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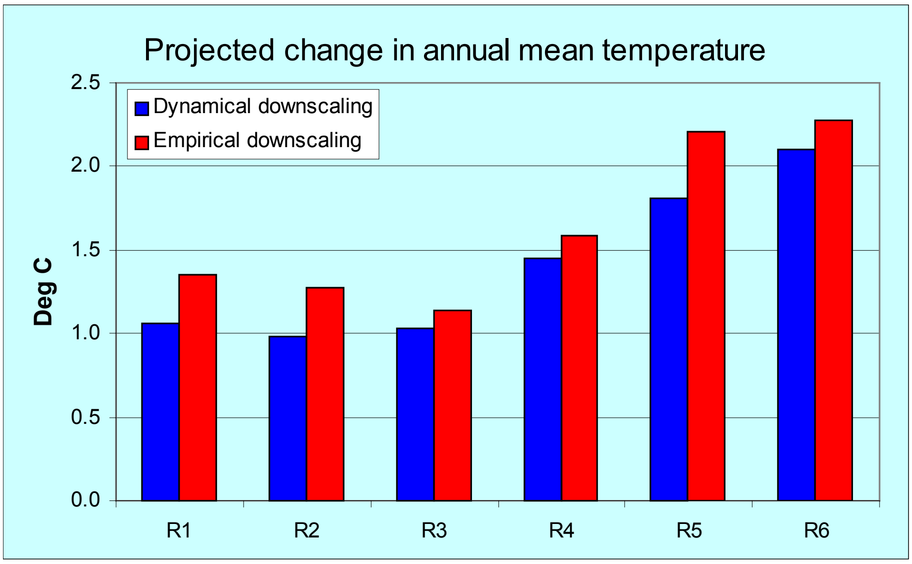
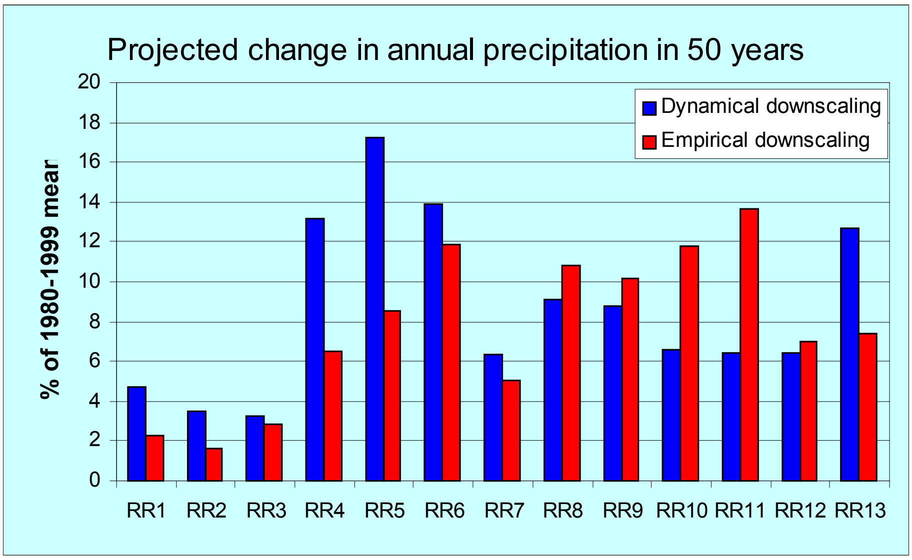
Report 06/03





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SUMMARY:

A scenario from the coupled atmosphere-ocean climate model ECHAM4/OPYC3 was downscaled by empirical and dynamical methods to show projected changes in temperature and precipitation in Norway under global warming. Both approaches project from 1980-1999 to 2030-2049 an increase in annual mean temperatures of between 1 and 2.5°C in various parts of the country. The projected warming is at minimum along the coast of southern Norway, while larger warming is projected in the inland and in northern Norway. Though the differences between the approaches are not statistically significant, empirical downscaling systematically leads to larger projected increase in annual mean temperature than dynamical downscaling does. The difference is at maximum during winter and/or spring at localities exposed for temperature inversions. Empirical downscaling projects larger winter warming in inland valleys than at more freely exposed localities, and thus implies a reduced intensity or frequency of winter inversions. It is argued that less favourable conditions for ground inversions are consistent with the future projection of increased winter wind speeds and reduced snow-cover.

For precipitation, both downscaling approaches project statistically significant increase in western Norway during autumn, and in southern Norway during winter. The only significant difference between the results is that dynamical downscaling projects increased summer precipitation in southwest Norway, while the empirically downscaled scenario shows no significant change. For summer precipitation the present empirical models do not include any predictor carrying the "climate change signal", and thus the results from the dynamical downscaling are probably more realistic concerning summer precipitation.

KEYWORDS:

Dynamical downscaling · Empirical downscaling · Temperature · Precipitation· Norway

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1. Introduction

Coupled atmospheric-ocean global general circulation models (AOGCMs) are the most sophisticated tools for modelling global warming. The resolution in the AOGCMs is presently probably sufficient for modelling large-scale features, but in general still too coarse to enable these models to reproduce the climate on regional or local scale (e.g. Yarnal et al. 2001). In order to produce regional scenarios it is thus a need for downscaling. Regional modelling (dynamical downscaling), statistical methods (empirical downscaling) or combinations of these techniques may be applied for this purpose (e.g. Giorgi et al. 2001). A few inter-comparisons of results from dynamical and empirical downscaling have been published (Kidson & Thompson 1998, Mearns et al. 1999, Murphy 1999, Hellström et al. 2001). In Norway, both dynamical and empirical techniques have now been applied to downscale results from the AOGCM ECHAM4/OPYC3 (Oberhuber 1993, Roeckner et al. 1996, 1999). The downscaling experiments are based upon the "GSDIO" integration (Roeckner et al. 1999), a transient integration based upon the IS92a emission scenario, and including greenhouse gases, tropospheric ozon, and direct as well as indirect sulphur aerosol forcing. The GSDIO integration did well in a comparative study where several integrations were compared to observed temperature anomalies during the period 1946-1996 (Allen et al. 2000).

