Importance of snow initial condition in seasonal forecasting

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1. Motivation

Exploring and assessing potential sources of seasonal climate predictability is a key challenge for the climate modelling community. Despite the chaotic nature of atmospheric variability, slowly-evolving and potentially predictable components of the Earth climate system indeed enable probabilistic forecasts of the atmosphere at the seasonal timescale (Palmer and Anderson 1994). Three majors forcings of the troposphere have been identified which could act as significant sources of predictability for the climate system: sea surface temperature (SST), land surface hydrology (e.g. Douville 2009a) and stratospheric processes (e.g. Douville 2009b). Seasonal forecasting is based on the influence of these lower or upper boundary forcings on the troposphere, and on our ability to anticipate their evolution several months in advance. It should be however emphasized that potential predictability studies based on a perfect model approach overestimate the skill of operational dynamical seasonal forecasting systems. It is therefore important to assess the skill against real observations and over a period that is long enough to draw robust conclusions.

The predictability linked to SST held most of the attention over recent decades because of the strong atmospheric sensitivity to the tropical Pacific SST anomalies (e.g. Rowell 1998). Indeed, the El Niño-Southern Oscillation (ENSO) is the largest single source of interannual variability in the tropics and has significant remote impacts on extratropical climate through teleconnections. Moreover, the skill of coupled ocean-atmosphere dynamical models to predict the occurrence of ENSO events has increased in the 1990's as they were shown to provide useful forecasts of the peak phase of the extreme warm and cold events up to two seasons in advance. After the 1997-1998 strong ENSO event, the ability to predict tropical climate fluctuations seems however to have reached a plateau with little subsequent improvement in quality (WCRP, 2008).

This statement has renewed the interest of the climate modelling community in looking for other sources of seasonal predictability. The influence of the land surface conditions has until recently received little attention, though the role of soil moisture boundary conditions in transition zones between dry and wet climates has been emphasized by several numerical studies (e.g. Koster et al. 2000). A major obstacle for such studies is the lack of global and multi-decadal land surface observations and/or reliable reanalyses. This is the reason why the land surface modelling community has launched the Global Soil Wetness Project (GSWP). The objective was to produce global soil moisture climatologies using off-line land surface models (LSM) driven by atmospheric forcings corrected for their monthly biases. Relaxation experiments towards such an "off-line" climatology were then conducted with global atmospheric GCMs (e.g. Douville and Chauvin 2000, Conil et al. 2008) and suggested that soil moisture could induce a significant atmospheric predictability at the monthly to seasonal timescales.

The focus of the present study is on the Northern Hemisphere snow cover, which is besides soil moisture another potential source of long-range predictability related to land surface conditions. On top of a strong annual cycle, the extent of the Northern Hemisphere snow cover exhibits a significant interannual variability and can reach about 50 % of the global land area during winter (Frei and Robinson 1999). Snow has particular physical properties, like a strong albedo, a strong emissivity, and a low thermal conductivity, and thereby exerts a strong influence on the land surface energy budget. Snow also alters the surface energy budget during and after snowmelt, through the latent heat necessary for melting and for subsequent evaporation of melting water. This hydrological effect extends the "memory" of the winter/spring snow mass anomalies into the spring/summer season.

Moreover, both observational and numerical studies suggested possible remote effects of the Eurasian snow cover anomalies. First, snow accumulation over the Himalayas in winter and spring has been related to the Indian monsoon rainfall in the subsequent summer (Blanford 1984). While subsequent studies based either on satellite observations (e.g. Bamzai and Shukla 1999) or on numerical sensitivity experiments (e.g. Barnett 1989, Douville and Royer 1996) confirmed the possibility of a snow-monsoon relationship, the focus was no more on the Himalayas but on a large fraction of the Eurasian continent. The proposed mechanism involves the modification of the thermal gradient between land and sea which is known to trigger the large-scale monsoon circulation. More snow, leading to a radiative surface cooling maintained throughout spring by soil moisture anomalies, could weaken the monsoon circulation during the subsequent summer. This topic is however still a matter of debate (e.g. Robock 2003). Using both observations and CMIP3 simulations, Peings and Douville (2009) found that the snow-monsoon link is not stationary in the instrumental record (Fig. 1) and appears as an artefact of poor ENSO teleconnections rather than as a causal relationship in several coupled ocean-atmosphere models.

