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Detection of the Greenhouse Effect in the Observations

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EXECUTIVE SUMMARY

Global-mean temperature has increased by 0.3-0.6°C over the past 100 years. The magnitude of this warming is broadly consistent with the theoretical predictions of climate models, but it remains to be established that the observed warming (or part of it) can be attributed to the enhanced greenhouse effect. This is the detection issue.

If the sole cause of the warming were the Man-induced greenhouse effect, then the implied climate sensitivity would be near the lower end of the accepted range of model predictions. Natural variability of the climate system could be as large as the changes observed to date, but there are insufficient data to be able to estimate its magnitude or its sign. If a significant fraction of the observed warming were due to natural variability, then the implied climate sensitivity would be even lower than model predictions. However, it is possible that a larger greenhouse warming has been offset partially by natural variability and other factors, in which case the climate sensitivity could be at the high end of model predictions.

Global-mean temperature alone is an inadequate indicator of greenhouse-gas-induced climatic change. Identifying the causes of any global-mean temperature change requires examination of other aspects of the changing climate, particularly its spatial and temporal characteristics. Currently, there is only limited agreement between model predictions and observations. Reasons for this include the fact that climate models are still in an early stage of development, our inadequate knowledge of natural variability and other possible anthropogenic effects on climate, and the scarcity of suitable observational data, particularly long, reliable time series. An equally important problem is that the appropriate experiments, in which a realistic model of the global climate system is forced with the known past history of greenhouse gas concentration changes, have not yet been performed.

Improved prospects for detection require a long term commitment to comprehensively monitoring the global climate system and potential climate forcing factors, and to reducing model uncertainties. In addition, there is considerable scope for the refinement of the statistical methods used for detection. We therefore recommend that a comprehensive detection strategy be formulated and implemented in order to improve the prospects for detection. This could be facilitated by the setting up of a fully integrated international climate change detection panel to coordinate model experiments and data collection efforts directed towards the detection problem.

Quantitative detection of the enhanced greenhouse effect using objective means is a vital research area, because it is closely linked to the reduction of uncertainties in the magnitude of the effect and will lead to increased confidence in model projections. The fact that we are unable to reliably detect the predicted signals today does not mean that the greenhouse theory is wrong, or that it will not be a serious problem for mankind in the decades ahead.

8.1 Introduction

8.1.1 The Issue

This chapter addresses the question Have we detected the greenhouse effect? , or, stated more correctly, have we detected changes in climate that can, with high statistical confidence, be attributed to the enhanced greenhouse effect associated with increasing trace gas concentrations? It is important to answer this question, because detecting the enhanced greenhouse effect will provide direct validation of models of the global climate system Until we can identify aspects of greenhouse gas induced changes in the observed climate record with high confidence, there will always be doubts about model validity and hence about even the most general predictions of future climatic change Even when detection has occurred uncertainties regarding the magnitude and spatial details of future changes will still remain

Previous reviews of the greenhouse problem (N R C 1983, MacCracken and Luther, 1985 Bolin et al 1986) have also addressed the detection issue They have concluded that the enhanced greenhouse effect has not yet been detected unequivocally in the observational record However, they have also noted that the global mean temperature change over the past 100 years is consistent with the greenhouse hypothesis, and that there is no convincing observational evidence to suggest that the model-based range of possible climate sensitivity [1] values is wrong The purpose of the present review is to re evaluate these conclusions in the light of more recent evidence

8.1.2 The Meaning Of "Detection"

The word "detection has been used to refer to the identification of a significant change in climate (such as an upward trend in global mean temperature) However identifying a change in climate is not enough for us to claim that we have detected the enhanced greenhouse effect, even if statistical methods suggest that the change is statistically significant (i e extremely unlikely to have occurred by chance) To claim detection in a useful and practical way, we must not only identify a climatic change, but we must **attribute** at least part of such a change to the enhanced greenhouse effect It is in this stricter sense that the word "detection is used here Detection requires that the observed changes in climate are in accord with detailed model predictions of the enhanced greenhouse effect, demonstrating that we understand the cause or causes of the changes

To illustrate this important difference consider changes in global-mean temperature A number of recent analyses have claimed to show a statistically significant warming trend over the past 100 years (Hansen et al 1988 Tsionis and Elsner, 1989, Wigley and Raper 1990) But is this warming trend due to the enhanced greenhouse effect? We have strong evidence that changes of similar magnitude and rate have occurred prior to this century (see Section 7) Since these changes were certainly **not** due to the enhanced greenhouse effect, it might be argued that the most recent changes merely represent a natural long-time-scale fluctuation

The detection problem can be conveniently described in terms of the concepts of signal and noise (Madden and Ramanathan 1980) Here the signal is the predicted time dependent climate response to the enhanced greenhouse effect The noise is any climatic variation that is not due to the enhanced greenhouse effect [2] Detection requires that the observed signal is large relative to the noise In addition in order to be able to attribute the detected signal to the enhanced greenhouse effect it should be one that is specific to this particular cause Global mean warming for example is not a particularly good signal in this sense because there are many possible causes of such warming

8.1.3 Consistency Of The Observed Global-Mean Warming With The Greenhouse Hypothesis

Global-mean temperature has increased by around 0 3-0 6°C over the past 80-100 years (see Section 7) At the same time, greenhouse gas concentrations have increased substantially (Section 1) Is the warming consistent with these increases? To answer this question we must model the effects of these concentration changes on global-mean temperature and compare the results with the observations Because of computing constraints and because of the relative inflexibility of coupled ocean atmosphere GCMs we cannot use such models for this purpose Instead we must use an upwelling-diffusion climate model to account for damping or lag effect of the oceans (see Section 6) The response of such a model is determined mainly by the climate sensitivity ($\Delta T_{2\times}$) the magnitude of ocean mixing (specified by a diffusion coefficient K) and the ratio of the temperature change in the regions of sinking water relative to the global-mean change (π) Uncertainties in these parameters can be accounted for by using a range of values

