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**Effect of year-to-year  
variations in climate on  
trends in acidification**

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**Abstract**

Climatic variations potentially mask long-term trends in acidification of surface waters. High inputs of seasalts due to severe storms can cause temporary decreases in ANC. Temperature and moisture may affect nitrate leaching. Concentrations of dissolved organic carbon are also potentially related to climate. The North Atlantic Oscillation provides a general index of climatic conditions in northwestern Europe. Although variations in the NAO index can account for some of the observed trends in surface water chemistry at sites in the UK, it does not appear to be a good explanatory factor for sites in Norway. More research is necessary to discover which climatic factors best explain natural variations in surface waters.

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CONVENTION ON LONG-RANGE  
TRANSBOUNDARY AIR POLLUTION

INTERNATIONAL COOPERATIVE PROGRAMME ON  
ASSESSMENT AND MONITORING OF ACIDIFICATION  
OF RIVERS AND LAKES

**Effects of year-to-year variations in climate on  
trends in acidification**

Note prepared for the ICP Waters, Task Force meeting,  
October 2000 Riga, Latvia

## **Preface**

At the 15th ICP Waters Task Force meeting held 6-8 October 1999 in Pallanza, Italy, the Programme Centre was asked to evaluate the effects of climatic variations on trends in the ICP Waters data. The evaluation was to be in the form of a note to be prepared with the assistance of the UK and presented to the TF meeting in 2000. A draft of this note was presented at the 16<sup>th</sup> Task Force Meeting held October 2000 in Riga, Latvia. This report is the final revised version of that note.

Oslo, December 2000

Brit Lisa Skjelkvåle

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## Summary

The purpose of this note is to evaluate changes in seasalts (chloride), nitrate and dissolved organic carbon (DOC) concentrations in Norwegian surface waters to see if the relationships found in the UK-AWMN also hold for Norway, and therefore might be of general importance for the entire ICP Waters dataset.

Variations in climate may mask ongoing trends in acidification due to changes in acid deposition. The North Atlantic Oscillation (NAO) provides an overall indicator of climatic conditions in the North Atlantic region. The NAO index is defined as the atmospheric pressure difference between the Azores (usually a high) and Iceland (usually a low). High values of the NAO index are high pressure gradients, and thus associated with relatively warm, wet weather, dominated by strong southwesterly and westerly air flows in the North Atlantic. Storms tend to be more frequent during high NAO index conditions.

Although storms with high inputs of seasalt cause temporary acidification in near-coastal areas, variations in chloride concentrations are not well explained by the monthly NAO index. The index is probably too coarse to be a good measure of storminess.

Temperature and soil moisture can both be expected to influence retention and release of nitrate in terrestrial catchments. Variations in the winter NAO index, however, do not explain nitrate concentrations in surface waters in Norway. The climatic control on nitrogen processes at the catchment scale requires further research.

In the 1990s there has been a general increase in dissolved organic carbon (DOC) concentrations in many surface waters in both the UK and Norway. This increase is probably due in some way to the climatic conditions in the 1990s, which were characterised by generally warmer temperatures. Again the NAO index is not a good explanatory measure of the variations in DOC, and further research is necessary to discover the factors that control the variations in DOC in surface waters.

The explanation of variations in seasalts, nitrate and DOC in surface waters is related to factors in the catchment such as hydrological condition, existence of snowpack, and acidification status of the soils. Unravelling of these factors requires detailed information on catchment hydrological conditions as well as water samples collected at weekly or better frequency. In general the ICP-Waters network is not well suited for this detailed type of analysis.

In conclusion it is clear that the data from the UK-AWN show that climatic variations affect trends in acidification during the 10-year period 1988-1998. The same analysis applied to coastal and inland sites in Norway, however, did not reveal statistically significant relationships. Climatic variations of short- and medium-term (0-10 years) duration can influence long-term trends in some areas.

# 1. Background

An analysis of 10-years' monitoring data from the UK Acid Waters Monitoring Network (UK-AWMN) indicated that there were statistically significant correlations between decadal variations in climate (temperature and precipitation) and the concentrations of seasalts (for example, chloride), nitrate and dissolved organic carbon (DOC) at some sites in the UK (Evans and Monteith 2000; Monteith et al. 2000). These variations in climate may mask ongoing trends in acidification due to changes in acid deposition.

The variations in climate were placed in context of the North Atlantic Oscillation (NAO), a frequently-used overall indicator of climatic conditions in the North Atlantic region in general (Bjerknes 1964, Hurrell 1999, Rodwell et al. 1999). The NAO index is defined as the atmospheric pressure difference between the Azores (usually a high) and Iceland (usually a low). High values of the NAO index are high pressure gradients, and thus associated with relatively warm and wet winters, dominated by strong southwesterly and westerly air flows in the North Atlantic. Storms tend to be more frequent during high NAO index conditions.

Evans and Monteith (2000) reasoned that

1. winters with high values for the NAO index had higher frequency of storms and seasalt deposition, and thus waters in the UK should have higher concentrations of Cl;
2. winters with high values for the NAO index were warmer, thus permitting more retention of nitrogen and thus waters should have lower concentrations of nitrate in late winter;
3. the general trend of increasing concentrations of dissolved organic carbon (DOC) at the UK sites was due to increased decomposition of terrestrial organic matter in turn the result of the generally higher temperatures during the 1990's, especially in the summer.

Variations in seasalts, nitrate and DOC during the 1990's apparently mask trends in acidification in waters in the UK-AWMN. As several of these sites are also in the ICP Waters programme, this may explain the lack of trends in sulphate in the UK sites reported in the regional trend analysis of Stoddard et al. (1999) and Skjelkvåle et al. 2000).

The relationships between NAO, temperature and precipitation, on the one hand, and variations in chemical conditions in surface waters on the other, should also be found in near-coastal parts of southern Norway, because Norway belongs to the same climatic region as the UK. The purpose of this note is to evaluate changes in seasalts (chloride), nitrate and dissolved organic carbon (DOC) concentrations in Norwegian surface waters to see if the relationships found in the UK-AWMN also hold for Norway, and therefore might be of general importance for the entire ICP Waters dataset.