In the present paper, temperature and precipitation scenarios for Norway resulting from the two downscaling approaches will be compared. Section 2 shortly describes the dynamical and empirical modelling tools. The results of the comparison are presented in section 3 and discussed in section 4.

2. Downscaling experiments

2.1 Dynamical downscaling

Since AOGCMs only supports large-scale and synoptic scale atmospheric features, regional climate models (RCMs) have been developed during the last decades for dynamical downscaling of AOGCMs at regional and local scales. The hypothesis behind the use of high-resolution RCMs is that they can provide meaningful small-scale features over a limited area at affordable computational cost compared to high-resolution GCM simulations. The HIRHAM RCM used in the present study, was run with 55 km grid distance nested within the global data available every 12 hours with a 300 km grid. The same physical parameterisations are used in the RCM as in the global model, except for tuning to account for the finer grid in HIRHAM. The same 19 model levels were used in the vertical direction. The integration area is shown in Fig. 1.

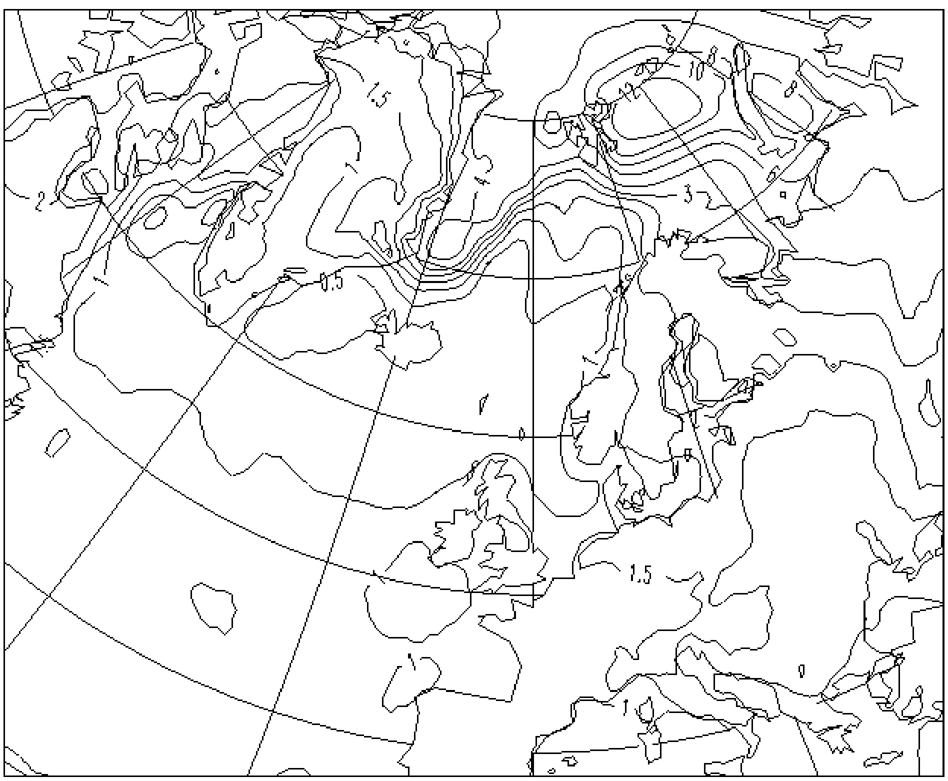

Figure 1. The HIRHAM regional climate model integration area with contours for increased winter temperature at 2 meter from 1980-1999 to 2030-2049 downscaled from ECHAM4/OPYC3 GSDIO simulation.

A successful implementation of a RCM depends on a number of conditions, e.g. nesting strategy, domain size, difference in resolution between the AOGCM and RCM, the physical parameterisations, quality of the driving data and spin-up time. Generally the RCM cannot be expected to improve errors in the AOGCM results on a large scale, but should be able to develop small-scale features, at least due to more realistic surface forcing. As for its global counterpart, it is certainly necessary to realistically simulate present climate where analysed and observed data can be used for validation, as a first attempt to trust the output from climate change experiments.

The HIRLAM model originates from the HIRLAM (High Resolution Limited Area Model) short-range weather prediction model (Källén 1996). The numerical formulation is a second-order finite difference scheme and the time-scheme is the Eulerian leapfrog, semi-implicit time-scheme with a time step of 4 min. In order to be better suited for long-term climate simulation, the physical parameterisations were adopted from the ECHAM4/OPYC3 AOGCM (Roeckner et al. 1996), and documented by Christensen et al. (1998). The experiments performed with the GSDIO data are reported in Bjørge et al. (2000). The physical parameterisations in HIRHAM include radiation, cumulus convection utilizing the mass flux scheme of Tiedke (1989), stratiform clouds, planetary boundary layer, gravity wave drag, sea surface and ice processes, and land processes including surface hydrology. In the land surface scheme temperature is calculated as prognostic variable for five soil layers and one moisture layer. A simple one-layer snow model is coupled to the land surface scheme (DKRZ 1992, Christensen et al. 1996). The albedo of snow (and ice) is parameterised to be temperature dependent near melting (decreasing albedo with increasing temperature). The effect on vegetation on albedo during snow-covered periods is parameterised over fractional forested area, effectively reducing the albedo with increasing forest coverage (Robock 1980).

The HIRHAM simulation from the GSDIO experiment was carried out in two time-slices, 1980-1999 and 2030-2049, with lateral boundary conditions for surface pressure, temperature, horizontal velocity components, specific humidity and liquid cloud water in 12-hourly intervals and with sea surface temperature and sea-ice conditions specified from the global model. Monthly concentrations of various greenhouse gases were tabulated as in the global counterpart according to the IS92a scenario with observed values until 1990 followed by 1% yearly increase in CO_2.

