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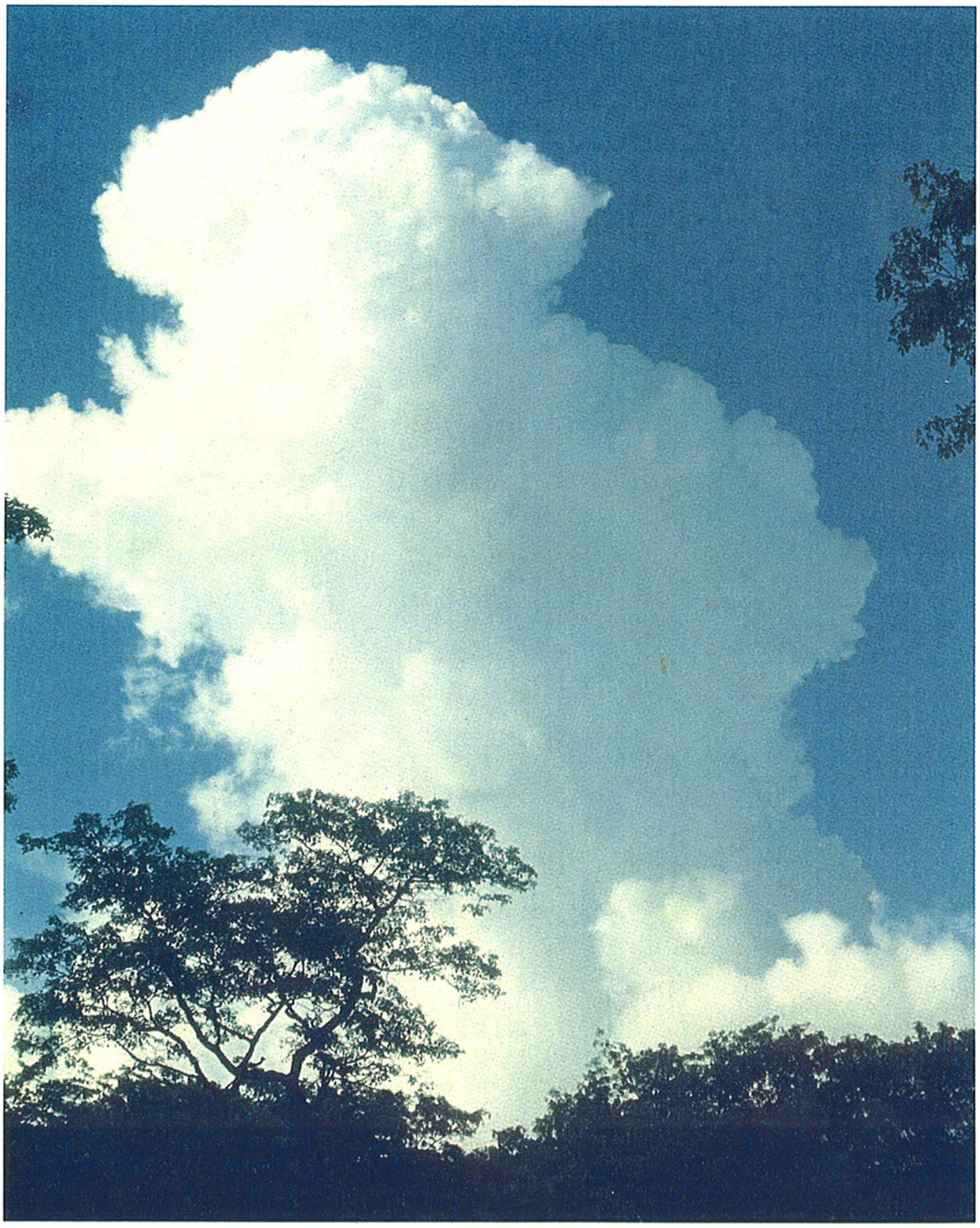

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ASSOCIATIONS BETWEEN THE SEA-ICE AND THE LOCAL CLIMATE ON SVALBARD

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April 8, 2002

ABSTRACT

The role of sea-ice for the local climate in the Svalbard region is investigated using observed temperature records from Arctic climate stations and gridded sea-ice data. The coupling between sea-ice and sea level pressure as well as 2-meter temperature is also examined. The quality of the sea-ice product from the HadISST1.1 project is evaluated in relation with variations in the sea level pressure, 2-meter temperature fields, and observed temperatures at Arctic climate stations. Furthermore, the gridded sea-ice analysis is compared with the 1990's climate described by 3 atmospheric-oceanic general circulation models.

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KEY WORDS: Svalbard sea-ice temperature canonical correlation analysis step-wise regression model evaluation

1 Introduction

The Arctic is an important region with respect to climatic processes as well as the ecology. For one thing, the seasonal cycle in the polar region is extreme, changing between long, cold, dark polar nights and mild summer with 24 hours day light. A key factor in this region is the sea-ice which may affect the climate system in various ways. The sea ice insulates the atmosphere from the ocean.There is a substantial heat transport from the ocean to the atmosphere in the ice-free regions during winter, and this coupling explains why the coastal winter climates are much milder than further in land. In the summer on the other hand, sea-ice reflects more short wave radiation than open sea, implying that less solar energy is absorbed in the climate system. The melting and freezing of ice furthermore involve substantial energy transfer, and while these phase changes take place, the local temperature tends to stay near the freezing point.

