INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **20**: 1693–1708 (2000)

TEMPERATURE AND PRECIPITATION VARIATIONS IN NORWAY 1900–1994 AND THEIR LINKS TO ATMOSPHERIC CIRCULATION

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Received 4 October 1999
Revised 24 March 2000
Accepted 24 March 2000

ABSTRACT

The main aim of the present study was to identify to what degree decadal scale variability and long-term trends in temperature and precipitation in Norway can be attributed to variations in the dominating atmospheric circulation patterns. Empirical models were developed and tested on monthly series of temperature and precipitation in different regions in Norway. The monthly mean sea level pressure (SLP) field over the northern North Atlantic and northern Europe was used as a predictor. Principal components (PCs) deduced from this field were used as a basis for stepwise multiple regression analysis. The downscaling models were developed using 1925–1969 as a training period, while 1900–1924 and 1970–1994 were used as validation periods. Model testing revealed that the temperature variability during 1970–1994 in most cases was better simulated than the variability during 1900–1924. The models reproduced most of the observed trends and decadal scale variability from 1940 to present. They also reproduced the precipitation trends in western Norway before 1940. However, the temperature increase observed over all the country in 1900–1940 was not reproduced. Nor was the increased winter precipitation in southeastern Norway during the same period. It is concluded that the temperature and precipitation changes observed in Norway during the last 40 years can mainly be attributed to variations in the SLP field. Variations in the precipitation conditions in the eastern parts of the country, and in temperature all over the country, during 1900–1940 are probably connected to changes in external forcings and/or atmosphere–ocean interactions. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: temperature trends; precipitation trends; atmospheric circulation; early 20th century warming

1. INTRODUCTION

The global mean temperature near the surface of the earth has increased by about 0.7°C in the 20th century (Parker and Horton, 1999). At least part of this temperature increase is most probably caused by an increased radiative forcing connected to the increased concentration of greenhouse gases in the atmosphere (Santer *et al*., 1996). During the same period, Norway has experienced a similar temperature increase (Hanssen-Bauer and Nordli, 1998), while precipitation has increased by 5–15% in most parts of the country (Hanssen-Bauer and Førland, 1998a). Regional and local climate variations can be caused directly by variations in external forcing or indirectly by variations in dominating atmospheric circulation. In Norway, the interannual climate variability is great, and several studies have shown a correlation between local temperature or precipitation and simple circulation indices, such as the North Atlantic Oscillation (NAO) index (e.g. Hurrell, 1995). The present paper is a more systematic study of how observed trends and decadal scale variations in temperature and precipitation in Norway during the 20th century have been related to variations in atmospheric circulation. Such connections can be valuable tools for application in empirical downscaling models. Should 'forecasting' the NAO prove possible (e.g. from sea surface temperatures (SSTs)), they could also be applied in seasonal forecasting.

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2. DATA

2.1. Predictands

Using a combination of principal component (PC) and cluster analyses (Singleton and Spackman, 1984) of 55 Norwegian temperature series, Hanssen-Bauer and Nordli (1998) concluded that the temperature variation in Norway during the last 100 years is described fairly well by standardized series of monthly temperature from six ‘temperature regions’ (Figure 1(a)). These regions are not characterized by internally uniform temperature, but rather by highly correlated time-series of temperature. Hanssen-Bauer and Førland (1998a) concluded from an analysis of 145 precipitation series that representative series of monthly values from 13 ‘precipitation regions’ (Figure 1(b)) are needed to give a satisfactory description of the time variation of precipitation in Norway. The method used for defining the precipitation regions is described by Hanssen-Bauer *et al.* (1997). The standardized temperature series are given as anomalies from the 1961–1990 monthly averages, while the precipitation series are given as percentages of the monthly averages for the same period. Standardizing precipitation in this alternative way makes it easy to reverse the calculation and deduce local precipitation series from the regional series (Hanssen-Bauer *et al.*, 1997).

The six regional temperature series and 13 regional precipitation series which are used as predictands in the present analysis are, as far as possible, based on series homogenized using the standard normal homogeneity test (Alexandersson, 1986). Basic results from testing the precipitation series were summarized by Hanssen-Bauer and Førland (1994). Using regional series rather than series from single stations reduces the risk of including local phenomena like the urban heat island effect. The possible effects of undetected inhomogeneities will also be reduced. In general, the regional series are thus of very high quality. An exception may be the first two decades in temperature regions R05 and R06 and precipitation regions R12 and R13, as few stations existed in the northernmost regions at the beginning of the century.

Results are presented for three locations (Oslo, Bergen and Tromsø; cf. Figure 1) in Section 4. Note that the ‘observed’ series used in this study are not series from the actual stations, but rather the regional series adapted to these locations. This kind of adaptation, which for precipitation includes multiplying by the 1961–1990 mean monthly sum, and for temperature includes multiplying by the monthly standard deviation (S.D.) and adding the mean value for the actual site, may be accomplished for any location in Norway.

Figure 1. The Norwegian (a) temperature and (b) precipitation regions used in the present study. The key locations mentioned in the text are shown

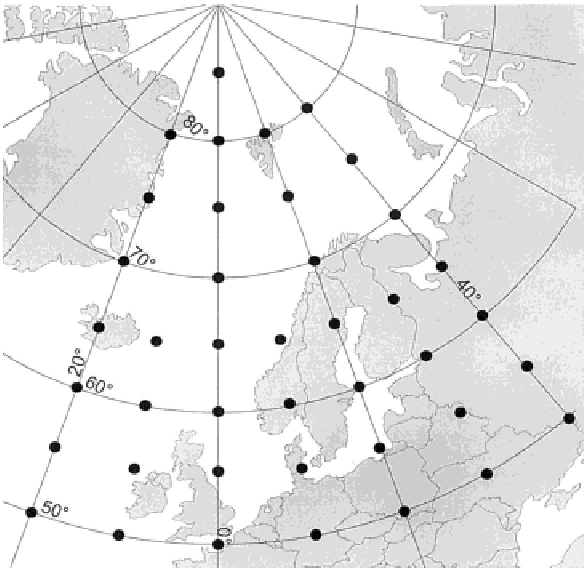

Figure 2. The SLP grid-points included in the predictor data-set

2.2. Predictor

The gridded sea level pressure (SLP) field in the area 50–90°N, 20°W–40°E (Figure 2) was used as the predictor. For the period 1900–1949, data from the UK Meteorological Office (UKMO) were applied. Jones (1987) warned about systematic errors in this data-set at the beginning of the present century over the polar basin, parts of Siberia and northern Canada, and over Greenland. These errors could affect only the two northernmost grid-points in the data-set used in the present analysis. In order to evaluate the possible influence of the errors, some of the model development described in Section 3 was repeated excluding the two northernmost grid-points. No major differences were found, and it was thus concluded that the effect of the errors mentioned by Jones (1987) is minor for the present models.

During 1950–1994, monthly SLP values for the grid-points in Figure 2 were deduced from the National Center for Environmental Prediction (NCEP) data-set. Comparisons of monthly SLP values from selected grid-points during 1949–1984 (not shown) revealed no systematic differences between the UKMO and the NCEP data-sets.