2.2 Empirical downscaling

Empirical downscaling of climate scenarios consists of revealing empirical links between large-scale patterns of climate elements (predictors) and local climate (predictands), and applying them on output from global or regional climate models. Successful downscaling depends on the following conditions: The climate model should reproduce the large-scale predictor fields realistically, the predictors should account for a major part of the variance in the predictands, the links between predictors and predictands should be stationary, and, when applied in a changing climate, predictors that "carry the climate change signal" should be included (Giorgi et al. 2001).

In the present study, monthly mean 2m temperature (T) and sea-level pressure (SLP) were used as predictors. The area 20°W-40°E, 50-85°N was applied as predictor domain for SLP, while just the grid-points over Norway were used for T. The ECHAM4/OPYC3 large-scale T fields over Norway are reasonably realistic, while the SLP fields are biased as the average north-south SLP gradient in the northern North Atlantic at average is too weak (Hanssen-Bauer and Førland 2001). The SLP anomaly fields are still realistic, and also the links between SLP anomalies and temperature anomalies. Hanssen-Bauer and Førland (2000) showed that SLP anomalies account for a large part of the observed variability of temperature and precipitation in Norway during the 20th century. The long-term trends especially for temperature were, however, not reproduced satisfactorily. Because of this, and in order to include the climate change signal, T was included as predictor. For temperature, T was used as the only predictor in the final models as the SLP field gave limited additional information. For precipitation both predictors were included initially, and T may be regarded as a proxy for precipitable water in the troposphere. In summer, the inclusion of T as predictor led to unrealistic results. This may be caused partly by poorer correlation between air temperature and humidity, and partly by weaker connection between air humidity and precipitation during summer (Wilby and Wigley, 2000). Consequently, in the final models, T was not applied as a predictor during the summer months.

Following monthly data were used for model development and validation: Homogenised temperature and precipitation series from Norwegian stations (source: Norwegian Meteorological Institute), gridded SLP dataset (source: UK Met Office) and gridded temperature dataset (source: University of East Anglia). Hanssen-Bauer et al. (2000, 2001) describe the downscaling methods and results in detail. A brief summary of the methods is given here. For temperature, a simple scaling method was applied. By a method suggested by Singleton and Spackman (1984), Norway was divided into 6 temperature regions (Fig. 2a) within which standardised monthly temperature series are similar.

Figure 2a. Stations (o) and regions (1-6) applied in empirical downscaling of temperature. Stations that are mentioned in the text are labelled with initials: T=Tromsø, S=Suolovuobmi, K=Karasjok, B=Bergen, G=Geilo, N=Nesbyen, O=Oslo.