Another suggested snow teleconnection is the apparent relationship between snow cover in October over Siberia and the extratropical Northern Hemisphere wintertime variability, which is dominated by the northern annular mode or Arctic Oscillation (AO). This pattern has a strong signature in the North Atlantic, namely the North Atlantic Oscillation (NAO), which controls to a large extent temperature and precipitation over Europe at interannual to multi-decadal timescales. Satellite-derived snow cover fractions averaged over Siberia in autumn show a significant correlation with AO and/or NAO indices in winter (Cohen and Entekhabi 1999). Numerical sensitivity studies conducted with atmospheric GCMs driven by more or less realistic snow cover anomalies (Gong et al. 2003, Fletcher et al. 2009) reproduced this AO/NAO response and proposed the following two-part mechanism. First, extensive Eurasian snow cover in autumn leads to a strong diabiatic cooling over the continent, amplifies the Siberian High and induces pulses of vertically propagating stationary waves towards the stratosphere. Second, wave-mean flow interaction causes a weakening of the stratospheric polar vortex and leads to a AO-like response of sea level pressure several weeks after the snow forcing. Using a large ensemble of atmospheric GCM integrations, Fletcher et al. (2009) showed that this teleconnection is strongly dependent on the prior state of the polar vortex and is not very sensitive to the vertical resolution in the stratosphere.

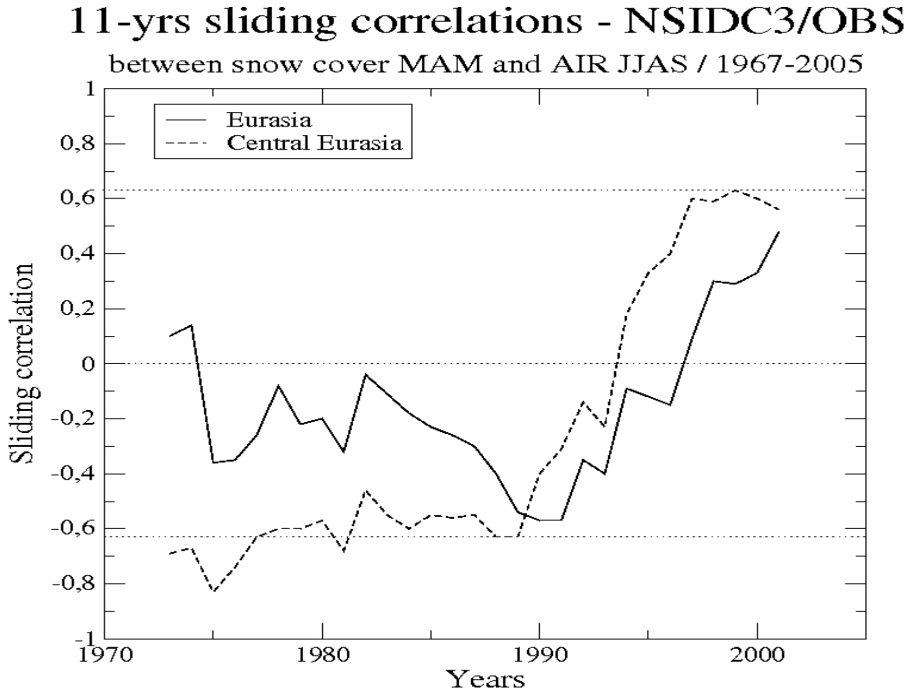

Figure 1: Sliding correlations between the spring snow cover from NSIDC over Eurasia (whole continent in solid line, Central Eurasia only in dashed line) and the subsequent summer monsoon rainfall over India. Horizontal dash lines represent the 95 % confidence level. The observed snow-monsoon relationship is not stationary and is not statistically robust over the whole 40-year period of the NSIDC satellite snow cover climatology. Source: Peings and Douville 2009.

