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DETECTION OF GREENHOUSE-GAS-INDUCED CLIMATIC CHANGE

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1. PROJECT SPECIFICATIONS

Title: Detection of Greenhouse-Gas-Induced Climatic Change

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

Principal Investigator: T.M.L. Wigley

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:

- o Estimates of greenhouse-gas concentration changes during the last 200 years.
- o Carbon cycle modeling (Scripps, IOS, Univ. New Hampshire, GFDL, and others).
- o Model estimates of the climatic response to external forcing agents including SO₂ (LLNL).
- o Model estimates of the regional and global climatic response to increasing greenhouse gas concentrations (all modeling groups).
- o Global precipitation analyses (Univ. Massachusetts).
- o General Circulation Model Validation studies (LLNL-PCMDI, SUNY).
- o 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 CO₂ 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 SO₂-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 SO₂-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 second year, 15 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

Hemispheric and Global Temperature [5, 6, 7*, 13, 15]

Maximum and Minimum Temperatures [2, 8, 9]

Improvements to our Gridded Temperature Data

Paleoclimatic Data and Reviews [4, 10]

15
publications

B. MULTIVARIATE DETECTION METHODS

[No new publications under this heading during year-2 of project.]

C. TRANSIENT RESPONSE STUDIES

Probabilistic Assessments of Future Temperature and Sea-level Change [1, 3, 14*]

Radiative Forcing Changes [12*]

Carbon Cycle Modelling [11]

Sulphate Aerosol Effects

D. GCM VALIDATION

[No new publications under this heading during year-2 of project.]

* denotes paper given in full in Appendices.

4. PUBLICATIONS ARISING TO DATE

Publications from year-1 (1991/92) of present project that were listed as "in press" in the June 30, 1992 Progress Report

Subsequently published

Briffa, K.R. and Jones, P.D., 1993: Global surface air temperature variations during the twentieth century. Part 2, Implications for large-scale high-frequency paleoclimatic studies. *The Holocene* 3, 77-88.

Kelly, P.M. and Wigley, T.M.L., 1993: Solar cycle length, greenhouse forcing and global climate. *Nature* 360, 328-330.

Raper, S.C.B., 1993: 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, 192-212.

Wigley, T.M.L., 1993: Future climate of the Mediterranean Basin with particular emphasis on changes in precipitation. In *Climatic Change and the Mediterranean. Environmental and Societal Impacts of Climatic Change and sea-level rise in the Mediterranean Region* (L. Jeftic, J.D. Milliman and G. Sestini, Eds.), Edward Arnold, Sevenoaks, 15-44.

Wigley, T.M.L. and Raper, S.C.B., 1993: 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, 111-133.

Still in press

Charlson, R.J. and Wigley, T.M.L., 1993: Sulfate aerosol and climate. *Scientific American* (in press).

Hulme, M. and Jones, P.D., 1993: Global climate change in the instrumental period. *Environmental Pollution* (in press).

Jones, P.D. and Briffa, K.R., 1993: 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).

Osborn, T.J. and Wigley, T.M.L., 1993: A simple model for estimating methane concentration and lifetime variations. *Climate Dynamics* (in press).

Santer, B.D., Wigley, T.M.L. and Jones, P.D., 1993: Correlation methods in fingerprint detection studies. *Climate Dynamics* (in press).

Wigley, T.M.L., 1993: Balancing the carbon budget: implications for projections of future carbon dioxide concentration changes. *Tellus* (in press).

Wigley, T.M.L., Jones, P.D. and Raper, S.C.B., 1993: 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 Osborn, T.J., 1993: Indirect global warming potentials for methane due to OH feedback. *Geophysical Research Letters* (in press).

Wigley, T.M.L. and Santer, B.D., 1993: Future climate of the Gulf/Caribbean Basin from atmospheric General Circulation Models. In, *Climatic Change in the Intra-American Seas* (G.A. Maul, Ed.) Edward Arnold, London (in press).