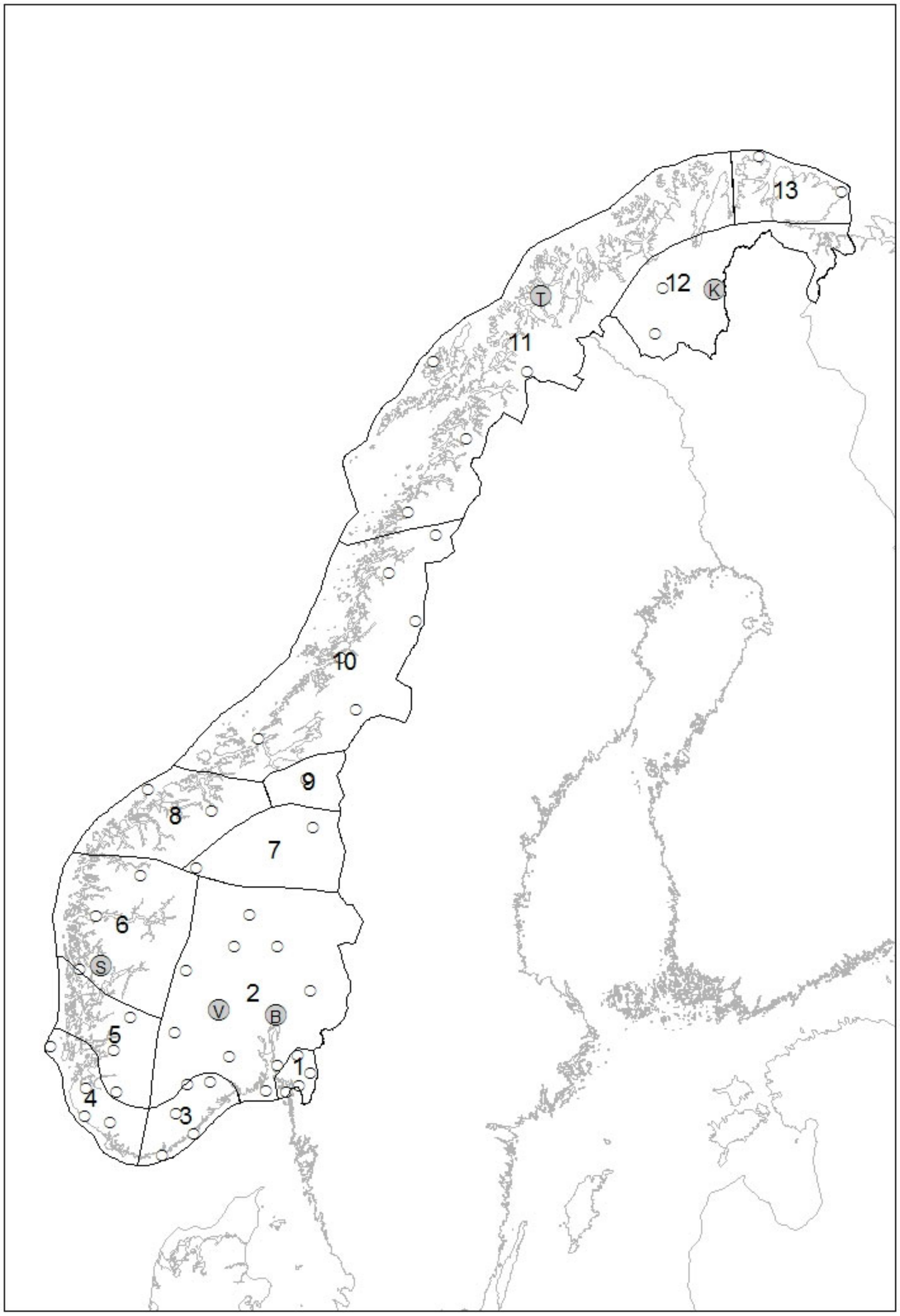

Figure 2b. Stations (o) and regions (1-13) applied in empirical downscaling of precipitation. Stations that are mentioned in the text are labelled with initials: T=Tromsø, K=Karasjok, S=Samnanger, V=Veggli, B=Bjørnholt.

Thus, a standardised temperature series from one station in a region is representative for the region. Comparisons with the gridded temperature data set (Jones et al. 1998) showed that also standardised series from grid-points within the respective regions are close to the regions' representative series. Thus the temperature at a station x in region n can be estimated by the temperature at the grid-point y within the same region:

$$T_{xn} = \{[T_{yn} - \mu(T_{yn})] / \sigma(T_{yn})\} \bullet \sigma(T_{xn}) + \mu(T_{xn}) \qquad (1)$$

Here T_{xn} is the local temperature, T_{yn} is the temperature at a nearby grid-point within the same region n, μ is the mean value and σ is the standard deviation. When working with observations, the method is rather robust concerning the choice of the periods for calculating mean values and standard deviations, as long as the same period is used. When applied for downscaling modelled values, however, it was found that 30 year was a too short period to get stable standard deviations. Thus the 90-year period 1901-1990 was chosen. Temperature series were downscaled for the 49 stations shown in Fig. 2a.

For downscaling precipitation, multiple linear regression models were developed using local standardised temperature series and the six leading empirical orthogonal functions (EOFs) from the SLP field as predictors:

$$[R_x] = a_0 + a_1 \bullet EOF1 + \ldots\ldots + a_6 \bullet EOF6 + a_7 \bullet [T_x] \qquad (2)$$

Here $[R_x]$ is the local precipitation given in percent of the 1961-1990 average, a_0 - a_7 are regression coefficients, and $[T_x]$ is the standardized local temperature. The EOFs are "common EOFs" based upon observed and GSDIO SLP fields (Benestad 2001). Models were developed for the 13 precipitation regions (Fig. 2b), which were defined by Hanssen-Bauer et al. (1997). For 55 individual stations, monthly precipitation series were estimated by multiplying the regional series by the 1961-1990 average.

3. Results

3.1 Present climate

The annual cycle of downscaled temperature and precipitation during the period 1980-1999 were for selected localities compared to observations. Empirically downscaled values were calculated specifically for the chosen meteorological stations. Dynamically downscaled values were chosen from the nearest grid-point, but the temperatures were adjusted for differences in altitude between model and real topography (0.65 ^{o}C per 100m). Both empirical and dynamical downscaling gave a realistic annual temperature cycle for most localities (Fig. 3, left panels), but dynamical downscaling tends to give too high winter temperatures at stations that are exposed for temperature inversions (e.g. Nesbyen and Karasjok). The regional model has too coarse resolution to resolve the ground inversions properly.

Also for precipitation, the main features of the annual cycle are reproduced at most stations (Fig. 3, right panels). At some stations, though, there are substantial differences in level between dynamically downscaled and observed values. Some of these differences are resulting from the smoothed topography in the dynamical downscaling model: This model underestimates the precipitation level in the maximum zone some tens of kilometres inland from the west coast (e.g. at Samnanger in Fig. 3), while it overestimates the level in the "rain shadow" east of the watershed (e.g. Veggli). But due to catch deficiency of the precipitation gauges during solid precipitation and strong winds (Førland and Hanssen-Bauer 2000), the measured precipitation levels are probably too low at stations where much of the annual precipitation is snow (e.g. Veggli and Karasjok).

