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Snow contribution to springtime atmospheric predictability over the second half of the twentieth century

Yannick Peings · H. Douville · R. Alkama · B. Decharme

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Abstract A set of global atmospheric simulations has been performed with the ARPEGE-Climat model in order to quantify the contribution of realistic snow conditions to seasonal atmospheric predictability in addition to that of a perfect sea surface temperature (SST) forcing. The focus is on the springtime boreal hemisphere where the combination of a significant snow cover variability and an increasing solar radiation favour the potential snow influence on the surface energy budget. The study covers the whole 1950–2000 period through the use of an original snow mass reanalysis based on an off-line land surface model and possibly constrained by satellite snow cover observations. Two ensembles of 10-member AMIP-type experiments have been first performed with relaxed versus free snow boundary conditions. The nudging towards the monthly snow mass reanalysis significantly improves both potential and actual predictability of springtime surface air temperature over Central Europe and North America. Yet, the impact is confined to the lower troposphere and there is no clear improvement in the predictability of the large-scale atmospheric circulation. Further constraining the prescribed snow boundary conditions with satellite observations does not change much the results. Finally, using the snow reanalysis only for initializing the model on March 1st also leads to a positive impact on predicted low-level temperatures but with a weaker amplitude and persistence. A conditional skill approach as well as some selected case studies provide some guidelines for interpreting these results and suggest that an underestimated snow cover variability and a misrepresentation of ENSO teleconnections may hamper the benefit of an improved snow initialization in the ARPEGE-Climat model.

Keywords Atmospheric predictability · Snow · Seasonal forecasting · Boundary and initial conditions · Conditional skill

1 Introduction

Despite the chaotic nature of atmospheric variability, some slowly evolving and potentially predictable components of the Earth climate system enable probabilistic forecasts of the atmospheric seasonal mean state (Palmer and Anderson 1994). Three major forcings of the troposphere have been identified which could act as significant sources of predictability for the climate system: sea surface temperature (SST) (e.g. Rowell 1998), land surface hydrology (e.g. Delworth and Manabe 1989) and stratospheric processes (e.g. Baldwin and Dunkerton 2001). 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 weeks or months in advance.

The predictability linked to SSTs held most of the attention over recent decades because of the strong atmospheric sensitivity to tropical Pacific SST anomalies. 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 (Trenberth et al. 1998). Moreover, the skill of coupled ocean–atmosphere dynamical models to predict the occurrence of ENSO events has increased in

Y. Peings · H. Douville · R. Alkama · B. Decharme
CNRM-GAME, Météo-France and CNRS, Toulouse, France

Y. Peings (✉)
CNRM/GMGEC/VDR, 42 Avenue Gaspard Coriolis,
31057 Toulouse Cedex 01, France
e-mail: yannick.peings@cnrm.meteo.fr

the 1990s 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 (Kirtman et al. 2001). 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 (Kirtman and Pirani 2009).

This statement has renewed the interest of the climate modelling community in looking for other potential sources of seasonal predictability. In particular the influence of the land surface conditions has recently received more attention (Dirmeyer 2000, 2005; Koster et al. 2000; Douville 2003, 2009). 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" reanalysis were then conducted with a global atmospheric general circulation model (GCM) (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. More recently, the second phase of the Global Land–Atmosphere Coupling Experiment (GLACE-2) explored the impact of soil moisture initialization on 2-month hindcasts in spring and summer and found a significant contribution over large portions of the North American continent (Koster et al. 2010).

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, a low thermal conductivity, and thereby exerts a strong influence on the land surface energy budget (Cohen and Rind 1991; Groisman et al. 1994). The presence of snow cover has local effects by increasing surface albedo, reducing shortwave radiation absorbed by ground and thus the surface temperature (Walsh and Ross 1988). Moreover, snow 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 (Yeh et al. 1983).

Besides its local impacts, snow could also play an active role on large scale atmospheric circulation. Numerous studies have investigated the role of the Eurasian snow cover on the South Asian/Indian summer monsoon variability, using either statistical analyses of observational data or numerical sensitivity experiments (Blanford 1884; Barnett et al. 1989; Douville and Royer 1996; Bamzai and Shukla 1999; Robock et al. 2003; Peings and Douville 2009). Another suggested influence on large-scale circulation is the relationship between snow cover in autumn over Siberia and the Artic Oscillation (AO) and/or North Atlantic Oscillation (NAO) indices in winter (Cohen and Entekhabi 1999; Bojariu and Gimeno 2003). This link is significant in observed timeseries and has been reproduced by several numerical experiments (Gong et al. 2003; Fletcher et al. 2007). Finally, other studies proposed a possible remote effect of the Eurasian snow cover on the North Pacific atmospheric circulation, by a stationary Rossby wave interaction with the Aleutian Low winter variability (Walsh and Ross 1988; Walland and Simmonds 1997; Watanabe and Nitta 1998; Clark and Serreze 2000).

In contrast with the relatively abundant literature about the potential snow influence on climate variability, few studies have dealt with the contribution of snow to climate predictability and with the possible improvement of seasonal forecasting through a more realistic initialisation of snow. Kumar and Yang (2003) realised a suite of global atmospheric experiments with suppressed interannual variability of either SST or snow boundary conditions. They found little snow impacts on the upper-troposphere circulation and concluded that the influence of snow variability was confined to the lower troposphere. Schlosser and Mocko (2003) used the US Air Force snow depth climatology to prescribe snow boundary conditions in ensembles of springtime atmospheric simulations with two GCMs. They showed a general improvement of simulated near-surface air temperature, but mixed results on skill scores that underscored the difficulty of GCMs to consistently translate the localized skilfull response into nonlocal/remote skill. More recently, Douville (2009) used a monthly snow depth dataset derived from the Global Soil Wetness Project (GSWP) to assess the relative contribution of realistic snow and SST boundary conditions on atmospheric variability over the 1986–1995 period. Twin ensemble experiments were also conducted using GSWP snow water equivalent initial conditions for spring simulations with prescribed observed SST. Although based only on a 10-year period, results suggested a significant potential contribution of snow to surface air temperature predictability from fall to spring, although the impact of snow initialisation was less clear than that of GSWP snow boundary conditions.

The present paper is an extension to the 1950–2000 period of the pilot study by Douville (2009). The main objective is to provide a more robust assessment of the influence of realistic snow boundary conditions on the interannual variability simulated by the ARPEGE-Climat atmospheric GCM. Ensembles of AMIP-type experiments driven by prescribed observed monthly mean SST are realised to quantify the additional seasonal forecasting skill resulting from the nudging of the model towards more realistic snow boundary conditions. A 51-year monthly snow mass reanalysis was obtained by driving the CNRM land surface model with hybrid atmospheric forcings combining 3-h reanalyses and monthly observations (Alkama et al. 2010). The availability of this original product makes it for the first time possible to quantify accurately the potential and actual contribution of realistic snow conditions to seasonal atmospheric predictability.

While our simulations cover the whole annual cycle, the focus is here on the boreal spring season (March–May) so that the possible winter (AO/NAO) and summer (Indian monsoon) remote impacts discussed in the introduction are beyond the scope of the study. Climate sensitivity to snow anomalies is highly dependent on the potential impact on the surface energy budget and primarily on absorbed solar radiation. This albedo effect increases with the amount of solar radiation at the surface. To determine the seasons when snow anomalies and solar irradiance are sufficient to cause strong modifications of the surface energy budget, we have computed a seasonal index similar to the one proposed by Schlosser and Mocko (2003). This index is computed as the product between snow cover standard deviation and climatological surface downward solar radiation. The Northern Hemisphere distribution of this index computed from satellite observations is shown in Fig. 1 for the four seasons. Spring appears as the season when snow forcing is expected to be the strongest, in line with snow retreat and ablation due to the seasonal warming (Ueda et al. 2003). Consequently, it is important to evaluate the atmospheric sensitivity during this favourable season before exploring more subtle impacts of snow cover anomalies.

The model and experiment design are further described in Sect. 2. Section 3 focuses on the validation of the monthly snow mass datasets that have been produced to nudge the atmospheric GCM. Section 4 describes the results of our atmospheric ensemble experiments and evaluates the impact of snow boundary conditions or initial conditions on springtime climate variability. Finally, Sect. 5 draws the main conclusions of this work.

2 Experimental design

2.1 Model description

We performed our ensemble simulations with version 4 of the ARPEGE-Climat spectral atmospheric GCM used with a T63 truncation, 31 vertical levels and a lid at 10 hPa. The land surface component is the Interaction-Sol–Biosphere–Atmosphère (ISBA) model with a single-layer snow model (Douville et al. 1995) and a simple force-restore soil hydrology with a variable infiltration capacity (VIC) runoff scheme. Unlike the original ISBA formulation, the snow cover fraction is diagnosed from snow water equivalent using the empirical relationship by Niu and Yang (2007) over bare ground. This formulation has been implemented in the ARPEGE-Climat model because it shows highest sensitivity to low snow amount and reduces some biases in the Northern Hemisphere snow cover. The masking effect of vegetation is taken into account according to the Douville et al. (1995) formulation and ensures a reasonable surface albedo over forested areas. Finally, the ARPEGE-Climat model offers the possibility to exert a strong control on the land surface hydrology (here the simulated snow mass) through a simple nudging (i.e. relaxation) technique applied at each time step. This methodology is more flexible than the “direct insertion” of land surface data during the course of the atmospheric simulation (e.g. Schlosser and Mocko 2003). More details about this technique can be found in Douville and Chauvin (2000) and Douville (2003).

2.2 Monthly snow mass datasets

The lack of global instrumental record for snow depth is the main limitation for an accurate assessment of the potential snow contribution to climate variability and predictability. In situ measurements do exist in many regions (Armstrong 2001) but are not necessarily dense enough to produce a gridded multi-year dataset, even at the medium horizontal resolution of atmospheric GCMs. Satellite-derived snow cover areas are available since the end of 1966 and have been used to prescribe realistic snow boundary conditions in atmospheric GCMs (Gong et al. 2003; Orsolini and Kvamsto 2009). This technique remains however fairly empirical given the relatively poor relationship between observed snow cover and snow mass at the interannual timescale (Ge and Gong 2008). A way to go through this problem is to produce an off-line snow reanalysis using a LSM driven by observed meteorological parameters. While limited by deficiencies in both the LSM and the atmospheric forcing, this technique allowed us to produce a 51-year snow mass reanalysis starting in 1950, i.e. before the availability of satellite snow cover estimates.

