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Downscaling of general circulation model outputs: simulation of the snow climatology of the French Alps and sensitivity to climate change

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Abstract. A downscaling method was developed to simulate the seasonal snow cover of the French Alps from general circulation model outputs under various scenarios. It consists of an analogue procedure, which associates a real meteorological situation to a model output. It is based on the comparison between simulated upper air fields and meteorological analyses from the European Centre for Medium-Range Weather Forecasts. The selection uses a nearest neighbour method at a daily time-step. In a second phase, the snow cover is simulated by the snow model CROCUS at several elevations and in the different regions of the French Alps by using data from the real meteorological situations. The method is tested with real data and applied to various ARPEGE/Climat simulations: the present climate and two climate change scenarios.

1 Introduction

In temperate climates, the snow cover in mountain areas is strongly related to meteorological conditions. If global warming occurs, seasonal snowfall as well as glaciers may be significantly perturbed. The consequences would be important in related domains such as the winter tourist economy, water resources, including hydro-power and ecology. Several studies have been conducted to evaluate the sensitivity of snow and glaciers to climate changes. Rango and Martinec (1994) tried to determine the effect of changed precipitation and air temperature on the areal extent of snow cover during the melting season. In a previous study, Martin et al. (1994) derived the snow climatology of the French Alps using two numerical models. The first is the elaborate meteorological analysis system SAFRAN (Durand et al. 1993) which uses all the available data to estimate a coherent set of hourly meteorological variables in the French Alps (divided into 23 regions or massifs, Fig. 1), at various elevations. The second is the physically based snow model CROCUS (Brun et al. 1989; 1992), which calculates snow cover evolution as a function of the meteorological data provided by SAFRAN. These tools were used to assess the sensitivity of the alpine snow cover to changes in meteorological conditions. The climate scenarios used in these studies consist of constant perturbations introduced in the input of the snow model. However, this method cannot be used in comprehensive impact studies because it does not account for relevant climatic processes such as seasonal modifications or changes in the weather types affecting the region.

Today, general circulation models (GCMs) are the main tools used to assess the impact of particular climate scenarios (e.g. an increase in atmospheric carbon dioxide or sulphate) on the climate of the Earth. However, their performance in reproducing regional climates (the surface of the French Alps is about 20 000 km^2) remains rather poor. Moreover, surface variables simulated by the model cannot be used in mountain areas because of the smoothed topography of the GCMs. In T42 resolution (grid mesh about 300 km) the maximum elevation of the Alps is below 1000 m a.s.l. Even at increased resolution, GCMs will probably never be able to account for the complex topography of the Alps, which induces drastic variations in the meteorological variables over distances of less than 50 km.

To fill the gap between large-scale GCM runs and regional climate, several methods are used (Giorgi and Mearns 1991). The "nested model" approach has been adopted by Marinucci and Giorgi (1992) and Giorgi et al. (1992) to elaborate climate scenarios over Europe. A 70 km grid mesh was used and the nested model improved the spatial distribution of precipitation and sur-

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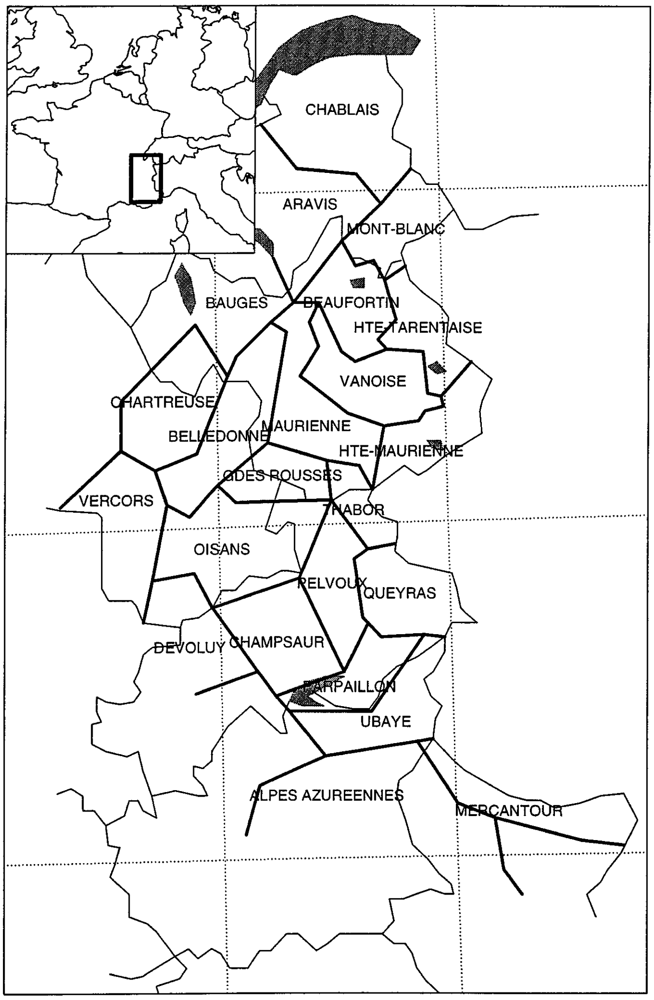

Fig. 1. Schematic map of the French Alps showing the 23 regions or massifs used in the study

face air temperature. However, the orography is again too smooth to provide accurate information on snow cover and, due to computer time, no full annual cycles were simulated (only selected months).

An alternative strategy is to apply empirically derived relationships between regional climate and large scale GCM information. Usually, these semi-empirical approaches use statistical techniques (such as regression or canonical correlation analysis) to derive relations between observed large-scale and small-scale (or local) variables (Giorgi and Mearns 1991). Karl et al. (1990) and Wigley et al. (1990) used this type of approach to estimate meteorological variables at selected sites in the USA. Storch et al. (1993) estimated the Iberian rainfall in winter. The results of such studies are reliable under two conditions: the relation between local variables and the large-scale flow explains a great part of the observed variability, and second, the relation can be assumed to be valid also for a changed climate. The semi-empirical method, with low computer costs, can be used to derive meteorological data at various elevations (including high summits or deep valleys) over complete annual cycles.

In this study we present, develop and validate a downscaling method well adapted to the snow modelling tools already used in Martin et al. (1994). The proposed method is described in the following section, then applied to real data of large-scale flows. Precipitation, temperature and snow cover from selected sites are used for validation. After this test, the method is used to derive the climatology of the French Alps from several ARPEGE simulations, corresponding firstly to the present climate and secondly to doubled atmospheric carbon dioxide scenarios.

