Snow in EC-EARTH

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Abstract

A new snow scheme for the European Centre for Medium-Range Weather Forecasts (ECMWF) land surface model has been tested and validated. The scheme includes a new parameterization of snow density, incorporating a liquid water reservoir, and revised formulations for the sub-grid snow cover fraction and snow albedo. Offline validation (covering a wide range of spatial and temporal scales) includes simulations for several observation sites from the Snow Models Intercomparison Project-2 (SnowMIP2), global simulations driven by the meteorological forcing from the Global Soil Wetness Project-2 (GSWP2), and by ECMWF ERA-Interim re-analysis.

1. Introduction

The extent and variability of snow cover are important parameters in weather and climate prediction systems, due to their effects on energy and water balances, justifying a strong dependency of surface temperature on the presence or absence of snow cover (Armstrong, 2008). Eurasian snow cover has been linked with the variability of the Indian summer monsoon (Douville and Royer, 1996; Liu and Yanai, 2002; Robock et al., 2003) and with significant changes in the hemispheric circulation (Cohen, 2007; Gong, 2007; Fletcher, 2009). Snow cover also acts as a water reservoir, which is released by snowmelt in spring, influencing runoff, soil moisture, evaporation, and thus precipitation and the entire hydrological cycle (e.g., Douville et al., 2002; Groisman et al., 2004). Therefore, an accurate simulation of snow processes is essential for many applications ranging from hydrological forecast to numerical weather prediction (NWP) and seasonal and climate modeling. Observed climate change during the 20th century, particularly visible in the northern hemisphere surface warming in spring, has been significantly enhanced by the associated depletion of snow cover (Groisman, 1994).

The present work describes a revision the ECMWF land surface model HTESSEL (Balsamo et al, 2009) snow scheme and its validation. The snow scheme revision includes four main processes: i) representation of liquid water content as a diagnostic, following a similar approach applied to soil phase changes by Viterbo et al.(1999); ii) new snow density parameterization following Anderson (1976) and Boone and Etchevers (2001); iii) revised snow cover fraction, and iv) revision of exposed snow albedo and new forest albedo in the presence of snow adapted from Moody et al.(2007). The changes to the model were performed keeping the same level of complexity (single explicit snow layer). This constraint allowed a simple integration with the ECMWF integrated forecast system (IFS) in its several applications ranging from data assimilation for short-range weather forecast to seasonal prediction.

The new snow scheme was implemented in EC-EARTH v2 (see another chapter in these proceedings by Bart van den Hurk). The atmospheric model of EC-Earth v2, which is the current reference version, is based in ECMWF's Integrated Forecast System (IFS), cycle 31r1, corresponding to the current seasonal forecast system of ECMWF. The standard configuration runs at T159 horizontal spectral resolution with 62 vertical levels. Some aspects of a newer IFS cycle have been implemented additionally, including a new convection scheme, and the new land-surface scheme HTESSEL. The ocean component is based in version 2 of NEMO model with a horizontal resolution of nominally 1 degree and 42 vertical levels. The sea ice model is the LIM2 model. The ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler.

The snow scheme was validated in offline mode covering several spatial and temporal scales considered (i) site simulations for several observation locations from SnowMIP2, and (ii) global simulations driven by the meteorological forcing from the Global Soil Wetness Project 2 (GSWP2) and by ECMWF ERA-Interim re-analysis (hereafter ERAI). GSWP2 Results are compared against basin scale runoff and terrestrial water storage variation (TWSV) using the basin scale water balance dataset (Hirschi, 2006). ERA-Interim simulations are validated with remote-sensing products: snow cover fraction (NOAA/NESDIS snow cover) and surface albedo (MODIS). A detailed description of the new snow scheme and its offline validation is presented in Dutra et al. (2009). Coupled IFS+NEMO and IFS only (forced with ERA40 SSTs and sea ice) simulations were performed to evaluate the impact of the new snow scheme in the model's climate.

2. Results

2.1. Site validation

HTESSEL, with its original snow scheme, participated in the SnowMIP2 intercomparison project. Rutter et al. (2009) and Essery et al.(2009) report the main conclusions of the project along with information regarding the different observational sites, which included five locations with data in both open and forest sites for two winter seasons. In the following text only the results in Fraser (39°53N, 105°53W, 2820 m, USA) will be analysed for the original snow scheme (CTR) and new (NEW).

