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Is there a link between the unusually wet autumns in southeastern Norway and SST anomalies?

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ABSTRACT

During November 2000, Bjørnholt (near Oslo, Norway) received 564 mm of rain, the highest ever recorded by far. The extreme rainfall over south-eastern Norway accompanied a persistent circulation pattern advecting moisture from the south, leaving no doubt as to the role of the prevailing winds. However, there may be additional factors affecting the total rainfall amount, and one candidate is SST. There were unusually warm SST anomalies off the coast of Newfoundland and one central question is: Did the North Atlantic SSTs play a role? An analysis of the historical record of November rainfall from Bjørnholt is presented in order to explore plausible connections with the sea surface temperature anomalies in the North Atlantic Ocean. It is found that the November rainfall is influenced by the sea surface temperature in addition to the sea level pressure. The sea surface temperature anomalies cannot account for all of the 564 mm of rain, but the sea surface temperatures can nevertheless explain as much of the rainfall during unusually wet November months in 2000 and 1970 as the sea level pressure. The November rainfall record coincides with the warmest sea surface temperature anomalies on record in parts of the North Atlantic, and it is speculated as to whether this incidence can be related to a warming trend.

KEY WORDS: rainfall sea surface temperature sea level pressure regression analysis

1 Introduction

The autumn in year 2000 will be remembered as a wet one in parts of northern Europe (Marsh, 2001), as there was widespread flooding and the rain never seemed to cease. The unusually high amount of rainfall accompanied a persistent circulation pattern (Figure 1a) advecting mild and moist air from the south, and the whole of south-eastern Scandinavia received extreme amounts of precipitation whereas northern and western Norway were unusually dry for this time of the year (Figure 1b). November brought record rainfall in Oslo (Norway), with 279mm (382% of the 1961–90 November mean) recorded at the Norwegian Meteorological Institute (met.no) at Blindern, almost trivializing the old record of 180 mm (1970). The rainfall recorded at nearby stations within Oslo's city limits was: Rustasaga 335 mm (403%), Nordstrand 290 mm (408%), Maridalsoset 327 mm (403%), Bjørnholt 564 mm (470%), Smestad 280 mm (384%), Tryvasshøgda 411 mm (340%), and Sørkedalen 448 mm (444%). Details on the distribution of daily rainfall amounts are shown in Table 1. Extreme rainfall amounts were also recorded over a substantial part of south-eastern Scandinavia (Figure 1c).

Since November 2000 rainfall is the highest value ever recorded, analysis of the likelihood of such occurrences must be based on an extrapolation of probabilities (Coles, 1999). The return time for the November rainfall in Bjørnholt (a settlement located on the south end of the Bjørnsjøen lake 360 m a.s.l. in the Nordmarka forest and within Oslo's city limit) is estimated to be around ∼600 years, assuming a Gumbel distribution (Wilks, 1995; von Storch and Zwiers, 1999) and that the rainfall data is stationary. However, this estimate is highly uncertain due to the assumption of a Gumbel distribution and only 118 years of observations. Nevertheless, a November rainfall at Bjørnholt exceeding 564 mm is a rare event indeed. From Table 1, we note that the November 2000 statistics of daily precipitation reveals that the number of wet days was extreme. It rained on all but two days, which gives an indication of the persistence of the circulation pattern.

The question is then: Was this extreme rainfall event solely due to the persistent circulation pattern or were other factors* also involved? In order to answer these questions one must look to the past rainfall measurements to identify underlying causes. Here, one plausible culprit is investigated: The North-Atlantic sea surface temperature (SST). The link between SST and sea level pressure (SLP) is also explored. It was established long ago that the atmospheric circulation influences the SSTs (Bjerknes, 1959), but the atmospheric circulation also controls the geographical rainfall distribution (Busuioc et al., 2001; Hanssen-Bauer and Førland, 2000). The question is whether unusual SST anomalies may affect the atmosphere in a reciprocal way so that the rainfall is enhanced further. The connection between SST anomalies and rainfall may be physically sound for several reasons: *i)* The total rainfall is sensitive to the available moisture and a high SST enhances the evaporation in addition to strong surface winds; *ii)* The SST may influence the circulation pattern; *iii)* High SSTs may provide an added source of energy for atmospheric cyclonic activity (Rodwell et al., 1999). The effect of SSTs on the atmosphere will depend on the atmospheric state, for instance with greater oceanic-atmospheric heat exchange during situations with cool northerly wind anomalies than when mild southerly winds occur (Bjerknes, 1959). However, some studies based on general circulation models suggest that the mid-latitude SST anomalies have few, if any, effects on the atmospheric circulation (Frankignoul, 1985; Lau, 1996). Some model studies have even suggested that

* The continuity equation can be written as $\frac{\partial \rho}{\partial t} + \vec{u} \cdot \nabla \rho = \text{source} - \text{sink}$, where ρ represents the humidity and $\vec{u}$ is the three-dimensional velocity. The source term is related of evaporation, which can be represented as a bulk-formula function of wind speed and the difference between SST and the surface air temperature. The sink term involves precipitation. If the humidity is approximately constant, $\frac{\partial \rho}{\partial t} \approx 0$, then $\text{sink} = \text{source} - \vec{u} \cdot \nabla \rho$. Hence, important factors affecting the precipitation include local rain-generating mechanisms, moisture convergence (circulation pattern), and evaporation (SST).

most of the low-frequency atmospheric variations are due to internal atmospheric dynamics (Lau, 1985). Lag-correlation studies yield higher correlation estimates when the atmosphere leads the ocean (Frankignoul, 1985). Johansson et al. (1998) conducted a study on the predictability of monthly mean temperatures in Europe based on empirical models and found little predictive information from the Atlantic Ocean SSTs.

But there are also some indications suggesting that the SST anomalies have some influence on the atmosphere (Drevillion et al., 2001; Rîmbu et al., 2001). Colman and Davey (1999) reported some skill in predicting summer-time temperatures based on January-February North Atlantic SST anomalies, implying a lagged atmospheric response to the ocean. Frankignoul (1985) observed that mid-latitude SST anomalies have a weak but significant influence on the short-term climatic fluctuations. Sutton et al. (2001), Robertson et al. (2000), Rodwell et al. (1999), Selten et al. (1999) and Palmer and Sun (1985) among others have used atmospheric models to study the relationship between the North Atlantic SST anomalies and the atmospheric circulation, and their conclusion is that the North Atlantic SST affect the atmospheric circulation. The atmospheric response to diabatic heating such as SST anomalies may include changes in the planetary wave propagation in addition to humidity changes, but the heating also depends on the dynamical response of the atmosphere (Frankignoul, 1985). Simulated atmospheric response tends to be model-dependent, sensitive to the time scale, and may vary from study to study. It is possible that the GCMs have serious shortcomings due to uncertainties in the description of the relationship between SST and diabatic heating, preventing them from giving a true description of the actual relationships.

On longer time scales, there is further evidence pointing towards the ocean modifying the atmosphere (Timmermann et al., 1998; Kushnir and Held, 1996). Rodwell et al. (1999) and Higuchi et al. (1999) suggest that the phase of the NAO is influenced by the

North Atlantic SST on decadal time scales.

2 The data

The monthly rainfall data for Bjørnholt was obtained from the Norwegian Meteorological Institute's (met.no) climatological database. The Oslo-Blindern (94 m a.s.l.) record is not homogeneous and values before 1937 have been reconstructed using neighbouring stations. The analysis for the two records gave qualitatively similar results, but only the Bjørnholt data, which has been homogenized and covers the period 1883-2001, will be discussed here.

In order to establish a link between large-scale anomalies over the North Atlantic Ocean and the autumn precipitation near Oslo, 101-year long data records of sea level pressure (SLP) were constructed for the period 1900-2000 by combining the SLP from University of East Anglia and NCEP reanalysis (Kalnay et al., 1996). The data were gridded using a optimal interpolation technique (Reynolds and Smith, 1994) and the construction, the evaluation and the data are described in Benestad (2000).