2 Description of the downscaling method

The spatial distribution of the meteorological variables (especially precipitation) in mountain areas is mainly governed by the interaction between large-scale flow and topography. Numerical models are not able to reproduce this interaction (even thought considerable progress has been made). Duband (1981) proposed using an analogue procedure to forecast the spatial distribution of precipitation in the Alps. It consists of a selection of past meteorological situations close to the results of the forecast model. The selection was based on a nearest neighbour method using meteorological variables of 37 radiosonde stations in Europe. The local observations in the analogue provided the precipitation forecast at the valley or catchment scale. Similar methods have also been used by Météo-France to assess precipitation amounts in the area of avalanche forecasting. Kruisinga and Murphy (1989) used an analogue procedure based on 500 hPa geopotential heights to formulate objective probabilistic temperature forecasts in the Netherlands.

We propose to use this type of approach to derive regional meteorological conditions from large-scale upper air GCM data. The method, adapted to climate impact studies, is sketched in Fig. 2. Each day simulated by the GCM is associated with a real, analogous day (or analogue) chosen in a set of reference situations, according to a criterion based on upper air fields. The meteorological system SAFRAN calculates the input data of the snow model by using all the data of the real, analogous day, including surface observations. Then, the model CROCUS simulates the snow cover.

The main advantage of the analogue procedure is to use input data (daily upper air flows) considered to be one of the most trustworthy of GCM outputs. The difficulty of the approach lies in the development (selection of the analogue) and validation of the first step, as the two last steps are based on validated tools. This procedure must be carefully validated in order to be used automatically on a long term basis. The determination of selection criteria for the analogue is crucial.

3 Data and test strategy

The method has been tested on a ten year dataset consisting of meteorological analyses from the European

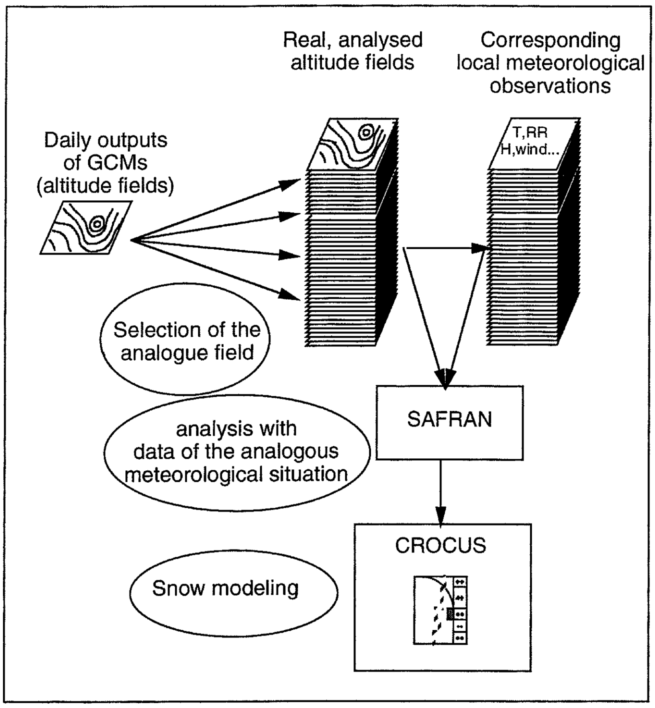

Fig. 2. Schematic of the principle of the downscaling method

Centre for Medium-Range Weather Forecasts (ECMWF). The upper-air fields are stored in grid points, with a 1°5 mesh in latitude and longitude. The limits of the spatial domain used are 3°/10°5E and 42°/48°N. As precipitation amounts used for validation are measured at 6 UTC daily, a day is presumed to begin at 6 UTC and end at 6 UTC the day after. Each day is characterised by the values of the geopotential height (Z), temperature (T) and humidity (H) at 12 and 0 UTC, at 700 and 500 hPa. As other variables, built from the three mentioned were also defined, a total of ten variables (Table 1) were used in total.

The selection of the analogue is based on a "nearest neighbour" method. For a given variable, a Euclidean distance is used at 700 and 500 hPa and 12 and 0 UTC (i.e. four different fields except for $Th75$, ΔZ and ΔT: two fields and grad$Z$: eight fields, as the latter variable is defined by its two components). The variables are previously normalised. The choice of two layers and two time steps accounts for the vertical structure and the temporal evolution of the atmosphere.

Each day of the dataset (called reference day) is associated with an analogue in the same dataset. The analogue must not pertain to a window of ± 10 days centred on the reference day, in order to avoid selection of an analogue belonging to the same meteorological situation. As we plan to use all meteorological data analysed by SAFRAN during the analogous day, additional constraints are necessary: solar radiation terms must be of the same order of magnitude, so the two days must belong to the same meteorological season: only fields whose dates differ from the reference date by at most 15 julian days are considered as potential analogues. Therefore, the analogue is selected in a subset of about 280 days [(10 years $\times$ 30 days) $-$ 20 close days]. Although this number is relatively small, the variability of the meteorological situation should be large enough to find good analogues.

Table 1. The variables used in the analogue procedure

Variable	Description
Z	Geopotential height
T	Temperature
H	Relative humidity
adv$T$	Temperature advection by geostrophic wind
grad$Z$	Horizontal geopotential gradient (defined by its zonal and meridional components)
$Gwsp$	Geostrophic wind speed
ΔZ	Change of geopotential height between 12 and 00 UTC
ΔT	Change of temperature between 12 and 00 UTC
$Th75$	Thickness of the 700–500 hPa
ξ_g	Geostrophic vorticity

Of course, the selection criterion may include two or more variables. But, because of differences in the statistical dispersion and spatial autocorrelation of the ten variables, one should not add Euclidean distances calculated with different variables. The following procedure was adopted to define distances using several variables. At first, the analogue procedure is applied for each of the ten variables on the dataset. Second, the mean distance between each reference day and its analogue is calculated. Then, the selection criterion combining two or three variables is the sum of the Euclidean distances for each of the variables, divided by their means calculated separately for each variable. Compared to more sophisticated statistical methods, this approach is very simple. However, it allows easy interpretation when combining two variables. To test the interest of this selection two other selection criteria were also considered: a random selection in the 280 potential analogues, and a persistence selection (the analogue is the preceding day).

A total of 55 criteria, based on the combination of the 10 variables of Table 1 were studied (the combination of two variables will be noted in the following by the sign '+'). The influence of other parameters, such as the spatial domain were also investigated. The test focused on the reconstitution of precipitation, air temperature and simulation of snow depth. Precipitation and air temperature were tested by using data from two meteorological stations: Bourg-Saint-Maurice (868 m, Vanoise, Northern Alps) and Embrun (876 m, Parpaillon, Southern Alps) belonging to two different climatic regions. The tests on snow depth were done on the results of the SAFRAN/CROCUS chain at two high elevation sites.

4 Results of the tests on the ECMWF analyses dataset

4.1 Precipitation

Precipitation is a crucial point for the validation, because of its very high spatial and temporal variability. Several approaches were used to evaluate the accuracy of the reconstitution of precipitation. The first is the frequency of good reconstitutions for a yes or no precipitation criterion at a daily step. As we are mostly interested in snow cover at middle elevation, the tests focus on the period November-March, i.e. the winter season and the two adjacent months.

