Comparison of Sunshine Records and Synoptic Cloud Observations: A case study for Ireland

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1 Abstract

We compare the trends and inter-annual variability of sunshine duration and synoptic cloud data for three sites in Ireland. Our results suggest that, although observers are usually consistent in their synoptic cloud estimates, they can show a significant personal bias which makes it difficult, if not impossible, to extract meaningful information on long term trends in synoptic cloud cover. A study of the frequency of totally clear skies, however, suggests that this parameter may be less affected by bias and could indicate meaningful trends in total cloud factor. It is concluded that sunshine measurements are likely to provide the most reliable indicators of long term trends in cloudiness.

2 Introduction

Comparisons of synoptic cloud records and sunshine duration have been made in several areas of the world. Angell (1990) and Angell et al. (1984) compared cloud and sunshine records for the United States for the period 1950-1988, and found a decrease in sunshine hours accompanied by an increase in cloud cover. A strong negative correlation between the two datasets was reported, even though the magnitude of the increase in cloud cover was greater than the decrease in sunshine records. This result was attributed to an increase in thin cirrus clouds which were not thick enough to interrupt the sunshine record but nonetheless were included in the cloud report. Changnon (1981) found virtually the same results for the midwest United States during the period 1901-1977. On the other hand, Raju and Kumar (1982) argued that the fraction of possible sunshine will closely approximate the fraction of possible clear weather when averaged over long periods in any given region, and they demonstrated how sunshine-derived cloud cover in India can be considered a better measurement of actual cloud cover than visual estimates of cloudiness.

In previous studies, it has been established that the annual total of bright sunshine hours has been decreasing over Ireland as a whole. Stanhill (1998) analysed several sunshine series for Ireland for the period 1954-1995, and noted that a statistically significant decrease had occurred at some of the stations. However, when he compared the decreasing sunshine trend with synoptic cloud observations at Valentia during the same period, he found no sign of increasing cloudiness. He concluded that the observed decrease in sunshine hours was to be attributed to other mechanisms such as increasing aerosol or pollution or changes in cloud types. Pallé and Butler (2001), extended this work over the period 1881-2000, reaching similar and statistically stronger results for the sunshine trends. Synoptic cloud data for Armagh, over the reduced period 1951-1998 available at that time, showed an increasing trend similar in magnitude to the decreasing trend in sunshine. Moreover, they found sunshine records and temperature to vary in the same direction, and attributed the sunshine decrease to a cloudiness increase, possibly as a result of increasing evaporation rates in the North Atlantic ocean.

It is important to establish the cause of the sunshine decrease in Ireland, since it may have major implications for local and regional climate. As Ireland lies near the Atlantic Ocean and westerly winds prevail for most of the year, trends in Ireland can be relevant for larger areas like the N. Atlantic ocean and oceanic mid-latitude regions in general (Pallé and Butler, 2001). A cloudiness increase during the last century would most probably introduce some additional feedback in the Earth's radiative budget and climate, the strength and sign of which will depend on the altitude and latitudinal distribution of the cloud change.

The purpose of this study is to establish whether or not the decrease in sunshine hours can be attributed to an increase in cloudiness. As a test case, we have compared the synoptic cloud data and the sunshine data for three stations in Ireland. In section (3), the synoptic cloud and sunshine data are described, and in section (4) their seasonal variability compared. In section 5, we have analysed the long-term trends in the two datasets and, in section 6, assessed the similarities and differences between the two. In section 7, the clear sky frequency at Armagh is shown to be a better indicator of cloudiness trend than the synoptic cloud cover. Our conclusions are presented in section 8.

3 Data

Sunshine records at four Irish stations have been obtained since 1881 by means of a standard Campbell-Stokes recorder. A Campbell-Stokes recorder consists of a glass ball that concentrates the sunlight into a thin beam which is focussed onto a card. If there are no clouds in the line of sight between the recorder and the Sun, the concentrated light burns the card and leaves a trace for the duration of the clear condition. Monthly and annual total sunshine hours were available to us for four stations, namely: Armagh, Valentia, Birr and Dublin (see Figure 1). Daily records are also available for Armagh for the period 1951-1998 and are currently being extended back to 1881. The sunshine factor is defined as the observed sunshine duration divided by the period during which the Sun lies above 3^o altitude - that is the maximum possible sunshine hours for that particular date. A more detailed description of the Irish sunshine records can be found at Pallé and Butler (2001).

Synoptic observations of the total cloud cover are taken in many meteorological stations worldwide. The procedure is simple; at specified times of the day, the observer estimates the number of oktas (1/8 th of the sky) covered by clouds. A totally overcast sky is registered as 8 and a clear sky as 0 (Observers Handbook, 1982). Estimation of the cloud coverage in oktas has been in use since 1949; measurements prior to this were made in tenths of the sky (1/10). Similarly as in the case of oktas a totally overcast sky is registered as 10 and a clear sky as 0. At some stations, the coverage by different cloud types is also recorded. It is evident that, to a greater or lesser extent, such estimates are observer dependent and therefore subject to personal bias.

The synoptic cloud data for Armagh Observatory goes back to 1884 and thanks to a grant from the Heritage Lottery Fund (Grant number: RF-98-01507) this data has recently been entered in digital form, together with many of the historical meteorological records from the Observatory archives. The Armagh cloud data consists of four series of total synoptic cloud measurements. Observations were made at 9:00 am GMT for the period 1884-2000 and also at 9:00 pm GMT for the period 1884-1964. In both series, clouds were measured in tenths for the period 1884-1948, and subsequently, in oktas.

