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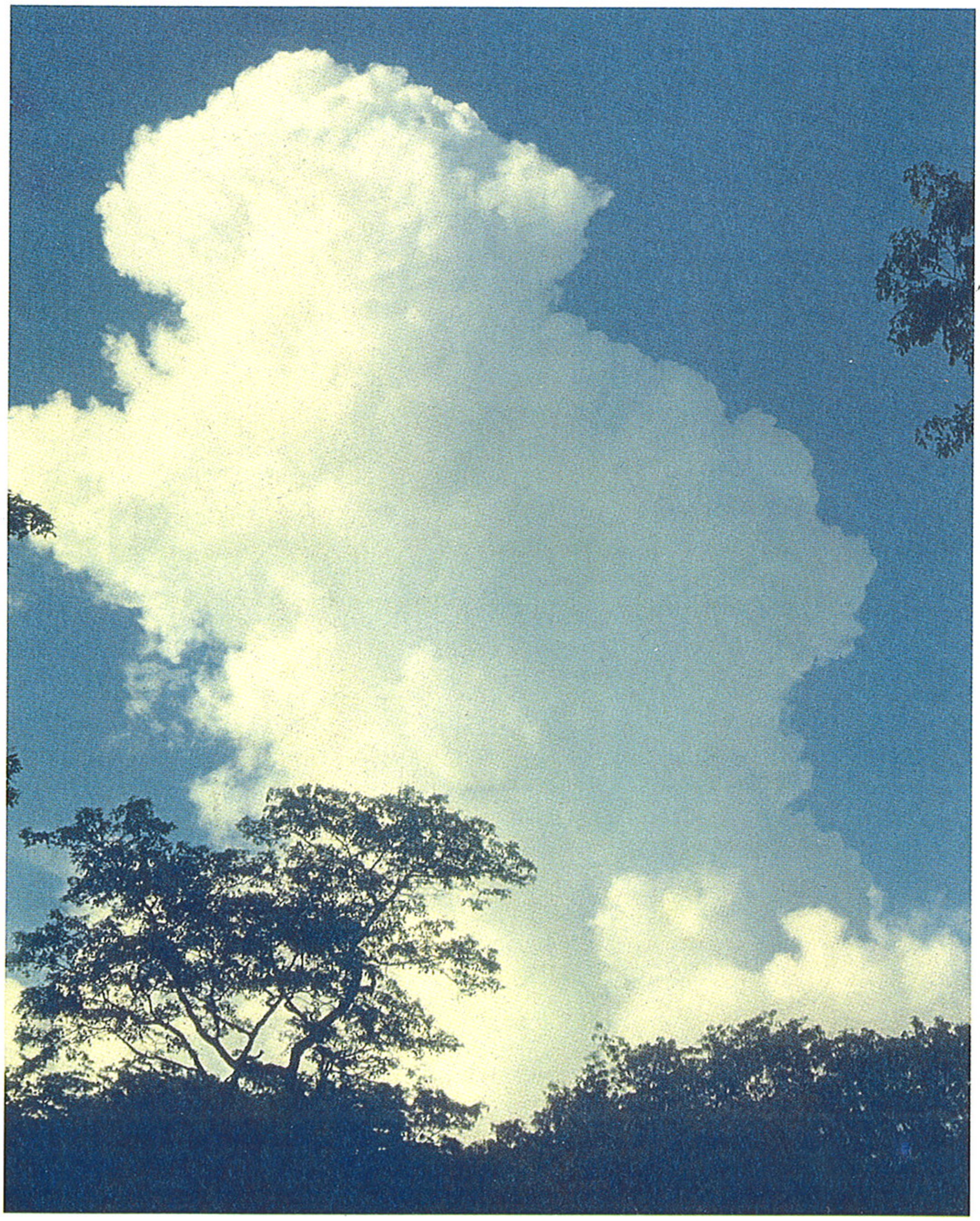
Under Global Warming

A survey of possible teleconnections affecting Fennoscandia

Rasmus E. Benestad and Ole Einar Tveito



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SUMMARY:

A regression analysis is used for identifying statistical relationships between sea-ice cover and 2 meter air temperature in Fennoscandia, and the relationships are shown as maps of the linear variance R^2 accounted by the sea-ice. The analysis is repeated with a time lag and with sea-ice cover replaced by sea surface temperature, the North Atlantic Oscillation index, an El Niño Southern Oscillation index, and an index describing latitudinal excursion of the Gulf Stream extension.

The analysis suggests there may be a weak influence of the Arctic sea-ice on the temperature and precipitation in Fennoscandia. The link between the sea-ice and temperature is strongest during winter, but there may also be a weak link between the sea-ice cover and precipitation winter, spring and autumn. There is furthermore a faint sign of a lagged relationship between sea-ice and temperature during spring and autumn.

The results from the same analysis applied to North Atlantic sea surface temperatures (SSTs) indicate a clear effect on the land air surface temperatures, especially in southern Scandinavia. The corresponding R^2 estimates for the precipitation suggest much weaker links with the North Atlantic SSTs.

Estimates of R^2 were computed from correlation analysis between the North Atlantic Oscillation Index (NAOI) and the respective station records. The well documented link between the winter-time temperatures in northern Europe and the NAOI is also found, as is the link between the NAOI and precipitation along the western coast of Norway and southern Sweden.

The study explored the latitudinal excursions of the Gulf Stream extension branching off from the north American continent to see if these can be associated with temperature or precipitation variations over northern Europe. The results suggests that any effects, if at all, are marginal. Likewise, the analysis could not find any links between ENSO and climatic variations over northern Europe.

KEYWORDS:
Teleconnection, sea-ice, sea surface temperature, NAO, land-temperature, precipitation, Gulf Stream.

SIGNATURES:

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11/02

A SURVEY OF POSSIBLE TELECONNECTIONS AFFECTING FENNOSCANDIA

By Rasmus E. Benestad and Ole Einar Tveito

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October 14, 2002

ABSTRACT

A regression analysis is used for identifying statistical relationships between sea-ice cover and 2 meter air temperature in Fennoscandia, and the relationships are shown as maps of the linear variance (R^2) accounted by the sea-ice. The analysis is repeated with a time lag and with sea-ice cover replaced by sea surface temperature, the North Atlantic Oscillation index, an EL Niño Southern Oscillation index, and an index describing latitudinal excursion of the Gulf Stream extension.

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The study explored the latitudinal excursions of the Gulf Stream extension branching off from the north American continent to see if these can be associated with temperature or precipitation variations over northern Europe. The results suggests that any effects, if at all, are marginal. Likewise, the analysis could not find any links between ENSO and climatic variations over northern Europe.

KEY WORDS: Teleconnection Temperature Sea-ice Sea surface temperature

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Contents

1 Introduction

In order to derive local or regional climate information from global climate models (atmospheric-oceanic general circulation models, AOGCMs) it is important to account for teleconnections. It is for instance well-known that the North Atlantic Oscillation (NAO) has a profound impact on the winter temperature and precipitation over Europe (*Marshall* et al., 2001; *Deliang & Hellström*, 1999; *Hurrel*, 1995). The possibility of the existence of other types of teleconnections should also be investigated. One important question is how important the Arctic sea-ice cover is for the regional and global climate (*Deser* et al., 2000; *Rind* et al., 1995; *Vinje*, 2001; *Holland* et al., 2001; *Parkinson* et al., 2001; *Benestad* et al., 2002a,b). Other types of teleconnection that could be important may include sea surface temperature (SST) (*Benestad & Melsom*, 2002) and variations in the Gulf Stream extension.

This study provides a statistical survey of statistical relationships between the sea-ice extent, SST, Gulf Stream variations and the NAO and local climate elements in the Nordic countries.

2 Methods & Data

The influence of sea-ice, sea surface temperature (SST) or the North Atlantic Oscillation (NAO) on the land surface temperature, precipitation or air pressure in northern Europe was inferred from a stepwise regression analysis based on R data-analysis language (*Ihaka & Gentleman*, 1996; *Ellner*, 2001; *Gentleman & Ihaka*, 2000)* and the functions *lm* and *step*. The predictor fields (explaining variable) were decomposed into EOFs and the 20 leading modes were used as input for the stepwise regression. The annual cycle is the most pronounced feature in the EOF products, but a sub-sampling of the data by analysing each calendar month individually eliminates the effect of the annual cycle on the outcome. The modes used for describing the local temperatures were determined according to whether they minimise the Akaike information criterion (AIC, *Wilks* (1995), p.301-302). The subset of selected modes obtained from the stepwise regression was subsequently used in a cross-validation analysis based on a least squares fit. The results from the cross-validation analysis were then compared with the actual observation based on Pearson correlation and variance (R^2) estimates. The p-values† were estimated from a correlation analysis confidence test‡.

One objective of this study was to assess the robustness of the teleconnection patterns, and one way to achieve this is to compare the results for adjacent calendar months, assuming that the patterns change slowly with the seasons. Thus, the analysis was carried out for each of the 12 months of the year. The analysis was also carried out for the NAO versus station observations in order to test the results against a well-known teleconnection pattern. Furthermore, the analysis was done for simultaneous observations as well as with a one month lag (ie the sea-ice leading the land temperature).

A crude analysis in the spirit of Monte Carlo was carried out to compare the observed spatial variance patterns with results obtained from the same analysis with stochastic values as inputs in order to test the significance of the patterns. Because the computer-intensive analysis, it is not feasible to generate a large sample on which a null-distribution can be derived. Here only 12 stochastic fields are produced, but these will nevertheless give an indication of the significance levels.

The station observations were taken from the Nordklim data (parameter codes 112,122,101,601) set (*Tuomenvirta* et al., 2001), the sea-ice and the SST were obtained from the HadISST1.1 product. The NAO index was obtained from the Climate Research Unit at the University of East Anglia (U.K.). The analysis was done for monthly mean temperature, maximum and minimum temperature (for a given month), monthly accumulated precipitation, maximum 24-hour precipitation (for a given month), and sea level pressure (SLP). The analysis was carried out on time series of various lengths, with the shortest time series spanning the 1965–1995 period§ and the longest series covered 1950–1999.

The latitude of the Gulf Stream's northern boundary ("The GSNW index") obtained from Plymouth

*A Freeware clone of S-plus URL: http://www.R-project.org/

†The probability that the null-hypothesis, e.g. that there is no correlation, holds. A "statistically significant" relationship is associated with a low p-value (typically less than 0.05). The p-value is often estimated from standard regression analysis of variance (ANOVA).

‡Using the R ctest package/library function cor.test: URL http://cran.r-project.org.

§The figure title shows only the shortest time periods.

Marine Laboratory¶ was used as an index for the Gulf Stream's position. These data have been derived from aircraft, satellite and surface observations (*Taylor*, 1996, 1995) covering the period 1966-2000. The latitudes of the north wall were estimated at six longitudes: 79°W, 75°W, 72°W, 70°W, 67°W and 65°W. The NINO3|| index was used to describe the temporal evolution of ENSO.

3 Results

3.1 Sea-ice and land temperature

Figure 1 shows one map for each calendar month on which the R^2-estimates between (simultaneous) monthly mean station temperatures and the sea-ice cover in the Greenland-Iceland-Norwegian (GIN) sea*, are indicated by the size of the circles. Unless there is an a physical reason for why there should be abrupt changes in the geographical distribution of R^2 known priori, the *true* geographical pattern should vary gradually throughout the year. A comparison between the 12 calendar months may therefore identify robust patterns or sampling fluctuations. Moreover, it is expected that some of the estimates may give spuriously high values for R^2 for isolated cases as a result of the problem of multiplicity (*Wilks*, 1995, p. 151–157). The fact that station records from different locations often are correlated, implies that spurious values may be expected for a groups of station series as well as for single (remote) locations.

The results shown in Figure 1 suggests that there is a weak ($R^2 \sim 20\%$) but robust association between the GIN Sea sea-ice cover and the monthly mean temperature over parts of the Norwegian Sea, particularly during winter. The same analysis applied to a greater region (domain: 90°W– 90°E, 70°N–85°N) only produced high R^2 estimates for January ($R^2 \sim 40\%$), which cannot be considered as a robust and real link (not shown). The larger domain gave similar results to those in Figure 1 for the other months.

Figure 2 shows the results of the same analysis applied on temperatures lagging the GIN sea-ice by one month. The results suggest that there may indeed be a connection between the sea-ice cover and the temperature of the following month during late winter and autumn, although this link is weak and still uncertain.

The analysis was applied to the absolute maximum and the minimum temperature of the month as well as the monthly mean value. The R^2 estimates for the maxima and minima are not expected to be as high as for the mean value, partly because these consist of single measurements (extremes) that are more prone to random noise† than mean values of many independent measurements‡ where random variations tend to (partially) cancel. On the other hand, extreme events may be related to particular (ephemeral) conditions occurring simultaneously, but may not exhibit a clear relationship with large-scale features averaged over a month. In other words, the signal-to-noise ratio is higher for the monthly mean than for minima or maxima.

The analysis for the monthly maximum temperature (Figure 3) suggest that the there is a weak statistical relationship between the maximum temperature and the GIN Sea sea-ice cover during winter. For the minimum temperature, there seems to be a stronger link with the sea-ice cover (Figure 4). The same analysis was repeated with EOFs for the domain 90°W– 90°E, 70°N– 85°N (not shown). For the maximum temperature, the results gave high values over Finland in April–May. Again, there seemed to be a more prominent link between the minimum temperature and the sea-ice cover.

A students paired t-test between the R^2 estimates between the sea-ice and maximum (mean value $= 0.130$) and minimum (mean value $= 0.170$) temperature (for all months) respectively suggests that their difference is statistically significant at the 0.1% level (p-value $=< 2.2 \times 10^{-16}$). Furthermore, the relationship between the lowest monthly minimum temperatures and the sea-ice appears to be stronger than for even the monthly mean values: the mean R^2 for all months' monthly mean temperature and sea-ice is 0.154 (paired t-test p-value $= 9.2 \times 10^{-6}$).

¶URL: http://www.pml.ac.uk/gulfstream/

||The spatial mean SST anomaly over the region 150°W–50°W, 5°S–5°N.

*Domain: 50°W– 50°E, 67°N– 85°N.

†Possibly due to several sources, including sampling fluctuations, instrumental uncertainties, instrumental failure (i.e. that the most extreme event was missed), reading errors, and mistyping.

‡The correlation analysis is not very sensitive to systematic errors as long as these are constant through out the analysis period.

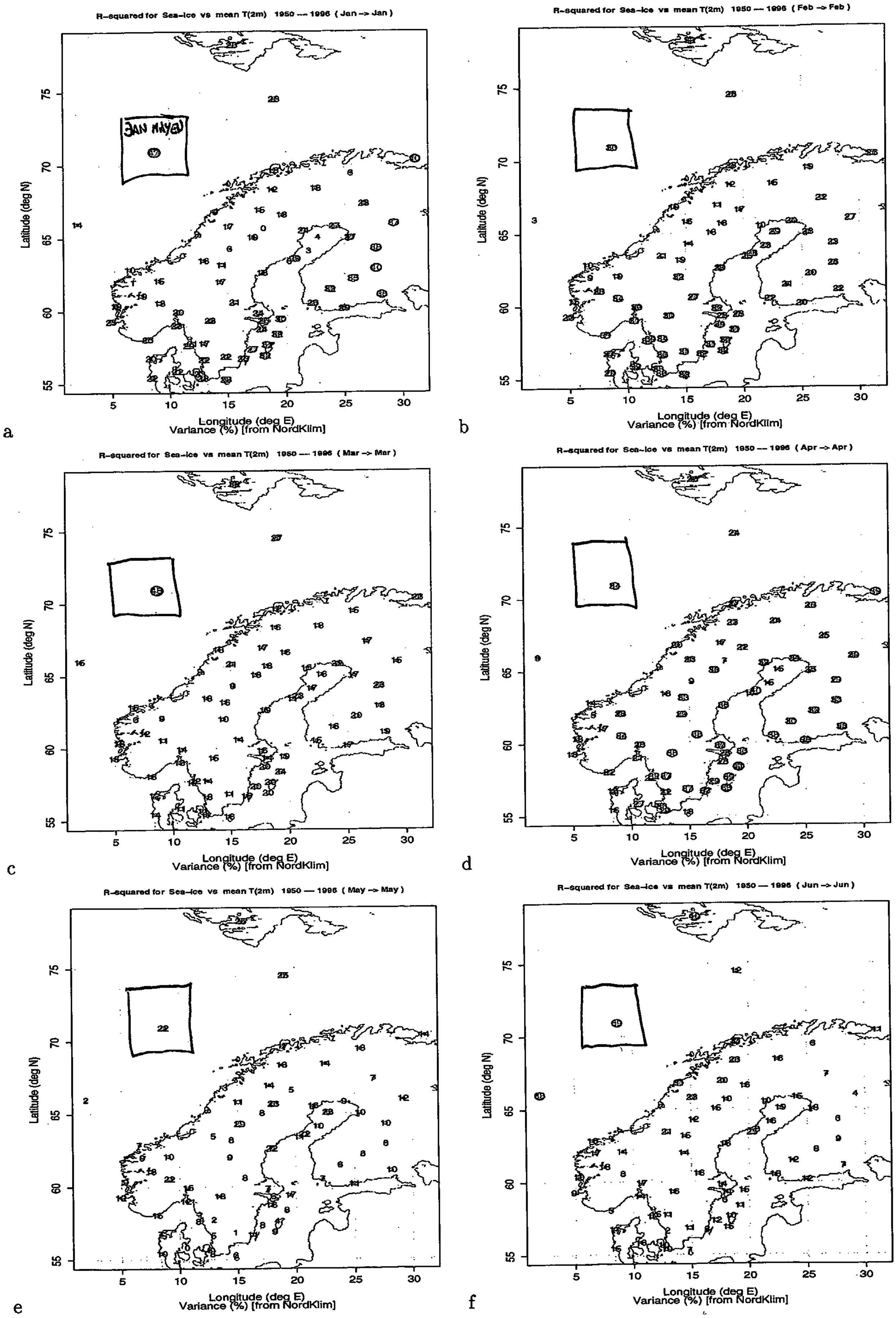


Figure 1. The variance (R^2) in % of the monthly mean temperature that can be explained by the sea-ice in the GIN Sea in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f). The size of the circles is proportional to R^2 with solid symbols representing statistically significant results at the 1% level whereas the open circles are not statistically significant. The results for Jan Mayen are shown at 9°W, 71°N.

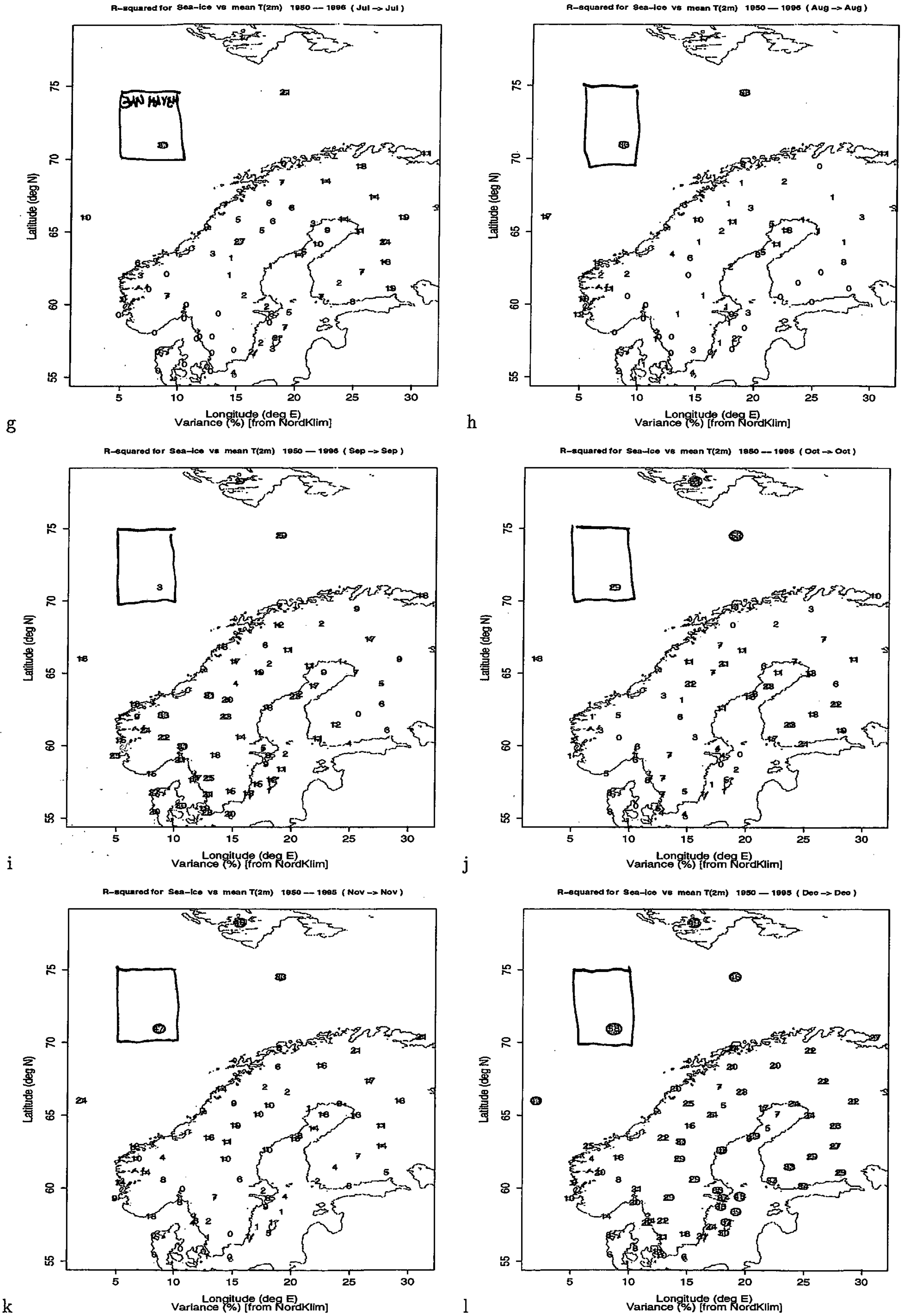


Figure 1. The variance (R^2) in % of the monthly mean temperature that can be explained by the sea-ice in the GIN Sea in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l). The size of the circles is proportional to R^2 with solid symbols representing statistically significant results at the 1% level whereas the open circles results that are not statistically significant.

