DETECTION OF GREENHOUSE-GAS-INDUCED CLIMATIC CHANGE

Progress Report to the U.S. Department of Energy

(1 July 1994 - 31 July 1995)

Grant No. DE-FG02-86-ER60397-A014

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

21 July 1995

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appendices removed to be processed separately. na. 8/15/95

1. PROJECT SPECIFICATIONS

Title: Detection of Greenhouse-Gas-Induced Climatic Change

Area: Environmental Sciences Division, Global Change Program.

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

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

Budget: 1995/96 192K, 1996/97 200K, 1997/98 200K.

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 anthropogenic forcing, including greenhouse gas and aerosol concentration changes, the global climate system exhibits a high degree of internally-generated and externally-forced natural variability. To detect the anthropogenic 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 and aerosol concentration changes and other factors. Analyses will be guided by a variety of models, from simple energy balance climate models to coupled atmosphere ocean General Circulation Models. These analyses are oriented towards obtaining early evidence of anthropogenic 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, and models and model analyses developed especially for this project.

Deliverables: Estimates of global- and hemispheric-mean near-surface temperature, based on land and marine data will be made on a monthly basis. Gridded datasets of temperature, precipitation and pressure, produced during earlier projects will be updated and made available through CDIAC. These will be specifically useful 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 SO_2 (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 Global Change Program (Environmental Sciences Division) are to improve assessments of anthropogenic 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 greenhouse gases and aerosols be first detected?

(4) Natural variability - what are the relationships between anthropogenic 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- and aerosol-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 changing greenhouse gas and aerosol concentrations. Transient response aspects (i.e., modeling the time-dependent response to realistic time-dependent changes in 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 anthropogenic climatic change. This is the detection problem. Detection research includes better defining the anthropogenic 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 human influences on climate 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, to estimate the sensitivity of the climate system to external forcing, 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 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 aerosol-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 aerosol-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 Global Change 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 three-year duration.

Summary of products keyed to aims

During the first year, 25 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 specific research areas. A full listing is given in Section 4 to which the numbers used here refer.

A. GLOBAL CLIMATE DATA

- A1. Temperature (1, 4, 5, 6*, 7, 8, 9, 10, 16*, 17, 21, 22)
- A2. Mean-sea-level pressure (MSLP)

B. MULTIVARIATE DETECTION METHODS

(3, 11, 12, 13, 14, 19)

C. TRANSIENT RESPPONSE STUDIES

- C1. Probabilistic assessment of future global-mean temeprature and sea-level changes (18, 24, 25*)
- C2. Gas cycle/climate mode (2, 15)
- C3. Inverse climate and sea level modelling
- C4. Comparison between UD model and GCM results
- C5. Generalization of the UD model
- C6. Sulphate aerosol effects
- C7. Low-frequency climate variability

D. GCM VALIDATION

(20*, 23)

*denotes given in full in Appendices (The paper by Raper et al., 1995 on p6 is also included as Appendix D)

4. PUBLICATIONS ARISING TO DATE

A number of publications were 'in press' 'accepted' or 'submitted' in the final report of the last project. These are listed again here with publication details. Some are still 'in press'. All these should be published shortly. One paper from an international conference will not be published and another was withdrawn. After this list, we give publications arising from the first year of the new project. Most of these are not yet formally published.

Subsequently Published (Last project)

Albritton, D.A., Derwent, R.G., Isaksen, I.S.A., Lal, M. and Wuebbles, D.J., 1995: (contributing author list includes T.M.L. Wigley and 7 others): Trace gas radiative forcing indices. In *Radiative Forcing of Climate Change,* IPCC Working Group I Report, Cambridge University Press, 205-231.

Briffa, K.R., Jones, P.D. and Schweingruber, F.H., 1994: Summer temperatures across northern North America: regional reconstructions from 1760 using tree-ring densities. *Journal of Geophsyical Research* **99**, 25835-25844.

Hulme, M., Raper, S.C.B. and Wigley, T.M.L., 1994: An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). In *Integrative assessment of mitigation, impacts and adaptation to climate change* (N. Nakicenovic and F.Töth, Eds.), IIASA Collaborative Paper Series, Laxenburg, Austria, pp289-308.

Jones, P.D., 1994: Hemispheric surface air temperature variations: a reanalysis and an update to 1993. *Journal of Climate* **7**, 1794-1802.

Jones, P.D., 1994: Recent warming in global temperature series. *Geophysical Research Letters* **21**, 1149-1152.

Jones, P.D., 1995: The instrumental data record: its accuracy and use in attempts to identify the 'CO_2 Signal'. In (H. von Storch and A. Navarra, Eds.). Proceedings of Autumn Teaching School on *Analysis of Climate Variability.* Springer-Verlag,53-75.

Jones, P.D., 1995: Maximum and minimum temperature trends in Ireland, Italy, Thailand, Turkey and Bangladesh. *Atmospheric Research* **37**, 67-78.

Jones, P.D., 1995: Global surface temperature changes since the 1850s. In *Environmental Data Problems - Mathematical, Computational and Statistical Analyses* (M. Wheeler, Ed.). Springer-Verlag 223-238.

Jones, P.D. and Kelly, P.M., 1994: The effect of large explosive volcanic eruptions on surface air temperature. In *Large Volcanic Eruptions* (G. Fiocco, Ed.) Accademia Nazionale dei Lincei, 125-134.

Parker, D.E., Jones, P.D., Bevan, A. and Folland, C.K., 1994: Interdecadal changes of surface temperature since the late 19th century. *Journal of Geophysical Research* **99**, 14373-14399.

Schimel, D.S., Enting, I., Heimann, M., Wigley, T.M.L., Raynaud, D., Alves, D. and Siegenthaler, U., 1995: CO_2 and the carbon cycle. In *Radiative Forcing of Climate Change,* IPCC Working Group I Report, Cambridge University Press, 35-71.

Wigley, T.M.L., 1994: Outlook becoming hazier. *Nature* (News and Views) **369**, 709-710.

Wigley, T.M.L., 1995: Global-mean temperatures and sea level consequences of greenhouse gas concentration stabilization. *Geophysical Research Letters* **22**, 45-48.

Wigley, T.M.L., 1994: The contribution from emissions of different gases to the enhanced greenhouse effect. In *Climate Change and the Agenda for Research* (ed. T. Hanisch), Westview Press 193-222.

Wigley, T.M.L., 1994: How important are carbon cycle model uncertainties? In *Climate Change and the Agenda for Research* (Ed. T. Hanisch), Westview Press 169-191.

Still in press (Last project)

Jones, P.D., 1995: Observations from the surface - projections from traditional meteorological observations. In, *Future Climates of the World, World Survey of Climatology* (A. Henderson-Sellers, Ed.), Elsevier (in press).

Jones, P.D. and Briffa, K.R., 1995: Decadal-to-century timescale variability of regional and hemispheric scale temperature. In *The Natural Variability of the Climate System on 10-100 Year Timescales* (D.G. Martinson et al., Eds.), National Academy Press, Washington D.C.(in press).

Jones, P.D. and Briffa, K.R., 1995: Growing season temperatures over the former Soviet Union. *International Journal of Climatology* (in press).

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., 1995: 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* (D.G. Martinson et al., Eds.), National Academy Press, Washington D.C. (in press).

Raper, S.C.B., Briffa, K.R. and Wigley, T.M.L., 1995: Glacier change in Northern Sweden from A.D. 500: A temperature-dependent model of Storglaciären. *Journal of Glaciology* (tentatively accepted).

Raper, S.C.B., Wigley, T.M.L. and Warrick, R.A., 1995: Global sea level rise: past and future. In *Proceedings of the SCOPE Workshop on Rising Sea Level and Subsiding Coastal Areas* (ed. J.D. Milliman), Kluwer (included as APPENDIX D).

Santer, B.D., Mikolajewicz, U., Brüggemann, W., Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E. and Wigley, T.M.L., 1995: Estimates of detection period and detection time for ocean greenhouse warming signals. *Journal of Geophysical Research* (in press).

Wigley, T.M.L. and Raper, S.C.B., 1995: 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* (D.G. Martinson et al., Eds.), National Academy Press, Washington D.C. (in press).

Will not be published (Withdrawn and the conference proceedings not being published)

Wigley, T.M.L. and Osborn, T.J. Indirect global warming potentials for methane due to OH feedback.

Wigley, T.M.L., Jones, P.D. and Raper, S.C.B. Detecting and quantifying the enhanced greenhouse effect.

First year of this project (July 1994-June 1995)

Published

1. Bradley, R.S. and Jones, P.D., 1995: Recent developments in studies of climate since A.D. 1500. In, *Climate Since A.D. 1500 2nd Edition* (R.S. Bradley and P.D. Jones, Eds.), Routledge, London, 666-679.

2. Enting, I.G., Wigley, T.M.L. and Heimann, M., 1994: *Future emissions and concentrations of carbon dioxide: key ocean/atmosphere/land analyses.* CSIRO Division of Atmospheric Research Technical Paper No. 31, 118pp.

3. Jones, P.D., 1994: Towards detection of the enhanced greenhouse gas effect. In, *Climate Variations in Europe* (R. Heino, Ed.), Silmu, Helsinki, Finland, 69-70.

4. Jones, P.D., 1994: Decadal-to-century timescale variability of regional and hemispheric scale temperature. In, *Climatic Variations in Europe* (R. Heino, Ed.), Silmu, Helsinki, Finland, 136-140.

5. Jones, P.D., 1994: Decadal-to-century timescale variability of regional and hemispheric scale temperature. In, *Global Climate Change: Science, Policy and Mitigation Strategies* (C.V. Mathai and G. Stensland, Eds.), Air and Waste Management Association, Pittsburgh, 98-101.

6. Jones, P.D., 1995: Recent variations in mean temperature and the diurnal temperature range in the Antarctic. *Geophysical Research Letters* **22**, 1345-1348.

7. Jones, P.D., Briffa, K.R. and Schweingruber, F.H., 1995: Tree-ring evidence of the widespread effects of explosive volcanic eruptions. *Geophysical Research Letters* **22**, 1333-1336.

8. Jones, P.D., Wigley, T.M.L. and Gregory, J.M., 1994: England and Wales area-average precipitation amount. In, *Trends '93: A compendium of Data of Global Change* (T.A. Boden, D.P. Kaiser, R.J. Sepanski and F.W. Stoss, Eds.), ORNL/CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 975-983.