Synoptic total cloud cover data for Valentia (1940-1999) and Birr (1956-1999) was kindly provided by Met Eireaan (Dublin). Data are given in monthly means and measurements have been made at 9:00 am GMT. Unfortunately observations of cloud type were not available to us for any of the three sites.

4 Seasonal variability

For the Armagh station, daily measurements of both total synoptic cloud cover and sunshine hours are available in digital format. This has allowed a straight forward comparison to be made. In Figure 2 (a), we plot the seasonal variability of synoptic cloud cover and the cloud factors (F_c) derived from the sunshine records for the period 1951-1988; where $F_c = 1 - F_s$. The sunshine factor F_s is the total number of sunshine hours divided by the total number of available sunshine hours. It is evident that there is a qualitative similarity in the annual variability of synoptic cloud cover at 9:00 am and the cloud factor derived from sunshine records, with a peak in cloudiness around mid-summer and another in mid-winter.

However, the overall level in summer relative to winter is different for the synoptic cloud measurements in the upper panels of Figure 2 to cloud factor derived from sunshine in the lower panels. One possible explanation could be that the sunshine records were more strongly affected by trees on the horizon in winter than in summer. Another explanation would relate to the time of measurement: whereas sunshine records cover the whole day light period, synoptic cloud observations are only made once a day (9:00 am). A seasonal effect resulting from under-recording of winter sunshine due to haze and wetter and cooler conditions may also contribute by reducing the ability of the Sun to burn a trace in the (cold and damp) card.

For Birr and Valentia the same procedure was applied to the data, but employing monthly means (Figures 2 (b) and (c) respectively), with similar results as in the case of Armagh. Because of the scarcity of trees on the western seaboard (where Valentia is situated), changes in the local horizon are unlikely to be responsible for seasonal differencies between cloud factor derived from sunshine and synoptic cloud cover.

5 Long-term trends in Ireland

5.1 Sunshine Records

The most prominent feature of the data, for all four sites, is a gradual decline in the total annual sunshine hours over much, if not all, of the 117 year period during which records have been obtained. In Figure 3, we plot the total number of hours of bright sunshine for the four Irish sites for the period 1881-1998. The effect is particularly conspicuous at the most westerly site of Valentia Island/Cahirciveen, on the County

Kerry coast, where the number of sunshine hours has dropped by $\sim 20\%$ since the end of the last century. If we plot the seasonal averages, the gradual decrease is seen in all stations in all seasons (not shown).

In Table 1, the slope of the decreasing trend and its statistical significance is shown for the annual and seasonal means. It is clear that the decreasing trend is present and highly significant for all of the stations except for Armagh, where the decrease is not so statistically significant due to the anomalously low sunshine at the beginning of the records, possibly due to a change in the condition of the local horizon (e.g. trees). We also observe that the trends are less significant in winter and strongest in spring and summer.

The four meteorological stations lie between approximately $52^o.0$ and $54^o.3$ North, and $6^o.3$ and $10^o.3$ West. Thus, although there is likely to be a strong degree of correlation between the sunshine records of the four sites, regional differences will occur. The correlation coefficients between the annual total sunshine hours at the four locations are listed in Table 2. In Table 2, we also show the correlation with the sunshine data for Kew Observatory near London, England over the years in common (1881-1964). A high degree of correlation between the data for the different sites is evident though, as expected, this becomes lower as the distance between the sites increases.

5.2 Synoptic Cloud Observations

All four cloud series for Armagh are shown in Figure 4 (a), with the two series measured in tenths converted to oktas. There is strikingly good agreement between the am and pm measurement trends, and no discontinuities at the changeover points(1948-1949) from tenths to oktas. Clouds in Armagh seem to indicate a decreasing trend during the first 50 years of the record and an increasing trend since the 1930's, except for the last decade or so.

The cloud data available to us for Valentia and Birr cover a much shorter time interval and are also shown in Figure 4 (b). In Table 2, the correlation coefficients between the three am cloud series for the period in common, 1956-1999, are given. The agreement between the Valentia and Birr series is quite strong, but unlike the Armagh data, neither show a long-term trend in cloud cover.

As might have been expected from eye estimates, different observers do not always record the same degree of cloud cover. In Figure 4 (c) we have again plotted the cloud series for Armagh (9:00am only), for the period during which meta-data relating to the observers identity is available. Since 1901 the names of the meteorological observer and deputy observers have been retrieved from the Meteorological Office inspection reports and the Observatory archives. It is often the case that when an observer leaves or retires he is substituted by one or a succession of temporary observers. In Figure 4 (c), we have also plotted the periods during which observers are known to have taken the measurements for the whole of the calendar year. Unshaded periods are times when it is uncertain if the preceding or leading observer was taking the measurements or, more often, a period when several temporary observers were responsible.

It looks likely, from the figure, that the mean recorded cloud cover strongly depends on the observer, and therefore we cannot rely on long-term trends indicated by synoptic cloud cover. Thus the disagreement in the long-term trends between synoptic cloudiness and sunshine can be explained, at least for the case of Armagh, through systematic errors introduced by the observers. Particularly clear is the jump in the Armagh cloud series in 1993, after a new observer started in December 1992. In Figure 5 (left top panel), the drop in sunshine and synoptic cloud towards the end of the series seem to agree, suggesting that the cloudiness drop may be real, however this is just an effect of the data normalisation. The drop in the synoptic cloud series occurs in 1993 and the cloudiness level remains lower than average for the whole duration of that observer's employment until 1998. At the same time, in 1993, there is a dip in sunshine which disagrees with the decrease in cloudiness (since we would expect them to vary in opposite directions). Two years later, in 1995, there is a peak in sunshine with a corresponding dip in cloudiness (respective to the mean level of that observer), as one would expect.

