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Greenhouse Statistics-Time Series Analysis

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With 3 Figures

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Summary

The relationship global mean temperature – atmospheric concentration of carbon dioxide is modelled by means of time series analysis as it is used in a non-experimental statistical context. The goal is to test the hypothesis that the global mean surface air temperature rises due to the rising atmospheric concentrations of greenhouse gases.

The common climatological approach to confirm this hypothesis has not yet succeeded because of the overly ambitious model design and the statistically less efficient manner of information processing in interpretating the output of general circulation models. Earlier statistical attempts to detect the greenhouse signal in the temperature record failed partly because of inefficient modelling.

Starting with some naive time series models we show that the enhanced greenhouse effect is plausible. Taking the long-term natural variability of the climate into account casts doubt on this claim but properly quantifying the size of the variability restores the significance of the greenhouse parameter.

Extending the model to explain part of the shorter term variability by including the influence of the sun, volcanoes and El Niño the hypothesis is again but stronger confirmed. A battery of tests reveals that this model describes the observed temperature record (statistically) well. We also show that the outcomes are robust, i.e. insensitive to changes in the model.

Although statistics cannot constitute a proof of the hypothesis, the results of this paper are strong enough to conclude that at least part of the recent high temperatures is, with high probability, caused by the increase in the atmospheric concentration of carbon dioxide.

1. Introduction

The greenhouse effect is a hot topic. Although there is some consensus on the *enhanced* greenhouse effect being real (Kerr, 1992), the question whether the present high temperatures may be attributed to this phenomenon is not expected to be answered before the turn of the century (Wigley and Barnett, 1990) though some expect it to take much longer (Tennekes, 1990). Recently Böttcher (1992) critized greenhouse science and scientists. His analysis, however, stresses the scientific uncertainties and the damping processes and exaggerates the reduction costs; the potential damages are mitigated and the dangers of a runaway greenhouse effect are ignored. The doubt and confusion surrounding the greenhouse effect is one of the causes of the delay in the policy-making on reducing the emission of greenhouse gases (de Freitas, 1991). But delay, if it takes too long, is likely to be harmful if the enhanced greenhouse effect is indeed (already) responsible for a change in climate.

This article aims at a statistical statement on the size and the significance of the impact of the rising atmospheric concentrations of carbon dioxide – as a proxy to all greenhouse gases – on the global mean surface air temperature. The analysis rests on the econometric discipline. In econometrics, the art of extracting information from associated time series in a non-experimental context is a central issue. During the last decades this art underwent, despite – or perhaps due to – many pitfalls, considerable development. David Hendry (1993, p. 466) describes the outcome as "developments wherein a clarification or new concept in one area resolves a major stumbling block in another, such that a comprehensive framework emerges from the shadows of an integrated network of ideas, concepts, tools and practices founded on successful empirical studies."

As measuring the greenhouse effect strongly resembles the economic puzzles, we think econometrics may contribute. This article is meant as a start. We study the global mean temperature with models ranging from simple time series analysis to complete 'explanations'. We show that the core of the discussion on the 'significance' of the greenhouse influence lies in the prior information from before our basic sample of the last century. We also discuss the question why our answers matter.

The usual way of climate modelling is the design of huge models which are meant to improve the physical understanding of the climatic processes. The building of climatological models is based on the theoretical knowledge of physics. This knowledge however is, in complicated situations such as the climate, still far from complete—the behaviour of clouds being a notorious example. Those parts of the models which cannot directly be based on physics are obtained from simplifications and educated guessing. Calibration of the model and flux-correction of the outcomes are necessary – explanation and prediction therefore remain defective (Schlesinger, 1986; Hadley Centre, 1992). This is widely acknowledged and some suggest that this is due to the restrictions in computercapacity but one may wonder, in the light of chaos theory, whether this is the main point. Whatever may be the reason, the present models are no more than rough descriptions of the climate – to some too rough to base any conclusion upon (Tennekes, 1990). On top of this, the models are so large that the major and minor points are not really distinguishable anymore. A careful statistical analysis is needed for the comparison of the outcomes of different model runs but most climate models are built from a deterministic viewpoint and therefore not really suited for statistical statements (Tol and de Vos, 1993a). The important question whether and by how much greenhouse gases influence the climate can therefore, with these models, not (yet) accurately be answered.

