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Land surface versus ocean influence on atmospheric variability and predictability at the seasonal timescale

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1.Introduction

Although the chaotic nature of the atmospheric dynamics (that is its sensitivity to initial conditions) is a fundamental limit to its deterministic predictability, it is now well known that predictability of seasonal weather statistics is possible (see reviews by Palmer and Anderson 1994). This arises from what may be termed “external” factors that alter the likelihood of residence in atmospheric attractors, enabling probabilistic forecasts to be made of the seasonal mean state, on condition that the external forcing is itself predictable.

It is commonly accepted that the primary source of such external forcing at seasonal timescales arises from anomalous sea surface temperature (SST) patterns (i.e. Rowell 1998). On the one hand, these can indeed be predicted, either using coupled dynamical models or statistical models. On the other hand, both observational and numerical studies suggest that interannual atmospheric variability is partly driven by SST variability, especially in the tropical Pacific given the major teleconnections associated with the El Niño Southern Oscillation (i.e. Wallace et al. 1998).

Further potential sources of predictive skill, in particular land surface anomalies, are generally believed to be much less important and are often neglected in studies about seasonal predictability. Nevertheless, an increasing body of literature suggests that land surface memory can also contribute to atmospheric variability and predictability at the monthly to seasonal timescale. The main objective of this paper is to relate a brief history of this research activity, to summarize some important results and to raise the issues to be further explored. It is not intended to be a comprehensive review of the subject, but rather to illustrate both advances and issues in the field, mainly using some of the studies conducted over the last few years at CNRM.

2. Land surface models and data

Land surface models (LSM) have evolved substantially from the original bucket model of Manabe (1969). While they were initially developed as simple parametrizations within the atmospheric general circulation models (GCM), their increasing complexity and the need of validating them in “off-line” mode (i.e. driven by more realistic atmospheric forcings than those simulated by climate models) has led to a progressive “emancipation” of LSMs that have moved from being subroutines to independent models which can be coupled to atmospheric models but also used “off-line” for other applications such as validation-calibration, but also hydrological predictions or impact studies (Polcher et al. 1998).

The status of LSMs is therefore getting closer to that of oceanic GCMs, but does it mean that their influence on atmospheric variability is of comparable relevance? One crucial issue for answering this question is the lack of observational datasets to document the land surface variability at the global scale. While *in situ* and - since the 1980s - satellite observations do exist to characterize the large-scale monthly SST variability over the 20th century, the task is much more difficult over land for at least three reasons. First, the land influence on atmosphere depends on several parameters, not only surface temperature but also hydrology, vegetation and topography. Second, some of these parameters, especially but not only the subsurface hydrology, are still difficult to retrieve from satellite observations. Third, land surfaces generally show a much stronger high-frequency variability as well as a much stronger spatial heterogeneity than ocean surfaces, so that the monitoring of land surface variability with *in situ* observations only is simply not possible.

Let us here examine the modeling implications of this last remark given the focus of the ECMWF seminar on the parametrization of subgrid physical processes. One of the main challenge in developing models for the land surface hydrology in numerical climate models stems indeed from the fact that the horizontal resolution of these models is incompatible with the characteristic scales of surface hydrologic properties. What cannot be explicitly resolved within the numerical model discretization must be parameterized. While in the 1980s, the development and local validation of LSMs has focused on improving the one-dimensional structure of the soil-snow-canopy system, more attention has been paid recently to the treatment of the horizontal subgrid variability of (i.e. Entekhabi and Eagleson 1989, Dümenil and Todini 1992, Koster and Suarez 1992).

