*Nordic Hydrology*, 28, 1997, 21-36

# Estimating Regional Precipitation Trends Comparison of two Methods

**I. Hanssen-Bauer, E.J. Førland,**

**O.E. Tveito and P.Ø.Nordli**

The Norwegian Meteorological Institute, Oslo, Norway

Two different methods were applied to estimate long-term precipitation trends representative for regions in Norway. A new method, comparative trend analysis (CTA), was applied on 142 homogeneous precipitation series of 70-100 years. In this way, 12 precipitation trend regions were identified. Principal component analysis (PCA) was applied on a subset of 30 series during the period 1896-1994. The results from both analyses were used to estimate precipitation trend series at several locations. The estimates based upon the PCA were of same quality as the estimates based upon the CTA. However, by CTA it is possible to visualize the trend in a distinct region by using just one trend curve, while trend curves based on PCA are composed of contributions from 5 principal components.

The resulting trend curves document that the annual precipitation level has increased by 8-14% throughout this century in most Norwegian regions. The increase occurred not simultaneously all over the country. The regional differences in precipitation trends and variability are probably connected to variations in the atmospheric circulation patterns.

## Introduction

### Background

Climate scenarios based on further increase in greenhouse gases implies that within 50 years, the precipitation in Northern Europe will increase by 5-15% both winter and summer (IPPC 1996). Studies of regional and global trends in precipitation are thus of great interest. Establishing *e.g.* a global-mean record of precipitation is how-

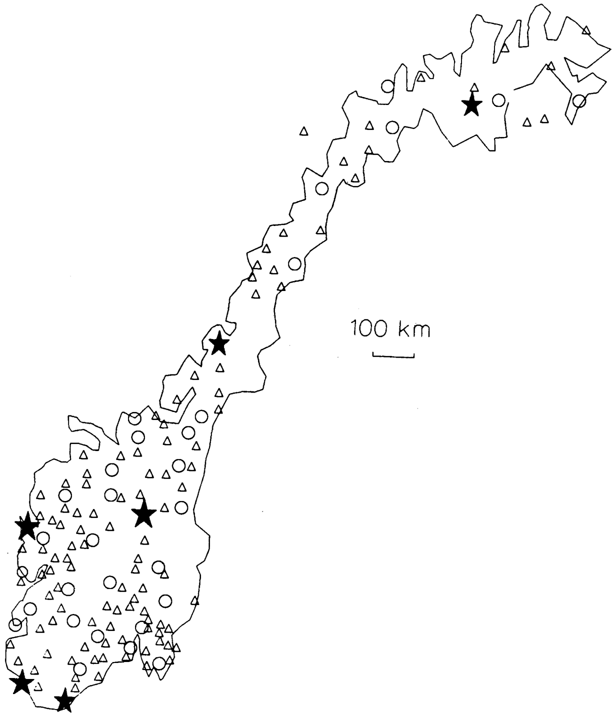


Fig. 1. Approximate position of the 142 stations which were used in the regionalization. Open triangles: stations used in CTA only. Open circles: stations used in CTA and PCA. Filled stars: stations used for evaluation.

ever associated with several problems. According to Hulme (1995), a major problem is "how to interpolate irregular site data".

The present article concerns interpolation of precipitation series representative for an arbitrary site (*e.g.* a grid point) or for an area. A new technique called "comparative trend analysis" (CTA), is introduced for defining regions of common precipitation trends and variability. Results from this analysis are summarized and compared to results from a principal component analysis (PCA).

## Data

Precipitation amount and variability may differ largely over small distances, due to orographic effects which are sensitive to small differences in circulation patterns. A denser network of stations is thus needed for analyzing precipitation variability, than for similar analyses of air temperature. The homogeneity of the series included in the analysis is also of crucial importance. It has been demonstrated that successive changes in gauge design (Groisman *et al.* 1994) or environments of gauges (Hanssen-Bauer and Førland 1994) may lead to virtual positive precipitation trends.

A high quality set of precipitation series for the period 1895-1994, covering the Norwegian mainland was recently completed (Hanssen-Bauer *et al.* 1995). The data set consists of series of monthly precipitation sums from 142 stations (Fig.1). In order to get satisfactory cover of the northernmost parts of Norway, two Finnish series are included. All the series were tested for homogeneity on an annual basis using the standard normal homogeneity test (Alexandersson 1986). Some general results from these tests were reported by Hanssen-Bauer and Førland (1994).

## Comparative Trend Analysis

### Methods

In Norway, mean annual precipitation varies from less than 300 mm at some stations to nearly 4000 mm at other stations. To suppress the influence of the large differences in annual precipitation, all precipitation series were standardized by dividing by their respective 1961-1990 average, i.e. the normal value ($PN_{61\text{-}90}$). This way of standardizing makes it easy to reverse the process and extrapolate a time series (in mm) for any location by multiplying by the official normal values $PN_{61\text{-}90}$ (Førland 1993). It is also convenient to standardize all series by using data from the same period, as differences between stations in observation periods would otherwise affect the relative levels of the curves.

Two low pass filters (F1 and F2) based on Gaussian weighting coefficients were used for smoothing the series. The standard deviation of the Gaussian distribution was 3 years for filter F1, and 9 years for F2. The ends of the filtered curves are very dependent on the first or last few values, which may influence the trends unreasonably much. The filtered curves were therefore cut 5 years from either ends of the time series.

The comparative trend analysis (CTA) includes subjective classification of standardized and filtered precipitation series showing similar trends (Hanssen-Bauer and Førland 1994). The method has the advantage of not demanding complete data series from all stations. Consequently, series from all 142 stations were used in this analysis. Correlation matrixes were computed between the 142 series smoothed by F1 and by F2, respectively. Clusters of high correlation coefficients appeared in these matrixes, and preliminary classes were defined based on the clusters. The preliminary classes did not include all series, and some series were included in more than one class. The preliminary classes were modified using following guidelines:

- all series should be included in the classification;
- all classes should contain at least 3 series;
- no series should be included in more than one class;
- the standard deviations between the curves within each class should be minimized.