The sea surface temperature (SST) were based on COADS (Slutz et al., 1985), GISST2.2 (Parker et al., 1995), Kaplan et al. (1998), and the Reynolds and Smith (1994) SSTs. The SST data was derived by Benestad using the same method as the 2-meter temperature described in Benestad (2000). Moreover, the reconstruction of the SST data was done by projecting a combination of past observations from various sources onto corresponding eigen-patterns estimated from the Reynolds and Smith (1994) SST. Since there are differences between the data from the various sources, the combination of the different sets is not a trivial task. The largest errors in the SSTs are estimated for the Labrador Sea and east of Greenland (not shown). There have been some studies which suggest that the North European weather is sensitive to the surface conditions in the Labrador Sea (Skeie and Kvamstø, 2000). Relatively large differences among the different SST data products, and hence large errors, were also found along the ice edge, so these SST products may not be ideal for studying the links between the Labrador Sea and climate anomalies associated with the storm tracks. Although the met.no SST reconstruction based on these different data sources is far from error-free, one may expect from the reasonable agreement among the different sources in the well-sampled regions over substantial parts of the North Atlantic that the reconstructed SST record (1900-2000) contains most of the climatic signals that can be related to climatic anomalies such as the wet spell in Oslo.

The robustness of the results was assessed by comparing the results with a similar analysis based on the HadISST1.1 product* from U.K. Met Office (UKMO) instead of the met.no SSTs. The UKMO data consists of monthly mean SST and sea-ice analyses on a global scale from 1871 to 1999. Thus, the data does not cover the most recent extreme wet event of November 2000, and was therefore merely used to check the consistency of the historical SST-rainfall connection derived from the met.no reconstruction. It is important to note that the HadISST1.1 data set is based on many of the same observations as the met.no reconstruction, and the two results are therefore not completely independent. Furthermore, these data are also susceptible to errors, particularly in the beginning of the record when the observations were scarce. The SST reconstruction was compared to the Modular Ocean Data Analysis System (MODAS) SST product for the period 1993–2000 that is based on remote sensing data only (Fox et al., 2001). The comparison suggests that the reconstructed SST may be too smooth. More important is the comparison of the year-to-year changes of the November SST anomalies, which is favorable for most

* URL http://www.cgd.ucar.edu/~asphilli/DataCatalog/Data/hadisst.html

of the common years but not for all. The mean November cloud cover in this domain is about 50% according to the NCEP reanalysis which may introduce errors to the satellite product, thus none of these products are perfect.

The gridded November mean rainfall values shown in Figure 1(c) were taken from the NCEP reanalysis obtained from the NOAA-CIRES Climate Diagnostic Center (CDC) in the USA. An alternative option was to use the ECMWF's analysis (EA) product. However, the EA only dates back to the late 1970s, and is not as suitable for the present purpose as the 53 years with NCEP reanalysis data. Furthermore, the NCEP reanalysis is much more easy to obtain for the science community at large, making it the preferred choice for this study.

In order to test the reconstructed data for a real climate signal a canonical correlation analysis (CCA) was applied to the SST and the SLP fields extracting spatial patterns which are associated with one another (not shown). The patterns bear similarities to the North Atlantic Oscillation (NAO). The first canonical correlation coefficient is 0.83 for the 1900–2000 interval, which is indicative of a coupled signal.

3 The Methods

The SST and SLP fields were subject to an empirical orthogonal function (EOF) (Lorenz, 1956; North et al., 1982; Benestad, 1999) decomposition in order to reduce the data size and hence reduce the degrees of freedom. Using only the 20 leading principal components from the EOF analysis, makes the analysis easier and reduces the computational demands (accounting for 99.96% of the variance in the SST and 99.19% of the variance in the SLP). Furthermore, throwing away the higher order EOFs discards much of the noise in the data. One disadvantage with this kind of "filtering", however, is that weak signals may also be excluded.

The November rainfall data [rr] were not normally distributed and the precipitation series was therefore normalized in three different ways: By taking $\log(rr)$, $rr^{0.2}$-power, or $rr^{0.5}$-power transforms of the series. The analysis was repeated for these transforms, and the results were similar. We therefore henceforth focus on the original data.

In order to explore any association between the SST (SLP) and the rainfall over south-eastern Norway, three different lines of analysis were conducted: *i)* Based on t-tests of SST principal components coinciding with the times when there were wet autumns, *ii)* the spatial extent of prominent SST anomalies, and *iii)* based on regressional analysis.

In the former approach *(i)*, the 1900–2000 November months were classified in terms of *dry*, *normal* and *wet* months by "binning" the data into 3 categories defined in terms of the mean value (μ) of rr and the standard deviation [s]: $rr_{\rm dry} < \mu - 0.42s$; $rr_{\rm wet} > \mu + 0.42s$, and $rr_{\rm norm}$ within or equal to $\mu \pm 0.42s$. If the rainfall data are normally distributed about the mean value, then the chance that the rainfall amount falls into each category is 33%. The actual fractions of cases in each category are given in Table 2, which shows that neither the original data nor most of the transformations give an equal distribution over categories. The observations tend to favour more dry cases whereas the transformations give more wet events (the years which fall under category 'wet' are listed in Table 3). The distributions of rr and $rr^{0.2}$ fall just outside the 95% confidence interval for normally distributed data estimated through Monte-Carlo simulations, whereas the $rr^{0.5}$ transformation gives a nearly equal distribution among the different categories.

Three sets of t-tests were conducted, all of which were applied to the principal components of the SST or the SLP grouped as wet, normal or dry autumns. In approach *(ii)* the asymmetry of the distribution of warm and cold pools in the North Atlantic Ocean were compared with the temporal variability of the original rainfall series, and the results were categorized and subjected to a bootstrap test. Finally, in *(iii)* a stepwise regression was used to develop multiple linear empirical models describing the November rainfall in terms of the respective SST or SLP principal components.

4 The Results

Figure 2 shows the results from the t-tests. In panel a, the t-test is applied to the respective populations of principal component values corresponding to wet and dry November months for the $rr^{0.5}$ transformation. The 3rd, 4th, 6th and 10th SST modes are statistically significant at the 5% level, indicating that some of the EOFs are in fact associated with wet November months. The t-test results for normal and dry months (Figure 2b) give some indications of a relationship between SST and rainfall that verges on being statistically significant at the 5% confidence level. A similar test for the populations of wet and normal months (not shown) point to statistically significant relationships with the SST modes, but these are not quite as strong as for the wet–dry differences. The t-tests were repeated using classifications based on rr, $\log(rr)$, and $rr^{0.2}$ respectively, which all, except the t-test between dry and normal November for the $\log(rr)$-based categorisation (not shown), pointed to statistical significant differences (at the 5% confidence level) between the mode-3 weighting for the different classes. The fact that one mode qualifies as statistically significant in nearly all these tests suggests that the results is not a coincidence, even though there is a good chance of finding one case which qualifies as "statistically significant" out of 20 independent estimates*.

A composite reconstruction of the met.no SST difference corresponding to the "wet" Novembers listed in Table 3 (column 2) and corresponding "dry" months is shown in

* Problem of multiplicity, Wilks (1995)

Figure 3a, indicating positive SST anomalies off the Newfoundland coast. High November rainfall is also accompanied with cold ocean surface west of the British Isles. The SST observations for November 2000 show strong anomalies southeast off Labrador, the interior North Atlantic and along the Norwegian coast (Figure 3b).

A comparison with the standard deviation of the November mean SST (1981–2000) shows that the amplitudes of the November 2000 SST anomalies south-east off Labrador were a factor of 2 higher than the 1981–2000 standard deviation as well as the 1900-2000 standard deviation derived from the 1900–2000 met.no SST reconstruction (not shown). The November 2000 temperatures in this region were in fact the highest in the entire Reynolds SST record (1981–2000, Figure 4a). The corresponding spatial mean temperatures derived from the 1900-2000 met.no SST analysis suggest that there is no evidence of past values being higher than in November 2000. Figure 4b compares the time series of the 60°W–30°W/30°N–45°N spatial mean SST from the met.no reconstruction with corresponding values from the HadISST1.1. The two curves tend to trace each other as well as the Reynolds data over their common interval, suggesting that the met.no reconstruction has captured most of the observed SST variations.

There are some cases in the period 1930-1960 when there were strongly positive SST anomalies around Bermuda, but few such cases since 1960, apart from the November 2000 anomalies which may be the strongest since 1871. The fact that the strongest anomalies coincide with the extreme November 2000 rainfall event in south-eastern Scandinavia is consistent with the rainfall event being related to the SSTs.