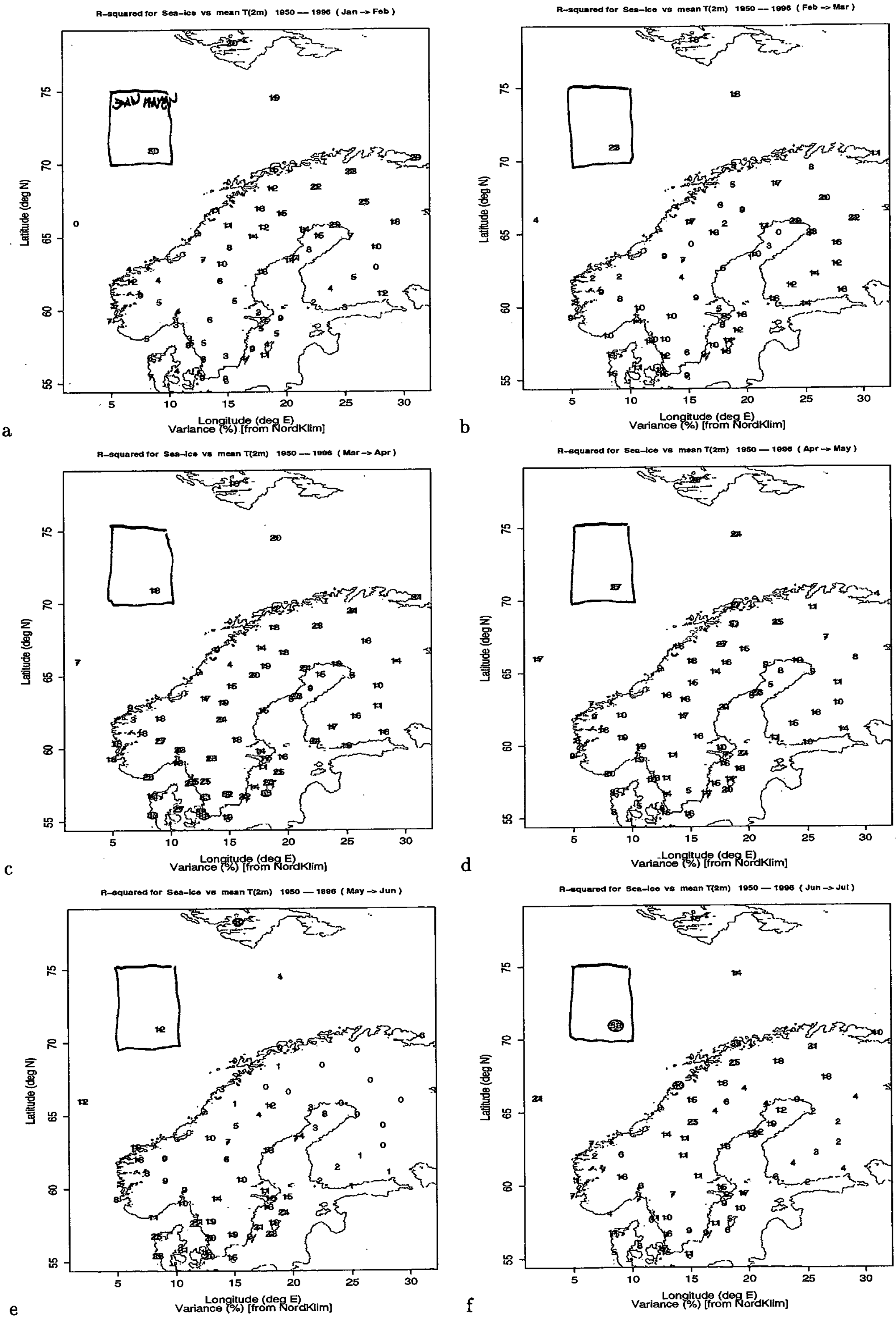
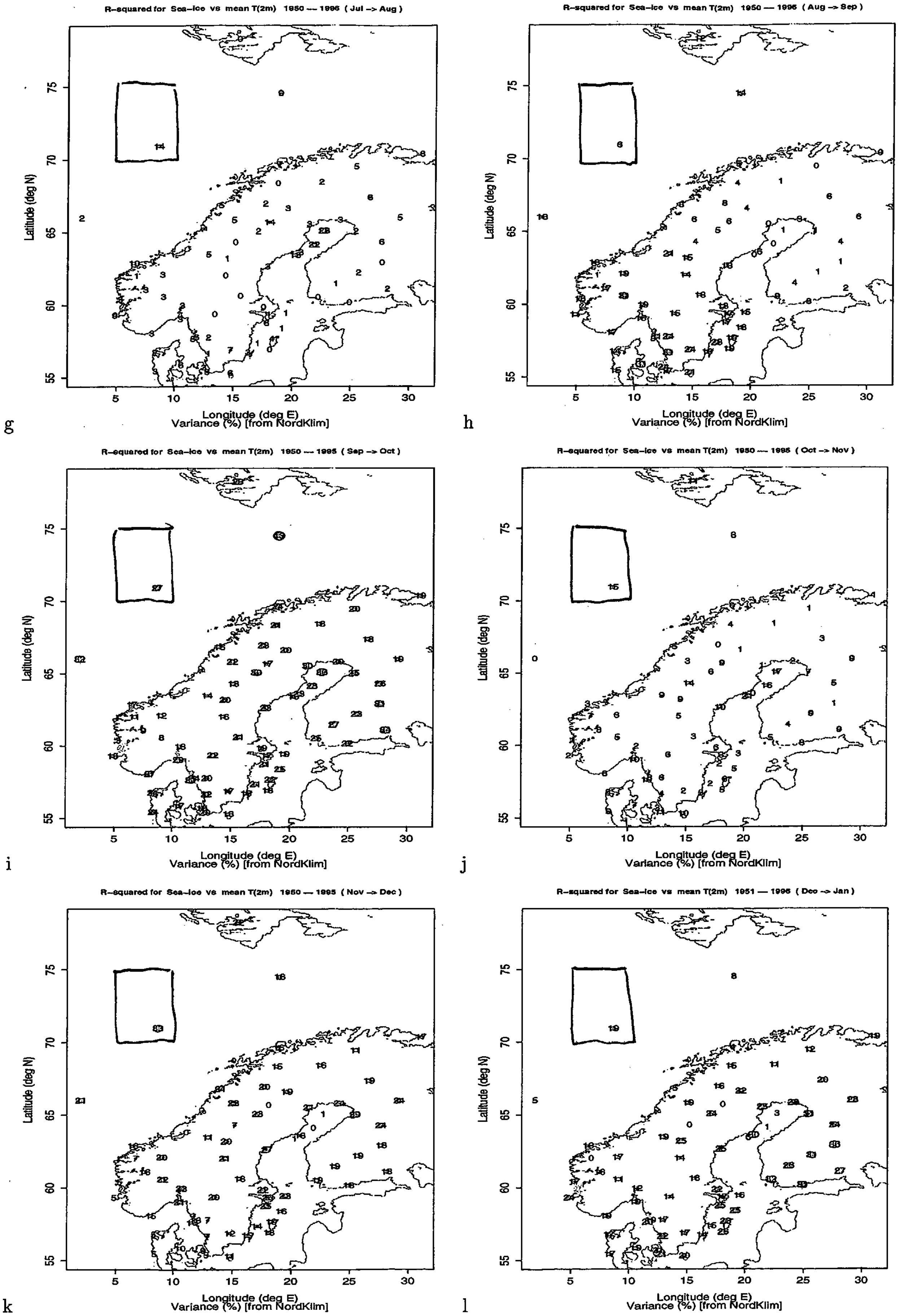


Figure 2. The variance (R^2) in % of the monthly mean temperature that can be explained by the January sea-ice at one month's lead time in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).



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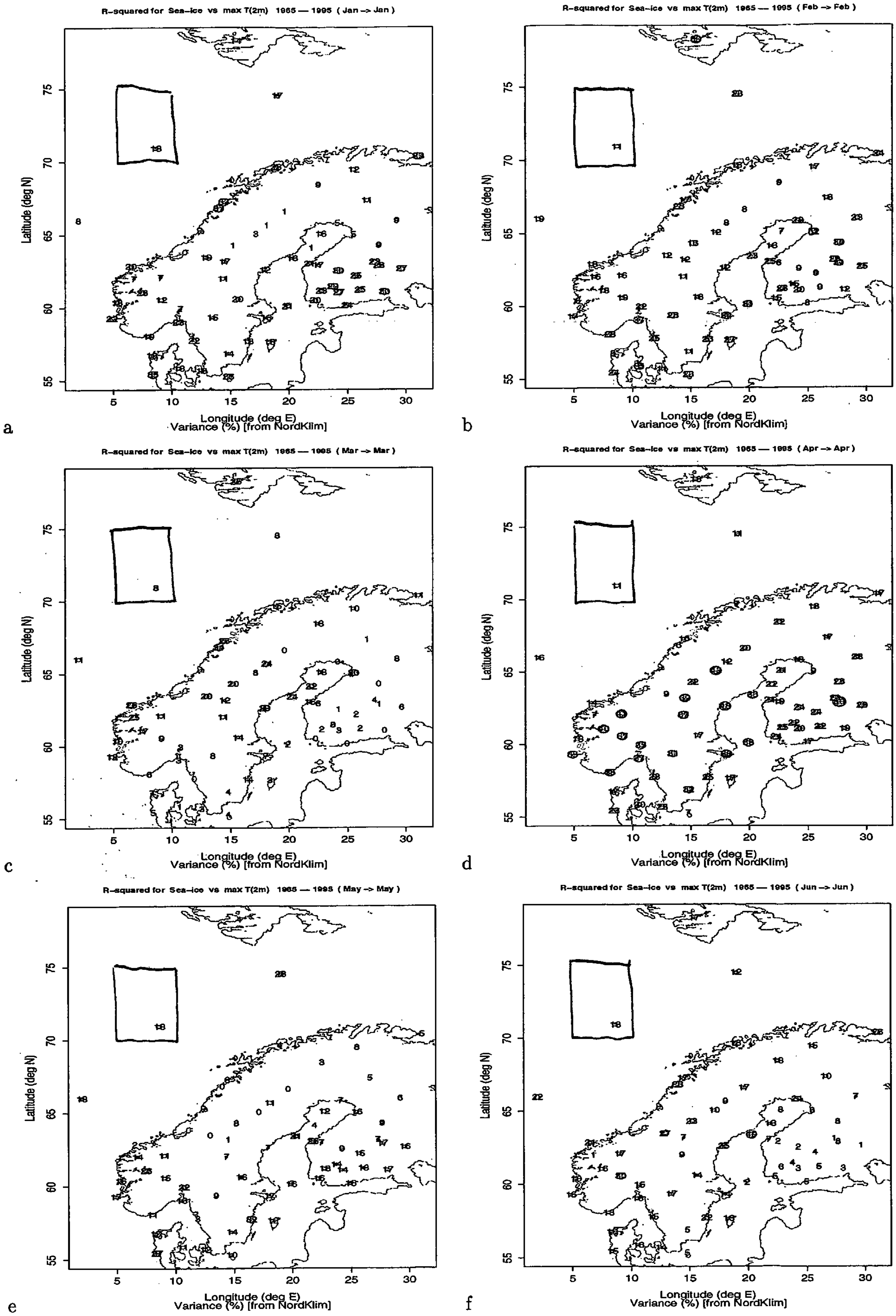
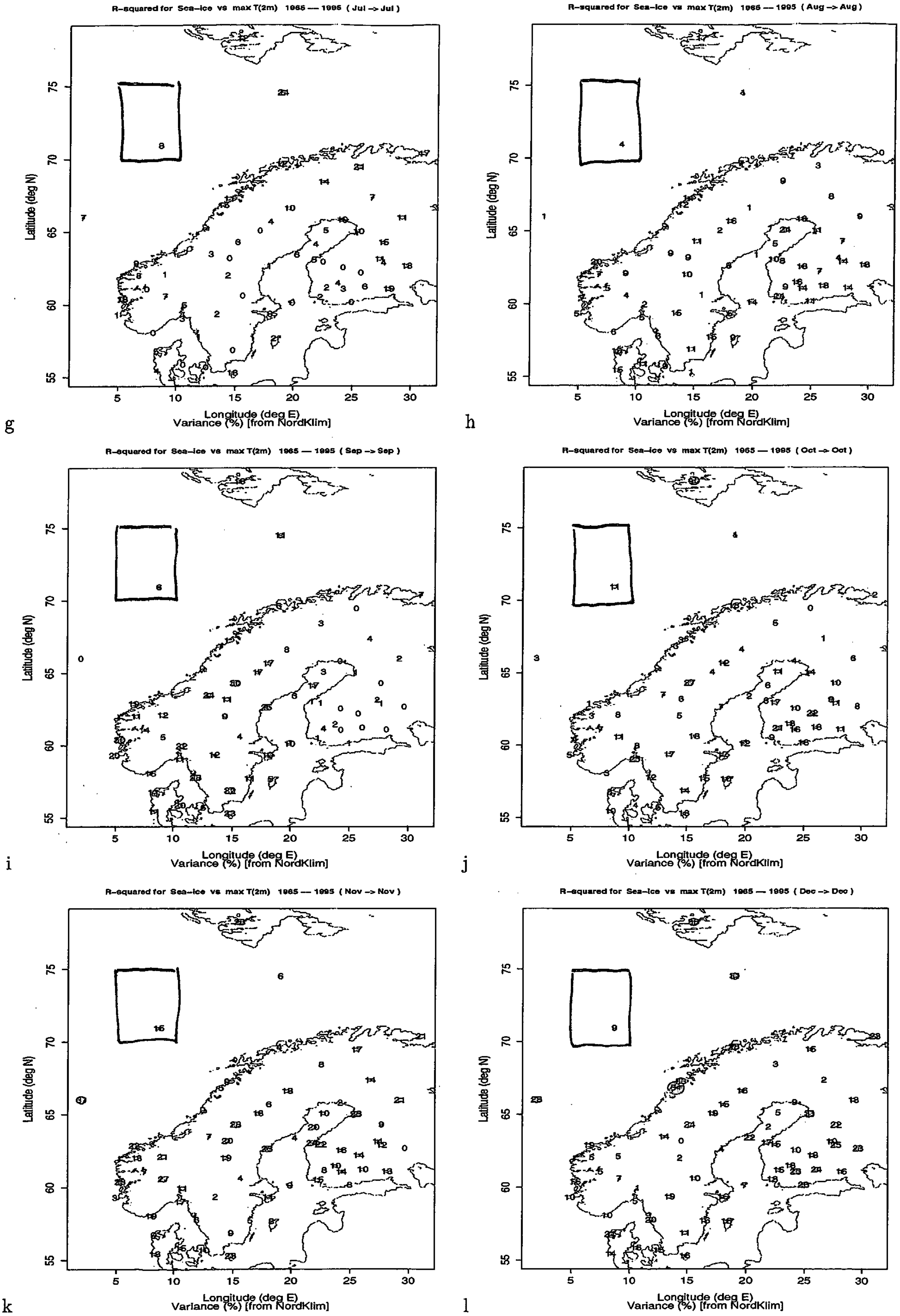


Figure 3. The variance (R^2) in % of the monthly maximum temperature that can be explained by the sea-ice in the GIN Sea in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).



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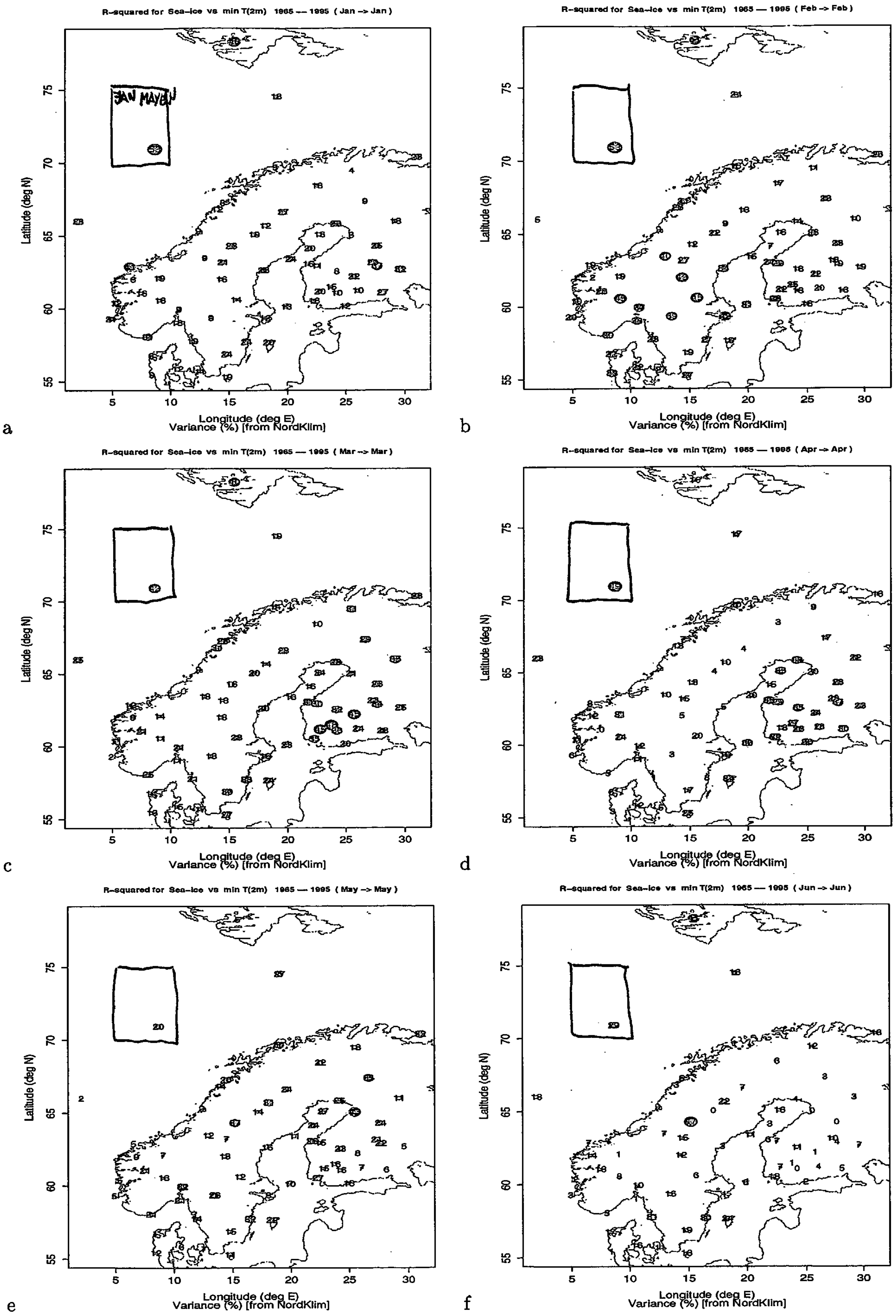


Figure 4. The variance (R^2) of the lowest monthly minimum temperature that can be explained by the sea-ice in the GIN Sea in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

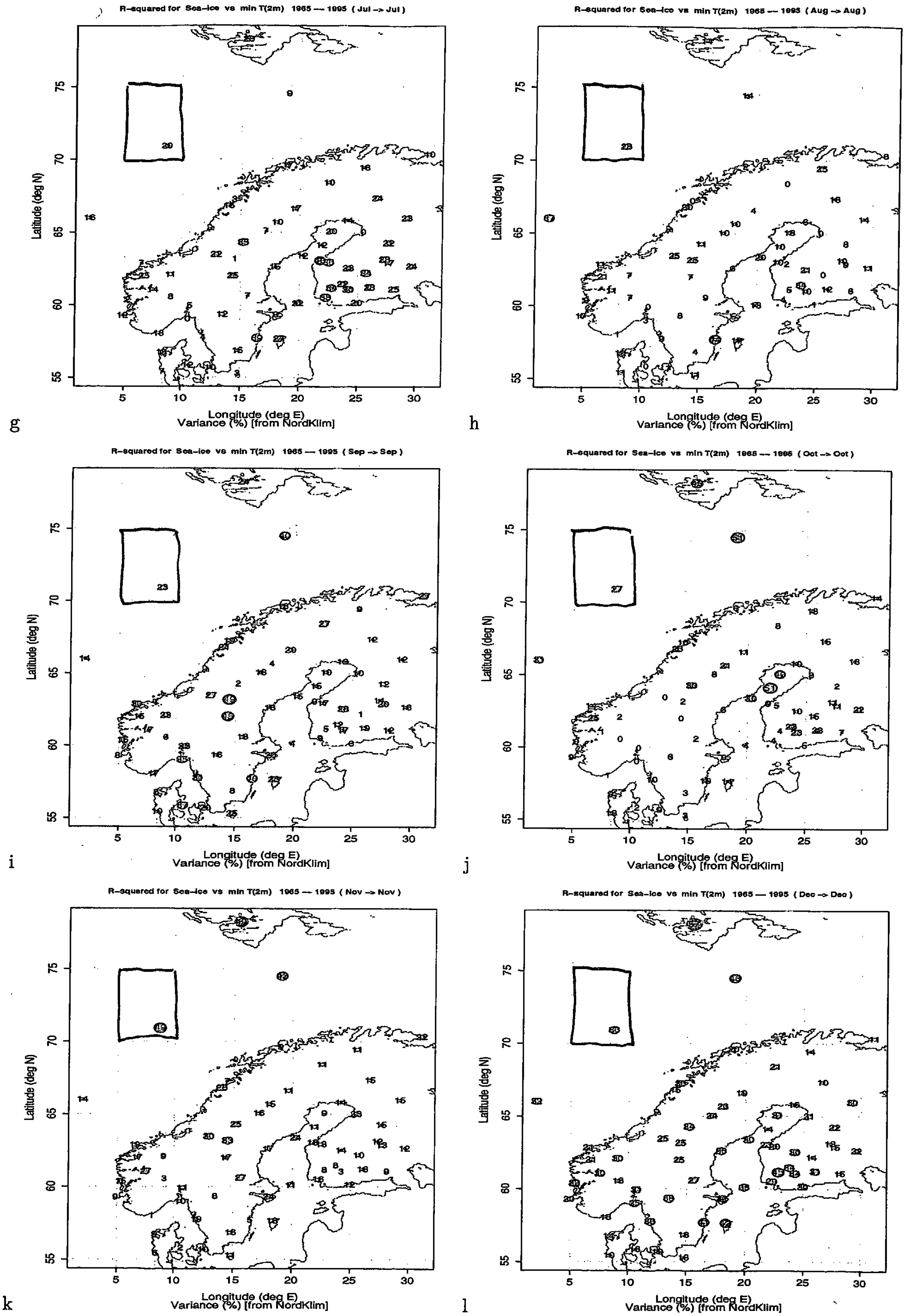


Figure 4. The variance (R^2) of the lowest monthly minimum temperature that can be explained by the sea-ice in the GIN Sea in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

The maximum R^2 value estimated for sea-ice is 0.71 for the Arctic domain (not shown, 0.64 for the GIN Sea in Figure 3). This extreme value was found for maximum December temperature at Glomfjord, and is unrealistically high (i.e. a coincidental result).