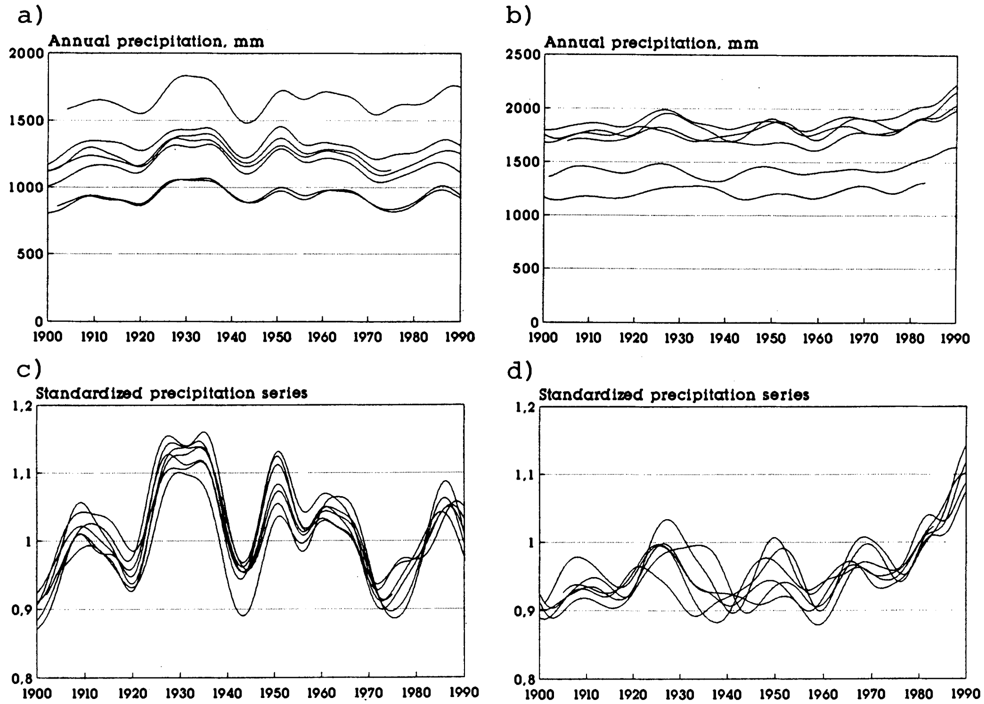


Fig. 2. Two examples of classes of precipitation series showing similar trends. The graphs in a) and b) show precipitation in mm, while c) and d) show the corresponding standardized curves. All series are smoothed by filter F1.

## Precipitation Trend Regions

Comparative trend analysis of the 142 precipitation series resulted in 12 classes with different patterns of precipitation variation in time. The classes included from 4 to 30 series. Two examples of classes of filtered series are shown in Fig.2. The upper diagrams show annual precipitation in mm for all stations within each class, while the lower diagrams show standardized curves.

It was possible to identify the 12 classes with geographical regions with clear boundaries. The 12 regions are shown in Fig.3. Regions 3 and 4 are corresponding to the classes presented in Fig.2. Note the major differences between the precipitation patterns in these neighbouring regions.

## Local and Regional Precipitation Trends

For each of the 12 precipitation regions, the standardized precipitation curve was defined as the average of the standardized, filtered precipitation curves from all stations within the region. The regional standardized precipitation curves based upon the series smoothed by F1 are shown in Fig.4. Time series of standard deviations between the individual series within each region were calculated, as a measure for