Further indications of North Atlantic SST anomalies' influence on the rainfall is found when the asymmetry of the SST anomalies (SSTA) is considered. We compute the fractional area of prominent SSTA (magnitudes greater than 0.5°C) exceeding 10% of the western-central North Atlantic Ocean (WC basin: 80°W–45°W, and 30°N–55°N) and the full width of the North Atlantic Ocean (FW: 80°W–10°W, and 30°N–55°N) respectively. Then, we compute a North Atlantic Asymmetry index (NAA index) describing the ratio of the WC basin's fractional area of anomalies to the corresponding area for the FW domain. Thus, an NAA index significantly larger than 1 is indicative of an asymmetric SSTA which is found predominately in the WC basin, and an index value that is significantly smaller than 1 corresponds to an anomaly in the eastern basin. A ratio of 1 indicates a symmetric anomaly. The results for the November months' NAA index are presented in Table 4 both for prominent warm anomalies (SSTA $> 0.5°$C) and cold anomalies (SSTA $< -0.5°$C). The November months in question have been subdivided into months with high rainfall at Bjørnholt (as seen in the leftmost column in Table 3), normal rainfall, and dry months.

We find that a warm anomaly in the WC basin enhances the probability of large amounts of rain at Bjørnholt. On the other hand, if the warm pool is in the eastern basin, the likelihood of large amounts of rain is low. A cold pool to the east enhances the probability of large amounts of rain, whereas a cold anomaly in the WC basin reduces this probability. A bootstrap test was used to test the significance of the entries in Table 4, selecting at random 10,000 different subsets of corresponding number of years as indicated in Table 4 column 2.

The results from the stepwise* regression applied to the 1900–2000 met.no SSTs and the November rainfall amount at Bjørnholt are shown in Figure 5. There is a clear indication that the model is able to reproduce part of the rainfall in the Oslo region. The F-statistics are high for SST, and the p-values indicate extremely high confidence. The

* The stepwise regression was carried out using the R-functions `lm` and `step` that perform backward-forward search, these functions are described in the R manuals. The stepwise regression aims to minimize the Akaike information criterion (AIC) (Wilks, 1995, 300–302).

(adjusted) R^2 value of 0.46 indicates that around 46%[†] of the interannual variations in the November rainfall may be related to the SST anomalies. The SSTs can account for 322 mm of the 564 mm received in November 2000. Similar regression analysis for September ($R^2 = 0.23$, p-value=1×10^{-4}), October ($R^2 = 0.27$, p-value=1×10^{-4}), and December ($R^2 = 0.28$, p-value=1×10^{-6}) gave indications of relationships statistically significant at the 5% (Table 5). The regression patterns for these months were also similar to that of November and t-tests similar to those in Figure 2 suggested statistically significant EOFs. Hence, the relationship is not only valid for the November months.

The analysis was repeated, but with EOFs computed using the met.no SSTs from 30°W–40°E/50°N–70°N, and seven[*] of the EOFs from the smaller region could be associated with wet and dry Novembers according to the t-test (not shown). The ANOVA results shown in Table 5 indicate with a high degree of confidence that the regressional fit is not likely due to chance. About 46% of the November rainfall variations can be attributed to the SSTs in the 30°W–40°E/50°N–70°N region, and 323 mm of the 564 mm received in November 2000 could be accounted for by the SST.

Similar analysis as for the met.no SST reconstruction, but using the HadISST1.1 SSTs, confirmed the statistically significant (at the 1% level) association between SSTs in the North Atlantic and the November rainfall around Oslo over the period 1871–1999. The ANOVA scores for these tests are summarized in Table 5. The results appear to be robust as the repeated analysis with different settings give the same qualitative picture. The analyses point to a clear association between the rainfall and the North Atlantic and North Atlantic SST pattern in November. The regression analysis was then repeated for SST *residuals* ($\mathrm{SST_{res}}$) where the linear SLP signal in the SST ($\hat{\mathrm{SST}} = \beta_1 \mathrm{SLP}$) had

† The unadjusted R^2 is 0.54

* The exact number of significant EOFs does not necessarily have any importance as long as some of the leading modes are related to the rainfall.

been removed prior to the analysis using a multivariate regression: $\mathrm{SST_{res}} = \mathrm{SST} - \hat{\mathrm{SST}}$ (Table 5). The results from the SST residuals suggest that all the predictability[†] in SST is related to the SLP.

As a reference, the t-test and regression analysis was repeated using SLP instead of SST. The results suggest that the interannual variations in the November rainfall indeed is related to changes in the circulation as expected. The t-test results shown in Figure 6 indicates that there are 8 spatial SLP modes that can be related to wet November months. The enhanced rainfall is associated with an anomalous southerly flow type bringing in moist air masses over southern Norway (Figure 7). The predictions based on regressional analysis, shown in Figure 8, suggest that the SLP is highly correlated with the autumn rainfall over south-eastern Norway, but the SLP variations fail to account for the extreme events. In fact, the linear SLP-based model predicts a lower value (284 mm of 564 mm) for November 2000 than does the SST-based model (322 mm).

The ANOVA table (Table 5) shows that the results are all highly significant and that there is an over-all stronger signal in the SLP than in the SST. It is likely that the circulation has a stronger effect on the rainfall, but the comparison between the ANOVA scores may also be affected by errors. The errors in the SLP are expected to be smaller than in the SST data since SLP often is easier to measure and the spatial SLP structures tend to be more extensive than the spatial SST patterns. Table 5 also shows the results from a regression analysis on the rainfall and SLP residuals, obtained by removing the linear SST signal in the SLP. The high p-value and low F-statistics suggests that most

[†] Here we use the term 'predict' when referring to model results in general, and this term may include forecast, nowcast, and hindcast. A model in this context may be a linear relationship between a single time series (predictand: $\hat{y}$) and a series of spatial fields of some quantity (predictor $\mathbf{X}$): $\hat{y} = b\mathbf{X} + c$. The concept predictability concerns the question whether there is a signal in $\mathbf{X}$ that can account for variations in $\hat{y}$.

of the predictability associated with the SLP also is related to SST variations. Hence, the Oslo rainfall appears to be related to a *coupled* SST–SLP mode, implying that SST is indeed important.

Lagged regression was also carried out between SST and the rainfall and between SLP and the rainfall (Table 5), and the results suggest that there may sometimes be a weak association between the SSTs and the next month's rainfall. However, the R^2-values for the lagged regression is greater for SLP than SST in two of the three autumn months.

An analysis counting how many entries fall into each rainfall category *dry*, *normal* and *wet* may be used to identify long-term shifts in the rain fall statistics. This statistic is not as sensitive to outliers as the extreme value analysis, and the results suggest that the high-rainfall frequency over Bjørnholt has changed over the last century (Figure 9) and there has been an increase in the frequency of wet November months. It appears from Figure 9 that most of the change in the wet-November frequency took place before the 1930s. The 1960s was the decade with highest wet-November frequencies. The implications of this change may be that the extreme value analysis referred to in the introduction overestimates the future return period and that extreme rainfall events exceeding 564 mm will not be as rare as initially estimated.

5 Discussion

The analyses suggest that SSTs are related to the rainfall over south-eastern Norway, although atmospheric circulation patterns tend to be the most important factor accounting for interannual variations in the November rainfall over Oslo. Our results support the conclusion of Rodwell et al. (1999), and it is especially interesting to note the association between the SST anomalies in their figure 3a and the positive precipitation anomaly over southern Norway in their figure 3d, albeit for the winter season. The results of this analysis are consistent with two hypotheses: *i)* The atmospheric circulation pattern produces both positive SST anomalies in the northwestern Atlantic Ocean and more autumn rain over south-eastern Norway; *ii)* Extensive and strong positive SST anomalies in the northwestern Atlantic Ocean affect the atmospheric circulation pattern and influence the rainfall in south-eastern Norway. The SSTs may play an active role for the rainfall in either scenario, as high SSTs may lead to enhanced evaporation (Rodwell et al., 1999) and higher moisture available for precipitation thus reinforcing the rainfall. The analyses on the SST and SLP residuals suggest that neither SST nor SLP alone can account for the November rainfall variations in south-eastern Norway but that rainfall may be associated with a coupled SST–SLP pattern.