9. Jones, P.D., Wigley, T.M.L. and Briffa, K.R., 1994: Global and hemispheric temeprature anomalies - land and marine instrumental records. In *Trends '93*: A compendium of Data of Global Change (T.A. Boden, D.P. Kaiser, R.J. Sepanski and F.W. Stoss), ORNL-CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 603-608.

10. Salinger, M.J., Basher, R.E., Fitzharris, B.B., Hay, J.E., Jones, P.D., MacVeigh, J.P. and Schmidely-Leleu, I., 1995: Climate trends in the southwest Pacific. *International Journal of Climatology* **15**, 285-302.

11. Santer, B.D., Mikolajewicz, U., Brüggemann, W., Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E. and Wigley, T.M.L., 1994: Ocean variability and its influence on the detectability of greenhouse warming signals. *PCMDI Report No. 14*, Lawrence Livermore National Laboratory, Livermore, California, 73pp.

12. Santer, B.D., Taylor, K.E., Wigley, T.M.L., Penner, J.E., Jones, P.D. and Cubasch, U., 1995: Towards the detection and attribution of an anthropogenic effect on climate. *PCMDI Report No. 21*, Lawrence Livermore National Laboratory, Livermore, California, 78pp.

13. Santer, B.D., Taylor, K.E., Wigley, T.M.L., Penner, J.E. Jones, P.D. and Cubash, U., 1995: Are Sulphate Aerosols masking a Greenhouse Warming Signal? *Proceedings of the Nineteenth Climate Diagnostics Workshop* (D.R. Rodenhuis, Ed.), U.S. Dept. of Commerce, NOAA, 49-52.

14. Santer, B.D., Jones, P.D., Taylor, K.E., Wigley, T.M.L., Penner, J.E. and Cubasch, U., 1995: Detecting and attributing an anthropogenic influence on climate. In *Proceedings of the Sixth International Meeting on Statistical Climatology* (I.G. O'Muircheartaigh, Ed.), Galway, Ireland, 1-4.

In Press

15. Hulme, M., Raper, S.C.B., Wigley, T.M.L., 1995: An Integrated Framework to Address Climate Change (ESCAPE) and Further Developments of the Global and Regional Climate Modules (MAGICC). *Energy Policy* special issue (in press).

16. Jones, P.D., 1995: Land surface temperatures - is the network good enough? *Climatic Change* (in *press*).

17. Jones, P.D. and Kelly, P.M., 1995: The effect of tropical explosive volcanic eruptions on surface air temperature. In (G. Fiocco Ed.) *The effects of the Mt Pinatubo erutpion on the atmosphere and climate*, Springer Verlag (in press).

18. Palutikof, J.P. and Wigley, T.M.L., 1995: Developing climate change scenarios for the Mediterranean region. In *Climate Change and the Mediterranean,* Volume **2**, (L. Jeftic, J.C. Pernetta and S. Keckes, Eds.), Edward Arnold, London, U.K. (in press).

19. Santer, B.D., Taylor, K.E., Wigley, T.M.L., Penner, J.E., Jones, P.D. and Cubash, U., 1995: Towards the detection and attribution of an anthropogenic effect on climate. *Climate Dynamics* (in press).

Submitted

20. Jones, P.D., Hulme, M., Briffa, K.R., Jones, C.G., Mitchell, J.F.B. and Murphy, J.M., 1995: Summer moisture availability over Europe in the Hadley Centre General Circulation Model based on the Palmer Drought Severity Index. *International Journal of Climatology* (submitted).

21. Kelly, P.M., Pengqun, J. and Jones, P.D., 1995: The spatial temperature response to large volcanic eruptions. *International Journal of Climatology* (submitted).

22. Parker, D.E., Wilson, H., Jones, P.D., Christy, J.R. and Folland, C.K., 1995: The impact of Mt Pinatubo on climate. *International Journal of Climatology* (submitted).

23. Srinivasen, G., Hulme, M., Jones, C.G., Jones, P.D. and Osborn, T., 1995: An evaluation of the spatial and interannual variability of tropical precipitation as simulated by GCMs. In, *Proceedings of the First International Atmospheric Model Intercomparison Project (AMIP) Scientific Conference* (in press).

24. Wigley, T.M.L., Hall, A., Raper, S.C.B. and Warrick, R.A., 1995: Past sea level rise from glaciers based on a regional degree-day model (submitted to *Journal of Geophysical Research*).

25. Wigley, T.M.L. and Raper, S.C.B., 1995: An heuristic model for sea level rise due to the melting of small glaciers *Geophysical Research Letters* (in press).

5. PROGRESS

A. Global Climate Data

A1 Temperature

Gridded Analyses

Two sets of gridded temperature anomalies from land stations are being produced at present. The first updates the original analysis (Jones *et al.*, 1986a,b) based on 5° latitude x 10° longitude grid point values, with a reference period of 1951-70. This dataset has been combined with sea surface temperature anomalies over marine regions into 5° x 5° boxes with the reference period adjusted to 1950-79 (Jones and Briffa, 1992). The second and more recent analysis (Jones, 1994) averages the land station temperature anomalies, with respect to a new reference period of 1961-90, directly into 5° boxes.

The first dataset has been used by the Intergovernmental Panel on Climatic Change (IPCC, Folland *et al.*, 1990, 1992). The second analysis is widely used in the 1995 full assessment which is currently being reviewed and will be published early in 1996. Both PIs are actively involved in this assessment in the areas of instrumental data, modelling, detection and radiative forcing.

Updates of first dataset and the second recent analysis have been made available to the Carbon Dioxide Information Analysis Center (CDIAC) in Oak Ridge, Tennessee. Over 100 requests have been made for the dataset and updates. Many more use the same data published in TRENDS 93 (Boden *et al.*, 1994). We have also released both data sets to many scientists in different countries.

Recent Trends

The period since the beginning of 1994 clearly shows much warmer temperatures than the preceding two years (1992, 1993). Figure 1 shows average hemispheric temperatures for land only and land and marine regions since 1980. The cooling has been due largely to the explosive volcanic eruption of Mt Pinatubo in the Philippines in June 1991. This has probably been the largest such tropical eruption since Krakatau in 1883. We have analysed the temperature patterns extensively during the last few years (see for example Jones and Kelly, 1995, and Parker *et al.*, 1995). The cooling pattern during 1992 and 1993 resembles the cooling patterns experienced after other explosive tropical eruptions since Krakatau (see Figure 2 and Kelly et al., 1995), strongly supporting the hypothesis that it was mainly volcanic in origin.

Figure 1 clearly shows the recent rise in temperature, particularly over Northern Hemisphere land areas. The rise has continued into the first five months of 1995, where January to May average temperatures have been the warmest yet recorded. February 1995 was the warmest month ever recorded over land (0.1°C warmer than the previous warmest in March 1990). The month was not quite so anomalous when combined with marine data. Here March 1990 was warmer.

The relative warmth of the period since 1987 owes much to the recurrent El Niño/Southern Oscillation (ENSO) conditions which have prevailed in all bar one year since

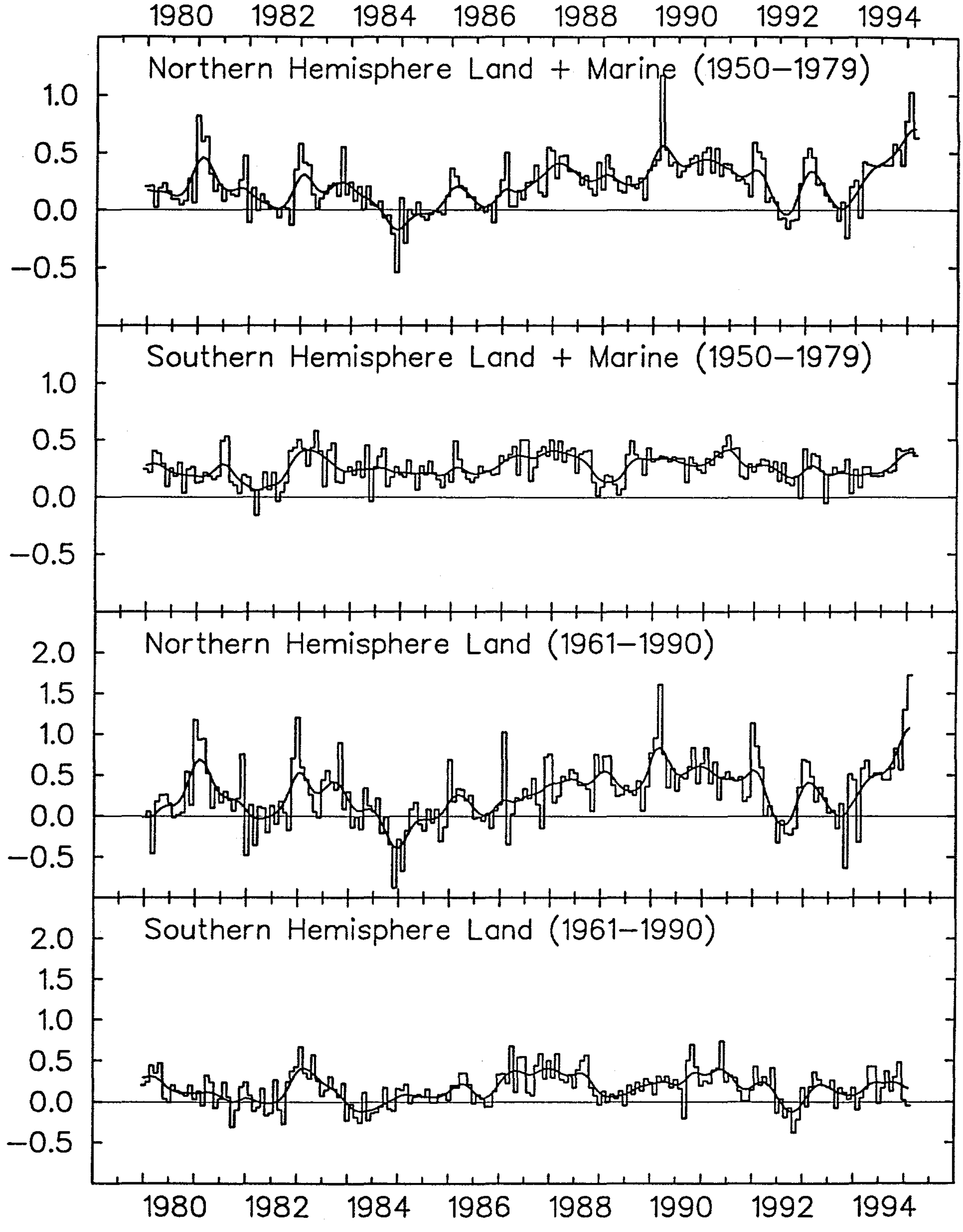

Figure 1: Monthly estimates of hemispheric-mean temperature over land only areas and land and marine regions since 1980. The land and marine data are expressed as anomalies from the 1950-79 reference period and the land only data from 1961-90.