Table 2 represents the percentage of success for the yes or no precipitation reconstitution at Bourg-Saint-Maurice (November-March), when considering distances calculated with the ten variables and pairs of variables. The figures vary from 65.3 to 78.0%, which means that the performances of the various criteria are highly variable, depending on the criterion considered. By comparison, the results of the random and the persistence selections are respectively 51% and 70%. Humidity (H) yields the best results when considering the three primary variables only, but derived variables, such as grad$Z$, $Gwsp$ and ξ_g obtain better results. It must be noted that these variables are closely related to the general circulation dynamics, which control the majority of precipitation events in winter. The same tests conducted over a period extended to the complete annual cycle showed a general reduction of the results (-1% to -6%). This is due to the increased part of convective precipitation in summer, poorly related to large-scale fields. When combining two variables, three cases can be encountered: the performances are situated above (20 cases), between (21 cases) or below (4 cases) the performances of the two individual variables. Diminutions are observed with variable ΔZ, whose results are usually poor, or with closely related variables (e.g. grad$Z+\xi_g$). In the latter case, the coupling of the two variables is not relevant as they are very similar. The same test for the data of Embrun (Parpaillon) gives slightly better results (between 70 and 81%). This increase is mainly due to climatic conditions: as the climate of Embrun is dryer (26% of days with precipitation, 38% at Bourg-Saint-Maurice) the reconstitution is easier from a statistical point of view. Concurrently, the performance of the random selection and the persistence are higher (61 and 74%).

The results of the analogue approach are coherent at both stations. It is encouraging to note that a good criterion at one site is usually good at the other. Humidity (H) and variables related to the general circulation dynamics obtain the best results. Variables introduced to account for the vertical structure of the atmosphere, or the temporal evolution of the atmosphere (Th75, ΔZ) do not provide useful information.

Two additional tests have been designed to evaluate the ability of the method to estimate accurate precipitation amounts. The first is concerned with the cumulative precipitation amount over the 10 years considered. Table 3 shows the error at Bourg-Saint-Maurice (in %) for the cumulative precipitation amounts for all the variables and pairs of variables (November-March period). Except for two cases, the reconstructed precipitation amounts are underestimated. The maximum error is -63%, however, a majority of the results are situated between 0 and -20%, which is an acceptable error. Adv$T$, ΔZ, ΔT and Th75 give strong underestimations. The behaviour of combined variables is not well defined, but usually degradation can be seen when variables of the same type are combined ($Z+\Delta Z$, $T+$adv$T$, grad$Z+\xi_g$).

The systematic underestimation of precipitation amounts found here is common to all analogue methods, which have difficulties in selecting extreme situations, associated with high precipitation amounts. However, a good estimation of cumulative precipitation does not guarantee a good reproduction of the temporal variability (for this criteria, a random selection gives quite perfect results!). The last test used is concerned with the reconstitution of the interannual variability. Figure 3 shows the reconstitution of the ten November-March periods precipitation amounts for three particular selection criteria : $Z+T$ (significant correlation at both sites, confidence level 95%), grad$Z$ (best correlation at Bourg-Saint-Maurice, not significant at Embrun) and $T+H$ (not significant at Bourg-

Table 2. Percentage of good reconstitution for a yes or no precipitation criterion at Bourg-Saint-Maurice (Vanoise) between 1981 and 1991 for November-March only. The values correspond to selections using two variables for the upper triangle or one variable over the diagonal. Extreme values are in bold

	Z	T	H	grad$Z$	adv$T$	$Gwsp$	ΔZ	ΔT	Th75	ξ_g
Z	70.2	69.2	73.1	72.8	70.6	73.4	69.9	71.0	68.8	73.4
T		69.0	73.4	74.8	70.0	74.2	65.4	68.8	69.0	76.6
H			71.4	75.7	72.4	73.1	70.5	73.2	72.2	76.4
grad$Z$				75.9	74.8	76.0	73.8	75.2	74.0	75.1
adv$T$					68.9	70.0	67.0	71.0	71.7	75.2
$Gwsp$						71.9	72.9	72.0	73.1	75.5
ΔZ							65.9	68.1	**65.3**	74.8
ΔT								67.1	68.7	**78.0**
Th75									67.8	75.4
ξ_g										76.8

Table 3. As Table 2 but for the percent of error on the reconstitution of the ten-year cumulative precipitation amounts (November-March only)

(%)	Z	T	H	grad$Z$	adv$T$	$Gwsp$	ΔZ	ΔT	$Th75$	ξ_g
Z	−16	−16	− 8	− 9	−34	−9	−27	−20	−24	−12
T		−21	−10	−15	−54	−1	−25	−23	−24	−11
H			−10	− 9	−60	+5	−21	−22	−16	− 7
grad$Z$				−14	−28	−4	−26	−11	−21	−17
adv$T$					−53	−8	**−63**	−55	−55	−20
$Gwsp$						0	−10	+ **3**	− 7	− 5
ΔZ							−25	−36	−28	−24
ΔT								−27	−27	−15
$Th75$									−26	−17
ξ_g										− 6

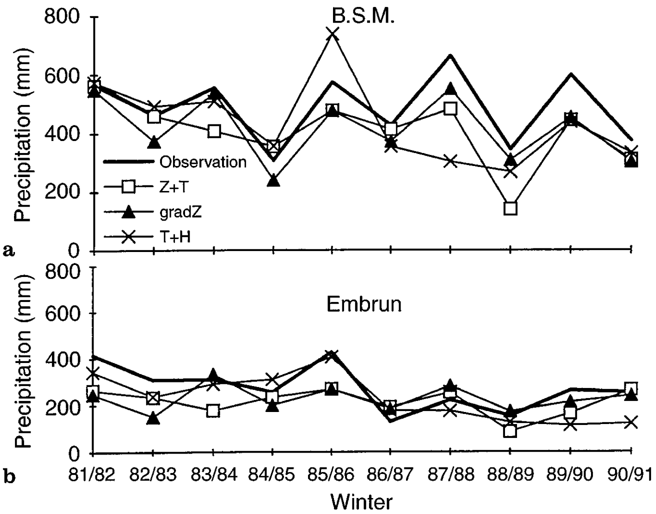

Fig. 3a, b. Comparison of the reconstructed total November-March precipitation using various criteria with observation. **a** Bourg-Saint-Maurice (Vanoise); **b** Embrun (Parpaillon)

Saint-Maurice, best correlation at Embrun). When considering all criteria, significant correlations at both sites are obtained with few variables: $Z+T$, $Z+\Delta Z$, $Z+Th75$, $H+Gwsp$, $H+\xi_g$.