The SST anomalies off Newfoundland tend to be anti-correlated with the sub-tropical SSTAs in the North Atlantic tri-pole pattern, and Sutton et al. (2001) report that these sub-tropical SSTs may produce an atmospheric response. They also suggest that the mid-latitude SSTAs may possibly affect the storm generation processes or the storm track. One indication of the SST playing an active role is the higher SST-based rainfall estimate for the extreme November 2000 event than the corresponding SLP-based estimate.

Based on previous model studies and lag-correlation analysis (Frankignoul et al., 1998) giving high correlation values when the atmosphere leads the ocean, it has been argued that the atmosphere tends to drive the ocean in the mid-latitudes. The lag-correlation result may point to a linear response in the ocean, but does not rule out important but non-linear atmospheric response to SST anomalies or a response depending on the atmospheric state (Bjerknes, 1959). Palmer (1993) has proposed that the most likely atmospheric response to a change in the diabatic heating, such as a SST anomaly, is a change in the population of weather regimes. Furthermore, additional factors such as imposed noise and different time scales in the atmosphere and ocean may affect the results from the lag-correlation. There is little doubt about a coupling between the SST and the SLP, but it is difficult to prove whether the SST influence the SLP most strongly or vice versa. The statistical analysis presented here says little about causality, apart from hinting to an active role for the SST in terms of the south-eastern Norwegian November mean rainfall. Some of the recent model studies suggest that the mid-latitude SST may influence the atmosphere. Although this issue is not yet resolved, our results support the hypothesis that the mid-latitude ocean is influencing the atmosphere.

The observations suggest that the SST anomalies in parts of the North Atlantic were the highest ever recorded. These findings lead to the question of whether there is a connection between the warming trend associated with increased atmospheric CO_2 concentrations and the extreme November rainfall amounts. If the extreme November rainfall is related to the warming trend, then one would expect a return period for such occurrences to be less than $\sim$600 years. On the other hand, the long-term shift in the number of wet November months shown in Figure 9 is due to the increase in incidences between 1900 and 1940, but the global warming is most pronounced since the 1960s (IPCC, 2001) when there is no significant trend in the number of wet Oslo autumns. Thus it is difficult to attribute a trend in the number of wet November months to an enhanced greenhouse effect.

Any relationship between SST and local rainfall is of great interest for climate analysis, seasonal forecasting and empirical downscaling of climate-change scenarios. The established link between the North Atlantic SSTs and precipitation over south-eastern Norway implies that in order for atmospheric-oceanic general circulation models to give reasonable scenarios for extreme monthly rainfall, they must be able to give a reasonable prediction of the North Atlantic SST fields.

6 Conclusions

There is clear evidence suggesting that the November rainfall in south-eastern Scandinavia is connected with the SST anomalies in the northwestern Atlantic along with low pressure system over the British Isles. Hence, a likely explanation for the wet November 2000 is the unusually warm SSTs off the North American east coast in addition to the persistent SLP pattern. The additional observation that the strongest SST anomalies around Bermuda in at least 100 years seem to coincide record-breaking November rainfall around Oslo further suggests that this extreme event was related to the warm anomaly in the North Atlantic ocean. The most important factor controlling the rainfall, however, is the SLP pattern responsible for the transport of moist air to south-eastern Norway.

There may have been a long-term shift in the frequency of wet-November events according to a trend analysis. If there is a real trend in the rainfall statistics then the return period of Bjørnholt November rainfall exceeding 564 mm may indeed be less than ~600 years, as estimated using a Gumbel extreme value analysis.

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out using the `R` (Ellner, 2001; Gentleman and Ihaka, 2000) data processing and analysis language*. The analysis was based on data stored in UCAR/Unidata's netCDF format and some of the figures are produced with NOAA-PMEL's tool *Ferret* (Hankin et al., 1992).

* URL http://cran.r-project.org/

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TABLE 1. 1961–1990 climatology of daily November rainfall amounts exceeding various threshold values for Bjørnholt (columns 2–3), the 1900–1999 extremes (columns 4–5), and the 2000 case (column 6).

Category	1961–1990		1900–1999		2000
(mm)	mean	st.d	min.	max.	
0	14.0	4.4	4	25	**2**
> 10	4.0	2.4	0	10	**17**
> 20	1.5	1.4	0	6	**11**
> 30	0.7	0.9	0	3	**6**
> 50	0.1	0.4	0	1	**3**

TABLE 2. Fraction (in percent) of wet, normal and dry November months. The total number of cases is 101 and the numbers shown in bold are outside the 95% confidence interval if the data were normally distributed. The confidence levels corresponding to p-values of 0.025 and 0.975 are shown in italics and were computed using 10,000 Monte-Carlo simulations.

Transform	Wet	Normal	Dry
rr	32	27	**41**
$\log(rr)$	**42**	25	33
$rr^{0.2}$	**41**	26	33
$rr^{0.5}$	36	31	34
p=0.025	*28*	*25*	*29*
p=0.975	*40*	*41*	*40*

TABLE 3. An overview of the wet November months at Bjørnholt over the period 1900–2000. The 1961–1990 normal value is 120 mm. The second column lists the wet November months defined using the raw data (not transformed and not normally distributed), whereas columns 3 and 4 show the wet events when using the transformed for the categorisation according to rr or the two transforms $< \mu(T(rr)) - s(T(rr))$.

Year	Original (mm)	log (log(mm))	$rr^{0.2}$ ($mm^{0.2}$)	$rr^{0.5}$ ($mm^{0.5}$)
2000	564.1	564.1	564.1	564.1
1929	291.5	291.5	291.5	291.5
1970	291.1	291.1	291.1	291.1
1916	246.2	154.9	246.2	246.2
1959	242.6	242.6	242.6	242.6
1926	240.1	240.1	240.1	240.1
1960	234.7	234.7	234.7	234.7
1991	232.9	232.9	232.9	232.9
1974	224.0	224.0	224.0	224.0
1992	220.0	220.0	220.0	220.0
1982	207.7	207.7	207.7	207.7
1931	193.1	193.1	193.1	193.1
1977	192.4	192.4	192.4	192.4
1967	185.2	185.2	185.2	185.2
1928	185.1	185.1	185.1	185.1
1935	180.1	180.1	180.1	180.1
1938	177.9	177.9	177.9	177.9
1939	176.3	176.3	176.3	176.3
1963	176.2	176.2	176.2	176.2
1961	172.9	172.9	172.9	172.9
1949	170.3	170.3	170.3	170.3
1981	169.5	169.5	169.5	169.5
1910	169.1	169.1	169.1	169.1
1954	166.1	166.1	166.1	166.1
1979	166.1	166.1	166.1	166.1
1951	165.9	165.9	165.9	165.9
1993	163.5	163.5	163.5	163.5
1950	157.9	157.9	157.9	157.9
1966	156.4	156.4	156.4	156.4
1943	155.0	155.0	155.0	155.0
1913	154.9	154.9	154.9	154.9
1946	153.4	153.4	153.4	153.4
1987	152.6	152.6	152.6	152.6
1989		140.9	140.9	140.9
1905		141.8	141.8	141.8
1986		141.4	141.4	141.4
1923		139.0	139.0	
1940		136.4	136.4	
1930		135.7	135.7	
1907		133.1	133.1	
1976		132.9		
1942		131.8		
limit	152.5	129.3	133.0	140
cases	33	42	40	36

TABLE 4. Number of November months when the area of SST anomaly magnitudes larger than 0.5°C in the North Atlantic exceed 10% of the entire domain. The results are categorized numbers of November months with warm and cold SST anomalies respectively. Column 2 (n) lists the number of November months in each category"wet" (at Bjørnholt, years listen in column 2 in Table 3), "normal" (months when the rainfall is within 0.42 standard deviation from normal), and "dry" (months when rr$< \mu - 0.42s$). The numbered categories reflect the asymmetry of the anomalies, and are the number of cases where the NAA index values < 0.8 (I), NAA $\in [0.8, 1.2]$ (II), or NAA > 1.2 (III). The entries accompanied with ** are outside the 99% confidence interval or same value as the confidence limit (estimating using a bootstrap method with 10,000 simulations) whereas the suffix * indicates those entries refer to the 95% confidence interval.

	months	*I*	*II*	*III*
High SST	n			
wet	*33*	0**	4	10*
normal	*29*	5	4	5
dry	*39*	9*	5	2*
Low SST				
wet	*33*	11**	4	0**
normal	*29*	4	6	1*
dry	*39*	2*	2	15**

