CLIMATE MODELING: USES AND LIMITATIONS

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OVERVIEW

- What are climate models?
- How good are climate models?
- How do we test climate models?
  - Validation
  - Detection
- How consistent are climate models?
- Application to future climate prediction
- Summary

CLIMATE MODELS

- Climate models are computer-run, mathematical simulations of the climate system—the atmosphere, ocean and cryosphere, and its land–surface boundary

- For detailed projections of future climate change, the primary tool is the General Circulation Model (GCM)

GENERAL CIRCULATION MODELS (GCMs)

- These are three-dimensional, mathematical representations of the atmosphere and ocean.

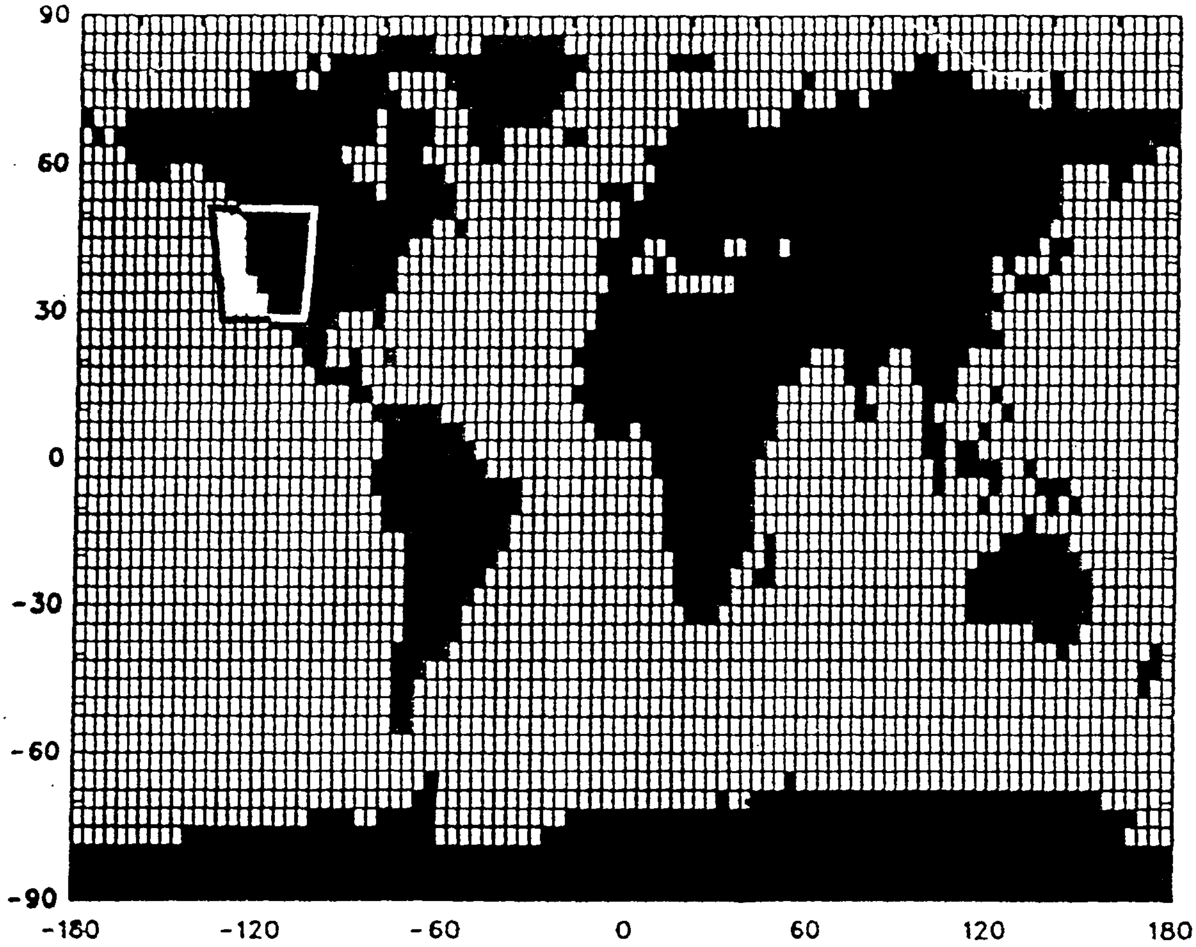
- Two types of model are widely used: atmospheric GCMs coupled to simple Mixed-Layer Ocean models (**MLO-AGCMs**), and coupled Ocean/Atmosphere GCMs (**O/AGCMs**).

- GCMs are the primary tool for predicting the response of the climate system to external forcing changes, both natural and/or anthropogenic.
    * MLO/AGCMs can only be used to determine equilibrium climate changes.
    * O/AGCMs allow fully transient (time-dependent) climate change simulations to be performed.

- GCMs are the *only* credible tool for predicting the regional (~1000 km or less) details of climate change.

- Most current global climate models used for climate change experiments have a horizontal resolution of 200–500 km.

- To provide higher resolution information, one may either use statistical "downscaling" techniques, or embed (or "nest") a limited-area, high-resolution model within the coarse-resolution global GCM.



Horizontal grid of GENESIS version 2.01 (3.75° × 3.75°) together with the smaller area in which RegCM2 is embedded.

HOW GOOD ARE GCMs?

GCM LIMITATIONS

- The primary limitation of GCMs is their is their spatial resolution.
- Related to this, GCMs are also limited in the way they "parameterize" sub-grid-scale details, such as cloud processes and land-surface processes.
- For future climate projections, correct specification of the forcing is difficult because of uncertainties in future anthropogenic forcing and its effects (for example, will the Greenland ice sheet disappear?)

GCM UNCERTAINTIES

Global Scale

- The most important uncertainty is the climate sensitivity. This is usually expressed as the equilibrium (i.e., eventual) global-mean warming that would occur if the level of CO_2 in the atmosphere doubled (ΔT_{2x}).
- The value of ΔT_{2x} is determined by feedback processes in the climate system. The most important of these involve changes in water vapor, clouds and sea ice.
- The value of ΔT_{2x} is between 1.5°C and 4.5° (with about 90% confidence). The best estimate is 2.5°C.

Regional Scale

- Uncertainties become larger as the spatial or temporal scale becomes smaller. Thus, regional details (spatial scales of 1000 km or less), and short timescale (daily or less) predictions involve large quantitative uncertainties.

