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Monthly precipitation and temperature at Svalbard modelled by mean sea level pressure.

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Monthly precipitation and temperature at Svalbard modelled by mean sea level pressure.

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Abstract

Monthly values of mean sea level pressure in 4 grid-points were used to develop models for monthly mean temperature at the Norwegian Arctic stations Svalbard Airport and Bjørnøya. The models account for 30-50% of the variance in the seasonal mean temperatures, while about 40% of the variance in the annual mean temperatures is accounted for. The correlation between observed and modelled values is at minimum for the summer season. For the autumn, the correlation coefficient is 0.66 at both stations. At Svalbard Airport this is the best seasonal correlation, but at Bjørnøya the spring values are best correlated.

For Svalbard Airport, a model for monthly precipitation sum was also developed. This model accounts for 15-35% of the variance in seasonal precipitation sums and about 30% of the variance in the annual precipitation. The correlation between observed and modelled values is lowest in winter, when the problems with drifting and blowing snow are at maximum.

Even though the observed and modelled seasonal values in most cases are better correlated for temperature than for precipitation, the precipitation model accounts for more of the decadal scale variability and long-term trends than the temperature models. The precipitation model reproduces the observed positive precipitation trends during the period of measurements both on seasonal and on annual basis. Concerning decadal scale variability, most of the main observed features are also modelled satisfactory. It is concluded that the major observed features concerning decadal scale variability and trends in precipitation at Svalbard Airport are connected to variability in the atmospheric circulation pattern.

The temperature models reproduce reasonably well the observed positive trends during the last 3 decades of the series of winter- and spring temperatures, and also of annual mean temperatures. The very low temperature level before 1920 and the temperature optima in the 1930s and the 1950s on the other hand, are not modelled satisfactory. Thus, while the temperature increase of the later decades mainly may be explained as a result from changes in the average advection conditions, the considerable temperature increase which was observed in the Norwegian Arctic from the beginning of the measurements to the 1930s cannot be explained in this way.

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Monthly precipitation and temperature at Svalbard vs. pressure gradients.

Contents

FOREWORD

During the years 1996-2001, the Norwegian Research Council Programme (NRC) is running the research programme «ALV» (Arctic Light and Heat»). The Norwegian Meteorological Institute (DNMI) is participating in this programme through the project «Long term variations in atmospheric circulation and climate in Norwegian Arctic» (NRC-No 112890/720).

The main aims of the DNMI-project is to:

a). Establish a climatological dataset of daily values for all Norwegian Arctic stations

b). Work out comprehensive surveys of climatological statistics for the Norwegian Arctic, and study the natural climatic variability.

c). Analyse long-term variations in atmospheric circulation and climate in the Norwegian Arctic, and distinguish between climate variations caused by changes in the frequencies of circulation patterns vs. changes in characteristics of the advected air-masses.

d). Work out climate changes scenarios for the Norwegian Arctic under global warming.

Results from activities a). and b). have been reported earlier. This report is presenting some results from pilot studies within activity c). of the project.

1. Introduction

General Circulation Model (GCM) simulations of climate under radiative forcing corresponding to doubling of the atmospheric CO_2 concentration, indicate a maximum annual mean warming in high northern latitudes (Kattenberg et al. 1996). This is true both for equilibrium and for transient experiments, though the latter show a smaller warming in the vicinity of the northern North Atlantic. The warming is largest in late autumn and winter, largely due to sea ice forming later in the warmer climate. The GCM-simulated maximum warming of the Arctic might lead to the suggestion that the «greenhouse signal» first can be detected in Arctic areas. This is not necessarily true, as the natural inter-annual climatic variation is also large in this region, and thus contributes to a reduced signal-to-noise ratio. Besides, IPCC states that the details of the modelled changes in the Arctic climate are sensitive to parameterization of sea ice, including the specification of sea ice albedo (Kattenberg et al. 1996). Still, monitoring long-term climatic variations in the Arctic is of great importance. Analyzing variation and covariation in climatic elements will increase our knowledge of the Arctic climate, which is poorly understood in many respects.

The weather conditions at a location is the result both from the atmospheric circulation conditions, and from the characteristics of the air masses which enter or dwell in the area under given circulation conditions. Thus, the local climate may become warmer, either because of changes in the average frequencies of different atmospheric circulation patterns (e.g. more frequent or stronger southerly winds), or because of higher temperature of the air-masses which are advected into the area under given circulation conditions (caused by e.g. changes in the radiation budget of the air-masses entering the area). These conditions are not independent, as the spatial distribution of air temperature affects the circulation conditions and vice versa. Thus, even if the initial effect of increased concentrations of greenhouse gases would be to affect the radiation budget of the air-masses, changes in the average circulation conditions may very well be a secondary effect, which for the local climate even may be the more important. Nevertheless, the above simplified concept may give an indication of the causes for observed climate variations. In the present report, an effort is made to see to which degree variations in monthly mean temperature and monthly precipitation in the Norwegian Arctic can be seen as a result from changes in atmospheric circulation alone, as expressed by the mean sea level pressure field.

2. Data

The present analyses are based upon monthly mean temperature and monthly precipitation series from Svalbard Airport and Bjørnøya, and monthly mean sea level air pressure from 4 grid-points (Figure 2.1). Temperature and precipitation series from the Norwegian Arctic stations were recently improved by quality control and homogeneity testing, and prolonged by gap-filling and combination of different series (Nordli et al. 1996). The series valid for Svalbard Airport start in 1912. Both the temperature and the precipitation series were composed from measurements at several locations along the coast of the fjord Isfjorden. Measurements from other locations were adjusted to represent the conditions at the present station at Svalbard Airport. The Bjørnøya series starts in 1920. The precipitation series was adjusted for introduction of a windshield and for one relocation, while the temperature series was found to be homogeneous. There were gaps in all series during World War II. Only the gaps in the temperature series were filled. Nordli et al. (1996) should be consulted for further details about adjustments and data quality.

The series were analyzed and presented by Førland et al. (1997), who concluded that the annual precipitation has been increasing in the Norwegian Arctic since the beginning of the measurements. The long-term variation in the precipitation series from Svalbard Airport, which is representative for the west coast of Spitsbergen, includes positive trends in all seasons except for winter. The long-term variation of temperature has been quite similar at all the Norwegian Arctic stations. There is no statistically significant trend in annual mean temperatures during the entire period 1912-1995, though there are 3 periods with statistically significant temperature trends. There is a positive trend during 1912 - 1930, a negative trend from the 1930s to the 1960s, and a positive trend from the 1960s to the end of the series. The spring is the only season which shows a positive temperature trend during the period as a whole.

The gridded set of monthly averaged sea-level air pressure during 1873-1993 developed at University of East Anglia, was used as source for the air pressure data. The dataset has 5° resolution in most areas, but the resolution north of 70°N is 10° prior to 1940. For the present

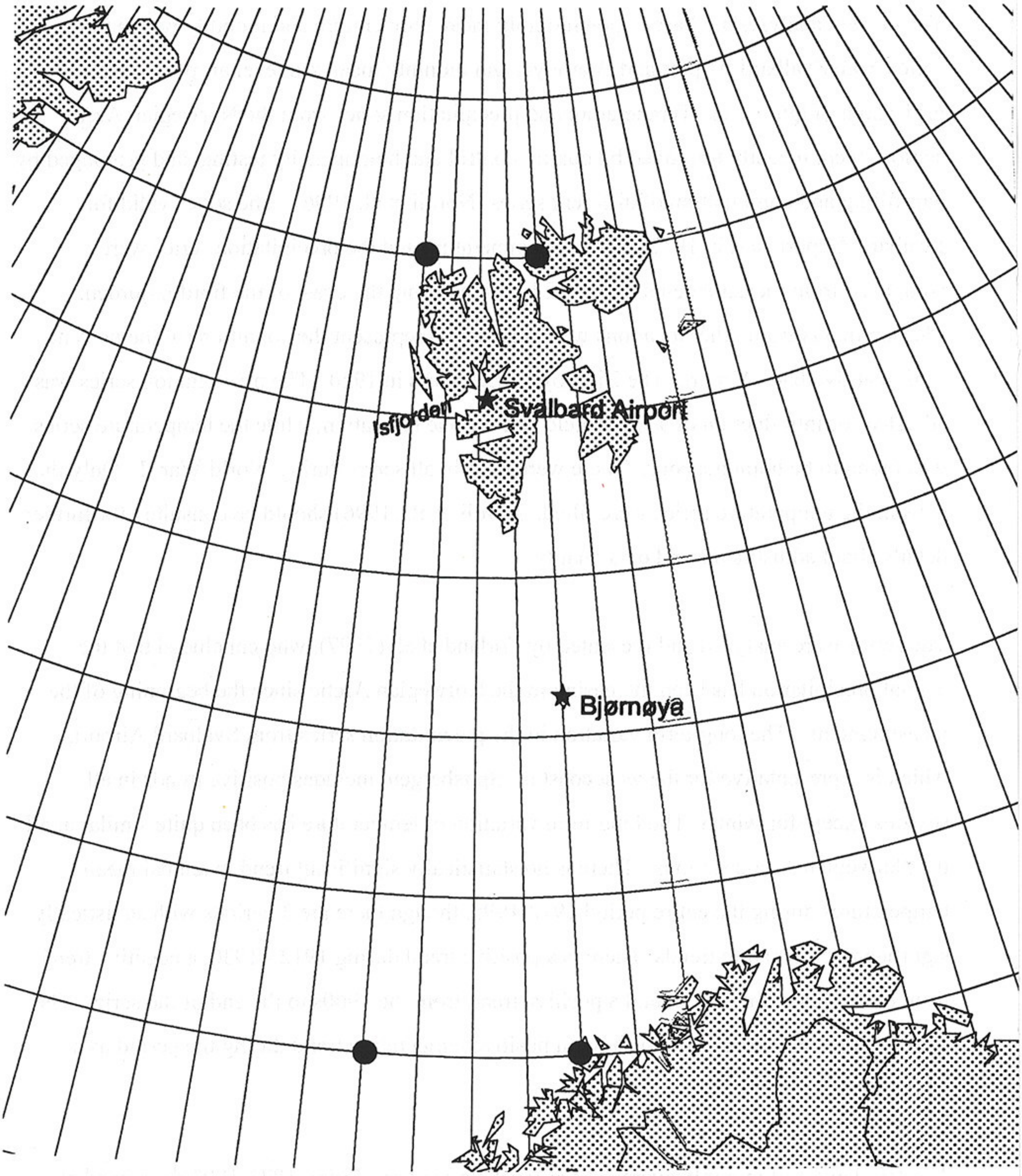


Figure 2.1. Map showing the positions of the stations Svalbard Airport and Bjørnøya (stars), and of the 4 grid-points (filled circles) for which mean sea level pressure was used.

study, data from the grid-points 70°N 10°E, 80 °N 10°E, 70°N 20°E and 80°N 20°E were applied (Figure 2.1). From these, mean sea level pressure **p,** longitudinal pressure difference $\Delta\mathbf{p}_{\mathbf{LON}}$, and latitudinal pressure difference $\Delta\mathbf{p}_{\mathbf{LAT}}$ representative for Svalbard Airport and Bjørnøya were defined. The following definitions were found to give the best results:

$$\Delta\mathbf{p}_{\mathbf{LON}} \equiv \tfrac{1}{2}\{(\mathbf{p}_{20,70} + \mathbf{p}_{20,80}) - (\mathbf{p}_{10,70} + \mathbf{p}_{10,80})\} \qquad (1),$$

$$\Delta\mathbf{p}_{\mathbf{LAT}} \equiv \mathbf{p}_{20,80} - \mathbf{p}_{20,70} \qquad (2),$$

$$\mathbf{p} \equiv \mathbf{p}_{20,80} \qquad (3).$$

3. Methods

3.1 Multiple linear regression

Multiple linear regression was used to establish relations between the monthly averaged geostrophic wind components and absolute pressure (predictors) and local monthly mean temperature and monthly precipitation sum (predictands). If air density ρ is assumed to be constant, the monthly averaged geostrophic wind components $\mathbf{u_g}$ and $\mathbf{v_g}$ are given as:

$$\mathbf{u_g} = -(1/\rho f)\ \delta\mathbf{p}/\delta\mathbf{y}\ , \quad \mathbf{v_g} = (1/\rho f)\ \delta\mathbf{p}/\delta\mathbf{x} \qquad (4).$$

Here, $\delta\mathbf{p}/\delta\mathbf{y}$ and $\delta\mathbf{p}/\delta\mathbf{x}$ are the monthly mean south-north and west-east horizontal pressure gradients, while ρ is mean air density and f is the Coriolis parameter. The monthly mean geostrophic wind components are consequently proportional to the monthly mean longitudinal and latitudinal pressure differences:

$$\mathbf{v_g} \propto \Delta\mathbf{p}_{\mathbf{LON}}\ , \quad \mathbf{u_g} \propto -\Delta\mathbf{p}_{\mathbf{LAT}} \qquad (5),$$

where $\Delta\mathbf{p}_{\mathbf{LON}}$ and $\Delta\mathbf{p}_{\mathbf{LAT}}$ are the monthly mean differences in sea level pressure between grid-points with different longitude or latitude (cf. eqs. (1) and (2)).

The multiple regression model for month number n may then be expressed by the equation

$$\mathbf{T_n} - \overline{\mathbf{T_n}} = (\Delta\mathbf{p}_{\mathbf{LON,\,n}} - \overline{\Delta\mathbf{p}_{\mathbf{LON,\,n}}})\cdot\mathbf{a}_{\mathbf{n}} - (\Delta\mathbf{p}_{\mathbf{LAT,\,n}} - \overline{\Delta\mathbf{p}_{\mathbf{LAT,\,n}}})\cdot\mathbf{b}_{\mathbf{n}} + (\mathbf{p_n} - \overline{\mathbf{p_n}})\cdot\mathbf{c}_{\mathbf{n}}\ , \ \ n\in\{1,12\} \quad (6),$$

for monthly mean temperature, and

$$\mathbf{P_n} - \overline{\mathbf{P_n}} = (\Delta\mathbf{p}_{\mathbf{LON,\,n}} - \overline{\Delta\mathbf{p}_{\mathbf{LON,\,n}}})\cdot\mathbf{k}_{\mathbf{n}} - (\Delta\mathbf{p}_{\mathbf{LAT,\,n}} - \overline{\Delta\mathbf{p}_{\mathbf{LAT,\,n}}})\cdot\mathbf{l}_{\mathbf{n}} + (\mathbf{p_n} - \overline{\mathbf{p_n}})\cdot\mathbf{m}_{\mathbf{n}}\ , \ \ n\in\{1,12\} \quad (7),$$

for monthly precipitation sums. Here, $\mathbf{T_n}$ is monthly mean temperature for a given month, $\mathbf{P_n}$ is monthly precipitation sum, while $\mathbf{a}_{\mathbf{n}}$, $\mathbf{b}_{\mathbf{n}}$, $\mathbf{c}_{\mathbf{n}}$, $\mathbf{k}_{\mathbf{n}}$, $\mathbf{l}_{\mathbf{n}}$ and $\mathbf{m}_{\mathbf{n}}$ are regression coefficients. Long-term averages are denoted by over-bar. The regression equations thus express the relations between deviations from the long-term averages.

