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Climate Change, the Enhanced Greenhouse Effect and the Influence of the Sun: A Statistical Analysis

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With 9 Figures

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Summary

Changes in solar activity are regularly forwarded as an hypothesis to explain the observed global warming over the last century. The support of such claims is largely statistical, as knowledge of the physical relationships is limited. The statistical evidence is revisited. Changing solar activity is a statistically plausible hypothesis for the observed warming, if short-term natural variability is the only alternative explanation. Compared to the enhanced greenhouse effect, the solar hypothesis loses a substantial part of its plausibility. Reversely, the size and significance of the estimated impact of the enhanced greenhouse effect on the global mean temperature is hardly affected by solar activity.

1. Introduction

The publication of Svensmark and Friis-Christensen (1997), following earlier publications by the same team (Friis-Christensen and Lassen, 1991; Lassen and Friis-Christensen, 1995), aroused renewed (public) interest in the question whether it is the accumulation of greenhouse gases in the atmosphere or changes in solar activity that are the prime cause for the observed warming over the last century. Earlier work on the solar hypothesis includes Eddy (1977), Foukal and Lean (1990), Hansen and Lacis (1990), Hoyt and Schatten (1993), Kelly and Wigley (1990, 1992), Lacis and Carlson (1992), Reid (1991, 1997), Schlesinger and Ramankutty (1992), Schneider and Mass (1975), Schönwiese

and Stachler (1991), and Woodard and Libbrecht (1993), although none of these articles contributes as large a role to the sun as do Friis-Christensen, Lassen and Svensmark.

This paper looks at statistical evidence that Svensmark and Friis-Christensen use to support their conclusion. Particularly, the analyses here compare the explanatory power of a variety of indices for solar activity for the observed warming to the explanatory power of the enhanced greenhouse effect. The analysis is a purely statistical analysis. The paper is restricted to an analysis of the global annual mean surface air temperature. An analysis of regional and seasonal temperatures yields useful insights as well but the global annual temperature is a good starting point, and brings relatively strong and straightforward conclusions. Hegerl et al. (1997) use regional and monthly temperature data to analyze potential influences of the sun. Their analysis is confined to only one index of solar activity (Hoyt and Schatten, 1993), and relies heavily on two experiments with a single general circulation model (Cubasch et al., 1997). Their approach and ours are thus complementary. It is reassuring that the conclusions are similar.

Section 2 describes the data used for this analysis. Section 3 discusses the statistical models applied to the data. Section 4 presents the results. Section 5 concludes.

2. Data

Temperature data used are directly taken from the record of the global mean surface air temperature of the Climate Research Unit, Norwich (Jones et al., 1986a, b; Jones, personal communication). The data cover the period 1860–1996, and are reported in deviation from the mean of 1951–1980.

The atmospheric concentration of carbon dioxide (UNEP, 1989) is used as a proxy record for the accumulation of all radiatively-active gases in the atmosphere. Concentrations of sulphate aerosols and most greenhouse gases show an increase that is similar to that of the CO₂ concentration. CO₂ is therefore a reasonable proxy, although the estimated climate sensitivity (the increase in global mean temperature due to a doubling of the atmospheric concentration of CO₂) is biased. This bias is corrected using a Bayesian technique described by Tol and De Vos (1997). The CO₂ record covers the period of 1800 to 1996.

Proxy records are used to describe solar activity. Sun-spot numbers (WMO World Data Centre C for Sunspot Index, <http://www.oma.be/ksb-orb/sidc/index.html>) are used, either directly or filtered. The length of the solar cycle is estimated by (1) the time interval between the sun-spot number minima, and (2) the interval between the maxima. The value for the length of the solar cycle is ascribed to the year in the middle between the minima or maxima. Values for other years follow by linear interpolation. The average of the two records thus obtained is used as a third proxy record for the length of the solar cycle. The average solar cycle length is used in its raw format, time-lagged, and filtered. Together, this makes seven alternative proxy records for the activity of the sun. The solar records cover the period 1800–1996.