Variables

- Uncertainties in precipitation change are larger than those in temperature change.
- Uncertainties in derived variables (such as soil moisture, infiltration, etc.) are, necessarily, even larger.

HOW DO WE TEST CLIMATE MODELS?

HOW DO WE TEST CLIMATE MODELS?

(The procedure is generally referred to as "validation")

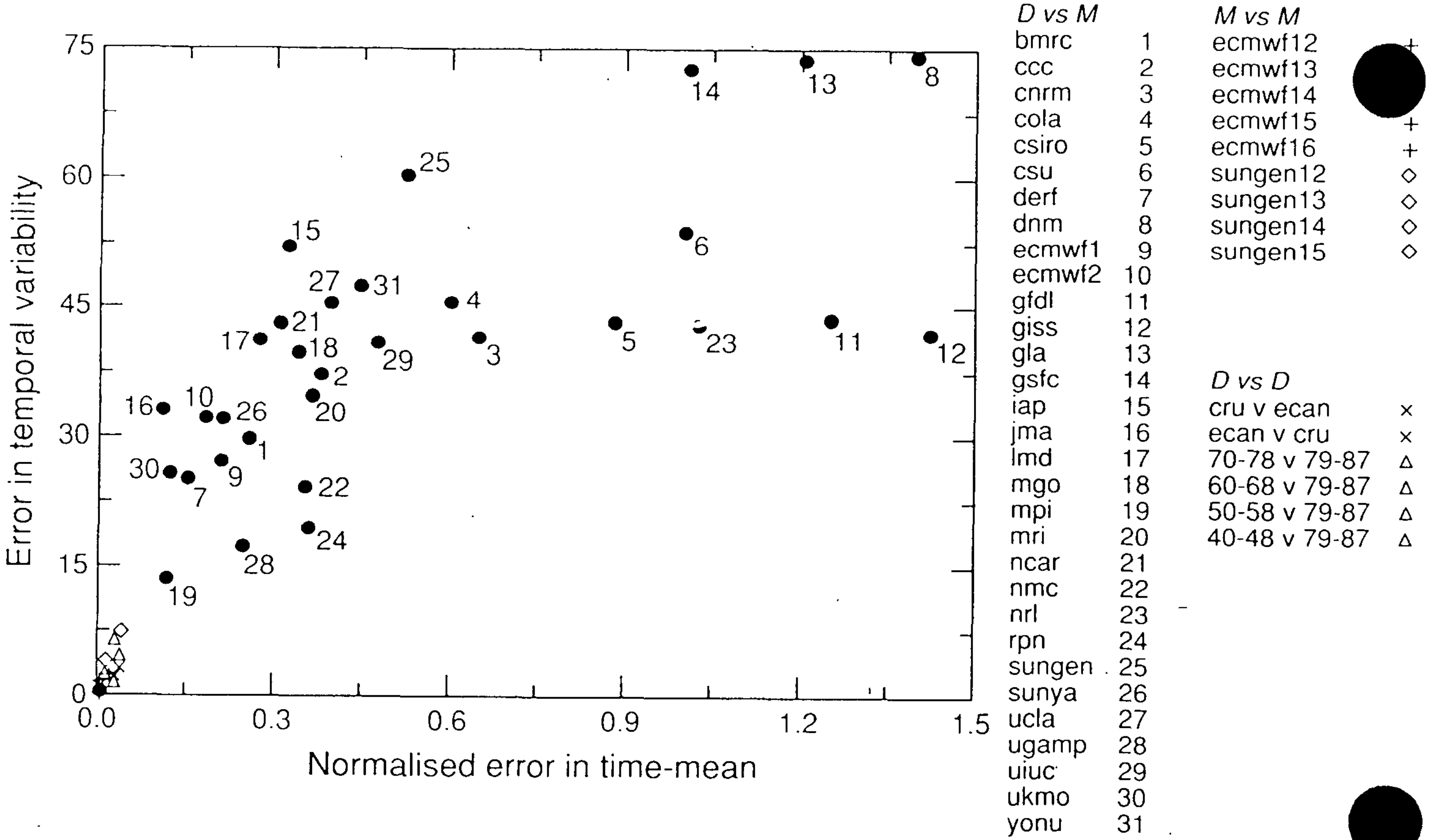
- Compare model simulations of current climate with observations.
- Compare model simulations of recent changes with observed changes. (This is the "detection" problem—can we detect the "signal" of human-induced climate change, as predicted by climate models, in the observed record?)
- Compare model simulations of past climate (e.g., during the last glacial maximum, or the early Holocene) with paleoclimatic data.