In general the geographical distribution of the R^2 values suggests that the monthly mean temperature in the mid-Norwegian mountain regions are less affected by the sea-ice during winter (Figure 1) and the sea-ice signal is most prominent in southeastern Sweden. The autumn values for the R^2 estimates appear to be homogeneous for the one-month-lagged analysis (Figure 2). With the exception of the December values at Glomfjord, the strongest associations between the sea-ice and the maximum and minimum monthly temperature are seen in Finland, Sweden and around the Baltic Sea.

Figure 3.1 shows the same analysis as before, but now applied to stochastic (random) series instead of principal components of real observations such as sea-ice. The results in Figure 3.1 therefore provide a reference level for how statistical fluctuations may cause spuriously high R^2 estimates, and can give an rough indication of the results obtained with the sea-ice data can be considered as real. The R^2 values estimated from the stochastic series are systematically lower than those estimated for the sea-ice, even for a one-month-lagged relationship, suggesting that there is a real link between the sea-ice cover and the temperatures in the Nordic countries. However, Figure 3.1 shows that R^2 up to 20% easily may occur by chance in 1–3 cases out of 12 (problem of multiplicity - see the discussion).

3.2 Sea surface temperature and land temperature

Figure 6 shows the R^2 estimates for the North Atlantic* SST-based analysis. The results suggest that there are strong links between the North Atlantic SST anomalies (SSTAs) and the monthly mean temperature, especially in southern Scandinavia. This link seems to be prominent in winter and summer and slightly weaker during spring and autumn.

The analysis was repeated for a smaller EOF domain† also indicating a prominent relationship between the SSTA and the monthly mean temperature (not shown).

The R^2 estimates for monthly mean temperatures lagging the North Atlantic SSTs by one month (Figure 7) are substantially lower than for the instantaneous monthly mean temperatures. The analysis nevertheless points to robust links during winter ($R^2 \sim 20\%$) and summer. A comparison with the stochastic results in Figure 3.1 suggests that there is indeed a real relationship between the SSTs and the following month's mean temperature in winter and summer. These results are in line with earlier studies on predictability (*Colman & Davey*, 1999; *Benestad*, 1999).

The regression analysis between the North Atlantic SST and the highest monthly maximum (Figure 8) and minimum (Figure 9)temperature produced R^2 estimates that in many locations were higher than for the monthly mean temperature in winter and summer. The better fit between these extreme values than for the monthly mean values are unexpected according to statistical considerations, since the signal-to-noise ratio is expected to be much higher for the monthly mean estimate than for a single observation. A physical reasoning, on the other hand, is required to explain why the SST may have a stronger effect on the extreme values. These results suggest that warm or cold periods do not occur unless the the conditions (SST) are right.

The mean value of the R^2 estimates for the monthly mean temperature was 0.402, 0.229 for the highest monthly maximum temperature, and 0.238 for lowest monthly minimum temperature. Again, the link was weaker for the maximum temperature than for the minimum temperature (the p-value from a paired t-test between the two estimate populations is 0.008). The highest R^2 estimates for the maximum and minimum temperature tend to cluster around southern Scandinavia, although high values can also be seen in Finland.

3.3 NAOI and land temperature

In order to explore the statistical relationship between climatic indices and the station records, the variance attributed to the local variability was estimated as $R_i^2 = \text{cor}(\text{NAOI}, y_i)^2$, i denoting the station station. Figure 10 shows the results for the station temperature, which are consistent with the well-known

*Domain: 90°W– 40°E, 40°N– 75°N.
†Domain: 20°W– 40°E, 50°N– 75°N.

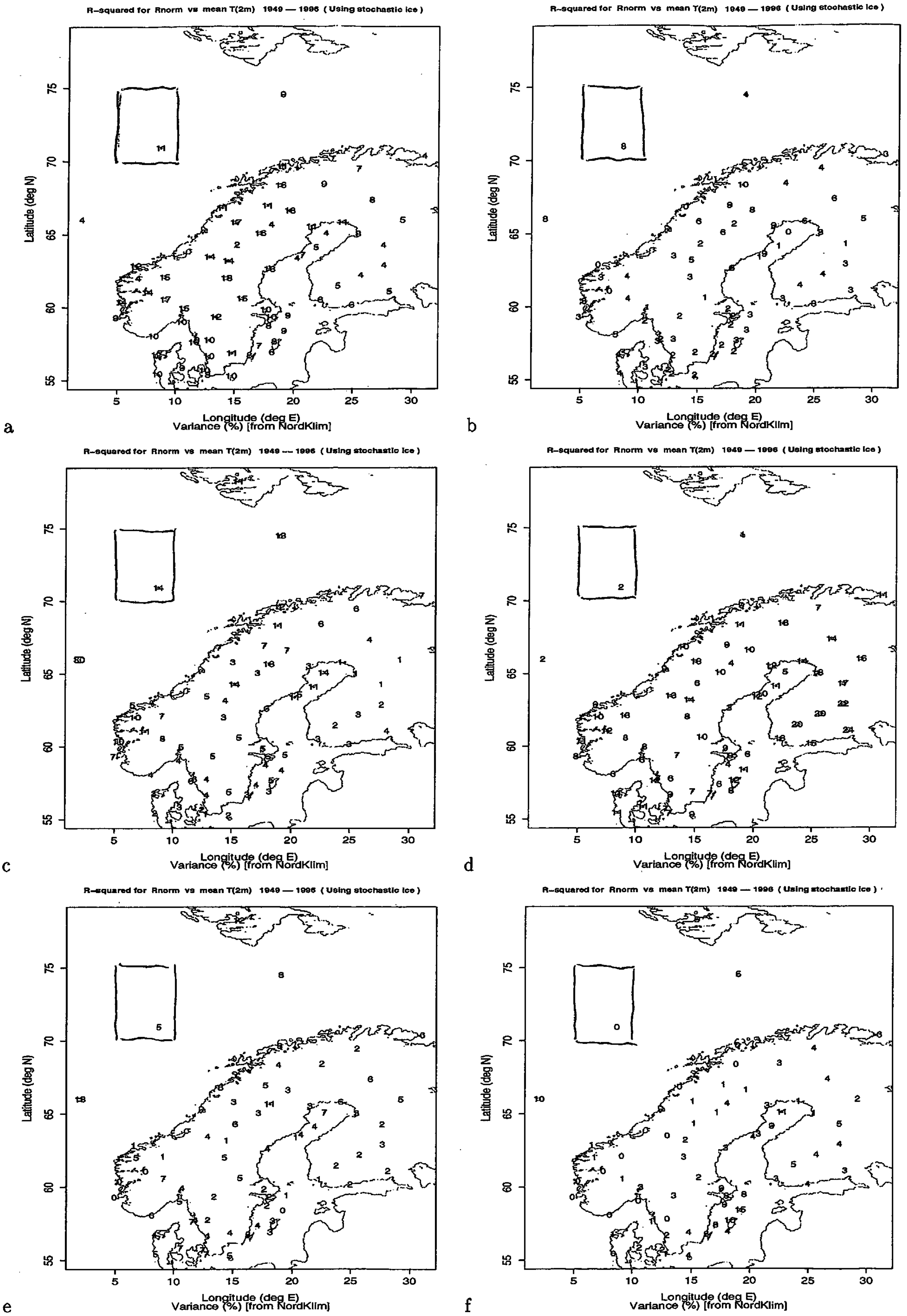
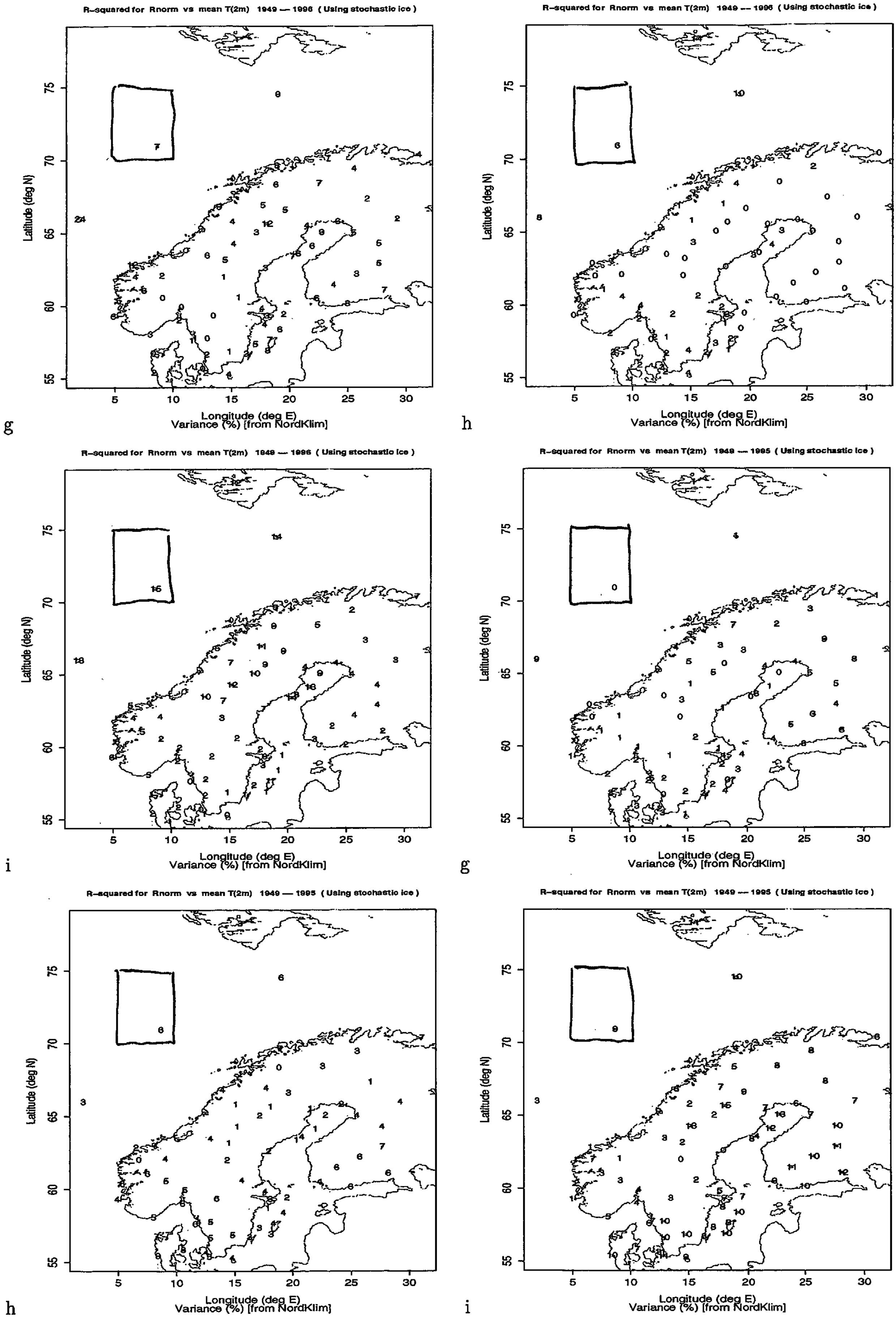


Figure 5. Similar analysis as for Figure 1 but carried out for synthesised (stochastic) data from a random number generator. The analysis is meant to illustrate typical results that can be obtained from random sampling fluctuations and is a poor substitute of an extensive Monte Carlo approach.



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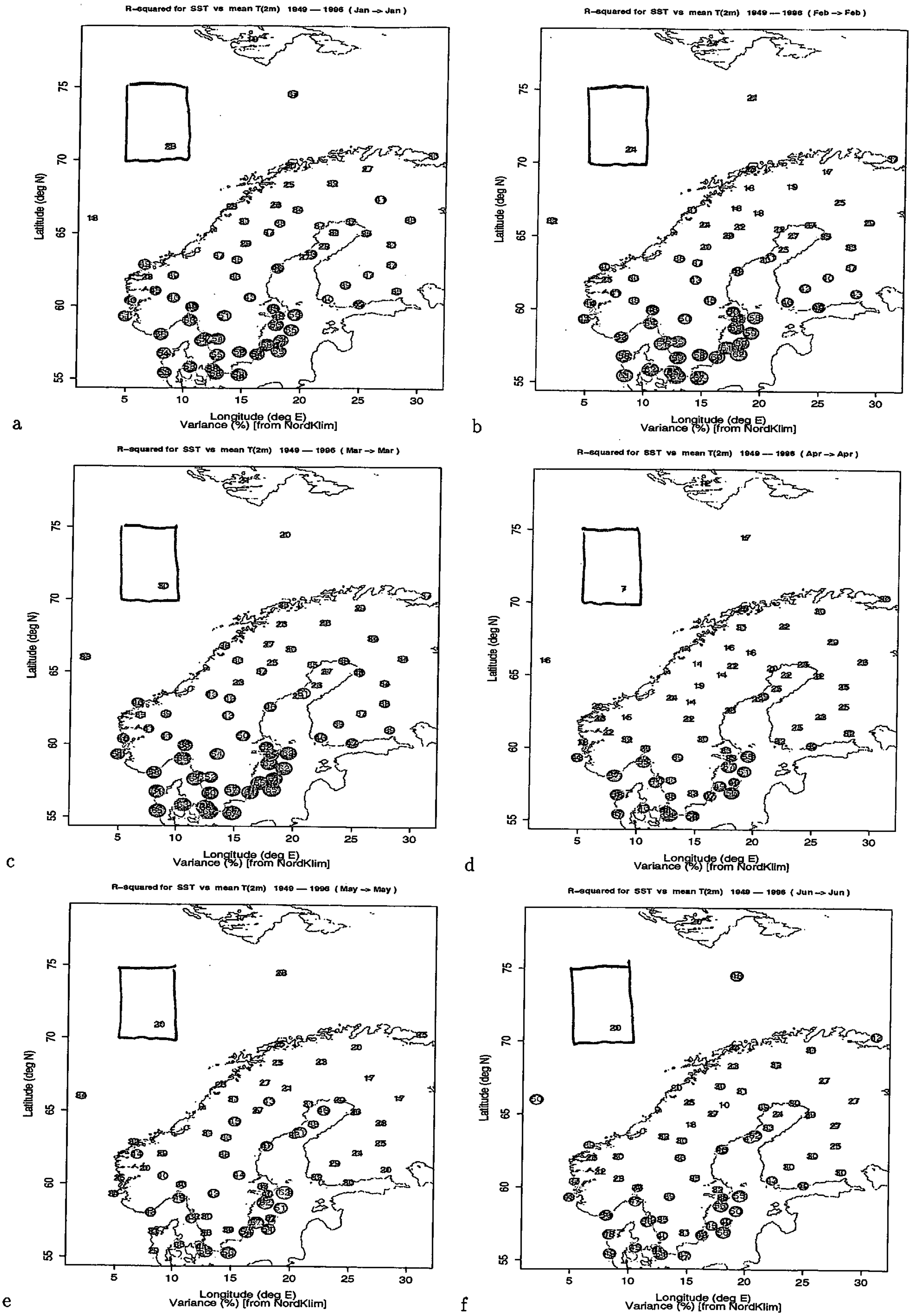


Figure 6. The variance (R^2) of the monthly mean temperature that can be explained by the North Atlantic SST in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

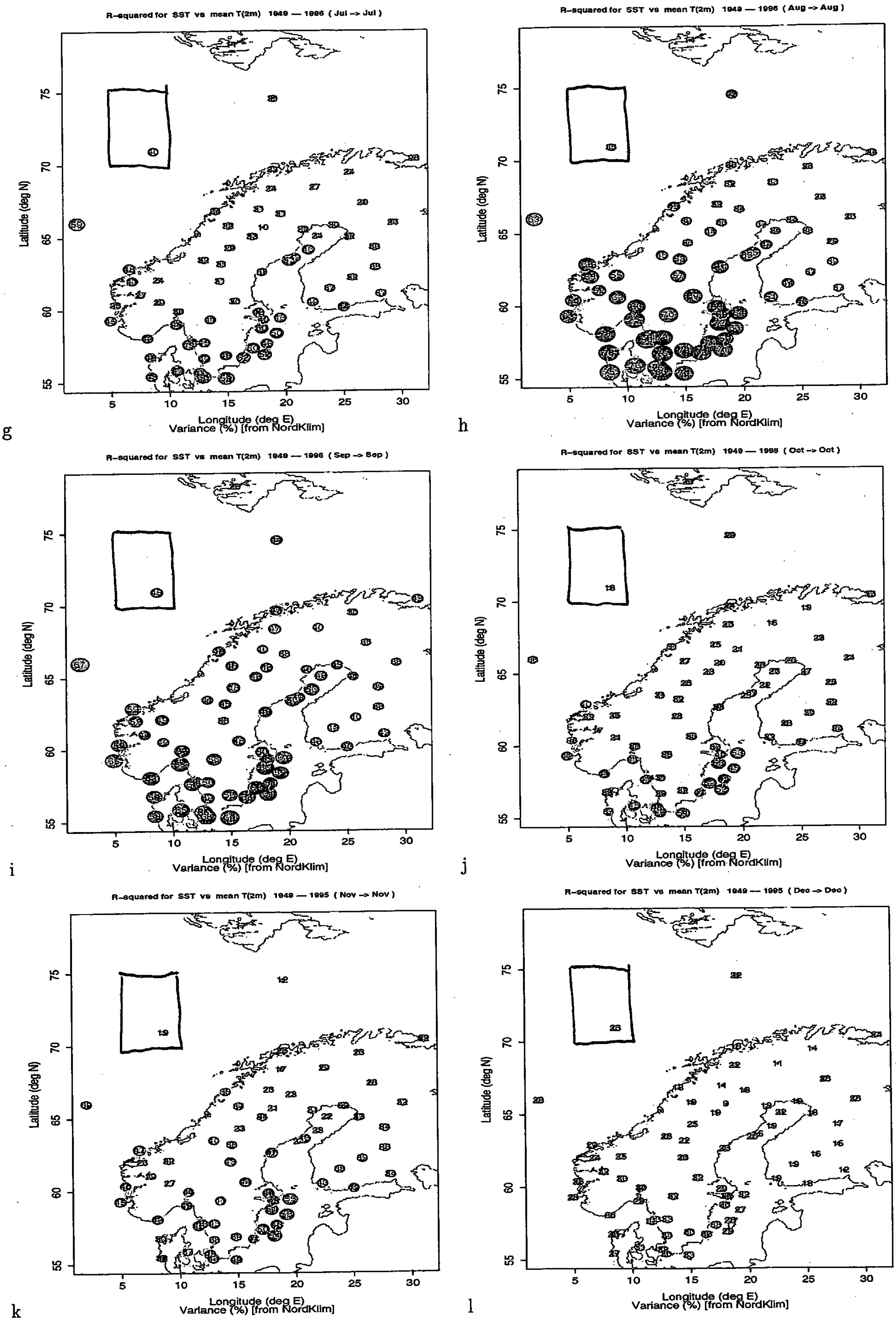


Figure 6. The variance (R^2) of the monthly mean temperature that can be explained by the North Atlantic SST in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

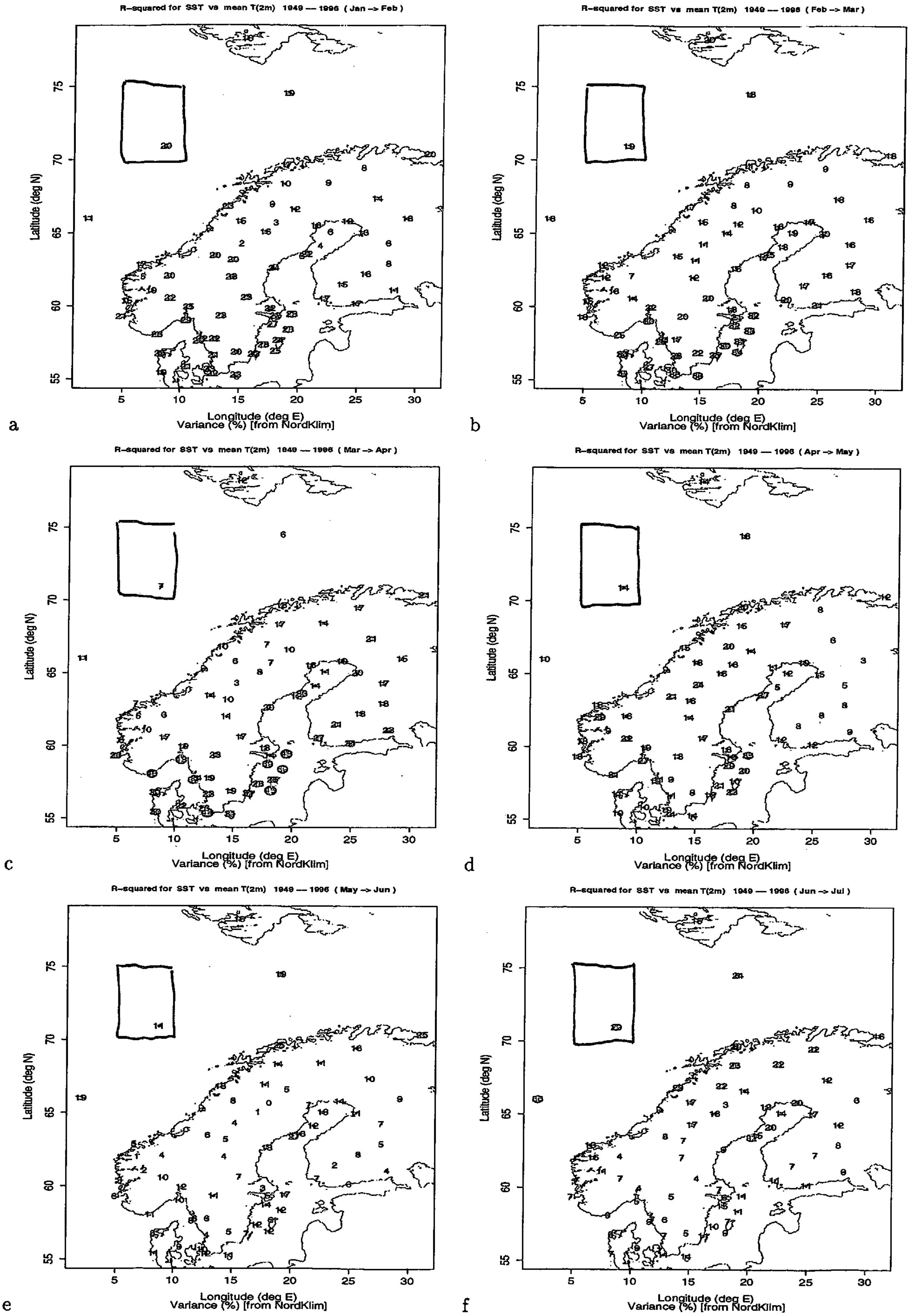


Figure 7. The variance (R^2) in % of the monthly mean temperature that can be explained by the North Atlantic SST with one month's lead time in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