This is explained by the fact that introducing a new observer changes the mean level of observed cloudiness, thus destroying the possibility of long-term trend studies, however during the interval in which the same observer is taking the measurements, the year-to-year variability matches well with the sunshine records. In other words, the observers are consistent in their own measurements but differ systematically from each other.

The cloud series for the Valentia and Birr stations do not show such observer-dependent discontinuities; or at least they are not evident at first glance. However we do not have access to the relevant data to check this in detail.

6 Comparison of Sunshine and Synoptic Cloud Trends.

Initially, only the monthly mean synoptic cloud cover for the period 1951-1988 was available in digital form for Armagh. For cloud cover we find a 15% increase over this period as compared to a 13.5% decrease in sunshine. These trends were so similar that, we concluded initially that, contrary to Stanhill's (1998) results, an increase in cloud cover was the most likely cause of the drop in sunshine over Ireland since the late 19th century (Pallé and Butler 2001).

In Figure 5, synoptic cloud cover and sunshine records at the three Irish stations are compared. Both series have been normalised to ease the comparison, and the sunshine series has been inverted. In the left hand panels we can see how except for Armagh the agreement between the cloud and sunshine series in their long-term trends is poor. However, the inter-annual variability is well matched for all stations. In the right hand panels, the sunshine records have been detrended with a chi-square linear fit. Once the linear decreasing trend in the sunshine is removed, the correspondence between the records for Birr and Valentia improves (see Table 3). The agreement is particularly good for the Valentia station, where the observations are taken by professional meteorological observers.

We find then, in general, that even though the inter-annual cloud and sunshine variability is strongly related, the trends in the two data series sometimes differ. A decrease in the sunshine records not accompanied by an increase in cloud cover is difficult to explain. One possible reason could be an increase in atmospheric pollution or aerosol concentration leading to changes in the transparency of the atmosphere or changes in the radiative properties of clouds (e.g thickening of cirrus clouds). It is also possible that observer changes can play a fundamental role and influence long-term cloud cover trends at a particular station, as we have seen in Armagh. This problem could be overcome through averaging the data for a large number of stations.

In Figure 6, the high-frequency variability of the Armagh sunshine and synoptic cloud series is shown. To derive this quantity we have smoothed the raw data for both series with a five year running mean, and then subtracted the running mean from the raw data. In this way, the long-term variability in both series has been eliminated. The resulting cloud and sunshine series correlate with each other, for the period 1884-1998, with a Pearson's correlation coefficient of -0.56 ($P << 10^{-4}$). Such a good agreement is striking and much more convincing than the removal of a simple linear trend as in Figure 5. For the restricted period 1949-1998 used in Figure 5 (to compare with Valentia and Birr), the correlation coefficient is -0.49, slightly lower than for the whole series but still reaching less than 99.9% probability of occurrence by chance. For Birr and Valentia this procedure leads to correlation coefficients of -0.6 and -0.79, respectively, both of them significant at higher confidence levels than Armagh during the same period. This method gives a very similar correlation coefficient to the detrended sunshine for Valentia (Figure 5), but results in a substantially improved correlation for Birr. Thus, the mismatch between sunshine and synoptic cloud observations involves more than a simple linear trend, which would tend to suggest that the long-term trends in the two series are not always physically related.

Another possible factor affecting cloud trends is the resolution of the measurements. Synoptic cloud cover is measured in integral numbers of oktas, i.e. a resolution of just 12.5%. Although it is difficult to translate percentage changes in cloud cover into percentage changes of sunshine or vice-versa, the decreasing trends detected in the sunshine records are around 14% for Valentia and around 11% for Armagh and Birr during the last five decades, very close indeed to the synoptic cloud resolution.

7 Clear Sky Frequency at Armagh

We have seen in the previous sections how synoptic cloud observations are subjectively biased by the observer making it difficult to obtain reliable information on long-term trends. This systematic error cannot be corrected easily (e.g, by calibrating the means for different observers) without destroying any long-term trends. Here however, we suggest another method to obtain reliable information on long-term trends in cloudiness - namely to use the clear-sky frequency.

One thing that all observers should agree on, independently of their subjective bias, is a sky completely free of clouds. The Observer's Handbook (1982) is very clear in this respect, synoptic cloud is recorded as 0 (clear sky) if there is absolutely no cloud visible. If a small cloud is present, even if it extends much less than one eighth of the sky, synoptic cloud has to be recorded as 1. With this in mind, we analysed the clear sky frequency at Armagh.

It must be noted that, whereas sunshine and cloudiness trends would be expected to vary oppositely, the clear sky frequency (absence of clouds) is expected to vary in the same way as sunshine. In Figure 7, the number of days per year in which the sky appeared clear at 9:00 am (a) and 9:00 pm (b) are plotted. We can see here how the number of clear mornings (9:00 am) has been monotonically decreasing during the last century, after an initial sharp increase between 1880 and 1900. Although the possibility of a systematic observer bias in the data cannot be excluded, the variability of this series is not the same as the total synoptic cloud and there are no apparent jumps in the series at the times when the observers changed. The am and pm series agree in their year to year variability, although the decreasing trend is only evident in the am series. Henderson-Sellers (1992) reported that synoptic cloud estimations at 8:00 or 9:00 am local time give the best estimate of the daily average.