In the present study, we used 2-monthly snow mass datasets to nudge the ARPEGE-Climat GCM:

- “SURFEX” snow mass: it was obtained “off-line” by driving the Surface Externalisé (SURFEX) LSM with the 1950–2000 atmospheric forcings of University of Princeton (Sheffield et al. 2006). These 3-h forcings

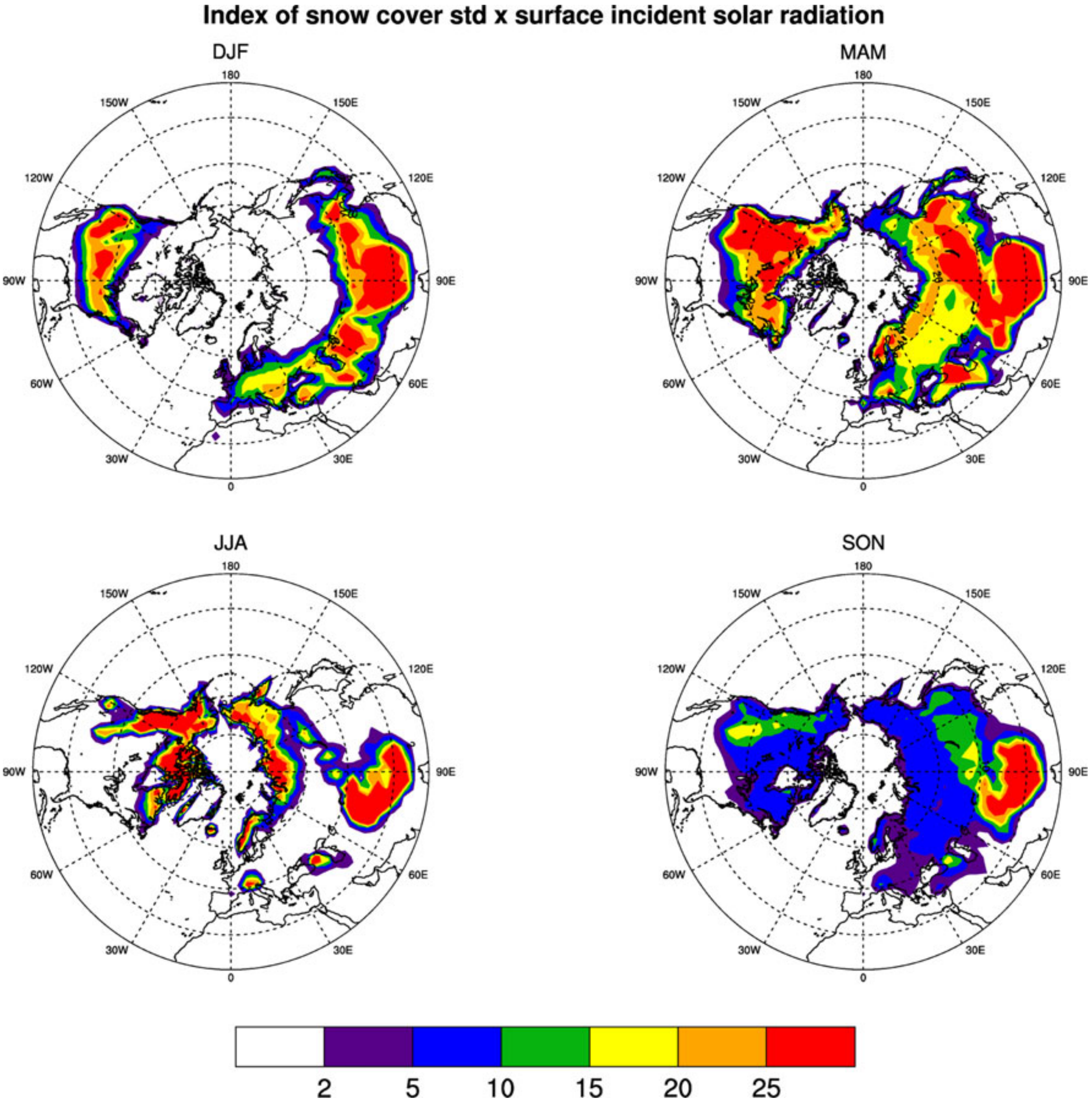


Fig. 1 Index of snow cover standard deviation multiplied by climatological incident solar radiation at the surface over the 1972–2006 period of NSIDC satellite data. Index similar to those from Schlosser and Mocko (2003)

were derived at a 1° resolution from the combination of monthly observations and National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis. SURFEX is a new platform for land surface simulation at CNRM (Centre National de Recherches Météorologiques) and includes the standard ISBA land surface scheme. More details about this model can be found on http://www.cnrm.meteo.fr/surfex/. Compared to the original ISBA scheme, one of the main improvements concerns the parametrisation of subgrid hydrological processes (Decharme and Douville 2007).

- “NSIDC” snow mass: this second snow mass dataset was constructed in a way to obtain a snow cover fraction as close as possible to the NSIDC snow cover observations. Given the limited length of the satellite record, this snow reconstruction covers only the 1972–2006 period. The aim is to correct the off-line SURFEX monthly snow reanalysis by adding or removing snow mass over particular regions according to snow cover observations. For this purpose, the NSIDC data were inverted using our empirical snow cover fraction formulation. Due to the non-linearity of this formulation, a maximum threshold of 98% snow cover was applied to avoid exaggerated snow depths. However, this method does not guarantee the consistency of snow mass and underestimates snow depth at high latitudes. To solve this problem, all snow mass estimates inferior to the SURFEX values were fixed to the SURFEX values over these regions. This method allows us to obtain a realistic simulation of snow extent in the ARPEGE-Climat model, without generating too unrealistic snow depth values.

Note that this *a posteriori* correction of the off-line SURFEX simulation is a “poor-man” data assimilation technique. Ideally, snow cover observations should have been assimilated in the course of the SURFEX integration. While such a strategy has been recently implemented in few operational numerical weather prediction models (Rodell et al. 2004), it is beyond the scope of the present study.

2.3 Ensembles of atmospheric simulations

To evaluate the impact of snow boundary and initial conditions, four types of experiments were realized. Each experiment is an ensemble of ten integrations differing only by their atmospheric initial conditions derived from a pre-existent control experiment (see Table 1). No attention is therefore paid to the impact of atmospheric initialization on seasonal predictability. For all experiments, the ARPEGE-Climat model is driven by observed monthly mean SSTs and sea-ice cover from the HadISST climatology (Rayner et al. 2006).

- CTL (for “Control”) consists of ten integrations running from 1st January 1949 to 31st December 2006 (including a 1-year spin-up). It is the control experiment with an interactive snow, i.e. snow evolves freely in the model and the prescribed SST is the only forcing.
- SBC (for “Snow Boundary conditions”) consists of ten integrations running from 1st January 1949 to 31st December 2000 (including a 1-year spin-up). Each integration is nudged towards the off-line SURFEX monthly snow mass reanalysis linearly interpolated on a daily basis. The difference between SBC and CTL therefore highlights the impact of the additional and hopefully realistic SURFEX snow forcing on seasonal atmospheric predictability.
- SIC (for “Snow Initial conditions”) consists of ten seasonal integrations running only from March to May over the 1950–2000 period. Each integration starts from SBC initial conditions on March 1st and is therefore a twin springtime simulation in which the nudging is suppressed. It allows us a more realistic assessment of the impact of snow initialization on atmospheric predictability.
- OSBC (for “Observed Snow Boundary conditions”) consists of 10 integrations running from 1st January 1971 to 31st December 2006 (including a 1-year spin-up). It is the ensemble experiment nudged towards the off-line SURFEX snow mass reanalysis corrected with the NSIDC snow cover observations.

Table 1 List of experiments

Ensemble	Description (all runs are with observed SST)
CTL	Control run with free evolving snow 1950–2006
SBC	Imposed SURFEX snow mass boundary conditions 1950–2000
SIC	Imposed snow initial conditions at the 1st of March 1950–2000
OSBC	Imposed NSIDC snow cover boundary conditions 1972–2006

Each experiment is an ensemble of 10 members with different initial conditions

2.4 Validation data

The snow cover data consists of observed weekly snow cover fractions, provided by the National Snow and Ice Data Center (NSIDC) on the EASE 25-km equal area grid. Version 3 of this dataset covers the 1967–2006 period but includes a significant number of missing data in the late 1960s and early 1970s so that the present study will concentrate on the 1972–2006 period. Near-surface air temperatures have been derived from version 2 of the Climate Research Unit climatology (CRU2, http://www.cru.uea.ac.uk/cru/data/). For pressure-level atmospheric fields, we use the NCEP2 reanalysis (http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml) available since 1948. Finally, observed surface radiative fluxes have been derived from the ISCCP2 satellite climatology available over the 1984–2000 period (http://www.isccp.giss.nasa.gov/index.html). All these datasets have been interpolated onto the GCM horizontal grid and averaged on a monthly basis for the evaluation of the ARPEGE-Climat simulations.

2.5 Statistical tools

Two metrics have been used to quantify predictability in the various experiments.

- *Potential predictability* (*hereafter PP*): one-way analysis of variance (ANOVA) is a powerful tool allowing us to estimate the fraction of the ensemble simulation variability that is forced by common boundary conditions (or initial conditions for SIC). The ratio of forced versus total variability is called potential predictability. Details on the methodology and its underlying hypotheses can be found in Von Storch and Swiers (1999). The total variance is estimated from the 500 (290 for OSBC) seasonal integrations each experiment consists of, while the forced variance ignores the contribution of the atmospheric initial conditions and is computed from the 10 ensemble mean seasons. It should be however emphasized that PP is based on a perfect model approach and only measures the spread of our seasonal simulations. It is therefore important to assess the skill against real observations and over a period as long as possible to draw robust conclusions. A Fisher test is used to evaluate the significance of variance changes.

- *Effective predictability* or model skill has been here simply measured as the temporal anomaly correlation coefficient (ACC) between the simulated climate anomalies and those derived from the observations or reanalyses. The significance of correlations is computed with a Student *t* test. Differences of ACC between two experiments are assessed at each grid point by computing the variance of correlations within each ensemble of simulations. Then, a Student *t* test is applied to test the significance of the ensemble mean difference.

3 Evaluation of snow forcing

A preliminary step of this work consists of assessing the realism of the off-line SURFEX snow cover climatology against the NSIDC satellite observations, which is the only hemispheric snow dataset available since the late 1960s.

