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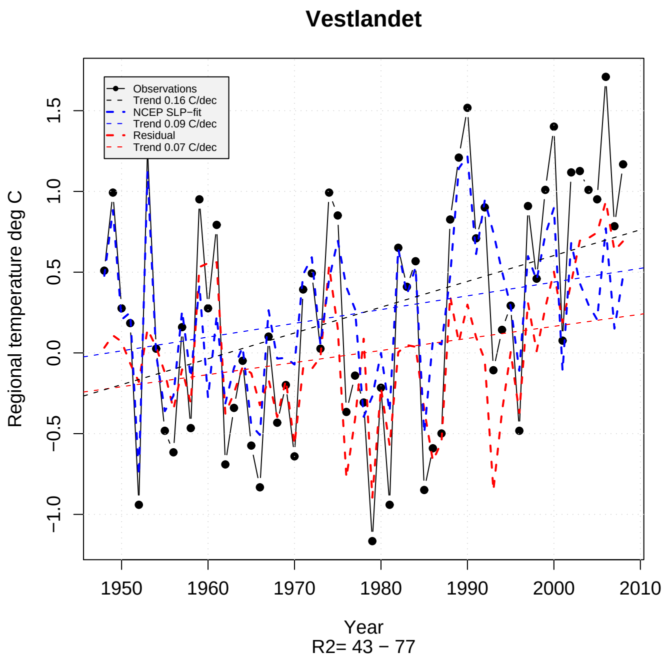
Climate

Warming trends and circulation

R.E. Benestad & I. Hanssen-Bauer



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Abstract

Time series describing regional temperature and precipitation evolution have been analysed together with sea level pressure patterns in order to explore to what degree long-term changes can be related to circulation changes. It is concluded that a part of the annual mean temperature increase since 1950 in Norway can be explained in terms of changes in the sea level pressure (atmospheric circulation) patterns, but there is also a part that cannot be related statistically to circulation changes. For annual mean precipitation, the analysis suggests that a greater fraction of the increase can be associated with the circulation over western Norway and less over eastern inland regions. The analysis involved a stepwise screening multiple regression on the 8 leading empirical orthogonal functions.

Keywords

Circulation, Empirical-Statistical downscaling, Climate change trends.

Disciplinary signature	Responsible signature
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Contents

1 Introduction

Hanssen-Bauer & Førland (2000) concluded that trends in temperature and precipitation in Norway during the period 1950-1994 to a large degree could be related to changes in the sea level pressure (SLP) patterns. However, they also found that the long-term temperature trends in Norway from 1900 to 1994 only partly could be accounted for by changes in the atmospheric circulation.

Benestad (2001) also compared trends of the North Atlantic oscillation (NAO) index and temperature over the period 1860-1997, and found that the long-term warming, as a whole, could not be explained in terms of changes in the NAO, despite the strengthening of the NAO-index after 1970. When focusing on the pronounced strengthening of the positive phase of the NAO in the 1990s, on the other hand, *Benestad & Tveito* (2002) concluded that this could explain part of the concurrent warming over Fennoscandia, especially during winter and over southern parts of the area.

Several papers indicate that also the warming in the Eurasian part of the Arctic from the 1970s to the 1990s can be related to changes in the NAO or other atmospheric circulation indices (e.g. *Hanssen-Bauer & Førland* (1998b), *Thompson* et al. (2000), *Rigor* et al. (2000)).

During the latest decade, however, the Arctic temperatures have continued to rise, while the NAO index has been variable. *Overland* et al. (2008b) conclude that the temperature anomalies in the Arctic during the most recent years, as well as the associated air pressure fields, differed in structure, compared to earlier part of the 20th century.

Benestad & Melsom (2002) suggested that there may be a link between the sea surface temperature (SST) in the western part of the north Atlantic and high monthly rainfall totals over parts of Norway. They only based their analysis on the long rainfall record from Bjørnholt near Oslo, and it is possible that a focus on different locations could give different results.

On this background, we want to re-examine the association between local climatic trends and SLP patterns for a number of climate regions in Norway during the last 5–6 decades.

2 Methods & Data

The analysis involved a multiple regression, based on the function `DS` from the `R`-package `clim.pact` (*Benestad* et al., 2008), and taking the predictor region to be 40°W–40°E of the region centre longitude, and 40° south and 40° north (but cut-off at 85°N) of the latitude. The regression was applied on a month-by-month basis, and the annual means were subsequently estimated by agrigating the results from all the calendar months.

The SLP was taken from NCEP re-analysis monthly mean values (`slp.mon.mean.nc`), spanning the years 1948–2008. The regional temperature and precipitation series are based on the homogeneous regions defined by *Hanssen-Bauer & Nordli* (1998) and *Hanssen-Bauer & Førland* (1998a), and are shown in Figure 1 (also referred to in *Benestad* (2008), but with a slightly different numbering)

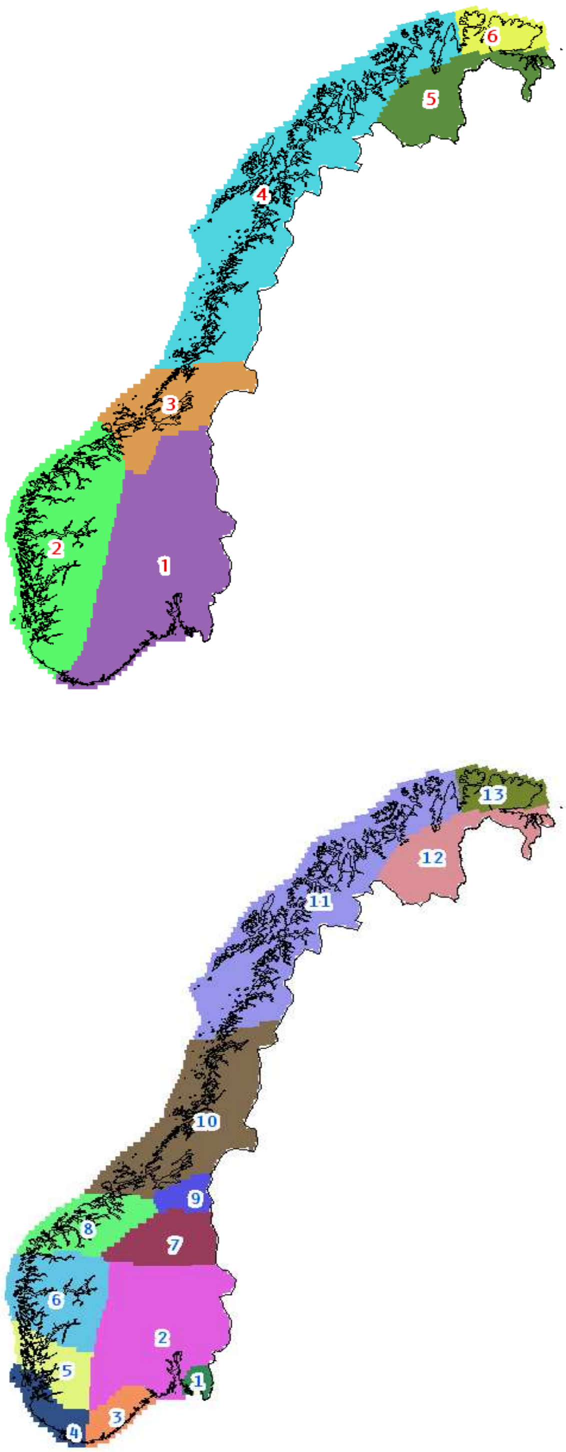

Figure 1: Temperature (upper) and precipitation (lower) regions defined as defined by *Hanssen-Bauer & Førland* (1998a) and *Hanssen-Bauer & Nordli* (1998).

3 Results

Figures 2–6 show the results of the regression and comparison with the observations for the annual mean temperature, whereas Figures 9–19 show similar results for the annual mean precipitation. The R^2 values given at the bottom of the figures are the lowest and highest of the monthly-based R^2 values. Usually, the correlation is at minimum in the summers and at maximum during winter. The figures show annual anomalies as well as linear trends both for observed temperature or precipitation, for the SLP-based regression, and for the residuals. Linear trends in observed series and residuals are also given in Table 1 (temperature) and 2 (precipitation).

In the tables, both the slope estimate for the linear trend is given as well as error estimates of 2 standard deviations (σ), roughly corresponding to the 95% confidence interval (*Wilks*, 1995). The estimated trend for the observed temperature ('observed trend') was positive (warming) and different from zero with a statistical significance at the 5%-level for the four first temperature regions, i.e. in all regions except for the northernmost ones (Table 1). The estimated uncertainties for warming related to circulation changes in southern Norway excluded zero with a probability greater than 95%. Thus, the 1948–2008 warming related to changes in the SLP patterns over southern Norway was statistically significant at the 5%-level. The residual trend was statistically insignificant at the 5%-level only at Finnmarksvidda.

The 1948–2008 trends for observed precipitation were statistically significant at the 5%-level in all regions exposed to maritime influence along the western coast (regions 4, 5, 6, 8, 10, 11, & 13). The error estimates for the slope of the linear trend had similar magnitude as the slope-estimate itself for precipitation associated with circulation (Table 2). However, the magnitude of slope-estimates were greater than the error estimates for the west-coast of Norway (Sunnhordland, Møre+Romsdal, & Sogn), suggesting that part of the circulation-based trend here was statistically significant at the 5%-level. The residual trends were statistically significant at the 5%-level only in Sør-Vestlandet and Dovre+Nord-Østerdal.

3.1 Temperature

The homogeneous temperature regions exhibited trends from +0.13 to +0.22°C per decade in annual mean temperature in the period 1948–2008 (Fig. 2–7, Table 1). Also the SLP-based regression series had positive trends in all regions, indicating that some of the warming was connected with variability in the atmospheric circulation. This is in accordance with *Oldenborgh* et al. (2009), who concluded that the observed changes in the westerly circulation pattern

Table 1: Summary of linear trends (1948–2008) and error estimates ($\pm 2 \times \sigma$) for annual mean temperature.

region	observed trend °C/decade	circulation °C/decade	residual °C/decade
1 Østlandet	0.22±0.12	0.13±0.08	0.09±0.08
2 Vestlandet	0.16±0.10	0.09±0.06	0.07±0.06
3 Trøndelag	0.20±0.12	0.10±0.08	0.10±0.06
4 Nordland + Troms	0.15±0.12	0.08±0.08	0.07±0.06
5.Finnmarksvidda	0.13±0.16	0.09±0.10	0.04±0.10
6 Varanger	0.15±0.14	0.06±0.08	0.09±0.08

Table 2: Summary of linear trends (1948–2008) and error estimates ($\pm 2 \times \sigma$) for annual precipitation.

region	observed trend mm/(month×dec.)	circulation mm/(month×dec.)	residual mm/(month×dec.)
1 Østfold	1.03±1.66	0.32±1.20	0.71±1.18
2 Østlandet	0.54±1.38	0.04±1.10	0.50±0.96
3 Sørlandet	0.75±2.78	0.28±2.14	0.47±1.84
4 Sør-Vestlandet	5.08±3.46	2.98±2.86	2.10±1.72
5 Sunnhordland	4.87±4.10	4.02±3.50	0.85±1.60
6 Sogn	4.41±4.24	3.84±3.60	0.57±1.68
7 Dovre+Nord-Østerdal	1.00±0.86	0.19±0.64	0.81±0.72
8 Møre+Romsdal	3.91±3.44	3.33±2.94	0.58±1.66
9 Inntrøndelag	1.80±1.86	1.16±1.54	0.65±1.16
10 Trøndelag+Helgeland	3.05±3.04	2.31±2.68	0.74±1.26
11 Halogaland	2.41±2.28	1.79±1.96	0.62±0.94
12 Finnmarksvidda	0.91±0.82	0.48±0.48	0.44±0.70
13 Varanger	1.21±1.06	0.48±0.78	0.73±0.70

in winter and early spring during 1950-2007 were much more substantial than any of the predictions of the global climate models from the CMIP3 (*Meehl* et al., 2007).