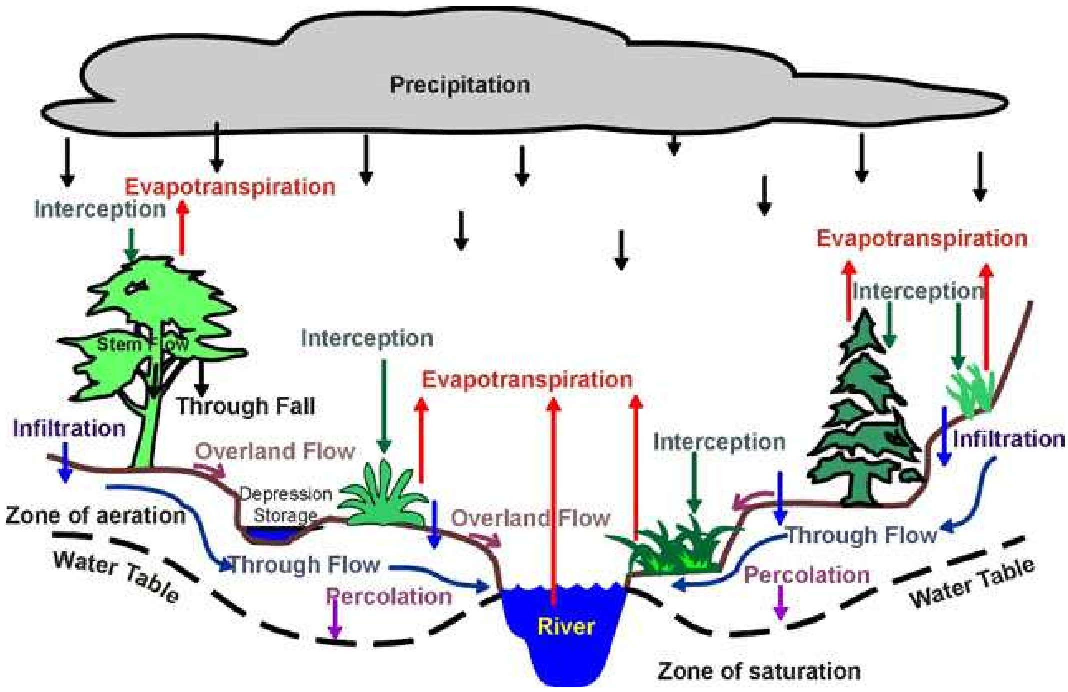

Fig. 1: The main sources of subgrid hydrological variability acoounted for in the ISBA-SGH land surface model of CNRM (Decharme and Douville 2006): precipitation, orography and vegetation.

Beyond numerical sensitivity studies showing the relevance of land surface heterogeneities for the calculation of the land surface energy and water fluxes, basin-scale field experiments have been a key stage in the development, calibration and validation of subgrid hydrological processes (i.e. Boone et al. 2004). River discharge observations indeed offer the opportunity to validate the simulated runoff (not all the components of the water budget) after integration over the drainage area. Depending on the size of the basin and on the frequency of interest, river routing models might be however necessary to account for the time lag between the production of runoff and the discharge response at the gauging station.

At CNRM, a coherent subgrid hydrology, ISBA-SGH, accounting for grid cell heterogeneities not only in soil and vegetation properties (tile or mosaic approach, Koster et al. 1992) but also in precipitation intensities (Entekhabi and Eagleson 1989) and orography (Topmodel approach, Beven and Kerby 1979) has been developed and tested over the French Rhône river basin (Decharme and Douville 2006). Off-line simulations at 8km driven by the SAFRAN meteorological analysis of CNRM have been compared with lower resolution (1°) simulations after linear interpolation of the high-resolution atmospheric forcing. For drainage areas exceeding a few 1° by 1° grid cells, results showed that the daily river discharge efficiencies of ISBA-SGH are not only less sensitive to horizontal resolution than those of the standard ISBA model, but also exceed at low resolution those obtained with ISBA at high resolution (Fig. 2).

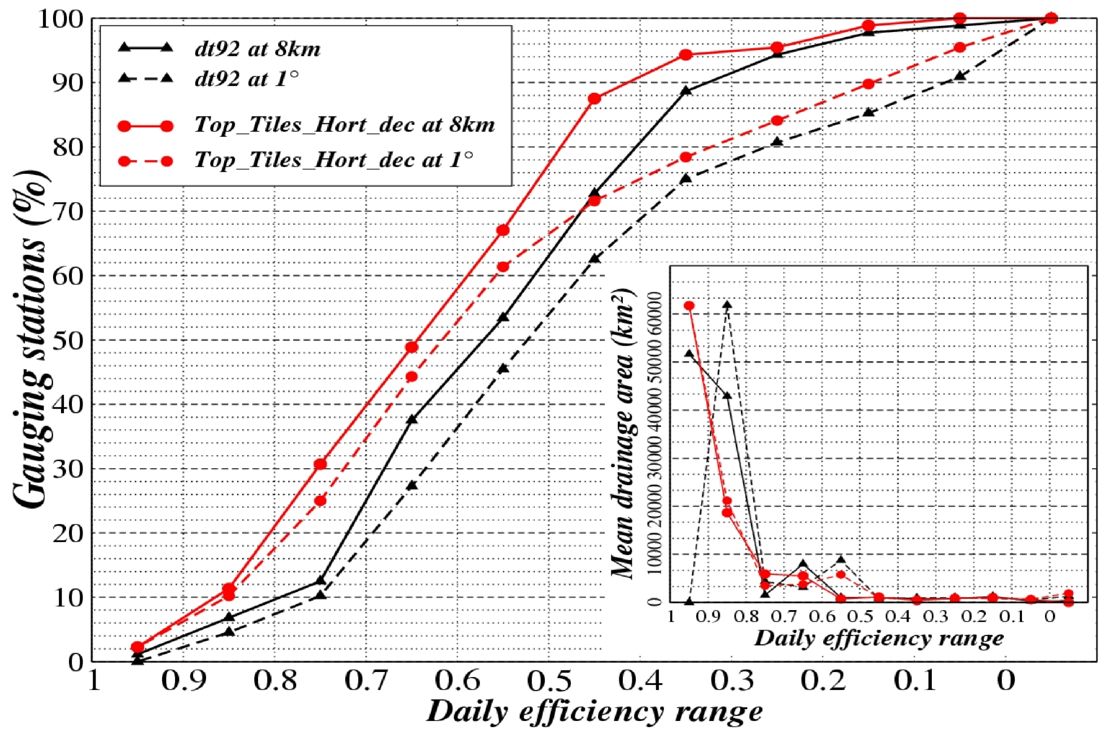

Fig. 2: Cumulative efficiency (Nash criterion) distribution of daily river discharges simulated at 88 gauge stations distributed over the Rhône river basin. All hydrological simulations are driven by observed atmospheric forcings either at a 8km (solid lines) or 1° (dashed lines) horizontal resolution and coupled to the MODCOU river routing model. ISBA-SGH (in red) is compared to the standard ISBA model (in black). From Decharme and Douville 2006.