3. MODEL DEVELOPMENT

The dimensionality of the gridded SLP data-set was reduced using PC analysis (e.g. Preisendorfer, 1988). The analysis was applied in S-mode according to the terminology used by Huth (1996), which implies that the eigenvectors (loadings) describe spatial patterns, while the PCs (amplitude functions) describe the time variation. The analysis was performed on the entire data-set without differentiating between the 12 calendar months. The anomalies associated with the first four PCs, which account for 88% of the variance in the SLP field (Table I), are shown in Figure 3. The first PC (PC1) is associated with a variation of the depth of the Icelandic low. Negative values for this component indicate anomalously low pressure over Iceland (high NAO index) and an intensified southwesterly wind field over Norway. PC2 is associated with anomalies in the northwesterly/southeasterly wind field over Norway. Positive values are associated with northwesterly wind anomalies. PC3 is connected to anomalies in the southerly/northerly wind fields over the country, and positive values are associated with southerly wind anomalies.

Models expressing regional temperature and precipitation as functions of the leading PCs were developed using multiple linear regression analysis. Models were developed separately for the 12 calendar

Table I. Eigenvalues and proportion of variance accounted for by the 20 leading principal components

	Eigenvalue	Difference	Proportion	Cumulative
PC1	644.88	327.37	0.43	0.43
PC2	317.52	26.63	0.21	0.64
PC3	290.89	217.45	0.19	0.83
PC4	73.44	9.81	0.05	0.88
PC5	63.64	13.66	0.04	0.92
PC6	49.98	31.18	0.03	0.95
PC7	18.80	7.54	0.01	0.97
PC8	11.26	3.03	0.01	0.97
PC9	8.23	2.20	0.01	0.98
PC10	6.03	0.69	0.00	0.98
PC11	5.34	2.27	0.00	0.99
PC12	3.07	0.63	0.00	0.99
PC13	2.44	0.59	0.00	0.99
PC14	1.85	0.13	0.00	0.99
PC15	1.72	0.20	0.00	0.99
PC16	1.53	0.40	0.00	0.99
PC17	1.12	0.15	0.00	0.99
PC18	0.97	0.13	0.00	1.00
PC19	0.84	0.07	0.00	1.00
PC20	0.76	—	0.00	1.00

months, and for temperature and precipitation in the regions shown in Figure 1(a and b), respectively. Regression analyses between the predictands and the 20 leading PCs were performed to decide the number of PCs to include as predictors in the final models. PC15 was the highest component, accounting for more than 10% of the variance in one of the predictands (September temperature in region R02). However, as the difference between the eigenvalues of PC15 and PC16 is small (Table I), it was decided that PC16 should also be included. Figure 4 shows some examples of how much of the variance in the predictands the first 16 PCs account for in January, April, July and October. In order to exclude components without significant influence in the specific models, stepwise regression was applied. A significance level of 0.15 was used as condition for entry of new components into the models. The models were developed using data from the period 1925–1969 (training period), while the rest of the data (1900–1924 and 1970–1994) were saved for testing the models (validation periods).

The 228 resulting models were presented in detail by Hanssen-Bauer (1999). Some main features are summarized in this paper. For winter temperatures, PC1 (Figure 3(a)) is dominating, especially in southern parts of the country (regions T01 and T02), where it accounts for almost 50% of the variance (Figure 4, left panels). The regression coefficients are negative, as the maritime southwesterly winds coming in over Norway are relatively warm in winter. In summer, PC2 and PC4 dominate the temperature variance along the entire west coast (regions T02 and T04). Both have negative regression coefficients, as a northwesterly wind anomaly in summer is associated with cold air. In southeastern Norway (T01), PC3 is most important for the summer temperatures. Southerly winds are associated with positive temperature anomalies. PC3 is also most important for the temperature in spring and autumn all over the country. For temperature, the regression coefficients associated with east/westerly wind anomalies over Norway change sign some time during spring and autumn (e.g. westerly winds are, relatively speaking, ‘warm’ in winter but ‘cold’ in summer).

For precipitation, the regression coefficient corresponding to a specific component usually does not change sign throughout the year. In region R05 in southwestern Norway, PC1 accounts for more than 60% of the precipitation variance in January, and it is also the dominating term in the other months. Southwesterly winds are associated with orographically enhanced precipitation, as the humid maritime air masses are then forced up over the central Norwegian mountains. In southeastern and northwestern

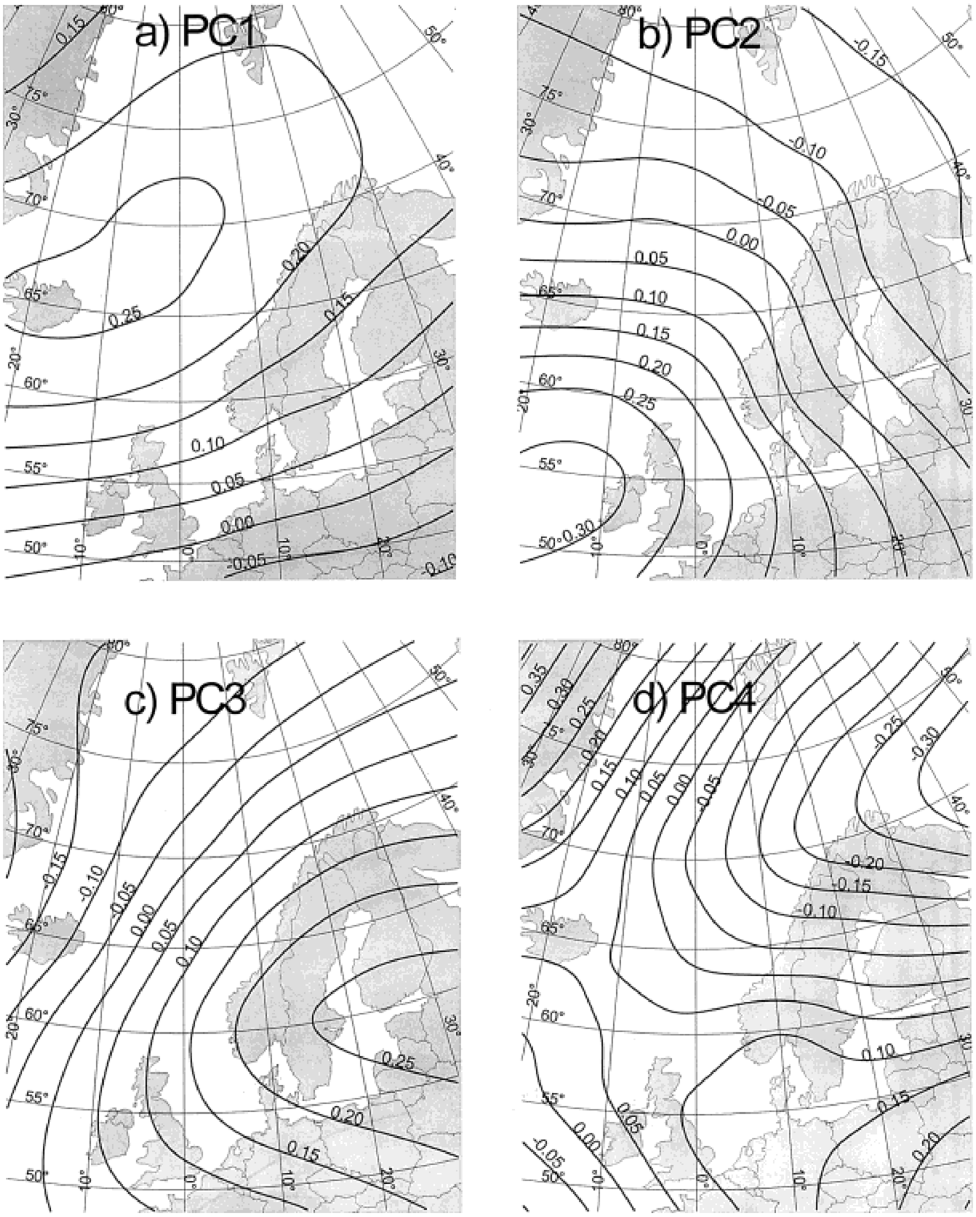

Figure 3. Anomaly pattern associated with the first four PCs

Norway (e.g. regions R02 and R11, respectively), PC2 is most important for the precipitation conditions (Figure 4, right panels). The orographic effects lead to opposite signs of the regression coefficients in the two regions, as northwesterly winds are associated with precipitation in region R11, while southeasterly winds are associated with precipitation in region R02.