In Norway, trends in the SLP regression series indicated that slightly more than half the observed temperature trends were accounted for by circulation changes (Table 1).

The regression analysis left trends in the residuals, which in most regions were comparable to the trend in the regression series. When studying the individual residual values in Fig. 2–7, it is clear that the major contribution to the trends in the residual series was a cluster of positive values within the latest decade or so, which was visible in all regions. While the warm years in Norway around 1990 to a large degree were accounted for by increased transport of warm air masses[1] from southwest (*Hanssen-Bauer*, 2000; *Benestad & Tveito*, 2002), and thus could be explained by SLP patterns, this was not the case for the latest decade. A similar situation has been reported for the Arctic by *Overland* et al. (2008a), who argued that high temperatures in the Arctic in the 1990s were connected with the positive phase of the Arctic Oscillation (AO)(*Thompson & Wallace*, 1998) and an anomalous transport of warm air into the Arctic, but not during the most recent years.

Considering results from climate models for the 20th century (*Meehl* et al., 2007), it is reasonable to believe that these residuals in the Norwegian temperature series at least partly reflect the local response of the global warming.

3.2 Precipitation

Also for annual precipitation, the linear trends in the period 1948–2008 were positive in all regions (Fig. 8–20, Table 2). The increase was largest in the western regions (4–7) followed by the northwestern regions (10–11), both measured in mm (shown in the figures and table) and in percent relatively to climatology (not shown). Except from the southwestern region 4, these were also regions where a major part of the precipitation trend was accounted for by trends in the SLP-based regression series. It is thus reasonable to suggest that increased advection of maritime air masses from the west accounted for a major part of the precipitation increase in the western and northwestern regions.

In the southwestern region 4, the trend in the residuals was almost as large as the trend in the SLP regression series, and clearly the largest of the residual trends. This indicates that a considerable part of the precipitation increase in this region was probably caused by increased precipitable water in the air masses for situations which gave a geographical precipitation maximum in this area, such as frontal cyclones coming from the southwestern sector. In such

[1] Which may be due to changes in the circulation patterns or their frequencies.

situations, the eastern regions (1–3 and 8) would also have their share of the precipitation. An increased amount of precipitable water in this kind of situations might thus explain why there has been a certain increase in precipitation also in these easterly regions, though the SLP regressions accounts for virtually none of long-term changes. Increased air moisture may also explain why the second largest residual trend is found in region 5, which also is likely to get precipitation from air masses advected in from the south-west.

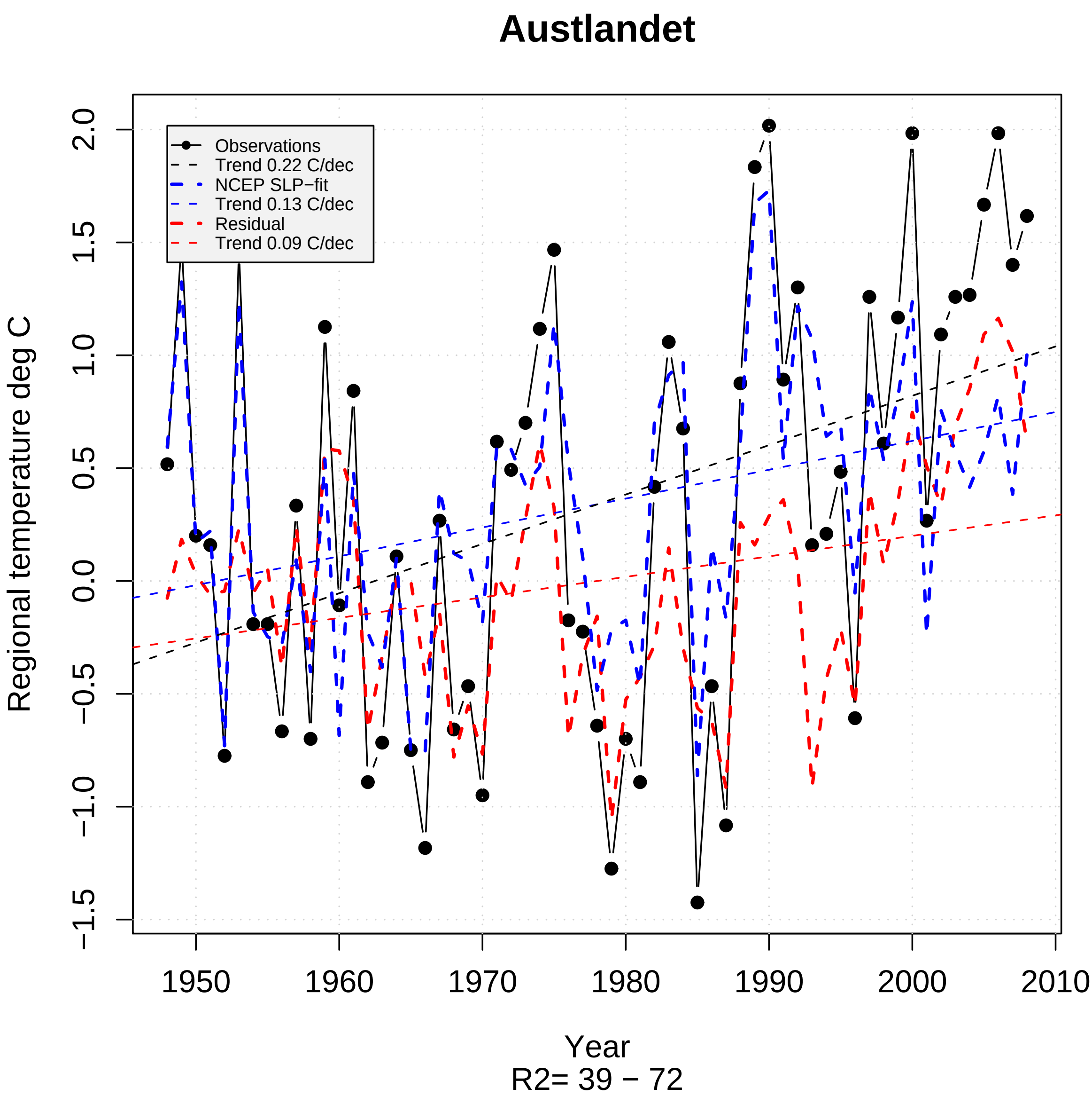

Figure 2: Observed (black), modelled based on SLP (blue), and residual (red) annual mean temperature for Østlandet. The time series show anomalies with respect to the 1961–1990 climatology.