a)

b)

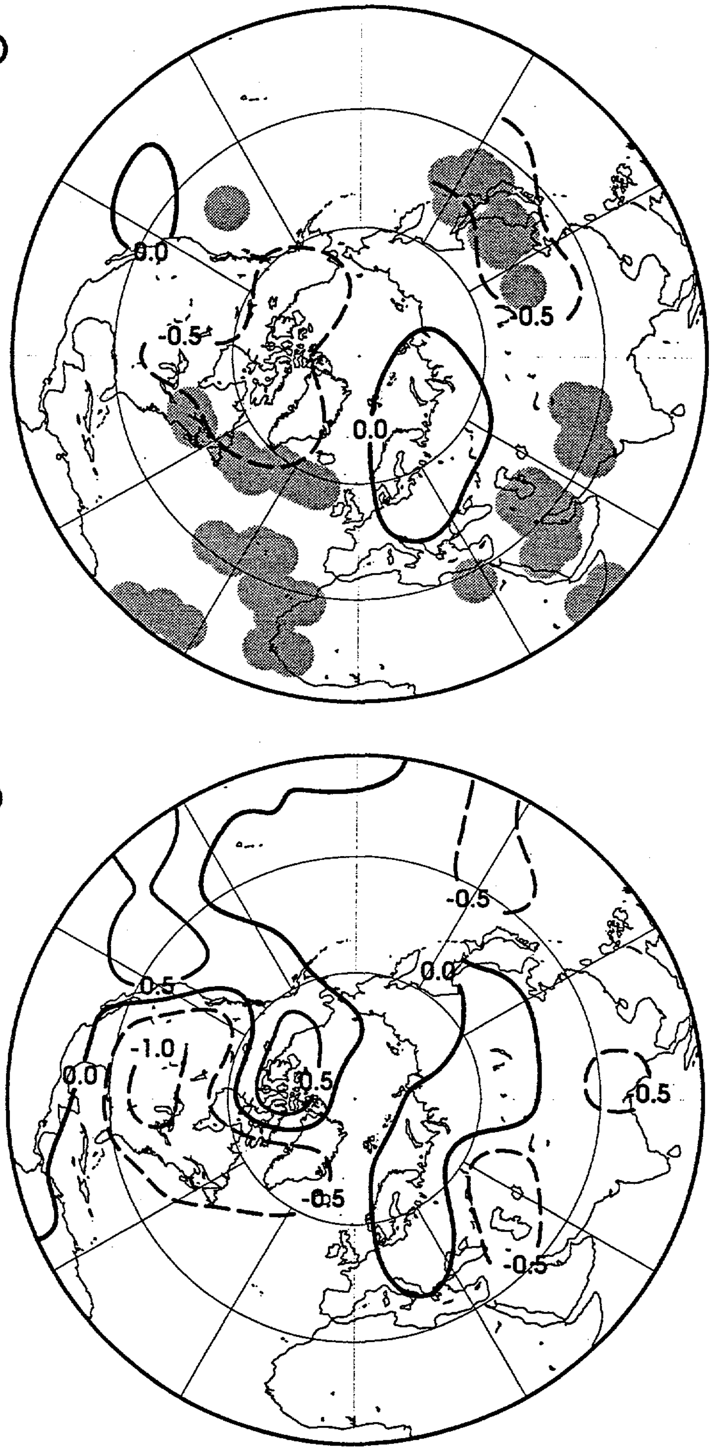

Figure 2: a) The composite spatial pattern of surface air temperature departures (degrees Celsius) in months 13-24 following the historic set of eruptions (Krakatau, 8.1883; Pelée and Soufrière combined with Santa Maria, as 5.1902; Agung, 3.1963; El Chichón, 4.1982). Departures in shaded areas are significant at the 5% level. b) The spatial pattern of surface air temperature departures (degrees Celsius) in months 13-24 following the Pinatub eruption (6.1991). In both cases, the reference period is the five years up to and including the month of the eruption (month zero). Contouring is omitted in data-sparse areas.

that time. Jones (1989) gave the first extraction of the ENSO effect from global-scale temperatures, showing that about 25% of the high frequency variance in hemispheric and global temperatures can be related to the phenomenon. Figure 3 shows the raw annual hemispheric and global temperature series with two sets of decadal smoothing - one for the raw values and one for the ENSO-removed temperatures. The difference between the two series during some of the 1980s and 1990s is the largest since the beginning of the ENSO-removed series in 1867. Temperatures in both hemispheres have been about 0.05° higher since the early 1980s because of the greater number of El Niño events.

Our attempts to extract the ENSO signal from the temperature record spatially as well as in time have begun using Principal Components Analysis. We have identified two patterns, the first relates to warming/cooling in the vicinity of the eastern/western parts of the tropical Pacific Ocean while the second relates to the near global-scale response several months later. Current work is looking at the stability of these patterns in time, particularly when data quality and quantity reduce before 1945 in the tropical Pacific.

Other temperature analyses

Countries have begun to issue mean monthly maximum and minimum temperatures over the World Meteorological Organization's (WMO) Global Telecommunication System (GTS). So far only two thirds of countries have been issuing the data (Jones *et al.*, 1995a - see Appendix A). We are hopeful of obtaining more national datasets of these temperatures, which can now be updated over the GTS. Additional data have been produced for New Zealand and the southwest Pacific Islands. These regions show little difference in temperature change between maximum and minimum temperatures and therefore no change in the diurnal temperature range. This is in marked contrast to most Northern Hemisphere land regions where minimum temperatures have warmed at three times the rate of maximums (Karl *et al.*, 1993). Jones has been involved in some of the analyses for the southwest Pacific regions and the results have recently been published (Salinger *et al.*, 1995).

The only other major region for which maximum and minimum data have become available is the Antarctic. We have received data from most countries operating stations on the continent. Data for both continental stations and mid-to-high latitude Southern Ocean islands have been received, digitised and checked. No change in the diurnal temperature trends are evident in the region since records began in 1957 (Jones, 1995b) (this paper is attached to this report as Appendix B). This is to be expected here, as in the southwest Pacific, since both regions are far from the pollution sources that may be increasing cloudiness in the land areas of the mid latitudes of the Northern Hemisphere.

Mean temperatures in the Antarctic have seen two of the coldest years recorded since records began in 1957, in 1993 and 1994. Only 1960 and 1962 were colder than 1993 in continental averages. Despite this, a linear trend fit to the annual temperatures over 1957 to 1994 shows a significant rise of 0.57°C. Visual inspection of the time series shows that most of this rise occurred before 1970 and there has been no change since then (Jones, 1995b). This paper briefly addresses the relationship between sea-ice extent and temperature; see also Raper *et al.* (1984).

Finally, in this section we are actively requesting 1961-90 climate 'normals' for all member countries of WMO. Data is still arriving and we should be in a position to produce analyses similar to those for Europe (Hulme *et al.*,1995) for all continents except Africa. Our

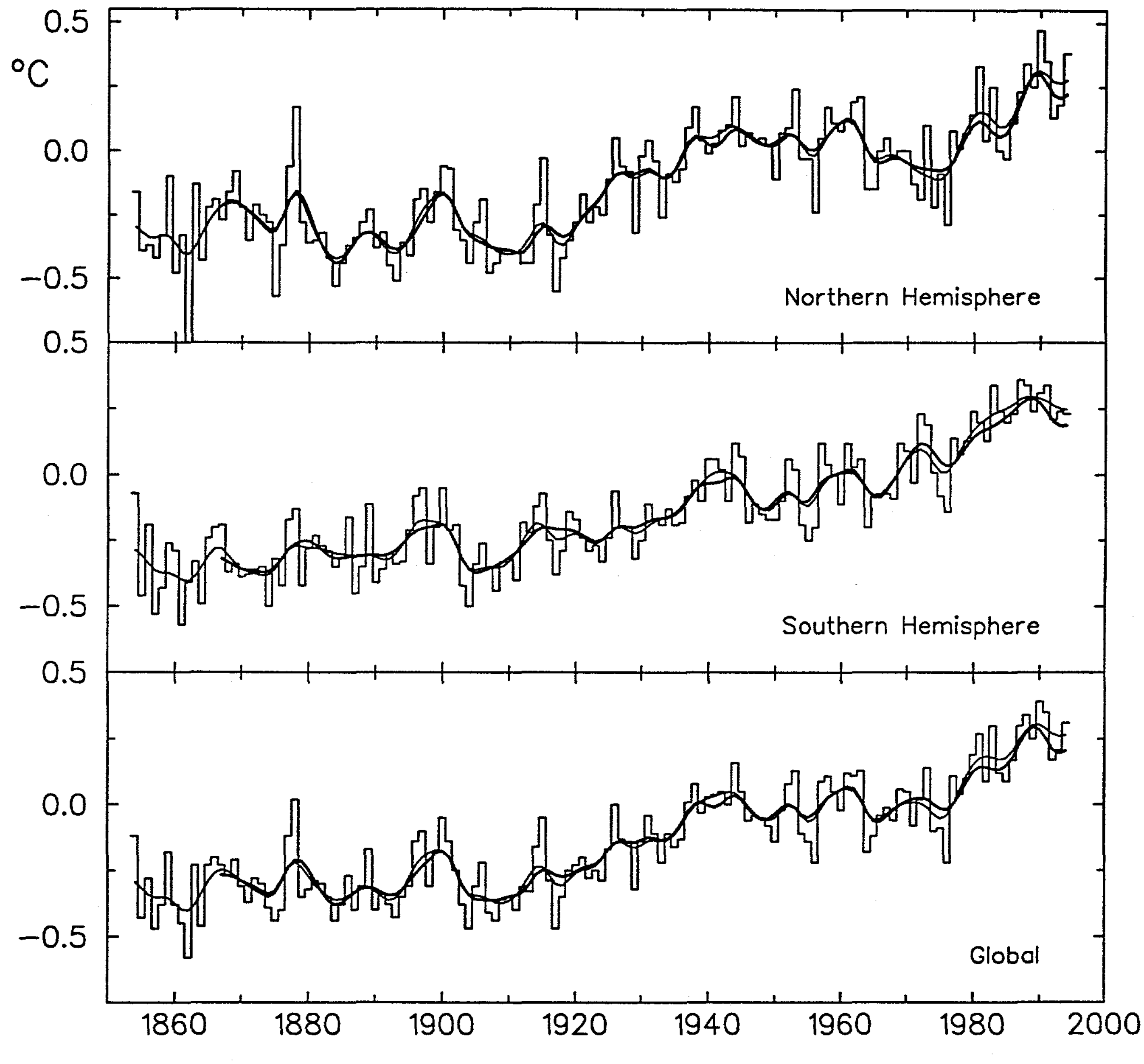

Figure 3: Average annual global and hemispheric temperatures since 1854. The thin smooth line represents a decadal filter fit through the data. The thick line is the same filter fit through the ENSO removed global and hemispehric average temperature series.