According to Arnold Zellner (1988), one of the world's leading econometricians, 'sophisticated simplicity' is a prerequisite for useful scientific investigation; in this he calls upon the work of a number of Nobel laureates in economics and reknown statisticians. Our approach fits in this tradition and is the opposite of the climatological approach: the models used here are extreme simplifications. We consider only one climatic characteristic: the yearly global mean surface air temperature. Although this is in no way an adequate description of the climate, it is probably the feature which is the least 'contaminated' by all kinds of processes which are of less relevance to the relationship CO_2-climate. Thus, the global mean temperature is the logical point to start looking for the 'greenhouse signal' – future work will extend this analysis to other and smaller-scale features of the climate. The explanatory part of our models are carefully chosen simple models with the atmospheric concentration of carbon dioxide as main component. Next to this deterministic part, a part of the temperature record is 'explained' by a stochastic (time series) model; later on we will add more explanatory variables. Fitting of the model to the data provides estimates of the parameters and their confidence; combined with tests of the statistical adequacy of the description, this results in justified probabilistic statements on the parameters, especially on the one of the greenhouse effect.

Modern econometric models are usually designed this way. This was a reaction to an earlier phase in which large models of the economy were built; around 1975 it was recognized that these models were too ambitious (Sims, 1980; Zellner, 1987); the analogy with the climatological models is clear. We think, however, that climatological models are more adequate than economic ones and we therefore consider our approach a complementary one to the usual way of proceeding in climatology, not a substitute, and a first step to the combination of non-experimental statistics with hardcore physics. In Tol and de Vos (1993a) we give a more elaborate treatment of the use of non-experimental statistics in climatology.

The *statistical* models of Schönwiese (1986, 1991a, 1991b; see also Schönwiese and Stähler, 1991) are in our, econometric, view of statistical methodology less efficient. See Tol (1992) for more critique. In Tol and de Vos (1993c) we treat the question of the use of the signal-to-noise ratio in a regression context. In Tol and de Vos (1993b) we give the results of this paper a *Bayesian* interpretation, incorporate theoretical knowledge on the subject and extend the discussion to *decision theory*, also involving the financial aspects.

2. The Overall Behaviour of the Data

The temperature record used in this study is the one published by the United Nations Environment Programme (UNEP, 1990) which is updated by Jones and Wigley (1991). It describes the *global mean* surface air temperature (GMT) in *yearly* deviations or anomalies from the average global mean temperature for 1951–1979, which is about 15 °C. The record covers the period of 1881 to 1990. From the starting point 1881 to about 1945 the series shows a steady rise, followed by a slight fall to the end of the seventies and again a – this time faster – rise to the end of the record in 1990; the total rise during this century was 0.5 °C (cf. Fig. 3). The main question is whether this rise is due to the increase in the greenhouse gases. The carbon dioxide record used is also from UNEP (1990). The series is obviously non-stationary, even explosive.

Both series show non-stationary behaviour though this may be discussed with respect to the temperature. Stationarity is a central concept in time series analysis. A stationary series remains, on the long run, in the neighbourhood of a fixed equilibrium level, a non-stationary series shows trendlike behaviour; see e.g. Harvey (1981) for details.

Relations between non-stationary series have received ample attention in the recent econometric literature. The apparent danger of nonsense (spurious) correlation between trending series led for a long time to the procedure to work with differenced record (differencing removes non-stationarity in most series). Two ideas changed this attitude.

The first idea, 'error correction', is developed by David Hendry and coauthors, starting with Davidson et al. (1978) – see Hendry (1993) for the complete story. The basic idea of error correction is that by differencing one loses sight of the equilibrium relations, and that by different specifications one may retain them without losing a proper dynamic description.

The second idea is 'cointegration', starting with Engle and Granger (1987). They show that if an equilibrium relation exists between two non-stationary series (in the sense that a linear combination of the two is stationary) this aspect dominates in the statistical inference in the sense that misspecification of the dynamics hardly alters the conclusions on the equilibrium relation. To avoid spurious correlation they study tests for cointegration by studying the behaviour of test statistics in the case that the series do not cointegrate.

In investigating the relation between the atmospheric concentration of greenhouse gases and the global mean temperature the issue of non-stationarity will appear to be the central one. Non-stationarity is somewhat less obvious in the GMT record than in the carbon dioxide one. The GMT seems to be trending; specifications that might apply, in decreasing order of non-stationarity are: random walk with drift; deterministic trend; random walk; process with a near unit root.

Unfortunately, due to the relatively volatile behaviour of the series, it is difficult to decide statistically what type of non-stationarity applies. Neither is it simple to derive a simple test for non-cointegration. The main problem in this respect is that the enhanced greenhouse effect – if real – is still relatively small. Besides that, it is in line with the theoretical expectation that temperature reacts slowly on changes in the atmospheric amount of greenhouse gases; as the strong increase in this amount is only of recent times, it might well be that temperature has not *yet* followed the change in nature of the CO_2-record or that temperature is just starting to follow the CO_2 explosion.