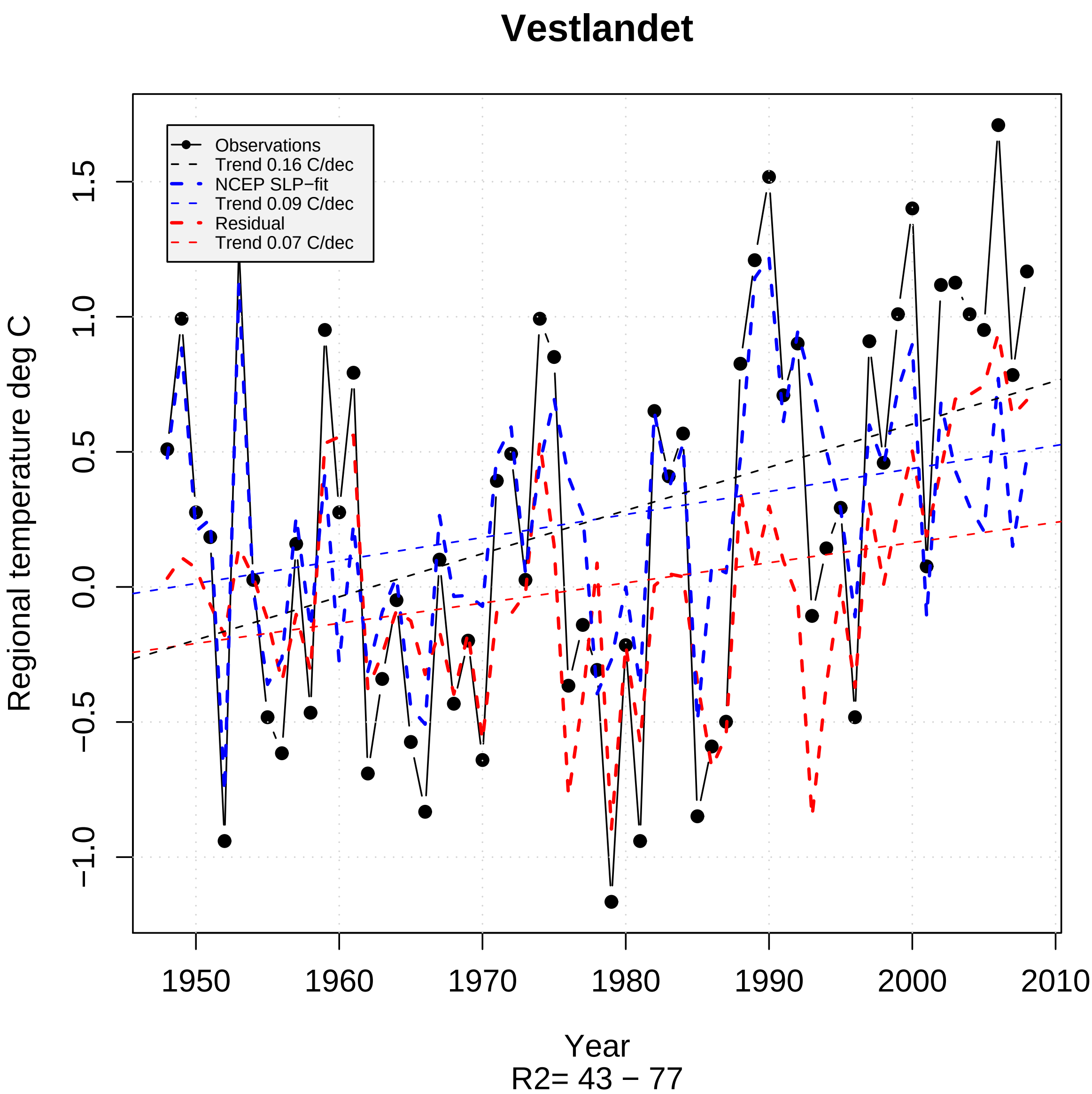

Figure 3: Same as Figure 2, but showing Vestlandet

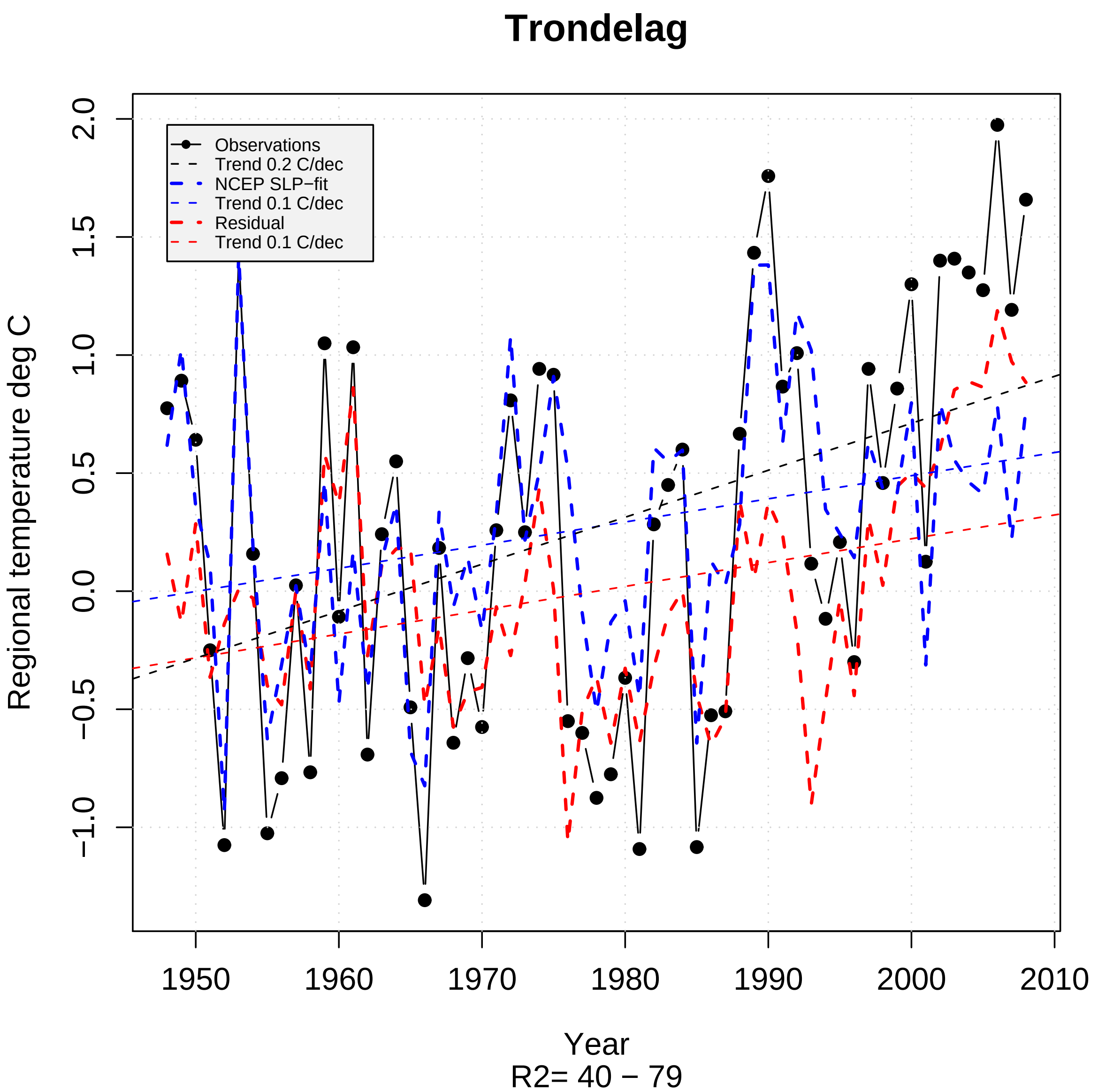

Figure 4: Same as Figure 2, but for Trøndelag

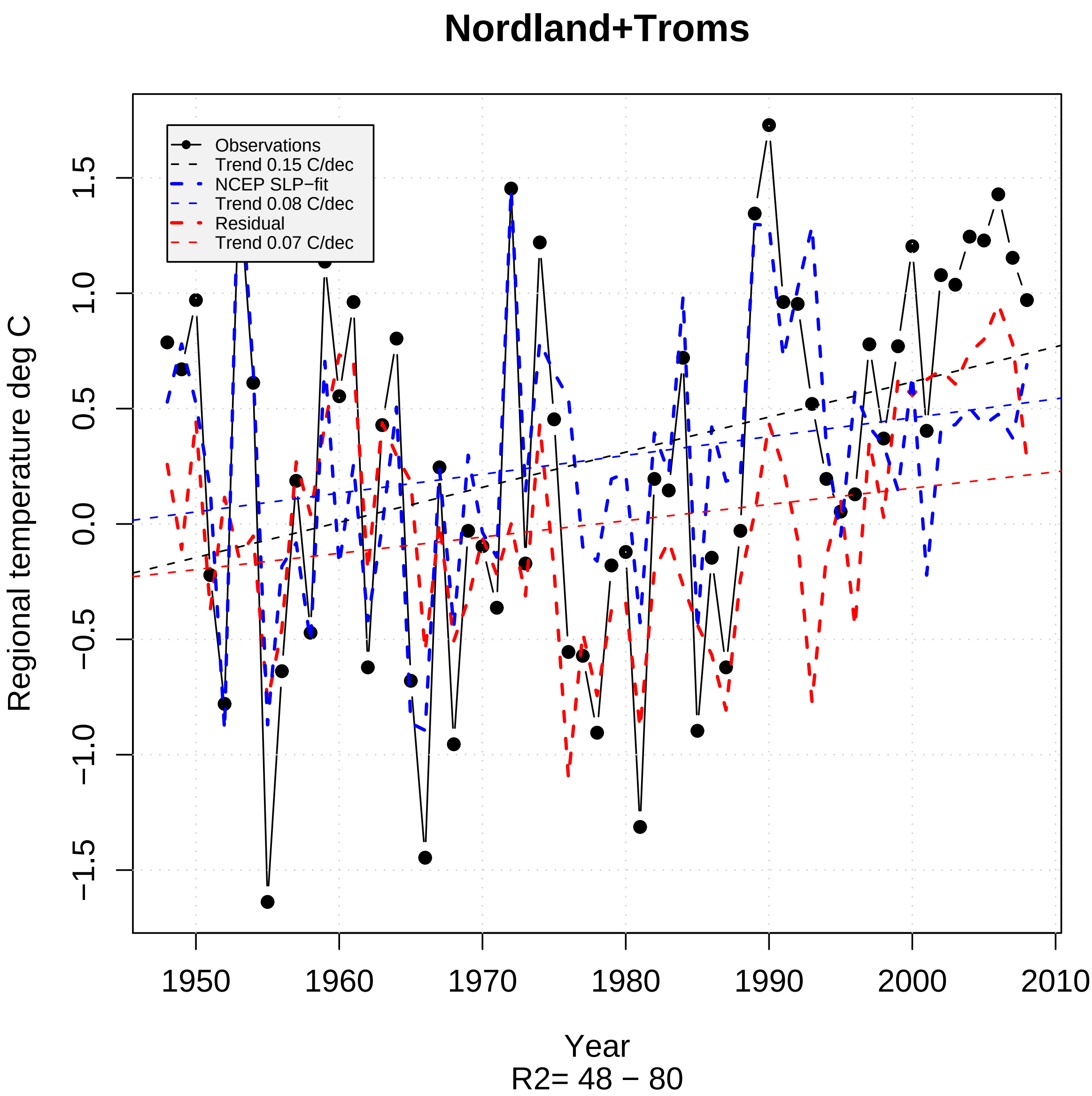

Figure 5: Same as Figure 2, but for Nordland+Troms

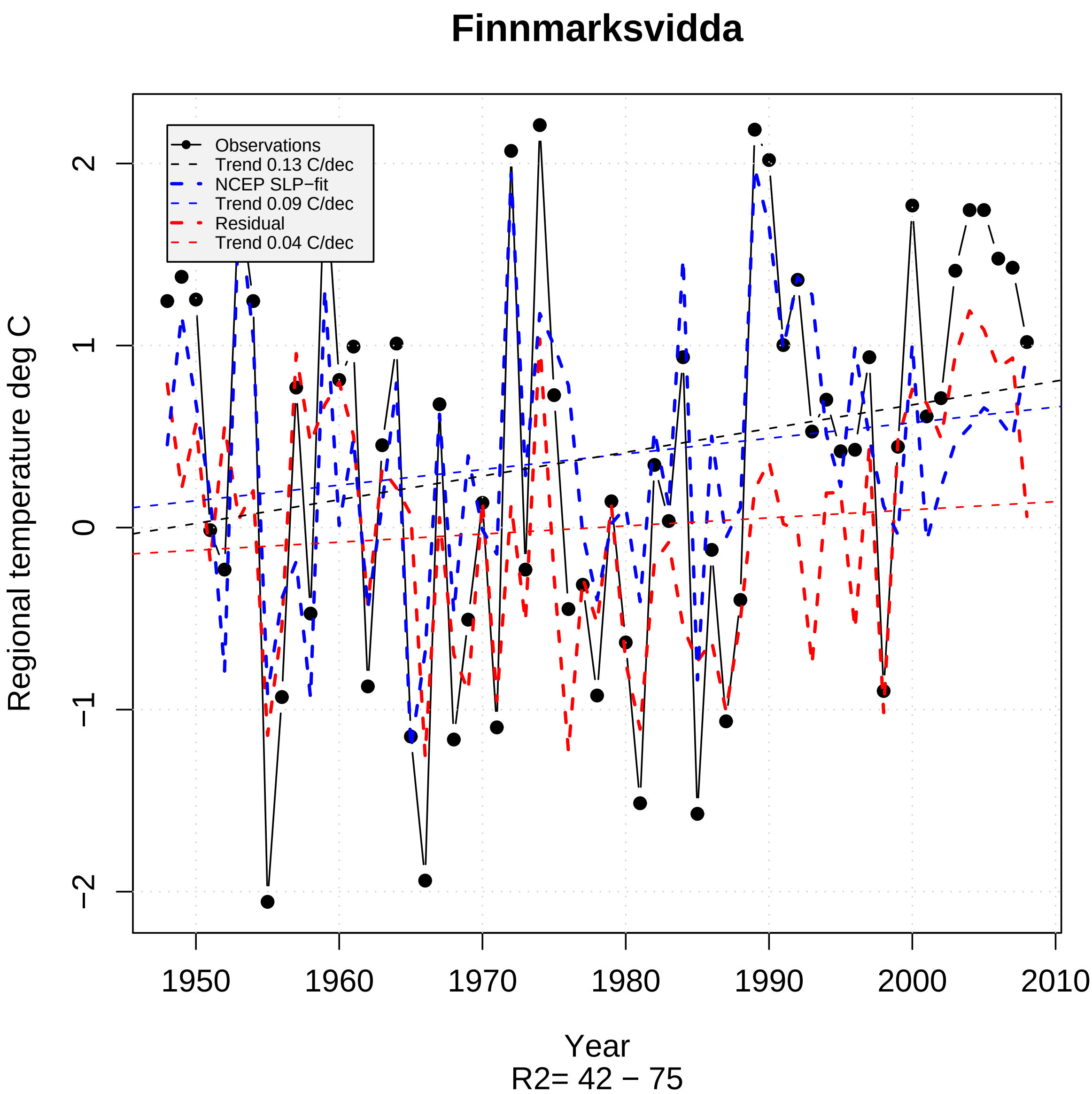

Figure 6: Same as Figure 2, but for Finnmarksvidda

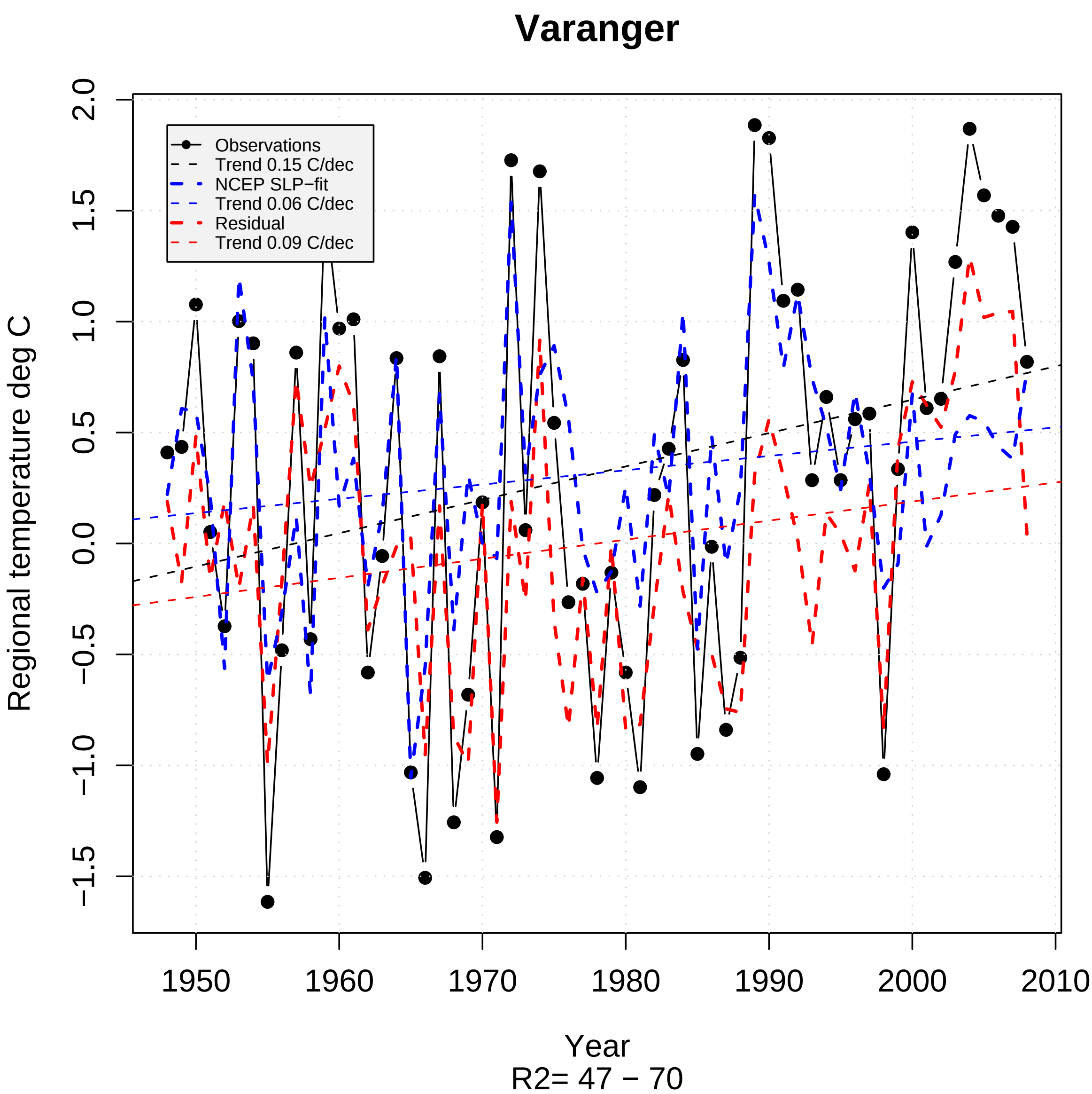

Figure 7: Same as Figure 2, but for Varanger

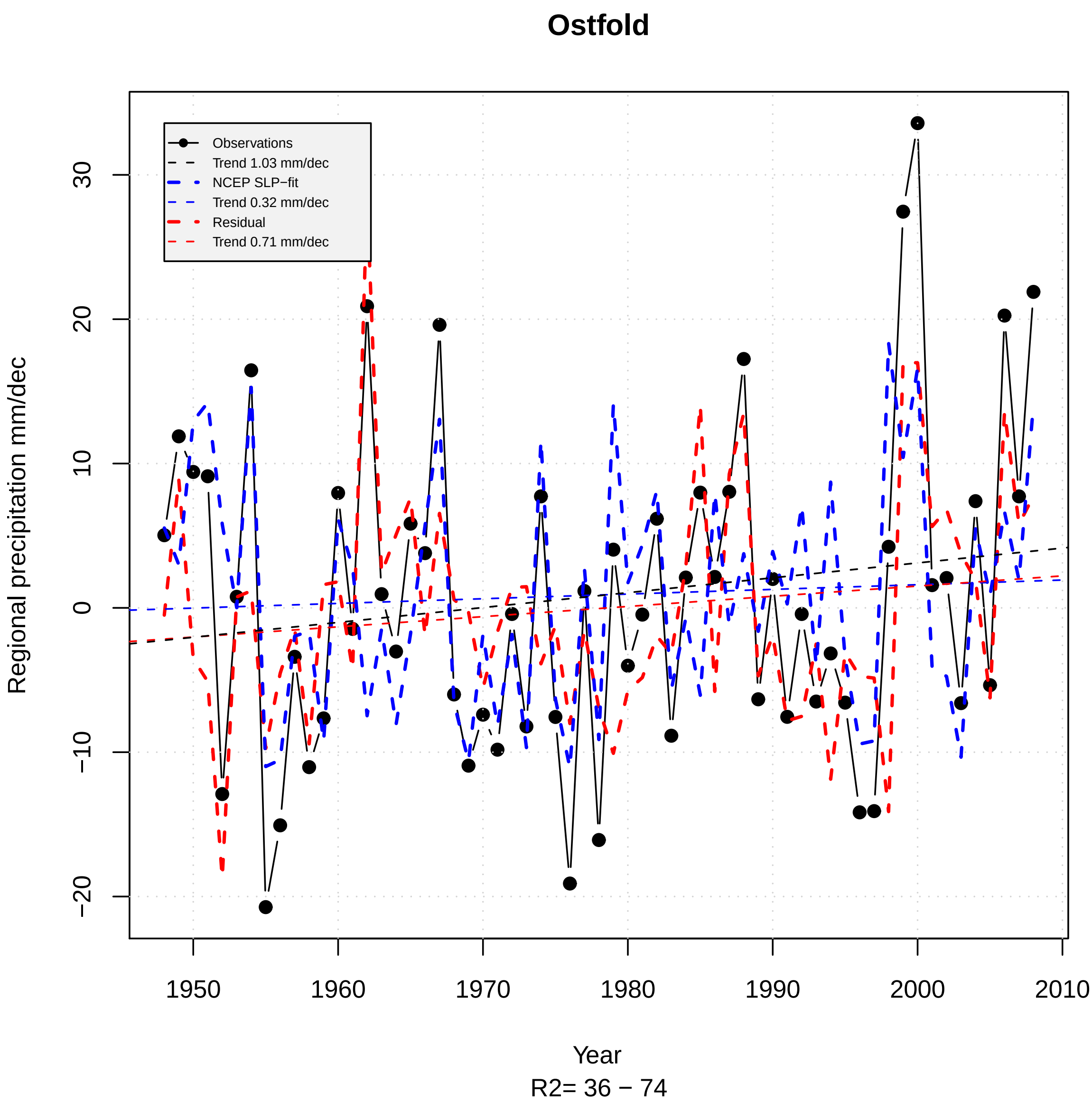

Figure 8: Same as Figure 9, but showing Østfold

4 Summary and conclusions

Empirical-statistical downscaling (ESD) has been used to associate temperature and precipitation trends with large-scale circulation patterns (*Benestad*, 2009, 2007; *Benestad* et al., 2008). New analyses of temperature series from different parts of Norway from the last 60 years, and their associations with variability in the SLP field over the same period, indicate that slightly more than half the warming for this period probably was connected with variation in the atmospheric circulation. The residual trend can - at least partly - be interpreted as a direct and local consequence of a global warming due to an enhanced greenhouse effect.

For precipitation, similar analyses showed that a major part of the observed increase in western regions could be explained in terms of changes in atmospheric circulation. The maximum increase was, however, observed in southwestern Norway, and almost half this increase was not accounted for by changes in the SLP field. One plausible explanation for the trends not associated with changes in the circulation[2] may be increases in precipitable water, but precipitation can also be affected by e.g. changes in the hydrostatic stability.

The analyses in the present study are not sufficient to reveal if there really has been an increase in the water vapor content in the atmosphere during specific weather situations. Additional analyses would be needed, which are out of the scope of the present report.

Acknowledgements

This work has been supported by the Norwegian Meteorological Institute. The climatological data archive is maintained and quality controlled by 'Seksjon for Klimadata' in the Climate Department of the Norwegian Meteorological Institute. Their work is invaluable. The analysis was carried out using the R (*Ellner*, 2001; *Gentleman & Ihaka*, 2000) data processing and analysis language, which is freely available over the Internet (URL http://www.R-project.org/).

[2] A global warming may potentially change the circulation patterns and their frequencies.