3.1 Mean state

The mean annual cycles of snow cover simulated in CTL, SBC and OSBC are depicted in Fig. 2a over the whole Northern Hemisphere, Central Europe and North America. As expected, the annual cycle in OSBC is very

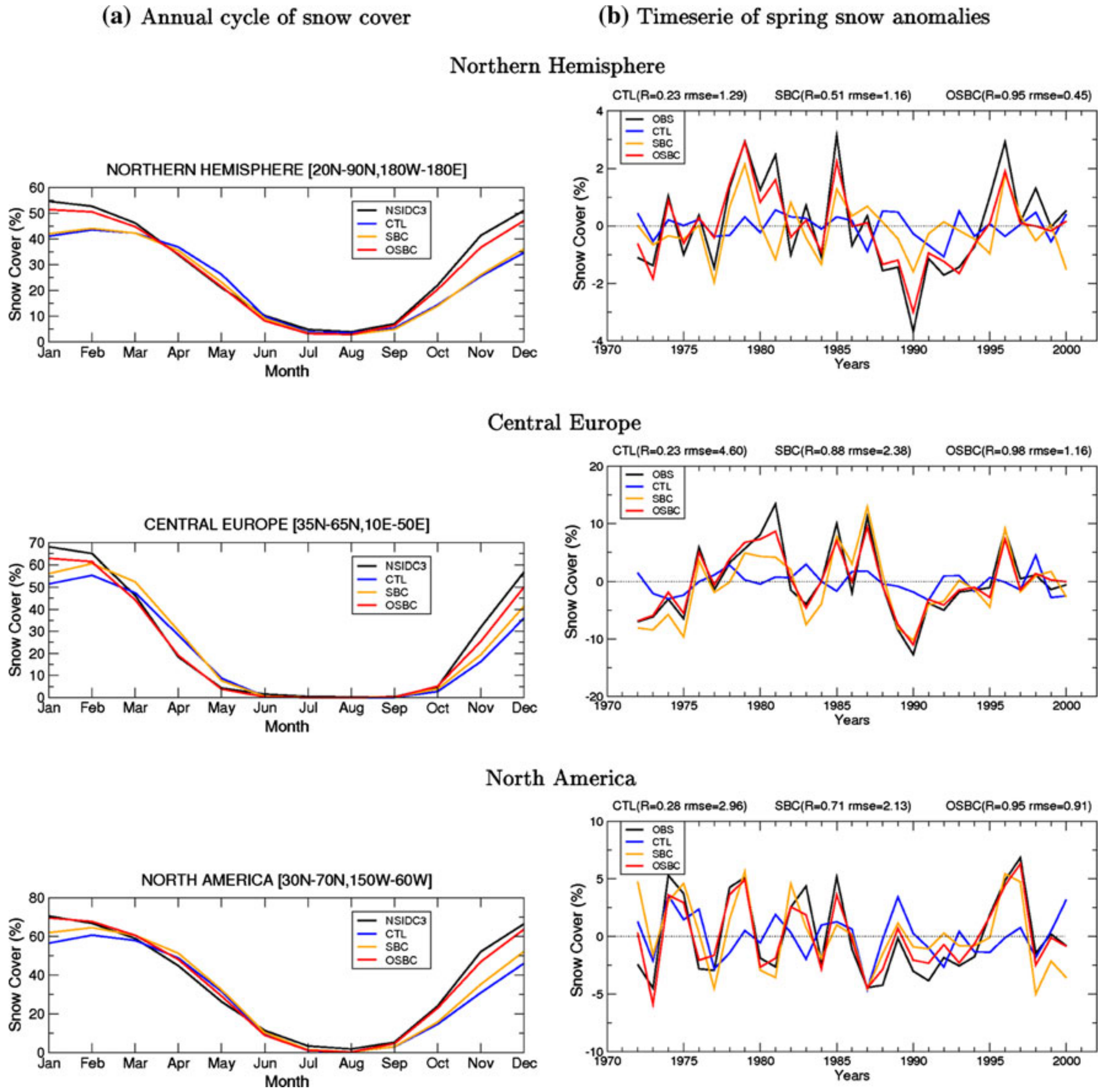


Fig. 2 **a** Annual cycle of snow cover over the 1972–2000 period for Northern hemisphere (*upper left*), Central Europe (*middle left*) and Noth America (*lower left*). NSIDC data are in *black*, CTL in *blue*, SBC in *orange* and OSBC in *red*. **b** Timeseries of springtime snow anomalies over the same regions. The root mean square error and correlations with observations are indicated for CTL, SBC and OSBC

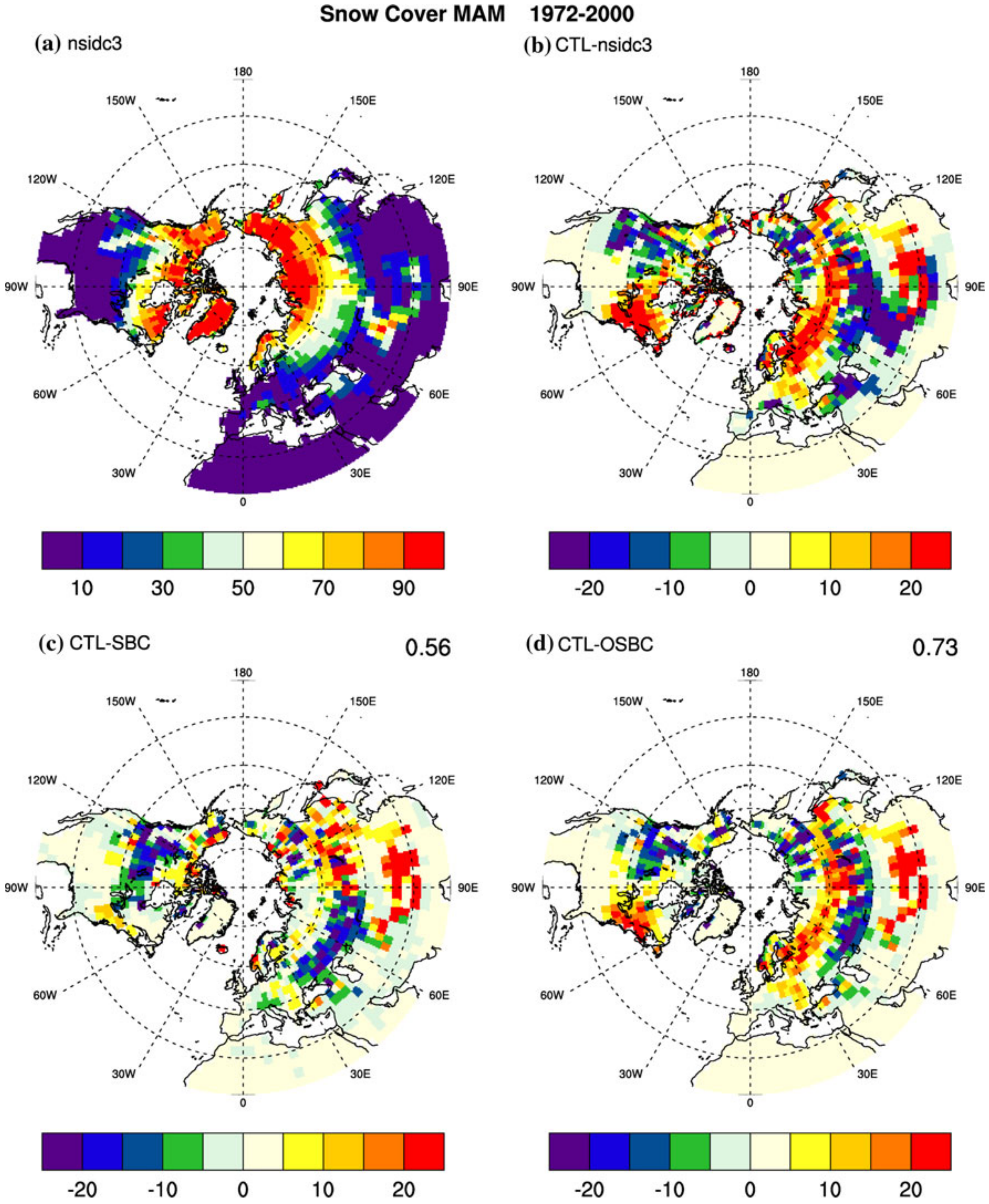


Fig. 3 Climatology of spring snow cover fraction over the 1972–2000 period: **a** NSIDC data, **b** CTL minus NSIDC, **c** CTL minus SBC and **d** CTL minus OSBC. Spatial correlations with **b** are indicated for **c** and **d**

close to the NSIDC observations. The slight underestimation is likely due to the non linearity of the snow cover–snow mass relationship: NSIDC snow cover were inverted on a weekly basis to produce the monthly OSBC snow mass boundary conditions while the monthly OSBC snow cover diagnostic was averaged from 6-h model outputs. Two biases are common to the CTL and SBC simulations: a delayed snow melt in spring and an underestimated snow cover in fall. Such biases are only slightly reduced in the SBC simulation, thereby suggesting that they are intrinsic to the ISBA snow physics and/or partly related to the empirical formulation used to diagnose snow cover in this model.

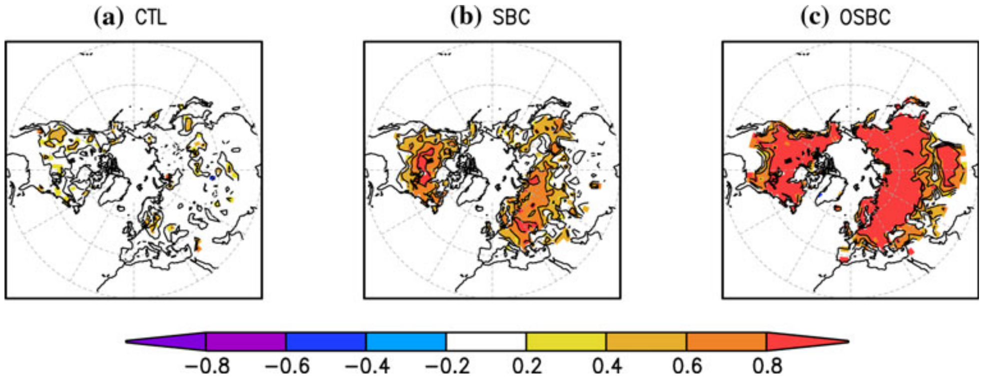


Fig. 4 ACC of spring snow cover between the simulations and the NSIDC observations over the 1972–2000 period for: **a** CTL; **b** SBC; **c** OSBC. Significant values at the 95% confidence level are *shaded*

The climatological Northern Hemisphere distribution of the springtime snow cover is depicted in Fig. 3a for satellite observations. Differences CTL-SBC (Fig. 3c) and CTL-OSBC (Fig. 3d) are also shown and compared to the biases of the control experiment (Fig. 3b). Same sign in SBC-CTL (OSBC-CTL) and CTL-observations means that the SBC (OSBC) simulation reduces biases compared to the control. Spatial correlations with CTL-observations are indicated to quantify the benefit of the nudging in SBC and OSBC. First, the control simulation shows that the model underestimates the southward extent of snow over Eurasia, but overestimates the snow fraction at higher latitudes due to a delayed melting. This overestimation is consistent with Fig. 2. It is also found over eastern America, while a lack of snow is on the contrary found over the western part of this continent. The snow relaxation in SBC improves the snow mean state over southwestern Eurasia by moving the snow line equatorwards. However, the delayed snowmelt over northern Eurasia is not corrected. By design, OSBC leads to same improvements that SBC, but with a better timing of snow according to the observed data over both Eurasia and North America. Also, we can see that the snow nudging in SBC and mostly in OSBC corrects the climatological model biases satisfactorily, as suggested by the positive spatial correlations (respectively 0.56 and 0.73).

3.2 Interannual variability

Beyond the mean annual cycle, Fig. 2b shows the time-series of springtime snow cover anomalies over the same three regions as in Fig. 2a. In contrast with the control experiment, SBC captures relatively well the observed interannual variability since the beginning of the satellite record. Not surprisingly, the variability is very close to the NSIDC data in OSBC but the simulated anomalies are weaker than observed, which can be explained by both the linear interpolation applied to the monthly snow mass reference fields before nudging and some systematic biases in the ARPEGE-Climat model.

Figure 4 shows the Northern Hemisphere distribution of the temporal grid-cell ACC between the simulated and observed springtime snow cover over the common 1972–2000 period. In the control experiment, only western North America shows significant correlations with the observed interannual variability, in line with the well-known ENSO footprint on North America circulation (Gutzler and Rosen 1992; Ge et al. 2009). Snow cover interannual variability is clearly improved in SBC, with an increase of the ACC over large portions of western Eurasia and North America. Correlations are however weaker over Siberia, which could be related to the lesser accuracy of the SURFEX atmospheric forcings over this region with sparse in situ observations. In line with the snow mass correction derived from the NSIDC data, correlations in OSBC reach 0.9 over the major part of the Northern Hemisphere. This last set of simulations are therefore valuable to explore the impact of more realistic snow boundary conditions on the springtime interannual variability simulated by the ARPEGE-Climat atmospheric GCM.

