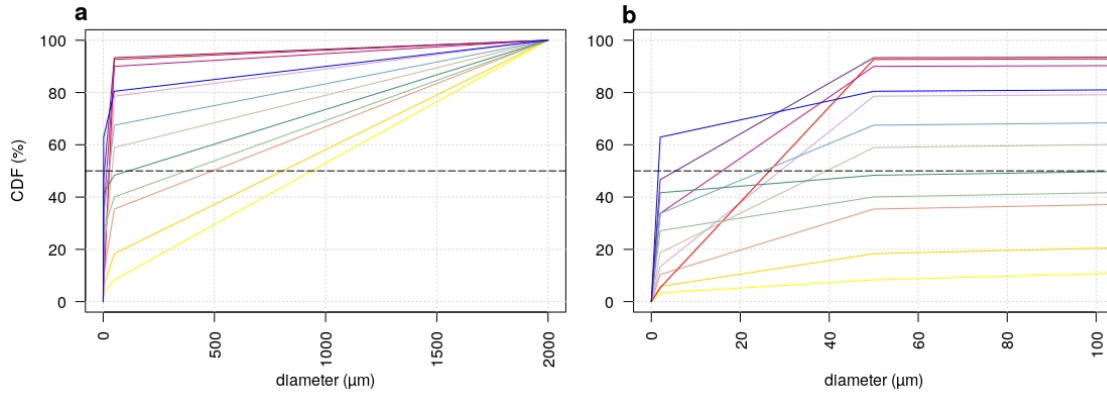


FIGURE 3.2 – (a) Cumulative grain size distribution curves of the 12 USDA soil texture classes and (b) zoom over diameter interval  $[0, 100 \mu\text{m}]$ . The dashed line defines the 50% cumulative value.

face remote sensing and meteorology). GLEAM (Martens et al., 2017) is another series of global evapotranspiration maps, provided by at the  $0.25^\circ$  resolution and the daily time step over 1980-2015. They strongly rely on remote-sensing datasets (radiation, precipitation, temperatures, surface soil moisture, vegetation optical depth, snow water equivalents), used as input to an evapotranspiration model based on Priestley and Taylor (1972). Finally, Rodell et al. (2015) quantified the mean annual fluxes of the water cycle at the beginning of the 21st century, at a coarser scale (continents and major ocean basins) but with the aim of providing consistent estimates of precipitation, evaporation, and runoff, by combining in situ and satellite measurements, data assimilation systems, and multiple energy and water budget closure constraints.

### 3.3 Results

#### 3.3.1 Comparison of the tested soil texture maps

Whichever the complex soil texture map, Loam is by far the most dominant texture (Table 3.3), covering between 44 to 64 % of the land surface. Other important soil textures in all maps are Sandy Loam, Clay Loam and Sandy Clay Loam, and these four medium textures alone cover 81, 86 and 100% of land based on Reynolds, SP-MIP, and the simplified Zobler map, respectively. The Silty Clay, Silty Clay Loam and Sandy Clay classes are poorly present in all three maps : altogether, they cover 0.9, 0.2 and 0% of land based on SP-MIP, Reynolds and the simplified Zobler map, respectively. The Silt texture class is absent from Reynolds and Zobler maps, while it is found in the SP-MIP map, but only to fill the no-data land points (3.3%). To better document the differences and similarities between the three soil texture maps, we also quantified the spatial overlap between each pair of

|                  | SP-MIP | Reynolds | Zobler |
|------------------|--------|----------|--------|
| SP-MIP           | 100.0  |          |        |
| Reynolds         | 41.2   | 100.0    |        |
| Zobler           | 46.0   | 52.0     | 100.0  |
| Unif. Loam       | 48.5   | 43.9     | 64.3   |
| Unif. Silt       | 3.3    | 0.0      | 0.0    |
| Unif. Loamy Sand | 2.1    | 6.0      | 0.0    |
| Unif. Clay       | 2.7    | 5.8      | 0.0    |

TABLE 3.3 – Percent overlap between the three tested soil texture maps.

complex maps (Table 3.3). It is always more than 41%, and the best agreement is found between the Reynolds and Zobler maps (52%). Nonetheless, this leaves 48% of the grid cells (in the best case) where the soil texture does change.

To explore if it changes for similar or very different soil textures, we compared several groups of three maps derived from the tested soil texture maps : the maps of the corresponding particle diameter  $dm$  (section 2.3), of  $K_s$  (as provided by the PTF, thus not including the impact of roots nor soil compaction), soil porosity  $\theta_s$ , field capacity  $\theta_{fc}$ , wilting point  $\theta_w$ , and available water content ( $AWC$ , integrated over the 2-m soil column). The values of these soil parameters for the 12 USDA soil texture classes are detailed in Supplementary S1 and depicted in Figure 3.12 section 3.5. Table 4 shows that, whichever the soil parameter, the difference of spatial mean between the three maps is smaller than the mean spatial standard deviation, even for the least variable map (Zobler). This demonstrates the large similarity of the three complex soil maps tested in our paper, not only regarding soil texture itself (as summarized by  $dm$ ), but also, very logically, for the derived soil hydraulic parameters. This similarity is also confirmed by the spatial correlations between each pair of maps, always positive, the best correlations being found between Zobler and Reynolds for most parameters (always larger than 0.35, and up to 0.58), and the weakest between the SP-MIP map and Reynolds.

### 3.3.2 Point scale sensitivity to the 12 USDA texture classes

To check if the ORCHIDEE model displays a realistic response to soil texture, we examined how the pluri-annual means of the main water budget variables relate to soil texture (Fig. 3.3). We clustered all the points with a similar texture, and sorted the texture classes based on their median particles diameter (section 3.2.3). The mean fluxes were also divided by mean precipitation to reduce the effect of misleading texture-climate associations, as between sandy classes and arid climates. We focused on EXP2, since the Reynolds map

|                         |                                     | SP-MIP | Reynolds | Zobler |
|-------------------------|-------------------------------------|--------|----------|--------|
| log(dm)                 | Mean (log $\mu\text{m}$ )           | 4.48   | 4.23     | 4.25   |
|                         | SD (log $\mu\text{m}$ )             | 1.51   | 1.65     | 1.15   |
|                         | Cor. SP-MIP                         | 1.00   | 0.38     | 0.35   |
|                         | Cor. Reynolds                       | 0.38   | 1.00     | 0.57   |
| $K_s$                   | Mean ( $\text{mm d}^{-1}$ )         | 740    | 643      | 428    |
|                         | SD ( $\text{mm d}^{-1}$ )           | 1539   | 1261     | 376    |
|                         | Cor. SP-MIP                         | 1.00   | 0.38     | 0.36   |
|                         | Cor. Reynolds                       | 0.38   | 1.00     | 0.57   |
| Saturated water content | Mean ( $\text{m}^3 \text{m}^{-3}$ ) | 0.414  | 0.416    | 0.422  |
|                         | SD ( $\text{m}^3 \text{m}^{-3}$ )   | 0.017  | 0.018    | 0.010  |
|                         | Cor. SP-MIP                         | 1.00   | 0.40     | 0.22   |
|                         | Cor. Reynolds                       | 0.40   | 1.0      | 0.35   |
| Field capacity          | Mean ( $\text{m}^3 \text{m}^{-3}$ ) | 0.177  | 0.182    | 0.170  |
|                         | SD ( $\text{m}^3 \text{m}^{-3}$ )   | 0.064  | 0.069    | 0.046  |
|                         | Cor. SP-MIP                         | 1.00   | 0.41     | 0.36   |
|                         | Cor. Reynolds                       | 0.41   | 1.00     | 0.58   |
| Wilting point           | Mean ( $\text{m}^3 \text{m}^{-3}$ ) | 0.104  | 0.107    | 0.092  |
|                         | SD ( $\text{m}^3 \text{m}^{-3}$ )   | 0.044  | 0.054    | 0.026  |
|                         | Cor. SP-MIP                         | 1.00   | 0.42     | 0.36   |
|                         | Cor. Reynolds                       | 0.42   | 1.00     | 0.58   |
| AWC                     | Mean (mm)                           | 146.7  | 150.2    | 156.5  |
|                         | SD (mm)                             | 56.9   | 54.4     | 39.8   |
|                         | Cor. SP-MIP                         | 1.00   | 0.34     | 0.31   |
|                         | Cor. Reynolds                       | 0.34   | 1.00     | 0.42   |

TABLE 3.4 – . Statistical descriptors of the soil parameter maps corresponding to the three complex soil texture maps (excluding Antarctica and Greenland) : mean and standard deviation (SD) of each parameter map ; and correlation coefficients between the three pairs of maps.

exhibits the largest range of soil textures (11 different classes).

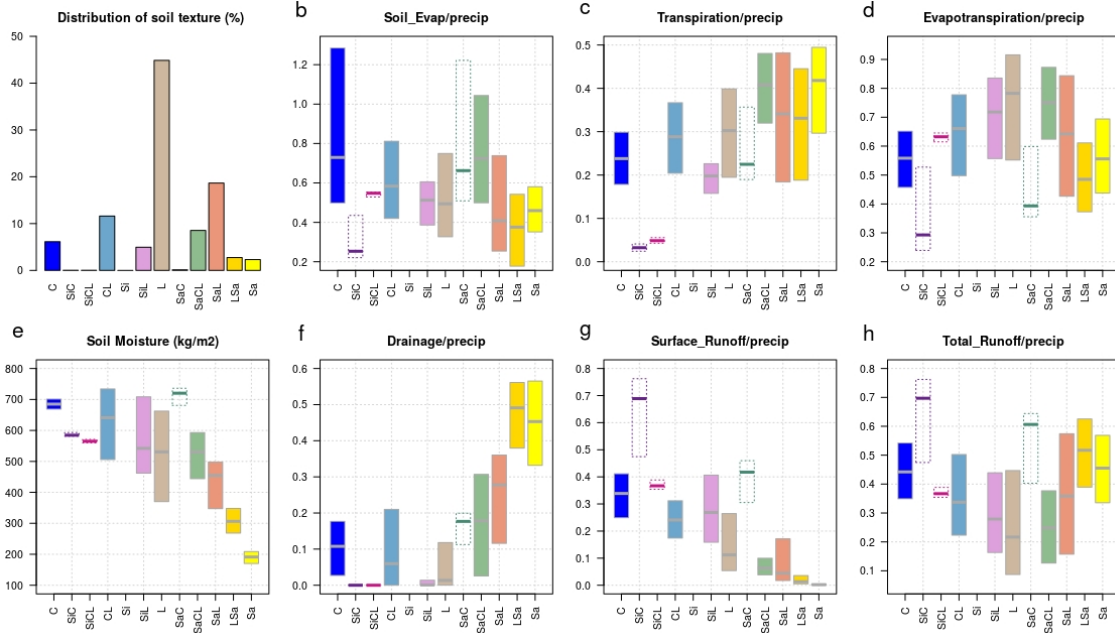


FIGURE 3.3 – Variability of simulated variables of EXP2 over the land surface excluding Antarctica and Greenland, over the period 1980-2010, within each soil texture class. Soil texture classes are sorted from the finest to the coarsest based on dm (from left to right). See Figure 3.1 for color codes. Note that the Silt class is absent from Reynolds map. Dashed boxes correspond to texture classes covering less than 0.2% of the land area. Water fluxes are expressed as percent of mean precipitation. Soil moisture is averaged over areas with similar annual precipitation (between 1 and 2 mm/d), to remove impact of precipitation variation. Transpiration and soil evaporation fluxes are averaged over vegetated and bare soil fractions of the grid cells respectively.

The simulated total soil moisture (over the 2-m soil depth), drainage and surface runoff exhibit a clear monotonic response to soil texture (sorted by median diameter). Increasing soil moisture for finer textures is explained by their higher water retention and field capacity. The opposite responses of drainage and surface runoff (Fig. 3.3f-g) both result from higher permeability in coarser soils, enhancing drainage and infiltration at the soil surface, thus reducing surface runoff. These responses to soil texture are coherent with experimental results (An et al., 2018; Song et al., 2010).

As it sums up two opposite responses, total runoff shows a larger spread and a non-monotonic (convex) behaviour, with smaller total runoff for medium textures. The opposite response (concave) is found for evapotranspiration (Fig. 3.3d), because precipitation is partitioned between evapotranspiration and total runoff in every grid cell. The highest evapotranspiration rates found for medium textures is consistent with the high available

water capacity for these loamy textures (Fig. 3.12). Transpiration, however, increases as soil gets coarser (Fig. 3.3c), with two explanations probably acting together. Firstly, the increase of matric potential when the texture gets finer, as shown in Figure 3.12 for particular values of the potential, defining the wilting point, field capacity and air entry suction point ( $1/\alpha$ ), makes root uptake thus transpiration more difficult for a given soil moisture if the soil texture is finer. Secondly, the high conductivity of coarse soils enhances water infiltration at the soil surface, quickly available for plant uptake. The increase of  $K_s$  for coarse textures also explains the associated drainage increase when its dependence on mean precipitation is filtered (Fig. 3.3f). The fact that soil moisture decreases when drainage and transpiration get higher indicates that annual mean soil moisture is the result more than the cause of these fluxes.

Soil evaporation shows more variability within a soil texture class than between the different soil texture classes (Fig. 3.3b), showing this flux strongly depends on other factors, like temperature, leaf area index, etc. (Martens et al., 2017; Wang et al., 2018). To filter their spurious effects, we also analysed in Figure 3.4 the effect of changing soil texture at the point-scale, thus under similar climatic and land cover conditions. Figure 3.4 shows the changes occurring where a soil texture class in the Reynolds map is replaced by another in the SP-MIP map. The Zobler map was excluded from this analysis since it contains only three soil texture classes. Switching maps from Reynolds to the SP-MIP map (i.e. from EXP2 to EXP4) results in a majority of land points with unchanged texture, and thus, identical simulated variables. These land points are represented by the diagonal pixels of the matrices and correspond to 41.2% of the land surface. Land points with coarser texture in the SP-MIP map represent 34.1% of the land surface (upper side of the diagonal line in the matrices) against 24.7% for finer textures (lower side of the diagonal line in the matrices).

Figure 3.4 highlights that simulated soil evaporation decreases from fine to coarse textures, so that capillary retention, which is the main limiting factor to soil evaporation in ORCHIDEE, depends more strongly on soil moisture (higher for fine soils; Fig. 3.4e) than on intrinsic capillary forces (stronger for fine soils). We fail to see this behaviour in Figure 3.3, which is likely due to the greater impact of diverse climatic conditions and vegetation associated with every soil texture. Figure 3.4 also confirms the results of Figure 3.3 for the other variables, including the decrease of soil moisture with coarser soils and the larger impact of soil texture on surface runoff and drainage than on transpiration and soil evaporation. In particular, we find that replacing fine textures with coarse textures (above the first diagonal of the matrices) results in higher drainage (due to the higher permeability of coarse-textured soils) and lower surface runoff, with changes that can exceed  $1 \text{ mm.d}^{-1}$  in absolute value for some textural changes (all involving medium texture classes).

The convex behaviour of total runoff with soil texture can also be seen in Figure 3.4h, which

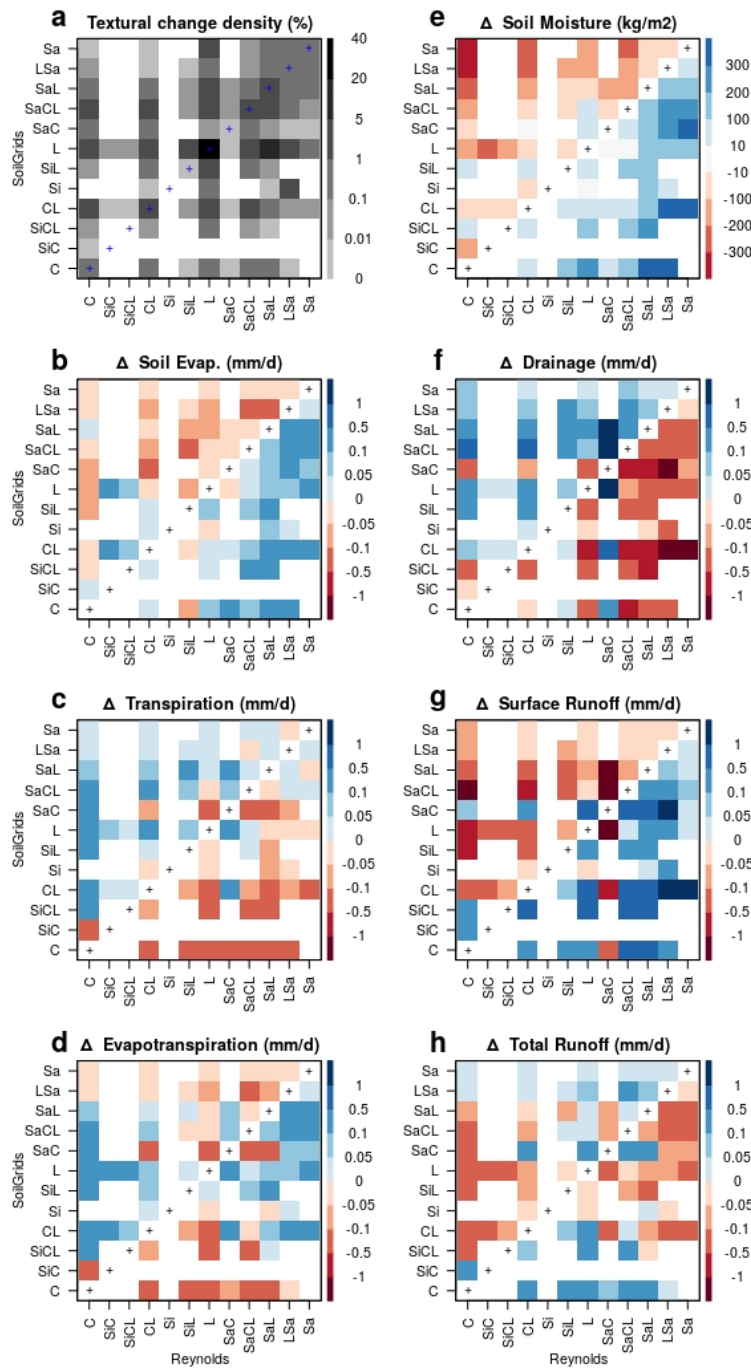


FIGURE 3.4 – Change in mean simulated variables over the globe land surface excluding Antarctica, averaged over the period 1980-2010, caused by changing the soil texture map from Reynolds to SP-MIP (EXP2 to EXP4). Soil texture classes are sorted from the finest (clay) to the coarsest (sand), in the x and y axis. The first plot illustrates the percentage of each textural change.

is antisymmetric along the two diagonals, thus defining four different kinds of total runoff response to soil texture change. This behaviour results from the fact that total runoff sums up two variables with an opposite response to soil texture change (surface runoff and drainage), the net response depending on the dominant component. Hence, changes to medium textures from either coarse or fine textures (left and right red triangles in Fig. 3.4h) lead to reduced total runoff, owing to reduced surface runoff in the first case, and reduced drainage in the second. In contrast, changes from medium texture to either coarse or fine textures lead to increased runoff (bottom and top blue triangles in Fig. 3.4h), owing to increased surface runoff or drainage, respectively. This pattern thus means that the medium textures correspond to the smallest total runoff. By means of long-term water conservation, the opposite patterns are found for total evapotranspiration changes (Figure 3.4d), because of the opposite responses of soil evaporation and transpiration to soil texture, and supporting the concave response of this flux to soil texture found in Figure 3.3.

### 3.3.3 Spatial patterns of simulated fluxes and evapotranspiration bias

Although ORCHIDEE exhibits a clear and physically-based response to soil texture at point-scale, the use of three different realistic soil texture maps (EXP2, EXP3, and EXP4) results in rather similar spatial distributions of the simulated fluxes. We mostly focus on evapotranspiration (Fig. 3.5, Fig. 3.13), since comparison is possible with a spatially-distributed observation-based product (GLEAM). At a grid cell scale, changing the soil texture map (Fig. 3.5a-c) results in weak changes in simulated evapotranspiration, which are statistically significant over less than 35% of the land surface, against 77% when switching the climate forcing (Fig. 3.5d). The very weak changes in evapotranspiration maps when switching from a uniform to a complex soil texture map (Fig. 3.5a) show that the spatial variability of soil texture is a weak driver of the spatial variability of evapotranspiration. In agreement with the concave response of evapotranspiration to soil texture (section 3.2), the largest increases are found when switching from very coarse or very fine textures to medium ones. This explains the dominance of evapotranspiration increase in the example cases of Figures 5a-b, since the Zobler and uniform Loam maps have the largest areal fractions of Loam (Table 1).

Consistently, the evapotranspiration biases are overall similar whichever the soil texture map (Fig. 3.5e-g), while climate forcing uncertainty appears as a first order driving factor of the bias patterns (with visible differences between Figs. 3.5g and 3.5h). We find that the simulated evapotranspiration better matches GLEAM with CRU-NCEP in equatorial rain belts, and with GSWP3 in the mid-latitudes. In a few spots, however, the different soil maps induce large changes of evapotranspiration biases, especially in Central Africa, Central America, India and the Amazon basin, which are discussed in the following subsection. The other simulated hydrologic variables display a stronger sensitivity to soil texture

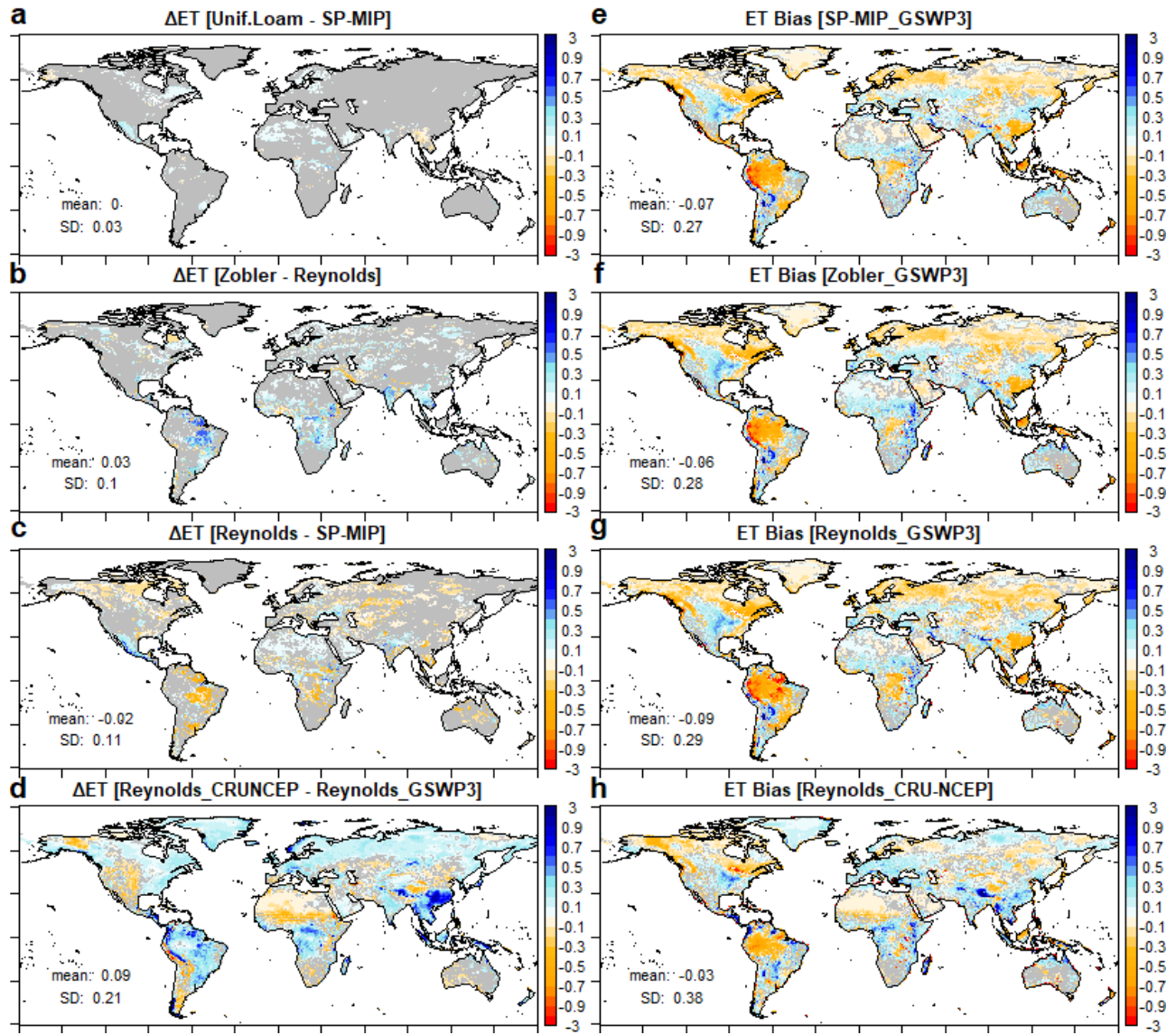


FIGURE 3.5 – Spatial distribution of simulated annual mean evapotranspiration (averaged over 1980-2010) : (left) differences between selected pairs of simulations (a : EXP6-EXP5, b : EXP3- EXP2, c : EXP2-EXP4, d : EXP1-EXP2) ; (right) biases with respect to GLEAM product (e : EXP4, f : EXP3, g : EXP2, h : EXP1). Grey color indicates that the difference is not statistically significant based on Student's t-test (with a p-value < 0.05). The printed means and standard deviation correspond to the full land area excluding Antarctica. Maps of GLEAM and simulated evapotranspiration of the 9 experiments are presented in Supplementary Figure 3.13 section 3.5.

maps, in agreement with section 3.2, but it remains weak and predominantly insignificant compared to inter-annual variability (Fig. 3.6, 3.14).

To provide a point-scale quantification of the differences between the three complex soil maps and the resulting simulated variables, we mapped the standard deviation of each group of three maps, using the mean diameter ( $dm$ ) of each texture class to get a quantitative proxy in case of texture (Fig. 3.7). Although the quantitative meaning of standard deviation can be questioned when calculated from a sample of three values, we used it here as a simple metric of similarity/difference between the three complex maps, and to identify points/regions where the three maps are all consistent (small standard deviation), or where at least one of them is departing (high standard deviation). Compared to the standard deviation of  $\log(dm)$ , the ones of the simulated fluxes are weak (less than 10 % of the maximum value) over larger fractions of the globe. They are also smaller than the local annual mean values of the variable itself, as shown by comparison to Figure 3.13 for evapotranspiration (not shown for the other variables).

Areas which stand out with high standard deviations in all maps are the four regions noted above, where the standard deviation between the three texture maps is very important (Fig. 3.7a). Aside from these areas, the tropical humid zones (South-East Asia, Indonesia) show rather large standard deviations of surface runoff and drainage (Fig. 3.7d,f), but without large standard deviation of  $\log(dm)$ , so this is rather due to the high values of these fluxes in these very humid zones. The overall resemblance between the standard deviation maps of soil texture on the one hand, and the simulated hydrologic variables on the other hand can be quantified at global scale by a spatial correlation coefficient, ranging between 0.49 for transpiration to 0.79 for soil moisture. The latter variable is the most impacted by soil texture change, as supported by this large correlation coefficient, and the large standard deviations on Figure 3.7b.

### 3.3.4 Regional zooms on greatly impacted areas

Figure 3.8 displays the four 40°x 60° areas where the different soil maps can lead to strongly different evapotranspiration biases, with a strong link to the (mis)representation of Clay soils, since the largest changes in evapotranspiration and total runoff are expected where soil texture changes between medium (loamy) and extreme (Clay or Sand) textures (Figs. 3.3 and 3.4). The Sand soil texture, however, does not induce a large impact on the simulated hydrological fluxes, as it is mostly found in arid areas where water is a limiting factor. This is the case in the Arabian Peninsula (Fig. 3.8b) and the Sahara, where the sandy soils mapped in the SP-MIP map are absent in Zobler and only weakly present in Reynolds, but the evapotranspiration bias hardly changes and remains negative.

In Tropical South America and Central Africa (Fig. 3.8c,d), the Reynolds map shows a larger presence of Clay compared to the other two maps, part of which results in an impor-

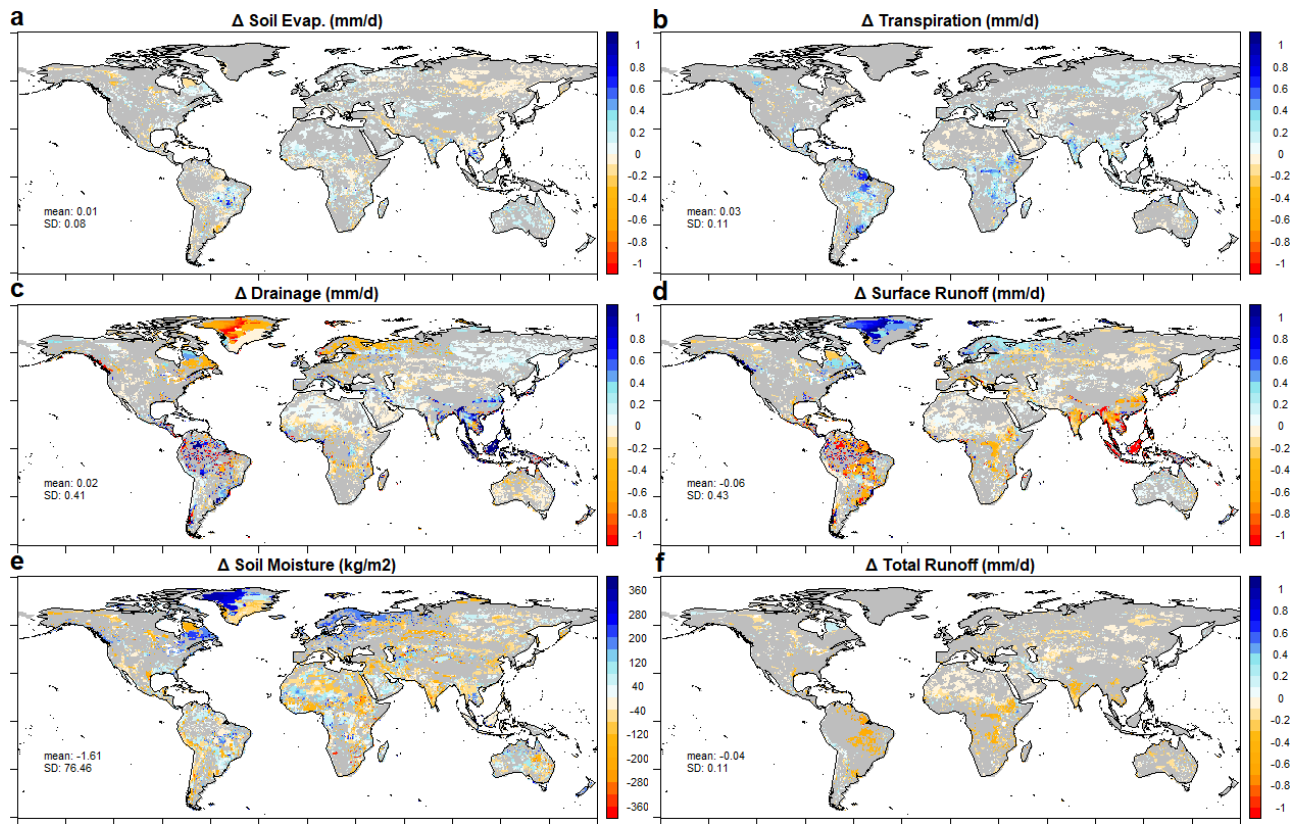


FIGURE 3.6 – Difference in simulated variables (averaged over the period 1980-2010) when Reynolds map is replaced by a Zobler map (EXP3 – EXP2). The corresponding difference for evapotranspiration is shown in Fig. 3.5b. Grey color indicates that the difference is not statistically significant based on Student's t-test (with a p-value < 0.05). Mean and standard deviation are averaged over the globe excluding Antarctica.

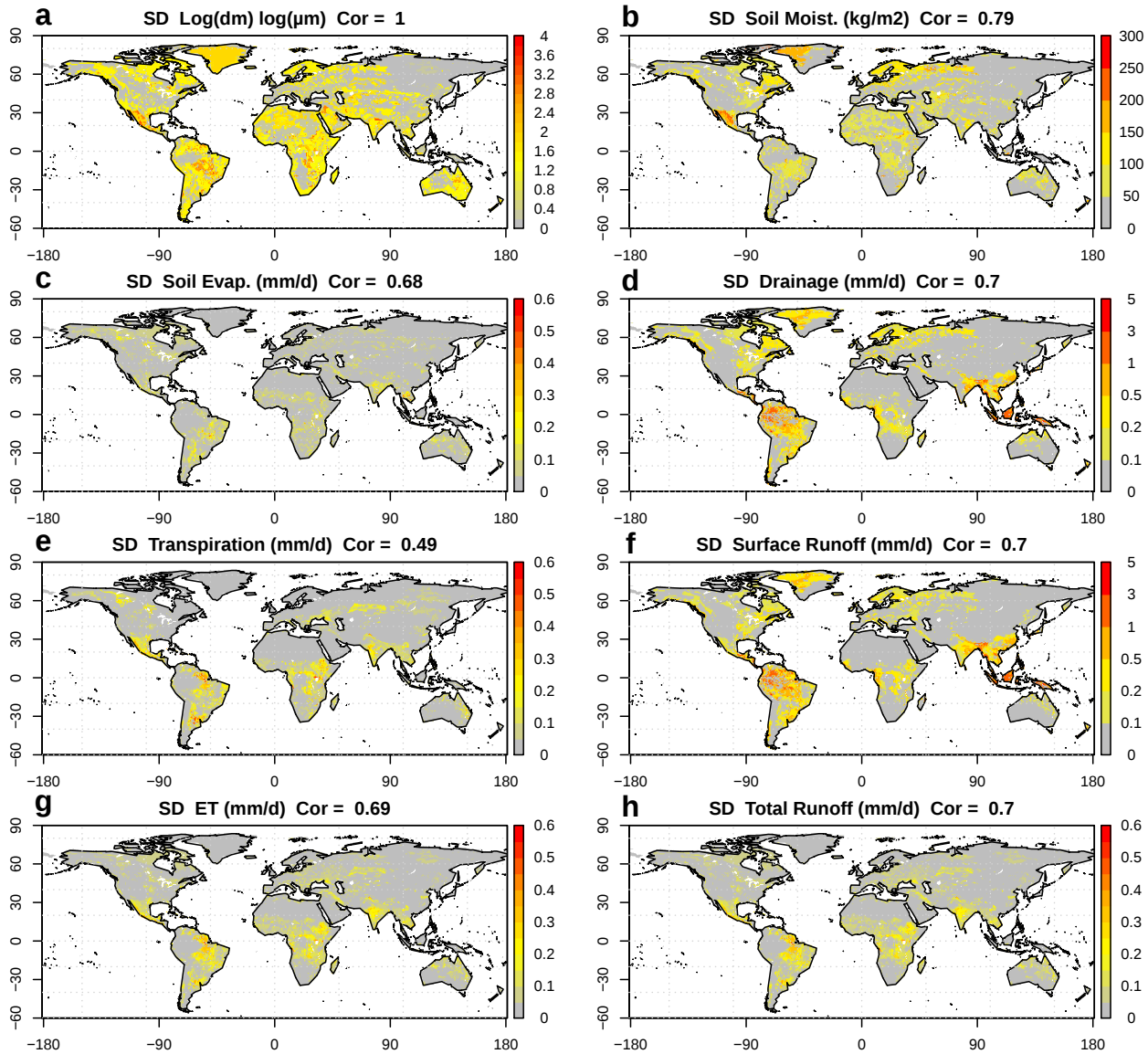


FIGURE 3.7 – Maps of the standard deviation (SD) of (a) the logarithm of median particle diameter (dm) given by the three complex soil texture maps (Reynolds, Zobler, SP-MIP), and (b-h) the mean annual simulated variables (in mm/d except for soil moisture in mm) using the three different maps. For easier comparison, each SD map is normalized by the maximum standard deviation of the map (maxSD), indicated in each map, with the spatial correlation coefficient (Cor) between the standard deviation of  $\log(dm)$  and the standard deviation of each variable.