4.2 Air temperature

A simple measure of the quality concerning air temperature is given by the mean and the rms error on the reconstructed daily mean temperature over the period November-March. As the results at both sites are very similar, only the case of Bourg-Saint-Maurice will be treated here. Although a general overestimation is observed with all criteria, a group of variables accounting directly (T) or indirectly (Z, $Th75$) for the temperature of the atmosphere are associated with the smallest errors (mean errors $<0.3\,°C$, rms error $<0.7\,°C$). The other variables, based on the circulation dynamics, tendencies or humidity give mean errors between 0.7 and 1.5 °C and rms errors between 1.2 and 1.7 °C.

The air temperature presents an important interannual variability over the period considered (1981/1991, Fig. 4): the temperature is lower in the first part of the dataset than in the second. The reconstitution with variable Z (first group) is rather coherent, but $Gwsp$ (second group) cannot reproduce the interannual variability, this confirms the results obtained with daily mean temperature errors.

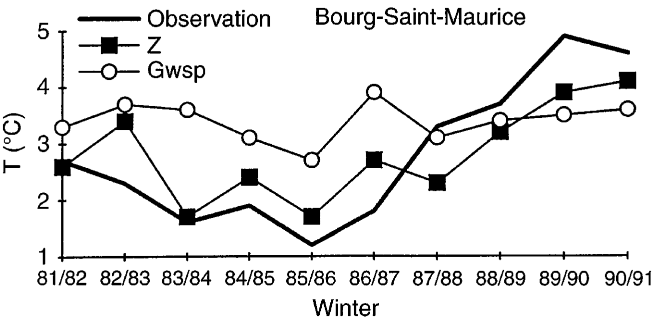

Fig. 4. Comparison of the reconstructed mean November-March temperature (°C) at Bourg-Saint-Maurice with observation

4.3 Snow depth simulations

Our principal goal is to study the quality of snow depth simulations, which is strongly related to the quality of the reconstitution of precipitation and temperature. In this subsection, the test of the overall procedure, as defined in Sect. 2 is performed in two high elevation sites: Flaine (1640 m, Chablais, Northern Alps) and Isola (1900 m, Mercantour, Southern Alps). For each site, the analysis system SAFRAN used all available data of the analogues, in order to feed the snow model CROCUS. The resulting snow depth is compared to a reference run in which all data are used.

The rms error on snow depth at a daily time-step is usually smaller at Flaine than at Isola, as a result of different climatic conditions (the rms corresponding to random selection is 55 cm for Flaine and 62 cm for Isola). It was found that the quality of the analogue selection concerning air temperature is crucial because the smallest rms errors are obtained when variables Z, T or $Th75$ are included in the selection criteria. Of course, when the precipitation deficit is very important, the results are also poor. The selection based on *Th*75 only is associated with a strong rms error because of precipitation deficit. Finally, six criteria, associated with rms errors smaller than 30 cm at Flaine and 40 cm at Isola were selected: $Z+T$, $Z+H$, $Z+Th75$, $T+Gwsp$, $T+H$, $Gwsp+Th75$.

4.3 Other tests

We also investigated the geographical domain used for the calculation of the Euclidean distances. With a reduced domain, a general decrease of the performance is observed. The analogue procedure is not able to select a close meteorological situation, because some important features of the altitude fields are not described. With an enlarged domain, it may be supposed that the meteorological situation is well described. However, for a domain covering Western Europe, there is no improvement of the results because the selection takes into account phenomena outside the region of interest. The results confirm the choice of a medium area for the selection.

The temporal resolution was also of some interest in the selection. While the criteria described already took into account distances calculated twice a day (00 H and 12 H UTC), distances calculated at 06, 12, 18 and 00 H UTC improved the results except for the cumulative precipitation amounts, whose deficit become worse. The results are symmetric when only fields at 00 H UTC are used.

4.5 Discussion

A total of 55 criteria were studied, but only a small number obtained reasonably good results in the various tests described above. Finally, the $Z+T$ criterion was chosen as it is very simple (two variables of the model) and well adapted to the use of GCM outputs (e.g. humidity, a variable not well simulated by atmospheric models was not selected). As a final test, the snow climatology reconstituted by the analogue procedure was compared to the climatology calculated with real data (Martin et al. 1994). The error on the mean annual snow cover duration is usually very small (±5 days at 1500 m, ±4 days at 3000 m). The reconstitution of the mean maximum snow depth is also well reproduced: the errors were found to be −9 to +21 cm at 1500 m (±20%) and −33 to +28 cm at 3000 m (±15%).

Almost all the difficulty of this approach is concentrated in the selection criteria. We found that the criterion $Z+T$ allows accurate snow depth simulation, including climatological differences between regions and interannual variability, which was the aim of this test. A possible explanation for the failure of more sophisticated criteria is that the solution proposed for combinations of several variables is rather simple but it is probably not appropriate when different kinds of variables are combined: in our case, the combinations with tendency variables (ΔZ, ΔT, adv$T$) did not yield satisfactory results. This is why combinations of three or more variables were not tested. Another problem encountered in the tests is due to the small number of potential analogues (about 280): the selection of a good analogue is not possible when extreme meteorological situations are encountered. One could also be critical of the fact that the final criterion is not tested on a separate dataset, but because of the amount of data necessary, it was not possible to introduce additional years in the dataset.

5 Application to a present day GCM simulation

5.1 Description of the simulation

The atmosphere GCM used in this study is the climatic version of the ARPEGE/IFS code developed jointly by Météo-France and the ECMWF for operational weather forecasting (Courtier et al. 1991). The ARPEGE/Climat version used is described in detail in Déqué et al. (1994). The model has a spectral T42 triangular horizontal truncation and a reduced Gaussian grid resolution of about 2°8 in latitude and longitude. The prescribed sea surface temperatures (SSTs) and seasonal ice extents are 1979–1988 average of the COLA-CAC sets used for AMIP simulations (Gates et al. 1992). The results of the five-year run are discussed in Timbal (1994). Comparisons with observational data indicated that the main global features are well simulated. Features at high altitude (mid-troposphere) or related to the dynamical structure are close to observations, in some case even for the regional scale. For example, the simulation of the Icelandic low (a key structure for winter weather types in Europe) is reasonable. At the continental scale, the model can reproduce with a good agreement the seasonal cycle of temperature (with biases lower than 2–3 °C over Europe) but fails for the climatic variables of the hydrological cycle (e. g. precipitation). This definitely proves the need for a downscaling approach to study a phenomenon at the scale of the Alps.

5.2 Results for the snow cover in the French Alps

The results of the downscaling procedure is strongly dependent on the quality of the GCM simulation of the regional climate: in our case temperature and geopotential fields. The monthly mean of air temperature at 700 and 500 hPa has been compared to the ECMWF analyses for a point situated in the centre of the French Alps (45°N, 6°5E) (Fig. 5). At 700 and 500 hPa, the temperature is overestimated from February to April. Possible consequences of this discrepancy is an enhanced snowmelt rate during spring.