3.2 Inflated multiple regression

A problem when using regression techniques for hindcasts or predictions is that the variability in the resulting time-series is underestimated. A method which helps preserving the observed variance of the predictands, is inflated multiple regression (Klein et. al. 1985). The inflated model is given by the equation

$$\mathbf{T}_{\mathbf{nI}} - \overline{\mathbf{T}}_{\mathbf{n}} = (\mathbf{T}_{\mathbf{n}} - \overline{\mathbf{T}}_{\mathbf{n}})/\mathrm{R}_{\mathbf{Tn}}\,, \qquad n \in \{1,12\} \qquad (8)$$

for temperature and

$$\mathbf{P}_{\mathbf{nI}} - \overline{\mathbf{P}}_{\mathbf{n}} = (\mathbf{P}_{\mathbf{n}} - \overline{\mathbf{P}}_{\mathbf{n}})/\mathrm{R}_{\mathbf{Pn}}\,, \qquad n \in \{1,12\} \qquad (9)$$

for precipitation. Here, $\mathbf{T}_{\mathbf{nI}}$ and $\mathbf{P}_{\mathbf{nI}}$ are inflated estimates of temperature and precipitation for month n. R_{Tn} (R_{pn}) is correlation coefficient between observed and modelled mean temperature (precipitation sum) for month n. Note that inflation does not improve single hindcasts. It actually increases the mean square error of the estimate. However, for climatological purposes, achieving the correct variance in the projected dataset may be of greater importance than minimizing the mean error.

3.3 Final models

In the final models, estimated mean temperature τ_n and precipitation sum π_n are given as

$$\tau_n = \overline{\mathbf{T}}_{\mathbf{n}} + (\Delta \mathbf{p}_{\mathbf{LON,\,n}} - \overline{\Delta \mathbf{p}_{\mathbf{LON,\,n}}})\cdot\alpha_n - (\Delta \mathbf{p}_{\mathbf{LAT,\,n}} - \overline{\Delta \mathbf{p}_{\mathbf{LAT,\,n}}})\cdot\beta_n + (\mathbf{p}_{\mathbf{n}} - \overline{\mathbf{p}_{\mathbf{n}}})\cdot\gamma_n\,, \quad n \in \{1,12\} \quad (10),$$

and

$$\pi_n = \overline{\mathbf{P}}_{\mathbf{n}} + (\Delta \mathbf{p}_{\mathbf{LON,\,n}} - \overline{\Delta \mathbf{p}_{\mathbf{LON,\,n}}})\cdot\kappa_n - (\Delta \mathbf{p}_{\mathbf{LAT,\,n}} - \overline{\Delta \mathbf{p}_{\mathbf{LAT,\,n}}})\cdot\lambda_n + (\mathbf{p}_{\mathbf{n}} - \overline{\mathbf{p}_{\mathbf{n}}})\cdot\mu_n\,, \quad n \in \{1,12\} \quad (11).$$

Here, the over-bar symbolizes averaging over the «model training period», which consist of all even years in the dataset. The coefficients α_n, β_n and γ_n (in °C/hPa), and κ_n, λ_n and μ_n (in mm/hPa) are neither identical to the regression coefficients from the multiple correlation analysis, nor to the inflated coefficients. Both these sets of coefficients are taken into account, but some adjustments are made in order to ensure consistent variation of the coefficients throughout the year, and also values which are reasonable from a physically point of view.

In order to define what is physically reasonable, some climatological considerations are made. In the temperature equation (10), the geostrophic wind terms may be interpreted as «monthly mean advection terms». The first one represents the south-north advection. The coefficient α_n should thus be proportional to some kind of «typical monthly north-south temperature gradient» for month n. As the air and sea surface temperature at average decreases northwards all year around, α is expected to be positive for all months. The coefficient β_n should be proportional to some kind of «typical monthly east-west temperature gradient» for month n. It should thus be positive for months when the temperature around the station normally decreases eastward. The value of the east-west temperature gradient in the Norwegian Arctic will depend on location as well as time of year. It may change sign throughout the year, but the variation should be reasonable from the location of the station for which the temperature is modelled.

The physical interpretation of the last term in (10) is not connected to advection, but rather to the energy budget of the air. High pressure is correlated to subsidence, and thus to low cloudiness, while low pressure is associated with convergence, and thus more cloudy sky. During winter and most of the autumn and spring, the Arctic clear-sky radiation budget is negative, and thus contributing to cooling of air-masses near the surface. As a cloudy sky would decrease this cooling, γ_n is thus expected to be negative during autumn, winter and spring. During summer, on the other hand, the clear-sky radiation budget is positive at most places, and γ_n is thus expected to be positive.

The physical interpretation of the precipitation equation (11) is somewhat different. The two geostrophic wind terms express that the station mainly is exposed for precipitation from one wind sector, and that it increases when the average pressure gradient in this direction increases. This is a fairly good description of the conditions at stations with strong orographic effects. Tveito (1996) found correlation coefficients ranging from 0.68 (August) to 0.93 (March) between monthly mean onshore geostrophic wind component and monthly precipitation sum at a station in western Norway. Hurrell et al. (1995) even found a correlation coefficient of 0.77 between the NAO index and the December through March precipitation in Bergen in Western Norway. Thus the κ_n and/or λ_n are expected to differ significantly from zero for stations with orographic effects. At such stations, κ_n (λ_n) would be expected to be positive if the station mainly was exposed to precipitation coming from south (west), and negative in the opposite case. The absolute values of κ_n and λ_n might vary throughout the year, but they should not change sign, and the ratio between them would be expected to be constant throughout the year.

The last term of eq. (11) is added to include the information connected to correlation between low pressure systems and precipitation. Because of the convergence effects of low pressure systems, the coefficient μ_n is expected to be negative for all months.

The final choices of coefficients α_n, β_n, γ_n, κ_n, λ_n and μ_n were thus based on multiple regression analyses, but the coefficients from these analyses were adjusted according to the above considerations. In case of major disagreement between these considerations and the results from the regression analyses, no model was suggested. The final models were tested using data from odd years as test dataset, and finally they were applied on the entire data-series in order to investigate if observed trends and variability in seasonal and annual values can be explained by variations in the mean sea level pressure field.

4. Temperature

4.1 Temperature regression analyses

Regression analyses were performed according to equation (6) on series of monthly mean temperature from Svalbard Airport in even years during 1912-1992, and from Bjørnøya in even years during 1920-1992. Average values of $\mathbf{T}$, $\Delta\mathbf{p}_{\mathbf{LON}}$, $\Delta\mathbf{p}_{\mathbf{LAT}}$ and $\mathbf{p}$ over the model training periods are given in Tables A.1 a-b in Appendix.

Multiple correlation coefficients for each month are given in last column of Table 4.1 for Svalbard Airport and Table 4.2 for Bjørnøya. For most months, the correlation is somewhat better at Bjørnøya than at Svalbard Airport. The correlation is generally better during autumn and winter than during summer, and at Bjørnøya it is also good during spring. This is confirmed by Figure 4.1, which shows R^2 for each month. At Svalbard Airport, the regression model accounts for 18-64% of the variance on monthly basis. At Bjørnøya, it accounts for 29-74% of the variance.

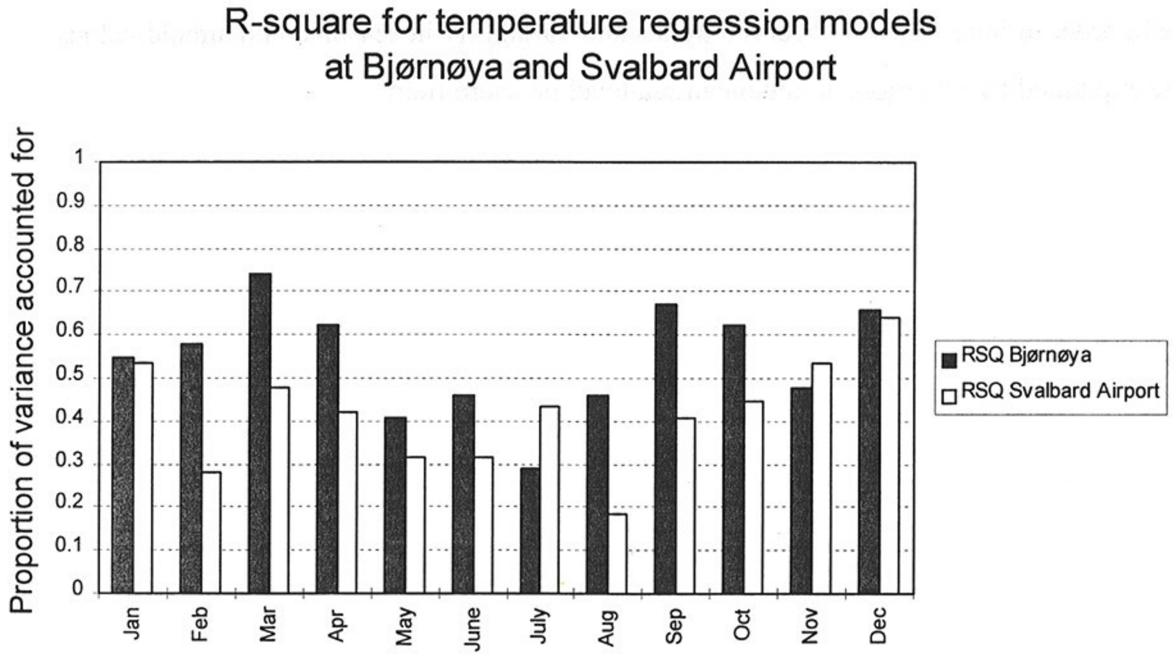


Figure 4.1 Multiple R^2 for temperature regression at Svalbard Airport and Bjørnøya.

Table 4.1 Results from regression analysis of monthly mean temperature at Svalbard Airport.
Model training period: Even years during 1912-92.

a, b, c: Regression coefficients referring to eq. (6). Italic values do not differ significantly from 0 (10 % level).
Order of entry in stepwise reg.: The order in which the terms of the (6) are included in stepwise regression.
R : Correlation coefficient between observed and modelled temperatures.

MONTH	a (°C/hPa)	b (°C/hPa)	c (°C/hPa)	Order of entry in stepwise reg.	R
January	2.34	0.36	*-0.09*	Δp_{LON}, Δp_{LAT}, p	0.73
February	0.98	0.13	*-0.12*	Δp_{LON}, Δp_{LAT}, p	0.53
March	1.19	0.33	*-0.11*	Δp_{LON}, Δp_{LAT}, p	0.69
April	1.78	*-0.01*	-0.15	Δp_{LON}, p, Δp_{LAT}	0.65
May	0.75	0.22	*0.08*	Δp_{LAT}, Δp_{LON}, p	0.56
June	0.75	*-0.03*	*-0.01*	Δp_{LON}, p, Δp_{LAT}	0.56
July	0.48	-0.11	0.09	Δp_{LAT}, Δp_{LON}, p	0.66
August	0.42	*0.02*	0.07	Δp_{LON}, Δp_{LAT}, p	0.43
September	1.07	*0.02*	*-0.05*	Δp_{LON}, Δp_{LAT}, p	0.64
October	1.14	*0.10*	-0.20	Δp_{LON}, p, Δp_{LAT}	0.67
November	2.10	*0.04*	-0.21	Δp_{LON}, p, Δp_{LAT}	0.73
December	2.70	0.37	*-0.01*	Δp_{LON}, Δp_{LAT}, p	0.80

Table 4.2 Results from regression analysis of monthly mean temperature at Bjørnøya.
Model training period: Even years during 1920-92.

a, b, c: Regression coefficients referring to eq. (6). Italic values do not differ significantly from 0 (10 % level).
Order of entry in stepwise reg.: The order in which the terms of the (6) are included in stepwise regression.
R : Correlation coefficient between observed and modelled temperatures.

MONTH	a (°C/hPa)	b (°C/hPa)	c (°C/hPa)	Order of entry in stepwise reg.	R
January	1.32	0.29	*-0.09*	Δp_{LON}, Δp_{LAT}, p	0.74
February	1.24	*0.09*	-0.15	Δp_{LON}, Δp_{LAT}, p	0.76
March	1.41	0.39	*-0.03*	Δp_{LON}, Δp_{LAT}, p	0.86
April	1.48	0.16	*-0.08*	Δp_{LON}, Δp_{LAT}, p	0.79
May	0.99	0.14	*-0.05*	Δp_{LON}, Δp_{LAT}, p	0.64
June	1.04	*0.05*	*-0.09*	Δp_{LON}, p, Δp_{LAT}	0.68
July	0.91	*0.02*	0.03	Δp_{LON}, p, Δp_{LAT}	0.54
August	0.75	0.14	*0.09*	Δp_{LON}, Δp_{LAT}, p	0.68
September	1.01	*0.06*	*-0.01*	Δp_{LON}, Δp_{LAT}, p	0.82
October	0.97	0.16	-0.16	Δp_{LON}, Δp_{LAT}, p	0.79
November	1.13	*0.04*	-0.12	Δp_{LON}, p, Δp_{LAT}	0.69
December	1.90	0.22	*-0.01*	Δp_{LON}, Δp_{LAT}, p	0.81

Tables 4.1 and 4.2 give regression coefficients at Svalbard Airport and Bjørnøya, respectively. They also indicate whether the coefficients significantly differ from zero at the 10% level, and in which order the 3 terms enter the model when applying stepwise regression. In most cases, $\Delta \mathbf{p}_{\mathbf{LON}}$ enters the model as the number one variable, and its coefficient **a** significantly differs from zero in all months. In accordance with what one might expect, **a** is positive in all months (positive temperature anomalies are connected to southerly winds, cf. section 2.4), and it has its minimum value in the summer, while it is at maximum in late autumn and winter. The reason for the annual cycle is probably that the average north-south temperature gradient around Svalbard is larger during winter than during summer (e.g. Vowinckel and Orvig 1970).

For most months, the term $\Delta \mathbf{p}_{\mathbf{LAT}}$ is included in the model at the second step. At Svalbard Airport, its regression coefficient **b** has statistically significant positive values during 5 winter- or spring months (westerly geostrophic wind component gives high temperature, easterly component gives low temperature), while it has a statistically significant negative value in July. The reason for this is probably that westerly winds advect marine air-masses to Svalbard Airport, which is situated on the western coast of Spitsbergen. During most of the year, these are warmer than the cold winds from the inland. In mid-summer, however, local warming makes land warmer than the sea. At Bjørnøya, the regression coefficient **b** has positive values all year around, though the values tend to be lower in summer than during the rest of the year. As Bjørnøya is a rather small and windy island, the values of **b** are probably more affected by large-scale features than by local land-sea contrasts. The values of **b** should then indicates that, at average, there is a large-scale east-west temperature gradient which is at maximum during winter and spring. This is, to some degree, supported by the frequency distributions of sea ice concentrations in the area (Vinje 1982), which show that at least from November through March, sea ice is far more frequent east of Bjørnøya than west of the island.