## 2. Norwegian data

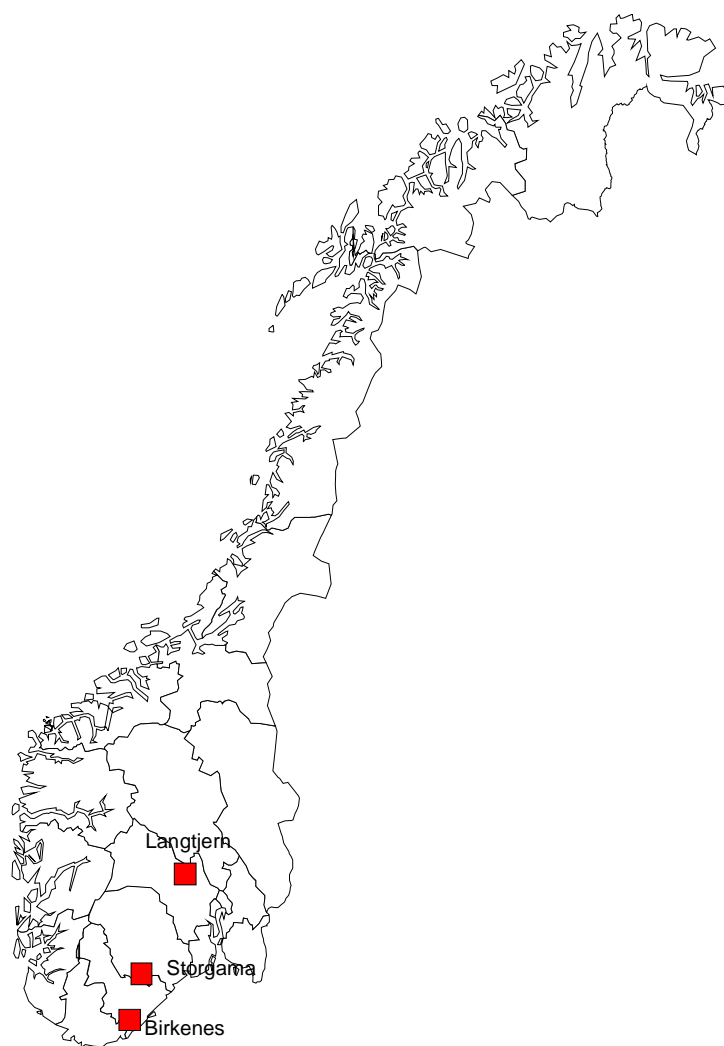
Data from the Norwegian national acid deposition monitoring programme were used for this analysis (SFT 1999). The water data are of two types:

1. About 100 lakes sampled once annually each autumn over the period 1986-1999; the lakes are located over all of Norway and grouped into 10 geographic regions (Figure 1). For this analysis the means within each group were used.
2. Three calibrated catchments (Birkenes, Storgama, and Langtjern) sampled approximately weekly over the period 1974/75 – 1999 (Figure 2). For this analysis the volume-weighted monthly mean and annual mean concentrations were used.



**Figure 1.** Map of Norway showing locations of lakes sampled each autumn, and the grouping into 10 regions. Region II = southeastern Norway; region IV = southernmost Norway; region V = southwestern Norway.