As the originality of the method is to take into account the daily weather types characterised by the shape of the geopotential and temperature fields, one may also verify the performances of the model in this

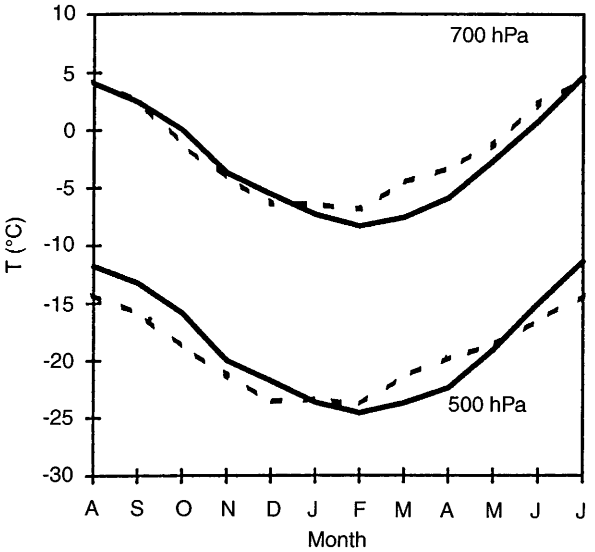

Fig. 5. Comparison of the monthly mean of air temperature at 500 (*bottom*) and 700 hPa (*top*) in the control run (*dashed lines*) to the ECMWF 1981–1991 climatology (*solid lines*). The values are calculated at 45 °N 6 °5E, in the centre of the French Alps

domain before using the downscaling procedure. For this purpose, we used geostrophic wind roses calculated at 45 °N, 6 °5E at 700 hPa for the control run and the 1981–1991 ECMWF analyses. The comparison between the roses (Fig. 6) indicates that the GCM atmospheric circulation is too zonal. The percentage of the westerly flows is greater than 40%, compared to 25% in the ECMWF analyses. Consequently, southerly and southeasterly flows are underestimated. This can lead to an underestimation of precipitation in this area, as these types of fluxes are associated with the presence of Mediterranean low-pressure areas and heavy precipitation in the south east part of the French Alps.

The snow cover duration at 1500 m elevation calculated with the downscaling procedure is compared to the climatology calculated by Martin et al. (1994) in Fig. 7. The values are systematically underestimated (−7 to −33 days/year) because of the too high temperature of the GCM in spring combined with a slight underestimation of precipitation in the south (−20% in the Mercantour massif). At higher elevations (3000 m) the results indicate a similar behaviour. Despite the discrepancies mentioned, some characteristics of the present snow climatology are very well reproduced, especially the relative variations between massifs. The maximum snow coverage is located in the northwest (Chablais-Chartreuse) and decreases regularly toward the southeast, because of combined effects of reduced precipitation in the interior of the Alps and the latitudinal effect on temperature. These very sharp variations of precipitation amounts in this region are impossible to deduce directly from the smooth results of the GCM, but they are well reproduced by the downscaled simulations.

In order to correct the GCM bias, monthly corrections were introduced in the simulated temperature and geopotential fields in order to obtain monthly averages identical to those of the ECMWF analyses. With this method, only the too warm temperatures from February to April are corrected, as it is not possible to modify the wind distribution. However, the application of the analogue procedure to these corrected outputs significantly improves the results (Fig. 7c). The simulated snow cover duration is now very close to the reference in the north and central part of the region. The south and southeast regions are still not well represented, due to the discrepancies in the simulated atmospheric circulation.

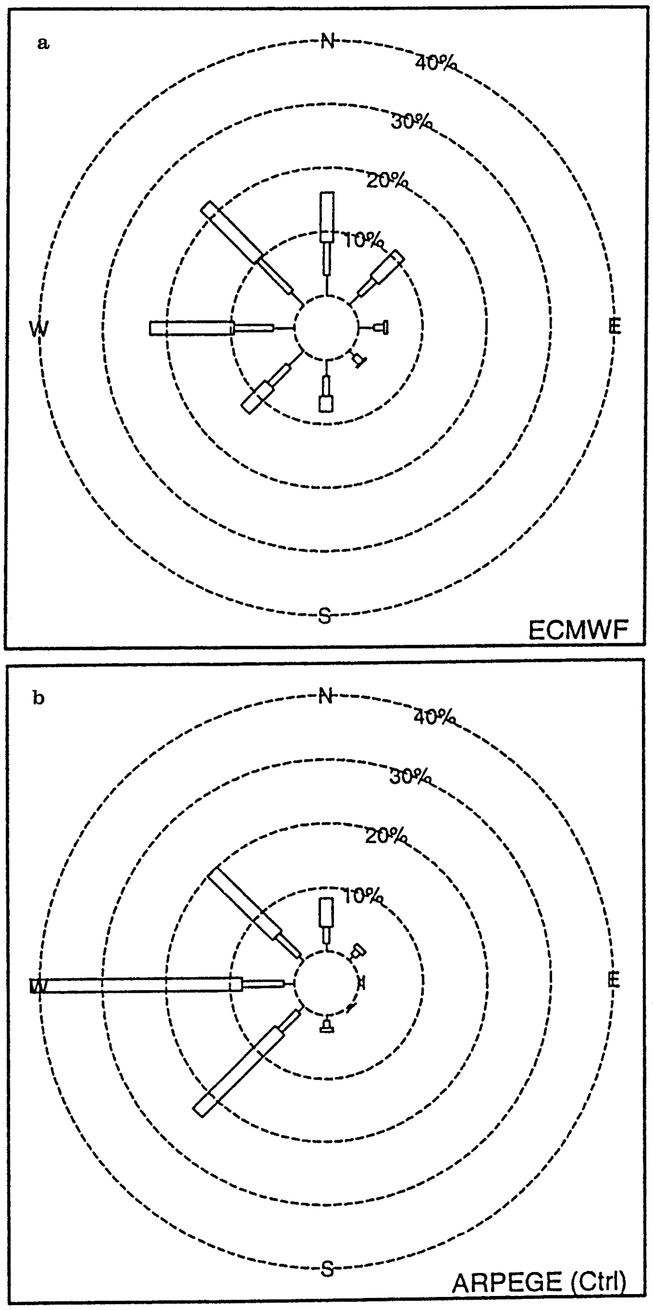

Fig. 6a, b. 700 hPa geostrophic wind roses at 45 °N, 6 °5E, November-March mean. **a** ECMWF analyses, **b** control run. Wind speed classes are: 0–5, 5–10, >10 m/s