A climate model study by *Parkinson* et al. (2001) indicates a strong sensitivity of the climate to the sea-ice cover. *Meehl* et al. (2000) compared the climate in two atmosphere ocean general circulation models (AOGCM) and found important differences in AOGCM's response to an increase in atmospheric CO_2 concentrations due to different sea-ice descriptions. The sea-ice retreat was found to be less in the National Center for Atmospheric Research Community System (climate) Model† (NCAR-CSM) model than in an older NCAR Department Of Energy (NCAR-DOE) model, and the sea-ice retreat was estimated to account for a 37% enhanced global warming in the DOE model compared to 20% in the NCAR-CSM.

Changes in the climatic conditions are likely to have severe consequences for the fragile ecosystem because of highly specialized species adapted to a harsh environment, low number of different species and low population density.

One important motivation behind this study is the implications of a global climate change for the Arctic region. An intercomparison over Arctic areas of 19 global climate change simulations (*Räisänen*, 2001) reveals that though the models generally show a larger increase in annual mean temperature over the Arctic than anywhere else in the world, the scatter among the individual models is substantial on a regional scale. E.g. there is serious disagreement concerning where in the Arctic the maximum warming is projected. This disagreement is partly connected to differences between the models concerning modeling and parameterisation of sea-ice.

In this paper historical data will be used to deduce how much the sea-ice controls the local climate and the question whether the description of the sea-ice in the climate models is adequate for making

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regional climate scenarios will be discussed. The outline of this paper is as follows: the data and methods are described in Section 2 followed by the results of the analysis and a discussion.

2 Data and method

The analysis was carried out on high quality temperature records from 3 different locations in the Svalbard region. Basic station details are given in Table 1. Further details concerning gap-filling and homogeneity analyses were given by (*Nordli* et al., 1996). The sea-ice cover data were from the U.K. Met. Office's HadISST1.1 data set. This data set has been derived using a reduced-space optimum interpolation (RSOI) technique and describes the sea-ice in terms of the fractional cover over the area represented by the grid box. The HadISST1.1 is based on a blend of bias-corrected Advanced Very High Resolution Radiometer (AVHRR,) SSTs from satellite measurements (after 1982), Met. Office Historical SST (MOHSST7), and the Comprehensive Ocean Atmosphere Data Set (COADS) (*Slutz* et al., 1985). Using the RSOI reconstruction and the MOHSST7 data leads to a more homogeneous product in terms of SST variance as well as a more realistic description of inter-monthly SST persistence (N. Rayner, personal communications). The sea level pressure [SLP] and 2-meter temperature [T(2m)] were taken from the monthly mean NCEP reanalysis (*Kalnay* et al., 1996).

The atmospheric-oceanic general circulation models evaluated in this study included the Max-Planck-Institute's ECHAM4 GSDIO (*Roeckner* et al., 1992; *Oberhuber*, 1993), U.K. Meteorological Office's HadCM3 GSA (*Gordon* et al., 2000), and the NCAR-CSM model (the *b006* experiment) (*Meehl* et al., 2000). The model output analysed comprises T(2m) and SLP for the time interval "1980"-"2050"‡. The MPI GSDIO experiment includes the direct and indirect effects of sulphur as well as greenhouse gas emission scenarios and tropospheric ozone. The HadCM3 integration includes the emission scenarios and the direct aerosol effects whereas the scenario from the NCAR-CSM describes a 1% per annum increase in CO_2. Neither the HadCM3 model nor NCAR-CSM use flux correction.

The data analysis involved principal component analysis (*Lorenz*, 1956; *North* et al., 1982; *Preisendorfer*, 1988) (in geophysical literature also known as "empirical orthogonal functions" or "EOFs") regression and canonical correlation analysis (CCA) (*Preisendorfer*, 1988; *Wilks*, 1995). The EOF analysis carried out here is described in detail by *Benestad* (1999). The records of gridded data, $\mathbf{X}$, were subject to a singular vector decomposition (SVD) (*Strang*, 1995; *Press* et al., 1989), where the data were expressed in terms of left and right inverse matrices: $\mathbf{X} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^T$, the time series are held in the singular vectors $\mathbf{V} = [\vec{V_1}, \vec{V_2}, ..]$ and the spatial patterns are held in the eigen-vectors represented by the columns of $\mathbf{U}$. The diagonal matrix $\mathbf{\Lambda}$ contains the eigen-values. The motivation for using the EOF products in the analysis is that they reduce the demand for computer resources, and the fact that the singular vectors are orthonormal simplifies the regression analysis. Only the 20 leading modes were used in this analysis.