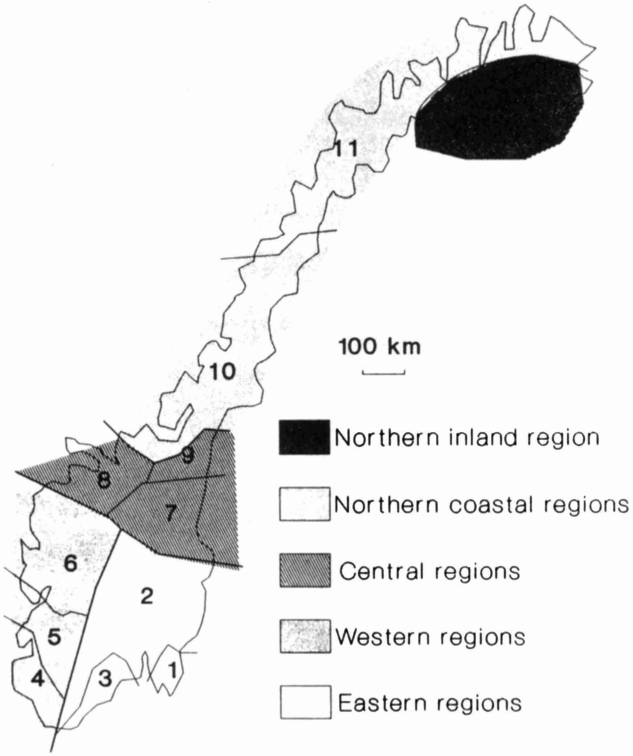
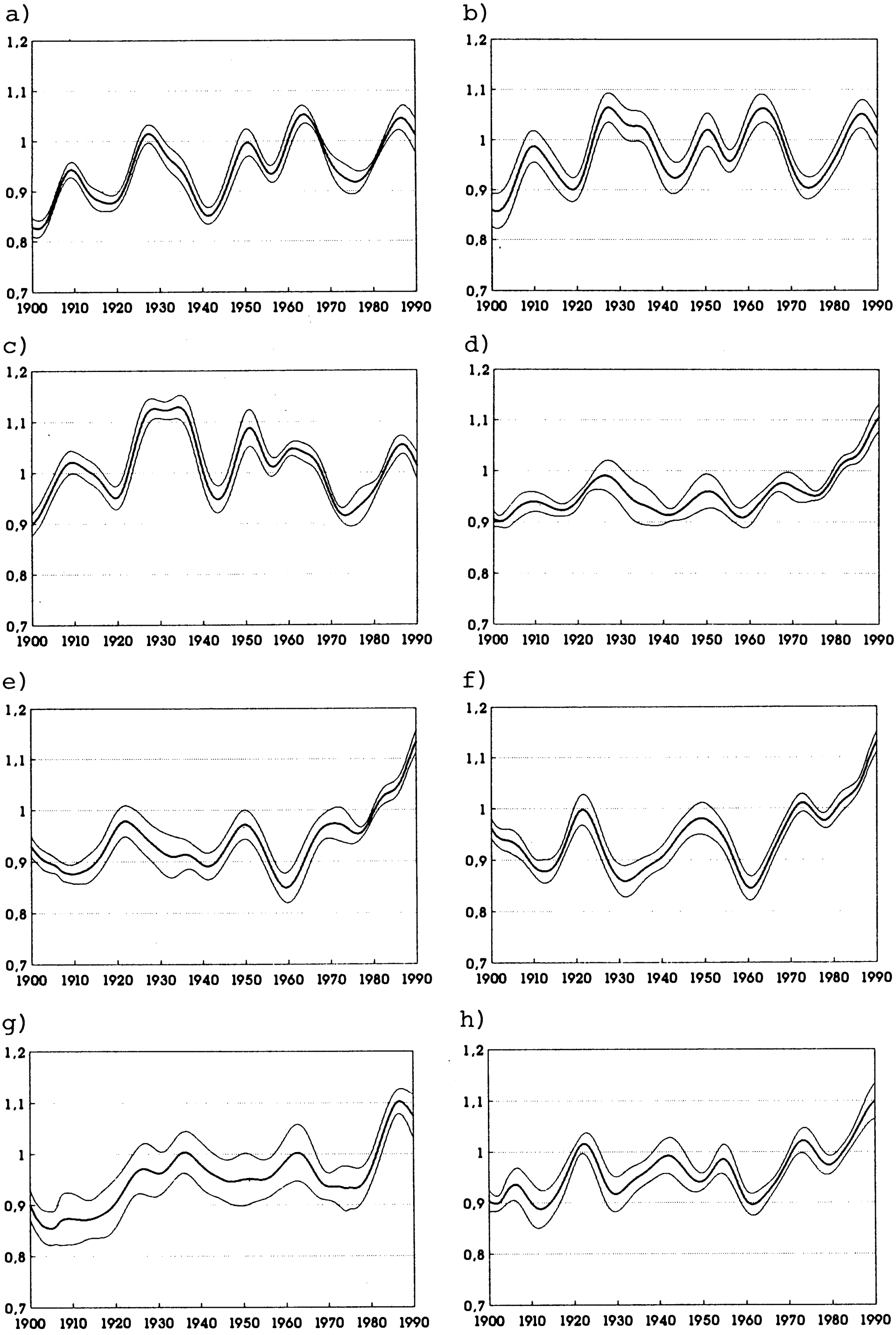


Fig. 3. The 12 precipitation regions and 5 groups of regions found by comparative trend analysis. The eastern group includes regions 1-3, the western group includes regions 4-6, the central group includes regions 7-9, the northern coastal group includes regions 10-11, and the northern inland group includes region 12.

the variation within the region. In Fig.4, the averaged curves +/- series of one standard deviation are shown. Regional series of annual precipitation, or regional precipitation curves smoothed by other filters (*e.g.* F2), are made equally simple.

Using Fig.4, the precipitation curve for any point or area within the defined regions (Fig.3) may be estimated by multiplying the regional trend curve by the 1961-1990 precipitation average, which can be deduced from the official precipitation normal maps (Førland 1993). Examples of estimates are shown in Fig. 8. The series of standard deviations for the region gives a measure for the uncertainty of the estimate.

The standard deviations of the regional curves based upon the series smoothed by F1 are generally within 2-5% (Fig.4). For the similar F2 curves, the standard deviations are usually within 1-3%. The standard deviations are largest within regions 7, 11 and 12 (Fig.4 g, k and l). Thus the quality of estimated precipitation curves will usually be poorer in these regions than elsewhere. This is partly caused by real differences between the precipitation patterns in different parts of these regions. In par-


a)
b)
c)
d)
e)
f)
g)
h)
1,2
1,1
1
0,9
0,8
0,7
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990