The absolute mean sea level pressure is included at step 3 in most months. Still, the regression coefficient **c** differs significantly from zero in some months. In summer, it tends to be positive, while it tends to be negative in autumn, winter and spring. This is in accordance with what one might expect (cf. section 2.4). Tables of net radiation in Ny-Ålesund, Svalbard, presented by Hisdal et al. (1992) indicate that the diurnal net radiation usually is positive during May through August, while it usually is negative during October through April. The shifts between negative and positive values are usually found late in April and in September. This is roughly in accordance with the shifts of sign of regression coefficient **c** at Svalbard Airport, while **c** at Bjørnøya changes from negative to positive first at mid-summer. Both at Svalbard Airport and Bjørnøya, the negative correlation between monthly mean air pressure and monthly mean temperature seems to be stronger in autumn than in winter. The reason for this is not obvious.

4.2 Temperature models: Final formulation and testing

The main impression is that the results from the regression analyses are reasonable from a physical point of view. Models were thus developed based on the analyses. Figures 4.2 and 4.3 show the regression coefficients a, b and c (eq. 6) for each month, and also the inflated regression coefficients (eq. 8) and the final model parameters α, β and γ (eq. 10). The final model parameters were, for most months, made by choosing values of α, β and γ between the regression coefficients and the inflated coefficients. However, some adjustments were made in order to give a more regular annual variation of the different terms (cf. section 2.5).

Tables 4.3 and 4.4 show the final coefficients α, β and γ for each month, and the correlation coefficient between observed and modelled temperature series when applying these models on the model training periods (even years) as well as the test periods (odd years). It is seen that, compared to the optimal regression models (Tables 4.1 and 4.2) the final models give somewhat reduced correlation coefficients, but the reduction is minor for most months.

At Svalbard Airport (Table 4.3), the model gives similar results during the training period as during the test period. For some months, the correlation between observed and modelled values is highest during the training period, while they for other months are higher during the test period. At Bjørnøya (Table 4.4), the correlation between observed and modelled values during spring and autumn is best during the training period, while the correlation during winter and summer tends to be better during the test period. This indicates that the connection

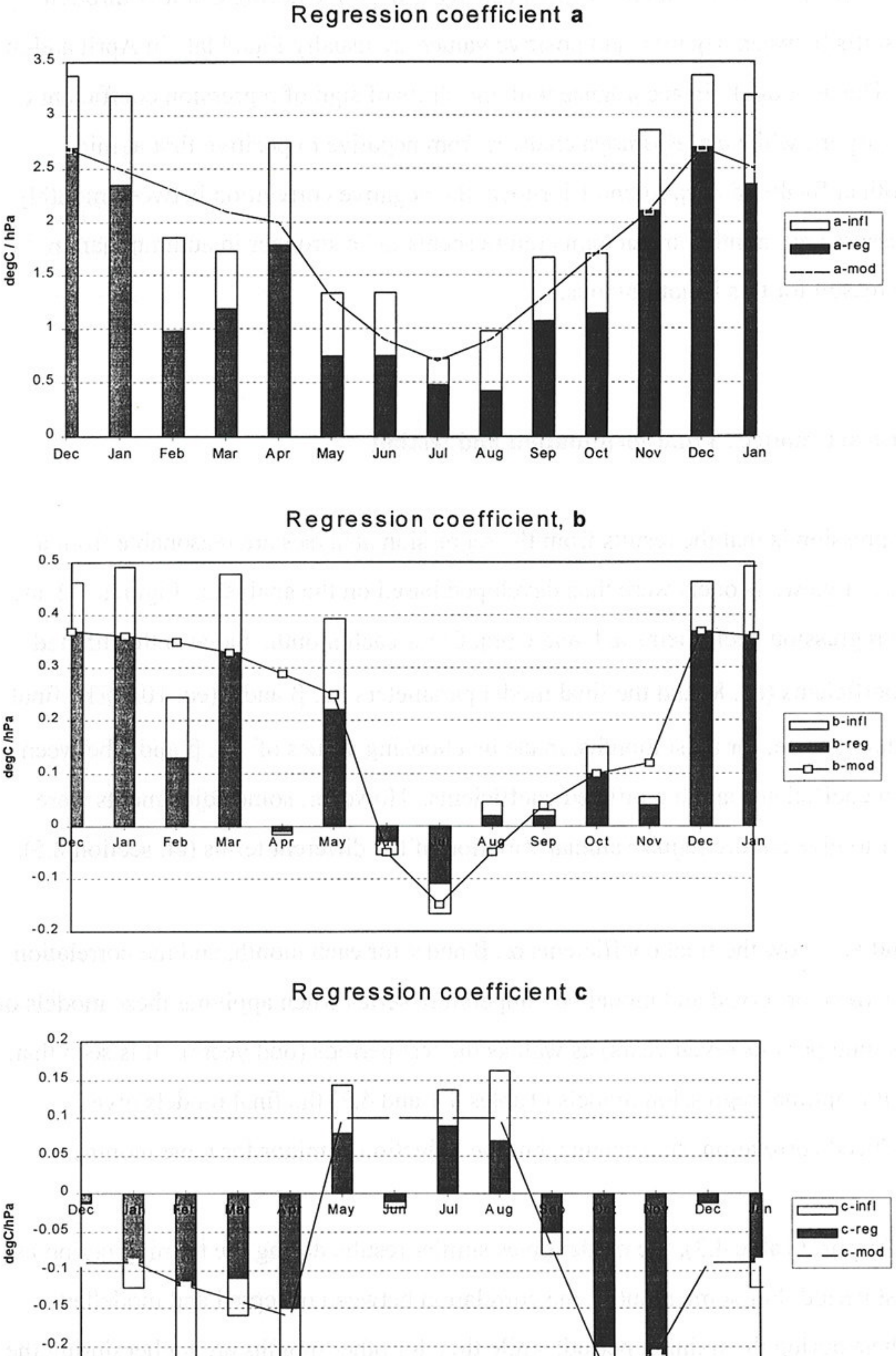
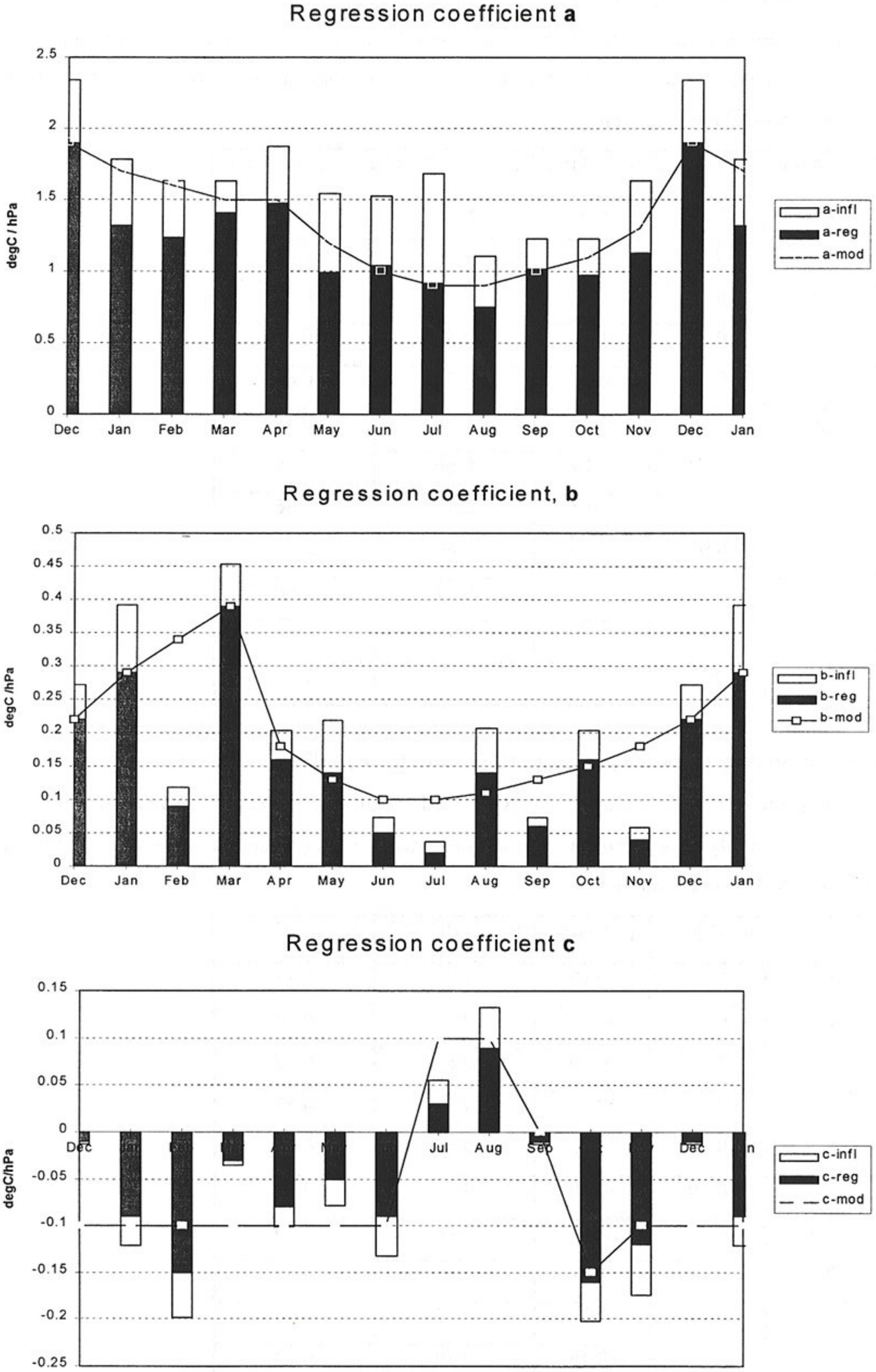


Figure 4.2 Coefficients from temperature regression analysis (eq. 6) (hatched coloumns) and from inflated regression (eq. 8) (white coloumns), and final model coefficients (eq. 10) (curve) for temperature at Svalbard Airport for all months. a) ***a*** *and* α*, b)* ***b*** *and* β*,c)* ***c*** *and* γ*.*



Regression coefficient **a**

Regression coefficient, **b**

Regression coefficient **c**

Figure 4.3 Coefficients from temperature regression analysis (eq. 6) (hatched coloumns) and from inflated regression (eq. 8) (white coloumns), and final model coefficients (eq. 10) (curve) for temperature at Bjørnøya for all months. a) ***a*** *and α, b)* ***b*** *and β, c)* ***c*** *and γ.*

Table 4.3 Model for monthly mean temperature at Svalbard Airport (cf. eq. 10)

α, β and γ are model parameters, R_{EVEN} 1912-92 and R_{ODD} 1913-93 are correlation coefficients between observed and modelled monthly mean temperatures during the model training period (even years 1912-92) and test period (odd years 1913-93), respectively.

MONTH	α(°C/hPa)	β(°C/hPa)	γ(°C/hPa)	R_{EVEN} 1912-92	R_{ODD} 1913-93
January	2.5	0.36	-0.09	0.73	0.73
February	2.3	0.35	-0.12	0.52	0.51
March	2.1	0.33	-0.14	0.67	0.45
April	2.0	0.29	-0.16	0.48	0.63
May	1.3	0.25	0.10	0.55	0.66
June	0.9	-0.05	0.10	0.48	0.33
July	0.7	-0.15	0.10	0.66	0.58
August	0.9	-0.05	0.10	0.41	0.46
September	1.3	0.04	-0.07	0.64	0.58
October	1.7	0.10	-0.23	0.67	0.66
November	2.1	0.12	-0.21	0.72	0.79
December	2.7	0.37	-0.09	0.79	0.71

Table 4.4 Model for monthly mean temperature at Bjørnøya (cf. eq. 10)

α, β and γ are model parameters, R_{EVEN} 1920-92 and R_{ODD} 1921-93 are correlation coefficients between observed and modelled monthly mean temperatures during the model training period (even years 1920-92) and test period (odd years 1921-93), respectively.

MONTH	α(°C/hPa)	β(°C/hPa)	γ(°C/hPa)	R_{EVEN} 1912-92	R_{ODD} 1913-93
January	1.7	0.29	-0.10	0.71	0.72
February	1.6	0.34	-0.10	0.72	0.60
March	1.5	0.39	-0.10	0.85	0.57
April	1.5	0.18	-0.10	0.78	0.55
May	1.2	0.13	-0.10	0.61	0.50
June	1.0	0.10	-0.10	0.65	0.71
July	0.9	0.10	0.10	0.48	0.60
August	0.9	0.11	0.10	0.66	0.33
September	1.0	0.13	0.00	0.77	0.61
October	1.1	0.15	-0.15	0.79	0.74
November	1.3	0.18	-0.10	0.66	0.77
December	1.9	0.22	-0.10	0.79	0.79

between predictors and predictands which were found during the training period can be applied also on independent data. Tables A.2 and A.3 in Appendix gives some additional information about observed and modelled temperatures during model training period and testing period, including mean values, standard deviations and extreme values for each month.