3. Statistical Models

Four types of statistical models of the global mean temperature are contrasted, that is, (1) models that are based on carbon dioxide as the explanation, (2) models that are based on solar activity as the explanation, (3) models that allow for both explanations, and (4) models that allow for neither. To start with the last, the basic model

is a simple autoregressive one, i.e.,

$$T_t = c + \rho T_{t-1} + u_t \quad (1)$$

where T denotes temperature, t time, and u white noise (that is, zero mean, no correlation or other time dependencies – the constant c is estimated such that u has a zero mean). Model (1) and all models below are estimated by the method of maximum likelihood, conditional on the observed temperature of 1859, using MicroTSP 6.53. Data are not detrended, centred to their mean or otherwise pre-processed. Although simple, (1) can display a widely varying behaviour. If $\rho = 0$, the temperature varies randomly around a constant value. If $0 < \rho < 1$, high temperatures tend to be followed by high temperatures. If

Fig. 1. The global mean surface air temperature as observed and as modelled by (1) (upper panel) and the difference between the two (lower panel)

$\rho = 1$ and $c = 0$, temperatures may wander up or down for a prolonged time. If $\rho = 1$ and $c > 0$, temperatures wander to and from a linear upward trend. If $\rho > 1$, temperatures tend to increase exponentially. Figure 1 displays the observed and the modelled values, together with the residuals. ρ is estimated to be 0.85, with a standard error of 0.05. The explained fraction of the temperature's variance (R^2) is 0.70. Figure 1 shows that indeed the autoregressive model is not a bad description. Alternative hypotheses, such as solar activity or greenhouse forcing, need to outperform the description of the temperature data by the simple autoregressive model. If an hypothesis is no better than this 'agnostic benchmark' than it is worth very little. Tol and de Vos (1998) use more elaborate ARMA models as benchmark. Although this significantly improves the description of the temperature record, the conclusions regarding the influence of greenhouse gases (or other non-stationary influences such as the sun) are not altered.

Equation (1) is extended with the influence of solar activity and greenhouse forcing:

$$T_t = c + \rho T_{t-1} + \alpha SUN + \beta GHG + \mu_t \quad (2)$$

Note that ρ is re-estimated so as to explain more of the short-term natural variability and less of the trend as it does in (1). The auto-regressive formulation is needed as a benchmark (see above), and, since the temperature is so strongly auto correlated, to properly estimate α and β . Below, we look at models with solar forcing only, with greenhouse forcing only, and with both forcings. The models are used to test the relative strength of the underlying hypotheses.

Seven alternative proxy records for solar activity are used in (2). Four original records are used, viz. sun-spot number, minimum solar cycle length, maximum solar cycle length and average solar cycle length. The hypothesis is that radiative forcing of solar activity is linear in the index used. The average solar cycle length is also used with a six-year time lag (that is, the temperature of 1996 depends on length of the solar cycle of 1990). The lag is chosen such that the correlation between temperature and solar cycle length is maximized.

In addition, two filtered records are used. The hypothesis is that climate reacts slowly to changes in solar activity. Suppose that the

temperature depends on lagged observations of sun-spot numbers:

$$T_t = c + \rho T_{t-1} + \alpha \sum_{i=0}^I a_i SSN_{t-i} + u_t \quad (3)$$

The number of parameters to be estimated is large if I is large. In addition, the sun-spot numbers follow a regular cycle so that current and past observations are multicollinear. In order to avoid this, the a_i s are assumed to lie on a polynomial:

$$a_i = \gamma_0 + \gamma_1 i + \gamma_2 i^2 + \dots + \gamma_n i^n \quad (4)$$

so that only $n+1$ γ_i s need to be estimated rather than I a_i s. After its inventor, (4) is known as an Almon-transformation (Almon, 1960) of order n with length I . (4) can be restricted so that a_0 or a_I is close to zero.

Thus, Almon-transformations are weighted averages of current and past observations, placing different values on different lags according to some assumed polynomial. Note that only current and past observations are used; some filtering techniques use future observations as well, which is physically impossible. The Almon-transformations are optimized. That is, I and n are chosen such that the transformed record of sun-spot numbers or solar cycle length best describes the temperature data. Figure 2 depicts the optimized weights for the sun-spot number record, Fig. 3 for the solar cycle length record. The data-preferred

Fig. 2. Weights of the Almon-transformation of the sun-spot number record. Order, length and restrictions are fitted to the data by maximum likelihood. Weights are normalized so as to sum to unity

Fig. 3. Weights of the Almon-transformation of the average solar cycle length record. Order, length and restrictions are fitted to the data by maximum likelihood. Weights are normalized so as to sum to unity

Fig. 4. Original and transformed record of sun-spot numbers

Almon-transformation of the sun-spot numbers is a second-order polynomial, with a peak at a lag of five years, and falling to zero after 12 years. This transformation looks reasonable. It does, however, substantially alter the nature of the sun-spot record (see Fig. 4). The transformation reduces the periodicity, amplifies the peak values, and introduces a five-year lag.