**Figure 2.** Map of Norway showing locations of the three calibrated catchments.

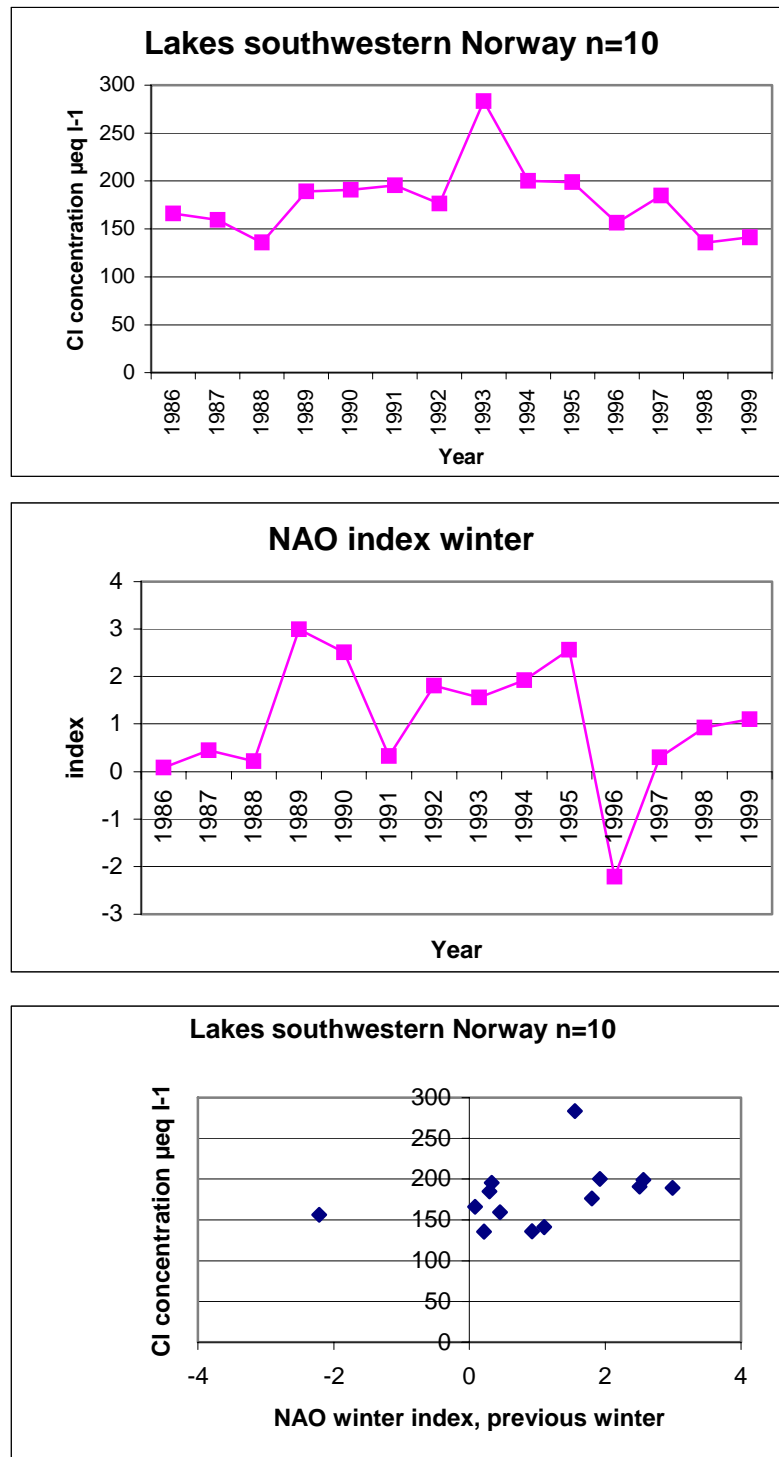
## 3. Results

### 3.1 Seasalts

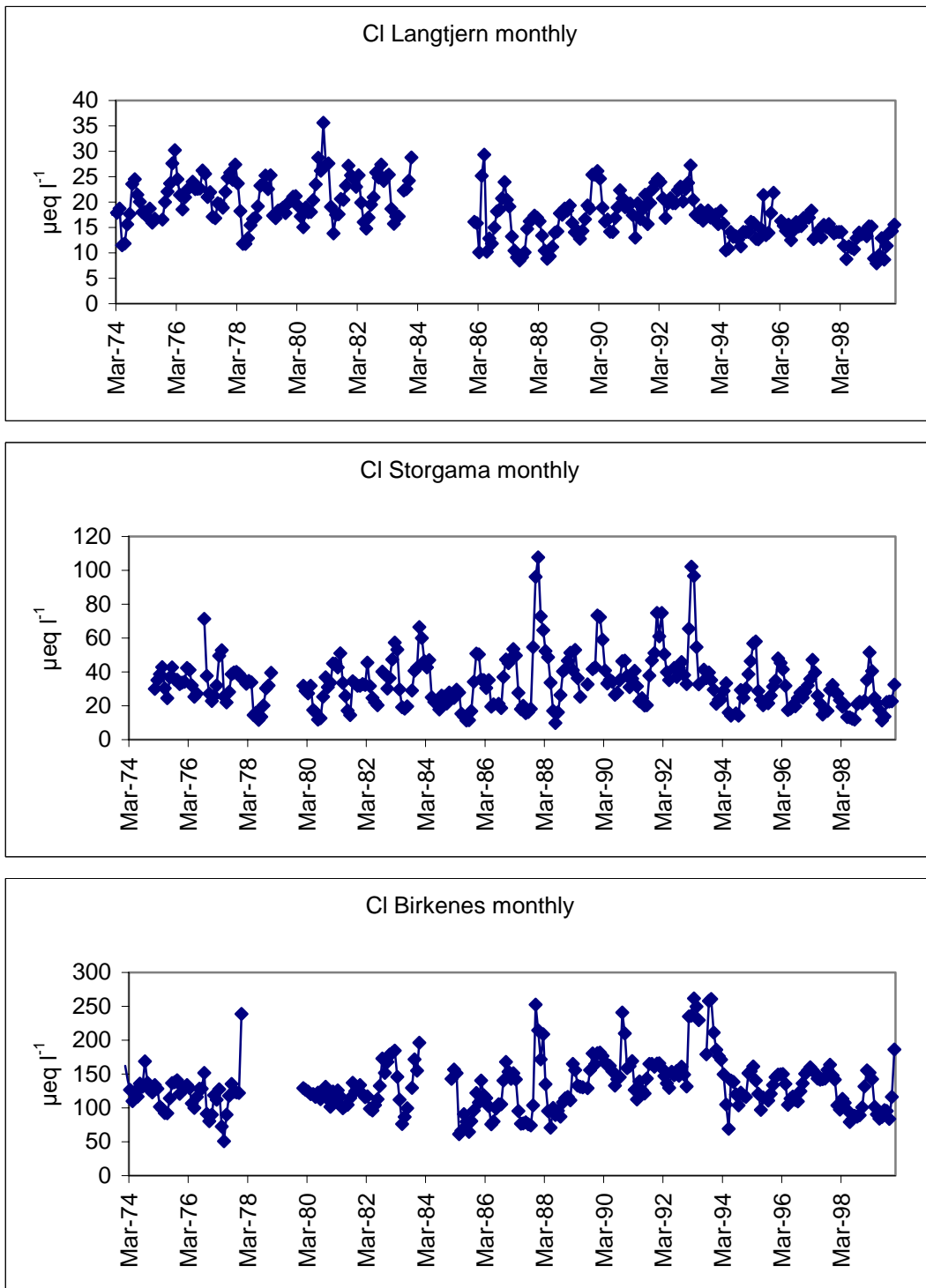
Chloride concentrations indicate the influence of seasalts. Lakes in southwestern Norway have the highest concentrations Cl, and thus this region is most likely to reflect changes in seasalt inputs. For the period 1986-1999 chloride concentrations were highest in the autumn 1993 samples (Figure 3). This peak is the aftermath of the exceptionally intense storm in January 1993, which caused severe episode of acidification and documented adverse effects to fish (Hindar et al. 1994). The data for the entire 13-year period, however, indicate no relation between the winter NAO index (December-March) and the concentration of Cl measured in the lakes the following autumn (Figure 3).

Chloride concentrations at the 3 calibrated catchments are highest at the coastal site Birkenes, and decrease inland (Figure 4). The exceptional storm of January 1993 is also seen in the record at Birkenes, and to a lesser extent at Storgama. Although the Cl concentrations appear to be somewhat higher during the years 1988-1994 at Birkenes, there is no significant correlation between chloride concentration in March (volume-weighted mean) and the winter NAO index at any of the 3 sites (Figure 5).

