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Aggregated and distributed modelling of snow cover for a high-latitude basin

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Abstract

A distributed land-surface model is used to simulate the seasonal cycle of snow cover for a high-latitude basin. In comparison with the distributed model, a simulation using surface parameters and meteorological data averaged over the entire basin overestimates the peak snow accumulation and underestimates the duration of snow cover. Dividing the basin into a small number of elevation bands and performing separate simulations for each band greatly improves the results. The improvement is less marked if information on the elevation dependence of vegetation cover and meteorological conditions is not used. Distributed simulations with different models produce a wider range of results than distributed and aggregated simulations with the same model.

Keywords: PILPS; aggregation; topography; snowmelt

1. Introduction

The nonlinear nature of energy and water exchanges between the land surface and the atmosphere makes the aggregation of surface parameters and fluxes a challenge for large-scale hydrological and atmospheric modelling. Melting snow is often patchy on scales smaller than model grids and presents particularly marked contrasts in surface characteristics between snow-covered and snow-free ground. Representations of heterogeneous snow cover have been discussed in a range of modelling contexts by Liston (1995), Walland and Simmonds (1996), Arola and Lettenmaier (1996), Essery (1997), Hartman et al. (1999), Liston et al. (1999) and Moore et al. (1999), and a systematic investigation of aggregation in land-surface models is currently being pursued by the Rhone-AGG experiment (http://www.cnrm.meteo.fr/mc2/projects/rhoneagg/).

For the PILPS 2(e) hydrological model intercomparison (Bowling et al., 2003-this issue), the basins of the Torne and Kalix rivers in northern Scandinavia were divided into 218 boxes on a 0.25° grid. This domain has a total area of 58 000 km^2, which is comparable to the area covered by a single grid box in a low resolution General Circulation Model (GCM); a $2.5 \times 3.75°$ grid box, as used in the HadAM3 version of the Met Office GCM (Pope et al., 2000), has an area of 44 360 km^2 at 67.5°N. The 0.25° data supplied for PILPS 2(e) show large contrasts in elevation, land cover and meteorological conditions across the domain, but computational limitations make the use of such high resolutions impractical for climate simulations.

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In this paper, the MOSES land-surface model (Cox et al., 1999; Essery et al., 2001) is used to simulate snow cover for the PILPS 2(e) domain. The domain is divided into elevation bands, and the performance of the model as a function of the number of bands used is assessed in comparison with a distributed simulation at the full 0.25° resolution. Simulations are performed with meteorological forcing both averaged over the elevation bands and obtained from domain averages by the application of an assumed temperature lapse rate. The significance of correlations between elevation and vegetation is investigated in comparison with simulations using the domain-average vegetation cover for all elevations.

2. Experiment design and model description

Surface characteristics and driving meteorology for PILPS 2(e) are described in detail by Bowling et al. (2003-this issue). Grid box-average elevations range from 20 to 1150 m and are positively skewed, as shown by the histogram in Fig. 1a. Land cover was specified from 1 km AVHRR data (Hansen et al., 2000) categorized into nine classes. Fig. 1b shows elevation distributions of land cover gathered into four broader classes within each of which similar surface parameters were specified in the PILPS 2(e) experimental design: forests (evergreen forests, mixed forest, woodland), grass (wooded grassland, grassland), shrubs (closed shrubland, open shrubland) and open (bare ground and water). With increasing elevation, forests give way to grassland, then increasingly sparse shrub tundra and bare ground. Altitude effects are compounded by latitude effects because the basin generally increases in elevation towards the northwest.

Time series of air temperature, humidity, wind speed, shortwave radiation, long-wave radiation, snowfall, rainfall and surface pressure over a 10-year period (1989–1998) were provided to drive the models participating in PILPS 2(e). These data were interpolated to the 218 grid boxes and an hourly time step from sparser and less frequent observations as described by Bowling et al. (2003-this issue).