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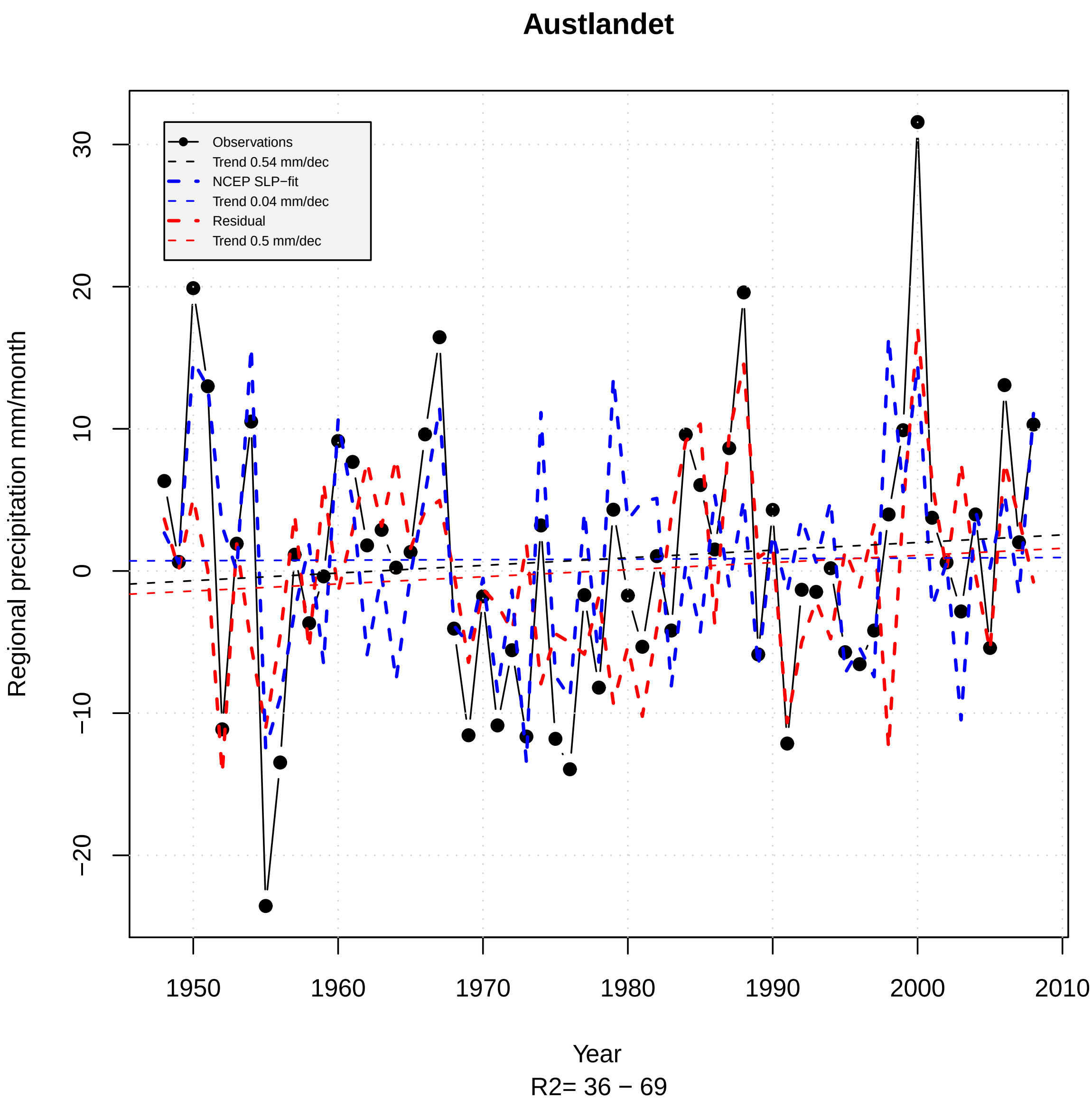