Obviously, the next years will provide a lot of information on the greenhouse effect but, faced with the question what the data up to 1990 reveal, we have to manoeuvre in a subtle way between the Scylla of spurious correlation and the Charybdis of throwing aside the relation by removing all non-stationary aspects. Fortunately, we have some help from history; we know more of the GMT than its behaviour during the last century. As a Bayesian statistician would say: we have prior information. It will turn out that this information provides the clue which allows us to make a probability statement about the enhanced greenhouse effect.

In the next section we will consider the conclusion form rather naive models, comparing (best fitting time series) models for GMT with and without the 'explanation' of CO_2. In section 4 we accommodate for the danger of spurious results by incorporating information about the behaviour of the GMT during a longer span of time. In section 5 we try to explain the recent history in more detail, with surprisingly good results, which strengthen our earlier conclusions. Section 6 examines the outcomes in further detail. Section 7 concludes.

3. Three Simple Models

In this section three rather simple models are used as preliminary investigations in order to get a general 'feeling' for the data. These models provide only a rough description of the observations but nevertheless some important conclusions can already be drawn at the end of this section.

The first model is an ARX(1)-model, temperature regressed on an intercept and the twenty-year lagged carbon dioxide record, combined with an AR(1)-disturbance. The regression results are

$$GMT_t = \underset{(0.5765)}{-4.6830} + \underset{(0.0019)}{0.0152} CO_{2;t-20} + \varepsilon_t \qquad (1a)$$

with

$$(1 - \underset{(0.0881)}{0.4410} L)\varepsilon_t = u_t \qquad (1b)$$

$LL = 84.8359$; $RSS = 1.3142$; $df = 105$; $\hat{\sigma} = 0.112$.

The u_t are independent identical zero-mean normal distributed; the figures in brackets are the standard errors of the estimates; L is the lag-operator. If we assume that the influence of the changing temperature on the atmospheric concentration of carbon dioxide is negligible this is a proper way to model the global mean temperature.

The linear specification arises as the most plausible one from the data: transforming the carbon series to a power (Box-Cox-transformation) resulted in a (maximum likelihood) estimate of this power of 1.0004 (for the sample-period 1883–1987) so we use the untransformed CO_2-series; other specifications would hardly change our conlusions on the significance of the greenhouse effect but would affect the longterm forecasts. The twenty-year lag for carbon dioxide is to express the slow response of temperature to changes in the amount of atmospheric CO_2. Investigators mention a range from ten to a hundred years but prefer 15–25 years; the data confirm this preference and so, for convenience, a twenty-year lag is chosen as the midpoint of this interval; Schönwiese (1986) uses the same time lag.

As to the criteria, we confine ourselves to the residual sum of squares (RSS), which may also be interpreted as the sum of the one-period ahead forecast errors, and the loglikelihood (LL). The number of degrees of freedom left (df) is the number of data minus the number of estimated parameters. We also report $\sigma = \sqrt{(RSS/df)}$, a robust estimator of the residual standard error, often used to judge the quality of a model, and having a straightforward interpretation (once in every twenty years the temperature deviates more than 2σ from the model estimate). To avoid technical difficulties in comparing the models we regress all models for the period 1883–1990, using when needed the 1881 and 1882 observations as starting values. We do not report other popular statistics, such as the R^2 and the Durbin-Watson (DW) statistic; the R^2 is a figure giving rise to many misunderstandings while not providing new information; the DW is, in dynamic models, of little use – in none of our outcomes it indicates model deficiencies.

We notice that already with this simple model the global mean temperature can reasonably be described and that carbon dioxide is not implausible an explanation of the rise in global mean temperature: its t-statistic is rather high (7.99). The parameter value yields somewhat higher predictions than climatology: it corresponds to a 4.5 °C temperature rise, with a 95% confidence interval from 3.4 °C to 5.7 °C, when the CO_2-record rises by 300 ppm. We stress that this is a legitimate probabilistic statement (though conditional upon the model) as opposed to the confidence intervals presented by climatologists which are mostly 'educated guesses'. The difference between our predictions and those of the IPCC (Houghton et al., 1990) are discussed later.

The second model investigates how well the global mean temperature can be 'explained' without any external forcing. It describes the temperature by the 'cycle plus noise' model of Harvey and Souza (1987) in its unrestricted ARMA(2,2)-representation (Box and Jenkins, 1976)

$$GMT_t = 0.5455 \underset{(4.2044)}{} + \varepsilon_t \tag{2a}$$

with

$$\begin{aligned}(1 - &\underset{(0.4226)}{1.1091}\,L + \underset{(0.4092)}{0.1195}L^2)\varepsilon_t \\ &= (1 - \underset{(0.4321)}{0.6357}L - \underset{(0.2340)}{0.1378}LL^2)u_t\end{aligned} \tag{2b}$$

$LL = 81.6793$; $RSS = 1.3933$; $df = 103$; $\hat{\sigma} = 0.111$.

The AR-roots are 0.9881 and 0.1209; the MA-roots are 0.8066 and -0.1709.

