

Global dimming and global brightening – an analysis of surface radiation and cloud cover data in northern Europe

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ABSTRACT: In the present study, surface solar radiation data from 11 stations in northwestern Europe and the European Arctic are presented in the context of the ongoing discussion on global dimming and global brightening. The surface solar radiation records are compared to records of cloud cover, and to qualitative information on aerosol concentrations and atmospheric circulation patterns, in order to explain the temporal variations.

Through simple statistical analyses, we examine annual trends as well as trends for individual months, and compare the results between the stations. Comparisons are also made between different time periods within the records. We find that surface solar radiation changes in the region considered, even at the remote arctic stations, correspond well with trends found in global studies, with a significant decrease from the 1950s to the 1980s, followed by a slight increase in recent years. At stations that stand out from the general pattern, the deviations can be explained by variations in cloud cover in most cases.

There has been a general tendency to attribute the majority of the observed surface solar radiation trends to aerosol changes caused by changes in anthropogenic emissions. This study stresses the importance of the contribution of clouds and the atmospheric circulation to global dimming and global brightening. Copyright © 2008 Royal Meteorological Society

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1. Introduction

Some 30 years ago, Suraqui *et al.* (1974) reported large decreases in surface solar radiation at Mt. St. Katherine in the Sinai between the mid-1930s and 1973. It would take another two decades before similar findings were reported in studies from the Arctic (Stanhill, 1995), Russia (Abakumova *et al.*, 1996), the Antarctic (Stanhill and Cohen, 1997), Germany (Liepert and Kukla, 1997) and finally even in global studies (Gilgen *et al.*, 1998). This trend was originally dubbed ‘global dimming’ due to the decrease in *global radiation* (the sum of direct and diffuse solar radiation measured at the surface). However, as the word global is more often used indicating spatial coverage, we will instead be using the terms ‘solar dimming’ and ‘surface solar radiation’ to avoid confusion.

Extensive studies show that stations worldwide have experienced solar dimming, and Stanhill and Cohen (2001) estimate the global mean decrease to 2.7% per decade or a total of 20 W m⁻² between 1950 and 1995. At the same time, temperature records show a strong global warming, which may seem paradoxical. However, Philipona and Dürer (2004) showed, for Europe,

that increased greenhouse warming outweighs the cooling effect of solar dimming, making it possible for temperatures to rise in spite of dimming. An observed decrease in surface evaporation over the past 50 years (Peterson *et al.*, 1995; Liu *et al.*, 2004) supports the credibility of the surface solar radiation trend. Roderick and Farquhar (2001) found that the decrease in evaporation from open pans of water, although debated (Brutsaert and Parlange, 1998), is an expected consequence of solar dimming, as the dimming reduces the amount of available energy at the surface and hence the level of evaporation. Moreover, a decrease in evaporation will cause a decrease in evaporative cooling, which could help increase the surface temperatures in spite of dimming.

As neither long-term changes nor cyclic variations in the sun’s irradiance are nearly large enough to explain the observed changes in surface solar radiation (Lean, 1997), the cause of the dimming must lie in changes within the earth’s atmosphere. Reports on surface solar radiation trends under different sky conditions reveal that changes in atmospheric transmission have occurred under clear skies as well as overcast skies (Liepert, 2002), indicating that aerosol burdens have changed. With changes in aerosol concentrations, modification of cloud properties may follow, as observed by Krüger and Graßl (2002). Also, changes in cloud cover, obviously affecting

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surface solar radiation values, have been observed in many regions (Tuomenvirta *et al.*, 2000; Houghton *et al.*, 2001).

During the last 20 years or so, there has been a reversal from dimming to brightening at stations worldwide (Power, 2003; Wild *et al.*, 2005). This turnaround has been attributed to decreased aerosol burdens as a result of efforts to reduce pollution, and changes in economic and political conditions. A typical example is eastern Europe, where pollution levels peaked in the 1980s and have been falling since the collapse of the East Block in 1989 (Krüger *et al.*, 2004). Even remote and relatively untouched areas experience pollution trends, often dominated by long-range transportation. See, for instance, the decrease in SO₂ levels in arctic Ny-Ålesund, Spitzbergen, shown in Figure 1. However, other factors like changes in cloudiness, the strength and frequency of volcanic eruptions, and circulation patterns such as the North Atlantic Oscillation (NAO) also contribute. Still, the turn to brightening is not apparent in all areas; dimming has continued in India, in general, (Wild *et al.*, 2005) and in parts of southern Africa (Power and Mills, 2005; Wild *et al.*, 2005). Several of the stations included in this study have also seen a continued dimming.

The objective of this work is to examine whether the variations of surface solar radiation in northwestern Europe follow the general global pattern, and to explore to what extent the variations can be explained by changes in cloud cover. We also relate the surface solar radiation variations to observed regional trends in aerosols, aerosol precursors and atmospheric circulation. The following article gives a short review of methods and an introduction of the stations; general results and special features is presented in Sections 3 and 4, respectively, and a conclusion is drawn in Section 5.

2. Data and methods

Surface solar radiation and cloud cover are studied for the 11 stations shown in Figure 2 and presented in Table I. The stations are located in northwestern Europe or in the Arctic, from Germany in the south to Spitzbergen in the north, and from Greenland in the west to Finland in the east. As can be seen from Table I, the length of the time series varies from station to station. For the purpose of

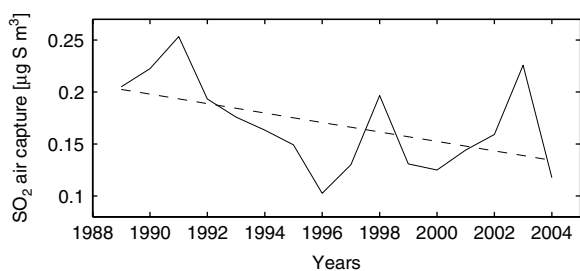


Figure 1. Ny-Ålesund SO₂ levels have declined by 34% between 1989 and 2004 (based on data from http://www.emep.int/index_data.html, 2006-12-20). Dashed line indicates linear regression fit.

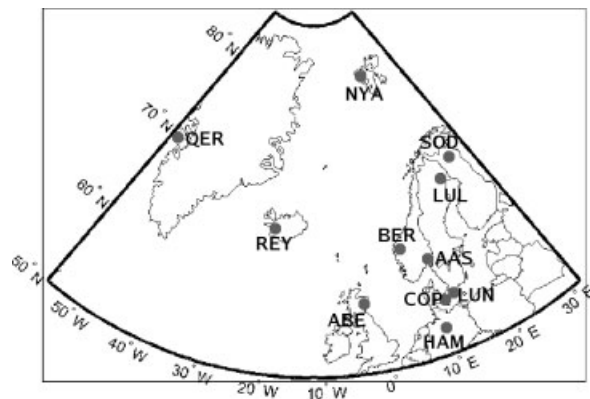


Figure 2. Map of the region analysed in this study. Stations are marked as dots (see Table I for abbreviations).

comparing trends between the stations, we will later be looking at the 1983–2003 period, which is the longest period for which surface solar radiation and cloud cover data are available from almost all stations simultaneously. The Qeqertarsuaq and Reykjavík stations will be omitted from this comparison as they lack some of the years within this period.