MODEL VALIDATION AGAINST OBSERVED CLIMATE

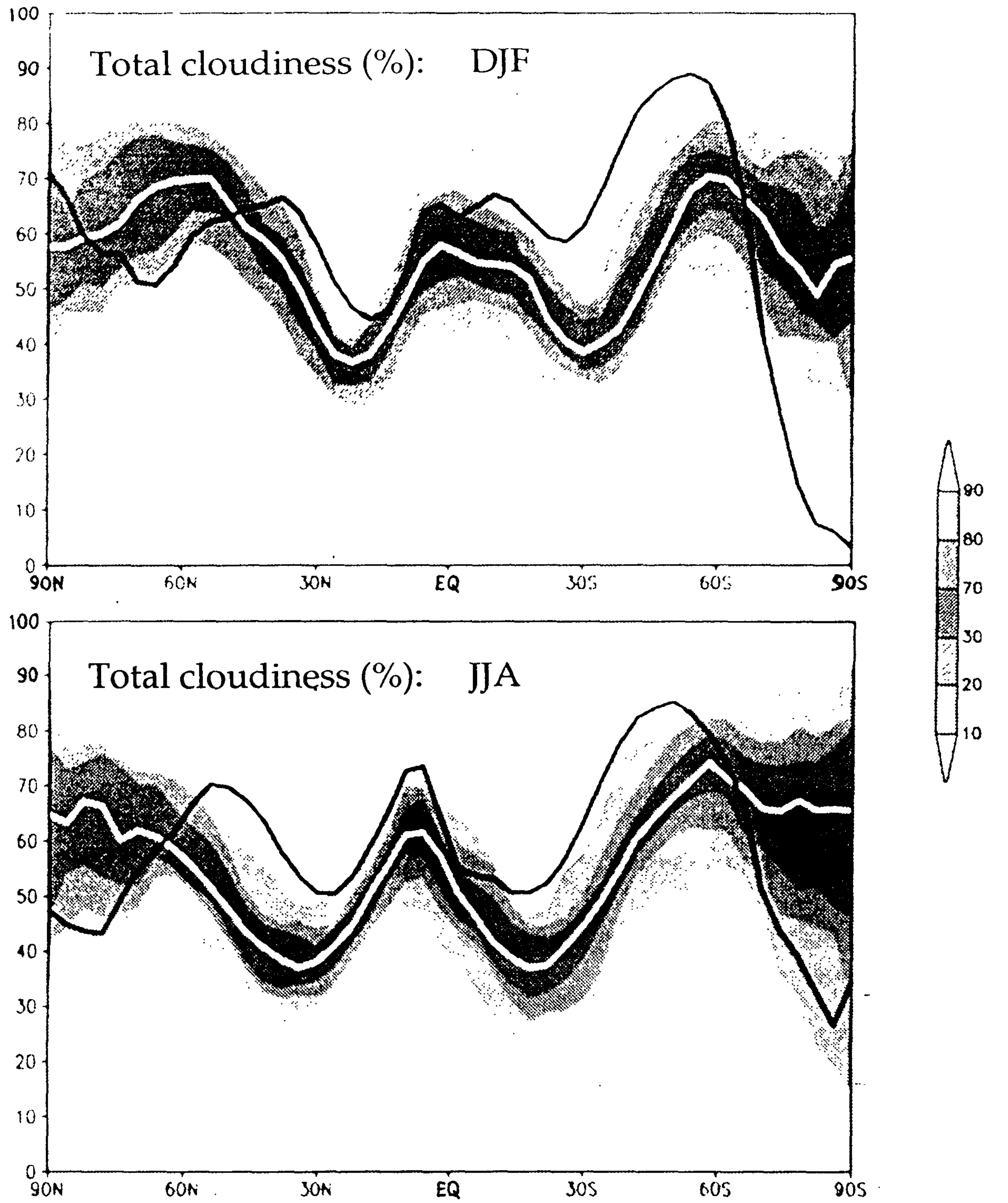
(Minimum requirements)

- To compare modeled results with observed data we need to consider, at least, the mean states[1], interannual variability about the mean state, and spatial patterns.
- The most easily interpreted variables are: temperature, precipitation, and mean sea level pressure.
- The most commonly used timescale is the monthly mean. However, for hydrologic and agricultural applications, one should also consider daily precipitation characteristics (e.g., Markov chain properties, wet-day amount distributions).
- Where possible the statistical significance of model/observed differences should be assessed. This generally requires permutation or Monte Carlo methods.
- For practical purposes, simply comparing model/observed differences or ratios with observed interannual variability is often illuminating.

1 For temperature, absolute model/observed differences are most useful. For precipitation, model/observed ratios should be used.