current status is given in Jones (1995a), which is reproduced here in Appendix A. Data are still being received from Africa but here there are still many countries with serious raw data gaps. A European study (Hulme *et al.*, 1995) provides baseline climatologies for 'Greater Europe' from eastern Greenland to the Ural mountains and from northern Norway to North Africa. Baseline (1961-90) fields have been interpolated to a 0.5° grid box resolution for maximum temperature, minimum temperature, precipitation, vapour pressure, sunshine hours, windspeed, rain days and the number of ground frosts per month. Such analyses will be extended to the other continents when the normals data are more complete.

A2 Mean sea-level pressure (MSLP)

We are collaborating informally in this work with the Division of Atmospheric Research, CSIRO, Australia and the Hadley Centre of the UK Meteorological Office. This involves making MSLP datasets produced in earlier work funded by the Dept. of Energy available to the two groups and giving advice about sources of early pressure data.

Interest is still high in the Southern Oscillation Index (SOI). We have been involved in extending the SOI series back to the late 1860s by locating early data for Tahiti (Ropelewski and Jones, 1987) and Darwin (Allan *et al.*, 1991). We have located, with help from a Dutch climatologist (Gunther Können) at KNMI (Dutch Met. Service), MSLP data for the 1840s and 1850s for Djakarta, Indonesia. It is hoped to find even earlier records through more searches in Dutch archives. Already we have found rainday counts for Djakarta back to the 1820s. Even these data appear useful in characterising early ENSO events.

As an additional aspect of the work on the Antarctic maximum and minimum temperatures, MSLP data for all stations on the continent have been updated. The exception to this are the stations operated by Chile. We hope to get these data from the country in the next few months. In the last few days we have received this data for Argentina, augmenting the work reported in Jones (1995b).

B. Multivariate Detection Methods

The major piece of work in this area is our application of the pattern correlation methods we have developed in earlier work (Santer *et al.*, 1993), to the CO_2-alone, aerosol-alone and the combined CO_2-aerosol response patterns from the Taylor and Penner (1994) GCM experiments. The work will be published shortly in the peer review literature (Santer *et al.*, 1995a), although a report is already available (Santer *et al.*, 1995b).

We believe that the results, which indicate that there is a statistically significant trend in the detection statistic, R(t), for the combined CO_2-aerosol forcing during JJA and SON is a potentially very important result (see Figure 4). No significant trend is evident for the CO_2-alone case. This paper will come in for much scrutiny by the scientific community as it is probably the strongest evidence produced to date for detection of an anthropogenic effect on climate. This work has a prominent place in the next full IPCC review. There are a number of reasons for caution in interpretation of the results, however. These will be investigated in the remaining years of the proposal. We briefly discuss the more important factors here.

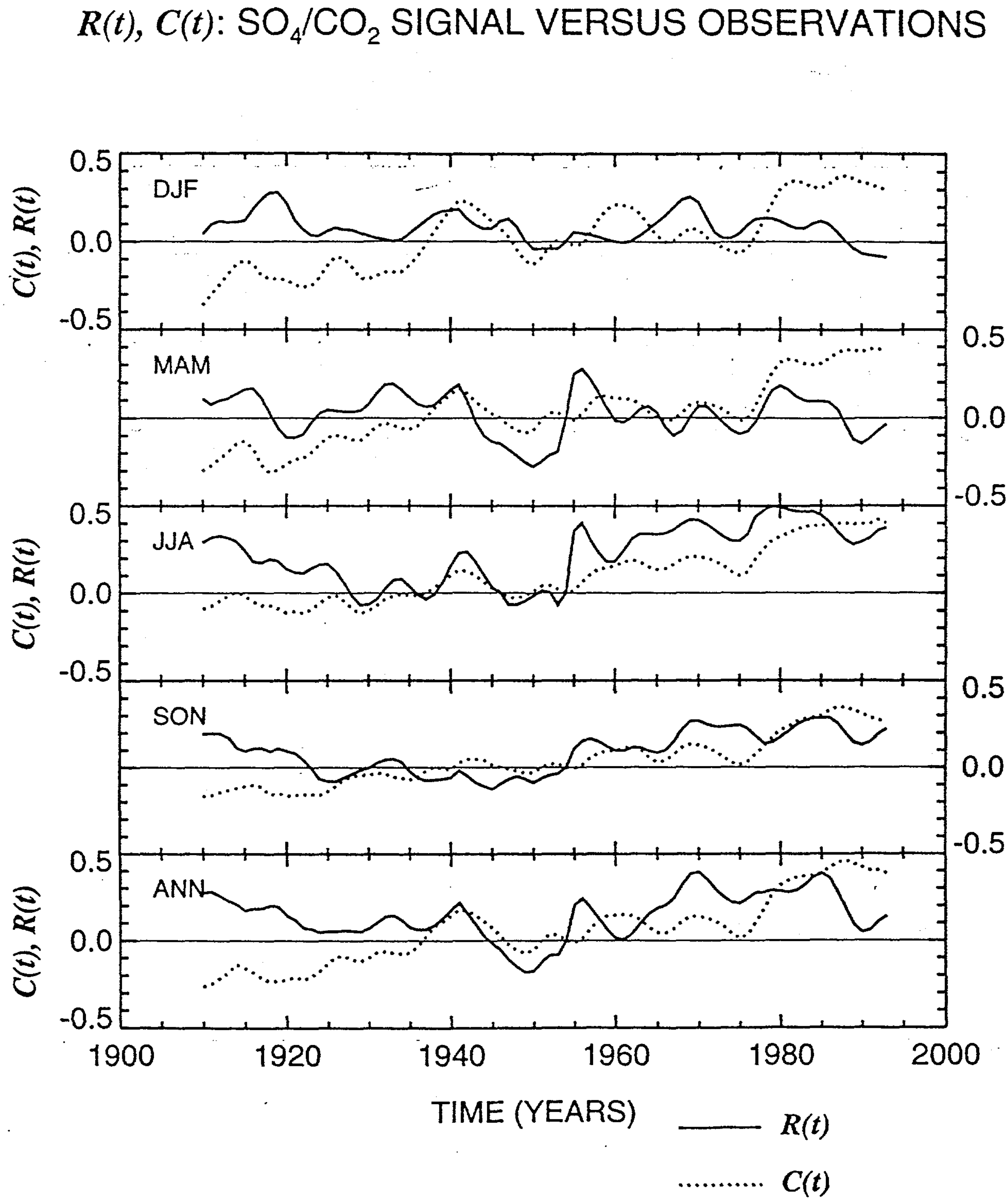

Figure 4: Pattern correlation statistic values (R(t)) between near-surface temperature data and the seasonal response of the Taylor and Penner (1994) model to combined CO_2-areosol forcing.

The first area of caution is that the model response patterns come from only one set of equilibrium model (Taylor and Penner, 1994) results and this model may have unusual characteristics. Similar experiments with combined CO_2-aerosol forcing have already been undertaken at MPI and at the Hadley Centre. We have applied the technique in a preliminary analysis of the Hadley Centre results (pers. comm. from J.F.B. Mitchell see also Mitchell *et al.* 1995a, b) and the same trend in R(t) has been found in JJA and SON. However, the result is only statistically significant in SON.

Another cause for concern relates to the use of millennial-long coupled O/AGCM control integrations to assess the statistical significance of the R(t) trends. We have used two long integrations from the MPI (Cubasch *et al.*, 1992, 1994) and GFDL (Manabe and Stouffer 1995) models and will use other integrations as they become available. How well these GCMs simulate natural variability on the decadal-to-century timescale is important - if they underestimate natural low frequency variability, then we may be overestimating the significance of the R(t) trends. While this is a vital question for detection, it is also an important area in model validation (discussed in more detail in section D).

Another issue which could affect the significance of the results is uncertainties in the aerosol forcing. So far, we have only considered the pattern of *direct* aerosol forcing. There are indications that the pattern of *indirect* forcing may be similar, but this has yet to be tested. A more important issue is the magnitude of the total aerosol forcing, which we plan to investigate using methods outlined in the proposal. Time variations in the pattern of emissions (and, hence, the temperature response) need also to be considered, once suitable coupled O/AGCM data become available.

The Taylor and Penner (1994) results have allowed us to investigate the linearity of the climate system to external forcing. Is, for example, the response pattern to CO_2-aerosol response similar to the sum of the individual CO_2-alone and aerosol-alone responses? If linear approximations are possible it might help resolve detection uncertainties arising from uncertainties in the magnitude of the aerosol forcing. A related issue is the similarity of the forcing and response patterns with aerosol forcing. We have carried out analyses showing that these are poorly related in general, but well correlated for NH mid-latitudes. The latter explains why Karl *et al.* (1995) obtained good results based on correlating temperatures directly with emissions data.