In Figure 7 (c) we have plotted together the sunshine records (scaled but not inverted) and the clear sky frequency. Although these two measurements are not equivalent, the correlation between the two series is about 0.4, significant at least at the 99.9% level. Overall this picture suggests that cloudiness has in fact increased during the past century over Armagh, in agreement with the sunshine records. Though, it is difficult to evaluate the implications of the change in clear sky frequency and its significance for climate, the downward trend is striking.

As well as the frequency of clear skies, our first thought was also to use the frequency of a completely overcast sky. However, analysis of the frequency of an overcast sky reveals the same discontinuities in the series as seen in the total synoptic cloud cover, coinciding with changes in the observer (see Figure 4 (c)). A possible explanation is that the Observer's Handbook (1982) is not so clear about this point. If there is a very small patch of the sky (far less than one okta) the observation can be qualified as 7 or 8 depending on the observer, although strictly it should be recorded as 7. The difficulty in recording an overcast sky resides in determining whether there is a clear patch in a sky full of clouds. The Observer's Handbook (1982) states that *"if even the smallest amount of blue sky is visible then you must report a 7."*, but also states that *"Sky during the day has a blue coloration. However, during conditions of haze or mist, the sky towards the horizon may become quite discoloured. Observers should beware of mistaking such phenomena with cloud"*. Thus, the decision as to whether the observer sees a small amount of 'blue sky' or not can be subjective. Angell et al. (1984) also signaled a tendency for ground-based observers to overestimate cloudiness because of their inability to detect clear patches at a distance when clouds have a significant vertical extent. It is also worth noticing how a clear sky is a relatively "rare" event at Armagh, going from around 30 days/year at the beginning of the century to around 10 days/year in the last couple of decades, and it is also easy to evaluate. On the other hand, an overcast sky is a quite common observation, around 150-200 days/year (almost 2/3 of the days in some years), which would lead to a much stronger effect (through accumulation) of the bias introduced by observers.

A final comment is that the decreasing trends in the sunshine records agree with the global trend in increasing cloudiness detected in studies all around the world (Norris, 1999; Sun and Groisman, 2000; Henderson-Sellers, 1992). Since those major studies involve thousands of stations the systematic errors introduced by the observers should be much reduced or eliminated.

8 Conclusions

A gradual decrease in the number of sunshine hours over Ireland is observed since records began in 1881. To assess whether or not this is due to increased cloudiness we have analysed the synoptic cloud and sunshine data from three stations.

The synoptic cloud records have a strong inter-annual correspondence with sunshine records, but they fail to show any consistent trend during the last 50 years. However we have demonstrated how trends in synoptic cloud cover have little weight due to their observer dependence. We conclude therefore that long-term trends in synoptic cloud records are not reliable for a single station, particularly for stations with non-professional observers. The data from Valentia could be an exception to this rule, however, the synoptic cloud cover at 9:00 am at Valentia has no significant trend over the past 50 years. The use of sunshine records in preference to synoptic cloud observations is recommended in view of the agreement between sites and because they are instrumental. Trends derived from synoptic cloud cover observations from a small number of stations should be confirmed if possible with the use of sunshine recorders.

Finally, we propose that the clear sky frequency is a good indicator of cloud trends and is less susceptible to observer bias than synoptic cloud cover. Clear sky frequency at Armagh, the only station for which daily data was available, show a very significant, robust, decreasing trend during the last century. These results seem to support the suggestion that increasing cloudiness is responsible for the observed decrease in sunshine hours over Ireland.

9 References

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Table 1: Seasonal and annual values for the trend in sunshine at the four Irish stations. The rate of the trend is given, as well as the determination coefficient for the trend fit and its statistical significance (ns: not significant). Also we give the seasonal and annual trends for the synoptic clear sky frequency at Armagh (both 9:00am and 9:00pm series).

Sunshine	**Period**	**Decr. [hours/year]**	r^2	**P value**
Armagh	Annual	-0.78	0.057	98%
	Winter	-0.03	0.002	ns
	Spring	-0.33	0.045	95%
	Summer	-0.28	0.021	ns
	Autumn	-0.14	0.021	ns
Valentia	Annual	-2.50	0.371	99.9%
	Winter	-0.25	0.072	99%
	Spring	-0.81	0.220	99.9%
	Summer	-0.82	0.151	99.9%
	Autumn	-0.63	0.227	99.9%
Dublin	Annual	-2.45	0.373	99.9%
	Winter	-0.20	0.058	99%
	Spring	-0.95	0.282	99.9%
	Summer	-0.90	0.182	99.9%
	Autumn	-0.39	0.118	99.9%
Birr	Annual	-1.74	0.219	99.9%
	Winter	-0.17	0.046	99%
	Spring	-0.54	0.116	99.9%
	Summer	-0.60	0.088	99.9%
	Autumn	-0.43	0.132	99.9%
Clear Sky Freq.	**Period**	**Decr. [days/decade]**	r^2	**P value**
9:00 am	Annual	-2.55	0.486	99.9%
	Winter	-0.77	0.395	99.9%
	Spring	-0.61	0.225	99.9%
	Summer	-0.31	0.099	99.9%
	Autumn	-0.85	0.430	99.9%
9:00 pm	Annual	1.45	0.047	ns
	Winter	1.02	0.184	99.9%
	Spring	0.56	0.042	ns
	Summer	-0.72	0.103	99.5%
	Autumn	0.59	0.056	95%

Table 2: The correlation coefficient between the mean annual sunshine hours over the four Irish sites and Kew (England). All coefficients are significant at the 99.9% level or higher (less than 0.001 probability of occurrence by chance). The distance (D) between the sites in kilometers is also indicated. Correlations Coefficients between the 9:00 am cloud data series for three Irish sites for the common period 1956-1999 (44 years) are also indicated. The correlation between Armagh site and either of the other two sites is not significant. Only the correlation between Valentia and Birr (r=0.39) is significant at the 0.01 level.