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[1] *Climate sensitivity is defined here as the equilibrium global-mean temperature change for a CO_2 doubling ($\Delta T_{2\times}$) $\Delta T_{2\times}$ is thought to lie in the range 1 5°C to 4 5°C (see Section 5)*

[2] *Noise as used here includes variations that might be due to other anthropogenic effects (see Section 2) and natural variability Natural variability refers to all natural climatic variations that are unrelated to Man s activities embracing both the effects of external forcing factors (such as solar activity and volcanic eruptions) and internally generated variability Uncertainties in the observations also constitute a form of noise*

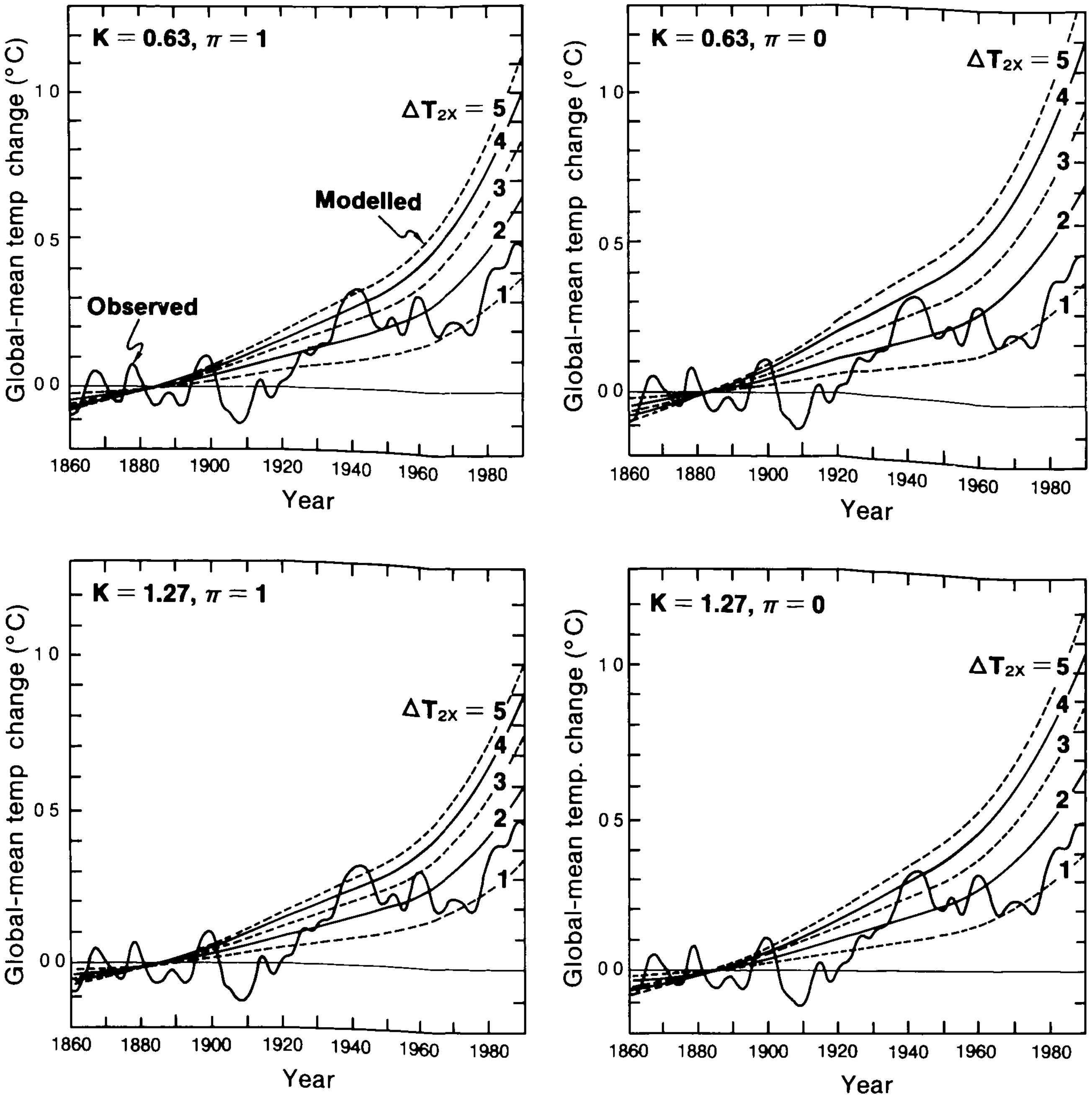

Figure 8.1: Observed global-mean temperature changes (1861 1989) compared with predicted values The observed changes are as given in Section 7 smoothed to show the decadal and longer time scale trends more clearly Predictions are based on observed concentration changes and concentration/forcing relationships given in Section 2 and have been calculated using the upwelling diffusion climate model of Wigley and Raper (1987) To provide a common reference level modelled and observed data have been adjusted to have zero mean over 1861 1900 To illustrate the sensitivity to model parameters model results are shown for ΔT_{2x} = 1, 2, 3 4 and 5°C (all panels) and for four K, π combinations The top left panel uses the values recommended in Section 6 (K = 0 63cm^{2}sec^{-1}, π =1) Since sensitivity to K is relatively small and sensitivity to π is small for small ΔT_{2x}, the best fit ΔT_{2x} depends little on the choice of K and π

The model is forced from 1765-1990 using concentration changes and radiative forcing/concentration relationships given in Section 2

Figure 8 1 compares model predictions for various model parameter values with the observed warming over 1861-1989 The model results are clearly qualitatively consistent with the observations on the century time-scale Agreement on long time-scales is about all that one might expect On shorter time-scales, we know that the climate system is subject to internal variability and to a variety of external forcings, which must obscure any response to greenhouse forcing Although we cannot explain the observed shorter time-scale fluctuations in detail, their magnitude is compatible with our understanding of natural climatic variability Essentially, they reflect the noise against which the greenhouse signal has to be detected