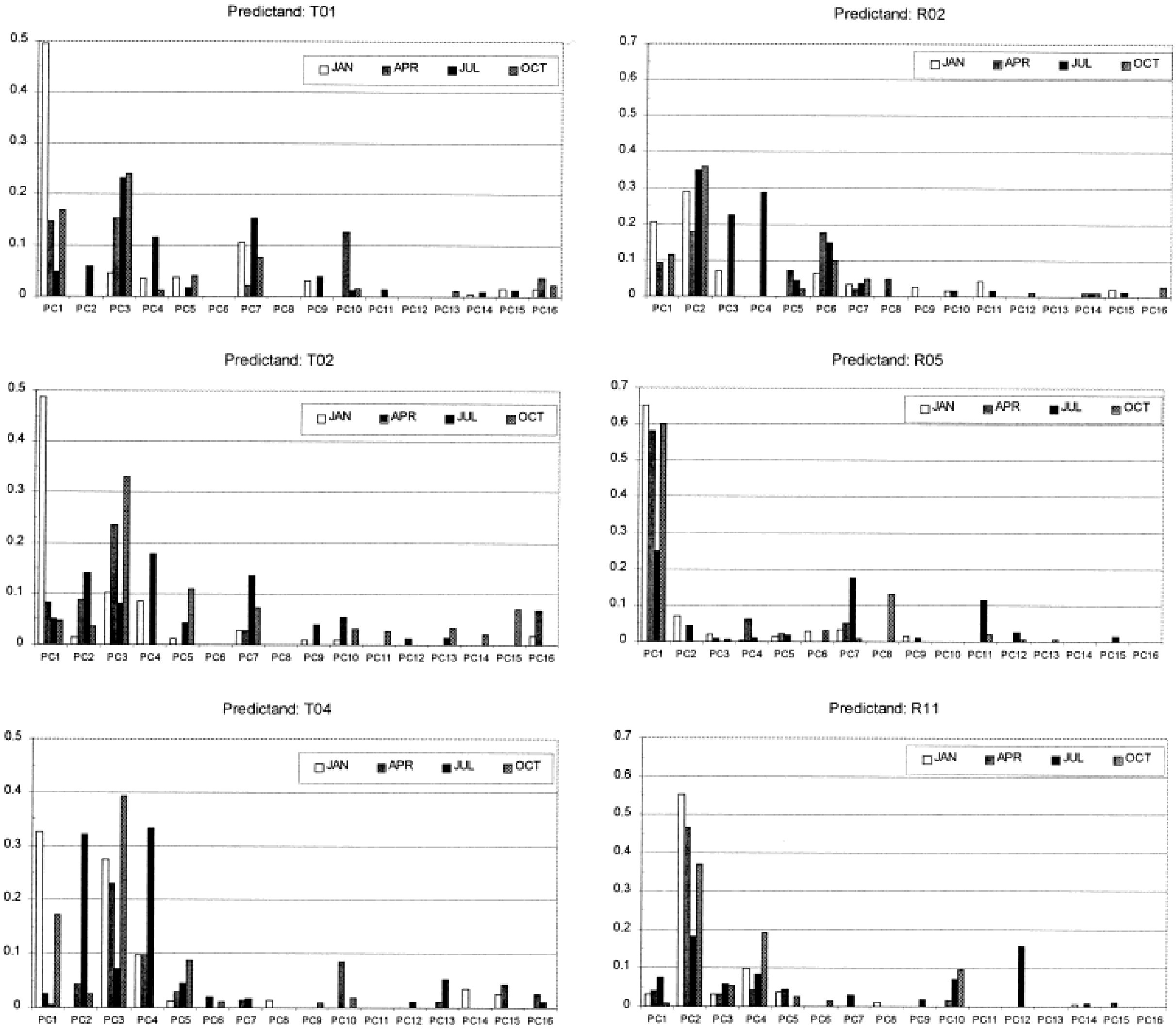

Figure 4. Variance contribution of the first 16 PCs when modelling temperature (left) and precipitation (right)

4. RESULTS

4.1. Comparing training and validation periods in January, April, July and October

Correlation coefficients between observed values and values modelled for the training period and for the two validation periods are shown in Figures 5 and 6 (temperature and precipitation, respectively). Most of the correlation coefficients based on the training period (black bars) are between 0.7 and 0.9, implying that 50–80% of the interannual variance in the training period is accounted for by the models. Exceptions are several precipitation models for the central region R07 and the northernmost regions R12 and R13 (Figure 1(b)), where the correlation coefficient is less than 0.7. The mountainous region R07 is a ‘transition zone’ between southeastern and northwestern regions rather than a uniform region (Hanssen-Bauer *et al.*, 1997). In the rugged terrain of this region, there are no distinct precipitation patterns connected to winds from different sectors. It is thus reasonable that precipitation models based on circulation indices do not work very well here. With regard to regions R12 and R13, the SLP grid-net used in the present analysis (Figure 2) is probably not optimal for modelling precipitation in this area.

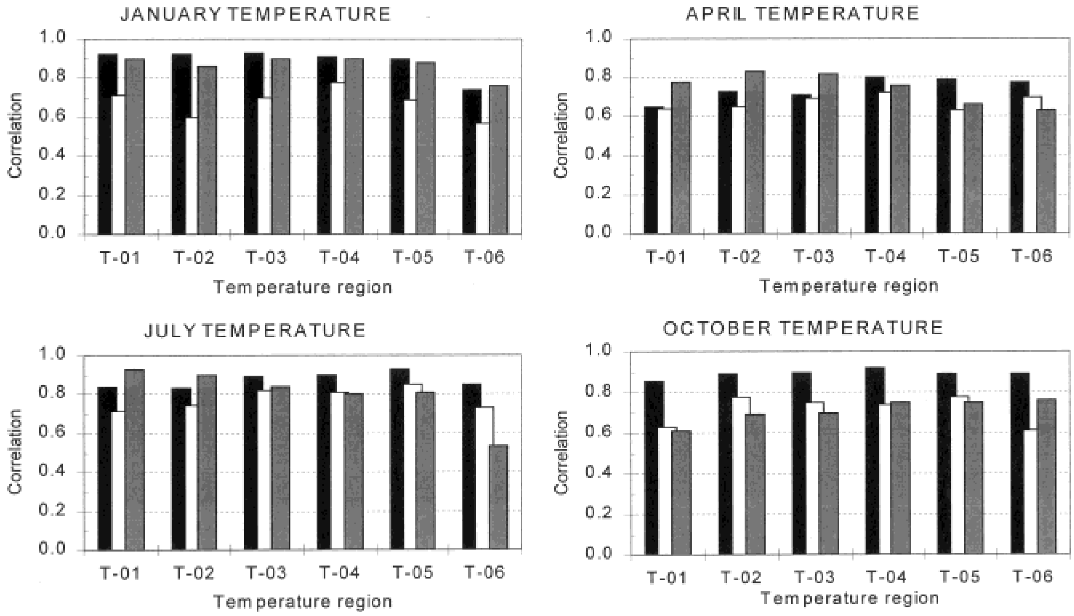

Figure 5. Correlation coefficients between series of observed and modelled monthly mean temperatures for the regions T01 to T06. Black bars show the results for the training period 1925–1969, while white and grey bars show the results for the validation periods 1900–1924 and 1970–1994, respectively