Model results and observations of SWE, snow depth, and snow density for the 2004-05 winter season in the Fraser open and forest sites are shown in Fig. 1. CTR and NEW underestimate SWE (Fig. 1a,d) from the beginning of the winter season throughout mid spring in both forest and open sites suggesting either too much melting or excessive sublimation. During the ablation period, CTR showed an early melting in the forest site (Fig. 1a), and a late melting in the open site (Fig. 1d). These distinct errors between open and forest sites during the ablation period were also observed in other SnowMIP2 locations (not shown). Averaged for all 18 CTR simulations, the final ablation is delayed by 11 days and accelerated by 15 days in open and forest sites, respectively. The NEW snow scheme prediction of final ablation is closer to observations with an average delay of 2 days in open sites and an acceleration of only 1 day in forest sites.

Figure 1c,f compare simulated versus observed snow density. Snow density is overestimated by CTR throughout the winter season until the final ablation period when it is underestimated. The simulations show a fast (exponential) density increase in the beginning of the winter, keeping snow density close to its maximum value of 300 kg m-3 during the remaining cold season. This behaviour was observed in all available locations. The NEW snow density is closer to the observations representing the low densities during the accumulation stage and the fast increase in the final ablation. Snow depth in CTR and NEW was underestimated in both sites (Fig. 1 b,e), resulting from the SWE underestimation. However, NEW snow depth has a reduced error, when compared with CTR, due to the significant improvement of snow density.

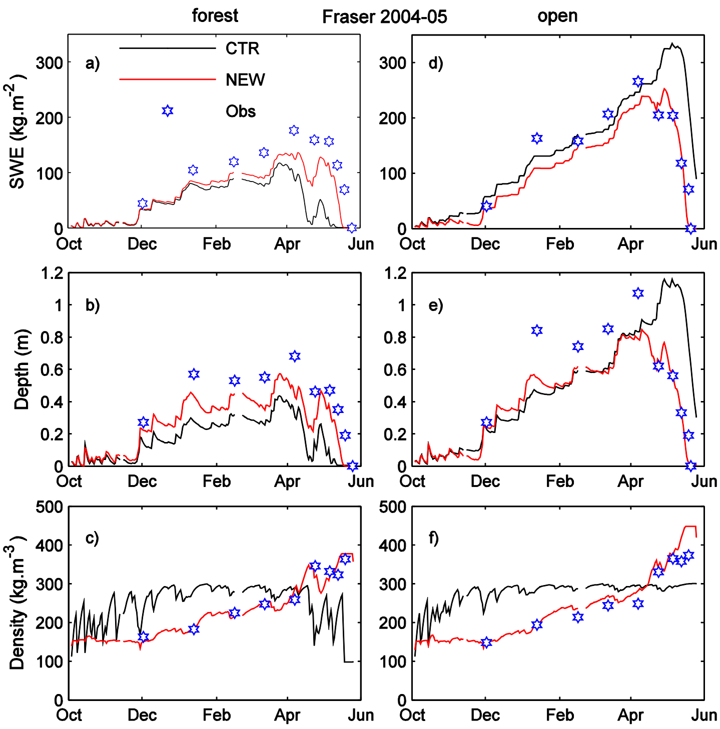

Figure 1: Simulations results for CTR (black) and NEW (red) for the 2004-05 winter season at Fraser forest (left) and open (right) sites: SWE (a, d), snow depth (b, e) and snow density (c, f). Observations are represented by open stars.

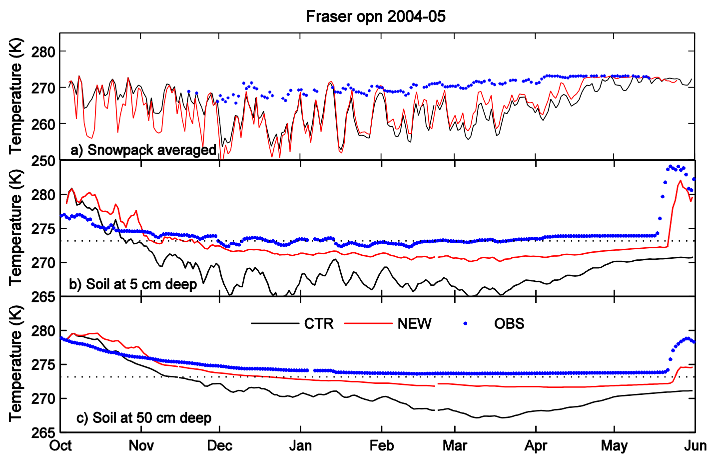

Figure 2: Model-simulated snow temperature (a) and soil layer temperature at 5 cm depth (b) and 50 cm depth (c) by CTR (black) and NEW (red) for the 2004-05 winter season in Fraser open site. The simulations and observations (open circles) represent daily means.