While the decadal time-scale noise is clear, there may also be substantial century time-scale noise This noise makes it difficult to infer a value of the climate sensitivity from Figure 8 1 Internal variability arising from the modulation of random atmospheric disturbances by the ocean (Hasselmann, 1976) may produce warming or cooling trends of up to 0 3°C per century (Wigley and Raper, 1990, see Figure 8 2), while ocean circulation changes and the effects of other external forcing factors such as volcanic eruptions and solar irradiance changes and/or other anthropogenic factors (see Section 2) could produce trends of similar magnitude On time-scales of order a decade, some of these (volcanic eruptions sulphate aerosol derived cloud albedo changes) clearly have a negative forcing effect, while others have uncertain sign If the net century time-scale effect of all these non greenhouse factors were close to zero, the climate sensitivity value implied by Figure 8 1 would be in the range 1°C to 2°C If their combined effect were a warming then the implied sensitivity would be less than 1°C, while if it were a cooling the implied sensitivity could be larger than 4°C The range of uncertainty in the value of the sensitivity becomes even larger if uncertainties in the observed data (Section 7) are accounted for

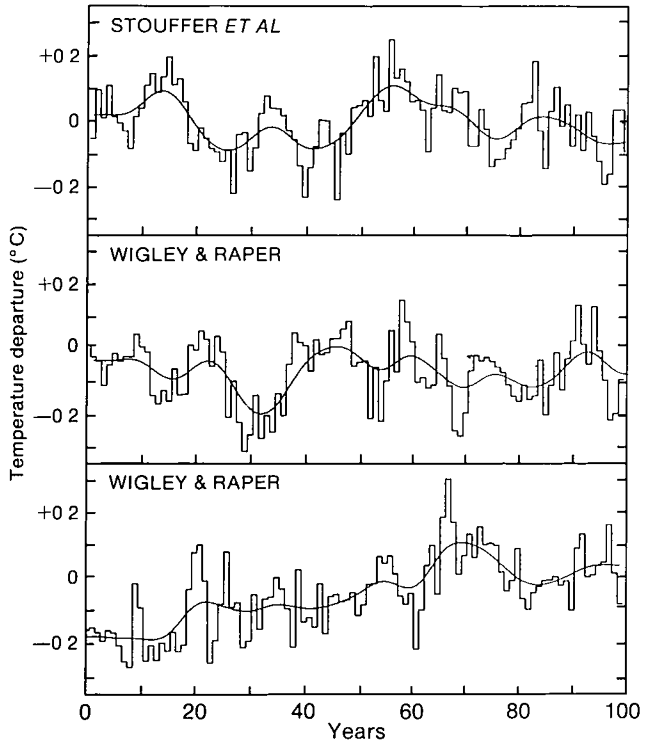

Figure 8.2: Simulated natural variability of global mean temperature The upper panel shows results from the 100 year control run with the coupled ocean/atmosphere GCM of Stouffer et al (1989) These data are also shown in Figure 6 2 The lower two panels are 100 year sections from a 100 000 year simulation using the upwelling-diffusion model employed in Figure 8 1 with the same climate sensitivity as the Stouffer et al model (ΔT_{2x} = 4°C) The upwelling diffusion model is forced with random inter annual radiative changes chosen to match observed inter annual variations in global-mean temperature (Wigley and Raper 1990) The consequent low frequency variability arises due to the modulating effect of oceanic thermal inertia Most 100 year sections are similar in character to the middle panel and are qualitatively indistinguishable from the coupled ocean/atmosphere GCM results However a significant fraction show century time scale trends as large or larger than that in the lower panel Longer GCM simulations may therefore reveal similar century time scale variability

From this discussion, one may conclude that an enhanced greenhouse effect could already be present in the climate record, even though it cannot yet be reliably detected above the noise of natural climatic variability The goal of any detection strategy must be to achieve much more than this It must seek to establish the credibility of the models within relatively narrow limits and to reduce our uncertainty in the value of the climate sensitivity parameter In this regard, global-mean temperature alone is an inadequate indicator of greenhouse gas induced climatic change Identifying the causes of any global-mean temperature change requires examination of other aspects of the changing climate, particularly its spatial and temporal characteristics

8.1.4 Attribution And The Fingerprint Method

Given our rudimentary understanding of the magnitude and causes of low-frequency natural variability it is virtually impossible to demonstrate a cause-effect relationship with high confidence from studies of a single variable (However, if the global warming becomes sufficiently large, we will eventually be able to claim detection simply because there will be no other possible explanation) Linking cause and effect is referred to as attribution This is the key issue in detection studies - we must be able to attribute the observed changes (or part of them) to the enhanced greenhouse effect Confidence in the attribution is increased as predictions of changes in various components of the climate system are borne out by the observed data in more and more detail The method proposed for this purpose is the fingerprint method namely, identification of an observed multivariate signal [3] that has a structure unique to the predicted enhanced greenhouse effect (Madden and Ramanathan 1980 Baker and Barnett, 1982, MacCracken and Moses 1982) The

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[3] *A multivariate signal could be changes in a single climate element (such as temperature) at many places or levels in the atmosphere or changes in a number of different elements or changes in different elements at different places*

current scientific focus in the detection issue is therefore on multivariate or fingerprint analyses The fingerprint method is essentially a form of model validation, where the perturbation experiment that is being used to test the models is the currently uncontrolled emission of greenhouse gases into the atmosphere The method is discussed further in Section 8 3 First, however, we consider some of the more general issues of a detection strategy