2.1. The stations and instrumentation

At all the stations, various models of Kipp and Zonen pyranometers have been used to measure surface solar radiation for all or the most part of the time series. Two of the stations, Copenhagen and Ny-Ålesund, changed to Eppley pyranometers in the mid-1990s. Cloud cover are based on manual SYNOPs (International Synoptic Surface Observations) and are given in octas.

The stations are a collection of both urban and rural sites, and while some of them are clearly affected by local air pollution, others are located far from any emission sources. Particularly remote are the two northernmost stations: The Qeqertarsuaq station is located at the western coast of Greenland on the island of Disko, while Ny-Ålesund is a minor community on the arctic island of Spitzbergen.

Cloud cover data were available in some cases for the same station as the radiation data, but in other cases they had to be obtained from nearby stations. This may have influenced the results at some of the stations, but the correlation between cloud cover and surface solar radiation is high in absolute value and significant at all stations, and we therefore consider these distances acceptable for our use.

2.2. Data analyses

The data analyses were based on monthly means. This coarse temporal resolution of the data precludes the separation of surface solar radiation values into clear and overcast sky conditions, as seen in Liepert and Kukla (1997), for instance, but is deemed good enough to allow for analyses of long-term trends and correlations. Also, using monthly means instead of daily data neutralizes some of the uncertainty of the subjective cloud cover

Table I. Information on the stations included in the present study.

Station	Abbreviation	Latitude	Longitude	Period	Cloud cover data from	Instrument changes or other comments
Hamburg, Germany	HAM	53.55 °N	10.00 °E	1954–2003	Same location	Instrument changes in 1971 and 1984, station moved in 1976
Copenhagen, Denmark	COP	55.68 °N	12.59 °E	1955–2004	20 km to the E	Instrument changes in 1983 and 1994
Lund, Sweden	LUN	55.72 °N	13.12 °E	1983–2003	40 km to the SW	Inhomogeneities in data prior to 1983
Aberdeen, Scotland	ABE	57.15 °N	2.14 °E	1967–2003	95 km to the SW	
Ås, Norway	AAS	59.66 °N	10.78 °E	1950–2003	40 km to the N	
Bergen, Norway	BER	60.37 °N	5.34 °E	1965–2003	Same location	
Reykjavík, Iceland	REY	64.12 °N	21.85 °W	1970–1999	Same location	Inhomogeneities in data after 1999
Luleå, Sweden	LUL	65.59 °N	22.17 °E	1983–2003	50 km to the NE	Inhomogeneities in data prior to 1983
Sodankylä, Finland	SOD	67.37 °N	26.63 °E	1971–2005	Same location	
Qeqertarsuaq, Greenland	QER	67.39 °N	53.38 °W	1991–2004	65 km to the S	
Ny-Ålesund, Spitzbergen	NYA	78.92 °N	11.83 °E	1975–2004	Same location	Some discontinuities in the years 1979–1981

measurements. At four of the stations, we performed a short study of daily cloud cover data in order to look at frequencies of overcast and clear sky conditions, similar to the study of Qian *et al.* (2006), as these are considered to be more robust estimates of cloud cover. The frequencies were then compared to our monthly mean cloud cover values. We found no significant differences between the two, and therefore we chose to use the monthly mean data.

Annual cloud cover values were found by taking the mean of the monthly values. In order to investigate seasonal changes, time series of individual calendar months were also calculated.

The following procedures were performed in case of a missing surface solar radiation value: if the correlation coefficient r between surface solar radiation and cloud cover (of that specific station for the given calendar month) was significant and satisfied a demand of $|r| > 0.70$, a first degree polynomial fit was used to estimate the expected value of surface solar radiation from the cloud cover value. The replacement was only made if no more than 2 years in a row were lacking a value for that specific month. If a year was lacking more than four monthly values, or if more than two of the lacking months were May, June or July, the annual mean of the year in question was excluded from the annual time series.

All data were tested for autocorrelations by finding the effective sample size n_{eff} , given by Kristjánsson *et al.*

(2002) as

$$n_{eff} = \frac{n}{1 + 2r_1r'_1 + 2r_2r'_2 + \dots + 2r_n r'_n} \quad (1)$$

Here, r_i (for values of i between 1 and sample size n) is the lag i autocorrelation of the data series of cloud cover values, and r'_i is the lag i autocorrelation of the data series of surface solar radiation values. In calculating the significance of the correlations between cloud cover and surface solar radiation, n_{eff} was used instead of the real sample size in the Student's t -test. This method improves the credibility of the significance, since Student's t -test requires that all n data points are independent, which is not the case for most geophysical time series. For a more rigorous treatment of autocorrelations, more complex significance tests can be used, but it was considered beyond the scope of the present study.

2.3. Errors in surface solar radiation measurements

The quality of a surface solar radiation time series depends on regular calibrations, careful logging, and corrections in case of changes in instrumentation or location. In order to assess the quality of a time series, it is also important that information about these changes is stored so that it is not lost when personnel changes occur. A common problem with surface solar radiation measurements is that degrading instruments and poor maintenance may induce fictitious negative trends. This

is because old uncalibrated instruments or instruments that are not regularly cleaned of dust and dew tend to lose measuring sensitivity, resulting in erroneous records of decreasing surface solar radiation values. It is worth noting that the recent brightening, which is a positive trend, is therefore not likely to have been caused by measuring errors.

3. Results

Figure 3 shows the mean surface solar radiation trend at the 11 stations, and gives an impression of the general tendency of this region. The 1955–2003 period shows a total trend of -18.3% or -21.5 W m^{-2} , while the 1983–2003 period experiences a 4.4% increase. Figure 4 shows the mean cloud cover, but here the trend is less pronounced.

Figure 5(a) and (b) show surface solar radiation and cloud cover for different time periods at all 11 stations. The majority of the stations with the longest time series have experienced dimming early in the record. As for

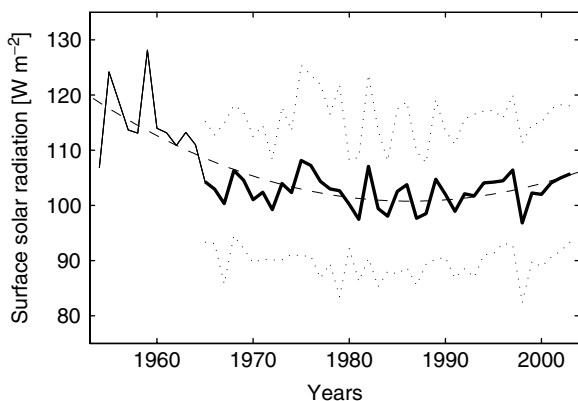


Figure 3. The mean surface solar radiation trend of the 11 stations. Solid line indicates that the mean consists of more than three stations, in which case an envelop of ± 1 standard deviation (dotted lines) is also included. The dashed line represents the second-degree regression fit.