Figure 9: Same as Figure 2, but for precipitation and Østlandet

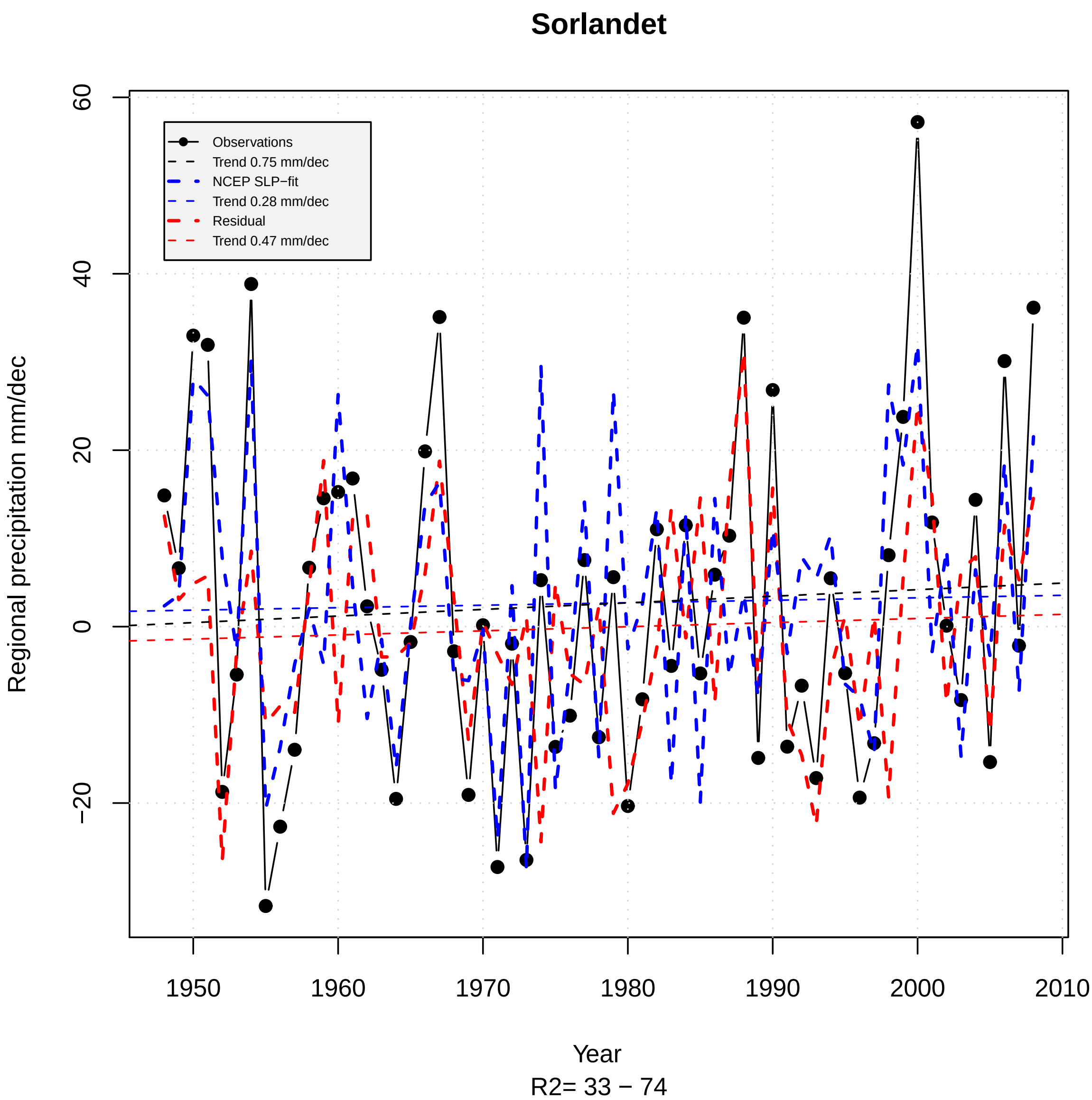

Figure 10: Same as Figure 9, but for Sørlandet

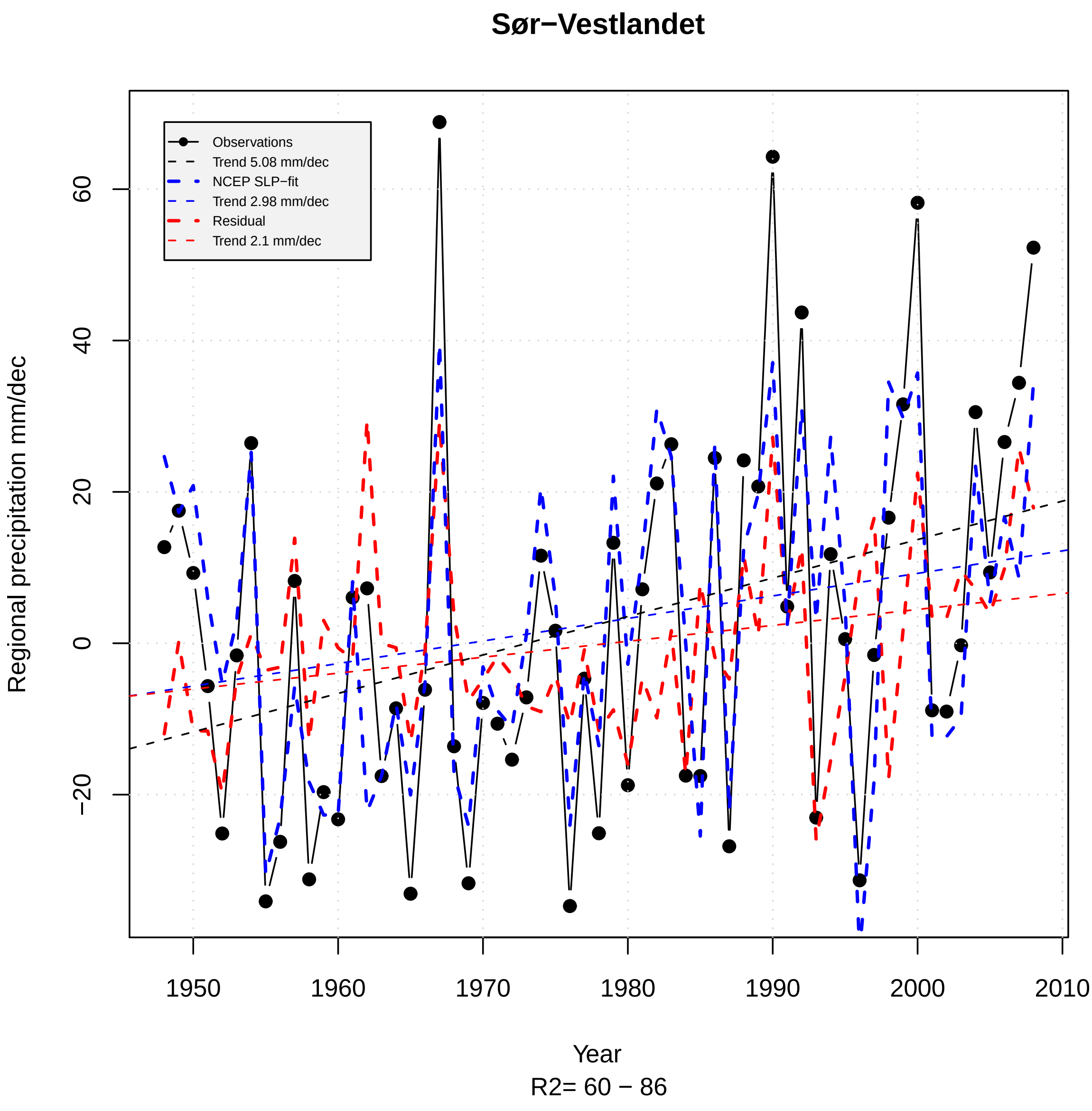

Figure 11: Same as Figure 9, but for Sør-Vestlandet

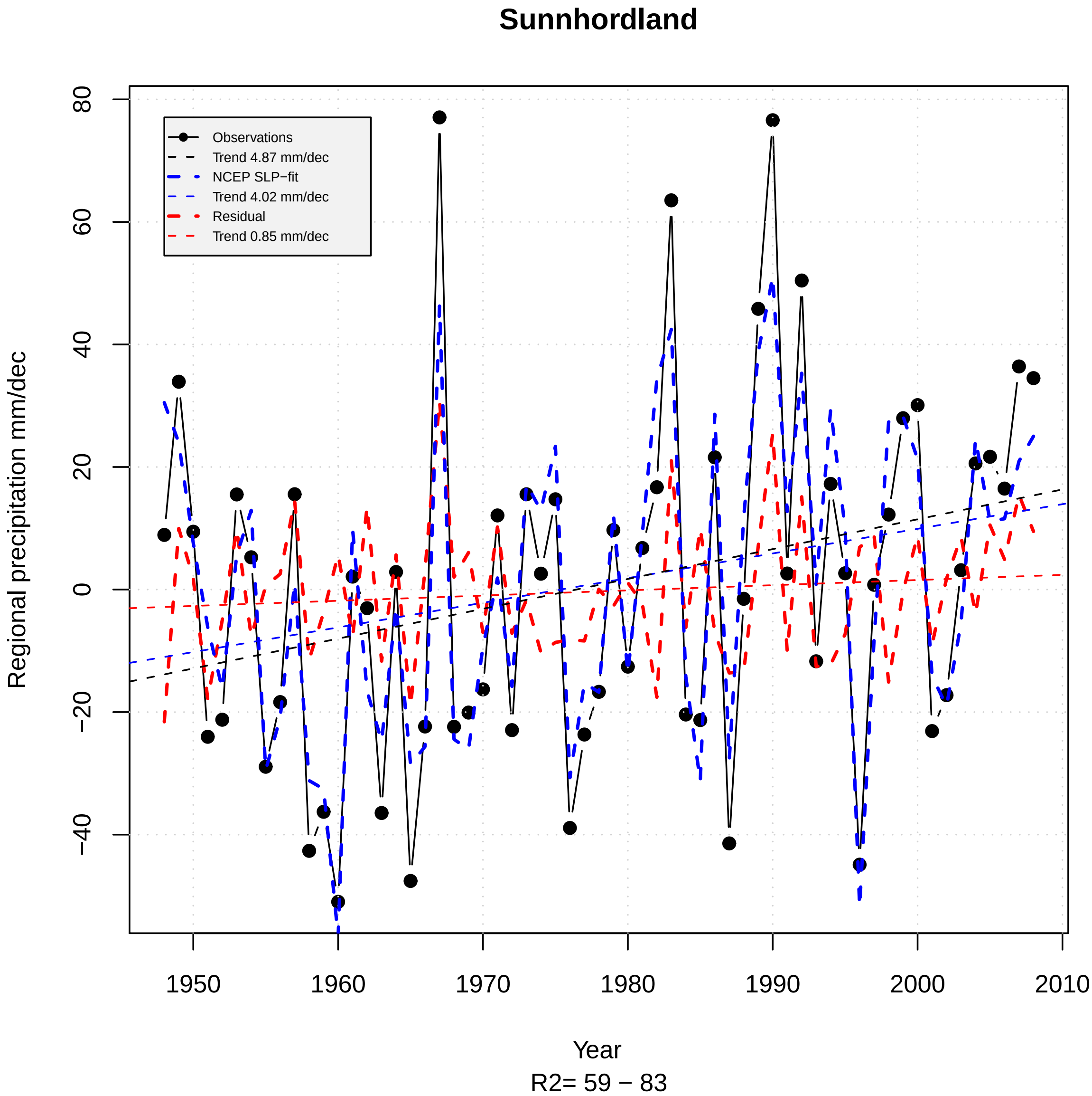

Figure 12: Same as Figure 9, but for Sunnhordland