4.3 Application of the temperature models

The temperature models were now applied on the whole period of measurements, and hindcasts were made of seasonal and annual temperatures at Svalbard Airport and Bjørnøya. The observed and modelled time series are shown in Figures 4.4 and 4.5. Table 4.5 shows observed and modelled mean values, standard deviations and extreme values as well as correlation coefficients on annual and seasonal basis. It is seen that the models account for only about 30% of the variance during summer, however, this does not affect the annual results seriously, as the variance in summer is quite small. In the other seasons, the models account for 35-50% of the variance. Some of the variance which is not accounted for, is probably connected to the inter-annual variability in the sea ice and SST conditions. The sea ice distribution, which in this area varies substantially from one year to another (Vinje,1982),

Table 4.5 Some features of observed and modelled temperatures at Svalbard Airport and Bjørnøya

a) Svalbard Airport

Period: 1912-93	Observed T				Modelled T				
Season↓	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.	Corr.
Year	-6.33	1.72	-12.2	-3.1	-6.40	1.09	-9.2	-3.9	**0.61**
Winter	-13.96	3.60	-23.2	-7.6	-14.06	2.53	-19.4	-9.0	**0.62**
Spring	-10.80	2.42	-19.3	-6.7	-10.80	1.84	-15.4	-7.4	**0.58**
Summer	4.27	0.69	2.5	6.1	4.20	0.52	2.9	5.6	**0.54**
Autumn	-4.82	1.96	-11.3	-1.3	-4.90	1.56	-8.9	-1.7	**0.66**

b)Bjørnøya

Period: 1920-93	Observed T				Modelled T				
Season↓	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.	Corr.
Year	-1.9	1.2	-5.5	0.4	-1.9	0.8	-3.8	-0.1	**0.62**
Winter	-6.4	2.5	-13.0	-1.6	-6.4	1.9	-10.4	-2.5	**0.60**
Spring	-4.8	2.0	-10.2	-0.6	-4.9	1.5	-8.9	-2.1	**0.70**
Summer	3.7	0.9	1.4	5.6	3.7	0.6	1.6	5.0	**0.53**
Autumn	-0.1	1.3	-4.7	2.4	-0.1	1.1	-2.5	2.2	**0.66**

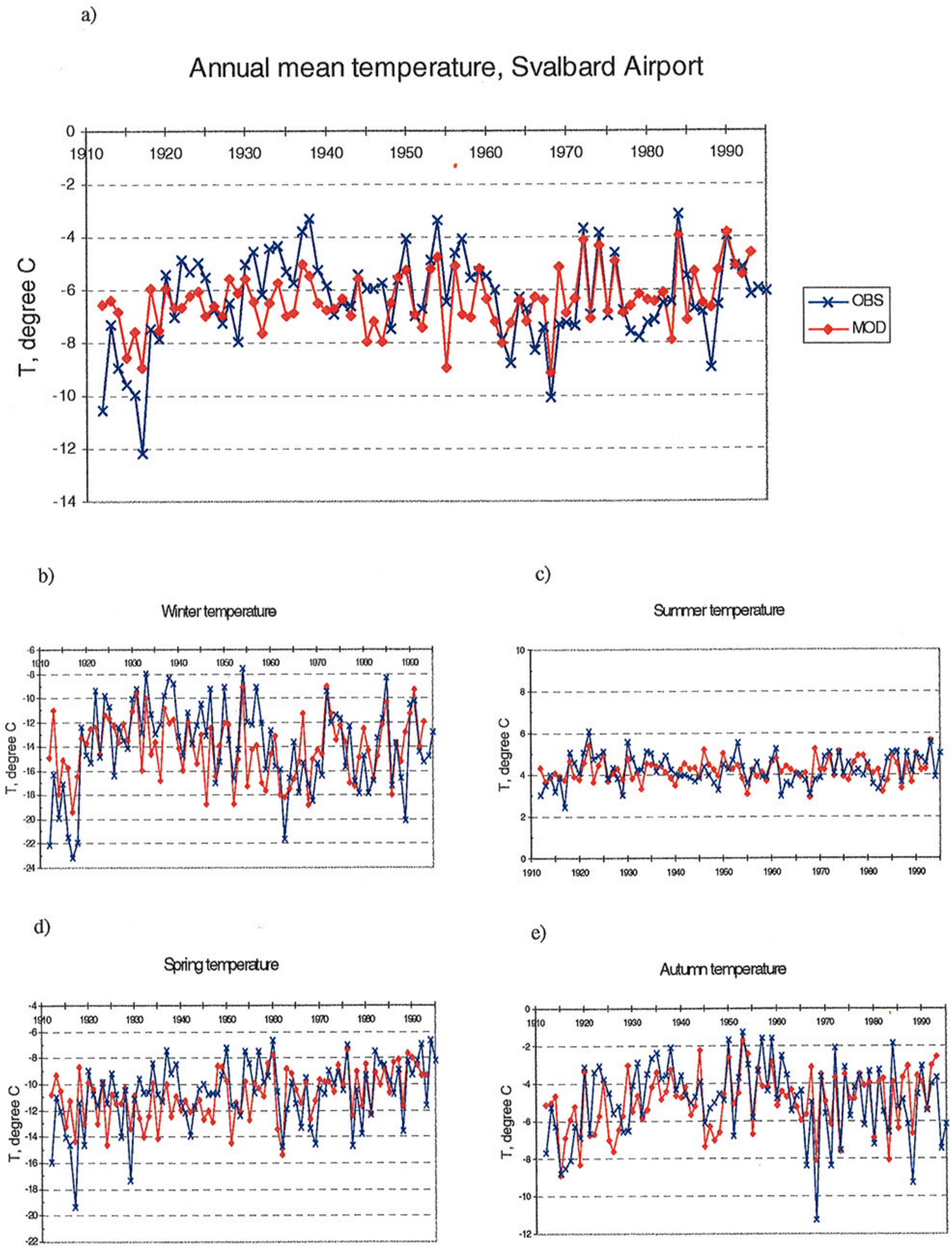


Figure 4.4 Observed and modelled time series of temperature valid for Svalbard Airport. a) Annual mean temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May), d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

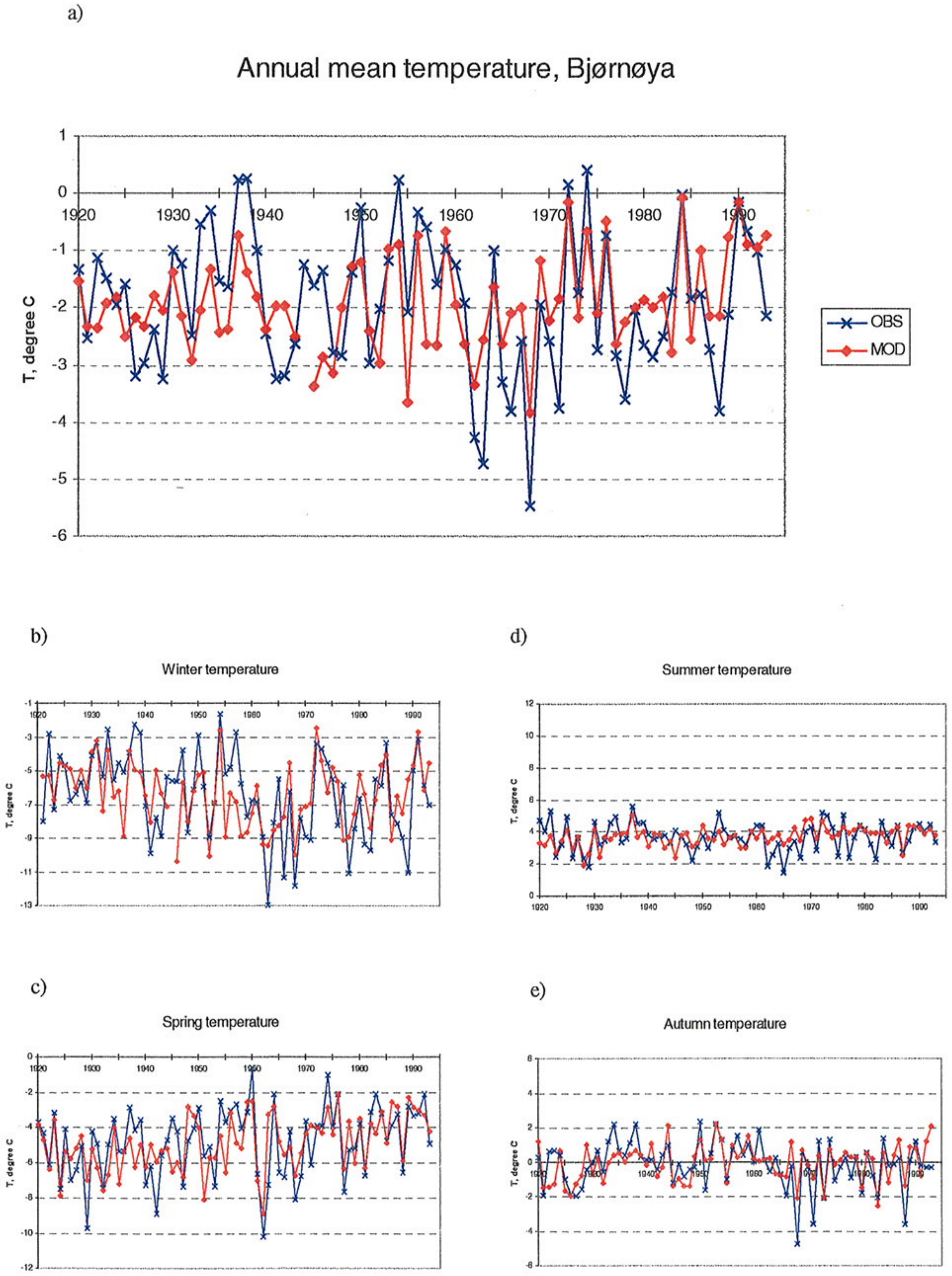


Figure 4.5 Observed and modelled time series of temperature valid for Bjørnøya.
a) Annual mean temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May), d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

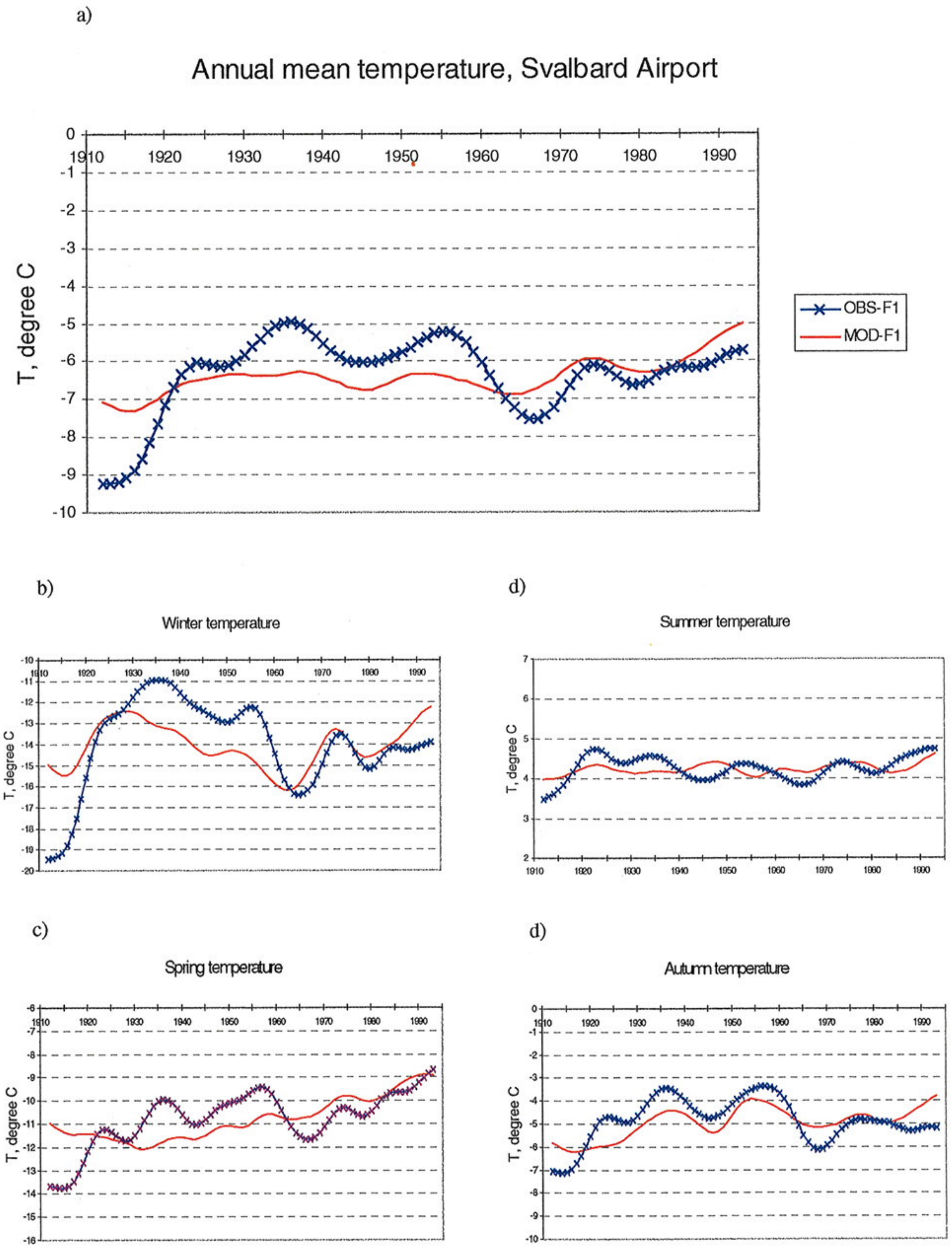


Figure 4.6 Filtered curves, observed and modelled temperature series, Svalbard Airport.
a) Annual temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May),
d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

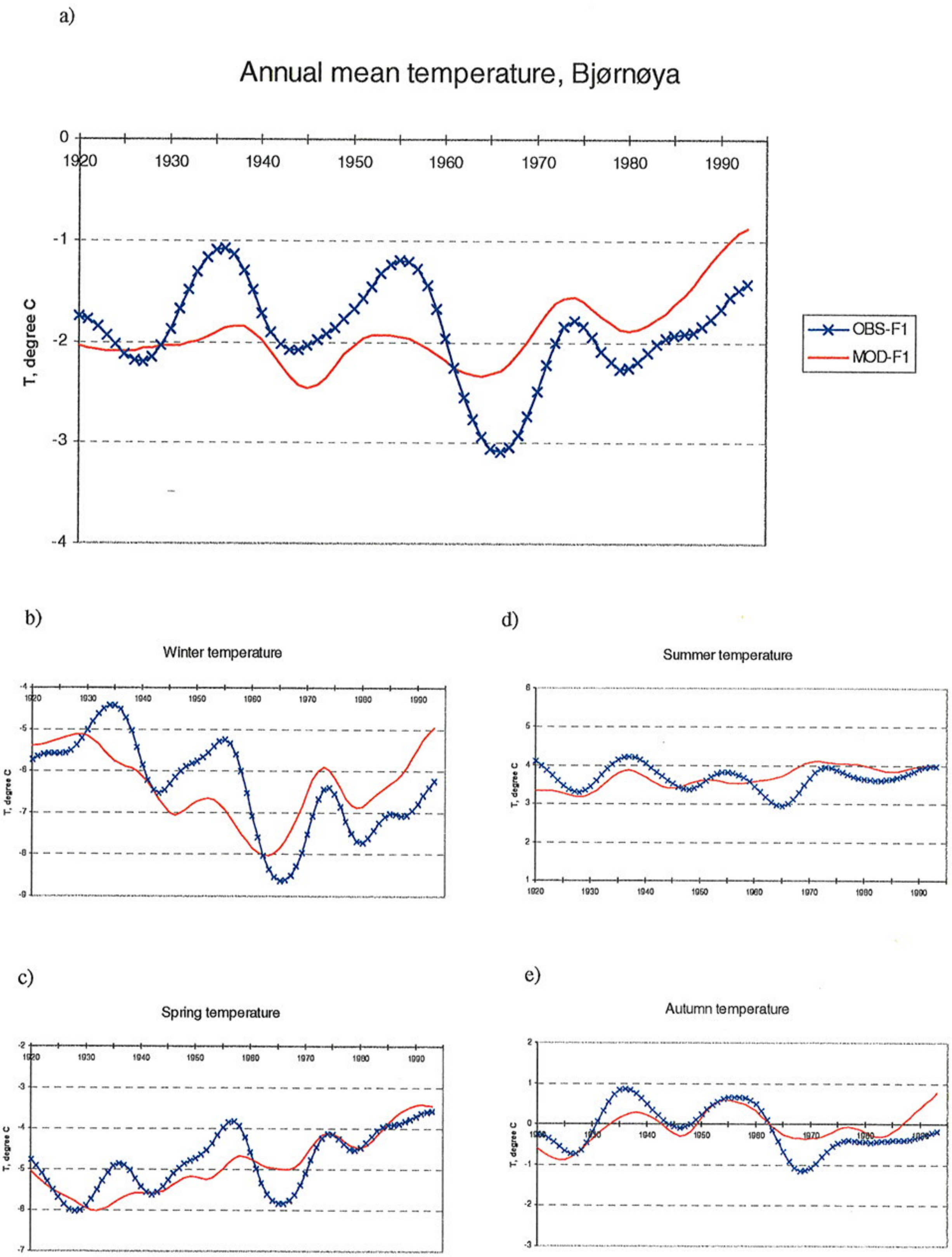


Figure 4.7 Filtered curves, observed and modelled temperature series, Bjørnøya.
a) Annual temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May),
d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

will obviously affect the temperature distribution, as the presence of sea ice radically affects sensible and latent heat fluxes at the surface, as well as the surface albedo.

