
Detection of Anthropogenic Climate Change using a Fingerprint Method

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Abstract

A fingerprint method for detecting anthropogenic climate change is applied to new simulations with a coupled ocean-atmosphere general circulation model (CGCM) forced by increasing concentrations of greenhouse gases and aerosols covering the years 1880 to 2050. In addition to the anthropogenic climate change signal, the space-time structure of the natural climate variability for near-surface temperatures is estimated from instrumental data over the last 134 years and two 1000 year simulations with CGCMs. The estimates are compared with paleoclimate data over 570 years. The space-time information on both the signal and the noise is used to maximize the signal-to-noise ratio of a detection variable obtained by applying an optimal filter (fingerprint) to the observed data. The inclusion of aerosols slows the predicted future warming. The probability that the observed increase in near-surface temperatures in recent decades is of natural origin is estimated to be less than 5 %. However, this number is dependent on the estimated natural variability level, which is still subject to some uncertainty.

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Introduction

Since the beginning of industrialization, the CO₂ content of the atmosphere has increased by 25 %. Enhancements in the concentration of other greenhouse gases such as methane and CFCs have yielded a comparable contribution to the greenhouse effect (2). There has been considerable debate whether the global warming of the order of 0.5 - 1.5° C which models predict for this increase in greenhouse forcing can be detected in observed climate data. The measured increase in global mean near surface temperature of the order of 0.7° C (1) since 1880 (3) is indeed consistent with the model predictions(4, 5). However, the general scientific consensus in the past has been that the observed mean temperature trend still lies within the range of natural climate variability, and that model predictions of global warming therefore cannot yet be verified with statistical significance by observed data (2, 6). Nevertheless, evidence of anthropogenic climate change is continually accumulating and is gradually approaching a statistically significant detection threshold (IPCC 1995 report, in preparation). In the following we add to this evidence and, applying an optimal fingerprint technique (7, 8, 9), attempt to quantify the probability that an anthropogenic climate signal can be detected in the observed temperature data.

Our estimate of the predicted global warming signal is based on two new simulations A, B with the Hamburg coupled ocean-atmosphere general circulation model (CGCM) with prescribed greenhouse gas and aerosol concentrations. The inclusion of aerosols can be expected to yield a more realistic prediction of the transient anthropogenic climate change than previous CGCM simulations for greenhouse gases alone (4, 10, 11), but we include also as reference a new simulation C for a CO₂ increase alone. Combining these results with estimates of the space-time structure of the natural near-surface temperature variability based on measurements, two 1000-year CGCM simulations of the present climate, and paleoclimatic data, we tentatively conclude that the probability that the observed temperature increase during the last decades is of natural origin is less than 5 %, i.e. that the observed global warming is very likely due to man's activities (12). An important caveat of this conclusion, however, is that our estimate of the varia-

bility level of multi-decadal scale climate variability is reasonably accurate - a point we discuss further below.

It has already been pointed out by (13) that estimates of natural climate variability based on long simulations with realistic CGCMs are insufficient to explain the observed 100-year trend of global mean temperature. (14) arrived at a similar conclusion using a simpler box diffusion model of the ocean driven by stochastic forcing. In the following we attempt a more quantitative analysis making use of the full space-time information of the signal and natural variability, as inferred from data and CGCM simulations. The method is based on the application of an optimal fingerprint to derive a suitably defined detection variable for which the signal-to-noise ratio is maximized.

The optimal fingerprint method has been applied previously by (15) to ocean data from a CGCM global warming simulation. They similarly came to the conclusion - based on model data alone - that an anthropogenic climate signal should be marginally detectable today in suitably defined ocean indices.

Although a rather pessimistic assessment of the potential of fingerprint methods has recently been given by (16), some form of fingerprint technique is, in fact, the only existing rational approach for the effective detection of an anthropogenic climate signal pattern in the presence of the multi-variate noise of natural climate variability. An attempt to derive a quantitative probability detection estimate using a fingerprint method appears promising today in view of the following recent developments:

(1) Transient simulations of the global warming for increasing greenhouse gas concentrations have recently been carried out with realistic coupled ocean-atmosphere general circulation models (CGCMs) by a number of groups (e.g. 4, 5, 10, 11, 17, 18, 19). The response patterns are qualitatively consistent (18), so that we now have some confidence of our ability to predict the space-time structure of the expected greenhouse climate change signal, including the range of uncertainty. In addition, the counteracting impact of aerosols produced by SO₂ emissions has been studied in recent experiments with atmospheric GCMs (20, 21) and CGCMs (5), so that these effects can now also be

included in the definition of the climate change signal. (22) have shown that the inclusion of aerosols enhances the agreement between the observed and predicted global warming temperature distribution, at least in the seasonal data. However, it should be cautioned that both the prediction of aerosols and the impact of aerosols on the radiation balance are not yet well understood, and that the present computations consider only the direct aerosol albedo effect not the indirect effects on clouds. Our analysis will be limited, as in the similar global warming detection study of (9), for a CO₂ increase only, to annually averaged near-surface temperatures (23).

(2) In contrast to earlier studies based on equilibrium computations with atmospheric GCMs, which assumed a rather linear increase in temperature during this century, most transient CGCM simulations, which include the warming delay due to the heat uptake by the oceans, yield a marked enhancement of the warming rate in recent decades ((18), and Fig. 1). This signature is found also in the observations and can be used as a more sensitive indicator of anthropogenic warming than the 100-year trend considered in most previous investigations (22). The focus on shorter time intervals has the additional advantage that the relevant level of natural variability can be estimated with higher statistical confidence and that the observed temperature time series can be included in the estimate (9).

(3) Long 1000-year CGCM simulations of the natural variability of the present climate have recently been carried out by two groups (13, 24, 25). Despite uncertainties regarding some sensitive feedbacks such as sea-ice interactions (26), these provide, when combined with paleoclimatic records and time series of the observed climate of the last decades and centuries (3, 27), a more reliable estimate of the space-time structure of the natural climate variability in the multi-decadal time scale range relevant for detection than has previously been available (28).

(4) Theoretical methods have been developed (7, 8, 29, 30) for the optimal detection of a climate signal of known space-time structure in the presence of noise with given space-time variability structure. These methods are considerably more powerful than the selection of arbitrary climate indices (normally the global mean temperature) as

detection variable, but require knowledge of the space-time structures of both the signal and the noise. In contrast to (16) earlier pessimistic appraisal, this information is now available, at least to a useful first approximation.

(5) The optimal fingerprint approach used here (8) is not critically dependent on accurate estimates of the space-time structure of the signal and natural variability. The fingerprint is applied only to reduce a multivariate detection problem to a univariate problem. A non-optimal choice of the fingerprint - due, for example, to poor estimates of the signal pattern and/or the pattern structure of the noise covariance matrix - reduces the chance of detection, but will not yield an erroneous detection claim. In this sense the technique is 'fail safe'. However, the method is directly dependent on the absolute noise level, which, as pointed out, is the main source of uncertainty in our results.

Global warming simulations

Fig. 1 compares the three simulated evolutions A, B, C of near-surface temperatures with observations (3). All simulations were carried out using a new version (ECHAM3 + LSG) (31), of the Hamburg CGCM (10, 32, 33). The greenhouse gas concentrations were expressed in terms of net equivalent CO₂ concentrations (2). For 1880 to the present these were taken from (34), and for the future from the IPCC Scenario A (2). Aerosol concentrations were calculated using the MOGUNTIA sulphur model (35) from historical SO₂ emissions, based essentially on (36) and (37), and from projected future emissions from the IPCC 1992 scenario A (38). The resulting global anthropogenic sulphur emissions increase from 10 Tg/yr in 1900 to 71 in 1980 and 151 in 2050. The impact of the computed aerosol concentrations was represented in the CGCM as an increased effective surface albedo. Indirect effects of aerosols on the formation and radiative properties of clouds were not included. These are generally estimated to be of comparable magnitude to the direct effects, so that our computations of the aerosol climate impact must be regarded as only qualitative. The two simulations A, B differ only through the introduction of a small perturbation in the aerosol field in run A. The independent fluctuations of the two simulations indicate the natural climate variability of the

CGCMs. The global warming for greenhouse gases alone (simulation C) exhibits a more rapid temperature increase, particularly in the next century. Our simulations agree very closely with similar simulations carried out recently by the Hadley Centre (5).

The curves strongly suggest that the observed increase in global warming in the last few decades is not simply a natural climate fluctuation, but the beginning of a strong upward trend which the models predict will continue into the next century for unabated emissions. The impression is that the anthropogenic climate change signal is now rapidly beginning to emerge from the natural variability noise.