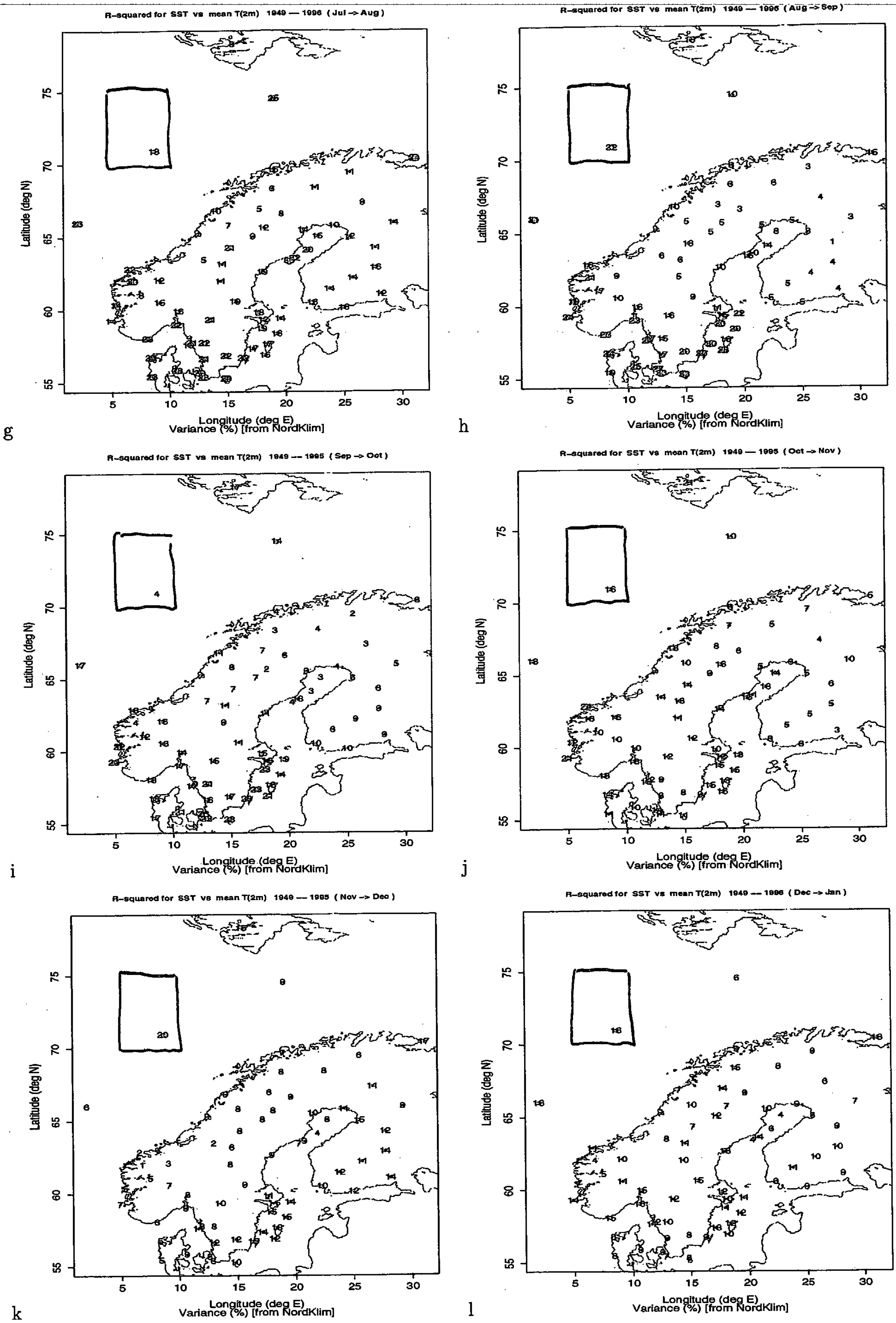


Figure 7. The variance (R^2) in % of the monthly mean temperature that can be explained by the North Atlantic SST with one month's lead time in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

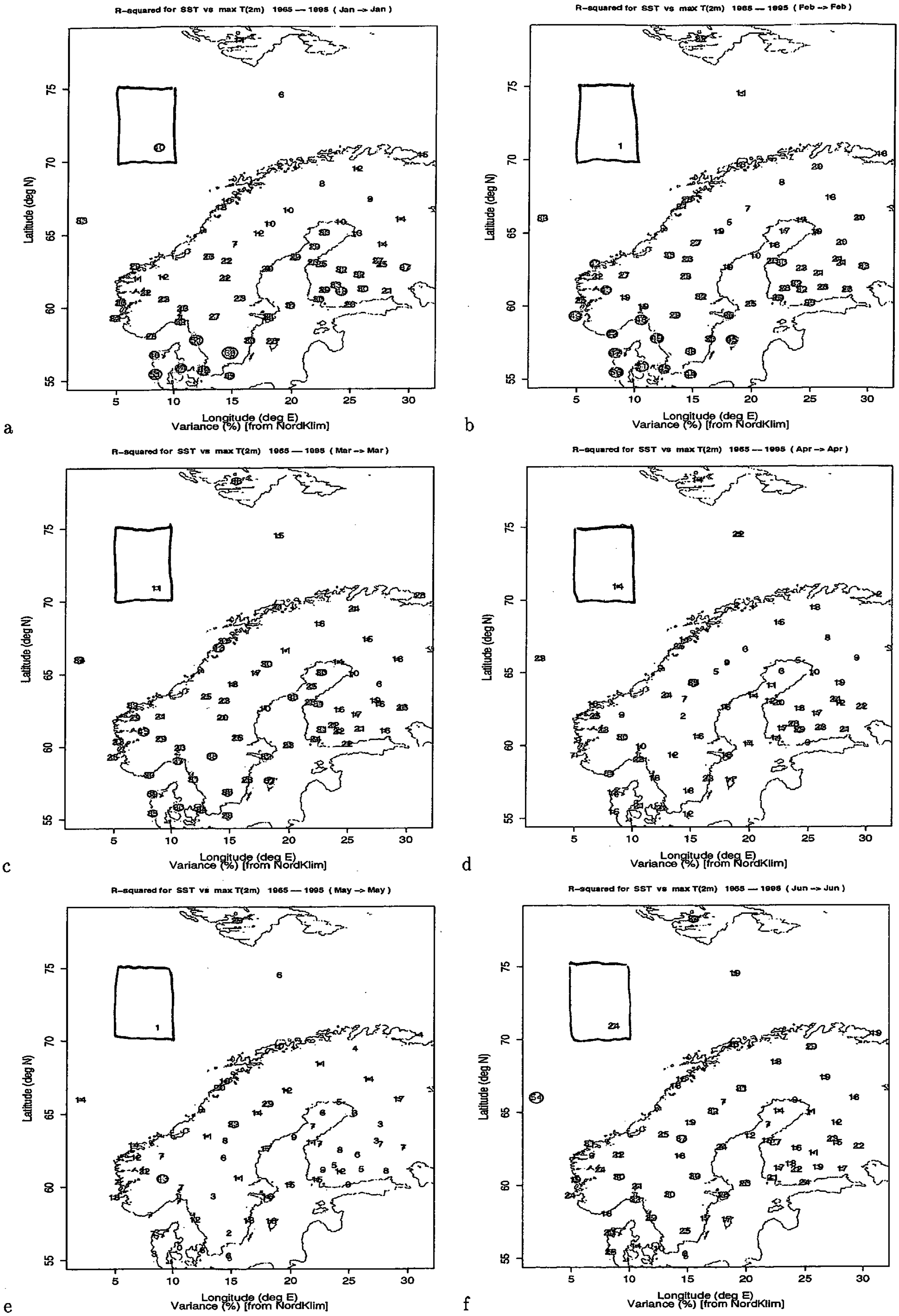
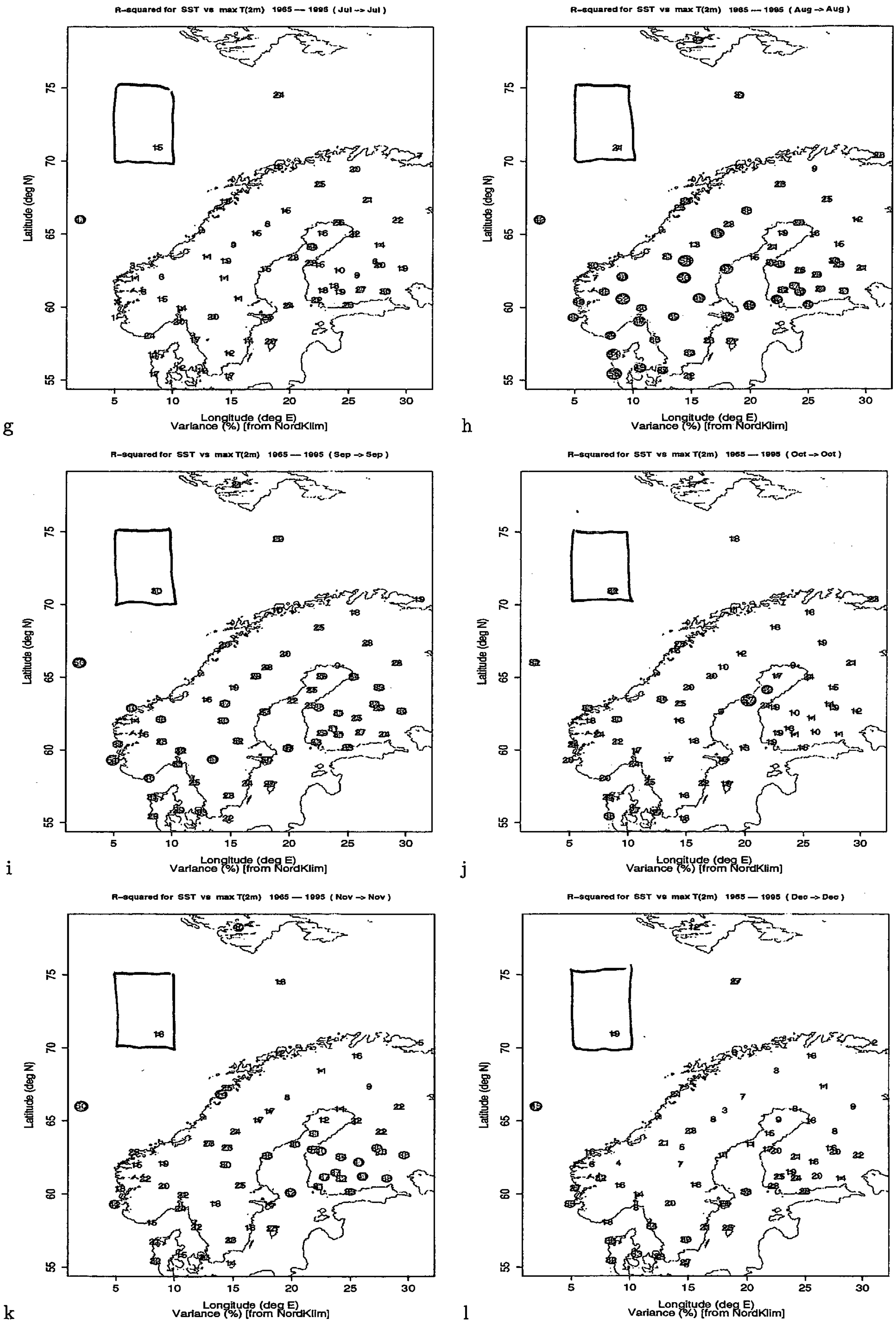


Figure 8. The variance (R^2) of the monthly highest maximum temperature that can be explained by the North Atlantic SST in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).



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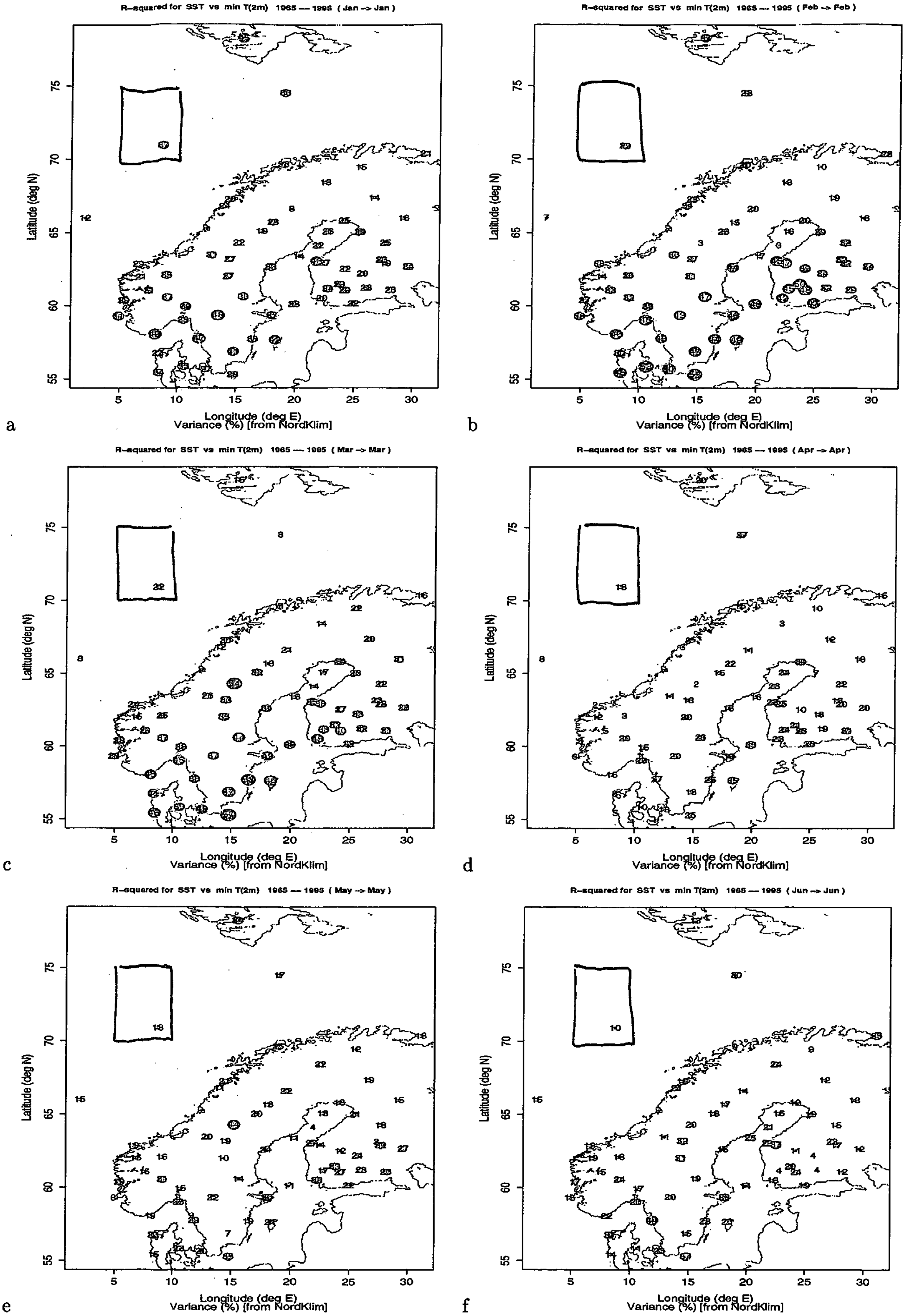

Figure 9. The variance (R^2) in % of the lowest monthly minimum temperature that can be explained by the North Atlantic SST in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

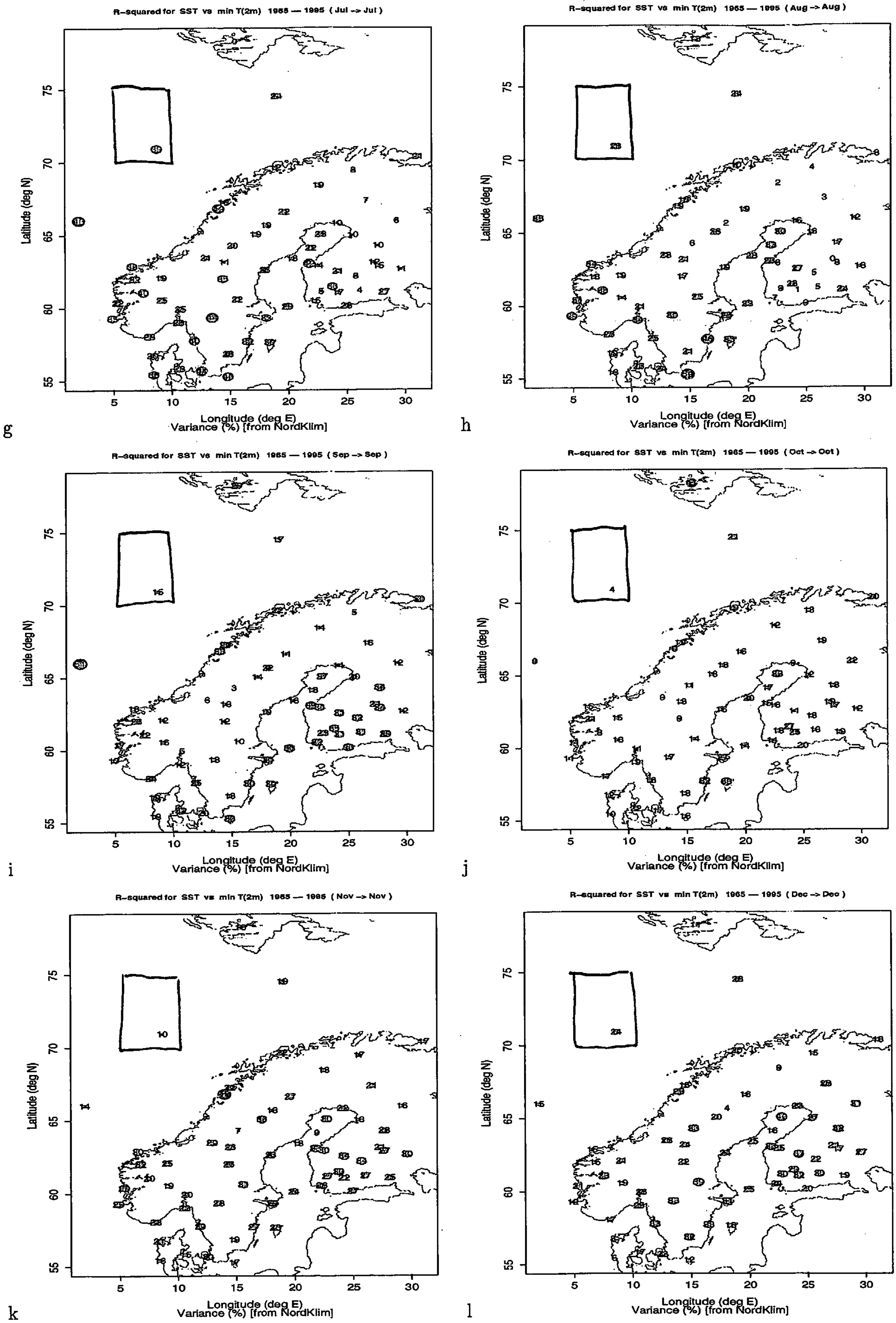

Figure 9. The variance (R^2) in % of the lowest monthly minimum temperature that can be explained by the North Atlantic SST in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