Beyond basin-scale simulations, there is a need of validating and/or comparing LSMs at the global scale at which they are used in atmospheric GCMs. This was the purpose of the International Satellite Land Surface Climatology Project (ISLSCP) that has been launched in the mid-1990s and has allowed land surface modelers to produce global soil moisture climatologies by driving their models with common atmospheric forcings and land surface parameters in the framework of the Global Soil Wetness Project (GSWP, http://grads.iges.org/gswp).

The ISBA land surface model of CNRM contributed to GSWP and was driven by the ISLSCP atmospheric forcings first from 1987 to 1988 (GSWP-1, Douville 1998), then from 1986 to 1995 (GSWP-2, Decharme and Douville 2007). Besides control runs using the common ISLSCP soil and vegetation parameters, parallel integrations have been achieved with the native ISBA land surface parameters to produce soil moisture and snow mass climatologies that are fully consistent with the CNRM atmospheric GCM. Such climatologies can be used to nudge global atmospheric simulations towards "realistic" land surface boundary conditions and compare the influence of soil moisture or snow mass versus SST on atmospheric variability and predictability at the seasonal timescale (see next section).

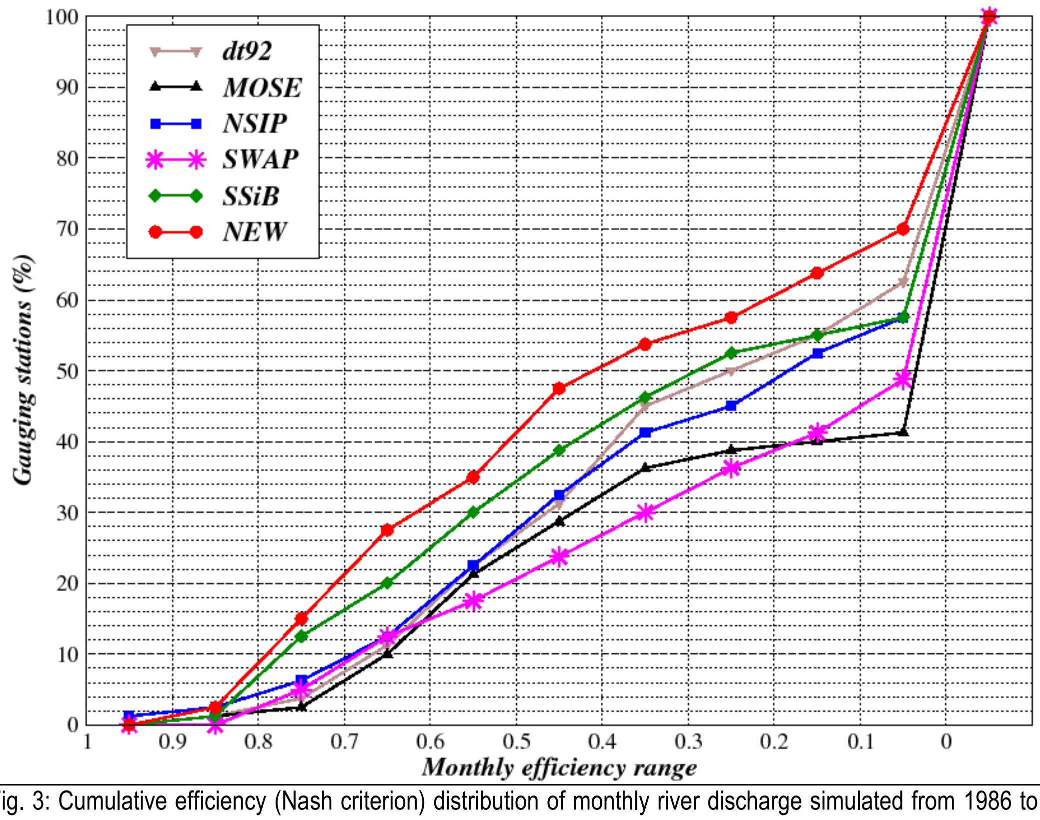

Fig. 3: Cumulative efficiency (Nash criterion) distribution of monthly river discharge simulated from 1986 to 1995 at 80 gauge stations distributed over the largest (>100000 km²) world's river basins. Six land surface models are compared : ISBA-SGH (NEW) and ISBA-standard (dt92), as well as four other LSMs having contributed to the international GSWP-2 intercomparison project (B3 atmospheric forcing). Runoff from all simulations has been converted into river discharge using the TRIP river routing model (Oki and Sud 1998). From Decharme and Douville 2007.

Moreover, the off-line GSWP simulations were also useful to test the ISBA-SGH hydrology at the global scale (Fig. 3). While only monthly observations of river discharge at 80 gauging stations distributed over the largest world's river basins were available over the 1986-1995 period, the results confirmed a general improvement of the simulated runoff relatively to the standard ISBA hydrology and compared favourably with the simulations obtained from other LSMs involved in GSWP, after converting the runoff into discharge using the same TRIP river routing model (Decharme and Douville 2007).