Climate change detection

Can we put numbers on the statistical significance of this finding? (39) To extract a signal $s(\underline{x}, t)$ with known space-time structure from a noise background with known space-time statistical variability the usual approach is to apply a suitable filter or 'fingerprint' $f(\underline{x}, t)$ which projects the observed data, in this case the near-surface temperature field $T(\underline{x}, t)$, on to a 'detection variable' $d = \int T(\underline{x}, t) f(\underline{x}, t) d\underline{x} dt$. One tests then whether the detection variable is significantly greater than expected from the natural variability noise. Intuitively, a natural choice is to set $f = s$. However, the optimal fingerprint which maximizes the square signal-to-noise ratio $d^2 / \langle \tilde{d}^2 \rangle$, where $\langle \tilde{d}^2 \rangle$ denotes the statistical mean square value of the random detection variable \tilde{d} due to the climate variability alone, is given by the convolution of the signal with the inverse covariance matrix of the natural variability (7, 8). The convolution with the inverse noise covariance matrix suppresses features of the signal pattern associated with high natural variability and enhances pattern features for which the variability is low. Represented in the space of the empirical orthogonal functions (EOFs) of the natural variability, the fingerprint pattern is obtained by simply dividing each EOF component of the signal by the corresponding EOF variance. This has the effect of rotating the fingerprint pattern away from the signal pattern towards the directions of lower noise.

Detection is said to be achieved if the „null“ hypothesis that the observed detection variable d can be explained by the natural variability alone is rejected at some prescribed significance level. It should be noted that the rejection of the null hypothesis implies the probable existence of a climate change signal of the assumed pattern, but not necessarily the attribution of the signal to the assumed generating mechanism. It is always conceivable that some other mechanism produced the detected pattern component. The attribution question can be meaningfully addressed only if the competing mechanisms (e.g., a change in the solar constant or volcanic activity) are specified and analysed in the context of a more general multi-pattern detection analysis (8). We do not pursue this question here and simply make the observation that if a climate change signal consistent with the predicted anthropogenic signal is detected, it is likely to have been produced by the assumed anthropogenic forcing.

In the following we apply a simplified form of the general space-time dependent method in which the optimization of the fingerprint is carried out with respect to the spatial coordinates only (9). The time dependence of the greenhouse warming signal is characterized by the linear trends over a finite interval τ . These are defined for each gridpoint time series by a running regression line fit. The trend interval is chosen as $\tau = 30$ years. This was found to be the best empirical compromise between an emphasis on the latest signal trends (requiring small τ) and the reduction of the natural variability noise (requiring large τ). The spatial signal pattern $s(x)$ for the CO₂-plus-aerosol simulation is defined as the dominant response pattern, i.e. as the first EOF, of the average of the two runs A, B. The time evolution of first EOFs captures essentially all of the model response to the increasing forcing. The remaining EOFs show no systematic time evolution and have the appearance of noise. The inclusion of aerosols reduces the rate of increase of the temperature and modifies the temperature pattern mainly in the northern hemisphere mid-latitudes, which are more strongly contaminated by aerosols.

The covariance matrix $C(x, x') = \langle \Delta T(x) \cdot \Delta T(x') \rangle$ is estimated from 30-year trend patterns derived from an independent 1000-year CGCM simulation of the present-day climate (without anthropogenic modification) (25). The optimization for all three runs is carried out in the space of the first 10 EOFs of the CO₂-plus-aerosol run A. The space is

sufficiently large to contain the signals of all runs, and has enough degrees of freedom to enable the fingerprint to be rotated away from the signal. The resulting optimally rotated fingerprint pattern for the mean CO₂ + aerosol run is then applied to the spatial patterns of the 30-year trends of the observed and simulated data (40, 41).

Fig. 3 shows the time evolution of the computed detection variables $d(t)$. The recent rapid increase in the detection variable for the observations agrees quite well with the model prediction, confirming the impression of Fig. 1 that the anthropogenic signal is now beginning to emerge from the natural variability noise.