The data-preferred Almon-transformation of the length of the solar cycle is a third-order polynomial, with a peak at the current value, rapidly falling and then increasing to a second peak at a lag of 45 years before falling to zero after 60 years. Note that the second peak at 45 years significantly contributes to the description

Fig. 5. Original and transformed record of average solar cycle length

of the observed global mean temperatures. Testing this specification against a second-order polynomial falling to zero after 20 years has a likelihood ratio test value of 16.6 compared to a 5%-critical value of 3.8.

It is hard to think of an explanation for the peak at a lag of 45 year. One possible explanation is that a 45-year lag would cancel the 90-year periodicity in solar activity. Figure 5 shows indeed that the filter substantially changes the original record. Most prominently, the through around 1930 cancels the peak around 1970. Data filters as powerful as Almon-transformations should be applied with great care, particularly if clear physical indications as to their shape lack. If (Almon) transformations are used without due care, correlations may be detected where there are in fact none.

The natural logarithm of the atmospheric concentration of carbon dioxide is also added to (1). This record is also Almon-transformed (second-order, with a length of 40 years), but the conclusions regarding its influence are robust to the specific filter chosen, because carbon dioxide increases so smoothly over time.

4. Results

The seven proxy records of solar activity are added to (1) and tested whether they significantly improve the description of the global mean surface air temperature or not. The test used is

Fig. 6. The significance of the influence of the sun on the global mean surface air temperature for 7 alternative specifications (from left to right: sun-spot numbers, filtered sun-spot numbers, length of the solar cycle based on sun-spot minima, solar cycle length based on maxima, average of the previous two, average solar length with a six-year lag, filtered average solar length). The bar denotes the χ^2 -statistic, the square its 5% critical value. The alternative hypothesis is natural variability only

the likelihood ratio test, which is computed as twice the difference in the log-likelihoods of the models with and without solar influence. The test statistic asymptotically follows a χ^2 -distribution with p degrees of freedom, where p equals the number of estimated parameters used to describe the influence of the sun. Figure 6 displays the test-statistics and their 5%-critical values (which vary, because Almon-transformations require additional parameters, including its order and length). In all cases, except the untransformed sun-spot numbers, the null hypothesis of no solar influence is clearly rejected. That is, the probability that the resemblance between the solar and the temperature records is accidental is less than 5%. The length of the solar cycle is a better predictor of the global mean temperature than is the sun-spot number. Transforming and lagging improves the fit. The R^2 s rise to between 0.71 and 0.77. The estimates of ρ fall to between 0.79 and 0.44. Lower ρ s indicate that solar activity describes more of the temperature trend and natural variability more of the short-term features of the observed temperatures. Note that only the Almon-transformed record substantially improve the fit and lower the estimate of ρ .

Next, the atmospheric concentration of carbon dioxide is added. Figure 7 depicts its signifi-

Fig. 7. The significance of the influence of the atmospheric concentration of carbon dioxide on the global mean surface air temperature for 8 alternative specifications of the influence of the sun (from left to right: ignore sun, sun-spot numbers, filtered sun-spot numbers, length of the solar cycle based on sun-spot minima, solar cycle length based on maxima, average of the previous two, average solar length with a six-year lag, filtered average solar length). The bar denotes the χ^2 -statistic, the square its 5% critical value. The alternative hypothesis includes natural variability

cance. Carbon dioxide significantly influences the global mean temperature, irrespective of the proxy record used for the influence of the sun. R^2 s vary between 0.76 and 0.78. ρ s vary between 0.52 and 0.37, so that in these models natural variability is really short-term.

CO₂'s significance is robust to the specification of solar activity. It is, however, not the other way around. Figure 8 displays the results of testing solar influence against the model that includes the enhanced greenhouse effect. The lagged and transformed records of the average length of the solar cycle are the only ones that significantly influence temperature.