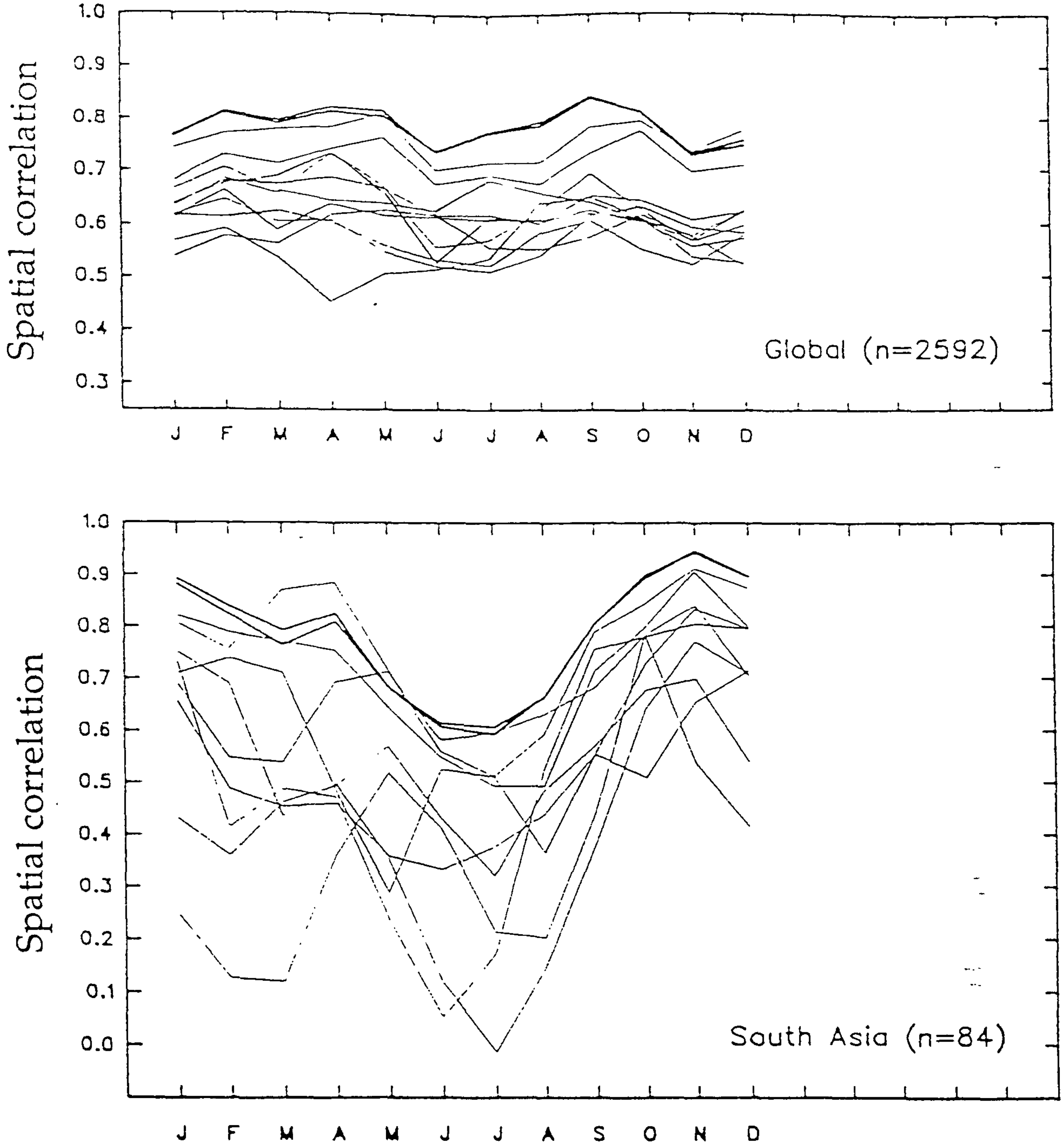


AMIP model validation results for mean sea level pressure (monthly-means for the Northern Hemisphere). The abscissa uses the SITES statistic of Wigley and Santer (1990) and the ordinate uses their NF1 statistic. SITES has an expected value of 0.0 for perfect agreement, while NF1 (which is the number of grid points with 1% significant observed-vs-model variance differences) has an expected value of 1. The cluster of points in the bottom left corner shows the range of values due to interdecadal climate variability and model initial conditions. The full annual cycle of monthly values is used. This presentation therefore tends to underestimate monthly timescale model errors, since it is biased towards the models' ability to simulate the annual cycle rather than interannual variability. Nevertheless, model performance, even for the best models, leaves much to be desired. (Results from Santer et al., 1995a, as reproduced by Gates et al., 1996.)

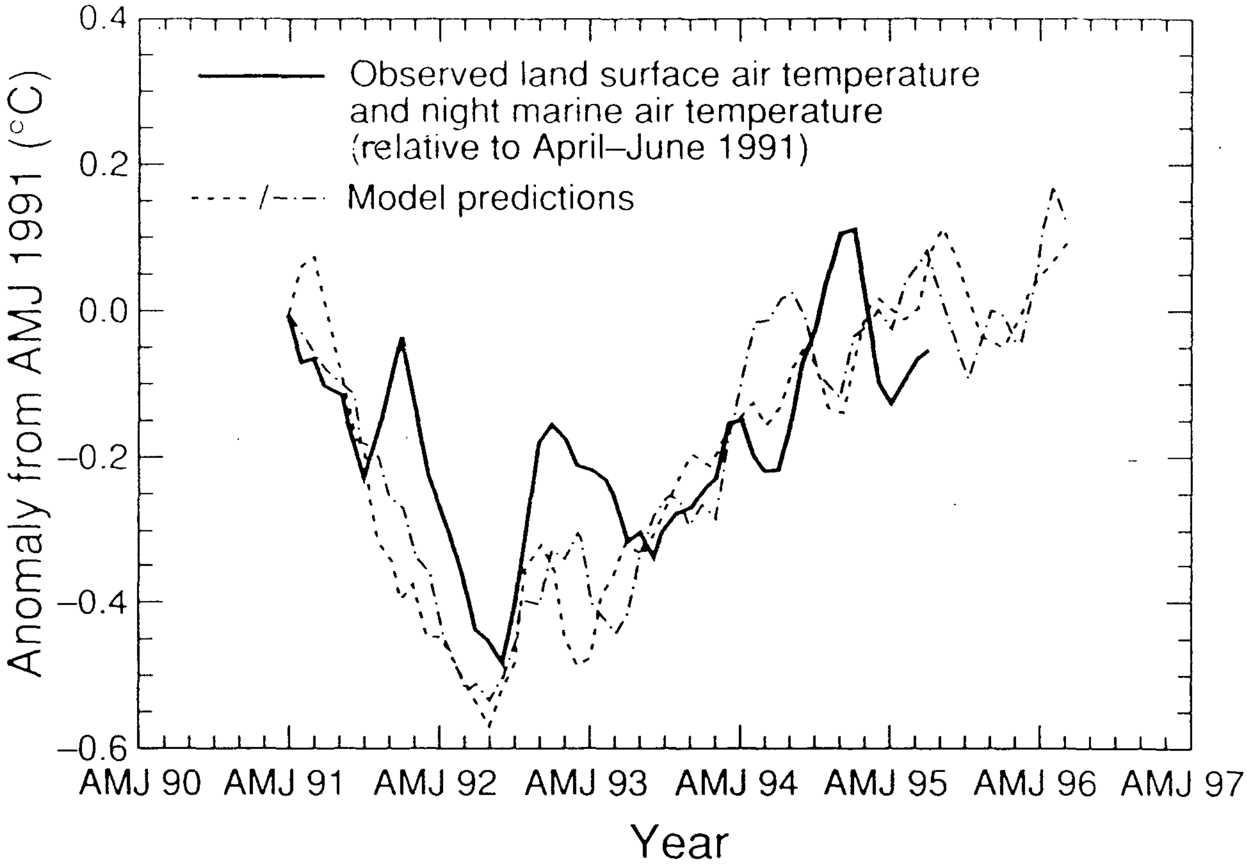


AMIP simulations of zonal-mean total cloudiness (%). Observed data are given by the black line (from Rossow and Schiffer, 1991). The white line shows the mean of 31 models while the shading shows inter-model variability. The full shaded area gives the range spanned by 80% of the models. Model/observed agreement is generally poor. (Reproduced from Gates et al., 1996.)

PRECIPITATION VALIDATION



Pattern correlations between observed and modeled monthly-mean precipitation for 11 (top) or 9 (bottom) GCMs. The data used are on a 5° by 5° latitude/longitude grid. Bold curves are for weighted and unweighted means of all models.

