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DETECTION OF GREENHOUSE-GAS-INDUCED CLIMATIC CHANGE

Progress Report to the U.S. Department of Energy

FY 91/92: 1 December 1991-30 June 1992

Grant No. DE-FG02-86ER60397-A009

T.M.L. Wigley and P.D. Jones

15 July 1992

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DISCLAIMER

C O N T E N T S

1. PROJECT SPECIFICATIONS

Title: Detection of Greenhouse-Gas-Induced Climatic Change

Area: Atmospheric and Climate Research Division, Carbon Dioxide Research Program, First Detection.

Principal Investigators: T.M.L. Wigley and P.D. Jones

Organization: Climatic Research Unit, University of East Anglia (UEA).

Budget: 1991/92 168K, 1992/93 176K, 1993/94 183K.

Objective: To assemble and analyse instrumental climate data and to develop and apply climate models as a basis for (1) detecting greenhouse-gas-induced climatic change, and (2) validation of General Circulation Models.

Product: In addition to changes due to variations in greenhouse gas concentrations, the global climate system exhibits a high degree of internally-generated and externally-forced natural variability. To detect the enhanced greenhouse effect, its signal must be isolated from the "noise" of this natural climatic variability. A high quality, spatially extensive data base is required to define the noise and its spatial characteristics. To facilitate this, available land and marine data bases will be updated and expanded. The data will be analysed to determine the potential effects on climate of greenhouse gas concentration changes and other factors. Analyses will be guided by a variety of models, from simple energy balance climate models to ocean General Circulation Models. These analyses are oriented towards obtaining early evidence of greenhouse-gas-induced climatic change that would lead either to confirmation, rejection or modification of model projections, and towards the statistical validation of General Circulation Model control runs and perturbation experiments.

Approach: Global surface climate data bases will be expanded and updated using the extensive resources available to the Climatic Research Unit. Data analyses will focus on the use and development of appropriate statistical techniques for signal detection and pattern recognition. Interpretations will be guided by appropriate climate models.

Deliverables: Estimates of global- and hemispheric-mean near-surface temperature, based on land and marine data will be made on a monthly basis. The following new gridded data sets will be produced: a revised, upgraded temperature data set using 1961-90 as a reference period; "best possible", near-global mean-sea-level pressure data set; and a reference land precipitation data set spanning 1951-80, specifically for model validation purposes.

Program Coordination:

- Estimates of greenhouse-gas concentration changes during the last 200 years.
- Carbon cycle modeling (Scripps, IOS, Univ. New Hampshire, GFDL, and others).
- Model estimates of the climatic response to external forcing agents including SO_2 (LLNL).
- Model estimates of the regional and global climatic response to increasing greenhouse gas concentrations (all modeling groups).
- Global precipitation analyses (Univ. Massachusetts).
- General Circulation Model Validation studies (LLNL-PCMDI, SUNY).
- Climate data compilation and dissemination (CDIAC).

2. INTRODUCTION

The aims of the U.S. Department of Energy's Carbon Dioxide Research Program are to improve assessments of greenhouse-gas-induced climatic change and to define and reduce uncertainties through selected research. Four major questions can be identified.

(1) What are the regional and seasonal details of the expected climatic changes?

(2) How rapidly will these changes occur?

(3) How and when will the climatic effects of CO_2 and other greenhouse gases be first detected?

(4) Natural variability - what are the relationships between greenhouse-gas-induced climatic change and changes caused by other external and internal factors?

The present project addresses all of these questions.

Many of the diverse facets of greenhouse-gas-related climate research can be grouped under three interlinked subject areas:

(a) Modeling. This involves the development, validation and use of climate models of different types to estimate the details of climatic change due to increasing greenhouse gas concentrations. Transient response aspects (i.e., modeling the time-dependent response to realistic time-dependent changes in greenhouse-gas forcing) are considered to be particularly important.

(b) First Detection. The most direct form of model validation is to be able to identify, in the observational record, the model-predicted, evolving signal of greenhouse-gas-induced climatic change. This is the detection problem. Detection research includes better defining the enhanced greenhouse signal, the signals of climatic change resulting from other forcing factors and the characteristics of natural climatic variability. Such information is central to determining how and when the enhanced greenhouse effect can be detected with a high level of confidence.

(c) Supporting Data. The compilation and homogenization of past instrumental and paleoclimatic data is essential to support activities in areas (a) and (b). Past data are required to elucidate the mechanisms and causes of climatic change, to define the range of past variations, to document possible analogs for future greenhouse-gas-induced climatic change, and to aid in model development and validation.

The main research areas covered by this proposal are (b), First Detection and (c) Supporting Data. The project will also include work under area (a), Modeling: specifically, analysis of climate forcing factors, the development and refinement of transient response climate models, and the use of instrumental data in validating General Circulation Models (GCMs).