The grid-net was chosen because Norway is situated in the westerlies. However, region R12, and especially region R13, will certainly receive precipitation from winds from the northeast. Several precipitation models for regions along the west coast, on the other hand, yield correlation coefficients greater than 0.9, and thus account for more than 80% of the variance during the training period. These high correlation coefficients are caused by orographic effects, which tend to intensify precipitation when westerly maritime air masses are forced up over the central Norwegian mountains, but leave the west coast in rain shadow when easterly winds are blowing (see Section 3).

In winter, spring and summer, the correlation coefficients for the temperature models (Figure 5) are, in most cases, rather similar for the training period and at least one (usually the last one) of the validation periods. Exceptions are found in the northernmost regions. In the autumn, both validation periods show considerably lower correlation coefficients than the training period in all regions. For precipitation, there is, in most cases, a good agreement between the correlation coefficients based on the training period and at least one of the validation periods for winter, spring and autumn (Figure 6). Exceptions are found in regions R07, R12 and R13, and also in summer in other regions.

The main impression is that the models account for a major part of the temperature and precipitation variability in southern and northwestern parts of Norway. They are, however, less satisfactory in the northeastern part of the country and, concerning the precipitation models, also in a ‘transition zone’ in mid-Norway. The best performance of the temperature models was found for the winter and summer seasons, while the autumn temperature models show an artificial skill in the training period. For precipitation, the best results were found during autumn and winter, while several models show an artificial skill during the summer.

4.2. Trends in annual and seasonal residuals

The models trained on the period 1925–1969 were then used on the entire period 1900–1994. In addition to the annual results, the results below are presented on a seasonal basis (Winter = December–February; Spring = March–May; Summer = June–August; Autumn = September–November) rather than month-by-month. Results are presented for three locations (Figure 1): Oslo in southeastern Norway

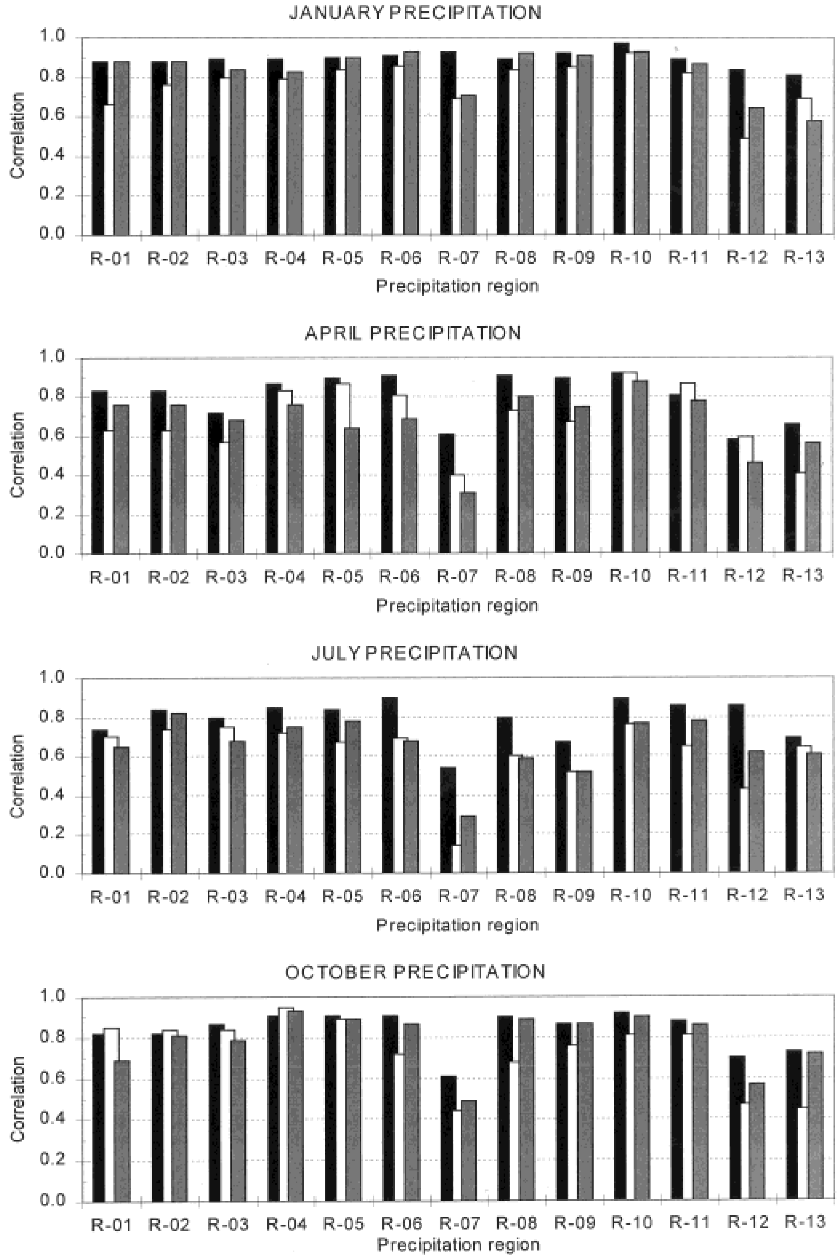

Figure 6. Correlation coefficients between series of observed and modelled monthly precipitation sums for the regions R01 to R13. Black bars show the results for the training period 1925–1969, while white and grey bars show results for the validation periods 1900–1924 and 1970–1994, respectively

(regions T01 and R02); Bergen in western Norway (T02 and R05); and Tromsø in northwestern Norway (T04 and R11). Results are presented partly as long-term trends in residuals, and partly as low-pass filtered curves of observed and modelled variables.