The regression involved a forward-backward stepwise test to select N skillful predictors which reduce the Akaike information criterion (AIC, *Wilks* (1995), p.301-302). The multiple regression was then carried out using a linear least-squares to describe the predictand in terms of these N predictors ($\vec{V_{iN}}$):

$$\hat{y} = b_{i1}\vec{V_{i1}} + b_{i2}\vec{V_{i2}} + ..b_{iN}\vec{V_{iN}} \quad (1)$$

The spatial patterns ($\hat{\beta}$) were constructed using the regression weights ($\vec{b}$) to compute a combination of EOF patterns:

$$\hat{\beta} = \mathbf{U}\mathbf{\Lambda}\vec{b} \quad (2)$$

The station time series were not detrended prior to the regressional analysis, but the gridded data had been detrended before applying the EOF analysis. Thus the length of records (1873-1999), zero-trend in the predictor fields, and pronounced interannual variations will swamp any undesirable influences of the relatively weak trends in the station records (*Benestad*, 2001).

Both time series were detrended prior to the CCA, which was applied to the EOF products ($\mathbf{V}$) in a similar fashions as described by *Barnett & Preisendorfer* (1987).

‡The NCAR-CSM b006 starts from a "1990's" climate, but we have for the sake of simplicity "shifted" the initial date from "1990" to "1980"

3 Results

Figure 1 shows the annual mean sea-ice extent over the period 1871-1999. As Svalbard is in the vicinity of the ice edge, it is expected that any climate change will be closely related to the changes in the ice conditions. The importance of sea-ice for the climate therefore needs to be addressed in connection with climate studies of the Svalbard region. One way to look at the role the sea-ice plays is to identify its coupling to SLP and T(2m). A high temporal correlation between the atmospheric fields and the sea-ice is a sign of a strong coupling, and CCA can be used to find spatial structures in the sea-ice and the atmosphere that are highly correlated. The results from a CCA shown in Figure 2a-b indicates that the displacement of the ice-edge in the vicinity of Svalbard and along the east coast of Greenland are associated with a large-scale a SLP pattern related to northeasterly geostrophic wind anomalies over eastern Greenland. In comparison, *Deser* et al. (2000) applied a regression analysis on the entire northern hemispheric sea-ice and SLP fields and found a coupling between sea-ice in the Labrador Sea and a SLP structure resembling the North Atlantic Oscillation (NAO) north-south diploe. The canonical correlation scores (0.92 for January months over 1948-1999) suggest that there is a real association between the sea-ice and the circulation pattern. One explanation for the role of this pattern is that the winds drive an Ekman drift that pushes the ice edge further southeast. Another explanation is that northerly wind anomalies are associated with cold air advection in this area. On the other hand, the sea-ice anomaly also affects the SLP anomaly as the ice-cover obstructs the heat flux from the ocean, and thus leads to production of heavy cold air masses (i.e. high pressure anomaly).

A similar CCA between the January T(2m) and sea ice gives canonical correlations of 1.00, hence there is little doubt that there is a close association between the T(2m) and the sea-ice extent. Positive temperature anomalies (Figure 2c) are accompanied with retreat of the ice edge (negative weights in Figure 2d). These high correlations also point to high quality of the sea-ice data after 1958.

The connection between sea-ice and the local climate is confirmed by a study of the relationship between the station data and the sea-ice cover. Figure 3 shows sea-ice cover anomalies related to the temperature at Bjørnøya for four different seasons, derived from a linear regression. The analysis attaches an extremely high level of confidence to the established relations (p-values for Jan, Apr, Jul, and Oct are 4^{-13}, 7^{-11}, 0, 0 respectively). The implications of the close association between the sea-ice and the climate elements is that the sea-ice plays a central role in explaining past climatic variations as well as in producing local to regional climate scenarios. An interesting observation was the close association between the temperature at Bjørnøya and the sea-ice cover during the extreme cold October in 1968. The mean observed temperature is -0.2°C, but in 1968 the measured October mean was -8.4°C whereas the prediction gave -8.3°C.

Substantial changes in the air temperature in the Svalbard region during the 20th century were documented by *Hanssen-Bauer & Førland* (1998). They found that the temperature increase from the 1960s to the 1990s to a large degree could be explained by changes in atmospheric circulation. However, variations in circulation accounted for only a fraction of the observed temperature increase from 1912 to the 1930s. They concluded that additional predictors as e.g. sea ice are needed to model the long-term temperature variations in the region. The observed time evaluation of the sea-ice cover within the 10°W-40°E/68°N-85°N region from 1871 to 1999 is shown in Figure 4a. The $\imath 10$-index represent the area (number of grid boxes) with a fractional sea-ice cover higher than 10%, and $\imath 90$-index the number of boxes with more than 90% sea-ice cover. The greatest reduction is seen in the grid boxes with a high fractional (over 90%) sea-ice cover as the difference between $\imath 10$ and $\imath 90$ is relatively small. Moreover, most of the changes are found in areas with high proportional sea ice cover.

There are periods in the curves shown in Figure 4a with constant values (before 1900 and between 1940 and 1950). These features are not realistic, as the pre-1900 sea-ice consists of 1901-1930 climatological values due to lack of real observations, and the period 1947-1952 was set to the 1947-1952 climatology (N. Rayner, personal communication). Data from the Nordic Seas in April indicate that the sea-ice conditions from the 1860s to 1900 at average actually were more severe and also more variable than they were during the 20th century (*Vinje*, 2001). Because of the lack of real observations, CCA carried out on the HadISST1.1 sea-ice together with SLP or T(2m) reconstructions for 1873-2000 (*Benestad*, 2000) gives poor fit for the period before 1950. The leading canonical correlations are relatively, as a result of this, low for the extended periods 1873-2000: 0.75 and 0.77 for SLP and T(2m) respectively.