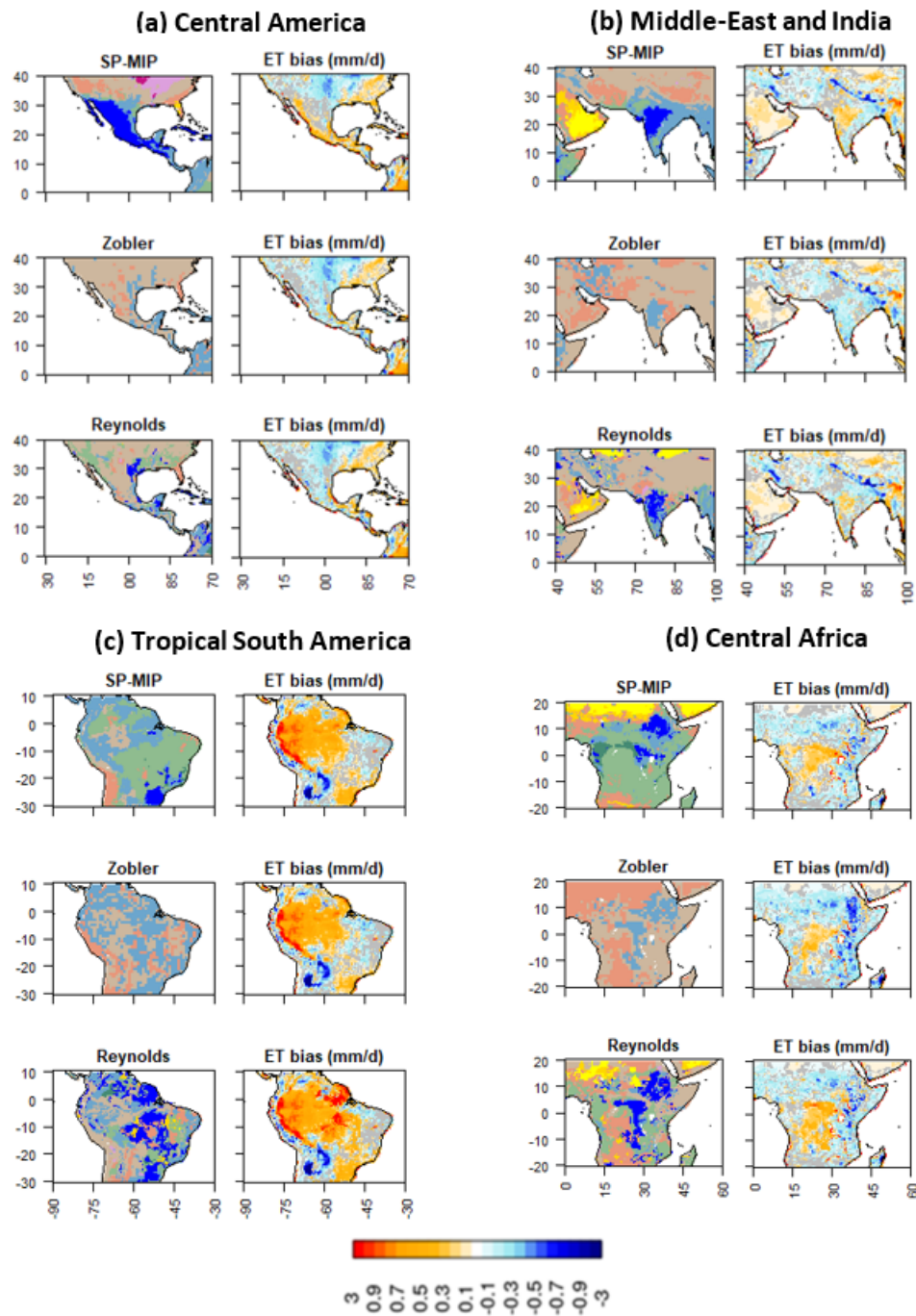


FIGURE 3.8 – Regional zooms on soil texture maps and the corresponding evapotranspiration bias maps (with respect to the GLEAM product) in four different areas. The colors scale on the right corresponds to the evapotranspiration bias maps, in which the grey color indicates that the bias is not statistically significant using Student's t-test with a p-value lower than 0.05. The colors of the soil texture maps are defined in Figure 3.1d.

tant negative evapotranspiration bias. When compared to the FAO soil order map (Fig. 3.15), it is found that the Clay class of the Reynolds map gathers different soil orders, including (i) Vertisols, which consist of swelling clay (smectites) with low permeability, and mostly found in dry regions like Sudan, Deccan (India), or eastern Australia (Deckers et al., 2003), and (ii) Oxisols, which are found in humid Tropics, exhibit a large textural variability, and contain non-swelling clay (kaolinite) with much higher permeability than Vertisols (Spaargaren and Deckers, 1998). The Oxisols mapped as Clay in the Reynolds map and inducing a large negative evapotranspiration bias call for a better representation of the Clay texture, with a soil texture map that distinguishes the two types of clays with different hydrologic behaviours. In contrast, neglecting Vertisols leads to overestimate evapotranspiration which is the case with the Zobler map in Deccan and Sudan (Fig. 3.8b,d), so the corresponding biases switch sign from negative to positive in Deccan, and become more positive in Sudan. These problems come from the simplification of the Zobler map in the ORCHIDEE model, which converts the original “very fine” soils to Clay Loam (section 2.2). Vertisols are also overlooked in Australia by the simplified Zobler map and by the SP-MIP map (Fig. 3.1), but with insignificant impact on evapotranspiration in this strongly water-stressed area (Fig. 3.6). Finally, in Central America, the SP-MIP soil map shows a much higher presence of Clay compared to the Zobler and Reynolds soil maps. It should be underlined that the original 1km SoilGrids from which the SP-MIP map was derived does not show this dominance of Clay in this area, and we think that this feature is an error in the SP-MIP map. This over-representation of Clay turned the evapotranspiration bias from null/positive (with the Reynolds and Zobler maps) to negative.

### 3.3.5 Sensitivity of the simulated water budget to global soil texture maps at different scales

At the global scale like at the point-scale, the three complex soil texture maps result in very similar terrestrial water budgets (Fig. 3.10). Whichever the hydrologic variable, the global mean differences induced by these three maps (EXP2, EXP3 and EXP4) are smaller than the ones induced by different meteorological forcing (EXP1 vs EXP2), which are comparable to the uncertainty range between several observation-based estimates of the terrestrial water budget (Section 2.4). Compared to these estimates, it is also worth noting that ORCHIDEE simulates fairly well the mean partition between evapotranspiration and total runoff with any of the complex texture maps.

In contrast, the use of spatially uniform soil texture maps (EXP6 to EXP9) induces major differences in surface runoff, drainage and soil moisture. The strong decrease of soil moisture from EXP4 to EXP5 is not only due to the PTF change between these simulation, but more importantly to the relaxation of the decrease of  $K_s$  with depth, which leads to larger  $K_s$  at the bottom of the soil column, favouring drainage, thus reducing soil moisture. The global water budgets resulting from the uniform maps are in agreement

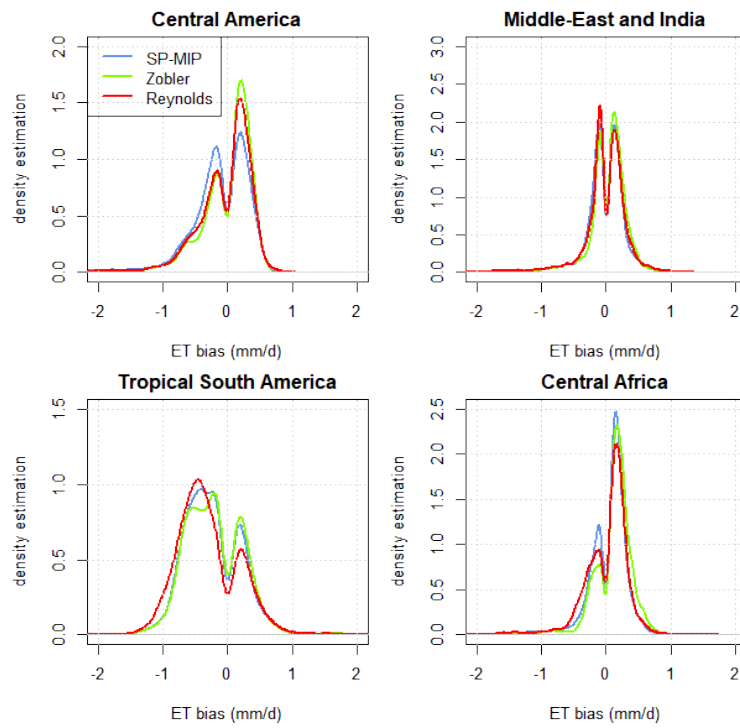


FIGURE 3.9 – Probability distribution of evapotranspiration bias in the 4 regions of Figure 3.8, for simulations EXP2, EXP3, EXP4 in red, green and blue respectively.

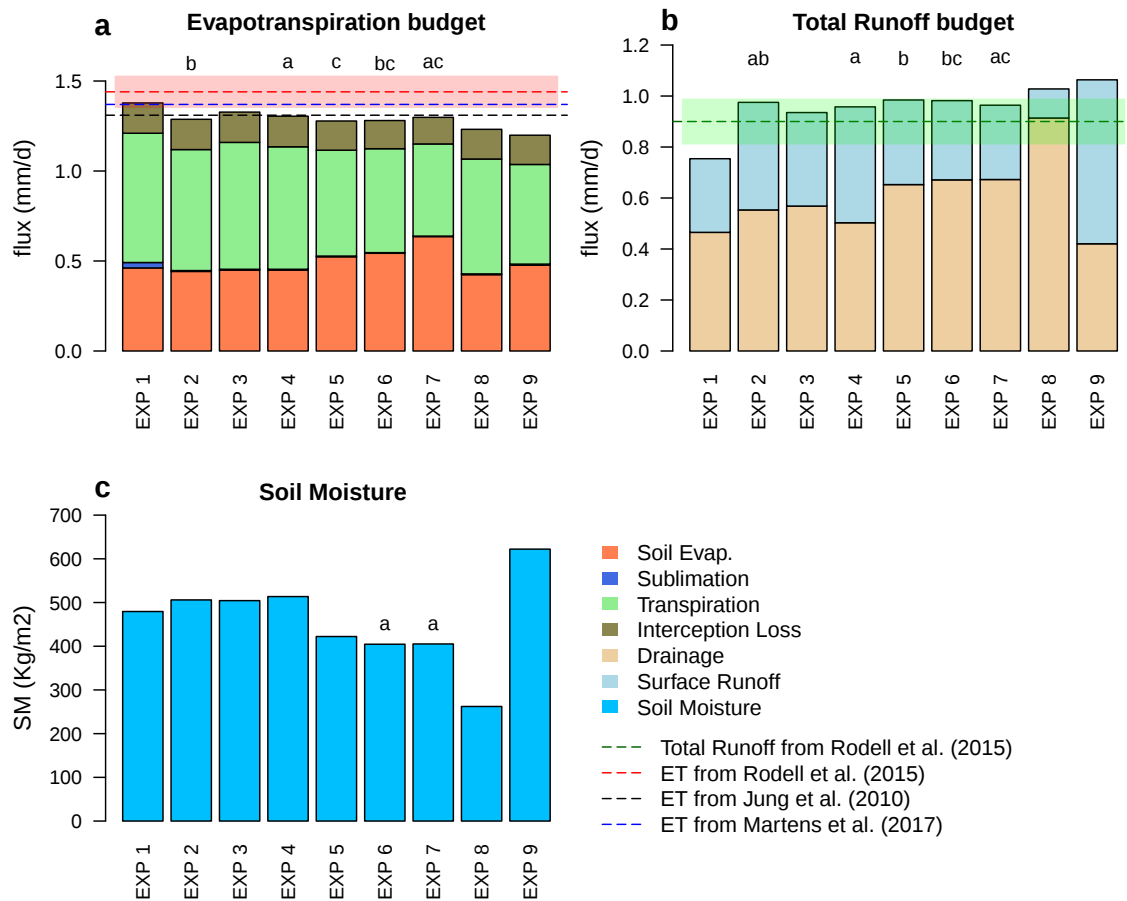


FIGURE 3.10 – (a-c) Global maps of soil texture classes used in this study. (d) Soil texture triangle of the 12 textural classes as defined by the USDA. For texture labels see (ref Table 2).

with the response of the model to soil texture (section 3.2). In particular, the uniform clay map (EXP9) induces high soil moisture and surface runoff, and low drainage, compared to the other uniform maps, while the uniform coarse map (Loamy Sand in EXP8, but Sand would give similar results based on Fig. 3.3) shows the opposite behaviour. Eventually, using a uniform coarse or fine texture (EXP8 or EXP9) brings the simulated global mean evapotranspiration and runoff considerably out of the observed range, contrarily to the uniform medium texture maps (EXP6, EXP7). Overall, these uniform experiments tell us the maximum range of change we can expect from any kind of soil texture map change. For instance, the largest difference in mean global scale evapotranspiration (between the uniform clay and silt experiments owing to the non-monotonic response underlined in Figs. 3.3 and 3.4) is 0.1 mm/d, i.e. 8% of the global mean evapotranspiration using the complex soil texture maps and the same climate forcing.

To analyse the scale-related impact of soil texture maps on simulated fluxes, we upscaled the map of annual mean evapotranspiration difference (EXP2-EXP4) to coarser resolutions, from 1° to the global scale, by averaging the values of the difference (Fig. 11). The resulting probability density functions are shown in Figure 12a, and Figure 12b-e shows how some metrics characterizing these distributions evolve with the averaging scale. The first noticeable impact of upscaling to coarser resolutions is the decrease of extreme evapotranspiration differences (Fig. 12b,d), leading to a less scattered distribution, also confirmed by the decreasing standard deviation (Fig. 12c). This figure shows that evapotranspiration difference follows a symmetrical distribution for the coarsest resolutions (above 5°), and starts showing a dissymmetric distribution below 5°, with a prevalence of negative values. This can also be seen in Figure 12d where the median of the evapotranspiration difference is all the more negative as the resolution gets finer. Thus, the strong impact of the soil texture map change that can be found locally (section 3.4) is mitigated at larger scales, and particularly at the global scale at which the terrestrial water budget shows a very weak sensitivity to the soil texture maps, even if it is statistically significant (Figs. 3.10 and 3.11).

### 3.4 Discussion and conclusions

Using the ORCHIDEE LSM and different soil texture maps, we found that the model shows a realistic sensitivity of surface runoff, drainage and soil moisture to soil texture compared to experimental and field studies (Rawls et al., 1993; Osman, 2013). These sensitivities lead to higher simulated evapotranspiration and lower total runoff for medium textures, which are discernable against other sources of variability when sorting the twelve USDA texture classes based on their median diameter.

Apart in some areas which exhibit important differences in evapotranspiration, often attributed to the Clay texture class, the three complex soil texture maps tested here lead

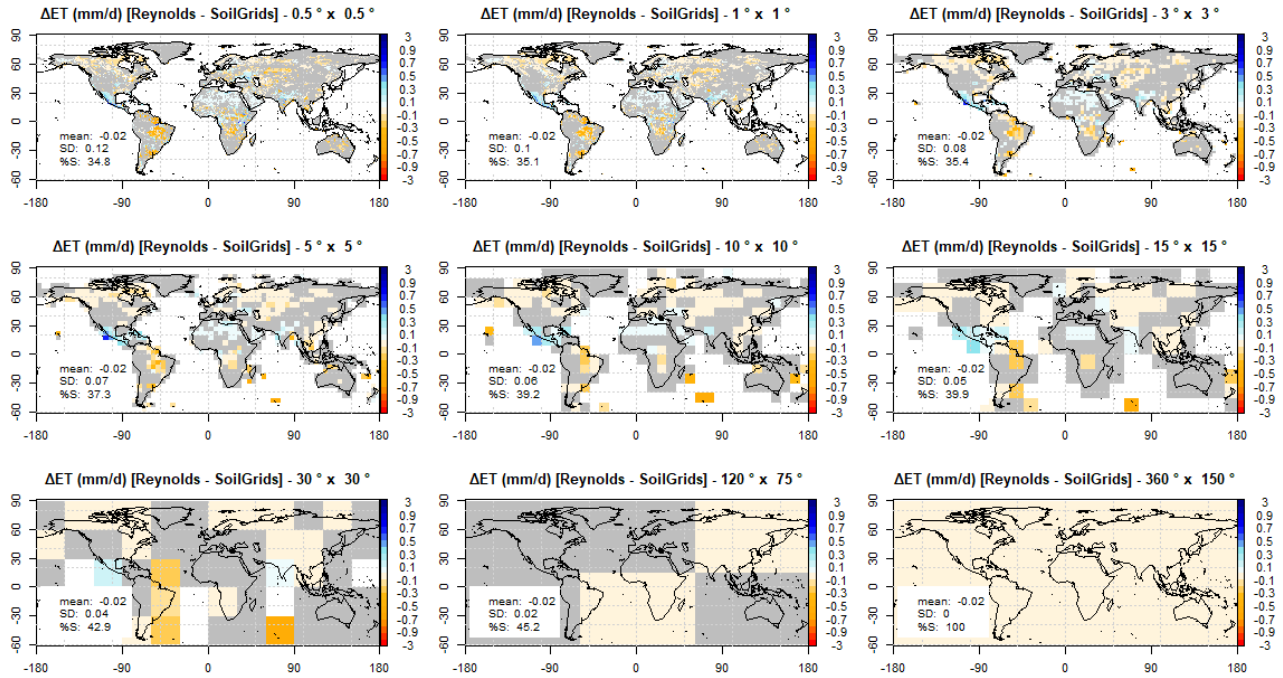


FIGURE 3.11 – Spatial distribution of simulated annual mean evapotranspiration : difference between EXP2 and EXP4 (Reynolds – SP-MIP), upscaled to different resolutions. Grey color indicates that the difference is not statistically significant at the tested resolution based on Student's t-test (with a p-value < 0.05). The printed means and standard deviations correspond to the full land area excluding Antarctica. %NS represents the percentage of land with non-significant differences.

to similar water budgets at all scales, and the large uncertainties in observation-based products and climate forcing datasets make it impossible to conclude which map gives the best simulation.

These numerical results are specific to the ORCHIDEE model and the selected maps, but this model and these maps are representative examples of most state-of-the-art LSM applications (Vereecken et al., 2019), and comparable results were obtained with another LSM and other maps (De Lannoy et al., 2014). Besides, preliminary analyses of the LSM simulations conducted for the SP-MIP project (Gundmundsson and Cuntz, 2017) seem to confirm that varying soil parameters (resulting from different soil texture maps and different PTFs) have a small impact on long-term mean simulated evapotranspiration at the global scale, compared to other relevant uncertainties, including inter-model differences.

As mentioned in Introduction, much stronger responses to soil properties have been reported from bucket-type LSMs. It must be underlined, however, that these papers considered much larger changes of soil properties, which reduces in bucket-type models to available water holding capacity (AWC), combining information on porosity, soil depth, and the difference between field capacity and wilting point. As an example, the main changes discussed in Stamm et al. (1994), Ducharne and Laval (2000), De Rosnay and Polcher (1998), and Milly and Dunne (1994), correspond respectively to AWC changes of +75%, +110%, +200%, and +1400%, while the AWC changes when switching among the three soil texture maps used in the present paper does not exceed 5% (Table 2).

The weak sensitivity of the model to the three complex soil maps but in very specific areas is probably largely explained by their spatial similarity, which can be primarily attributed to their shared dependence on the FAO/UNESCO Soil Map, although weaker in SoilGrids thus in the SP-MIP map. Another reason is the coarse spatial resolution at which soil texture is used in ORCHIDEE and most LSMs, since selecting the dominant soil texture in every grid cell (here with  $0.5^\circ$  side, ca. 50 km) statistically enhances medium textures. As the latter lead to higher evapotranspiration and smaller total runoff than more extreme textures (with larger percent of sand or clay particles), an important consequence, from a water budget point of view, is that dominant soil textures should favor excessive evapotranspiration and insufficient total runoff.

Many alternative parameter upscaling methods were proposed to better preserve high resolution soil information, often based on averaging operators (usefully optimized to match coarse-scale observed streamflow in Samaniego et al. (2010), while Montzka et al. (2017) deduce upscaled parameters from theoretically upscaled hydraulic conductivity and diffusivity curves. More invasive approaches would consist in describing the effects of high resolution soil information directly in the model equations, as frequently done for the effect of  $K_s$  on infiltration owing to tractable statistical distributions (Vereecken et al., 2019). We lack similar developments for the full range of simulated water fluxes, apart from the

partitioning of each grid cell into three soil columns with different soil textures, tested by [De Rosnay et al. \(2002\)](#) in ORCHIDEE but now abandoned.

The soil texture maps themselves can also be questioned. When compared to the FAO soil order map (Fig. 3.15), the SP-MIP map (following SoilGrids) tends to amplify the extent of sandy soils in Sahara and Saudi Arabia but ignores most sandy soils in Asia (e.g. Taklamakan desert). The largest evapotranspiration changes in our simulations were found in areas where the three soil texture maps disagree in their representation of clay soils, which calls for a better representation of this class in the soil texture maps. Of particular relevance is the distinction between Vertisols and Oxisols because of their very different hydrological properties. More generally, the use of simple PTFs based on soil texture classes only is increasingly questioned. Firstly, they overlook the first-order influence of bulk density and soil structure, which require information on organic matter content ([Smettem, 1987](#); [Rahmati et al., 2018](#); [Sun et al., 2018](#)) and coarse fragments exceeding 2 mm, frequent in many soils ([Brakensiek and Rawls, 1994](#); [Valentin, 1994](#)). Secondly, the simplifying assumption that soil texture is homogeneous vertically throughout the soil column should be revised. A particular attention should be paid on surface soil properties in areas prone to soil crusting ([Valentin et al., 2008](#)) ([Gal et al., 2017](#)), which mainly include loamy soils ([Rawls et al., 1990](#)) and also arid and semi-arid soils ([Valentin and Bresson, 1992](#)), producing high total runoff ([Yair, 1990](#); [Casenave and Valentin, 1992](#); [Karambiri et al., 2003](#); [Bouvier et al., 2018](#)). Thus, using other sources of information than soil texture to derive the geographic distribution of soil properties may lead to clearer and broader improvements of the simulated water budget than the ones analysed here owing to mineral soil texture maps alone.

## 3.5 Supplementary

### Soil texture classes characteristics

Figure 3.12 presents the soil hydraulic parameters used in ORCHIDEE LSM :  $K_s$ ,  $\alpha$  (inverse of air entry suction, corresponding to the capillary forces close to saturation, at the top of the capillary fringe),  $n$  (Van Genuchten scale parameter),  $\theta_r$  and  $\theta_s$ . Their values for each USDA texture class are taken in [Carsel and Parrish \(1988\)](#). Water contents corresponding to the wilting point and the field capacity, noted  $\theta_w$  and  $\theta_{fc}$ , are derived from the Van Genuchten water retention curve :  $\theta_w$  is the water content corresponding to a water potential of -150m, and  $\theta_{fc}$  corresponds to a potential of -3.3 m except for the texture sand which corresponds to -1m. AWC is the available water capacity of the 2-meter soil column, it is calculated in mm as  $AWC(2m) = 2000(\theta_{fc} - \theta_w)$ .

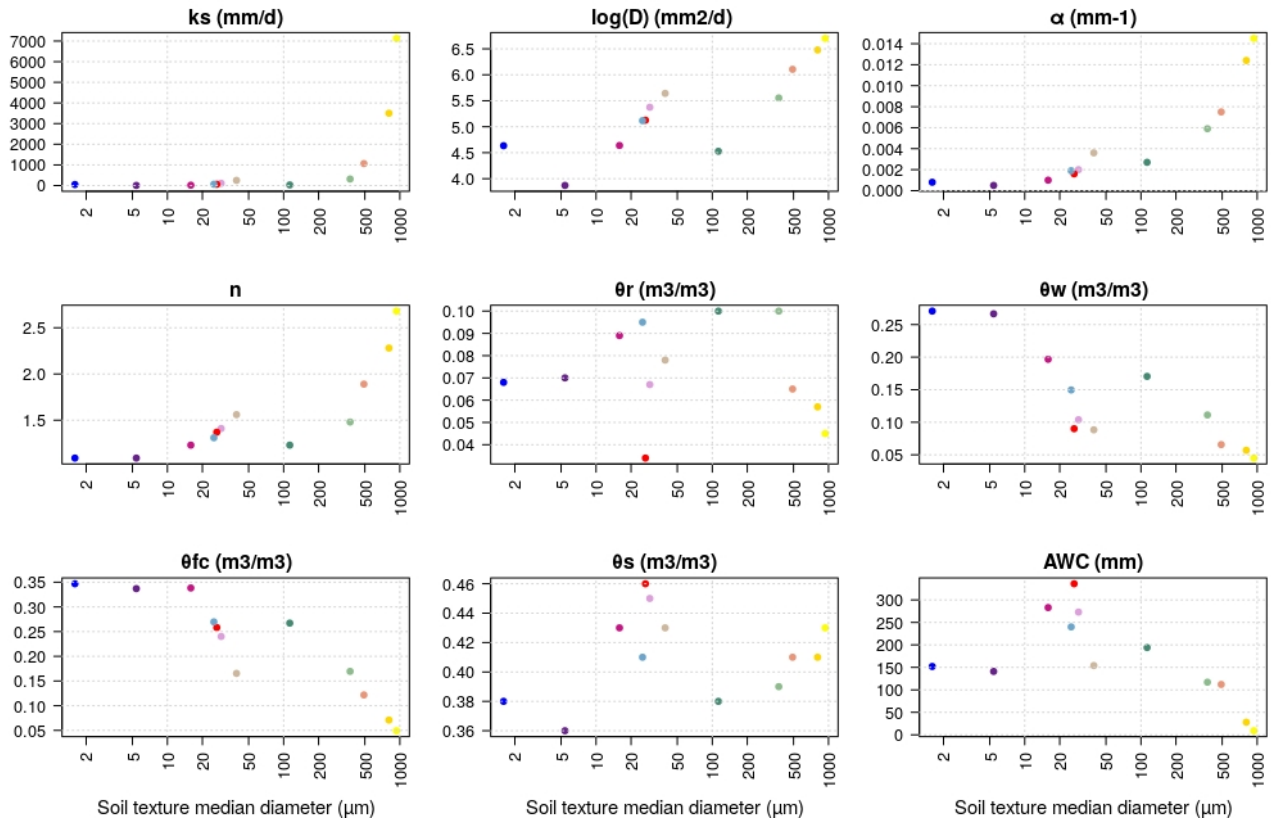


FIGURE 3.12 – Soil parameters of the 12 USDA texture classes, for color codes see Figure 1.  $D$  : maximum hydraulic diffusivity,  $\alpha$  : inverse of air entry suction,  $n$  : Van Genuchten parameter,  $\theta_r$  : residual water content,  $\theta_w$  : wilting point,  $\theta_{fc}$  : field capacity,  $\theta_s$  : saturated water content,  $AWC$  : available water content.

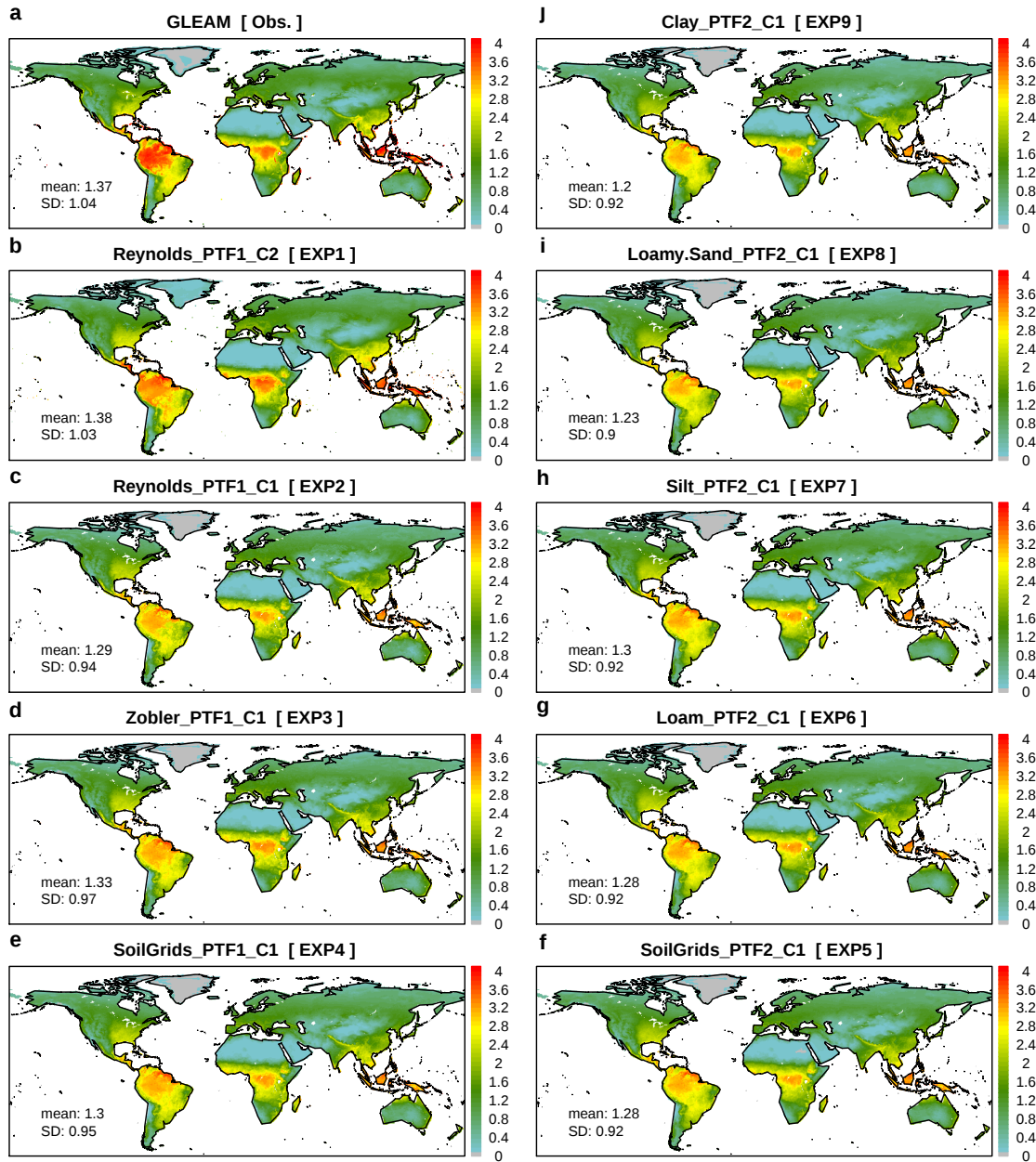


FIGURE 3.13 – Maps of evapotranspiration averaged over 1980-2010 (a) estimated by [Martens et al. \(2017\)](#) and (b-j) for the nine experiments. PTF1 is the default PTF in ORCHIDEE found in [Carsel and Parrish \(1988\)](#), PTF2 is the PTF of [Schaap et al. \(2001\)](#), C1 is the climate forcing GSWP3, C2 is the climate forcing CRU-NCEP.

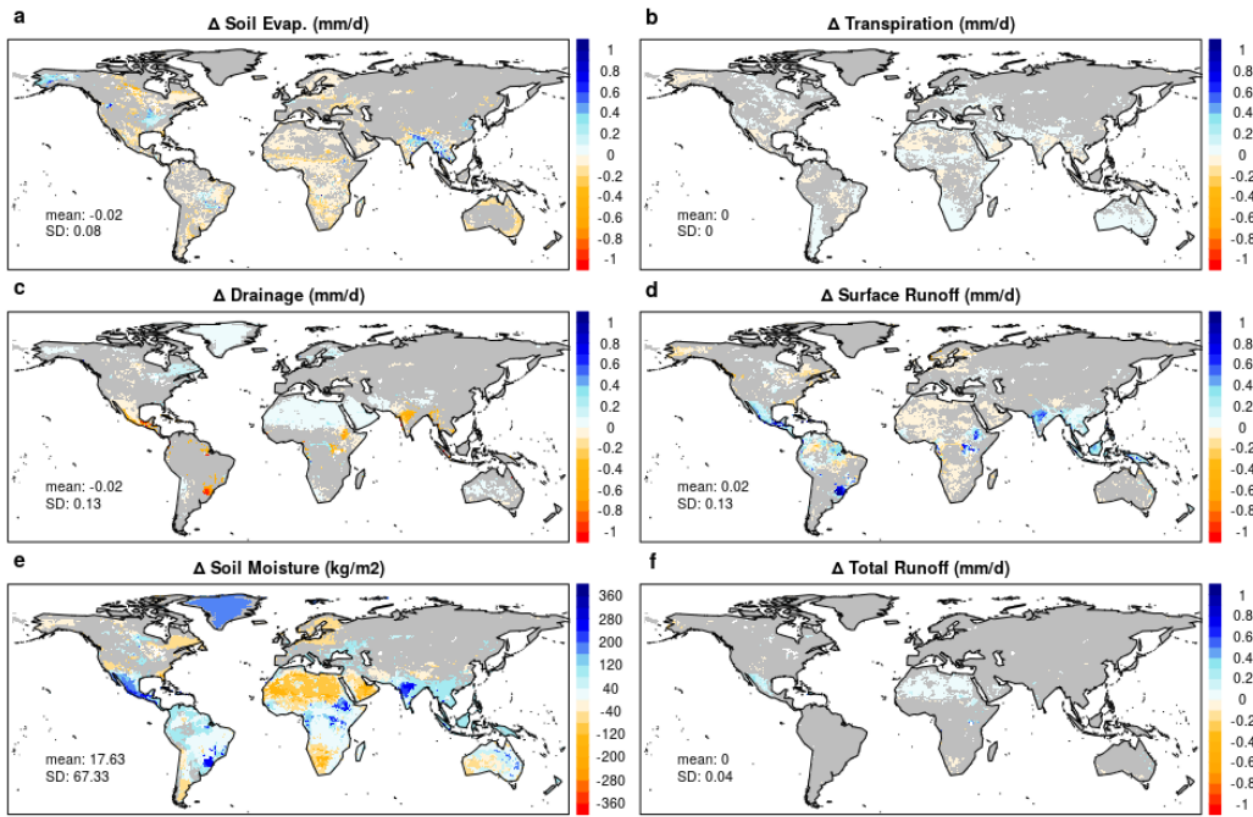


FIGURE 3.14 – Difference in simulated variables when the SP-MIP map is replaced by a uniform Loamy map (EXP6 - EXP5), averaged over the period 1980-2010. The corresponding difference for evapotranspiration is shown in Fig. 3.5a. Grey color indicates that the difference is not statistically significant based on Student's t-test (with a p-value < 0.05%). Mean and standard deviation are averaged over the globe excluding Antarctica.

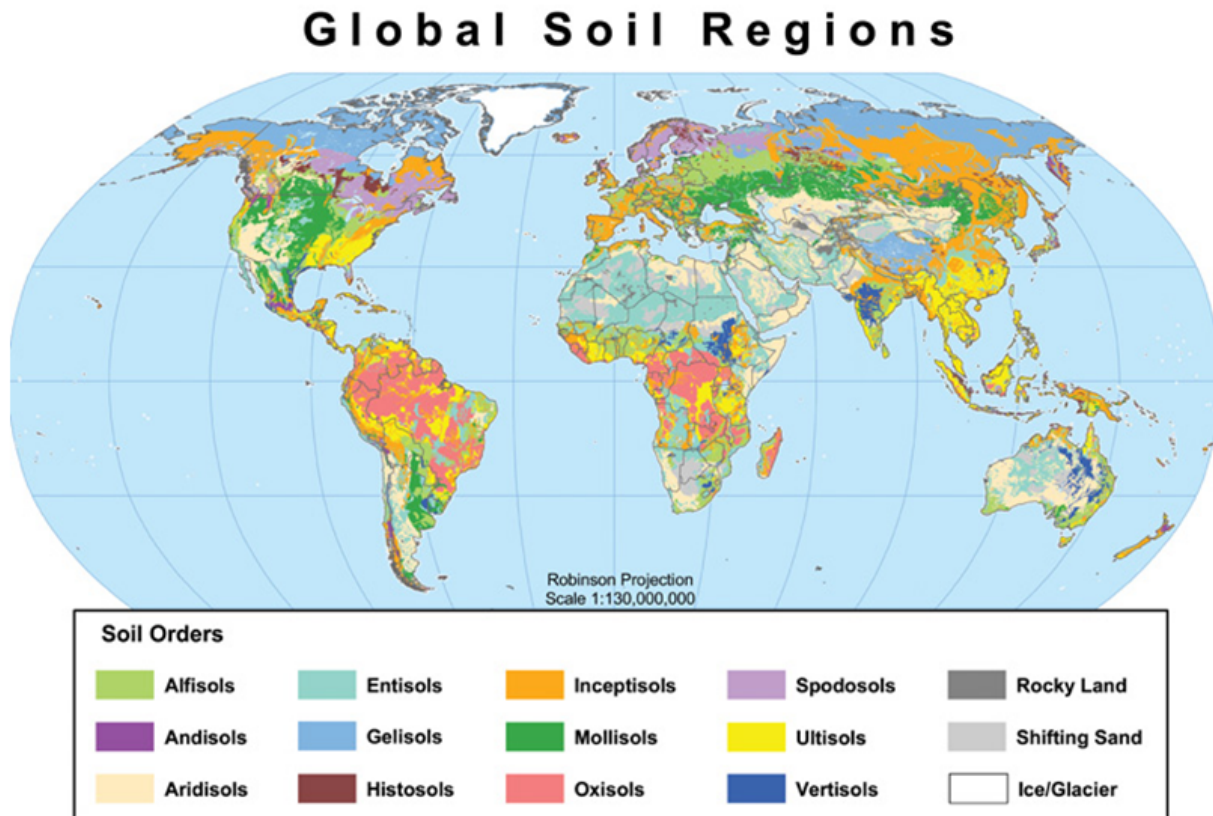


FIGURE 3.15 – FAO Soil Order Map. This map is a simplification of the FAO/UNESCO Soil Map of the World ([Eswaran et al., 2012](#)), accessible on [this link](#).



# Chapitre 4

## Introduction d'une nouvelle classe de texture de sol

Comme évoqué dans le chapitre précédent, la mauvaise représentation de la classe de sol Argile peut induire de forts biais d'ET. La présence d'Argile en Amérique du Sud tropicale dans la carte Reynolds entraine ainsi de forts biais négatifs d'ET qui n'ont pas été retrouvés avec les deux autres cartes où l'Argile est absente dans cette région. Comparée à la FAO Soil Order Map (Fig. 3.15), la classe Argile dans Reynolds regroupe des ordres de sol différents, dont principalement les Vertisols et les Oxisols. Les premiers consistent en des argiles gonflantes de type smectite avec une perméabilité réduite, alors que les deuxièmes peuvent présenter une variabilité texturale plus large, et contiennent des argiles non gonflantes (illite, kaolinite) avec une perméabilité beaucoup plus élevée que celle des Vertisols, comparable à celle du sable. Cela s'explique par la formation dans ces Oxisols (appelés également sols ferrallitiques, ferralsols ou latosols) de micro-agrégats très stables, constitués d'argile et d'hydroxydes de fer et d'aluminium, et pour les horizons superficiels de matière organique. Ils assurent une porosité inter-agrégats bien plus importante que celle d'autres sols ayant les mêmes teneurs en argile. Du fait de leur taille et de leurs propriétés, ces micro-agrégats sont souvent désignés sous le terme de « pseudo-sables » (Martinez and Souza, 2020). Dans ORCHIDEE, les propriétés hydrauliques de la classe Argile sont fournies par Carsel and Parrish (1988), ces derniers se sont basés dans leur étude sur des échantillons de sols issus des Etats-Unis continentaux, où les Oxisols sont totalement absents. Alors que la classe Argile a un Ks de 48 mm/j, celui des Oxisols s'élève jusqu'à 18700 mm/j (Drescher et al., 2016). Il en est de même des autres propriétés hydrauliques. Les propriétés hydrauliques de la classe Argile utilisées dans ORCHIDEE ne sont donc pas adaptées aux Oxisols.

Afin de distinguer ces deux types de sol argileux dans ORCHIDEE, on introduit dans ce

chapitre, une nouvelle classe de texture de sol pour représenter les Oxisols argileux. Cela revient à partager la classe texturale Argile en « Argile gonflante » et « Argile Oxisol ». On commence dans un premier temps par déterminer la distribution géographique des Oxisols argileux, pour l'introduire dans la carte de sol de Reynolds. Ensuite, on lui attribue des paramètres de Van Genuchten adaptés. Enfin, on analyse les résultats de simulations forcées par la carte de Reynolds originale et par celle modifiée, et on conclut quant à l'apport de cette nouvelle classe de sol, ainsi que ses limitations.

## 4.1 Introduction

The soils in the humid tropics are different from temperate soils. Most often, they are strongly weathered and show a great diversity in age, parent material and soil structure. Climate and age of the soils are important controlling factors of the soil properties in these regions.