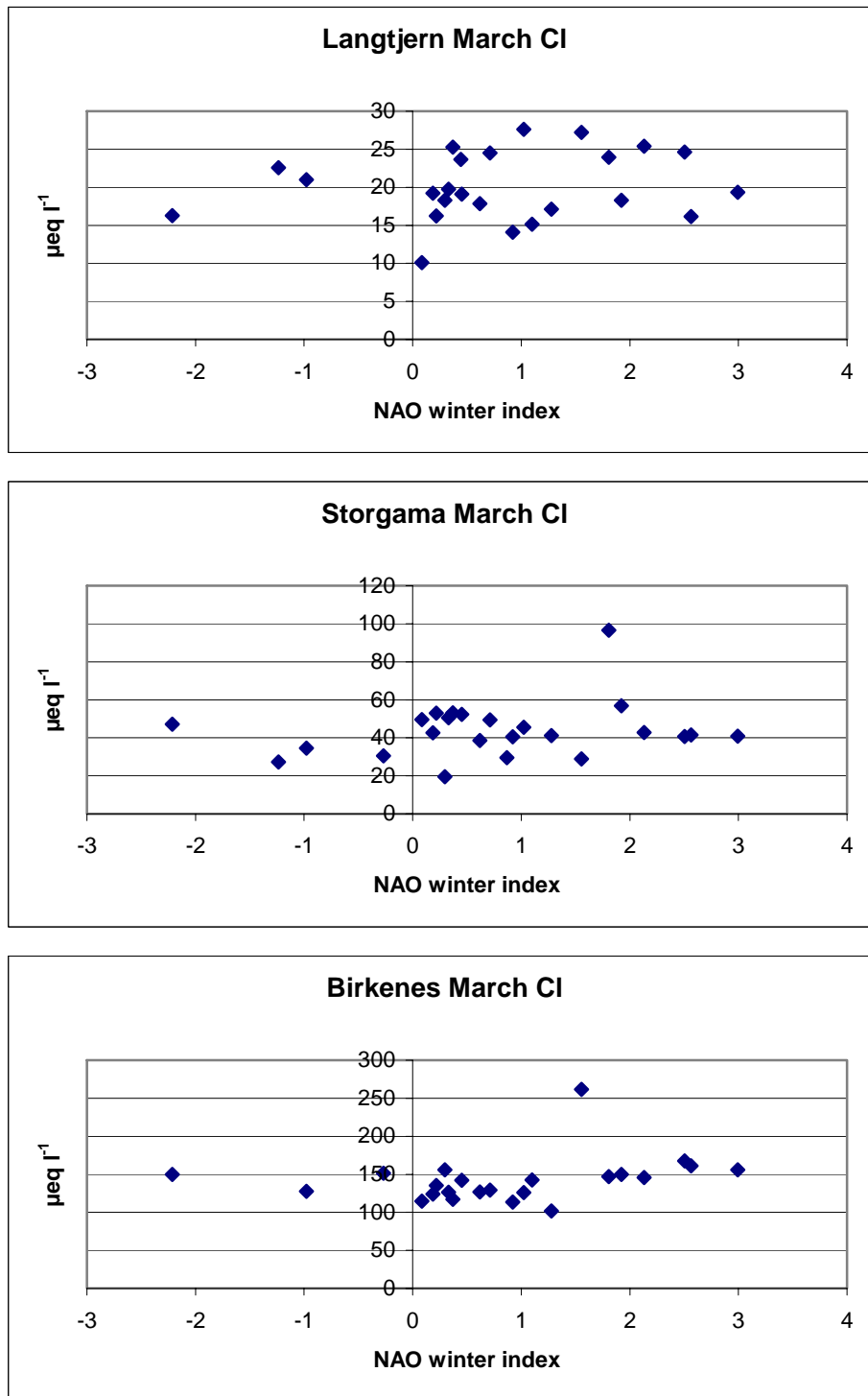
Going to finer time resolution at Birkenes still does not give a significant relationship between NAO index and Cl concentrations in runoff (Figure 6). Here the monthly data for individual months (rather than the winter index) are used.



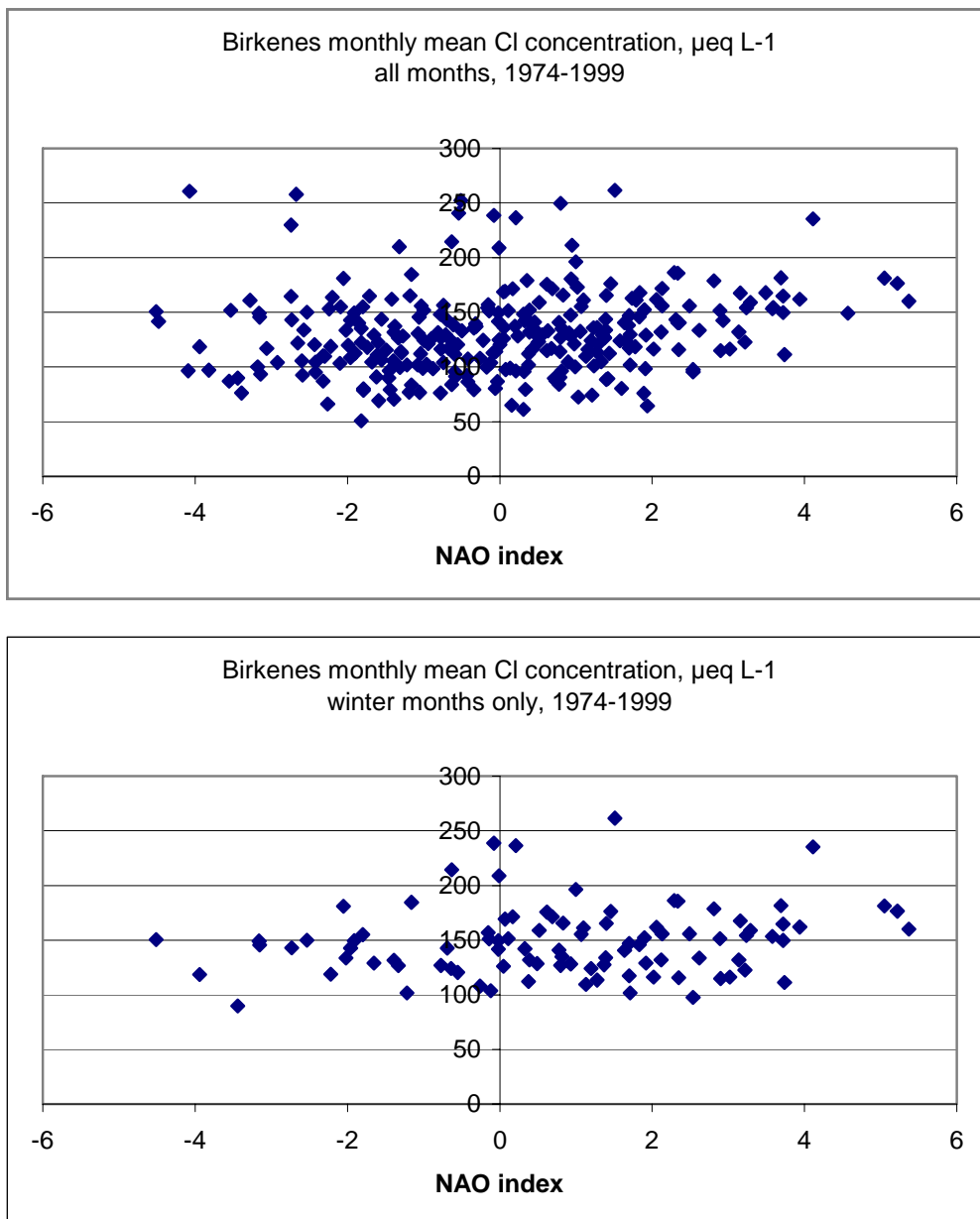
**Figure 3.** Relationship between seasalts and NAO index for lakes in southwestern Norway. Top panel: mean concentration of chloride in the 10 lakes sampled autumn. Middle panel: NAO index winter (December-March) (data from University of East Anglia, Climate Research Unit; <http://www.cru.uea.ac.uk/cru/data/nao.htm>). Bottom panel: scatter plot of Cl concentration against NAO winter index. The correlation is not significant.