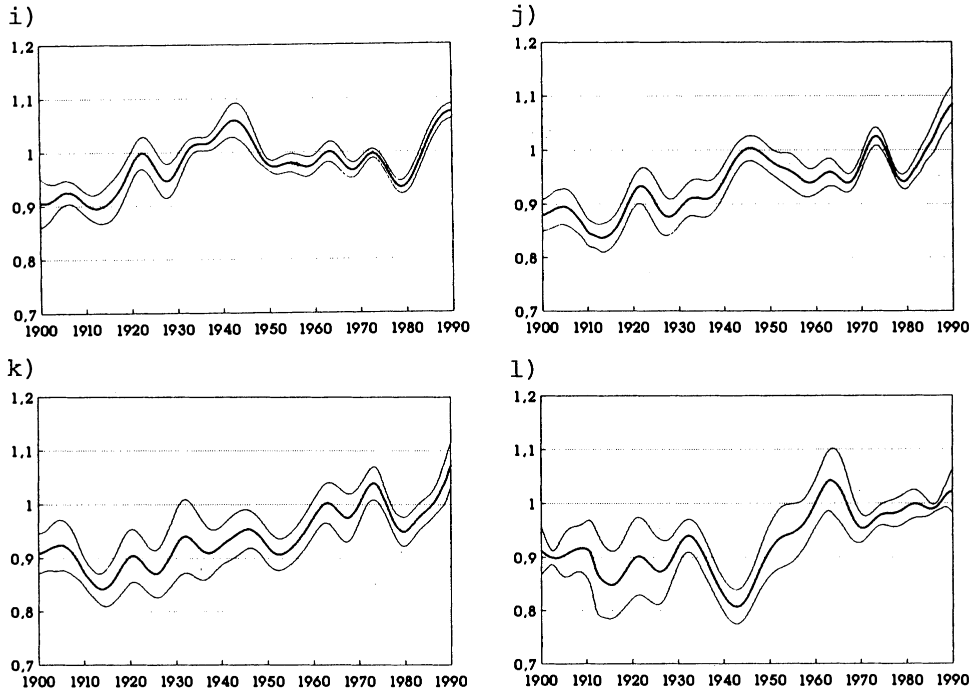


Fig. 4. Averages and standard deviations of the standardized F1 precipitation series from stations within: a) region 1 (7 series), b) region 2 (30 series), c) region 3 (7 series), d) region 4 (6 series), e) region 5 (8 series), f) region 6 (25 series), g) region 7 (11 series), h) region 8 (7 series), i) region 9 (4 series), j) region 10 (15 series), k) region 11 (15 series) and l) region 12 (7 series).

ticular, region 7 may be considered as a "transitional zone" between eastern, western and northern regions. However, there are also other reasons for these larger standard deviations. In regions with small amounts of precipitation, a few local rain showers or errors of a few mm will give high relative standard deviation, and affect the standardized precipitation curves more than in more humid regions. Regions 7 and 12 are the "driest" regions in Norway. Another factor which should be considered, is the fraction of annual precipitation falling as snow. This fraction is at maximum in region 11. As the errors connected to snowfall measurements generally are larger than the errors connected to rainfall measurements, one should expect larger random variations in this region.

## Long Term Trends in 5 Regional Groups

Fig.4 shows that there are similarities between the precipitation curves in some neighbouring regions. For instance, the F1 curves for the eastern regions 1-3 have local maxima and minima almost simultaneously (Fig.4 a-c). The same is true for

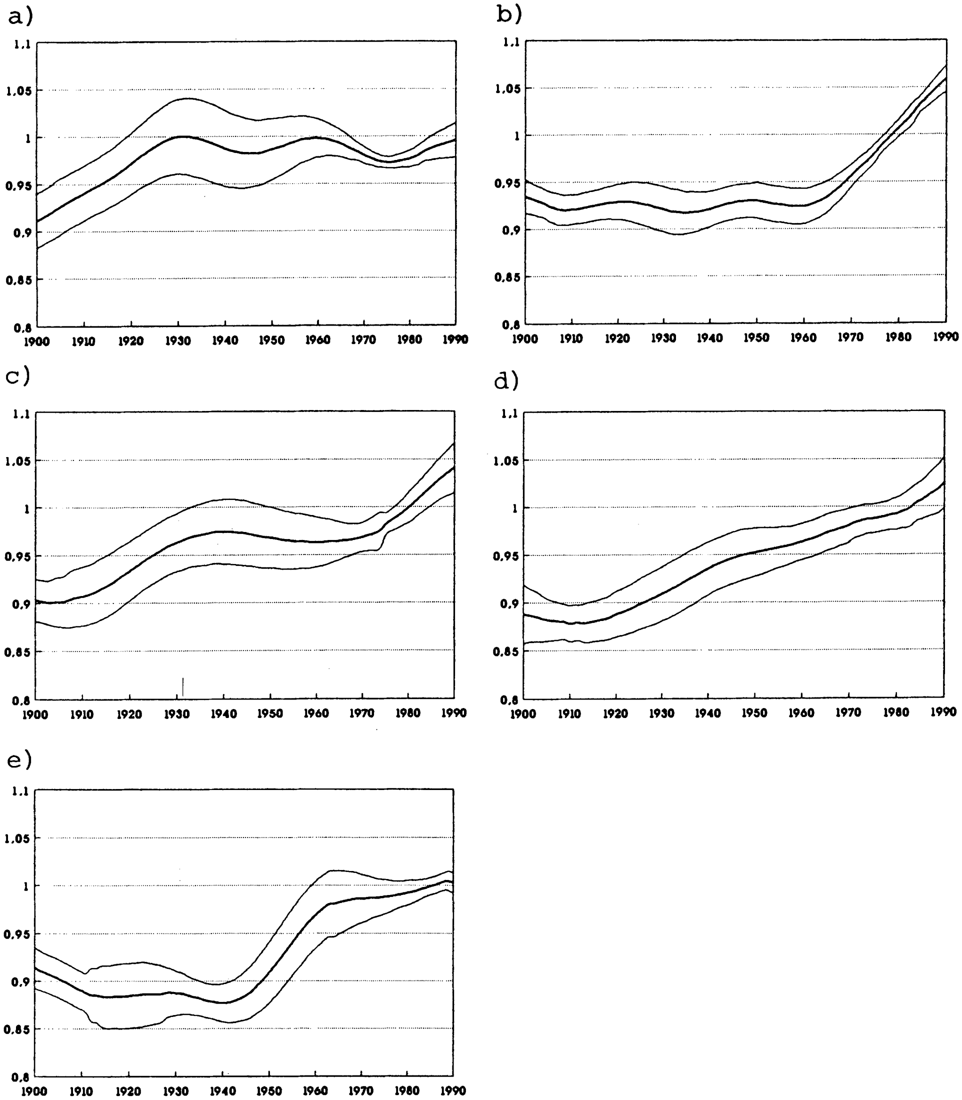


Fig. 5. Averages and standard deviations of the standardized F2 precipitation series within the different regional groups: a) eastern group (44 series), b) western group (39 series), c) central group (22 series), d) northern coastal group (30 series), e) northern inland group (7 series).

the F1 curves in the western regions 4-6 (Fig.4 d-f), while the precipitation variations in these regions are quite different from those in regions 1-3. If the aim is to describe the main features in the variations of climatic elements in Norway as a whole, it may thus be convenient to define larger regional groups.