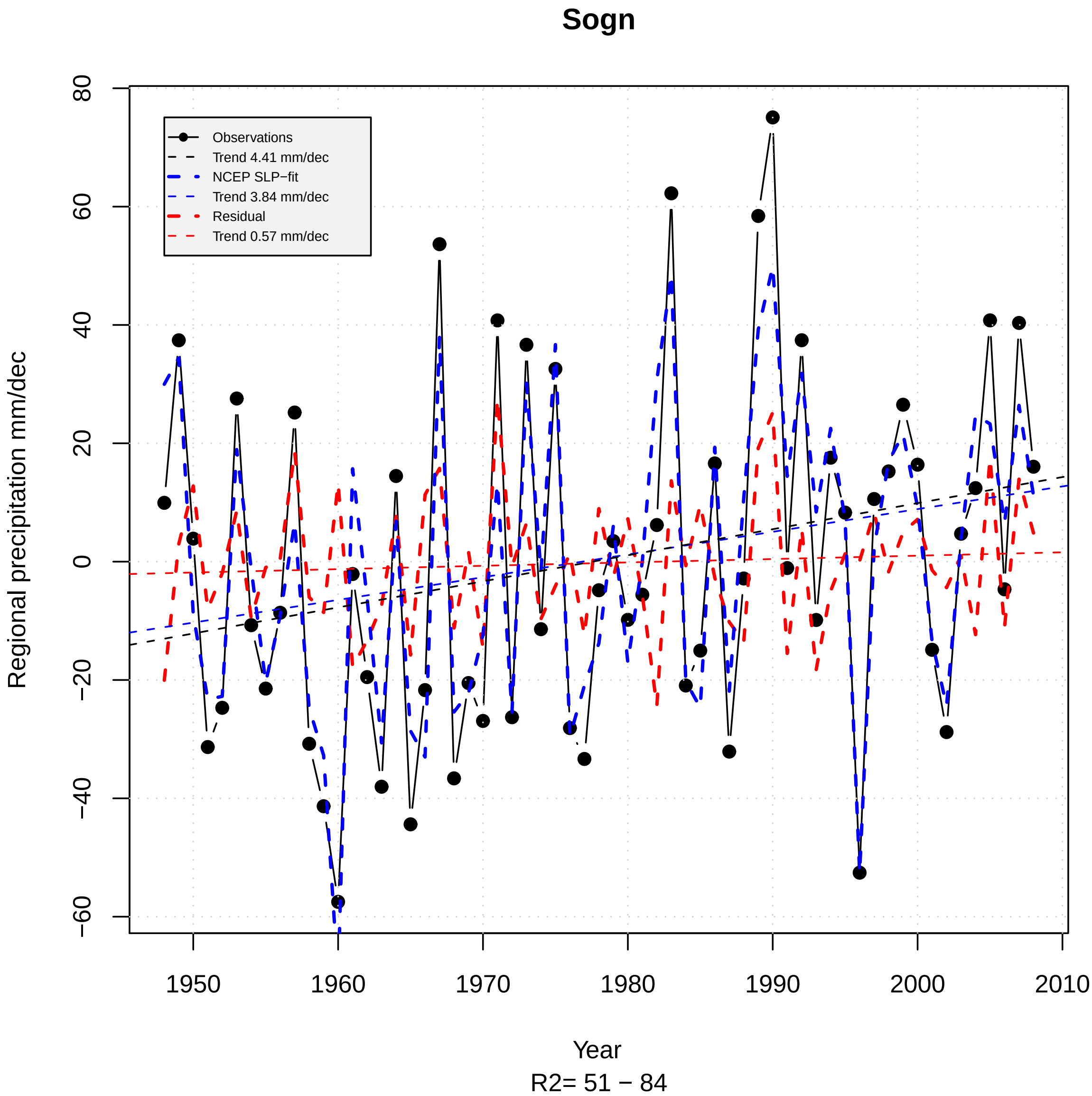

Figure 13: Same as Figure 9, but for Sogn

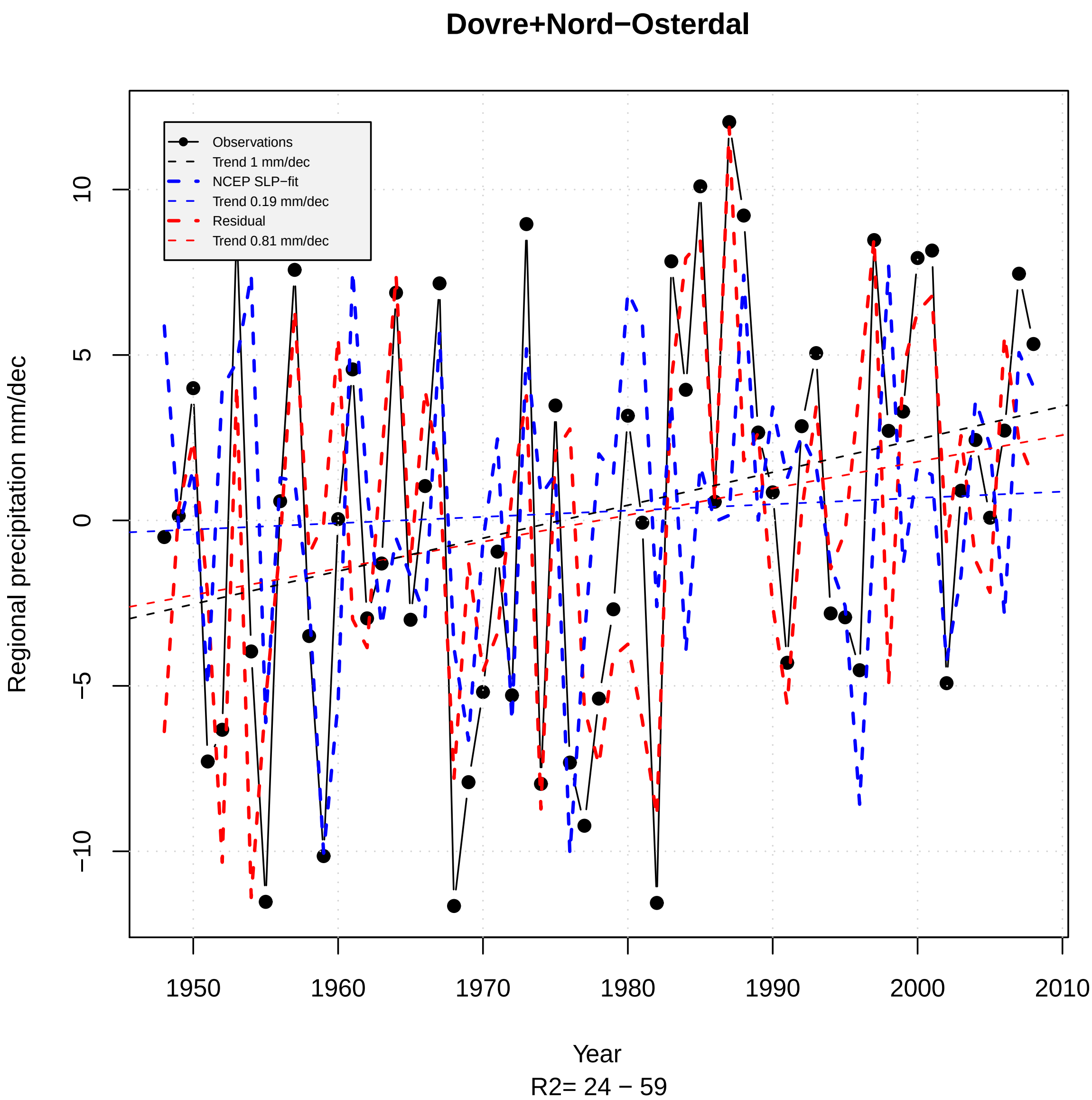

Figure 14: Same as Figure 9, but showing Dovre+Nord-Østerdal

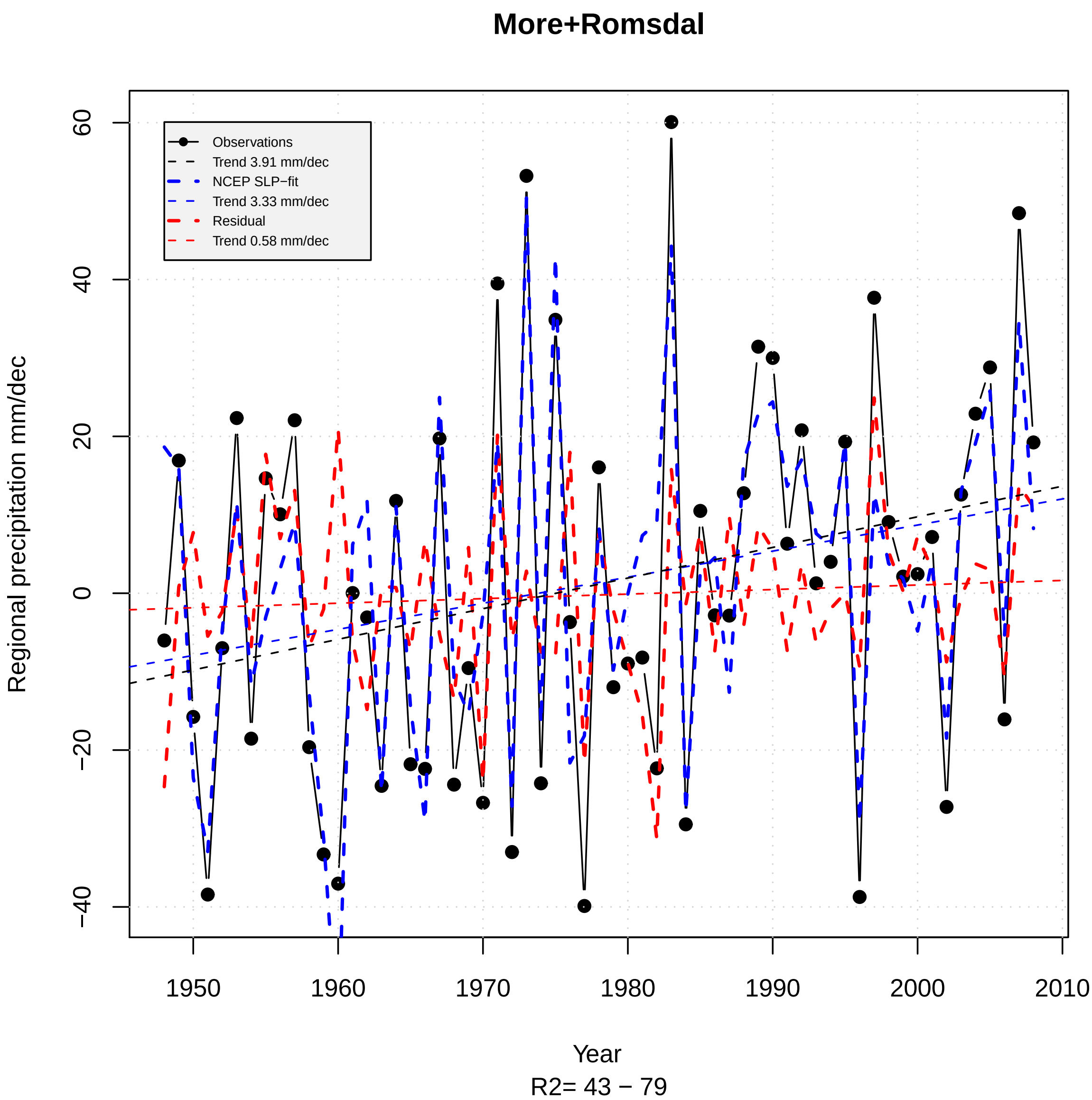

Figure 15: Same as Figure 9, but for Møre+Romsdal

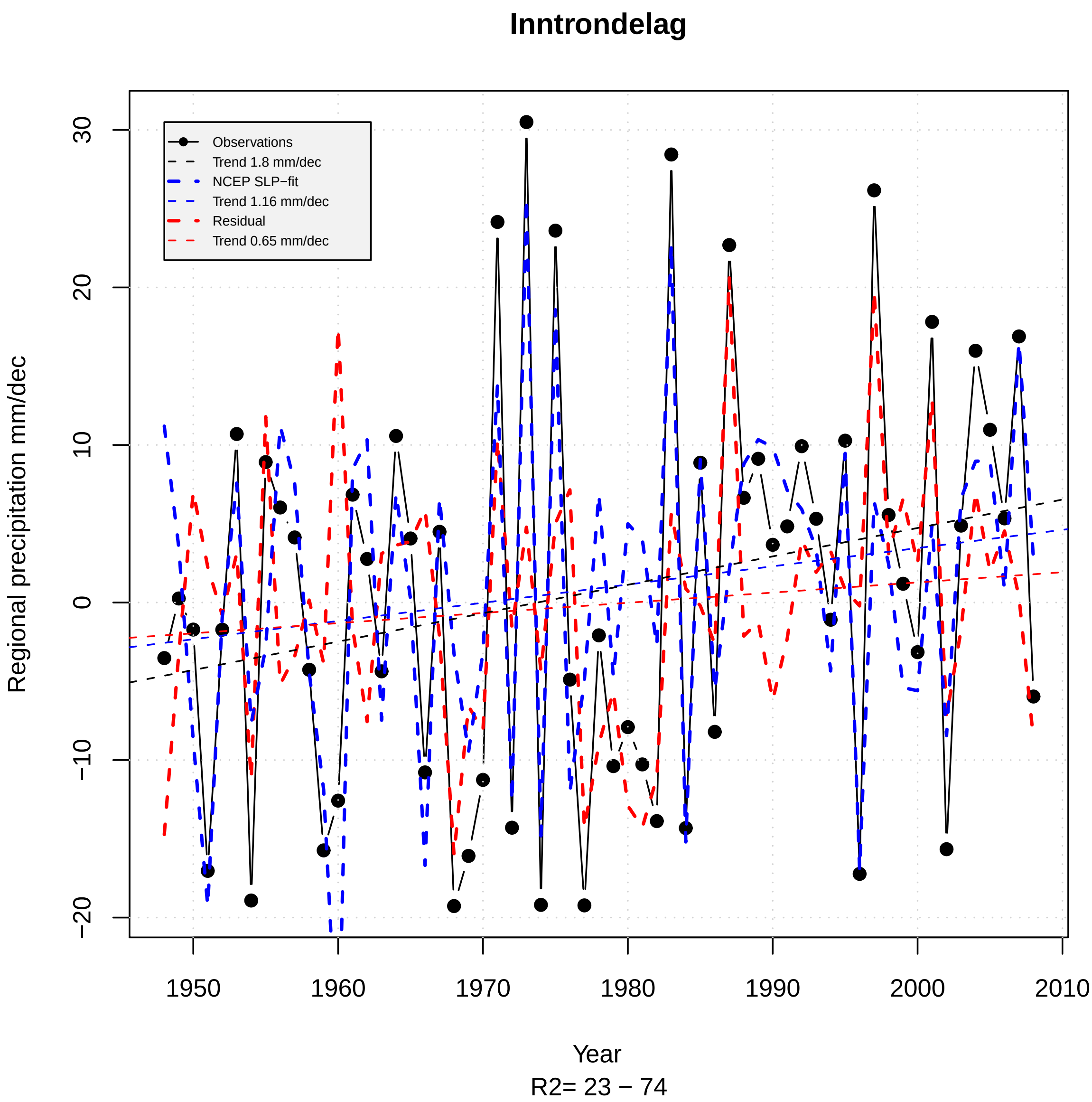

Figure 16: Same as Figure 9, but for Inntrøndelag