Publications produced during year-2 (1992/93) of present project
(A-C denotes included in full in Appendix under stated letter)

Published

1. Warrick, R.A., Barrow, E.M. and Wigley, T.M.L. (eds), 1993: *Climate and sea-level change: Observations, Projections and Implications*, Cambridge University Press, 424 pp.
2. Jones, P.D. and Lindesay, J.A., 1993: Maximum and minimum temperature trends over South Africa and the Sudan. In, *Preprints, 4th International Conference on Southern Hemisphere Meteorology and Oceanography*, American Meteorological Society, Boston, 359-360.
3. Wigley, T.M.L. and Raper, S.C.B., 1993: Global mean temperature and sea level projections under the 1992 IPCC emissions scenarios. In, *Climate and sea-level change: Observation, Projections and Implications* (R.A. Warrick, E.M. Barrow and T.M.L. Wigley, Eds.), Cambridge University Press, 401-404.

In press

4. Bradley, R.S. and Jones, P.D., 1993: "Little Ice Age" summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* (in press).
5. Jones, P.D., 1993: Global surface temperature changes since the 1850s. In, *Environmental Data Problems - Institute of Mathematics and its Applications Proceedings Volume* (M. Ghil et al., eds.). Springer-Verlag (in press).
6. Jones, P.D., 1993: Is Climate Change Occurring? Evidence from the Instrumental Record. In, *Agricultural Dimensions of Global Climate Change* (H.M. Kaiser and T.E. Drennen, eds.), St. Lucie Press, Delray Beach, Florida (in press).
- A 7. Jones, P.D., 1993: Observations from the surface - projections for traditional meteorological observations. In, *Future Climates of the World, World Survey of Climatology* (A. Henderson-Sellers, ed.), Elsevier (in press).

8. Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindesay, J. and Peterson, T.C., 1993: Asymmetric trends of daily maximum and minimum temperature: empirical evidence and possible causes. *Bulletin of the American Meteorological Society* (in press).
9. Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindesay, J., Charlson, R.J. and Peterson, T.C., 1993: A new perspective on recent global warming: asymmetric trends of daily maximum and minimum 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).
10. Wigley, T.M.L. and Raper, S.C.B., 1993: Modelling low-frequency climate variability: the greenhouse effect and the interpretation of paleoclimatic data. 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).
11. Wigley, T.M.L., 1993: How important are carbon cycle model uncertainties? In, *Proceedings CICERO Conference on the Policy Implications of the Greenhouse Effect* (I. Isaksen, Ed.) (in press).
- B 12. Wigley, T.M.L., 1993: The contribution from emissions of different gases to the enhanced greenhouse effect. In, *Proceedings CICERO Conference on the Policy Implications of the Greenhouse Effect* (I. Isaksen, Ed.) (in press).

Submitted

13. Parker, D.E., Jones, P.D., Bevan, A. and Folland, C.K., 1993: Interdecadal changes of surface temperature since the late 19th century. *Journal of Geophysical Research* (submitted).
- C 14. Raper, S.C.B., Briffa, K.R. and Wigley, T.M.L., 1993: Glacier Change in Northern Sweden from A.D. 500: A temperature-dependent model of Storglaciären. *Journal of Glaciology* (submitted).
15. Briffa, K.R., Jones, P.D. and Hulme, M., 1993: Summer moisture availability across Europe, 1892-1991: An analysis based on the Palmer Drought Severity Index. *International Journal of Climatology* (submitted).

5. PROGRESS

The following description of progress during the period 1 July 1992 to 30 June 1993 is keyed to the 'Summary of Aims' given in Section 3.

A *GLOBAL CLIMATE DATA*

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 CLIMAT network and marine (sea surface temperatures) data from formal collaboration with the Hadley Centre of the U.K. Meteorological Office. This enables us to produce, within a few months of real time, data on a $5^{\circ} \times 5^{\circ}$ grid box resolution.

Updates of the dataset are to be made available to the scientific community through the Carbon Dioxide Information Analysis Center (CDIAC) in their TRENDS 92 and 93 reports (Boden et al., 1992). The data continue to be made available to interested scientists for use in other projects (e.g. David Robinson, Rutgers University, Robinson, 1993; Alan Robock, University of Maryland, Robock and Mao, 1992; and Henning Rodhe, University of Stockholm, Engardt and Rodhe, 1993).

The dataset has been used extensively by the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 Report in their supplementary update report (Folland et al., 1992). Intercomparisons have been made with other groups who also monitor atmospheric temperatures; land-only data from the Goddard Institute for Space Studies (Hansen and Lebedeff, 1987); upper-air data from the conventional radiosonde network since 1958 (Angell, 1988); and data obtained using the microwave sounding unit (MSU) on the NOAA series of polar orbiters since 1979 (Spencer and Christy, 1990). These show the agreements between each dataset to be as good as expected, considering that each measures different, but closely related, parameters. The agreements have been confirmed by the analysis of the longest series of records to 1992 (Jones, 1993). A detailed spatial analysis of our surface data set with the Hadley Centre is about to be submitted for publication (Parker et al., 1993).