The most dominant soil order in the tropics is Oxisols (term used in the US taxonomy), covering 25% of the tropical soils ([Sanchez, 2019](#)). These soils are known for their strong granular structure and large textural variability, ranging from Loamy Sand to Clay, and are mostly poor in silt. Oxisols with a Clay texture largely differ from other clay-textured soils, such as Vertisols. Clay Oxisols contain Kaolinite minerals, which are non-swelling clays, while Vertisols consist of Smectites, which are swelling/shrinking clays. Secondly, because they are highly aggregated, Clay Oxisols have a high permeability contrarily to other clays known for their very low permeability. Most PTFs estimating soil hydraulic properties are built using soils from temperate regions, and these PTFs are being used all over the globe in land surface models. However, these PTFs are not adequate for tropical Oxisols, since they have a different clay mineralogy and weathering history ([van den Berg et al., 1997](#); [Tomasella and Hodnett, 2004](#)).

Although it contains a high amount of clay, Clay Oxisols exhibit very different retention properties compared to the usual clay soils found in the other regions of the world. They have a high microporosity due to the prevalence of clay particles, combined to a high macroporosity, which is mainly caused by biological activity (roots and insects) and fine cracking of the soil ([Chauvel and Chauvel, 1982](#)). This bi-modal distribution of pore size leads to a double behavior of Clay Oxisols; at a low matric potential, it's the water held in the macropores that flows due to gravity, so that the soil behaves like a sandy soil, while at a high matric potential, when the soil is dry, soil water is rather held in the micropores by suction due to capillary forces, which causes a higher retention that can reach the retention of pure clay ([Chauvel and Chauvel, 1982](#))(Fig. 4.1).

In the ORCHIDEE LSM, soil hydraulic properties are provided by [Carsel and Parrish \(1988\)](#). The latter study is based on soil samples from the CONUS (Continental US), where Oxisols are totally absent, therefore, in ORCHIDEE, Clay Oxisols are given the

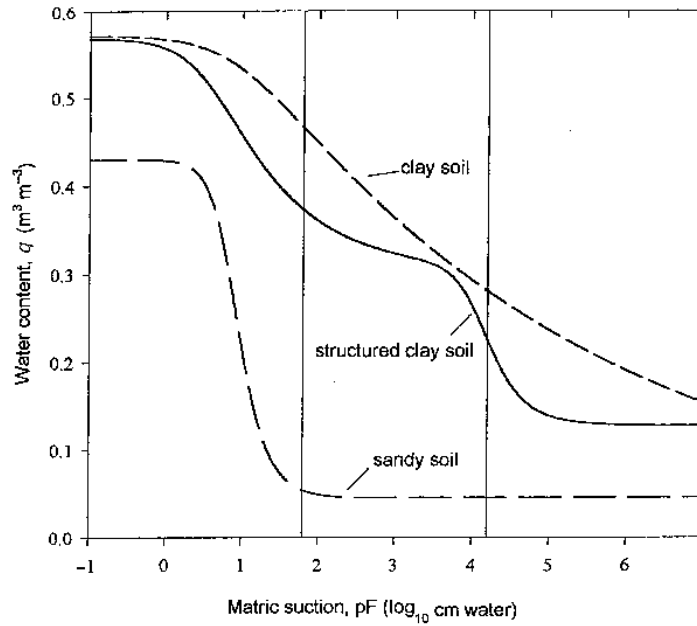


FIGURE 4.1 – Water retention curve of Clay Oxisols (solid line) as compared to the retention curves of sandy soils and clay soils. The vertical lines indicate field capacity and wilting point. Source : [Schroth and Sinclair \(2002\)](#)

same hydraulic properties as the other swelling clays found in the CONUS. This results in large negative evapotranspiration biases in areas effectively covered by Clay Oxisols, and mapped as Clay (section 3.3.4). In order to distinguish these two types of clays in ORCHIDEE, we introduce in this chapter a new soil class to represent Clay Oxisols. This is equivalent to splitting the Clay soil texture into two sub-classes : **Swelling Clay** and **Clay Oxisols**. First, we modified the Reynolds soil texture map such as to represent Clay Oxisols based on the FAO Soil Order Map (Fig. 3.15). Then we collected the corresponding Van Genuchten parameters from the literature. In the Results section, we evaluated the model’s response to the modified Reynolds map, by analyzing the simulated water fluxes and comparing the simulated evapotranspiration and river discharge to observation-based data. Finally, in the closing section, we point out the limitations of the used methods and discuss some perspectives.

## 4.2 Methods

### 4.2.1 Locating the Clay Oxisols

Oxisols mapped as Clay in the Reynolds soil texture map were assigned to the Clay Oxisols texture class, considering that the main map units were represented by Vertisols, especially

in Northern Sudan, India, China and Australia, the other Clay areas are considered to belong to the Swelling Clay texture class (Fig. 4.2).

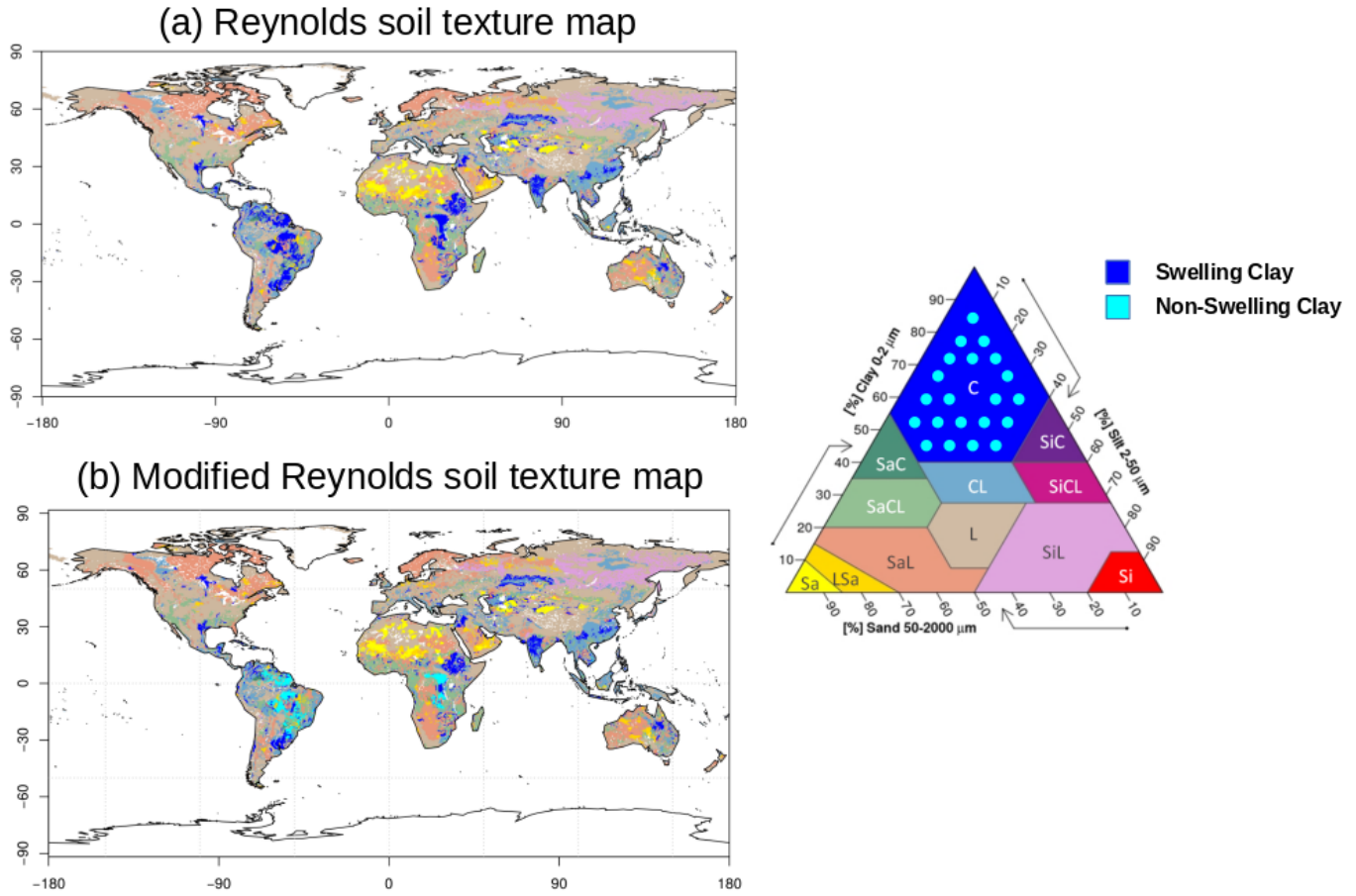


FIGURE 4.2 – (a) Original and (b) modified Reynolds soil texture map.

Based on this, the original Clay texture class was split into 72% of Swelling Clay and 28% of Clay Oxisols, the latter mostly located in tropical South America and Central Africa.

#### 4.2.2 Pedotransfer functions for the Clay oxisols

To use the modified Reynolds soil texture map in ORCHIDEE, a PTF corresponding to Clay Oxisols is needed. Many previous studies have derived PTFs that predict the Van Genuchten parameters for Clay Oxisols. [Tomasella and Hodnett \(1996\)](#) provided an optimized set of Van Genuchten parameters based on in situ measurements of a single Brazilian soil. All of the Van Genuchten parameters were estimated simultaneously from the measurements of hydraulic conductivity and water retention, by a nonlinear least square fitting. They found that their fitting of the water retention curve and the hydraulic

conductivity curve was only good in the low tension part of the curve; at higher tensions, the fitting was poorer. A high value of  $\theta_r$  was needed to obtain a better fit of the hydraulic conductivity curve, but in counterpart, it deteriorated the fitting of the water retention curve at high tensions. The  $k_s$  provided by [Tomasella and Hodnett \(1996\)](#) is also a result of the optimization of the hydraulic conductivity curve, the real values measured on site were eight times lower. This is all due to the Van Genuchten model not being suited for Clay Oxisols, which have a hybrid character, instead, the Van Genuchten model is only suited for soils with unimodal pore size distribution ([Tomasella and Hodnett, 2004](#)).

In a subsequent study, ([Tomasella et al., 2000](#)) used soil data from multiple soils across Brazil to derive the water retention parameters of the Van Genuchten model, and relate them in a second step to basic soil data such as sand, silt, clay and carbon contents. For each soil sample, these parameters (excluding hydraulic conductivity) were estimated simultaneously by fitting the Van Genuchten model to the water retention data. The resulting mean values are presented in Table 4.1. [Hodnett and Tomasella \(2002\)](#) used a broader range of tropical soils from multiple countries to derive the Van Genuchten parameters for Oxisols. They used the same fitting method as in [Tomasella and Hodnett \(1996\)](#) and [Tomasella et al. \(2000\)](#). Their soil samples cover a wide range of textural classes, with a predominance of the Clay class. The Van Genuchten parameters estimated for the Clay class are given in Table 4.1.

We gathered different studies from the literature such as to cover a wide range of tropical soils from different sites, as well as a wide range of methods; either using their own measured data ([Tomasella and Hodnett, 1996](#); [Ruiz and Medina, 2004](#)), or already available data from existing databases ([Tomasella et al., 2000](#); [Hodnett and Tomasella, 2002](#)). A list of the Van Genuchten parameters found in these different studies is given in Table 4.1.

Figure 4.3 displays the averaged Van Genuchten parameters from Table 4.1, after discarding the outlier values (shown in red in Table 4.1).  $K_s$ , which controls the flow at saturation, as well as  $\alpha$ , which depends on pore size, are closer to the coarse textures. The higher  $\alpha$  for Clay Oxisols compared to Swelling Clay indicates that they drain more rapidly at saturation ([Hodnett and Tomasella, 2002](#)).

The shape parameter  $n$  corresponds to medium textures. The saturated water content is higher than for all other USDA soil texture classes. This can be explained by the relatively high organic matter content in tropical Oxisols, which tends to increase soil aggregation, and thus, porosity, while in ORCHIDEE,  $\theta_s$  (as taken from Carsel and Parrish, 1988) is given for a pure mineral soil, without considering the impact of organic matter content. High values are found for  $\theta_r$  as well, ranging from 0.18 to 0.32, while it does not exceed 0.1 for the other texture classes in ORCHIDEE.  $\theta_r$  represents the water content which is strongly absorbed by soil particles, and not released under any tension, it is linked to the surface area of the soil particles. Since clay particles have a high surface area, the high  $\theta_r$  in tropical clay soils is linked to their higher content of clay particles (ranging from

|                                       | Ks (mm/d)      |                | n            |               | $\alpha$ (mm-1) |                | $\theta_r$ (m3/m3) |               | $\theta_s$ (m3/m3) |               |
|---------------------------------------|----------------|----------------|--------------|---------------|-----------------|----------------|--------------------|---------------|--------------------|---------------|
|                                       | mean           | SD             | mean         | SD            | mean            | SD             | mean               | SD            | mean               | SD            |
| Drescher et al. (2016)                | 18733          | -              | -            | -             | -               | -              | -                  | -             | 0.56               | -             |
| Carducci et al. (2011)                | -              | -              | -            | -             | -               | -              | -                  | -             | -                  | -             |
| Ferreira et al. (1999)                | 7684           | 4104.75        | -            | -             | -               | -              | -                  | -             | -                  | -             |
| Tomasella & Hodnett (1996)            | 13104          | 1678.6         | 1.5          | -             | 0.0075          | -              | 0.315              | -             | 0.458              | -             |
| Zimmerman et al. (2006)               | 4944           | -              | -            | -             | -               | -              | -                  | -             | -                  | -             |
| Balbino et al. (2004)                 | 1814           | -              | 1.56         | -             | 0.0100          | -              | 0.322              | -             | 0.59               | -             |
|                                       | 3110           |                |              |               |                 |                |                    |               |                    |               |
| Hodnett & Tomasella (2002)            | -              | -              | 1.531        | 0.27          | 0.0048          | 0.0036         | 0.214              | 0.084         | 0.536              | 0.081         |
| Tomasella et al. (2000)               | -              | -              | 1.571        | 0.184         | 0.0104          | 0.0112         | 0.187              | 0.0275        | 0.502              | 0.0131        |
| Bonetti et al. (2019)                 | -              | -              | 1.114        | -             | 0.024           | -              | 0                  | -             | 0.556              | -             |
| Rocha et al. (2016)                   | -              | -              | 1.492        | -             | 0.1167          | -              | 0.190              | -             | 0.420              | -             |
| Pires et al. (2008)                   | -              | -              | 1.344        | -             | 0.01992         | -              | 0.263              | -             | 0.519              | -             |
| Ruiz & Medina (2003)                  | 28400          | -              | 1.867        | -             | 0.016           | -              | 0.176              | -             | 0.388              | -             |
| <b>Mean and SD of the mean values</b> | <b>6131.36</b> | <b>4477.97</b> | <b>1.552</b> | <b>0.0976</b> | <b>0.0132</b>   | <b>0.00578</b> | <b>0.238*</b>      | <b>0.0530</b> | <b>0.503</b>       | <b>0.0544</b> |

TABLE 4.1 – Synthesis of the Van Genuchten parameters derived for tropical Oxisols in the literature. The last line shows the mean and standard deviation (SD) of the mean values, excluding the values shown in red, considered as outliers. The mean value of  $\theta_r$  is not used for Clay Oxisols as described in the text.

60% to 90%, [Tomasella and Hodnett \(2004\)](#). Compared to the soil samples from which most PTFs are derived (e.g. in [Carsel and Parrish \(1988\)](#), clay content in the Clay texture class ranges from 5% to 60%). To be consistent with the PTFs used in ORCHIDEE, we will assume that both Clay Oxisols and Swelling Clay classes have the same texture, and thus, are supposed to have the same clay content, therefore, the same  $\theta_r = 0.068 m^3.m^{-3}$  will be used for both classes. The resulting water retention curve is within the range of the 12 USDA soil texture classes, except for the saturation water content, which is higher than any other texture class ([Fig.4.4](#)). [Figure 4.4](#) shows clearly that the retention curve of Clay Oxisols is closer in behavior to the sandy textures, which correspond to the field measurements.

### 4.2.3 Simulation description

To analyze the impact of adding the new Clay Oxisols class to the Reynolds map, we conducted two simulations with ORCHIDEE (tag 2.2); one reference simulation SIMU-REF with the unchanged Reynolds soil texture map, and one simulation SIMURM with the modified Reynolds map. The ORCHIDEE tag 2.2 is a newer version of ORCHIDEE tag 2.0 which was used in the previous chapter. This new version brings mainly adjustments of the model to the new change of the computing machines, along with some bug corrections. The two versions are therefore equivalent and their results are comparable. Since the clay-related anomaly was identified with the GSWP3 meteorological forcing (described in [section 3.2.2](#), we used the same forcing in these simulations, in order to indicate whether the modification of the soil texture map improves this anomaly. We ran the model at 0.5° resolution, and followed the same protocol as in the previous chapter. The simulation period is 1980-2010, following a 20-year spin-up since 1960.

## 4.3 Results and discussion

### 4.3.1 Impact on simulated water fluxes

Replacing Swelling Clay with Clay Oxisols in the Reynolds map results in an increase of evapotranspiration ([Fig. 4.5a](#)), the changes are statistically significant over 96% of the pixels with modified texture. Transpiration is the only ET flux which increased ([Fig. 4.5c](#)), and thus, is responsible for the ET increase. The high sensitivity of transpiration to the texture change is certainly due to the important density of vegetation in the concerned areas. Transpiration increases by more than 30% in 44% of the switched pixels. This increase can be explained by both the high porosity of Clay Oxisols compared to Swelling Clay ([Fig. 4.3](#)), which allows more water to be stored in the soil, and thus, more water available for plant uptake, as well as the low soil retention ([Fig. 4.4](#)), which allows the water to be easily released to plants. Oppositely, soil evaporation decreases ([Fig. 4.5b](#)), likely as a result of the increase in the leaf area index (LAI), which decreases the effective

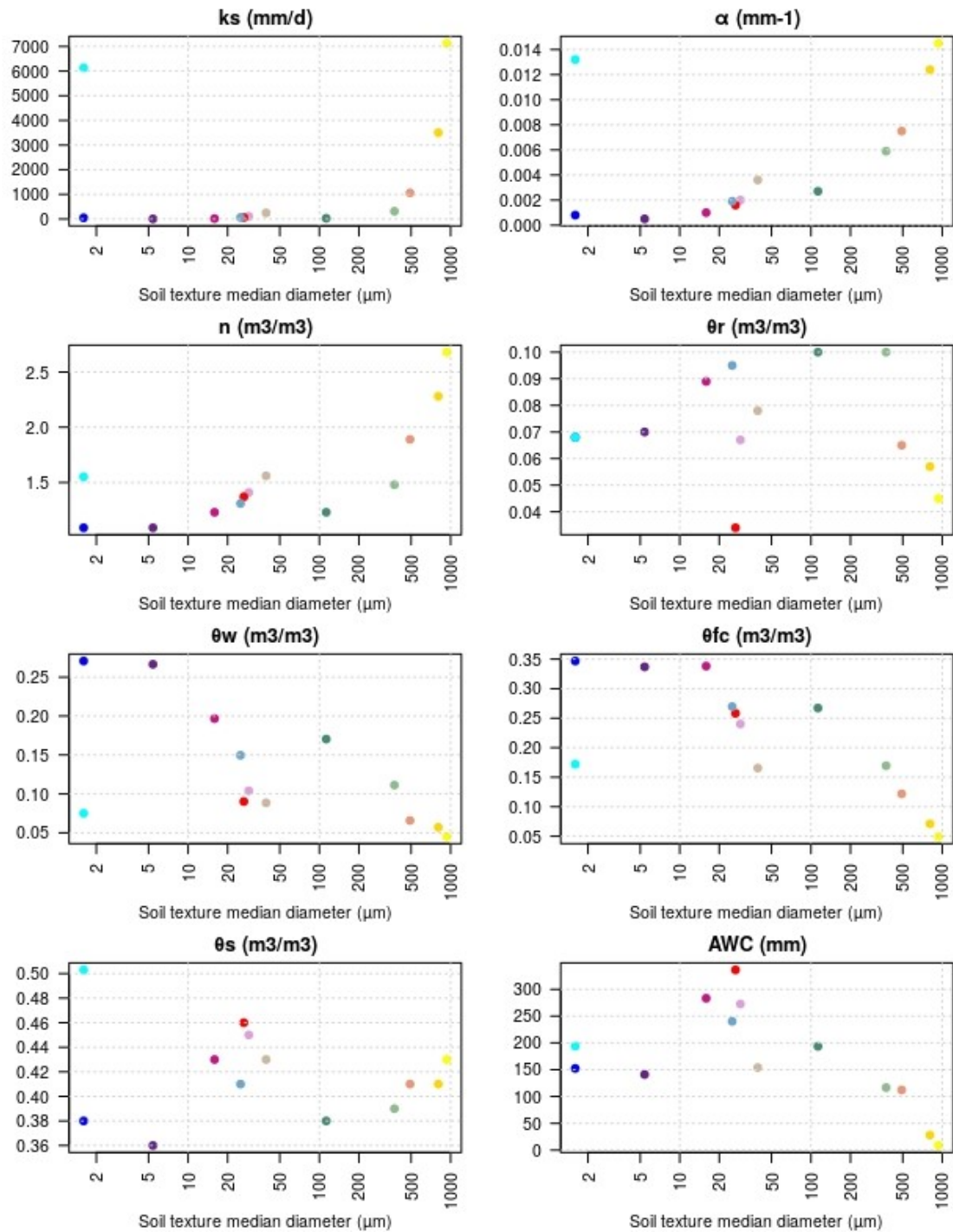


FIGURE 4.3 – Soil parameters of Clay Oxisols (in cyan color) as compared to the 12 USDA texture classes.

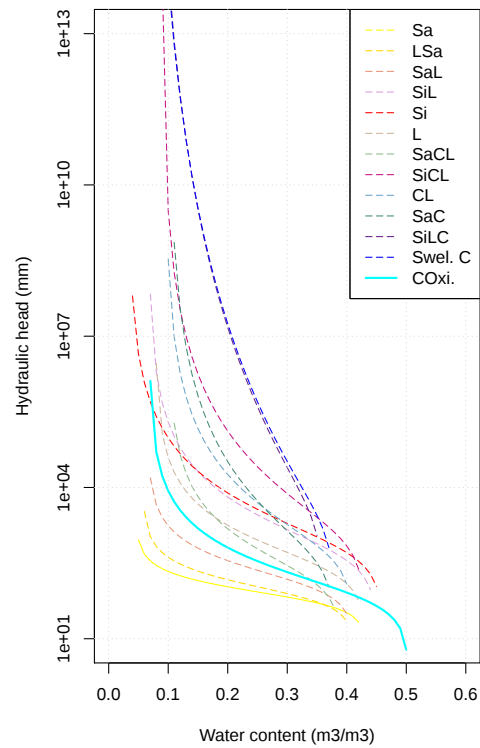


FIGURE 4.4 – Water retention curve of Clay Oxisols as compared to the other texture classes.

bare soil fraction.

To balance the overall increase in evapotranspiration, total runoff decreases by the same order (Fig. 4.5f). Its components (surface runoff and drainage) show a much larger change when Swelling Clay is replaced by Clay Oxisols (Fig. 4.5e,f). In fact, soil permeability skyrockets from an extremely low value to an extremely high value (multiplied by +100). Soils with high permeability infiltrate faster resulting in an increased drainage, while low permeability soils infiltrate slower, and the excess water is transferred to surface runoff. Finally, the decrease in soil moisture was a direct result of the increased drainage and evapotranspiration (Fig. 4.5e). Overall, the different water fluxes responses to replacing Swelling Clay with Clay Oxisols are consistent with the results of Chapter 3, considering that Clay Oxisols are supposed to have a sand-like behavior.

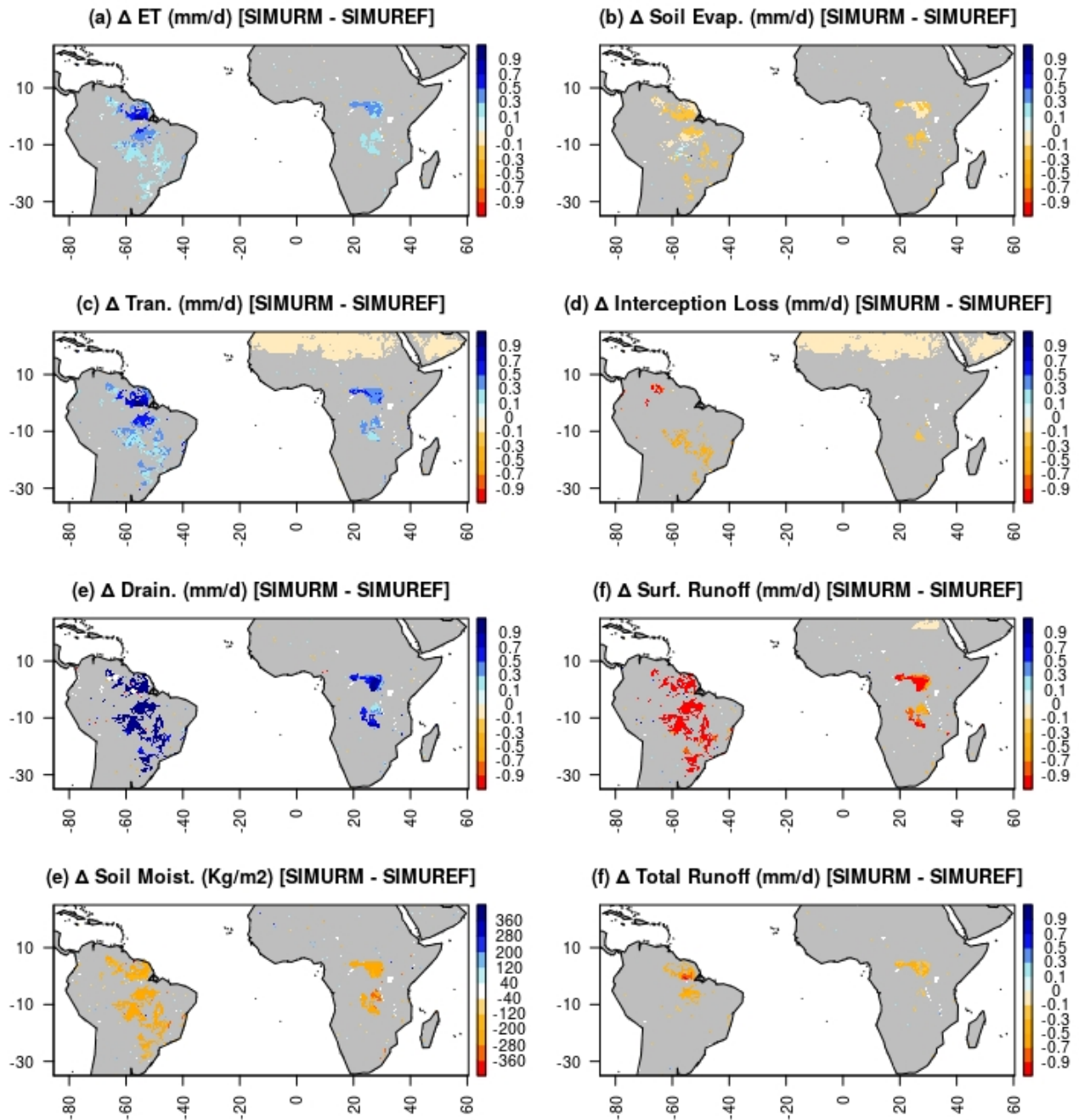


FIGURE 4.5 – Difference in simulated variables, averaged over the period 1980-2010, when the original Reynolds map is replaced by the modified Reynolds map (SIMURM-SIMUREF). Grey colour indicates that the difference is not statistically significant based on a Student t-test (with a p value  $\leq 0.05$ ).

### 4.3.2 Evapotranspiration bias

Compared to GLEAM (Miralles et al., 2011), ORCHIDEE underestimates ET in tropical south America and central Africa, whatever the soil texture map (Fig. 3.8). Differentiating Clay Oxisols from Clay in the Reynolds map enables the correction the important negative biases in the Guiana Shield and the eastern part of the Amazon basin, as well as in central Africa (Fig. 4.6).

In these regions, ET bias resulting from the modified Reynolds map is comparable to the one found with the Zobler map (Fig. 3.8c,d). This is due to the concave behavior of ET (section 3.3.2). In fact, the areas covered by Clay Oxisols in the modified Reynolds map, are covered by Clay Loam in the Zobler map, the first texture class is medium to coarse (in behavior), while the second one is medium to fine, these two textures are symmetrical about the medium textures, and therefore, result in similar ET. This suggests that although the Zobler soil map reduces the ET bias (Fig. 3.8), it does not necessarily represent the best the soil texture in these areas.

### 4.3.3 Impact on simulated river discharge

To assess the impact of the modified Reynolds map on river discharge, we analyzed the simulated hydrographs over seven basins, which cover the areas with texture change. Clay Oxisols in central Africa are mainly located in the Congo river basin, while in south America they can be found in multiple river basins, including the Amazon, the Araguaia/Tocantins and the Guianas complex. We compared the simulated river discharge to observed streamflow data from the World Meteorological Organization’s Global Runoff Data Centre (GRDC) database in order to evaluate the model ability to simulate river discharge over these basins. The GRDC database provides global data of monthly river discharge collected from many basin agencies around the world, and is hosted by the German Federal Institute of Hydrology. Although the time period covered by the GRDC varies from a station to another, and no uncertainty quantification of the observations is provided, it remains the most complete global river discharge database available (Wang et al., 2018; Fekete et al., 2002).

Since Clay Oxisols cover small fraction of the Amazon basin (only 11% of the total basin area), the change in river discharge at the outlet of the river basin was insignificant. We therefore focused on the most impacted sub-basins; the Rio Tapajos and the Rio Xingu, which are almost entirely covered by Clay Oxisols. Both of these tributaries flows show a dramatic change when Swelling Clay is replaced by Clay Oxisols (Fig. 4.7c,d). The peak flow is delayed by one month, as well as the whole seasonal cycle. Although the mean annual discharge is improved by 9% in the Tapajos, with regard to the observed discharge, the seasonal cycle is deteriorated (Nash coefficient changes from 0.48 to 0.07). The same impact is found for the Tocantins and its main tributary the Araguaia, but with a less

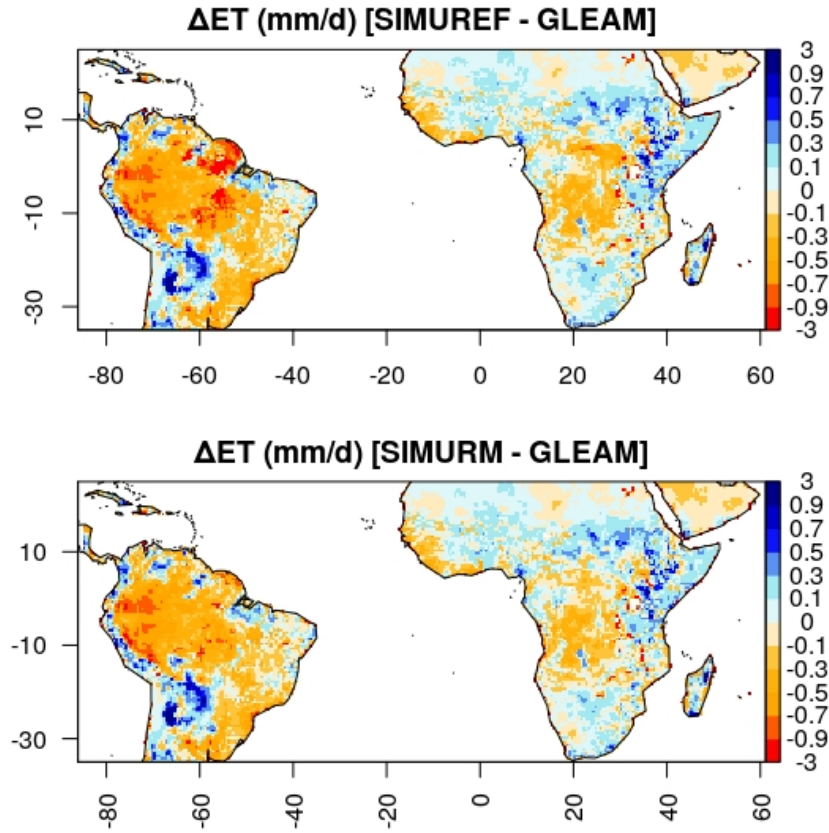


FIGURE 4.6 – Spatial distribution of simulated annual mean evapotranspiration bias, averaged over 1980-2010, with respect to the GLEAM product : (a) for the reference simulation (SIMUREF) and (b) for the simulation with modified Reynolds map (SIMURM).

dramatic change. The peak flow in Tocantins occurs in April, instead of May, similarly to the observations. In the Araguaia, the seasonal cycle is slightly improved, with a Nash coefficient of 0.48, instead of 0.46.

In the Guianas complex, watersheds are of smaller drainage areas (e.g. Essequibo and Maroni river basins, Table 4.2). ORCHIDEE captures fairly well the seasonality of the Essequibo river discharge with the original Reynolds map. Using the modified Reynolds map worsened the seasonal cycle (Nash coefficient changed from 0.77 to 0.63), while the mean annual discharge slightly decreased. The seasonality of the Maroni river discharge was also worsened (NSE changed from 0.55 to 0.42), but the mean annual discharge was improved by 10%.

In the Congo river basin, neither the seasonality nor the amplitude of the streamflow is well captured by ORCHIDEE (Fig. 4.7g). The important positive bias in this river is due to two reasons, possibly acting together : the precipitation forcing data over the Congo

basin might be poor, due to the low rain gauge density in this area (Fekete et al., 2004); and secondly, the Congo river basin is subject to a massive anthropogenic stress, which strongly alters the flow regime, and this impact is not represented in ORCHIDEE.

Overall, mapping Clay Oxisols in the Reynolds map results in a lower flow at the rising limb, and a higher flow at the recession, for all the impacted basins. For most of these basins (Maroni, Xingu, Tapajos and Tocantins/Araguaia), the seasonal streamflow cycle is delayed by one month. These impacts are due to the change in the partitioning between surface runoff and drainage. In fact, the modified Reynolds map favors drainage over surface runoff, and since drainage is routed to a slow reservoir (with a higher residence time) before arriving to the streamflow, it results in a delay of the peak flow, and a smoothing of the hydrograph. The mean annual discharge is overall reduced (Table 4.2), which is in adequacy with the increased annual ET (Fig. 4.5a). It is worth noting that ORCHIDEE tends to overestimate river discharge in most of the river basins; which is consistent with the underestimation of ET in these areas. The biases are mostly improved with the modified Reynolds map, but the seasonal cycles are deteriorated. This is mainly because in ORCHIDEE, the seasonality in river flow is calibrated through a time constant representing the residence time (Schneider et al., 2017; Guimberteau et al., 2012). It should be also noted that in the version of ORCHIDEE used in this study, floodplains are not represented. In reality, the hydrology of the Amazon basin is strongly affected by floodplains (Guimberteau et al., 2012). Moreover, the high uncertainty of climate forcing datasets over the Amazon basin and the Congo basin can be a source of misrepresentation of the river flow in these areas (Guimberteau et al., 2017; Fekete et al., 2004).

## 4.4 Conclusion

Introducing a new soil texture class in the Reynolds map to be used in the ORCHIDEE LSM allowed us to distinguish between two types of clay of different hydrological behaviors. This led to a more realistic representation of the tropical clay soils, which differs in behavior from the temperate clay soils, from which most PTFs are derived. Although they contain a high amount of clay, these soils behave more like sands, due to their high porosity and hydraulic conductivity.

Using the modified Reynolds map and the corresponding PTF, ORCHIDEE simulated more evapotranspiration (+0.33% globally) and less total runoff. The important negative ET biases in the Guyanas shield and the eastern Amazon were corrected. As expected, Clay Oxisols behaved like sandy soils, favoring drainage over surface runoff, and transpiration over soil evaporation, which resulted in less moisture in soils, and smoother hydrographs. The mean annual river discharge decreased, consistently with the observations, but the flow seasonal cycle was deteriorated.