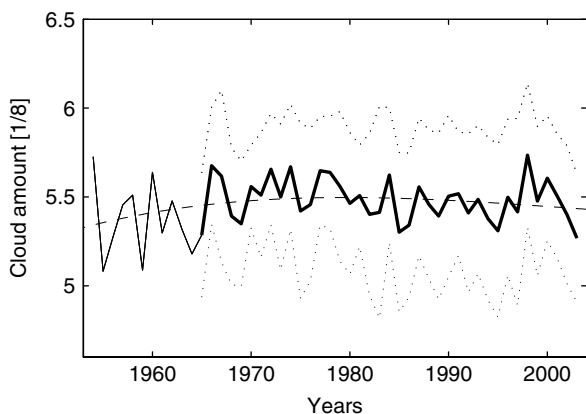


Figure 4. The mean cloud cover trend of the 11 stations. Solid line indicates that the mean consists of more than three stations, in which case an envelop of ± 1 standard deviation (dotted lines) is also included. The dashed line represents the second-degree regression fit.

the years after 1983, Ås, Reykjavík, and Qeqertarsuaq have had a continued dimming, while Hamburg, Lund, Luleå, and Sodankylä have seen a turn to brightening. Ny-Ålesund also experienced brightening in the last two decades. The time series at the remaining stations do not display any significant trends.

Figures 6 and 7 illustrate the monthly trends in surface solar radiation and cloud cover. While Figure 6 displays trends for the entire time periods available at each separate station, Figure 7 shows the mean regional trend over the 1983–2003 period. Qeqertarsuaq and Reykjavík are excluded from the Figure 7 mean because they lack some of the years in this time interval.

Total and 1983–2003 annual trends are also presented in Table II, and it becomes apparent from this table that the radiation changes of Copenhagen and Ås are the only ones that compare well in magnitude to the 2.7% per decade global decreases between 1950 and 1995 found by Stanhill and Cohen (2001). At Copenhagen, the 1955–1995 dimming amounts to -9.7% (-11.7 W m^{-2}) or -2.4% per decade, while at Ås the 1950–1995 dimming amounts to -13.1% (-15.8 W m^{-2}) or -2.9% per decade.

When comparing the solar radiation trends to cloud cover changes, we see that the solar dimming in Copenhagen is associated with a strong increase of 7.6% in annual cloud cover, possibly explaining the dimming. Figure 8 clearly shows that these opposite trends in clouds and radiation have an annual mean correlation coefficient of -0.77 (Table III). However, the annual cloud cover trend of merely 1.1% in Ås does not seem to explain the dimming there. A similar feature can be seen in the 1983–2003 trends, where the brightening in Hamburg, Lund, Luleå, Sodankylä, and Ny-Ålesund appears to be caused by cloud changes only in Luleå, which has experienced a 9.6% decrease in cloud cover. On a monthly basis, Copenhagen again displays a particularly close connection between surface solar radiation and cloud cover trends, as does Bergen. At these stations, Figure 6 shows that every single month has opposite radiation and cloud cover trends of similar magnitude, indicating that the influence of cloud cover variations dominates the surface solar radiation record. Indeed, the annual mean correlation coefficients (Table III) between surface solar radiation and cloud cover are high in absolute value and significant (95% significance or better) for all stations, but particularly at these. A recurring feature is the slight tendency for correlations to be of larger magnitude in the spring/summer months than during late fall/winter (Figure 9). A likely explanation lies in the fact that the aerosol concentration (particularly within cities) tends to be higher during stable winter days than during more convective summer conditions, lowering the surface solar radiation values on clear days in the winter, and thus, weakening the monthly correlation with cloud cover.