Figure 1 shows monthly values of hemispheric- and global-mean combined (land + marine) temperatures for the 1980-1993 (April) period. The most dramatic feature of the recent two years has been a cooling of about 0.4°C (NH) and 0.2°C (SH) from values prevailing during late 1990 and early 1991. Cooling began in the NH during the summer and autumn seasons in 1991 and recurred again during April to November 1992. This cooling is probably related to the volcanic dust veil associated with the eruption of Mt Pinatubo in the Philippines in June 1991. Effects following other eruptions have tended to have a much more marked effect during the warm season months. The lack of any noticeable effect in the winter (NH) months (December to March) has been commented on by Robock and Mao (1992) using the temperature data base developed by this project. The lack of any response to the dust veil during the latest winter (1992/93) confirms their findings. The response over the Southern Hemisphere is much less marked, as one would expect. To some extent, the response there is a damped version of the Northern Hemisphere despite the two hemispheres being out of phase with each other.

Figure 1: Monthly estimates of hemispheric- and global-mean combined (land+marine) temperatures for the 1980 to April 1993 period. Data are expressed as anomalies from the 1950-79 period.

In our previous reports, we have tried to estimate the average temperature for the year from that recorded in the first four months. Last year's estimate of 0.25°C was in error by +0.06°C (real value 0.19°C) because the Pinatubo cooling was greater than anticipated. An estimate for this year would also give a value for 1993 of about 0.25°C, the year being warmer than the last because the Pinatubo effect this year should be smaller than last year (1992).

Maximum and Minimum Temperatures

Analyses have been made of maximum and minimum temperatures for countries comprising 50% of the land area in the Northern Hemisphere and 10% of the Southern Hemisphere land area. These reveal that minimum (night-time) temperatures are rising three times faster than maximums (day-time) (Karl et al., 1993). We are actively involved with Tom Karl of the National Climate Data Center in Asheville, NC, to extend these analyses to as many countries of the world as possible. We have already included data for Sudan, South Africa and Japan. ✓

During the last year we have added data for 17 stations for Bangladesh for the period 1948 to 1990. Figure 2 shows the average time series for maximum, minimum, the mean and the diurnal temperature range of the 17 sites.

Improvements to our Gridded Temperature Data

We are planning a new gridding of our land-based data set using the new World Meteorological Organization (WMO) reference period (1961-90). As initial preparation for this exercise, we have begun incorporating many additional temperature stations into our basic database. Initially, we have added all the stations with maximum and minimum temperatures used in the Karl et al. (1993) study. The data are first averaged to mean temperature then merged with our present data base. ✓

For English-speaking countries this is a relatively easy exercise as the monthly-mean data for stations we already had in the database are calculated using the same $(\text{maximum} + \text{minimum})/2$ method. Checks must still be made with each temperature value where the difference is beyond tolerable limits. For the remaining countries (e.g. ex-USSR, China, Japan) monthly values for stations common to both our present and the Karl et al. (1993) datasets will be different because the method of calculation is different. Data from these countries from the CLIMAT network will have been calculated as the average of a number of fixed observations each day. Merging of the datasets is not a simple task and we must be very careful when adding data from the Karl et al. dataset for these countries to our existing database.

Paleoclimatic Data and Reviews

Four papers written during the first two years of the project, consider the relevance of the paleoclimatic record and the early instrumental record to the climate-change detection issue. The first (Briffa and Jones, 1993) looks at the interpretation of proxy-climatic data in terms of large-scale, hemispheric and global averages. In this we address the question "To what extent are regionally-derived proxy temperature data likely to reflect changes on hemispheric or even global

Annual – Bangladesh 17 site average

Figure 2: Average temperature series based on 17 temperature sites for Bangladesh, 1948-1990. Data are expressed as anomalies from the 1948-1990 period. The range is the difference between maximum and minimum temperature, while the mean is the average of the maximum and minimum temperature.

spatial scales?" The second and third (Jones and Briffa, 1993 and Wigley and Raper, 1993a), were written for a National Academy meeting held in Irvine, CA, in September 1992, and look at decadal-to-century timescale variability in long instrumental and paleoclimatic series.