The MOSES land-surface model has recently been extended to include a tiled representation of subgrid heterogeneity; separate heat and moisture fluxes and snow depths are calculated for each land cover class

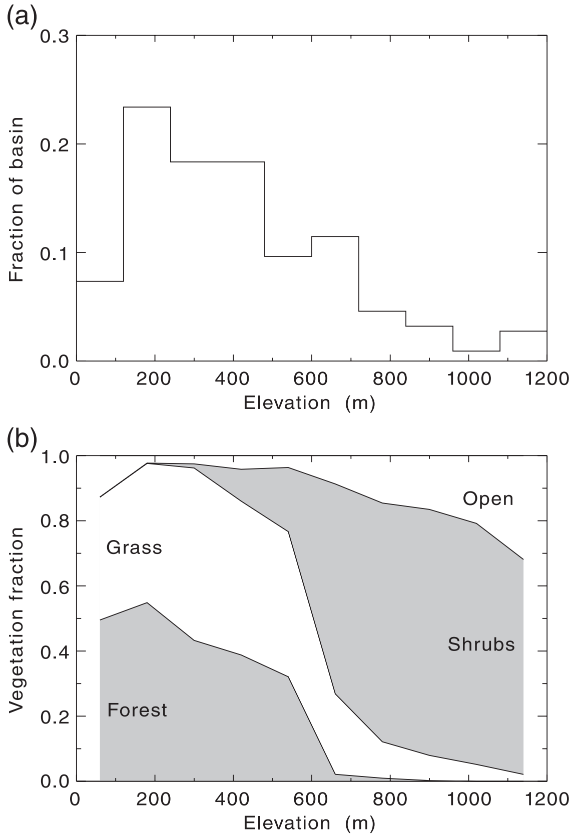

Fig. 1. Elevation and vegetation distributions for the PILPS 2(e) domain.

within a grid box. In comparison with observed runoff for two sub-basins of the Torne/Kalix system, MOSES produced a peak runoff during snowmelt that was too small and too early (Nijssen et al., 2003-this issue). Subsequent model developments, described by Essery and Clark (2003-this issue), significantly improved the simulation of runoff; it is this modified version of MOSES that is used here.

Results from several simulations are presented in the next section. Meteorological data and fractions of land cover classes were averaged over the PILPS 2(e) domain for use in an aggregated simulation. Three sets of partially aggregated simulations dividing the domain into varying numbers of elevation bands were performed with:

(a) meteorological and land cover data averaged on elevation bands,

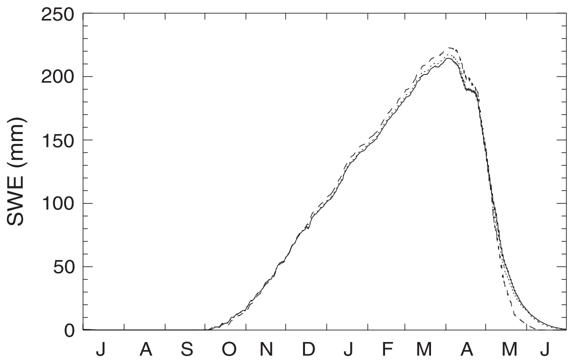

Fig. 2. Average SWE simulated by the fully distributed model (solid line), the aggregated model (dashed line) and a distributed model with 10 elevation bands (dotted line).

(b) domain-average land cover data,
(c) meteorological data obtained from domain-averages by applying a temperature lapse rate.

A simulation with fully distributed surface parameters and meteorology is taken as "truth" in assessments of aggregated simulations; comparisons of distributed simulations with observations for PILPS 2(e) are presented by Nijssen et al. (2003-this issue).

3. Results

Fig. 2 shows the evolution of the domain-average snow water equivalent (SWE) depth as simulated by the distributed model (solid line) and the aggregated model (dashed line), averaged over the nine complete winters in the simulations. Compared with the distributed model, the aggregated model overestimates the maximum snow accumulation but underestimates the duration of snow cover because it fails to represent winter melt at low elevations and delayed spring melt at high elevations. Results from each year of both simulations in Fig. 3 show that the aggregated model consistently underestimates the duration of snow cover and does not give enough interannual variability; the error is largest for the year with the latest-lying snow. The peak snow accumulation is not, however, consistently overestimated, and the average overestimation is dominated by 5 years for which the distributed model predicts early winter melt.