3. OUTLINE AND SUMMARY OF THE PROPOSED RESEARCH

We propose to continue the research work carried out in previous contracts in four main areas:

A. Global climate data. Updating, improvement and analysis of our global (land and marine) temperature data set.

B. Multivariate detection methods. The further development and use of multivariate techniques for the detection of both greenhouse-gas-induced and SO_2-related climatic change.

C. Transient response studies. The use of both simple and more complex transient-response climate models in order to throw further light on the natural variability of the climate system and the possible effects of SO_2-related forcing.

D. GCM validation. Validation of General Circulation Models using a variety of test statistics.

The way these items contribute to the major questions addressed by the Department of Energy's Carbon Dioxide Program (see Section 2 above) is summarized in the following Table.

Project elements / Major questions	Global climate data (A)	Multivariate detection methods (B)	Transient response studies (C)	GCM validation (D)
Details of future changes (1)				X
Rapidity of future changes (2)			X	
First detection of effects (3)	X	X	X	X
Natural variability (4)	X	X	X	

Work on all items will be carried out continuously throughout the project's 3-year duration.

Summary of products keyed to aims

During the first year, 24 scientific papers have been produced that were either fully or partially supported by the project. These products are listed below under the four main aims of the project, with more specific subheadings given to identify particular research areas. A full listing is given in Section 4, to which the numbers used here refer.

A. Global climate data

A1. Continued monitoring, and updating of our global temperature data base [12 (under C3 as well)]

A2. Analyses of instrumental climate data [6, 7, 9*, 15 (under A3 as well), 17, 18 (under A3 as well)]

A3. Paleoclimatic data and analyses [1, 8, 15 (under A2 as well), 19 (under A2 as well)]

A4. Review papers [2, 4]

B. Multivariate detection methods

B1. Spatial correlation (fingerprint) studies [10, 22*]

B2. Review papers [12]

C. Transient response studies

C1. Radiative forcing (including gas cycles and GWPs) [3, 5, 16, 19, 21, 23, 24]

C2. Future temperature and sea level changes [11, 14* (under C3 as well)]

C3. Interpretation of past climate changes (including estimation of ΔT_{2x}) [12 (under A1 as well), 14* (under C2 as well), 20]

D. GCM validation

[No publications under this heading during year-1 of project.]

* denotes paper given in full in Appendices.

4. PUBLICATIONS ARISING TO DATE

As the present project is a continuation of an earlier project spanning 1 December 1988-30 June 1991, we first give a list of papers that were produced during year 3 of the previous projection but which were still "in press" when that project ended. We then give a list of new publications produced during year 1 of the present project.

<u>Publications from year-3 (1990/91) of previous project that were listed as "in press" in the June 30, 1991 Progress Report</u>

Subsequently published

Barnett, T.P. and Jones, P.D., 1992: Intercomparison of two different Southern Hemisphere sea level pressure data sets. *Journal of Climate* 5, 93-99.

Hulme, M., 1991: An intercomparison of model and observed global precipitation climatologies. *Geophys. Res. Letts.* **18**, 1715-1718.

Hulme, M., 1992: A 1951-80 global land precipitation climatology for the evaluation of general circulation models. *Climate Dynamics* 7, 57-72.

Jones, P.D., 1991: Southern Hemisphere sea level pressure data: an analysis and reconstructions back to 1951 and 1911. *Int. Journal of Climatology* 11, 583-607.

Jones, P.D. and Bradley, R.S., 1992: Climatic variations in the longest instrumental records. In *Climate Since A.D. 1500* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 246-268.

Wigley, T.M.L., 1991: A simple inverse carbon cycle model. *Global Biogeochemical Cycles* 5, 373-382.

Wigley, T.M.L. and Raper, S.C.B., 1991: Detection of the enhanced greenhouse effect on climate. In *Climate Change: Science, Impacts and Policy* J. Jäger and H.L. Ferguson, Eds.), Cambridge University Press, Cambridge, 231-242.

Still in press

Raper, S.C.B., 1992: Observational data on the relationships between climatic change and the frequency and magnitude of severe tropical storms. In *Climate and Sea Level Change: Observations, Projections and Implications* (R.A. Warrick, E.M. Barrow and T.M.L. Wigley, Eds.), Cambridge University Press, Cambridge (in press).

Wigley, T.M.L., 1992: Future climate of the Mediterranean Basin with particular emphasis on changes in precipitation. In *UNEP Regional Seas Report: Implications of Climatic Change in the Mediterranean* (J.D. Milliman and G. Sestini, Eds.), Edward Arnold, Sevenoaks (in press).

Wigley, T.M.L., Jones, P.D. and Raper, S.C.B., 1992: Detecting and quantifying the enhanced greenhouse effect. In *Oceans, Climate and Man, Proceedings of the International Conference held in Turin, 15-17th April 1991* (E. Gabetti and M. Zavatarelli, Eds.) (in press).

