SUNSHINE, CLOUDS AND COSMIC RAYS.

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ABSTRACT

Our analysis of the new ISCCP (International Satellite Cloud Climatology Project) D2 cloud data reveals that there is a correspondence between the low cloud cover and the galactic cosmic ray flux. Using several proxies for solar activity and the radiative forcing for the ISCCP cloud types, we estimate the possible impact that such a solar-terrestrial connection may have on climate and find that much of the warming of the past century could be quantitatively accounted for by the direct and indirect effects of solar activity. We have also analysed the behaviour of the available proxies for cloud cover existing for the last century, searching for the cloud cover decrease predicted by the low cloud- cosmic ray flux correlation. The sunshine records and the synoptic cloud records both indicate that the total cloud cover over the oceans has increased during the past century but the evidence for a low cloud decrease is unclear.

Key words: Sunshine, Clouds, Cosmic Rays, Climate.

1. INTRODUCTION

The extent to which the recent global warming has an anthropogenic origin (e.g. via the enhanced greenhouse effect) as opposed to a natural origin (e.g. through volcanic activity or solar variability) is of crucial importance for our understanding of how the Earth's climate has varied in the past and how it may vary in future. Detailed fits of global and hemispherical temperatures since the mid-19th century with empirical models involving the enhanced greenhouse effect and solar variability require at least one parameter linked to solar activity for a satisfactory fit in the mid-20th century (Kelly & Wigley, 1992; Soon et al., 1996).

A possible modulation of the Earth's albedo by changes in cloudiness resulting from changes in the flux of galactic cosmic rays was proposed by Svensmark & Friis-Christenssen (1997). This mechanism looked particularly promising after a strong correlation between cloud factor over mid-latitude oceans and cosmic ray flux was found by these authors for the period 1984-1991. They suggested that cosmic rays promote the formation of terrestrial clouds through ionization of particles in the troposphere. As both the flux and the energy spectrum of cosmic rays are known to be modulated by the interplanetary magnetic field, which in turn is strongly influenced by the magnetic field of the Sun, it is feasible that cosmic rays provide the link whereby solar activity affects the global climate (Svensmark, 1998). Here we will analyse recent evidence to support this link.

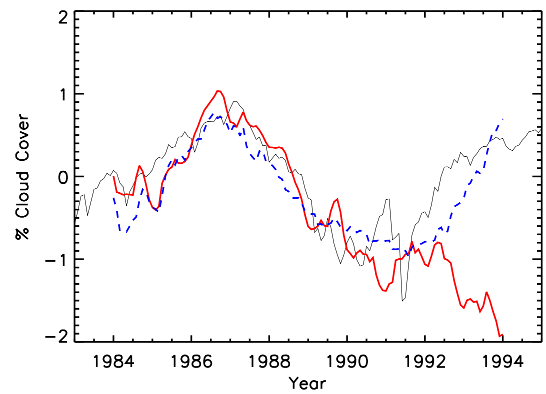

Figure 1. Total cloud cover (solid thick line) and low cloud cover (broken line) over the SFC areas as obtained with the D2 dataset from infrared (low clouds) and visual plus infrared (total cloud) observations. The solid thin line represents the Climax Cosmic Ray Flux scaled for comparison. (from Palle and Butler, 2000a)

2. CORRELATION BETWEEN COSMIC RAY FLUX AND CLOUD FACTORS

Our first objective was to ascertain whether or not previous reports (Svensmark & Friis-Christenssen, 1997; Svensmark, 1998), that the total cloud cover over mid-latitude oceans, excluding the tropics, (hereafter SFC zones) correlates strongly with cosmic ray flux, are substantiated by a new improved satellite cloud data set (ISCCP D2). In Figure 1 we plot the total cloud cover over this latitude range together with the cosmic ray flux, suitably scaled for overlap. We note that a close correspondence between the cosmic ray flux and total cloud cover is maintained from 1983 till 1991, the period previously