Simulated snow and soil temperatures at the Fraser open site during the 2004-05 winter are compared against observations in figure 2. Observations of snow temperature were conducted using a thermocouple string at fixed depths, every 10 cm up to 180 cm. Mean snowpack temperature was derived by averaging the thermocouple observations covered by snow, where snow depth was measured using an acoustic sensor. The observed mean snowpack temperature (Fig 1a) has a lower thermal amplitude than CTR and NEW, and both simulations underestimate snow temperature throughout the cold season. In a single layer snow scheme it is not possible to represent properly the thermal insulation within the snowpack. This explains the differences between simulated and observed mean snowpack temperature. However, at the end of the cold season, NEW reaches the freezing point faster than CTR and stays in an isothermal state, as the observations suggest, while CTR shows some cooling cycles.

Simulated soil temperatures respond to the different basal heat fluxes, due to the increase isolation in NEW, with a faster cooling in CTR when compared with NEW (Fig. 2 b,c). This behaviour is observed both near the surface and at 50 cm deep. Averaged from December to mid May CTR has a negative bias of -5.4 and -4.1 K at 5 and 50 cm deep, respectively. NEW reduces significantly the soil temperature bias to -2 and -1.4 K at 5 and 50 cm deep, respectively. NEW improves the prediction of final ablation (see Fig. 1d) which affects soil heating after snow disappearance. There is a reduction of the soil temperature bias near the surface by the end of May from -11.4 K in CTR to -3.4 K in NEW.

2.2. Global offline

The NOAA/NESDIS data is a daily product allowing for a more detailed comparison with simulations. Figure 3 presents the spatial distribution of the frequency of missing snow cover in the simulations during spring, defined as the frequency of occurrence of snow-covered NOAA/NESDIS (csn>0.75) and simulated snow-free (csn<0.25). Drusch et al. (2004) applied a similar diagnostic to validate the snow depth analysis system in ECMWF. Scandinavia, western Russia and central/eastern Canada are dominated by high frequency snow cover missing in CTR (Fig 3a), reaching one month (30%) in some localized areas. NEW reduces the missing snow cover during spring, when compared with the CTR up to a factor of two in areas where CTR has higher errors.

Figure 4 represents the mean (2000-2008) spring MODIS albedo and respective simulated differences. The differences between simulated and MODIS albedo (Fig. 4b,c) are shown only for snow-covered grid-boxed flagged by MODIS with at least 50% of feasible data (excluding areas with systematic missing values in MODIS). The negative bias of CTR albedo during spring spreads widely over the entire northern hemisphere. There are three main regions with an accentuated bias: Northeast Asia, Central Asia (north of Caspian and Aral Seas) and Northern Canada. These areas are dominated by low vegetation (tundra and short grass). NEW partially reduces the albedo bias over low vegetation areas while over high vegetation areas the bias is close to zero. There are some small positive biases in NEW on the southern borders of tundra regions (areas dominated by bogs and marshes) in both continents.

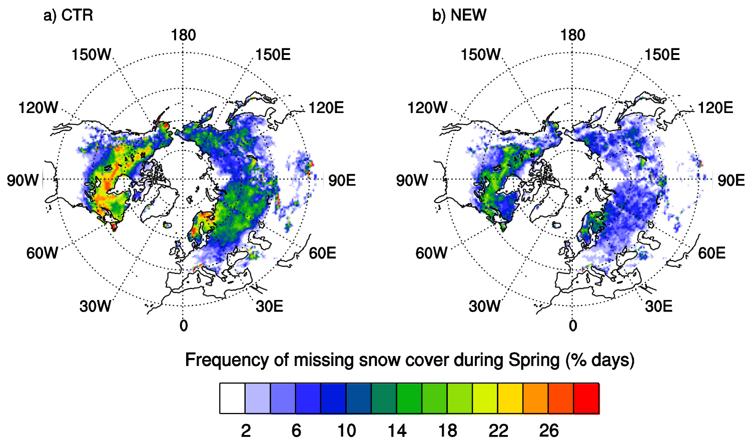

Figure 3: Frequency of occurrence of snow-covered NESDIS data (csn >0.75) and simulated snow-free (csn>0.75) during spring (March-April-May) for ERAI simulations in the period 2001-2008 by CTR (a) and NEW (b). The number of days in each grid box is normalized by the total number of days of the season.