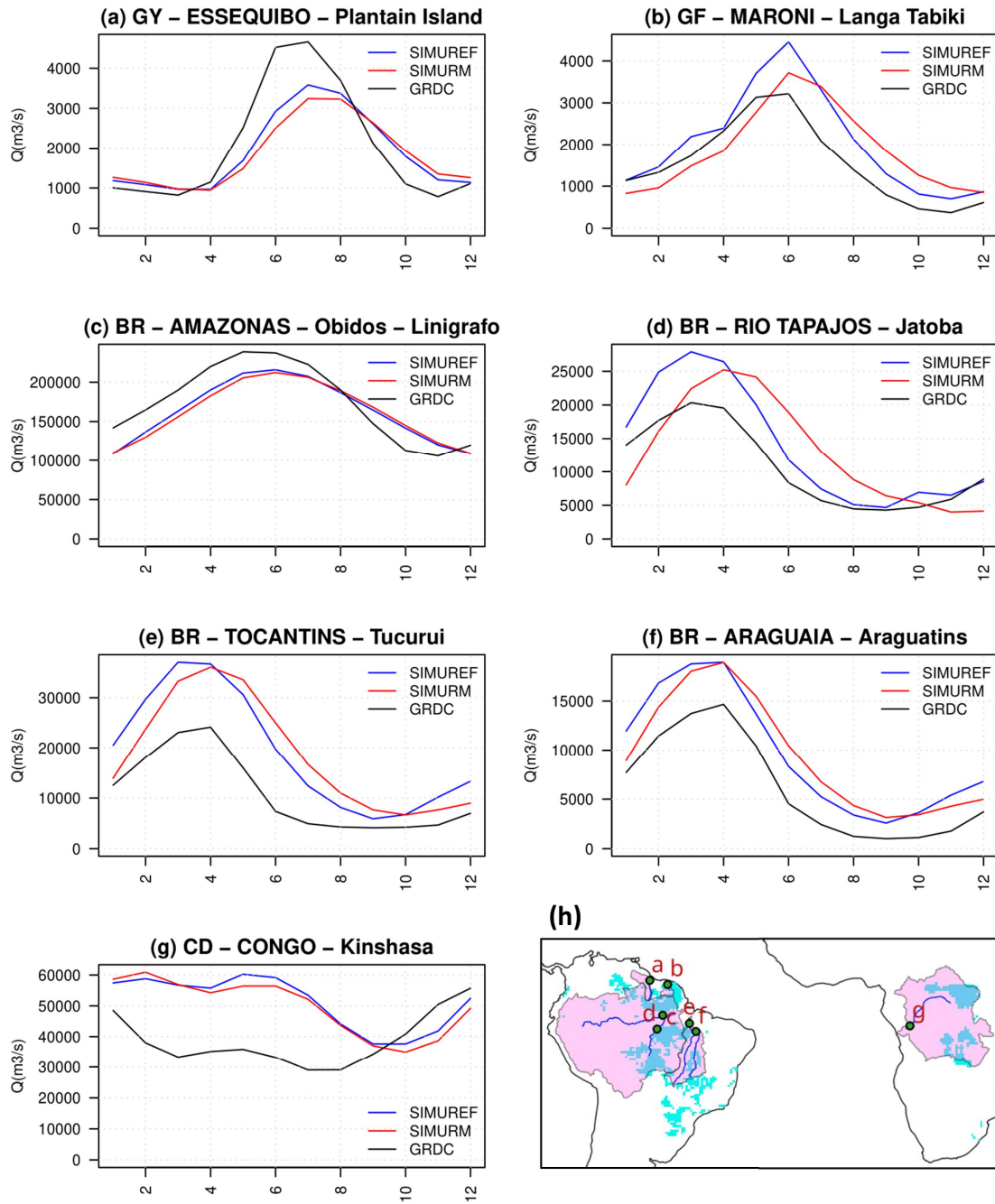


FIGURE 4.7 – (a-g) Mean monthly simulated discharge at different observation stations, for SIMUREF and SIMURM and from GRDC. Title of the captions indicates the location as follows : “country-river-station”; (b) The location of the different stations. The Simulated flow series were masked by the data available in GRDC.

| <i>River basin</i>   | <i>Drained area (km<sup>2</sup>)</i> | <i>Mean annual river discharge (mm/d)</i> | <i>Bias SIMUREF</i> | <i>Bias SIMURM</i> | <i>NSE SIMUREF</i> | <i>NSE SIMURM</i> |
|----------------------|--------------------------------------|-------------------------------------------|---------------------|--------------------|--------------------|-------------------|
| (a) <i>Essequibo</i> | 66 600                               | 2 033                                     | -156                | -202               | 0.77               | 0.63              |
| (b) <i>Maroni</i>    | 60 930                               | 1 549                                     | 489                 | 324                | 0.55               | 0.42              |
| (c) <i>Xingu</i>     | 446 203                              | 8 060                                     | 6 904               | 5 801              | -0.10              | -0.08             |
| (d) <i>Tapajos</i>   | 387 000                              | 10 688                                    | 3 321               | 2 357              | 0.48               | 0.07              |
| (e) <i>Tocantins</i> | 742 300                              | 10 858                                    | 8 388               | 7 820              | -0.67              | -0.74             |
| (f) <i>Araguaia</i>  | 376 660                              | 6 150                                     | 3 480               | 3 279              | 0.46               | 0.48              |
| (g) <i>Congo</i>     | 3 475 000                            | 38 617                                    | 12 652              | 11 314             | -3.52              | -3.27             |

TABLE 4.2 – List of the gauge stations of Fig. 7 and their main characteristics. The mean annual discharge and drained area are taken from the GRDC database. NSE is the Nash Sutcliffe Efficiency of the simulated river discharge as compared to the observed one.

Although the modified Reynolds map provides a more realistic representation of clay, the used PTF is still questionable. While ORCHIDEE uses the Van Genuchten model to solve the diffusion equation, the latter model is only suitable for soils with a uni-modal pore-size distribution, which is not the case for Clay Oxisols. A more accurate representation of Clay Oxisols would require a modification of the VG model to be able to deal with the bi-modal pore-size distribution. In an attempt to represent these soils, (Othmer et al., 1991) split the conductivity and the water retention curves in two; one curve characteristic of the intra-pedal pores system and the second one for the inter-pedal pores system. The resulting curve represented well the double behavior of the soil by exhibiting a double inflexion. Ross and Smettem (1993) and Durner (1994) suggest a similar approach by overlapping multiple unimodal retention curves to obtain a complex water retention curve, describing more accurately the multi-modal behavior of certain aggregated soils. Using a similar approach in ORCHIDEE would allow a further more realistic representation of Clay Oxisols.



# Chapitre 5

## Introduction de l'effet de la matière organique dans l'hydrologie d'ORCHIDEE

La texture est le principal contrôle des propriétés du sol, mais elle n'en est pas l'unique. Les propriétés hydrauliques d'un sol riche en matière organique (MO) diffèrent largement de celles d'un sol minéral, en particulier dans les zones de hautes latitudes où les basses températures favorisent l'accumulation de la MO dans le sol, ainsi que dans les zones tropicales humides où les sols saturés en permanence sont riches en MO. La présence de la MO dans le sol favorise son agrégation, et par conséquent, réduit sa densité apparente et augmente sa porosité. De plus en plus de LSMs tiennent compte de l'effet de la MO sur les processus hydriques de surface. Dans ce chapitre, on introduit l'effet de la MO sur les paramètres hydrauliques du sol dans ORCHIDEE, à l'échelle globale, de trois approches différentes : (i) en remplaçant la carte de porosité dans ORCHIDEE par une nouvelle carte issue de mesures directes de la densité apparente du sol, (ii) en utilisant des PTFs continues ayant pour variables prédictives la texture et la densité apparente, (iii) en considérant les paramètres du sol comme une combinaison pondérée des paramètres du sol minéral et de ceux du sol organique. On évalue ensuite ces trois approches en confrontant l'évapotranspiration et les débits simulés à des produits de référence. Enfin, en conclusion, on reprend les principaux résultats et on discute les limitations des méthodes utilisées.

### 5.1 Introduction

Soil organic carbon (SOC) has an important impact on soil physical properties, both hydraulic and thermal. This impact is more important in peatlands found in the high latitudes and high altitudes, where the low temperatures cause a slow decomposition of organic matter, leading to an accumulation of SOC, especially in the top soil layers.

Peatlands can also be found in permanently saturated tropical soils (Amazonia, Malaysia, Indonesia. . .) where the bacterial activity is limited by anoxia.

The presence of organic matter increases the aggregation of the soil, leading to a lower density and a higher porosity. While the porosity of mineral soil does not exceed 0.46 (Carsel and Parrish, 1988), organic matter porosity can reach 0.9 (Farouki, 1981). This results in a higher holding capacity and a lower suction (Khaleel et al., 1981; Yang et al., 2005), as well as a lower thermal conductivity and increased heat capacity (Lawrence and Slater, 2008). Churchman and Landa (2014) indicates metaphorically that texture and mineralogy are the “genetics” of soils, while organic matter content is the “diet”. Both should be considered equally while deriving soil physical properties and omitting the representation of the second in land surface models, which is often the case, is not a valid simplification, especially in the high latitudes, where SOC is high.

Many previous studies have confirmed the importance of representing SOC in LSMs. Letts et al. (2000) incorporated peatland in the Canadian Land Surface Scheme (CLASS), they distinguished three soil layers with three different set of characteristics, the top layer having the highest content of SOC. The deepest layer, which controls the drainage, was found to be the most sensitive to the change in soil parameters. Overall, they found that the representation of SOC improved the simulation of soil moisture and temperature. Lawrence and Slater (2008) represented SOC in the Community Land model (CLM) using the Global Soil Data Task (IGBP, 2000) soil carbon map. They computed soil hydraulic and thermal parameters as a weighted combination of the mineral parameters and the pure organic matter parameters, the weights being the mineral and the organic fractions respectively. They found more humid soils because of the increased soil porosity, but low soil saturation at the surface soil layer because of the high permeability at the surface, resulting in a decreased soil evaporation. Decharme et al. (2016) included the dependency of soil hydraulic and thermal parameters on SOC in the Interaction Soil-Biosphere-Atmosphere (ISBA) LSM, based on the work of Letts et al. (2000) and Lawrence and Slater (2008). They first computed a vertical peat soil profile for each hydraulic property before averaging mineral and organic properties. These changes, along with other changes in snow parametrization, resulted in improved simulated soil temperature profiles in cold regions, allowing the soil to remain cooler in the summer.

In a first effort to represent SOC in the ORCHIDEE LSM, Guimberteau et al. (2018) developed the ORCHIDEE-MICT, which is an updated version of ORCHIDEE, with an improved representation of high latitude processes, including the effects of SOC on soil porosity and thermal parameters. Soil parameters are computed in the same way as in Lawrence and Slater (2008), except that the SOC stocks are simulated by ORCHIDEE. Qiu et al. (2018) developed peat-specific hydrology in an ORCHIDEE version specific for peatland. It was introduced as a subgrid process, represented as a new PFT in a separate

soiltile, with different hydraulic properties. Surface runoff from other tiles is routed to the peat tile, in which drainage at the bottom is null. This study, however, only covers the high latitudes.

In this chapter, we analyze the impact of introducing SOC in the hydrology simulated by ORCHIDEE, at the global scale. Three different soil configurations are tested to this end, and the results are presented as follows. We first assess how the different tested configurations impact the simulated hydrological variables. We then evaluate evapotranspiration against two different products to see if introducing SOC improves the ET bias. The simulated river discharge is also evaluated against observed data, for two different climate datasets. Finally, the concluding section sums up the main results and discusses the limitations of the used methods.

## 5.2 Methods

Three different approaches for introducing SOC in the hydrology of ORCHIDEE are tested :

- Soil parameters based on direct measurements of bulk density,
- Soil parameters based on both texture and bulk density through a PTF
- Soil parameters calculated from the mineral fraction and the organic fraction of soil

### 5.2.1 Global soil porosity map

Because of the strong link between SOC content and soil porosity, this parameter can be used as a proxy of SOC. Soil porosity indicates the aeration of the soil, its compactness and the degree of aggregation of the soil, largely due to organic matter. Porosity is therefore a good indicator of SOC in organic-rich soils ([Saini, 1966](#)).

In ORCHIDEE, soil porosity is almost spatially uniform (Fig. 5.1a), it ranges between 0.36 and 0.46 when using the Reynolds soil texture map, and between 0.41 and 0.43 when using the Zobler soil texture map. However, it has been established that soil porosity has a much higher spatial variability and can reach high values often exceeding  $0.8 \text{ m}^3/\text{m}^3$  in northern peatlands and tropical organic-rich soils ([Radforth and Brawner, 1977](#)). Porosity depends on both the fraction of organic matter in the soil and its degree of decomposition. The largest porosities (over 0.9 ) are found in the undecomposed, uncompressed peat (Fibric peat) on the soil surface, and decrease with depth ([Boelter, 1968](#)).

Thus, soil porosity derived from soil texture alone, as it is done by default in ORCHIDEE, does not represent the actual physical condition of the aggregated organic-rich soils. Due

to their higher porosity, these soils will have a higher water holding capacity at saturation, and thus a different hydrological functioning.

Many studies provide global maps of soil porosity, either from direct measurements of bulk density, or through PTFs. The latter ones should necessarily have bulk density or organic carbon as a predictive variable, in addition to soil texture, in order to account for SOC influence (e.g. [Rawls et al., 2003](#); [Batjes, 1996](#)).

To analyse the impact of a realistic soil porosity that takes into account SOC, we run a simulation SIMUSOC1 forced by the soil porosity map provided by [Reynolds et al. \(2000\)](#), which was directly derived from a soil bulk density map by :

$$\theta_s = 1 - \frac{\rho_b}{\rho_s} \quad (5.1)$$

$\rho_b$  : bulk density  $\rho_s$  : soil particle density ( $= 2.65g.cm^{-3}$ )

To define  $\theta_s$  in this framework, we chose to use the Reynolds soil porosity map, for two reasons. Firstly, this map is consistent with the soil texture map, as it follows the same methodology, and is based on the same soil samples. Secondly, it is based on actual measurements of soil bulk density, and not derived using PTFs. The soil bulk density was measured using the core method ([fao, 1996](#)). The resulting soil porosity map is presented in Fig. 2.5b. It exhibits a wider range of variability, and is globally higher than in the original porosity in ORCHIDEE (Fig. 5.1a), with the highest values in tropical humid areas and northern peatlands.

We underline that the spatial patterns of the bias in simulated ET (as in Fig.3.5) is close to the spatial patterns of soil porosity in the Reynolds map (Fig. 5.1b). This is especially clear for the north American peatlands, where ORCHIDEE results in negative ET bias with both GSWP3 and CRUNCEP climate forcings (Fig. 3.5g,h). We expect an increase in evapotranspiration in these areas where porosity is increased, reducing the above-mentioned bias.

### 5.2.2 Global maps of soil hydraulic properties

Soil porosity is not the only parameter impacted by SOC. Due to the large pore size of organic-rich soils, permeability can be very high at the surface ([Boelter, 1968](#)). The water retention curve also presents different characteristics than that of mineral soils. In general, there is less retention compared to a mineral soil : at a given matric potential, less water content is found.

In this study, we tested two methods to account for the impact of SOC on hydraulic parameters.

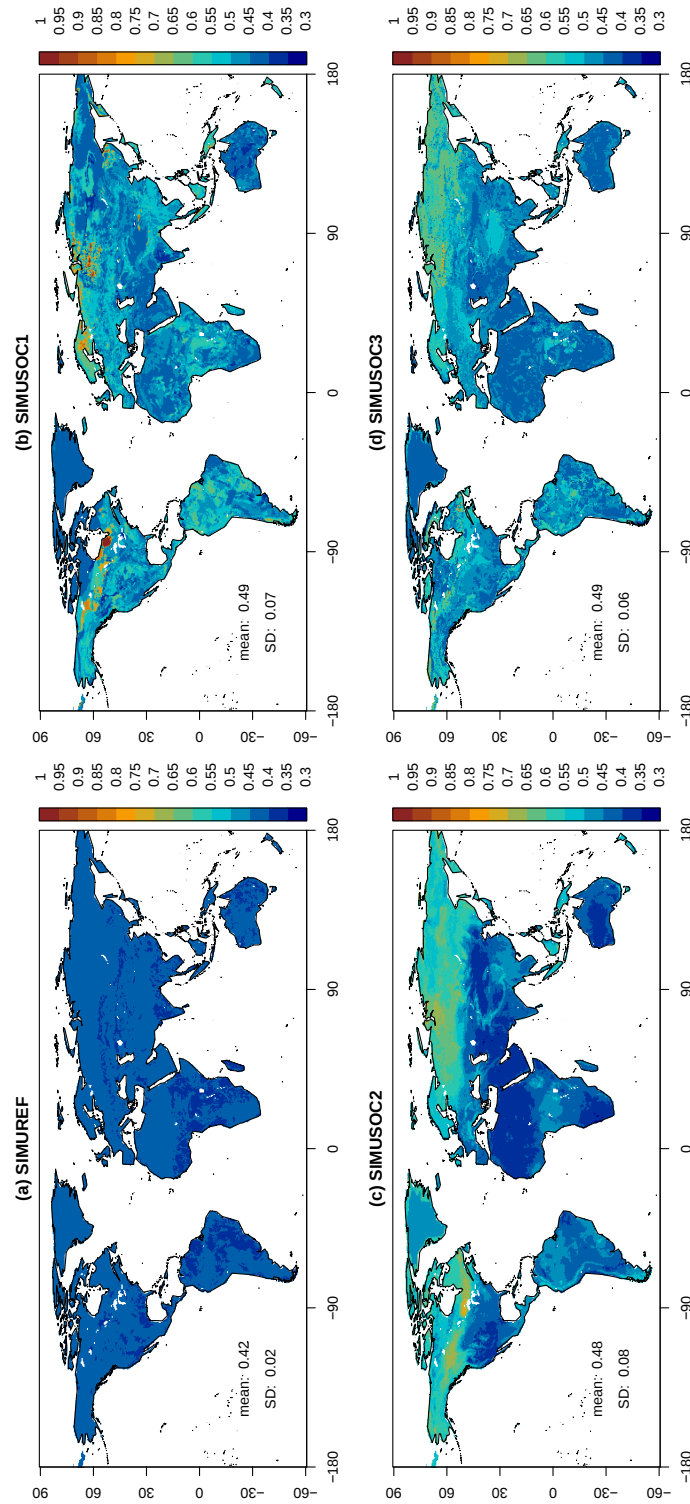


FIGURE 5.1 – Soil porosity maps (a) used by default in ORCHIDEE using the Reynolds soil texture map (b) from [Reynolds et al. \(2000\)](#) (c) from [Zhang et al. \(2018\)](#) (d) derived from a SOC map combined to a soil texture map.

First, we used already existing soil parameter maps derived from soil texture and soil bulk density using PTFs from [Zhang et al. \(2018\)](#), which defines the SIMUSOC2 simulation.

In the second run, we used a SOC map simulated by ORCHIDEE, which we combined to soil texture to derive the soil parameters (SIMUSOC3).

For SIMUSOC2, we directly use the soil parameter maps provided by [Zhang et al. \(2018\)](#). They are provided globally at a high resolution of  $1km^2$ , and were built using PTFs that were constructed using a machine learning approach. In their paper, [Zhang et al. \(2018\)](#) developed five different PTFs with different predictive variables. We selected the PTF that utilizes bulk density and fractions of sand, silt and clay as predictive variables, the bulk density being the representative variable of SOC. The resulting maps are produced for only three Van Genuchten parameters ( $K_s, \theta_s, \theta_r$ ), required for the model of [Kosugi \(1994\)](#), and are based on the sand, silt, clay and bulk density given by SoilGrids ([Hengl et al., 2014](#)).

As they provided the soil parameters of the Kosugi model ([Kosugi, 1994](#)), we only could use the  $k_s$ ,  $\theta_r$  and  $\theta_s$  parameters which are common with the Van Genuchten model. To stay consistent with their method, we derived  $n$  and  $\alpha$  from the same soil texture map (SoilGrids), and the PTFs of [Schaap et al. \(2001\)](#), which were constructed along similar lines to those of [Zhang et al. \(2018\)](#).

For SIMUSOC3, we assume that soil is a combination of mineral soil and organic matter, following [Lawrence and Slater \(2008\)](#), and compute soil physical properties as the weighted averages of mineral soil and pure organic soil. The fraction of organic soil was defined as :

$$f_{SOC} = \frac{\rho_{SOC}}{\rho_{SOC,max}} \quad (5.2)$$

where  $f_{SOC}$  is fraction of SOC,  $\rho_{SOC}$  is soil carbon density in a given pixel, and  $\rho_{SOC,max}$  is the maximum soil carbon density, which is the bulk density of peat; it is equal to  $130 \text{ kgC.m}^{-3}$  ([Lawrence and Slater, 2008](#)).

Hydraulic parameters of the mineral fraction are the default parameters in ORCHIDEE, derived using the modified Reynolds soil texture map and the [Carsel and Parrish \(1988\)](#) PTF. Hydraulic parameters of pure organic matter depend on the state of decomposition of the organic matter.

At the soil surface, SOC is mostly found under undecomposed and uncompressed form. This layer is called fibric peat and is characterized by an important porosity and hydraulic conductivity. These parameters decrease with depth. Overall, we can distinguish three soil layers in the organic soil column; the top layer is fibric peat, which is only few centimeters deep. The second and third layers are hemic and sapric peat respectively. These layers have different hydraulic properties. For each layer, [Letts et al. \(2000\)](#) designed a Van Genuchten

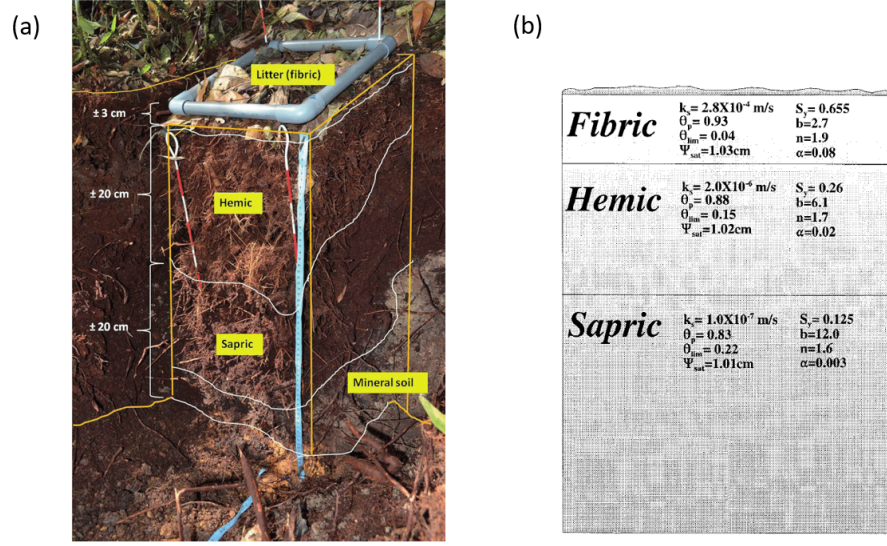


FIGURE 5.2 – (a) Soil organic matter profile (Jeyanny et al., 2016) and (b) the corresponding hydraulic parameters (adapted from Letts et al. (2000)).

water retention curve based on organic soils data from multiple studies. The resulting Van Genuchten parameters are shown in Figure 5.2.

We used the weighted average of the parameters of the three layers. The weights being the corresponding depths to each layer (Fig. 5.2a) :

$$P = f_{SOC} \cdot P_{SOC} + (1 - f_{SOC}) \cdot P_{mineral} \quad (5.3)$$

where  $P$  is the soil parameter (including both mineral and organic fractions),  $P_{SOC}$  is the value for pure organic soil, and  $P_{mineral}$  its value for mineral soil.

Large differences are found between the existing soil carbon stock maps, especially in the boreal regions (Tifafi et al., 2018). In this study, we decided to use the global SOC map simulated by ORCHIDEE (Fig. 5.3), which we combined to the modified Reynolds soil texture map to derive the soil parameters.

### 5.2.3 Simulation summary

All the simulations were run using ORCHIDEE version tag.2-2 (described in section 4.2.3), following the same protocol as described in chapter 4. The simulations were driven by two different climate datasets : the GSWP3-v1 meteorological dataset (Kim, 2017), with a 3-

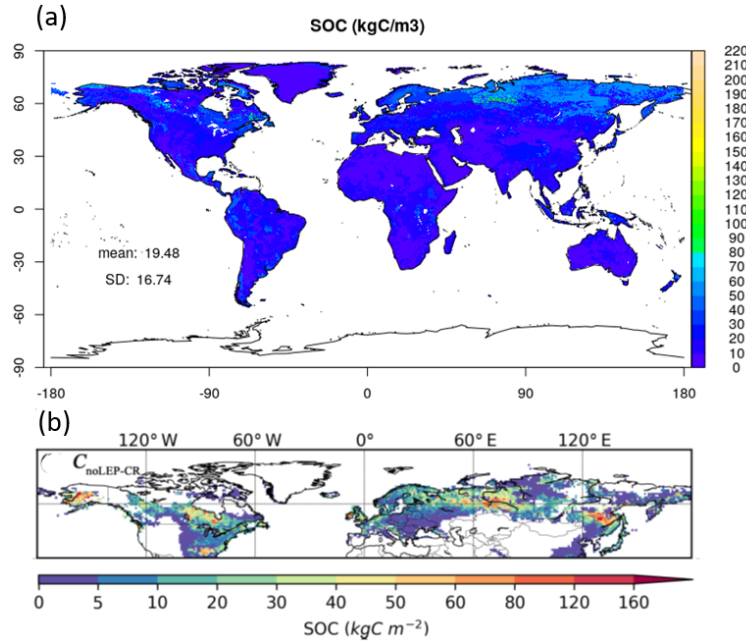


FIGURE 5.3 – SOC map simulated by ORCHIDEE : (a) The global simulated SOC map with a linear legend scale, and (b) Simulated SOC in the northern peatlands, with a non-linear legend scale, taken from (Qiu et al., 2019).

hourly time step and based on the 20th Century Reanalysis (20CR; Compo et al. (2011), and the CRU-NCEPv7 (Wei et al., 2014b), which is a 6-hourly meteorological dataset based on the NCEP/NCAR reanalysis (Kalnay et al., 1996) and extended beyond 1957–1996 in near-real time. We run a total of 8 simulations, including two reference simulations, for each climate forcing (Tablee 5.1).

Global soil porosity is globally 17% higher in SIMUSOC1 and SIMUSOC3 as compared to SIMUREF, and 14% higher in SIMUSOC2 (Fig. 5.1). Although the global averaged porosity is equivalent among SIMUSOC1, SIMUSOC2 and SIMUSOC3, the spatial distribution differs substantially. In SIMUSOC2, the high porosity values are mostly gathered in the high latitudes, whereas in the SIMUSOC1 and SIMUSOC2, high porosity values are also found in the tropics.

In SIMUSOC1, the soil porosity map is the only driver of change compared to SIMUREF, while in SIMUREF2 and SIMUREF3, all the soil parameters change (Table 5.1). SIMUREF is the reference simulation to which SIMUSOC1 and SIMUSOC2 will be compared to analyze the impact of the soil parameter change. SIMURM is used here as the reference simulation for SIMUSOC3, since the latter one uses the modified Reynolds soil texture map as an input, like in SIMURM.

|          | Climate forcing | Soil texture map              | Parameters derived from texture                                    | Other parameters from                              |
|----------|-----------------|-------------------------------|--------------------------------------------------------------------|----------------------------------------------------|
| SIMUREF  | GSWP3           | Reynolds                      | $K_s, n, \alpha, \theta_s, \theta_r$<br>(Carsel & Parrish, 1988)   | -                                                  |
|          | CRU-NCEP        |                               |                                                                    |                                                    |
| SIMURM   | GSWP3           | Modified Reynolds for Oxisols | $K_s, n, \alpha, \theta_s, \theta_r$<br>(Carsel & Parrish, 1988)   | -                                                  |
| SIMUSOC1 | GSWP3           | Reynolds                      | $K_s, n, \alpha, \theta_r$<br>(Carsel & Parrish, 1988)             | $\theta_s$ from Reynolds et al. (2000)             |
|          | CRU-NCEP        |                               |                                                                    |                                                    |
| SIMUSOC2 | GSWP3           | SoilGrids                     | $n, \alpha$<br>(Schaap et al., 2001)                               | $K_s, \theta_s, \theta_r$ from Zhang et al. (2018) |
|          | CRU-NCEP        |                               |                                                                    |                                                    |
| SIMUSOC3 | GSWP3           | Modified Reynolds for Oxisols | $K_s, n, \alpha, \theta_s, \theta_r$ *<br>(Carsel & Parrish, 1988) | -                                                  |

TABLE 5.1 – List of the simulations used in this chapter. \* these parameters are derived both from soil texture and SOC.

## 5.3 Results

### 5.3.1 Impact of the Reynolds soil porosity map

The change in soil porosity map impacts differently the simulated water fluxes. Global soil porosity increases by 17%, resulting in an increase by 16% in soil moisture and 1.7% in evapotranspiration. Soil moisture is the most impacted variable, with very similar change patterns to that of porosity (Fig. 5.4, with a spatial correlation of 0.88. This is a direct result of the increase in the field capacity. In fact, two other soil parameters are impacted by the change of porosity : the field capacity and the wilting point. They both increase with an increasing porosity. As the field capacity increases faster, the available water capacity increases. The change in ET is mostly limited to the equatorial zones, although the highest increase in porosity is found in the boreal zones. The reason is that the main limiting factor for ET in these zones is not water, but energy. Even with a higher moisture content in the soil, there is not enough energy to increase its evaporation. Thus, the excess water in these areas is routed to runoff (Fig. 5.4. The opposite happens in the tropical humid areas, where the ET limiting factor is water. In these areas, the higher soil moisture results in an increased ET, and surface runoff remains unimpacted. Introducing a realistic soil porosity map only weakly impacts the simulated ET and does not bring a noticeable improvement to ET bias.

### 5.3.2 Impact of the change in soil parameter maps

#### Simulated water fluxes

SIMUSOC2 and SIMUSOC3 lead to quite different results, in both amplitude and behavior. Replacing soil parameters in ORCHIDEE by the ones from (Zhang et al., 2018) (change from SIMUREF to SIMUSOC2) has a similar effect to the one we have with the

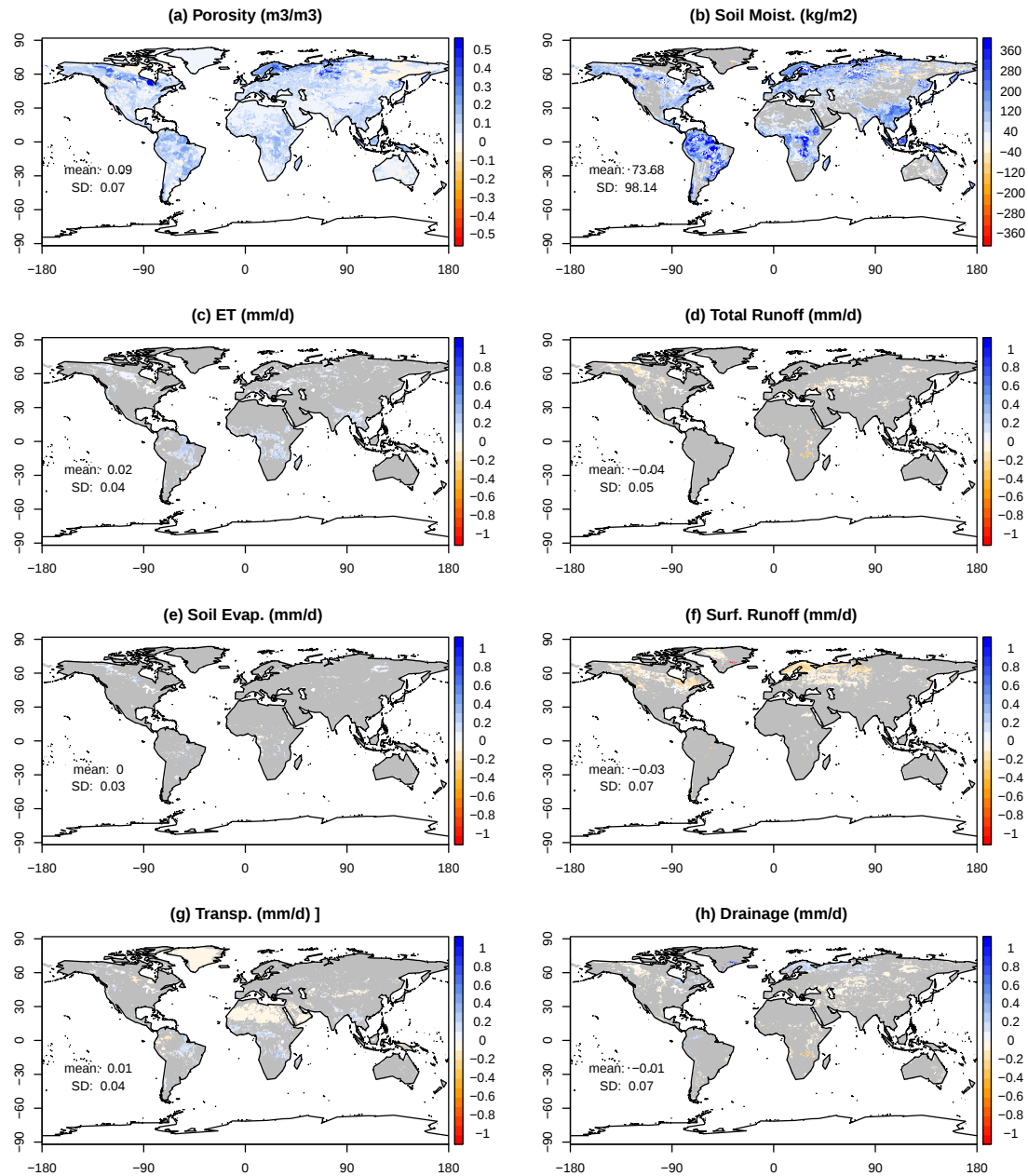


FIGURE 5.4 – (a) Difference in soil porosity and (b)-(h) difference in simulated variables (averaged over the period 1980-2010, using the GSWP3 forcing), between SIMUSOC1 and SIMUREF. Grey color indicates that the difference is not statistically significant based on a Student's t-test (with a p value lower than 0.05). Mean and standard deviation are averaged over the globe excluding Antarctica.

Reynolds (2000) soil porosity map (change from SIMUREF to SIMUSOC1), except that the effect are more intensified with the first change (Fig. 5.5, 5.6).

Evapotranspiration significantly increases in both the high latitude areas and the tropical areas. In the high latitudes, the increase in ET is entirely due to an increase in soil evaporation (Fig. 5.5e), while the increase of ET in the tropics was due to the increase in transpiration (Fig. 5.5g). The spatial patterns of transpiration change (Fig. 5.5g) are a consequence of the change in the  $\alpha$  parameter. In fact, in SIMUSOC2,  $\alpha$  was very low compared to  $\alpha$  in SIMUREF. Since  $\alpha$  was the inverse of air entry suction, it became therefore more difficult for soil water to be discharged by the roots, which explained the lower transpiration. In the tropics, and more specifically in the clay soils of Reynolds,  $\alpha$  in SIMUSOC2 was very high compared to the one in SIMUREF, the opposite process happened, leading to an increase in transpiration.

### Evapotranspiration bias

The increase of evapotranspiration in both SIMUSOC2 and SIMUSOC3 resulted in an improvement of the evapotranspiration bias, in respect to the GLEAM product (Fig. 5.7). The mean global bias changed from -0.09 to -0.02 with SIMUSOC2 and to -0.06 with SIMUSOC3. The important negative biases in SIMUREF related to the misrepresentation of clays disappeared in SIMUSOC2, which suggests that the parameters of Zhang et al. (2018) allow the distinction of the different types of clays.

Before bringing any change to soil parameters (in SIMUREF), ORCHIDEE underestimates evapotranspiration in the northern part of the globe ( $lat > 40^\circ$ ) and in the equatorial zone between  $-20^\circ$  and  $10^\circ$ , compared to both the GLEAM and the Jung products (Fig. 5.8). SIMUSOC2 significantly improves the evapotranspiration simulation in the northern areas, and to a less extent in the equatorial area. In Fig. 5.8, the curves of SIMUSOC3 closely follow the ones of SIMUREF, even in the high latitudes where, however, soil porosity was largely higher compared to SIMUREF (Fig. 5.9a). This is due to the available water capacity being very similar in both SIMUREF and SIMUSOC3 (Fig. 5.9b). This suggests that soil porosity change was not the main driver of the ET change. This can also be seen around latitudes  $35^\circ - 40^\circ$  where porosity in SIMUSOC2 was lower than in SIMUREF (Fig. 5.9), but the simulated ET was higher (Fig. 5.8), in line with the available water capacity (Fig. 5.7b).

Although the parameters combined from SOC and texture maps (SIMUSOC3) had a small impact on the evapotranspiration components (Fig. 5.5), they strongly impacted the partitioning of runoff between surface runoff and total runoff (Fig. 5.6), the global partition runoff-drainage changed from 37% – 63% to 21% – 79%. Which had a direct impact on hydrographs (Fig. 5.10).

### Simulated river discharge

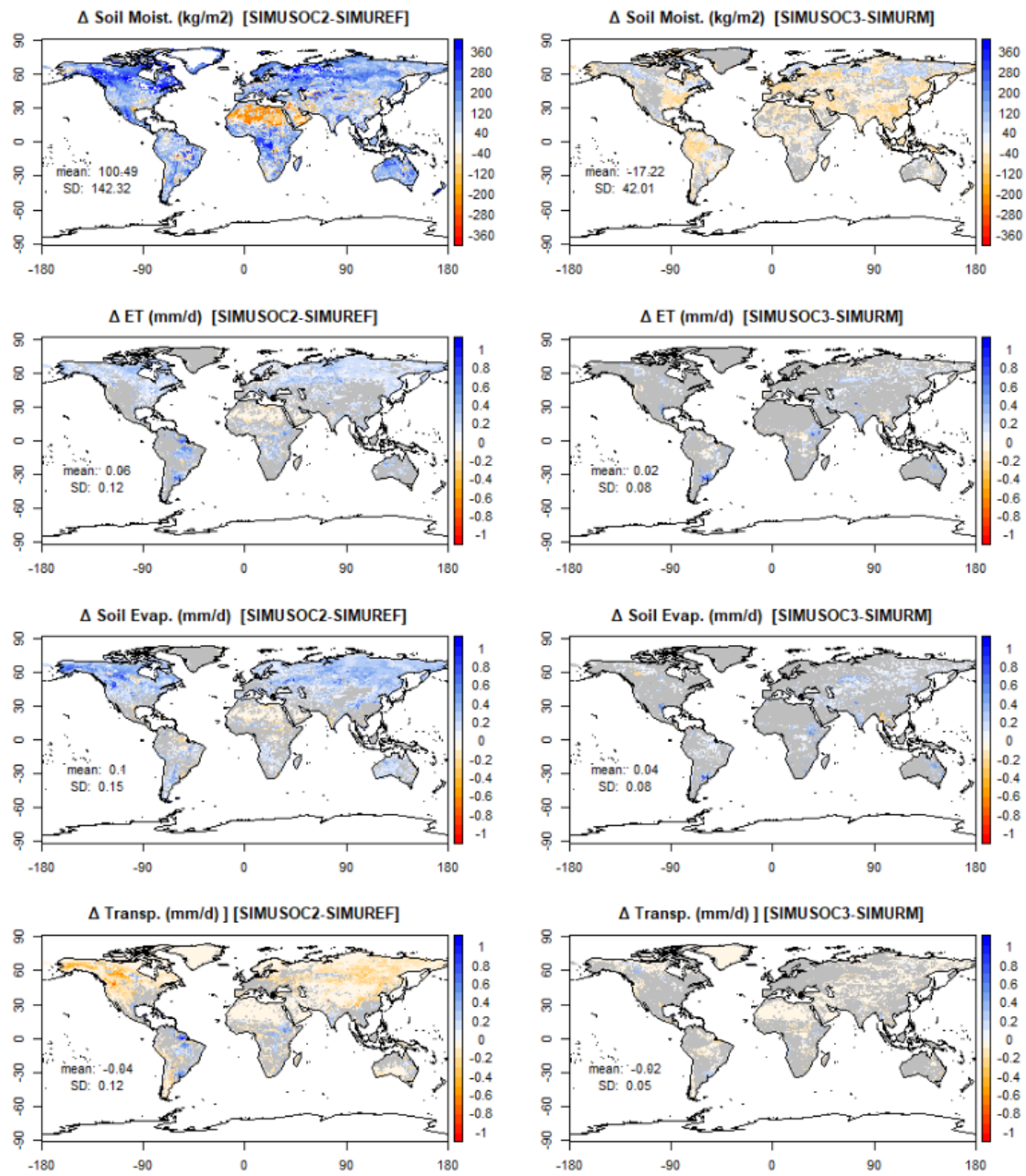


FIGURE 5.5 – Difference in simulated soil moisture and evapotranspiration variables (averaged over the period 1980-2010, using the GSWP3 forcing), using the GSWP3 forcing, in the left column : between SIMUSOC2 and SIMUREF; in the right column between SIMUSOC3 and SIMURM. Grey color indicates that the difference was not statistically significant based on a Student/s t-test (with a p value lower than 0.05). Mean and standard deviation are averaged over the globe excluding Antarctica.