3. Land-atmosphere coupling

In June 2007, the first WCRP Workshop on Seasonal Prediction was held in Barcelona to define a road-map for the next decade. While the need of carrying on the development of coupled ocean-atmosphere GCMs and of ocean data assimilation techniques was recognized, it was also highlighted that other components of the global climate system could contribute to improved forecast skill, and that *land-atmosphere interactions are perhaps the most obvious example of the need to improve the representation of climate system interactions and their potential to improve forecast quality* (WCRP 2008).

Since the pioneering works of Charney (1975) and Manabe (1975), an increasing body of numerical sensitivity studies indeed suggests that atmospheric variability is strongly influenced by the land-atmosphere coupling. After a preliminary study in the mid-1990, Koster et al. (2000) were the first to provide a robust comparison of the land versus ocean influence on interannual precipitation variability using a series of atmospheric GCM simulations (Fig. 4). They concluded that land and ocean processes have different domains of influence (that is the amplification of precipitation variance by land-atmosphere feedback is most important outsides of the Tropics that are most affected by SSTs) and that the strength of the land-atmosphere feedback is controlled largely by the relative availability of energy and water. Using a perfect model approach, they also showed that, besides SSTs, the foreknowledge of soil moisture contributes significantly to predictability in transition zones between dry and humid climates, thereby suggesting that soil moisture initialization could enhance the performance of seasonal forecasting systems in such areas.

Subsequent similar numerical studies (i.e. Dirmeyer 2005), including those conducted at CNRM by Douville (2003, 2004), also found a significant influence of "perfect" soil moisture boundary conditions for the simulation of surface temperature and precipitation, especially in the summer mid-latitudes. However, besides a series of simulations in which the soil moisture variability was suppressed, Douville (2004) also conducted a boreal summer ensemble in which the soil moisture variability was removed only in the initial conditions. An analysis of variance (ANOVA) was used to show that, despite the significant influence of soil moisture boundary conditions on atmospheric variability, soil moisture appears as a very limited source of potential seasonal predictability in the CNRM atmospheric GCM, the main exception being the North American continent.

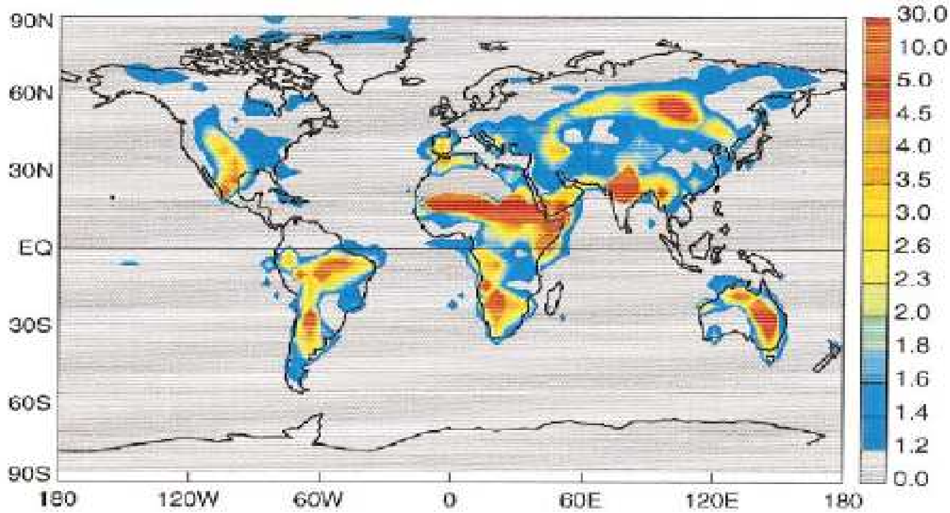

Fig. 4: Amplification of annual precipitation variance due to land-atmosphere feedback in the NASA GEOS-ARIES atmospheric GCM, estimated as the ratio of variance between two ensembles of simulations driven by observed SSTs, but using interactive versus climatological land surface boundary conditions (that is climatological land surface evaporation efficiency). From Koster et al. 2000.

The GSWP project (cf. section 2) allowed modellers to go one step further by using soil moisture climatologies derived from “off-line” rather than “on-line” LSM integrations, and thereby more realistic land surface boundary conditions. Prescribing or nudging the GSWP-1 climatology in their atmospheric GCMs, Dirmeyer (2000) and Douville and Chauvin (2000) suggested that seasonal contrasts between boreal summers 1987 and 1988 were better simulated than in a control experiment with interactive soil moisture. Douville and Chauvin (2000) however again suggested that the impact of soil moisture initial conditions was much less, thereby suggesting that soil moisture itself is generally not predictable beyond a few weeks.