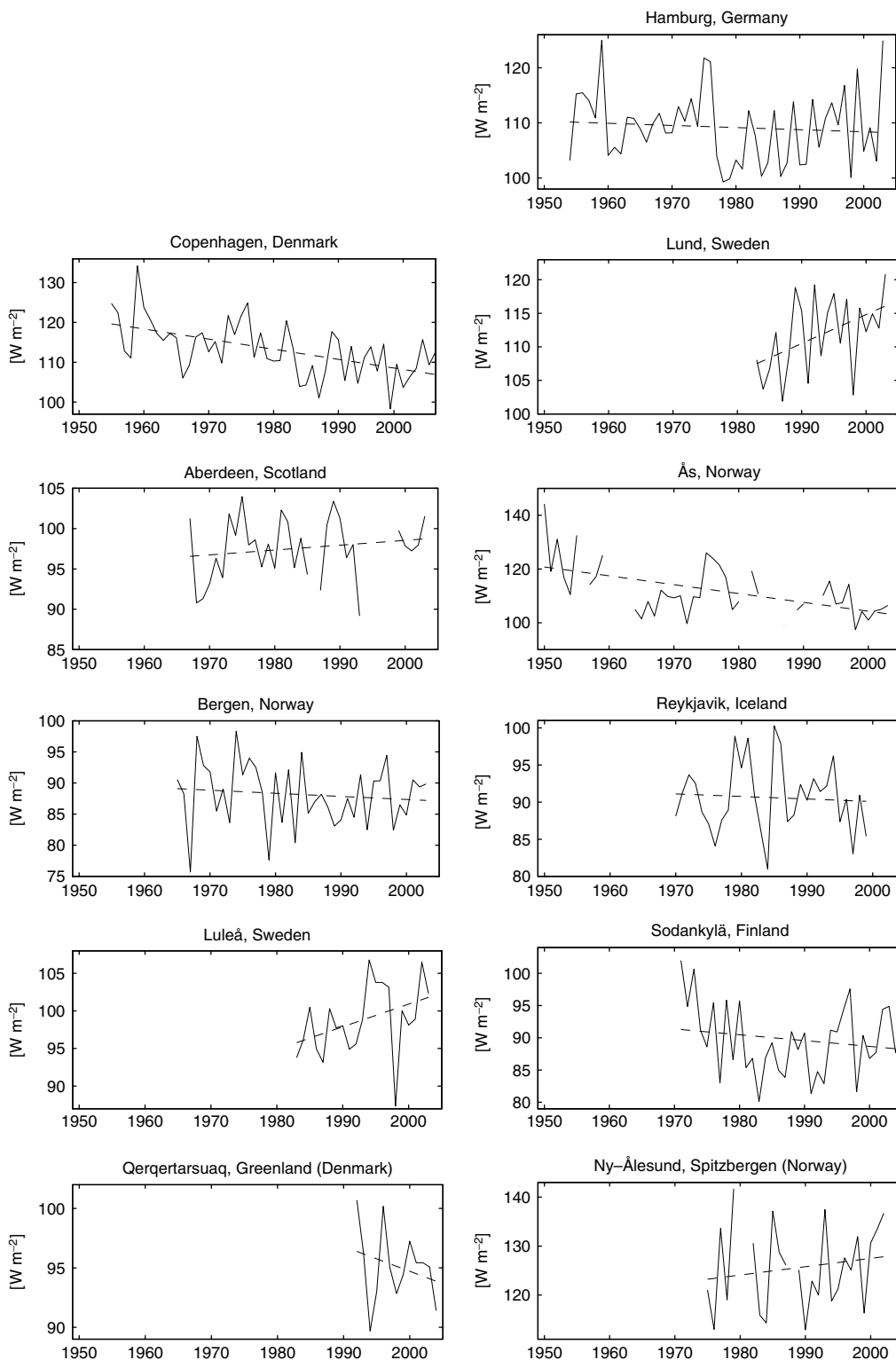


Figure 5a. (a) Annual mean surface solar radiation for all 11 stations, 1950–2005. Dashed lines indicate linear regression fits. (b) Annual mean cloud cover for all 11 stations, 1950–2005. Dashed lines indicate linear regression fits.

Lund and Copenhagen, which are only separated by some 40 km, display different surface solar radiation trends for the 1983–2003 period, in spite of similar changes in cloud cover. A detailed study of possible causes gave no definite answer, and measuring errors at one of the two stations cannot be ruled out.

4. Special features at individual stations

When the relation between annual surface solar radiation and cloud cover trends is less clear than at, for example, Copenhagen and Bergen, it seems natural to ascribe the radiation changes to variations in aerosol burdens. However, a closer look at the monthly trends reveals a

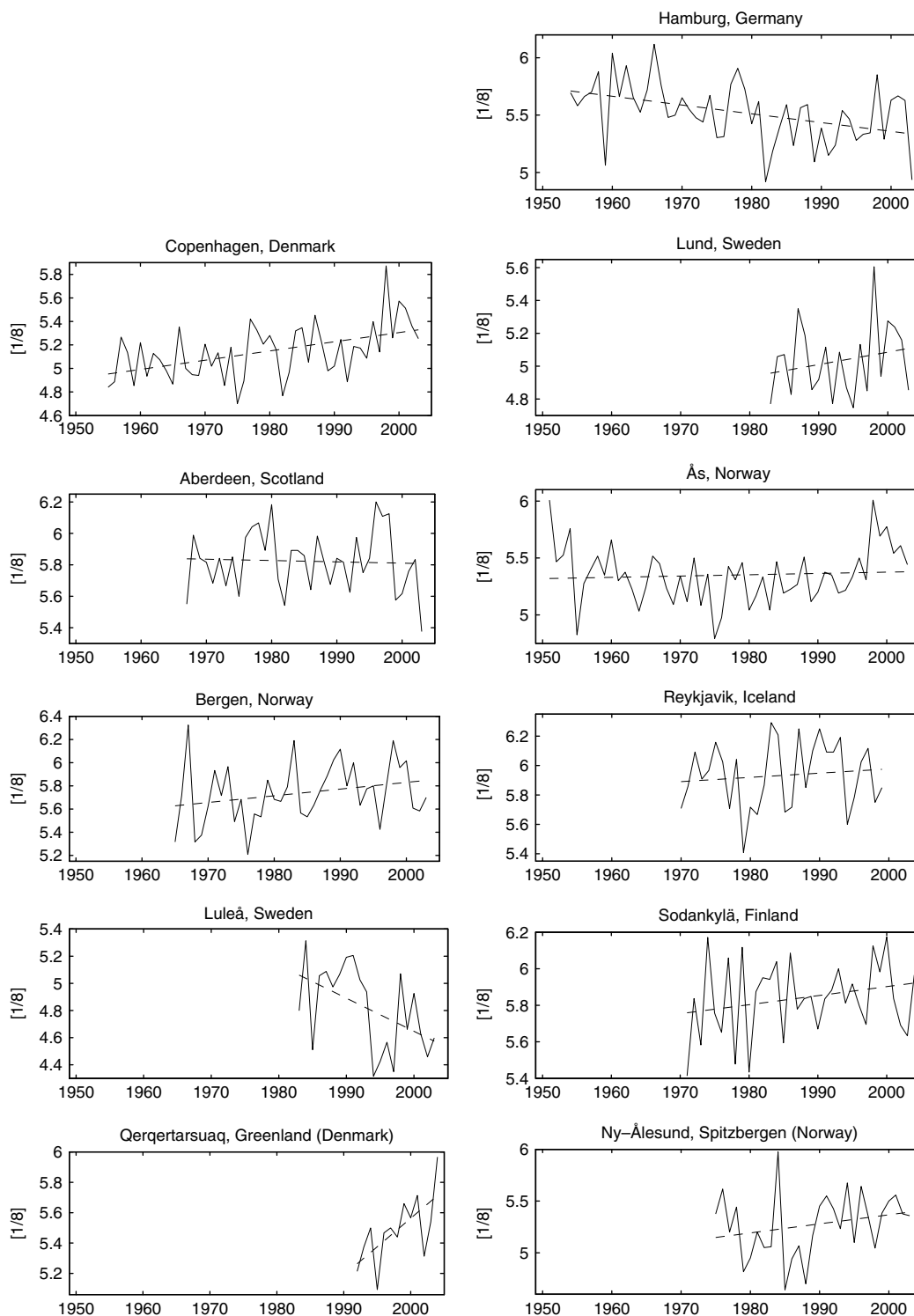


Figure 5b. (Continued).

more complex relationship, whereby cloud cover changes limited to specific seasons or months may induce dimming or brightening. We now present examples of surface solar radiation trends from some of the stations analysed in this study.