TABLE 5. ANOVA scores for linear stepwise regression models for monthly mean precipitation developed on SST or SLP. The adjusted R^2 is based on the ordinary R^2 statistic, but is "adjusted" to penalise for higher p-values. Fourth row (rr†) shows regression analysis for 1900–1999 with the November 2000 event excluded. The residual SSTs were obtained by subtracting the best-fit $\hat{SST} = \beta_1$SLP based on SLP from the original SST. Similarly, SLP residuals = SLP $- \beta_2$SST. The three last rows show the ANOVA statistics where the original precipitation record has been replaced by residuals from a regression of the NAOI onto precipitation.

elements	Month	d.f.	F-stat	P-value	R^2
SST(90°W–40°E/40°N–75°N) rr	Sep	10 & 90	4.1	1×10^{-4}	0.23
SST(90°W–40°E/40°N–75°N) rr	Oct	15 & 85	3.5	1×10^{-4}	0.27
SST(90°W–40°E/40°N–75°N) rr	Nov	15 & 85	6.6	4×10^{-9}	0.46
SST(90°W–40°E/40°N–75°N) rr†	Nov	6 & 93	13.8	3×10^{-11}	0.44
SST(90°W–40°E/40°N–75°N) rr	Dec	6 & 94	7.4	2×10^{-6}	0.28
SST(30°W–40°E/50°N–70°N) rr	Nov	16 & 84	7.6	7×10^{-10}	0.46
SST(90°W–40°E/40°N–75°N) log(rr)	Nov	16 & 84	5.2	2×10^{-7}	0.40
SST(90°W–40°E/40°N–75°N) rr$^{0.2}$	Nov	11 & 89	7.9	2×10^{-9}	0.43
HadISST1.1(90°W–40°E/40°N–75°N) rr	Sep	10 & 106	3.7	4×10^{-4}	0.19
HadISST1.1(90°W–40°E/40°N–75°N) rr	Oct	8 & 108	4.8	5×10^{-5}	0.21
HadISST1.1(90°W–40°E/40°N–75°N) rr	Nov	3 & 113	16.1	9×10^{-9}	0.28
HadISST1.1(90°W–40°E/40°N–75°N) rr	Dec	9 & 107	4.2	1×10^{-4}	0.20
HadISST1.1(20°W–40°E/50°N–75°N) rr	Nov	6 & 110	7.5	8×10^{-7}	0.25
HadISST1.1(0°E–30°W/55°N–75°N) rr	Nov	6 & 110	6.6	6×10^{-6}	0.22
HadISST1.1(90°W–40°E/40°N–75°N) rr$^{0.2}$	Nov	5 & 111	9.8	9×10^{-8}	0.27
HadISST1.1(20°W–40°E/50°N–75°N) rr$^{0.2}$	Nov	8 & 108	6.1	2×10^{-6}	0.26
HadISST1.1(0°E–30°W/55°N–75°N) rr$^{0.2}$	Nov	6 & 110	6.5	7×10^{-6}	0.22
SLP(90°W–40°E/40°N–75°N) rr	Nov	8 & 92	20.5	1×10^{-16}	0.57
SLP(90°W–40°E/40°N–75°N) log(rr)	Nov	10 & 90	18.5	0	0.61
SLP(90°W–40°E/40°N–75°N) rr$^{0.2}$	Nov	10 & 90	18.5	0	0.64
SLP(90°W–40°E/40°N–75°N) rr^2	Nov	9 & 91	7.3	6×10^{-08}	0.36
SLP(90°W–40°E/40°N–75°N) rr$^{1.5}$	Nov	10 & 90	10.0	4×10^{-11}	0.47
SST residual (90°W–40°E/40°N–75°N) rr	Nov	20 & 80	0.6	0.91	-0.09
HadISST1.1 res.(90°W–40°E/40°N–75°N) rr	Nov	20 & 79	0.4	0.99	-0.15
SLP residual(90°W–40°E/40°N–75°N) rr	Nov	20 & 80	1.1	0.35	0.02
SST(90°W–40°E/40°N-75°N) rr–NAOI	Nov	14 & 86	6.4	1×10^{-8}	0.43
HadISST1.1(90°W–40°E/40°N–75°N) rr-NAOI	Nov	3 & 113	13.6	1×10^{-7}	0.25
SLP(90°W–40°E/40°N–75°N) rr-NAOI	Nov	8 & 92	14.3	2×10^{-13}	0.52
SST(90°W–40°E/40°N–75°N) rr	Sep-Oct	3 & 97	4.71	4×10^{-3}	0.10
HadISST1.1(90°W–40°E/40°N–75°N) rr	Sep-Oct	7 & 109	3.75	1×10^{-3}	0.14
SST(90°W–40°E/40°N–75°N) rr	Oct-Nov	15 & 85	1.23	0.26	0.03
HadISST1.1(90°W–40°E/40°N–75°N) rr	Oct-Nov	8 & 108	1.76	0.09	0.05
SST(90°W–40°E/40°N–75°N) rr	Nov-Dec	9 & 91	2.34	0.02	0.11
HadISST1.1(90°W–40°E/40°N–75°N) rr	Nov-Dec	13 & 103	2.21	0.01	0.12
SLP(90°W–40°E/40°N–75°N) rr	Sep-Oct	5 & 95	1.98	0.09	0.05
SLP(90°W–40°E/40°N–75°N) rr	Oct-Nov	6 & 94	5.19	1×10^{-4}	0.20
SLP(90°W–40°E/40°N–75°N) rr	Nov-Dec	8 & 92	3.78	7×10^{-4}	0.18

Figure 1 The prevailing SLP pattern for November 2000 (a), the 1900–2000 mean November SLP pattern (b), and the November 2000 rainfall anomalies over northern Europe according to the NCEP reanalysis (c). The rainfall is expressed in terms of percentage of the November mean and the contour intervals are 1 hPa in panel a and 25% in b. Negative values in panel (a) are shown with dashed contours, whereas dashed contours in panel (b) indicate precipitation lower than normal. Note: The rainfall from the NCEP reanalysis shows the smoothed large-scale structure, but does not capture the extreme values seen in the station records (e.g. Oslo-Blindern: Observed 279mm = 382%, whereas the NCEP reanalysis only suggests values of the order 100%).

Figure 2 Welch two-sample t-test scores for two populations of principal component values corresponding to wet and dry Novembers (a) and dry-normal (b). The dashed horizontal line marks the 5% confidence level.

Figure 3 a) Composite difference between met.no SST anomaly pattern of all the 1900–2000 November months coinciding with high and low rainfall. b) Reynolds and Smith (1994) SST anomalies of November 2000. The contour intervals are 0.25°C.

Figure 4 Time series showing the evolution of November SST anomalies (in °C) averaged over 3 different regions: 60°W–30°W/30°N–45°N, 60°W–40°W/40°N–45°N, and 50°W–10°W/40°N-55°N. a) From the Reynolds and Smith (1994) (1981–2000) data and b) from the 1900–2000 analysis discussed above (The first years were removed due to poor data quality) and the U.K. Met. Office GISST2.2 data set. Tick marks correspond to the beginning of the year.

Figure 5 Observed November rainfall amount in Oslo (grey) and predictions based on a regressional model using SST as inputs (black dashed). The R^2 is 0.46.