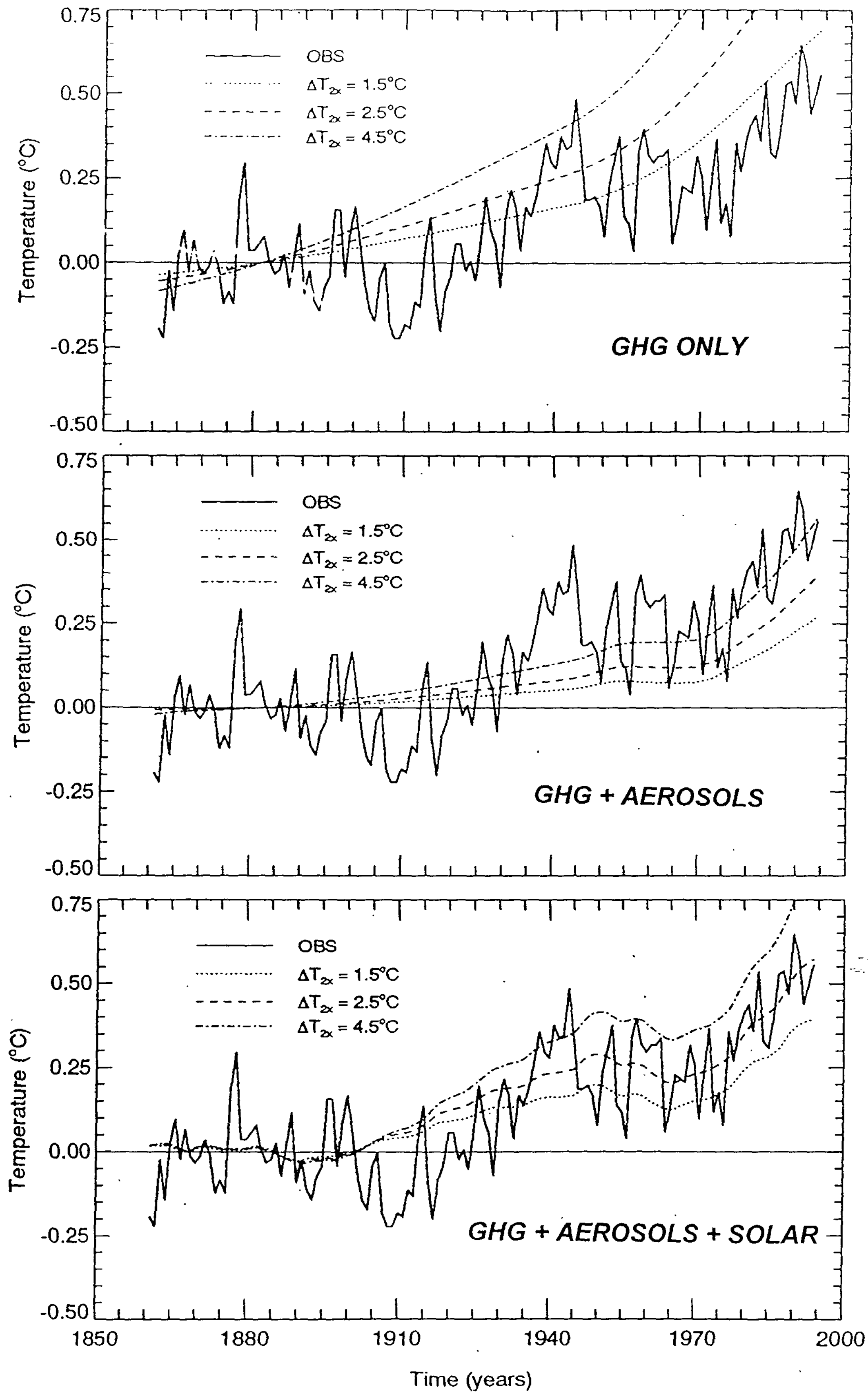


Predicted global-mean temperature variations (3-month running means) following the eruption of Pinatubo in June 1991 using the GISS model, compared with observations. (Reproduced from Gates et al., 1996; originally from Hansen et al., 1992.)

DETECTION

Is the model-predicted signal of recent anthropogenic climate change identifiable in the observed record?

HOW WELL DO MODELLED AND OBSERVED CHANGES IN GLOBAL-MEAN TEMPERATURE COMPARE FOR DIFFERENT FORCINGS AND SENSITIVITIES?



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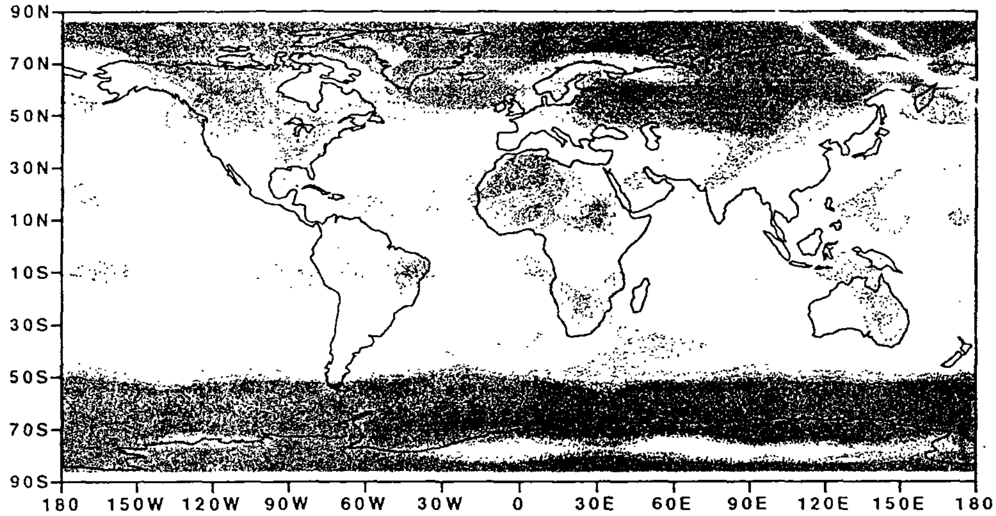
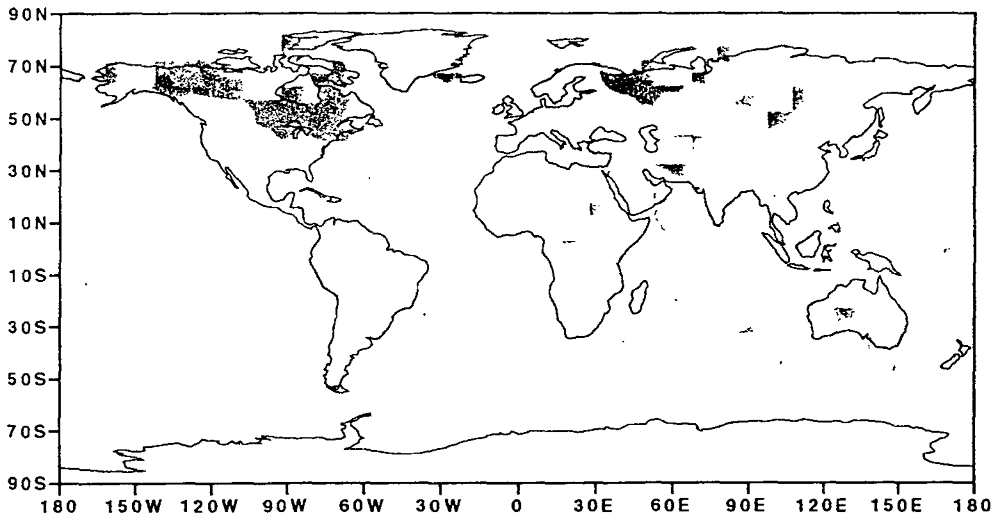
From Santer et al. (1996a)