More recently, Conil et al. (2007, 2008) performed similar experiments, but nudging or initializing the CNRM atmospheric GCM with the 10-yr GSWP-2 soil moisture climatology (1986-1995). They confirmed the dominant influence of soil moisture boundary conditions on atmospheric variability and predictability in the northern summer mid-latitudes. Not so surprisingly, the interannual variability of surface temperature and precipitation simulated in the nudged experiments is sometimes more realistic when using climatological rather than observed SSTs. Additional ensembles of boreal summer hindcasts driven by observed SSTs in which the soil moisture nudging is removed at the end of May were also conducted. It was shown that the GCM is better than simple (auto-regressive) statistical models for predicting the persistence of soil moisture anomalies. The results also suggested that soil moisture memory is able to sustain a significant atmospheric predictability at the monthly to seasonal timescale where and when the initial anomalies show a sufficient magnitude and spatial extent. Besides North America (summer 1993 minus 1988, Fig. 5) already highlighted by Koster et al. (2000) and Douville (2004), Europe (summer 1992 minus 1987, Fig. 6) also appears as a region where the land-atmosphere coupling is strong enough to expect a benefit from a better initialization of soil moisture in seasonal forecasting, at least in summer.

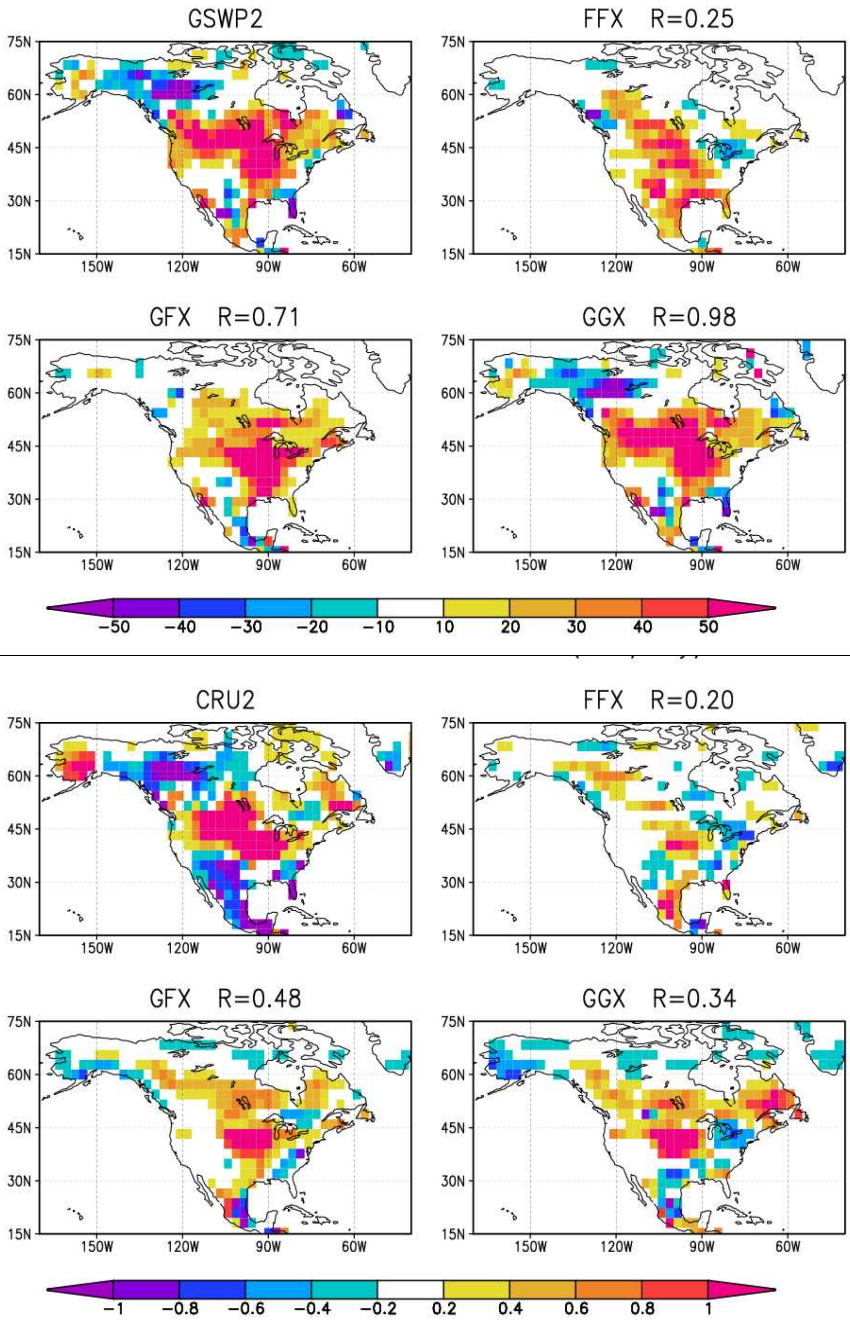

Fig. 5: Observed (GSWP-2 and CRU2 climatologies) and simulated (ensemble mean) differences (1993 minus 1988) in summer soil moisture (kg/m², upper panel) and precipitation (mm/day, lower panel) over North America. Three ensembles driven by observed monthly SST are compared using free soil moisture (FFX, no nudging), GSWP-2 initial conditions of soil moisture (GFX, nudging until the end of May), GSWP-2 boundary conditions of soil moisture (GGX, nugding until the end of September). R denotes the spatial anomaly correlation coefficient between observations and simulations. Adapted from Conil et al. 2008.