Site		**Armagh**		**Valentia**		**Birr**		**Dublin**	
		Correl	D	Correl	D	Correl	D	Correl	D
Armagh	*Sunshine*	–	–	0.55	367	0.74	175	0.69	116
	Cloud	–		0.09		0.14		–	
Valentia	*Sunshine*	0.55	367	–	–	0.71	212	0.76	317
	Cloud	0.09		–		0.39		–	
Birr	*Sunshine*	0.74	175	0.71	212	–	–	0.76	113
	Cloud	0.14		0.39		–		–	
Dublin	*Sunshine*	0.69	116	0.76	317	0.76	113	–	–
Kew	*Sunshine*	0.55	612	0.34	750	0.56	600	0.52	510

Table 3: Correlation coefficients and significance level between sunshine records and synoptic total cloud cover at three Irish stations. Two case have been considered, using raw data with no corrections and removing a chi-square linear fit trend to the sunshine records. Also indicated is the period for which both datasets are available at each site.

Site		Raw Data		Detrended Sunshine		High-Frequency	
	Years	**r**	**P**	**r**	**P**	**r**	**P**
Armagh	1949-1998	-0.55	<<99.9%	-0.49	<99.9%	-0.56	<<99.9%
Valentia	1940-1998	-0.64	<<99.9%	-0.81	<<99.9%	-0.8	<<99.9%
Birr	1956-1998	-0.14	ns	-0.42	99.5%	-0.6	<<99.9%

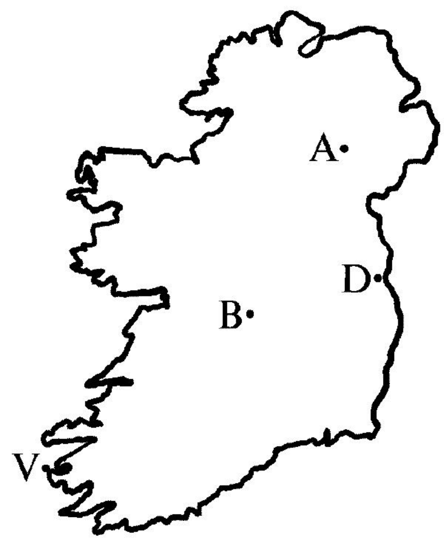
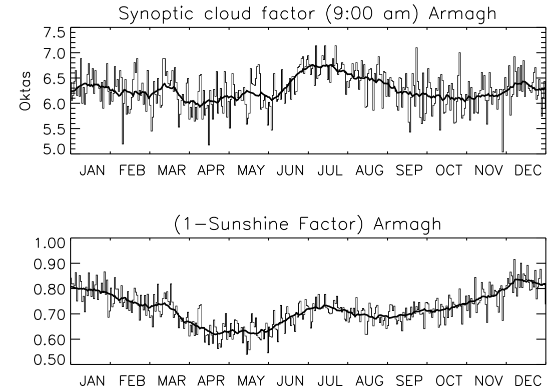
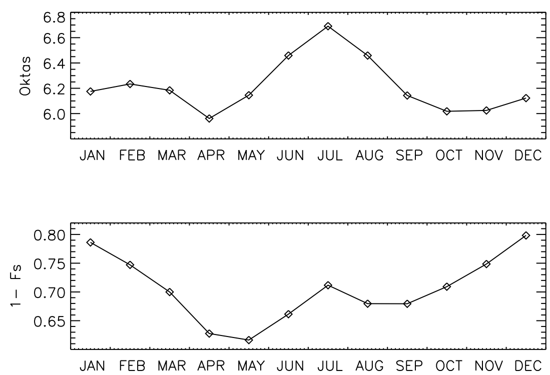


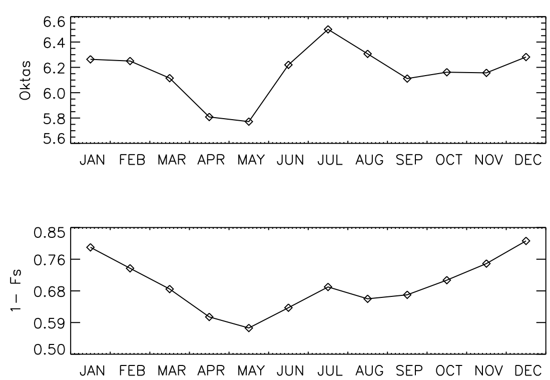
Figure 1: Outline map of Ireland. The geographical locations of the four Irish stations (A:Armagh; D:Dublin; B:Birr; V:Valentia) are shown.



(a) Armagh



(b) Birr



(c) Valentia

Figure 2: The average seasonal cloud variability at (a) Armagh for the period 1951-1988, (b) Birr and (c) Valentia. Top panels: seasonal variability from synoptic cloud observations at 9:00 am GMT. Lower panels: seasonal variability of the cloud factor (1-Sunshine factor) from the sunshine records. Note that daily data have been used for Armagh (a) and monthly data for Birr (b) and Valentia (c).