4 Results

4.1 Influence of snow boundary conditions

The first step of the study is to assess the impacts of nudging towards the SURFEX off-line snow mass reanalysis product. The 10-member SBC experiment is compared to the 10-member control (CTL) experiment. Changes in standard deviation, PP, and ACC analysis have been assessed for 2-m temperature, sea-level pressure and geopotential height at different pressure levels.

Impacts on 2-m temperature variability and predictability are shown in Fig. 5a–f. The total variability is decreased in SBC compared to CTL in the areas where snow nudging results in more snow mass and thereby in a

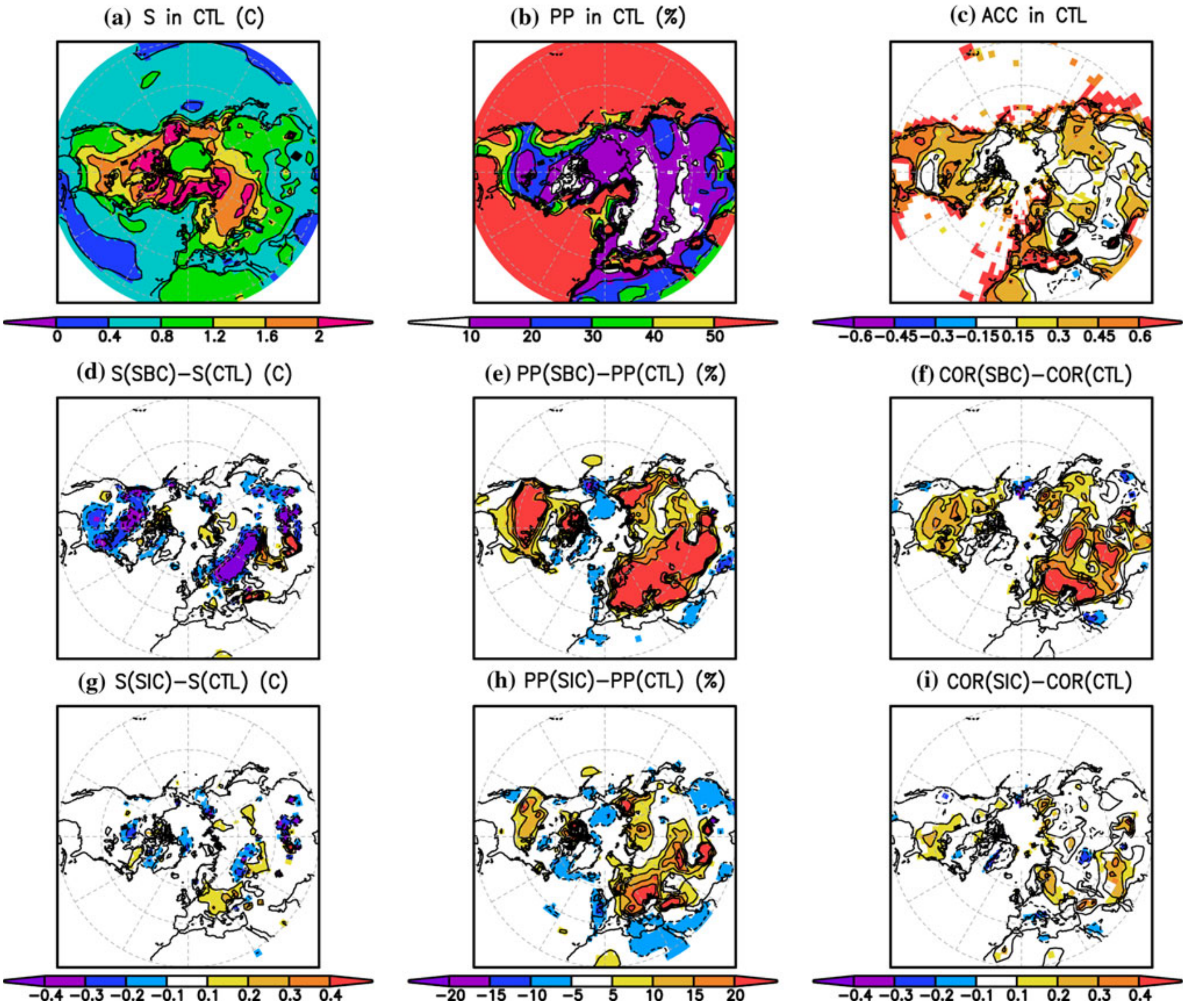


Fig. 5 Standard deviation (S), PP and ACC for 2-m temperature in CTL (*upper panels*), differences between SBC and CTL (*middle panels*), and differences between SIC and CTL (*lower panels*), over the 1950–2000 period. For S and ACC, significant values at the 95% confidence level are *shaded*

stronger control on the surface energy budget (Fig. 5d). Two factors explain this response in SBC: the decrease of the total variance, and the increase of the forced variance. Note that these modifications in SBC are mainly an improvement regarding the observed variability of surface temperature, which is too strong in CTL due to lack of snow (not shown). PP is low in the control experiment over the continents, except over North America due to the significant ENSO teleconnection (Fig. 5b). It is increased by more than 20% in SBC over North America and a major part of Eurasia (Fig. 5e). The ACC is also generally improved in these regions with the best results obtained over central/East Europe, West Siberia and North America (Fig. 5f). These results are consistent with Schlosser and Mocko (2003), who identified western Russia and eastern Canada as regions where the near-surface temperature is most sensitive to changes in snow cover.

Figure 6 depicts ACC over land surface for the three components of the surface energy budget that are mostly affected by the snow relaxation. Upward radiative fluxes are evaluated against the ISCCP2 satellite data and the sensible heat flux is compared to the off-line SURFEX simulation. All calculations are made over the common 1984–2000 period. The observed variability of the radiative fluxes is not captured in our control simulation, except over Southwest US due to the ENSO influence. In SBC, snow relaxation leads to an improved surface albedo and therefore an improved variability of upward shortwave radiation. More realistic upward longwave radiation and sensible heat flux are also found and consistent with the

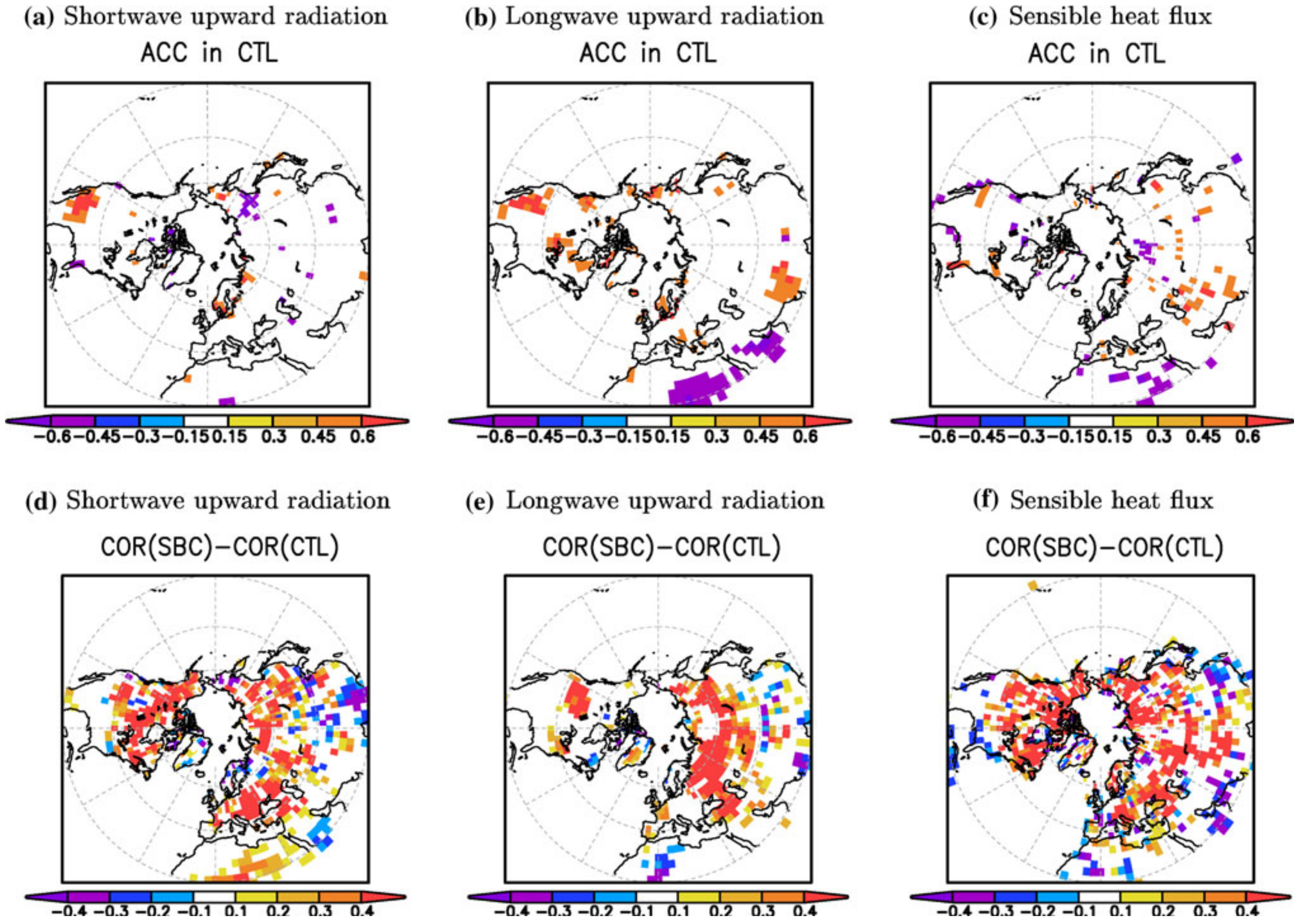


Fig. 6 ACC for surface radiative and heat fluxes in CTL: **a** Shortwave upward radiation; **b** longwave upward radiation and **c** sensible heat flux. Difference of ACC between SBC and CTL: **d** Shortwave upward radiation; **e** longwave upward radiation and **f** sensible heat flux. ACC are computed over the 1984–2000 period. Only correlations significant at the 95% confidence level are shown

more realistic near-surface temperature. In contrast, no clear signal was found on downward radiative fluxes (not shown) suggesting no significant cloud feedbacks in our simulations.

Moving to sea level pressure (Fig. 7a–f), the results are less positive. While snow nudging leads to an increase in PP and therefore to a lesser spread in our ensemble simulations, the ACC results do not show a systematic improvement of the simulated variability. Improving near surface temperature therefore does not guarantee a better representation of the lower troposphere dynamics. Nevertheless, a positive response is found over the US where the significant snow forcing found in PP is also a realistic one. The signal over this region is also found on geopotential height at various pressure levels (not shown) and has therefore a robust and barotropic signature. This large-scale circulation response remains an exception and our simulations suggest that the impacts of snow boundary conditions are mainly confined to the lower troposphere.