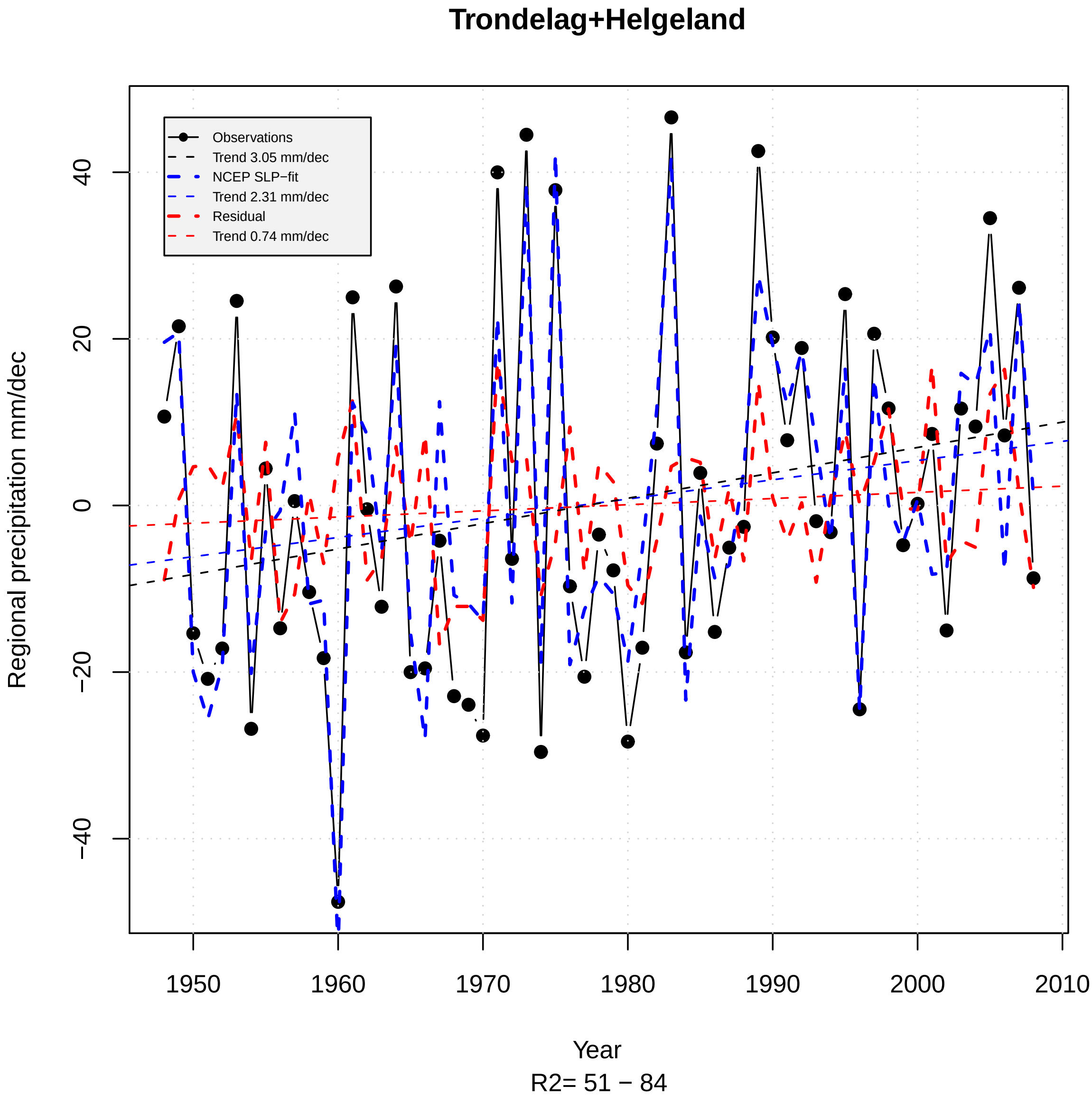

Figure 17: Same as Figure 9, but for Trøndelag+Helgeland

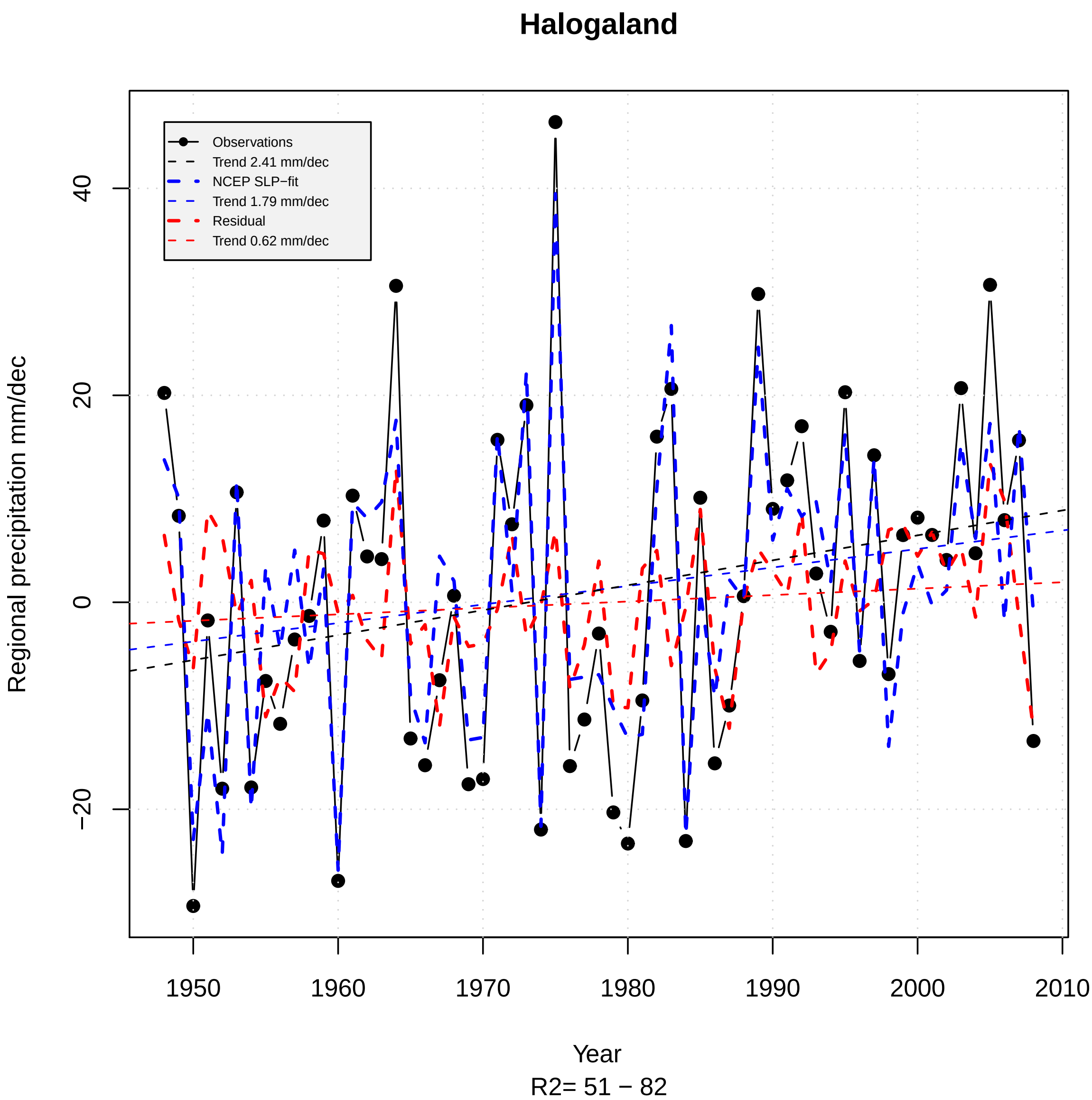

Figure 18: Same as Figure 9, but for Halogaland

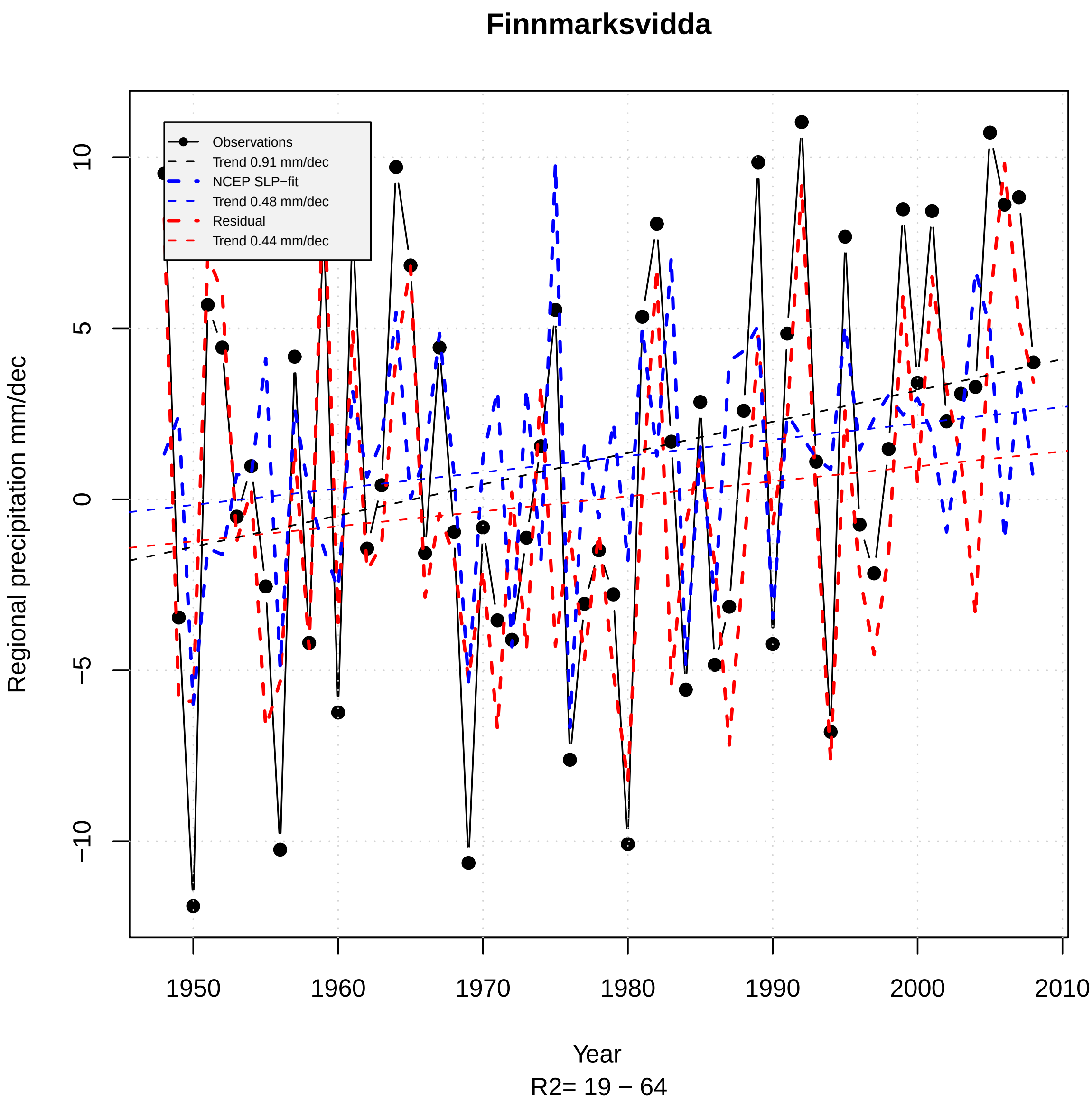

Figure 19: Same as Figure 9, but for Finnmarksvidda

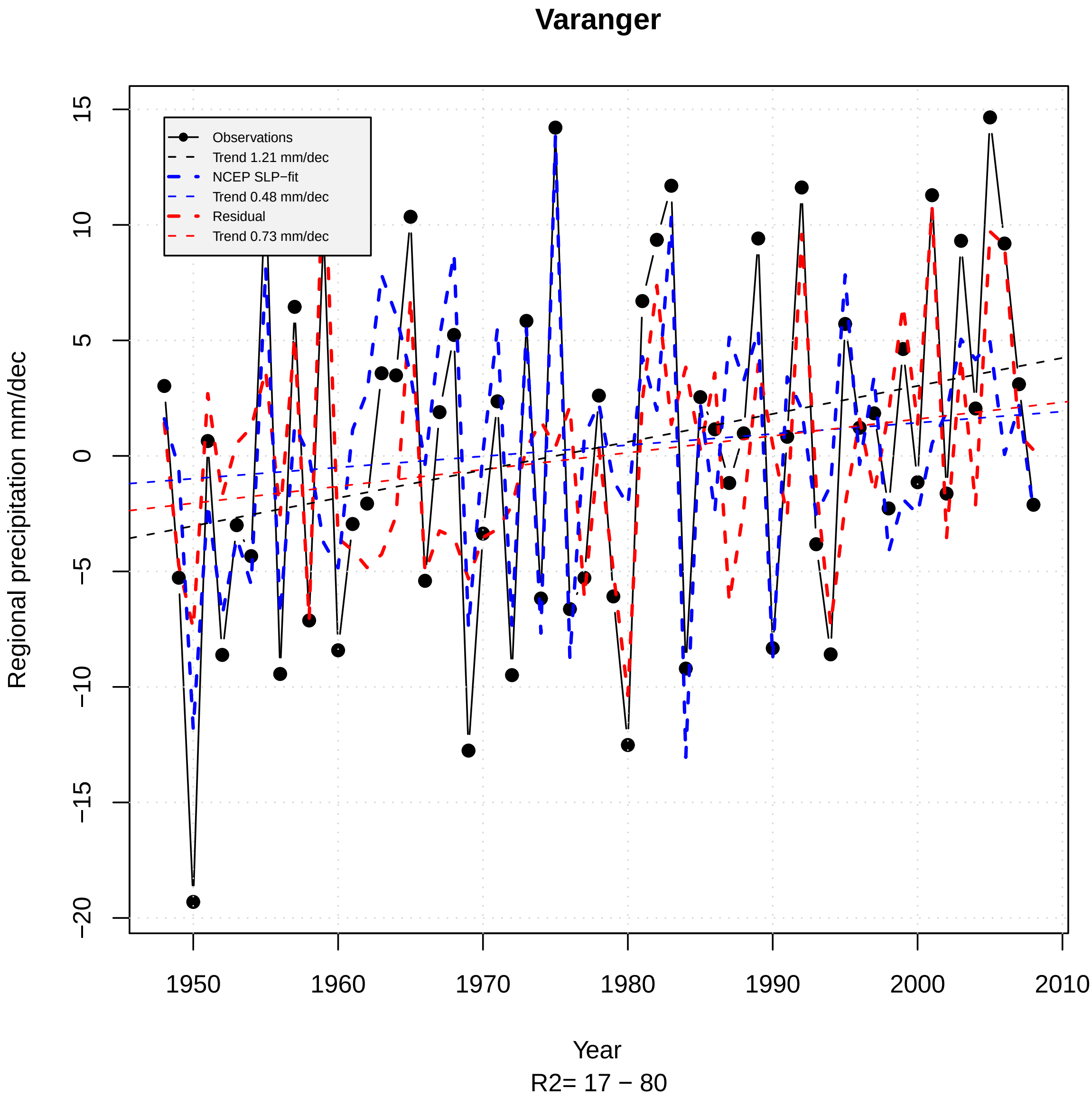

Figure 20: Same as Figure 9, but for Varanger