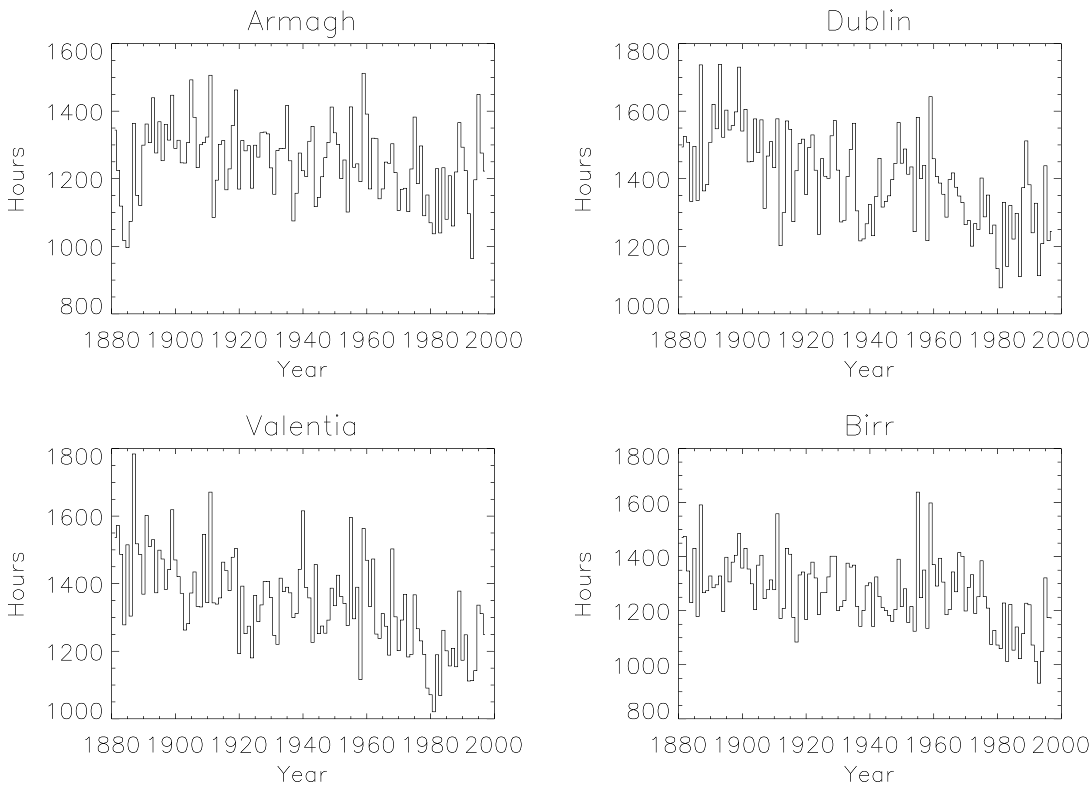
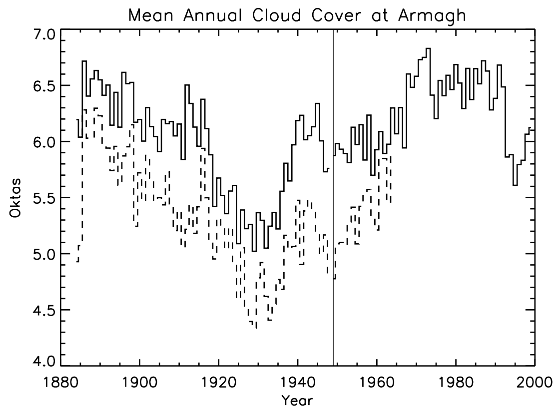
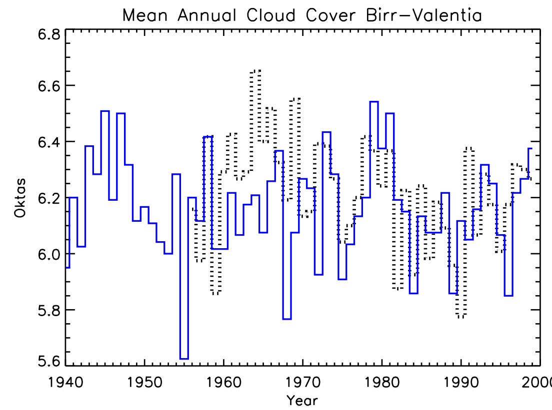


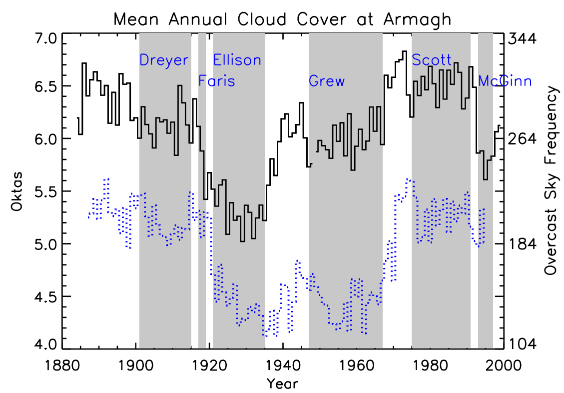
Figure 3: Total annual sunshine hours for four Irish sites 1881-1998.



(a)



(b)



(c)

Figure 4: (a) Synoptic cloud observations at Armagh Observatory. The thick solid line represents the observations taken at 9:00am GMT and the thin broken line observations taken at 9:00pm GMT. Data for the period 1884-1948 were measured in tenths of the sky and have been scaled by the factor 0.8. The vertical line at 1949 marks the change from tenths to oktas. (b) Synoptic total cloud observations at Valentia (solid line) and Birr (dotted line) stations. Observations are taken at 9am GMT.(c) Total synoptic cloud observations at 9:00am GMT for Armagh (solid line, as in panel (a)) and overcast sky frequency at 9:00am at Armagh (broken line). Shaded areas are periods for which a single observer is believed to have made the observations. Note how discontinuities in both series tend to coincide with the start or end of a shaded period.