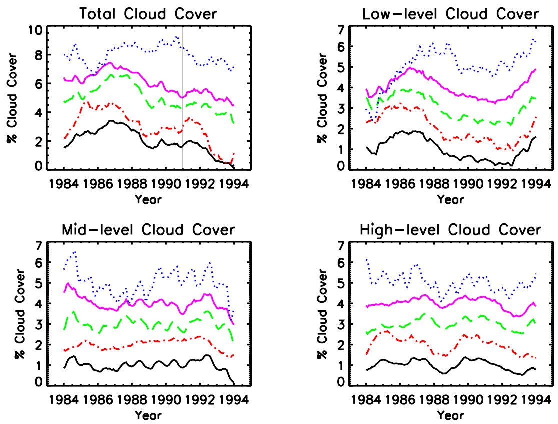

Figure 2. The 12-month running mean of the total, low-level, mid-level and high-level cloud cover for the period 1983-1995 covered by the ISCCP D2 dataset. Five different series are represented in each panel, ordered from bottom to the top as follows: Cloud cover over the whole Earth, the tropics (±22°.5), mid-latitudes (± 22°.5 ⇒ ± 60°), the SFC zones (ocean areas excluding the tropics) and poles (± 60° ⇒ ± 90°). Cloud cover is measured as the fraction of the sky covered by clouds. The amplitude of the cloud cover variation is real, but the mean value is shifted for plotting purposes. (from Palle and Butler, 2000a)

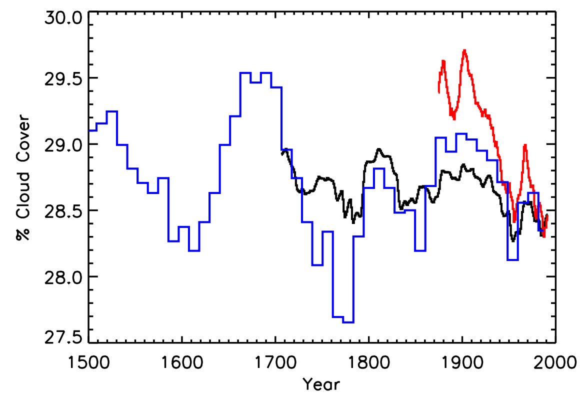

Figure 3. The 11-year smoothed reconstructed cloud cover for the whole Earth derived from the Zurich Sunspot number (middle line) and the aa *index (top line). In addition we plot the reconstructed cloud cover factor for the whole Earth derived from the 11-year mean Heliocentric potential (longer line).*

studied by Svensmark and Friis-Christenssen (1997), but that subsequent to this, the curves diverge. Thus, when we include the data from 1992 to 1994, we find that the new D2 data series does not confirm the previous findings in respect to the total cloud cover. Instead the correlation with the galactic cosmic ray flux now appears more strongly correlated with the low cloud cover.

In Figure 2 we show the mean monthly cloud factors for selected regions (described on the caption) for low, medium and high altitude clouds (2, 4.5 and 10 km mean altitude respectively), each smoothed with a twelve-month filter to eliminate seasonal effects. We note the following: (1) the good correlation between total cloud factor and cosmic ray flux from 1983-91 breaks down after 1991; (2) the high level and mid-level clouds show no systematic variation over the period 1983-94; (3) the low-level clouds for all latitude zones excluding the poles are well correlated with the cosmic ray flux over the period 1983-94.

3. ESTIMATING CLOUD FORCING

The role of clouds in climate is still not well understood; they have two opposite effects. On the one hand they tend to cool the climate by reflecting short-wave solar radiation back to space, and on the other to warm the climate by trapping the long-wave radiation emitted from the Earth's surface. The balance of these two effects is in part determined by the cloud height; on average low clouds are believed to cool and high clouds to warm the climate (Ockert-Bell & Hartmann, 1992; Ramanathan et al., 1989). Provided the above correlation is maintained over long periods, a reduced low-cloud factor would be expected during high solar activity, and the increased solar activity in recent decades would translate into a global decrease in the low, cooling clouds thereby contributing to global warming (Svensmark, 1998).