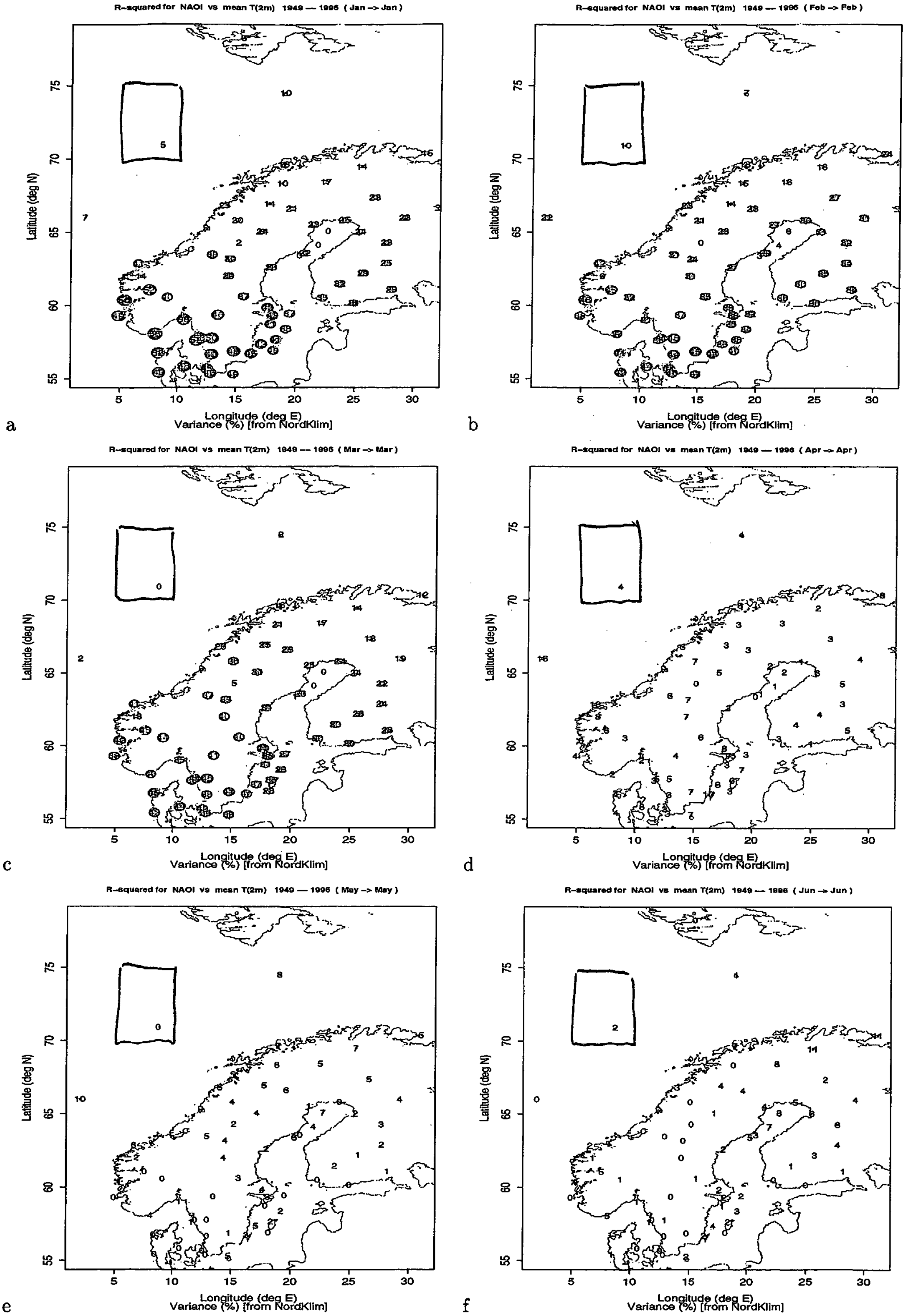

Figure 10. The variance (R^2) of the monthly mean temperature that can be explained by NAOI in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

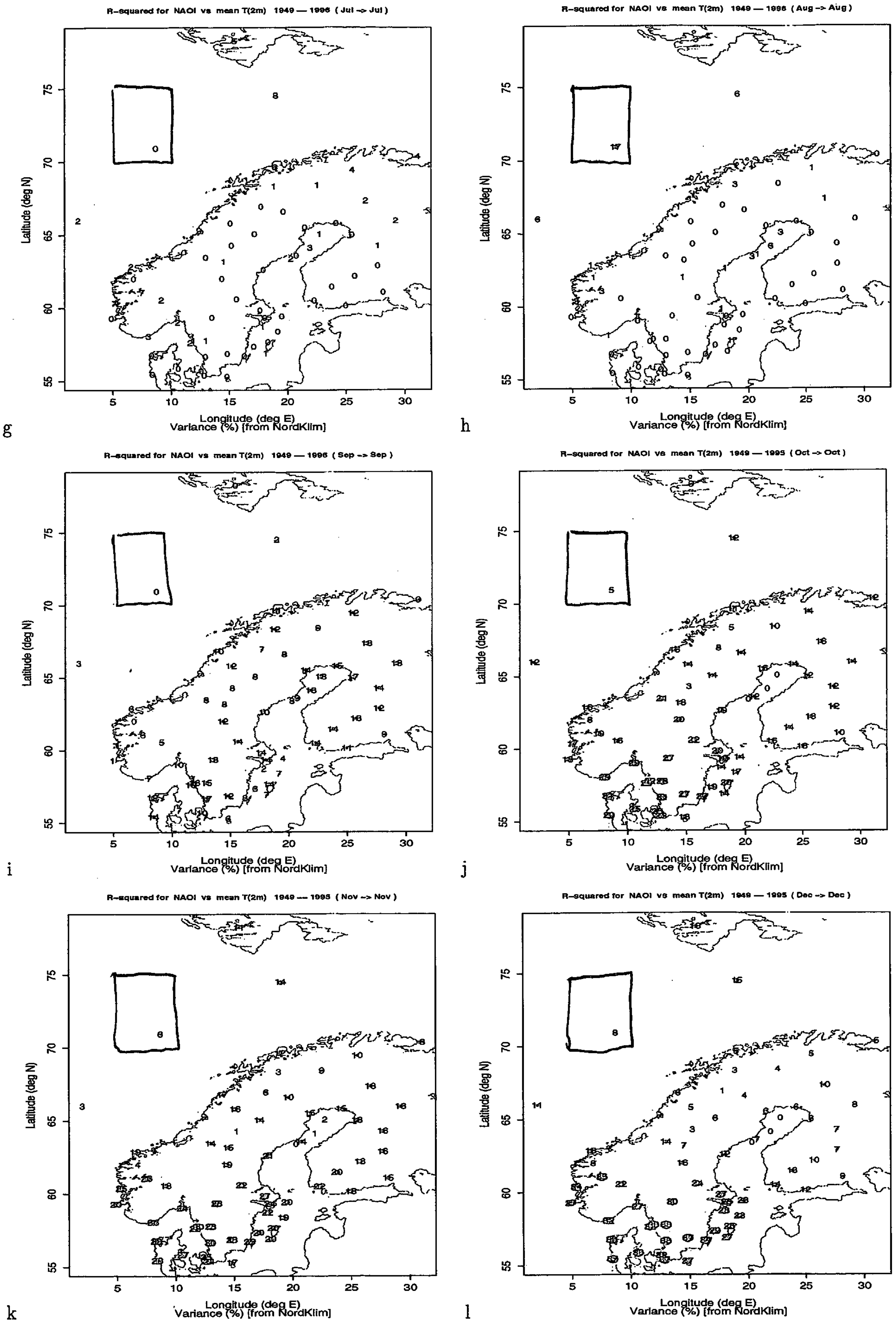

Figure 10. The variance (R^2) of the monthly mean temperature that can be explained by NAOI in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

connection between the NAO and the north European temperatures. There is a clear difference in the autumn–winter months (October–March) and the spring–summer (April–September) months where the NAO association is pronounced for the former, but there is no association between the NAO and the spring- to summer-time temperatures.

3.4 The Gulf Stream and land temperature

Figure 11 shows the results of a similar analysis to that applied to the NAOI and station temperature (Figure 10) but now carried out on the GSNW index and the station temperatures. The analysis suggests that little, if any, of the temperature variations in the Nordic countries can be attributed to the latitudinal excursions of the Gulf Stream in the western North Atlantic. The exception may possibly be for December, for which the R^2 estimates are considered high ($R^2 \sim 30\%$). The interesting question is whether these are just coincidental (problem of multiplicity) or whether there really is a physical link between the latitudinal excursions of the Gulf Stream and the temperature in December. A comparison with the stochastic results in Figure 3.1 points to statistical fluctuation as the explanation for the higher December values. The one-month-lagged analysis (not shown) did not produce any convincing evidence of any lagged relationships between the GSNW index and the temperatures. Thus, there seems to be no link between the GSNW index (latitudinal excursions of the Gulf Stream extension in the western part of the North Atlantic) and the temperature in the Nordic countries.

3.5 ENSO and land temperature

The relationship between ENSO and the monthly mean temperature in the Nordic countries was explored through an analysis similar to that for the NAOI and the GSNW index (Figure 12). The results suggests that ENSO has no effect on the temperature in the Nordic counties. The same conclusion can be made for the one-month-lagged temperature (not shown).

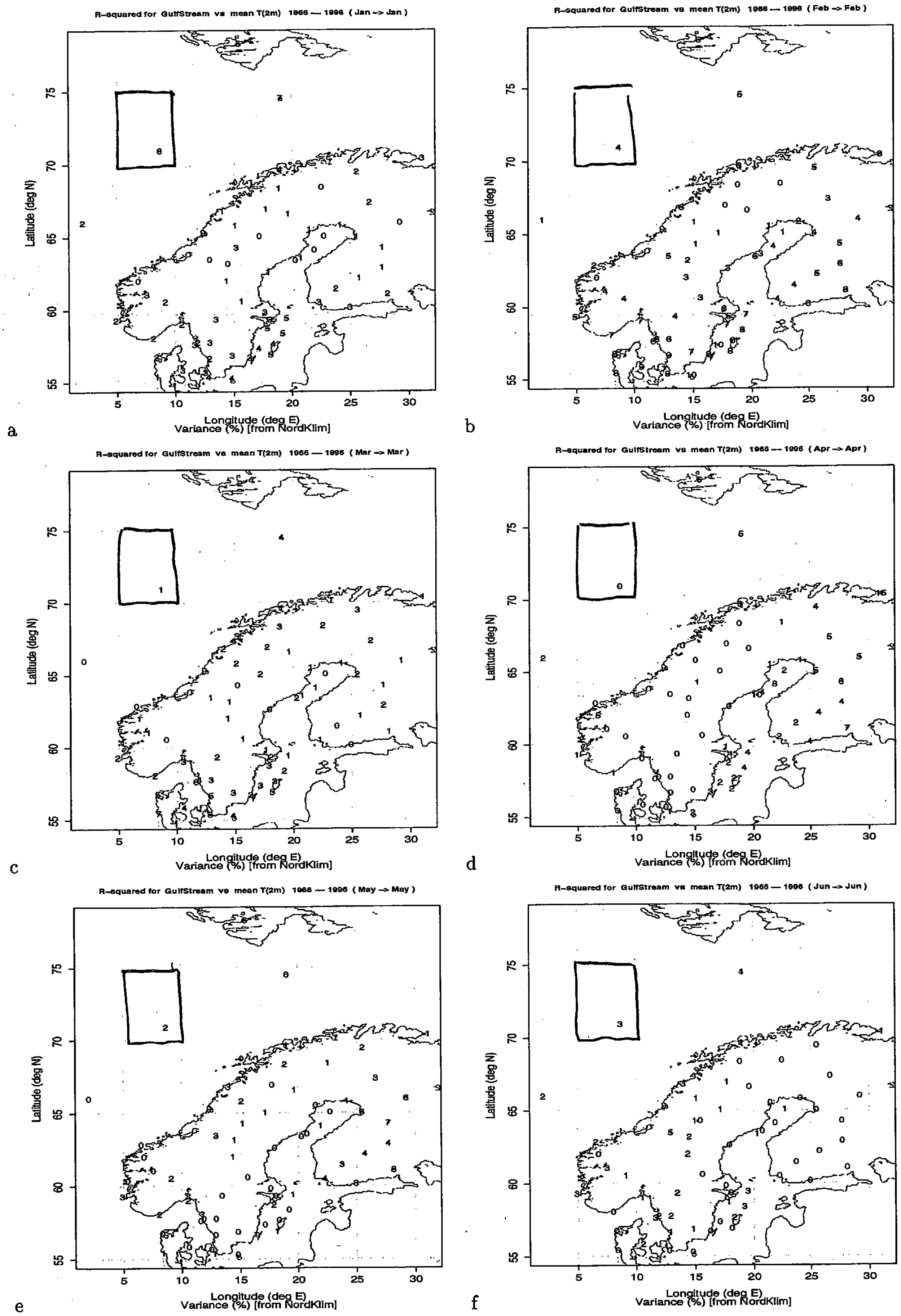

Figure 11. The variance (R^2) in % of the monthly mean temperature that can be explained by the GSNW index in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

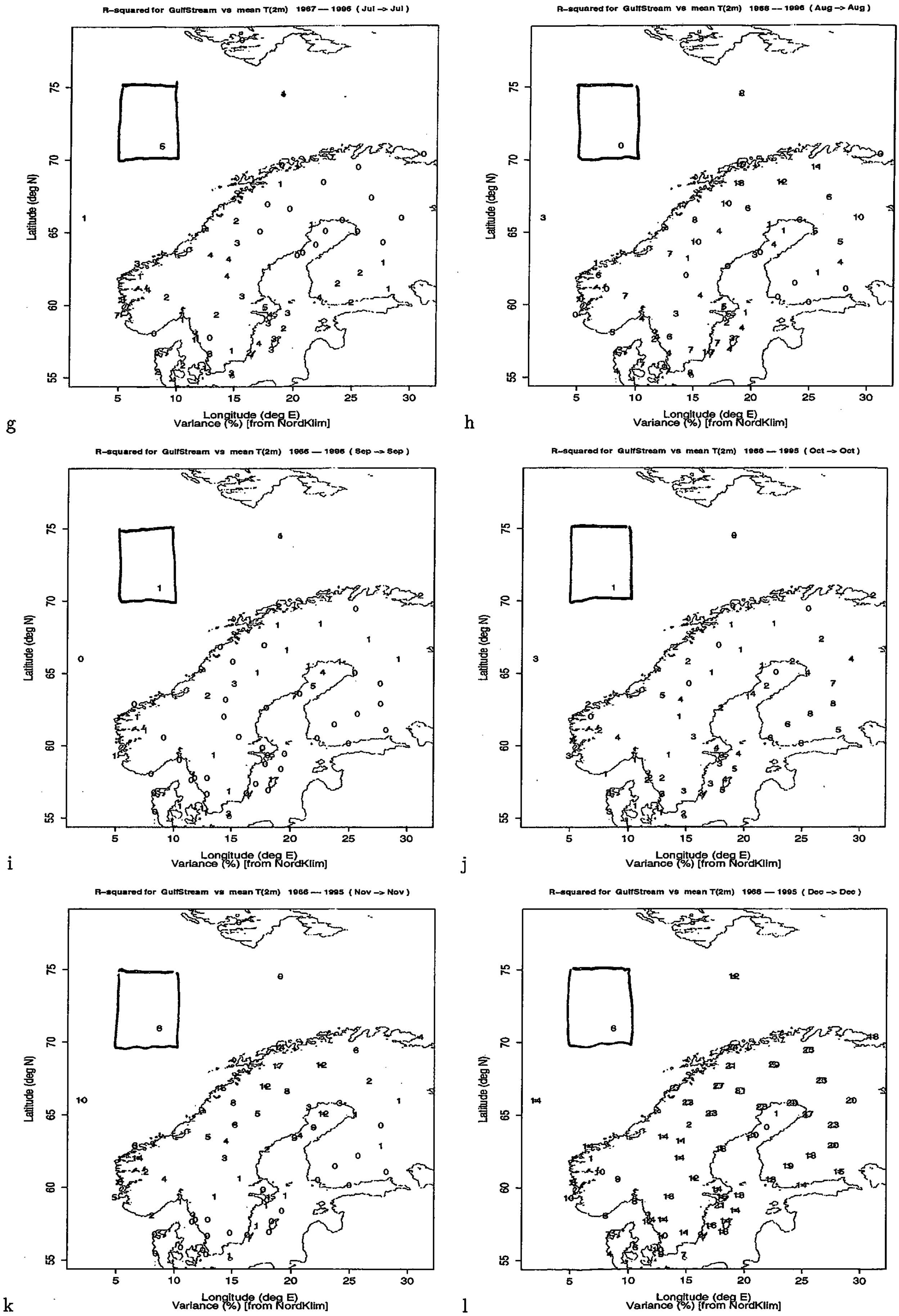

Figure 11. The variance (R^2) in % of the monthly mean temperature that can be explained by the GSNW index in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

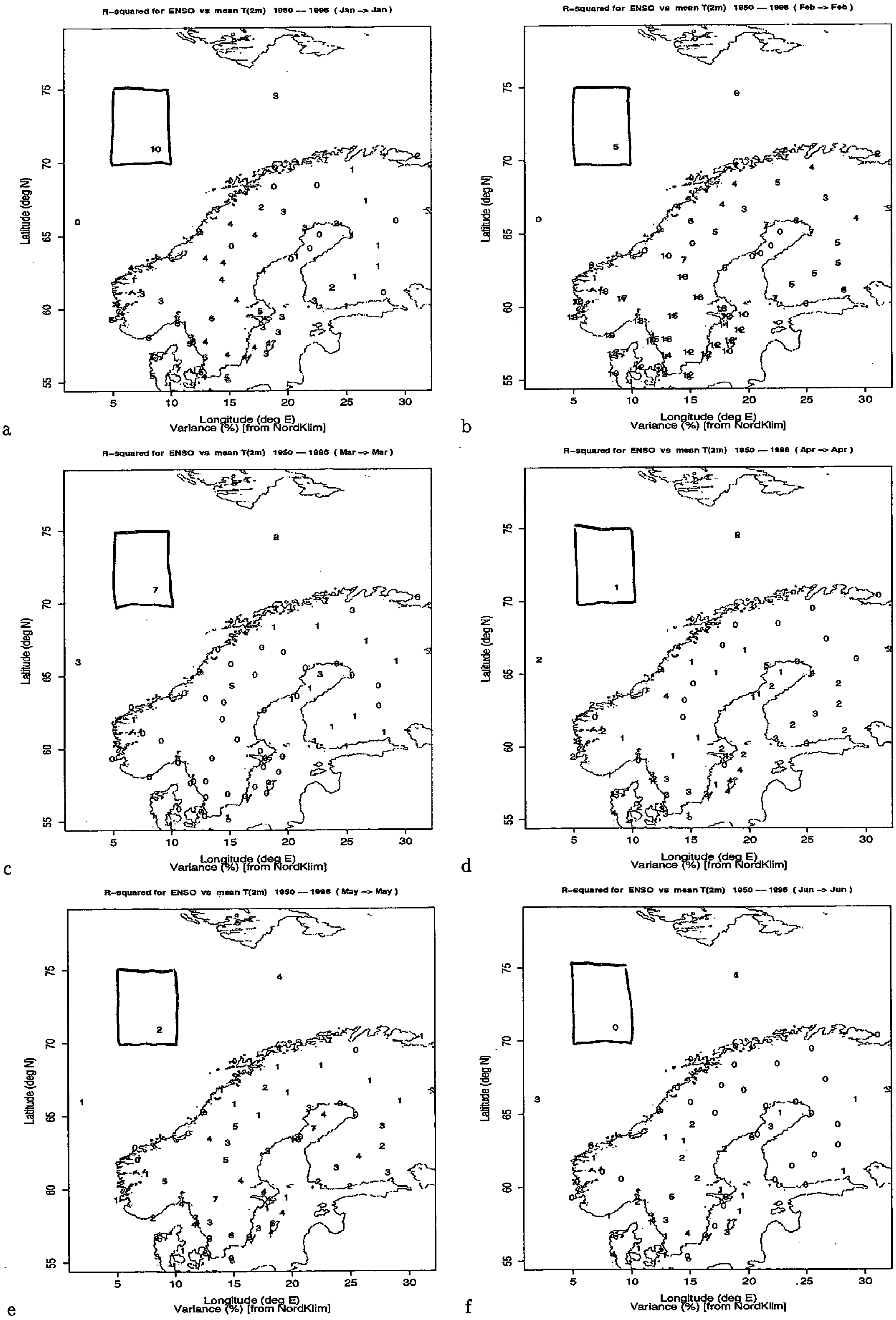

Figure 12. The variance (R^2) in % of the monthly mean temperature that can be explained by NINO3 in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

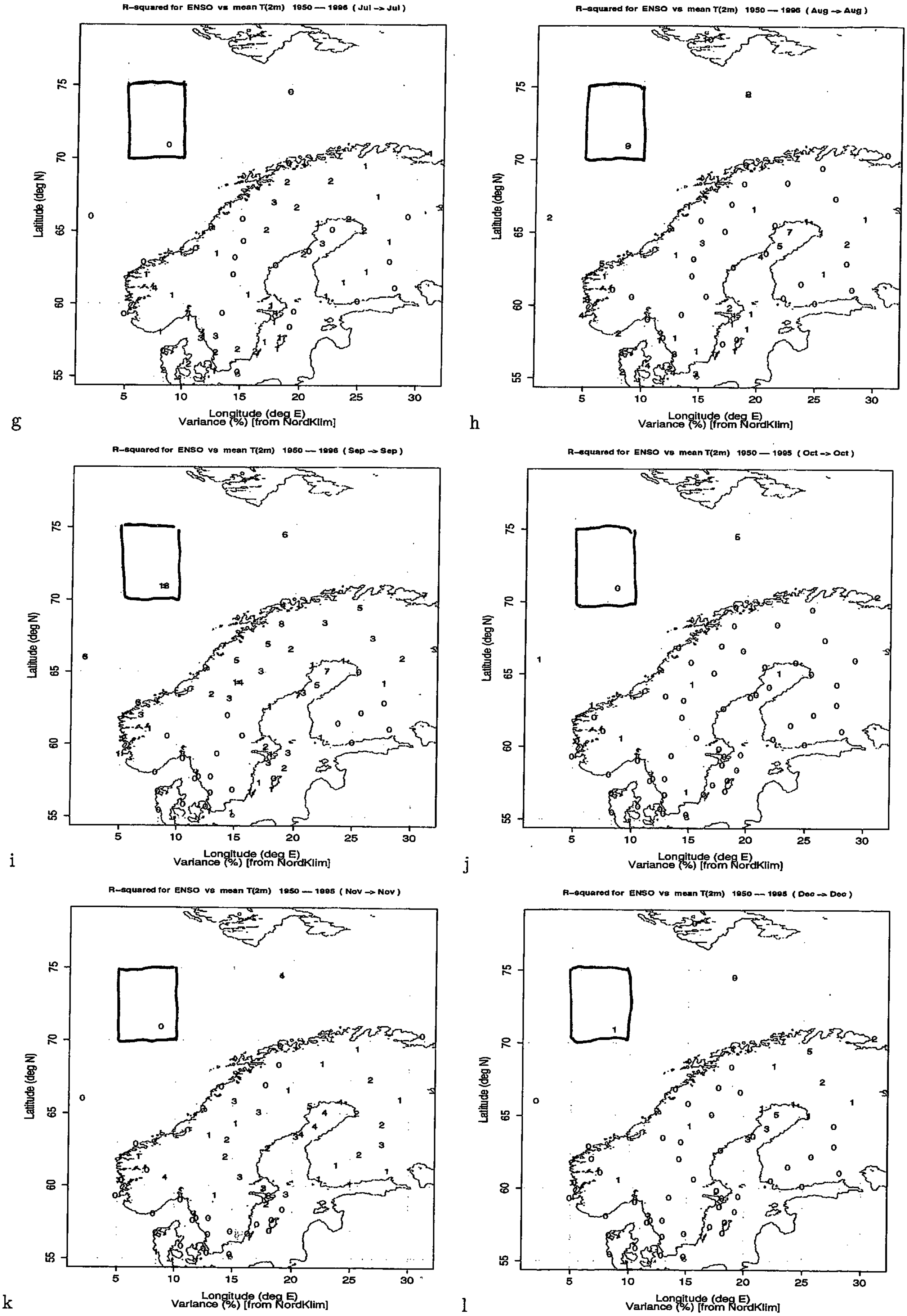

Figure 12. The variance (R^2) in % of the monthly mean temperature that can be explained by NINO3 in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

3.6 Sea-ice and precipitation

Figure 13 shows the results of an analysis in a similar way as in Figure 1, but for precipitation instead of temperature. The results indicate that the sea-ice has some ($R^2 \sim 20-40\%$) influence on the precipitation during winter, spring and autumn. The link appears to be most pronounced in the southern part of Fennoscandia.