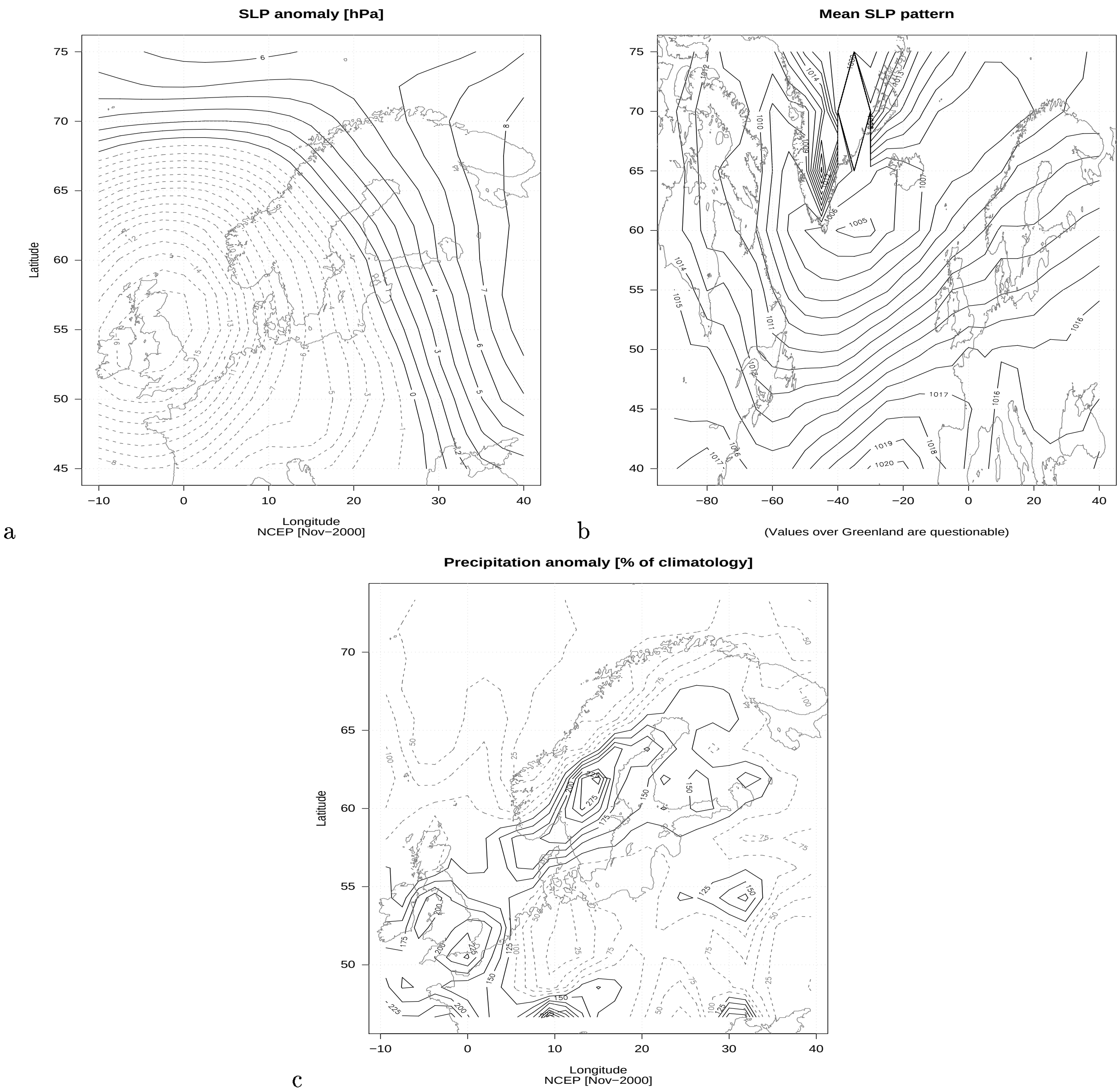
Figure 6 The same as in Figure 2a, but using SLP instead of SST.

Figure 7 The difference between composite of SLP for the wet and the dry November months.

The contour intervals are 1 hPa.

Figure 8 The prediction of the rainfall using a SLP-based regression models. The R^2 is 0.57.

Figure 9 The long-term trend in the number of wet (solid) and dry (dashed) November months per decade (running mean). The occurrence of the wet and dry events are also indicated at the bottom of the plot.



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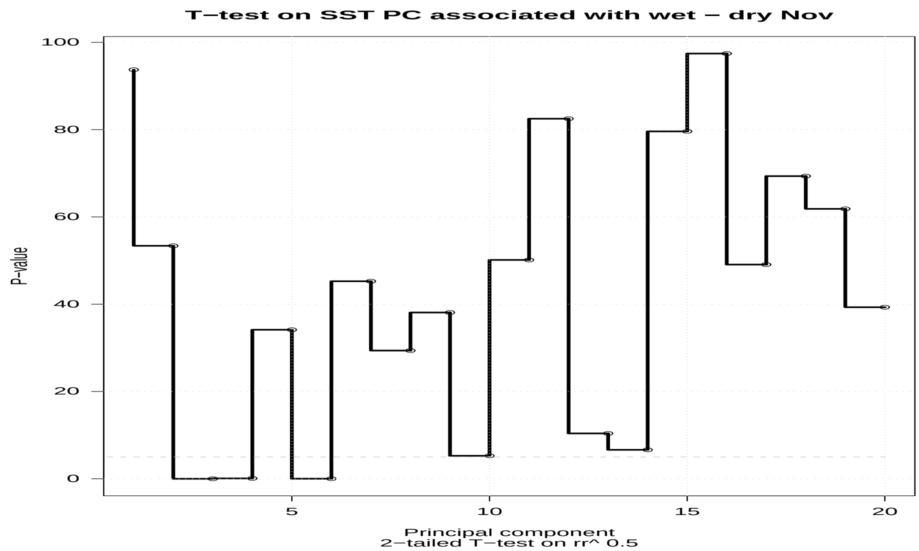
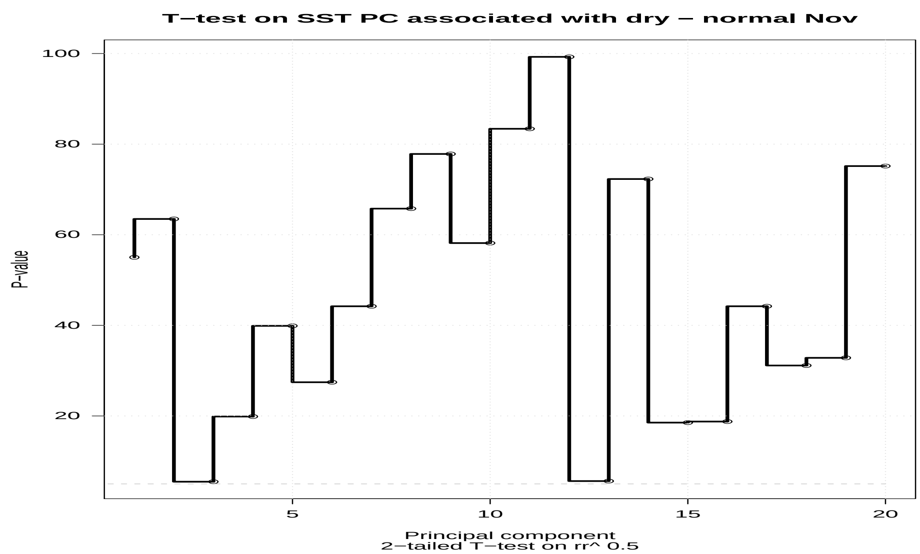
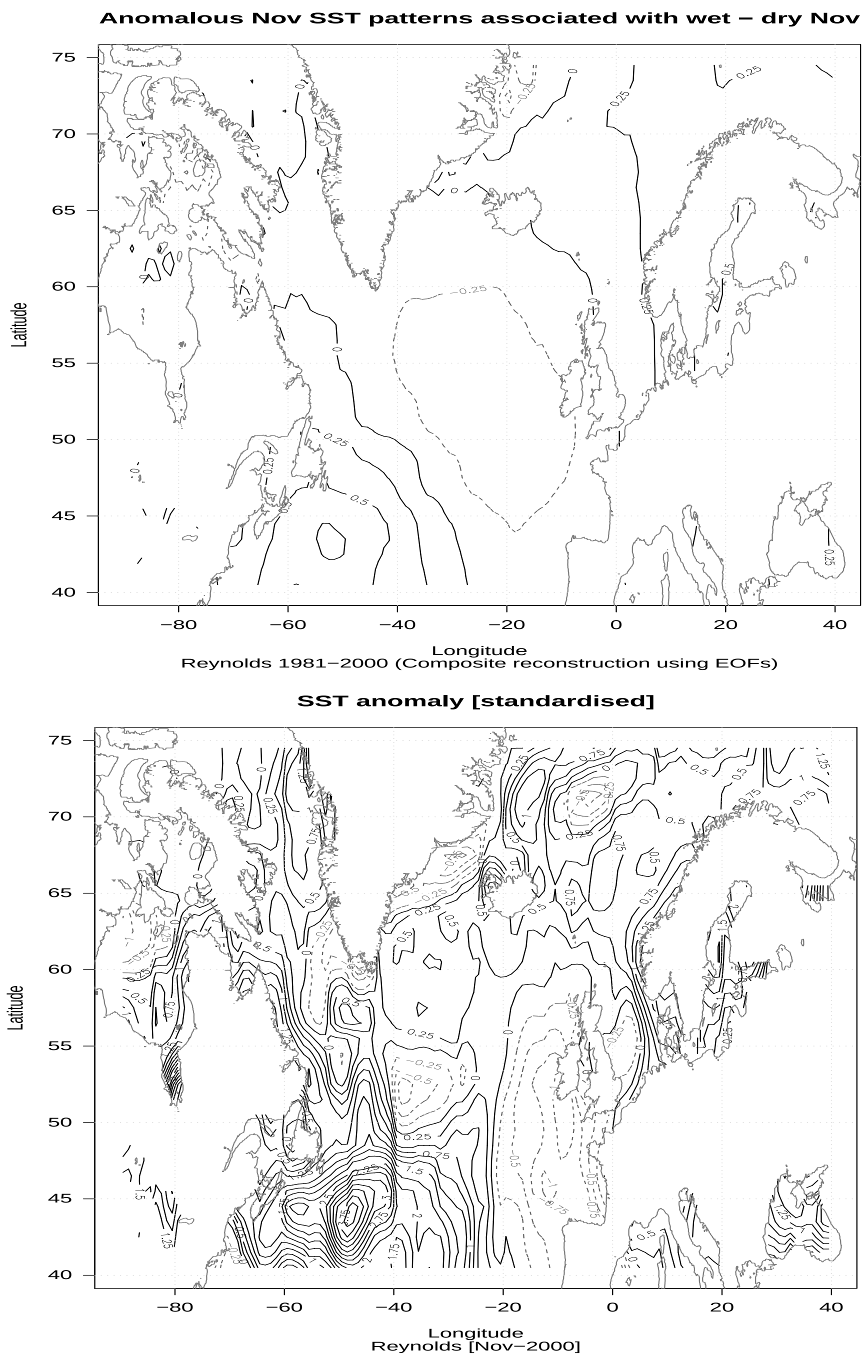