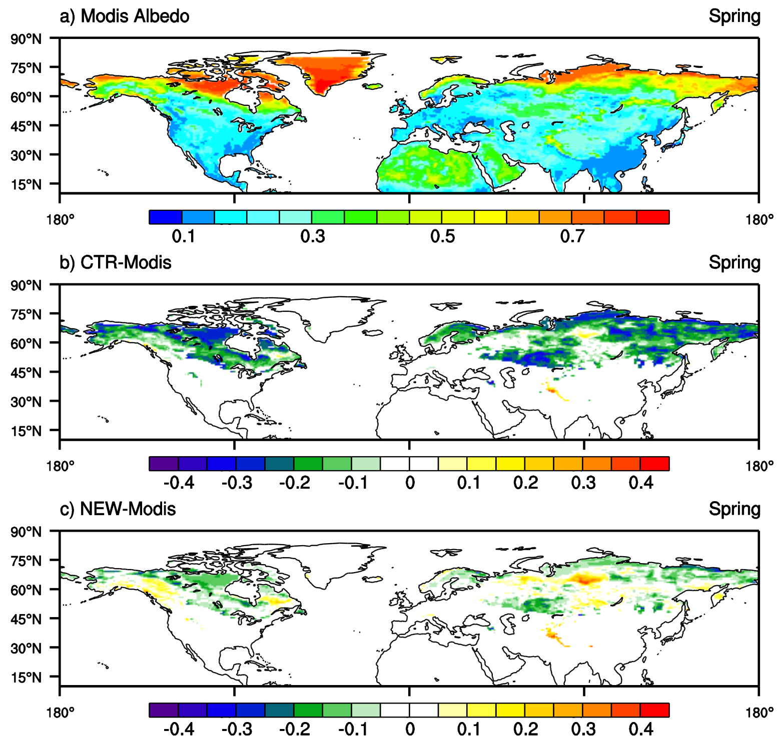

Figure 4: Mean observed maps of spring albedo by MODIS for the period 2000-2008 (a) and differences between simulated albedo and MODIS (b) and (c) for CTR and NEW respectively. The differences panels (b and c) show only snow-covered grid-boxes with less than 50% MODIS missing data. Note the different colour scales between panel a) and panels b) and c).

2.3. EC-EARTH simulations

The IFS ran at T159 horizontal spectral resolution with 62 vertical levels, and NEMO model (version 2) with horizontal resolution of nominally 1 degree and 42 vertical levels. The sea ice model is the LIM2, and the ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler. Coupled simulations ran for 40 years, where the first 20 years are discarded from the analysis due to spin up; Atmospheric only simulations ran for 30 years (1970-2000). Coupled EC-EARTH IFS+NEMO and IFS only simulations, showed significant improvements in the near surface temperature fields during winter and spring (see Figs 5 and 6). In both simulations, there is a reduction of about 50 % of the 2m temperature cold bias, a known problem in the model. The coupled results are coherent with the offline tests, showing the importance of snow insulation in the model climate.