The sea-ice cover also seems to have a weak influence on the following month's precipitation both during late winter and autumn (Figure 14). The R^2 estimates are 10 – 30%, and the relationship is strongest in late winter and spring.

3.7 SST and precipitation

There is a robust relationship between the North Atlantic SSTs and the precipitation during winter and late summer (Figure 15). The geographical pattern of R^2 values bears some similarities to the results obtained using the monthly mean NAOI (Figure 17). A couple of interesting observations can be made regarding the comparison with the results obtained with the NAOI: (i) high values of R^2 appear to be more (geographically) wide-spread for the SST link during winter; (ii) there is substantially stronger SST than NAO signal in the monthly rainfall during summer. Although the NAO involves both circulation shifts (SLP variations) and SST anomalies, it appears that the SST contain information which is not embodied in the NAO.

It is interesting to focus on the November rainfall around Oslo and compare the R^2 value of 11% with the results of *Benestad & Melsom* (2002), who argued that there is a definite link between the North Atlantic SST and that the extreme November 2000 rainfall (564 mm at Bjørnholt, just north of Oslo city) could partly be explained by unusually strong SST anomalies in the western North Atlantic. *Benestad & Melsom* (2002) reported R^2 in the range 22 – 46%, depending on the geographical region of SST and time interval (1900–2000 and 1883–1999). The results obtained here are lower than the results in *Benestad & Melsom* (2002), partly because a different time interval was used here (1928–1990) and partly because this study also incorporated a cross-validation analysis in addition to the step wise regression. In both cases, however, the results suggests there indeed is a relationship between the North Atlantic SSTs and the rainfall around Oslo.

The mean value of all R^2 estimates between precipitation and SST is 0.123 where (for the two domains 90°W– 40°E [the "North Atlantic" domain], 40°N – 75°N and 20°W– 40°E, 50°N – 75°N [the "Nordic Seas" domain]) and the corresponding value for the NAOI-based analysis is 0.0563. The difference between these two values is statistically significant at the 0.0% level (paired t-test between the results from the North Atlantic domain and the NAOI p-value $=< 2.2 \times 10^{-16}$).

The one-month-lagged analysis suggests a weak connection between the North Atlantic SSTs and the following month's precipitation, which is most pronounced for the February – March precipitation and the June–August rainfall. A comparison with Figure 3.1 suggests that the link between SSTs at one month's lead time and the precipitation is real, but marginal.

3.8 NAO and precipitation

The R^2 estimates indicate a prominent ($R^2 \sim 40\%$) and robust relationship between the NAOI and the precipitation along the western coast of Norway and southern Sweden (Figure 17). The link between the NAO and the precipitation is strongest during winter, and is seen for the west coast of Norway throughout the year. The analysis suggests that the NAO has little impact on the precipitation over Finland and the eastern part of Fennoscandia. This pattern is consistent with the well-known relationship between the NAO and the rainfall pattern over Europe.

3.9 The Gulf Stream and precipitation

The strength of the relationship between the GSNW index and the precipitation in the Nordic countries is shown in Figure 18. The analysis does not point to a convincing link, perhaps with the exception southwestern Sweden and southeastern Norway in November, January and February and the Stockholm-Gotland region in June–August and November. However, R^2 values $\sim 20\%$ may also arise from statistical fluctuations.

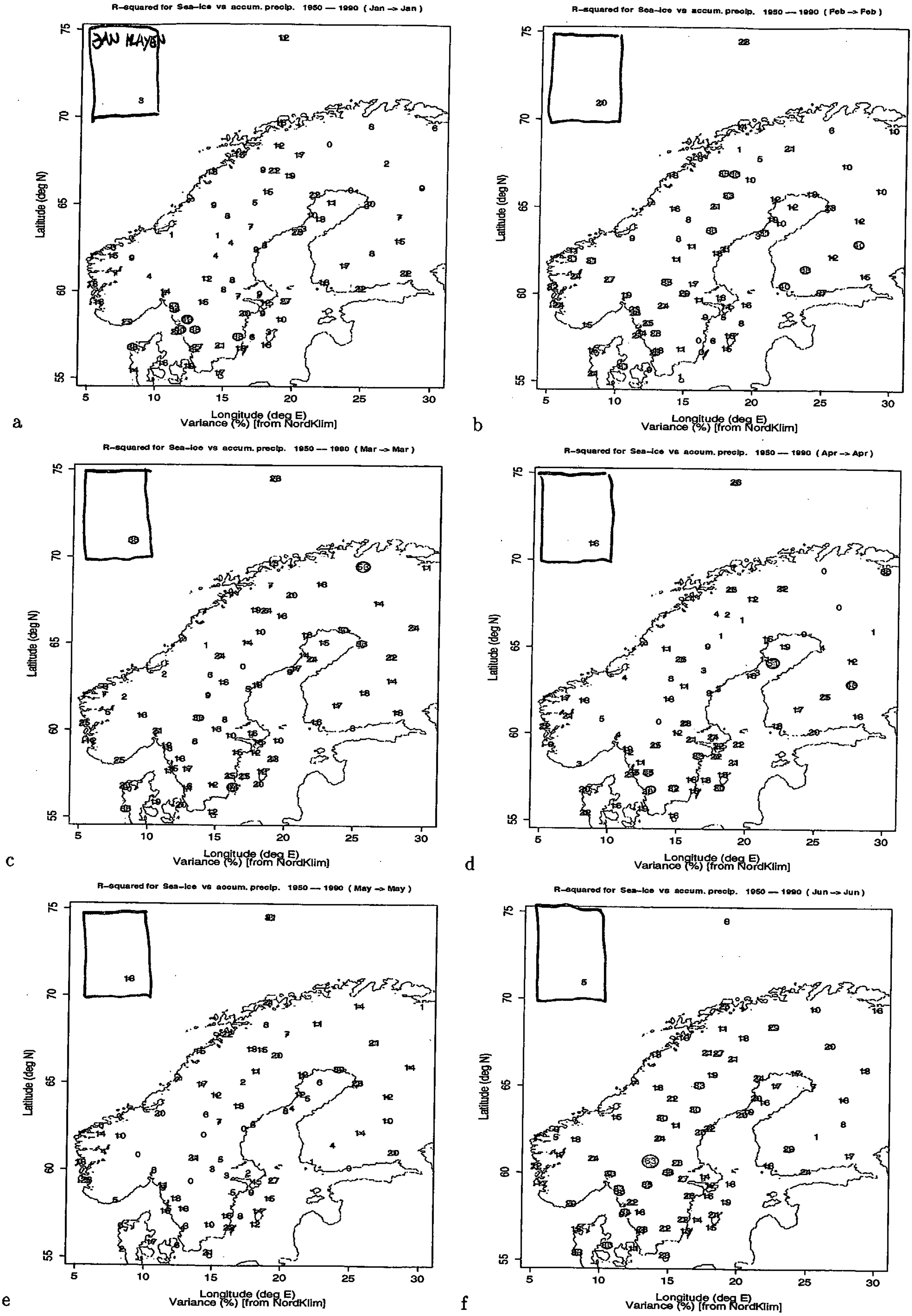

Figure 13. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the sea-ice in the GIN Sea in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

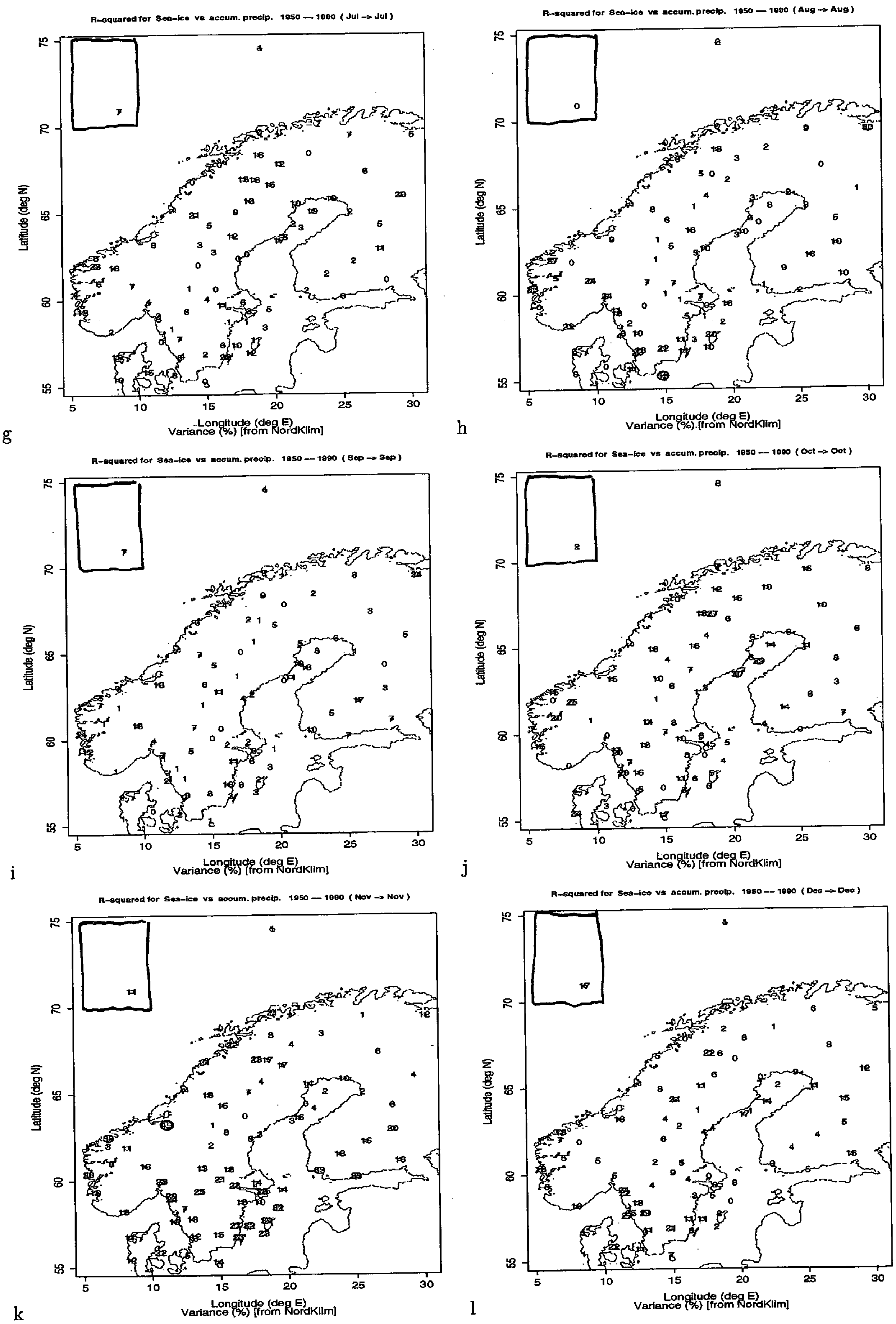

Figure 13. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the sea-ice in the GIN Sea in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

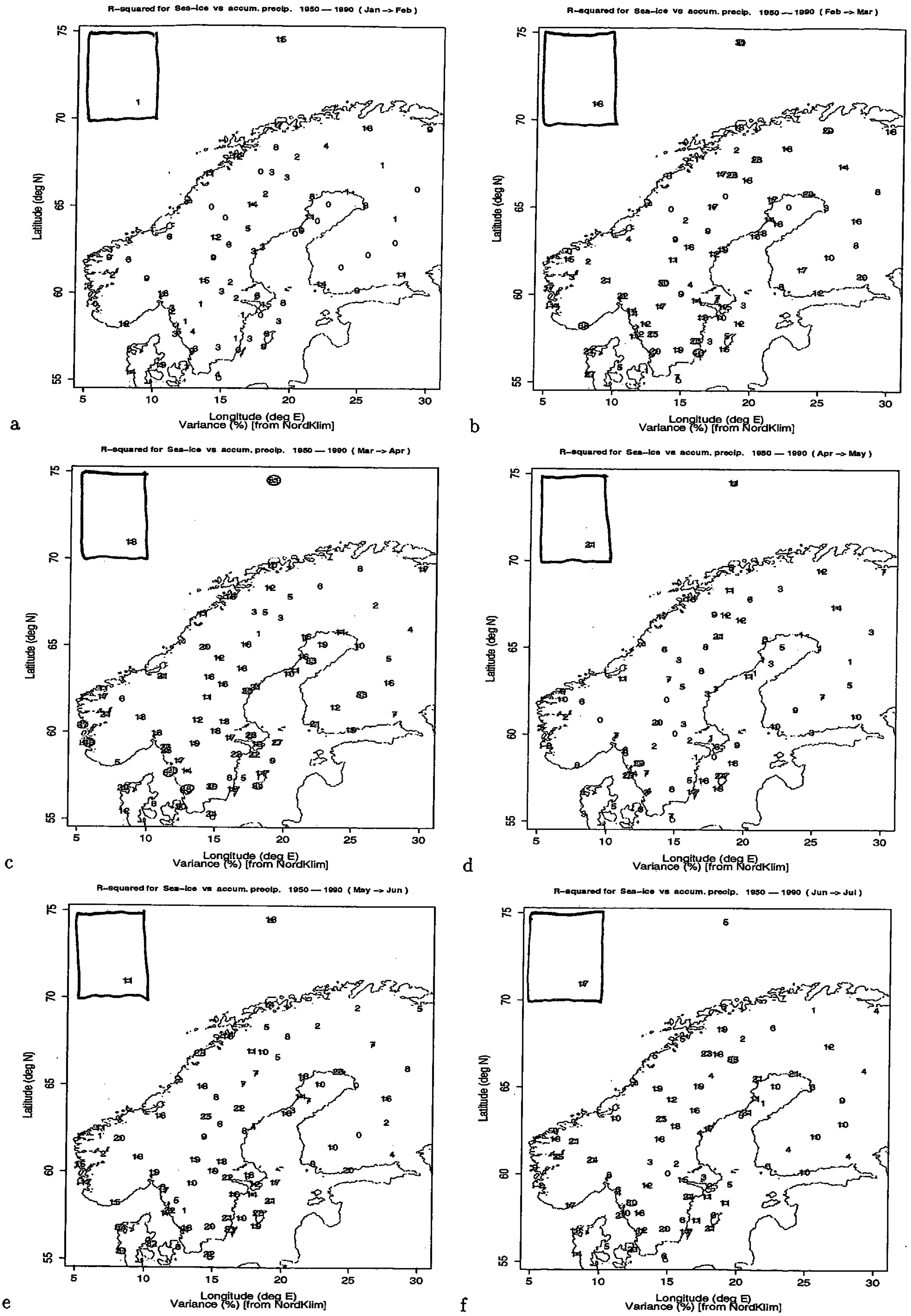

Figure 14. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the January sea-ice at one month's lead time in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

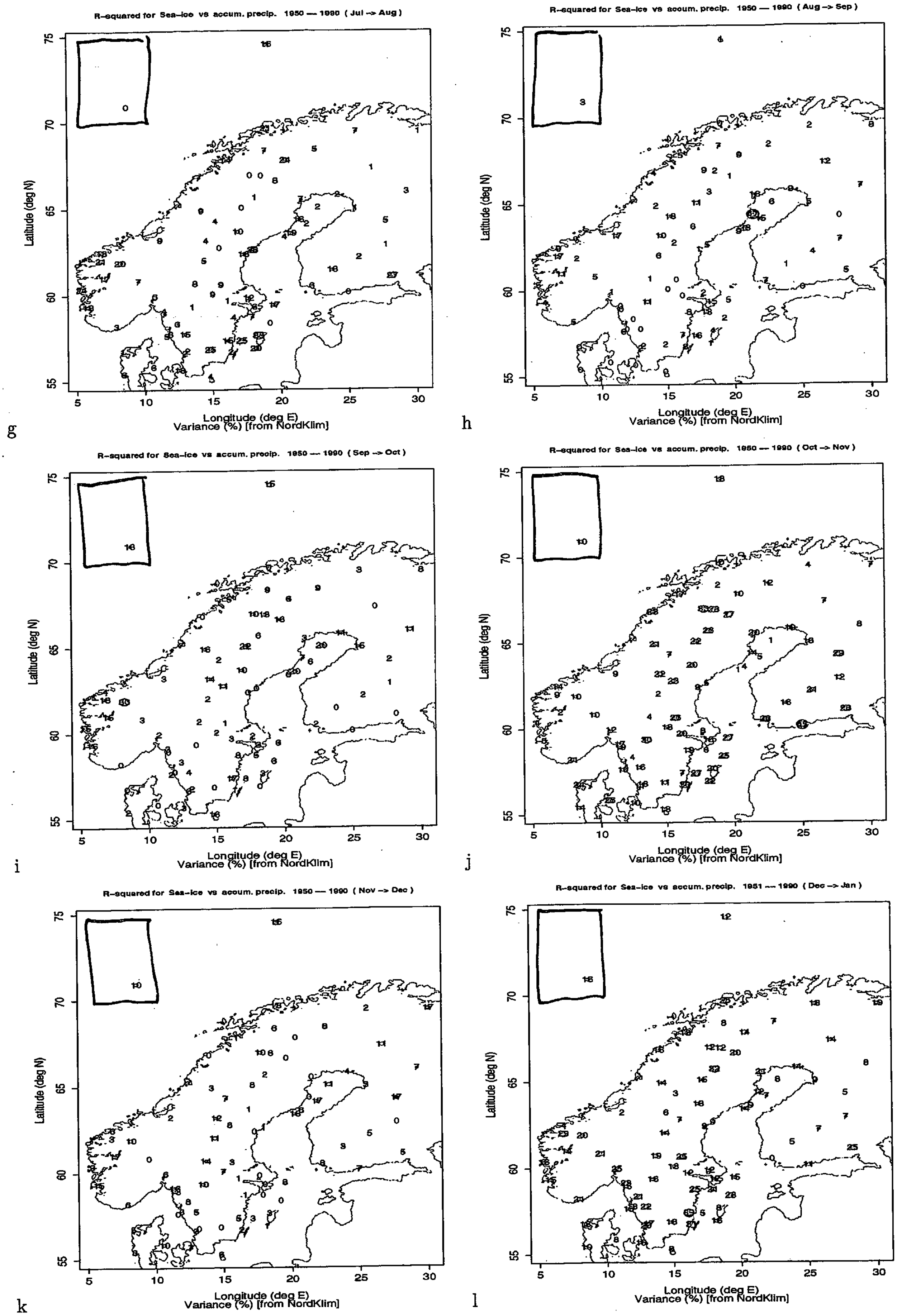

Figure 14. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the January sea-ice at one month's lead time in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

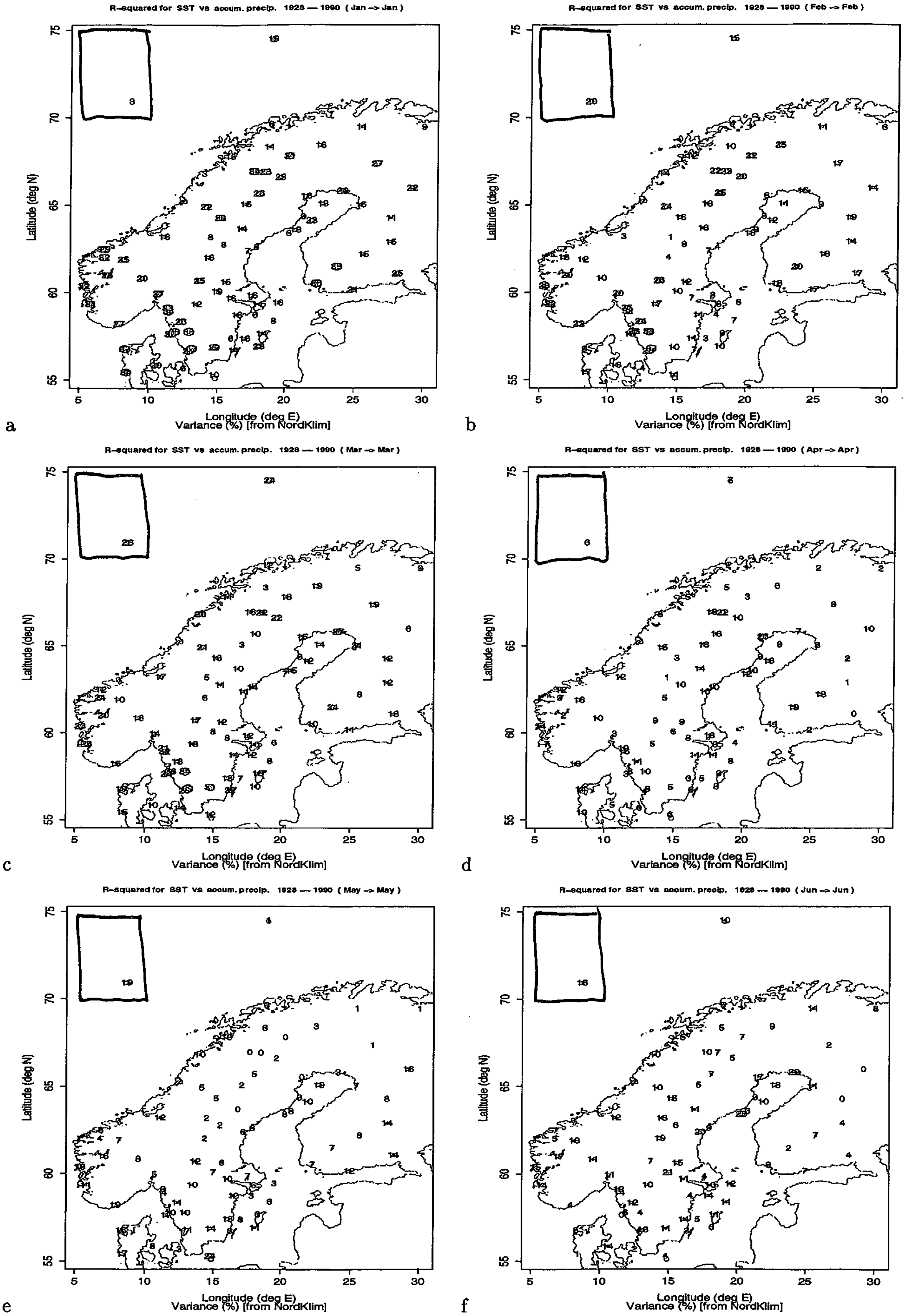

Figure 15. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the North Atlantic SST in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