**Figure 4.** Monthly volume-weighted concentrations of chloride in runoff at 3 calibrated catchments in southern Norway. Data from the Norwegian national monitoring programme (SFT 1999).



**Figure 5.** Scatter plot of Cl concentration in March samples (monthly volume-weighted mean) at the 3 calibrated catchments against NAO winter index for the period 1974-1999. The correlations are not significant.

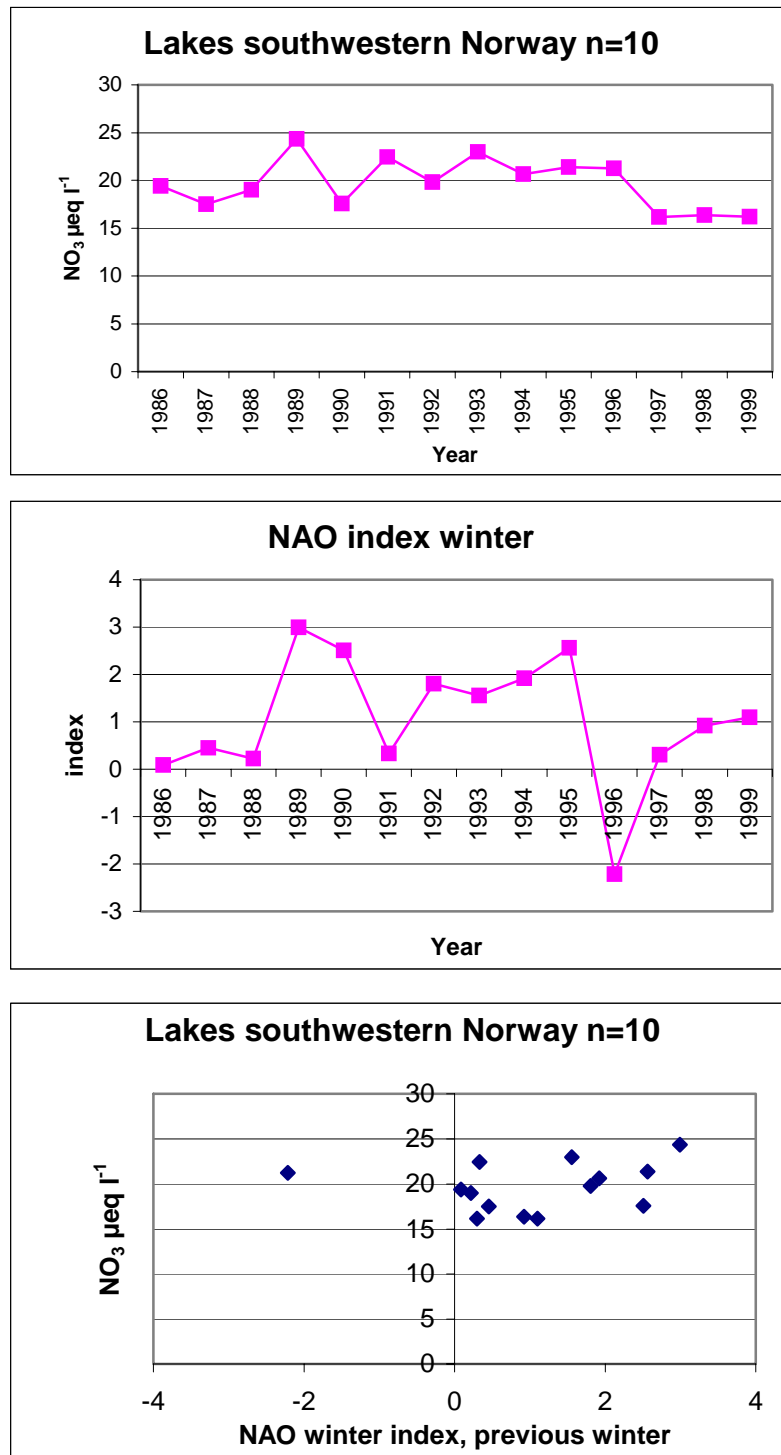


**Figure 6.** Scatter plot of Cl concentration in runoff at Birkenes (monthly volume-weighted mean) against NAO monthly index for the period 1974-1999. Top panel: all months. Bottom panel: December-March month only. The correlations are not significant.