Based upon similarities between the precipitation patterns in neighbouring regions, the 12 regions were divided into 5 regional groups: an eastern group (regions 1-3) which includes areas east and south of the watershed of the central Norwegian mountain areas, a western group (regions 4-6) including areas west of the watershed, a central group (regions 7-9) which may be regarded as a transitional zone, a northern coastal group (regions 10 and 11) which includes coastal areas north of the central mountains, and a northern inland group (region 12).

F2 curves for the 5 regional groups were calculated. Fig.5 shows that the average level of annual precipitation has increased by 8-14% in all the regional groups during the present century. A similar increase was found in the zonally averaged precipitation for "high latitudes" (Hulme 1995). It is, however, worth noting that the increase did not occur simultaneously all over Norway. In the eastern group, there was a positive precipitation trend from 1900 to 1930, while the level has been relatively stable after 1930. In the western group the precipitation level was about the same from 1900 to the middle of the 1960s, after which there has been a positive trend. In the central group, the precipitation level increased from 1900 to the 1930's and from 1970 to present, while there were only minor changes from the 1930's to 1970. In the northern coastal group, the precipitation trend was positive from 1915 to the end of the series. In the northern inland region on the other hand, the precipitation level increased in the period 1945 through 1965, while it was relatively constant before 1945 and after 1965.

The differences in precipitation trends between the groups are probably connected to variations in the atmospheric circulation patterns. For instance, an increase in the frequency or strength of westerly winds would increase the orographic precipitation in regions 4-6 and 10-12. On the other hand, a change in the frequency of southeasterly winds would mainly affect the precipitation in regions 1-3.

## Principal Component Analysis

### Methods

Principal component analysis (PCA) may be performed using the correlation matrix or the covariance matrix (Preisendorfer 1988). Tveito and Hisdal (1994) analyzed Norwegian precipitation and runoff series using the correlation matrix, which should always be used for combined datasets. In the present work, however, the covariance matrix was used, which is suggested for univariate studies by several authors (*i.e.* Mills 1995). More information is retained in this way, and it also simplifies the estimation of precipitation trends. However, to avoid influence on the principal components of differences in precipitation levels, the standardization used in the CTA was applied.

PCA is less time consuming to accomplish than CTA. It is also basically an objective method, even if the interpretation of the results will include subjective considerations. Contrary to the CTA, PCA demands complete series from all stations. The number of available data series thus rapidly decreases as the length of the analyzed period increases. The main results from PCA of annual precipitation series from 30 stations (marked by circles Fig.1) during the period 1896-1994 are given in the present paper. In order to investigate the stability of the results, PCA was also applied on other periods and on station networks of different densities. Results from these analyses were reported by Hanssen-Bauer *et al.* (1995).

## Results From Analyses of Annual Precipitation 1896-1994

The main results from the present analyses are in agreement with the results from Tveito and Hisdal (1994), in spite of differences in station network, time interval, standardization *etc.* In the present analyses, the first 5 principal components were needed to obtain more than 80% of the variance of the original series. Eigenvalues and proportions of the total variance contained by the principal components are given in Table 1.

The PCA produces loadings (weight coefficients) at each station, and time series of scores (amplitude functions) for each principal component. Fig.6 a-b shows contour maps of the 2 first principal components (PC1 and PC2). Fig.7 a-e shows the scores of PC1-PC5 smoothed by the low pass filters F1 and F2. Table 2 shows the percentage of the variance explained by each of the 5 PC's at selected stations.

The loadings of PC1 (Fig.6a) are at maximum in the western regions and in the western parts of the northern regions. Table 2 indicates that PC1 typically explains 60-85% of the variance in the western regions and 50-60% in regions 8-10. In eastern regions the loadings of PC1 are close to zero. Fig.7a shows that the trend and variability in the scores of PC1 are very similar to the precipitation curves of the western regions (Fig.4 d-f). There are also similarities to the curves representing regions 8-11 (Fig.4 h-k). The loadings of PC1 indicate that this component contains the variability connected to changes in the westerly winds. A suggestion is that pos-

Table 1 – Eigenvalues and proportion of total variance accounted for by the first 5 principal components from PCA of 30 series during 1896-1994.

| | Eigenvalue | Proportion of total variance | Cumulative proportion |
|---|---|---|---|
| PC1 | 0.418 | 0.40 | 0.40 |
| PC2 | 0.248 | 0.24 | 0.64 |
| PC3 | 0.091 | 0.09 | 0.72 |
| PC4 | 0.071 | 0.07 | 0.79 |
| PC5 | 0.036 | 0.03 | 0.82 |