In order to investigate to which degree the models reproduce decadal scale variability and long-term trends, a low-pass filter implying Gaussian weighting of the observed and modelled series was applied. The standard deviation of the Gaussian distribution was set to 3 years. Figures 4.6 and 4.7 show the low pass filtered series of modelled vs. observed temperatures. It is seen that the models reproduce some of the observed decadal scale variability and long-term trends, but not all features. The warm periods in the 1930s and 1950s are not satisfactorily reproduced by the models, mainly because the winter and spring temperatures were higher than modelled. Neither is the cold period before 1920 reproduced (Figure 4.6). Consequently, the observed positive trend in annual mean temperatures before the 1930s, and the negative temperature trend from the 1930s to the 1960s, are not satisfactory accounted for by the model. The observed positive trend in annual mean temperature from the 1960s to present, on the other hand, is fairly well reproduced by the model. This indicates that the positive temperature trend of the last 3 decades to a large degree may be explained by variations in the mean sea level air pressure field. It is not obvious why the model seems to work better during this period of temperature increase than it did in the period prior to the 1930s. Possible explanations are discussed in chapter 6.

5. Precipitation

5.1 Precipitation regression analyses

Regression analyses were performed according to equation (7) on series of monthly precipitation sums from Svalbard Airport in even years during 1912-1992, and from Bjørnøya in even years during 1920-1992. The period 1941-45 was excluded, as precipitation data are missing. Average values of **P**, $\Delta\mathbf{p}_{\mathbf{LON}}$, $\Delta\mathbf{p}_{\mathbf{LAT}}$ and **p** over the model training periods are given in Tables A.1 c-d in Appendix.

Multiple correlation coefficients for each month are given in last column of Table 5.1 for Svalbard Airport and Table 5.2 for Bjørnøya. For most months, the correlation is better at Svalbard Airport than at Bjørnøya. This is confirmed by Figure 5.1, which shows R^2 for each month. At Bjørnøya, there is no single month where the model accounts for more than 50% of the variance in the precipitation sum.

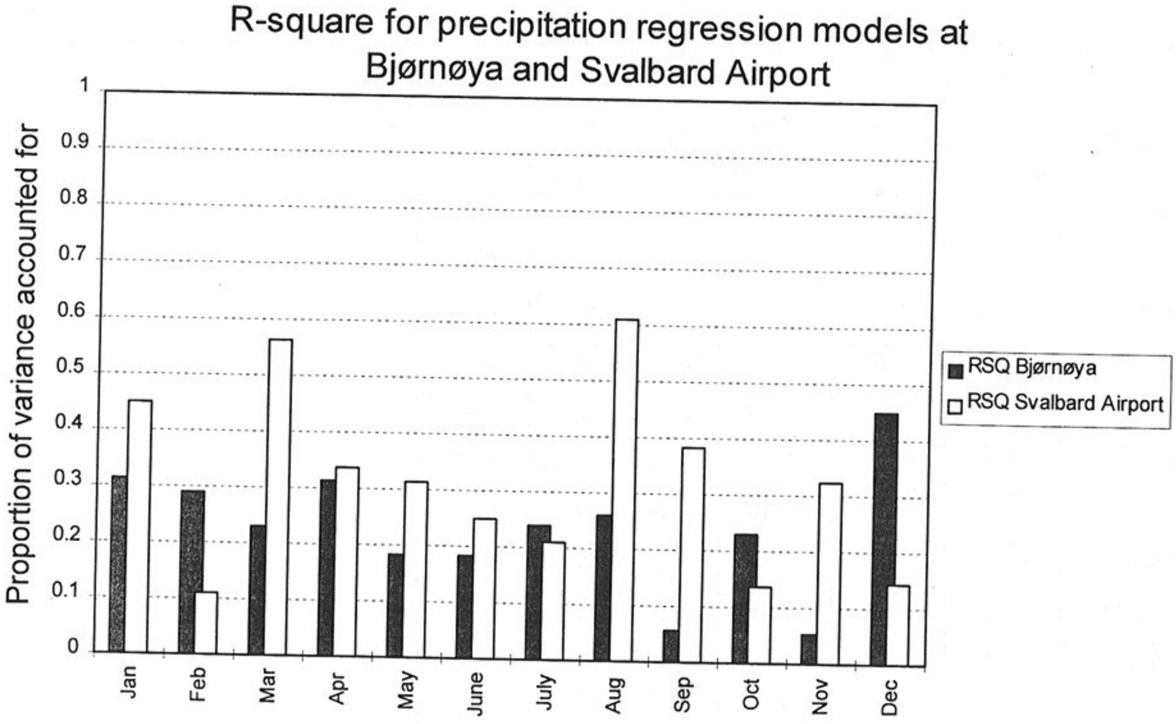


Figure 5.1 Multiple R^2 for precipitation regression at Svalbard Airport and Bjørnøya

Table 5.1 Results from regression analysis of monthly precipitation sum at Svalbard Airport.
Model training period: Even years during 1912-92 except 1942 and 1944.

k, l, m: Regression coefficients referring to eq. (7). Italic values do not differ significantly from 0 (10 % level).
Order of entry in stepwise reg.: The order in which the terms of the (7) are included in stepwise regression.
R : Correlation coefficient between observed temperatures and regression model.

MONTH	k mm/hPa	l mm/hPa	m mm/hPa	Order of entry in stepwise reg.	R
January	*1.24*	1.22	*0.06*	Δp_{LAT}, Δp_{LON}, p	0.67
February	*1.22*	*0.41*	*0.19*	Δp_{LAT}, Δp_{LON}, p	0.33
March	*2.29*	1.87	*0.11*	Δp_{LAT}, Δp_{LON}, p	0.75
April	*0.83*	0.79	*-0.07*	Δp_{LAT}, Δp_{LON}, p	0.58
May	*1.03*	0.54	*-0.18*	Δp_{LAT}, Δp_{LON}, p	0.56
June	*-0.19*	*0.62*	*-0.40*	Δp_{LAT}, p, Δp_{LON}	0.50
July	*0.32*	1.08	*-0.85*	Δp_{LAT}, p, Δp_{LON}	0.46
August	4.29	2.16	*-0.50*	Δp_{LAT}, Δp_{LON}, p	0.78
September	5.01	1.08	*-0.61*	Δp_{LAT}, Δp_{LON}, p	0.62
October	*0.23*	0.72	*0.15*	Δp_{LAT}, Δp_{LON}, p	0.37
November	*1.32*	1.16	*0.16*	Δp_{LAT}, Δp_{LON}, p	0.57
December	*1.38*	0.94	*0.25*	Δp_{LAT}, Δp_{LON}, p	0.38

Table 5.2 Results from regression analysis of monthly precipitation sum at Bjørnøya.
Model training period: Even years during 1920-92 except 1942 and 1944.

k, l, m: Regression coefficients referring to eq. (7). Italic values do not differ significantly from 0 (10 % level).
Order of entry in stepwise reg.: The order in which the terms of the (7) are included in stepwise regression.
R : Correlation coefficient between observed temperatures and regression model.

MONTH	k mm/hPa	l mm/hPa	m mm/hPa	Order of entry in stepwise reg.	R
January	*-1.51*	0.69	-0.93	p, Δp_{LAT}, Δp_{LON}	0.56
February	4.55	*0.38*	*-0.73*	Δp_{LON}, p, Δp_{LAT}	0.54
March	3.58	*-0.07*	-0.80	p, Δp_{LON}, Δp_{LAT}	0.48
April	3.19	*0.88*	*-0.86*	Δp_{LON}, p, Δp_{LAT}	0.56
May	4.30	*-0.02*	*-0.73*	Δp_{LON}, p, Δp_{LAT}	0.43
June	*-2.10*	-1.26	-2.11	p, Δp_{LAT}, Δp_{LON}	0.43
July	*4.81*	-2.27	-2.36	p, Δp_{LAT}, Δp_{LON}	0.49
August	*-4.62*	*1.67*	*-1.11*	Δp_{LAT}, Δp_{LON}, p	0.51
September	*3.24*	*-0.04*	*-1.64*	p, Δp_{LON}, Δp_{LAT}	0.24
October	*2.69*	*0.76*	-1.62	p, Δp_{LON}, Δp_{LAT}	0.48
November	*0.32*	*0.23*	*-0.54*	p, Δp_{LON}, Δp_{LAT}	0.23
December	*-1.74*	*0.45*	-1.82	p, Δp_{LON}, Δp_{LAT}	0.67

Tables 5.1 and 5.2 give regression coefficients at Svalbard Airport and Bjørnøya, respectively. They also indicate whether the coefficients significantly differ from zero at the 10% level, and in which order the 3 terms enter the model when applying stepwise regression. Table 5.1 shows that at Svalbard Airport, $\Delta \mathbf{p}_{\mathbf{LAT}}$ enters the model as the number one variable, and that its coefficient **l** is positive in all months, and significantly differs from zero in all months except February and June. The term $\Delta \mathbf{p}_{\mathbf{LON}}$ enters the model as number 2 most months, its coefficient **k** is positive for all months but June, though it significantly differs from zero only in two months. The reason is probably that the precipitation at Svalbard Airport is orographicly enhanced for westerly and southwesterly winds, while easterly and northeasterly winds leaves this west-coast station in the rain shadow. The coefficient **m** does not differ significantly from zero in any month, though it tends to be positive during winter and negative during summer.

At Bjørnøya, **p** enters the model as the number one variable most months (Table 5.2), and its coefficient **m**, which is always negative, significantly differs from zero in 6 months. For most months, the term $\Delta \mathbf{p}_{\mathbf{LAT}}$ is included in the model before $\Delta \mathbf{p}_{\mathbf{LON}}$. The regression coefficient **k** has statistically significant positive values in the spring, while it does not differ significantly from zero during the rest of the year. The regression coefficient **l** has statistically significant negative values June and July, while it has a statistically significant negative value in January. Both **k** and **l** show irregular variation from month to month. It is concluded that the mountain areas at Bjørnøya are probably too small to create a distinct rain shadow zone, and the Bjørnøya station may thus receive precipitation with winds from all directions.

5.2 Precipitation models: Final formulation and testing

Figures 5.2 and 5.3 show the regression coefficients k, l and m (cf. eq. 7) for each month. Because the coefficients k and l vary quite irregularly throughout the year at Bjørnøya (Figure 5.3), and because the regression model accounts for only a modest part of the variance of the monthly precipitation (Figure 5.1), no model was made for Bjørnøya. For Svalbard Airport on the other hand, the main impression is that the regression coefficients to a large degree show a reasonable systematic variation throughout the year (Figure 5.2).

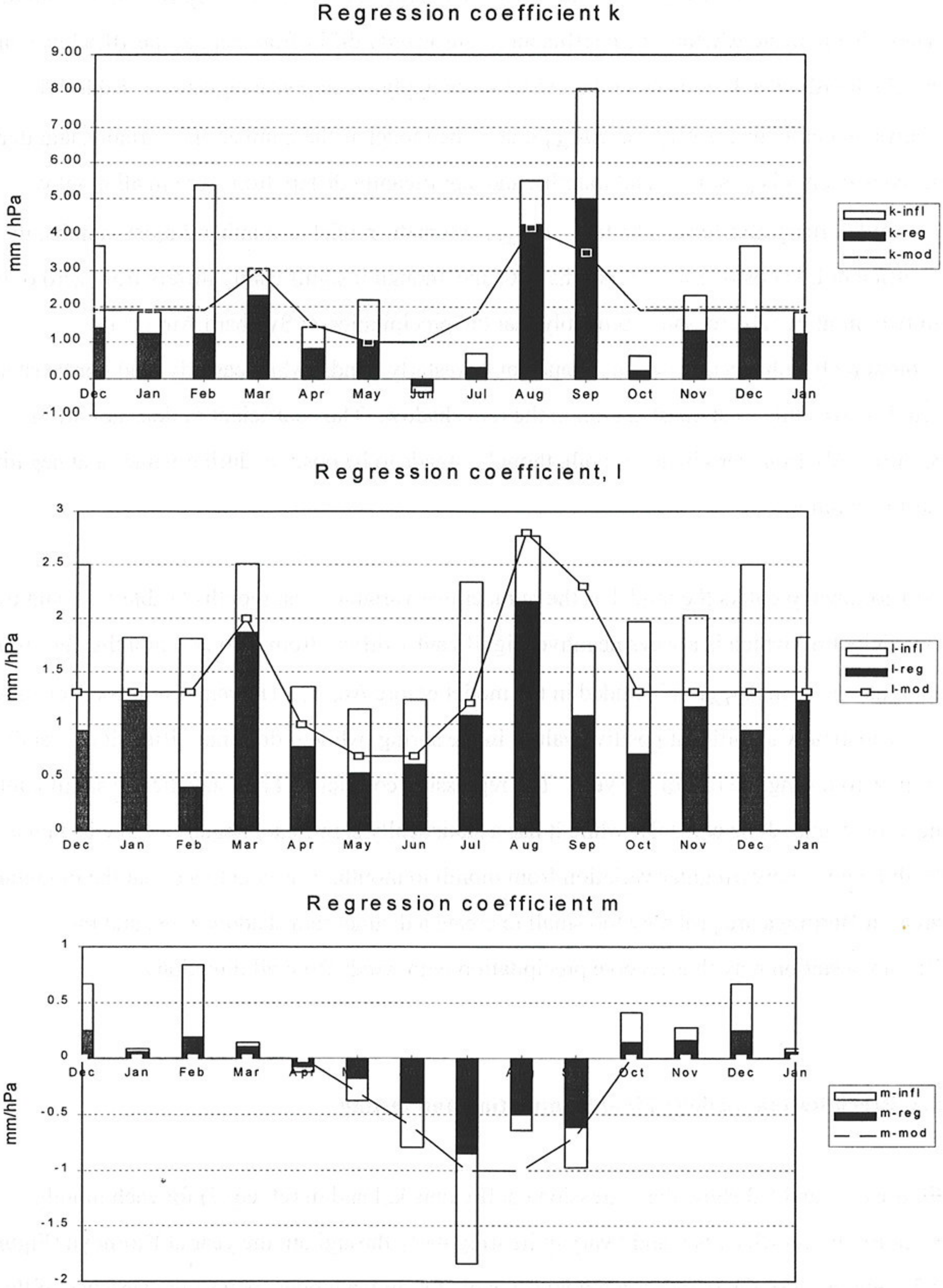


Figure 5.2 Coefficients from precipitation regression analysis (eq. 7) (hatched coloumns) and from inflated regression (eq. 9) (white coloumns), and final model coefficients (eq. 11) (curve) at Svalbard Airport for all months. a) ***k*** *and* κ*, b)* ***l*** *and* λ*,c)* ***m*** *and* μ*.*