Linear trends in temperature residuals (observed minus modelled temperature) during 1900–1994 in Oslo, Bergen and Tromsø are positive on annual and seasonal bases (Figure 7(a)). A majority of these trends are statistically significant at least at the 5% level according to the Mann–Kendall non-parametric test (Sneyers, 1995). The positive trends in the annual residuals, which are statistically significant in Oslo

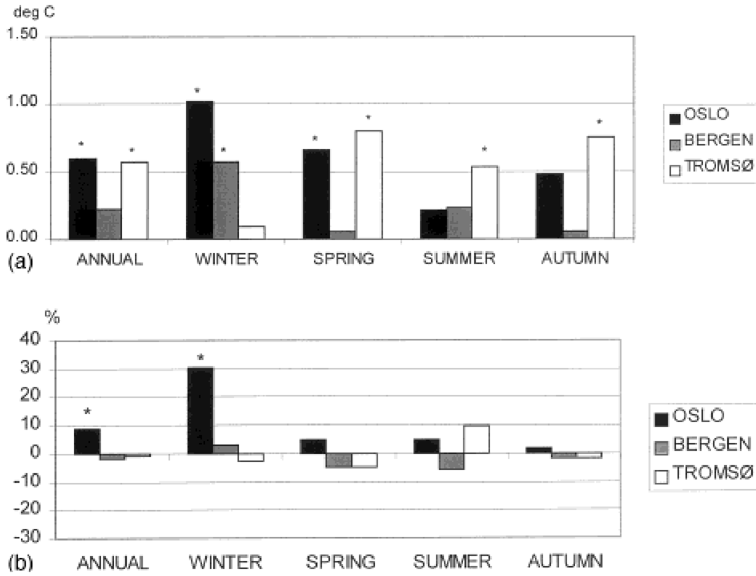

Figure 7. Trends in observed minus modelled (a) temperature and (b) precipitation during 1900–1994. Bars marked by asterisks symbolize trends that are statistically significant at the 5% level according to the Mann–Kendall non-parametric test

and Tromsø, appear because the series of observed temperature show an increase of about 0.5°C, which is not satisfactorily modelled. In spring, summer and autumn, the trends are also caused by the models' lacking ability to reproduce the observed temperature increases. In winter, on the other hand, the positive trends in the residuals appear because the models give negative trends, which are not found in the observations. In Tromsø, the trends in the temperature residuals are statistically significant in spring, summer and autumn, while in Oslo and Bergen the trends in temperature residuals are statistically significant during winter. In order to investigate closer the mismatch between observed and modelled temperature trends, trends in the residuals were also studied during different sub-periods (Hanssen-Bauer, 1999). These studies revealed that trends in the residuals are mainly caused by discrepancies between model results and observations in 1900–1940.

The trends in annual and seasonal precipitation residuals during 1900–1994 (Figure 7(b)) are mostly small and not statistically significant. The only exception is found during winter in Oslo. The significant positive trend there appears because the model gives a significant negative trend in winter precipitation, which is not found in the observations. This discrepancy is also reflected in the annual values.

4.3. Low-pass filtered annual and seasonal time-series

The conclusions concerning trends in residuals are confirmed by the low-pass filtered time-series (Figures 8–12) of observed and modelled temperature and precipitation anomalies at the three key locations. On an annual basis (Figure 8), the temperature models are unable to reproduce the warming before 1940, while the trends and decadal scale variability after 1940, to a large extent, are reproduced by the models. For annual precipitation, the models give very good results for the decadal scale variability in Bergen and Tromsø (except for the first decade in Tromsø), while they are unable to reproduce the observed trends and decadal scale variability before 1940 in Oslo.

Comparisons of the seasonal time-series (Figures 9–12) show that the inability of the models to reproduce the observed positive temperature trends before 1940 is caused by a malfunction of the models in all seasons. In Oslo and Bergen, the malfunction is least serious during summer, while in Tromsø it is least serious during winter. After 1940, seasonal trends and decadal scale variability in temperature are reproduced fairly well. An exception is autumn temperature (Figure 12), for which the observed negative trends after 1960 are not modelled satisfactory in Bergen and Oslo.

With regard to the discrepancy between observed and modelled precipitation in Oslo before 1940, it is clear that malfunction of the models during the winter season is the main reason for this (Figure 9). In Bergen and Tromsø, long-term trends and decadal scale variability in precipitation are modelled fairly well in all seasons.

4.4. *Summary of main results*

Temperature:

(i) Long-term trends and decadal scale variability were reasonably well accounted for after 1940, at least during winter, spring and summer.

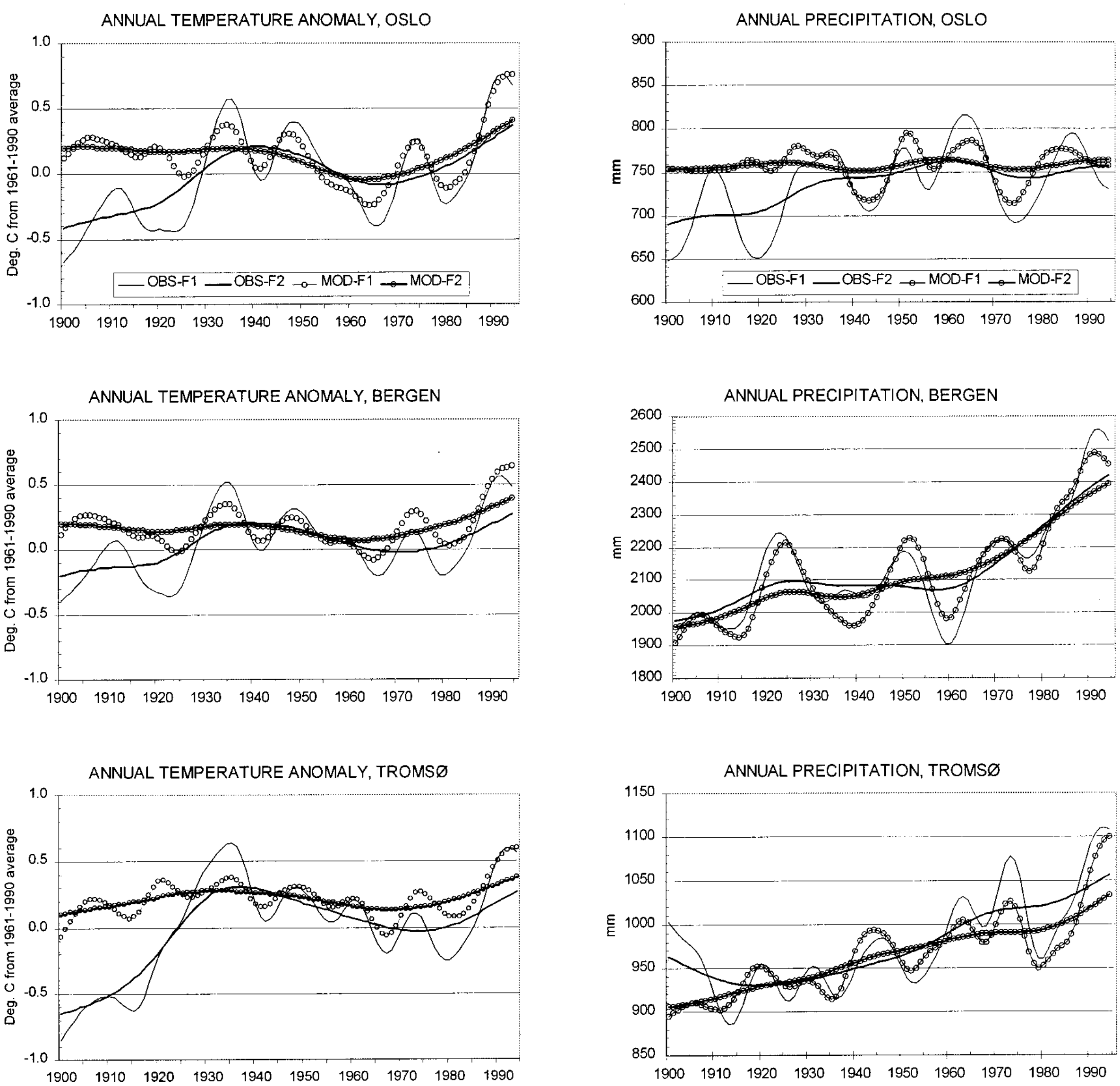

Figure 8. Low-pass filtered series of observed (solid curves) and modelled (dotted curves) *annual* temperature anomalies (left) and precipitation (right). The filters include a Gaussian weight function, where the S.D.s of the distributions are 3 (F1) and 9 (F2) years