### 3.2 Nitrate

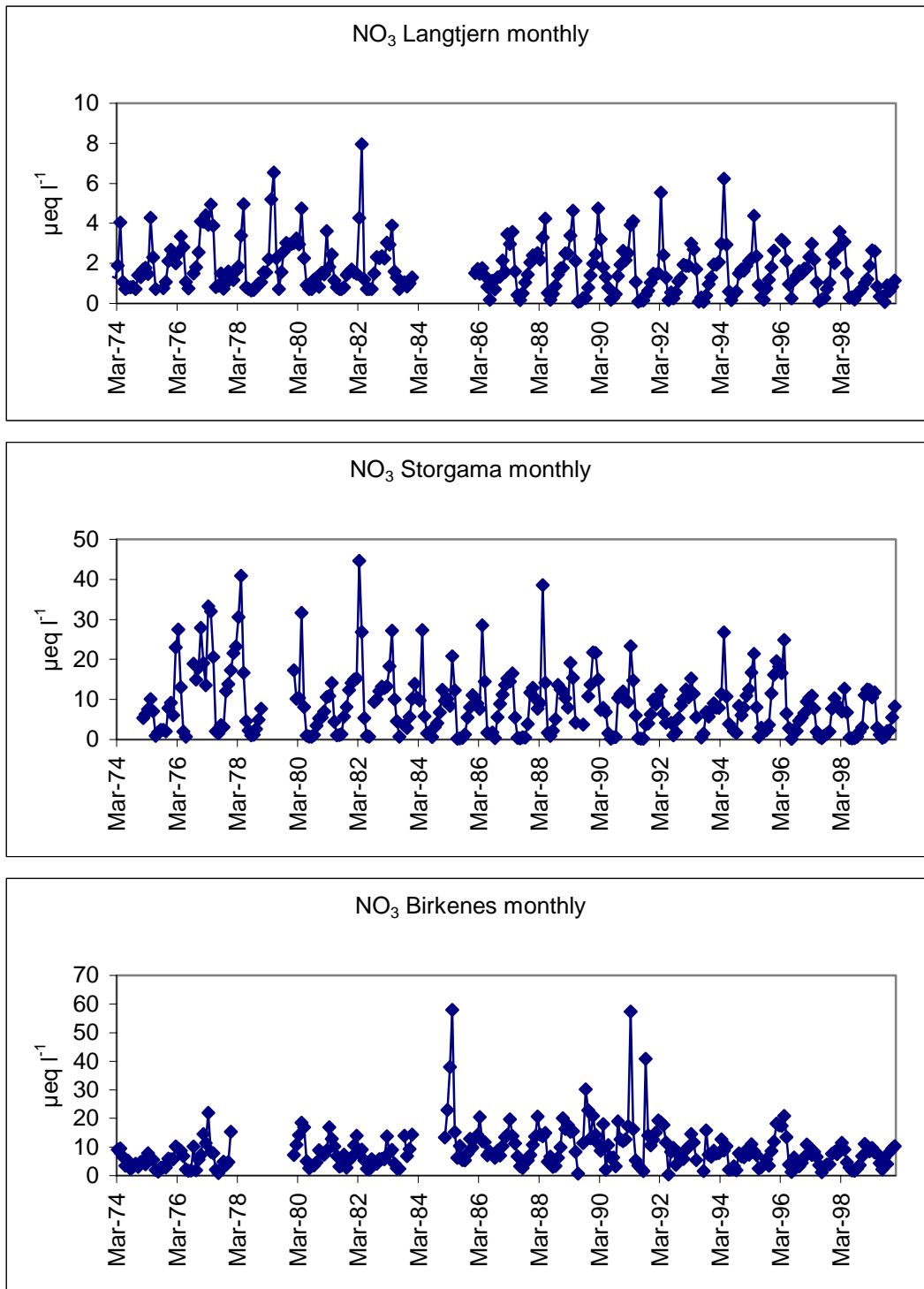
Nitrate concentrations are also generally highest in lakes in southwestern Norway. This region is dominated by heathlands and receives the highest deposition of nitrogen (due to both high concentrations as well as high amounts of precipitation) and has the highest leaching of nitrate (in terms of fraction of deposited N) (Henriksen and Brakke 1988, Henriksen et al. 1997). Response in nitrate concentrations as the result of climatic variations could be expected to be most pronounced in this region. During the 13-year period, however, there have not been any clear trends in nitrate concentrations in the lakes; if anything the levels have decreased somewhat during the past 3 years (Figure 7). Thus there is also no significant correlation with the winter NAO index (Figure 7).

The nitrate data from the calibrated catchments show clear seasonal patterns with highest concentrations during the late winter and lowest during the summer (Figure 8). An analysis of the 25-year record from these 3 catchments indicates no significant changes at Birkenes and Langtjern, but an increased retention of nitrogen during the summer at Storgama (SFT 1999). The correlations between March  $\text{NO}_3$  concentration and winter NAO index are not significant (not shown).



**Figure 7.** Relationship between nitrate concentration and NAO index for lakes in southwestern Norway. Top panel: mean concentration of nitrate in the 10 lakes sampled autumn. Middle panel: NAO index winter (December-March). Bottom panel: scatter plot of NO<sub>3</sub> concentration against NAO winter index. The correlation is not significant.