The most remarkable features of this model are *(i)* the almost unit root in the AR-part (0.99), replacing the explanation of nonstationary behaviour by CO_2 in model (1) and *(ii)* the fact that, despite this 'explanation', the criteria score worse. Even the sum of squared residuals, which does not include the fact that we used more parameters, and so lost degrees of freedom, is higher than for model (1). Obviously, model simplifications would not change the conclusion that a simple model with CO_2 describes temperature better than a rather advanced time series model without CO_2 influence.

The third model combines the former two

$$GMT_t = \underset{(2.4808)}{-4.5987} + \underset{(0.0050)}{0.0150}\,CO_{2;t-20} + \varepsilon_t \tag{3a}$$

with

$$\begin{aligned}(1 - &\underset{(0.6263)}{1.0686}\,L + \underset{(0.4100)}{0.1797}\,L^2)\varepsilon_t \\ &= (1 - \underset{(0.6349)}{0.6838}\,L - \underset{(0.2461)}{0.0666}\,L^2)u_t\end{aligned} \tag{3b}$$

$LL = 86.8761$; $RSS = 1.2655$; $df = 102$; $\hat{\sigma} = 0.111$.

The AR-roots are 0.8594 and 0.2091; the MA-roots are 0.7703 and -0.0865.

Compared to model (2), (3) performs clearly better. The likelihood ratio test, twice the gain in loglikelihood ≈ 10.3935, has a p-value of 0.0013 (χ_1^2). The F-test, used as if it concerns simple regression outcomes, has a value of 10.3040; a p-value of 0.0018. Compared to model (1), the estimate of the carbon coefficient (0.015) hardly changes. The estimated standard error, however, increases from 0.002 to 0.005. This reflects the fact that the richer parameterization of the 'unexplained' – an ARMA(2,2) model – increases the doubt whether the temperature change is due to the influence of CO_2 or due to the unexplained part. The ARMAX model seems overspecified so we might drop some terms and come closer to model (1). But, we think that overspecification is wise in view of model uncertainty and that the increased standard error for the CO_2 effect is realistic. Exchanging the CO_2 record with a deterministic time trend results in an overall loss in performance; the sum of squared residuals rises by 0.06 and the loglikelihood falls by 2.48. Based on these models we thus conclude that the effect of the atmospheric concentration carbon dioxide on the global mean temperature is significant at the 5% (and even at the 2%) level.

To conclude, this section shows that the global mean temperature anomaly of the period 1883–1990 is better described with than without carbon dioxide (as a proxy to the total greenhouse effect) and provides thus a (preliminary) confirmation of the general climatological theory. It also justifies a further modelling of the phenomenon; this is presented in the section 5.

4. Natural Variability

We have shown in the preceding section that the atmospheric concentration of greenhouse gases plus stationary noise is a plausible description of the temperature record. We did not yet provide sufficient evidence that our results are not 'spurious'. There still may be other explanations than the enhanced greenhouse effect which could have resulted in the observed rising temperatures. There are good reasons to suppose that the natural variability of the temperature is, at all time-scales, high. The variability at the shorter time-scales can be modelled 'agnostically' by ARMA-models, as in section 3, or partly explained by El Niño and volcanoes and such, as in section 5. The longer term variability poses more trouble. If one looks at the figures of Folland et al. (1990, p. 202), it occurs that a century facing rising temperatures is not uncommon. In this light, the approach in the previous section is a bit naive. Therefore, we return to model (1) (the models (1) and (3) perform about equally well but (3) involves more complex computations). If we include a linear trend, reflecting 'spontaneous' rising (and falling) of the temperature, we get the following result:

$$GMT_t = -4.6699 + 0.0152\,CO_{2;t-20} \quad (4a)$$
$$(2.5471) \quad (0.0095)$$
$$+ 0.0164t + \varepsilon_t$$
$$(3.0295)$$

with

$$(1 - 0.4411\,L)\varepsilon_t = u_t \quad (4b)$$
$$(0.0898)$$

$LL = 84.8359$; $RSS = 1.3142$; $df = 104$; $\hat{\sigma} = 0.112$.

The estimated trend parameter and standard deviation are multiplied by one thousand. The only actual difference between the model (1) and (4) is the significance of the greenhouse parameter; from the highly significant 7.99 the t-statistic drops to 1.60, with a p-value of 0.94. Does this disclaim our earlier conclusions? The first reaction could be no: the linear trend is extremely insignificant and may therefore be dropped. Insignificance, however, only means that the trend does not contribute enough to the description of the data; it does not imply in itself that the explanation by the trend is implausible. The indeterminacy of the results is caused by strong multicollinearity: the estimates of the coefficients of carbon dioxide and trend are strongly negatively correlated. Coefficients of 0.005 for t and 0 for $CO_{2;t-20}$ – meaning that the observed rise of 0.5° C is attributed to the trend – cannot be excluded. Statistical devices cannot solve this problem, only additional information can. Fortunately, we have proper information from the past which allows us to obtain a result which is a compromise between (1-no trend) and (4-implicitely using the prior thought that all trend coefficients are equally likely).