Figures 4b-c show the temperature reconstructed at Svalbard airport using a regression model based on the sea-ice data from HadISST1.1. There is in general a good fit for the most recent period, but the results indicate that the winter-time sea-ice variations before 1940 are underestimated (17% of the variance before 1940 and 54% after 1950) in the HadISST1.1 product (Figure 4b) if the relationship between the station temperature and the ice cover is stationary. The same results are found for the autumn (October: 16% before 1940, 58% after). The regression between the temperature in April (Figure 4c: 44% and 47%) and July (40% and 27%), on the other hand, is able to describe most of the variance also before 1950. In fact, the analysis for July indicates that the fit after 1950 is worse in terms of the variance explained than before 1940, however, this difference is not statistically significant at the 5% level according to a simple Monte Carlo test where T(2m) is replaced by 10,000 stochastic series of same length. This regression analysis was repeated for Bjørnøya and Hopen, which confirmed these results.

4 Discussion and Conclusion

According to the results from the present study, the best available sea-ice data give a good description of the conditions after 1950. Before 1950 the data quality is reduced because of poor data coverage during autumn and winter. In spring and summer, on the other hand, the data quality seems to be satisfactory also from 1900 to 1940.

The empirical evidence leaves no doubt about the close link between the local air temperature and the sea-ice cover, although the physical connection between these variables is not trivial. The sea-ice and the atmosphere are interacting with each other in a non-linear way, but they are also both interacting with the ocean. *Deser & Blackmon* (1993) have suggested that the decadal fluctuations in the SSTs east of Newfoundland are associated with variations in the sea-ice in the Labrador Sea. They found that the periods of extensive ice cover tend to precede cold conditions east of Newfoundland by approximately 2 years, suggesting that the sea-ice does indeed have an important influence on the regional climate. Moreover, their results suggests that the sea-ice condition is a pre-cursory signal for the temperature in the north-western Atlantic Ocean, and may therefore be a valuable factor for seasonal forecasting. *Vinje* (2001) and *Deser* et al. (2000) found that decadal scale variations in sea-ice distribution in the Nordic Seas and Labrador Sea to a large degree can be attributed to atmospheric circulation. In the Nordic Seas the April sea-ice extent and the winter NAO index are negatively correlated, while they are positively correlated in the Labrador sea. On the other hand, *Vinje* (2001) concluded that the long-term negative trend in the sea-ice cover in the Nordic Seas from the 1860s to 2000 mainly is attributed to oceanic rather than atmospheric forcing.

Hanssen-Bauer & Førland (1998) suggested that applying sea-ice as predictor for local temperature might account for the warming at Svalbard from 1912 to the 1930s. The present results support this idea, but reduced quality of the sea-ice data during this period makes it difficult to draw a decisive conclusion. The reconstructed April temperatures (Figure 4) indicate that the present model with sea-ice as the only predictor reproduces the warming prior to 1940 somewhat better than the model based upon SLP (*Hanssen-Bauer & Førland*, 1998). Furthermore, the long-term temperature trends since the 1960s can mostly be attributed to sea-ice changes whereas the temperature trends before the 1940s appears to a lesser degree to be associated with ice. According to *Vinje* (2001), SST may be an alternative or supplementary candidate as predictor, especially for long-term climatic trends.

The description of sea-ice given by various climate models varies considerably. The close connection between sea-ice extent and local temperatures implies that these differences have important implications for regional climate change studies. In *Benestad* et al. (2002), local climate scenarios derived using the 3 AOGCM discussed here are presented and the differences between the various scenarios are explored. It has been documented that climate models have a hard time giving a realistic description of the sea ice (*Meehl* et al., 2000; *Rind* et al., 1995). This problem can be illustrated by comparing the Arctic climates of various climate models. Figure 5 shows the "1980-1999" mean temperature maps of the 3 AOGCMs. A striking feature is the much colder conditions over Arctic in the NCAR-CSM, with sub-zero temperatures over most of the Greenland-Iceland-Norwegian (GIN) and Barents Seas. The HadCM3 describes partially ice-free conditions in the Barents Sea, but also this models shows too cold conditions in the Norwegian Sea. *Holland* et al. (2001) reported that this type of bias is a common problem in coarse-resolution coupled models and probably due to insufficient oceanic heat transport. They also observe that this region is in better agreement in models with flux adjustment, such as ECHAM4/OPYC3 GSDIO in panel d, where the low heat transport is "fictitiously" compensated for. These different 1990s conditions must be kept in mind when using the climate models to produce local and regional climate scenarios for the Arctic region.

The future climate projection in the Svalbard region is extremely sensitive to sea-ice conditions in the GIN and Barents Seas. The response in this region will depend on what happens to the THC and the polar cap. The realism of climate scenarios for the Arctic hinge on the sea-ice description in the models. Thus it is absolutely essential for the climate models to have a good representation of the sea-ice. At the present, the state-of-the-art climate models are probably not able to account for a future climate change in the Svalbard region.