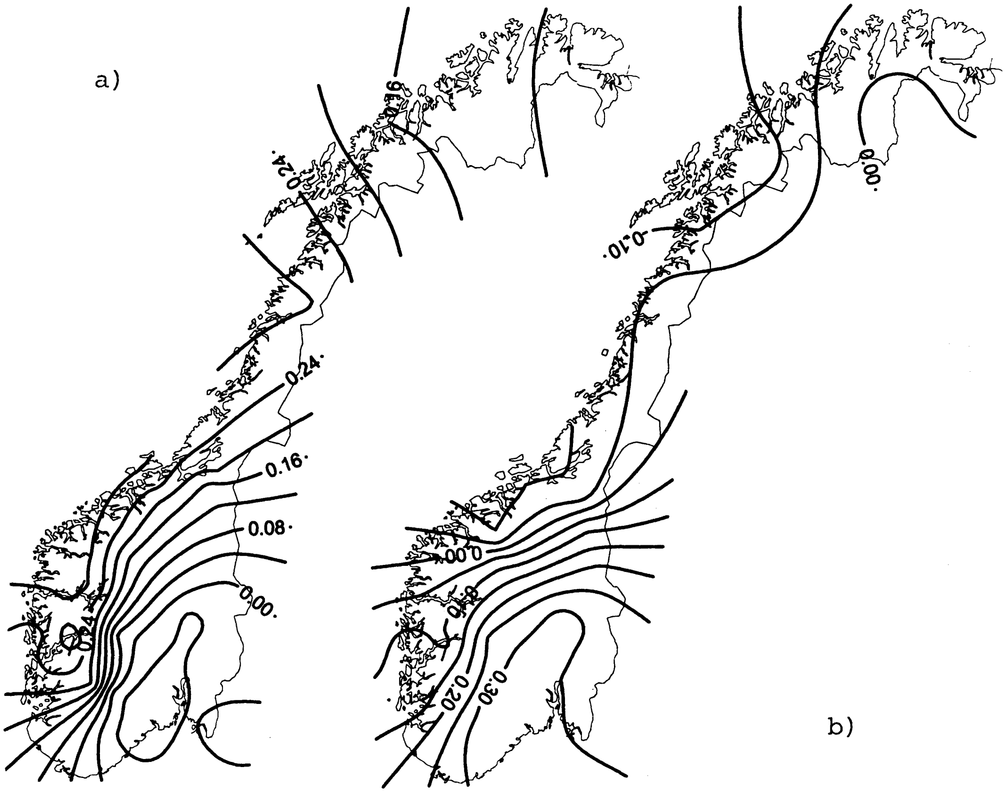


Fig. 6. Contour plots of loadings of a) PC1, b) PC2.

Table 2 – Percentage of the variance accounted for by each of the principal components for one station in each of the CTA trend regions.

| station | CTA - | % of variance accounted for by | | | | | |
|---|---|---|---|---|---|---|---|
| no. | region | P1 | P2 | P3 | P4 | P5 | ALL |
| 0123 | 1 east | 1 | 68 | 6 | 0 | 2 | 77 |
| 1870 | 2 east | 2 | 73 | 7 | 3 | 1 | 86 |
| 3880 | 3 east | 1 | 75 | 1 | 2 | 2 | 81 |
| 4702 | 4 west | 60 | 13 | 2 | 3 | 8 | 86 |
| 4750 | 5 west | 69 | 12 | 3 | 3 | 3 | 90 |
| 5632 | 6 west | 83 | 2 | 5 | 1 | 1 | 92 |
| 1040 | 7 central | 17 | 8 | 4 | 37 | 0 | 66 |
| 6155 | 8 central | 51 | 5 | 1 | 17 | 1 | 75 |
| 6955 | 9 central | 55 | 5 | 0 | 21 | 0 | 81 |
| 7974 | 10 north c. | 62 | 0 | 13 | 4 | 5 | 84 |
| 8980 | 11 north c. | 33 | 9 | 39 | 2 | 3 | 86 |
| 9945 | 12 north i. | 23 | 1 | 33 | 0 | 25 | 82 |