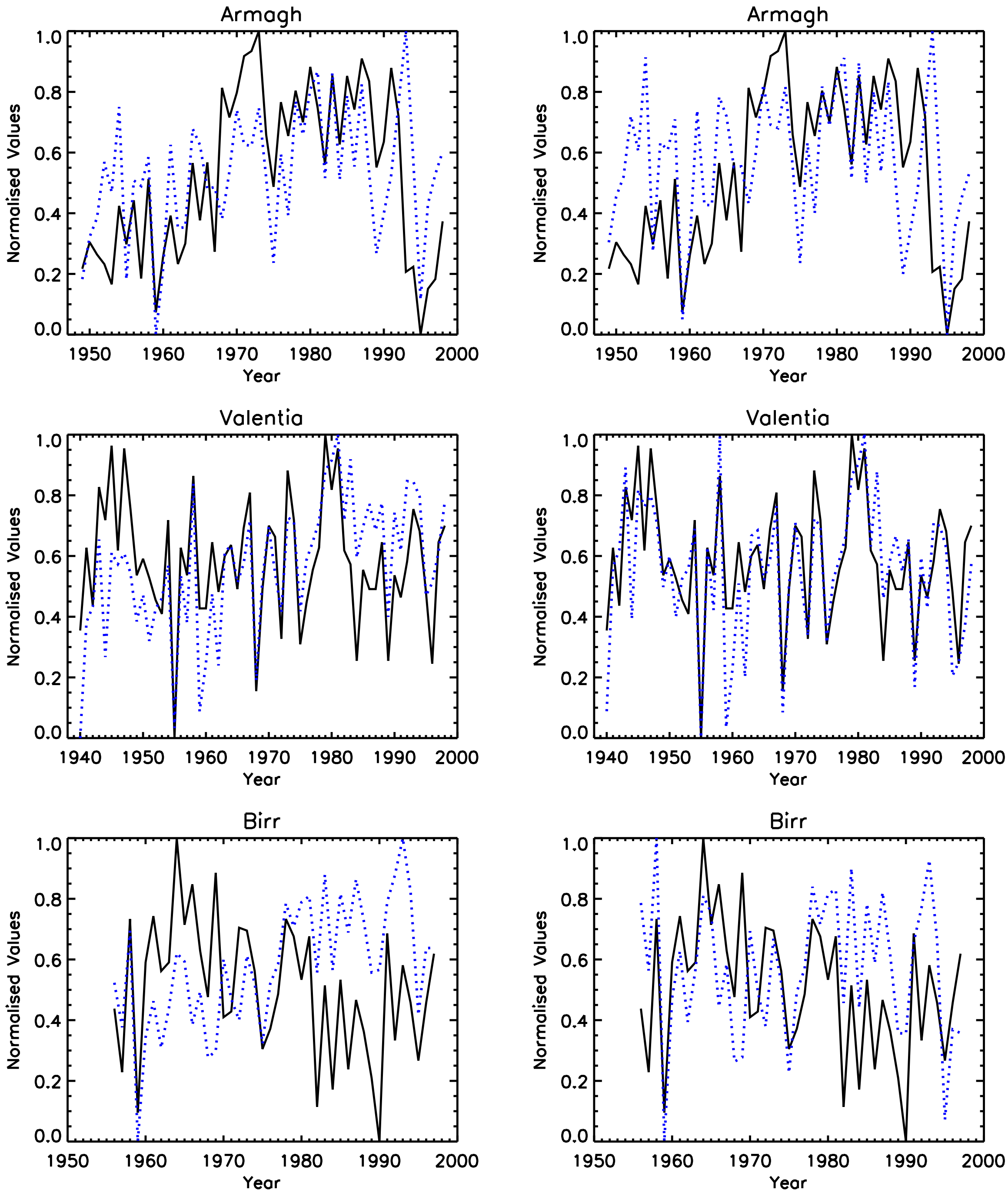


Figure 5: Total synoptic cloud cover (solid line) and sunshine (dotted line) observations at Armagh (top), Valentia (middle) and Birr (bottom) sites. Both series have been normalised to allow a more straight forward comparison and the sunshine series have been inverted. In the left panels both datasets are as measured. In the right panels the sunshine data is detrended.