Finally, other studies proposed a third possible remote effect of the Eurasian snow cover on the North Pacific atmospheric circulation and in particular on the winter variability of the Aleutian Low (e.g. Clark and Serreze 2000). Based on observations and modelling works, they suggested that extensive Eurasian snow cover over Eurasia is associated with a deeper than normal Aleutian Low. This teleconnection could involve a stationary Rossby wave-train extending over North Pacific (Walsh and Ross 1988). Interestingly, the winter to spring North Pacific atmospheric circulation was also emphasized as a useful precursor of the Indian summer monsoon over recent decades (Peings et al. 2009). This result might suggest that the previously discussed snow-monsoon relationship is not necessarily disconnected from other remote effects found in the northern extratropics.

2. Pilot studies at CNRM

The lack of consensus and of realistic sensitivity experiments about the Northern Hemisphere snow cover influence on global climate variability is partly related to the difficulty of measuring snow water equivalent (i.e. snow mass) at continental to hemispheric scales. In situ snow depth measurements do exist in many regions but are probably too sparse to produce a reliable global climatology and only provide a crude estimate of snow mass given the possible range of snow density. Passive microwave satellite snow mass products are available, but there remain many concerns about their reliability. Visible imagery is another useful remote sensing technique but only provides snow cover area and is more sensitive to cloudiness. Nevertheless, the NOAA/NESDIS snow charts are available since the late 1960's and have been compiled to produce a high-resolution hemispheric weekly snow cover extent dataset available at NSIDC (http://nsidc.org/data/nsidc-0046.html).

The NSIDC climatology is commonly used to evaluate the Northern Hemisphere snow cover simulated by global climate models. Recent analyses of the latest IPCC coupled ocean-atmosphere 20th century simulations indicate a reasonable reproduction of the seasonal cycle at continental scales (Roesch et al. 2006). Interannual variability is also realistic over both Eurasia and North America in winter and spring. It is however generally underestimed, not only during snow melt (Roesch et al. 2006) but also in early fall which might have consequences on the simulation of wintertime climate variability (Hardimann et al. 2008). Moreover, and despite the reasonable simulation of snow cover, the surface albedo is generally too high over snow-covered forests in state-of-the-art global climate models due to the neglected or insufficient masking effect of the vegetation canopy (Roesch et al. 2006).

NSIDC data have also been used to prescribe snow boundary conditions in atmospheric GCMs (e.g. Gong et al. 2003, Orsolini et al. 2009). This technique remains however questionable for a number of reasons. Snow cover is not a prognostic variable in climate models. Deriving snow mass from observed snow cover through an empirical relationship is possible but remains fairly uncertain since the relationship is highly non-linear. Using gridded continental-scale snow depth and snow cover observations, Ge and Gong (2008) show that the relationship is not strong at interannual timescales. Snow depth and extent anomalies are largely unrelated over broad high-latitude regions north of the snow line. They vary more consistently in the vicinity of the snow line, especially in autumn and spring, but snow memory is probably much better constrained by snow mass than by snow cover fraction.

Another drawback of several former sensitivity studies is the crude "direct insertion" technique used to prescribe snow mass estimates, derived either from satellite snow cover fractions (e.g. Orsolini et al. 2009) or from in situ snow depth measurements (e.g. Schlosser and Mocko 2003). This leads to abrupt changes in the simulated snow field at regular intervals, without consistent modifications of related surface variables, and is probably not the best practice to "assimilate" snow data in a climate model.

A possible way to go through these problems is to derive a snow mass climatology from an off-line simulation of the land surface model and to use a simple nudging technique to relax the GCM at each time step towards this "consistent" monthly climatology (e.g. Douville 2009a). Such a strategy was first tested with soil moisture in the framework of the international Global Soil Wetness Project (GSWP, http://grads.iges.org/gswp). The ISBA land surface model of CNRM was driven by the International Satellite Land Surface Climatology Project (ISLSCP) atmospheric forcings first from 1987 to 1988 (GSWP-1, Douville 1998), then from 1986 to 1995 (GSWP-2, Decharme and Douville 2007).