4.2 Influence of snow initialization

Beyond the impact of more realistic snow boundary conditions, what is the relevance of snow initialization for the simulation of springtime climate variability? SIC, the ensemble of 3-month simulations with interactive snow mass (as well as albedo and density) initialized on March 1st from the nudging experiment (i.e. SBC) will allow us to address this question.

Figure 5 and Fig. 7g, h illustrates the impact of snow initialization on 2-m temperature and sea level pressure. PP and ACC are compared with the values obtained in CTL. Not surprisingly, the main signal is again obtained for 2-m temperature (Fig. 5). The patterns are close to those obtained with a persisted snow forcing, but with weaker amplitude. Such a consistency between the results of SBC and SIC gives us further confidence in the robustness of the results. Nevertheless, an increase in PP (i.e. a decrease in spread) does not necessarily translate into an increase in skill and eastern Europe, central North America and some

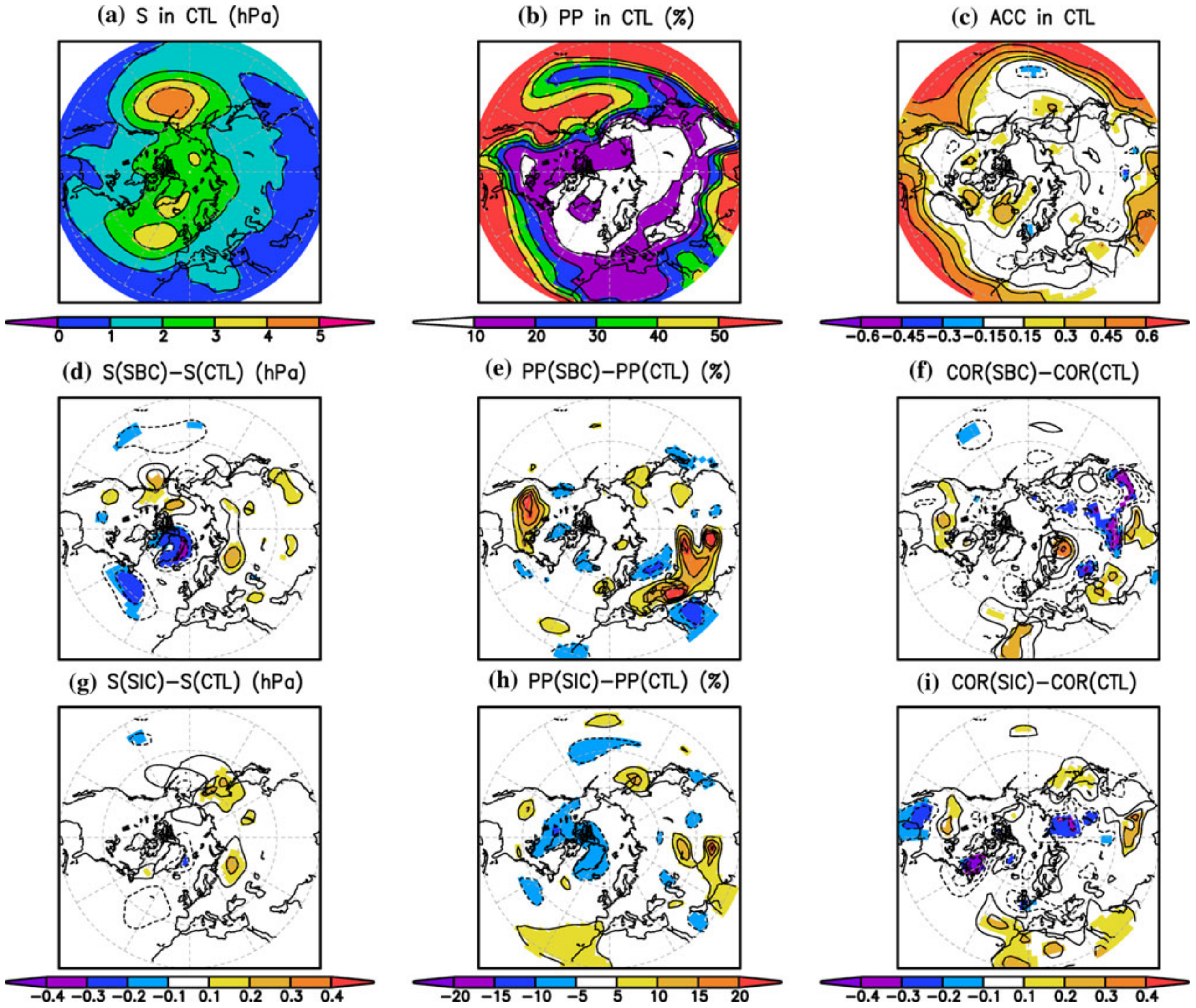


Fig. 7 Standard deviation (S), PP and ACC for sea level pressure in CTL (*upper panels*), differences between SBC and CTL (*middle panels*), and differences between SIC and CTL (*lower panels*), over the 1950–2000 period. For S and ACC, significant values at the 90% confidence level are *shaded*

regions of Asia appear as the areas where snow initialization has a significant impact on near-surface temperature predictability in the ARPEGE-Climat model. In line with the results of SBC, snow initialization has no systematic impact on sea level pressure variability and predictability (Fig. 7). Positive ACC anomalies are found over the US, Scandinavia, and portions of south Eurasia, which are presumably robust given their relative consistency with the results of SBC. They should however be interpreted with caution given the very limited PP in these regions.

4.3 Conditional skill: focus on strong snow anomalies

The last section suggests the importance of snow initialisation for an accurate prediction of springtime near-surface temperatures in the mid-and-high northern latitudes. Despite the limitations of our SURFEX snow reanalysis, we have identified a potential improvement of the March–May hindcast skill, in particular in the regions where this dataset shows high correlations with satellite snow cover data (Fig. 4). Such a condition is however not sufficient to guarantee a strong improvement of seasonal predictability, especially in areas where atmospheric anomalies are not sensitive to snow influence. In the present section, we repeat our ACC analysis but considering only the grid cells and seasons when snow anomalies exceed one standard deviation. The sample size is therefore different from one grid cell to another, but is a minimum of 10 years to guarantee the robustness of the results. In addition to the snow anomaly criterion, a minimum incident surface shortwave radiation of 100 W/m^2 is also used which excludes the high-latitude grid cells where a strong snow anomaly does not necessarily lead to a strong radiative forcing. On average, about 20 years are selected at each grid cell among the 51 available.

Results for spring near-surface temperature in SIC are shown in Fig. 8. Patterns are relatively noisy because of the sample size differences, but indicate a general increase of skill in the snow-covered areas highlighted in Fig. 5. Therefore, the conditional skill approach strengthens our conclusions about the snow contribution to seasonal predictability of near-surface temperature. When a strong signal does exist in the initial conditions, it has a significant impact on springtime temperature which can be predicted by the ARPEGE-Climat model even with a crude initialization technique based on an off-line land surface modelling strategy. However, the conditional approach is not very useful for the understanding of sea level pressure predictability given the fundamental non-local nature of the atmospheric dynamics.

4.4 Persistence of the snow initialization footprint

Another important question is to assess whether the impact of snow initialization is felt during the whole springtime season or only during the first month of the atmospheric integration. Figure 9 shows the ACC with and without conditional skill for 2-m temperature in SIC for each month of the March–May season. Upper panels show the ACC differences between SIC and CTL, while lower panels show the increase of ACC due to conditional skill in SIC (years with strong snow forcing minus all years). Not surprisingly, the snow influence is maximum 1 month after initialisation and decreases gradually during the season. The main improvements are found in March over Central Europe and North America. In April, the region with the strongest skill is displaced eastwards because of snow melting and retreat. Interestingly, ACC in May suggest negative impacts of snow initialization over both North America and Eurasia, which might be related to the overestimated snow accumulation and/or the delayed snowmelt in the ARPEGE-Climat model (cf. Fig. 2). It could lead to unrealistic water content in the ground and alter the balance energy through the hydrological effect of snow. Thus, if they do not have impact in early spring when radiative effect is the most important, these systematic biases can offset the benefit of snow initialization after a few weeks of integration and lead to unrealistic surface temperature anomalies 3 months after initialization.

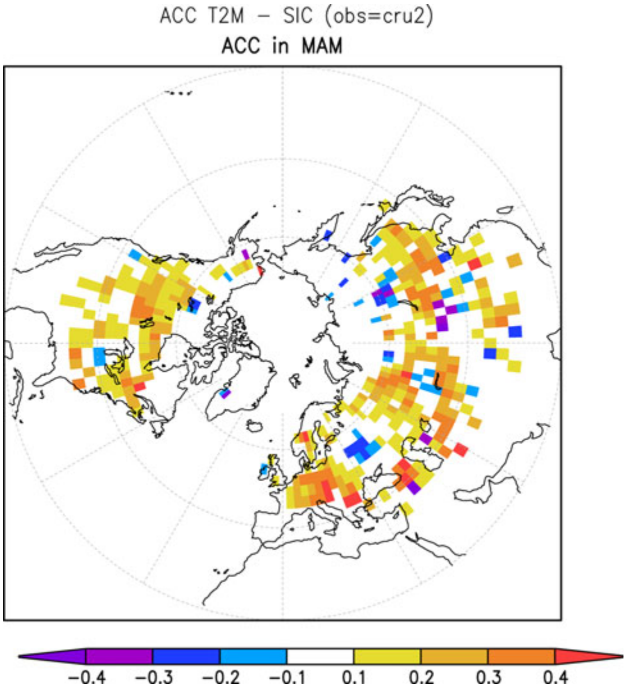


Fig. 8 Conditional versus all-year skill in SIC for 2-m temperature (i.e. ACC for years with strong snow forcing minus ACC for the 51 years)

4.5 Sensitivity of the results to snow forcing

This section is motivated by the analysis of SBC which showed improved temperature predictability over regions where the SURFEX snow reanalysis is most realistic (i.e. Central Europe and North America). In contrast, no positive impact of snow nudging was found over regions like Siberia where the SURFEX interannual variability is not consistent with the observed snow cover variability (see Fig. 4). To assess the relevance of an accurate snow forcing, we have constructed another snow mass reanalysis by inverting the satellite snow cover data. In the resulting OSBC experiment, we therefore nudge the model towards an *a priori* more realistic Northern Hemisphere snow cover extent (but not necessarily snow mass) and we expect a stronger impact on atmospheric predictability compared to SBC. Due to the limited availability of satellite observations, this last ensemble of simulations runs only from 1972 to 2006 and the comparison with SBC is limited to the 1972–2000 period.