4.1. Hamburg

The Hamburg solar radiation series in Figure 5(a) can be separated into different periods. The years between

1960 and 1975 are characterized by a decrease in cloud cover together with an increase in surface solar radiation, and are followed by high annual mean cloud cover between 1977 and 1979, which are reflected in a depression in the surface solar radiation values. However, as can be seen in Figure 5(a) and (b) and in Table II, the 1983–2003 surface solar radiation trend does not seem to have been caused by cloud cover changes. While the cloud cover has increased by 1.9%

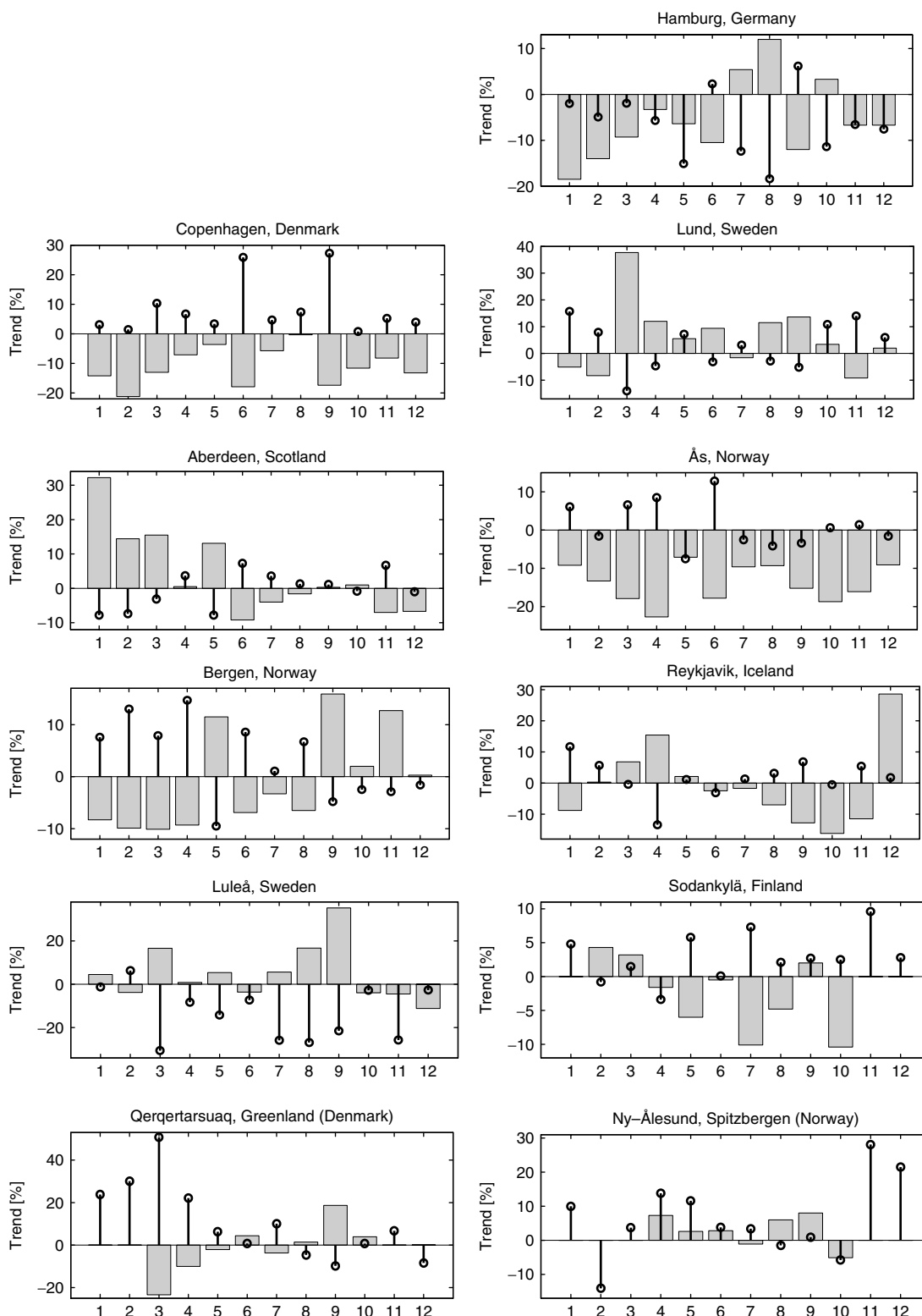


Figure 6. Relative (%) monthly trends in surface solar radiation (bars) and cloud cover (stems) for the entire time period available at each individual station.

(not significant), the annual surface solar radiation has also increased. However, this 8.8% brightening, corresponding to 9.1 W m^{-2} , may be explained by aerosol changes: European aerosol levels – having increased dramatically for decades – started to fall in the late 1980s (Krüger *et al.*, 2004). Reduced extinction of surface solar

radiation by scattering and absorption (direct aerosol effect) has inevitably contributed significantly to the observed brightening. Furthermore, Krüger and Graßl (2002) presented evidence for a decreasing influence of aerosols on clouds (indirect aerosol effect) over Europe. In a study of global radiation trends in Germany in which

Hamburg was one of the stations analysed, Power (2003) also concluded that aerosol changes were the cause of the brightening.

On the basis of the above, we hypothesize that aerosol changes have contributed strongly to the surface solar

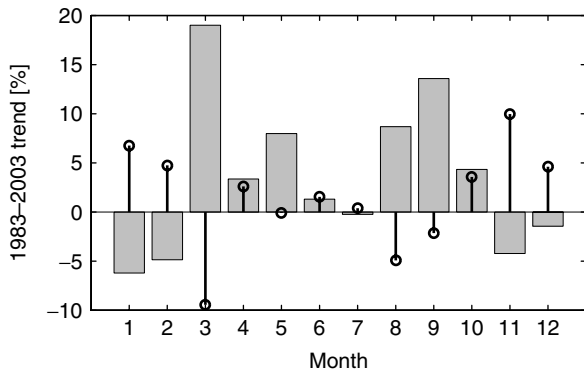


Figure 7. Mean relative (%) monthly trends in surface solar radiation (bars) and cloud cover (stems) of all 11 stations, 1983–2003.

Table II. Annual trends in percent (%) in surface solar radiation (R) and cloud cover (CA) for the total period available at each station and for the 1983–2003 period. Bold numbers indicate 90% significance or better. See Table I for the lengths of the total time periods.

	R	CA	R	CA
	Total	Total	1983–2003	1983–2003
Hamburg	-1.7	-2.7	8.8	1.9
Copenhagen	-9.6	7.6	-0.7	6.1
Lund	8.0	3.1	8.0	3.1
Aberdeen	1.4	-0.5	1.3	-2.0
Ås	-14.4	1.1	-2.6	9.3
Bergen	-1.8	3.1	3.4	-0.8
Reykjavík	-1.2	1.4	-	-
Luleå	6.3	-9.6	6.3	-9.6
Sodankylä	-3.4	2.9	8.7	-0.5
Qeqertarsuaq	-2.6	8.6	-	-
Ny-Ålesund	3.7	4.8	7.2	6.7
All	-18.3	1.8	4.4	0.3

radiation changes in Hamburg. In the beginning of the time series, the increasing concentration of aerosols together with a period of increasing cloud cover induced dimming. During the past two decades, on the other hand, the falling aerosol level has been profound enough to override the increase in cloud cover, allowing for brightening.