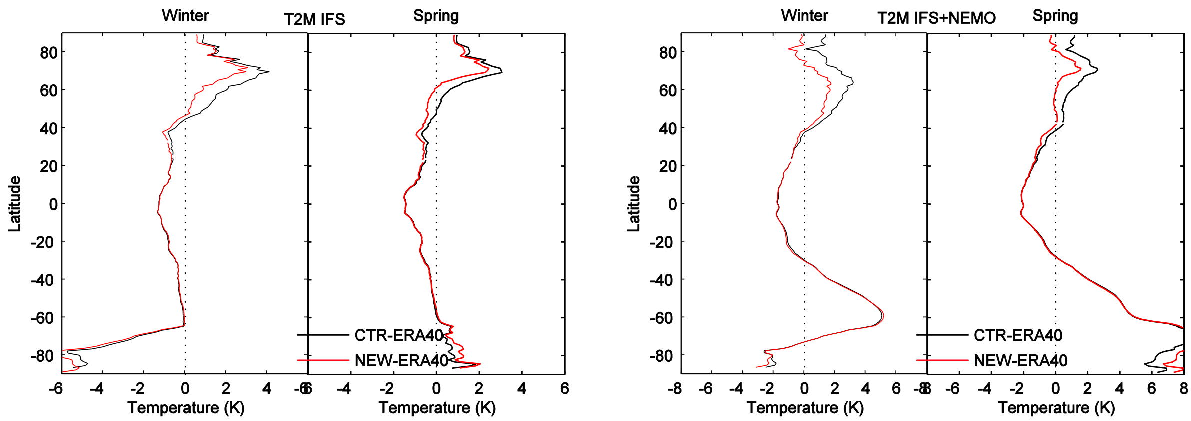

Figure 5: Zonally averaged simulated 2 metre temperature bias for winter and spring (with respect to ERA-40). Left: Atmospheric only 30 years run 1970-2000 (IFS+ SSTs/sea ice from ERA-40). Right: Coupled (IFS+NEMO) 20 years runs (with 20 years spin-up)

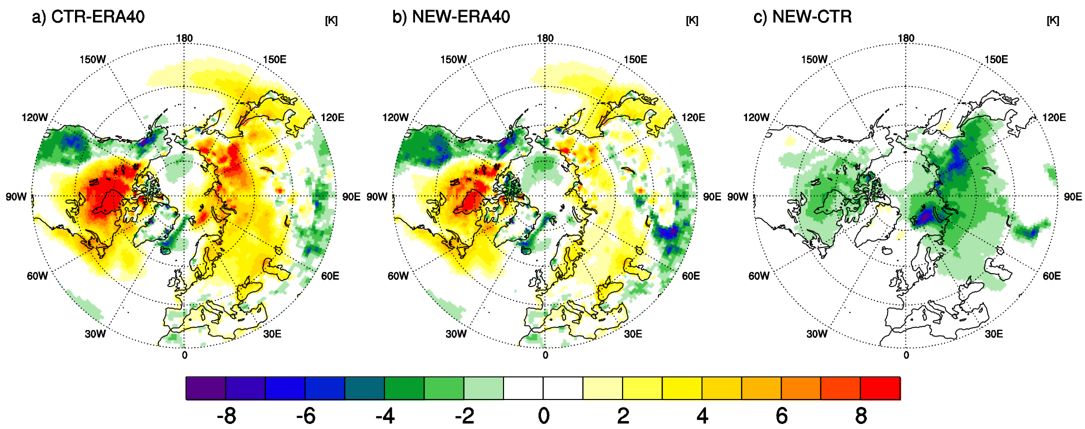

Figure 6: Coupled IFS+NEMO simulated winter 2 metre temperature differences: CTR-ERA40(left), NEW-ERA40 (center), NEW-CTR(right). Coupled 20 years runs (with 20 years spin-up).

3. Conclusion

The present offline methodology is recurrent in validations of land surface models (e.g. Boone and Etchevers 2001) and in intercomparison projects (e.g. Rutter et al. 2009). However, the associated nature of the one-way coupling has shortcomings due to the absence of atmospheric response. A complete validation can only be achieved with atmospherically coupled simulations. Tests have been performed in the EC-EARTH framework and the new snow scheme showed improvements in the simulated near-surface temperature during winter over snow-covered areas. Future developments of HTESSEL snow scheme will focus on improvements of the physics representation of the snowpack (e.g. development of a multi-layer scheme), on the coupling with the atmosphere, especially in forested regions, and on the representation of the sub-grid scale snow cover variability. The snow scheme was introduced in the ECMWF operational forecast system in September 2009 (CY35R3) and is part of EC-EARTH version 2.

Acknowledgments

The authors would like to thank and Richard Essery and Nick Rutter for the Snowmip2 project organization and useful comments. The BSWB dataset was kindly provided by Martin Hirschi. We also thank the MODIS Land and Albedo teams and in particular Crystal Schaaf for the valuable support and comments regarding the use of MODIS albedo product. The technical implementation of the IFS+NEMO was only possible due to the effort of the EC-EARTH community, and especially Simona Stefanescu and Camiel Severijns. Emanuel Dutra acknowledges the financial support of FCT under grant SFRH/BD/35789/2007 and Fundação Calouste Gulbenkian.

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