8.2 Detection Strategies

8.2.1 Choosing Detection Variables

There are many possible climate elements or sets of elements that we could study to try to detect an enhanced greenhouse effect In choosing the ones to study, the following issues must be considered

the strength of the predicted signal and the ease with which it may be distinguished from the noise,

uncertainties in both the predicted signal and the noise, and

the availability and quality of suitable observed data

8 2 1 1 Signal to noise ratios

The signal-to-noise ratio provides a convenient criterion for ranking different possible detection variables The stronger the predicted signal relative to the noise, the better the variable will be for detection purposes, all other things being equal For multivariate signals, those for which the pattern of natural variability is distinctly different from the pattern of the predicted signal will automatically have a high signal-to noise ratio

Signal to-noise ratios have been calculated for a number of individual climate elements from the results of 1xCO_2 and 2xCO_2 equilibrium experiments using atmospheric GCMs coupled to mixed-layer oceans (Barnett and Schlesinger 1987, Santer et al , 1990 Schlesinger et al 1990) The highest values were obtained for free troposphere temperatures, near-surface temperatures (including sea-surface temperatures), and lower to middle tropospheric water vapour content (especially in tropical regions) Lowest values were found for mean sea level pressure and precipitation While these results may be model dependent, they do provide a useful preliminary indicator of the relative values of different elements in the detection context

Variables with distinctly different signal and noise patterns may be difficult to find (Barnett and Schlesinger, 1987) There are reasons to expect parallels between the signal and the ***low-frequency*** noise patterns at least at the zonal and seasonal levels, simply because such characteristics arise through feedback mechanisms that are common to both greenhouse forcing and natural variability

8 2 1 2 Signal uncertainties

Clearly a variable for which the signal is highly uncertain cannot be a good candidate as a detection variable Predicted signals depend on the models used to produce them Model-to-model differences (Section 5) point strongly to large signal uncertainties Some insights into these uncertainties may also be gained from studies of model results in attempting to simulate the present-day climate (see Section 4) A poor representation of the present climate would indicate greater uncertainty in the predicted signal (e g , Mitchell et al , 1987) Such uncertainties tend to be largest at the regional scale because the processes that act on these scales are not accurately represented or parameterized in the models Even if a particular model is able to simulate the present-day climate well, it will still be difficult to estimate how well it can define an enhanced greenhouse signal Nevertheless, validations of simulations of the present global climate should form at least one of the bases for the selection of detection variables

A source of uncertainty here is the difference between the results of equilibrium and transient experiments (see Section 6) Studies using coupled ocean-atmosphere GCMs and time-varying CO_2 forcing have shown reduced warming in the areas of deep water formation (i e , the North Atlantic basin and around Antarctica) compared with equilibrium results (Bryan et al , 1988, Washington and Meehl, 1989, Stouffer et al , 1989) These experiments suggest that the regional patterns of temperature change may be more complex than those predicted by equilibrium simulations The results of equilibrium experiments must therefore be considered as only a guide to possible signal structure

The most reliable signals are likely to be those related to the largest spatial scales Small-scale details may be eliminated by spatial averaging, or, more generally by using filters that pass only the larger scale (low wave number) components (Note that some relatively small-scale features may be appropriate for detection purposes, if model confidence is high) An additional benefit of spatial averaging or filtering is that it results in data compression (i e , reducing the dimensionality of the detection variable), which facilitates statistical testing Data compression may also be achieved by using linear combinations of variables (e g , Bell, 1982, 1986, Karoly, 1987, 1989)

8 2 1 3 Noise uncertainties

Since the expected man-made climatic changes occur on decadal and longer time-scales, it is largely the low-frequency characteristics of natural variability that are important in defining the noise Estimating the magnitude of low frequency variability presents a major problem because of the shortness and incompleteness of most instrumental records. This problem applies particularly to new satellite-based data sets.

In the absence of long data series, statistical methods may be used to estimate the low frequency variability (Madden and Ramanathan, 1980, Wigley and Jones, 1981), but these methods depend on assumptions which introduce their own uncertainties (Thiebaux and Zwiers, 1984). The difficulty arises because most climatological time-series show considerable persistence, in that successive yearly values are not independent, but often significantly correlated. Serially correlated data show enhanced low frequency variability which can be difficult to quantify.

As an alternative to statistically-based estimates, model simulations may be used to estimate the low-frequency variability, either for single variables such as global-mean temperature (Robock, 1978, Hansen et al., 1988, Wigley and Raper, 1990) or for the full three-dimensional character of the climate system (using long simulations with coupled ocean-atmosphere GCMs such as that of Stouffer et al., 1989). Internally-generated changes in global-mean temperature based on model simulations are shown in Figure 8.2.

8.2.1.4 Observed data availability

The final, but certainly not the least important factor in choosing detection variables is data availability. This is a severe constraint for at least two reasons, the definition of an evolving signal and the quantification of the low-frequency noise. Both require adequate spatial coverage and long record lengths, commodities that are rarely available. Even for surface variables global scale data sets have only recently become available (see Section 7). Useful upper air data extend back only to the 1950s and extend above 50mb (i.e., into the lower stratosphere) only in recent years. Comprehensive three-dimensional coverage of most variables has become available only recently with the assimilation of satellite data into model-based analysis schemes. Because such data sets are produced for meteorological purposes (e.g. model initialisation), not for climatic purposes such as long-term trend detection, they contain residual inhomogeneities due to changes in instrumentation and frequent changes in the analysis schemes. In short, we have very few adequately observed data variables with which to conduct detection studies. It is important therefore to ensure that existing data series are continued and observational programmes are maintained in ways that ensure the homogeneity of meteorological records.

8.2.2 Univariate Detection Methods

A convenient way to classify detection studies carried out to date is in terms of the number of elements (or variables) considered, i.e., as univariate or multivariate studies. The key characteristic of the former is that the detection variable is a single time series. Almost all published univariate studies have used temperature averaged over a large area as the detection parameter. A central problem in such studies is defining the noise level, i.e., the low frequency variability (see 8.2.1.3).