4.2. Lund

In Lund, the 1983–2003 period has seen a statistically significant brightening of 8.0%, corresponding to 8.6 W m^{-2} (Table II). Simultaneously, the cloud cover has increased by roughly 3%. The situation is much like the one in Hamburg, rendering it likely that decreasing aerosol concentrations cause the brightening. However, a closer look at the monthly trends reveals an alternative explanation. The annual mean cloud cover has increased due to increased cloudiness from October through February (see stems in Figure 6), creating negative trends in solar radiation for these months (see bars in Figure 6). However, most of the remaining months are associated with *decreasing* cloud cover trends. As a response to the decrease in cloudiness in these particular months, solar radiation values increase from March through September (with exception of July), creating a total increase in annual mean solar radiation over the 21-year period. This illustrates the importance of investigating monthly as well as annual trends in order to find the cause of surface solar radiation changes.

4.3. Ås

Surface solar radiation data from Ås were first presented by Grimenes and Thue-Hansen (2006), and display the most distinct dimming trend of all the stations considered here. This applies to the longer period (-14.4% , corresponding to 17.5 W m^{-2} , between 1950 and 2003) and to the more recent years (-2.6% between 1983 and 2003) (Table II). However, the cause of the dimming seems to have changed: before the mid-1980s, Ås experienced dimming in spite of decreasing cloud cover, as can be seen from Figure 5(a) and (b), respectively. It is likely that the effect of increasing aerosol

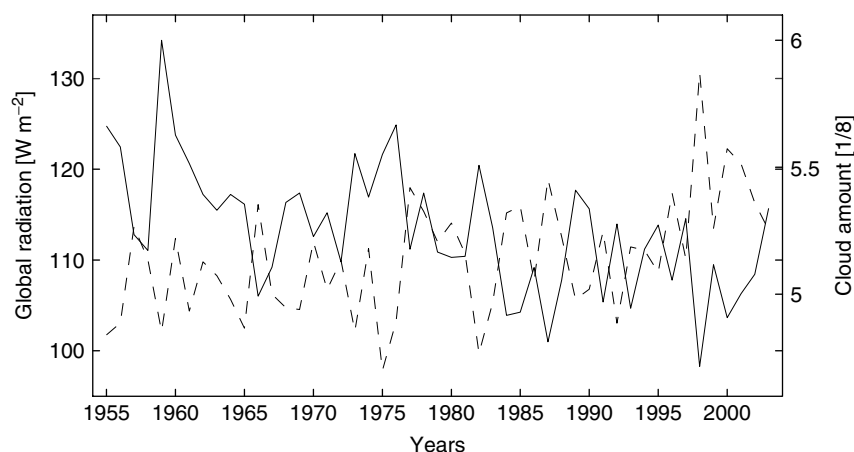


Figure 8. Annual mean values of Copenhagen solar radiation (solid) and cloud cover (dashed) for 1955–2004.

Table III. Solar radiation and cloud cover correlation coefficients, based on the entire time period available at each station. Bold numbers indicate less than 90% significance (calculated using n_{eff} instead of n , see Section 2.2), and stars indicate lacking data due to the dark arctic season.

	HAM	COP	LUN	ABE	AAS	BER	REY	LUL	SOD	QER	NYA
January	-0.71	-0.89	-0.84	-0.80	-0.73	-0.86	-0.44	-0.71	-0.64	***	***
February	-0.62	-0.76	-0.82	-0.86	-0.67	-0.90	-0.76	-0.79	-0.57	***	***
March	-0.83	-0.84	-0.74	-0.87	-0.81	-0.94	-0.73	-0.90	-0.91	-0.78	***
April	-0.88	-0.88	-0.90	-0.78	-0.76	-0.88	-0.90	-0.78	-0.82	-0.64	-0.60
May	-0.89	-0.87	-0.91	-0.90	-0.77	-0.92	-0.88	-0.87	-0.91	-0.49	-0.76
June	-0.87	-0.92	-0.89	-0.81	-0.79	-0.94	-0.92	-0.79	-0.89	-0.89	-0.82
July	-0.89	-0.86	-0.92	-0.82	-0.66	-0.96	-0.94	-0.70	-0.94	-0.96	-0.88
August	-0.85	-0.83	-0.86	-0.75	-0.71	-0.97	-0.94	-0.94	-0.91	-0.85	-0.70
September	-0.87	-0.89	-0.90	-0.92	-0.70	-0.95	-0.87	-0.92	-0.85	-0.84	-0.80
October	-0.85	-0.88	-0.70	-0.68	-0.82	-0.88	-0.64	-0.87	-0.70	-0.35	-0.11
November	-0.78	-0.88	-0.84	-0.61	-0.75	-0.73	-0.49	-0.78	-0.74	***	***
December	-0.71	-0.76	-0.79	-0.62	-0.76	-0.86	-0.19	-0.56	-0.33	***	***
Annual	-0.54	-0.77	-0.67	-0.60	-0.32	-0.75	-0.58	-0.77	-0.67	-0.25	-0.54

loads dominated over the effect of falling cloud cover in the first decades of the time series, but since the late 1960s, according to Myrvtveit and Lützenkirchen (2005), there has been a decrease in SO_2 levels and particulate matter concentrations in Oslo, which should have induced corresponding aerosol concentration changes at the nearby station in Ås. With pollution levels lower, aerosols would have become a less important factor to the local surface solar radiation changes. The cloud cover, which started to increase in the late 1980s, may thus have become the dominating factor again, driving a continued dimming in spite of falling aerosol concentrations.

Conclusively, the surface solar radiation record in Ås has been subject to changes in both aerosol concentration and cloud cover, but the two effects have been dominant in different periods.

4.4. Ny-Ålesund brightening and trends in the arctic haze phenomenon

Ny-Ålesund is the northernmost station included here. Figure 5(a) shows that Ny-Ålesund has experienced a brightening, particularly over the past 15 years or so. The surface solar radiation in the 1983–2003 period has increased by 7.2%, equivalent to 8.7 W m^{-2} . It is difficult to say whether or not there was dimming prior to this, as the time series only goes back to 1975.

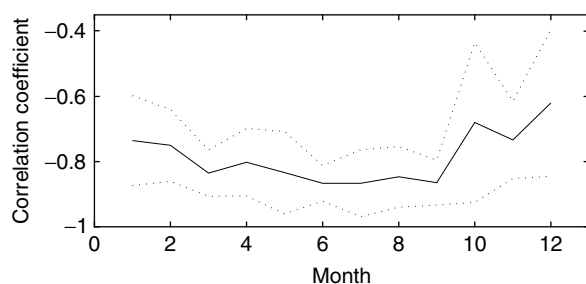


Figure 9. Mean correlation coefficients between solar radiation and cloud cover for all stations, by month.