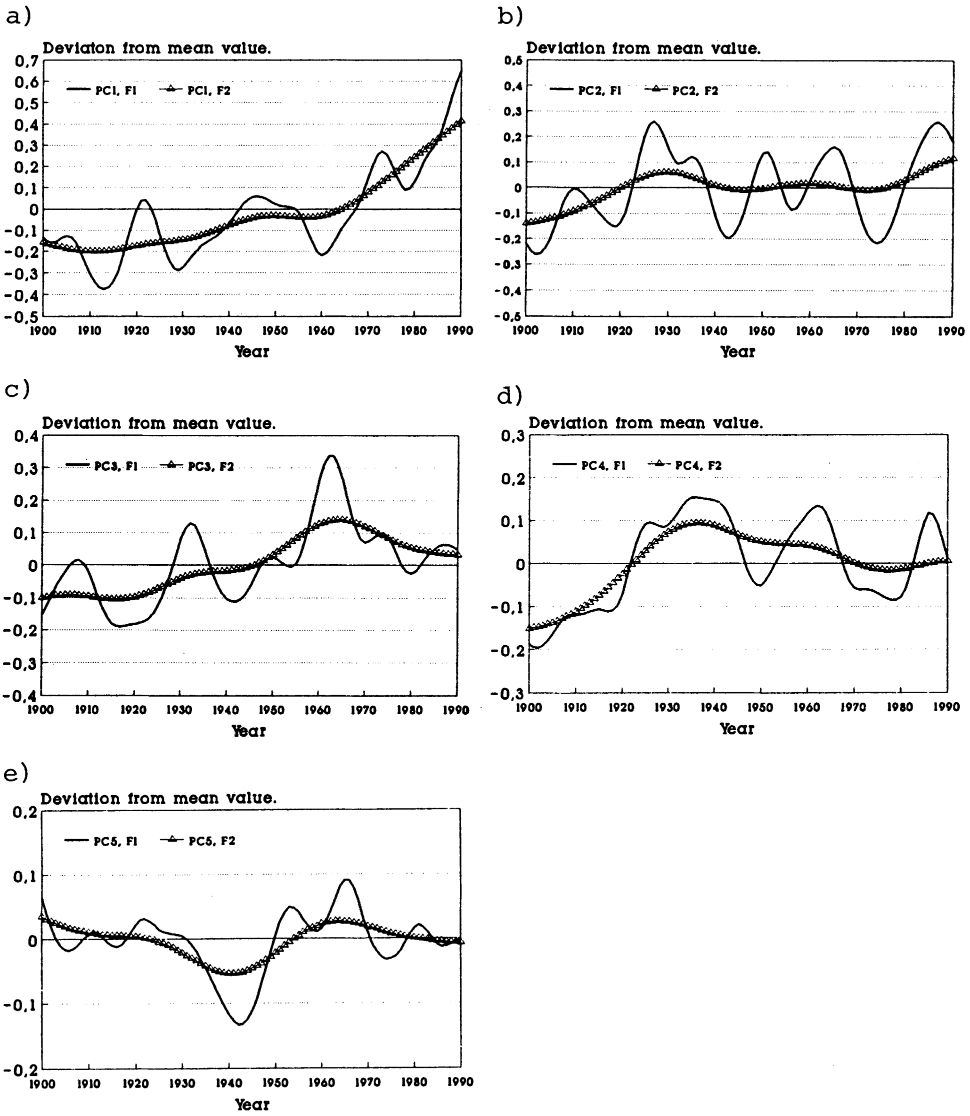


Fig. 7. Filtered (F1 and F2) timeseries of PC-scores of: a) PC1, b) PC2, c) PC3, d) PC4, e) PC5.

itive score means high frequency of westerly winds, while high negative score means low frequency of these winds. High absolute loadings then implies that changes in the frequency or strength of these winds are of great importance for the annual precipitation at the place. Positive loadings means that the precipitation will be above average when the frequency is above average.

The loadings of PC2 (Fig.6b) are at maximum in the eastern and southern regions, and negative or close to zero in the northern regions. According to Table 2, PC2 typically explains 70% of the variance at eastern stations, and 10-15% of the variance at the southwestern stations. In the northern region 11, it typically explains 5-10% of the variance. However, the loadings are negative in this area. The trends and variability in the PC2 score (Fig.7b) resemble the precipitation curves representing the eastern regions (Fig.4 a-c). A possible explanation is that PC2 scores represent the frequency of southeasterly winds. Positive loadings thus means that high frequencies of southeasterly winds give above average precipitation. Negative loadings, on the other hand, mean that high frequencies of southeasterly winds give below average precipitation.

The loadings of PC3 are at maximum in the 2 northernmost regions. They are negative in western regions and positive in eastern regions. According to Table 2, PC3 typically explains 30-40% of the variance in the northern stations, while it is of little importance elsewhere. The loadings of PC4 are at maximum in the central regions. They are negative in western regions and positive in eastern regions. PC4 typically explains 15-40% of the variance in the central regions, while it accounts for less than 5% in all other regions. The loadings of PC5 are at maximum in the northern region 12. According to Table 2, PC5 typically explains 25% of the variance in this area. In the western region 4, it accounts for about 8%. The loadings there are negative.

Trends and variability in the scores of PC3, PC4 and PC5 (Fig.7 c,d,e) are not easily connected to one or more regional trend curves as were the cases for the first two components. Neither are the geographical patterns of the loadings easily connected to a certain wind direction. No suggestion is thus made for a physical interpretation of PC3, PC4 and PC5. The interpretations of PC1 and PC2 are also highly speculative. Wind direction and strength are not sufficient for describing the precipitation regimes of Norway. The positions of the polar and arctic fronts are obviously of great importance for the distribution of precipitation.

More detailed studies of seasonal or monthly precipitation in connection with pressure anomalies are demanded to connect regional precipitation trends to variations in the general circulation pattern. However, Førland (1986) has documented that the precipitation patterns in western and central Norway are strongly dependent on the predominant wind direction.

## Estimates of Precipitation Time Series Using CTA and PCA

The precipitation series of an arbitrary point may now be estimated in two different ways. Output from the CTA may be used in combination with the precipitation normal of the point (Førland 1993). Alternatively, PC loadings found from maps (*e.g.* Fig.6), PC scores (Fig.7), and the precipitation normal of the point may be used to

