North Atlantic SST patterns and their effect on rainfall in Norway

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Introduction

A study of the relationship between the North Atlantic sea surface temperature (SST) anomaly patterns and rainfall in southeastern Scandinavia has been performed. The starting point of the investigation was the fact that there were unprecedented data recorded for both of these variables in the fall of 2000. In southeastern Norway, the November precipitation reached values of about four times the November mean value. These extremes were accompanied by a southerly atmospheric flow, as opposed to the normal situation with westerly winds. Thus, in November 2000, Southeastern Norway was not in the usual position at the lee side of the mountains in southern Norway, and unusually high amounts of precipitation resulted. At the same time, the SSTs in a large part of the northwestern Atlantic were outside their range of reference (mean value ± the standard deviation). An analysis of the historical records of November rainfall from a number of stations in southern Norway is presented in order to explore plausible connections between rainfall amounts and the sea surface temperature anomalies in the North Atlantic Ocean.

The data

In the present study, we used homogeneous precipitation records for Bjørnholt (Oslo; 10.7°E, 60.1°N), Samnanger (Hordaland; 5.9°E, 60.5°N), Ørje (Østfold; 11.7°E, 59.5°N), and Beito (Oppland; 8.9°E, 61.2°N) for the same period (1900−2000). The monthly rainfall data were obtained from the climate data base at the Norwegian Meteorological Institute (DNMI).

Moreover, a 101−year long data record of SSTs was constructed for the period 1900−2000 by combining the SST data from COADS [*Slutz* et al., 1985], GISST2.2 [*Parker* et al., 1995], *Kaplan* et al. [1998], and *Reynolds and Smith* [1994] SSTs. The reconstruction of SST data was done by projecting a combination of past observations from the various sources onto corresponding eigenpatterns estimated from the *Reynolds and Smith* [1994] SSTs, as described by *Benestad* [2000] for the DNMI reconstruction of 2−meter temperature. This monthly data set covers the North Atlantic Ocean and the Nordic Seas, from 30°N to 80°N at a spatial resolution of one degree.

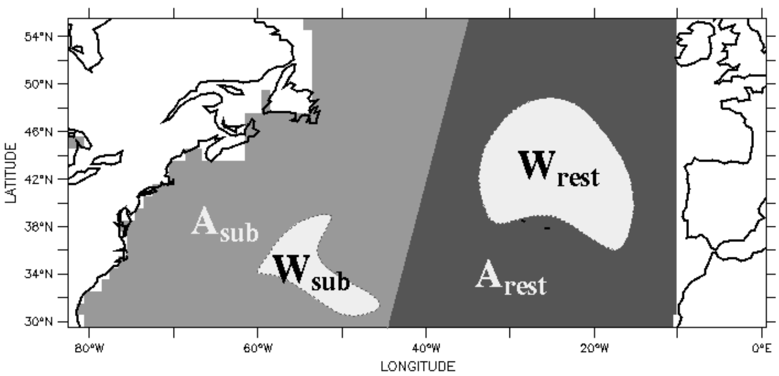

Figure 1: Sketch for the definition of the North Atlantic Asymmetry Index (NAAI), see the text for details.

We then define r_w (r_c) as the fractional region where the warm (cold) SST anomaly in November exceeds 0.5°C, *i.e.*,

$$r_w = W/A$$

where W is the area in the North Atlantic (between 30°N and 55°N) with warm anomalies ≥ 0.5°C, and A is the total area (r_c is defined analogously for cold anomalies ≤ -0.5°C). Furthermore, we divide the North Atlantic along a line that runs from 45°W at 30°N to 35°W at 55°N (see Figure 1). W_{sub} and W_{rest} denote areas with anomalously warm SSTs in the western and eastern subdomain, respectively. A_{sub}/A_{rest} are the total areas in the corresponding subdomains. For the months with $r_w \geq 0.1$, we define a warm North Atlantic Asymmetry Index ($NAAI_w$) as

$$NAAI_w = (W_{sub}/A_{sub}) / r_w$$

A cold index ($NAAI_c$) is defined analogously.