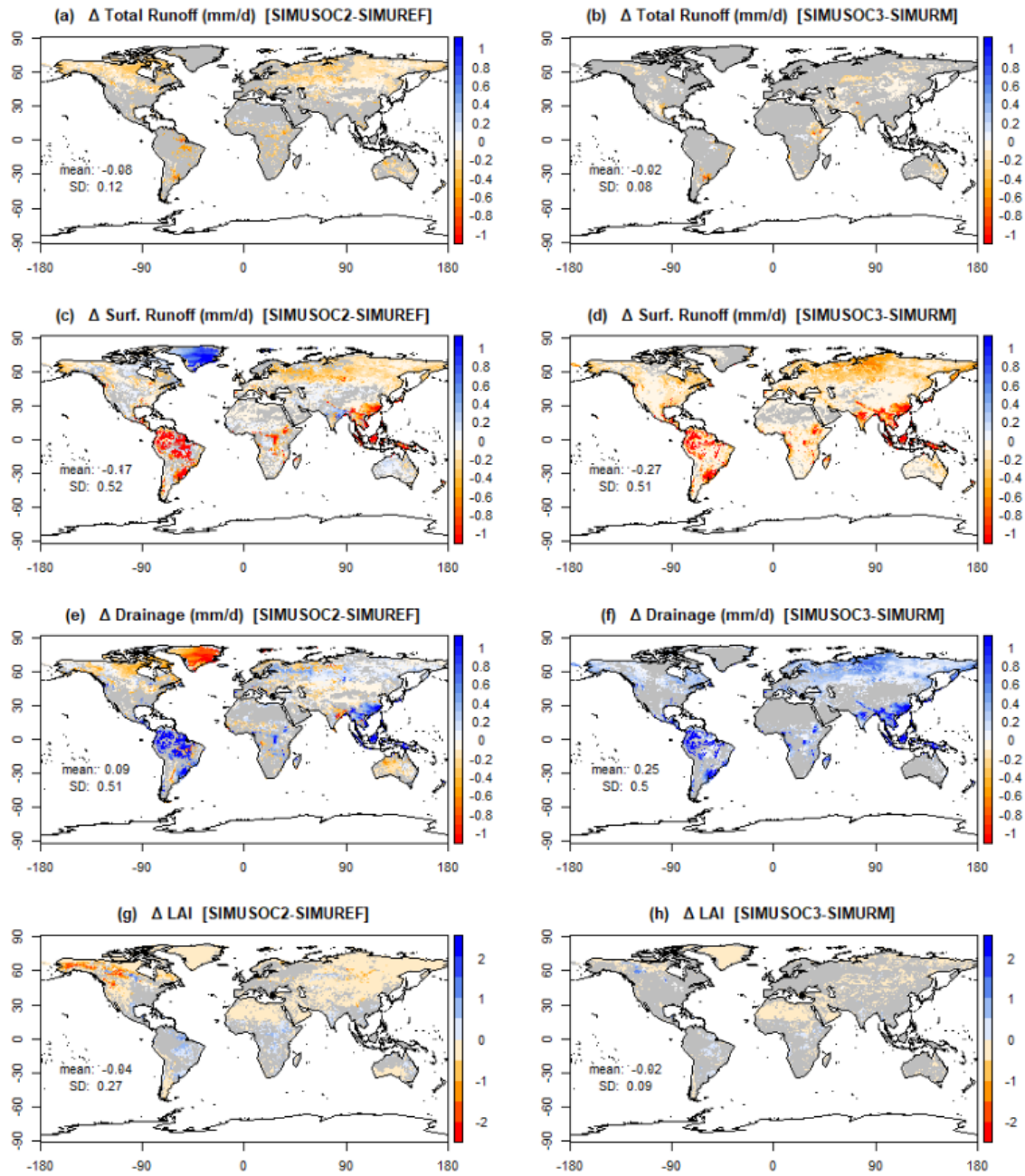


FIGURE 5.6 – Difference in simulated runoff variable and Leaf Area Index (LAI) (averaged over the period 1980-2010, using the GSWP3 forcing), in the left column : between SIMUSOC2 and SIMUREF ; in the right column between SIMUSOC3 and SIMURM. Grey color indicates that the difference was not statistically significant based on a Student's t-test (with a p value lower than 0.05). Mean and standard deviation were averaged over the globe excluding Antarctica.

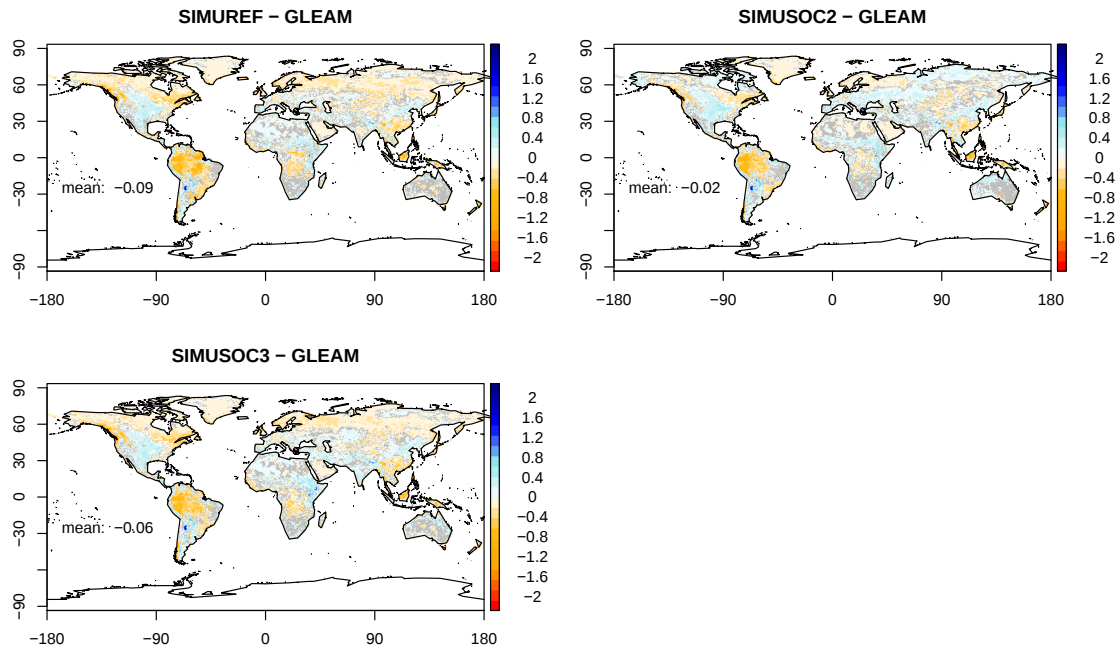


FIGURE 5.7 – Evapotranspiration bias maps with respect to the GLEAM product (with GSWP3 forcing). Grey color indicates that the difference was not statistically significant based on a Student's t-test (with a p value lower than 0.05). Mean and standard deviation were averaged over the globe excluding Antarctica.

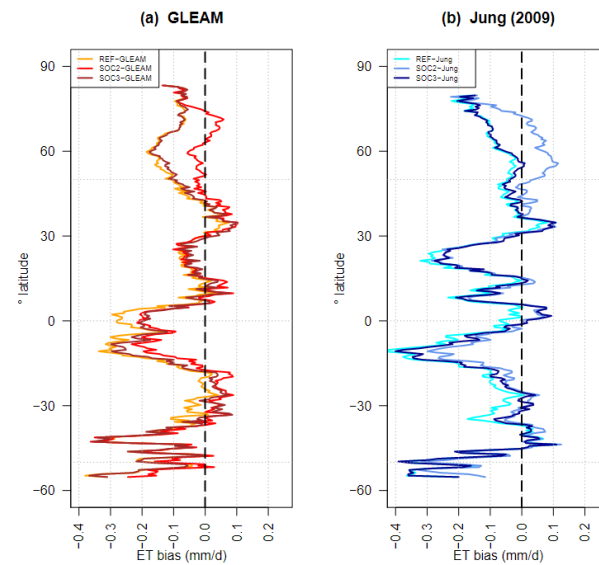


FIGURE 5.8 – Zonal averages of evapotranspiration bias in respect to (a) the GLEAM product and (b) the Jung (2009) product.

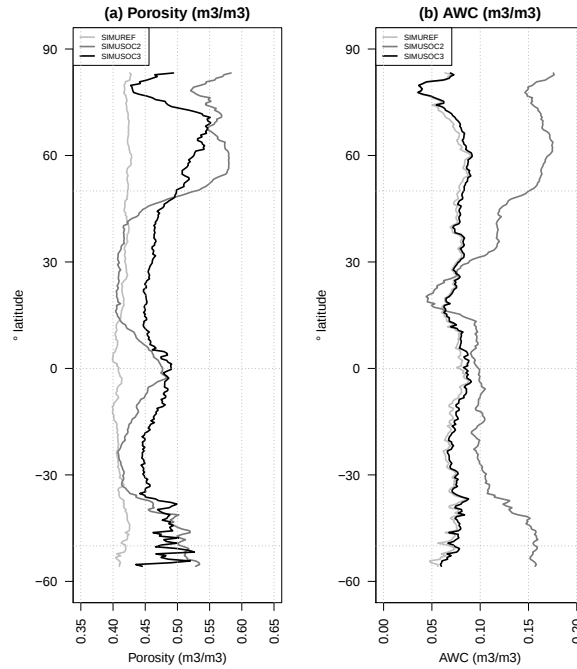


FIGURE 5.9 – Zonal averages of (a) soil porosity and (b) available water capacity for all the simulations used in this chapter (listed in Table 5.1).

The impact of changing the soil parameter maps on the hydrographs varied depending on the basin. The common effect however was a light delay of the peak flow, except in the Mississippi river where an opposite lag was observed with SIMUSOC3. SIMUSOC2 resulted in the lowest mean annual discharge (Table. 5.2), which was consistent with the important increase in ET. Combining soil texture and SOC to estimate soil parameters (SIMUSOC3) resulted in a delayed peak flow and a smoother hydrograph in most basins. This was due to the important change in the partitioning of total runoff between surface runoff and drainage, the latter became the main component of total runoff, and drainage reached the streamflow slower, which explained the delay. It is worth to note the important improvement of the hydrographs in the Ob, with both SIMUSOC2 and SIMUSOC3, when using the GSWP3 climate forcing (Fig. 5.10g). The peak flow significantly decreased to better match the observed one. SIMUSOC3 overestimated the flow at the recession, while SIMUSOC2 stayed in line with the observed flow. ORCHIDEE highly underestimated the river discharge in some basins of the boreal regions (eg. The Lena, the Yenisey). Floodplains were not represented in this version of ORCHIDEE which might explain the underestimation of the river discharge. In another version specifically developed for the high latitudes (ORCHIDEE-MICT), ORCHIDEE performed better in these basins (Guimberteau et al., 2018). An important difference in the hydrograph amplitude was observed

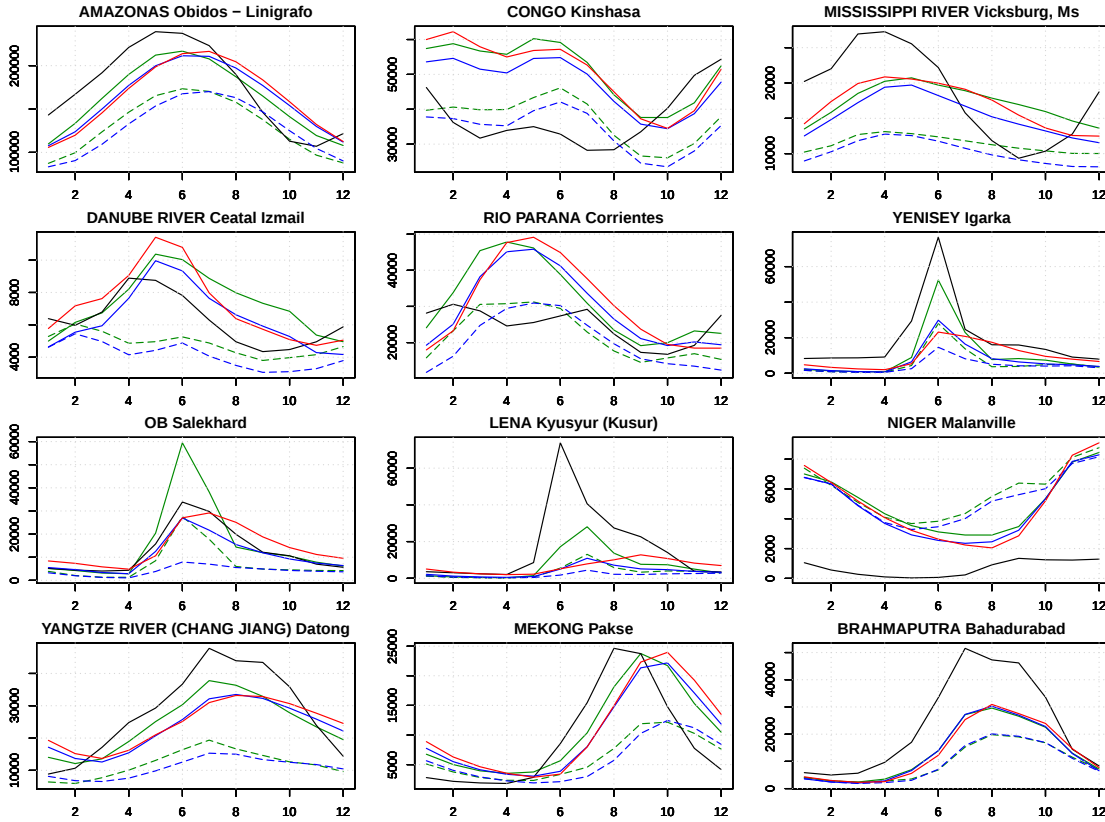


FIGURE 5.10 – Simulated river discharge of the main river basins, against observed river discharge from GRDC, between 1980-2010. Green for SIMUREF, blue for SIMUSOC2 and red for SIMUSOC3. Solid line is for GSWP3 climate forcing and dashed line is for CRU-NCEP.

between GSWP3 and CRUNCEP-forced simulations. The latter mostly underestimated the observed river discharge (Table 5.2), and ORCHIDEE better captured the seasonality with GSWP3 in most basins (Fig. 5.10).

To further evaluate the simulated river discharge, we selected 714 GRDC stations, which have an upstream area error below 5% compared to ORCHIDEE, and have data available within the period 1980-2010. We first notice that in many stations, the bias is very high, exceeding 100% in more than 100 stations, when using GSWP3, and more than 200 stations, when using CRUNCEP (Fig. 5.11). Most strongly biased stations are located in the northern hemisphere. Most stations however are positively correlated to the observations, with 42 to 60% (depending on the simulation) of the stations with a correlation higher than 0.5 (Fig. 11). Looking at Figures 5.11-5.13, we clearly see that ORCHIDEE performs better in simulating river discharge with GSWP3 than with CRUNCEP, especially in the high latitudes.

|                    | Drained area<br>(km <sup>2</sup> ) | Mean annual<br>river discharge<br>(mm/d) | Bias<br>SIMUREF<br>GSWP3<br>(%) | Bias<br>SIMUREF<br>CRUNCEP<br>(%) | Bias<br>SIMUSOC2<br>GSWP3<br>(%) | Bias<br>SIMUSOC2<br>CRUNCEP<br>(%) | Bias<br>SIMUSOC3<br>GSWP3<br>(%) |
|--------------------|------------------------------------|------------------------------------------|---------------------------------|-----------------------------------|----------------------------------|------------------------------------|----------------------------------|
| <b>Amazon</b>      | 4680000                            | 175000                                   | -7                              | -26                               | -7                               | -27                                | -6                               |
| <b>Congo</b>       | 3475000                            | 37546                                    | 37                              | -1                                | 26                               | -9                                 | 35                               |
| <b>Mississippi</b> | 2964255                            | 18583                                    | -7                              | -39                               | -17                              | -45                                | -9                               |
| <b>Danube</b>      | 807000                             | 6291                                     | 16                              | -23                               | 2                                | -35                                | 15                               |
| <b>RIO PARANA</b>  | 1950000                            | 24790                                    | 26                              | -11                               | 19                               | -18                                | 24                               |
| <b>Yenisey</b>     | 2440000                            | 18950                                    | -47                             | -69                               | -62                              | -78                                | -49                              |
| <b>Ob</b>          | 2949998                            | 12729                                    | 21                              | -43                               | -16                              | -68                                | 13                               |
| <b>Lena Kusur</b>  | 2430000                            | 17113                                    | -58                             | -80                               | -78                              | -90                                | -63                              |
| <b>Niger</b>       | 1000000                            | 694                                      | 630                             | 738                               | 580                              | 683                                | 606                              |
| <b>Yangtze</b>     | 1705383                            | 28064                                    | -13                             | -57                               | -17                              | -61                                | -14                              |
| <b>Mekong</b>      | 545000                             | 9221                                     | 16                              | -33                               | 11                               | -37                                | 19                               |
| <b>Brahmaputra</b> | 636130                             | 23165                                    | -43                             | -60                               | -43                              | -61                                | -42                              |

TABLE 5.2 – List of the river basins in Fig.5.10 and their main characteristics. The mean annual discharge and drained area were taken from the GRDC database.

The Nash coefficients are higher with GSWP3 in the high latitudes, but lower in the tropical areas (Fig. 12). Using the soil parameter maps from Zhang et al. (2018) improves the Nash coefficient in many stations. 362 stations have an  $NSE \geq 0$  with SIMUREF while there are 433 stations with SIMUSOC2 (using the GSWP3 forcing). The relative bias however worsens, with 237 stations exceeding 100% bias, while they are 118 with SIMUREF.

To examine whether the bias in the simulated river discharge (noted Q hereafter) is consistent with that of the simulated evapotranspiration (noted ET), we compare both these biases over 10 basins, using two different ET products for bias calculation. Results are displayed in Figure 5.14.

A good consistency between the ET bias and the Q bias is found when the ET bias has the opposite value of the Q bias; in Figure 5.14, the perfect consistency would be the curve  $y=-x$ . We observe a good consistency between ET bias and Q bias in the Danube, Mississippi, the Ob and the Mekong basins, whichever the used forcing datasets. This indicates that precipitation over these basins was correctly represented in the climate forcings.

In the Amazon and the Brahmaputra basins, CRUNCEP led to a higher discrepancy between ET bias and Q bias. The high negative Q bias in the Amazon, together with its negative ET bias might be due to the forcing datasets underestimating precipitation over this basin (Guimberteau et al., 2012).

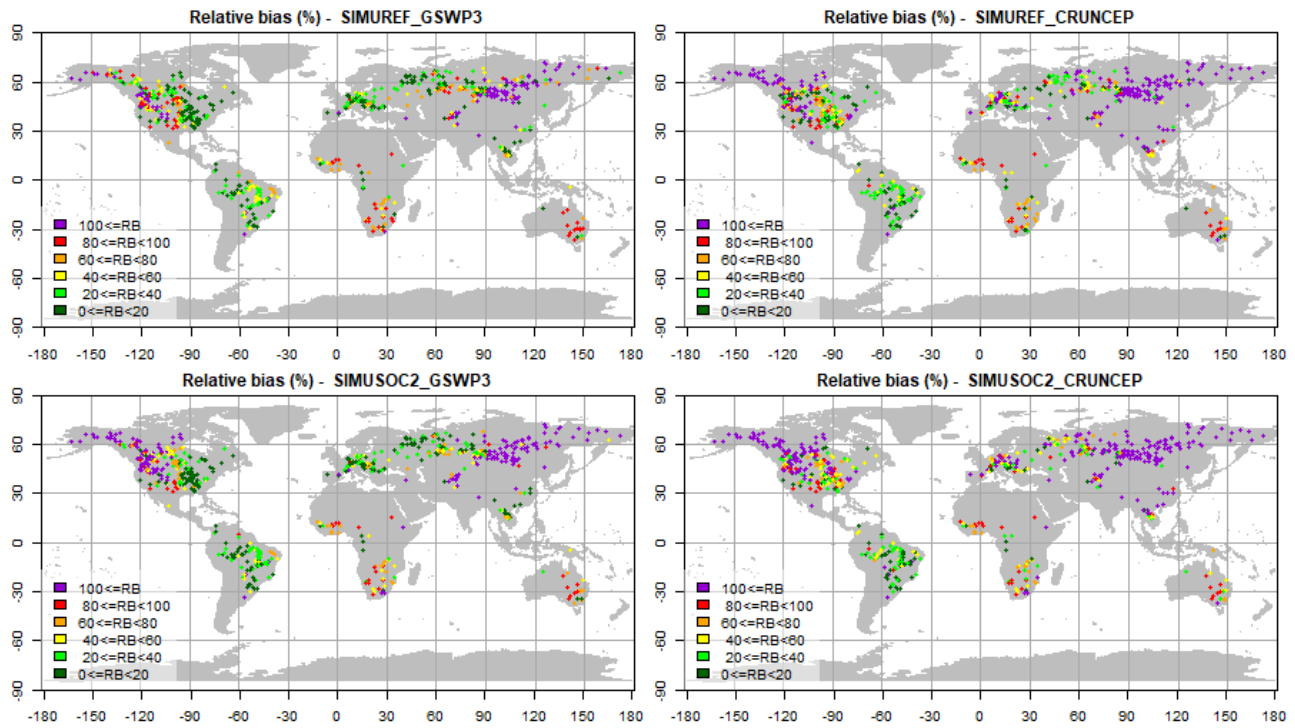


FIGURE 5.11 – Absolute value of the relative Bias calculated for 714 GRDC discharge stations which have the same upstream area as in ORCHIDEE (with a 5% tolerance), for SIMUREF (top line) and SIMUSOC2 (bottom line), using GSWP3 (in the left) and CRUNCEP (in the right).

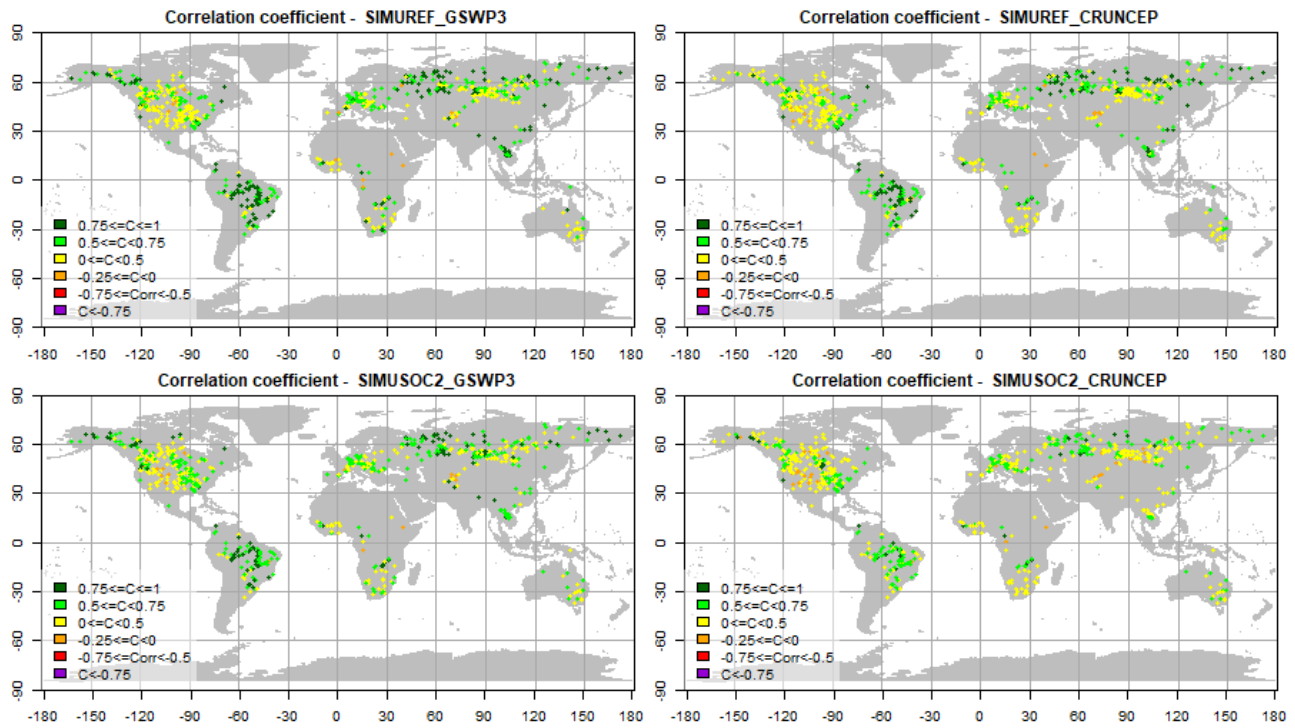


FIGURE 5.12 – Correlation coefficients calculated for 714 GRDC discharge stations which have the same upstream area as in ORCHIDEE (with a 5% tolerance), for SIMUREF (top line) and SIMUSOC2 (bottom line), using GSWP3 (in the left) and CRUNCEP (in the right).

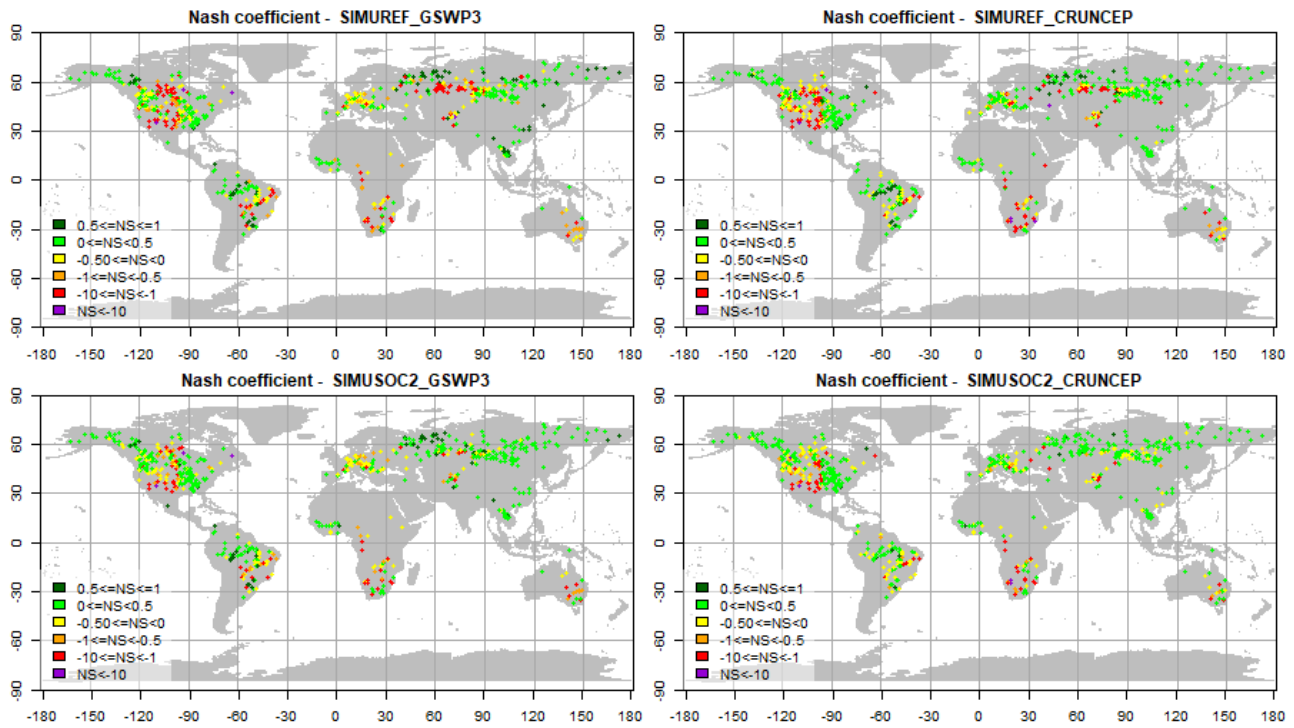


FIGURE 5.13 – Nash-Sutcliffe coefficients calculated for 714 GRDC discharge stations which have the same upstream area as in ORCHIDEE (with a 5% tolerance), for SIMUREF (top line) and SIMUSOC2 (bottom line), using GSWP3 (in the left) and CRUNCEP (in the right).

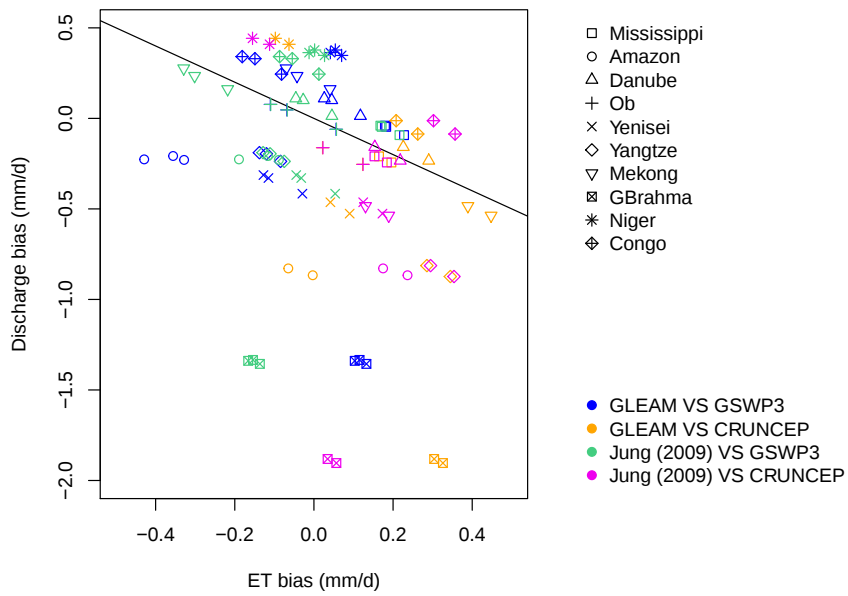


FIGURE 5.14 – Comparison of the discharge bias and the ET bias over 10 basins, over the period 1980-2010, resulting from SIMUREF, SIMUSOC2 and SIMUSOC3, using both the GSWP3 and the CRUNCEP climate forcings. ET bias was computed in respect to the GLEAM product and the product from [Jung et al. \(2009\)](#). The strain line represents  $y=-x$ .

## 5.4 Conclusion and discussion

This study consists in an effort to represent SOC in the hydrology simulated by ORCHIDEE. Initially, ORCHIDEE derives soil hydraulic parameters from soil texture alone; this does not allow a realistic representation of peatlands, which cover around 3 to 5% of the Earth's land surface (Qiu et al., 2018).

We introduce the SOC in ORCHIDEE by replacing the soil parameter maps with new ones that include the impact of SOC. We start by replacing the soil porosity map alone, then we replace all the soil parameters by the PTFs provided by Zhang et al. (2018), and finally, we combine a soil texture map to a SOC map to derive the soil hydraulic parameters.

Replacing the soil porosity alone had a weak impact on the simulated water fluxes. The combination of texture and SOC had a weak impact on simulated evapotranspiration components, but an important impact on the runoff components; the global partition runoff-drainage changes from 37%-63% to 21%-79%, which leads to a reduction of the peak flow and a smoothing of the simulated hydrographs, since drainage takes longer time to reach the stream. The soil parameter maps provided by Zhang et al. (2018) significantly improve the evapotranspiration bias in both the boreal areas and the tropical areas. The global ET bias increases from -0.09 to -0.02 (improved by 78%). The simulated river discharge is also relatively improved with these parameter maps. However, no conclusion can be drawn as to whether introducing SOC improves the simulation of river discharge, since the performance of ORCHIDEE is mediocre in capturing river discharge in many stations, additionally, there remains a high uncertainty in the climate forcing, which is the main driver of the simulated river discharge.

Introducing SOC in the soil hydrology allows a more realistic representation of soils in ORCHIDEE. However, the presence of organic matter does not only impact the soil hydraulic properties, but the thermal ones as well. Organic-rich soils are known to have a lower thermal conductivity and higher heat capacity compared to mineral soils (Farouki, 1981), leading to cooler soils (Bonan and Shugart, 1989; Lawrence and Slater, 2008), which in turn could affect the latent heat flux, and thus, the evapotranspiration.

Soil parameter maps from Zhang et al. (2018), which show encouraging results, are based on the SoilGrids SOC map. Tifafi et al. (2018) found that large differences exist between SoilGrids and other existing databases (Fig. 5.15). SoilGrids estimates a total soil carbon stock of 3400 Pg while, for example, it is only estimated at 2500 Pg in the HWSD. It is also shown that SoilGrids underestimates the carbon stocks by up to 40% when compared to field data in the USA, which suggests an important underestimation of SOC in SoilGrids. The choice of the SOC map is therefore a source of uncertainty in the deriving the soil parameters. It would be interesting to apply the PTFs developed by Zhang et al. (2018) on a different SOC map, to analyze to which extent the choice of the SOC map impacts

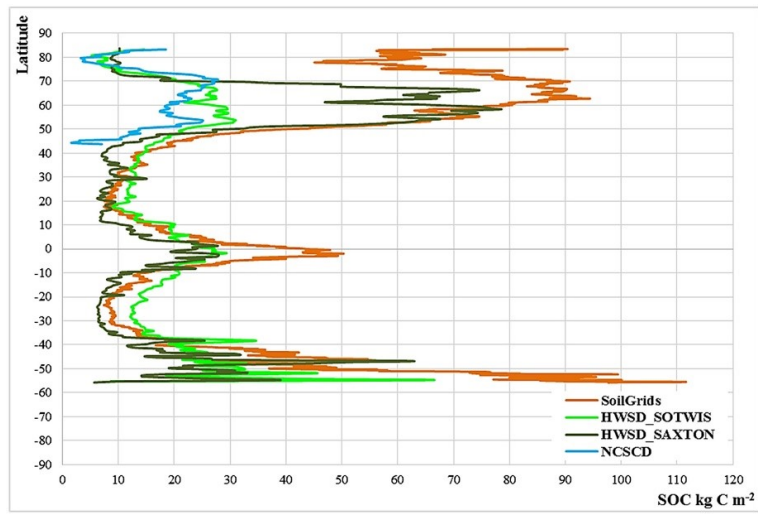


FIGURE 5.15 – Zonal averages of the total carbon stock ( $\text{kgC}/\text{m}^2$ ) on the (0, 1m) upper layer for different databases. (taken from [Tifafi et al. \(2018\)](#)).

the hydrology in ORCHIDEE.



# Chapitre 6

## Etude régionale en Afrique de l'Ouest

### 6.1 Introduction

Dans les chapitres précédents, nous avons vu que les propriétés du sol sont déterminantes dans le partitionnement de l'évapotranspiration et de l'écoulement. Leur impact est d'autant plus important que l'on descend en échelle. Afin de pousser plus loin notre étude sur le lien entre les sols et les processus hydriques de surface, nous nous intéressons dans ce chapitre à une modélisation locale de petite échelle. En effet, à cause de la faible résolution à laquelle opèrent la plupart des LSM, une maille couvre une large surface avec potentiellement de fortes hétérogénéités des surfaces, que ce soit dans l'occupation du sol, dans la topographie ou dans les propriétés du sols ([Hills and Reynolds, 1969](#)). Moyenner ces propriétés à l'échelle de la maille est d'une faible pertinence, à cause des fortes non-linéarités qui caractérisent l'hétérogénéité de ces surfaces ([De Rosnay, 1999](#)) ([Essery et al., 2003](#)).

Le site choisi pour cette étude est l'Afrique de l'Ouest, caractérisée par de fortes hétérogénéités de surface. Cette région est marquée par un fort gradient climatique, accompagné par un gradient de végétation. Les précipitations augmentent fortement entre le Sahara et la côte Guinéenne, c'est aussi le cas de la végétation et la profondeur des sols et leurs teneurs en matière organique; ces derniers sont globalement plus sableux vers le nord, et plus argileux vers le sud.

Etant située dans une zone de transition climatique, appelée le Sahel, l'Afrique de l'Ouest constitue un hotspot des interactions surface-atmosphère, l'humidité du sol a une incidence considérable sur les précipitations et l'évapotranspiration ([Koster et al., 2004](#); [Seneviratne et al., 2010](#)). Les interactions entre climat, végétation et processus hydriques de surface sont complexes et parfois contre-intuitives ([Descroix et al., 2013](#)).

En particulier, l'évolution de l'occupation du sol dans ces zones a entraîné des phénomènes en apparence paradoxaux. La succession des sécheresses des années 1970 et 1980 a donné

suite à une croissance des écoulements, accompagnée par une hausse du niveau des nappes (Descroix et al., 2013; Leduc, 2005). Cette sécheresse a en effet entraîné une diminution de la couverture végétale laissant place à un sol nu (Fig. 6.1). L'accroissement de l'écoulement est donc une conséquence de la dégradation des sols. Ces derniers, dépourvus de végétation naturelle, deviennent vulnérables et favorables à l'encroûtement (Casenave and Valentin, 1989). La figure 6.1 représente l'évolution des sols dans le bassin de Tondi Kiboro à l'ouest du Niger, où on voit qu'en 15 ans, la surface des sols encroûtés a doublé, ce qui a favorisé le ruissellement, qui finit par rejoindre des ravines et s'infiltrer (Descroix et al., 2013). Ce processus propre aux sols arides et semi-arides résulte de la réorganisation des particules à la surface du sol, sous l'effet du vent ou de la pluie, formant une fine couche superficielle avec des propriétés différentes du sol sous-jacent, en particulier, caractérisée par une forte imperméabilité. Dans les zones arides et semi-arides, l'état du sol en termes d'encroûtement et de couvert végétal constitue le principal contrôle dans l'écoulement et l'infiltration (Casenave and Valentin, 1989). Ce processus reste cependant complexe à modéliser vu que les croûtes évoluent dans le temps et sont affectées par les épisodes de pluie (Peugeot, 1995).