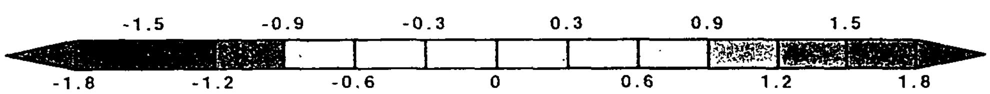
MODELLED AND OBSERVED PATTERNS OF NEAR-SURFACE TEMPERATURE CHANGE

MODEL SIGNAL: CO_2-ONLY



OBSERVED CHANGES



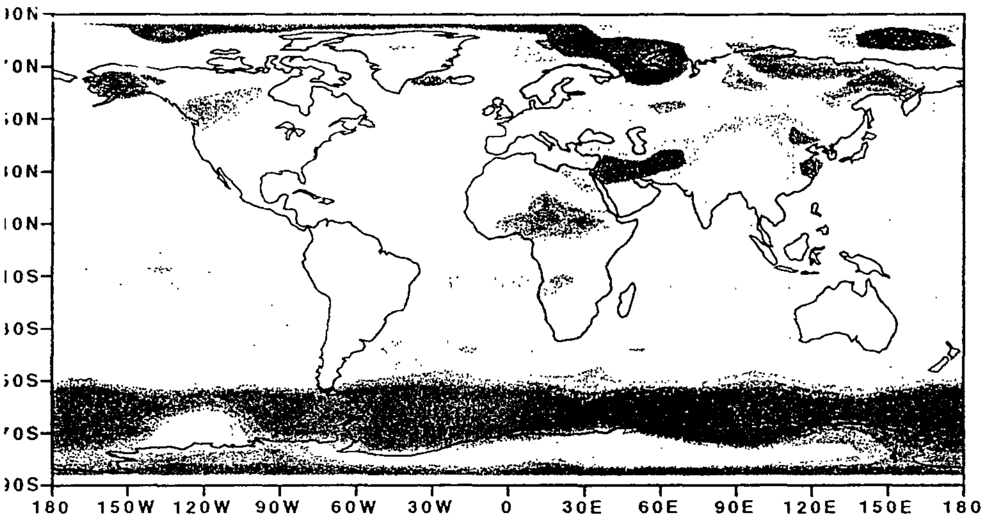


ALL TEMPERATURE CHANGES FOR SEPT-OCT-NOV, °C

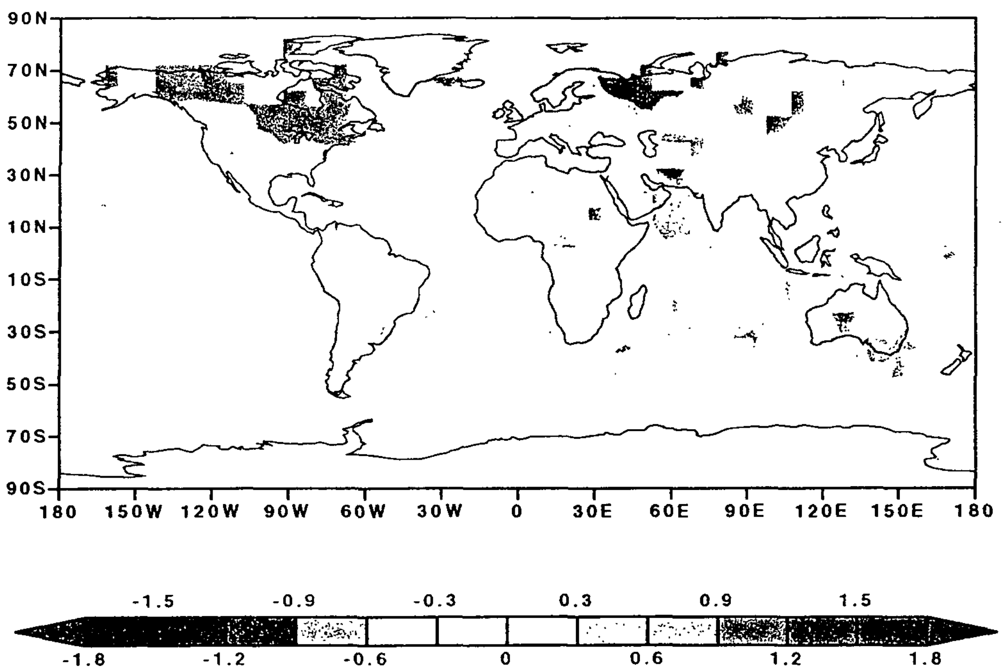
Based on Santer et al. (1995b)