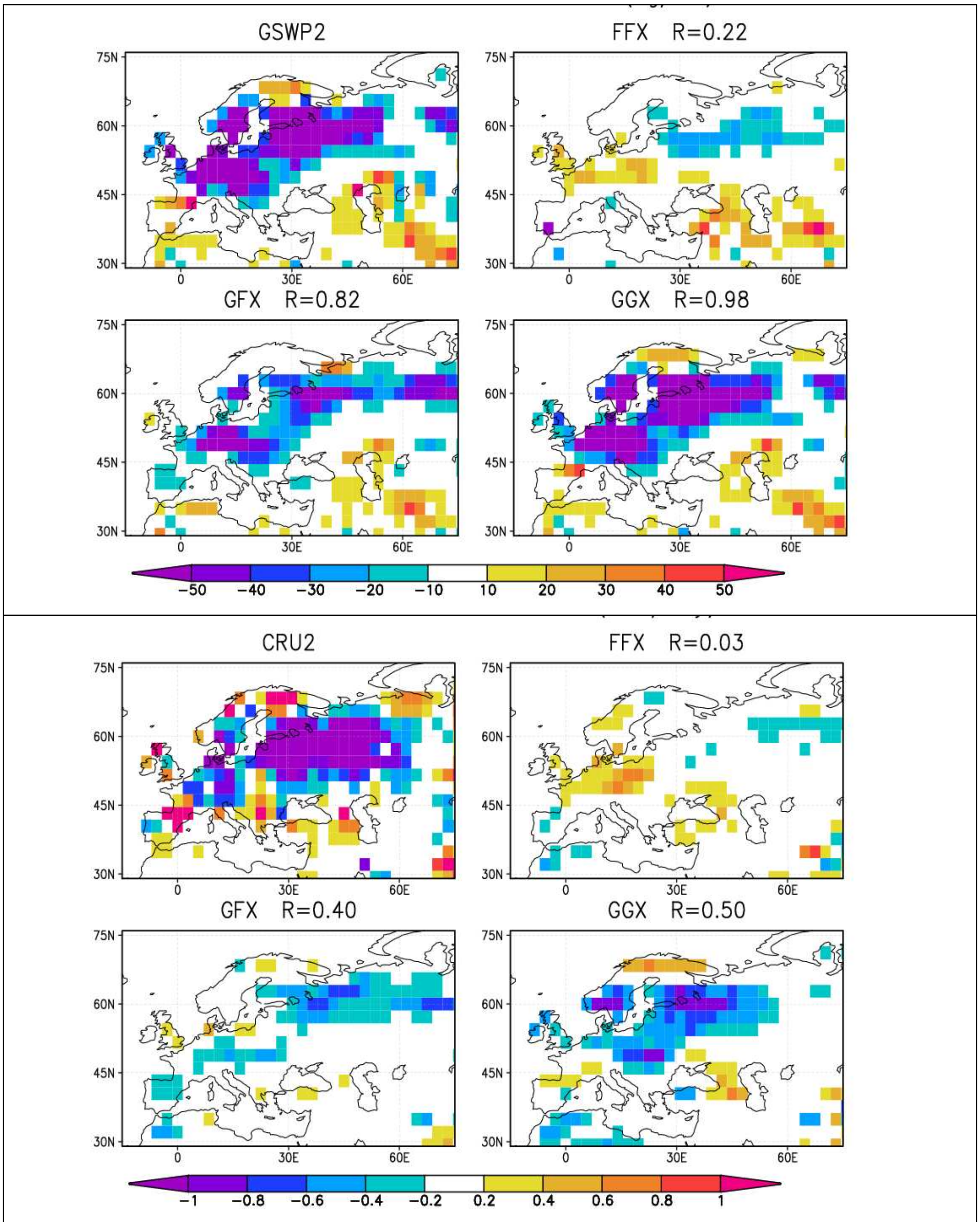

Fig. 6: Observed (GSWP-2 and CRU2 climatologies) and simulated (ensemble mean) differences (1992 minus 1987) in summer soil moisture (kg/m², upper panel) and precipitation (mm/day, lower panel) over Europe. Three ensembles driven by observed monthly SST are compared using free soil moisture (FFX, no nudging), GSWP-2 initial conditions of soil moisture (GFX, nudging until the end of May), GSWP-2 boundary conditions of soil moisture (GGX, nugding until the end of September). R denotes the spatial anomaly correlation coefficient between observations and simulations. Adapted from Conil et al. 2008.

Obviously, the strength and spatial distribution of the land-surface coupling is highly model-dependent given the diversity of atmospheric GCMs. This issue was tackled by the GLACE intercomparison project (Koster et al. 2004) aimed at comparing where and to what extent boreal summer precipitation is controlled by soil moisture in a dozen of models. The results showed a large spread between the models, but highlighted three "hotspots" where the coupling appears as relatively strong in a majority of models: North America, Sahel and northern India (Fig. 7). Nevertheless, the conclusions of GLACE should not be overestimated. First, no observational counterpart of the coupling strength is available to confirm this distribution. Moreover, the metric that was used to measure the coupling strength was focused on subseasonal rather than seasonal variability. Finally, the experiment design was based on seasonal hindcasts driven by the 1994 monthly SST and the results might have been somewhat different with another SST forcing.