There have been a number of published variations on the univariate detection theme. One such has been referred to as the noise reduction method. In this method the effects of other external forcing factors such as volcanic activity and/or solar irradiance changes or internal factors such as ENSO are removed from the record in some deterministic (i.e., model-based) or statistical way (Hansen et al., 1981, Gilliland, 1982, Vinnikov and Groisman, 1982, Gilliland and Schneider, 1984, Schonwiese, 1990). This method is fraught with uncertainty because the history of past forcings is not well known. There are no direct observations of these forcing factors and they have been inferred in a variety of different ways leading to a number of different forcing histories (Wigley et al., 1985, Schonwiese, 1990). The noise reduction principle, however, is important. Continued monitoring of any of the factors that might influence global climate in a deterministic way (solar irradiance, stratospheric and tropospheric aerosol concentrations, etc.) can make a significant contribution to facilitating detection in the future.

As noted above in the case of global-mean temperature univariate detection methods suffer because they consider change in only one aspect of the climate system. Change in a single element could result from a variety of causes making it difficult to attribute such a change specifically to the enhanced greenhouse effect. Nevertheless it is useful to review recent changes in a number of variables in the light of current model predictions (see also Wood, 1990).

8.2.3 Evaluation Of Recent Climate Changes

8.2.3.1 Increase of global mean temperature

The primary response of the climate system to increasing greenhouse gas concentrations is expected to be a global-mean warming of the lower layers of the atmosphere. In Section 8.1.3 the observed global mean warming of 0.3-0.6°C over the past century or so was compared with model predictions. It was noted that the observed warming is compatible with the enhanced greenhouse hypothesis but that we could not claim to have detected the greenhouse effect on this basis alone. It was also noted that the directly implied climate sensitivity (i.e. the value of ΔT_{2x}) was at the low end of the expected range, but that the plethora of uncertainties surrounding an empirical estimation of ΔT_{2x} precludes us drawing any firm quantitative conclusions. The observed global warming is far from being a steady monotonic upward trend but this does not mean that we should reject the greenhouse hypothesis. Indeed although our understanding of natural climatic variability is still quite limited, one would certainly expect substantial natural fluctuations to be superimposed on any greenhouse-related warming trend.

8.2.3.2 Enhanced high-latitude warming particularly in the winter half-year

Most model simulations suggest that the warming north of 50°N in the winter half of the year should be enhanced due to feedback effects associated with sea-ice and snow cover (Manabe and Stouffer, 1980, Robock, 1983, Ingram et al., 1989). In the Southern Hemisphere, results from simulations with atmospheric GCMs coupled to ocean GCMs do not show this enhancement (Bryan et al., 1988, Washington and Meehl, 1989, Stouffer et al., 1989). Figures 8.3 and 8.4 show observed annual and winter temperature changes for various latitude bands. Over the past 100 years, high northern latitudes have warmed slightly more than the global mean, but only in winter and spring. Since the 1920s, however, the annual-mean temperature for the area north of 50°N shows almost no trend, except in recent years. Summer and autumn temperatures have actually cooled since the mid to late 1930s. High-latitude Southern Hemisphere data are inadequate to make any meaningful comparisons.

The observed northern high-latitude winter enhancement is broadly consistent with model predictions. However, some of the latitudinal and seasonal details of observed temperature changes are contrary to equilibrium model predictions. This result has little bearing on the detection issue for two reasons. First, the variability of temperatures in high latitudes is greater than elsewhere and published calculations have shown that this is not an optimum region for signal detection based on signal-to-noise ratio considerations (Wigley and Jones, 1981). Second, there are still considerable doubts about the regional and seasonal details of the evolving greenhouse signal. Failure to identify a particular spatial pattern of change could be because the signal has not yet been correctly specified, although it is equally likely to be because the noise still dominates.

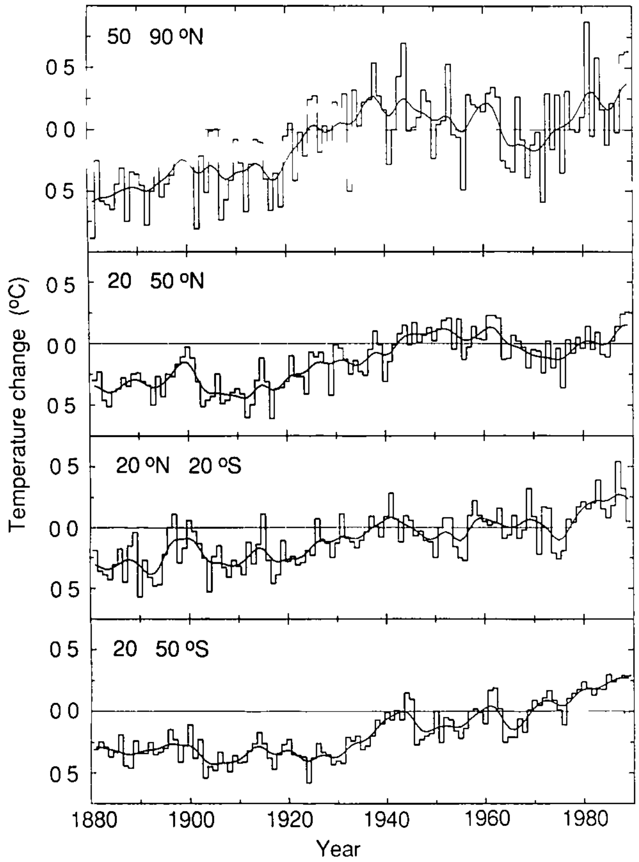

Figure 8.3: Observed variations in annual mean temperature for various latitude bands. The temperatures used are air temperature data over land areas and sea-surface temperature data for the oceans as described in Section 7. The smooth curves are filtered values designed to show decadal and longer time scale trends more clearly.