MODELLED AND OBSERVED PATTERNS OF NEAR-SURFACE TEMPERATURE CHANGE

MODEL SIGNAL: CO_2 + AEROSOLS



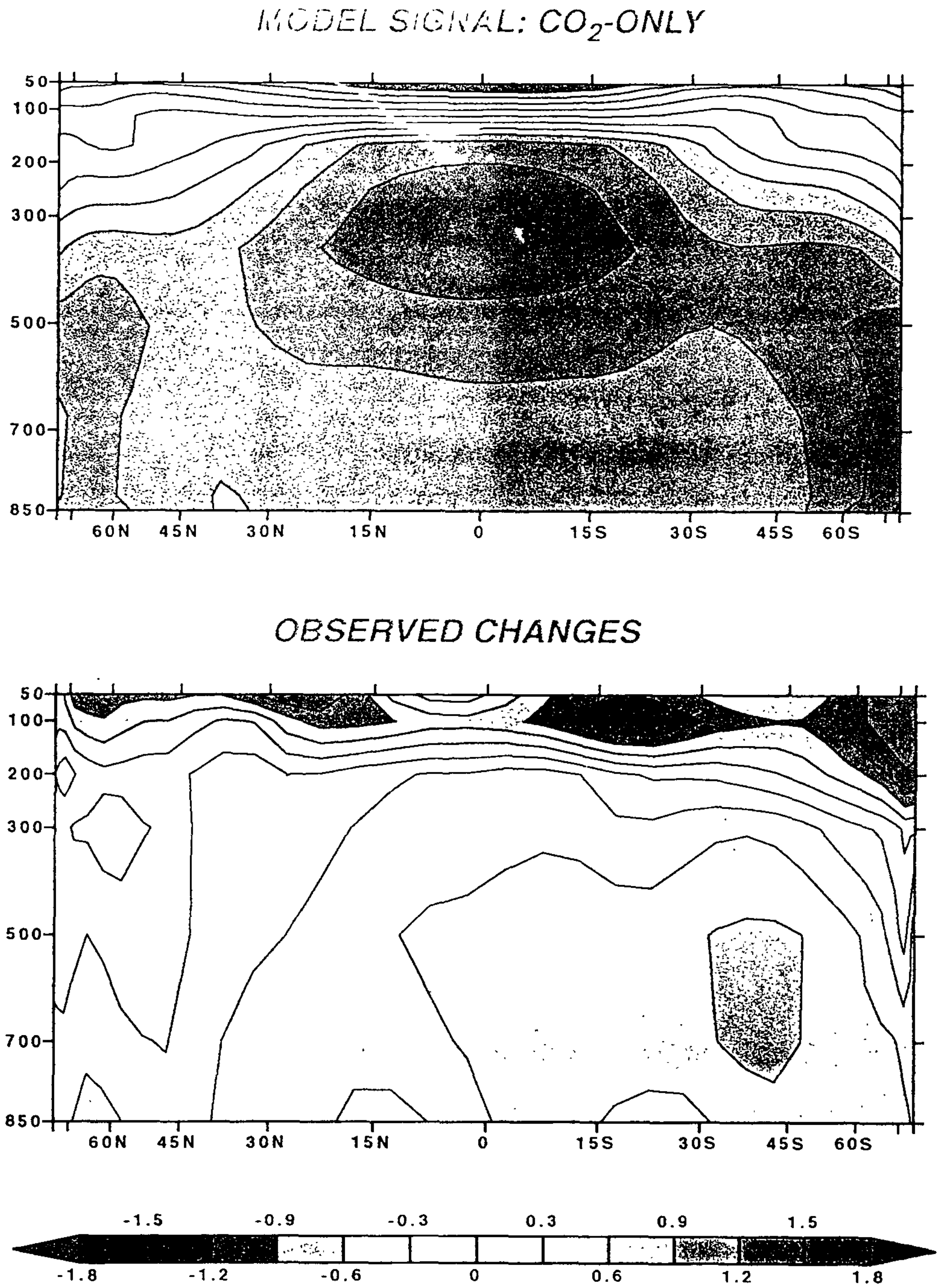
OBSERVED CHANGES



ALL TEMPERATURE CHANGES FOR SEPT-OCT-NOV, °C

Based on Santer et al. (1995b)