Wigley, T.M.L. and Raper, S.C.B., 1992: Future changes in global-mean temperature and sea level. In *Climate and Sea Level Change: Observations, Projections and Implications* (R.A. Warrick, E.M. Barrow and T.M.L. Wigley, Eds.), Cambridge University Press, Cambridge (in press).

Wigley, T.M.L. and Santer, B.D., 1992: Future climate of the Caribbean Basin. In, *UNEP Regional Seas Report on Climatic Change in the Caribbean Basin* (G. Maul, Ed.) (in press).

<u>Publications produced during year-1 (1991/92) of present project</u>
(A-D denotes included in full in Appendix under stated letter)

Published

1. Bradley, R.S. and Jones, P.D., 1992: When was the Little Ice Age? In *Proceedings of the International Symposium on the Little Ice Age Climate* (T. Mikami, Ed.), Dept. of Geography, Tokyo Metropolitan University, 1-4.

2. Bradley, R.S. and Jones, P.D., 1992: Climate since A.D. 1500: Introduction. In *Climate Since A.D. 1500* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 1-16.

3. Bradley, R.S. and Jones, P.D., 1992: Records of explosive volcanic eruptions over the last 500 years. In *Climate Since A.D. 1500* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 606-622.

4. Folland, C.K., Karl, T.R., Nicholls, N., Nyenzi, B.S., Parker, D.E. and K.Ya. Vinnikov (contributing author list includes P.D. Jones and T.M.L. Wigley and 33 others), 1992: Observed Climate Variability and Change. In *Climate Change 1992, The IPCC Scientific Assessment* (J.T. Houghton, B.A. Callander and S.K. Varney, Eds.), Cambridge Univeristy Press, Cambridge, 135-170.

5. Isaksen, I.S.A., Ramaswamy, V., Rodhe, H. and Wigley, T.M.L., 1992: Radiative forcing of climate. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (J.T. Houghton, B.A. Callander and S.K. Varney, Eds.), Cambridge University Press, Cambridge, 47-67.

6. Jones, P.D. and Bradley, R.S., 1992: Global-scale temperature changes during the period of instrumental records. In *Proceedings of the International Symposium on the Little Ice Age Climate* (T. Mikami, Ed.), Dept. of Geography, Tokyo Metropolitan University, 253-259.

7. Jones, P.D. and Bradley, R.S., 1992: Climatic variations in the longest instrumental records. In *Climate Since A.D. 1500* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 246-268.

8. Jones, P.D. and Bradley, R.S., 1992: Climatic variations over the last 500 years. In *Climate Since A.D. 1500* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 649-666.

A 9. Jones, P.D. and Briffa, K.R., 1992: Global surface air temperature variations over the twentieth century: Part 1. Spatial, temporal and seasonal details. *The Holocene* 2, 165-179.

10. Jones, P.D., Santer, B.D. and Wigley, T.M.L., 1992: Fingerprint detection using spatial correlation technieques. In *Proceedings of the Fifth International Meeting on Statistical Climatology* (F.W. Zwiers, Ed.), Environment Canada, Atmospheric Environment Service, 437-444.

11. Raper, S.C.B. and Wigley, T.M.L., 1991: Short-term global mean temperature and sea level change. In *Proceedings of the International [Nirex] Workshop on Future Climate Change and Radioactive Waste Disposal* (C.M. Goodess and J.P. Palutikof, Eds.), University of East Anglia, Norwich, 203-213.

12. Wigley, T.M.L., Jones, P.D., Kelly, P.M. and Hulme, M., 1992: Recent global temperature changes: Ozone and aerosol influences. In *Proceedings of the Sixteenth Annual Climate Diagnostics Workshop*, U.S. Dept. of Commerce, NOAA, 194-202.

13. Wigley, T.M.L., Pearman, G.I. and Kelly, P.M., 1992: Indices and indicators of climate change: Issues of detection, validation and climate sensitivity. In *Confronting Climate Change. Risks, Implications and Responses* (I. Mintzer, Ed.), Cambridge University Press, Cambridge, 85-96.

B 14. Wigley, T.M.L. and Raper, S.C.B., 1992: Implications for climate and sea level of revised IPCC emissions scenarios. *Nature* **357**, 293-300.

In press

15. Briffa, K.R. and Jones, P.D., 1992: Global surface air temperature variations during the twentieth century. Part 2, Implications for large-scale high-frequency paleoclimatic studies. *The Holocene* 2 (in press).

16. Charlson, R.J. and Wigley, T.M.L., 1992: Sulfate aerosol and climate. *Scientific American* (in press).

17. Hulme, M. and Jones, P.D., 1992: Global climate change in the instrumental period. *Environmental Pollution* (in press).

18. Jones, P.D. and Briffa, K.R., 1992: Decadal-to-century timescale variability of regional and hemispheric scale temperature. In *The Natural Variability of the Climate System on 10-100 Year Timescales* (W.A. Sprigg, Ed.), National Academy of Sciences, Irvine, California (in press).