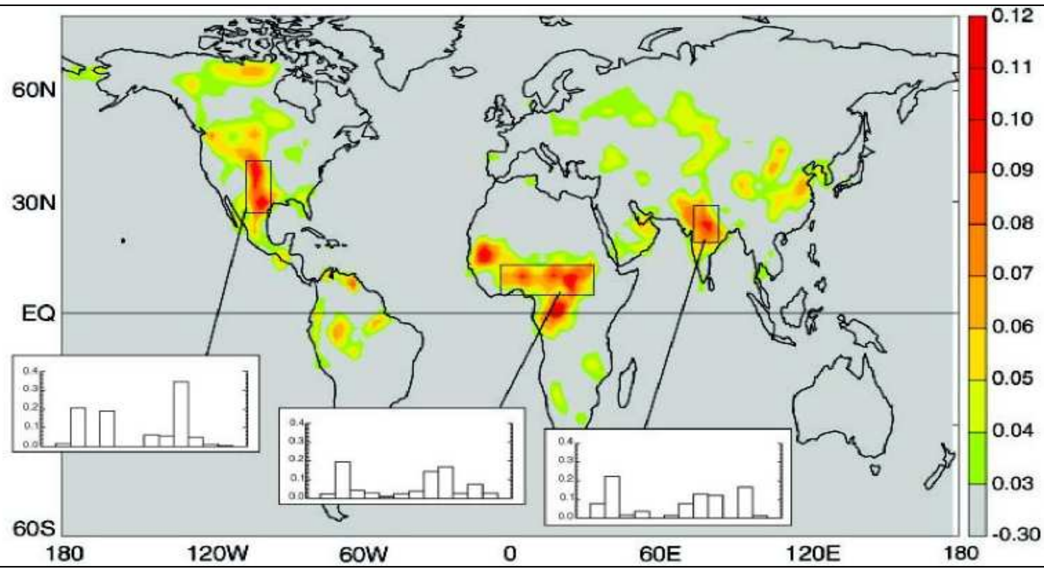

Fig. 7: Land-atmosphere coupling strength diagnostic (dimensionless index describing the impact of soil moisture on precipitation) for boreal summer averaged across 12 models. Areally averaged coupling strengths for the 12 individual models over the outlined hotspot regions. From Koster et al. 2004.

The CNRM atmospheric GCM did not participate in GLACE, but also shows a strong precipitation sensitivity to soil moisture over the Sahel (Douville and Chauvin 2000, Douville et al. 2001, Douville 2002) and North America (Douville 2003, 2004). In contrast with the results of GLACE, India does not appear as a region of strong coupling due to a negative dynamical feedback (less moisture convergence) that cancels the positive evaporation feedback over this region when the whole summer monsoon season is considered (Douville et al. 2001). Conversely, the CNRM model suggests that Europe could be another region of significant coupling (Douville and Chauvin 2000, Conil 2007, 2008). This result is consistent with recent observational and numerical studies highlighting the potential contribution of soil moisture deficit to heat and drought waves over Western Europe (Ferranti and Viterbo 2006, Vautard et al. 2007).

As far as the Sahel is concerned, Douville et al. (2007) highlighted the fact that the relatively strong coupling found in most GCMs including the CNRM model does not guarantee a strong sensitivity of summer monsoon precipitation to soil moisture. In the CNRM model, the contribution of surface evaporation to precipitation becomes important only in the second half of the monsoon season (when soil becomes wet) and the all-summer precipitation variability is dominated by moisture convergence that is not much sensitive to soil moisture boundary conditions (Douville et al. 2001, 2007). Moreover, the model does not show any soil moisture variability over the Sahel at the beginning of the monsoon season and the apparent relationship between the second (September to November) rainy season over the Guinean Coast and the subsequent summer (June to September) rainy season over the Sahel could be an artefact of a common tropical SST influence (Douville et al. 2007).

4. Issues

Many issues have to be further explored to get a more robust assessment of the land surface contribution to seasonal climate predictability and a fair comparison with the SST contribution. Beyond the results of individual models, a multi-model evaluation is necessary that goes beyond the objectives of the GLACE initiative (Koster et al. 2004). This is the reason why GLACE will be followed by an ambitious GLACE-2 intercomparison project (http://glace.gsfc.nasa.gov) that is supported by WCRP (2008). The aim is to analyse the impact of GSWP-2 versus random soil moisture initial conditions on ensembles of 2-month atmospheric and/or coupled ocean-atmosphere forecasts over the 1986-1995 summer seasons. The experiment design is therefore very similar to the one employed by Conil et al. (2008), but is open to coupled ocean-atmosphere GCMs to get closer to the operational dynamical seasonal forecasting systems.