The bootstrap analysis

We define "wet", "normal" and "dry" months by normalizing the precipitation data. We also divide months by the NAAI, into predominantly "western", "symmetric" and "eastern" SST anomalies, when $NAAI > 1.2$, $0.8 \leq NAAI \leq 1.2$, $NAAI < 0.8$, respectively. The precipitation data and SST asymmetries were categorized as outlined, and the result was subjected to a bootstrap test, selecting at random 10,000 shuffled sets of the two original sets of 101 years of category entries. The results of this statistical analysis are presented in Table 1a (using $NAAI_w$) and Table 1b (for $NAAI_c$).

We found that the east/west distribution of North Atlantic SST anomalies affect the Bjørnholt rainfall in November. Warm pools in the western basin in November, and cold pools in the eastern basin, coincide with wet spells at Bjørnholt, with a confidence >99%. When the distribution of anomalies is reversed with cold anomalies in the western basin, there are frequently dry spells at Bjørnholt, also with a confidence >99%.

For the other precipitation records from southeastern Norway (Ørje and Beito), the results are the same, albeit with a lower degree of confidence. Hence, the *very high* degree of confidence in the relationship between the NAAI and Bjørnholt precipitation seems to be valid on a fairly small scale. It is difficult to attribute such a localized response (for precipitation) to such a large−scale integrated measure as the NAAI by a dynamical approach, and the quoted confidence levels for Bjørnholt of >99% may be spurious.

On the other hand, for a station in western Norway (Samnanger, not far from Bergen), no such relationship was found, as almost all combinations of categories of precipitation and SST asymmetries in the North Atlantic Ocean lacked any hints of a statistical relationship between these properties.

Bjørnholt, Oslo				
	western	symmtrc	eastern	
wet	<u>**10**</u>	3	<u>**1**</u>	14/33
neutral	5	3	6	14/29
dry	<u>**1**</u>	5	10	16/39
Samnanger, Hordaland				
	western	symmtrc	eastern	
wet	4	5	5	14/37
neutral	8	2	5	15/30
dry	4	4	7	16/33
Ørje, Østfold				
	western	symmtrc	eastern	
wet	6	4	3	13/33
neutral	7	3	4	14/29
dry	3	4	10	17/39
Beito, Oppland				
	western	symmtrc	eastern	
wet	**9**	6	**2**	17/34
neutral	5	2	6	13/29
dry	**2**	3	9	14/38

Table 1a. Distribution frequencies for precipitation *vs.* warm SST asymmetries, for years when $r_w \geq 0.1$. Numbers in <u>**bold underlined**</u>, **bold** and regular black correspond to t−tests outside the <u>**99%**</u>, **95%** and 90% confidence intervals, respectively. Remaining frequencies are in gray.

The geographical distribution of warm anomalies in the fall of 2000 does not fit into this description, since the main area where the SST anomaly is above 0.5°C is in the central North Atlantic Ocean. However, a more advanced statistical approach as the one outlined in the next section, reveals that a substantial fraction of the November 2000 precipitation at Bjørnholt may be explained by the SST anomalies. Also, if the dividing line in Figure 1 is shifted to the meridian of 45°W, the statistical relationship between precipitation and the NAAI is only slightly different than the results in Table 1. Then, the November 2000 case becomes a warm, western" SST anomaly in a "wet" November, in concord with the results from Table 1a [*Benestad and Melsom*, 2001].

Bjørnholt, Oslo				
	western	symmtrc	eastern	
wet	**1**	3	**11**	15/33
neutral	**0**	**7**	4	11/29
dry	**13**	3	**3**	19/39
Samnanger, Hordaland				
	western	symmtrc	eastern	
wet	6	6	6	18/37
neutral	6	1	7	14/30
dry	2	5	5	12/33
Ørje, Østfold				
	western	symmtrc	eastern	
wet	**1**	5	9	15/33
neutral	2	**7**	5	11/29
dry	**11**	**1**	4	19/39
Beito, Oppland				
	western	symmtrc	eastern	
wet	**1**	4	9	14/34
neutral	4	4	4	12/29
dry	**9**	5	5	19/38

Table 1b. Same as Table 1a, but for cold SST asymmetries, for years when $r_c \geq 0.1$.