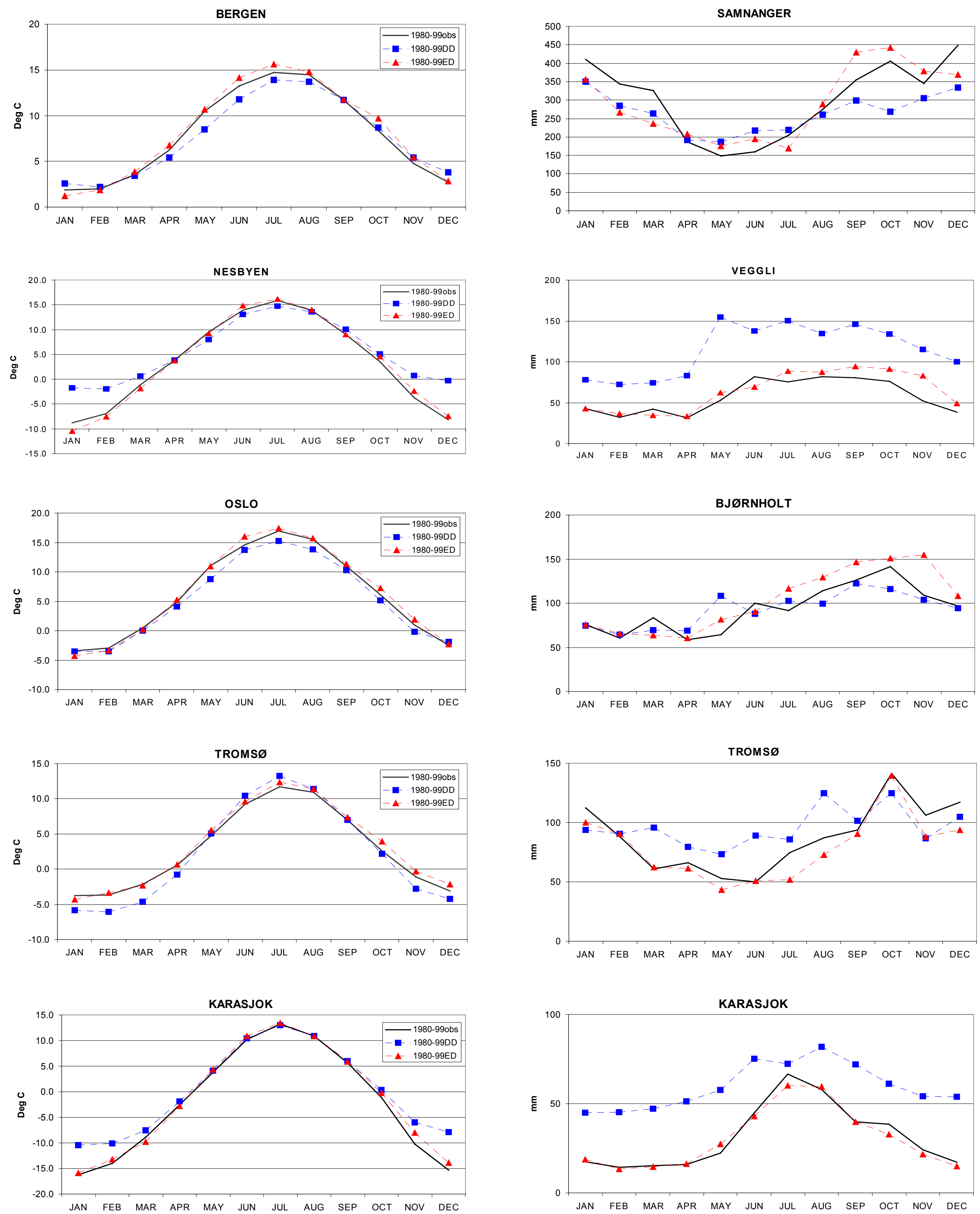

Figure 3. Seasonal cycle of temperature (left) and precipitation (right) during the period 1980-1999 at selected stations (cf. Fig. 2). Black: Observed; Blue: Dynamically downscaled; Red: Empirically downscaled.

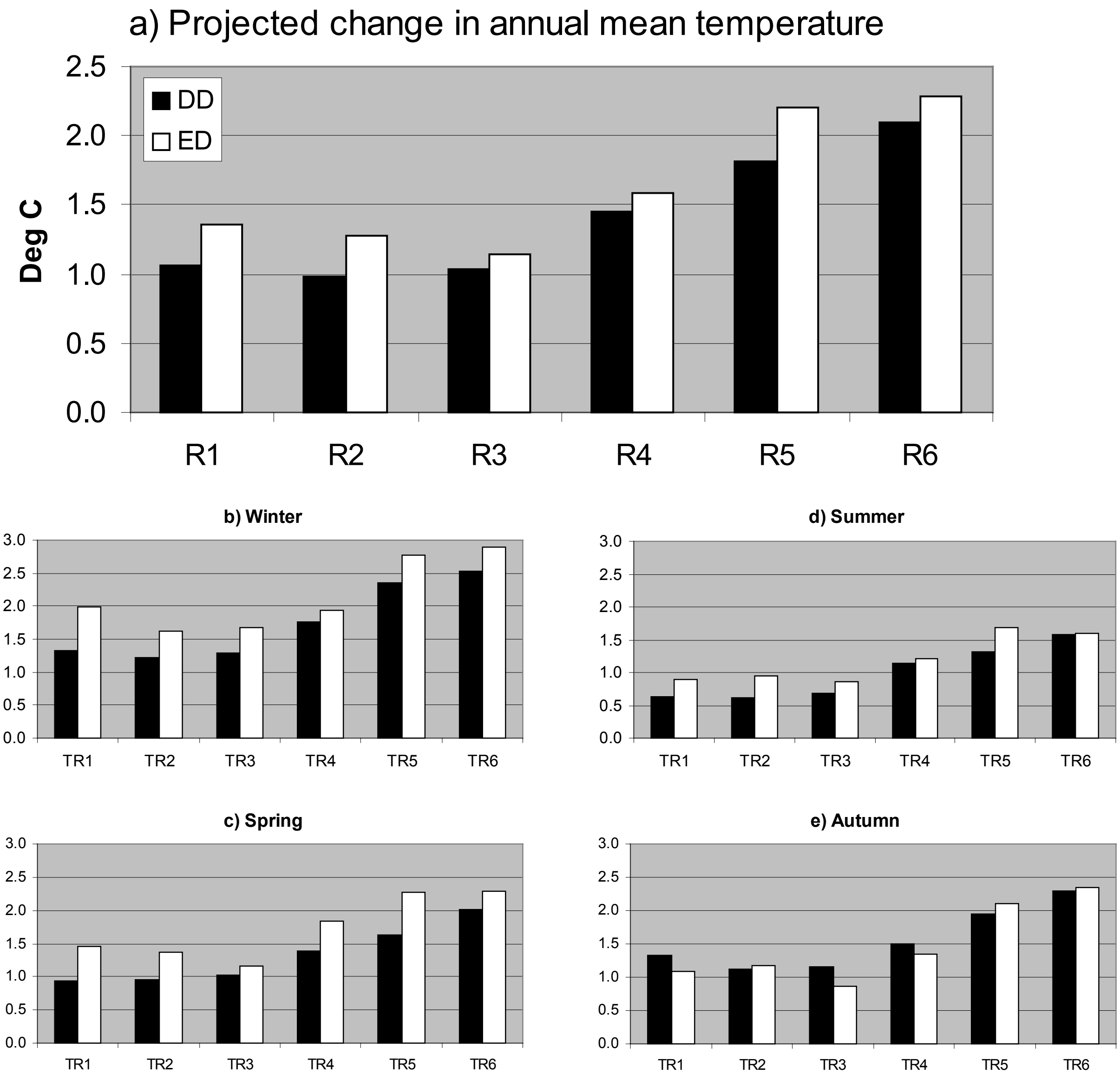

Figure 4. Projected warming from 1980-99 to 2030-49 in different regions according to results from dynamical (black bars) and empirical (white bars) downscaling. Unit: °C. Changes in annual (a) and seasonal (b-e) temperature are given. Winter=DJF; Spring=MAM; Summer=JJA; Autumn=SON.