a



b

Figure 2. Welch two-sample t-test scores for two populations of principal component values corresponding to wet and dry Novembers (a) and dry-normal (b). The dashed horizontal line marks the 5% confidence level.



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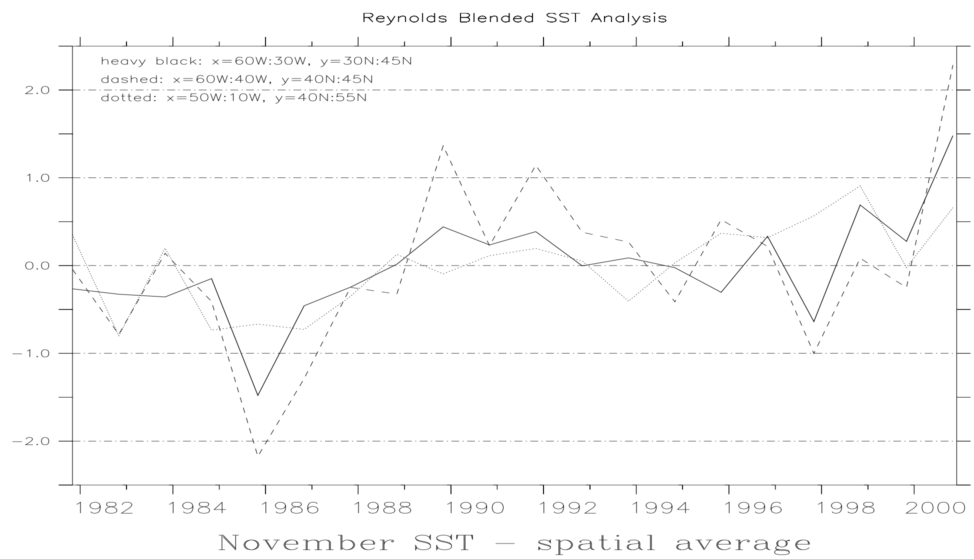
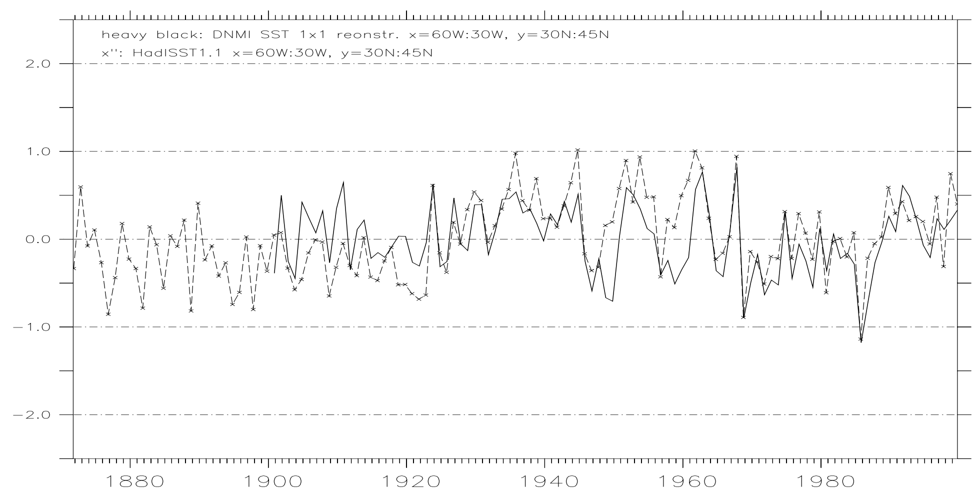
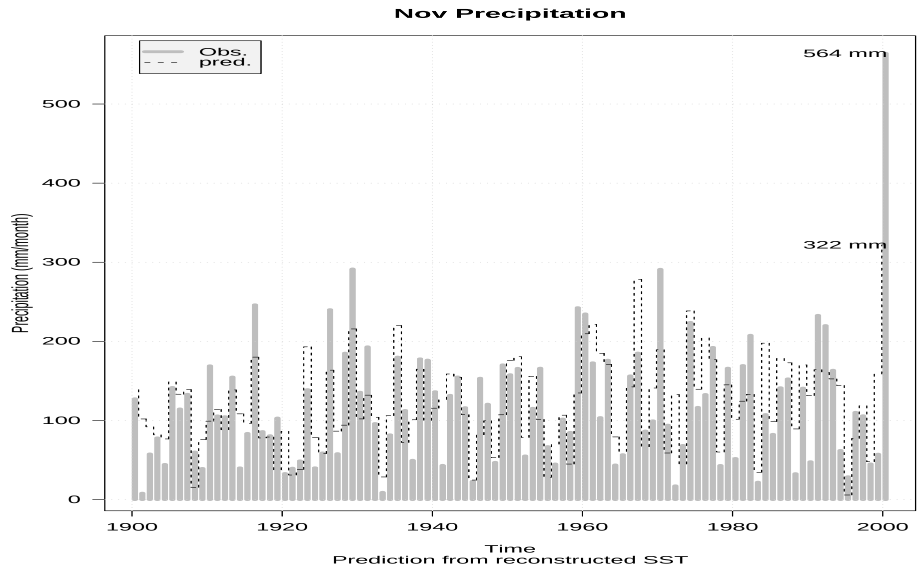


a



b

Figure 4. Time series showing the evolution of November SST anomalies (in °C) averaged over 3 different regions: 60°W–30°W/30°N–45°N, 60°W–40°W/40°N–45°N, and 50°W–10°W/40°N-55°N. a) From the Reynolds and Smith (1994) (1981–2000) data and b) from the 1900–2000 analysis discussed above (The first years were removed due to poor data quality) and the U.K. Met. Office GISST2.2 data set. Note that year 2000 is not shown in panel (b), and that the November 2000 spatial mean SST anomaly is ∼ 1.25°C higher than in November 1999. Tick marks correspond to the beginning of the year.