19. Wigley, T.M.L., 1992: Balancing the carbon budget: implications for projections of future carbon dioxide concentration changes. *Tellus* (in press).

Submitted

C 20. Kelly, P.M. and Wigley, T.M.L., 1992: Solar cycle length, greenhouse forcing and global climate. *Nature* (submitted).

21. Osborn, T.J. and Wigley, T.M.L., 1992: A simple model for estimating methane concentration and lifetime variations. *Climate Dynamics* (submitted).

D 22.*Santer, B.D., Wigley, T.M.L. and Jones, P.D., 1992: Correlation methods in fingerprint detection studies. *Climate Dynamics* (submitted).

23. Wigley, T.M.L. and Osborn, T.J., 1992: Indirect global warming potentials for methane due to OH feedback. *Geophysical Research Letters* (submitted).

24. Wigley, T.M.L., 1992: Negative global warming potentials for halocarbons. *Nature* (submitted).

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* A version of this paper was listed as "submitted to *Nature*" in our previous progress report. We subsequently withdrew the paper from *Nature* and submitted a revised and expanded version to *Climate Dynamics*.

5. PROGRESS

The following description of progress during the period 1 December 1991 to 30 June 1992 is keyed to the 'Summary of Aims' given in Section 3.

A *GLOBAL CLIMATE DATA*

A1. Continued monitoring and updating of our global temperature data base

Hemispheric and Global Temperature

During the course of the project we have continued to make hemispheric- and global-mean temperature estimates on a monthly basis using station data (from the internationally exchanged CLIMAT network) and marine data obtained from formal collaboration with the U.K. Meteorological Office (C.K. Folland and D.E. Parker). This enables us to produce, within about two months of real time, gridded hemispheric analyses on a 5°x5° grid box resolution. At the time of writing, we have data available up to and including April 1992.

The dataset, both the gridded and hemispheric analyses, has been extensively used by the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 Report (Chapter 7, Observed Climate Variations, Folland et al., 1990) and the recent update report (Section C, Observed Climate, Folland et al., 1992). Other groups also monitor global and hemispheric temperatures in real time. The Goddard Institute for Space Studies (GISS; Hansen and Lebedeff, 1987) monitor land-only temperatures. Angell (1988) and Spencer and Christy (1990) monitor tropospheric and stratospheric mean temperatures from a 63-station radiosonde network and from the microwave sounding unit (MSU) instruments on the NOAA polar orbiters, respectively. Both these records are very short, only extending back to 1958 and 1979, respectively. These and other datasets were extensively compared in the two IPCC reports (Folland et al., 1990, 1992). Agreement between the datasets was shown to be as good as expected considering that each measures different (albeit closely related) parameters. Our temperature dataset is the only synthesis of surface temperatures over both land and ocean areas.

Updates of the dataset are made available to the scientific community through the Carbon Dioxide Information Analysis Center (CDIAC) (see, for example, the latest report "*TRENDS 91*", Boden et al., 1992). A large fraction of the Climatic Research Unit's extensive data holding has been released as a CD-ROM software package in conjunction with the Hadley Centre of the U.K. Meteorological Office and Chadwyck Healey Limited of Cambridge, U.K. Although the development of the package was financed by the software house, the support of the Department of Energy over the last decade in the development and maintenance of the datasets was acknowledged.

Table 1 shows annual values of hemispheric- and global-mean temperatures for the 1981-1991 period. Slight reworking since the original submission of this proposal and the incorporation of additional data for some years has resulted in minor alterations to some values. Data up to April 1992 gives January-April average values for the two hemispheres of 0.40(NH) and 0.30(SH).

In Wigley et al. (1992) we show that the correlation between January-April and calendar year estimates is high, r=0.94. This leads

Table 1: Hemispheric- and global-mean temperature estimates from land and marine areas. Data expressed as anomalies from 1950-79.

	NH	SH	Global
1981	0.33	0.20	0.26
1982	0.04	0.13	0.08
1983	0.25	0.34	0.30
1984	0.00	0.24	0.12
1985	-0.03	0.20	0.08
1986	0.11	0.23	0.17
1987	0.23	0.36	0.30
1988	0.34	0.34	0.34
1989	0.25	0.24	0.24
1990	0.47	0.31	0.39
1991	0.35	0.32	0.34

to an estimate of the 1992 global value of 0.25°C, exactly the same as the estimate for 1991 we made in our original proposal. In making our estimate for 1991, we modified the correlation-based result to allow for the effects of the 1991/92 El Niño event and the eruption of Mount Pinatubo. Our assumption then that the volcanic event would dominate over the ENSO event appears to have been erroneous. Up until March 1992, there was no significant hemispheric cooling at the surface. (This is in contrast to the MSU-based free troposphere data, which show a marked cooling in the Northern Hemisphere since the eruption.) However, surface data for April and preliminary data for May show evidence of much cooler temperature anomaly values compared to the earlier months of 1992. At the present time, it is too early to say whether this cooling may be related to the volcanic event. Given this and the fact that the 1991/92 ENSO event appears to be ending, we expect the 1992 global temperature estimate to be about the 0.25°C value obtained from the regression. Such a value would make 1992 the sixth warmest year on record, easily exceeded by 1991, 1990, 1988, 1987 and 1983 and comparable to 1981 and 1989.