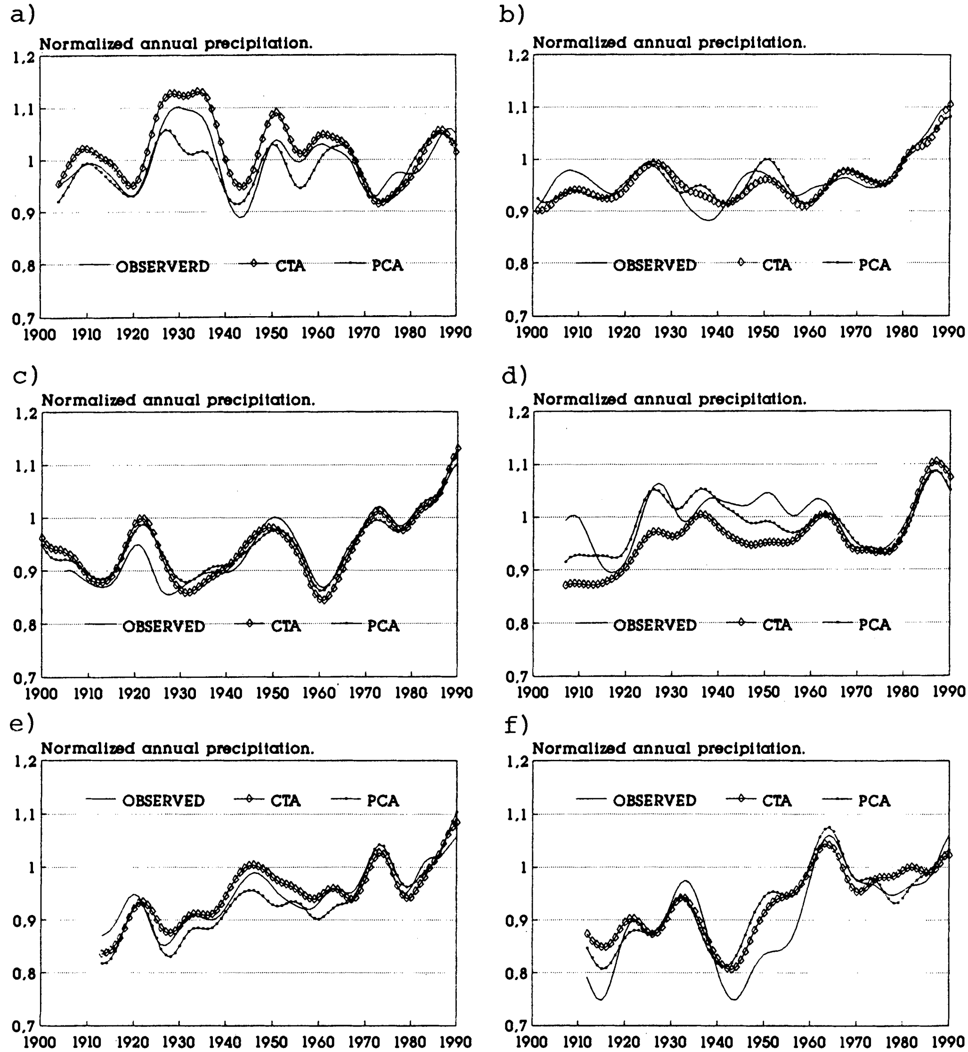


Fig. 8. Observed and estimated precipitation curves smoothed by F1 at the 6 stations marked by stars in Fig.1: a) the station in region 3; b) the station in region 4; c) the station in region 6; d) the station in region 7; e) the station in region 10; f) the station in region 12.

make similar estimates based upon PCA. Estimates of standardized precipitation were made for 6 stations (marked by stars in Fig.1) using both techniques. None of these series were included in the PCA, and most of them are in areas of strong gradients in the PC loadings. Low pass filtered series (F1) of the estimated standardized precipitation are given in Fig.8. The corresponding observed series are also shown.

Table 3 – Root mean square error for the estimates of smoothed precipitation curves at 6 stations. RMSE is given for estimates by CTA and PCA, and for estimates of F1 curves as well as F2 curves.

| Station | Comp.Trend Analysis<br>F1 | F2 | Princ.Comp.Analysis<br>F1 | F2 |
|---|---|---|---|---|
| 3922 | 0.034 | 0.028 | 0.031 | 0.014 |
| 4336 | 0.021 | 0.010 | 0.024 | 0.010 |
| 5275 | 0.024 | 0.018 | 0.022 | 0.016 |
| 0872 | 0.055 | 0.046 | 0.035 | 0.025 |
| 7510 | 0.021 | 0.011 | 0.023 | 0.014 |
| 9330 | 0.048 | 0.028 | 0.050 | 0.034 |

The root mean square error for the two estimates are given in Table 3 for the F1 curves (Fig.8) as well as for the F2 curves. Table 3 and Fig.8 illustrate that the PCA estimates generally are of the same quality as the CTA estimates, even if they are based upon a network of 30 series only. However, by CTA it is possible to visualize the trend in a distinct region by using just one trend curve, while the PCA estimates are based upon 5 principal components.

## Conclusions

- Comparative trend analysis (CTA) and principal component analysis (CPA) may both be used to estimate long term precipitation trends representative for any location.
- In Norway, the present level of annual precipitation is higher than the level around 1900. The increase lies between 8 and 14% in most parts of Norway. There are, however, substantial differences between the geographical regions regarding the period during which the precipitation has increased.
- The regional differences in precipitation trends and variability are probably connected to variations in the atmospheric circulation patterns. In order to investigate such relations closer, it will be necessary to analyze seasonal or monthly data rather than annual.

## Acknowledgements

This study was partly founded by the Norwegian Research Council through the Environmental Programme of the European Commission (Contract EV5V-CT93-0277) and by the Nordic Environmental Research Programme NMR (Contract FS/ULF/93001).

## References

Alexandersson, H. (1986) A homogeneity test applied to precipitation data, *J.Climatol., Vol. 6*, pp. 661-675.

Førland, E.J. (1986) Orographic precipitation caused by high mountains. In: Dahlström, B. (ed.) Estimation of Areal precipitation, NHP-Report No. 18, Oslo, Norway, pp. 9-13.

Førland, E.J. (1993) Annual precipitation, *National Atlas for Norway, map 3.1.1,* Statens Kartverk, Hønefoss, Norway.

Hanssen-Bauer, I., and Førland, E.J. (1994) Homogenizing long Norwegian precipitation series, *J. Climate, Vol.7,* pp. 1001-1013.

Hanssen-Bauer, I., Førland, E.J., and Tveito, O.E. (1995) Trends and variability in annual precipitation in Norway, DNMI Klima No. 27, 25 pp.

Groisman, P.Y., and Easterling, D.R. (1994) Variability and trends of precipitation and snowfall over the United States and Canada, *J.Climate, Vol. 7,* pp. 184-204.

Hulme, M. (1995) Estimating global changes in precipitation, *Weather, Vol. 50,* No.2., pp. 34-42.

IPCC (1996) *Climate Change 1995 - The Science of Climatic Change.* The second assessment report of the Intergovernmental Panel on Climate Change: Contribution of Working Group 1, Cambridge University Press, Cambridge, UK.

Mills, G.F. (1995) Principal Component Analysis of Precipitation and Rainfall Regionalization in Spain, *Theor. Appl. Climatol., Vol. 50,* pp. 169-183.

Preisendorfer, R.W (1988) *Principal Component Analysis in Meteorology and Oceanography,* Elsevier, 425 pp.

Tveito, O.E., and Hisdal, H. (1994) A study of regional trends in annual and seasonal precipitation and runoff series, NVE Report No. 9, 30 pp.

Received: 13 November, 1995
Revised: 28 May, 1996
Accepted: 17 October, 1996

**Address:**
The Norwegian Meteorological Institute,
P.O.Box 43, Blindern,
N-0313 Oslo,
Norway.