3.2 Temperature scenarios

Annual and seasonal temperature increase from 1980-1999 to 2030-2049 in the 6 temperature regions in Fig. 2a were calculated based on the results from dynamical and empirical downscaling (Fig. 4). The results for dynamical downscaling are averages for all grid-points within the respective regions, while the results for empirical downscaling are averages for the stations within the regions. The significance of the temperature change was tested at 4 localities (Oslo, Bergen, Tromsø and Karasjok, Fig. 2a). All changes were significant at least at the 5% level, except the dynamically downscaled summer scenario in Oslo. The two approaches show similar geographical patterns for increase in annual mean temperatures: Minimum warming is projected in temperature regions 1-3, while the warming rates gradually are increasing towards north. The warming rates also tend to be larger in the inland than along the coast. There are, however, systematic differences: The empirical downscaling tends to give larger warming than dynamical downscaling in all regions and in all seasons except autumn. Maximum differences are found in winter and spring. The significance of the differences was tested in Oslo, Bergen, Tromsø and Karasjok, and none of them were significant at the 5% level. It was, however, noted that the differences between the dynamically and empirically downscaled scenarios concerning winter- and spring- warming rates are at maximum at inversion exposed inland localities, while they are small along the coast and at mountain stations. This is illustrated in Fig. 5 by comparing the estimated winter warming rates at valley floor stations to more freely exposed stations in regions 1 and 5.

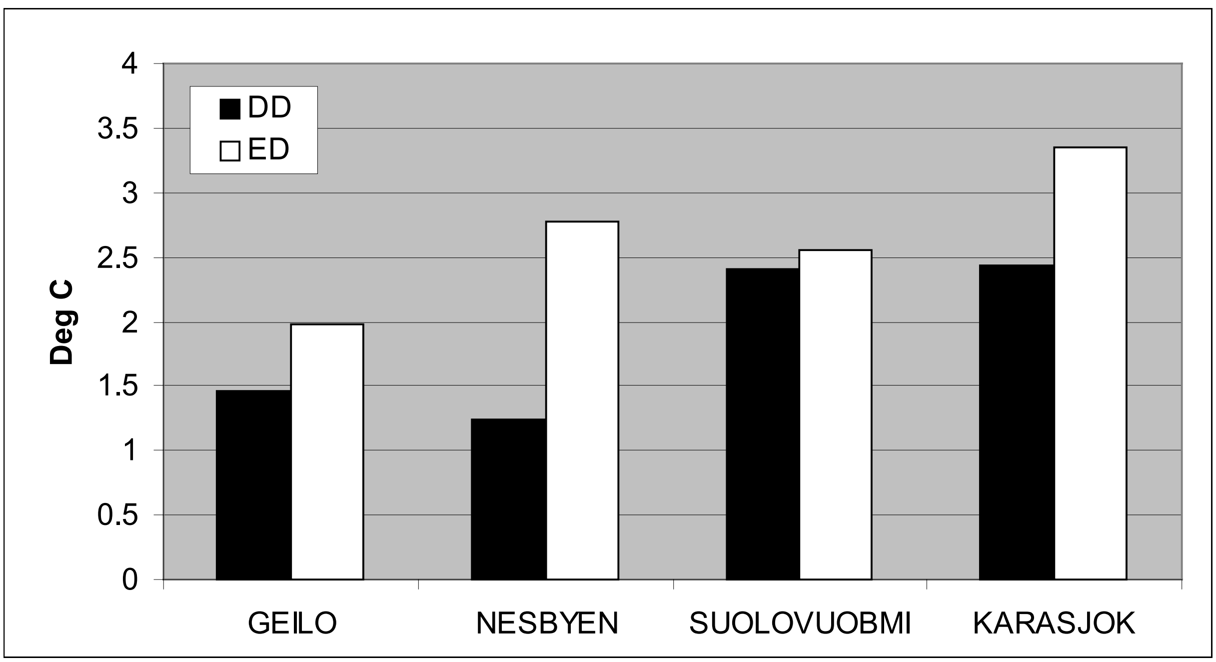

Figure 5. Projected winter (DJF) warming from 1980-99 to 2030-49 according to results from dynamical (black bars) and empirical (white bars) downscaling at the valley station "Nesbyen" and the more freely exposed "Geilo" in temperature region 1 (Fig 2a), and at the similar stations "Karasjok" and "Suolovuobmi" in region 6.

3.3 Precipitation scenarios

Fig. 6 shows precipitation changes from 1980-1999 to 2030-2049 projected by the dynamically and empirically downscaled scenarios for the 13 precipitation regions in Fig. 2b. The significance of the projected changes at 4 localities is given in Table 1. The two approaches show some common geographical patterns: Significant increase in autumn precipitation is projected along the western coast of Norway, while significant increase in winter precipitation is projected in southern parts of the country. The dynamical downscaling, however, projects maximum increase in annual as well as autumn precipitation further south along the west coast than the empirical downscaling.