Both these issues are addressed in Santer *et al.* (1995a, b). The linearity assumption with regard to the patterns appears reasonable, with the correlation between the CO_2-aerosol pattern and the sum of the CO_2- and aerosol-alone patterns being 0.86 for the Taylor and Penner (1994) integrations. Again such work needs to be assessed with other GCMs. Forcing and response patterns for aerosol only and CO_2-aerosol forcing are in little agreement when large-scale spatial patterns are compared but they are similar if the patterns are averaged zonally along latitude bands as in the work by Karl *et al.* (1995).

C. Transient Response Studies

C1. Probabilistic assessment of future global-mean temperature and sea-level changes

With a view to carrying out a new probabilistic assessment, work has progressed in updating the gas cycle/climate model as described in C2.

Improved Ice Melt Model

The controversial aspects of our ice melt model reported on in FY 93/94 have now been resolved. Our model showed a large sensitivity of the equilibrium volume (V_∞) to temperature change and a long response time (τ). This was primarily due to our assumption of spatially and temporally uniform accumulation. We have now revised the ice melt model to include the altitudinal gradient in accumulation (Raper et al. 1995a). This revision, together with parameter values appropriate for very steep sided glaciers, brings our results in line with current knowledge.

We are reapplying this model to Storglaciären in northern Sweden. Because we now include accumulation we can exactly reproduce the declining glacier volume over 1946-1992. The results show that this decline is primarily due to low accumulation over 1946-1989, although higher ablation over 1946-1960 made some contribution. This illustrates the importance of considering both temperature and precipitation for glacier volume. The revised model has the advantage that both variables may be used in future projections.

As an intermediate step, we have applied a simplified temperature-dependant version of the above model to estimate the glacier and small ice sheet (GSIC) contribution to sea level rise (Wigley and Raper, 1995 see Appendix C). The starting point for this model is an ice volume (V) equation for a single glacier written in simple first-order decay form

$$dV/dt = (V_\infty - V)/\tau$$

where τ is a characteristic response time. For climate forcing, we specify V_∞ as a function of temperature. We use the simpliest dependence which is to assume that V_∞ decreases linearly with increasing temperature $\Delta T = T - T_0$, giving

$$V_\infty = V_{\infty,0}(1 - \Delta T/\Delta T^*)$$

where ΔT^* is the temperature at which V_∞ is zero. Although still driven by global mean temperature changes, for the first time, we have taken into account the regional variations in the altitudinal range of the world's glaciers and hence the fact that some glaciers will disappear before others with a global warming. We do this by using a range of values for ΔT^*_i and τ_i. The resulting set of model equations give a non-linear response of glacier melt to temperature change because, at some time after ΔT exceeds ΔT^*_0 ice regions with smaller ΔT^* and τ begin to disappear, changing the average values of these parameters and so altering the characteristics of the global response.

Calibration of this model still requires information about the past contribution of GSICs to sea level rise, information that is highly uncertain. We have partly resolved the large discrepancies between the results of Meier(1984) and Oerlemans and Fortuin (1992) in an analysis based on degree-day modelling techniques (Wigley et al., 1995), but important uncertainties remain. We now use values considerably less than those (of Meier, 1984) used in our earlier work (Wigley and Raper, 1993).

Wigley and Raper (1995) gives a detailed comparison of the methodology and results of the old and the new ice melt models. We conclude that the new model has a much sounder theoretical basis. Even though the new model is calibrated using much lower past ice melt estimates, future estimates with the new model tend to be higher than with the old model. This is largely because, in the old model, the driving force for melting (unrealistically) decreased with increasing warming. In the new model the driving force for melting increases steadily as the globe warms. For an idealized scenario of past and future temperature changes, that has a 1990-2100 warming of 2.2^0C, GSIC-induced sea level rise over 1880-1990 is estimated to be in the range 1.6-5.8 cm, and over 1990-2100 it ranges between 12 and 19 cm.

C2. Gas cycle/climate model

Although our carbon cycle model (Wigley, 1993) has not been changed, the 1980s-mean net deforestation values required for its initialization have been revised downwards (from a central value of 1.6 GtC/yr used previously to 1.1 GtC/yr - see Schimel *et al.*, 1995). This leads to slightly higher CO_2 concentration projections for any given emissions scenario, since the terrestrial biospheric sink term is reduced. This change has implications also for CO_2 concentration stabilization, requiring new pathways to stabilization to be devised (updating those given in Enting *et al.*, 1994). Further work on the stabilization issue will be carried out as part of the present project.

We have updated our coupled gas cycle/climate model incorporating the above gas cycle model revisions, the revisions to the UD-model described in C5, and the improved temperature-dependant ice melt model (see C1). Using slightly modified versions of the IS92 emissions scenarios we have used the updated model to revise our temperature and sea level projections (see Raper et al. 1995b; see Appendix D). In this paper we also show temperature and sea level projections for CO_2 concentration stabilization, revised from those originally published in Wigley (1995).

C3. Inverse climate and sea level modelling

We have deferred further work on inverse modelling pending the inclusion of recent and planned improvements in the models.

C4. Comparison between UD model and O/AGCM results

We have completed some UD model O/AGCM comparisons.

The rational behind these comparisons is that while O/AGCMs are physically more realistic, UD models are still required for three reasons: to provide a uniform and comprehensive assessment of uncertainties; to facilitate comparisons between O/AGCMs; and to give projections for a wide range of future forcing possibilities.

We have developed a methodology for UD model-O/AGCM comparisons. There are a number of factors which need to be considered.

(1) It is crucial that the same forcing is used in both models.

(2) It is important for the UD model to be sufficiently complex so that it can simulate the main features of O/AGCM responses. Recent O/AGCM results have shown that this requires; spatial disaggregation to distinguish, at least, land and ocean areas in each hemisphere; and the ability to include variations in the strength of the thermohaline circulation (parameterized by the upwelling rate in UD models). Our UD model was designed at the outset to have both of these features (Wigley and Raper, 1987, see also C5.).

(3) If the O/AGCM experiments show marked drift in the control run, this must be accounted for.

(4) Agreement of temperature changes for a single forcing case does not necessarily ensure that the UD model will give valid results for other forcing cases. Validation of the physical realism of the UD model is obtained if one also compares oceanic thermal expansion results. Correctly estimating the oceanic lag effect requires that heat transport into the ocean be realistically simulated, and thermal expansion provides a key integrated heat transport variable for validation. Further validation may be carried out by comparing results for a range of forcing cases (using the same set of UD model parameters, of course).

First, we describe our comparison between the UD model and MPI ECHAM-1/LSG results (Cubasch et al., 1992, 1995). Since this O/AGCM's climate sensitivity is not known precisely we consider this to be a free parameter which we tune in the UD model to optimize the fit for one forcing case. The optimization is carried out for the average temperatures over the last (10th) decade of the simulation thus maximizing the signal-to-noise ratio, both the land and ocean sensitivities are tuned separately.

We account for the climate drift in the control run in two ways. The first method is to use the Definition 2 O/AGCM results which have the control run drift subtracted, thus assuming that it is a common factor in both perturbation and control cases. We tune the UD model to the Def2 results for the 2xCO_2 perturbation experiment and compare the results for the other forcings. In the second method we artificially impose the equivalent of a control-run drift in the UD model. We do this by starting the UD model runs in a (warm) disequilibrium state with the model's hemispheric-mean vertical temperature profiles equal to those for decade-1 minus decade-10 in the O/AGCM control run. All we seek to do here is to simulate the temperature-change characteristics of the O/AGCM experiment, not the physical reasons for drift. We do not retune the model for this second comparison. We can now compare the case 2 UD model results with the Def1 O/AGCM results directly (Definition 1 results are the perturbation run results relative to their inital value). It is not clear *a priori* whether agreement should be better for the first method, case 1 UD model with Def2 O/AGCM results or for the second method, case2 with Def1 comparisons.

We show the calibration (i.e., tuning) results in Figure 5a for the land and ocean areas. In Figure 5b-e we show the global mean results for both methods for the four available forcing scenarios (since there is no suitable control run for the EIN experiment we use method two, assuming that the initial disequilibium is the same as before). The results are summarised in Table 1.