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*URL http://www.R-project.org/

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Location	Start of obs.	altitude m a.s.l	Lon	Lat	$\overline{T}_{DJF}$ (°C)	$\overline{T}_{MAM}$ (°C)	$\overline{T}_{JJA}$ (°C)	$\overline{T}_{SON}$ (°C)
BJØRNØYA	1920	16	19.01°E	74.31°N	−7.6	−4.8	3.5	−0.5
HOPEN	1944	6	25.04°E	76.30°N	−13.3	−9.9	1.3	−3.7
SVALBARD AIRPORT	1912	28	15.28°E	78.15°N	−15.0	−10.7	4.2	−5.2

TABLE 1. Basic information about the climate stations used in the analysis. The 1961-1990 climatological temperatures for the winter, spring, summer and autumn seasons are listed in columns 7-10.

6 Figures

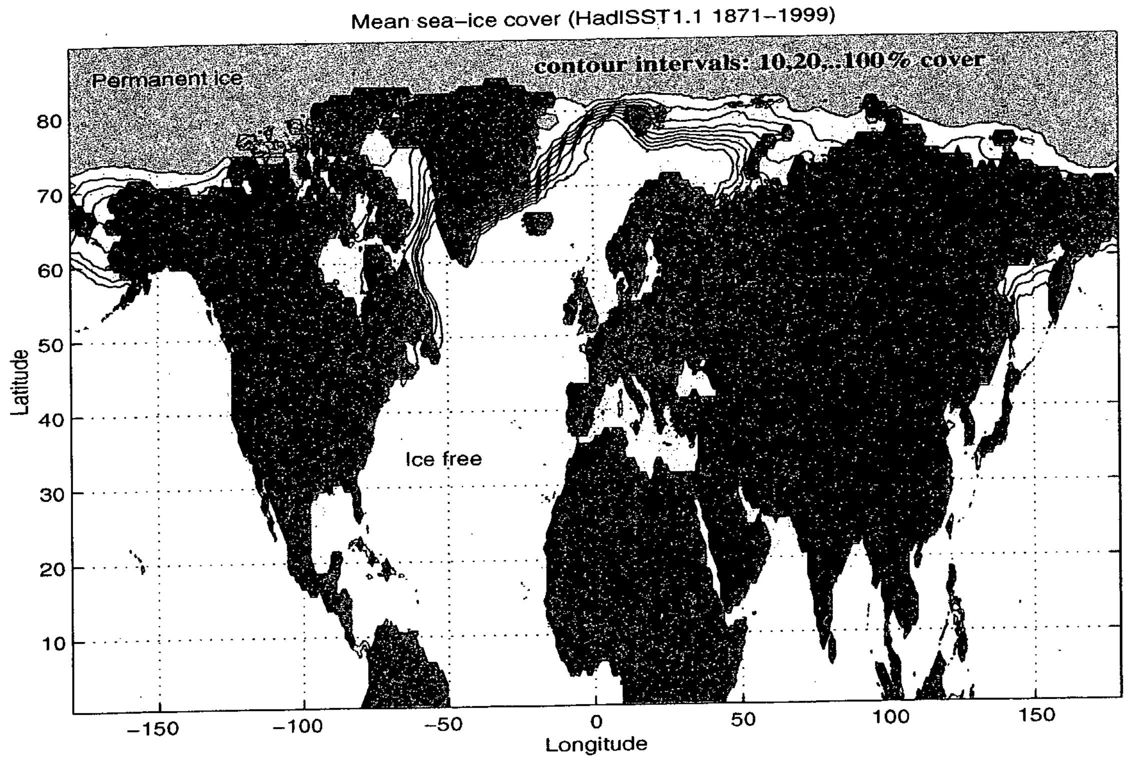
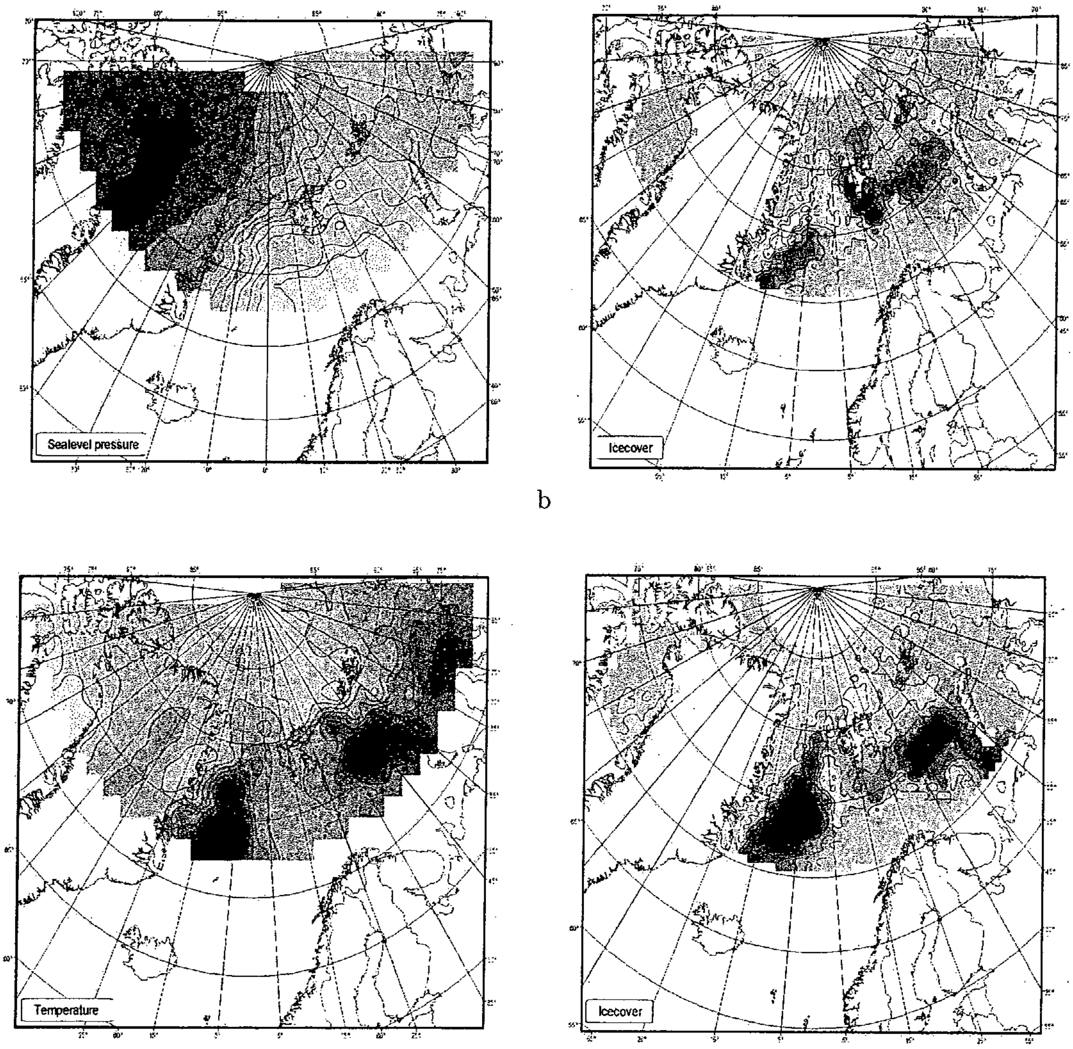