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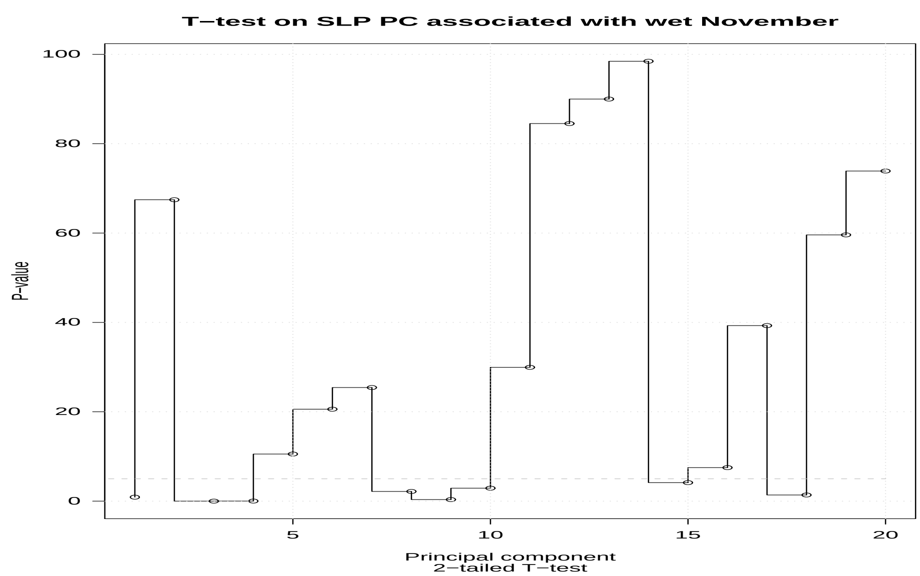


Figure 6. The same as in Figure 2a, but using SLP instead of SST.

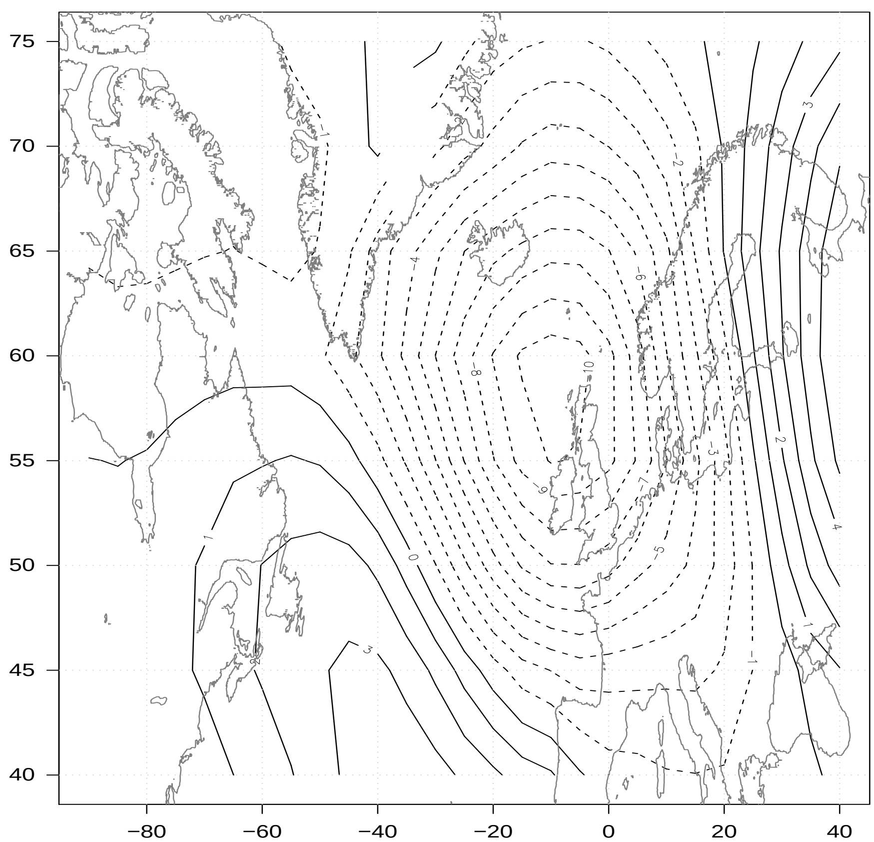
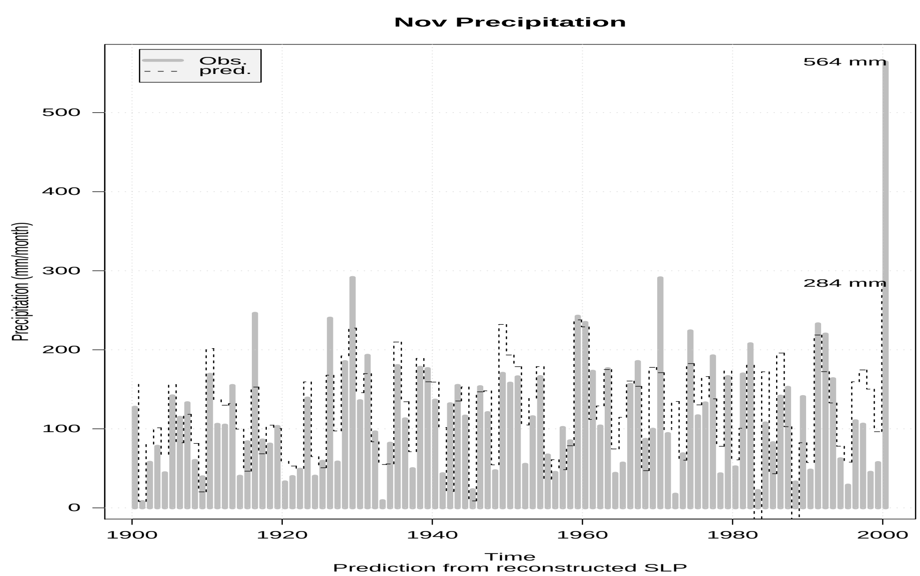


Figure 7. The difference between composite of SLP for the wet and the dry November months. The contour intervals are 1 hPa.



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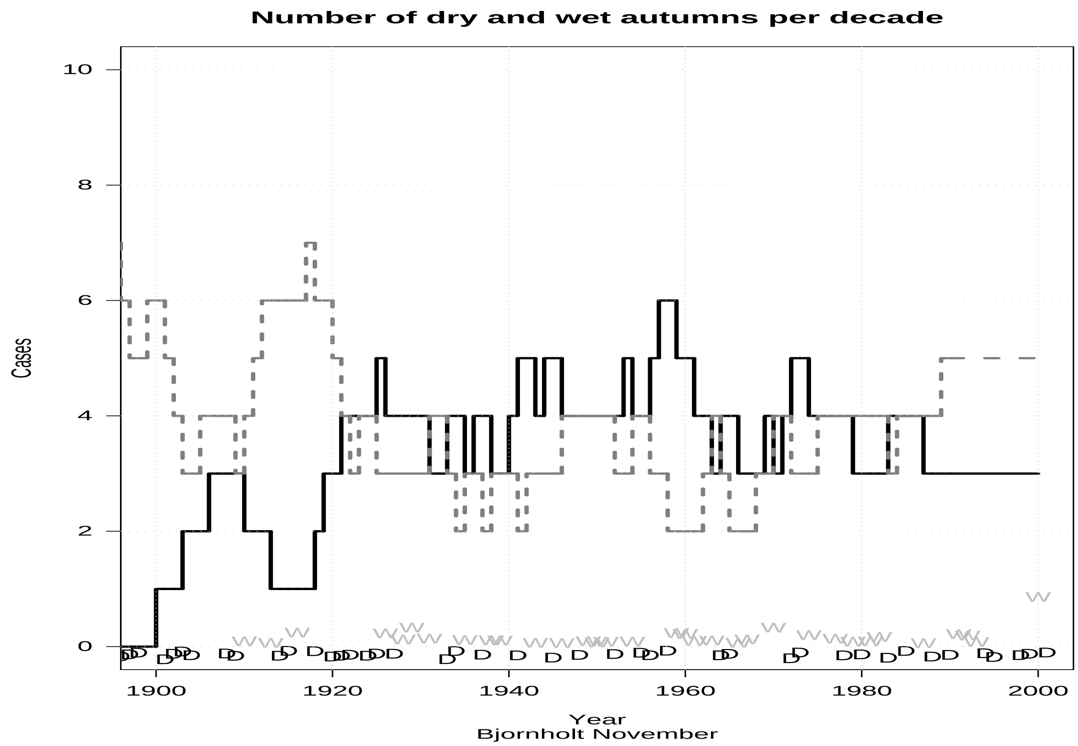

Figure 9. The long-term trend in the number of wet (solid) and dry (dashed) November months per decade (running mean). The occurrence of the wet and dry events are also indicated at the bottom of the plot.