Advanced analysis

In order to further explore any association between the SSTs and the precipitation over southeastern Norway, a more advanced statistical analysis was performed. A step-wise regression was used to develop multiple linear empirical models describing the November precipitation at Bjørnholt in terms of the respective SST principal components. There is a clear indication that the model is able to reproduce part of the rainfall, as around 46% of the interannual variations in the November precipitation may be related to the SST anomalies. The analysis was repeated, but with EOFs computed using the SSTs from a subdomain only (30°W − 40°E/50°N − 70°N). Again, about 46% of the November rainfall variations can be attributed to the SSTs in this region, and 323 mm of the 564 mm received at Bjørnholt in November 2000 could be accounted for by the SSTs. Further regression analysis for October, September and December also gave indications of statistically significant relationships. Hence, the relationship is not only valid for the November months.

The stepwise regression analysis was repeated for a sea level pressure (SLP) reconstruction for 1900−2000 [*Benstad*, 2000] based on data from the University of East Anglia and the NCEP reanalysis [*Kalnay* et al., 1996]. The results show that the SLP is highly correlated with the autumn rainfall over southeastern Norway. The SLP anomalies accompanying enhanced rainfall are associated with a southerly flow type, bringing in moist air masses over southern Norway. However, the SLP variations fail to account for the extreme events. 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) [*Benestad and Melsom*, 2001].

Quality of SST data

Although SST probably is the best sampled ocean variable, data with "high quality" and "relevant resolution" (preferably on the horizontal scale of mid−latitude mesoscale ocean eddies) are available only from the past 20 years or so. And even the “best” SST data, *i.e.*, radiometer data from satellites, have their shortcomings due to the lack of data that results in cloud−covered regions. (The mean cloud cover in the Atlantic sector from 30°N to 70°N is around 50% in November, according to the NCEP reanalysis.) Obviously, reconstructing a reliable 100−year long SST record is a formidable task, and the resulting reconstruction will contain errors whose magnitude, be it small or large, may not be determined.

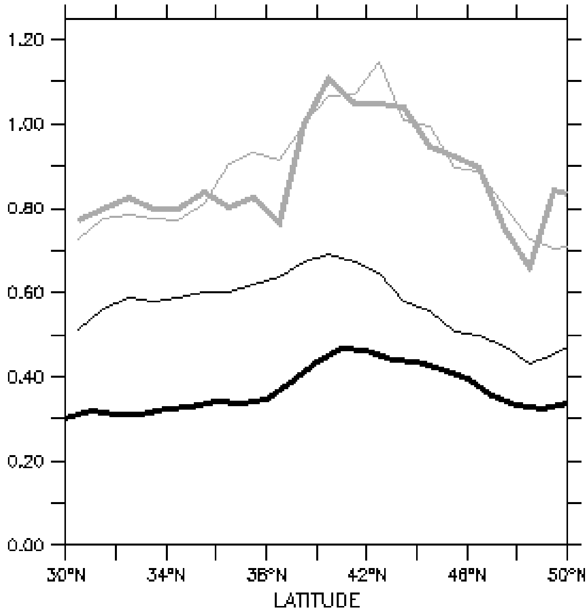

Figure 2: Zonally averaged standard deviation (StD) for the Atlantic Ocean, from four different SST data sets: DNMI reconstruction (thick black), COADS (thick gray), Reynolds (thin black), and MODAS (thin gray). Only data for the November months in the period 1993−1997 have been used. Numbers on the vertical axis are StD values in °C.

In the present approach, it is assumed that the recent SST patterns from the *Reynolds and Smith* [1994] data are representative for the patterns throughout the 20th century. This was done in order to let the “high quality” *Reynolds and Smith* data shed as much light on the SST patterns in years when data are much more sparsely distributed in space. Nevertheless, this approach has inherent problems. The main problem in the present study is that the Reynolds and Smith data cover a period in which the North Atlantic Oscillation signal has a strong bias compared to its 20th century mean.