Figure 1. Map showing the annual mean sea-ice extent according to the HadISST1.1 data over the period 1871-1999. The contours show the areas with 10, 20, ..100% fractional ice coverage.



a b

c d

Figure 2. Results from *Barnett & Preisendorfer* (1987) CCA showing coupled SLP and sea-ice [a,b] and T(2m) sea-ice [c,d] structures.

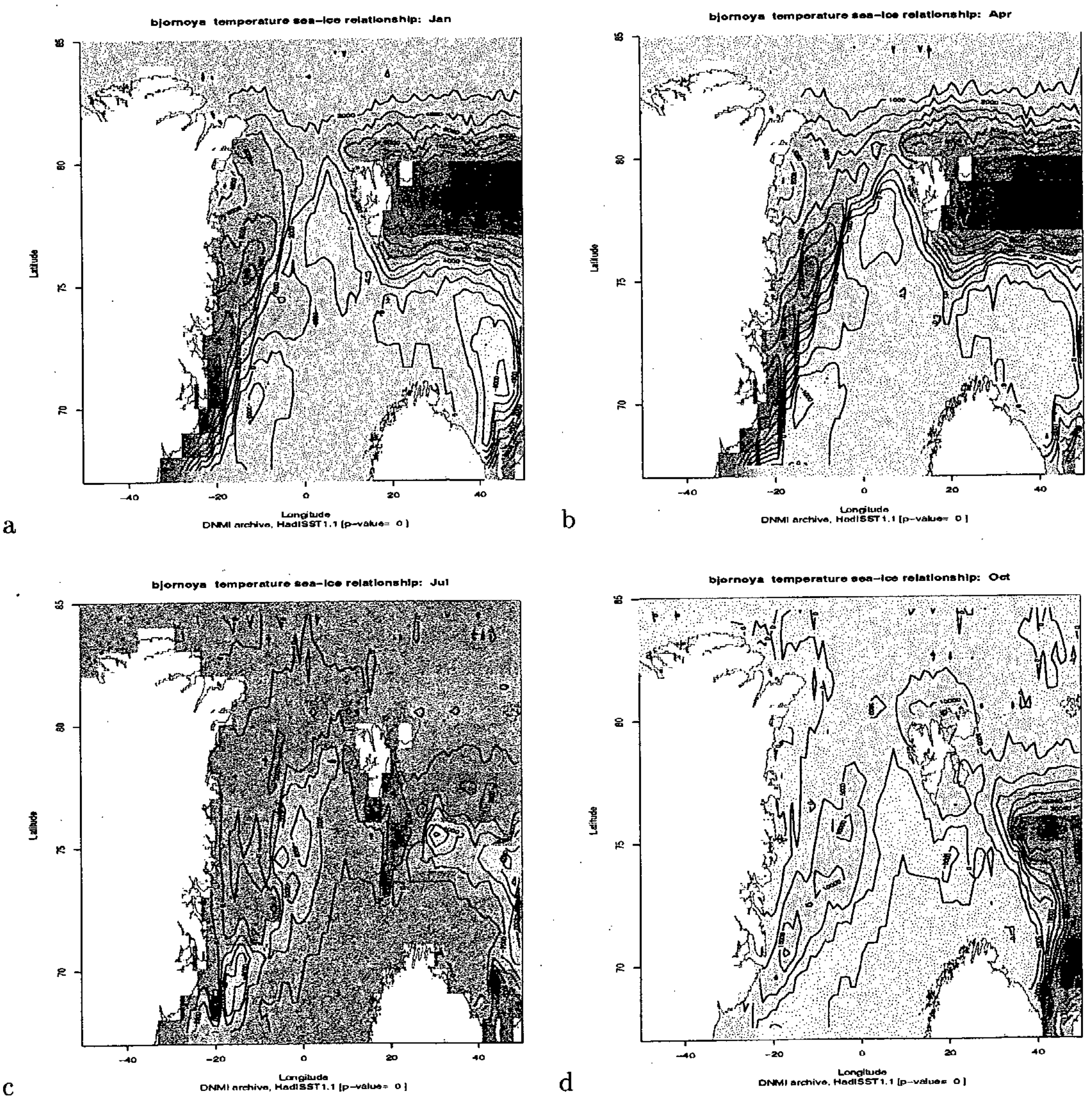
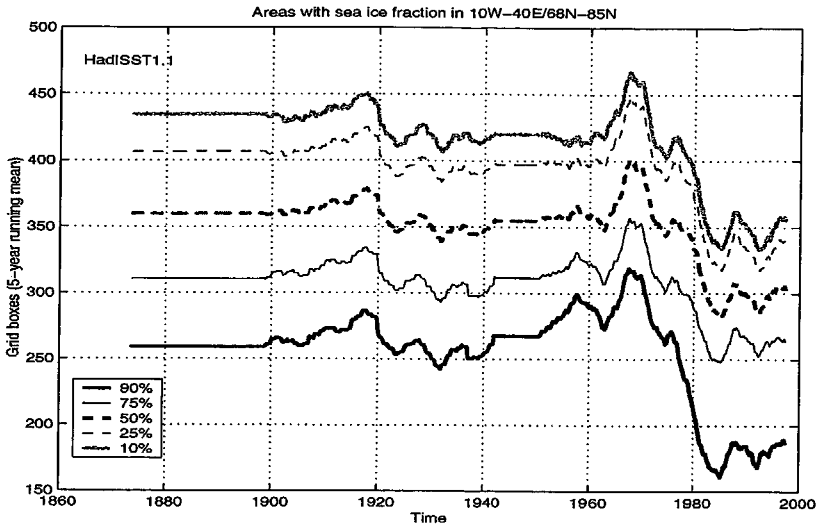
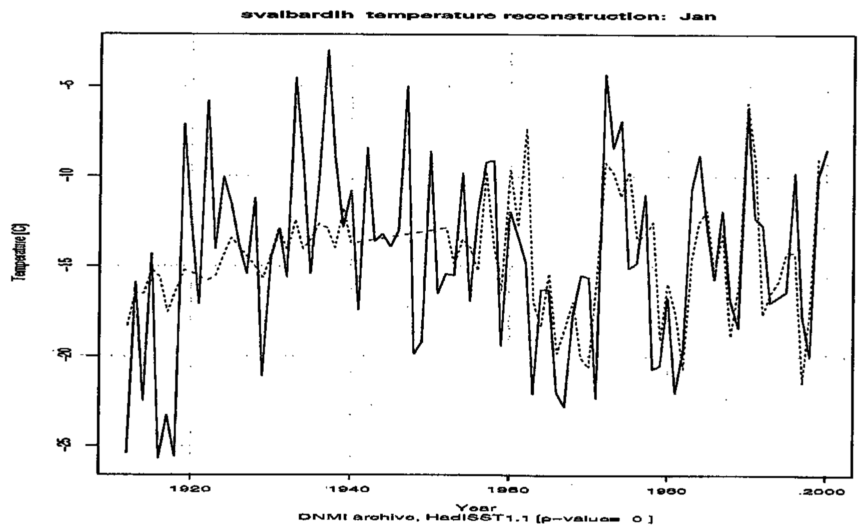


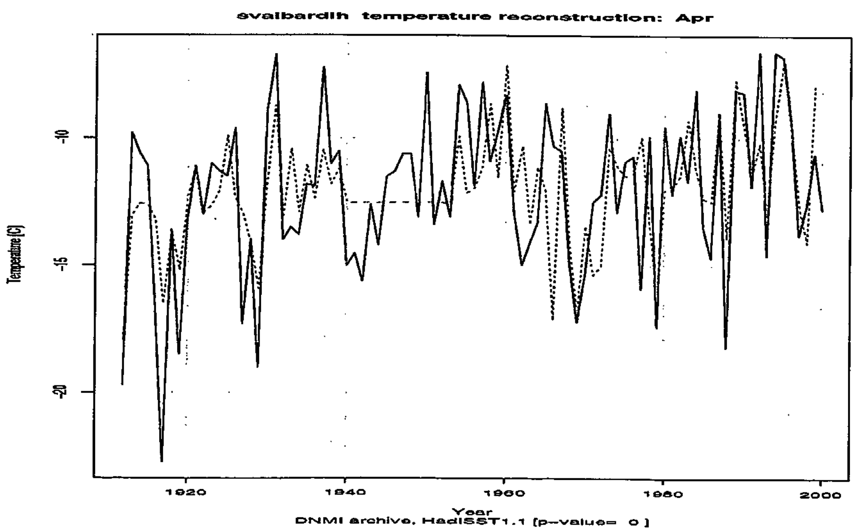
Figure 3. Regression weights for the sea-ice fractions and the January temperature at Bjørnøya.