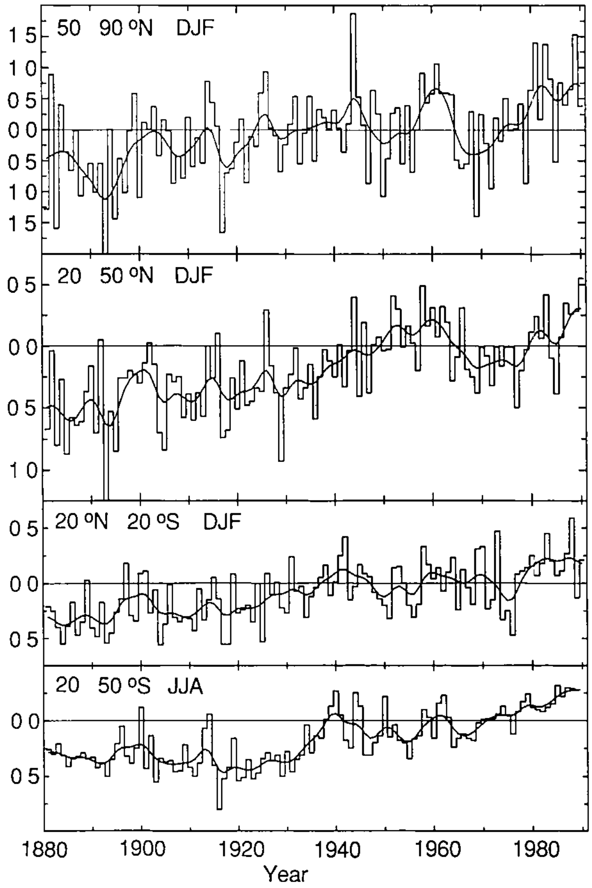

Figure 8.4: Observed variations in winter temperature for various latitude bands (DJF dated by the January in the Northern Hemisphere and tropics, and JJA in the Southern Hemisphere). The temperatures used are air temperature data over land areas and sea-surface temperature data for the oceans, as described in Section 7. The smooth curves are filtered values designed to show decadal and longer time scale trends more clearly. Note the compressed scale in the upper panel.

8.2.3.3 Tropospheric warming and stratospheric cooling

All equilibrium model simulations show a warming to near the top of the troposphere (Section 5). Trends near the tropopause and for the lower stratosphere, at least up to 50mb, differ in sign between models. Above 50mb, all models show a cooling. It has been suggested that this contrast in trends between the troposphere and stratosphere might provide a useful detection fingerprint (Epstein, 1982, Parker, 1985, Karoly 1987, 1989), but this is not necessarily the case for a number of reasons. First, identification of such a signal is hampered because observations above 50mb are of limited duration and generally of poorer quality than those in the troposphere. Second, there are reasons to expect natural variability to show a similar contrast between stratospheric and tropospheric trends (Liu and Schuurmans 1990).

Stratospheric cooling alone has been suggested as an important detection variable, but its interpretation is difficult because it may be caused by a number of other factors, including volcanic eruptions and ozone depletion. Furthermore, the physics of greenhouse gas induced stratospheric cooling is much simpler than that of tropospheric warming. It is quite possible for models to behave correctly in their stratospheric simulations yet be seriously in error in the lower atmosphere. Validation of the stratospheric component of a model while of scientific importance, may be of little relevance to the detection of an enhanced greenhouse effect in the troposphere.

Nevertheless, there is broad agreement between the observations and equilibrium model simulations. While the observations (Angell 1988) show a global-mean cooling trend from 1958 between 100hPa and 300hPa (Section 7, Figure 7.17), which appears to conflict with model results, this cooling is apparent only between 10 and 30°N (where it is not statistically significant) and south of 60°S (where it is associated with the ozone hole). There are no noticeable trends in other regions. Data compiled by Karoly (1987, 1989) show a warming trend since 1964 up to around 200hPa in the Southern Hemisphere to 100hPa in the Northern Hemisphere to 60°N and a more complex (but largely warming) behaviour north of 60°N. Near the tropopause and in the lower stratosphere temperatures have cooled since 1964. The main difference between recent observations and model simulations is in the level at which warming reverses to cooling. Although the models show large model-to-model differences, this level is generally lower in the observations. This difference may be associated with poor vertical resolution and the inadequate representation of the tropopause in current climate models.

8.2.3.4 Global-mean precipitation increase

Equilibrium experiments with GCMs suggest an increase in global-mean precipitation as one might expect from the associated increase in atmospheric temperature. However the spatial details of the changes are highly uncertain (Schlesinger and Mitchell 1987, and Section 5). Observations from which the long term change in precipitation can be determined are available only over land areas (see Bradley et al., 1987, Diaz et al., 1989, and Section 7), and there are major data problems in terms of coverage and homogeneity. These difficulties, coupled with the recognized model deficiencies in their simulations of precipitation and the likelihood that the precipitation signal-to-noise ratio is low (see 8.2.1.1), preclude any meaningful comparison.

8.2.3.5 Sea level rise

Increasing greenhouse gas concentrations are expected to cause (and have caused) a rise in global-mean sea level due partly to oceanic thermal expansion and partly to melting of land-based ice masses (see Section 9). Because of the strong dependence of sea level rise on global mean temperature change, this element, like global mean precipitation, cannot be considered as an independent variable. Observations show that global-mean sea level has risen over the past 100 years, but the magnitude of the rise is uncertain by a factor of at least two (see Section 9). As far as it can be judged, there has been a positive thermal expansion component of this sea level rise. Observational evidence (e.g., Meier, 1984, Wood, 1988) shows that there has been a general long term retreat of small glaciers (but with marked regional and shorter time-scale variability) and this process has no doubt contributed to sea level rise. Both thermal expansion and the melting of small glaciers are consistent with global warming, but neither provides any independent information about the cause of the warming.