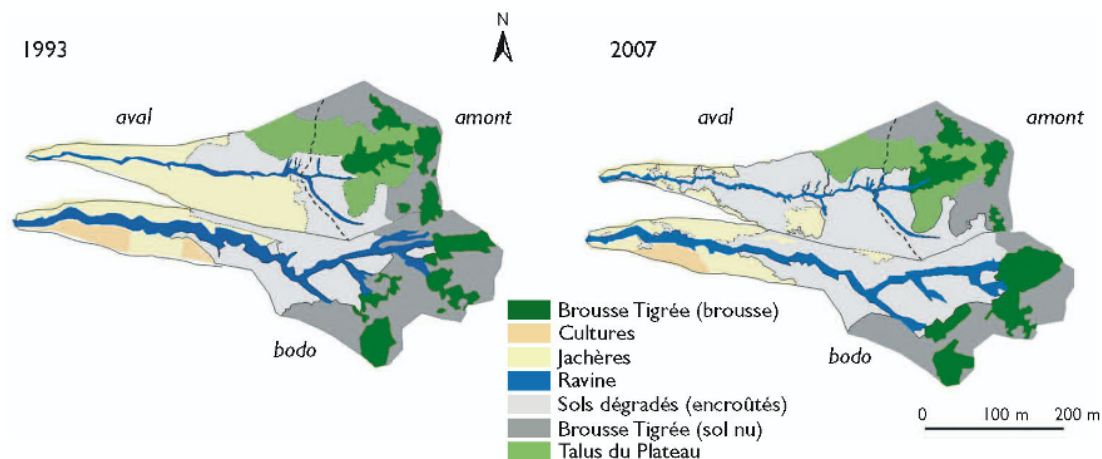


FIGURE 6.1 – Evolution de l'occupation du sol entre 1993 et 2007 dans le bassin Tondi Kiboro à l'ouest du Niger. (Descroix et al., 2012).

Dans ce chapitre, on effectue des modifications des paramètres du modèle ORCHIDEE en rapport avec l'hydrologie du sol et la végétation, afin de caractériser la sensibilité du modèle à ces différents paramètres. Seize simulations ont été menées pour modéliser le bilan d'eau à l'échelle locale de deux sites de l'Afrique de l'Ouest, en utilisant différents forçages de sol et de végétation, à des résolutions différentes, tout en testant plusieurs configurations du sol, soit par des modifications du code ou par des mots-clés déjà définis. Le but est d'évaluer les performances du modèle à l'échelle locale de ces deux sites, et

d'identifier les poids des différents paramètres dans la calibration du modèle, pour arriver à améliorer les flux simulés dans ces sites. Ces deux sites sont choisis à la fois pour la complexité des processus de surface qui les caractérisent, pour la disponibilité des données atmosphériques et de végétation à entrer au modèle et pour la disponibilité des mesures des flux hydriques pouvant être utilisés pour évaluer le modèle.

## 6.2 Description des sites d'étude

Deux sites de méso-échelle de l'AMMA-CATCH (Analyse Multidisciplinaire de la Mousson Africaine - Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique) (Lebel et al., 2009), aux caractéristiques contrastées, ont été sélectionnés pour cette étude (Fig. 6.2). L'AMMA-CATCH est un système d'observation de la zone critique en Afrique de l'Ouest, fournissant des mesures de flux d'eau, d'énergie et de l'évolution de la végétation, depuis 1990 (Galle et al., 2018). Les deux sites étudiés dans ce chapitre sont ceux du Bénin et du Niger.

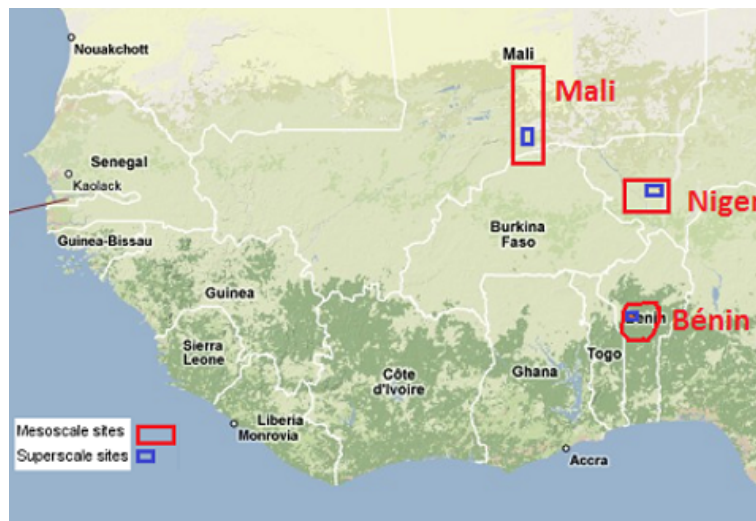


FIGURE 6.2 – Les méso-sites d'observation de AMMA-CATCH. Les deux sites utilisés dans ce chapitre sont ceux de Niamey au Niger et de l'Ouémé au Bénin.(D'après Galle et al. (2018) ).

### Bénin

Le premier site est situé au nord du Bénin ( $8.95^{\circ}\text{N}$ - $10.15^{\circ}\text{N}$  et  $1.45^{\circ}\text{E}$ - $2.85^{\circ}\text{E}$ ), comprenant la haute vallée de l'Ouémé qui draine une superficie de  $14400 \text{ km}^2$ . Il est caractérisé par un climat soudanien-guinéen sub-humide, avec une pluviométrie de  $1\,200$ - $1\,300 \text{ mm/an}$  (Ségui et al., 2011), s'étendant sur une seule saison humide de mars à octobre. Ce site est caractérisé par la présence de nappes perchées saisonnières qui alimentent les cours

d'eau. Les terres sont principalement couvertes de savane, de forêts, de jachères et de terres cultivées (Fig. 6.3).

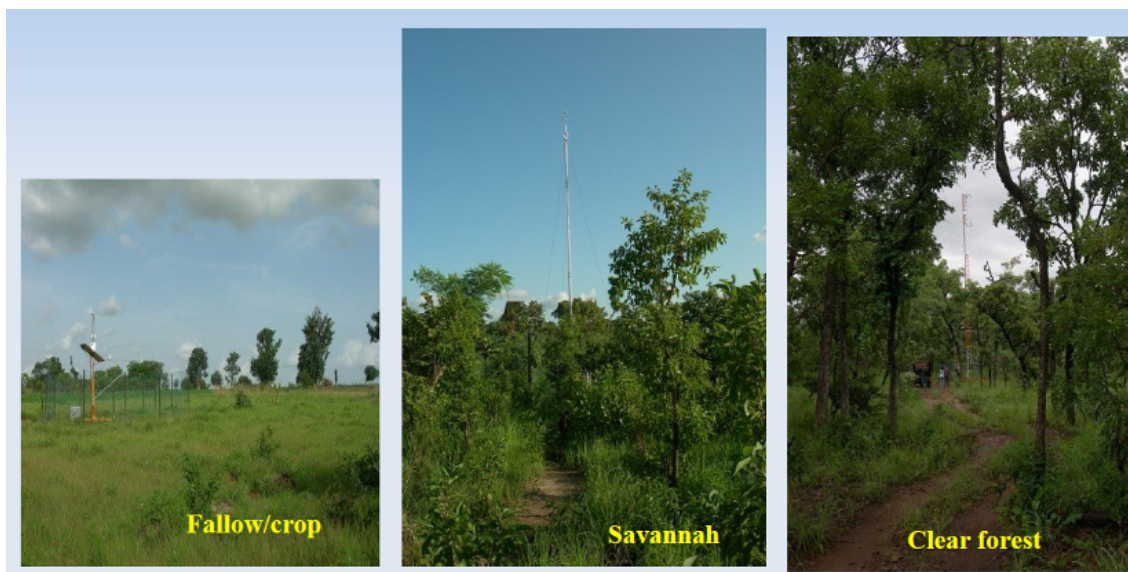


FIGURE 6.3 – Les principales occupations du sol en haute vallée de l’Ouémé au Bénin (Peugeot et al., 2013)

## Niger

Le site du Niger est situé dans la région de Niamey ( $12.85^{\circ}\text{N}$ - $14.15^{\circ}\text{N}$  et  $1.55^{\circ}\text{E}$ -  $3.15^{\circ}\text{E}$  et). Il est caractérisé par un climat sahélien semi-aride (pluviométrie de 450-600 mm/an) avec une longue saison sèche suivie d’une saison humide de 4 à 5 mois (Cappelaere et al., 2009). Le paysage est caractérisé par une large diversité, comprenant des plateaux, des collines et les vallées du fleuve Niger (Fig. 6.4). La nappe est profonde (profondeur supérieure à 20 m). Les terres sont essentiellement couvertes de cultures de mil, de jachère, de brousse tigrée et de sol nu (Beaugendre et al., 2017).

## 6.3 Données de validation

### Données d’évapotranspiration

Trois données d’évapotranspiration différentes sont utilisées pour valider les résultats de simulations.

Les données **GLEAM** (Martens et al., 2017) et **MPI** (Jung et al., 2010), décrites dans la section 3.2.4 ; ainsi que les données NTSG (Numerical Terradynamic Simulation Group) (Zhang et al., 2010). Ces dernières sont basées sur un modèle semi-empirique d’évapotranspiration. Des données globales sont fournies sur une période de 1983 à 2006 en utilisant des données

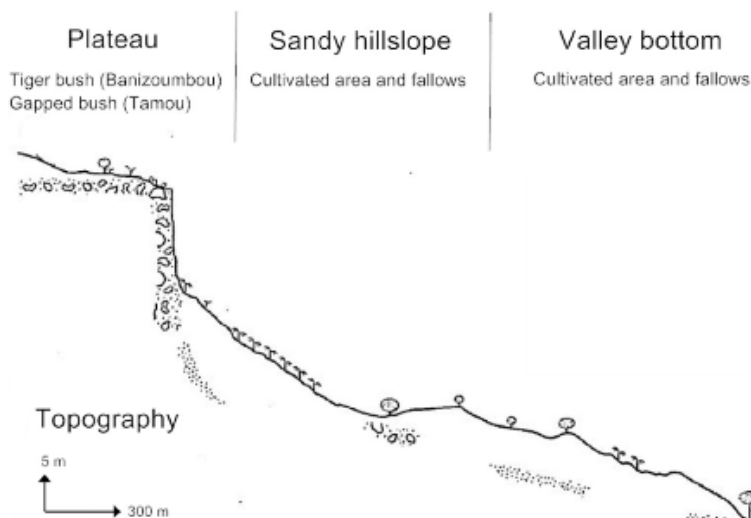


FIGURE 6.4 – Schéma représentatif de la topographie caractéristique du site du Niger (Beaugendre et al., 2017).

de télédétection de l'occupation du sol, ainsi que des données atmosphériques issues de réanalyses. Le produit NTSG utilise également des mesures *in situ* des tours FLUXNET (Jung et al., 2010).

### Débits au Bénin

Le site du Bénin bénéficie d'un riche historique de débits observés dans plusieurs stations (Fig. 6.5) (observatoire de l'AMMA-CATCH). Parmi les différentes stations de la haute vallée de l'Ouémé, celle du Bétérou draine la plus grande surface (près de 10000 km<sup>2</sup>). On utilise donc pour la suite les débits observés de cette station comme référence pour évaluer les écoulements simulés sur le site du Bénin.

### Bilan hydrologique issu du modèle SiSPAT

Velluet et al. (2014) ont fourni une estimation du bilan d'eau sur deux parcelles de 15 ha comprises dans notre domaine d'étude (Fig. 6.6). Ces deux parcelles sont un champ de culture de mil et un couvert de jachère. Cette différence d'occupation du sol impacte fortement la répartition du bilan d'eau (Fig. 6.6). Ces estimations ont été fournies par le modèle SiSPAT (Simple Soil-Plant-Atmosphere Transfers) (Braud et al., 2005). Il s'agit d'un LSM de type SVAT (Soil-Vegetation-Atmosphere Transfer) décrivant les échanges d'eau et d'énergie entre le sol, les plantes et l'atmosphère, sur des bases physiques. Ce modèle présente l'avantage de décrire les hétérogénéités verticales du sol, y compris les croûtes de surface (Velluet et al., 2014). Le sol est composé de plusieurs horizons, et les paramètres hydrauliques de chaque horizon sont issus de mesures *in situ* et de calage sur

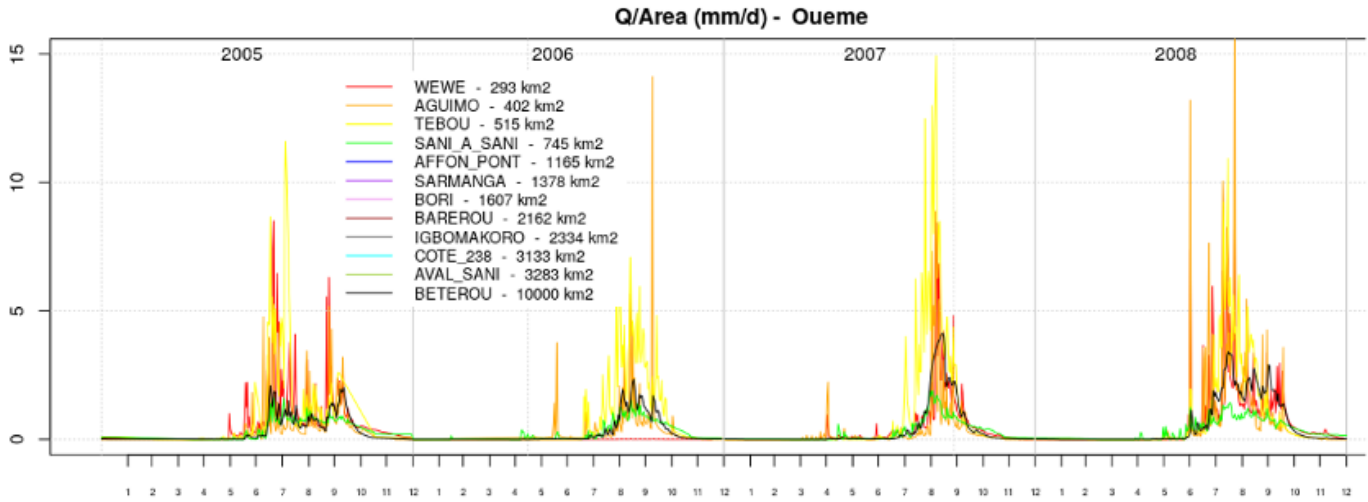


FIGURE 6.5 – Débits observés dans plusieurs stations de la vallée de l’Ouémé, normalisés par la surface drainée (spécifiée dans la légende pour chaque station).

des observations. Ces bilans d’eau sont utilisés dans cette étude comme référence pour l’évaluation des flux hydrologiques simulés sur le site du Niger.

## 6.4 Modifications de la configuration du sol

Dans un premier temps, on remplace les cartes de sol et de végétation usuellement utilisées dans ORCHIDEE, qui sont les mêmes que celle utilisées dans les simulations CMIP6 (Eyring et al., 2016) par des cartes plus détaillées et plus réalistes, ensuite, on teste différentes modifications des paramètres qui contrôlent l’hydrologie du sol afin de quantifier l’effet de chaque paramètre :

### 1. Profil vertical de la conductivité hydraulique à saturation ( $K_s$ )

Comme décrit dans le chapitre 2,  $K_s$  décroît exponentiellement avec la profondeur du fait de l’augmentation de la compaction. Le taux de décroissance est par défaut égal à 2. On teste d’autres valeurs du taux de décroissance : 0.5 et 5 (Fig. 6.7).

### 2. $K$ du front d’infiltration

A l’interface entre deux couches de sol, l’infiltration est limitée par la moyenne de la conductivité hydraulique à saturation de la couche supérieure, et de la conductivité de la couche inférieure. Afin de favoriser l’infiltration, on teste la configuration où ce flux est limité uniquement par la conductivité hydraulique à saturation.

### 3. Distribution horizontale de la conductivité hydraulique

ORCHIDEE permet de caractériser la variabilité sous-maille de l’infiltration en supposant

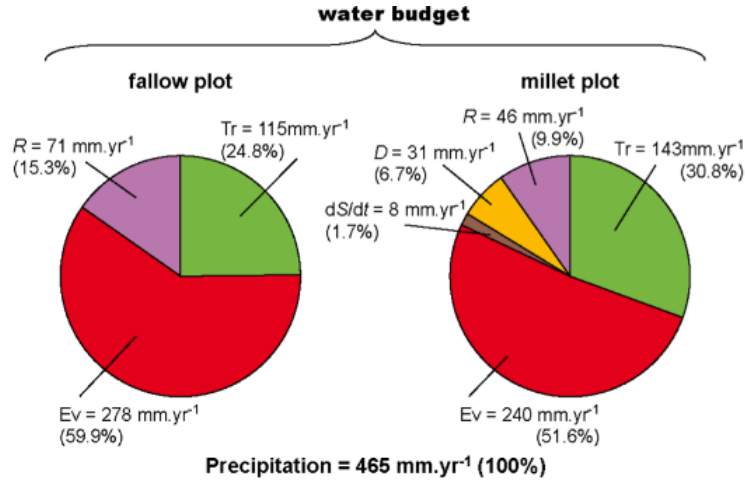


FIGURE 6.6 – Bilan d'eau estimé par le modèle SiSPAT sur deux sites différents du Niger (Velluet et al., 2014).

une distribution exponentielle de  $K_s$  dans chaque maille, ce qui limite l'infiltration. On remplace la distribution horizontale exponentielle de  $K_s$  par une distribution uniforme, afin de favoriser l'infiltration.

#### 4. Pente seuil de réinfiltration

Ce seuil permet de représenter les hétérogénéités de la topographie dans la maille : l'eau ruisselée en fortes pentes pourrait s'infiltrer plus loin au niveau de la vallée. Une fraction de l'eau ruisselée peut se réinfiltrer lorsque la pente est inférieure à 0.5%. On modifie cette valeur du seuil de réinfiltration en testant les valeurs : 0.25%, 1% et 5%.

#### 5. Résistance du sol à l'évaporation

Dans ORCHIDEE, il y a la possibilité de limiter l'évaporation du sol en introduisant une résistance du sol à l'évaporation  $R_{\text{soil}}$  :

$$r_{\text{soil}} = \exp(8.206 - 4.255L/L_s), \quad (6.1)$$

où  $L$  est l'humidité du sol dans les 4 premières couches de sol et  $L_s$  est l'humidité correspondante à saturation.

L'évaporation du sol  $E_g$  s'écrit :

$$E_g = \min\left(\frac{E_{\text{pot}}}{(1 + \frac{r_{\text{soil}}}{r_a})}, Q_{\text{up}}\right). \quad (6.2)$$

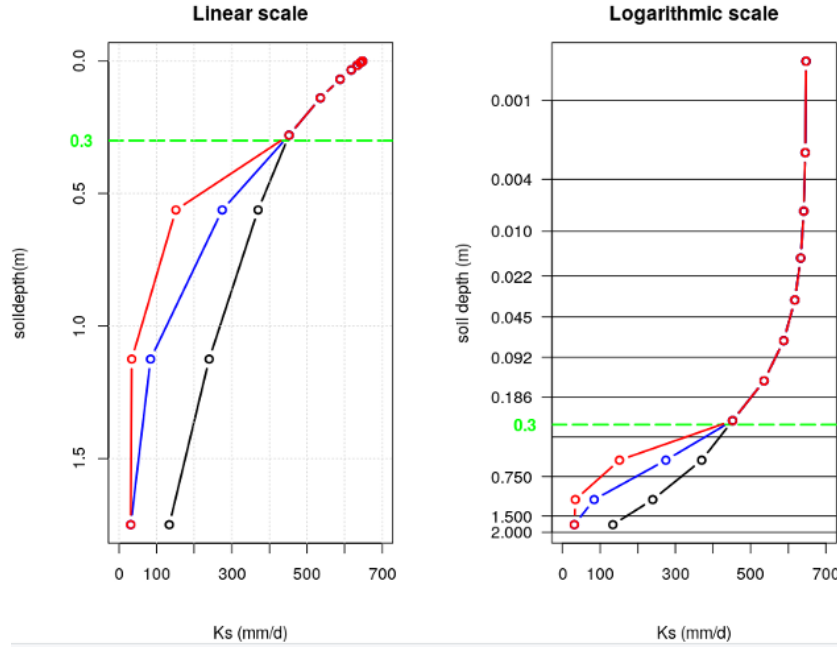


FIGURE 6.7 – Profil vertical de  $K_s$ , avec différents taux de décroissance : en noir :0.5, en bleu : 2 et en rouge 5. La décroissance commence au dela de 30 cm de profondeur.

où  $E_{\text{pot}}$  est l'évaporation potentielle incluant une correction de Milly (1992),  $r_a$  est la résistance aérodynamique, et  $Q_{\text{up}}$  est l'alimentation par diffusion ascendante. Ici, on active cette résistance pour voir son effet sur le bilan d'eau simulé.

## 6. Profil racinaire

Dans ORCHIDEE, les racines de la végétation sont décrites par un profil racinaire :

$$R(z) = \exp(-cz) \quad (6.3)$$

Où  $c$  est le taux de décroissance racinaire propre à chaque PFT ( cf. le tableau des PFT).  $K_s$  en zone racinaire est liée au profil racinaire pour tenir compte de l'effet des racines sur la perméabilité du sol. Il en résulte une croissance exponentielle de  $K_s$  vers la surface. La modification du profil racinaire engendre donc une modification du profil de  $K_s$ . Ici, on teste des valeurs plus élevées et d'autres plus faibles du paramètre  $c$ , qui est propre à chaque PFT. Dans une première simulation, on multiplie le  $c$  initial de chaque PFT par deux (EXP15), et dans une autre, on le divise par deux (EXP16) (Tableau 6.1).

## 6.5 Description des simulations

Un total de 16 simulations à une résolution de  $0.05^\circ$  ont été réalisées sur les deux sites du Niger et Bénin, en suivant le protocole AMMA-Land Model Intercomparison Project, phase 2 (ALMIP2, [Boone et al. \(2009\)](#)). Les forçages atmosphériques ont été développés dans le cadre du projet ALMIP2, à une résolution de  $0.05^\circ$ , et une résolution temporelle de 30 minutes. La procédure de construction de ces forçages est détaillée dans [Boone et al. \(2012\)](#). Les cartes de sol et de végétation sont issues de la base de données ECOCLIMAP-II ([Kaptue Tchuente et al., 2010](#)). Chaque site couvre une surface d'environ 104 km<sup>2</sup>. Les simulations s'étendent sur la période de 2005-2008, suivant un spin-up de 2002-2004 pour atteindre un état d'équilibre. L'ensemble des simulations réalisées est décrit dans le Tableau 6.1.

| Simulation | Carte veget. | Carte sol | Resistance du sol | Pente seuil de réinfiltration | K au front d'infiltration | distrib. horizontale de Ks | Facteur de décroissance de Ks | c                  |
|------------|--------------|-----------|-------------------|-------------------------------|---------------------------|----------------------------|-------------------------------|--------------------|
| EXP1       | CMIP6        | Zobler    | Sans              | 0.5                           | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP2       | ECOCLIMPAP   | Zobler    | Sans              | 0.5                           | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP3       | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP4       | ECOCLIMPAP   | ECOCLIMAP | Avec              | 0.5                           | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP5       | ECOCLIMPAP   | ECOCLIMAP | Avec              | 0.25                          | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP6       | ECOCLIMPAP   | ECOCLIMAP | Sans              | 1                             | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP7       | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.25                          | mean(kn, kn-1)            | Exponentielle              | 2                             | inchangé           |
| EXP8       | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Exponentielle              | 2                             | inchangé           |
| EXP9       | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.25                          | Kn-1                      | Exponentielle              | 2                             | inchangé           |
| EXP10      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 5                             | Kn-1                      | Exponentielle              | 2                             | inchangé           |
| EXP11      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Exponentielle              | 5                             | inchangé           |
| EXP12      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Exponentielle              | 0.5                           | inchangé           |
| EXP13      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Uniforme                   | 2                             | inchangé           |
| EXP14      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 1                             | Kn-1                      | Uniforme                   | 2                             | inchangé           |
| EXP15      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Exponentielle              | 2                             | multiplié par deux |
| EXP16      | ECOCLIMPAP   | ECOCLIMAP | Sans              | 0.5                           | Kn-1                      | Exponentielle              | 2                             | divisé par deux    |

TABLE 6.1 – Liste des simulations et les paramètres correspondants. Les groupes de simulations comparées sont indiquées par la même couleur, avec un paramètre qui change à la fois.

## 6.6 Résultats

### Bilan d'eau

Les bilans d'eau des différentes simulations sont illustrés sur la Figure 6.8. Le principal constat est que le modèle surestime l'écoulement comparé aux écoulements de référence. Lors de l'expérience ALMIP2, qui a été menée pour évaluer la capacité de différents LSM à reproduire les processus de surface sur ces sites ([Boone et al., 2009](#)), il a été retrouvé que la plupart des modèles surestiment l'écoulement ([Grippa et al., 2017](#); [Getirana et al., 2017](#)). Sur le site du Bénin, cette surestimation serait due à la non-représentation des processus d'infiltration profonde (i.e. les nappes), ce qui limite l'accès des racines à l'eau dans les

couches profondes du sol (Getirana et al., 2014). Dans la savane tropicale, les racines des arbres ont une profondeur moyenne de 15 m, or dans ORCHIDEE l'absorption de l'eau par la végétation est limitée à 2 m, ce qui entraîne une sous-estimation de la transpiration. Au Niger, l'écoulement simulé varie fortement entre les différentes simulations. Les coefficients de ruissellement de référence sont issus d'estimations sur deux sites ne dépassant pas 15 ha de superficie, tandis que le site utilisé dans cette étude a une superficie de 25 000 km<sup>2</sup>. Cette différence d'échelle peut être - au moins en partie - à l'origine des écarts observés entre les écoulements simulés et ceux de référence.

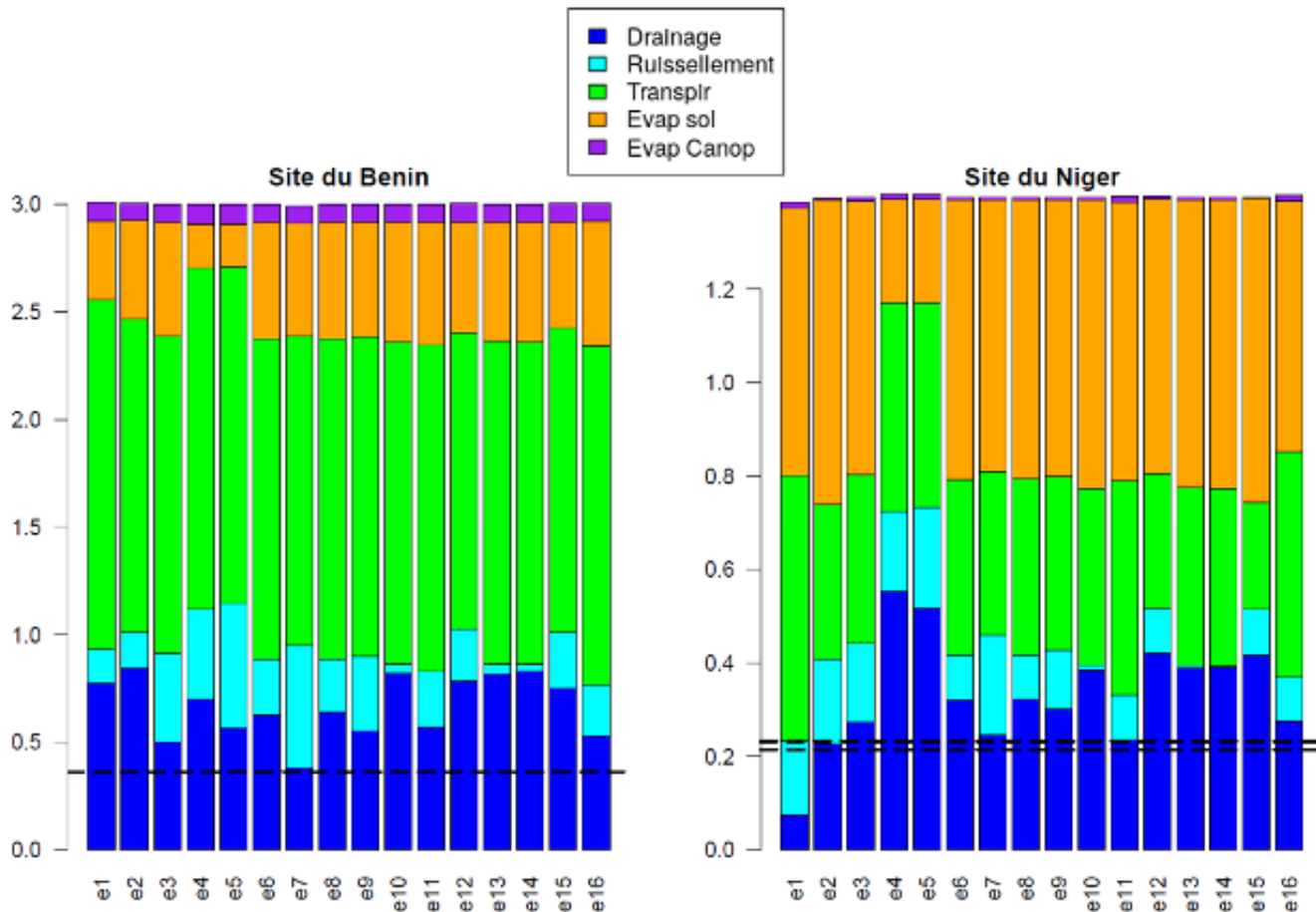


FIGURE 6.8 – Composantes des bilans d'eau (en mm/j) des différentes simulations listées sur le Tableau. 1, moyennées sur la période 2005-2008, sur les sites du Bénin et du Niger. Les tirets représentent les écoulements de référence : au Bénin, il s'agit du débit observé à la station de Bétérrou normalisé par la surface drainée ; au Niger il s'agit des écoulements estimés par le modèle SiSPAT dans deux parcelles différentes, de culture de mil et de jachère.

### Effet de la végétation et de la texture du sol

La première étape dans cette étude consiste à analyser l'effet d'introduire des cartes de sols et de végétation plus détaillées et plus réalistes des deux sites. Pour cela, deux cartes de végétation : CMIP6 (EXP1) et ECOCLIMAP (EXP2- EXP18) et deux cartes de texture de sol, Zobler (EXP1-EXP2) et ECOCLIMAP (EXP3-EXP18) sont utilisées.

La carte Zobler décrit un sol uniforme de texture Sandy loam sur les deux sites, tandis que la carte ECOCLIMAP décrit un sol de texture Sandy Clay Loam au Bénin et un sol dominé par les Sandy loam au Niger, avec une présence de Sand sur la vallée du fleuve Niger. Les bilans d'eau simulés avec ces deux cartes sont illustrés sur la Figure 6.5. Sur les deux sites, on retrouve un écoulement fortement surestimé par rapport aux coefficients de ruissellements issus d'observations. Sur le site du Bénin, le partitionnement ruissellement-drainage est fortement sensible au choix de la carte de texture du sol, la carte ECOCLIMAP, indiquant une texture plus fine que celle dans Zobler, résulte en un ruissellement plus élevé au détriment du drainage, ce qui est plutôt un résultat attendu.

Au Niger, on voit une grande différence entre les deux cartes de végétation testées, avec environ 50% de sol nu dans ECOCLIMAP et une dominance des savanes herbeuses, et uniquement 10% de sol nu dans CMIP6 avec une dominance des Cultures (Fig. 6.9). Cette différence a fortement impacté le bilan hydrologique (Fig. 8 EXP1 et EXP2). La carte ECOCLIMAP consistant principalement en sol nu réduit considérablement la transpiration, en faveur de l'écoulement (Fig. 6.8).

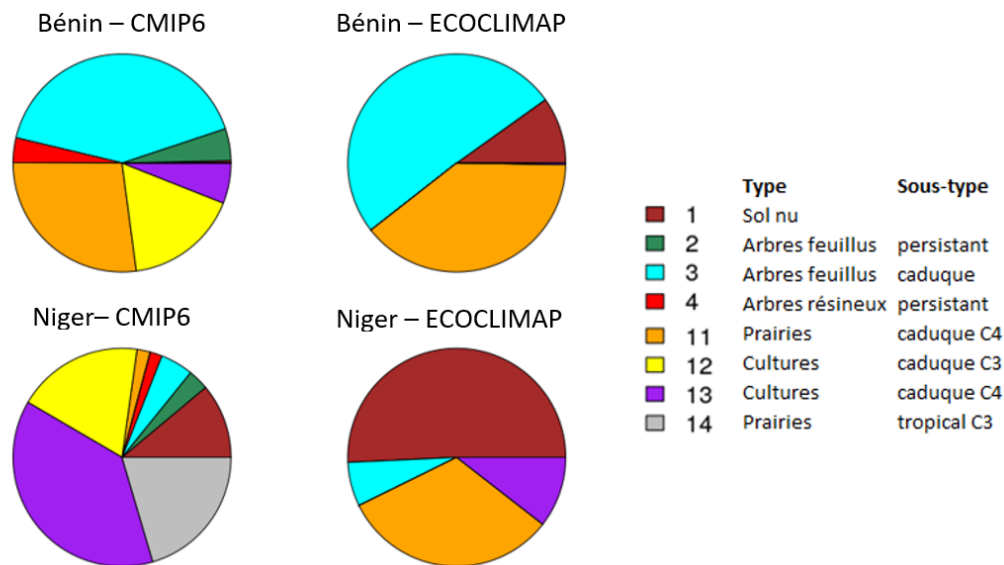


FIGURE 6.9 – Distribution de l'occupation du sol dans les cartes CMIP6 et ECOCLIMAP-II sur les deux sites du Bénin et du Niger.

## 6.7 Impact des paramètres d'infiltration

Après avoir introduit des cartes de sol et de végétation décrivant plus en détails les sites étudiés, on cherche maintenant à modifier les paramètres liés à l'hydrologie du sol. On cherche en particulier à réduire l'écoulement et favoriser l'évapotranspiration.

### Résistance du sol à l'évaporation

L'activation de la résistance du sol à l'évaporation (EXP4) a un impact très fort sur le bilan d'eau. L'évaporation du sol est fortement réduite, et la surestimation des écoulements est aggravée. Toutefois, ce changement ne présente pas d'intérêt dans notre étude puisqu'on cherche, au contraire, à limiter les écoulements.

### Conductivité hydraulique au front d'infiltration

Les simulations EXP3 (sans modification) et EXP8 (avec modification) sont comparées. Cette modification augmente la valeur de  $K_s$  et donc favorise le drainage, cependant, l'écoulement total diminue (Fig. 6.8). En effet, en augmentant la conductivité entre les couches du sol, l'écoulement hortonien est réduit, cette réduction est plus importante que l'augmentation du drainage, ce qui résulte en un écoulement total plus faible.

### Pente seuil de réinfiltration

On teste, de différentes manières, une valeur plus élevée et une autre plus faible de la pente seuil de réinfiltration initialement utilisée dans ORCHIDEE. L'augmentation du seuil de réinfiltration (e.g. EXP10) a permis d'augmenter la part de ruissellement qui s'infiltre, qui est en grande partie drainée (Fig. 6.8). Cette modification a principalement permis de répartir la fraction ruissellement-drainage avec un léger impact sur l'évapotranspiration.

### Taux de décroissance de $K_s$

$K_s$  décroît exponentiellement au-delà de 30 cm de profondeur. Ici, on teste différentes valeurs de taux de décroissance. On constate que ce paramètre n'a aucun impact sur le ruissellement, quelle que soit la valeur utilisée. En augmentant ce paramètre (EXP11 par rapport à EXP12),  $K_s$  diminue rapidement en profondeur, ce qui réduit le drainage au fond, favorisant la transpiration et l'évaporation du sol (Fig. 6.8). Sur le site du Niger, le changement du taux de décroissance de  $K_s$  de 2 à 5 a permis une baisse du drainage de 45%, ce qui présente une amélioration considérable l'écoulement simulé, comparé à l'écoulement de référence.

### Distribution horizontale de l'infiltration

La distribution horizontale uniforme de  $K_s$  (dans EXP13) a permis de favoriser le drainage par rapport au ruissellement (par rapport à la distribution exponentielle dans EXP8). Une augmentation du drainage est retrouvée en période humide, accompagnée d'une forte baisse de ruissellement (Fig. 6.10). L'écoulement total est légèrement réduit.

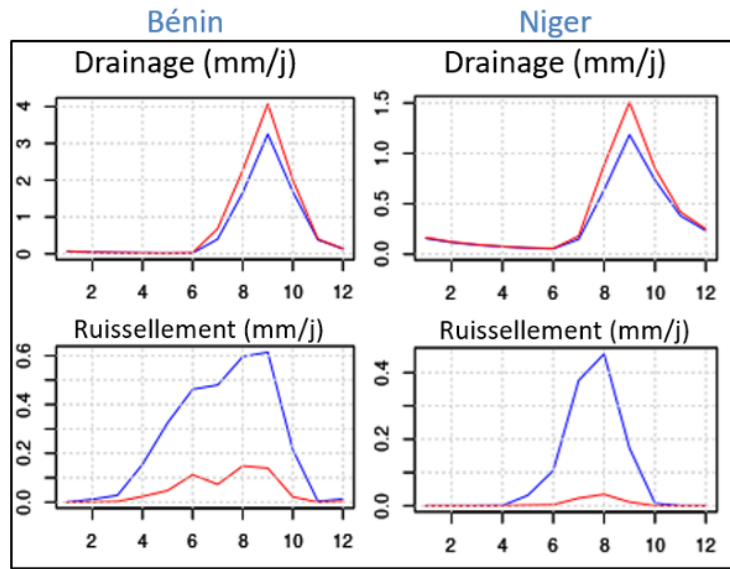


FIGURE 6.10 – Cycles saisonniers du drainage et du ruissellement simulés par EXP8 avec une distribution exponentielle de  $K_s$  (en bleu) et EXP13 avec une distribution uniforme de  $K_s$  (en rouge), moyennés sur la période 2005-2008.

### Profil racinaire

Dans ORCHIDEE, le profil vertical de  $K_s$  est corrélé au profil racinaire. Plus les racines sont denses, plus  $K_s$  augmente. Le profil racinaire, étant défini par un taux de décroissance exponentielle,  $K_s$  en est également dépendant. On teste plusieurs valeurs de ce paramètre afin d'analyser son impact sur les différents flux hydriques. L'augmentation du taux de décroissance du profil racinaire (EXP15) aggrave la surestimation de l'écoulement, alors que sa diminution réduit les écoulements (EXP16) (Fig. 6.8). En plus d'impacter le  $K_s$ , ce paramètre permet de contrôler l'extraction racinaire en fonction de la profondeur, lorsqu'il diminue, les racines sont plus denses ce qui favorise la demande racinaire, et par conséquent, réduit le drainage.