In order to make a prediction of the low cloud factor, earlier in the 20th century and in the 19th century when cosmic ray fluxes are unavailable, we have also determined the regression relations between the Sunspot Number, the <aa> index and the low cloud factor as determined from the ISCCP-D2 data. For even longer periods, extending back before the 19th century, we use the Heliocentric Potential, an interplanetary magnetic field index calculated by O'Brien (1979) which is based on the carbon isotope concentration in tree-rings.

From the regression between the various activity indices and the low cloud factor over the interval 1983-1994, we can make a prediction of the change in average low cloud factor since the late 19th century. The results indicate a decrease in low cloud factor by about 1% over the past one hundred years (see Figure 3), leading to a reduced albedo and positive radiation forcing in recent decades. Together with the increased forcing from the increase in solar irradiance, this leads to a total solar activity induced change in the global mean temperature of ∼ 0.5°C which is close to the observed increase of 0.55°C since 1900 (Lean & Rind, 1998; Jones & Briffa, 1992).

Similarly, we can compute from the change in ^{14}C levels, (via the Heliocentric Potential), the effect of activity induced cloudiness on temperatures in the late 17th and early 18th centuries during the Maunder Minimum. We derive a cloud induced global cooling of 0.5° during this period compared to modern temperatures. This together with a cooling of 0.32°C from an inferred reduced solar irradiance of ∼0.25% at that time (Rind & Overpeck, 1993) implies a combined cooling of 0.82°C, reasonably close to the value of ∼ 1.0°C believed to have occurred at this time.

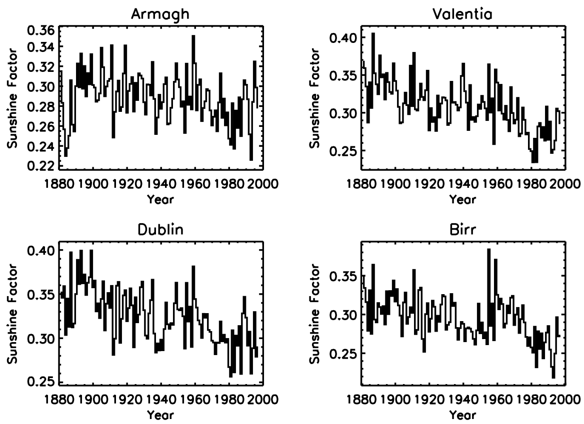

Figure 4. Total annual sunshine hours for the four Irish sites (1881-1998).

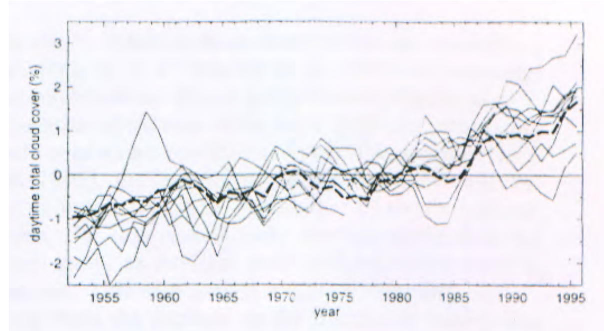

Figure 5. Adapted from Norris (1999). Yearly global mean departure (thick dash) and zonal mean departures (thin) from long-term mean daytime total cloud cover over the ocean. Zonal means are for 10^o-lat bands between 60^oN and 40^oS. Units are percent sky cover. Three-year running mean smoothing was applied.

The details of these calculations are given in Palle & Butler (2000a). They are subject to several assumptions, including: (1) the correlation between low cloud and cosmic ray flux is maintained over long time scales; (2) other cloud types remain constant; (3) that there is no additional change in the cloud factor from global warming, i.e. no feedback.