The idea is to derive a prior for the coefficient of the trend from the long-term history of the global mean temperature, in other words, to derive probability statements about the possible 'spontaneous' changes. To do so, we derived a numerical record of the temperature during the past 10,000 years using the middle figure of Folland et al. (1990, page 202) and extended it to the 19th century (cf. Fig. 1). Both an AR(2) and an ARI(1, 1) model, when fitted to the data, predict a rise in the 20th century of 0.01 °C, with a standard error of 0.12 °C. The mean seems reasonable but the accuracy of the estimated standard deviation is low. On the one hand, the record is to a high extent subject to smoothing, as comparison of the three figures of Folland et al. (1990) reveals. Thus, the standard error may be downward biased. On the other hand, we neglected the fact that some of the observed variations in the past are explained by processes we suspect not to occur at present, such as changes in the Earth's orbit. This may result in an upward bias. Therefore, we perform the following analysis with standard errors of the estimated 0.12 °C and the more conservative 0.24 °C, the latter implying that we assume the chance on a 0.5 °C (or larger) 'unexplained' temperature change in a century to be

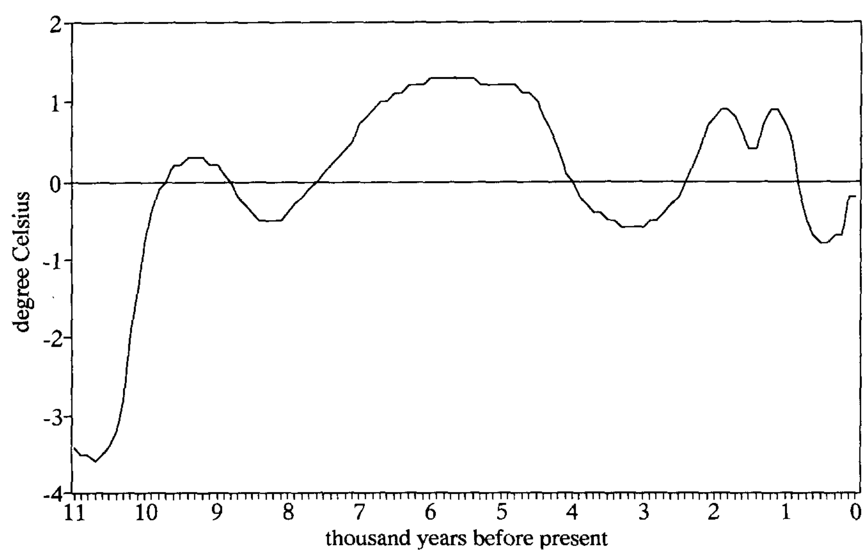

Fig. 1. Global mean temperature (the last ten thousand years)

about 5%. Wigley and Raper (1990) remark "that natural trends of up to 0.3 °C may occur over intervals of up to 100 years"; our choice of the standard errors therefore seems sufficiently conservative.

To incorporate the prior information on the possible size of the trend, 'mixed estimation' (Theil and Goldberger, 1961) is used, a technique analogue to Bayesian estimation procedures. Model (4) is extended with

$$\beta = \frac{0.01}{100} + \eta; \quad \eta \sim N(0, \sigma_\beta^2) \tag{4c}$$

with β denoting the time trend parameter, $\sigma_\beta = 0.12/100$ or $\sigma_\beta = 0.24/100$, rescaling from centuries to years.

Estimation of the extended model (4) (again) hardly changes the estimate of the CO_2 parameter but is does change its significance. If the standard deviation of β is set to 0.24 the t-statistic of α is 2.21 (p-value 0.985), if it is set to 0.12 the resulting t-statistic is 2.69 (p-value 0.994).

In conclusion, if the criticism that the observed rise in the global mean temperature may be due to natural processes is taken into account the hypothesis that the rise is due to the enhanced greenhouse effect becomes doubtful. If, however, a probability density function is attached to the size of the natural rise the greenhouse hypothesis restores its significance up to close to the 99% level.

5. Extensions of the Model

This section extends the model for the temperature record in two directions: other explanations known from theory are added and the twenty-year lagged carbon dioxide is replaced by a more sophisticated lag-structure.