The latest trends (1965 - 1994) are seen to have exceeded the estimated 95 % significant detection level (42). This level was inferred as a conservative upper limit from observations (3), after subtraction of a model derived estimate of the greenhouse warming signal (Hegerl et al., 1995), and the long CGCM simulation of (13). The CGCM simulation (25) used to estimate the covariance matrix C was excluded in estimating $\langle \hat{d}^2 \rangle$, as this would have yielded an artificially suppressed value due to the non-independence of the data. In computing $\langle \tilde{d}^2 \rangle$, gaps in the time series of the observed data before 1949 were filled by least-square regression. To provide a common reference for comparison, identical algorithms were applied to the observed and simulated data. The ratio of the model-simulated to the observed rms variability of \tilde{d} is 0.73. This appears not unreasonable, since the model does not include the effect of volcanoes, solar radiation changes and stochastic forcing by sub-grid scale processes, and possibly other neglected mechanisms. The estimate of the 95 % significance detection level from the variance of the observations was corrected for sampling bias of the relatively short time series by Monte Carlo simulations of a first-order auto-regressive process with the same autocorrelation time as the data (9).

We note that the detection variable exceeds the 95 % mark not only for the last years, but also around 1945 (corresponding to the trend between 1916 and 1945, see also Fig. 1). We attribute this earlier increased warming to a superposition of natural climate variability (the detection variable can be expected to lie outside the 95 % confidence band 5 % of the time) and the anthropogenic signal.

This interpretation is supported by a 570 year paleoclimatic record of northern hemisphere summer mean temperatures (27). The paleoclimate time series, smoothed as decadal means, was calibrated against the instrumental data (3) for the approximately 100 year period of overlap, for which the two time series exhibited a high correlation of 0,90. The computed 30-year trends for these data confirm that the warming in the early part of this century was an unusual event, yielding the largest 30-year trend in the entire paleoclimatic record.

The application of pattern information on the signal and noise enhances the detection probability relative to the straightforward analysis of the global mean temperature in two respects: the signal is better defined, and noisy signal components are suppressed. In the present case, both effects are found to be comparable, of the order of 10 - 12 %, yielding a net signal-to-noise enhancement of the order of 20 - 25 %.

The enhancement factor is significant, but nevertheless modest. This indicates that most of the climate change signal is contained already in the global mean temperature (9; 43). This explains also why there is little difference between the detection levels for the observed data using the fingerprint derived from the mean response of runs A, B or from the response for run C. A two-pattern analysis in which the observed data are projected on to the plane spanned by the CO₂-only and CO₂ + aerosol signal patterns indicates that the observed 30 year temperature trends cannot be uniquely attributed to either signal pattern, the observed pattern fluctuates between the two signal patterns.

That the signal pattern structure after subtraction of the dominant global mean component nevertheless contributes to signal detection is demonstrated by Figure 2, which shows the spatial correlation between the observed trend data and the signal patterns with and without subtraction of the global mean (panels a and b, respectively). In contrast to Fig. 3, separate signal patterns were used here for the mean CO₂ + aerosol simulation (A + B)/2 and the CO₂-only simulation C. The correlations for the mean-subtracted patterns in panel b are higher for the recent warming than for the warming period in the 20's (corresponding to the trend maximum in the 40's), giving some additional support to the thesis that the warming in the 20's, in contrast to the recent warm-

ing, was largely natural rather than anthropogenic. Between 1970 and 1990 the correlations are higher for the $\text{CO}_2 + \text{Aerosol}$ signal $(A + B) / 2$ than for the CO_2 -only signal C , in accordance with the findings of (22). However, the effect is weak. Santer et al. (1995) shows that the impact of aerosols which is strongest in the northern mid-latitudes in the summer, is seen more clearly if the data is seasonally stratified.

The most critical aspect of our analysis is clearly the estimate of the natural variability of the detection variable. Nevertheless, we believe that the availability of improved model simulations, the application of optimal fingerprint detection methods and the focus on the more pronounced recent 30-year trends instead of the net 100 year warming considered in most previous studies, justifies our attempt at a quantitative detection probability estimate. Our present tentative estimate is that the probability that the observed recent change in near-surface temperatures is of natural origin is less than 5 %. Furthermore, the fact that the recent warming coincides closely with the increased greenhouse warming predicted by coupled ocean-atmosphere general circulation models is strong circumstantial evidence that the observed temperature change is indeed anthropogenic.

References and Notes

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the CO₂-only run C, to provide a common comparison base. The results using the fingerprint for run C are not significantly different, cf. discussion later.