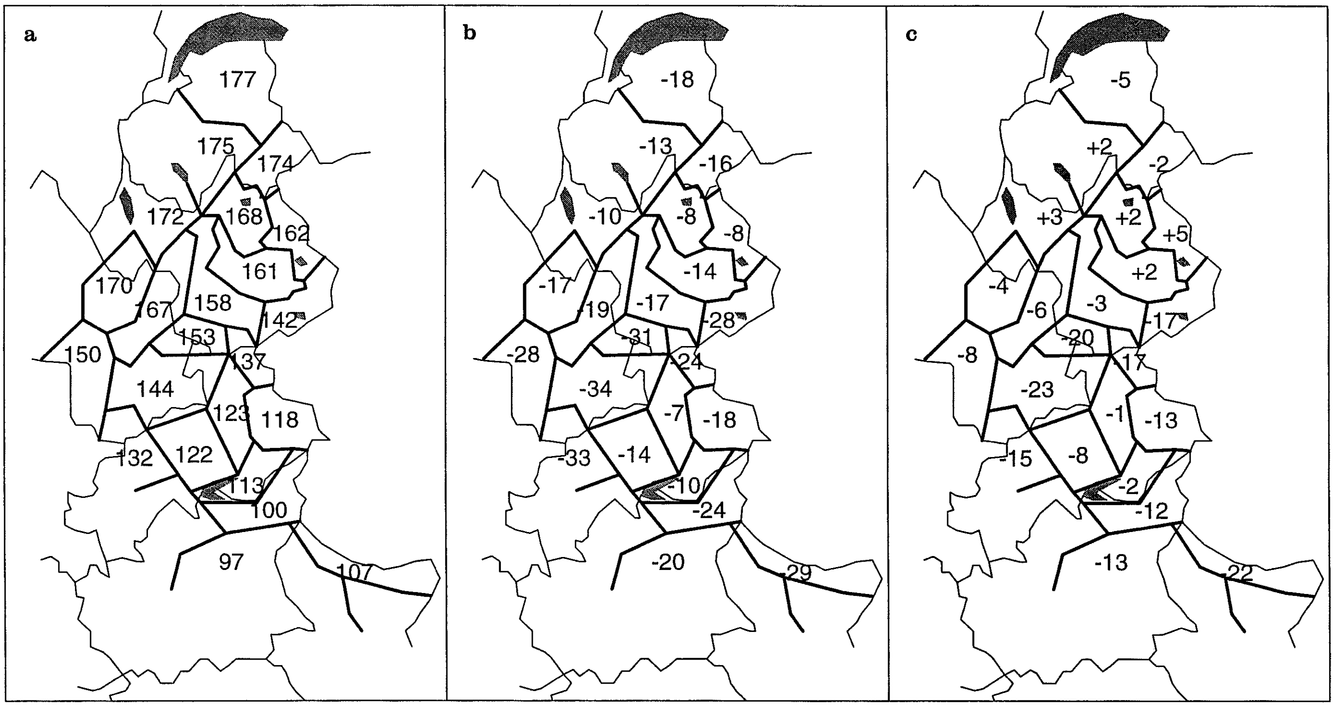

Fig. 7a–c. Simulation of the mean annual snow cover duration (days/year) at 1500 m a.s.l. **a** reference SAFRAN/CROCUS climatology. **b** difference (from the reference) for the reconstitution with the analogue procedure, **c** difference for the reconstitution with the analogue procedure using corrected GCM outputs

However, the results described prove that, after correction of the ARPEGE temperature biases, the analogue procedure is able to reproduce the snow climatology of the French Alps. The fact that a partial correction of the bias of the model allows a very good reconstitution of the snow coverage is also encouraging.

6 Application to doubled CO_2 experiments

6.1 Presentation of the experiments

For the two $2 \times CO_2$ time-slice experiments, mean sea ice extent and prescribed SST changes, obtained from transient experiments performed by coupled atmosphere-ocean GCMs were used as boundary conditions for ARPEGE/Climat. The two models considered were the ECHAM1/LSG developed at the Max Planck Institut für Meteorologie (MPI) (Cubasch et al. 1992) and the model developed at the Hadley Centre (HC) of the United Kingdom Meteorological Office coupled with a global ocean model (Murphy 1994; Murphy and Mitchell 1994). The perturbations of the SSTs are the average of the ten year period corresponding to a doubled atmospheric CO_2. The main differences in the SST forcings are located in the Northern Hemisphere, between 30 °N and 60 °N. The global annual mean of SST changes is +0.96 for MPI and +1.14 for HC.

Two five year runs (hereafter MPIe for the experiment with MPI SST and HCe for the experiment with HC SSTs) were performed (Timbal et al. 1995). The global warming of the surface air temperature in the experiments is 1.6 for MPIe and 1.9 for HCe. At the continental scale, the results show particular contrasts between the two experiments over Europe due to the different North Atlantic patterns for SST anomalies. The difference is maximum in summer but starts in spring and shows up through the downscaling procedure.

6.2 Corresponding impact on the snow cover of the French Alps

In both $2 \times CO_2$ experiments there is a temperature increase at 700 and 500 hPa over the Alps: the annual temperature increase is +1.3 °C at 700 hPa and +1.9 °C at 500 hPa for MPIe, and +2.6 °C and +3.0 °C for HCe at 45 °N, 6.5 °E. The changes of the geostrophic wind roses at 700 hPa (period November-March) between the control run and the MPIe are relatively small. However, the proportion of the southwesterly winds increases from 24% to 29%. In the HCe, a slight diminution in the frequency of the westerly and northwesterly flows is observed, but the main point to be noted is that the wind speed decreases: the percentage of days with a 700 hPa wind speed lower than 10 m/s is 33% for HCe, 28% for the control run and 22% for MPIe.

The analogue procedure has been applied to the outputs of MPIe and HCe. It has been decided to use the monthly corrections already introduced in the outputs of the control run, assuming that they account for a constant bias of the GCM in this region. The changes of the mean November-March temperature and annual precipitation are given in Table 4 for the Mont-Blanc massif and the Mercantour. The precipitation deduced from the analogue procedure shows a discrepancy between the two experiments. For MPIe, annual precipitation amounts are almost stable, although winter precipitation increases (not shown). As a consequence snowfalls increase at 3000 m a.s.l in spite of the climate warming. At 1500 m, there is a slight decrease of snowfall, except for some massifs in the southwest (e.g. Dévoluy where snowfall increases: 240 mm/year instead of 232 mm/year). These facts can be related to the increase of southwesterly fluxes, associated with heavy precipitation in this part of the Alps. For HCe, precipitation amounts decrease drastically at all levels. This is coherent with increased temperature and the diminution of wind speeds at 700 hPa, associated with weak precipitation events. The temperature variation is coherent with the variation observed in the upper air fields. However, the difference in temperature variations between 1500 and 3000 m is not understood. It is perhaps an artefact of the analogue procedure.