The fourth (Bradley and Jones, 1993) attempts to construct a hemispheric index of past temperatures from some 20 high-resolution temperature proxies for the period 1500 to the present. This paper concludes by stating that, since the 1920s, temperatures in the Northern Hemisphere have been higher than those reconstructed from the proxy evidence for at least 500 years. This suggests that some new forcing factor has become important in recent decades and anthropogenic greenhouse-gas increases are the most likely explanation.

B. MULTIVARIATE DETECTION METHODS

Our work in this area has centered around the paper by Santer et al. now "in press" in *Climate Dynamics* (see Section 4). An early version of this paper, as originally submitted to *Climate Dynamics*, was included in full in our previous Progress Report. Referees' comments and other considerations lead to minor changes before the paper was finally accepted; the culmination of more than three years' effort on this pattern correlation technique for detection of a greenhouse-gas climate change "fingerprint". The overall results were negative in that detection could not be claimed. The various possible explanations for this are given in the paper. Publication is expected within the next few months.

C. TRANSIENT RESPONSE STUDIES

Probabilistic Assessments of Future Temperature and Sea-level Change

Preliminary results were given in the previous renewal proposal. Our work during 1992/3 has concentrated on improving the models used for projecting the melt-water component of future sea-level rise. In the 1990 IPCC Working Group 1 report, the sea level chapter (Warrick and Oerlemans, 1990) used ice-melt models developed by the Climatic Research Unit (Wigley and Raper, 1993b) to predict a range of future sea level changes. (In fact, the models described in Wigley and Raper (1993b) are improved versions of those used in IPCC90.) These models, while adequate for short-term (up to 100 years) projections, have some conceptual weaknesses. In seeking to improve them, we have devised a new type of small glacier model. This has been tested on a single glacier, with exceptionally good results (Raper et al., 1993 - see item C in the Appendix to this Progress Report). We are currently in the process of extending it to a global-scale version, and developing a conceptually equivalent model for Greenland and Antarctica. When these models are completed, we will be in a position to produce revised (and improved) probabilistic estimates of future sea-level change.

Our new time-dependent small glacier model is based on the standard mass balance relationship $dV/dt = AB$, where V is the glacier volume, A is the glacier area and B is the net mass balance. The key assumption in the model is that $B = B(T^*)$ where T^* is the temperature at a *non fixed* representative point on the glacier at height h above a fixed reference level. T^* is related to a fixed point temperature T using a lapse rate and the height difference. To fully determine the model, A and h are related to the glacier volume (V) with parameters n and m . The model equation can be written in the form

$$\frac{dV}{dt} = \frac{\gamma E - \gamma}{\tau}$$

where $\gamma = V^n/m$ and $\gamma E = VE^n/m$ and VE is the temperature-dependent equilibrium value of V and τ is a glacier response time.

In the Raper et al. (1993) paper, see Appendix C, we have applied the model to Storglaciären a small glacier in northern Sweden. This glacier has measured mass-balance data over 1946-1990, but this data period is too short to determine the model parameters accurately. A long tree-ring-based temperature reconstruction for Northern Fennoscandia (Briffa et al., 1992) provides an opportunity to determine these parameters better and to reconstruct the glacier volume over the period A.D. 500-1980. Starting the integration in A.D. 500, the model parameters are adjusted to make the modelled glacier volumes for 1946-1980 coincide as closely as possible with "observed values".

VE and τ are fundamental to the response of a glacier to climate change, and we plan to use this model to help us in future estimates of contributions of small glaciers to global-mean sea level rise. For a given rate of change of glacier volume the model equation shows that a long/short response time implies a large/small VE sensitivity. Our results indicate that VE is very sensitive to temperature change: a 1°C temperature decrease increases VE by a factor of 5-10 and a 1°C temperature increase decreases in VE by a factor of 10 or more.

The expression for the glacier response time shows that τ is

proportional to

$$\left(\frac{V}{V_R}\right)^{1-n-n/m}$$

where V_R is the reference volume.

For our tuned values of m and n the index $1-n-n/m$ is positive, so that τ increases with increasing volume. The estimated response time for the present glacier volume is in the range 276-316 years. This is in agreement with the general theoretical results for a glacier terminus of 10^2 - 10^3 years (Nye 1960, 1963, 1965a,b), but longer than previous estimates for Storglaciären (Nye, 1965a; Holmlund, 1988; Jóhannesson et al., 1989).