Table 1. Significance (according to t-test) of precipitation changes from 1980-99 to 2030-49 for dynamically (DD) and empirically (ED) downscaled scenarios. (N=Not significant ; S=Significant; Sign. level in brackets.)

STATION	SCENARIO	WIN	SPR	SUM	AUT	ANNUAL
Bjørnholt	DD	S(10%)	N	N	N	N
	ED	S(5%)	N	N	N	N
Samnanger	DD	S(10%)	N	S(1%)	S(1%)	S(1%)
	ED	S(5%)	N	N	S(1%)	S(5%)
Tromsø	DD	N	N	N	S(5%)	S(10%)
	ED	S(10%)	N	N	S(1%)	S(1%)
Karasjok	DD	N	N	N	S(10%)	N
	ED	N	S(5%)	N	S(1%)	S(5%)

Table 2. Significance (according to t-test) of differences between dynamically and empirically downscaled precipitation scenarios. (N=Not sign.; S=Sign; Sign. level in brackets.)

STATION	WIN	SPR	SUM	AUT	ANNUAL
Bjørnholt	N	N	N	N	N
Samnanger	N	N	S(1%)	N	S(5%)
Tromsø	N	N	N	N	N
Karasjok	N	N	N	N	N

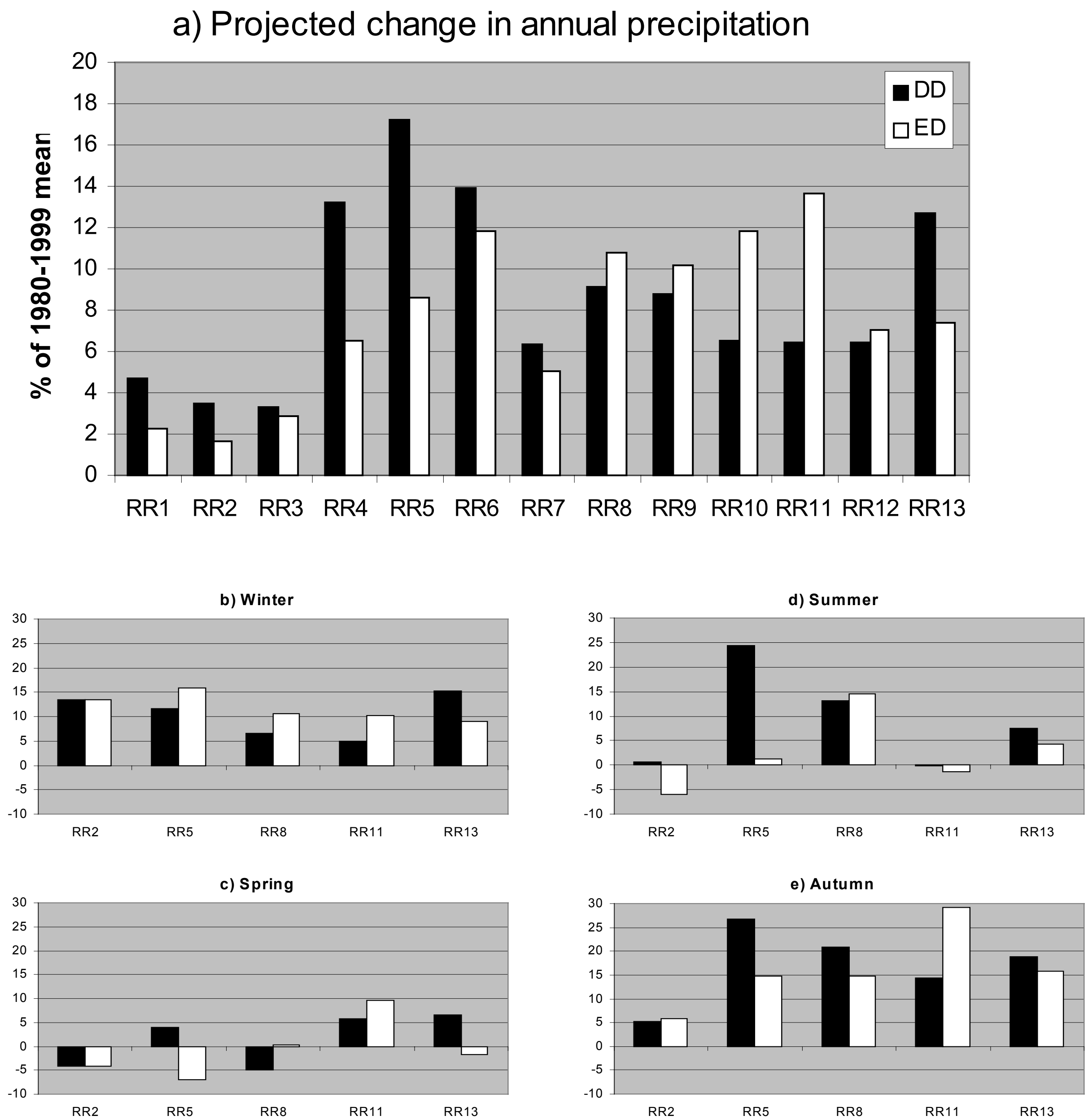

Figure 6. As Figure 4, but for precipitation. Unit: % of 1980-1999 mean precipitation. Changes in annual (a) and seasonal (b-e) precipitation are given.

There is also a difference between the downscaling approaches concerning summer precipitation in south-western Norway (Fig. 6d, RR5) as the dynamical downscaled precipitation scenario shows a significant increase, while the empirically downscaling projects no change. When applying a t-test on the differences between the seasonal scenarios at 4 localities (Table 2), this difference in summer precipitation is actually the only significant difference between the seasonal precipitation projections.