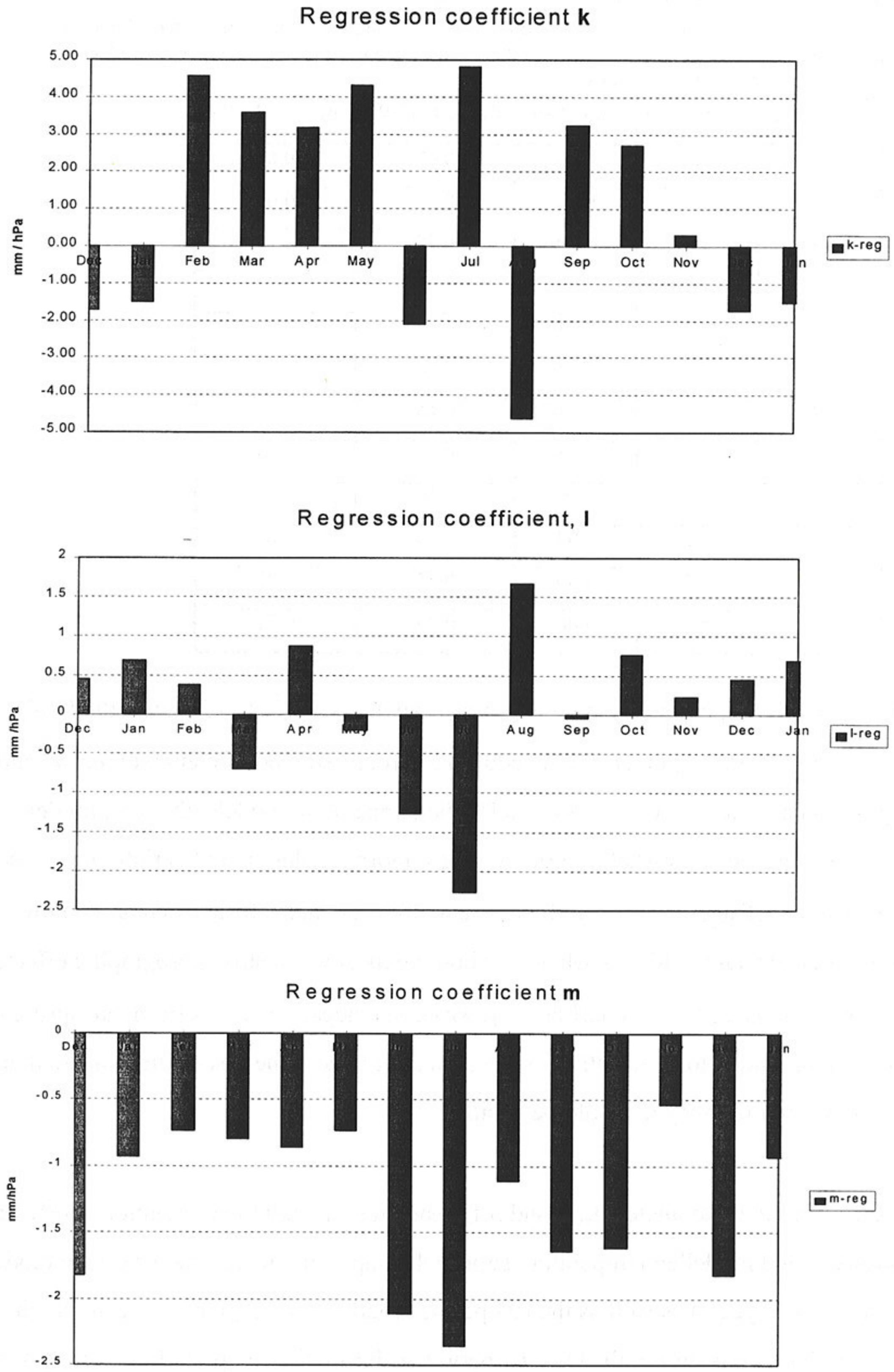


Figure 5.3 Coefficients from precipitation regression analysis (eq. 7) at Bjørnøya for all months. a) ***k*** *, b)* ***l*** *, c)* ***m.***

Table 5.3 Models for monthly precipitation at Svalbard Airport (cf. eq. 10)

κ, λ and μ are model parameters. R_{EVEN} 1912-92 and R_{ODD} 1913-93 are correlation coefficients between observed and modelled monthly precipitation during the model training period (even years1912-92) and test period (odd years 1913-93), respectively.

MONTH	κ(mm/hPa)	λ(mm/hPa)	μ(mm/hPa)	R_{EVEN} 1912-92	R_{ODD} 1913-93
January	1.9	1.3	0.00	0.67	0.65
February	1.9	1.3	0.00	0.33	0.69
March	3.0	2.0	0.00	0.75	0.66
April	1.5	1.0	0.00	0.56	0.47
May	1.0	0.7	-0.30	0.47	0.36
June	1.0	0.7	-0.60	0.50	0.53
July	1.8	1.2	-1.00	0.46	0.27
August	4.2	2.8	-1.00	0.78	0.53
September	3.5	2.3	-0.70	0.54	0.57
October	1.9	1.3	0.00	0.34	0.61
November	1.9	1.3	0.00	0.57	0.82
December	1.9	1.3	0.00	0.35	0.71

A model was thus developed based on the regression analyses. Figure 5.2 shows the final model parameters κ, λ and μ (cf. eq. 11) in addition to regression coefficients (cf. eq. 7) and inflated regression coefficients (cf. eq. 9). As for the temperature models, the final model parameters were adjusted somewhat in order to give a more regular annual variation than the original regression coefficients. The coefficients κ and λ were also chosen so that the ratio between them was constant, which is what one should expect when strong orographic effects are present (cf. sections 2.5). The coefficient μ was given negative values from late spring to early autumn, as **m** tended to be negative, while it was set to zero the rest of the year, as there is no physical explanation why it should be positive.

Table 5.3 show the final parameters κ, λ and μ for each month, and the correlation coefficient between observed and modelled temperature series when applying these models on the model training periods (even years) as well as the test periods (odd years). Again it is seen that the model gives similar results during the training period as during the test period. Table A.4 in Appendix gives some additional information about observed and modelled precipitation during model training period and test period, including mean values, standard deviations and extreme values for each month.

5.3 Application of the precipitation model

The model was now applied on the whole period of measurements, and hindcasts were made of seasonal and annual precipitation at Svalbard Airport. The observed and modelled time series are shown in Figure 5.4, while Table 5.4 shows observed and modelled mean values, standard deviations and extreme values as well as correlation coefficients on annual and seasonal basis. It is seen that the precipitation model accounts for only 16% of the inter-annual variance in winter precipitation. This is probably partly caused by errors in the measurements.

During the homogenization of the Arctic precipitation series (Nordli et al. 1996), some suspicious high precipitation values were noted in the winter seasons around 1960. Figure 5.4 indicate some high precipitation values also during winter and spring in the early 1920s. A closer inspection of the series revealed that these high observed values are caused by drifting or blowing snow. During 1921-23 the composite Svalbard Airport series is based on data from a private station in Longyearbyen, and comparison to other series reveals that this site evidently was very exposed for drifting/blowing snow. As a rule, influence from blowing/drifting snow is corrected by the quality control routines at DNMI. However these routines have varied throughout the years, and the high winter and spring precipitation around 1960 evidently are due to non-corrected events of drifting/blowing snow. Neither of these values have been adjusted for the present analysis, as such corrections should only be made after careful examination of the whole series. Thus it seems highly probable that non-corrected contributions of blowing/drifting snow, are the main reasons why the correlation between observed and modelled precipitation is at minimum during winter.

Table 5.4 Some features of observed and modelled precipitation at Svalbard Airport

Period: 1912-93	Observed P				Modelled P				
Season↓	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.	Corr.
Year	180.7	49.8	86.4	317.0	178.1	37.4	85.6	295.3	**0.54**
Winter	53.4	24.3	16.8	140.0	52.3	14.8	15.7	96.5	**0.40**
Spring	35.6	10.4	6.4	125.9	34.2	14.6	7.5	67.2	**0.60**
Summer	43.7	21.2	3.0	114.0	43.9	19.8	8.1	103.2	**0.57**
Autumn	48.1	17.0	18.4	109.0	47.7	14.7	15.3	85.2	**0.54**

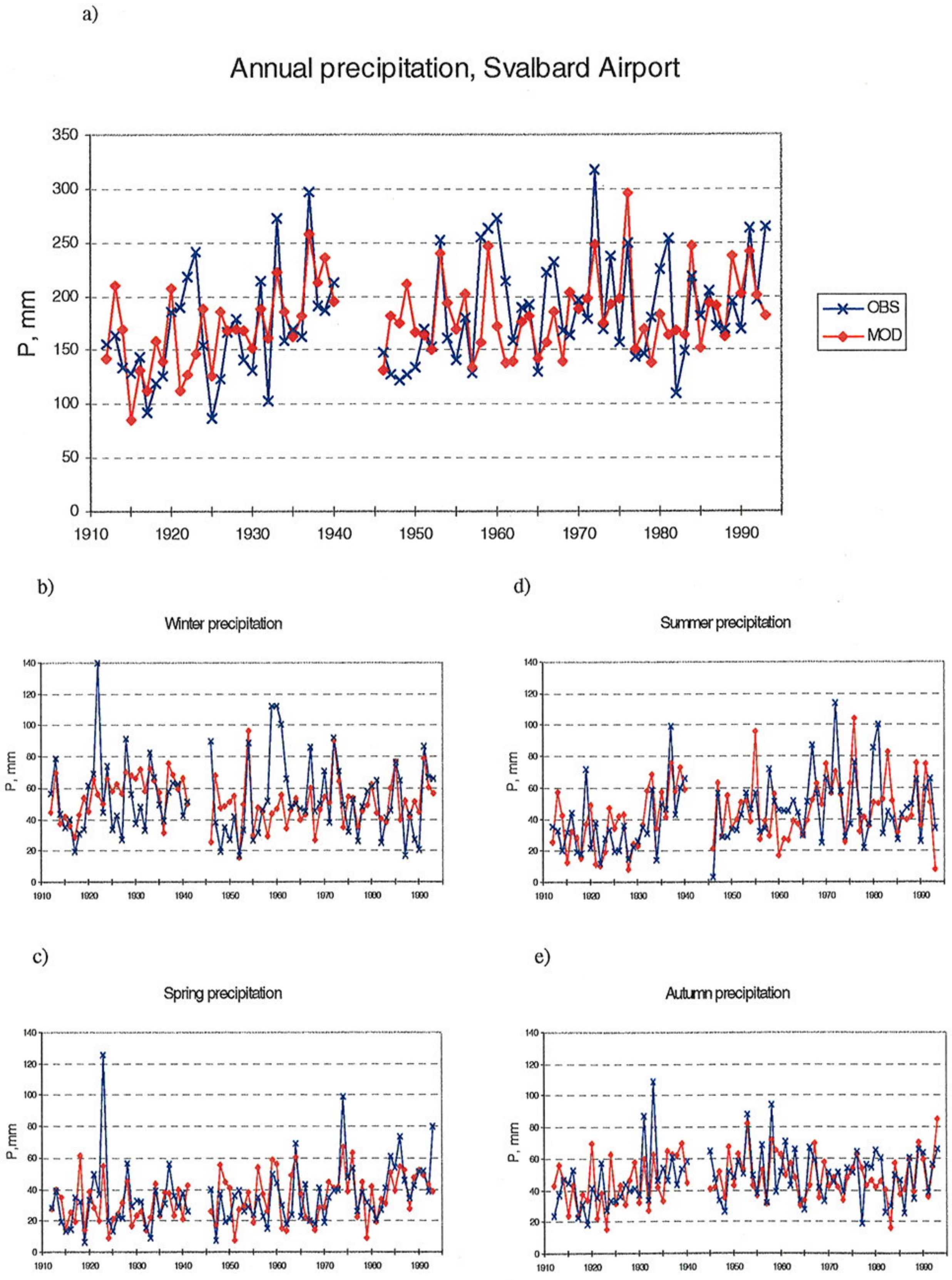


Figure 5.4 Observed and modelled time series of precipitation valid for Svalbard Airport. a) Annual mean temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May), d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

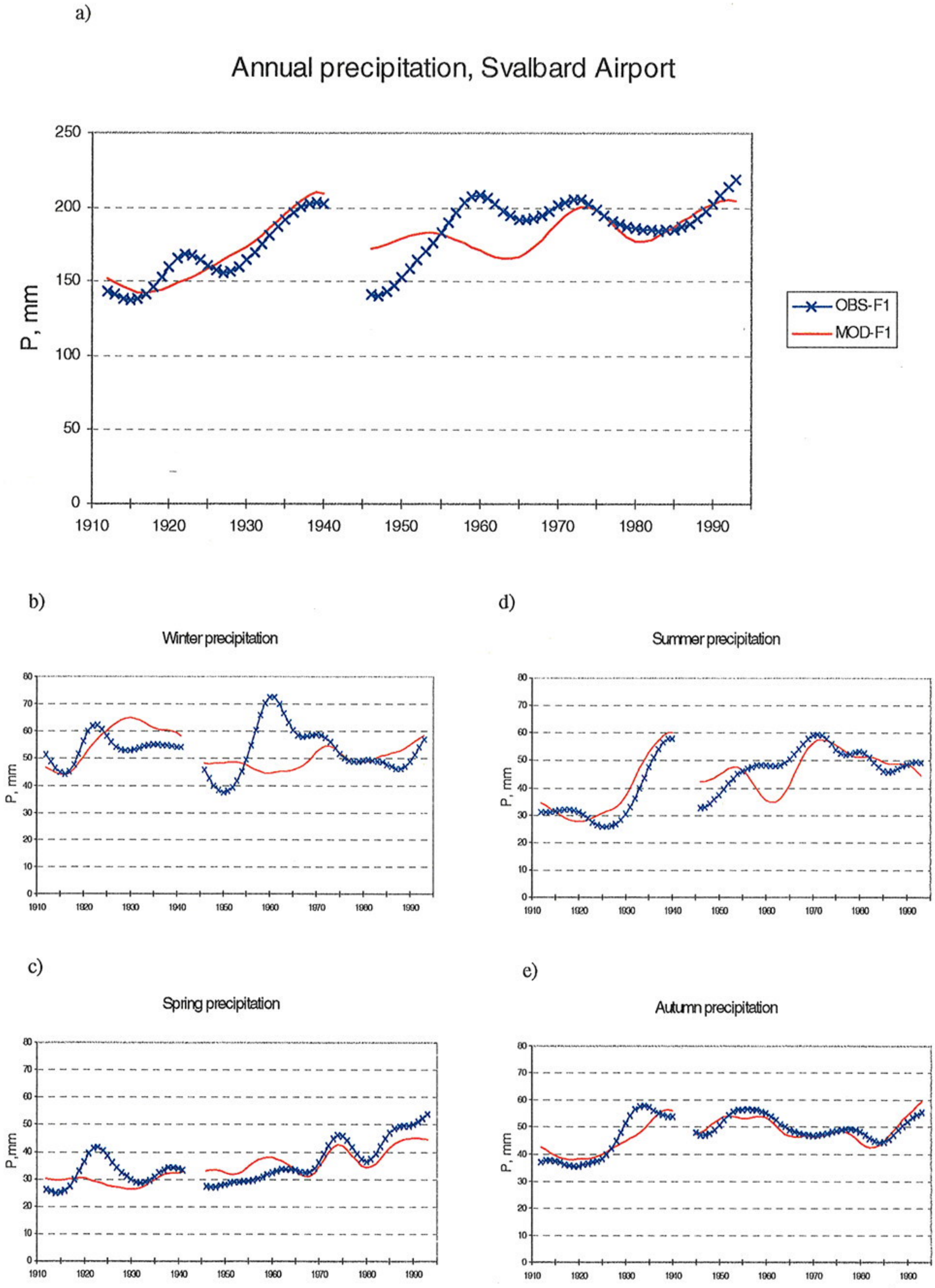


Figure 5.5 Filtered curves, observed and modelled precipitation series, Svalbard Airport: a) Annual temperature, b) Winter (Dec-Jan-Feb), c) Spring (Mar-Apr-May), d) Summer (Jun-Jul-Aug), and e) Autumn (Sep-Oct-Nov)

About 30% of the variance in annual precipitation is accounted for by the model. The main reason why the correlation coefficients between observed and modelled values in most cases are somewhat lower for precipitation than for temperature, is probably that precipitation results from highly non-linear processes. The distributions of precipitation in time and space are thus generally less regular than the similar temperature distributions.