As suggested by Arola and Lettenmaier (1996), the simulation can be improved by using a distributed model with just a few elevation bands. The dotted line in Fig. 2 and the crosses in Fig. 3 show that a model with 10 elevation bands gives a close agreement with the fully distributed model. Root mean square (RMS) errors in SWE, fractional errors in peak SWE and average errors in the duration of snow cover for simulations with varying numbers of elevation bands are shown by diamonds in Fig. 4; the errors decrease rapidly as the number of bands is increased from one (the aggregated model) to three or four, but there is little further improvement with an increase to 10 bands.

Elevation and land cover data are generally obtained from different sources, and information on their subgrid co-distributions may not be available to a model. To investigate the impact of neglecting

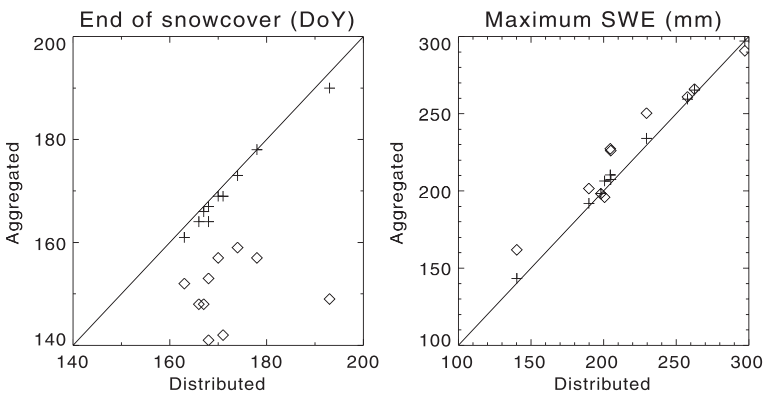

Fig. 3. Last day of snow cover and peak accumulation for each year in the aggregated simulation (◇) and simulated with 10 elevation bands (+), plotted against results from the fully distributed simulation.

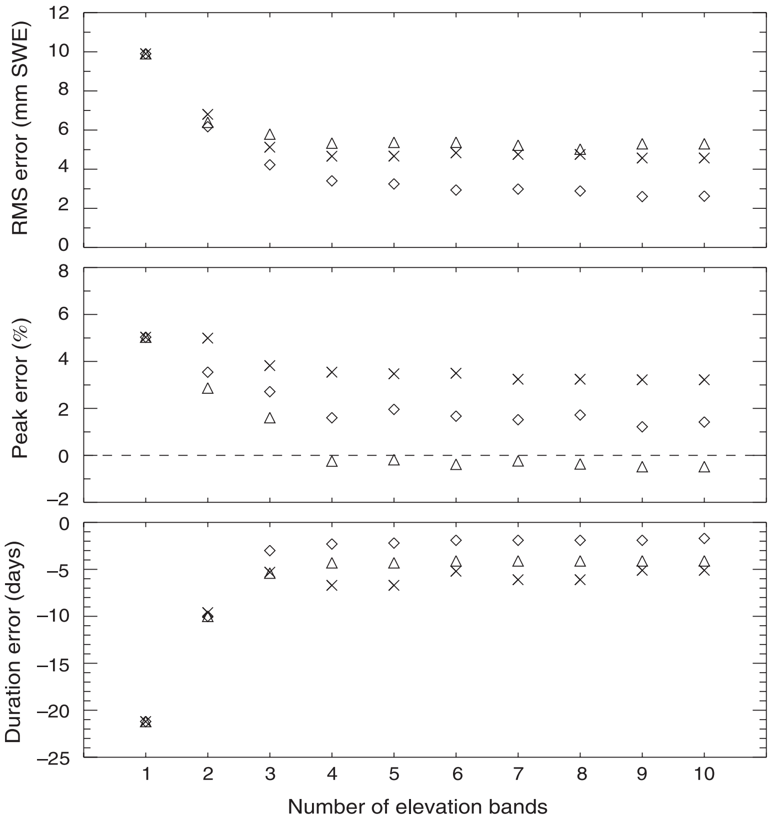

Fig. 4. RMS errors in SWE, fractional errors in peak SWE and average errors in snow cover duration for simulations with distributed meteorology and land cover on elevation bands (◇), domain-averaged land cover (×) and meteorological data obtained from domain averages using a temperature lapse rate (△).

changes in vegetation with elevation, MOSES was run with land cover fractions for each elevation band set to domain-average values. This increases the fraction of tall vegetation at higher elevations, decreasing the snow-covered albedo and increasing the surface roughness. As shown by the crosses in Fig. 4, there are again improvements in simulations with increasing numbers of bands, but the asymptotic errors are larger. Because surface fluxes have nonlinear dependencies on surface characteristics, changes in the energy and water budgets of snowpacks at different elevations with altered vegetation distributions do not cancel out in domain averages.