If correct, the long response time and high sensitivity values we have obtained for a relatively small glacier imply that the response time and sensitivity used in our previous global mean small glacier melt model may have been, respectively, too short and too low. In addition, recently published results (Oerlemans and Fortuin, 1992) and work that we have undertaken under another contract indicate that the small glacier melt contribution to sea level rise over the 1900-61 period may have been substantially less than Meier's (1984) estimate of 28mm. Our revised estimate is less than 10mm. We therefore anticipate that our projections for the contribution to sea level rise from the melting of small glaciers (out to 2100) will be revised downwards.

We also plan to use this model for our estimates of sea level rise from Greenland and Antarctica. The present models are based on a sensitivity expressed as a rate of change of sea level per degree warming. Such a model cannot come to equilibrium so there is no limit to the amount of ice that can melt. Because of the very long response times of Greenland and Antarctica, this has not been a problem for projections over the next century. However, for projections of the sea level rise commitment, it is clearly desirable to have models which have temperature-dependent steady-state solutions.

Radiative Forcing Changes

The only comprehensive projections of global-mean temperature and sea-level change under the latest IPCC emissions scenarios are those produced by us under the present contract (Wigley and Raper, 1992). Radiative forcing changes for these projections were calculated using our own gas cycle models (also developed as part of the present project). During 1992/3 we have further developed these models.

The reduced-form methane model is due to appear shortly in *Climate Dynamics* (Osborn and Wigley, 1993). In this model lifetime changes are expressed as a function of CH_4 concentration and emissions of NO_x , CO and NMHCs. The model parameters define the relative sensitivities of lifetime to these determining factors. The parameterized model has been fitted to results from five more complex atmospheric chemistry models and to 1990 IPCC concentration projections. The IPCC data and four of the five models are well fitted, implying that the models have similar relative sensitivities. However, overall sensitivities of lifetime to changes in atmospheric composition vary widely from model to model. The parameterized model is used to estimate the history of past methane emissions, lifetime changes and OH variations, with estimates of uncertainties. The pre-industrial lifetime is estimated to be 15-34%

lower than today. This implies that 23-55% of past concentration changes are due to lifetime changes. Pre-industrial emissions are found to be much higher (220-330 TgCH₄/yr) than the best estimate of present natural emissions (155 TgCH₄/yr). The change in emissions since pre-industrial times is estimated to lie in the range 160-260 TgCH₄/yr, compared with the current best guess for anthropogenic emissions of 360 TgCH₄/yr. These results imply either that current estimates of anthropogenic emissions are too high and/or that there have been large changes in natural emissions. 1992 IPCC emissions scenarios have been used to give projections of future concentration and lifetime changes, together with their uncertainties. For any given emissions scenario, these uncertainties are large. In terms of future radiative forcing and global-mean temperature changes over 1990-2100 they correspond to uncertainties of at least $\pm 0.2 \text{ Wm}^{-2}$ and $\pm 0.1^\circ\text{C}$, respectively.

As an extension of this analysis of future radiative forcing change uncertainties due to methane emissions and lifetime uncertainties, we have considered uncertainties in the other contributions to greenhouse-gas-related radiative forcing changes (Wigley, 1993a,b). These two papers were used as background documents for an IPCC Working Group 1 meeting on radiative forcing (Hamburg, Germany, May, 1993). The second paper, which calculates the relative radiative forcing importance of different greenhouse gases under the 1992 IPCC emissions scenarios and assesses the inherent uncertainties in these calculations, is presented in full as item B in the Appendix to this Progress Report.

Carbon Cycle Modelling

Substantial improvements have been made to the coupled climate-carbon cycle model developed earlier under this contract. The paper describing this model was accepted for publication in *Tellus* some time ago (Wigley, 1993c), but has yet to appear because of manuscript modifications required to cover these new improvements.

A very flexible inverse version of this model was developed during 1992/93. This was done specifically to consider the recommendation made in the 1992 UNCED Climate Convention that emissions protocols be introduced with a view to stabilizing future CO₂ concentrations. Just what emissions are required in order to stabilize concentrations at different levels? Preliminary results are shown here in Figures 3 and 4. The most striking results here are: the very rapid emissions reductions required to achieve stabilization during the transition from an "existing policies" emissions scenario (a 50-year transition period is assumed in all cases); and the requirement for continued emissions reductions even after stabilization is first achieved in order to maintain the status quo. This second result arises because, once stabilization is achieved, the flux of CO₂ into the ocean must continue to decrease slowly over time as oceanic pCO₂ increases. Emissions reductions are required to compensate for this reducing sink.