It has been some time since we have reviewed our instrumental database. In Part 1 (Jones and Briffa, 1992) of a two part series, we consider seasonal, temporal and spatial aspects of temperature change over the last 100 years. The second part (Briffa and Jones, 1992) will look at the interpretation of proxy-climatic data in terms of large-scale, hemispheric or global averages.

The conclusions from Part 1 relate to remaining uncertainties in the instrumental database and to the patterns of change over the twentieth century. The greatest remaining uncertainties are associated with sea surface temperature adjustments during the nineteenth century. Although this uncertainty is only of the order 0.1-0.2°C, its magnitude is sufficiently large to allow a wide range of temperature change since the mid-nineteenth century (0.3-0.6°C; Folland et al., 1990).

A number of recent studies have raised questions about the basic data sets. During the last contract period we addressed urbanization issues (Jones et al., 1990). Discussion has now turned to the reliability of the hemispheric means, given the variable and sometimes limited coverage, an issue we have addressed using the "frozen grid" method for both land-only (Jones et al., 1986a,b) and land-plus-marine data (Jones et al., 1991). We concluded that the error of individual annual estimates during the nineteenth century was about twice that of estimates during the mid-to-late twentieth century, but that the level of temperatures during the nineteenth century was reliably recorded by the relatively sparse network. Further work, using different approaches, by Trenberth et al. (1992) and Madden et al. (1993) has confirmed our earlier results.

The warming since the last century has not been equal everywhere, nor equal throughout the seasons (Jones and Briffa, 1992). While most areas have warmed, a few have cooled. The greatest warming has occurred over the land areas of the Northern Hemisphere. Despite this, the warming is most spatially coherent and statistically significant over mid-to-low latitudes of both hemispheres, particularly over the tropical oceans. Temperature trends have varied seasonally, particularly in the Northern Hemisphere. Here they are greatest and most significant in spring and least significant in autumn.

Maximum and Minimum Temperatures

An important area of study in the global warming debate is the relative contribution of maximum and minimum temperatures to the changes in land-based mean temperatures over the present century. Karl et al. (1991) have analyzed maximum and minimum temperatures over the contiguous United States, the former Soviet Union and the People's Republic of China. They show that much of the increase in mean temperatures is due to an increase in minimum temperatures with little change in maximum temperatures.

We are actively involved with Tom Karl of the National Climatic Data Center in Asheville, N.C. in extending these analyses to as many countries of the world as possible. With this in mind we have collected and analyzed data for the Sudan and South Africa. We are also in the process of obtaining and analyzing data for Japan and Australia and hope to extend these analyses to cover Argentina and India.

The South African study comprises data for 18 stations covering the entire country. Over the 1951-91 period, the national average indicates a warming trend in all months for both minimum and maximum temperature, except for September and October where the warming is only in the maxima. For minimum temperatures, the warming is greatest in late winter and early spring. It is greatest for maximum temperatures during late autumn and early winter. Decreases in the temperature range are evident during eight months of the year. Taken annually, minimum temperatures have increased by 0.80°C over the 41-year period, while maximum temperatures have risen by only 0.45°C.

For the Sudan, we have data for 15 stations for the 1950 to 1987 period. Warming is evident in both maximum and minimum temperatures. For maximum temperatures, there is a marked seasonal cycle with the greatest warming during July to September and a cooling between November and January. Annually maximum temperatures have warmed by 0.31°C, while minimum temperatures have warmed by 1.01°C. The marked warming of maximum temperatures during the summer rainy season is consistent with the marked reduction in rainfall. Decreases in the diurnal range have occurred in all months except June to August.

A2,3,4. Instrumental data, paleoclimatic data and reviews

A number of papers have been produced under these general headings, identified in Section 3 and listed in Section 4 (numbers 1, 2, 4, 6, 7, 8, 9, 15 and 18). As an example, we include paper no. 9 as an Appendix (A) in this Progress Report.

Most of these papers deal with instrumental temperature data, or proxy temperature data. In our proposal, we also include work on mean sea level pressure data as a topic. No further work in this area was carried out during year-1 of the project. The comparison of the Southern Hemisphere reconstructions (produced during the previous contract; Jones, 1991), with the earlier work of Barnett (1985) has now been published (Barnett and Jones, 1992). At large spatial and temporal scales the two sets are virtually identical in the zone 20°-40°S.