## 6.8 Validation

Les modifications qui ont induit une forte baisse de l'écoulement sont l'augmentation du taux de décroissance de  $K_s$  (EXP11) et la baisse du taux de décroissance du profil racinaire (EXP16). Dans cette section, on évalue ces simulations en plus d'une simulation de référence (EXP8). A noter que dans ces trois simulations la conductivité au front d'infiltration est égal à  $K_s$ .

La Figure 6.11 montre que EXP11 et EXP16 résultent toutes les deux en une évapotranspiration élevée par rapport à EXP8. Il existe une grande divergence entre les données d'évapotranspiration

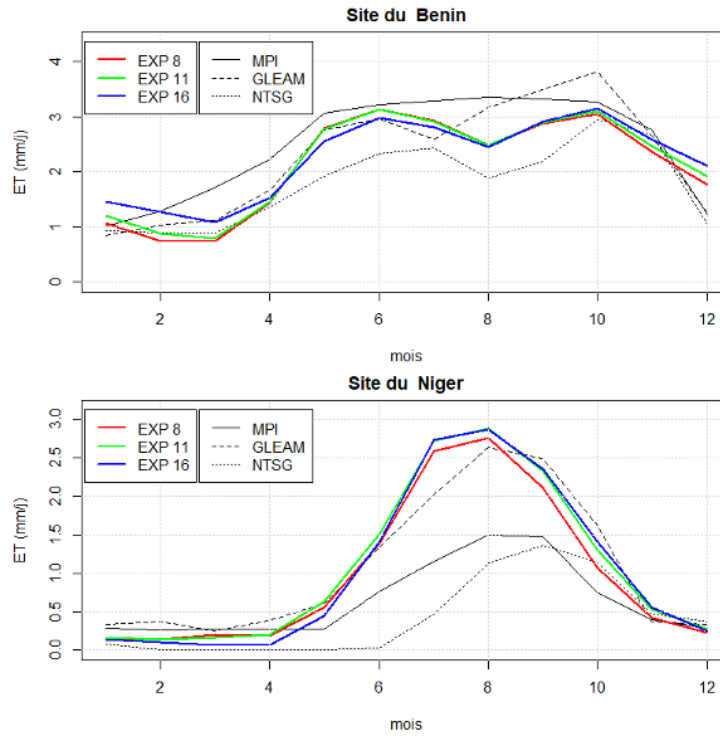


FIGURE 6.11 – Cycles saisonniers d'évapotranspiration simulée comparée à celle de différents produits, moyennés sur la période 2005-2006.

issues d'observations sur ces sites, l'évapotranspiration simulée est plus proche du produit GLEAM. Par exemple, pour l'EXP11 sur le site du Niger, on trouve des biais de +0.6%, +67% et +153% par rapport aux produits GLEAM, MPI et NTSG respectivement. Sur le site du Bénin, les biais sont de -4%, -12% et +20% pour les mêmes produits. Sur les deux sites, le produit NTSG sous-estime l'évapotranspiration par rapport aux deux autres produits et aux simulations. Les écarts d'évapotranspiration simulée entre les trois simulations restent cependant faibles comparés à la grande incertitude des différents produit d'ET.

Sur le site du Niger, la saisonnalité des différents flux a été estimée par le modèle SiSPAT (Velluet et al., 2014) (Fig. 6.12a). Les cycles saisonniers des différents flux hydrologiques simulés par ORCHIDEE sont illustrés dans la Figure 6.12b. L'évaporation du sol et le ruissellement étant des processus rapides, ils suivent directement le cycle des précipitations. Le drainage étant retardé par un temps de latence, son cycle est plus lisse et retardé d'un mois par rapport à celui des précipitations. Il en est de même pour la transpiration qui est également retardée par les processus liés à la végétation. Le pic de ces deux dernières variables est au mois de septembre alors le pic des précipitations est en août.

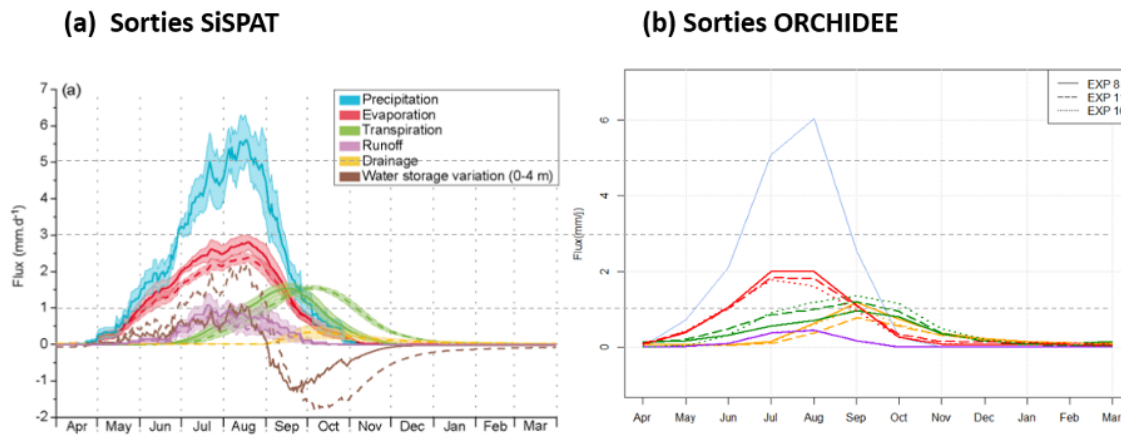


FIGURE 6.12 – Cycles saisonniers des précipitations et des différents flux hydrologiques (a) estimés par SiSPAT et (b) simulés par ORCHIDEE sur le site du Niger.

La saisonnalité des flux hydrologiques simulés sur ce site est proche de celle estimée par le modèle SiSPAT, à quelques exceptions près. Le cycle de transpiration ne débute qu'au mois de Juillet dans SiSPAT alors qu'il débute plus tôt dans ORCHIDEE. Il en est de même pour le drainage qui commence au mois d'août dans ORCHIDEE et en septembre dans SiSPAT. Il existe également des différences d'amplitude, principalement en évaporation du sol, qui ne dépasse pas 2 mm/j dans ORCHIDEE alors qu'elle est d'environ 2.5 mm/j dans SiSPAT. Le pic de transpiration est également sous-estimé dans ORCHIDEE, mais comme elle commence plus tôt, la transpiration annuelle moyenne reste du même ordre que celle estimée par SiSPAT (Fig. 6.12).

Le drainage est fortement surestimé par ORCHIDEE, et le ruissellement légèrement sous-estimé. Ceci peut être expliqué par la présence des croûtes superficielle sur le sol nu qui favorisent le ruissellement de surface, et qui ne sont pas représentées dans ORCHIDEE. Le rapport entre l'écoulement total simulé par ORCHIDEE et les précipitations est de 29.8%, 23.6% et 26.4% pour EXP8, EXP11 et EXP16 respectivement, dans SiSPAT il est de 16.6% et 15.3% pour deux types d'occupation du sol (culture de mil et jachère respectivement). L'écoulement dans ORCHIDEE reste donc surestimé, la modification des propriétés hydrauliques du sol permet de réduire l'écoulement mais n'est pas suffisante pour retrouver des valeurs de flux réalistes.

Le débit observé à la station de Bétérou, divisé par la surface de drainage, est comparé aux écoulements simulés dans EXP11 et EXP16 sur la période de simulation (Fig. 6.13). On observe que l'écoulement simulé est largement surestimé par ORCHIDEE. Il faut noter cependant qu'on compare un débit observé au niveau d'un exutoire à des écoulements générés localement, ce qui explique les fluctuations rapides dans les écoulements simulés qu'on ne retrouve pas dans le débit observé (Fig. 6.13), ce dernier en effet présente une

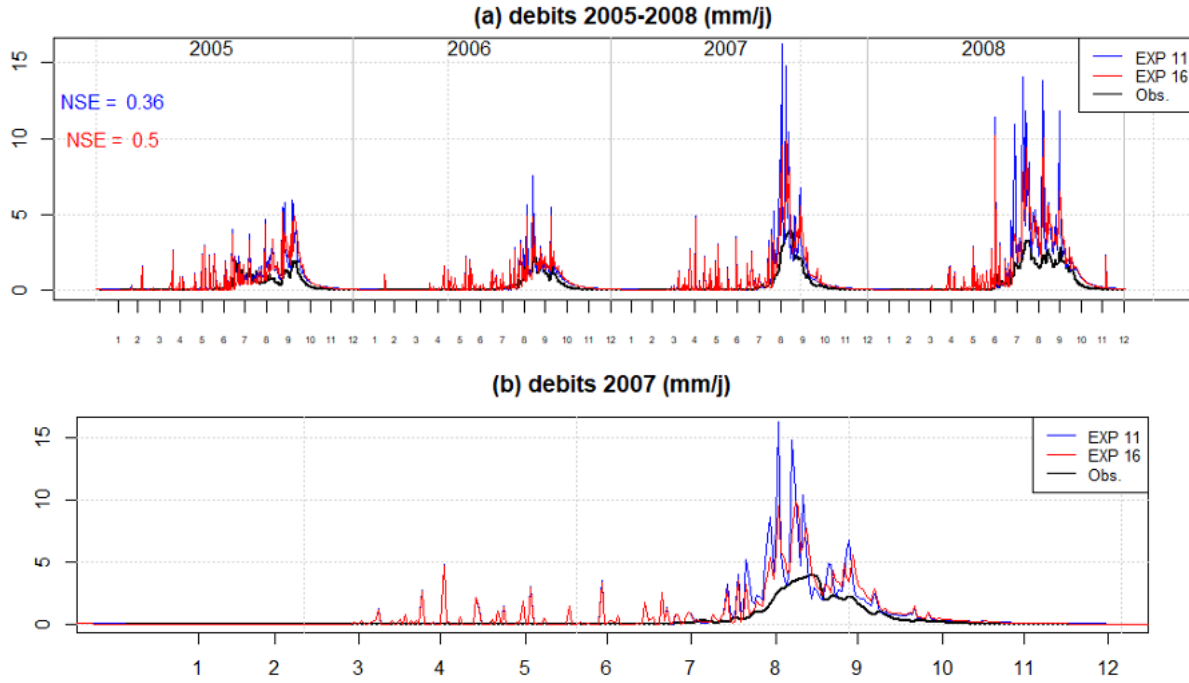


FIGURE 6.13 – Séries temporelles des écoulements (ruissellement et drainage) simulé sur le site du Bénin, comparées au débit observé à la station de Bétérrou.

allure plus lisse, du fait de l'atténuation des fluctuations en cours de l'acheminement de l'eau vers l'exutoire. Ces fluctuations, caractérisant les réponses rapides aux précipitations, sont d'autant plus importantes dans EXP11. En effet, en accentuant la décroissance de  $K_s$ , on limite le drainage et on favorise le ruissellement qui a une réponse plus rapide aux précipitations, ce qui accentue les pics de débit. L'écoulement dans EXP16 est plus en accord avec le débit observé, aussi bien en forme qu'en amplitude, même si les fluctuations persistent. Le coefficient de Nash est de 0.5 pour EXP16 tandis qu'il est de 0.36 pour EXP11.

## 6.9 Conclusion et perspectives

Dans ce chapitre, on a testé la sensibilité du modèle ORCHIDEE à plusieurs paramètres qui contrôlent l'hydrologie du sol, sur deux sites sahéliens de méso-échelle aux caractéristiques contrastées. Le site du Niger a montré une plus grande sensibilité aux modifications effectuées, puisqu'il est en grande partie couvert de sol nu. Le bilan d'eau sur le site du Bénin, qui est couvert par une végétation dense, reste dominé par le flux de transpiration, quelle que soit la modification apportée au sol.

L'activation de la résistance du sol a engendré le plus fort impact sur le bilan hydrologique, mais son effet était plutôt aggravant sur les écoulements simulés. Par ailleurs, l'augmentation du taux de décroissance verticale de  $K_s$ , et la diminution du taux de décroissance du profil racinaire ont permis une amélioration non-négligeable des écoulements simulés. Sur le site du Bénin, les écoulements ont diminué de 6% et 14% dans EXP11 et EXP16 respectivement, et sur le site du Niger, ils ont diminué de 31% et 11.4% respectivement.

Malgré l'amélioration dans la répartition évapotranspiration-écoulement apportée par ces deux modifications, les écoulements simulés restent encore largement surestimés par rapport aux données de référence. Ce chapitre constitue une phase initiale d'un travail destiné à améliorer la représentation des processus hydriques dans la zone du Sahel, afin d'obtenir des bilans d'eau plus réalistes dans ces zones.

Dans la version d'ORCHIDEE utilisée dans cette étude, on impose un drainage libre au fond de la colonne du sol, ce qui est une hypothèse valable lorsque la nappe est assez profonde. Vu la présence de nappes perchées de bas-fond sur le site du Bénin, le modèle n'arrive pas à modéliser correctement les processus de surface. L'utilisation de la version ORCHIDEE-Ground Water Fraction sur ce site serait pertinente, cette version permet en effet de représenter les nappes de proche surface à travers un module d'eau souterraine (Ducharne, 2019), en se basant sur une carte globale de la distribution des zones humides (Tootchi, 2019), permettant ainsi une meilleure représentation des réservoirs d'eau profonds, au-delà de la colonne du sol représentée dans le module hydrologique. Cette version d'ORCHIDEE constitue un effort de représentation de l'hétérogénéité intra-maille de la topographie. Une fraction de bas fond, correspondant à la zone de convergence des écoulements de surface et de subsurface, est représentée dans chaque maille, ce qui correspond bien au fonctionnement hydrologique de la haute vallée de l'Ouémé.

Les hétérogénéités de surface et les processus de petite échelle restent complexes à représenter dans les modèles à faible résolution tels que ORCHIDEE, ce qui requiert des simplifications sur les processus de second ordre. Par exemple, le phénomène d'encroûtement des sols n'est pas représenté dans ORCHIDEE, pourtant, dans les zones arides, il constitue un contrôle principal des écoulements (Casenave et Valentin, 1989). Les sols susceptibles à l'encroûtement couvrent une fraction importante des surfaces continentales (Fig. 6.14), leur prise en compte dans les LSM permettrait donc une représentation plus réaliste des

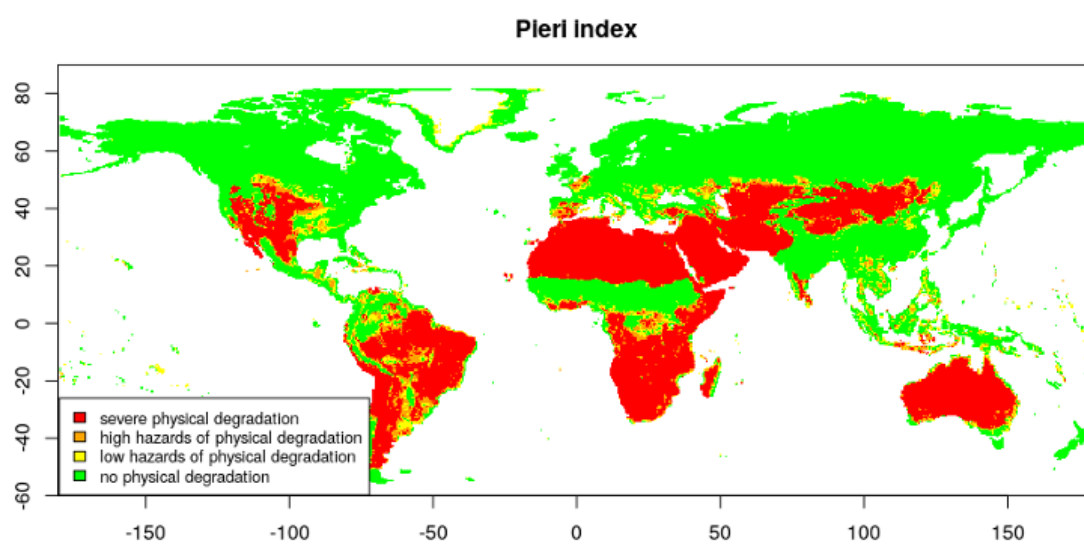


FIGURE 6.14 – Distribution globale de l'indice de Pieri (1989), décrivant les sols susceptibles à l'encroûtement. Indice calculé à partir de la texture et de la teneur en matière organique du sol.

# Chapitre 7

## Conclusions et perspectives

Le cours de cette thèse a fortement été orienté par le projet SP-MIP ([Gundmundsson and Cuntz, 2017](#)), durant lequel plusieurs simulations globales ont été menées pour permettre d'étudier à quel point les paramètres du sol sont responsables des écarts entre les différents LSMs. On a profité de ces simulations, et rajouté d'autres, pour étudier l'effet des paramètres du sol sur l'hydrologie simulée par ORCHIDEE.

Les travaux de l'article présenté au Chapitre 3 ont permis de tester plusieurs cartes globales de texture de sol, et de conclure que le choix de la carte de texture n'est pas crucial dans la modélisation du bilan d'eau à l'échelle globale. Par ailleurs, ces différents tests ont permis de relever des anomalies sur la carte de texture de [Reynolds et al. \(2000\)](#) utilisée dans ORCHIDEE : avec cette carte, on obtient des biais importants d'évapotranspiration dans certaines zones couvertes d'argile, et que l'on ne retrouve pas avec les autres cartes de texture. Ceci a motivé le travail mené dans le chapitre 4, où on a distingué deux types d'argiles aux propriétés hydrauliques différentes, qui étaient initialement regroupés dans la même classe de texture. Cette modification de la carte de Reynolds, en plus de fournir une représentation plus réaliste des sols, a permis de corriger les biais importants d'évapotranspiration dans les zones tropicales.

La faible sensibilité d'ORCHIDEE aux cartes de texture du sol nous a mené à remettre en question les PTFs utilisées : la texture seule n'est en effet pas suffisante à la description de l'état des sols, et de leur paramètres hydrauliques. En effet, de plus en plus de LSMs tiennent compte maintenant de la matière organique (MO) présente dans le sol pour déterminer les paramètres hydrauliques, ce qu'on a exploré dans le chapitre 5 en comparant trois approches différentes. Ceci a permis de mieux décrire les sols riches en MO, notamment dans les tourbières qui couvrent une grande fraction des surfaces continentales. La représentation de la MO a permis de corriger les biais négatifs d'évapotranspiration dans certaines régions, et dans une moindre mesure, d'améliorer les débits simulés.

En parallèle à ces études à l'échelle globale, on s'est intéressé dans le chapitre 6 à une modélisation régionale en Afrique de l'Ouest. L'intérêt de cette région provient de la complexité des processus de surface et de l'hétérogénéité du paysage qui la caractérisent. Les premiers tests de sensibilité présentés dans le chapitre 6 suggèrent que la modification des paramètres qui contrôlent l'hydrologie du sol dans ORCHIDEE n'est pas suffisante pour réussir à modéliser avec plus de réalisme les différents flux hydrologiques. En particulier, dans les sites où la nappe phréatique est proche de la surface, comme le Bénin, l'hypothèse d'un sol de deux mètres à drainage libre au fond n'est plus valable. L'hypothèse d'un sol homogène sur la maille est également contestable. La fraction de sol nu dans une maille peut en effet développer des croûtes superficielles, ce qui imperméabilise la surface du sol et limite l'infiltration. Il serait donc intéressant de représenter ce processus et analyser son impact sur le bilan d'eau, puisque les sols susceptibles à l'encroûtement couvrent une fraction importante du globe.

Comme expliqué plus haut, ORCHIDEE est amené à faire des hypothèses sur les conditions aux limites inférieures, en supposant un drainage libre sans prise en compte des nappes. Récemment, ([Ducharne A, 2019](#)) ont développé une version d'ORCHIDEE qui permet la prise en compte des nappes. Il serait donc intéressant de tester cette version sur le site du Bénin pour analyser son apport sur le bilan d'eau simulé.

L'ensemble des simulations dans cette thèse ont été forcées par des données atmosphériques. Ces derniers constituent le principal contrôle des flux hydrologiques simulés. L'utilisation de plusieurs données atmosphériques a révélé une forte incertitude liée au choix des forçages atmosphériques. Par ailleurs, le fait que les simulations soient forcées n'a pas permis de relever l'impact des propriétés du sol sur le climat. Il conviendrait donc de mener des simulations couplées avec le modèle atmosphérique de l'IPSL, afin d'examiner dans quelle mesure les propriétés du sol pourraient améliorer les performances d'un modèle de climat. Dans un premier temps, il serait intéressant de vérifier si la faible sensibilité d'ORCHIDEE aux cartes de texture de sol reste valable en étant couplé à un modèle atmosphérique.

# **Annexe A**

## Protocole SP-MIP

# Soil Parameter Model Intercomparison Project (SP-MIP): Assessing the influence of soil parameters on the variability of Land Surface Models

## Coordination

Lukas Gudmundsson ([lukas.gudmundsson@env.ethz.ch](mailto:lukas.gudmundsson@env.ethz.ch))

Matthias Cuntz ([Matthias.Cuntz@inra.fr](mailto:Matthias.Cuntz@inra.fr))

## Scientific Advisory Committee

Sonia I. Seneviratne, Dani Or, Harry Vereecken, Anne Verhoef, Tomislav Hengl, Aaron Boone

## Background and Purpose

Land surface models (LSMs) simulate the movement of water and energy through the plant-soil system, amongst other things. There is currently a considerable spread among different land surface models regarding their outputs of water-balance variables such as evapotranspiration, soil moisture or runoff. It is not clear, however, whether this spread is related to model structure (i.e. equations used to describe the underlying processes) or model parameters (i.e. physical properties of the Earth system such as soil porosity).

To approach the question to which degree LSM spread is related to model parameters, controlled multi-model experiments were proposed at the GEWEX-SoilWat workshop held in Leipzig on June 28-30, 2016.

Two steps are necessary to produce soil model parameters such as soil porosity or saturated hydraulic conductivity in each LSM: 1. an input soil map is needed, which may contain soil classes or soil texture information, and 2. the required model parameters must be calculated from the information given by the soil map, for example with look-up tables, given soil classes in the soil map, or via the use of pedotransfer functions given soil textures in the soil map. SP-MIP aims at quantifying the differences between LSM model results that stem from either of the two preparation steps for soil parameters.

There is an intermediate step in the preparation of LSM input data that is not treated within SP-MIP, which is the aggregation of the soil map information or the soil parameters onto the model resolution, instead, all models are run at the same 0.5° resolution with soil information provided through SP-MIP.

## Model Experiments

The experiments closely follow the LS3MIP protocol (van den Hurk *et al.* 2016). The models are run globally on 0.5° with GSWP3 forcing (Kim *et al.* in prep.) from 1980-2010 (see below) with the same soil properties throughout the soil column. There will be 4 Tier 1 experiments, leading to 7 model runs (see also Figure 1):

### **Experiment 1: Soil-hydraulic parameters provided by SP-MIP**

Models are run using soil hydraulic parameters that are provided by SP-MIP (Table 2). The *purpose* of this experiment is to establish a baseline of inter-model variability that comes from model components other than the soil parameters, in order to assess to which degree between-model variability can be reduced by enforcing common soil hydraulic properties.

### **Experiment 2: Soil-hydraulic parameters derived from common soil textural properties**

Each modelling group runs their model using relevant soil hydraulic parameters derived based on global maps of soil textural properties provided by SP-MIP (Table 3). The soil hydraulic parameters should be derived using the lookup tables or pedotransfer functions that are commonly used for each individual model. The *purpose* of this experiment is to quantify to which degree between-model variability is related to differences in transferring soil texture information to soil hydraulic properties.

### **Experiment 3: Reference run with all models in their status quo**

All models are run in their default settings, with the exception that all soil layers use the same soil properties through the whole soil column. The *purpose* of this experiment is to assess the variability that comes from both the original soil information used by the corresponding model and the model-specific transfer of these soil information into model parameters.

### **Experiment 4a, b, c, d: Spatial uniform soil parameters**

All models are run four times using spatially uniform soil-hydraulic parameters for the whole globe. For this, four “design soils” corresponding to loamy sand (experiment 4a), loam (experiment 4b), clay (experiment 4c), and silt (experiment 4d) (previously considered by Montzka *et al.* 2011) are provided by SP-MIP, together with the relevant soil hydraulic parameters. The *purpose* of this experiment is (i) to quantify the effect of spatial variability of soil parameters (or the lack thereof) on between-model-variability, (ii) to systematically assess the sensitivity of each model to soil hydraulic parameters and (iii) to investigate to which degree between grid-cell variability of key water- and energy balance outputs is controlled by soil-properties in the model world.

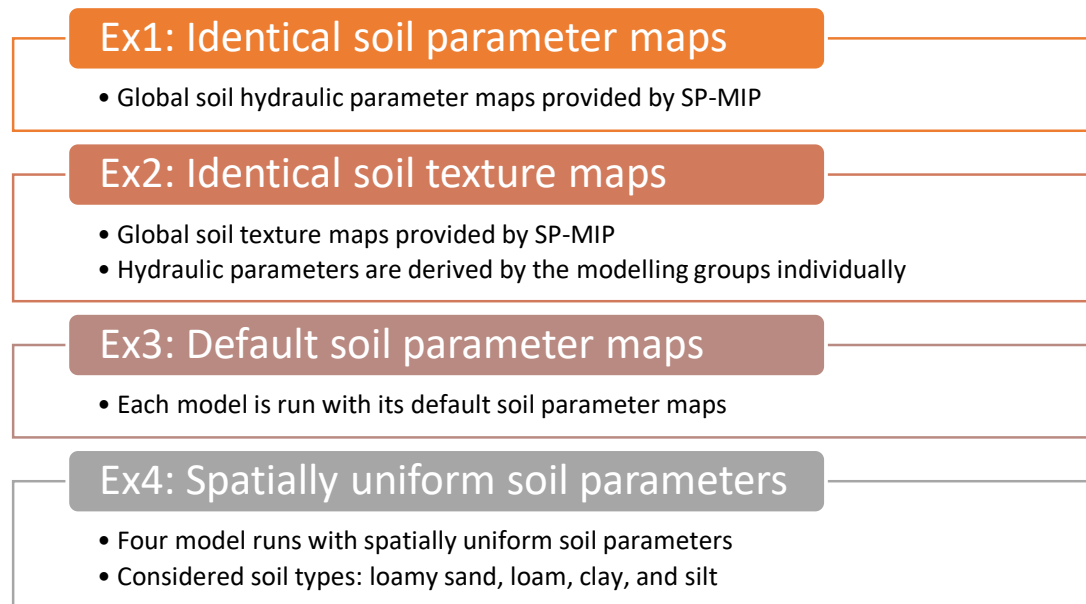


Figure 1: Overview on the four SP-MIP experiments.

### **Analysis of experiments**

Differences between the model experiments will allow the assessment of the inter-model variability that is introduced by the different stages of preparing model parameters.

Comparison of Experiment 1 and Experiment 2 gives the variability between the models that is introduced by the usage of different pedotransfer procedures from soil information to model parameters. Comparison of Experiment 2 and Experiment 3 gives the variability that comes from different soil maps and aggregation schemes used for the different models.

### **Analysis of variance**

An ANOVA-type of analysis is proposed to approach the question to which degree between model variability can be reduced by prescribing common soil hydraulic parameters or soil maps. The between model spread at each grid-cell will first be quantified for experiment 1 and subsequently compared to

the spread of the remaining experiments. To assess the impact of soil hydraulic parameters on different dynamical aspects the analysis will be conducted on numerous time scales including daily, monthly and annual resolution as well as climatology's (long-term means).

### **First order sensitivity analysis**

To quantify to which degree errors in soil-hydraulic parameters impact complex LSM simulations, a first-order sensitivity analysis will be conducted using the simulations of Experiment 4. In a first step, the spread among the model runs from Experiment 4 with spatially uniform soil parameters will be quantified at each grid-cell for each model individually. Subsequently, the spread will, for example, be stratified along climatic gradients, biomes or plant functional types (etc.) to determine under which conditions simulation results are most sensitive in soil-hydraulic parameters.

### **Timeline**

|                 |                                            |
|-----------------|--------------------------------------------|
| 10-12/2017      | Conduct model simulations.                 |
| 01/2018 onwards | Data analysis; preparation of publication. |

### **Forcing Data**

The GSWP3 forcing data (Kim *et al.* in prep) will be used to drive offline LSM simulations. The GSWP3 forcing data is available in NetCDF format and comprises the essential atmospheric variables for modelling land surface processes in 0.5° spatial and 3 h temporal resolutions (Table 1). Although the GSWP3 data is available from the early 20<sup>th</sup> century onwards, the SP-MIP simulations will be conducted for the period 1980-2010. An atmospheric CO<sub>2</sub> concentration of 380 ppm is assumed.

Note: There are issues with negative precipitation (snow) in some grid-cells of the current version (version 1) of the GSWP3 forcing data. Please set these values to zero.

**Table 1:** 3 h variables related to the energy and water cycles. The dimension (Dim.) column indicates T: time, Y: latitude, X: longitude.

| Name   | long_name (netCDF)             | Unit                               | Dim. |
|--------|--------------------------------|------------------------------------|------|
| LWdown | Downward Longwave Radiation    | W m <sup>-2</sup>                  | TYX  |
| SWdown | Downward Shortwave Radiation   | W m <sup>-2</sup>                  | TYX  |
| Tair   | Near surface air temperature   | K                                  | TYX  |
| PSurf  | Surface Pressure               | Pa                                 | TYX  |
| Qair   | Near surface specific humidity | kg kg <sup>-1</sup>                | TYX  |
| Wind   | Near surface wind speed        | m s <sup>-1</sup>                  | TYX  |
| Rainf  | Rainfall                       | kg m <sup>-2</sup> s <sup>-1</sup> | TYX  |
| Snowf  | Snowfall                       | kg m <sup>-2</sup> s <sup>-1</sup> | TYX  |

### **Soil Properties**

Soil parameters for Experiments 1 and soil textures for Experiment 2 at 0.5° resolution were prepared from dominant soil classes of the 0-5 cm layer of SoilGrids (Hengl *et al.* 2014) at 5 km resolution. Brooks and Corey parameters come from Table 2 of Clapp and Hornberger (1978), Mualem-van Genuchten parameters are ROSETTA class average hydraulic parameters (Schaap *et al.* 2001), and soil textures are from Table 2 of Cosby *et al.* (1984). Experiments 4 a-d use the USDA soil classes Loamy sand, Loam, Silt, and Clay, respectively, as in Montzka *et al.* (2011), using the same transfer functions for Brooks and Corey and Mualem-van Genuchten parameters as in Experiment 1.

Parameter filenames have the form: sp-mip\_parameter\_experiment\_#number.nc

Files with information on soil parameters or soil-texture for Experiment 1, Experiment 2 as well as for Experiments 4a,b,c,d are available for **download** at

<ftp://sp-mip:sp-mip2017@data.iac.ethz.ch>

in the sub-directory "soil\_input\_files".

Note that no soil-parameter input files are provided for Experiment 2.

### **Soil Parameters (Experiment 1)**

It is currently assumed that all models solve the Richards equation. Soil parameters and textures are provided and it should be assumed that they are uniform throughout the whole soil column.

For experiments 1 and 4, models have to set soil parameters given by SP-MIP (Table 2). For definitions see section "Soil Physics Background" below. Two mathematical descriptions of water retention curves are considered: Brooks and Corey (1964) and Mualem-van Genuchten (van Genuchten 1980). Models that use different forms have to derive their input parameters from the given parameters of Table 2 for the closest match of the soil water retention curves. The file name of the soil parameters for Experiment 1 is: sp-mip\_parameter\_experiment\_1.nc.

**Table 2:** Soil parameters for the three considered water retention curves provided as input by SP-MIP for experiments 1 and 4a-d. For definitions see section on Soil Physics Background.

| Name       | long_name (netCDF)                                   | Unit                       |
|------------|------------------------------------------------------|----------------------------|
| he         | air entry potential                                  | m                          |
| mbc        | Brooks-Corey m parameter = Clapp-Hornberger b        | –                          |
| thetar     | residual soil moisture                               | $\text{m}^3 \text{m}^{-3}$ |
| thetas     | saturated soil moisture, porosity                    | $\text{m}^3 \text{m}^{-3}$ |
| ks         | Hydraulic conductivity at saturation or at air entry | $\text{m s}^{-1}$          |
| lambdac    | Corey lambda parameter                               | –                          |
| alphavg    | van Genuchten alpha parameter                        | $\text{m}^{-1}$            |
| nvg        | van Genuchten n parameter                            | –                          |
| mvg        | van Genuchten m parameter                            | –                          |
| thetafcbc  | Brooks-Corey field capacity                          | $\text{m}^3 \text{m}^{-3}$ |
| thetafcvg  | van Genuchten field capacity                         | $\text{m}^3 \text{m}^{-3}$ |
| thetafwcbc | Brooks-Corey permanent wilting point                 | $\text{m}^3 \text{m}^{-3}$ |
| thetafwvvg | van Genuchten permanent wilting point                | $\text{m}^3 \text{m}^{-3}$ |

### **Soil Textural Properties (Experiment 2)**

For experiment 2, soil textural properties are provided, given in Table 3. The modelling groups have to derive their required parameters in their own usual way from the given texture. The file name of the soil textures for Experiment 2 is: sp-mip\_parameter\_experiment\_2.nc.

**Table 3:** Soil textural properties provided by SP-MIP for experiment 2.

| Name    | long_name (netCDF)     | Unit                  |
|---------|------------------------|-----------------------|
| fclay   | fraction of clay       | –                     |
| fsilt   | fraction of silt       | –                     |
| fsand   | fraction of sand       | –                     |
| rhosoil | dry bulk density       | $\text{kg m}^{-3}$    |
| omsoil  | organic matter content | $\text{g(C) kg}^{-1}$ |

### **Spatially Uniform Soil Parameters (Experiments 4a, b, c, d)**

Global files with spatially uniform soil parameters (same as in Experiment 1) corresponding to loamy sand (experiment 4a), loam (experiment 4b), clay (experiment 4c), and silt (experiment 4d) (cf. Montzka *et al.* 2011) are provided with file names, for example, sp-mip\_parameter\_experiment\_4a.nc, etc.

## Spin-up

All modelling groups perform their standard spin-up procedure, making sure that reliable data are available from 1980 onwards.

## Model Output Data

Primary target variables are hydrological fluxes and states, i.e. evapotranspiration, surface and sub-surface runoff, soil moisture in soil layers, and root zone soil moisture.

Secondary target variables are related to energy (sensible heat flux, surface and soil temperatures, etc.) but SP-MIP shall focus on hydrology. All target variables are listed in Table 4. Most target variables are a subset of those variables listed as  $p^* = 1$  variables of Tables A1 and A2 of van den Hurk *et al.* (2016). Additionally, hydraulic and thermal conductivities as well as heat capacity in the soil are included.

Daily model outputs should be submitted as NetCDF files with variable names of Table 4. The NetCDF files will have a time (T), a latitude (X) and a longitude (Y) dimension for all variables and a level dimension for soil state variables (Z). All variables should be stored in the same file. To facilitate data handling, model outputs should be saved as annual chunks with the following file naming convention:

`<model>_experiment_<number>_<yyyy>.nc`

with

`<model>`: name of the model

`<number>`: the number of the experiments (i.e. 1, 2, 3 or 4a, 4b, 4c, 4d) see section on experiments

`<yyyy>`: the year, e.g. 1995

yielding for example: `cable_experiment_1_1995.nc` for experiment 1 (Soil-hydraulic parameters provided by SP-MIP) or `cable_experiment_4a_1995.nc` for experiment 4a (spatially uniform loamy sand).

**Table 4** Daily variables related to the energy and water cycles. The dimension (Dim.) column indicates T: time, Y: latitude, X: longitude, and Z: soil or snow layers. "Direction" identifies the direction of positive numbers. Variable names/descriptions are made compatible with CMIP6 definitions (<http://clipc-services.ceda.ac.uk/dreq/index.html>) were possible.

| Name              | long_name (netCDF)                             | Unit                               | Unit (netCDF) | Direction       | Dim. |
|-------------------|------------------------------------------------|------------------------------------|---------------|-----------------|------|
| <i>Energy</i>     |                                                |                                    |               |                 |      |
| rss               | Net Shortwave Surface Radiation                | W m <sup>-2</sup>                  | W m-2         | downward        | TYX  |
| rls               | Net Longwave Radiation                         | W m <sup>-2</sup>                  | W m-2         | downward        | TYX  |
| hfls              | Surface Upward Latent Heat Flux                | W m <sup>-2</sup>                  | W m-2         | upward          | TYX  |
| hfss              | Surface Upward Sensible Heat Flux              | W m <sup>-2</sup>                  | W m-2         | upward          | TYX  |
| hfdss             | Downward Heat Flux in Soil                     | W m <sup>-2</sup>                  |               | downward        | TYX  |
| ts                | Surface Temperature                            | K                                  | K             | –               | TYX  |
| albsrfc           | Surface Albedo                                 | –                                  | 1             | –               | TYX  |
| snc               | Snow Area Fraction                             | –                                  | 1             | –               | TYX  |
| tsl               | Soil Temperature                               | K                                  | K             | -               | TZYX |
| <i>Water</i>      |                                                |                                    |               |                 |      |
| et                | Total Evapotranspiration                       | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | upward          | TYX  |
| ec                | Interception Evaporation                       | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | upward          | TYX  |
| tran              | Transpiration                                  | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | upward          | TYX  |
| es                | Bare Soil Evaporation                          | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | upward          | TYX  |
| mrro              | Runoff Flux                                    | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | out             | TYX  |
| mrrob             | Subsurface Runoff Flux                         | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | out             | TYX  |
| snm               | Surface Snow Melt Flux                         | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | solid to liquid | TYX  |
| rzwc              | Root Zone Soil Moisture                        | kg m <sup>-2</sup>                 | kg m-2        | –               | TYX  |
| cw                | Total Canopy Water Storage                     | kg m <sup>-2</sup>                 | kg m-2        | –               | TYX  |
| snw               | Surface Snow Amount                            | kg m <sup>-2</sup>                 | kg m-2        | –               | TZYX |
| snwc              | SWE intercepted by the vegetation              | kg m <sup>-2</sup>                 | kg m-2        | –               | TYX  |
| mrlsl             | Water Content per Unit Area of Soil Layers     | kg m <sup>-2</sup>                 | kg m-2        | –               | TZYX |
| tw                | Terrestrial Water Storage                      | kg m <sup>-2</sup>                 | kg m-2        | –               | TYX  |
| mrsofr            | Mass Fraction of Frozen Water in Soil Moisture | –                                  | 1             | –               | TZYX |
| snd               | Surface Snow Thickness                         | m                                  | m             | –               | TYX  |
| <i>Additional</i> |                                                |                                    |               |                 |      |
| preshead          | Soil Pressure Head                             | kg m <sup>-2</sup>                 | kg m-2        | –               | TZYX |
| hydcnd            | Soil Hydraulic Conductivity                    | kg m <sup>-2</sup> s <sup>-1</sup> | kg m-2 s-1    | –               | TZYX |
| thrmcnd           | Soil Thermal Conductivity                      | W m <sup>-1</sup> K <sup>-1</sup>  | W m-1 K-1     | –               | TZYX |
| heatcap           | Soil Thermal Capacity                          | J kg <sup>-1</sup> K <sup>-1</sup> | J kg-1 K-1    | –               | TZYX |
| lai               | Leaf Area Index                                | -                                  | 1             | -               | TYX  |
| omsoil            | Organic Matter Content                         | g(C) kg <sup>-1</sup>              |               |                 | TZYX |

## File Submissions

### Data compression

To stay within reasonable disk space only variables listed in Table 4 should be included in the files that are submitted. In addition, all model output will be converted automatically to NetCDF-4 format and compressed 32-bit variables with the following CDO (<https://code.mpimet.mpg.de/projects/cdo/>) command:

```
cdo -f nc4 -z zip -b F32 copy netcdf.nc tmp.nc ; mv tmp.nc netcdf.nc
```

Model groups are encouraged to perform this transformation before uploading results.