In addition, we have considered the climate and sea level implications of CO₂ concentration stabilization (Figure 5). The most important result here is that sea level will continue to rise at appreciable rates for many centuries into the future. This is partly because of the huge inertia of the oceanic thermal expansion component of sea level rise (and the century-to-millennium time scale of deep ocean warming), and partly due to continued ice melt from Greenland (and, to a lesser extent, from small glaciers).

Figure 3: CO₂ concentration stabilization scenarios (upper panel) and corresponding total emissions requirements (lower panel). Concentrations are assumed to follow the IS92a (IPCC) projection initially and then relax towards different stabilization levels following a quadratic in time. To simplify the scenario specification, the IS92a concentration projection was approximated by a quadratic

$$C(t) = 2.94.7 + 1.58(t + 64.7)^2/110 \quad [t = \text{years after 1990}]$$

so the implied emissions curve (the increasing $E(t)$ segment in the lower panel) does not quite follow the IS92a emissions scenario (dots in lower panel).

Figure 4: Indication of uncertainties in the emissions requirements for CO₂ concentration stabilization (500ppmv case). The upper and lower bounds (H and L) correspond to high and low estimates of the 1980s-mean deforestation flux (2.6 GtC/yr and 0.6 GtC/yr), which require relatively high or low values of the fertilization parameter to produce a balance of the contemporary carbon budget. The central case (M) is the same as shown in Figure 3 and corresponds to a 1980s-mean deforestation flux of 1.1 GtC/yr.

Figure 5: Global-mean temperature and sea level changes for the various CO₂ concentration stabilization scenarios. For the full curves, radiative forcing changes after 1990 due to other gases were set to zero. The dashed curves show results for the 500ppmv stabilization case with IS92a forcing changes for the other gases out to 2100 (and zero changes subsequently). The climate and sea level models used are those used in Wigley and Raper (1992) and by IPCC. For the melt-water contribution to sea level, minor modifications have been made from IPCC (Warrick and Oerlemans, 1990) as detailed in Wigley and Raper (1993b). Only "best guess" model parameters have been used (Wigley and Raper, 1992).

This work is currently being extended under the auspices of IPCC Working Group 1 via a major multi-institutional project to carry out stabilization calculations with a variety of different models, coordinated by Wigley and I. Enting (CSIRO, Australia).

Sulphate Aerosol Effects

We have attempted to estimate the magnitude of sulphate aerosol forcing by empirical means (cf. Schlesinger et al., 1992). Assuming a zero net effect for natural variability and $\Delta T_{2x} = 2.5^{\circ}\text{C}$, the forcing is adjusted to give a best fit between the prediction of an upwelling-diffusion model and the observed temperature data. The tuned value is 0.614 times our best estimate based on the data of Charlson et al., 1991 (as given and explained in Wigley and Raper, 1992). In absolute terms, this is equivalent to a best-fit global-mean aerosol forcing to date of -0.46W/m^2 . This is much less than some estimates (which go up to -2W/m^2 ; Charlson et al., 1992), but it is still highly significant in terms of its climate implications. There are four possible explanations for this discrepancy

- (1) The aerosol forcing is less than suggested by Charlson and collaborators.
- (2) The climate sensitivity is greater than 2.5°C .
- (3) Natural variability has had a significant low-frequency effect.
- (4) Some combination of (1) to (3).

Further analyses are in progress.

D. GCM MODEL VALIDATION

As an extension of the work already published by Hulme (1991), and in order to investigate the validity of using composite GCM results as climate change scenarios (i.e., averaging the results of a number of different GCMs), we have carried out validation studies of such composites. The results are surprising: the composite obtained by averaging seven models validates noticeably better than any of the individual models. The results are shown in Figure 6.

Figure 6: Monthly pattern correlations between the observed (CRU5180, Hulme, 1991) and modelled land only precipitation (top) and observed (Legates and Willmott, 1990) and modelled land and ocean precipitation (bottom). W shows the correlations of the weighted average of 7 GCMs and U the unweighted average with the same 7 GCMs. The thinner lines show the pattern correlations for the individual GCMs. The weighted series places more emphasis on the GCMs with higher individual pattern correlations.

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