B. *MULTIVARIATE DETECTION METHODS*

One of the main problems in the issue of greenhouse-gas-induced climatic change is the detection problem. This involves the detection of a statistically significant change in climate, and the parallel or subsequent attribution of a fraction of the observed change to the enhanced greenhouse effect. The method advocated for attribution is called the fingerprint method (Wigley and Barnett, 1990), which involves the identification of a multivariate greenhouse signal (or pattern) in the observed data and the elimination of alternative explanations for the existence of such a signal. A possible pattern identification method was proposed by Barnett (1986) and further explored by Barnett and Schlesinger (1987). In Santer et al. (1992), as a year-1 contribution to the present project, we have investigated and evaluated a range of related methods (including the original ideas put forward by Barnett) - see Appendix D. The different methods are distinguished by their use of centered products (as in Wigley and Santer, 1990, and Santer and Wigley, 1990) versus uncentered products (as used by Barnett), and by whether or not the data are point-wise normalized using local standard deviations.

The four statistics we have evaluated are two which were introduced by Barnett, C(t) and $\tilde{C}$(t), based on uncentered products, and R(t) and $\tilde{R}$(t), which are standard (spatial) correlation coefficients. The tilde denotes that the fields compared have been point-wise normalized in an attempt to focus the test on regions with high signal-to-noise ratios. The underlying idea of the use of these statistics for detection is that, as time goes by and the signal becomes increasingly strong in the observed data, one should see an increasing trend in C(t), $\tilde{C}$(t), R(t) and $\tilde{R}$(t). In our year-1 work we have radically revised our assessment of these statistics. We have carried out theoretical analyses to show that C(t) and $\tilde{C}$(t) lead to statistics that are equivalent to the time series of the spatial means (of the raw or normalized data, respectively). This negates their values as <u>multivariate</u> test statistics. We have also shown that $\tilde{R}$(t) can give entirely misleading results, and that trends in $\tilde{R}$(t) say nothing about detection. This leaves R(t), the conventional spatial correlation coefficient, as the only viable test statistic. We have used R(t) to compare the results of five different GCMs against the spatial patterns of observed near-surface temperature changes. No significant trends are observed - indeed, the various trends are all close to zero. The theoretical results are summarized below.

Suppose $\Delta D(x,t)$ is the observed change in a variable at (x,t) - i.e., $\Delta D(x,t)$ is the difference between the average over some interval characterized by time t and the average over a reference period. "x" is an ordered spatial coordinate, not necessarily restricted to two dimensions. For the averaging interval, Barnett (1986) and Barnett and Schlesinger (1987) use one year; in our work we use 10 years. Further, suppose $\Delta M(x)$ is the model value at (x). $\Delta M(x)$ could be the difference between the model time-mean fields for $2xCO_2$ and $1xCO_2$ as given by equilibrium AGCM experiments, or could be derived from transient response experiments with coupled O/AGCMs. $\Delta M(x)$ is the signal we seek in the observations. ΔD and ΔM may either be raw fields or normalized fields; we use lower case d and m to denote the latter.

The detection strategy is to compare the $\Delta M(x)$ and $\Delta D(x,t)$ fields for t beginning with (e.g.) the beginning of the century and progressing through to the present. As time goes by, and the enhanced greenhouse signal presumably becomes stronger in the observed record, so ΔD and ΔM

should become more similar - i.e., there should be a positive trend in the statistic used to measure similarity. Barnett's statistic "C(t)" is defined by

$$C(t) = [\sum_{x=1}^{n_x} \Delta D(x,t)\ \Delta M(x)]/[\sum_{x=1}^{n_x} \Delta M(x)^2] \qquad ...(1)$$

This is an example of an uncentered cross-moment statistic. Our test statistic, R(t), is defined by

$$R(t) = [\sum_{x=1}^{n_x} (\Delta D(x,t) - \overline{\Delta D}(t))(\Delta M(x) - \overline{\Delta M})]/[n_x\ v_D(t)\ v_M] \qquad ...(2)$$

where the overbar denotes a spatial average and the v terms are spatial standard deviations.

We have shown that R(t) and C(t) are related by

$$C(t) = a\ R(t) + b\ \overline{\Delta D}(t) \qquad ...(3)$$

where

$$a = v_D(t)\ v_M/(v_M^2 + \overline{\Delta M}^2) \qquad ...(4)$$

$$b = \overline{\Delta M}/(v_M^2 + \overline{\Delta M}^2) \qquad ...(5)$$

Thus, C(t) has two components, one of which parallels R(t) and another which parallels the time series of variations in the unweighted mean of the observed data. In Santer et al. (1992) we show that, for near-surface temperature data, b is an order of magnitude larger than a, so that the $\overline{\Delta D}(t)$ term dominates in determining C(t). Thus, even if R(t) has no trend but $\overline{\Delta D}(t)$ does, there will still be a trend in C(t); but it will tell us nothing more than the trend in $\overline{\Delta D}(t)$. The value of the C(t) statistic as a measure of model-data pattern similarity is therefore limited. This is a general result that applies to all variables or variable combinations, not just near-surface temperature. $\tilde{C}(t)$ suffers from the same problem, as we have shown in Jones et al. (1992).