The 10-year GSWP-2 monthly climatology was recently used to compare the influence of soil moisture or snow mass versus SST on atmospheric variability and predictability at the seasonal timescale (e.g. Douville 2009a, Fig. 2). Ensemble simulations were performed with nudged versus free snow mass boundary conditions. Such experiments have highlighted the potential contribution of snow to climate predictability, measured as the fraction of the ensemble variance explained by snow boundary conditions. Not surprisingly, this contribution was mainly found in fall and spring in the northern mid-and-high latitudes. Nevertheless, the 10-year period of the GSWP-2 climatology was not sufficient to get a robust evaluation of effective predictability (i.e. skill scores) at the seasonal timescale. Results suggested that the added value of the snow forcing (compared to the SST forcing) is confined to the low-level temperature and is not very persistent if the snow mass nudging technique is only used to prescribe initial conditions (rather than boundary conditions).

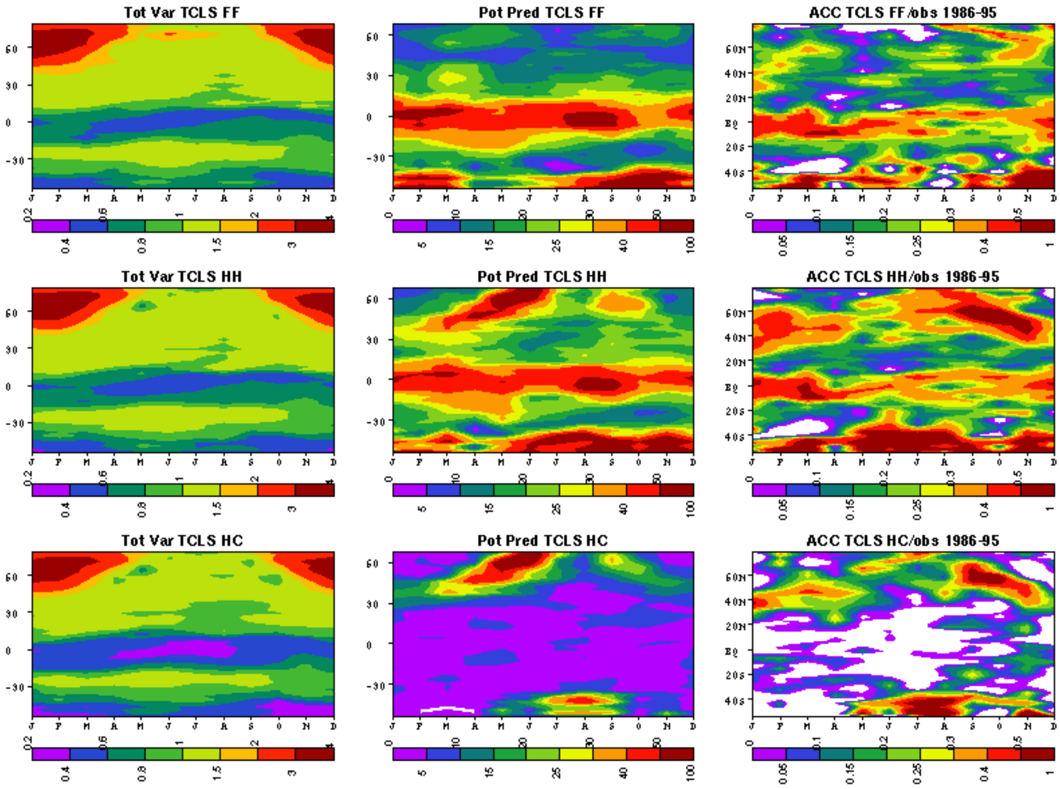

Figure 2: Zonal mean annual cycle of standard deviation (left column in K), potential predictability (middle column in %) and anomaly correlation against the CRU climatology (right column) for surface air temperature over land. Results are derived from 10-member ensembles of Arpege-Climat global atmospheric simulations driven by prescribed monthly mean sea surface temperature (SST) over the 1986-1995 period. Three ensembles are compared: control experiment with observed SST (FF, upper panels), sensitivity experiment with observed SST and nudged snow mass (HH, middle panels), sensitivity experiment with climatological SST and nudged snow mass (HC, lower panels). The snow forcing exerts a strong influence on the potential and effective predictability of surface air temperature in the high latitudes, mainly in spring and fall. Source: Douville 2009a.