The corresponding cloud cover plot in Figure 5(b) also shows a slightly increasing trend, and the poor agreement between monthly surface solar radiation and cloud cover trends (Figure 6) makes it difficult to attribute the radiation trend to cloud cover changes.

Looking at individual months, we learn that the April insolation trend contributes strongly to the increasing 1983–2003 trend. Curiously, this month also experiences a large significant increase in cloud cover, which seems contradictory. An explanation to this could be found in trends in the arctic haze phenomenon.

Arctic haze was discovered in the 1950s (Mitchell, 1956), but the recognition of the haze as pollution transported from Eurasia and (to a lesser extent) northern America was not made until two decades later (Shaw, 1982). Being composed mainly of sulfate aerosols and particulate organic matter, the haze is highly scattering in nature, and has a large impact on the amount of solar radiation reaching the surface. There is a strong seasonal variation in the haze, with maximum occurrence in late winter and early spring, typically March, April, and May (Shaw, 1995). This is related to seasonal variations in atmospheric circulation patterns, precipitation and static stability, which control transport pathways, as well as sink processes for the aerosols that constitute the haze.

According to Bodhaine and Dutton (1993), measurements at Barrow, Alaska, showed a maximum in the haze in 1982 followed by a decrease between 1982 and 1992. More recent data from Barrow show a clear falling trend in the April haze since the late 1980s (Douglas and Sturm, 2004). If a similar development has taken place at Ny-Ålesund, this could be the explanation of the April brightening, which has taken place in spite of increasing cloud cover.

While Herber *et al.* (2002) found a slight increase (not significant) in the annual mean aerosol optical depth at Ny-Ålesund between 1991 and 1999, indicating an increase in arctic haze, other evidence support the findings of Douglas and Sturm. For instance, data from the

European Monitoring and Evaluation Program (EMEP) show a 34% annual mean decrease in SO₂ concentrations at Ny-Ålesund between 1989 and 2004 (Figure 1). Moreover, Wild *et al.* (2005) found a strong increase in clear-sky surface solar radiation at Ny-Ålesund in the 1992–2002 period, indicating that the non-cloudy air is becoming less turbid.

While changes in emission levels (particularly in Eurasian countries) affect the trends in arctic haze, the NAO probably also contributes significantly. On the basis of data from the Climate Research Unit of the University of East Anglia, Norwich (<http://www.cru.uea.ac.uk/cru/data/nao.htm>, 2006-12-20), the temporal evolution of the NAO index in Figure 10 shows a falling trend since the early 1990s. Since the positive NAO phase generally enhances transport of aerosols into the Arctic (Eckhardt *et al.*, 2003), the recent change towards more negative NAO situations is possibly a contributing cause to the observed negative trend in arctic haze.

It seems probable that the air over Ny-Ålesund has indeed cleared, and the resulting decrease in the direct aerosol effect could thus be responsible for the recent brightening. Additionally, Garrett *et al.* (2004) found that the indirect effect of haze aerosols on low-level clouds is much more efficient in the Arctic than at lower latitudes, as long-range transport gives the aerosols time to grow to sizes more efficient for cloud droplet nucleation. A decrease in the occurrence of arctic haze may, therefore, efficiently have lowered the reflectance of arctic clouds through the indirect aerosol effect, allowing even more solar radiation to pass through to the surface.

Altogether, it seems that the surface solar radiation trends at Ny-Ålesund have been mainly controlled by factors other than cloud cover. More thorough analyses, particularly of aerosol trends, are needed to assess whether or not it is the arctic haze phenomenon that is the main cause of the brightening.

4.5. No brightening at Qeqertarsuaq

The haze also affects the Greenland station, but here the surface solar radiation has fallen by 2.6% (not statistically

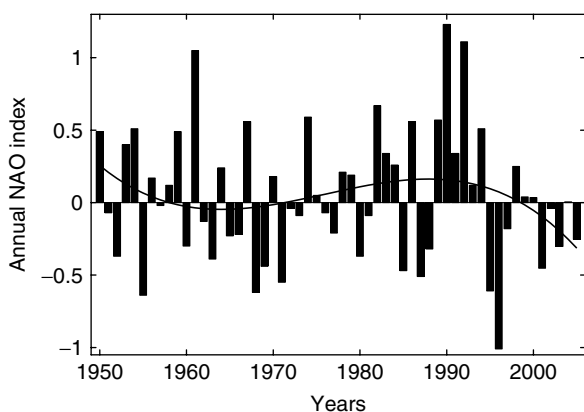


Figure 10. Annual NAO index from 1950 to 2005, based on the Azores–Iceland normalized sea-level pressure difference. Data from the Climate Research Unit of the University of East Anglia, Norwich (<http://www.cru.uea.ac.uk/cru/data/nao.htm>, 2006-10-15).

significant) over the 1992–2004 period, which seems to be mainly due to the decrease in March and April. As can be seen from Figure 6, these months also have very large and significant increases in cloud cover. It seems probable that the increase in cloud cover has dominated over the effect of a potential trend in arctic haze, leaving cloud changes as the main cause of the Greenland dimming.

5. Summary and conclusion

Solar radiation drives the energy balance at the earth's surface, and any changes in this quantity will tend to influence the hydrological cycle as well as other components of the climate system. This makes it imperative to understand the causes of solar dimming and solar brightening. While global studies are important to get a general picture, regional and local studies provide more detailed information on the response of surface solar radiation to variables such as clouds and aerosols, as well as circulation changes.

Here, we have examined surface solar radiation and cloud cover data from the 11 stations in northwestern Europe, some of which are located within or in the vicinity of larger cities, others are relatively rural, and yet others are located in the European Arctic. Simple statistical analyses were performed to investigate the correlations between the two variables, and to determine annual and monthly trends.

We find that the majority of the stations have experienced dimming from the beginning of the time series and up to the late 1980s, corresponding well with the global tendency reported by Gilgen *et al.* (1998). In the more recent decades, most of our stations show a turn to brightening, which agrees with the new global trend described by Wild *et al.* (2005).

No discernible differences were found between urban, rural or arctic sites, possibly because varying cloud cover changes disturbed the aerosol signal. While Stanhill (1995) reported widespread dimming in the Arctic up to the mid-1990s, the present study shows a turn to brightening.

There has been a general tendency to attribute changes in surface solar radiation to opposite trends in aerosol concentration due to changes in emissions, and such changes have clearly contributed and dominated the trend in surface solar radiation in some cases. In Europe, in general, Krüger *et al.* (2004) found an increasing trend in pollution up to the late 1980s, while Vestreng *et al.* (2007) reported a 60% decrease in sulphur emissions between 1990 and 2004. These trends support both the previous dimming and the present brightening. However, observations show that over many continental regions there was a general increase in cloud cover between the 1950s and 1990 (Figure 2.3, Houghton *et al.*, 2001), while satellite data from the International Satellite Cloud Climatology Project show a decrease in global cloud cover from the late 1980s until 2000 (based on data from <http://isccp.giss.nasa.gov>, 2005-08-09). Additionally, the

decrease in the NAO index over the last 10–15 years has probably provided less efficient transport of pollution into the Arctic, and contributed to a falling trend in arctic haze.