The idea that the atmospheric concentration of carbon dioxide has an effect on the global mean temperature which is concentrated at twenty years is obviously wrong. It is more reasonable to think that the temperature reaction on a change in the atmospheric content of CO_2 is at first small, reaches its mean after two or three decades and then slowly converges to the total impact. This type of behaviour may be modelled by a polynomially distributed lag structure (shortly: Almon (1962) lag) for the CO_2 influence. In a number of experiments the form of the distributed lag appeared to make little difference empirically. This is not amazing: by the smooth nature of the CO_2 series it changes little when transformed in time. We choose the Almon lag of second order with 40 lags and zero restrictions at both sides; this leaves only one CO_2-parameter to be estimated (which simplifies the interpretation) and puts the mean effect of CO_2 on temperature again after twenty years. We tried alternatives: a specification with an error correction mechanism combined with a Koyck lag – temperature adjusting slowly to an equilibrium level – but this did not lead to clear results.

We have also taken up a couple of popular other explanatory variables of the global mean temperature to describe part of the shorter term natural variability. The first is volcanic activity; a measure for this is the Dust Veil Index (DVI) of Lamb (1970). The record used here is updated by Robock (1991) and extended with 1976 – St. Augustine: 250. The volcanic dust veil is assumed to remain for about three years in the atmosphere. The second explanatory added is solar activity; this is represented by the Sun Spot Numbers (SSN), to be found in Waldmeier (1960), updated by Coops (personal communication, 1992). We put a one-year lag on this record; this is purely data instigated. The third one is the El Niño-Southern Oscillation phenomenon (ENSO); the index used from Lamb (1977). The record is extended from 1975 to 1990 by its mean.

As we concentrate on the impact of the enhanced greenhouse effect on the climate, we have not performed a sensitivity analysis to the choice of indices or have tried to explain the one year lag of the SSN; we acknowledge the problems with the DVI but do not think they really influence our conclusions.

The next feature in the general model is the one-year lagged temperature (with a parameter φ) to capture the first-order auto-correlation; it performs clearly better than an AR(1) disturbance.

The difference lies in the effect of the explanatory variables, which get a longer lasting influence on GMT, which slowly tampers off. As the strange observation of 1978 (a typographical error?) kept bothering us (combined with the eruption of the St. Augustine two years earlier) and because this strange observation is absent in the Hansen and Lebedeff (1987) temperature record a dummy for 1978 is introduced; the 1979 observation is corrected for the combined influence of the 1978 dummy and the lagged temperature.

The final feature of the model is the time trend, βt, to capture the long-term natural variability; the standard deviation of the natural trend, σ_β, is set to 0.12 °C per century, the standard deviation of the parameter in model (5) is calculated using the estimated variance of φ and covariance of φ and β in the case without prior knowledge – the calculation is based on the first-order Taylor expansion. The regression results are:

$$\begin{aligned} GMT_t = & -3.0940 + 0.3909\, GMT_{t-1} \\ & \;(0.7634) \quad (0.0993) \\ & + 0.0167(1-0.3909)CO_{2;ALM(40,2)} \\ & \;(0.0034) \\ & + 0.2118\, SSN_{t-1} - 0.1343\, DVI_t \\ & \;(0.1876) \qquad (0.0378) \\ & - 0.1240\, DVI_{t-1} - 0.1903\, DVI_{t-2} \\ & \;(0.0614) \qquad (0.0305) \\ & - 0.0736\, ENSO_t - 0.4142 I_{\{t=1987\}} \\ & \;(0.0106) \qquad (0.0378) \\ & - 0.0494t + u_t \qquad (5) \\ & \;(0.6113) \end{aligned}$$

$LL = 110.0523$; $RSS = 0.8201$; $df = 98$; $\hat{\sigma} = 0.091$.

The *RSS* is considerably lower than in the previous models; the *LL* considerably higher. The reported volcanic, solar and trend parameters and their standard errors are multiplied by one thousand. The Almon-transformed carbon dioxide record is scaled back as to enable easy comparison to the earlier models; its parameter is multiplied by $(1-\varphi)$ so the reported estimate equals the *equilibrium* reaction of the global mean temperature on a change in the atmospheric concentration of carbon dioxide; its standard deviation is calculated using a first-order Taylor expansion. For a CO_2 rise of 300 ppm, the resulting 95% confidence interval of the forecast ranges from 2.99 °C to 7.02 °C. This statement is of course conditional on the model. But, in view of the overall performance of the model plus the coherence with earlier results we feel confident to call it a statistically sound statement.

The reaction patterns of the global mean temperature on a unit change in the atmospheric concentration of carbon dioxide, i.e. the step response function, is drawn in Fig. 2.