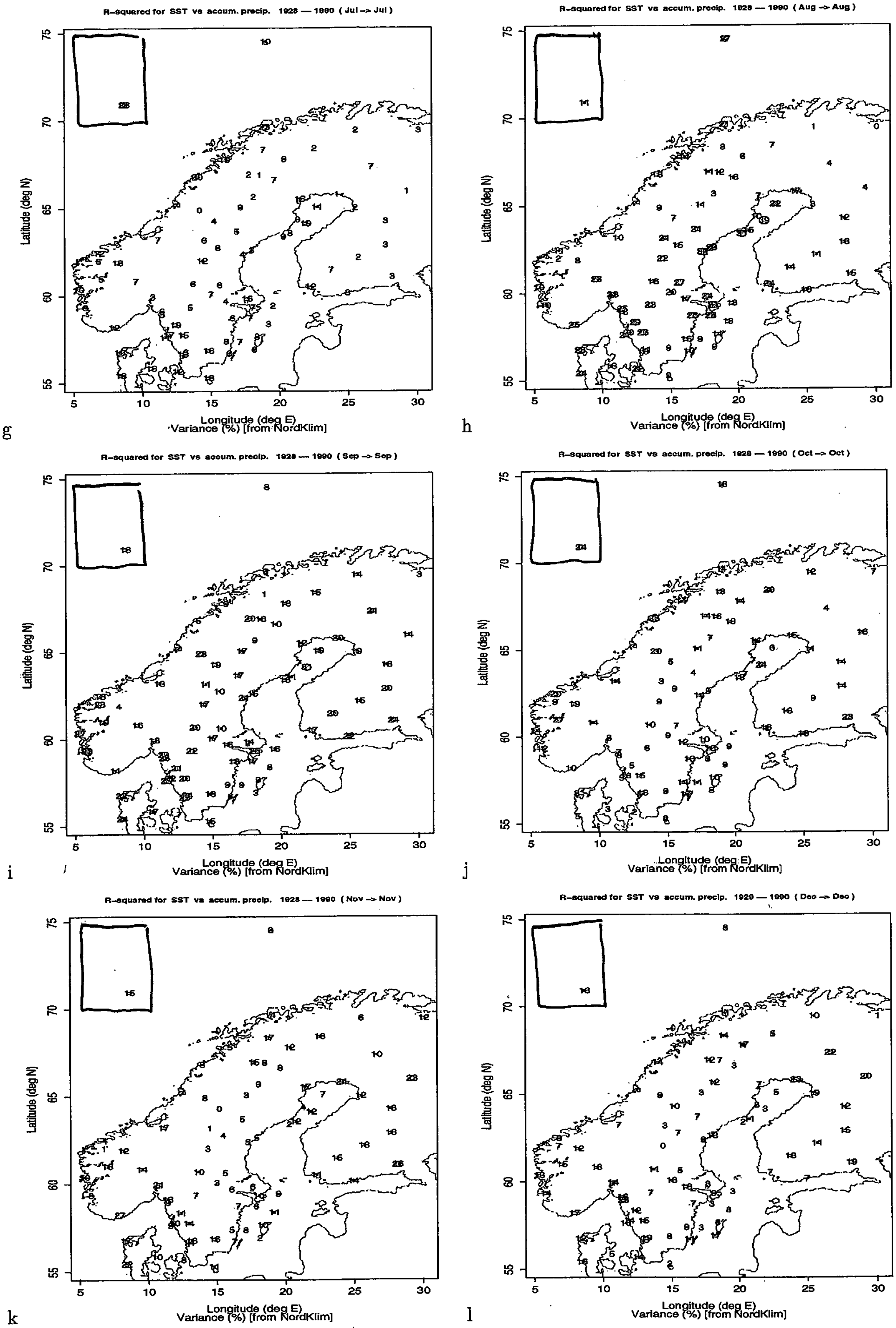

Figure 15. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the North Atlantic SST in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

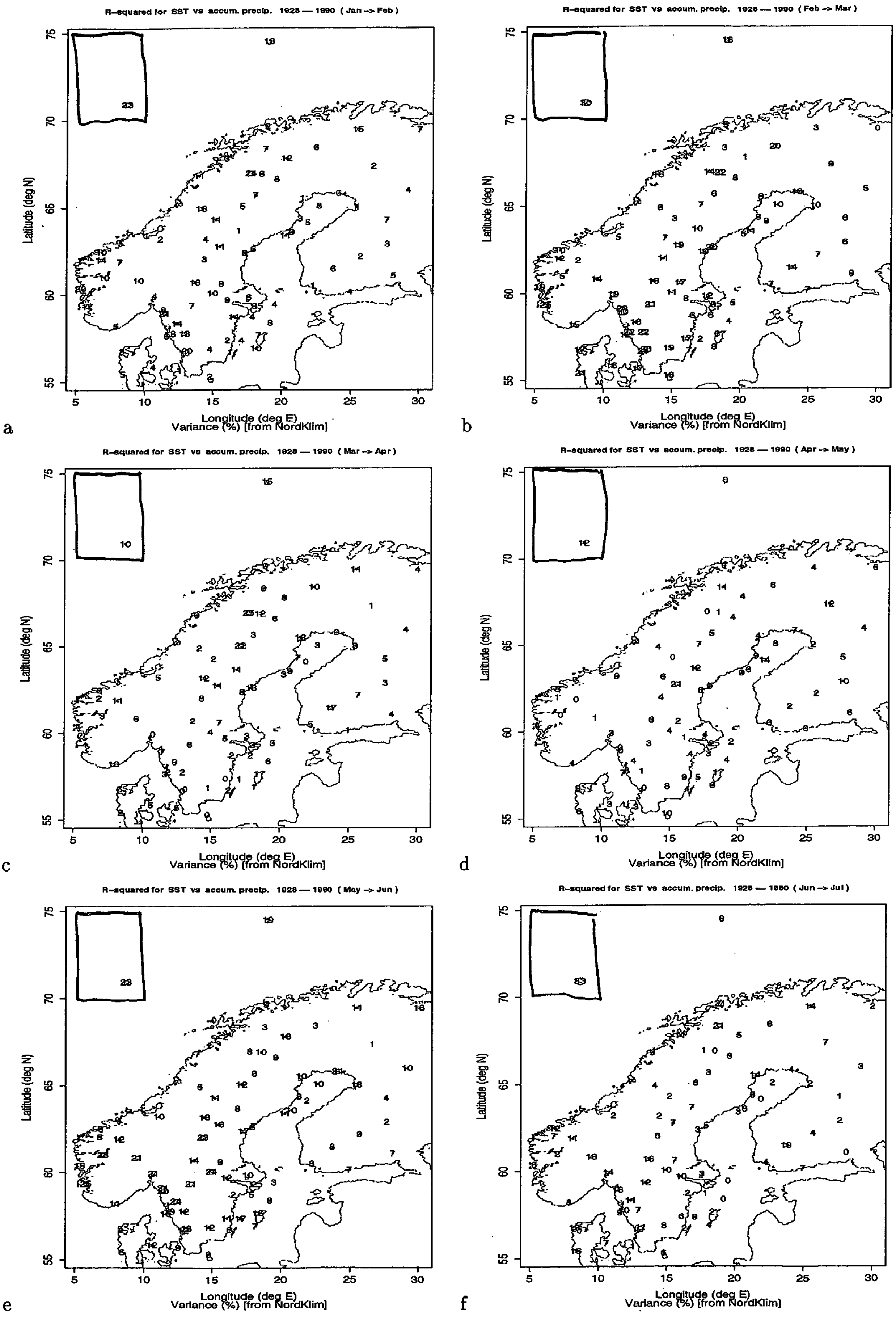

Figure 16. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the North Atlantic SST with one month's lead time in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

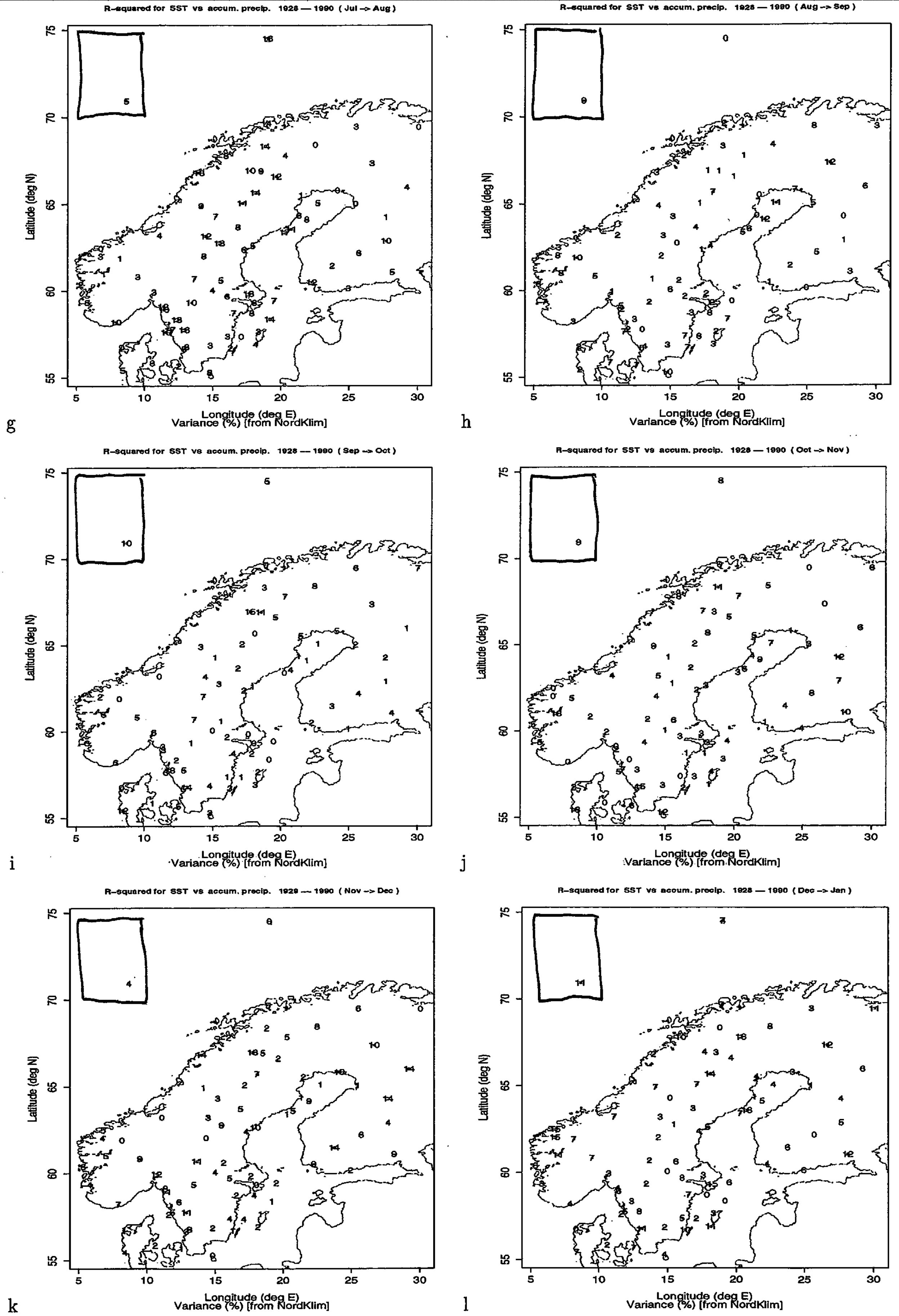

Figure 16. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by the North Atlantic SST with one month's lead time in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

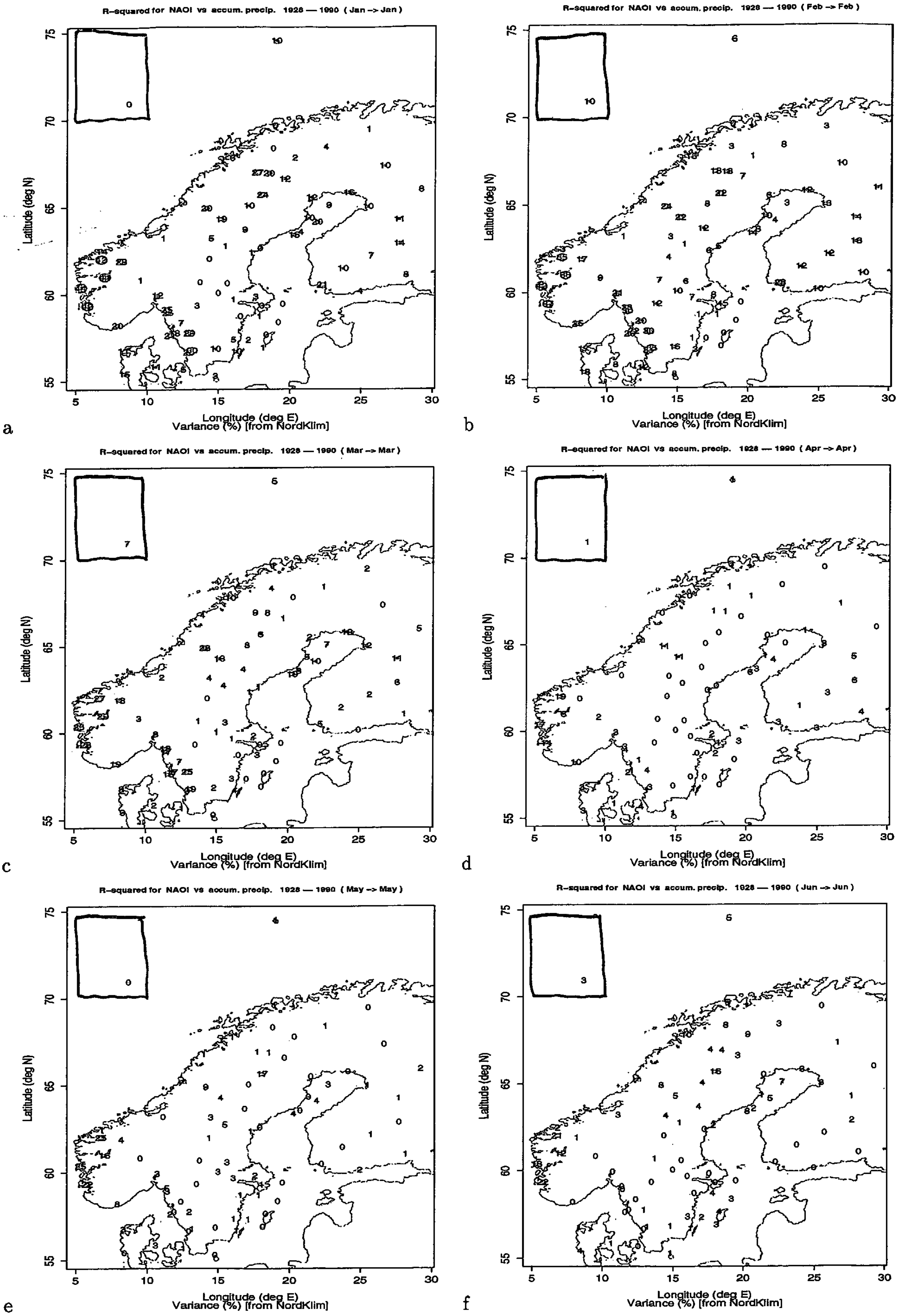

Figure 17. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by NAOI in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

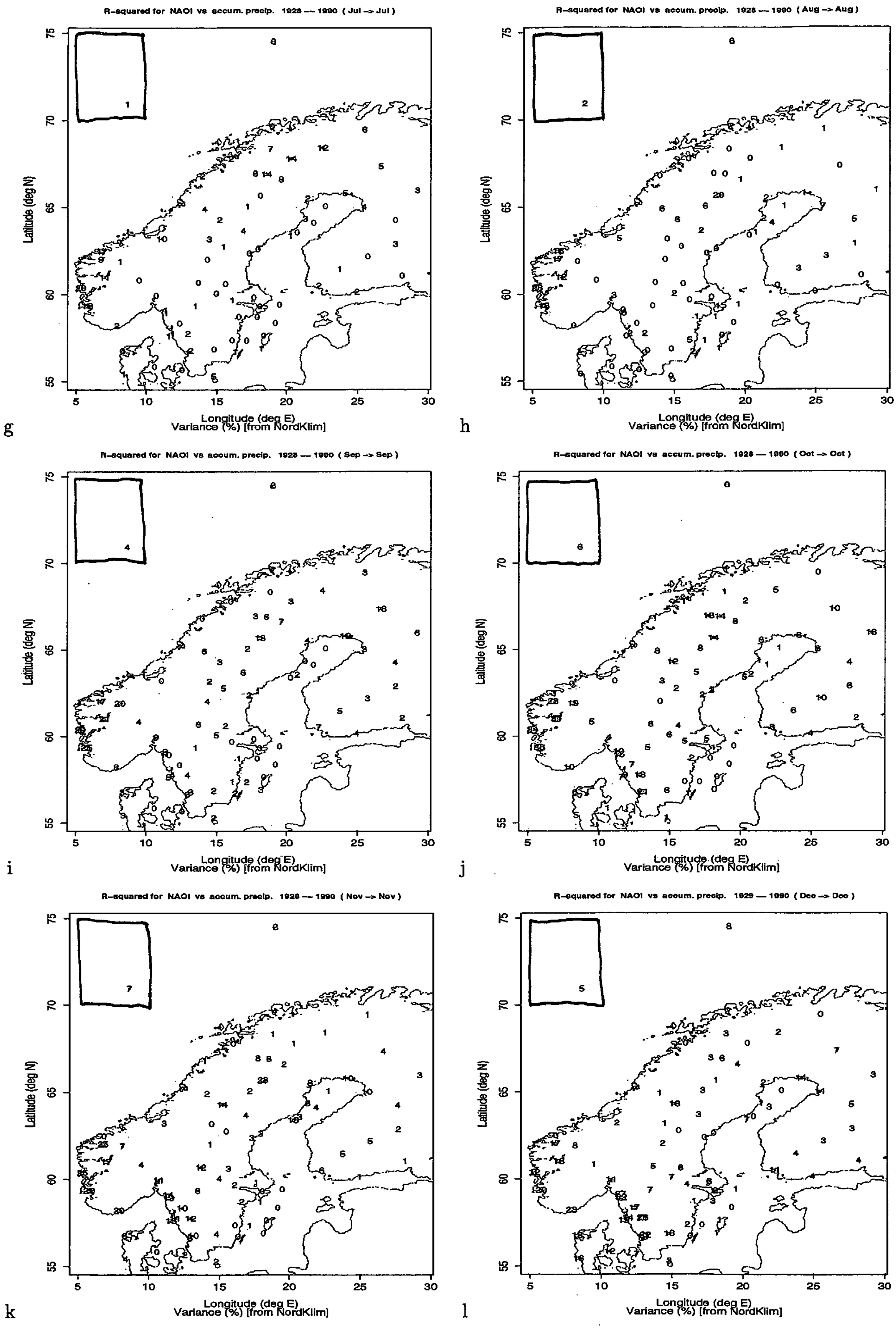

Figure 17. The variance (R^2) in % of the accumulated monthly precipitation that can be explained by NAOI in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