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References

- Abakumova GM, Feigelson EM, Russak V, Stadnik V. 1996. Evaluation of long-term changes in radiation, cloudiness, and surface temperature on the territory of the Former Soviet Union. *Journal of Climate* **9**: 1319–1327.
- Bodhaine BA, Dutton EG. 1993. A long-term decrease in arctic haze at Barrow, Alaska. *Geophysical Research Letters* **20**(10): 947–950.
- Brutsaert W, Parlange M. 1998. Hydrological cycle explains evaporation paradox. *Nature* **360**: 30.
- Douglas TA, Sturm M. 2004. Arctic haze, mercury and the chemical composition of snow across northwestern Alaska. *Atmospheric Environment* **38**: 805–820.
- Eckhardt S, Stohl A, Beirle S, Spichtinger N, James P, Forster C, Junker C, Wagner T, Platt U, Jennings SG. 2003. The North Atlantic Oscillation controls air pollution transport to the Arctic. *Atmospheric Chemistry and Physics* **3**: 1769–1778.
- Garrett TJ, Zhao C, Dong C, Mace GG, Hobbs PV. 2004. Effects of varying aerosol regimes on low level Arctic stratus. *Geophysical Research Letters* **31**: L17105, DOI: 10.1029/2004GL019928.
- Gilgen H, Wild M, Ohmura A. 1998. Means and trends of shortwave irradiance at the surface estimated from Global Energy Balance Archive (GEBA) data. *Journal of Climate* **11**: 2042–2061.
- Grimenes AA, Thue-Hansen V. 2006. The reduction of global radiation in south-eastern Norway during the last 50 years. *Theoretical and Applied Climatology* **85**: 37–40.
- Herber A, Thomason LW, Gernandt H, Leiterer U, Nagel D, Schulz KH, Kaptur J, Albrecht T, Notholt J. 2002. Continuous day and night aerosol optical depth observations in the Arctic between 1991 and 1999. *Journal of Geophysical Research* **107**: D10, DOI: 10.1029/2001JD000536.
- Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA, (eds). 2001. *Intergovernmental Panel on Climate Change (IPCC), Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.
- Kristjánsson JE, Staple A, Kristiansen J, Kaas E. 2002. A new look at possible connections between solar activity, clouds and climate. *Geophysical Research Letters* **29**(23): 2107, DOI: 10.1029/2002GL015646.
- Krüger O, Graßl H. 2002. The indirect aerosol effect over Europe. *Geophysical Research Letters* **29**(19): 1925, DOI: 10.1029/2001GL014081.
- Krüger O, Marks R, Graßl H. 2004. Influence of pollution on cloud reflectance. *Journal of Geophysical Research* **109**: D24210, DOI: 10.1029/2004JD004625.
- Lean J. 1997. The Sun's variable radiation and its relevance for Earth. *Annual Review of Astronomy and Astrophysics* **35**: 33–67.
- Liepert B. 2002. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. *Geophysical Research Letters* **29**(10): 1421, DOI: 10.1029/2002GL014910.
- Liepert B, Kukla G. 1997. Decline in global solar radiation with increased visibility in Germany between 1964 and 1990. *Geophysical Research Letters* **10**: 2391–2401.
- Liu B, Xu M, Henderson M, Gong W. 2004. A spatial analysis of pan evaporation trends in China, 1955–2000. *Journal of Geophysical Research* **109**: D15102, DOI: 10.1029/2004JD004511.
- Mitchell JM. 1956. Visual range in the polar regions with particular reference to the Alaskan Arctic. *Journal of Atmospheric and Terrestrial Physics Special Supplement* **1**: 195–211.
- Myrtveit I, Lützenkirchen S. 2005. Air quality in Oslo – status 2005, City of Oslo, Health and Welfare Department, *Annual Report 2005*, Appendix. Available in Norwegian at http://www.luftkvalitet.info/data/reports/Aarsrapport_luftkvalitet_2005.pdf.
- Peterson T, Golubev V, Grolsman P. 1995. Evaporation losing its strength. *Nature* **377**: 687–688.
- Philipona R, Dürr B. 2004. Greenhouse forcing outweighs decreasing solar radiation driving rapid temperature rise over land. *Geophysical Research Letters* **31**: L22208, DOI: 10.1029/2004GL020937.
- Power H. 2003. Trends in solar radiation over Germany and an assessment of the role of aerosols and sunshine duration. *Theoretical and Applied Climatology* **76**: 60–61.
- Power H, Mills DM. 2005. Solar radiation climate changes over southern Africa and an assessment of the radiative impact of volcanic eruptions. *International Journal of Climatology* **25**: 295–318.
- Qian Y, Kaiser DP, Leung LR, Xu M. 2006. More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000. *Geophysical Research Letters* **33**: L01812, DOI: 10.1029/2005GL024586.
- Roderick M, Farquhar G. 2001. The cause of decreased pan evaporation over the past 50 years. *Science* **298**: 1410–1411.
- Shaw GE. 1982. Evidence for a central Eurasian source area of Arctic haze in Alaska. *Nature* **299**: 815–818.
- Shaw GW. 1995. The Arctic Haze phenomenon. *Bulletin of the American Meteorological Society* **76**: 2403–2412.
- Stanhill G. 1995. Solar irradiance, air pollution and temperature changes in the Arctic. *Philosophical Transactions of the Royal Society of London, A* **352**: 247–258.
- Stanhill G, Cohen S. 1997. Recent changes in solar irradiance in Antarctica. *Journal of Climate* **10**: 2078–2086.
- Stanhill G, Cohen S. 2001. Solar dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Journal of Agricultural and Forest Meteorology* **107**: 255–278.
- Suraqui S, Tabor H, Klein W, Goldberg B. 1974. Solar radiation changes at Mt. St. Katherine after forty years. *Solar Energy* **16**: 155–158.
- Tuomenvirta H, Alexandersson H, Drebs A, Frich P, Nordli P. 2000. Trends in Nordic and Arctic temperature extremes and ranges. *Journal of Climate* **13**: 977–990.
- Vestreng V, Myhre G, Fagerli H, Reis S, Tarrason L. 2007. Twenty-five years of continuous sulphur dioxide emission reduction in Europe. *Atmospheric Chemistry and Physics* **7**: 3663–3681.
- Wild M, Gilgen H, Roesch A, Ohmura A, Long C, Dutton E, Forgan B, Kallis A, Russak V, Tsvetkov A. 2005. From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. *Science* **308**: 847–850.