8.2.3.6 Tropospheric water vapour increase

Model predictions show an increase in tropospheric water vapour content in association with increasing atmospheric temperature. This is of considerable importance since it is responsible for one of the main feedback mechanisms that amplifies the enhanced greenhouse effect (Raval and Ramanathan 1989). Furthermore, a model-based signal to noise ratio analysis (see Section 8.2.1.1) suggests that this may be a good detection variable. However the brevity of available records and data inhomogeneities preclude any conclusive assessment of trends. The available data have inhomogeneities due to major changes in radiosonde humidity instrumentation. Since the mid 1970s there has been an apparent upward trend, largest in the tropics (Flohn and Kapala 1989, Elliott et al. 1990). However the magnitude of the tropical trend is much larger than any expected greenhouse-related change, and it is likely that natural variability is dominating the record.

8.3 Multivariate or Fingerprint Methods

8.3.1 Conspectus

The fingerprint method, which involves the simultaneous use of more than one time series, is the only way that the attribution problem is likely to be solved expeditiously In its most general form one might consider the time evolution of a set of three-dimensional spatial fields, and compare model results (i e , the signal to be detected) with observations There are, however, many potential difficulties both in applying the method and in interpreting the results, not the least of which is reliably defining the greenhouse-gas signal and showing ***a priori*** that it is unique

In studies that have been performed to date, predicted changes in the three-dimensional structure of a single variable (mean values, variances and/or spatial patterns) have been compared with observed changes The comparison involves the testing of a null hypothesis namely that the observed and modelled fields do not differ Rejection of the null hypothesis can be interpreted in several ways It could mean that the model pattern was not present in the observations (i e in simplistic terms that there was no enhanced greenhouse effect) or that the signal was obscured by natural variability or that the prediction was at fault in some way, due either to model errors or because the chosen prediction was inappropriate We know ***a priori*** that current models have numerous deficiencies (see Sections 4 and 5), and that even on a global scale, the predicted signal is probably obscured by noise (Section 8 1 3) Furthermore, most studies to date have only used the results of equilibrium simulations rather than the more appropriate time-dependent results of coupled ocean-atmosphere GCM experiments[4] Because of these factors published work in this area can only be considered as exploratory, directed largely towards testing the methods and investigating potential statistical problems

8.3.2 Comparing Changes In Means And Variances

Means, time variances and spatial variances of the fields of observed and predicted changes have been compared for a number of variables by Santer et al (1990) Predicted changes were estimated from the equilibrium $1xCO_2$ and $2xCO_2$ simulations using the Oregon State University (OSU) atmospheric GCM coupled to a mixed layer ocean (Schlesinger and Zhao, 1989) In all cases (different variables, different months) the observed and modelled fields were found to be significantly different i e , for these tests the null hypothesis of no difference was rejected and the model signal could not be identified in the observations As noted above this is not an unexpected result

8.3.3 Pattern Correlation Methods

The basic approach in pattern correlation is to compare the observed and modelled time-averaged patterns of change (or changing observed and modelled patterns) using a correlation coefficient or similar statistic The word "pattern is used in a very general sense - it may refer to a two point pattern involving two time series of the same variable or to a many-point pattern involving the full three-dimensional spatial fields of more than one variable In some studies time-standardized variables have been used This has the advantage of giving greater emphasis to those spatial regions in which the time variance (i e , the noise) is smallest

Four examples of pattern correlation detection studies have appeared in the literature, all involving comparisons of observed and modelled temperature changes (Barnett, 1986, Barnett and Schlesinger, 1987, Barnett, 1990, Santer et al , 1990) Barnett (1986) and Barnett and Schlesinger (1987) used the covariance between the patterns of standardized observed and modelled changes as a test statistic Equilibrium $1xCO_2$ and $2xCO_2$ results from the OSU atmospheric GCM coupled to a mixed-layer ocean were employed to generate the multivariate predicted signal This pattern was then correlated with observed changes relative to a reference year on a year-by-year basis A significant trend in the correlation would indicate the existence of an increasing expression of the model signal in the observed data which could be interpreted as detection of an enhanced greenhouse signal A marginally significant trend was apparent, but this was not judged to be a robust result

Santer et al (1990) used the same model data and the spatial correlation coefficient between the time-averaged patterns of observed and predicted change as a detection parameter The observed changes used were the differences between two decades 1947 56 and 1977-86 Statistically significant differences between observed and model patterns of temperature change were found in all months but February (for which the amount of common variance was very small, less than 4%)

Barnett (1990) compared observed data with the time-evolving spatial fields from the GISS transient GCM run (Hansen et al , 1988) The model run uses realistic time-dependent forcing beginning in the year 1958, and accounts for the lag effect of oceanic thermal inertia by using a diffusion parameterization of heat transport below the mixed layer Comparisons were made using spatial correlation coefficients between decadal means of the evolving signal and the equivalent pattern in the

[4] *In this regard the correct experiment simulation of changes to date in response to observed greenhouse gas forcings has not yet been performed Because a realistic model simulation would generate its own substantial natural variability a number of such experiments may be required in order to ensure that representative results are obtained*

observations. There was virtually no similarity between modelled and observed temperature patterns.

The largely negative results obtained in these studies can be interpreted in a variety of ways, as noted in Section 8.3.1. Because of this, failure to detect the model signal in the data cannot be taken as evidence that there is no greenhouse-gas signal in the real world. Future multivariate detection studies should employ coupled ocean-atmosphere GCMs forced with observed greenhouse-gas concentration changes over more than just the past few decades.

8.4 When Will The Greenhouse Effect be Detected ?

The fact that we have not yet detected the enhanced greenhouse effect leads to the question: when is this likely to occur? As noted earlier, detection is not a simple yes/no issue. Rather it involves the gradual accumulation of evidence in support of model predictions, which in parallel with improvements in the models themselves, will increase our confidence in them and progressively narrow the uncertainties regarding such key parameters as the climate sensitivity. Uncertainties will always remain. Predicting when a certain confidence level might be reached is as difficult as predicting future climate change - more so, in fact, since it requires at least estimates of both the future signal and the future noise level.