The model including carbon dioxide yields information about the influence of the enhanced greenhouse effect on the world's climate. This can be used to further test the appropriateness to the model, and the validity of the solar hypothesis. The equilibrium effect on temperature of change in radiative forcing equivalent to a doubling of the atmospheric concentration of carbon dioxide (the climate sensitivity) is not readily estimated. The new equilibrium temperature is almost reached roughly 50 years after emission, due to the combined effect of the Almon

Fig. 8. The significance of the influence of the sun on the global mean surface air temperature for 7 alternative specifications (from left to right: sun-spot numbers, filtered sun-spot numbers, length of the solar cycle based on sun-spot minima, solar cycle length based on maxima, average of the previous two, average solar length with a six-year lag, filtered average solar length). The bar denotes the χ^2 -statistic, the square its 5% critical value. The alternative hypothesis is natural variability plus the enhanced greenhouse effect

transformation and the autoregression in the temperature. The equilibrium reaction to an unit change in carbon dioxide equals, in terms of Eq. (2), $\beta/(1-\rho)$, properly accounting for the Almon and logarithmic transformations of the original record. More problematic is the fact that carbon dioxide is not the only radiatively active gas the concentration of which is anthropogenically increased; methane, nitrous oxide and sulphate aerosols are notable others. The IPCC Special Report on Radiative Forcing (Houghton et al., 1994) gives 1.5 Wm^{-2} as the best guess for the change in radiative forcing since pre-industrial times due to carbon dioxide only, whereas total forcing changed about 1.1 Wm^{-2} over the same period. Thus, the estimated climate sensitivity should be multiplied by about 1.4 to account for this. Ignoring the influence of the sun, the best estimate (mode, mean and median) of the climate sensitivity is about 4.3°C , with a 95% confidence interval ranging from 2.2°C to 6.4°C . The estimate of the standard deviation is derived using a first-order Taylor approximation. The influence of the sun reduces the estimated climate sensitivity, but not a whole lot (best estimates varying from 3.2°C to 4.1°C), except for the filtered average length of the solar cycle (best

Fig. 9. Estimated climate sensitivity for 8 alternative specifications of the influence of the sun (from left to right: ignore sun, sun-spot numbers, filtered sun-spot numbers, length of the solar cycle based on sun-spot minima, solar cycle length based on maxima, average of the previous two, average solar length with a six-year lag, filtered average solar length). Triangles and pluses denote the mode and the bounds of the 95% confidence interval if the change in radiative forcing over the last century is known for certain. Squares and asterisks denote the mode and the bounds of the 95% confidence interval if a triangular (0.0, 0.7, 1.4) prior distribution is assumed for the change in radiative forcing

estimate: 1.9°C). Even in that case, however, the estimated climate sensitivity significantly deviates from zero. Figure 9 displays the estimates. This adds to the findings of Tol and De Vos (1997) that the enhanced greenhouse effect is quite robust to alternative hypotheses. It also reconfirms that empirical estimates of the climate sensitivity are higher than estimates based on physical reasoning. Our understanding of climate models is insufficient to explain this discrepancy.

The actual forcing over the last century is uncertain, primarily because of limited knowledge about sulphate aerosols. Tol and De Vos (1997) develop and apply a Bayesian method to account for this. Instead of supposing that total forcing is 70% of carbon dioxide forcing, a prior distribution is assumed to represent the uncertainty about this figure. Inspired by Houghton et al. (1994), a triangular distribution is used, with end-points at 0% and 140% and the peak at 70%. No prior information is used for the climate sensitivity, that is, the climate sensitivity is estimated using only the temperature, carbon dioxide and solar data. Figure 9 displays some

characteristics of the resulting posterior distribution of the climate sensitivity. The best estimate (mode) decrease somewhat. Ignoring the sun, it is 3.9°C. Including the sun, it varies between 2.8°C and 3.6°C, with 1.6°C if the solar cycle length is filtered. The lower bounds of the 95% interval hardly change, but the upper bounds increase substantially to 12–14°C, because it cannot be excluded that the negative forcing of sulphate aerosols largely compensate the positive forcing of greenhouse gases.

5. Conclusions

Reviewing the influence of changes in the solar activity, particularly the length of the solar cycle, on the observed warming of the last 135 years, there is indeed strong statistical evidence for such an effect, that is, if one ignores alternative explanations for the increased temperatures. If one simultaneously considers the influence of the enhanced greenhouse effect, then the sun's case considerably weakens. One needs to manipulate the observed record of the length of the solar cycle to a considerable extent, perhaps beyond physical plausibility, in order to find a significant influence of the sun on the global mean temperature. It is not the other way around. The accumulation of carbon dioxide in the atmosphere significantly influences the temperature, regardless of the way the influence of the sun is included in the statistical model. The estimated climate sensitivity is only substantially affected if one allows the sun maximum influence, perhaps beyond physical plausibility.

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