Beyond the influence of soil moisture, other land surface state variables are likely to show a significant memory and therefore to represent a source of long-range predictability. The role of the northern hemisphere snow cover is currently investigated at CNRM (Peings and Douville 2008, Douville and Peings 2008). Snow impacts on interannual variability are not only confined to the lower troposphere, but could also affect large-scale modes (Artic and/or North Atlantic Oscillation) of winter extratropical variability (i.e. Cohen and Entekhabi 1999) as well as possibly the Indian summer monsoon through a remote influence of the Eurasian snow cover (i.e. Douville and Royer 1996) though this hypothesis is still a matter of debate (Robock et al. 2003, Peings and Douville 2008). Subsurface soil temperature was also found to increase surface air temperature variability and memory, but with a negligible impact in many regions of the world, particularly during boreal summer (Mahanama et al. 2008). Vegetation is also likely to amplify climate variability at least at the multi-decadal timescale (i.e. Zeng et al. 1999, Delire et al. 2004), but its role at the seasonal timescale is very uncertain and probably deserves further statistical (i.e. Liu et al. 2006) and numerical (i.e. Gao et al. 2008) studies. Finally, floodplains or groundwaters also show a significant low-frequency variability that could have regional impacts on interannual climate variability (Bierkens and van den Hurk 2007), but have not been yet included in most LSMs and have to be parametrized in a sufficiently robust way to be coupled with global atmospheric GCMs (i.e. Decharme et al. 2008).

The lack of observational data and the current limitations of land surface data assimilation systems is another important issue. Satellite observations of the global vegetation photosynthetic activity are available since the early 1980s, but the correspondence with the biophysical properties of vegetation is still uncertain as revealed by the comparison of different algorithms and of the vegetation parameters used in different climate models. The situation is even worse for soil moisture and snow mass (while northern hemisphere satellite observations of snow cover do exits since the late 1960s) given the sensitivity of microwave instruments to vegetation and topography as well as their lack of sensitivity to the subsurface water content (see Houser et al. 2004 for a review about terrestrial data assimilation). For this reason, the forcing of LSMs with meteorological analyses remains an interesting strategy to produce land surface reanalyses. It should be however noticed that GSWP datasets represent an upper limit of what can be done routinely given the difficulty to get accurate real-time precipitation analyses in many regions of the world. Many efforts are currently devoted to assimilate satellite data in LSMs and/or NWP models and should provide improved global high-resolution soil moisture, snow mass and vegetation products in the near future. Nevertheless, it will be necessary to wait still for many years before testing how useful such products are for understanding climate variability and initializing dynamical seasonal forecasts.

Other issues are related to the fact that most sensitivity studies aimed at exploring the land surface influence on climate variability have been based on atmospheric GCMs driven by prescribed SSTs. On the one hand, such an experiment design indicates that ocean variability is generally considered to be insensitive to land surface variability. Such an hypothesis denies a possible direct influence of river discharge into the ocean as well as an indirect influence through the atmospheric bridge. It is only valid if the land surface contribution to atmospheric variability is a second-order effect or at least confined to the continental areas, which is still a matter of debate (Hu et al. 2004). On the other hand, the use of prescribed SST can lead to an overestimation of atmospheric sensitivity to land surface perturbations given the fact that negative SST feedbacks are thereby potentially neglected. A growing body of evidence indeed suggests that the high-frequency ocean-atmosphere coupling is a fundamental feature of the climate system that is necessary to simulate and understand interannual variability (i.e. Douville 2005).

5. Conclusions

Over recent decades, the recognition that slowly-evolving boundary conditions can be a source of atmospheric predictability at the seasonal timescale has promoted the development of coupled ocean-atmosphere GCMs as well as the design of ocean data assimilation techniques. Pilot studies such as the PROVOST and DEMETER projects in Europe have demonstrated the potential of seasonal forecasts, which are now operated routinely by several countries.

Nevertheless, it has been recently suggested that our ability to predict regional climate anomalies at the seasonal timescale has reached a plateau (WCRP 2008). While the 1997-1998 El Niño event was faily well predicted up to six months in advance, the equatorial Pacific is not the only driver of interannual climate variability and its global teleconnections are still poorly simulated in many coupled ocean-atmosphere GCMs (Joly et al. 2007). Over recent years, the multi-model ensemble forecasting has been the most efficient strategy to increase seasonal hindcast skill scores. It should be however recognized that the success of this pragmatic approach mainly relies on the fact that different models show different systematic errors. It therefore suggests that individual models can be significantly improved and it is widely believed that the skill of current seasonal forecasting systems is still far from its theoretical limit (WCRP 2008).

Besides improving the models, it is also important to look for other potential sources of long-range atmospheric predictability. In this respect, the land surface contribution is an obvious candidate but is difficult to explore given the lack of observed multi-year climatologies. Nevertheless, a growing body of numerical studies suggests that various components of the land surface are likely to amplify the low-frequency variability of the atmosphere and are potentially predictable at the monthly to seasonal timescales. In the next decade or so, the availability of new land surface datasets and their use for a multi-variable (soil moisture, snow, vegetation) initialization of multi-model seasonal hindcasts should provide a more precise and robust evaluation of the potential land surface contribution to seasonal predictability. Such an objective should not obviate the need to improve the ocean-atmosphere coupling and the fact that tropical SST still represents the main source of seasonal-to-decadal predictability but is probably underestimated in state-of-the-art climate models.

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