Peings et al. (2010) proposed an extension of the pilot study by Douville (2009a) over the 1951-2000 period. The 3-hourly atmospheric forcings were derived from the 1° by 1° Princeton University dataset (http://hydrology.princeton.edu) based on bias corrections applied to the NCEP re-analyses (Sheffield et al. 2006). The ISBA land surface model was integrated with a 20-min time step over the 1950-2006 period after a two-year spin up. The simulation has been evaluated against in situ river discharge observations and satellite gravimetry by Alkama et al. (2009). Comparisons with in situ snow depth measurements and satellite-derived snow cover areas however suggest that the off-line snow climatology does not accurately reproduce the NSIDC snow cover variability (more details in Peings et al. 2010). Therefore, the off-line ISBA snow mass climatology must be considered cautiously and not as a perfect snow forcing on atmospheric variability in the Arpège-Climat GCM.

In line with the experiment design proposed by Douville (2009a), a nudging technique was used to prescribe “as realistic as possible” versus “random” snow mass boundary conditions in Arpège-Climat. Ten-member ensemble simulations with prescribed observed SSTs were conducted over the 1951-2000 period. Besides the effect of snow boundary conditions, the nudging technique was also used to test the impact of snow initial conditions using additional ensembles of seasonal integrations from March 1st to May 31st. On-going analyses confirm the conclusions of Douville (2009a) about the limited impact of snow boundary conditions on the seasonal mean atmospheric circulation variability simulated by Arpège-Climat. In particular, there is no evidence of remote snow effects either on the wintertime extratropical variability or on the summertime Indian monsoon variability. The main sensitivity is found in springtime surface air temperature (Fig. 3) and suggests that snow initialization in early spring has a significant impact on skill scores even at the seasonal timescale. More results will be hopefully soon available in Peings et al. (2010).