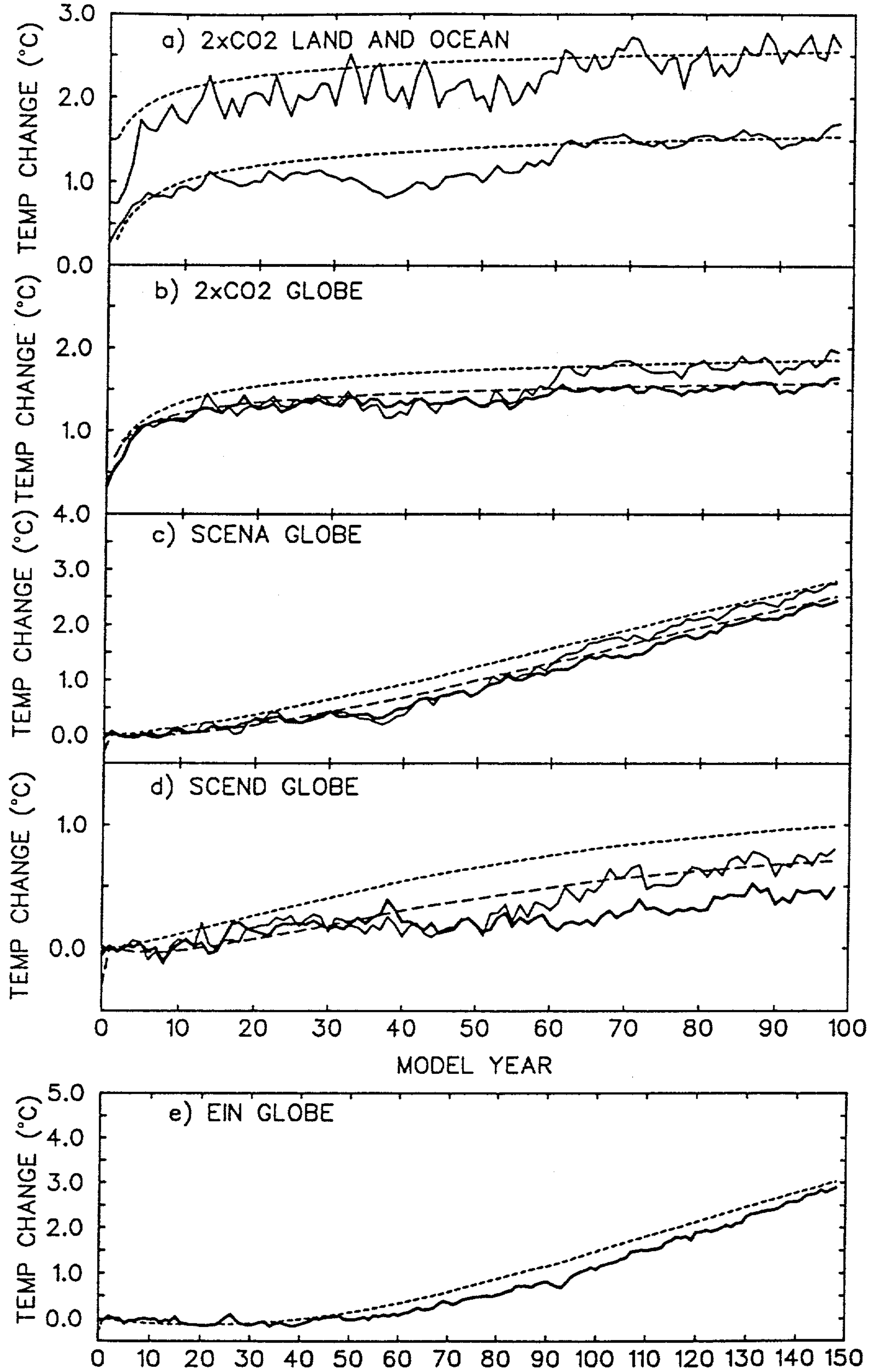

Figure 5: a) Time series of land (top two lines) and ocean (bottom two lines) mean surface air temperature change for $2xCO_2$ forcing. The ECHAM-1/LSG results are for Def2 (solid lines) and the UD model results are for Case1 (dashed lines). b) Time series of global mean temperature change, for 2xCO2 forcing, for the ECHAM-1/LSG Def2 results (thin solid) and the UD model Case1 results (dash). Also shown are the ECHAM-1/LSG Def1 results (thick solid) and the UD model Case2 results (long dash).

c) As in b) but for scenario A forcing

d) As in b) but for scenario D forcing

e) As in b) but for the EIN experiment (Def1 and Case2 only).

In each case, the UD model results simulate the O/AGCM results with fair consistency, and in each case, the case2/Defl comparisons are superior over the first half of the simulation. This implies that the drift in O/AGCM perturbation experiments is more similar to the simulated UD model drift than to the O/AGCM control run drift, the latter being concentrated around year 60.

For all the UD model case1 and case2 results the thermal expansion is substantially overestimated. The lower climate sensitivity over the ocean compared to the land has tended to decrease the thermal expansion but this effect is more than compensated by the inclusion of time varying upwelling. However, it is necessary to simulate the changes in the upwelling. We have identified one cause of the large expansion results. In the UD model we have assumed that the surface air temperture change above the ocean is the same as the ocean mixed layer temperature change. In the O/AGCM, the global-mean warming of the former is noticably greater than that of the first ocean layer (1.2 times). As a consequence the UD model results show greater heat penetration into the top layers of the ocean.

Second we consider some results from, a UD model, GFDL O/AGCM comparison. In this case no tuning is required because the O/AGCM climate sensitivities are known (Manabe and Stouffer, 1993). Also, since there is no drift in the control run we may compare the Defl results directly with the UD model results for the same forcing. The UD model upwelling rate is linearly related to the ocean mixed layer temperature. Global mean surface temperature change and thermal expansion results are compared in Figure 6. For the $2xCO_2$ forcing experiments the UD model accurately reproduces the O/AGCM results. For the $4xCO_2$ forcing experiments, though the agreement between the two models is good during the transient forcing buildup, the UD model gives a noticably slower approach to equilibrium. Consistant with the slower warming in this case, the UD model gives greater thermal expansion (i.e. implying greater heat flux into the ocean).

C5. Generalization of the UD model

In order to facilitate comparisons between our UD model and coupled O/AGCM results (see Section C4.), we have had to implement two features originally built in to the model: time variable upwelling rate and land/ocean differential climate sensitivity. These aspects are important features of O/AGCMs (see, e.g., Murphy, 1995; Manabe and Stouffer, 1993). They must be considered in any comparison, and in any application of the UD model to the production of future climate change projections. The variable upwelling rate option has been used previously (Wigley and Raper, 1987; Jones *et al.*, 1987). However, the differential sensitivity code has not previously been used.

The way we originally coded this aspect was in terms of the feedback parameters in the energy balance equations - i.e., each box in the model has a $\lambda_i \Delta T$ term representing the feedback, with the various λ_i specifiable independently. Independent specification of λ_i is, however, very inconvenient. In the present situation, λ_L (land) and λ_O (ocean) need to be input to the model, but the information usually available from GCMs is the *global* sensitivity (ΔT_{2x}) and the corresponding equilibrium warming differential between land and ocean ($R = \Delta T_{eq,L}/\Delta T_{eq,O}$). We have therefore derived analytical relationships between the equivalent pairs (λ_L, λ_O) and (ΔT_{2x},R), which allows the latter to be input directly. The method used is as follows:

Table 1: Hamburg model results compared with UD-model results for last decade of experiments (tuned to 2 x CO_2). For other UD-model parameter values, we use our central estimates.

	1 $\Delta T_{2xglobe}$	2 R	3 λ_{land}	4 λ_{ocean}	5 ΔT_{globe}	6 ΔT_{land}	7 ΔT_{ocean}	8 EX	9 ΔT_{NH}	10 ΔT_{SH}
Hamburg 2xCO_2 Def1					1.56	2.05	1.37	15.7	1.58	1.54
Hamburg 2xCO_2Def2					1.85	2.60	1.56	17.1	2.18	1.52
UD-model Case 1	2.33	1.45	0.61	2.71	1.86	2.55	1.54	25.7	2.11	1.60
UD-model Case 2	"	"	"	"	1.58	2.27	1.26	22.5	1.73	1.43
UD-model Case 3	2.02	1.6	0.56	3.34	1.86	2.58	1.53	16.3	2.13	1.60
Hamburg Scenario A Def1					2.31	3.21	1.96	13.8	2.41	2.21
Hamburg Scenario A Def2					2.60	3.75	2.15	15.2	3.00	2.19
UD-model Case 1	2.33	1.45	0.61	2.71	2.68	3.84	2.14	25.7	3.11	2.25
UD-model Case 2	"	"	"	"	2.40	3.57	1.86	22.4	2.72	2.08
Hamburg Scenario D Def1					0.44	0.59	0.37	4.4	0.34	0.53
Hamburg Scenario D Def2					0.72	1.13	0.56	5.7	0.93	0.52
UD-model Case 1	2.33	1.45	0.61	2.71	0.98	1.37	0.79	10.5	1.12	0.83
UD-model Case 2	"	"	"	"	0.70	1.09	0.52	7.2	0.73	0.66
Hamburg EIN Def1					2.76	3.77	2.38	15.4	2.71	2.82
UD-model Case 2	2.33	1.45	0.61	2.71	2.92	4.29	2.29	30.6	3.31	2.53

1 $\Delta T_{2xglobe}$, equilibrium global mean temperature change for a CO_2 doubling (°C)
2 R, ratio of the land/ocean equilibrium global mean temperature change for a CO_2 doubling (°C)
3 λ_{land}, inverse of the feedback parameter over the land (Wm^{-2} °C^{-1})
4 λ_{ocean}, inverse of the feedback parameter over the ocean (Wm^{-2} °C^{-1})
5 ΔT_{globe}, global mean temperature change °C
6 ΔT_{land}, mean land temperature change °C
7 ΔT_{ocean}, mean ocean temperature change °C
8 Ex, the thermal expansion (cm)
9 ΔT_{NH}, mean Northern Hemisphere temperature change °C
10 ΔT_{SH}, mean Southern Hemisphere temperature change °C