The use of point-wise normalization to focus R(t) on regions of high signal-to-noise ratio also turns out to be of little value. The practice to date has been to normalize both fields (ΔD and ΔM) by the same standard deviation field

$$Y = 1/v_D(x) \qquad ...(6)$$

In Santer et al. (1992) we show that the "normalized" R(t) statistic, $\tilde{R}(t)$, then reduces to

$$\tilde{R}(t) \simeq r\{\Delta m, Y\}\ r\{\Delta d(t), Y\} \qquad ...(7)$$

where r{Δm,Y} denotes the pattern correlation between the Δm (i.e., normalized ΔM) and Y fields (r{Δd,Y} similarly). As noted in our earlier proposal, $\tilde{R}(t)$ does show a significant trend for the signals generated by a range of GCMs. However, equ. (7) demonstrates that these trends have no detection relevance. This is because trends in $\tilde{R}(t)$ can only arise from trends in $r\{\Delta d,Y\}$ (since $r\{\Delta m,Y\}$ is effectively constant), and $r\{\Delta d,Y\}$ doesn't involve any model results. We refer to this as the "common factor" effect. (Different models give slightly different $\tilde{R}(t)$ trend results because equ. (7) is only approximate. Further details, and an explanation for the observed trends in $r\{\Delta d,Y\}$ are given in Santer et al., 1992 - see Appendix D.)

While we have shown that R(t) is the preferred multivariate test statistic for detection studies, there are still a number of aspects of its use which need to be resolved. One of the most important results of our work to date is the fact that R(t) (i.e., the pattern correlation statistic based on raw, non-normalized data) shows practically no trends to date. In other words, R(t) seems to be insensitive as a detection statistic - it appears to be even less informative than the use of global-mean temperature as a detection statistic. Why? The two most likely reasons are that the signals as determined by GCMs are wrong (wrong pattern and/or strength), or that other factors are obscuring the signal and making detection more difficult. Since "detectability" using R(t) is determined partly by the magnitude of the spatial variance in the signal (more spatially variable signals are easier to detect), a relatively weak but highly variable signal (such as that due to sulphate aerosol effects) could obscure a stronger but more coherent greenhouse signal. A range of studies is proposed for years 2 and 3 of this project to investigate this problem.

C. *TRANSIENT RESPONSE STUDIES*

The original proposal identified four areas of research under this heading (expanded to six in the present renewal proposal). The original four areas were: coupled climate/carbon cycle modeling; sulphate aerosol effects; generalizations of simple 1D upwelling-diffusion (UD) climate models; and comparisons between UD and coupled O/AGCM models.

In the latter two areas, no substantial outputs were generated during year-1 of the project. A considerable effort in these areas, however, has gone into installing the isopycnal ocean GCM of Josef Oberhuber (Max Planck Institute for Meteorology, Hamburg) on our own computer in order to facilitate the design of experiments to be run on the Cray YMP at MPI. Work comparing a hierarchy of models (1D UD model, generalized 1D UD model with diffusivity and upwelling rates both a function of depth, and an idealized geometry version of the isopycnal OGCM) will begin in late 1992 using the MPI Cray YMP. This work will form the foundation for a larger study of the natural internal variability of the OGCM.

In addition to work in the other two areas, coupled climate/carbon cycle modeling and sulphate aerosol effects, a number of other contributions have been made related either to the determination of radiative forcing inputs to 1D UD models, to the use of such models in projecting future climatic change at the global level, or to their use in interpreting past climatic variability. These results are itemized below.

C1. Radiative forcing (including gas cycles and GWPs)

Two major papers have been produced during year-1 that contribute to our knowledge and understanding of past and possible future radiative forcing changes. The first is the 1992 IPCC "update" chapter on radiative forcing (Isaksen et al., 1992), to which Wigley contributed. The second is a paper in *Nature* (Wigley and Raper, 1992 - see Appendix B) which uses the new IPCC emissions scenarios (Leggett et al., 1992) to derive projections of concentration changes for greenhouse gases, calculates the implied radiative forcing changes, and then uses these to estimate future global-mean changes in temperature and sea level.

The 1992 IPCC report did not give any systematic revision of future temperature and sea level changes, and our paper fills this crucial gap. The need to revise these projections arises from the fact that the emissions scenarios have been revised substantially from those given in 1990, and because various advances have been made in our understanding of the processes leading to radiative forcing changes. Specifically, we include in our work the possibility of reduced increases in future atmospheric CO_2 levels due to the effects of CO_2 fertilization on plant growth, the effect of stratospheric-ozone-depletion feedback on the radiative forcing due to halocarbons, and the negative forcing effects of sulphate aerosols.