The more random nature of precipitation should, however, not affect the decadal scale variability and long-term trends seriously, and the precipitation model is thus not necessarily less skilled than the temperature model when it comes to such features. Figure 5.5 shows low pass filtered series of modelled vs. observed precipitation. The filter is the same as was applied on the temperature series. The figure indicates that the precipitation model actually is better skilled than the temperature models when it comes to decadal scale variability and long-term trends. The winter curves show some disagreements which are probably (at least partly) caused by measuring problems. Except from these, the model accounts for most of the observed features in all seasons. It also accounts for the observed positive long-term trends in spring, summer and autumn precipitation, as well as in annual precipitation. Thus, even if the inter-annual and inter-seasonal variability in the precipitation at Svalbard Airport is not very well modelled, the decadal scale variability and the long-term trends are closely related to variations in the mean sea level pressure field.

6. Discussion and conclusions

About 40% of the inter-annual variance in annual mean temperature is accounted for by the present simple temperature models, while the similar percentage for the precipitation model is about 30%. Still, the decadal scale variability as well as the long term trends of annual and seasonal precipitation are better modelled than the similar features for temperature. This indicates that the long-term features of precipitation, at least at stations where there is a distinct orographic influence, are more easily modelled than long-term features of temperature, when using the sea level pressure as the only predictor field. Concerning temperature, the main observed decadal scale and long-term features from the 1960s to the end of the series were modelled reasonably well, while this is not true for the first 5 decades.

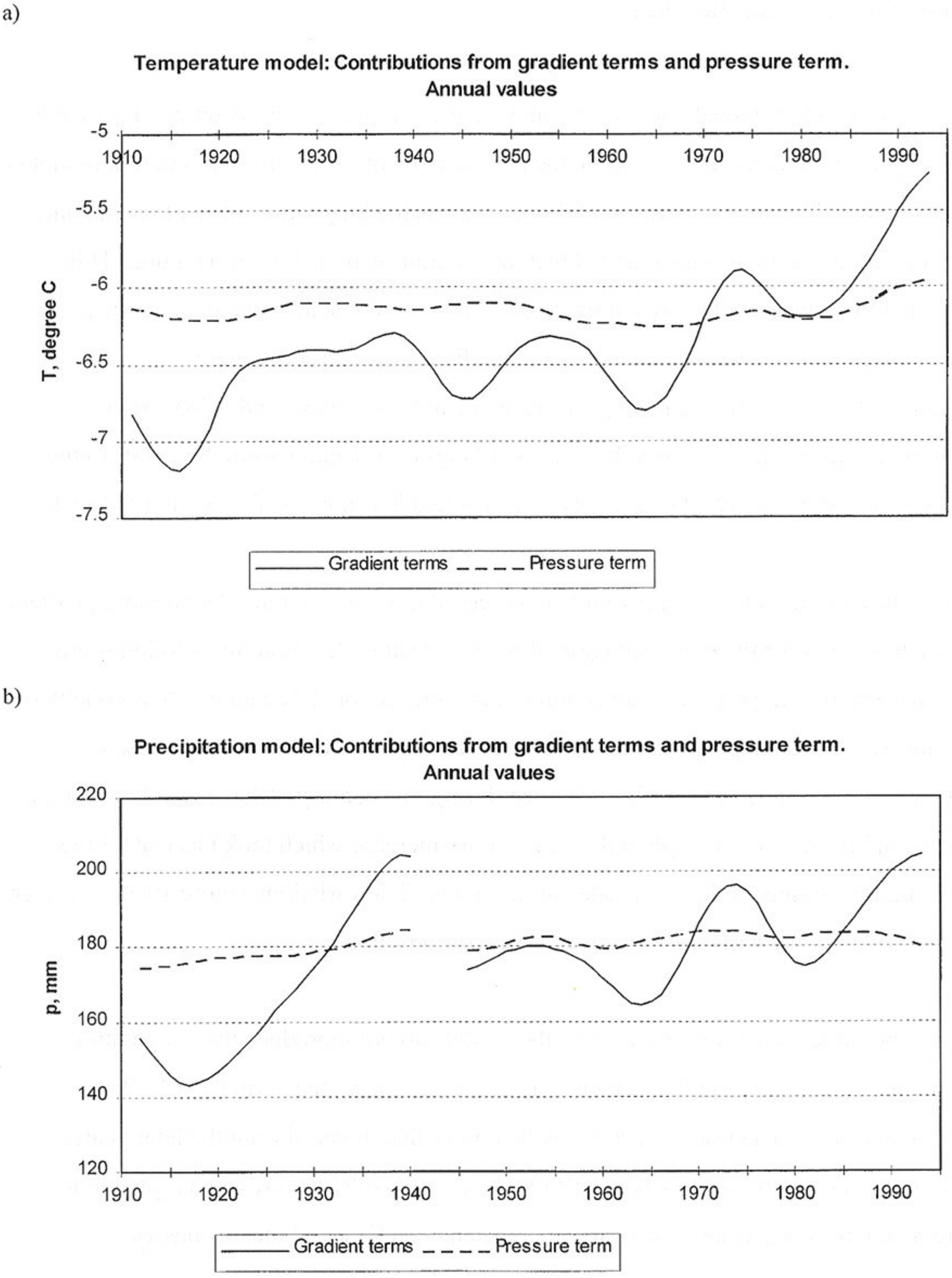
Figure 6.1 shows that both for temperature and precipitation, it is mainly the pressure gradient terms which account for the modelled parts of both decadal scale variability and long-term trends. These were interpreted as «advection terms» (cf. section 2.5), and it is thus concluded that variations in the average advection conditions can explain the observed increase in precipitation at the western coast of Spitsbergen during this century. Changes in the average advection conditions can also explain the temperature increase which took place at all the Svalbard stations during the last 3 decades of the series. The variations before 1960, however, can not be explained by variations in advection conditions alone.

There are 3 possible groups of reasons why the models do not reproduce the temperature trends and decadal scale variability which were observed during the period 1912-1960:

- 1) The quality of the data prior to 1960 may be poorer than it was during the later years,
- 2) the circulation conditions may be insufficiently described by the present simple models,
- 3) there may have been systematic changes in the characteristics of the air-masses.

1) Data quality

Concerning data quality, it is a fact that the long Svalbard Airport temperature series was composed of data from several stations (Nordli et al. 1996), and that the adjustments to «Svalbard Airport conditions» especially of the older data series are more or less uncertain. Note, however, the agreement between the Svalbard Airport series and the Bjørnøya series



Temperature model: Contributions from gradient terms and pressure term. Annual values

Precipitation model: Contributions from gradient terms and pressure term. Annual values

Figure 6.1 Contribution to decadal scale variability and long-term trends from pressure gradient terms (full-drawn lines) and pressure terms (dotted lines).
a) Temperature model, Svalbard Airport. b) Precipitation model, Svalbard Airport.

concerning all major features from the beginning of this series in 1920 (Figures 4.6 and 4.7). It is thus concluded that the observed temperature optima of the 1930s and the 1950s in the Norwegian Arctic are real, though neither the Svalbard Airport model nor the Bjørnøya model are able to reproduce them. Concerning the very low temperatures at Svalbard Airport before 1920 it is more difficult to get these confirmed by other measurements. However, a certain support may be deduced from Vinje (1998), who published a time series of the latitude of the average August ice edge (corresponding to maximum seasonal retreat) in the sector between 20 and 45°E over the last 250 years. It is seen from this plot that the average August ice edge in this area between 1910 and 1920 was further south than it has been in any of the later decades, including the 1960s. According to the model, the temperature in the 1960s should be almost as low as during the period before 1920. It is therefore concluded that the modelled values are biased, while the observations from the period prior to 1920 probably are reasonably good.

Poor data quality is still not excluded as explanation of the mismatch between observed and modelled values, as a reduced quality of the gridded air pressure data in the beginning of the series might affect the modelled temperature values in this period. The gridded air pressure data in Arctic areas are based upon a quite coarse network of observations in the earlier years. However, if this is the reason for the malfunction of the temperature models, it is difficult to explain the ability of the precipitation model to reproduce the main observed decadal scale variations and long-term trends in precipitation during the whole series. The skills of the precipitation model are thus supporting the suggestion that the mismatch between observed and modelled temperatures not primarily is a result from poor quality of the pressure series.

2) Insufficient circulation model

Description of the atmospheric circulation by using monthly averages of sea level pressure values from 4 grid-points implies a substantial simplification. Using pressure data from 9 grid-points would allow the introduction of vorticity in the model. Using the mean sea level pressure field from a larger area would include even more information. Zorita and von Storch (1997) describe several techniques for statistical downscaling, including classification methods, the analog method and linear methods, which may be used for modelling local precipitation and/or temperature from the mean sea level pressure field over a given area. It is highly probable that e.g. the analog technique would be more skilled than the present simple model, especially when it comes to modelling the inter-annual variability of seasonal precipitation and temperature. Still, it is a question if any of these more advanced techniques would be able to reproduce the observed low temperatures before 1920 and the high temperatures of the 1930s and the 1950s. Again, the fact that the observed long-term precipitation variations actually are modelled reasonably well by the present simple model, indicates that the long-term variability of the circulation conditions actually is described relatively well by the simple model. So even if substantially more of the year-to-year and season-to-season variance might be accounted for by using more advanced methods and sea level pressure data from a larger area, this would probably not solve the problems connected to modelling of the long-term temperature trends.

3) Changes in the characteristics of the air-masses

The hypothesis is thus that the temperature models fail to produce the observed decadal scale variability and longterm trends in the earlier decades, because these features were not primarily caused by variations in the average circulation conditions. In section 4.3 it was mentioned that variations in the sea-ice distribution and SST-anomalies very well may be responsible for some of the variance which the models do not account for. As the ocean and the sea-ice has a better «memory» than the atmosphere, this could explain the similarity which is found in the temperature residuals (observed - modelled temperatures) for all seasons, both for Svalbard Airport and Bjørnøya. The average August ice edge latitude timeseries valid for the sector between 20 and 45°E, (Vinje 1998), supports the hypothesis that at least the low temperatures in the beginning the series may be caused by (for our century) unusually much sea-ice in the area, which would effectively isolate the air-masses entering the area from the sea below. The ice-edge series also shows that the August ice edge was rather far north in most of the 1930s and 1950s. In several of these years the average August ice edge was 80 °N or more. One might thus suggest that unusually light sea ice conditions in these decades, or rather the feedbacks from these conditions on the air temperature, explains the shortcoming of the pure advection model during these decades. This explanation would also be satisfactory as the temperature optimum of the 1930s, relatively speaking, is more pronounced in the Norwegian Arctic than further south in the North Atlantic and region, and also than the average for the Northern Hemisphere (Førland et al. 1997). It should be mentioned, though, that the average August ice-edge in the 1980s was even further north than in the 1930s and the 1950s, so it is still a question why the pure circulation model is able to reproduce the high temperatures of this decade.

Another potential candidate for changes in the characteristics of air-masses advected into the Svalbard region, is the changes in aerosol forcing. The increased tropospheric aerosol concentration during this century and especially after World War II (Kattenberg et al. 1996) may significantly have influenced the radiation budget of the air-masses, and thus affected cloudiness and other characteristics. It is suggested to study this further by analyzing long-term trends of cloudiness and maximum/minimum temperatures.

Main conclusions

No final conclusion can be drawn concerning the reason why a pure circulation model based upon mean sea level pressure from 4 grid-points is able to reproduce the observed temperature increase at Svalbard from the 1960s to the 1990s, but only a fraction of the observed increase from 1912 to the 1930s. To investigate this further, it is suggested to develop models for local temperature based upon the mean sea level pressure field and additional predictors. These could be the SST-field, the average ice-edge position or a thickness field. The inclusion of additional predictors is obviously important if the intention is to use the model for statistical downscaling of temperature. The present analyses indicate that orographically influenced precipitation more easily than temperature may be simulated by using the mean sea level pressure field only. However, as increased temperature leads to increased amounts of precipitable water in the atmosphere, it might be wise to include an additional predictor in the precipitation model as well.

It should be noted that the linear models which were developed in the present report were not designed for statistical downscaling, but rather for investigating to which degree the observed variation in temperature and precipitation in the Norwegian Arctic could be explained by variation in the atmospheric circulation patterns alone. Although the models fail to give a good description of temperature variations prior to 1960, the major conclusion is that the increased precipitation during this century and the temperature increase in the Norwegian Arctic since 1960 are mainly caused by changes in the atmospheric circulation in the area.