4.5.1 Predictability analysis

Figure 10 shows the total standard deviation, PP and ACC for 2-m temperature in CTL, OSBC minus CTL and OSBC minus SBC over the common 1972–2000 period. Compared to the control experiment (Fig. 10d–f), OSBC shows similar patterns of PP and ACC increase as SBC (cf Fig. 5). However, the skill is not improved over North America where the ACC in CTL is stronger than over the

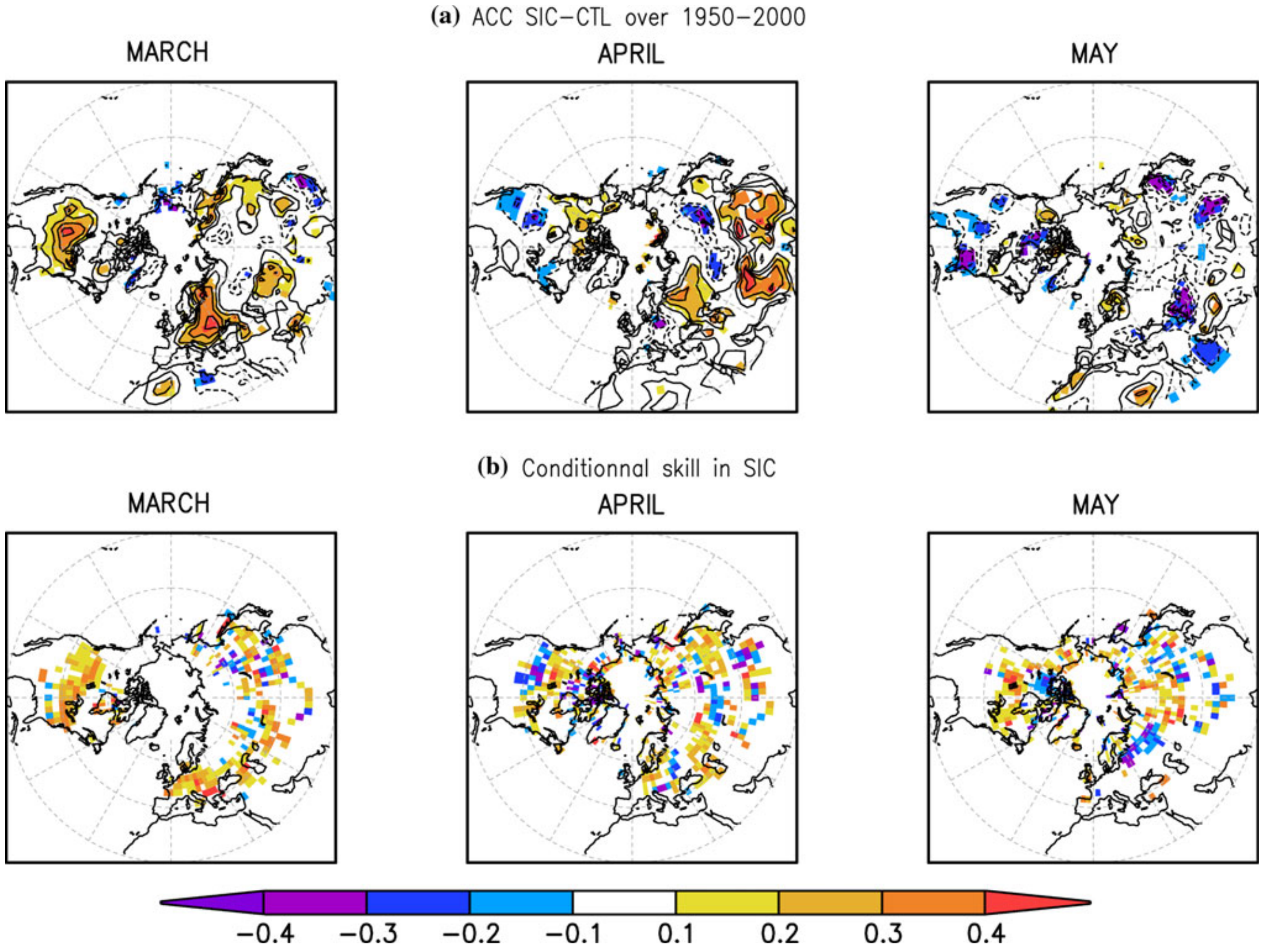


Fig. 9 Month by month ACC for: **a** SIC-CTL over all years; **b** conditional versus all-year skill in SIC. For **a**, significant values at the 95% confidence level are *shaded*

whole 1950–2000 period. A possible explanation is the strong ENSO activity in the 1980s and 1990s. Compared to SBC (Fig. 10g, h), potential predictability of near-surface temperature decreases near the snow line in accordance with a weaker total variance. Surprisingly, while the interannual variability of the Northern Hemisphere snow cover is strongly improved in OSBC compared to SBC (Fig. 4), the nudging impact on near-surface temperature skill is quite similar. The only significant improvements of ACC are found over eastern Siberia, where the snow correction is the most important. In contrast, ACC is decreased over south Eurasia. A month by month analysis reveals that this seasonal mean response hides some contrasts between early and late spring (Fig. 11). On the one hand, the OSBC experiment leads to stronger ACC than SBC near the southern line of the Eurasian snow cover in March, where and when the SURFEX reanalysis has been shown to underestimate the observed snow cover (cf Fig. 3). On the other hand, the impacts are fewer positive in April and become negative in May, highlighting the possible limitations of our snow mass corrections. Given the empirical snow cover fraction used in the ARPEGE-Climat model, our strategy can lead to a systematic overestimation of snow mass and thereby of snowmelt, with a detrimental impact on surface evaporation after melting. Conversely, in early spring, the radiative effect of snow still dominates the hydrological effect and improved snow cover boundary conditions can lead to improved low-level temperature predictability. A quick look at the other seasons (not shown) seems to confirm this hypothesis, the ACC for 2-m temperature being also improved for OSBC in winter and fall.

In line with these results, a slight improvement is also found in March for sea level pressure (not shown). However, it is confined to limited areas and vanishes when considering the MAM seasonal mean. Therefore, the

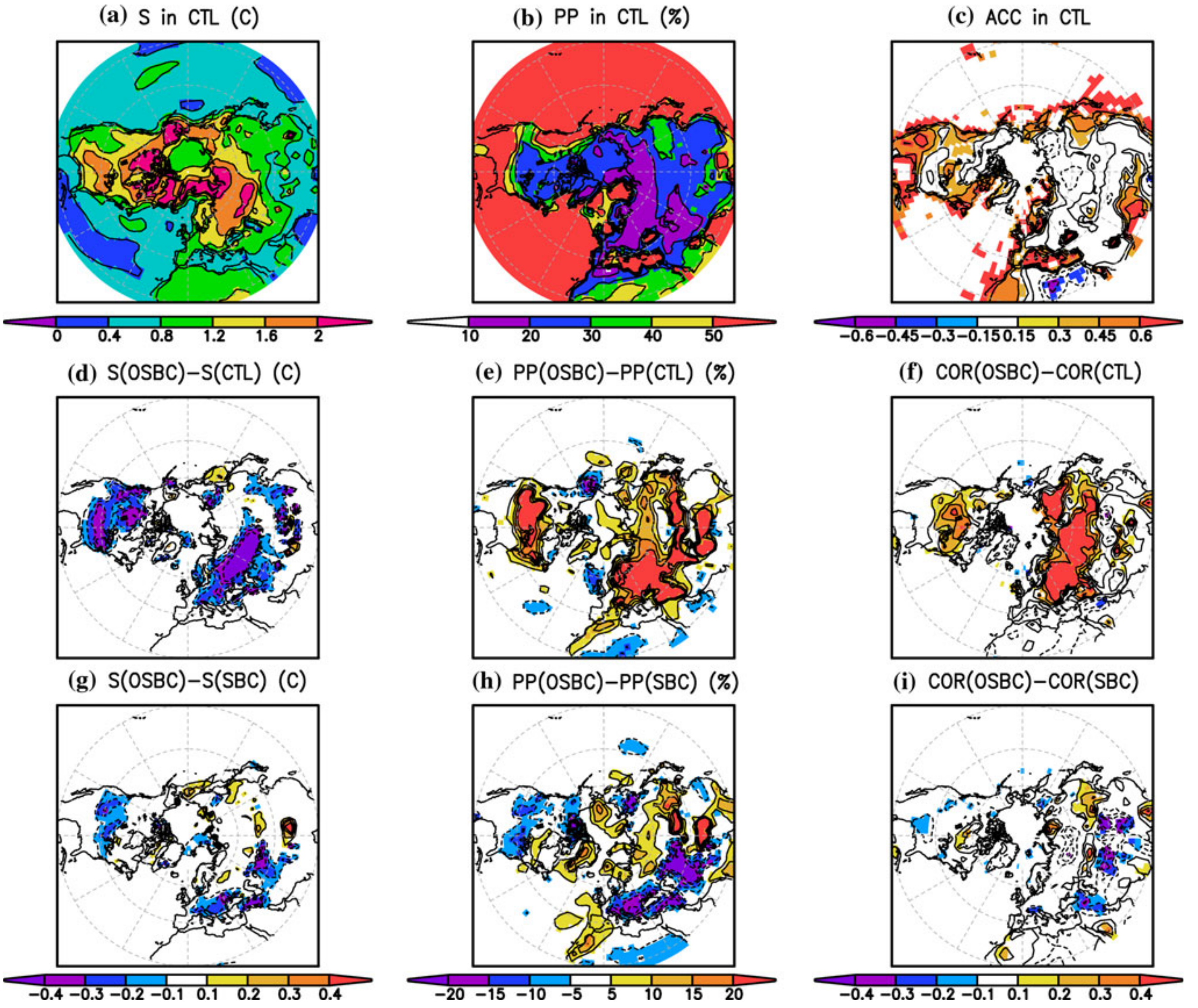
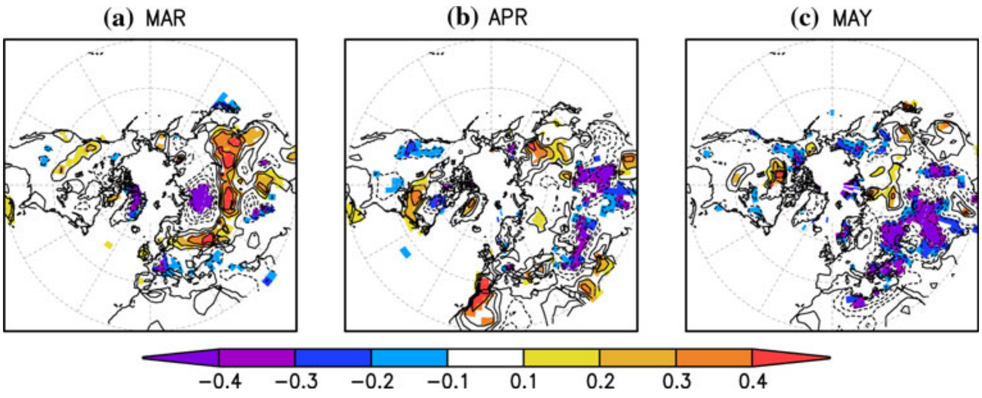


Fig. 10 Standard deviation (S), PP and ACC for spring 2-m temperature in CTL (*upper panels*), differences between OSBC and CTL (*middle panels*) and differences between OSBC and SBC over the 1972–2000 period. For ACC, significant values at the 95% confidence level are *shaded*

Fig. 11 Differences OSBC-SBC of 2-m temperature ACC: **a** in March; **b** in April; **c** in May. Significant values at the 95% confidence level are *shaded*



apparent deficiencies in the off-line SURFEX reanalysis are not necessarily the main obstacle for improving the skill of our seasonal hincasts and such a simple strategy without any snow data assimilation might be sufficient to get a large fraction of the potential benefits of snow initialization on springtime predictability.