At 1500 m, the snow cover duration is principally linked to temperature, consequently it is reduced everywhere. For the MPIe (Fig. 8), the largest changes

Table 4. Variation of the mean November-March temperature and annual precipitation for the Mont-Blanc massif (north) and the Mercantour massif (south) deduced from the analogue procedure for the control run and variations for MPIe and HCe

		Mean annual precipitation (mm/year) Total precipitation (snowfall)			November-March mean air temperature (°C)		
		Control run	Variation MPIe-control	Variation HCe-control	Control run	Variation MPIe-control	Variation HCe-control
Mont-Blanc:	1500 m	1680 (636)	−58 (−62)	−255 (−184)	1.0	+1.0	+1.6
	3000 m	1915 (1597)	−65 (+49)	−274 (−158)	−6.9	+1.2	+2.0
Mercantour:	1500 m	785 (267)	−17 (−49)	−256 (−118)	1.6	+0.8	+1.4
	3000 m	861 (725)	− 9 (−23)	−270 (−232)	−5.7	+1.2	+2.1

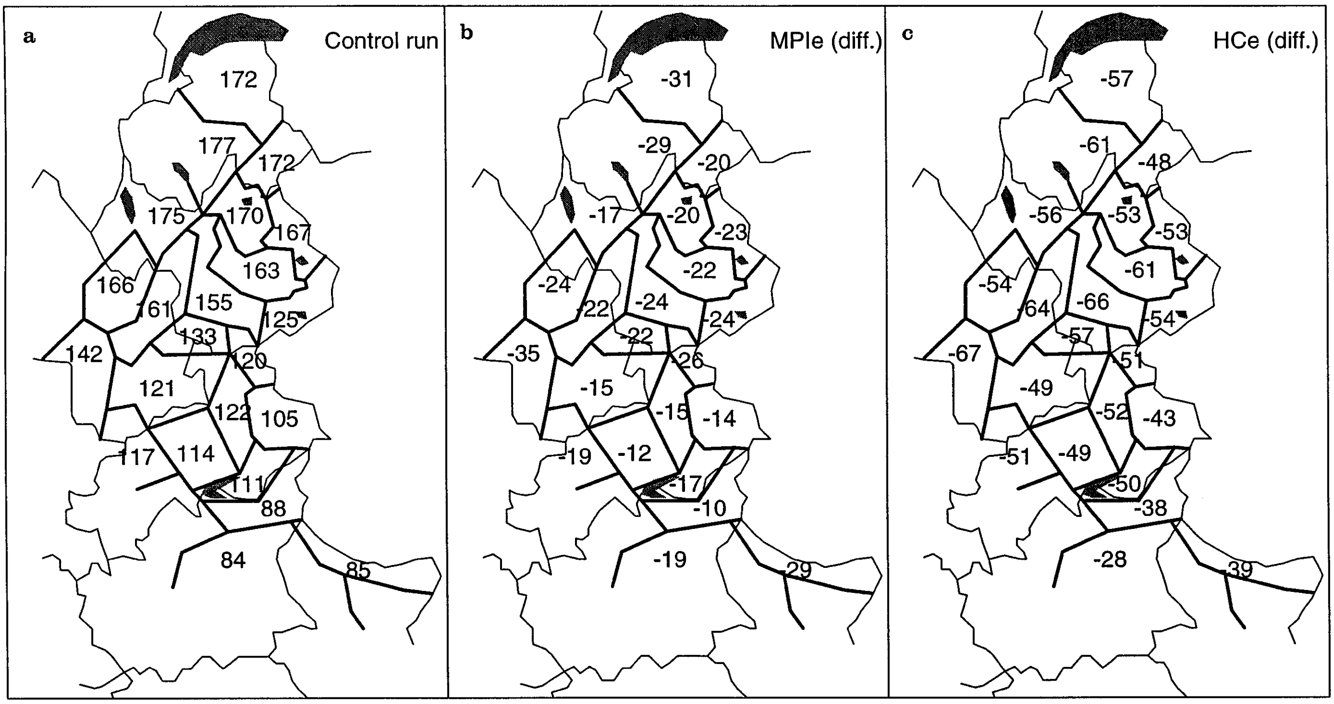

Fig. 8a–c. Mean annual snow cover duration (days/year) at 1500 m a.s.l calculated by the analogue procedure for **a** the control run **b** anomalies for MPIe and **c** anomalies for HCe

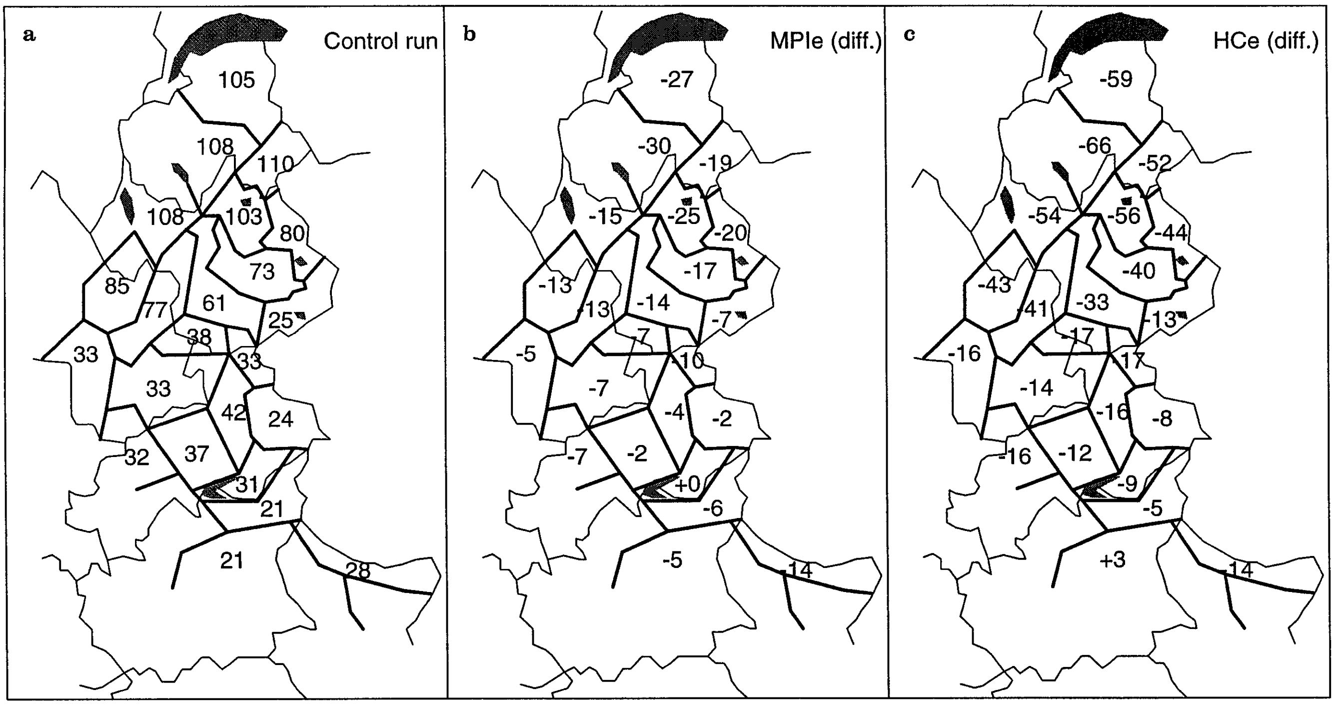

Fig. 9a–c. As Fig. 8, but for the mean maximum snow depth (cm) at 1500 m a.s.l

are observed in the northwest (Vercors-Chablais, up to −35 days/year). The reduction is less pronounced in the south because of the lower temperature increase (+0.7 °C against +1.0 in the north). In the HCe, the reduction is larger than in the MPIe (higher temperature increase), but the distribution is much more homogeneous. At 3000 m, the variations of the snow cover duration are limited to less than 10 days/year for MPIe. This is not the case for the HCe (−10 to −43 days/year) because of the temperature effect and the drastic precipitation reduction, especially in the south (Mercantour, see Table 4).