a



b



c

Figure 4. a) The time evolution of the area with fractional sea-ice cover exceeding 10%, 25%, 50%, 75% and 90%. Note the flat sections of the curves: these are most probably due to questionable data quality and shortcomings in the model description of the sea-ice. b) Observed and reconstructed January temperature at Svalbard airport. The reconstruction was based on a regression analysis between the station record and the HadISST1.1 sea-ice product. c) the same as in b, but for April.

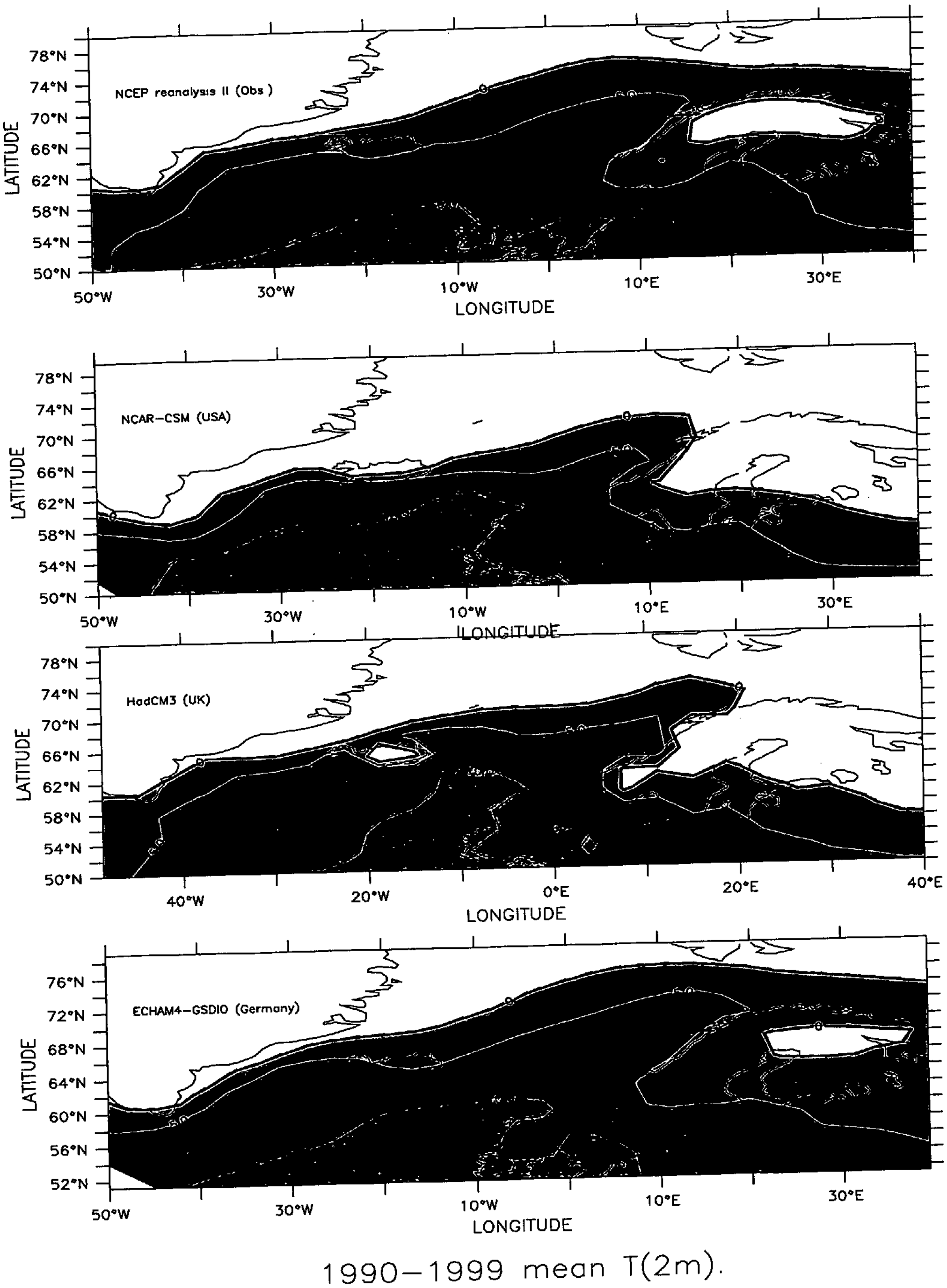


Figure 5. Comparisons between the "1990-1999" temperatures between the different AOGCM scenarios shows that the NCAR-CSM describes cooler conditions than the ECHAM4-GSDIO and HadCM3 models. A similar analysis based on the NCEP reanalysis II (observations) is also shown (top panel) for comparison.