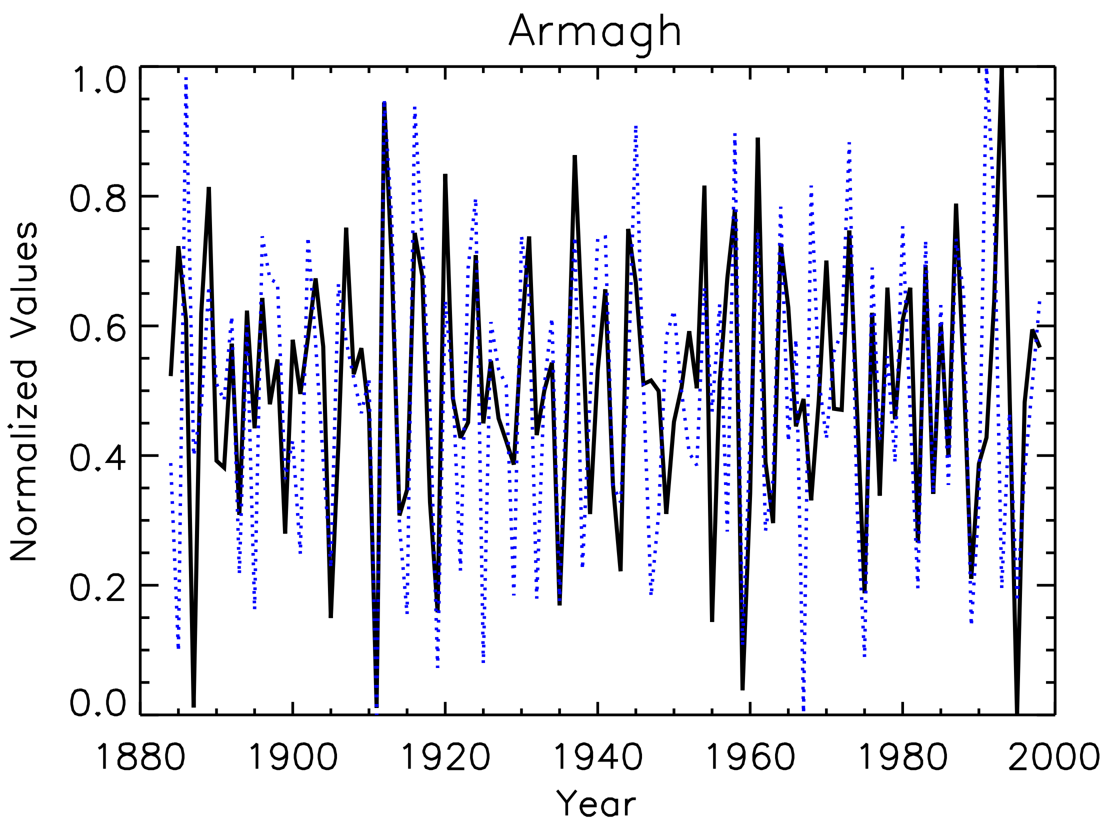
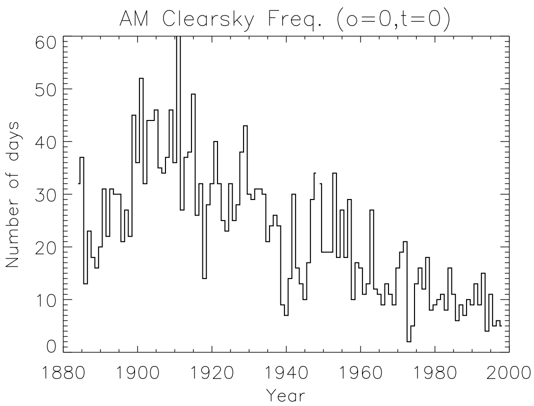
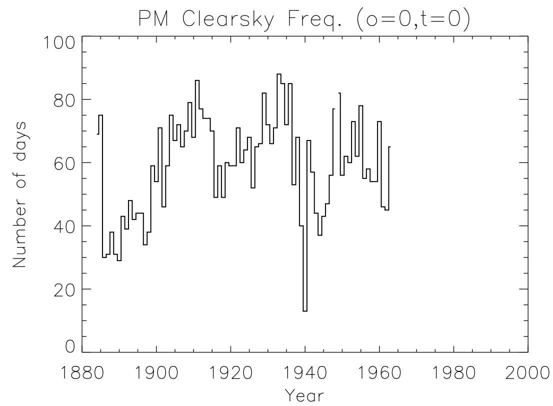


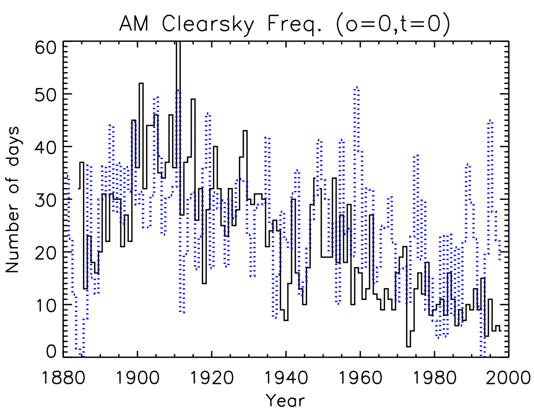
Figure 6: High frequency variability at Armagh for the sunshine records (dotted line) and synoptic cloud cover (solid line). Both sets of data are normalised and sunshine is inverted. The raw data for both series have been smoothed with a 5-year running mean and the smooth values subtracted from the raw data.



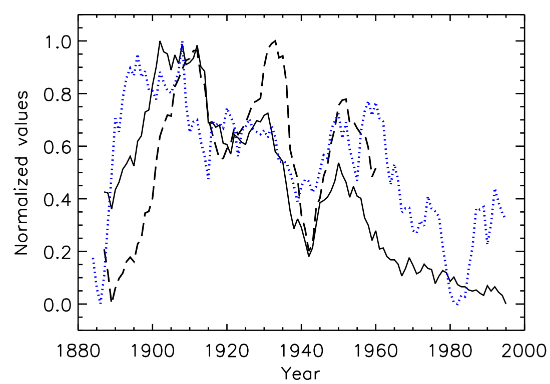
(a) am



(b) pm



(c) am-sunshine



(d) all

Figure 7: Top panels: Clear sky frequency at Armagh for the 9:00am series (a) and 9:00pm series (b). In panel (c) the 9:00am clear sky frequency (solid line) is plotted together with the sunshine records at Armagh (dotted line) arbitrarily scaled for comparison. The correlation between the two series is of 0.4 ($P << 0.001$). In panel (d) the clear sky frequency at 9:00am (solid line), clear sky frequency at 9:00pm (dashed line) and sunshine records (dotted line) have been smoothed with a 3-year running means to allow an easier comparison of the long-term variability of the three series.