4. OTHER CLOUD DATA AND CLOUD PROXIES

The above analysis, working from the observed correlation of low cloud factor with cosmic rays and solar activity indices, has serious implications for our understanding of the causes of climate change in the past century as it suggests that most of the global warming during this period can be attributed to the combined direct (irradiance) and indirect (low cloud factor) effects of solar activity. However the actual amount of the variation in cloud factor predicted is small (∼1%) and could easily be swamped by other factors. In this respect we note that the above correlation applies only to low clouds whereas a comprehensive forcing computation would require knowledge of the variability of clouds at all levels. It is important, therefore, to examine any other evidence we can find that could give us actual measured cloud factors over the past century.

Since satellite-based cloud records do not extend for more than a couple of decades and calibration problems between the existing datasets do not allow a straight forward comparison, we have examined cloud proxy records and synoptic cloud observations, both measured from ground stations, to study the cloud cover behaviour on time scales longer than a decade.

One such relevant cloud proxy is sunshine duration. Daily records of the duration of bright sunshine have been obtained at four stations in Ireland since May 1880 using a standard *Campbell-Stokes* sunshine recorder (Observers Handbook, 1982). Two are located in the east of Ireland; at Armagh Observatory and The Ordnance Survey Office, Phoenix Park, Dublin; one in the extreme west at valentia Island/Cahirciveen, Co Kerry; and the fourth, in the midlands, at Birr Castle, Co Offaly.

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 118 year period during which records have been obtained (see Figure 4). 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 most seasons. Similar results were reported by Stanhill (1998) using records of sunshine duration over Israel, though over a shorter time than the Irish records.

The sunshine data has been shown to be a very good proxy for total cloud cover over monthly to yearly time scales, at least over the Irish region (Pallé & Butler, 2000b). Unfortunately the sunshine records are related only to the total cloud factor and do not give us any information on cloud type. It can also be argued that the sunshine records are a local measurement and that the observed trends are not necessarily similar for other areas. However, Pallé & Butler (2000b) compared the variability of the ISCCP D2 satellite cloud records over Ireland and other areas of the globe and found that the Irish cloud variability is very similar to the whole North Atlantic region and in general to all mid-latitude oceanic regions, over the period comprised by the data (July 1983- August 1994). Thus it seems that the sunshine factor over Ireland could be particularly useful in indicating wider trends.

If the Irish sunshine data are indeed relevant to the global trend they would indicate a rise in the total cloud factor since the late 19th century, whereas the low cloud - cosmic ray correlation would predict a fall in low cloud factor over the same period. One explanation could be that high cloud has increased in this period to a greater extent than low cloud has decreased. As, on average, high clouds warm and low clouds cool the climate, increased high cloud and decreased low cloud would both give an additional positive radiative forcing increment to the solar irradiance forcing thereby leading to further enhanced global warming.

Table 1. Sunshine records and synoptic cloud data compilations from the ground. Satellite cloud measurements from different satellite measurements are also displayed, however the short duration of those records makes them unsuitable for long-term studies. References: [1]Palle and Butler, 2000b; [2]Stanhill, 1998a; [3]Stahle et al., 1991; [4]Sun and Groissman, 2000; [5]Norris, 1999; [6]Sun and Groissman, 2000; Karl et al., 1995; Liepert, 1997; DCSCVC, 1998 and therein; [7]Stanhill, 1998b and therein; Liepert, 1997; [8]Kernthaler et al., 1999; [9]Palle and Butler, 2000a; [10]Kristjansson and Kristiansen, 2000; [11]Menzel et al., 1996.