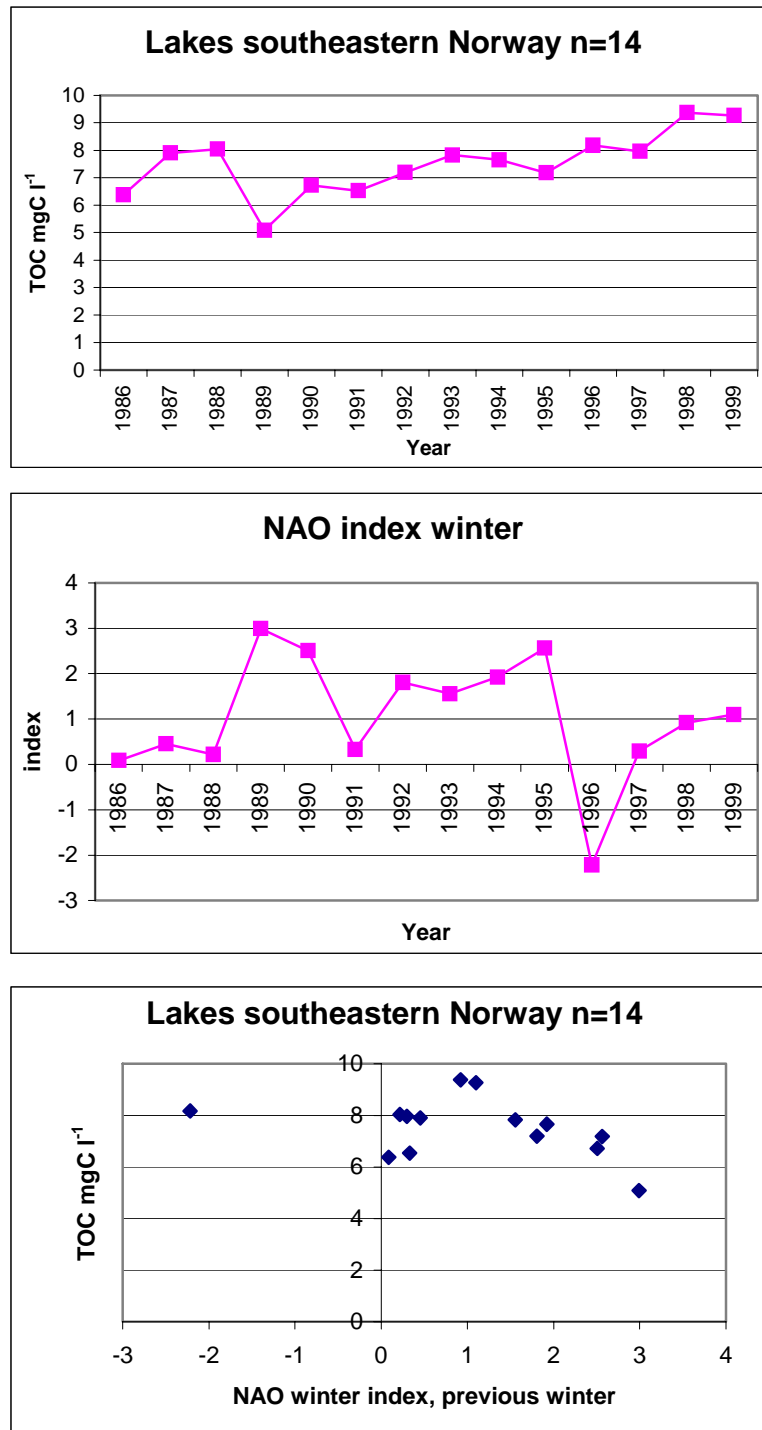
**Figure 8.** Monthly volume-weighted concentrations of nitrate in runoff at 3 calibrated catchments in southern Norway. Data from the Norwegian national monitoring programme (SFT 1999).

### **3.3 Total organic carbon.**

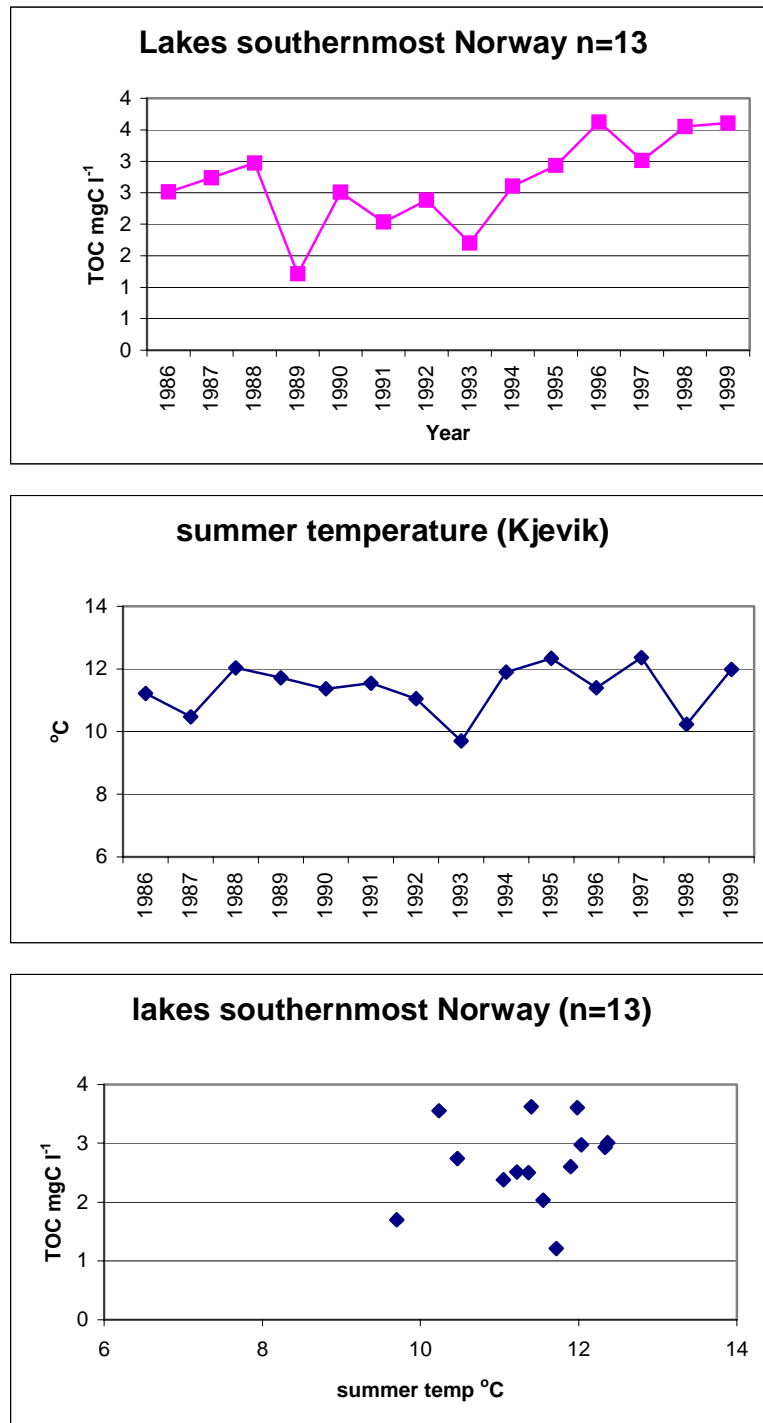
Concentrations of total organic carbon (TOC) have increased significantly in Norwegian surface waters since the late 1980's (SFT 1999). TOC levels are highest in waters in the eastern part of the country. The increasing trend is similar to that found in upland waters in the UK (Evans and Monteith 2000). (In Norway the analytical method for organic carbon does not involve filtering the samples, but in these waters most of the TOC is in the dissolved form. Thus TOC is quite comparable to DOC).