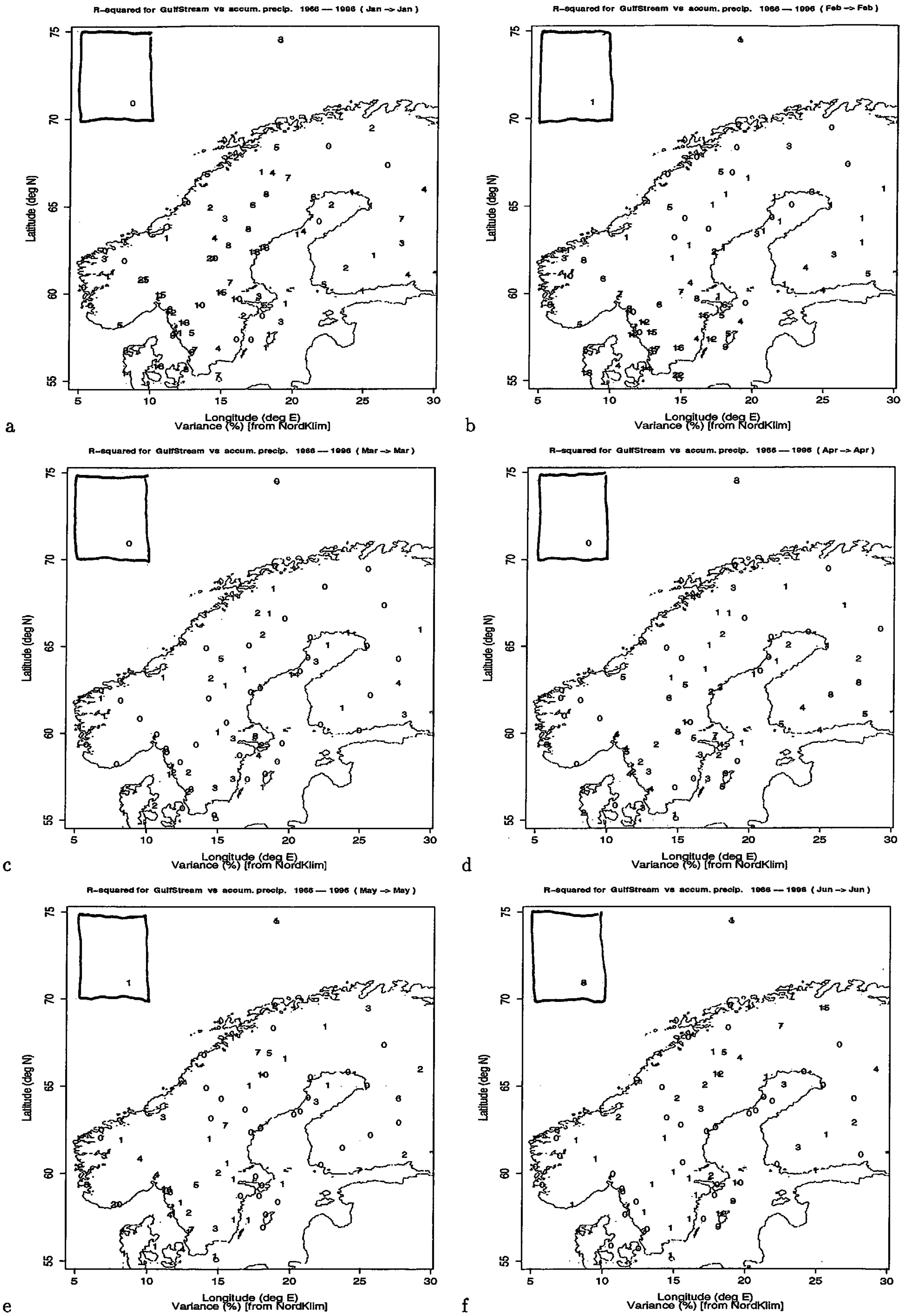

Figure 18. The variance (R^2) in % of the monthly precipitation that can be explained by the GSNW index in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

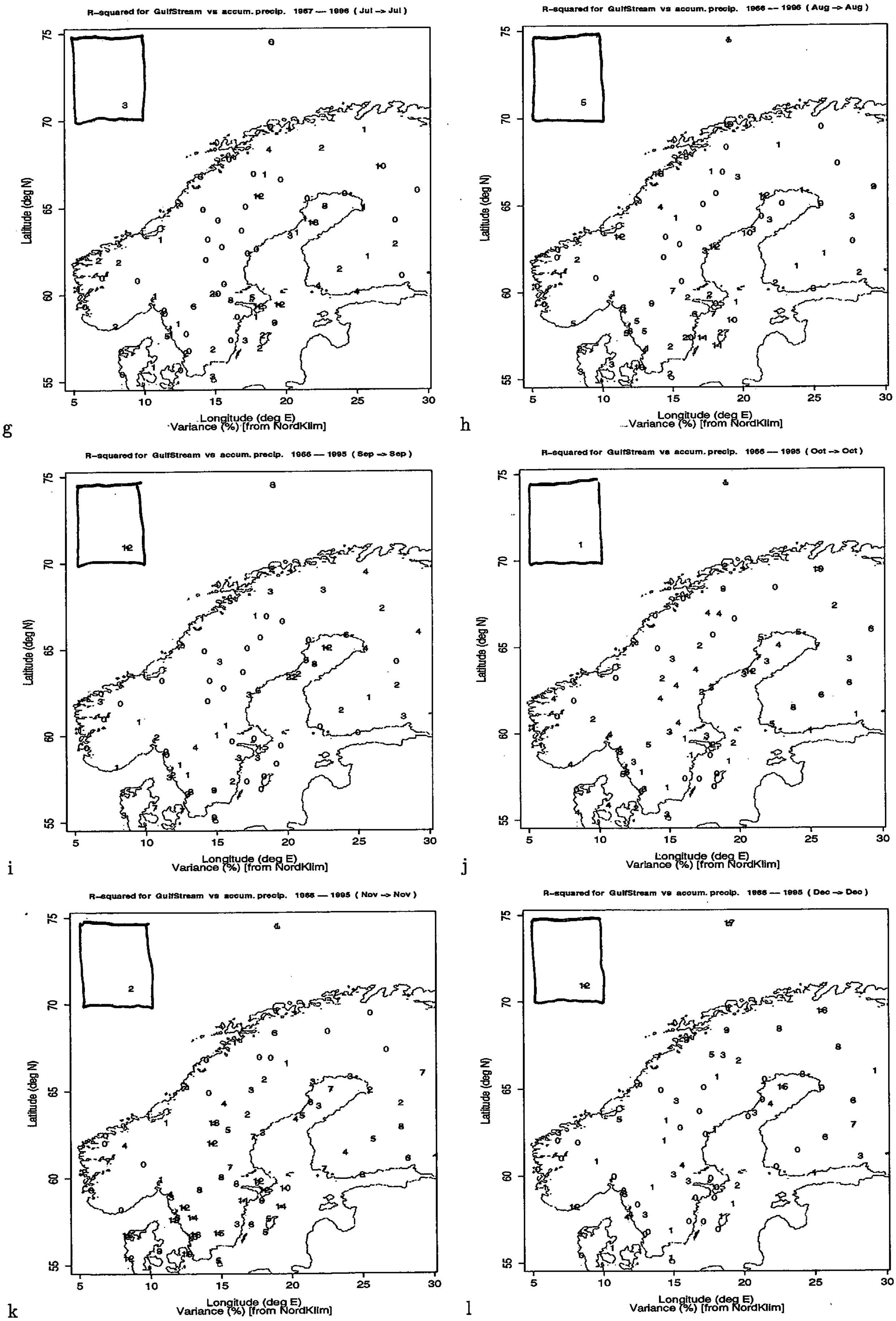

Figure 18. The variance (R^2) in % of the monthly precipitation that can be explained by the GSNW index in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

3.10 ENSO and precipitation

The results of an exploration of statistical links between ENSO and the precipitation in the Nordic countries are shown in Figure 19. The results do not give strong evidence for a real association between ENSO and the rainfall, but shows a similar picture as the GSNW index in Figure 18.

4 Discussion & Conclusions

The problem of multiplicity implies that there is a greater probability of obtaining coincidentally (spurious) high confidence values for N independent observations than if only one single case is considered. The probability of finding n cases that qualify as statistically significant at the 5% confidence level ($X > x$) can be estimated from a binomial distribution:

$$P(n \text{ incidents with} X > x) = \sum_{i=1}^{n} \frac{N!}{i!(N-i!)} P(X > x)^i \left[1 - P(X > x)\right]^{N-i} \quad (1)$$

Taking 12 individual months (these are almost independent since the month-to-month correlation tend to be small), $N = 12$. The probability of finding one set of results exceeding the 5% confidence limit out of 12 months is according to equation (1) 34%, and the respective probabilities for finding two or three cases are 10% and 2%. The climate variations recorded at the different stations tend to be correlated. Thus, the spatial degree of freedom is substantially lower than the number of stations. It is therefore not straight forward to estimate the probability of observing more than one station with statistically significant estimate of R^2.

One interesting observation was that there seemed to be a stronger statistical link between the sea-ice cover and the minimum temperature than there is for maximum temperature for all of the 12 calendar months. *Trigo* et al. (2002) studied the relationship between the NAO phases and maximum and minimum temperatures in the NCEP re-analysis (*Kalnay* et al., 1996) and observed that the NAO has a stronger effect on the minimum temperature than the maximum temperature. They explained this asymmetry in terms of associated changes in the cloudiness, and they argued that positive NAO winter phase favours a more anti-cyclonic circulation pattern over central Europe and the Iberian Peninsula. The enhanced anti-cyclonic activity is associated with reduced precipitation and reduced cloud cover. A similar asymmetry between the maximum and minimum temperature response to variations in the sea-ice or the SST can be at least partly be explained in terms their connection between the NAO.

This survey explored the data and identified some statistical relationships. The next step is to look for physical explanations for some of these associations. If the links can be explained in terms of physical mechanisms, then models can be constructed that can be used for prediction studies. If the verification of the predictions (using independent data) suggest that the models are skillful, then these links can be considered as being real.

The fact that the North Atlantic SSTs may have an impact on the climate in the Nordic countries is important in terms of climate scenarios, since this implies that the global climate models (GCMs) must give a realistic description of the ocean currents and the air-sea interaction which are believed to be important for the SSTs. Furthermore, it is important that the GCMs can reproduce the statistical relationships between the local climate parameters and the large-scale SSTs.

The connection between the sea-ice and the regional climate over the Nordic countries puts severe requirements on the GCMs in terms of producing climate scenarios under a global warming. Various climate models different descriptions of the present-day ice-edge (*Benestad* et al., 2002a) and the retreat of the sea-ice is inconsistent in the global climate scenarios (*Benestad* et al., 2002b). Furthermore, the analysis presented here shows the statistical links between the sea-ice and the local climate elements in the Nordic countries for only modest changes in the ice-cover. The model scenarios, on the other hand, suggest a much more substantial retreat of the Arctic sea-ice than has been observed until now, and it is not know if the response in the Nordic countries (or the rest of the world) will be the same as in the past for such large perturbations to the Arctic climate.

Acknowledgments: This work was done under the Norwegian Regional Climate Development

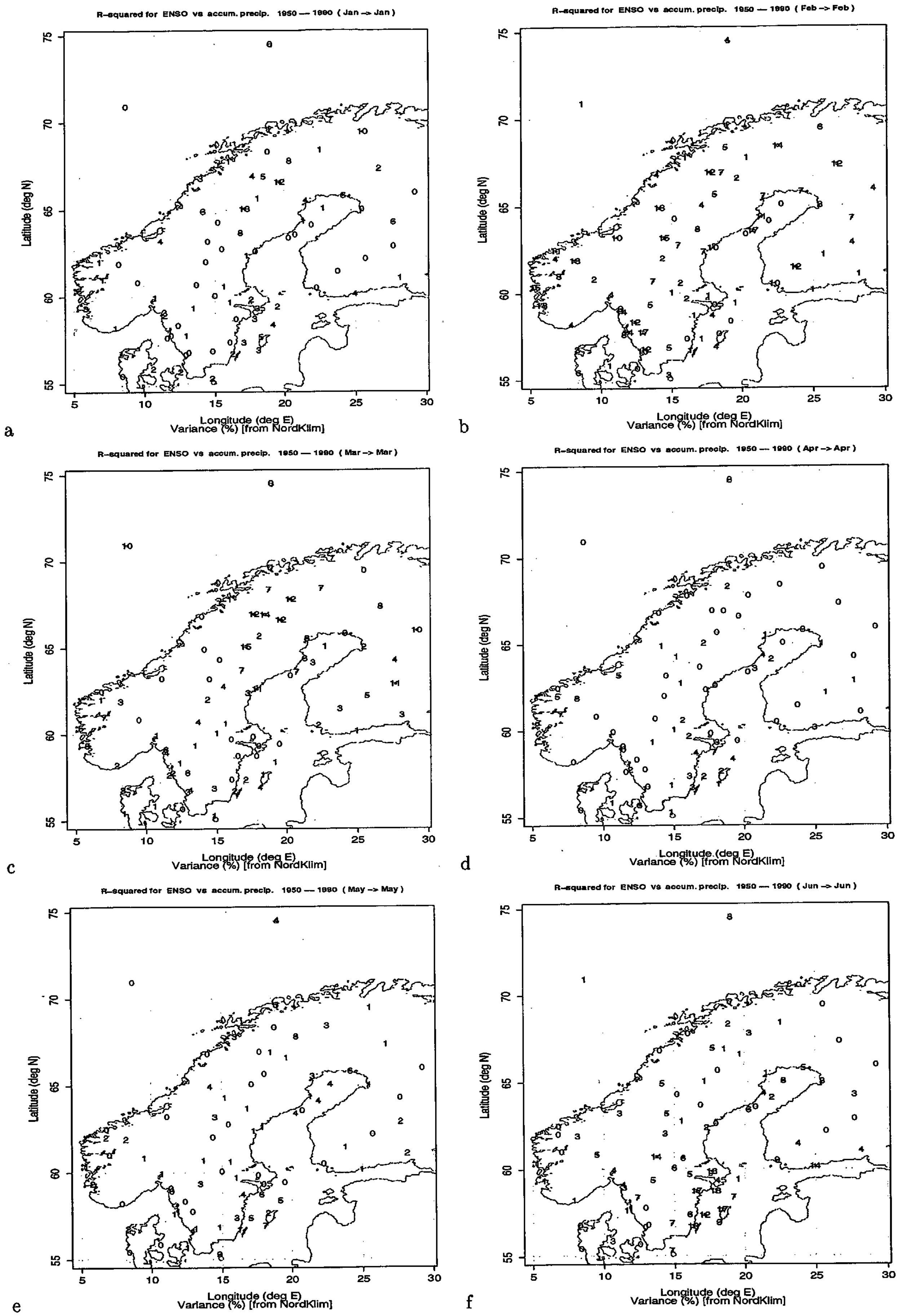

Figure 19. The variance (R^2) in % of the monthly precipitation that can be explained by NINO3 in Jan (a), Feb (b), Mar (c), Apr (d), May (e), Jun (f).

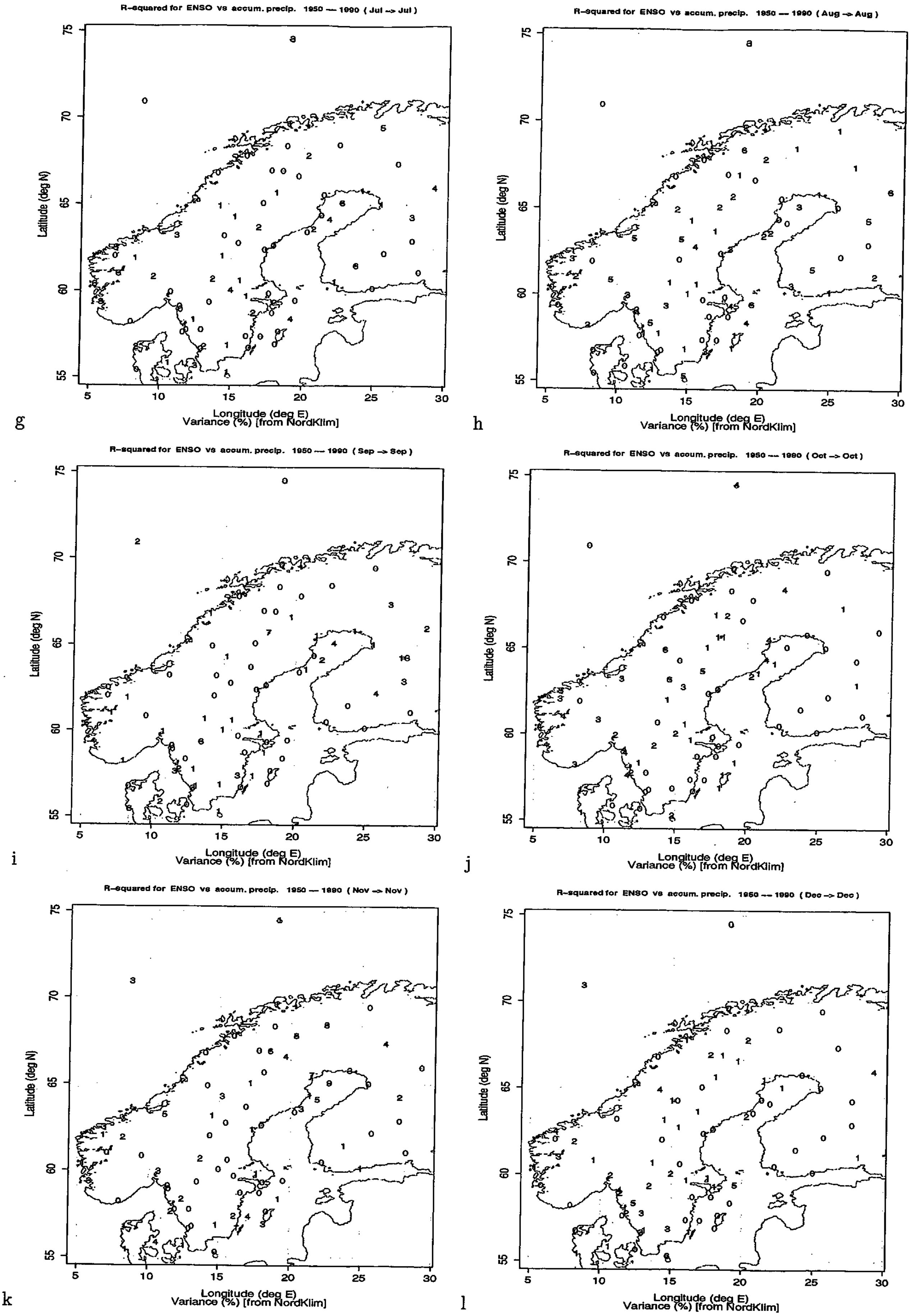

Figure 19. The variance (R^2) in % of the monthly precipitation that can be explained by NINO3 in Jul (g), Aug (h), Sep (i), Oct (j), Nov (k) and Dec (l).

under Global Warming (RegClim) programme, and was supported by the Norwegian Research Council (Contract NRC-No. 120656/720) and the Norwegian Meteorological Institute. Jim Arnott of the Hadley Centre, U.K. Met Office kindly provided SSTs from the HadISST1.1 analysis. Part of the analysis was carried out using the R (*Ellner*, 2001; *Gentleman & Ihaka*, 2000) data processing and analysis language, which is freely available over the Internet (URL http://www.R-project.org/).

References

Benestad, R.E., 1999. *Evaluation of Seasonal Forecast Potential for Norwegian Land Temperatures and Precipitation using CCA.* Klima 23/99. DNMI, PO Box 43 Blindern, 0313 Oslo, Norway.

Benestad, R.E., & Melsom, A., 2002. Is there a link between the unusually wet autumns autumns in southeastern Norway and SST anomalies? *Climate Research*, **accepted**, C426.

Benestad, R.E., I. Hanssen-Bauer, T.E. Skaugen, & Førland, E.J., 2002a. *Associations between the sea-ice and the local climate on Svalbard.* KLIMA 07/02. met.no, PO Box 43 Blindern, 0313 Oslo, Norway.

Benestad, R.E., Hanssen-Bauer, I., & Førland, E.J., 2002b. Empirically downscaled temperature scenarios for Svalbard. *Atmospheric Science Letters*, September 18, doi.10.1006/asle.2002.0051.

Colman, A., & Davey, M., 1999. Prediction of summer temperature, rainfall and pressure in Europe from preceding winter North Atlantic Ocean temperatures. *International Journal of Climatology*, **19**, 513–536.

Deliang, C., & Hellström, C., 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. *Tellus*, **51A**(4), 505–516.

Deser, C., Walsh, J.E., & Timlin, M. S., 2000. Arctic Sea Ice Variability in the Context of Recent Atmospheric Circulation Trends. *Journal of Climate*, **13**(February), 617–633.

Ellner, Stephen P., 2001. Review of R, Version 1.1.1. *Bulletin of the Ecological Society of America*, **82**(2), 127–128.

Gentleman, R., & Ihaka, R., 2000. Lexical Scope and Statistical Computing. *Journal of Computational and Graphical Statistics*, **9**, 491–508.

Holland, M.M., Bitz, C.M., & Weaver, A.J., 2001. The influence of sea ice physics on simulations of climate change. *Geophys. Res. Lett.*, **106**(C9), 19,639–19,655.

Hurrel, J., 1995. Decadal trends in the North Atlantic Ocsillation and relationships to regional temperature and precipitation. *Science*, **269**, 676–679.

Ihaka, Ross, & Gentleman, Robert., 1996. R: A Language for Data Analysis and Graphics. *Journal of Computational and Graphical Statistics*, **5**(3), 299–314.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Wollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., & Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**(3), 437–471.

Marshall, J., Kushnir, Y., Battisti, D., Change, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R., & Visbeck, M., 2001. North Atlantic Climate Variability: Phenomena, impacts and mechansims. *International Journal of Climatology*, **21**, 1863–1898.

Parkinson, C.L., Rind, D., Healy, R.J., & Martinson, D.G., 2001. The impact of Sea Ice Concentration Accuracy on Climate Model Simulations with the GIS GCM. *Journal of Climate*, **14**(June), 2606–2623.

Rind, D., Healy, R., Parkinson, C., & Martinson, D., 1995. The Role of Sea Ice in 2 $\times CO_2$ Climate Model Sensitivity. Part 1: The Total Influence of Sea Ice Thickness and Extent. *Journal of Climate*, **8**(March), 449–463.

Taylor, A.H., 1995. North-south shifts of the Gulf Stream and their climatic connection with the abundance of zooplankton in the UK and its surrounding seas. *ICES Journal of Marine Science*, **52**, 711–721.

Taylor, A.H., 1996. North-south shifts of the Gulf Stream: ocean-atmosphere interactions in the North Atlantic. *International Journal of Climatology*, **16**, 559–583.

Trigo, R.M., Osborn, T.J., & Corte-Real, J.M., 2002. The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Climate Research*, **20**, 9–17.

Tuomenvirta, H., Drebs, A., Førland, E., Alexandersson, O.E. Tveitoand H., Laursen, E.V., & Jónsson, T., 2001. *Nordklim data set 1.0.* KLIMA 08/01. met.no, P.O.Box 43 Blindern, N-0313 Oslo, Norway.

Vinje, T., 2001. Anomalies and Trends of Sea-Ice Extent and Atmospheric Circulation in the Nordic Seas during the Period 1864-1998. *Journal of Climate*, **14**, 255–267.

Wilks, D.S., 1995. *Statistical Methods in the Atmospheric Sciences.* Orlando, Florida, USA: Academic Press.