Dataset	Total Cloud Cover	Low Clouds	High Clouds	Period
Ground Data				
[1]Sunshine in Ireland (decrease)	Increase	–	–	1881-1998
[2]Sunshine in Israel (decrease)	Increase	–	–	1979-1995
[3]Sunshine (?) Central USA (tree-rings)	Stable	–	–	1700-1980
[4]Synoptic Clouds over FUSSR	Increase	Decrease	Increase	1936-1990
[5]Synoptic Cloud over Oceans	Increase	Increase	–	1952-1995
[6]Synp. Cloud (Austr, N.Am, India, Europe,..)	Increase	–	Increase	1900-1990
[7]Ground-based solar radiation (various)	Increase	–	–	1960-2000
Satellite Data				
[8]ISCCP C2	Stable	–	Increase	1983-1991
[9]ISCCP D2	Stable	CRF-Decrease	Stable	1983-1994
[10]DMSP (water clouds over Oceans)	Increase	–	–	1988-1998 !
[11]HIRS (only Cirrus)	–	–	Increase	1989-1996

A second set of records we explore are the synoptic cloud observations. Synoptic observations of total cloud cover are taken in many observatories worldwide. The procedure for the measurements is simple, at certain times of the day, the observer notes the number of ocktas (1/8 th of the sky) covered by clouds. A totally overcast sky is registered 8 and a clear sky 0. At some stations, coverage by different cloud types is also recorded.

Observations of synoptic cloud cover over the oceans from volunteer ships since 1952 have been compiled and analysed by Norris (1999). Norris found that the global mean cloud cover over the oceans has increased by 1.9% (sky cover) between 1952 and 1995 (see Figure 5). Global mean low cloud cover is observed to increase by 3.6% during the same period. Trends in zonal mean cloud cover in 10^o-lat bands between 60^oN and 40^oS were all found to be positive. Several possible artifacts were examined but it was considered unlikely that they could explain the observed interdecadal variability. Norris (1999) concludes, however, that the trends cannot be accepted as real until they have been corroborated by related meteorological parameters and satellite-based measurements.

Sun & Groissman (2000), have studied synoptic cloud cover variations over the former USSR from 1936 to 1990. They find high cloud to be increasing and low cloud decreasing with the total cloud increasing over this period. Though for a continental, as opposed to a maritime climate region, these findings are pretty much in line with the sort of trends suggested earlier by the Irish sunshine data and the cosmic ray - low cloud correlation. Though the total cloud trends are similar, it is difficult to reconcile the results by Norris (1999) and by Sun & Groissman (2000) on low clouds, other than to point out that they refer to very different regions. However, it should be noted that the Sun & Groissman trends are very statistically significant whereas those by by Norris are prone to many systematic effects such as might arise from a change in the latitude of preferred shipping lanes.

Similar reports to those of Norris (1999) and Sun and Groissman (2000), using cloud synoptic observations are described in Table 1. They all show an increasing trend in total cloud cover. No other general studies (involving more than one particular station) about specific synoptic cloud type variability are known to the authors.

In Table 1 we refer also to the reduction in ground solar radiation levels reported at a world-wide range of sites during the last 40 years (Stanhill, 1998 and references therein), suggesting a total cloud cover increase. However, such radiation decreases have not been always accompanied by an increase in cloud cover and its possible that changes in cloud type or atmospheric or cloud transparency could be responsible.

Thus it appears that the 'historical' cloud datasets (sunshine and synoptic cloud) indicate a general increase in the total cloud cover during the last century or at least in recent decades. The evidence for low cloud trends is less clear though it does not rule out a decrease in line with the prediction from solar activity levels.

A compilation of cloud satellite measurement is given in Table 1, however the short time span of the datasets (the longest is the ISCCP D2 covering little more than 11 years), makes them unsuitable for such long-term studies. Cloud types reported as stable as in the case of ISCCP C2 and D2 are in fact quite variable and a definite trend can not be clearly established. In fact the only two clear trends are the increasing trends found for DMSP (Defence Meteorological Satellite Project) satellites, detecting liquid clouds over the oceans, and the cirrus clouds detected by the HIRS (High-resolution Infrared Radiation Sounder). The decreasing trend in the low cloud cover from the ISCCP D2 is inferred only on basis of the possible cosmic ray influence. However the satellite measurements do not dispute the general conclusions reached using the 'historical' data.