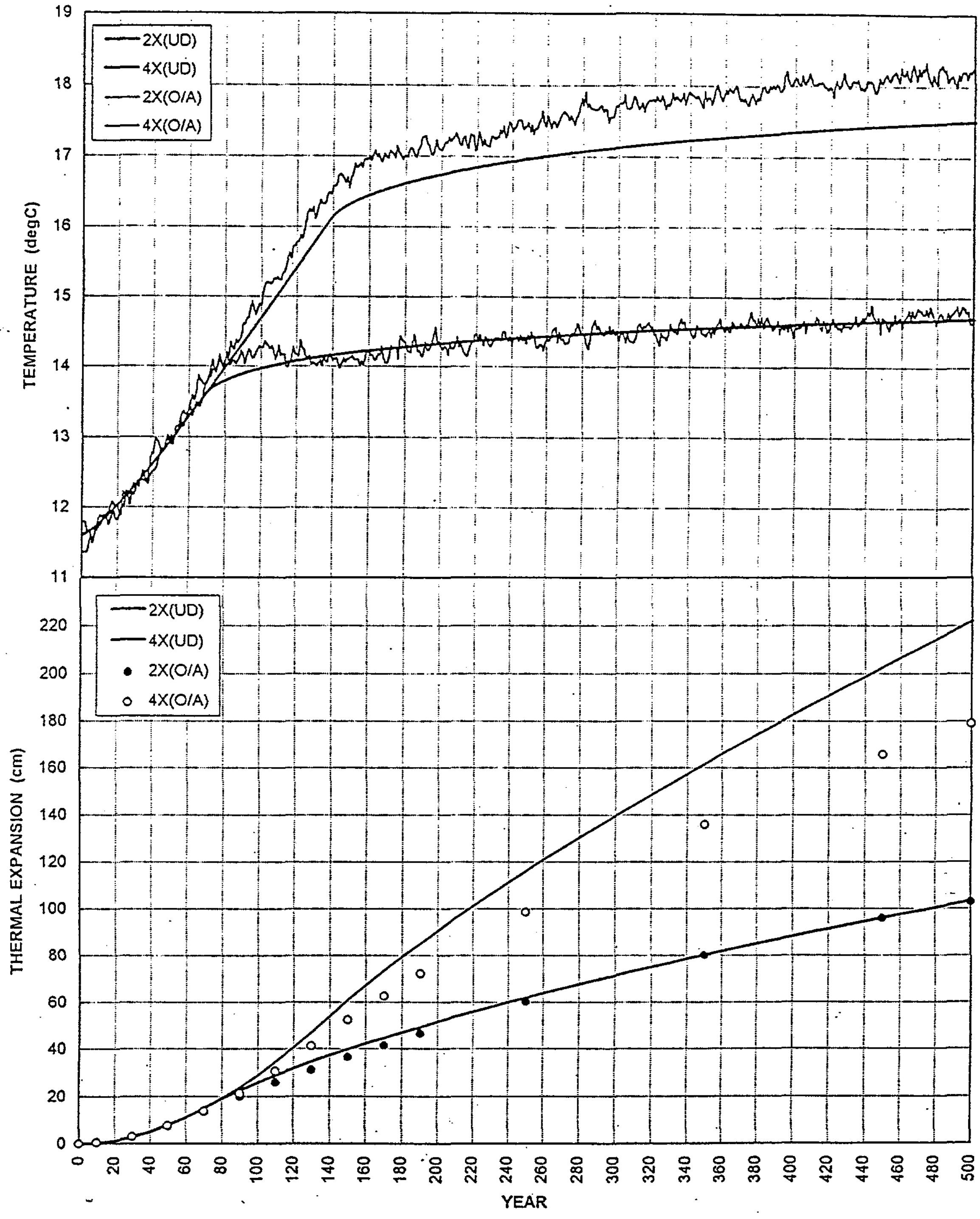

Figure 6: a) Time series of global mean temperature change from the 2 x CO_2 and 4 x CO_2 GFDL O/AGCM perturbation experiments (Manabe and Stouffer, 1993) compared with equivalent UD model results. b) As in a) but for thermal expansion.

The aim is to specify the ratio of equilibrium temperature changes over land versus ocean and the global-mean sensitivity, and calculate λ_O and λ_L for direct input into the UD model.

If changes in upwelling rate are ignored, the energy balance equation for box i (where i = 1, 2, 3, 4 corresponds to NH ocean (NO), NH land (NL), SH ocean (SO) and SH land (SL)) is of the form

$$f_i(C\, d\Delta T_i/dt + \lambda_i \Delta T_i) = f_i \Delta Q_i - f_i \Delta F_i + k(\Delta T_j - \Delta T_i) + k_H(\Delta T_k - \Delta T_i) \quad (1)$$

Here, f_i is the fraction of the area in box i (sum over i equal to 1), $C = \rho ch$ is the heat capacity and ΔF_i is the change in flux to the deep ocean (both zero for land boxes) and the k terms specify the inter-box exchanges. Subscript H on k identifies the interhemisphere exchange term.

For the present calculations, we only need the steady state result, which is

$$f_i \lambda_i \Delta T_i = f_i \Delta Q_i + k(\Delta T_j - \Delta T_i) + k_H(\Delta T_k - \Delta T_1) \quad (2)$$

This also holds for the variable upwelling rate case. In this case, ΔF_i is not zero, but it is compensated for by the term involving Δw. If this didn't happen, the global-mean steady-state temperature would be inconsistent with $\lambda \Delta T = \Delta Q$.

We now write equ. (2) in full, assuming the ΔQ_i are the same in each box and noting $f_{NO} + f_{SO} = f_O$ and $f_{NL} + f_{SL} = f_L$:

$$f_{NO}\lambda_O \Delta T_{NO} = f_{NO}\Delta Q + k(\Delta T_{NL} - \Delta T_{NO}) + k_H(\Delta T_{SO} - \Delta T_{NO}) \quad (3)$$
$$f_{NL}\lambda_L \Delta T_{NL} = f_{NL}\Delta Q + k(\Delta T_{NO} - \Delta T_{NL}) \quad (4)$$
$$f_{SO}\lambda_O \Delta T_{SO} = f_{SO}\Delta Q + k(\Delta T_{SL} - \Delta T_{SO}) + k_H(\Delta T_{NO} - \Delta T_{SO}) \quad (5)$$
$$f_{SL}\lambda_L \Delta T_{SL} = f_{SL}\Delta Q + k(\Delta T_{SO} - \Delta T_{SL}) \quad (6)$$

Adding these gives

$$\lambda_O f_O \Delta T_O + \lambda_L f_L \Delta T_L = \Delta Q = \lambda \Delta T = \lambda(f_O \Delta T_O + f_L \Delta T_L) \quad (7)$$

where $f_O = f_{NO} + f_{SO}$, etc., and all temperatures are equilibrium values.

Now denote the ratio $\Delta T_L/\Delta T_O$ by R. Equ. (7) becomes

$$\lambda_O f_O + \lambda_L f_L R = \lambda(f_O + f_L R)$$

Hence

$$\lambda_L = \{\lambda(f_O + f_L R) - \lambda_O f_O\}/f_L R \quad (8)$$

Here both R and λ (= $\Delta Q_{2X}/T_{2X}$) are known. Hence, if λ_O were given, λ_L could be calculated.

The problem now is to determine a consistent value of λ_O. An effecient way to do this is iteratively. First, a trial value is chosen. From this, equ. (8) gives λ_L and then ΔT_{NO}, ΔT_{NL} ΔT_{SO} and ΔT_{SL} can be calculated from equs. (3)-(6). From these, the land/ocean temperature ratio can be calculated and compared with the input value. Iteration on λ_O until the output and input R values are the same leads to a fully consistent set of values for all quantities.

To solve equs. (3)-(6), we write these in matrix form:

$$\underline{\underline{C}}\,\underline{\Delta T} = \underline{Q} \qquad (9)$$

where

$$[\Delta T]^T = [\Delta T_{NO}, T_{NL}, \Delta T_{SO}, \Delta T_{SL}] \qquad \text{(Superscript T = transpose)}$$
$$[Q]^T = [f_{NO}\Delta Q, f_{NL}\Delta Q, f_{SO}\Delta Q, f_{SL}\Delta Q]$$

and

$$\underline{\underline{C}} = \begin{bmatrix} f_{NO}\lambda_O + k + k_H & -k & -k_H & 0 \\ -k & f_{NL}\lambda_L + k & 0 & 0 \\ -k_H & 0 & f_{SO}\lambda_O + k + k_H & -k \\ 0 & 0 & -k & f_{SL}\lambda_L + k \end{bmatrix}$$

(Superscript T denotes the transpose.) The solution to equ. (9) is

$$\underline{\Delta T} = \underline{\underline{C}}^{-1}\underline{Q} \qquad (10)$$

Since $\underline{\underline{C}}$ is symmetric with some convenient zero elements, its inverse is easy to calculate.

The above calculation algorithm has been inserted into our model code. We have tested the algorithm with a stand-alone program, inserting the λ_O and λ_L values directly into the original code, and verified that the correct asymptotic values for the equilibrium global-mean temperature change and land/ocean temperature ratio are obtained.

C6. Sulphate aerosol effects

No significant progress has been made in this area during the past year.

C7. Low-frequency climate variability

Variability of the ocean circulation is believed to occur over a wide range of timescales, and could affect surface climate through changes in heat transport, changes in convection and subsequent heat release to the atmosphere, and changes in the depth of the surface mixed layer. The broad range of timescales involved currently precludes the use of coupled O/AGCMs to investigate such possibilities fully (including the parameter and resolution sensitivity of any variability obtained), although improved computer resources now allow some preliminary A/OGCM investigations to be made (e.g., Delworth *et al.*, 1993; Lunkeit *et al.*, 1994; Santer *et al.*, 1995a, b). For the longer timescales, and for more exhaustive investigations, either uncoupled OGCMs or OGCMs coupled to simple atmospheric models (i.e., hybrid-coupled models, after Neelin, 1989) must be used. Initial experiments (e.g., Mikolajewicz and Maier-Reimer, 1990) used uncoupled OGCMs. This is a very important first step, but that is what it should be regarded as - a first step. The reason is that it assumes that the atmosphere is time-invariant, despite any changes that are occurring in the OGCM (since the atmospheric boundary conditions are simply fixed at their climatological values). Power and Kleeman (1993) have shown that the time-invariant atmosphere assumption is not satisfied for variability that involves large changes in ocean convection in high-latitudes (such as the oscillations found by Mikolajewicz and Maier-Reimer, 1990). Any study of low-frequency variability should therefore address the possible modifying effect of atmospheric feedback.

Whilst the uncoupled OGCM study is certainly a vital step, it should be regarded as the first step in a hierarchy of *coupled* model studies. In the hierarchy that we envisage, an OGCM is coupled to a series of atmosphere models, which increase in complexity (and, presumably, realism) with each step up the hierarchy. The details of each step depend on the range of atmosphere models available. One possible realisation of the atmosphere model hierarchy (in order of increasing complexity) might be:

(i) a time-invariant atmosphere (with the addition of spatially incoherent white noise, if that is necessary to excite any modes of variability of the OGCM);

(ii) a time-invariant atmosphere with the addition of anomalies that have spatial and/or temporal structures similar to the real atmosphere;

(iii) an empirical atmosphere model (i.e., based on statistical relationships derived from observations or other modelling studies) to predict the air-sea fluxes of fresh-water, momentum and heat from the OGCM's sea surface temperature. In this way, active atmospheric feedback is included;

(iv) a two-dimensional (latitude-longitude) energy-balance atmosphere model, to predict air-sea heat fluxes and subsequent atmospheric transport of heat anomalies;

(v) a combination of the energy-balance atmosphere to predict heat fluxes, and the empirical atmosphere to predict fresh-water and momentum air-sea fluxes;

(vi) a full AGCM.

Such a hierarchy leads eventually to (vi), a fully coupled O/AGCM, but with the advantages of being far less computationally expensive in the early steps, and of being able to identify key processes as the complexity is gradually increased. Whilst the entire hierarchy should be studied for one particular OGCM, the hierarchy should, ideally, also be repeated with a range of OGCMs.

The first and second steps in this hierarchy have already been performed for the Hamburg LSG OGCM (Maier-Reimer and Hasselmann, 1987) by Mikolajewicz and Maier-Reimer (1990) and by Barnett *et al.* (1995a). Significant variability was discovered in that model, an example of which is shown in Fig. 7a. Here, Southern Ocean convection is characterised by variations in the strength of the Antarctic Circumpolar Current (ACC). Pierce *et al.* (1995a) presented a physical mechanism to explain the existence of such variability. We have now extended these investigations in two ways.