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Appendix

Table A.1 Long-term averages of meteorological variables during even years.

a) Table for Svalbard Airport, even years with temperature measurements during 1912-1992

T : Temperature, Svalbard Airport

Δp_{LON} : Longitudinal pressure difference, $\frac{1}{2}\{(p_{20,70} + p_{20,80}) - (p_{10,70} + p_{10,80})\}$,

Δp_{LAT} : Latitudinal pressure difference, $(p_{20,80} - p_{20,70})$,

p : Mean sea level pressure, $p_{20,80}$

MONTH	T (°C)	Δp_{LON} (hPa)	Δp_{LAT} (hPa)	p (hPa)
January	-14.0	0.96	3.43	1007.7
February	-15.5	0.46	2.80	1009.5
March	-15.5	0.36	3.67	1011.6
April	-12.1	0.01	4.93	1015.5
May	-3.9	-0.22	2.37	1017.2
June	2.4	-0.22	1.72	1013.7
July	6.0	0.08	1.64	1012.8
August	4.6	0.10	1.50	1012.6
September	0.3	0.03	2.16	1009.7
October	-5.3	0.49	2.23	1009.8
November	-9.4	0.67	3.33	1007.7
December	-11.2	1.28	3.22	1007.3

b) Table for Bjørnøya, even years with temperature measurements during 1920-1992

T : Temperature, Bjørnøya

Δp_{LON} : Longitudinal pressure difference, $\frac{1}{2}\{(p_{20,70} + p_{20,80}) - (p_{10,70} + p_{10,80})\}$,

Δp_{LAT} : Latitudinal pressure difference, $(p_{20,80} - p_{20,70})$,

p : Mean sea level pressure, $p_{20,80}$

MONTH	T (°C)	Δp_{LON} (hPa)	Δp_{LAT} (hPa)	p (hPa)
January	-6.2	1.09	3.10	1007.8
February	-7.3	0.42	2.46	1009.4
March	-7.3	0.39	3.57	1011.3
April	-5.4	0.01	5.46	1016.0
May	-1.2	-0.22	2.23	1017.1
June	2.1	-0.18	1.67	1013.7
July	4.6	0.14	1.72	1012.5
August	4.6	0.12	1.26	1012.2
September	3.0	0.16	1.96	1009.7
October	-0.2	0.44	2.58	1009.8
November	-2.9	0.74	3.27	1007.8
December	-4.7	1.25	2.89	1006.9

Appendix

Table A.1 continued...

c) Table for Svalbard Airport, even years with precipitation measurements during 1912-1992

P : Precipitation, Svalbard Airport

Δp_{LON} : Longitudinal pressure difference, $\frac{1}{2}\{(p_{20,70} + p_{20,80}) - (p_{10,70} + p_{10,80})\}$,

Δp_{LAT} : Latitudinal pressure difference, $(p_{20,80} - p_{20,70})$,

p : Mean sea level pressure, $p_{20,80}$

MONTH	P (mm)	Δp_{LON} (hPa)	Δp_{LAT} (hPa)	p (hPa)
January	16.2	0.95	3.62	1007.8
February	19.9	0.52	2.92	1009.5
March	19.3	0.38	3.61	1011.4
April	9.9	0.07	5.08	1015.6
May	7.4	-0.23	2.35	1017.3
June	9.8	-0.24	1.64	1013.6
July	12.1	0.08	1.59	1012.7
August	19.0	0.11	1.59	1012.7
September	18.1	-0.02	2.30	1009.8
October	14.4	0.45	2.30	1009.9
November	14.9	0.70	3.46	1007.8
December	18.1	1.28	3.33	1007.5

d) Table for Bjørnøya, even years with temperature measurements during 1920-1992

P : Precipitation, Bjørnøya

Δp_{LON} : Longitudinal pressure difference, $\frac{1}{2}\{(p_{20,70} + p_{20,80}) - (p_{10,70} + p_{10,80})\}$,

Δp_{LAT} : Latitudinal pressure difference, $(p_{20,80} - p_{20,70})$,

p : Mean sea level pressure, $p_{20,80}$

MONTH	P (mm)	Δp_{LON} (hPa)	Δp_{LAT} (hPa)	p (hPa)
January	32.2	1.09	3.30	1007.9
February	32.5	0.48	2.56	1009.5
March	30.2	0.42	3.49	1011.1
April	21.4	0.08	5.65	1016.1
May	18.4	-0.22	2.20	1017.2
June	23.3	-0.20	1.58	1013.6
July	25.1	0.15	1.67	1012.4
August	31.9	0.13	1.36	1012.4
September	44.6	0.13	2.10	1009.9
October	37.8	0.40	2.63	1009.9
November	31.6	0.78	3.41	1007.9
December	36.5	1.26	3.01	1007.0

Appendix

Table A.2 Characteristics of observed and modelled temperatures at Svalbard Airport.

Mean: Mean monthly mean temperature.
Std.dev.: Standard deviation of monthly mean temperature.
Min.: Minimum observed or modelled monthly mean temperature.
Max.: Maximum observed or modelled monthly mean temperature.
All values in degrees C.
a) Model training period, even years 1912-1992. b) Test period, odd years 1913- 1993.

a)

Even years 1912-92	Observed T				Modelled T				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	-14.0	*5.5*	-25.7	*-4.3*	-14.0	*4.2*	-22.0	*-4.2*	**0.73**
Feb	-15.5	*4.3*	-27.3	*-6.9*	-15.5	*4.8*	-24.4	*-4.9*	**0.52**
Mar	-15.5	*4.3*	-22.1	*-7.6*	-15.5	*3.8*	-27.4	*-7.5*	**0.67**
Apr	-12.1	*3.0*	-19.7	*-6.6*	-12.1	*2.8*	-17.6	*-4.8*	**0.48**
May	-3.9	*1.6*	-7.9	*-0.3*	-3.9	*1.3*	-6.3	*-1.3*	**0.55**
Jun	2.4	*1.0*	0.7	*4.8*	2.4	*0.9*	0.4	*4.8*	**0.48**
Jul	6.0	*0.8*	3.6	*7.8*	6.0	*0.8*	4.5	*7.5*	**0.66**
Aug	4.6	*0.8*	2.3	*6.4*	4.6	*0.8*	3.0	*5.8*	**0.41**
Sep	0.3	*1.9*	-3.2	*5.2*	0.3	*1.5*	-2.0	*4.7*	**0.64**
Oct	-5.3	*2.6*	-14.8	*-0.9*	-5.3	*2.4*	-11.5	*-0.5*	**0.67**
Nov	-9.4	*3.6*	-17.9	*-4.1*	-9.4	*2.8*	-14.8	*-3.1*	**0.72**
Dec	-11.2	*4.9*	-22.5	*-1.3*	-11.2	*4.0*	-18.0	*-2.0*	**0.79**

b)

Odd years 1913-93	Observed T				Modelled T				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	-14.8	*5.0*	-23.3	*-3.0*	-15.0	*5.1*	-24.5	*-0.3*	**0.73**
Feb	-15.4	*4.6*	-27.2	*-7.5*	-14.6	*4.6*	-23.0	*-7.1*	**0.51**
Mar	-16.4	*4.2*	-26.3	*-8.7*	-16.8	*3.7*	-24.0	*-9.4*	**0.45**
Apr	-12.4	*3.4*	-22.7	*-6.7*	-12.2	*3.0*	-19.0	*-6.4*	**0.63**
May	-4.5	*1.8*	-9.6	*-1.5*	-4.3	*1.3*	-7.4	*-1.3*	**0.66**
Jun	2.1	*1.1*	-0.5	*4.3*	2.2	*0.8*	0.8	*3.7*	**0.33**
Jul	5.7	*1.0*	3.8	*7.8*	5.6	*1.0*	3.3	*8.1*	**0.58**
Aug	4.7	*0.8*	2.7	*6.5*	4.7	*0.9*	2.5	*6.7*	**0.46**
Sep	0.3	*1.1*	-3.1	*2.8*	0.4	*1.5*	-3.6	*3.6*	**0.58**
Oct	-5.3	*2.4*	-8.8	*0.6*	-5.6	*2.3*	-9.3	*-0.5*	**0.66**
Nov	-9.5	*4.1*	-20.4	*-1.6*	-10.1	*3.9*	-16.6	*1.2*	**0.79**
Dec	-12.8	*4.0*	-21.9	*-4.2*	-14.1	*4.5*	-21.8	*-4.3*	**0.71**

Table A.3 Characteristics of observed and modelled temperatures at Bjørnøya.

Mean: Mean monthly mean temperature.
Std.dev.: Standard deviation of monthly mean temperature.
Min.: Minimum observed or modelled monthly mean temperature.
Max.: Maximum observed or modelled monthly mean temperature.
All values in degrees C.
a) Model training period, even years 1920-1992. b) Test period, odd years 1921- 1993.

a)

Even years 1920-92	Observed T				Modelled T				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	-6.1	*3.4*	-13.5	*-0.4*	-6.1	*3.0*	-12.2	*1.1*	**0.71**
Feb	-7.3	*3.5*	-15.4	*-1.6*	-7.3	*4.1*	-15.3	*1.3*	**0.72**
Mar	-7.3	*4.0*	-17.7	*0.2*	-7.3	*3.6*	-17.4	*-0.6*	**0.85**
Apr	-5.4	*2.3*	-10.9	*-1.3*					**0.78**
May	-1.2	*1.7*	-5.8	*1.8*	-1.2	*1.2*	-3.0	*0.9*	**0.61**
Jun	2.1	*1.3*	-0.5	*4.1*	2.1	*1.0*	-0.7	*4.4*	**0.65**
Jul	4.6	*1.1*	2.8	*6.7*	4.6	*0.7*	3.0	*5.9*	**0.48**
Aug	4.6	*1.0*	2.6	*6.5*	4.6	*0.7*	3.3	*6.1*	**0.66**
Sep	3.0	*1.4*	0.6	*6.5*	3.0	*1.3*	0.1	*6.6*	**0.77**
Oct	-0.2	*2.1*	-8.4	*2.8*	-0.2	*1.8*	-4.8	*3.2*	**0.79**
Nov	-2.9	*2.1*	-9.6	*0.1*	-2.9	*1.9*	-6.4	*0.9*	**0.66**
Dec	-4.7	*3.4*	-12.8	*1.8*	-4.7	*2.8*	-9.5	*1.6*	**0.79**

b)

Odd years 1921-93	Observed T				Modelled T				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	-7.3	*3.8*	-14.4	*0.4*	-7.2	*3.9*	-14.5	*4.2*	**0.72**
Feb	-6.9	*3.5*	-17.5	*-1.7*	-6.5	*3.7*	-12.9	*-0.7*	**0.60**
Mar	-7.7	*3.1*	-13.5	*-3.0*	-8.4	*3.1*	-13.2	*-2.9*	**0.57**
Apr	-5.7	*2.5*	-13.0	*-1.6*	-5.6	*2.0*	-8.7	*-1.7*	**0.55**
May	-1.6	*1.0*	-3.6	*0.9*	-1.4	*1.0*	-3.5	*1.5*	**0.50**
Jun	1.6	*1.2*	-0.4	*4.4*	1.9	*1.1*	-0.6	*4.1*	**0.71**
Jul	4.4	*1.2*	1.3	*6.6*	4.6	*0.7*	2.8	*6.1*	**0.60**
Aug	4.8	*1.1*	2.3	*7.0*	4.7	*1.0*	0.9	*6.1*	**0.33**
Sep	2.7	*0.9*	0.6	*4.7*	3.2	*1.1*	0.8	*5.4*	**0.61**
Oct	-0.3	*1.5*	-3.5	*3.1*	-0.2	*1.7*	-3.1	*3.6*	**0.74**
Nov	-2.9	*2.8*	-10.8	*1.2*	-3.2	*2.9*	-8.5	*5.6*	**0.77**
Dec	-6.1	*3.5*	-13.4	*0.5*	-6.8	*3.1*	-12.1	*-0.1*	**0.79**

Appendix

Table A.4 Characteristics of observed and modelled precipitation at Svalbard Airport.

Mean: Mean monthly precipitation sum.
Std.dev.: Standard deviation of monthly precipitation sum.
Min.: Minimum observed or modelled monthly precipitation sum.
Max.: Maximum observed or modelled monthly precipitation sum.
All values in degrees C.
a) Model training period, even years 1912-1992. b) Test period, odd years 1913- 1993.

a)

Even years 1912-92	Observed P				Modelled P				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	16.2	*10.3*	2.0	*47.0*	16.2	*7.8*	2.4	*41.4*	**0.67**
Feb	19.9	*14.2*	3.6	*68.6*	19.9	*10.3*	0	*37.4*	**0.20**
Mar	19.3	*15.5*	1.0	*75.0*	19.6	*12.4*	0	*47.2*	**0.75**
Apr	9.9	*6.7*	1.3	*31.8*	9.9	*4.8*	0	*22.1*	**0.56**
May	7.4	*6.0*	0.8	*22.8*	7.4	*3.8*	0	*16.4*	**0.47**
Jun	9.8	*8.1*	0.8	*32.8*	9.9	*4.8*	0	*22.6*	**0.50**
Jul	12.1	*12.1*	0	*70.0*	12.2	*6.3*	0	*28.4*	**0.46**
Aug	19.0	*13.9*	0	*60.3*	19.1	*14.7*	0	*71.0*	**0.78**
Sep	18.1	*10.8*	1.0	*37.7*	18.1	*9.9*	0.0	*41.7*	**0.54**
Oct	14.4	*7.3*	1.3	*30.4*	14.5	*5.6*	0.6	*26.6*	**0.34**
Nov	14.9	*9.9*	1.4	*51.0*	14.9	*6.8*	3.8	*28.4*	**0.57**
Dec	18.1	*12.6*	3.0	*62.0*	18.1	*6.6*	4.3	*33.8*	**0.35**

b)

Odd years 1913-93	Observed P				Modelled P				
Month↓	Mean	*Std.dev.*	Min.	*Max.*	Mean	*Std.dev.*	Min.	*Max.*	**Corr.**
Jan	16.1	*10.5*	3.0	*62.0*	15.6	*9.0*	0	*40.9*	**0.64**
Feb	17.5	*14.8*	1.4	*72.2*	20.8	*9.0*	3.3	*38.5*	**0.69**
Mar	18.0	*18.8*	1.7	*106.6*	14.8	*11.3*	0	*40.0*	**0.66**
Apr	9.6	*7.0*	0	*31.7*	9.8	*5.1*	0	*21.5*	**0.47**
May	7.0	*4.7*	0.5	*19.4*	7.1	*3.2*	0	*15.6*	**0.36**
Jun	8.7	*7.1*	0.7	*30.0*	9.8	*4.8*	0	*19.1*	**0.53**
Jul	14.6	*8.7*	2.0	*39.0*	14.7	*7.0*	0	*31.6*	**0.27**
Aug	23.1	*14.9*	0.9	*69.2*	22.7	*15.1*	0	*57.0*	**0.53**
Sep	17.2	*8.6*	1.0	*34.0*	20.6	*11.3*	0	*41.7*	**0.57**
Oct	14.8	*9.9*	1.7	*44.6*	13.5	*7.1*	0.6	*29.5*	**0.61**
Nov	16.8	*11.2*	0.2	*46.5*	14.0	*9.7*	0	*48.1*	**0.82**
Dec	19.2	*14.4*	2.3	*58.1*	14.2	*8.8*	0	*38.5*	**0.71**