In an attempt to assess the quality of the DNMI reconstruction, the NAAI was also computed from a data set of *in situ* observations that was partially filled in space using an iterative Laplacian solver, as described by *Melsom* et al. [2001]. (The original dataset was the COADS one degree resolution SST product [*Woodruff* et al., 1985] for the period 1960−1997). Due to the higher variability in the COADS data (see Figure 2), the limit for the SST anomaly was set to ±1°C in the computation of the NAAI. For twelve of the years, the November $NAAI_w$ was defined in both sets. Of these, six instances were of the same asymmetry categories and the remaining six were shifted to the east in the COADS product. For the period 1960−1980, these numbers were six instances with four to the east. Hence, in 1981−1997, there were six mutual years, with two instances shifted to the east. This may indicate a slight deterioration in the reliability of the SST patterns in the years that precede the *Reynolds and Smith* [1994] data. However, inspection reveals that “noisy data” have a significant impact on the large magnitude of the SST standard deviation in the COADS product that is seen in Figure 2. Due to the contribution of “noise”, the COADS product may not be well suited for determination of a quantity such as the NAAI. Moreover, the $NAAI_c$ from these sets and this period compares better, with sixteen mutual years, twelve of which belong to the same asymmetry categories. Also, no systematic east/west shift of the SST asymmetries can be detected in the cold index.

In Figure 2 the variability in the DNMI reconstruction is also compared to the variability in the *Reynolds and Smith* [1994] data, and the Modular Ocean Data

Assimilation System (MODAS) data [*Fox* et al., 2001]. The latter is based on remote sensing data only (multi−channel SST). We suspect that the MODAS product captures SST variability related to circulation features on a smaller scale that the other data sets, leading to the relative high variability. The most striking feature is the low variability of the DNMI reconstruction, which may well be overly smooth. However, in the present context, it is the spatial distribution of SST anomalies that affect the results, not the magnitude. Also, we note that the zonal variations in the SSTs' standard deviation are qualitatively similar for all data sets, with a maximum in a latitudinal band from about 40°N to 45°N. This maximum is attributed to the variability in the pathway of the Gulf Stream Extension.

References

Benestad, R. E., 2000: Analysis of gridded sea level pressure and 2−meter temperature for 1873−1998 based on UEA and NCEP re−analysis II. *Klima* **03/00**. DNMI, P.O.Box 43, N−0313 Oslo, Norway.

Benestad, R. E. and A. Melsom, 2001: Is there a link between the unusually wet autumns in southeastern Norway and SST anomalies? *Tellus* (submitted).

Fox, D. N., W. J. Teague, C. N. Barron, M. R. Carnes and C. M. Lee, 2001: The Modular Ocean Assimilation Data System (MODAS). *J. Atm. Ocean Tech.* (in press).

Kalnay, E. and 21 others, 1996: The NCEP/NCAR 40−year reanalysis project. *Bull. Am. Meteor. Soc.*, **77**, 437−471.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumentahl and B. Rajagopalan, 1998: Analyses of global sea surface temperature 1856−1991. *J. Geophys. Res.*, **103**, 18,567−18,589.

Melsom, A., H. Drange and R. E. Benestad, 2001: Propagating SST anomalies in COADS and MICOM−NERSC. *NOClim Tech. Rep.*, **1**, ed.: S. S. Hjøllo (Bjerknes Center), 29−36.

Parker, D. E., M. Jackson and E. B. Horton, 1995: The 1961−1990 GISST2.2 sea surface temperature and sea−ice climatology. *Clim. Res. Tech. Note* **63**, Hadley Centre, Meteorological Office, Bracknell.

Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analysis using optimum interpolation. *J. Climate*, **7**, 929−948.

Skeie, P. and N. G. Kvamstø, 2000: Atmospheric response to variations in the Labrador Sea ice−cover as indicated by ensemble simulations with ARPEGE. *RegClim Gen. Tech. Rep.*, **4**, ed.: T. Iversen and B. A. Høiskar (NILU), 135−138.

Slutz, R. J., S. J. Lubker, J. D. Hiscox, S. D. Woodruff, R. L. Jenne, P. M. Steurer and J. D. Elms, 1985: Comprehensive ocean−atmosphere data set; Release 1. *Tech. Rep. Clim. Res. Prog.*, Boulder, CO.

Woodruff, S. D., H. F. Diaz, J. D. Elms and S. J. Worley, 1985: COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields. *Phys. Chem. Earth*, **23**, 517−527.