First, we have improved and extended our understanding of this variability, by showing that: (i) the generation of the variability is entirely a Southern Ocean mechanism, and that the anomalies which propagate around the Atlantic thermohaline circulation (Mikolajewicz and Maier Reimer, 1990) are signals emitted from that source region; (ii) there is a second mode of propagation of thermohaline anomalies, which is westwards around Antarctica. This propagation travels against the flow of the ACC, via an unusual type of coastally-trapped wave. It is certainly important in determining the structure of the model's variability and may also control the period. A similar propagation has been found in the HOPE OGCM too (Drijfhout *et al.*, 1995).

Second, we have investigated the sensitivity of the variability to some of the model's physical and dynamical parameterisations. A simplification, which accounts for much of the LSG model's computational efficiency, is that some terms in the velocity equations are held constant during a model integration. We have shown that this simplification is acceptable, since it has little effect on the simulation of internal ocean variability. On the other hand, the convection parameterisation and the sea-ice coupling to the ocean have more importance. The LSG OGCM currently *interchanges* statically unstable water masses. If this is changed to a scheme in which such water masses are *mixed* (as is used in many other OGCMs), the variability is dramatically reduced (Fig. 7b, cf. Fig. 7a). The present coupling between the sea-ice model and the ocean model can create unrealistic fluxes of heat and salt. Improving this coupling corrects this unrealism, and also greatly reduces the magnitude of the internal variability.

In addition, we have continued the hierarchy of investigations by coupling an empirical atmosphere model to the LSG OGCM (i.e., step (iii)). The empirical model uses principal-component-based statistical relationships to compute patterns of heat, fresh-water and momentum flux anomalies, given a pattern of sea surface temperature anomalies generated by the OGCM. The statistical relationships were derived from an AMIP AGCM simulation (Gates, 1992). The behaviour of this hybrid-coupled model (Fig. 7c), is again, somewhat different from the purely noise-forced LSG OGCM, with slightly reduced magnitude variability. The feedback in the fresh-water-flux has less effect, however, than do the changes to the model's physical parameterisations. The momentum flux feedback has little effect, other than being able to trigger the same internal variability without the need to add stochastic forcing to the fresh-water flux. The heat flux feedback remains under investigation, but preliminary results indicate that the internal variability of the LSG OGCM is still present when this feedback is included.

Relevant related work has been carried out by Pierce *et al.* (1995b), who found that the LSG OGCM no longer exhibited the same internal variability when coupled to the surface energy balance model (EBM) of Hyde *et al.* (1989) - under some configurations. Under alternative configurations, the coupled model could be induced to oscillate, as before. Their work addresses step (iv) of the hierarchy. We have now begun to investigate step (v), the three-way coupling between the LSG OGCM, the EBM (to predict the heat fluxes) and the empirical atmosphere model (to predict the fresh-water and momentum fluxes).

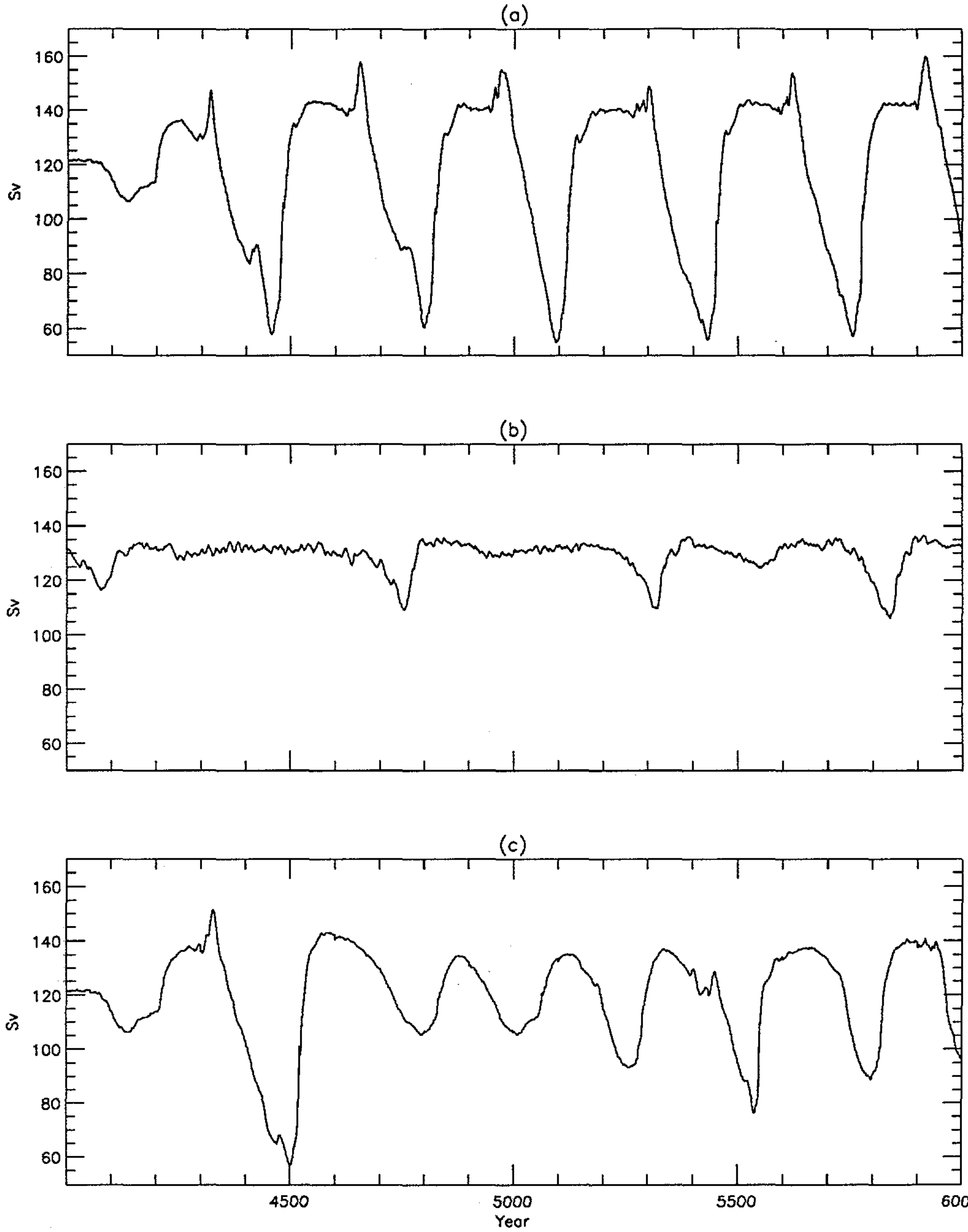

Figure 7: Strength of the Antarctic Circumpolar Current (Sv) for three LSG OGCM simulations: (a) coupled to a time-invariant atmosphere with white noise forcing - step (i); (b), as (a) but with an alternative convection parameterisation; (c) coupled to an empirical atmospheric model, with fresh-water flux feedback and noise forcing - step (iii).

D. Model Validation

Two main pieces of analysis have been undertaken in this area. The principal work has extended our analyses of drought over Europe using the Palmer Drought Severity Index (PDSI) with GCM control and perturbed simulations. The rationale behind the work is to see how well a GCM can reproduce patterns and other characteristics of drought in this region. The model results are compared with real world analyses over 'greater' Europe (35-70°N; 10°W-60°E), which are available for 1892-1991 (Briffa *et al.*, 1994).

The GCM integrations used were from the high-resolution coupled ocean-atmosphere model at the Hadley Centre (Murphy, 1995, and Murphy and Mitchell, 1995). Both control and perturbed integrations are 75 years in length. In the perturbed integration, CO_2 increases from a starting value of 323ppm at a compound rate of 1% per year, doubling in year 71. PDSI values for the European region were calculated from the control integration. These PDSI data were then analysed by unrotated and VARIMAX rotated Principal Components Analysis as had been done for the real world (Briffa *et al.*, 1994). The PDSI patterns from the control run were then projected on to the perturbed integration results.

PDSI values in the control integration show similar features to the real world, but are different particularly with respect to low frequency aspects. Variability on timescales beyond 20 years is absent in the various control run area-average drought, principal component (PC) and rotated principal component (RPC) time series. However, the model PC and RPC patterns show many of the features of the real world. The first three PCs of the observations are clearly present in the control run.

The perturbed integration shows a dramatic change to drought conditions affecting most of Europe by year 75. In some regions the PDSI quickly approaches (within 30-40 years) severe drought values of -3 to -4 before stabilizing at this level until year 75, while in a few areas little change in drought severity is seen. The pattern of change in PDSI during the last 10 years of the perturbed integration is somewhat different from that shown by soil moisture internally calculated by the GCM.

A paper (Jones *et al.*, 1995 - included here as Appendix E) has been submitted about the work stressing the differences in summer moisture availability over Europe. Differences relate to the time step (monthly in soil moisture calculations in the observed and model produced PDSI, daily in the direct GCM soil moisture calculations), the treatment of snowfall, and the soil moisture accounting procedure. Further work is necessary but the differences suggest markedly different impacts from the PDSI patterns than implied by the GCM soil moisture changes.

The other area studied in this section relates to the veracity of low-frequency characteristics in the millennial control runs of GCMs. In section B on Multivariate Detection Methods such long model integrations provide the background statistical distributions against which to detect trends in statistics like R(t). How reliable are these models at simulating the correct levels of natural variability on decade-to-century timescales? All such variability in the GCM must be due to the inherent structure of the ocean and atmosphere's interaction with it as the GCMs do not consider changes in natural external forcing. (Incorporating the latter is difficult anyway as the past history of such forcing is poorly known even over the last 100 years.)

The only means of testing the potential usefulness of the models is to took at long paleoclimatic reconstructions for the last 500-1000 years. The proxy data are not ideal - they are generally limited to the summer or growing season, rarely explain more than 50% of the variance when compared to instrumental data, and only exist for about 20 sites around the world. We have been involved in the first such comparison of paleoclimatic and GCM results on these timescales (Barnett *et al.*, 1995b). The results are somewhat alarming for modellers and especially for detection studies as the GCMs underestimate natural variability by a factor of at least two (implying that other external factors affect the real world rather than that the model internal variability is too low) and the patterns of natural variability produced by the GCMs (as estimated by principal components analysis) do not resemble those produced by the paleo-data.

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