42 We adopt here the common but formally imprecise terminology in place of the correct statement that the null hypothesis is rejected at the 5 % significance level. Since our test is one-sided - we test for the probability of a *positive* temperature change exceeding some prescribed level - the indicated level can in fact be interpreted as the 97,5 % (2,5 %) significance level.

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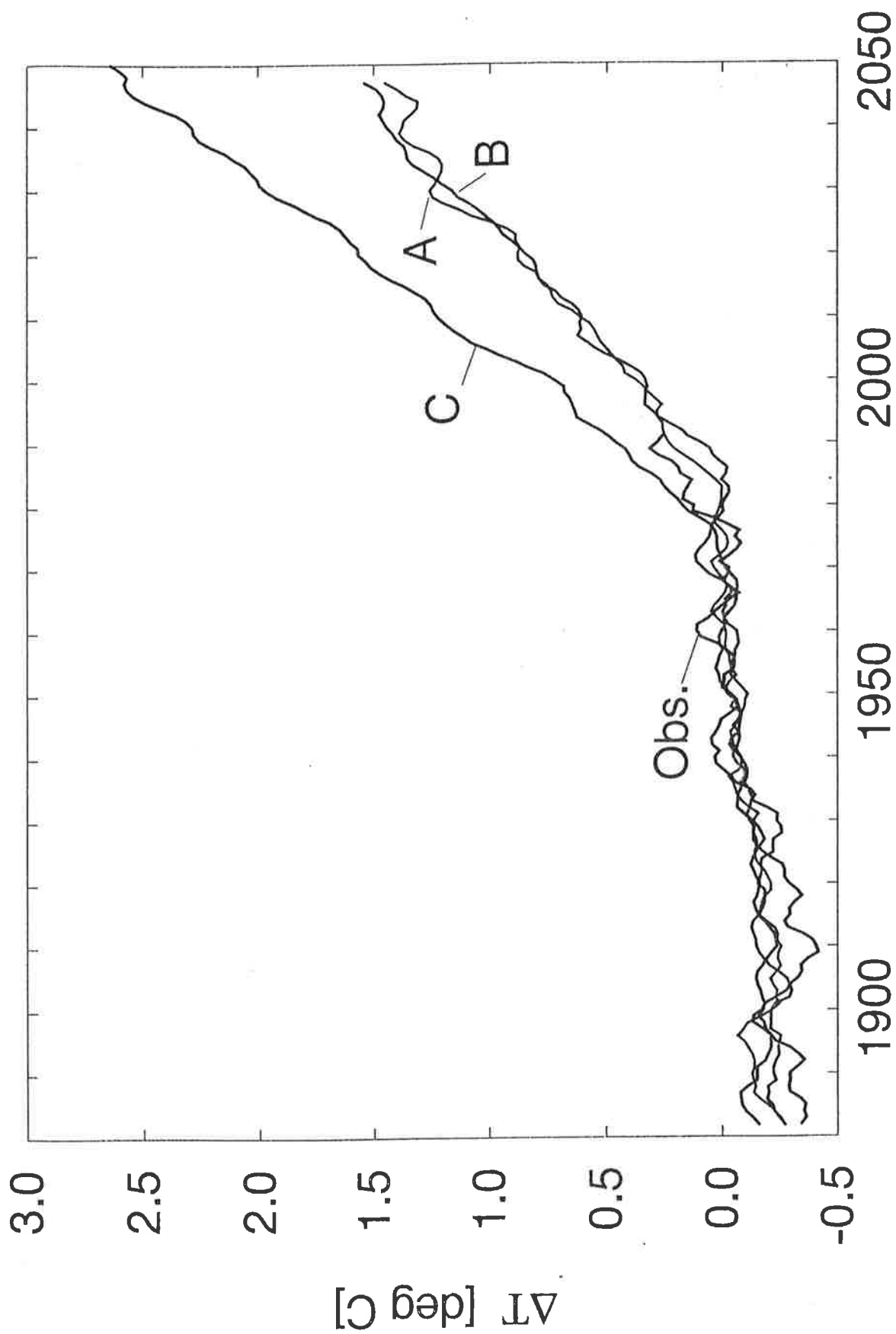


Fig.1 Observed (Obs) and computed globally averaged near-surface (2 m) 5-year mean temperature changes. Averages are restricted to areas with adequate observational data coverage (9). The two equivalent CO₂ + aerosol simulations A, B differ only through the insertion of a weak noise perturbation in the run A. Simulation C is for equivalent CO₂ only. Future CO₂ and aerosol concentrations correspond to IPCC Scenario A.