As Evans and Monteith 2000) point out, the increase in TOC has occurred both at sites receiving significant acid deposition and also at the relatively clean sites. There does not appear to be any relation to acidification. The fact that the increase has been synchronous in both the UK and Norway indicates that it is caused by some regional phenomenon most likely associated with climate. But as Evans and Monteith 2000) found in the UK, there is no apparent relation to the NAO index (Figure 9).

Evans and Monteith 2000 suggest that higher summer temperatures of the late 1990's may be the cause of the increasing TOC levels. This explanation does not appear to work for lakes in southernmost Norway, as TOC levels have increased but there has been no systematic trend in summer temperature, and thus no significant correlation between summer temperature and TOC levels (Figure 10). For the 3 calibrated catchments there is also no significant correlation between summer temperature and TOC levels (not shown).



**Figure 9.** Relationship between total organic carbon (TOC) concentration and NAO index for lakes in southeastern Norway. Top panel: mean concentration of TOC in the 14 lakes sampled autumn. Middle panel: NAO index winter (December-March). Bottom panel: scatter plot of TOC concentration against NAO winter index. The correlation is not significant.



**Figure 10.** Relationship between total organic carbon (TOC) concentration and summer temperature for lakes in southernmost Norway. Top panel: mean concentration of TOC in the 13 lakes sampled autumn. Middle panel: summer temperature (May-November) at the meteorological station at Kjevik (Kristiansand airport) (DNMI station 39040) (data from the Norwegian Meteorological Institute). Bottom panel: scatter plot of TOC concentration against summer temperature. The correlation is not significant.

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## 4. Discussion

It is clear that variations in climate can affect surface water chemistry. Processes in terrestrial catchments such as uptake of mineral nutrients by plants, decomposition of organic matter in soil, and release of base cations by chemical weathering are all affected by both temperature and moisture. In addition the input of ions from seasalts is related to the frequency and intensity of storms. All these factors can influence long-term trends in acidification in sensitive waters.

The North Atlantic Oscillation index offers a potential overall measure of climatic conditions in the North Atlantic and adjacent land regions such as the UK and western Scandinavia. The NAO influences temperature, wind and precipitation. It is useful to test if the NAO index can explain observed variations in freshwater chemistry in the ICP-Waters sites as well as the more extensive data held at the national level.

Trend analyses of monitoring data collected during the past 10-25 years indicate significant response to changes in acid deposition, especially due to the major declines in emissions and deposition of sulphur during the late 1980's and 1990's (e.g. Stoddard et al. 1999, Skjelkvåle et al. 2000, Skjelkvåle et al. 1998, Kopáček et al. 1998, Wilander 1998). The general pattern of decreasing concentrations of sulphate, decreasing concentrations of base cations and increasing acid neutralising capacity (ANC) observed in many areas of Europe and eastern North America (Stoddard et al. 1999) is only partially seen in data from the UK (Evans and Monteith 2000). This is in part because the major decrease in S deposition in the UK occurred already in the early 1980's, before the UK AWMN was in place. In several cases in the UK where surface water records go back to the 1970's, however, there has been clear recovery with decreased SO<sub>4</sub> concentrations and increased ANC and/or pH (Harriman et al. 1995, Tipping et al. 1998, Wright et al. 1994).

Regional increases in DOC (or TOC) levels in surface waters during the 1990's have been reported from many areas, including relatively pristine waters in the UK and Norway. This general trend is most likely due to regional variations in climate. There does not appear to be any simple explanation for the increased DOC levels, however, as they are not related to any single climatic variable such as summer temperature, nor are they related to the index of NAO. This does not mean, however, that the increased DOC levels are not the result of climatic variations. It may be that the appropriate set of climatic variables has not yet been tested. For example, it is conceivable that there are substantial delays in the response of the terrestrial ecosystem, such that increased DOC levels might appear first the year following a warm summer, or as a result of several warm winters in a row. Certainly more research is needed on the role of climate in influencing DOC concentrations in surface waters.

Nitrate concentrations in surface waters in regions receiving significant deposition of nitrogen have for many years been predicted to increase, yet available long-term monitoring data from national and international programmes give a generally mixed picture. Here again climate can play an important moderating role, and the data from the UK Acid Waters Monitoring Network suggest that years with a high NAO index in the winter are followed by lower concentrations of nitrate in the late winter (Monteith et al. 2000). The analysis applied to comparable data from Norway does not show this relationship, however. For the 3 calibrated

catchments fully 25 years of nitrogen inputs have failed to result in significant increases in nitrate concentrations in runoff. For Norway the year-to-year variations in nitrate are not related to the winter NAO index. The factors regulating concentrations of nitrate in surface waters still require further research.

Seasalt episodes in near coastal regions clearly produce acidification episodes of varying length and intensity that can disturb long-term trends in acidification. Clearly the frequency and intensity of these seasalt inputs are related to meteorological conditions such as wind strength and amount of precipitation. Although these factors may well be integrated satisfactorily by the North Atlantic Oscillation index, the time resolution of one month may be too coarse to pick up the frequency and magnitude of storms that are of 2-5 days duration.

Thus the lack of statistical relationship between NAO and water chemistry at these sites in Norway does not mean that climatic variations are not important drivers for variations in water chemistry. NAO index is perhaps too coarse a measure, at least when expressed in terms of monthly mean values.

The magnitude of the acidification pulse resulting from seasalt inputs is related to pre-existing factors in the catchment such as hydrological condition, existence of snowpack, and acidification status of the soils. Unravelling of these factors requires detailed information on catchment hydrological conditions as well as water samples collected at weekly or better frequency. In general the ICP-Waters network is not well suited for this detailed type of analysis.

In conclusion it is clear that the data from the UK-AWN show that climatic variations affect trends in acidification during the 10-year period 1988-1998. The same analysis applied to coastal and inland sites in Norway, however, did not reveal statistically significant relationships. Climatic variations of short- and medium-term (0-10 years) duration can influence long-term trends in some areas.

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