Three tests for normality are performed: the scaled third and fourth moments of the residuals are in the range of non-rejectance (cf. Harvey, 1990; p. 159); the Jarque-Bera (1980) statistic confirms this, normality can therefore be accepted. The Box-Pierce (1970) test as well as its Ljung-Box (1979) modification are passed for one to twenty lags, serial correlation is therefore not considered to impose problems. The heteroskedasticity test-statistic in Harvey (1989; p. 259) has a value 1.9486 – this statistic has a $F_{36;36}$ distribution, resulting in a p-value of 0.024; homoskedasticity is therefore rejected. Ramsey's (1969) RESET test strongly confirms this for the powers three up to ten (weakly for power two) – the reason for this might lie in the weak representation of El Niño; the covariance matrix used in model

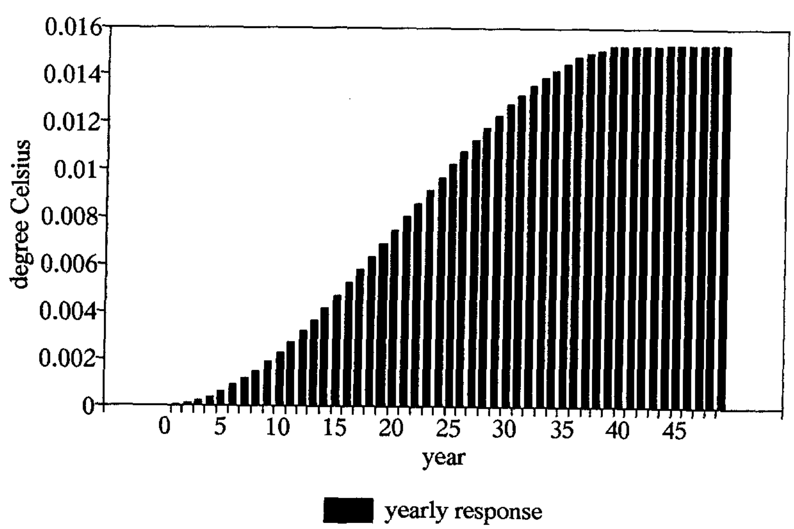

Fig. 2. Step response function [unit step (ppm)]

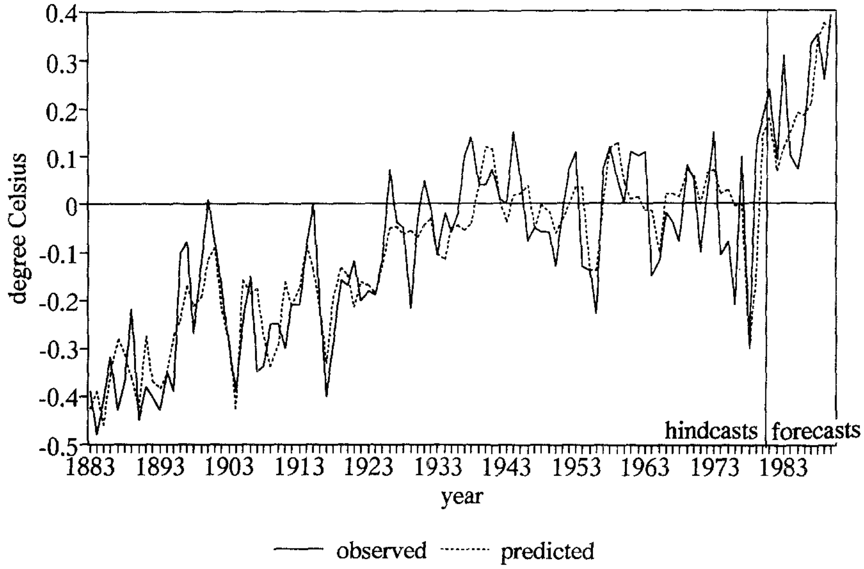

Fig. 3. Global mean temperature (observed and predicted)

(5) is White's (1980) heteroskedasticity consistent variant. The McLeod and Li (1983) test for non-linearity is passed for one to twenty lags. The BDS-test for non-linear dependence (Kräger and Kugler, 1990; Kugler and Lenz, 1990) rejected the null hypothesis in four times four parameter combinations; this is not uncommon (*ibid.*) and might be due to the test itself; its small sample properties are probably very poor (Rosser, 1991; Lorenz, 1991). Taking up powers and cross-products of the lagged temperature does not alter the model's performance nor yields significant parameters. Re-estimating of model (5) with $\beta = 0$ for the periods 1883–1985 and 1833–1980, and forecasting the years 1986–1990 and 1981–1990, respectively, with these estimates reveals that the forecast and observations do not significantly deviate – the test performed is the χ^2. The temperatures as observed and as predicted (hindcasted for 1883–1980, forecasted for 1981–1990) are drawn in Fig. 3. We admit that the hindcast part of these kind of pictures may be highly decieving; if compared to sortlike pictures from GCM's (see e.g. Hansen et al., 1981; p. 963) one easily notes the difference in signal-detection efficiency.