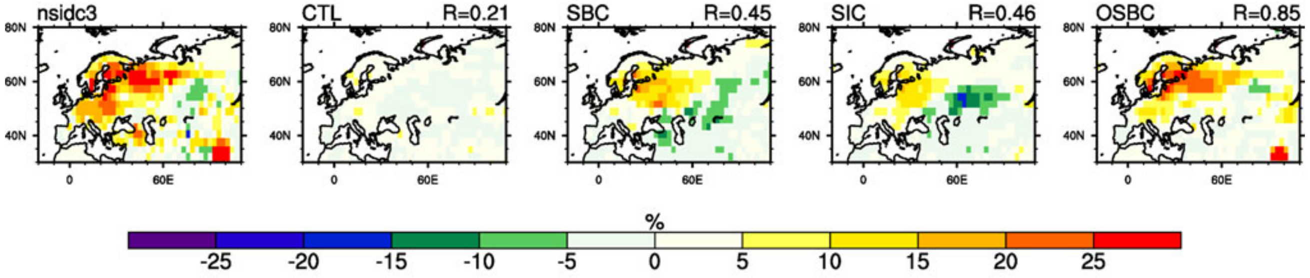
4.5.2 Regional cases studies

To go one step further in the understanding of the regional effects of snow, we looked at two selected cases studies over Europe. Several parameters are analysed for spring 1981 and 1985 characterized by strong positive anomalies of snow cover over this region (see Fig. 2b). We chose these case studies because they show contrasted results despite similar snow cover anomalies.

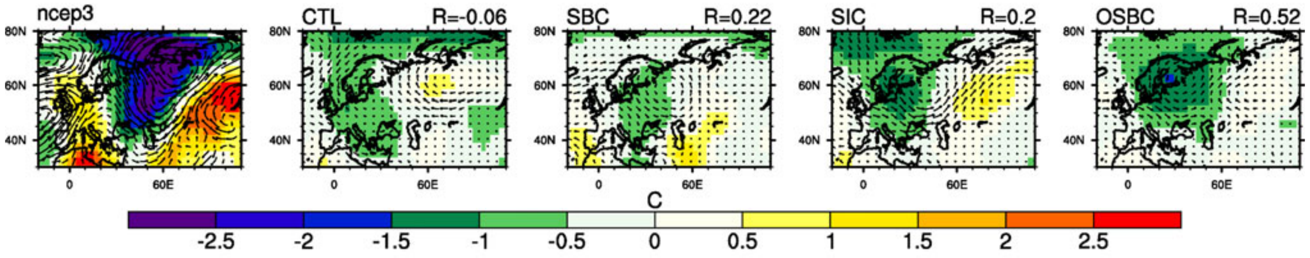
Results for 1981 are depicted in Fig. 12. Regional anomalies of snow cover, 850 hPa temperature and winds, and 500 hPa geopotential height (Z500) simulated in our four ensemble experiments are compared with the observed ones. For each ensemble, the spatial correlation between the simulated and observed anomalies is indicated. In the NCEP2 reanalyses, the excessive snow cover over northwest Europe is associated with a cold low-level anomaly over central Europe. This eastward shift is consistent with the dominant westerly circulation and the fact that the snow radiative influence is not necessarily merely local but can also produce remote temperature perturbations through the large-scale circulation of air masses. In line with the thermal wind relationship, a cyclonic anomaly is found over Central Europe, which appears at both 850 and 500 hPa. The positive anomaly of snow cover is not captured in CTL, is partly present in SBC but is closer to observations in OSBC (with $R = 0.85$). Note that the anomaly persists through the whole season in SIC. The simulated 850 hPa temperature anomalies are consistent with the snow patterns. They are more pronounced and better correlated with NCEP2 in OSBC than in SBC, in line with the stronger and more realistic snow forcing. The Z500 anomalies are also strongly improved in OSBC compared to SBC and mostly CTL, which shows a negative correlation with NCEP2. This

1981

(a) Snow Cover



(b) 850mb temperature and wind



(c) 500mb geopotential height

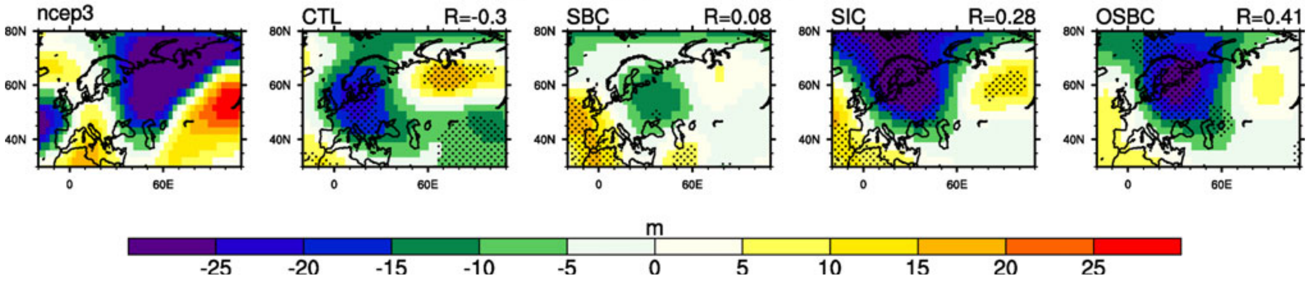


Fig. 12 Spring 1981 case study: MAM anomalies relative to the 1972–2000 climatology for observations, CTL, SBC, SIC and OSBC, respectively: **a** snow cover; **b** 850 hPa temperature and winds; **c** 500 hPa geopotential height (*stipples* indicate statistical significance at the 95% level)

case study therefore illustrates that a more realistic snow forcing can lead to a more realistic simulation of both low-level temperature and large-scale dynamics over Europe. Surprisingly, the impact of snow initialization in SIC compares favourably with the impact of snow nudging in SBC despite a slightly weaker snow forcing. While this result must be interpreted with caution given the limited size of our ensemble experiments (only 10 members), it confirms our former conclusion whereby strongly positive snow anomalies in the initial conditions can persist long enough to have a significant and realistic impact on springtime seasonal forecasts over Europe.

Results for 1985 are shown in Fig. 13. The observed positive snow cover anomalies are close to the 1981 ones, but are weaker and located southward of their 1981 counterpart. Here again, the cold low-level anomaly found in the NCEP2 reanalyses is associated with a cyclonic anomaly but shows a strong eastward shift relative to the snow cover excess which might suggest a remote rather than a regional origin. Unlike the previous case study, the atmospheric response is not improved by the snow nudging. Indeed, the Z500 response is fairly well captured in CTL, with a wave train structure that resembles the NCEP2 reanalyses (Fig. 13c). While this pattern is still found in SIC but is less significant, it disappears in the nudging experiments thereby indicating that the snow relaxation leads to a deterioration of the model response to the prescribed boundary conditions. Thus, this case study illustrates that a better representation of snow anomalies does not necessarily lead to an improved simulation of atmospheric circulation. It explains the mixed results of our predictability analysis over the 1972–2000 period and the weak differences in skill between SBC and OSBC.

The reasons for such contradictory results from one case study to another are not obvious. Nevertheless, the SST conditions for these 2 years are quite different, with a neutral ENSO phase in spring 1981 and an emerging La Niña event in spring 1985. These SST anomalies are shown

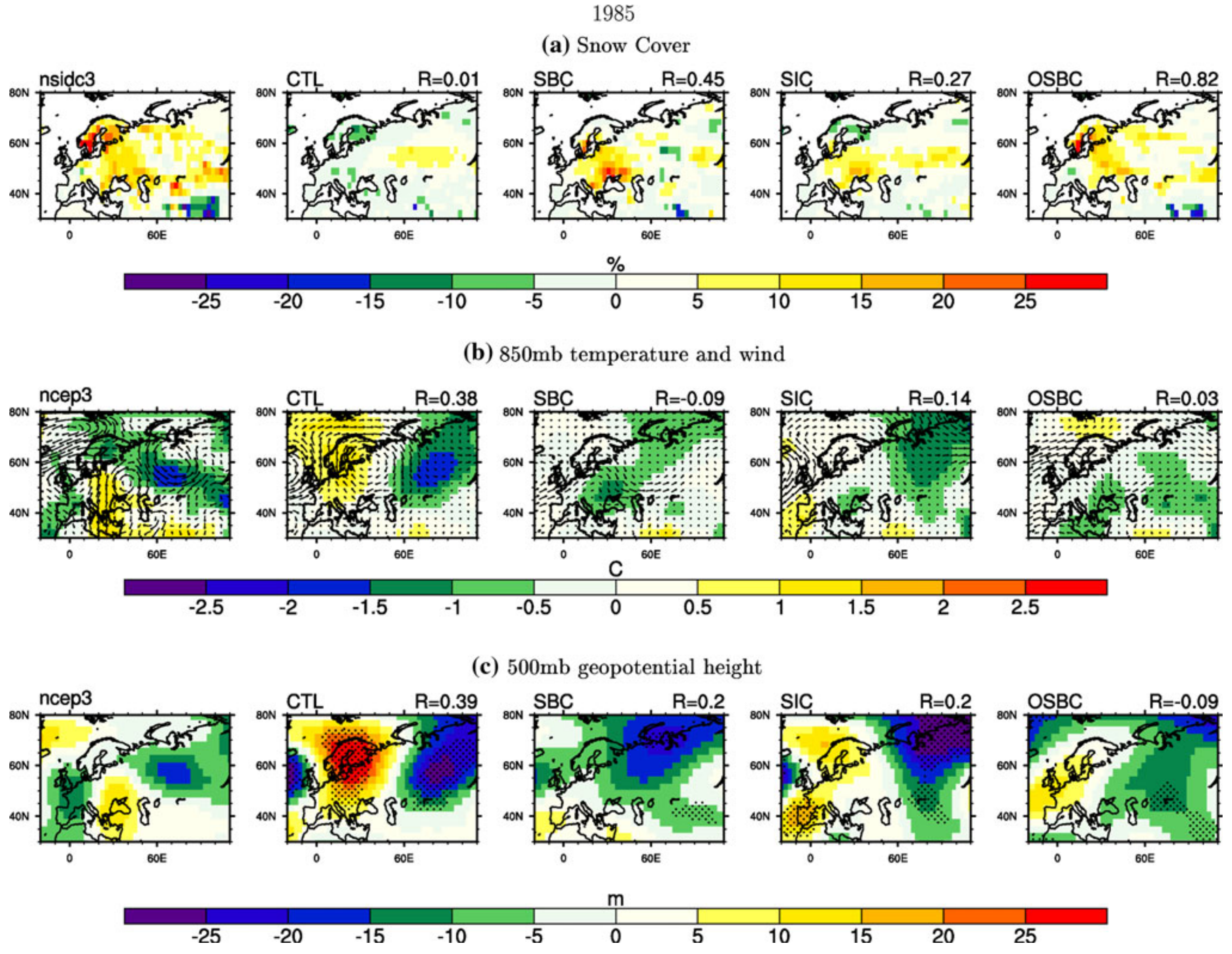


Fig. 13 Spring 1985 case study: MAM anomalies relative to the 1972–2000 climatology for observations, CTL, SBC, SIC and OSBC respectively: **a** snow cover; **b** 850 hPa temperature and winds; **c** 500 hPa geopotential height (*stipples* indicate significance at the 95% level)

in Fig. 14, as well as the associated 200 hPa stream function anomalies over the Northern Hemisphere. In line with the cold anomalies prescribed in the equatorial Pacific in spring 1985, all experiments show a similar and fairly realistic planetary-scale atmospheric response. Nevertheless, the stream function anomalies are too strong over Europe. This too high sensitivity of European climate to tropical forcing in ARPEGE-Climat was noted by (Cassou and Terray 2001) and is due to an unrealistic eastward extension Pacific-North America teleconnection pattern. This systematic error suggests that in 1985 the simulated European climate is mostly influenced by remote SSTs and could explain why the results are not improved by the snow nudging. Conversely, the planetary scale circulation is more zonal in 1981 as tropical SSTs influence is weak, in line with low spatial correlations of 200 hPa streamfunction. Consequently, in this case, snow influence is more dominant and more realistic since the tropical SST forcing is weaker.