Nevertheless, we can provide some information on the time-scale for detection by using the unprecedented change concept mentioned briefly in Section 8.1.4. This should provide an upper bound to the time for detection since more sophisticated methods should produce earlier results. We take a conservative view as a starting point, namely that the magnitude of natural variability is such that all of the warming of the past century could be attributed to this cause. (Note that this is not the same as denying the existence of an enhanced greenhouse effect. With such a noise level the past warming could be explained as a 1°C greenhouse effect offset by 0.5°C natural variability.) We then assume, again somewhat arbitrarily, that a further 0.5°C warming (i.e., a total warming of 1°C since the late nineteenth century) is required before we could say, with high confidence, that the only possible explanation would be that the enhanced greenhouse effect was as strong as predicted by climate models. Given the range of uncertainty in future forcing predictions and future model-predicted warming, when would this elevated temperature level be reached?

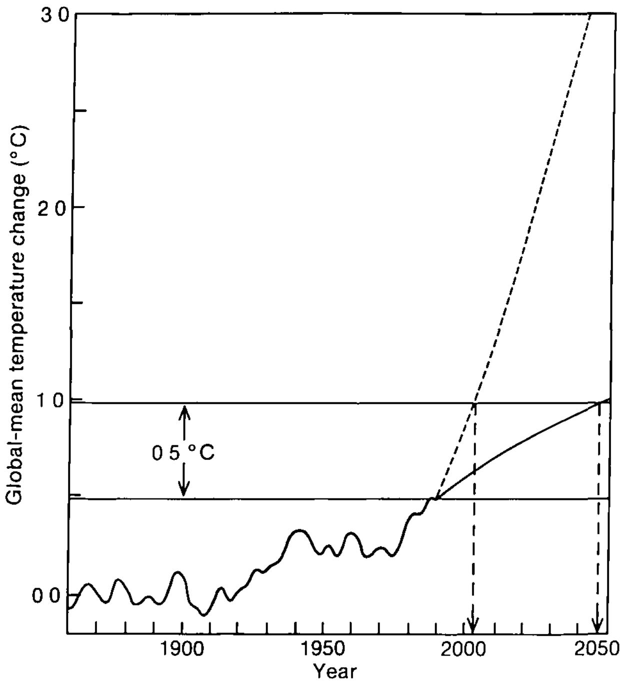

Figure 8.5: Observed global-mean temperature changes (as in Figure 8.1) and extreme predictions of future change. If a further 0.5°C warming were chosen as the threshold for detection of the enhanced greenhouse effect, then this would be reached sometime between 2002 and 2047. In practice, detection should be based on more sophisticated methods which would bring these dates closer to the present.

The answer is given in Figure 8.5. The upper curve shows the global mean warming for the Business-as-Usual Scenario (see Appendix 1) assuming a set of upwelling diffusion climate model parameters that maximizes the warming rate (viz., ΔT_{2x} = 4.5°C, K = 0.63 cm^2 sec^{-1} and π = 0). Under these circumstances, detection (as defined above) would occur in 12 years. The lower curve shows the global-mean warming for the lowest forcing Scenario (D in the Annex) with model parameters chosen to minimize the warming rate (viz., ΔT_{2x} = 1.5°C, K = 1.27 cm^2 sec^{-1} and π = 1). Detection does not occur until 2047.

On the basis of this simple analysis alone we might conclude that detection with high confidence is unlikely to occur before the year 2000. If stringent controls are introduced to reduce future greenhouse gas emissions and if the climate sensitivity is at the low end of the range of model predictions, then it may be well into the twenty first century before we can say with high confidence that we have detected the enhanced greenhouse effect.

The time limits inferred from Figure 8.5 are, of course, only a rough guide to the future and they are almost certainly upper bound values. Nevertheless the time frame for detection is likely to be of order a decade or more. In order to detect the enhanced greenhouse effect within this time frame it is essential to continue the development of models and to ensure that existing observing systems for both climate variables and potential climate forcing factors be maintained or improved.

8.5 CONCLUSIONS

Because of the strong theoretical basis for enhanced greenhouse warming, there is considerable concern about the potential climatic effects that may result from increasing greenhouse-gas concentrations However, because of the many significant uncertainties and inadequacies in the observational climate record in our knowledge of the causes of natural climatic variability and in current computer models, scientists working in this field cannot at this point in time make the definitive statement Yes we have now seen an enhanced greenhouse effect

It is accepted that global-mean temperatures have increased over the past 100 years and are now warmer than at any time in the period of instrumental record This global warming is consistent with the results of simple model predictions of greenhouse gas induced climate change However, a number of other factors could have contributed to this warming and it is impossible to prove a cause and effect relationship Furthermore when other details of the instrumental climate record are compared with model predictions, while there are some areas of agreement there are many areas of disagreement

The main reasons for this are

1) The inherent variability of the climate system appears to be sufficient to obscure any enhanced greenhouse signal to date Poor quantitative understanding of low frequency climate variability (particularly on the 10-100 year time scale) leaves open the possibility that the observed warming is largely unrelated to the enhanced greenhouse effect
2) The lack of reliability of models at the regional spatial scale means that the expected signal is not yet well defined This precludes any firm conclusions being drawn from multivariate detection studies
3) The ideal model experiments required to define the signal have not yet been performed What is required are time-dependent simulations using realistic time-dependent forcing carried out with fully coupled ocean-atmosphere GCMs
4) Uncertainties in, and the shortness of available instrumental data records mean that the low frequency characteristics of natural variability are virtually unknown for many climate elements

Thus it is not possible at this time to attribute all or even a large part of the observed global mean warming to the enhanced greenhouse effect on the basis of the observational data currently available Equally however we have no observational evidence that conflicts with the model based estimates of climate sensitivity Thus because of model and other uncertainties we cannot preclude the possibility that the enhanced greenhouse effect ***has*** contributed substantially to past warming nor even that the greenhouse gas induced warming has been greater than that observed, but is partly offset by natural variability and/or other anthropogenic effects

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