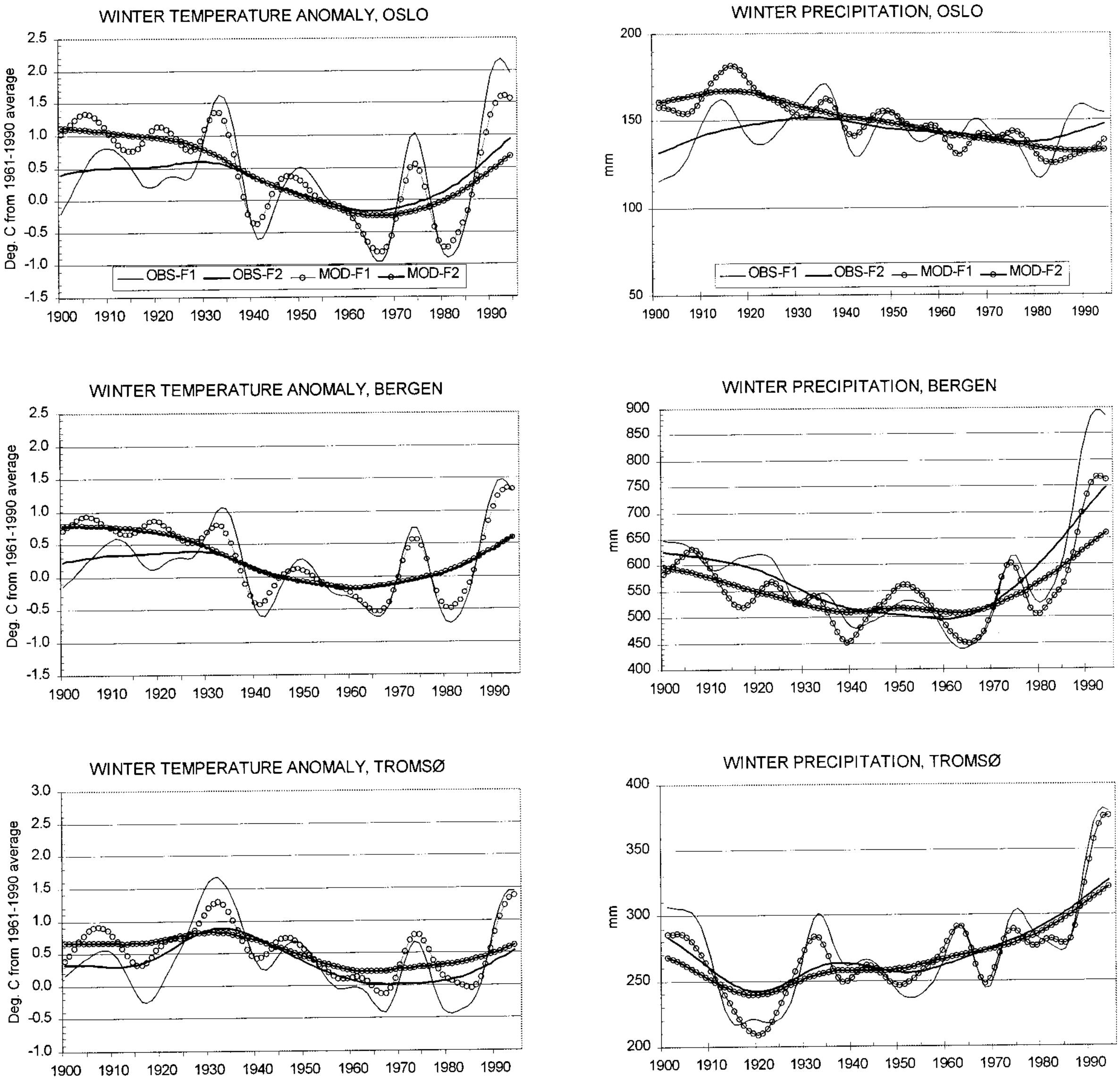

Figure 9. As for Figure 8, but for *winter*

(ii) The main discrepancy between the modelled and the observed temperature trends is that the models give little or no warming in 1900–1940, while observations from the entire country show a statistically significant warming during this period.

Precipitation:

(i) Long-term trends and decadal scale variability in annual and seasonal precipitation in western parts of Norway (both north and south) are very well accounted for by the models.
(ii) The only serious discrepancy between the model results and the observed precipitation in southeastern Norway is that winter precipitation increased during the period 1900–1940, while the model gave no such increase.

5. DISCUSSION AND CONCLUSIONS

The following discussion will focus on two aspects of the above results, before some conclusions are drawn concerning the use of the present type of statistical models for the empirical downscaling of future climate scenarios.

5.1. The precipitation models: why are they superior to the temperature models?

Precipitation is the result of highly non-linear processes and, in general, it is more difficult to model precipitation variation than to model temperature variation. It is thus tempting to ask why the present circulation-based regression models more successfully reproduce the observed trends in precipitation than in temperature. The close connection between atmospheric circulation and precipitation, which in the present study was revealed especially along the west coast of Norway, is the result of orographic effects.