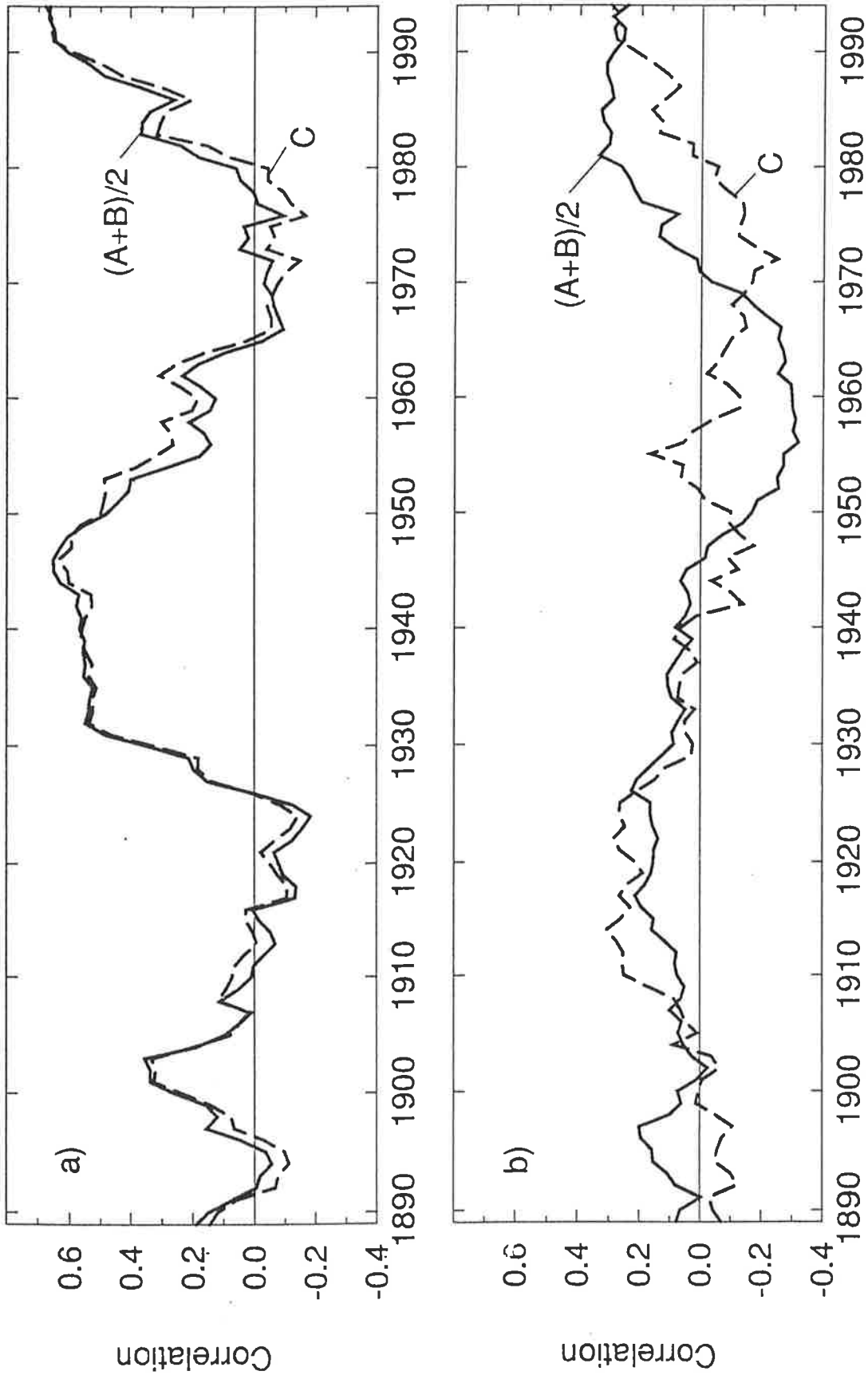


Fig. 2 Pattern correlations between observed 30-year trends and the dominant climate change signal of the averaged equivalent CO₂ + aerosol simulations (full line) and for simulation C (equivalent CO₂ only; dashed line)

Panel (a): correlation including spatial mean of the pattern

Panel (b): correlation with spatial mean subtracted.