In the simulations discussed above, distributed meteorological data were averaged over elevation bands to provide forcing data on sub-basin scales. This information would not normally be available in an atmospheric model, and some downscaling scheme would be required to obtain subgrid distributions from grid box-average forcing data. Further simulations were performed to test a minimal downscaling scheme: temperatures were derived from domain-averages using a constant lapse rate with elevation, the domain-average precipitation was partitioned into snow or rain falling in an elevation band according to whether the downscaled temperature was below or above 0 °C, and domain-averages were used for other variables. Similar procedures were used in distributed snowmelt simulations by Walland and Simmonds (1996), Liston et al. (1999) and Moore et al. (1999). For PILPS 2(e), interpolated temperatures in data-sparse regions were lapsed to grid box-centre elevations at a rate of 6.5 °C/km (Bowling et al., 2003-this issue), but 9 °C/km, close to the dry adiabatic lapse rate, fits the gridded temperatures better. Although precipitation, wind speed and radiation all vary significantly with elevation in the distributed forcing data, this simple downscaling of temperature and precipitation phase still gives a marked improvement, shown by triangles in Fig. 4, over the aggregated model. Years with underestimates and overestimates of the maximum accumulation balance to give a very small average error if four or more elevation bands are used.

4. Conclusions

In comparison with a distributed version of the MOSES land-surface model, an aggregated version of MOSES overestimated the peak snow accumulation and underestimated the duration of snow cover for a high-latitude basin. Dividing the basin into three or four elevation bands and performing separate simulations for each band greatly improved the results without incurring the computational expense of a fully distributed model. Improved results were still obtained by using elevation bands if information on spatial distributions of land cover or meteorological variables was unavailable, as it would be in a large-scale model, although the errors were larger.

When coupled to an atmospheric model, rather than driven by meteorological observations, errors in the timing of snowmelt and associated errors in surface fluxes predicted by a land-surface model could be amplified by atmospheric feedbacks (Jacobs and De Bruin, 1992). But although aggregation influences the simulation of snow cover in the uncoupled simulations presented here, the differences between aggregated and distributed versions of MOSES are rather less than those among different distributed models in PILPS 2e (Bowling et al., 2003-this issue; Nijssen et al., 2003-this issue); Table 1 compares aggregated and distributed results from MOSES with PILPS 2(e) ranges for average March SWE and average annual runoff. Large differences among simulations of snow cover were also found in the PILPS 2(d) (Slater et al., 2001) and SnowMIP (Eric Martin, personal communication) intercomparison projects. Quite apart from the problem of aggregating subgrid processes for large-scale modelling, it appears that there is still uncertainty in the modelling of fundamental processes governing snow accumulation and ablation.

Table 1
Average March SWE and average annual runoff from aggregated and distributed versions of MOSES compared with the highest and lowest values produced by models participating in PILPS 2(e)

	March SWE (mm)	Runoff (mm/year)
Aggregated MOSES	200	352
Distributed MOSES	207	380
PILPS 2e range	119–268	301–480
Observed	–	403

The models participating in PILPS 2(e) only represent the direct influences of vegetation on the albedo and roughness of snow-covered surfaces. Vegetation can also trap wind-blown snow, influencing sublimation and the distribution of snow cover prior to melt (Pomeroy and Gray, 1995; Liston et al., 2002). Moreover, snow distributions are strongly controlled by topography and vegetation distributions on scales far smaller than the 0.25° grid used in the distributed simulation. Such influences are beyond the scope of PILPS 2e but could be investigated using high-resolution models of snow redistribution (Liston and Sturm, 1998; Essery et al., 1999; Hartman et al., 1999).

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