The mean maximum snow depth at 1500 m (Fig. 9) is much more linked to the spatial distribution of precipitation anomalies, as shown in Martin et al. (1994). For the MPIe, the changes of the mean maximum snow depth varies from 0 to −27 cm. The smaller changes in the south are due to the combined effects of smaller temperature changes and increased snowfall. The HCe changes are larger than those of the MPIe. At 3000 m, the difference between the two experiments is very marked (Fig. 10). In the MPIe, there is a general increase of the maximum snow depth (except for Mercantour) up to +32 cm. In the HCe, the reduction is drastic (−39 to −72 cm).

7 Discussion and conclusions

The downscaling procedure developed in this study has been validated against real data and applied to several GCM runs. With real data a systematic underestimation of seasonal and long-term accumulated precipitation was found. This is common to analogue methods, which have difficulties in selecting extreme situations, associated with high precipitation amounts. Although the quality of the ARPEGE/climat simulation for the control run over the area of interest is in relatively good agreement with observations (upper air monthly temperature biases less than 2–3 °C in the area of interest), the high sensitivity of the snow cover to small temperature or precipitation changes does not allow an accurate simulation of the snow climatology. The introduction of corrections of monthly temperature in the outputs of ARPEGE is a partial response to this problem. However, because of the difficulty encountered by GCMs in simulating the atmospheric circulation in the Mediterranean Sea (and the fact that the resulting biases were not corrected), the snow coverage in the south of the Alps is not well reproduced from the control run. This discrepancy should be accounted for before analysing the impact in this region. By applying the bias corrections to the temperature fields of the $2 \times CO_2$ ARPEGE runs it is assumed that the biases in these runs are the same as in the control run, despite the climate change. The correctness of this assumption is difficult to verify.

There are other limitations concerning the use of the analogue procedure. The first is due to the assumption that the relation between upper air fields and local meteorological conditions is unchanged whatever the climate. This assumption cannot be verified: it is a common limitation of all semi-empirical downscaling techniques. The second is due to the fact that it is necessary to find good daily analogues. The addition of supplementary years in the ECMWF analyses dataset

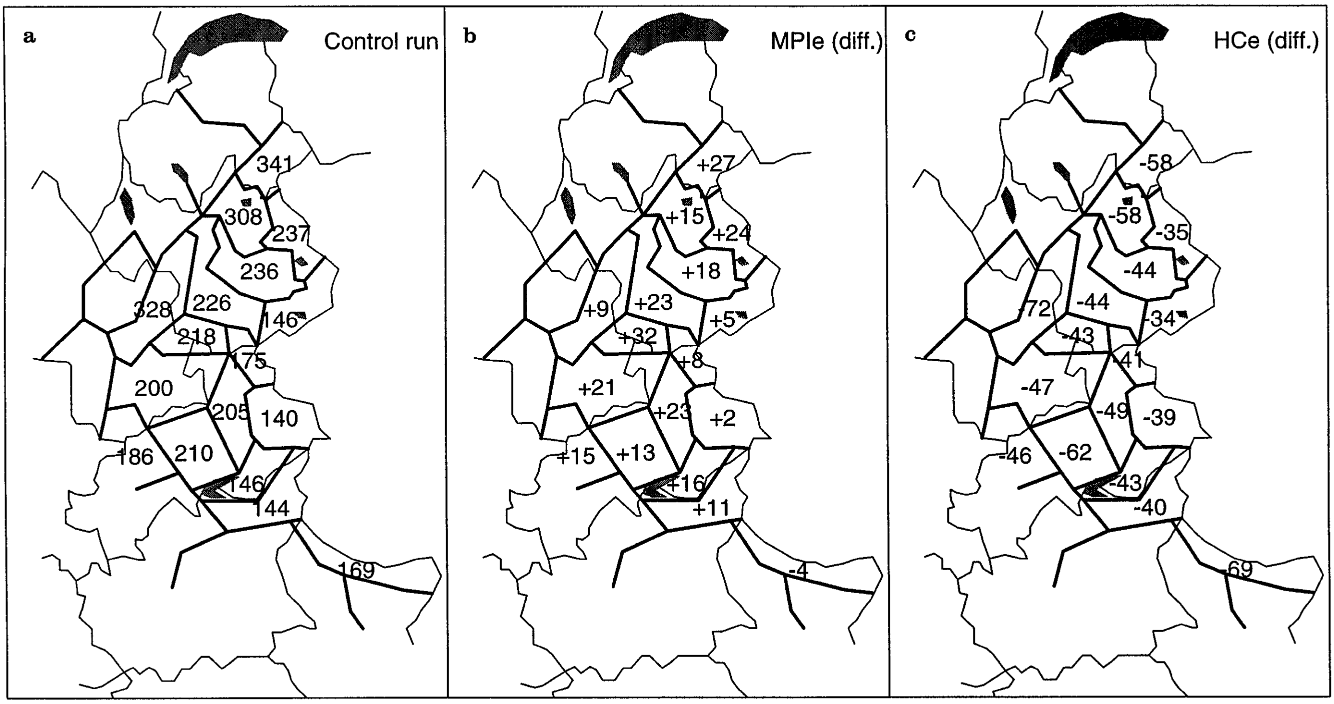

Fig. 10a–c. As Fig. 8, but for the mean maximum snow depth (cm) at 3000 m a.s.l

should improve the quality of the downscaling procedure.

The comparison between the MPIe and the HCe, whose difference lies in SST anomalies entered in ARPEGE highlight the difficulty of impact assessment at the regional scale: significant differences are found in the changes of the snow climatology in the two experiments. These results are in agreement with those of Martin et al. (1994) and confirm the high sensitivity of snow cover to climate variations. In the MPIe, a moderate increase of winter temperature (+1 °C) is compensated at high elevation by an increase of precipitation. This is not the case in the warmer HCe with decreased precipitation. At the middle elevations (e.g. 1500 m a.s.l) the snow coverage decreases in both cases, but more drastically in the HCe.

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