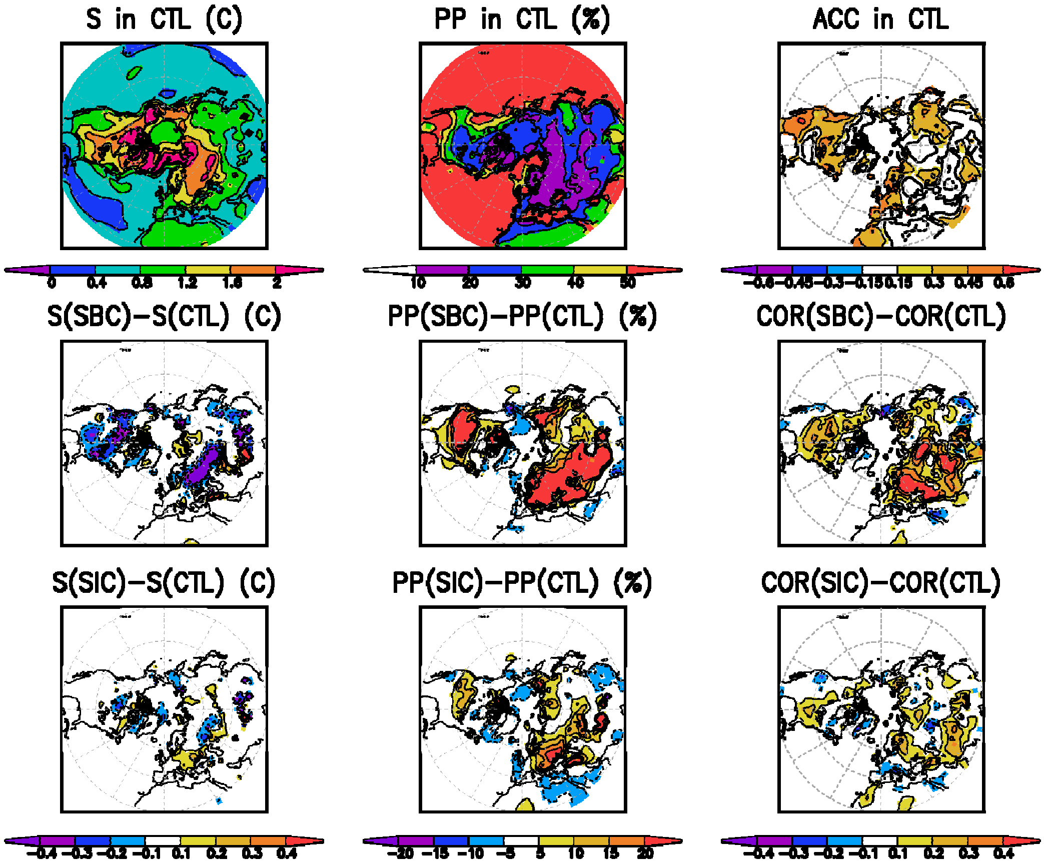

Figure 3: Northern Hemisphere distribution of standard deviation (left column in K), potential predictability (middle column in %) and anomaly correlation against the ISBA off-line climatology (right column) for springtime surface air temperature over land. Results are derived from 10-member ensembles of Arpege-Climat global atmospheric simulations driven by prescribed monthly mean sea surface temperature (SST) over the 1951-2000 period. Three ensembles driven by observed SST are compared: control experiment without snow nudging (CTL, upper panels), sensitivity experiment with prescribed snow mass boundary conditions (SBC, middle panels show SBC minus CTL), sensitivity experiment with prescribed snow mass initial conditions (SIC, lower panels show SIC minus CTL). The springtime snow forcing exerts a strong influence on the potential and effective predictability of surface air temperature, mainly over North America and Central Europe, but is weaker when the nudging is only used to initialize snow on March 1st. Source: Peings and Douville 2010 (in preparation).

3. Conclusion

While observational studies and numerical case studies or idealized sensitivity experiments all suggest a potential contribution of the Northern Hemisphere snow cover to climate predictability, such a contribution has never been assessed in operational dynamical seasonal forecasting systems. Preliminary assessments based on atmospheric GCMs driven by prescribed SST over at least one decade (Schlosser and Mocko 2003, Douville 2009a, Peings et al. 2010) show no discernible impact on large-scale atmospheric circulation, but a significant improvement of surface air temperature predictability, particularly in the springtime mid-latitudes where the snow forcing on the surface energy budget is favored by both a large year-to-year variability in snow cover and a strong insolation. Such a positive impact is however overestimated when using prescribed snow boundary conditions and the benefit is still significant but weaker when snow reconstructions are only used to initialize snow mass at the beginning of the seasonal integrations.

The main exception to the lack of remote impacts on atmospheric variability is the recent study by Orsolini and Kvamsto (2009) which was also based on the Arpege-Climat atmospheric GCM of CNRM but relies on 5-day snow mass corrections derived from the NSIDC weekly snow cover dataset. While the study did not assess the impact of snow initialization, it suggested that the year-to-year variability of the Aleutian-Icelandic Seesaw teleconnection in February is partly controlled by snow variability over eastern Eurasia through the triggering of a wave-train across North Pacific. Such a hypothesis however needs further investigation given the limited size of the ensembles and the lack of consistency with the results of Peings et al. (2010). A possible reason for this paradox is related to the stronger control of the Arpege-Climat snow cover fraction in Orsolini and Kwamsto (2009).

Ideally, satellite-derived snow cover areas should be assimilated rather than directly converted into snow mass. Such a strategy has been recently implemented in several NWP centres and in particular at ECMWF (Drusch et al. 2004). Nevertheless, it is necessary to wait for a new global and multi-decadal re-analysis before testing how useful such products are for understanding climate variability and initializing dynamical seasonal forecasts. In the meantime, a multi-model evaluation of snow-atmosphere interactions would be probably useful as it was done recently for soil moisture-atmosphere coupling in the framework of the GLACE-2 project (http://glace.gsfc.nasa.gov). A particular attention should also be paid to the surface energy budget in snow-covered forests, as it was emphasized by the Snowmip2 intercomparison project (http://xweb.geos.ed.ac.uk/~ressery/SnowMIP2.html). Finally, besides the NOAA/NESDIS visible imagery, other satellite observations could be used in "off-line" and/or "on-line" land surface data assimilation systems to produce more reliable snow mass reanalyses.

4. References

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