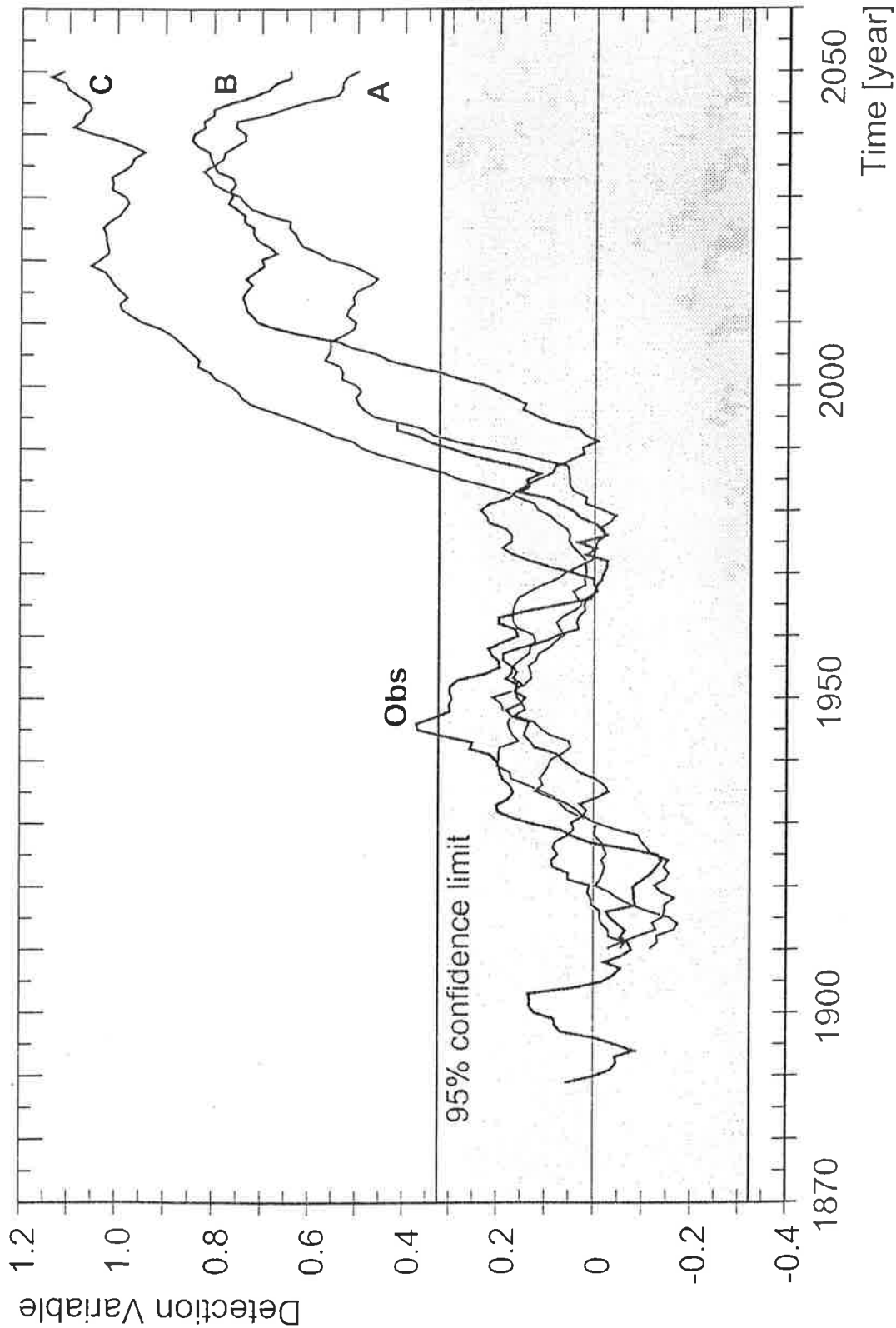


Fig. 3 Evolution of the detection variable for the observed and simulated near-surface temperature data. The detection variable has been computed by a projection of 30-year trend fields onto the optimal fingerprint for the CO₂ + aerosol climate change pattern. A, B describe the two equivalent CO₂ + aerosol simulations, Obs the observations and C the equivalent CO₂ only simulation.