In order to make these climate projections, we had to develop specific models for CO_2 and CH_4. The CO_2 model (Wigley, 1992a) is a coupled climate/carbon cycle model which contains terms that account for temperature feedbacks - although these particular feedbacks were not considered in Wigley and Raper (1992). The methane model (Osborn and Wigley, 1992) is a highly parameterized mass balance model with a variable lifetime. Lifetime variations are determined by changes in the concentrations of CH_4, CO, NO_x and NMHCs, so emissions scenarios for all of these gases are required as input data. Both the CO_2 and CH_4 models are highly efficient computationally (designed to run century time scale simulations in fractions of a second on 80386-based personal computers), and allow one to assess uncertainties.

As a "spin off" from the above work, we have also made contributions to the literature on Global Warming Potentials (GWPs) (Wigley and Osborn, 1992; Wigley, 1992b). GWPs are indices of the radiative forcing effects of different gases per unit of emissions relative to CO_2. Revised direct GWP values were given in Isaksen et al. (1992), updating those given by IPCC in 1990 (Shine et al., 1990). Indirect GWP values were given in 1990, but were not given in 1992 because of the realization that important new uncertainties exist which were not accounted for in 1990.

The contributions we have made to this issue during year-1 of the project concern indirect GWPs. The first (Wigley and Osborn, 1992) is an estimation of the indirect GWP for CH_4 due to OH feedback (i.e., due to CH_4 lifetime changes induced specifically by CH_4 concentration changes, through their effects on OH). These calculations make use of our parameterized methane model. The second is a quantification of the total GWPs for halocarbons accounting for the possible offsetting effects on radiative forcing changes due to halocarbon-induced depletion of ozone in the lower stratosphere. The quantification method employs a technique developed in Wigley and Raper (1992). For some halocarbons, the GWP values go from large positive quantities for the direct GWPs (as given by IPCC in Isaksen et al., 1992) to large negative quantities.

In addition to the above, we have made two contributions to the issue of sulphate aerosol forcing, estimates of past and future forcing (with uncertainties) in Wigley and Raper (1992), and a review of the issue for *Scientific American* with Charlson (Charlson and Wigley, 1992).

C2. Future temperature and sea level changes

Our main contribution here is the Wigley and Raper (1992) paper described above - given in full in Appendix B of this Progress Report. This gives a range of projections of global-mean temperature and sea level change (using models developed under earlier Department of Energy contracts) for the new IPCC emissions scenarios, together with uncertainty estimates. Our "best guess" projections are noticeably less than the 1990 IPCC "best guess" projections (for a range of reasons), but the ranges of uncertainty are slightly larger (because of the inclusion of new forcing contributions, such as that from sulphate aerosols, with their own uncertainties). In addition, we produced a small review paper based on earlier work (Raper and Wigley, 1991).

C3. Interpretation of past changes (including estimation of ΔT_{2x})

Three papers on this subject were produced that contribute to this topic. The first is the Wigley and Raper (1992) paper mentioned above. This includes a section on the match between observed global-mean temperature changes and modelled changes. In 1990, IPCC noted that the match was best for low values of ΔT_{2x} (1.5°C or less) (Wigley and Barnett, 1990), although the uncertainty in any empirical estimate of ΔT_{2x} was very large, large enough to cover the full range of GCM-based ΔT_{2x} values (1.5-4.5°C) (Wigley and Raper, 1991). When ozone depletion and sulphate aerosol effects are included, however, the past forcing changes are reduced, leading to smaller model-estimated changes in global-mean temperature. This, in turn, leads to a best fit ΔT_{2x} value substantially higher than previously estimated, around 3.4°C. Uncertainties in this estimate remain very large.

In a second, related contribution (Kelly and Wigley, 1992 - given in full in Appendix C) we have considered how the situation changes if solar irradiance variations are taken into account. As an irradiance proxy we use the length of the solar cycle, following Friis-Christensen and Lassen (1991). Our paper serves both as a critical assessment of the work of these authors, and as an exploration of possible solar effects on climate. We conclude that any cycle-length-related solar forcing effect must be substantially less than that due to man-made emissions of greenhouse gases and SO_2 on the century time scale, but could be of comparable or even greater importance on the decadal time scale. Inclusion of an optimized solar effect leads to a significant reduction in the implied (best fit) value of ΔT_{2x} (down to 1.7-1.8°C). We remain skeptical of the specific solar effect proposed by Friis-Christensen and Lassen, but open minded about the possibility of some form of intermediate frequency contribution - see the accompanying Renewal Proposal, Section 4 (p. 5).

Our final contribution under this heading (Wigley et al., 1992) is an analysis of the patterns of temperature change during the present century compared with the direct sulphate aerosol forcing pattern published by Charlson et al. (1990). This work also contributes to the issue of detection of the aerosol effect, although it does not use any sophisticated detection methods. We find some interesting similarities, adding support to the aerosol hypothesis. However, the results are inconclusive because of the unknown, but possibly similar effects of natural variability - i.e., the aerosol signal cannot be convincingly distinguished from the background noise (as we noted some time ago in Wigley, 1989).

D. *GCM MODEL VALIDATION*

No work has been carried out on this aspect during year-1.

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