4. Discussion

4.1 Temperature

Though not statistically significant, the main difference between the empirically and dynamically downscaled temperature scenarios is that empirical downscaling projects considerably larger winter warming in inland valleys than the dynamical downscaling does. This indicates that the main difference is connected to inversion-exposed inland areas. The topographical resolution applied in the dynamical downscaling is too coarse to dissolve ground inversions. Thus, if the future winter warming will be associated with a weakening of ground inversions, the dynamical downscaling model would not be able to include this part of the warming. The empirical downscaling, on the other hand, projects weaker ground inversions in the future warmer winters, because the ground inversions historically have been weaker in mild winters than in cold winters. The physical reason is that mild winters have been associated with weather conditions that are unfavourable for ground inversions, i.e. more cyclone activity and consequently more cloudy and windy conditions. Besides, the snow cover on the valley floors have probably been less persistent in mild winters, contributing to a positive feed-back on the temperature, while the snow cover in the Norwegian mountains has been persistent even during mild winters. The empirical downscaling technique implies the assumption that the future winter warming will follow the patterns of the warm winters in the past, and it may be questioned is if this is reasonable.

Hanssen-Bauer and Førland (2000) showed that the GSDIO integration at average gives a strengthened north-south pressure gradient over Norway during the scenario period. Bjørge et al. (2001) concluded that the results from the dynamical downscaling give an increase, both in average mean 10 m wind-speed and in precipitation, and that these changes probably are connected to larger cyclonic activity in the area. Knippertz et al. (2000) concluded that also the GHG integration (including increasing concentrations of greenhouse-gases only) with the ECHAM4/OPYC3 gives increase in wind speeds and cyclonic activity in winter. It thus seems reasonable that the future winter warming will be accompanied by increased average wind speed and cloud cover, which most likely will lead to weaker and/or less frequent inversions. The expected general reduction of the period with snow-covered ground will also make the conditions less favourable for ground inversions. This may seem to be contradictory to the results from e.g. Giorgi et al. (1997), which show that projected winter warming rates in the Alps increase with elevation, at least up to 2 km. However, the physical explanation of the projected increasing warming rates with elevation is that the winter snow cover in the mountains is reduced in the Alps (Giorgi et al. 1997). In Norway (and other locations at higher latitude), it is reasonable to suggest that the reduction in winter snow-cover will be larger in the lowlands than at the mountain, at least during the first decades of the warming. The results from the empirical downscaling, which include higher winter warming rates in valleys and at other inversion exposed locations than in the mountains and along the coast, are thus probably right in a qualitative sense. It is still likely that the empirical downscaling technique exaggerates this effect, as the future warming may be less related to increased cyclone activity than mild winters in the past.

4.2 Precipitation

The only statistically significant difference between the results of the two downscaling approaches was found during summer, when the dynamical downscaling projects increased precipitation in southwestern Norway, while empirical downscaling projects no significant change. The present empirical downscaling method has a clear weakness concerning summer precipitation, as only changes connected to changes in the SLP field are modelled in this season. Eventual changes connected to the expected intensification of the hydrological cycle are not included. The empirical model may be improved by inclusion of air humidity as predictor. Hellström et al. (2001) compared empirically and dynamically downscaled precipitation scenarios for Sweden based upon HadCM2 (Johns et al. 1997) and ECHAM4. They included the humidity at 850hPa as predictor in their empirical downscaling model. Still, the largest spread in the downscaling results occurred in summer. Wilby and Wigley (2000) pointed out that also dynamical climate models may have problems with modelling summer precipitation: In summer, the correlation between specific humidity and precipitation was stronger in the HadCM2 than in observations, probably a result from oversimplification of the precipitation process. This may potentially lead to a too rapid increase in precipitation when specific humidity increases. Hellström et al. (2001) found, however, that the summer precipitation scenarios based upon dynamical and empirical downscaling of ECHAM4 were more in agreement than the similar based upon HadCM2. We thus suggest that in the present analysis, the dynamical downscaled results probably are most realistic concerning summer precipitation.

Though not significant, there were also differences between the downscaled precipitation scenarios concerning the location of the area of maximum precipitation increase. Both scenarios showed maximum increase along the western coast, but the empirically downscaled scenario showed maximum increase further north than the dynamically downscaled scenario. The reason for this difference is unclear, but preliminary experiments suggest that the exact position of maximum precipitation change may be sensitive to the choice of predictor area or integration area applied in the models. The present analysis gives no clue concerning which of the downscaling results that is most realistic on this point.

5. Summary and conclusions

Analysis of differences between results from dynamical and empirical downscaled climate scenarios based on the same global model run, may reveal weaknesses of the respective methods. In the present investigation empirical downscaling tends to give higher warming rates than dynamical downscaling, especially during winter at sites that are exposed for temperature inversions. Though the differences are not statistically significant at the 5% level, it is discussed whether the geographical signature of the empirically downscaled warming rates, which implies a reduction in the average strength of ground inversions during winter, is reasonable. The dynamical downscaling model does not resolve ground inversions properly, and is thus not able neither to support nor contradict this feature. It is concluded that a reduction in frequency and/or average strength of winter inversions is consistent with the projected increase in wind speed and reduced winter snow cover in the lowlands. The results from the empirical downscaling are thus probably qualitatively right, although they may exaggerate this feature.

For precipitation, a statistically significant difference between dynamically and empirically downscaled scenarios was found in summer in southwest Norway. The results from the dynamical downscaling are probably the most reliable, as the empirical downscaling models for the summer months only can reproduce changes caused by changes in atmospheric circulation. There are also some differences between dynamically and empirically downscaled scenarios concerning the exact areas of maximum precipitation increase, but these are not statistically significant.

The empirical and dynamical downscaling results agree on central points. The projected temperature increase is at maximum in winter and at minimum in summer. The warming rate increases from south to north and from coast to inland. Both downscaling techniques give statistically significant precipitation increase of winter-precipitation in southern Norway and of autumn-precipitation in western and northern regions. Agreement between the downscaling models is no guarantee for the realism of the modelled climate change, but it adds credibility to the results, given that the large-scale scenario is realistic.

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