6. General Discussion

Our outcomes are higher than the climatological ones, $3.0 \pm 1.5\,°C$ (Houghton et al., 1990). The reason for this is probably the difference between the carbon dioxide record and the carbon dioxide *equivalents* record, the latter being the relevant one for prediction; as the CO_2 concentration rose by 25% whereas the CO_2-equivalent amount rose by 40% our coefficient is about 5/8 of the one we would have obtained had we used the equivalent series. A rough adjustment thus cuts 3/8 of the prediction; a $3.12(\pm 1.26)\,°C$ rise results. Results using a preliminary carbon dioxide equivalent record indicate indeed that in this case our predictions differ less from the climatological ones; ours are about 0.3 °C higher. The fact that we take the damping influence of volcanic activity into account and climatological models do not, contributes only about 0.1 °C to the contradiction.

Table 1 is a survey of our outcomes, adjusted as described above, for the enhanced greenhouse effect. Included are the models (except the ARMA and ARMAX(2,2)) for various choices of the 'prior trend variation' σ_β ($\sigma_\beta = \infty$ implies unrestricted inclusion of the trend). The conclusions of the general model (5) are stronger due to the better description of the temperature. Noteworthy is that in the general model the greenhouse effect is also significant for $\sigma_\beta = \infty$.

Table 1. *Equilibrium Temperature Change (°C) due to 300 ppm CO_2 Rise*

Model	$\sigma_\beta = \infty$	$\sigma_\beta = 0.24$	$\sigma_\beta = 0.12$	$\beta = 0$
ARX(1)	2.8481	2.8261	2.8182	2.8547
	(1.7787)	(1.2801)	(1.0470)	(0.3577)
General	3.2988	3.1887	3.1270	3.1679
	(1.3285)	(0.9399)	(0.6360)	(0.2967)

There are good reasons to think that the general model represents too optimistic a picture of our knowledge, and to discount for 'data mining'. A balanced statement on the enhanced greenhouse effect would therefore be somewhere in the middle of Table 1, say a coefficient of 3 with a standard error of 1. The fact that our standard error is lower than the one of the climatological models can be attributed to the use of prior knowledge on the natural variability and to the quality of our general model.

As a final comment, we want to stress that Table 1 contains in a nutshell the general message on possible inference on the greenhouse effect. There are two major aspects that matter: (*i*) the discussion on natural variability, which concentrates on the overall behaviour of the series and (ii) the possibility to model incidental (stationary) deviations. The point estimate of the effect is hardly changed by variations in the model, a result in line with the literature on cointegration mentioned before. Other models for the stationary aspects (different dynamics, additional or alternatively represented explanatory variables) will only change the estimated standard error, probably close to our models. Only alternative theories about the recent large temperature rise are able to fundamentally change the outcomes.

7. Conclusion

In this paper we described the way an econometrician would look at the important question of the relationship between the enhanced greenhouse effect and the global mean temperature. Considering the large gaps in the knowledge of both the economic and the climatological sciences we thought it worthwhile to apply one of the more specifically economic tools in the field of the climate.

We are well aware of the fact that many climatologists classify this type of results as 'correlation calculations', which refers to the many wrong and misleading results obtained by this type of analysis. Most econometricians are well aware of the risks, Leamer (1983) being the outspoken example. But there are good examples as well. For a number of reasons we have faith that we belong to the latter category:

– the exogeneity of the carbon dioxide record is almost beyond doubt; as far as there is an effect of the global mean temperature on the atmospheric concentration of carbon dioxide, it is dominated by human intercourse;
– the central issue – the influence of changing concentrations of greenhouse gases on the climate – is theoretically formulated by Arrhenius (1896) long before the main empirical evidence occurred;
– we tried many more models than are reported here; none of them gave conflicting answers;
– we applied a battery of tests and the model survived them.

Let us state it this way. We have casted the hypothesis that the increase in atmospheric greenhouse gases causes global warming in a sophisticatedly simple model which enables efficient statistical testing; we have examined the model thoroughly and analyzed a number of alternatives. The hypothesis of no influence is rejected. We have not found a proof or an explanation of the phenomenon though we can describe it. We have shown with much statistical care that the data are in line with the climatological hypothesis; the combination of the econometric techniques and climatological theory confirmed it in sign; the significance we obtained is higher. Thus, we have enlarged the empirical content of this hypothesis and reduced the uncertainties.

We hope to have stimulated the discussion between the different branches of science, each looking at often sortlike problems from a different point of view. We think that the methodology used in this article is sound and also applicable to more realistic models of the climate. As a description of the consequences of the increase in greenhouse gases our model is obviously terribly naive. Future models should include more of the (well-established) knowledge of the climate, especially if the level of aggregation is lowered (we only looked at yearly and global averages) or e.g. the impact of atmospheric aerosols is taken into account.

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