To confirm this hypothesis, we have conducted additional ensemble simulations for the two cases studies, similar to OSBC but with climatological SST (not shown). The dynamical response is improved for the 1985 spring season, thereby corroborating our hypothesis about the perturbing influence of the tropical SST teleconnection. In contrast, prescribing climatological SST deteriorates the atmospheric response in spring 1981. Indeed, for the 1981 year we remove the local cold SST anomaly in the Norway Sea visible in Fig. 14. Thus, in this case the model is not perturbed by remote SST induced teleconnections, but the local SST anomaly is crucial to simulate the atmospheric response. These results suggest that both SST and snow conditions are potentially important to capture the interannual variability of the springtime atmospheric circulation over Europe, but that the remote model response to the global SST forcing is highly dependent on the patterns of the prescribed anomalies.

5 Summary and discussion

The present paper aimed at evaluating the impact of prescribed snow boundary or initial conditions on the springtime climate variability simulated by the ARPEGE-Climat atmospheric GCM driven by observed SST. Two snow mass climatologies have been constructed to nudge (initialise) the model towards (with) as realistic as possible snow fields. The first global snow mass dataset covers the 1950–2000 period and was obtained by forcing the SURFEX LSM with the meteorological reanalyses provided by the University of Princeton. Though some biases persist in the resulting snow cover climatology, its spatial extent and interannual variability is better than in the control ARPEGE-Climat simulation and is therefore useful to constrain snow mass in the GCM through a simple nudging technique. ANOVA and ACC statistics have been used to quantify the potential and effective predictability associated with the prescribed SST forcing in the control experiment, and their sensitivity to the additional snow mass forcing in the nudging experiment. Focus has been on the spring season when strong solar radiation and snow cover variability favour the potential snow influence on climate.

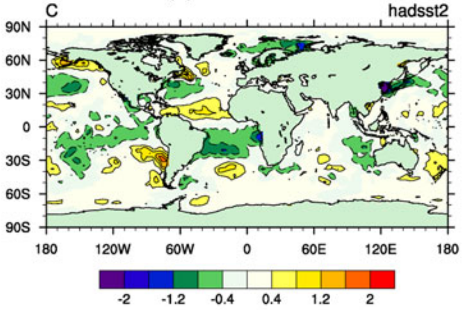
In agreement with previous similar studies, the SST related predictability of near surface temperature over land is low outside the tropics, except over coastal regions and in the southwest of North America where tropical Pacific SST exerts strong teleconnections. In comparison with the control experiment, the snow nudging leads to positive impacts on both potential and effective predictability. The skill improvement is particularly high over Central Europe and North America, which are populated regions where seasonal forecasting has economic benefits. However, and in line with the results of Kumar and Yang (2003) or Schlosser and Mocko (2003), the positive snow impacts are confined to the lower troposphere and no clear signal is discernible on large scale dynamics.

A second step of our study was to determine the benefit of snow initialization in seasonal hindcasts again driven by observed SST. The results of SBC on March 1st were used to initialize twin spring simulations with interactive snow cover. The 2-m temperature skill is still improved compared to the control experiment, though to a lesser extent than in the nudging experiment. Snow initialization appears particularly important for an accurate prediction of near surface temperature over Central Europe and North America. The influence of snow initialization is mostly detectable in the first 2 months and vanishes in late spring due to the limited persistence of the initial snow anomalies, the seasonal retreat of the Northern Hemisphere snow cover, but also the delayed snow melting in the ARPEGE-Climat model.

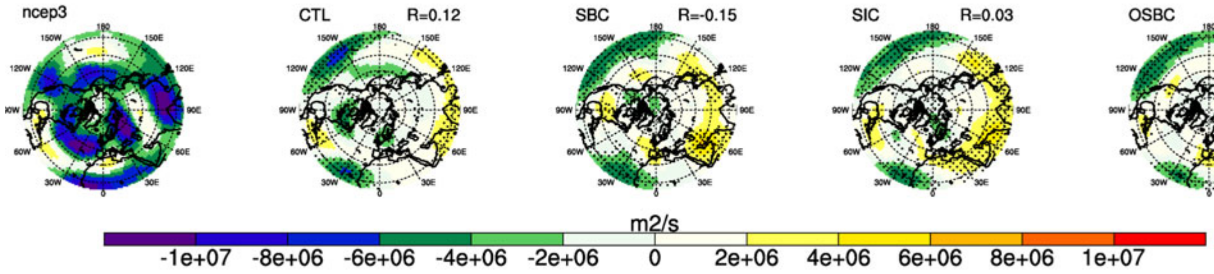
A conditional skill approach, whereby local skill is evaluated only for years with large snow anomalies, further emphasized the relevance of snow initialization for predicting springtime near-surface temperature in the northern extratropics. Nevertheless, this approach remains limited for understanding the impact on the troposphere given the possible remote effects of snow cover anomalies on temperature through the large-scale modification of air masses.

Our nudging experiments did not show any systematic improvement of large-scale circulation. This relatively disappointing result raised the issue of the quality of our reconstructed snow forcing. Nevertheless, despite some positive impacts in early spring, the use of another snow mass reanalysis constructed by a direct inversion of the NSIDC snow cover data does not lead to a significant

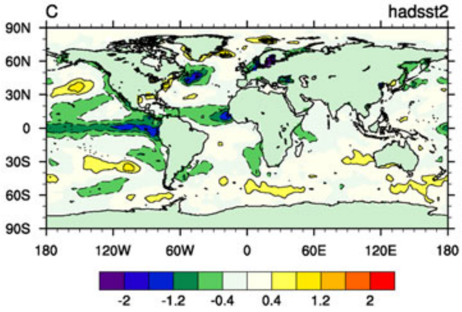
(a) SST 1981



(b) SF200 1981



(c) SST 1985



(d) SF200 1985

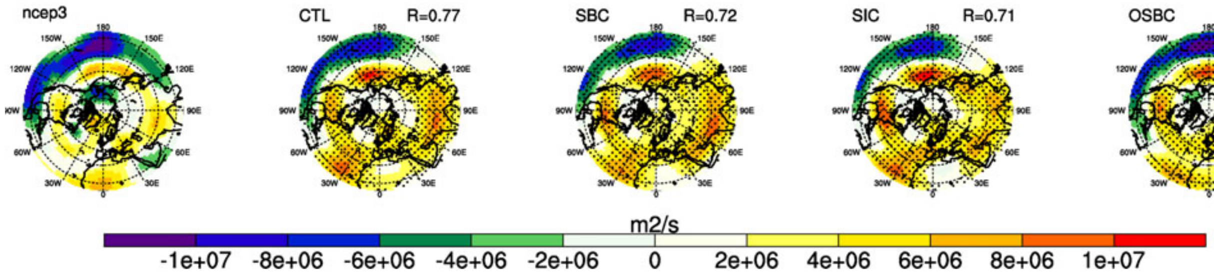


Fig. 14 **a** Observed spring SST anomaly in 1981, **b** 200 hPa stream function anomalies for NCEP2 reanalyses and all experiments in spring 1981, **c** observed spring SST anomaly in 1985, **d** 200 hPa stream function anomalies for NCEP2 reanalyses and all experiments in spring 1985. *Stipples* on stream function maps indicate significance at the 95% level

increase of the springtime averaged model skill, even for 2-m temperature. This result suggests that the limited sensitivity of atmospheric predictability in our first 51-year ensemble is not primarily due to deficiencies in our snow forcing but is probably more fundamental or at least intrinsic to the ARPEGE-Climat GCM. Some case studies illustrated the fact that an improved snow simulation does not necessarily lead to more realistic atmospheric circulation at the regional scale. In particular, the model response to snow nudging can be overwhelmed by irrealistic teleconnections with tropical Pacific SSTs. Consequently, an improved simulation of tropical-extratropical teleconnection remains a priority for improving the seasonal forecasting skill of the ARPEGE-Climat model. Such a conclusion is probably model-dependent and it might be interesting to repeat our experiments with other atmospheric GCMs, either with prescribed or interactive SSTs, as in the recent GLACE-2 intercomparison project (Koster et al. 2010).

While the focus was here on boreal spring, other seasons showed some weaker, but significant, impacts of snow nudging on surface temperature (not shown). However, we did not observe improvements concerning the simulated interannual variability of large-scale circulation, as the summer Asian monsoon and the main modes of wintertime variability (AO/NAO, and PNA) in the northern extra-tropics. In line with the recent study by Orsolini and Kvamsto (2009), the only exception might be an improved simulation of the Aleutian Icelandic Seesaw in February, whose correlation with NCEP/NCAR reanalyses increases from 0.16 in the control experiment to 0.27 and 0.41 in SBC and OSBC, respectively. Further analyses are however necessary to assess the robustness and the physical mechanisms of this result.

To sum up, while the improvement of 2-m temperature skill due to local effects of snow is encouraging for seasonal prediction prospects, the lack of remote response to snow nudging and initialization raises a number of questions. How can we reconcile this result with the more significant and/or consistent response found in former numerical sensitivity experiments based on idealized snow forcing (e.g. Fletcher et al. 2007) or on selected case studies (e.g. Gong et al. 2003)? How model-dependent is the atmospheric response to snow boundary conditions? How reliable is our snow mass reconstruction and what can be done to produce more realistic snow forcing? Finally, did the lack of interactive SST and/or of a well-resolved stratosphere represent a significant obstacle for the evaluation of the role of snow boundary and/or initial conditions in our ensemble simulations? While such questions are beyond the scope of the present study, they emphasize the need of a multi-year global or hemispheric snow reanalysis based on both in situ and satellite observations as well as of an extension of the GLACE-2 model intercomparison to the role of snow boundary conditions. Further sensitivity experiments should be probably conducted with coupled ocean–atmosphere (Shongwe et al. 2007) versus purely atmospheric GCMs, as well as with high-top versus low-top models. In line with the previous results of Kumar and Yang 2003 and Schlosser and Mocko (2003), the snow contribution to seasonal predictability of large-scale modes of atmospheric circulation remains to be demonstrated, at least with the current generation of atmospheric GCMs.

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