5. WHAT IS CAUSING THE TOTAL CLOUD INCREASE?

We have seen in the previous section how the available proxies for clouds seems to indicate that total cloud cover has been increasing over the last century. But what are the reasons for the change? Certainly a connection between energetic particles entering the atmosphere and the cloud formation would explain a decrease, but not the opposite trend.

Could the long term trend in total cloud result from a mean air and sea surface temperature increase? An increase in cloud formation might be expected from an increase in evaporation rates following the rise in sea-surface temperatures which have accompanied global warming (Reid, 1987). Little is known about the effects that a change in temperature will have on clouds. Global circulation models predict a cloud amount decrease when climate warms (Cess, 1996) which has not been seen. A progressive moistening of the atmosphere has been seen (Wentz and Schabel, 2000). However, since the relative humidity has remained constant, an increase in the water content of the atmosphere would not necessarily lead to an increase in cloud factor.

An increase in tropospheric aerosols could also give rise to increased cloud formation. However Norris (1999) stated that the 10^o-lat bands trends in synoptic cloud observations between 60^oN and 40^oS, are generally larger for the Southern Hemisphere and Tropics than trends in the mid-latitude Northern Hemisphere. For Norris (1999), this argues against attribution of increased cloud cover to increased anthropogenic aerosols, and suggests that it is possible that global cloud cover is responding to some other global parameter, perhaps global temperature. Pallé & Butler (2000b) found a correlation between the sunshine records over Ireland and the solar cycle length. Since the sunspot cycle length was shown to be strongly related to the NH air temperature (Friis-Christenssen & Lassen, 1991), they concluded that in the vicinity of Ireland, it seems likely that decreased sunshine hours (increased cloudiness) results from the increased temperatures associated with global warming

Another effect to take into consideration is the effect of increased aircraft traffic. In many of the sites where a decrease in total solar irradiance has been found, an increasing trend of cirrus cloud formation has also been detected. A shift from stratiform to higher frequencies of convective clouds has also been observed (Liepert, 1997; Stanhill, 1998). Finally, another possibility could be natural weather variability associated with shifts in weather patterns.

6. CONCLUSIONS

There appears to be a significant correspondence between the low cloud cover as seen from modern satellite data and the galactic cosmic ray flux. However the extent of this dataset is short and gives space for many uncertainties when trying to establish the long-term behaviour of the cloud cover. The potential effect of such a relationship has been explored and the authors demonstrated that, if it were true, it would be of dramatic importance to the climate.

In order to assess the validity of the prediction over long time scales, some proxies have been compared. Sunshine records and the synoptic cloud cover over many areas of the Earth seem to agree that the total cloud cover has been increasing over the last century. This is in the opposite direction to the trend predicted for low clouds by the cosmic ray - low cloud correlation. The reliability of the datasets though is uncertain, but the agreement in the trends suggest that they are real, and maybe caused by the temperature rise which has occurred during the last century or other causes not related with energetic particles entering the atmosphere. It seems then that the overall picture of the cloud variability during past times can be far more complicated than suspected. The importance of such changes will depend on the variability of the different cloud types and on the geographical distribution of those changes. However, both mechanisms, a long term trend and a direct cosmic ray influence, present a challenge to present and future global circulation models and will have a crucial role on our understanding of the climate change. Until the cloud behaviour on temporal and geographical scales is understood, via long and reliable datasets, global circulation models and predictions will be seriously handicapped.

ACKNOWLEDGMENTS

We would like to thank Dr. K. O'Brien for discussions and M. Murphy for assistance with computing. The sunshine data for Dublin, Birr and Valentia Island/Cahirciveen were kindly provided by D. Fitzgerald of Met Eireann, Dublin. Research at Armagh Observatory is grant-aided by the Department of Culture, Arts and Leisure for Northern Ireland.

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