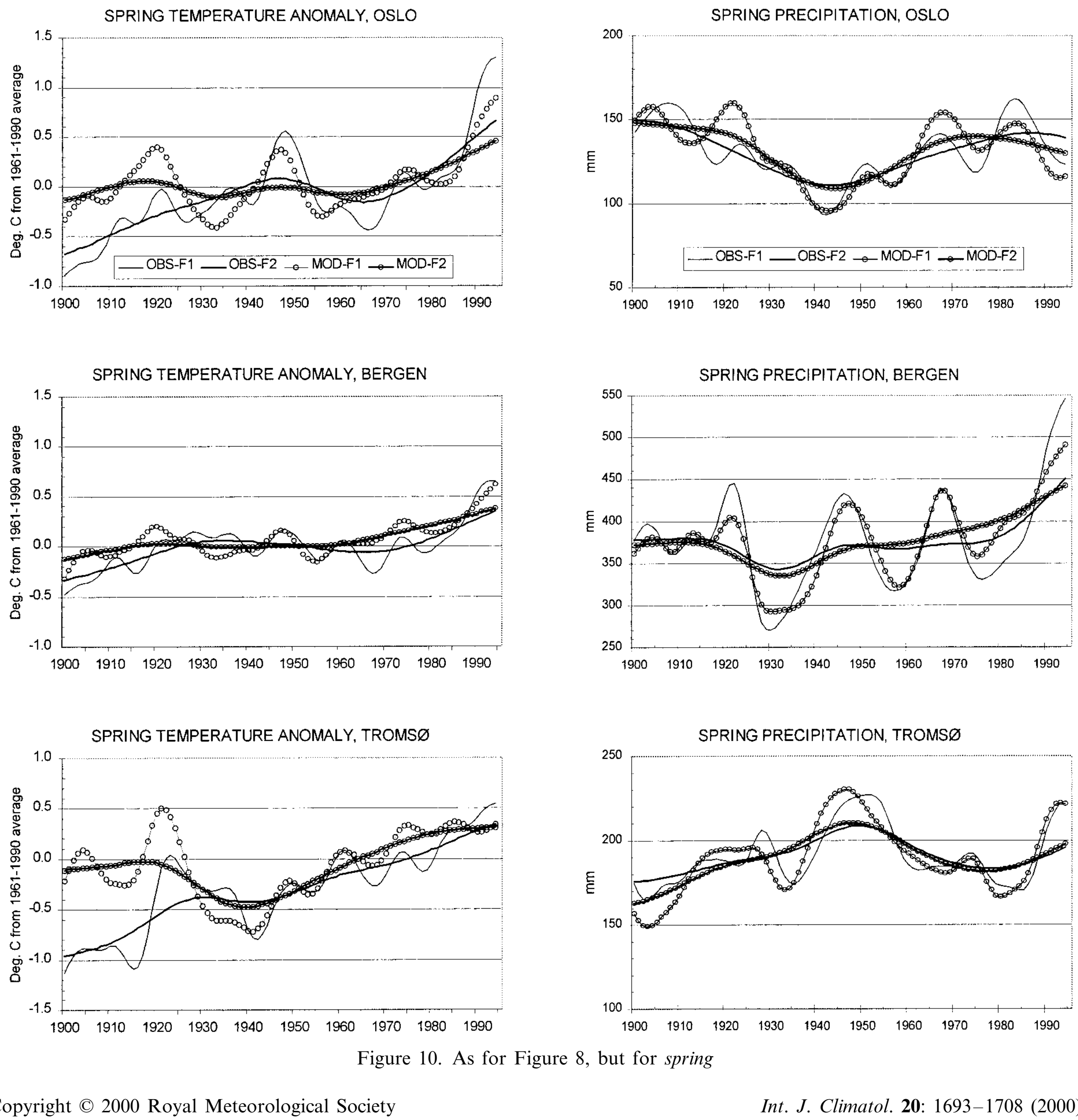

Figure 10. As for Figure 8, but for *spring*

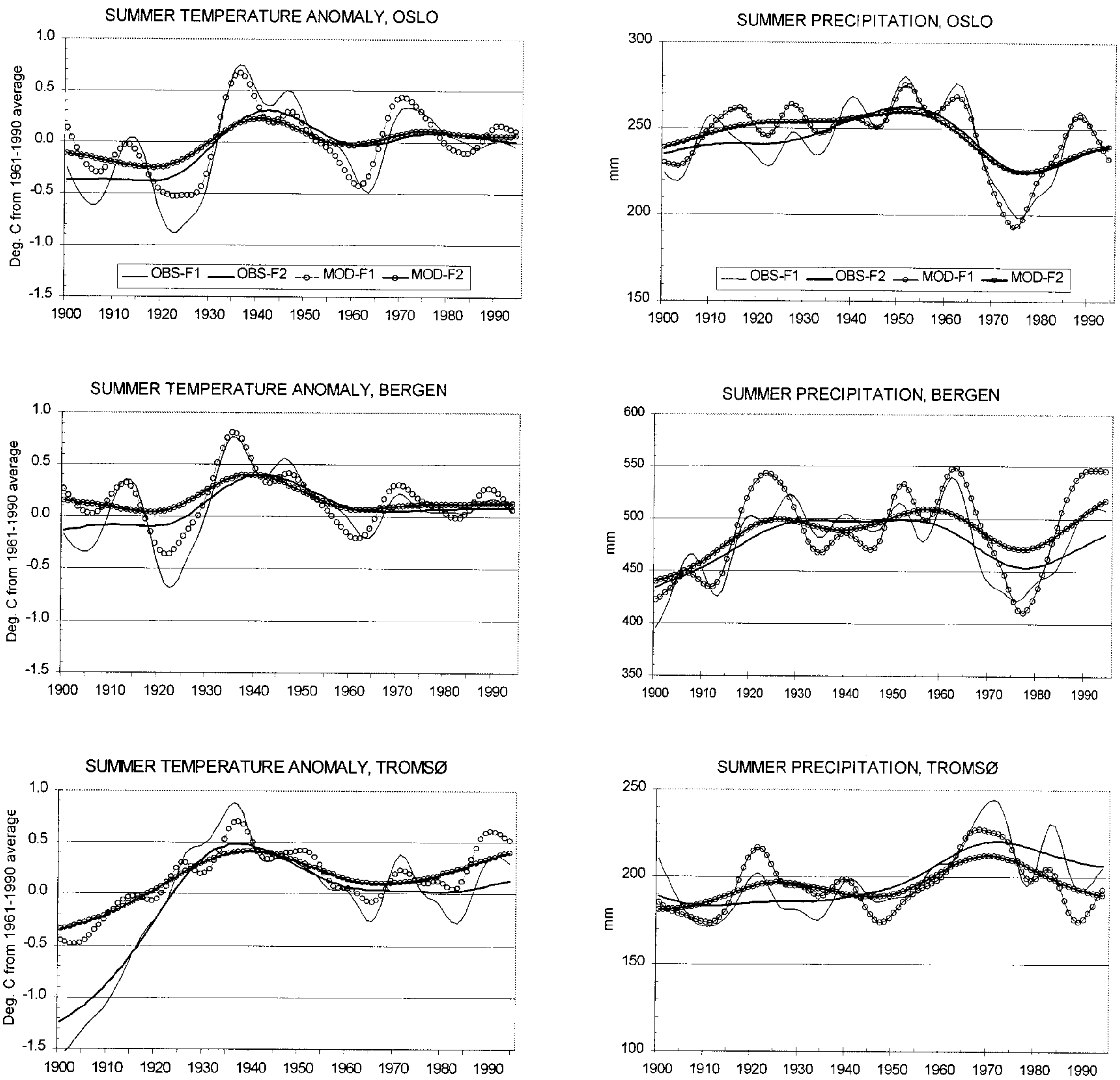

Figure 11. As for Figure 8, but for *summer*

Norway's geographical position at the west coast of a continent and in the westerlies, combined with the country's mountainous topography, makes the precipitation pattern very sensitive to changes in the SLP pattern. It can thus be concluded that the long-term trends and decadal scale variability of precipitation in Norway during the 20th century are mainly caused by variation in the atmospheric circulation patterns, while the temperature variations are probably also influenced by other factors.

5.2. The temperature models: why do they reproduce the trends after, but not before, 1940?

Norwegian series of annual mean temperature show two periods of statistically significant warming within the 20th century (Hanssen-Bauer and Nordli, 1998), one from the beginning of the century to 1940 and another from 1970 to the end of the series. Why is the first period of warming not satisfactorily modelled by the present circulation-based regression models while the second one is?

The second period of warming was associated with a strengthening of the average westerly wind field over Norway, especially during winter. In the present analysis, this is mainly seen as a negative trend (not shown) in the scores of PC1 of the SLP field (Figure 3(a)), and it is accompanied by positive trends in winter precipitation along the entire western coast. The warming after 1970 may thus, to a large degree, be explained by more frequent and/or stronger westerly winds, especially during winter. This intensified westerly wind field may be the result of natural variability, or it may be a response to the greenhouse warming effect, which, according to certain climate models, leads to an intensification of the storm track over northern Europe (Ulbrich and Christoph, 1999).