### File Upload

Model output files, corresponding to the format described above should be uploaded to

<ftp://sp-mip-up:sp-mip2017.upload@data.iac.ethz.ch>

Files can be removed up to 30 minutes after the upload is completed. Afterwards they cannot be deleted through ftp, to reduce the risk of accidentally overwriting or removing files.

## Soil Physics Background

The most commonly used soil water retention curves are Brooks and Corey (1964), Clapp and Hornberger (1978) and van Genuchten (1980). We use solely the Mualem (1976) model to link water retention curves with hydraulic conductivity.

Brooks and Corey (1964) defined:

$$h = h_e S^{-m} \quad (1)$$

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (2)$$

$$K = K_s S^\lambda \quad (3)$$

with

- $h$  pressure head (m)
- $h_e$  air entry potential/head (m)
- $S$  relative saturation
- $m$  Brooks-Corey  $m$  parameter
- $\theta$  volumetric soil moisture ( $\text{m}^3 \text{m}^{-3}$ )
- $\theta_r$  residual soil moisture ( $\text{m}^3 \text{m}^{-3}$ )
- $\theta_s$  porosity = saturated soil moisture ( $\text{m}^3 \text{m}^{-3}$ ).
- $K$  hydraulic conductivity ( $\text{m s}^{-1}$ )
- $K_s$  hydraulic conductivity at air entry ( $\text{m s}^{-1}$ )
- $\lambda$  Corey lambda parameter
- $\lambda = 5/2 + 2m$  (Mualem).

Clapp and Hornberger (1978) simplified Brooks and Corey (1964) by using

$$S = \frac{\theta}{\theta_s}, \quad (4)$$

all else equal but the Brooks-Corey  $m$  parameter is often called Clapp-Hornberger  $b$ .

van Genuchten (1980) defined:

$$h = \frac{1}{\alpha} \left( S^{-\frac{1}{m}} - 1 \right)^{\frac{1}{n}} \quad (5)$$

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (6)$$

$$K = K_s \sqrt{S} \left( 1 - \left( 1 - S^{\frac{1}{m}} \right)^m \right)^2 \quad (8)$$

if

$$m = 1 - 1/n \quad (8)$$

with

- $h$  pressure head (m)

|            |                                                                    |
|------------|--------------------------------------------------------------------|
| $S$        | relative saturation                                                |
| $n$        | van Genuchten $n$ parameter                                        |
| $m$        | van Genuchten $m$ parameter<br>$m = 1 - 1/n$ (Mualem)              |
| $\theta$   | volumetric soil moisture ( $\text{m}^3 \text{ m}^{-3}$ )           |
| $\theta_r$ | residual soil moisture ( $\text{m}^3 \text{ m}^{-3}$ )             |
| $\theta_s$ | porosity = saturated soil moisture ( $\text{m}^3 \text{ m}^{-3}$ ) |
| $K$        | hydraulic conductivity ( $\text{m s}^{-1}$ )                       |
| $K_s$      | hydraulic conductivity at saturation ( $\text{m s}^{-1}$ ).        |

Soil water limitation functions for plants often use (pressure heads at) field capacity and permanent wilting point. The former can be defined as the volumetric soil moisture at a pressure head of 3.3 m. The latter can be defined (in soil science) as the volumetric soil moisture at a pressure head of 150 m:

$\theta_{fc}(h_{fc} = 3.3 \text{ m})$  field capacity ( $\text{m}^3 \text{ m}^{-3}$ )

$\theta_{pwp}(h_{pwp} = 150 \text{ m})$  permanent wilting point ( $\text{m}^3 \text{ m}^{-3}$ ).

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## **Annexe B**

Préparation des forçages atmosphériques  
GSWP3-v1 pour SP-MIP

## Preparing GSWP3 V1 Official forcing to be read by ORCHIDEE

Salma Tafasca, Agnès Ducharne, April 2018

### 1- Formatting the GSWP3 V1 forcing

GSWP3 V1 is the official v1 release of GSWP3 forcing [Kim et al. in prep]. In this document, we describe how we formatted the GSWP3 V1 forcing in order to be read by ORCHIDEE.

The following forcing notations will be used in this document:

**F0** : GSWP3 v0 forcing formatted by Jinfeng Chang for ISIMIP2 simulations.

**F1** : GSWP3 v1 official forcing after being formatted to be used by ORCHIDEE.

**D1**: dim2driver interpretation of **F1** forcing.

**F1** forcing has been prepared based on the official V1 release of GSWP3 at the global 0.5° resolution. It covers the period 1901-2010 and the files are stored in the shared repositories of ORCHIDEE. The script used to prepare the forcing is located in the same directory, it was adapted from Jinfeng Chang's script for preparing **F0**, based on the reflexions of Agnès Ducharne and Nicolas Vuichard.

The Rscript creates netcdf-3 forcing files, which were converted to netcdf-4 using the command `ncks -4 GSWP3_halfdeg_3h_YYYY.nc GSWP3_v1_halfdeg_3h_YYYY.nc`. Except for the first 19 years (from 1901 to 1919), which were created originally as netcdf-4 files.

#### 1-1-Time axis

**F1** forcing is prepared to be read by the old driver (dim2driver), which assumes that scalar variables (Tair, Qair, Psurf and Wind) are instantaneous, while flux variables (Rainf, Snowf, SWdown, LWdown) are averaged over the previous time interval. Furthermore, dim2driver considers that the first value of the year corresponds to the time instant: 00:00 UTC+dt\_forcing, regardless of the time axis. Since the original GSWP3 forcing provided by Kim (2017) starts every year at 00:00 UTC, the time axis was shifted in **F1** forcing, for all the forcing variables, to respect the assumption of dim2driver. Figure 1 shows the transformation in time axis of GSWP3 v1 to obtain **F1**. For every yearly file, we discard the first record which corresponds to 00:00, and we add the first record of the next year, which corresponds to 24:00. For the last year file, since we don't have the record of 24:00, the last record (21:00) is repeated twice.

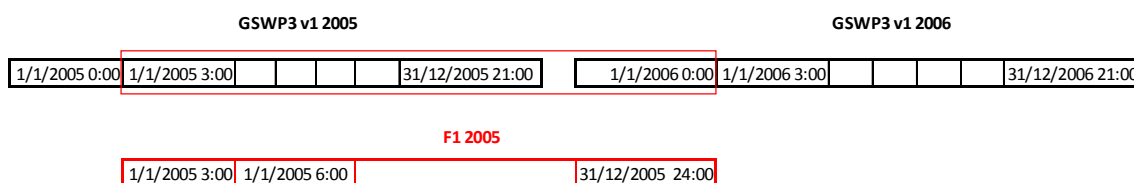


Fig.1 Time axis transformation from F0 to F1

In order for the **F1** forcing to be read by the new driver, an attribute was added to all variables explaining that the values represent backward averaging, which means that a record at 00:00 is a mean of the time interval [-3:00, 00:00] (cf. mail of Hyungjun Kim on 17/01/2018). The attribute is the following:

*cell\_method time : mean (end)*

This attribute determines if the variable is an instantaneous value or an average over a time step. If it is an average, then the term between () determines if the specified date corresponds to the start, the center or the end of the interval over which the variable is averaged [Jan Polcher, Content of ORCHIDEE forcing files, May 2014] ([http://forge.ipsl.jussieu.fr/orchidee/raw-attachment/wiki/Documentation/Forcings/Description\\_Forcings\\_Files.pdf](http://forge.ipsl.jussieu.fr/orchidee/raw-attachment/wiki/Documentation/Forcings/Description_Forcings_Files.pdf)).

Note that the old driver (dim2driver) does not consider attributes, it assumes that all scalar variables are time : instantaneous, instead of time : mean (end), which leads to a small error on the scalars. Figure 2

illustrates how dim2driver interprets F1 scalar variables (dashed blue line), while the correct interpretation is represented by the dashed red line, since the values provided by GSWP3 v1 are averaged values over the previous time step.

According to Jan Polcher, when cell method = time: mean (end), the new driver positions the scalar values at the center of the interval, leading to a more correct interpolation.

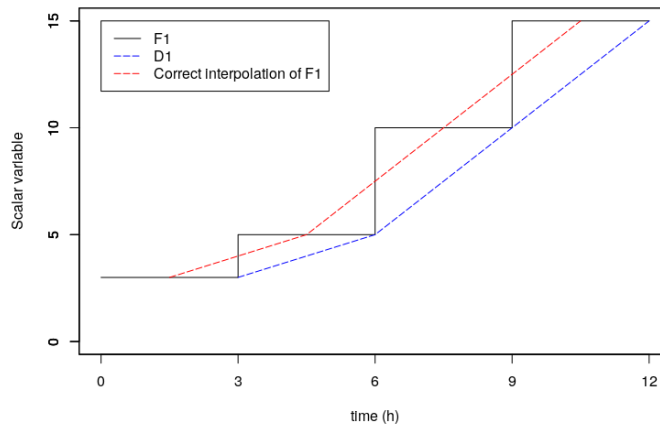


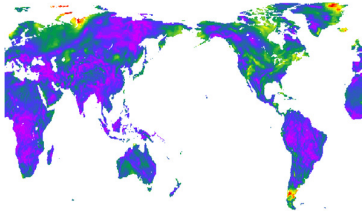
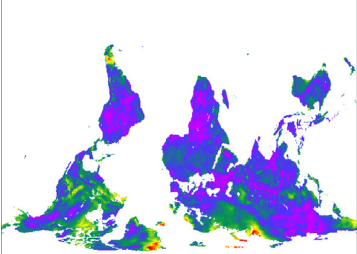
Fig.2 dim2driver interpolation of F1 forcing (dashed blue) VS correct interpolation (dashed red)

## 1-2-Mask

In the original GSWP3 V1 official forcing, data covers the whole globe including oceans except for the variable Wind, where data covers only land surface points. Wind data was therefore used to mask all variables. The formatted variables are kept 2D.

Table 1 summarizes the main differences between the original GSWP3 v1 forcing provided by Kim (2017), and the processed GSWP3 (referred to as F1). Note that GSWP3 v1 has leap years.

Table 1 Differences between original GSWP3 v1 official forcing and formatted one (F1)

|                         | Original GSWP3 v1 (Kim, 2017)                                                                    | Processed GSWP3 (F1)                                                                             |
|-------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| <b>Organizing files</b> | One file for every year for every variable                                                       | One file for every year containing all variables                                                 |
| <b>Masking</b>          | Only Wind is masked                                                                              | All variables are masked                                                                         |
| <b>Time axis</b>        | Year starts at January 1 <sup>st</sup> 00:00 UTC and ends at December 31 <sup>st</sup> 21:00 UTC | Year starts at January 1 <sup>st</sup> 03:00 UTC and ends at December 31 <sup>st</sup> 24:00 UTC |
| <b>Map orientation</b>  |               |             |

## 2- Testing the F1 forcing

A test has been performed with the trunk revision of ORCHIDEE using F1 forcing, to make sure it is read correctly by the old driver of ORCHIDEE. Description of the protocol of the test and results are described in section 2.1 and 2.2, respectively.

### 2.1 Protocol of the test

#### 2-1-1 ORCHIDEE simulation

ORCHIDEE was run using F1 forcing, under the following conditions:

- Period of simulation: 5 days, from 01/01/2005 to 05/01/2005
- Output frequency: highest possible frequency, ie, 30 minutes
- LWdown conserved. By default, ORCHIDEE performs an interpolation of LWdown between two time instants, which does not conserve the amount of energy over a time step interval. This configuration can be changed by adding in run.def file: LWDOWN\_CONS = y.

#### 2-1-2 The diurnal cycle

All forcing variables are plotted in section 2.2 on 01/01/2005 over the point 10°N and 0°E (north Togo), except for rainfall and snowfall variables which were examined at north Australia (13.5°S, 130°E) and north India (31°N, 80°E), respectively, where rainfall and snowfall values are important. For each variable, we plot GSWP3 V1 forcing curve (in purple), F1 forcing curve (in green), which both vary at a 3h time step, and D1, which is the interpretation of F1 by dim2driver at a 30min time step (in red). In order to show if dim2driver conserves the values while interpolating over a forcing time-step, an additional curve (red dashed line) is plotted, representing the average of D1 over a 3h time-step (= forcing time-step).

## 2.2 Results

### 2-2-1- The variables Tair, Qair and Psurf

dim2driver linearly interpolates the scalar variables Tair, Qair and Psurf, which are provided at 2m height.

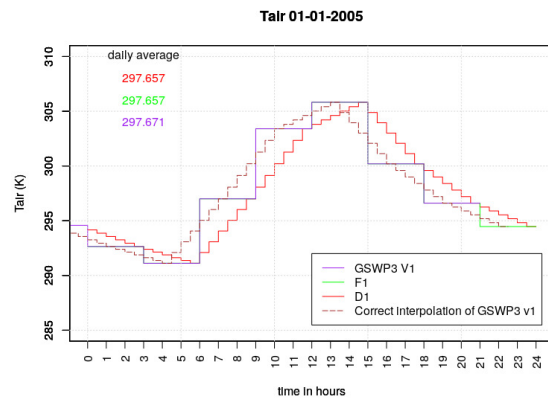


Fig.3 Air temperature on landpoint ( $x=0^\circ$ ,  $y=10^\circ\text{N}$ )

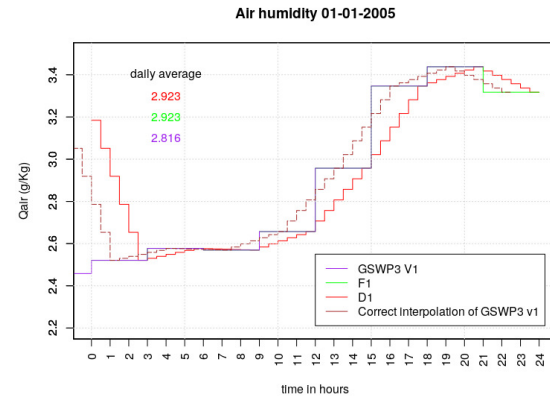


Fig.4 Air humidity on landpoint ( $x=0^\circ$ ,  $y=10^\circ\text{N}$ )

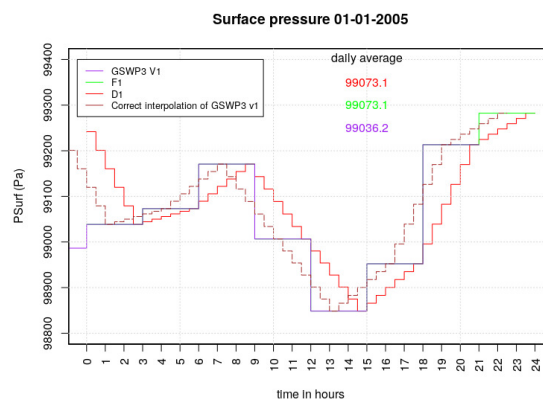


Fig.5 Surface pressure on landpoint ( $x=0^\circ$ ,  $y=10^\circ\text{N}$ ).

To interpolate the scalar variables over the first time step [0:00, 3:00] of the first year, and since no value is provided for the time instant 0:00, dim2driver uses the record of the last time step of the day (24:00) in order to complete the interpolation. This explains why the red curve does not follow the purple curve in the first forcing time step.

At a time instant  $t_0$ , GSWP3v1 provides mean records over the time interval preceding the time instant  $t_0$ . dim2driver treats the scalar records as if they were instantaneous, which leads to an error (red curve VS brown dashed curve in fig.3) (see section 1.1).

## 2-2-2- The variables SWdown and LWdown

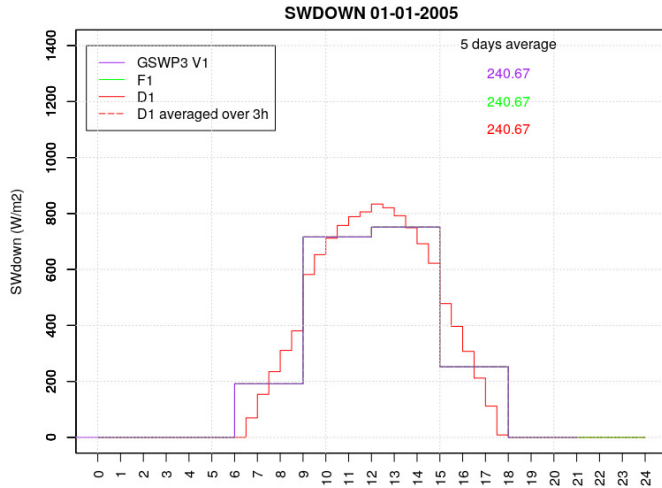


Fig.6 Downward short wave radiation. ( $x=0^\circ$ ,  $y=10^\circ N$ ).

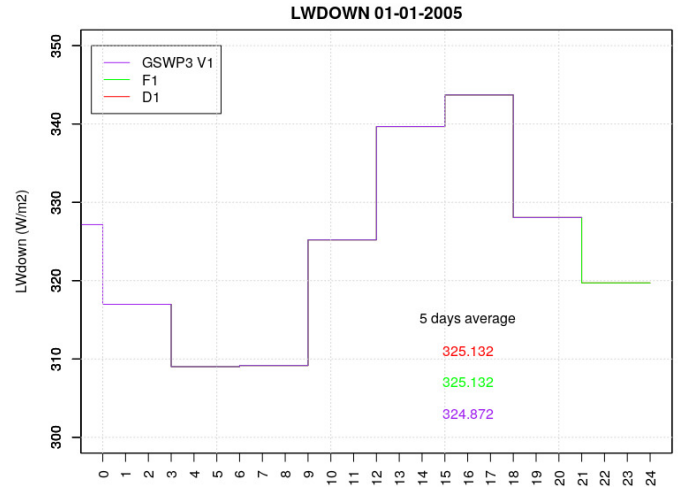


Fig.7 Downward long wave radiation. ( $x=0^\circ$ ,  $y=10^\circ N$ ).

dim2driver respects two conditions while disaggregating SWdown variables:

- 1- The provided average flux should be preserved during a time step interval.
- 2- SWdown should be distributed proportional to the zenith angle.

In the absence of noise induced by clouds, the diurnal cycle of SWdown should be relatively smooth and well centered at noon. Figure 6 shows that the downward solar radiation for D1 is consistent with the zenith angle (presence of the mid-day peak) and that SWdown is conserved, over the land point  $10^\circ N$ ,  $0^\circ E$ . However, a global analysis points out a small energy conservation violation over some particular regions of the globe (Figure 8).

Figure 8a shows that the 5-day average value of SWdown in F1 differs from the one in D1, in some regions of the globe. The shape of these zones reminds the shape of a SWdown plot at the sunset zones (Fig 8b and c).

For a better understanding of what is happening in these zones, we selected the landpoints in which SWdown is not conserved ( $41^\circ W$ ,  $14^\circ S$ ) for which we analysed SWdown curves (Fig. 9). F1 and D1 forcings seem to be overlapped, but a visualization of the difference (Fig. 9b) reveals a tiny difference of around  $1 W/m^2$  occurring at the last forcing time step of the day. This difference is barely visible so we did not work on a correction in dim2driver to fix it.

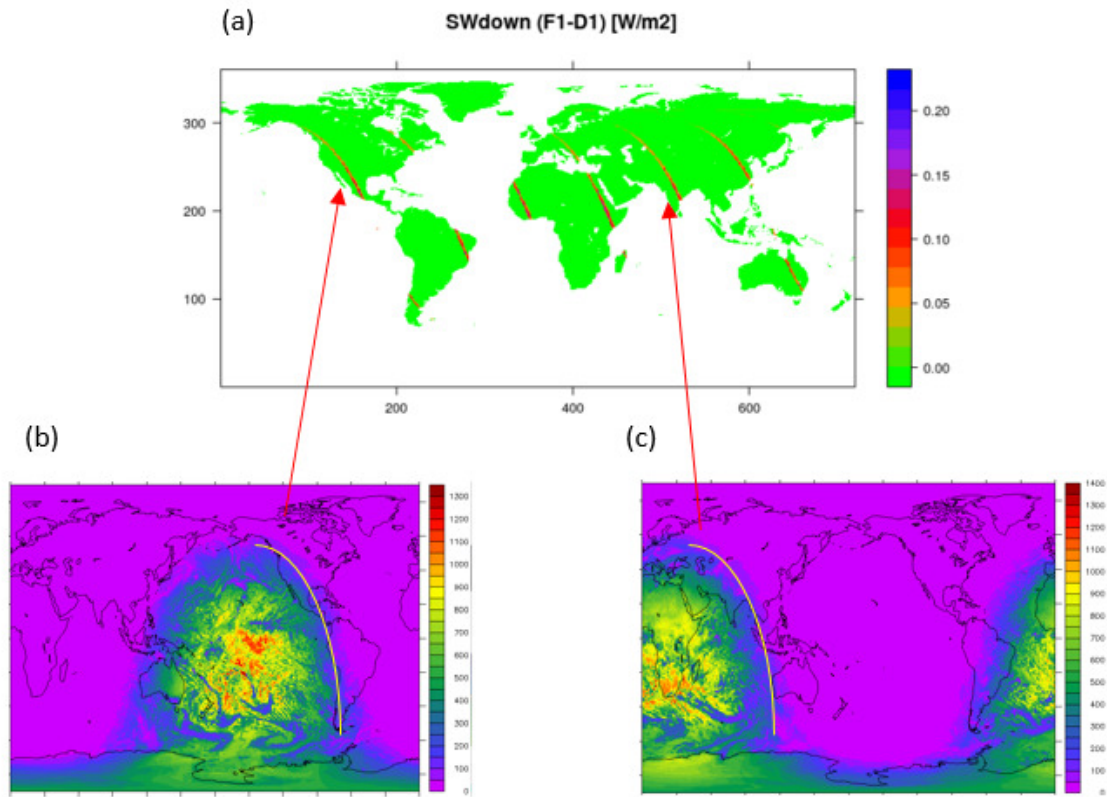


Figure 8 (a) Difference in averaged SWdown over 5 days, between the forcing F1 and D1 (1<sup>st</sup> to 5<sup>th</sup> January 2005). (b) Global SWDOWN plot on 01-01-2005 at 00:00 and at (c) 12:00 UTC, from forcing F1.

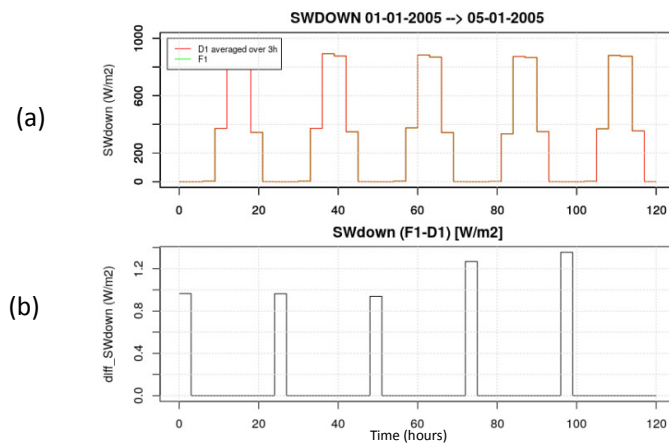


Fig.9 Downward short wave radiation. Green and red curves are not completely overlapped, the difference between the two curves is plotted in fig (b). ( $x=41^{\circ}W$ ,  $y=14^{\circ}S$ ).

By default, ORCHIDEE does a linear interpolation of LWdown between  $t$  and  $t+dt$ , in this case, the mean value of LWdown over the interval  $[t, t+dt]$  is  $(LW(t)+LW(t+dt))/2$ , which is different from the real mean value, which is  $LW(t+dt)$ , so the amount of energy is not conserved. (for more details, refer to the discussion on the differences between the two drivers that can be found on: [https://forge.ipsl.jussieu.fr/orchidee/wiki/Branches/Driver\\_Improvements](https://forge.ipsl.jussieu.fr/orchidee/wiki/Branches/Driver_Improvements)).

In the present simulation, we added `LWdown_cons = y` in the `run.def` file, in order to preserve the average flux provided by the forcing during the temporal disaggregation. It was checked that `LWdown` is perfectly conserved over the whole globe.

### 2-2-3 The variable Wind:

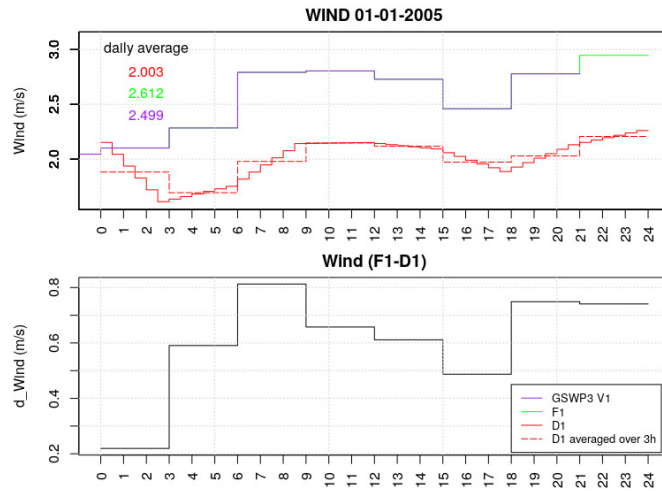


Fig.10 Wind curve on land point ( $x=0^\circ$ ,  $y=10^\circ N$ ).

According to Hyungjun Kim, GSWP3 relies on wind speed measured at heights above the surface of between 2 and 20 m. Measurement height varies both within and between countries, and in many cases, the heights were not specified, consequently, no corrections were made to wind data. The large majority of known heights were 10 m, and the interpolated wind field should be assumed to represent the wind speed at this height (New et al., 2002). This means we could assume GSWP3 winds as values at 10 m.

The wind is treated like a scalar, and both `dim2driver` and the new driver assume by default that it is measured at a height of 10m. Consequently, the drivers apply an interpolation to get wind values at a height of 2m needed for ORCHIDEE land surface variables. Figure 10 shows the difference between wind from forcing F1 (measured at 10 m) and the 2-m interpolated values (forcing D1).

### 2-2-4 The variables Rainf and Snowf:

**dt\_force** : time-step of the forcing

**dt** : time-step of sechiba

**split** =  $\text{int}(\text{dt\_force}/\text{dt})$

When `dt_force` is less than 3 hours, the precipitation is uniformly distributed over `dt_force`, otherwise, by default, the old and new drivers non-uniformly distribute precipitation at ORCHIDEE's time resolution, using the parameter `nb_spread`, which is the number of the first time steps of ORCHIDEE over which the precipitation is distributed, within one forcing time step. When `nb_spread` = `split`, the precipitation is uniformly distributed over the forcing time step. By default `nb_spread`=`split`/2. Ideally, to be closer to the real world, the value of `nb_spread` should be climate dependent and it is therefore not realistic to use one single value for the whole globe, as it is done in ORCHIDEE, due to lack of sufficient information (30-min precipitation data over the whole globe). Figures 11 and 12 show the effect of `nb_spread` on the high frequency distribution of `Rainf` and `Snowf` respectively, with good conservation of the input values (the small differences between the simulations and GSWP3 come from the initial time step).

To assess the effects of the `nb_spread` value over the water balance variables and 1-st layer soil temperature, we ran twice the same 5-day simulation with two different configurations. The first one uses the default value of `nb_spread` while the second one uses a uniform distribution of precipitation,

ie,  $nb\_spread = split$ . These simulations were run regionally over the domain between 120 and 150°E and 0 and 15°S (north Australia, Indonesia, New Guinea, Fig. 13).

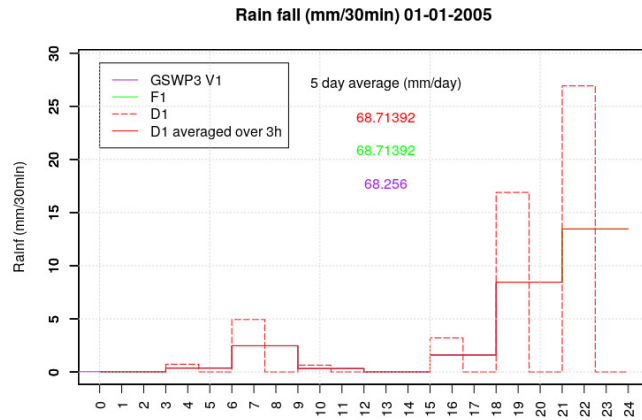


Fig.11 Rain fall curve on land point ( $x=130^\circ$  east,  $y=13.5^\circ$ S) (north Australia)

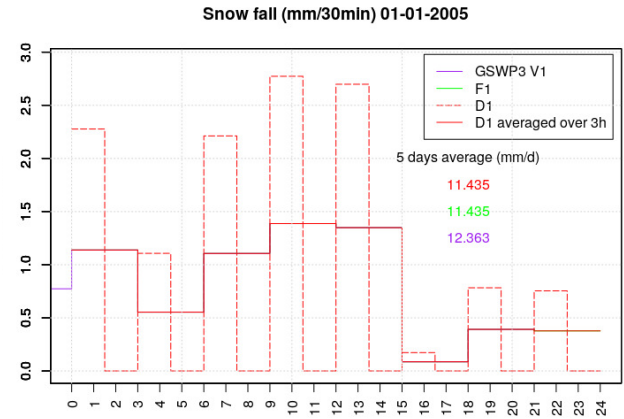


Fig.12 Snow fall curve on land point ( $x=80^\circ$  E,  $y=31^\circ$ N). (north India)

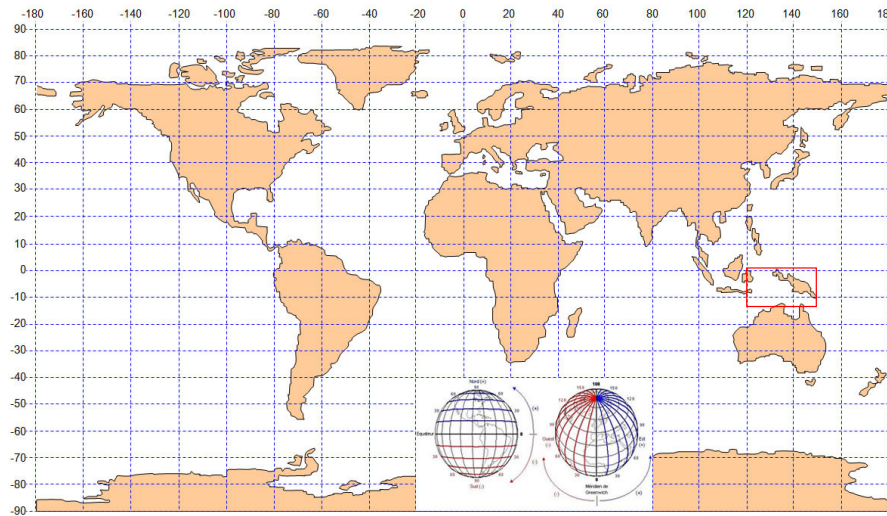


Fig.13 Simulated region  $X \in (120^\circ, 150^\circ)$ ,  $Y \in [-15^\circ, 0^\circ]$

Figure 14 shows the time series of ORCHIDEE outputs at a half-hourly time step, represented at point ( $x=130^\circ$ E,  $y=13.5^\circ$ S  $\rightarrow$  north of Australia) for the last three days of the simulations. The first two days were discarded to avoid misinterpreting effects caused by initialization from restart. For each variable, a 3-day regional average is calculated.

The high frequency variation of surface soil moisture (Fig. 14c) comes primarily from the rain (Fig. 14a), while the drainage variations do not seem to be affected by the high-frequency precipitation variation (Fig. 14e). Mean drainage, however, is reduced in case of non-uniform precipitation which leads to increased surface runoff (Fig. 14g) thus reduced surface soil moisture. In fact, soil permeability is limiting the infiltration, thus intense precipitation leads to more infiltration-excess runoff. As a result, the dependency of surface runoff on rainfall rate is highly non-linear, and a uniform distribution of precipitation reduces runoff considerably over the simulated region (from 1.845 mm/d to 1.165 mm/d, with a decrease of the ratio runoff/drainage from 44 to 28%). Note that this may not be true in regions with flat areas, where we can have reinfiltration during the second half of  $dt\_force$ , during which no rainfall is simulated, and therefore, increase drainage.

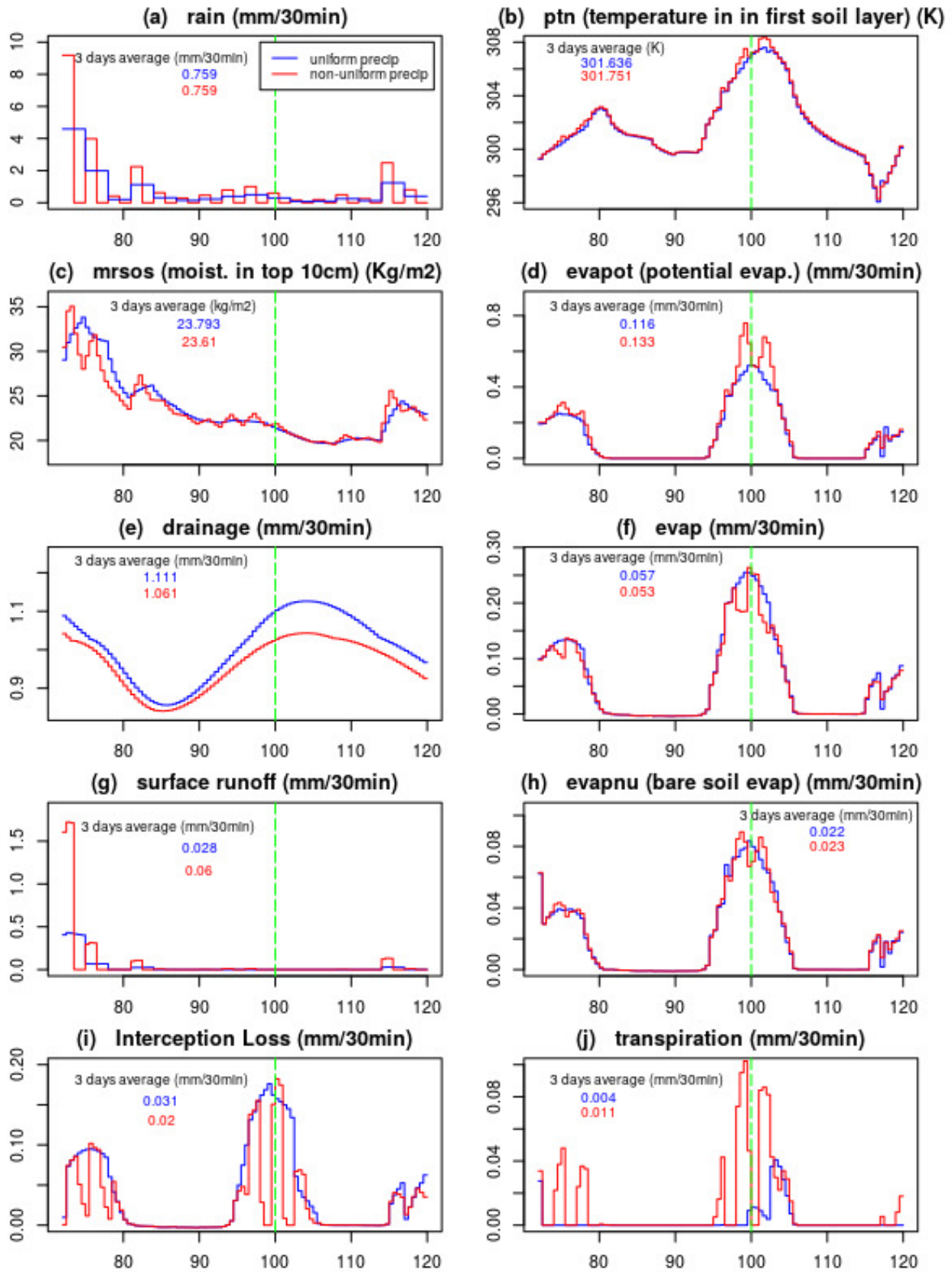


Fig.14 time series of (a) rain, (b) soil moisture in top 10 cm of soil, (c) drainage, (d) surface runoff, (e) temperature in soil top layer, (f) potential evaporation, (g) evaporation, (h) bare soil evaporation, (i) interception loss, (j) transpiration, on landpoint X=130°E, Y=13°30'S (north Australia)

A non-uniform distribution of precipitation also leads to peaks of potential evaporation over time steps without rainfall (Fig. 14d), thus with a higher surface temperature (Fig. 14 b). In addition, it produces discontinuities in transpiration and interception loss (Fig. 14 i and j). Evaporation (Fig. 14f) and potential evaporation are phase shifted, because the main component of evaporation (interception loss) is itself in opposite phase with potential evaporation. This is due to the fact that canopy water storage is the limiting factor of the interception loss: the water storage on the canopy is always small and can quickly become zero when precipitation ceases, thus shutting down interception loss. In contrast, the other components of evaporation (transpiration and bare soil evaporation (Fig. 14j and h) are in phase with potential evaporation because it is the main driving factor. Besides, there is no transpiration in ORCHIDEE until interception loss ceases, which explains the transpiration being phase shifted with interception loss.

In the studied case, in addition to reducing peaks of all evaporation variables, a uniform distribution of precipitation slightly increases total evaporation (from 3.242 to 3.317 mm/d), even though the potential evaporation decreases. This comes mostly from the response of interception loss, which is the main component of evaporation, and is much high under uniform precipitation loading, to the detriment of transpiration. Note, however, that these quantitative results might not be true in other places/situations.

Based on these analyzes, the simulations for the SP-MIP experiments will be run using a uniform distribution of precipitation, to prevent from spurious hourly variability of evaporation.

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