During the first period of warming, there was no strengthening of the average westerly wind field over Norway. In the present analysis, a positive trend (not shown) was seen in the PC3 scores of the SLP field (Figure 3(c)) during this period, indicating an increasing southerly wind anomaly over Norway. Still, according to the temperature models, this alone does not account for the observed warming from 1900 to

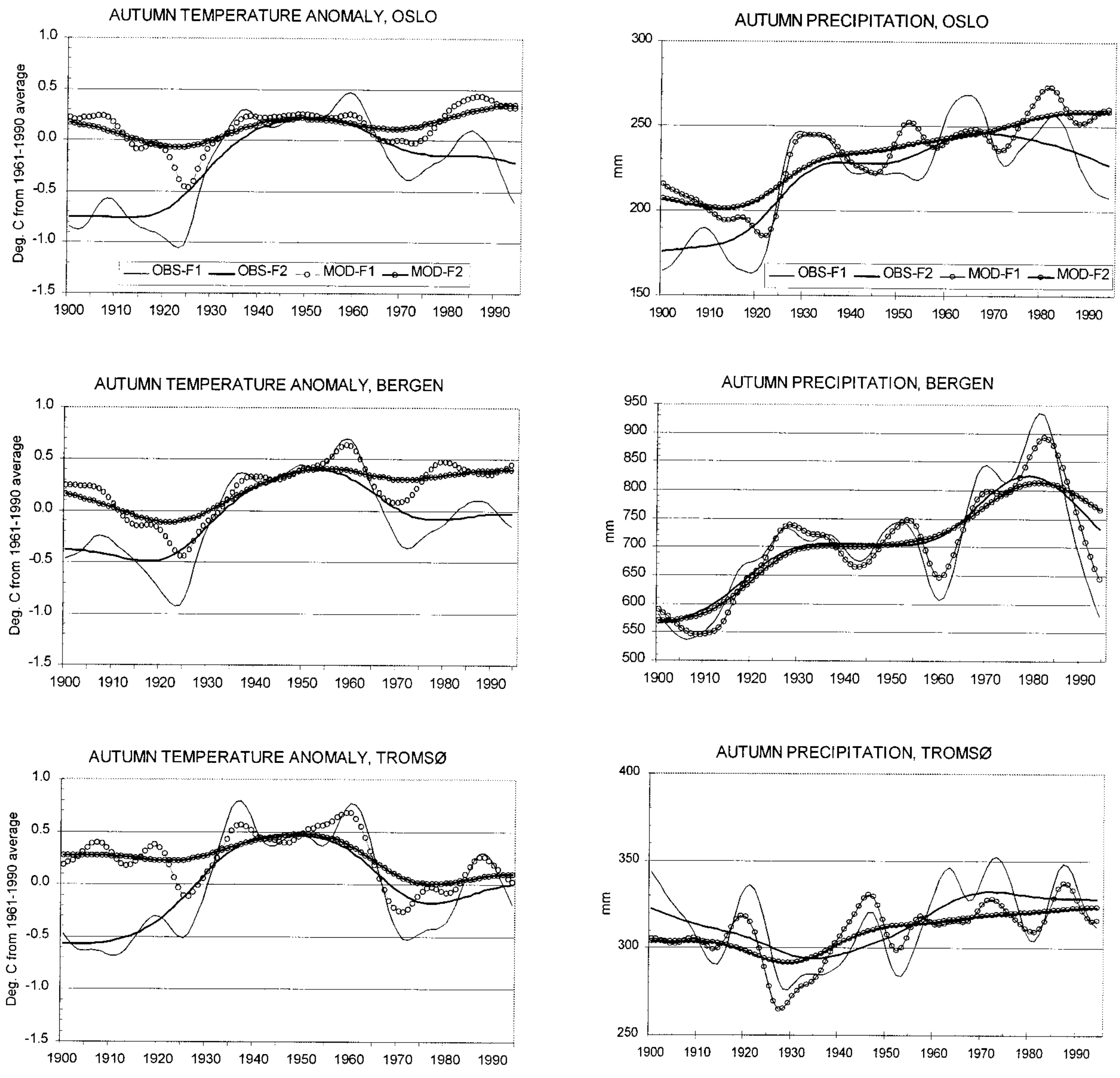

Figure 12. As for Figure 8, but for *autumn*

1940. This may be dependent on the data quality. The predictands are mainly based on homogenized meteorological series (see Section 2), but the predictors (the SLP data) might be inhomogeneous as they are derived from two different sources (NCEP and UKMO, respectively). However, if inhomogeneity of the SLP data led to a malfunction of the temperature models during 1900–1940, it would be difficult to explain the satisfactory modelling of precipitation in Tromsø and Bergen during this period. It can thus be concluded that the reason why the temperature models do not reproduce the temperature increase from 1900 to 1940 is because this increase was caused not only by systematic changes in the atmospheric circulation, but also by changes in the air mass characteristics for one or several of the circulation types. This is in accordance with Hanssen-Bauer and Førland (1998b), who concluded that the substantial warming that occurred at Svalbard in the European sector of the Arctic before 1940 was not caused by changes in the atmospheric circulation alone. It also supports Werner and von Storch (1993), who concluded that on time scales of several decades, low-frequency variations of Atlantic SSTs, in addition to the atmospheric circulation, control the central European winter temperature.

Global temperature series also show a temperature increase during 1900–1940. The geographical signature of this warming is different to the global warming of the last 30 years, as 'the early 20th century warming' is mainly seen at high northern latitudes in the Atlantic sector. Model simulations show that this warming may only partly be explained by the increase of greenhouse gases (e.g. Mitchell *et al*., 1995; Santer *et al*., 1996). Tett *et al*. (1999) concluded that, after considering several candidates, solar forcing may have contributed to the temperature changes early in the century. Fu *et al*. (1999) argued that a major part of the early 20th century warming might be explained as the result of short-term positive feedback effects, including both atmospheric and oceanic circulation. It is thus suggested that the temperature increase in Norway during 1900–1940 is part of this early 20th century warming, which might be caused either by changes in one of the external forcings of the climate system (e.g. solar forcing) and/or by internal air–sea or air–sea–ice interactions.

5.3. Conclusions and implications for empirical downscaling

The above results illustrate the importance of using long time-series when training and testing empirical downscaling models. One might jump to conclusions when studying model results based on the last 3–5 decades only. Regretfully, most empirical downscaling studies are based on data from these decades only. There exist relatively few digitized and quality controlled data for the period before 1950, and upper air data (which are used as predictors in several studies) are not available at all.

The present study also shows that the dominating atmospheric circulation patterns have a large influence on the climate in Norway. Changes in the frequencies of such patterns, whether they are natural or not, will thus influence the local climate. Empirical downscaling models, including relevant circulation indices, will account for this aspect. However, local climate is also affected directly by changes in the external forcings. A central point when using empirical downscaling to improve future scenarios on the local scale, therefore, is that the climate signals caused directly by changes in external forcings should also be expressed by at least one of the large scale predictors. The geopotential thickness might be a satisfactory predictor in this respect (although the time period available for developing and testing the models is then reduced).

Still, no downscaling model can describe changes or variability that is not somehow included in the global climate model from which the predictor fields are taken. It is thus important that all relevant changes in the external forcings are described by the global climate models. Changes in the 'greenhouse-forcing' are taken into account by these models, and the effects of increased concentrations of anthropogenic aerosols are included in several of the later model runs. However, the inability of the climate models to reproduce the global warming before 1940 indicates that there still exists mechanisms that are not sufficiently well described by these models.

ACKNOWLEDGEMENTS

This report results from the project 'Regional Climate Development under Global Warming' (Reg Clim) (Iversen *et al*., 1997), which received financial support from the Norwegian Research Council (NRC Contract No. 120656/720). The authors are indebted to two anonymous reviewers for their constructive suggestions.

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