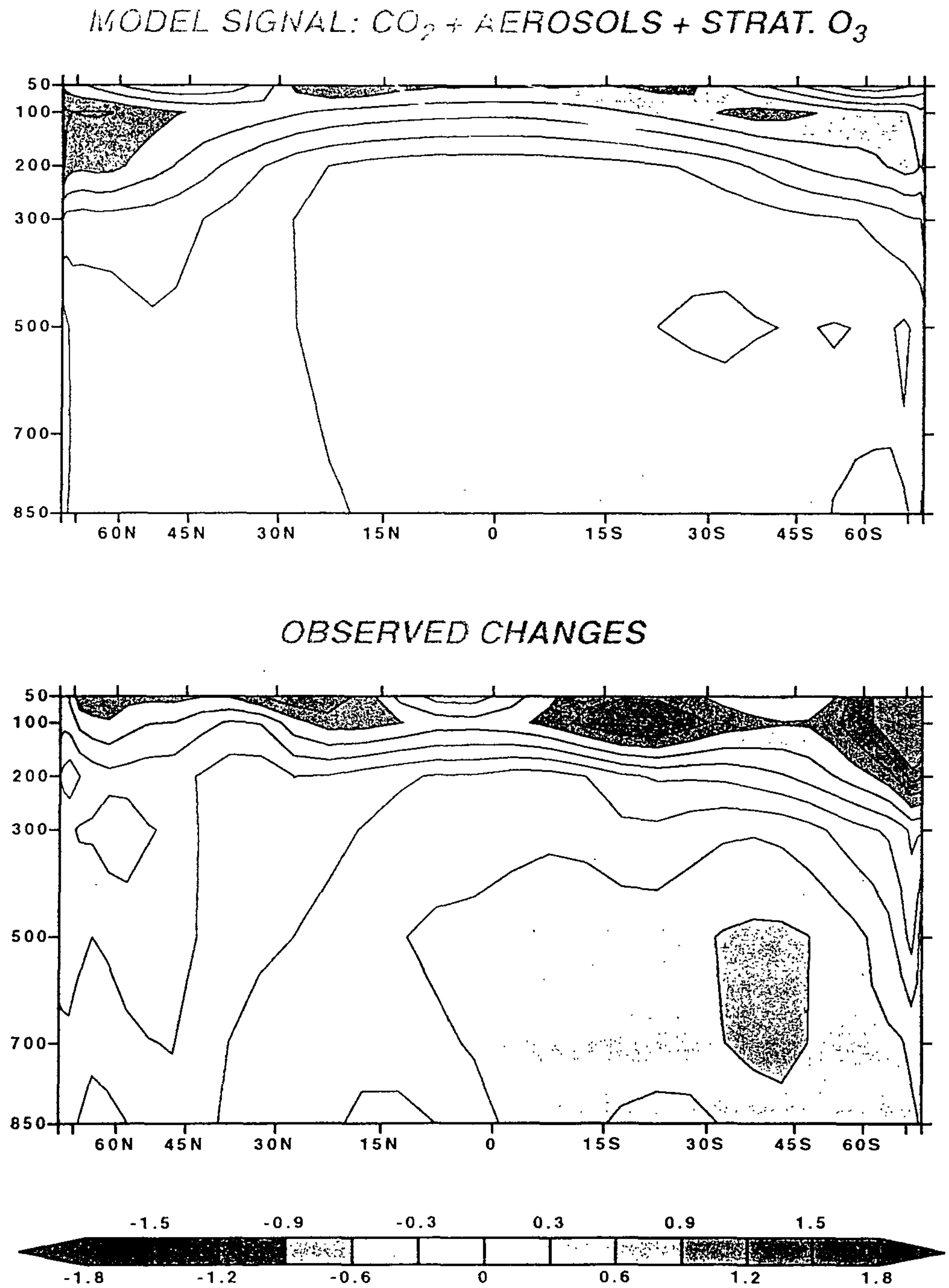
MODELLED AND OBSERVED PATTERNS OF VERTICAL TEMPERATURE CHANGE



ALL TEMPERATURE CHANGES FOR ANNUAL AVERAGES, °C

Based on Santer et al. (1996b)

MODELLED AND OBSERVED PATTERNS OF VERTICAL TEMPERATURE CHANGE

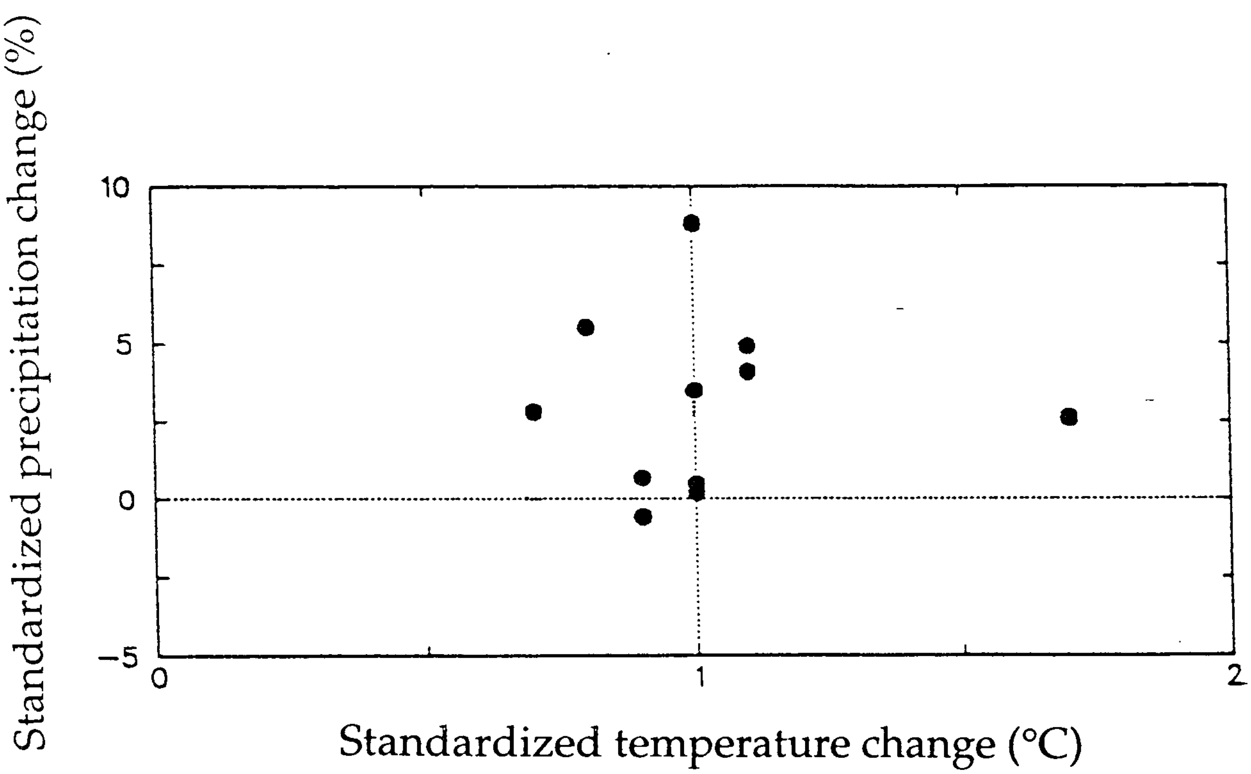


ALL TEMPERATURE CHANGES FOR ANNUAL AVERAGES, °C

Based on Santer et al. (1996b)

DO INDIVIDUAL MODELS AGREE?

INTER-MODEL DIFFERENCES



CO_2-induced standardized precipitation and temperature changes (i.e., per degree global-mean warming) for 11 GCMs for the 5° by 5° grid box centered over eastern England (black dots). This Figure shows that, even if we could predict the global-mean temperature change, large uncertainties would remain in regional temperature and precipitation due to inter-model differences in the patterns of response.

APPLICATION TO FUTURE CLIMATE PREDICTION

PREDICTING FUTURE CLIMATE CHANGE

- Predictions of the details of future climate are likely to be better for larger and more spatially heterogeneous external forcing.

- Most predictions to date have addressed the problem of anthropogenic climate change.
  * The global-mean anthropogenic forcing to date has been "only" 1–2 W/m^2.
  * Future forcing (to 2100) is expected to be 3–7 W/m^2.
  * Future forcing is relatively spatially homogeneous.

- Very few GCM-based predictions have been made of future 1000-year timescale climate change.
  * For such changes, the global-mean forcing is very small.
  * However, regional and seasonal forcing changes are very large—up to 40 W/m^2.

PREDICTION NEEDS

Variables

- Daily precipitation
- Air temperature — preferably daily
- Cloudiness — preferably daily

Spatial Scale

- Less than 1000m

SUMMARY: 1

- GCMs are the only credible tool for estimating the regional details of future climatic change.
- While based on sound physical principles, GCMs have many known weaknesses. Nevertheless, the best GCMs simulate the large scale features of current climate reasonably well.
- Global GCMs have relatively coarse resolution, but smaller-scale climate change details (down to scales of order 50km) can be improved by embedding high-resolution limited-area models within coarse-resolution global GCMs.
- For very large forcings (such as those due to orbital effects on timescales of 1000s of years), GCM projections of future climate change should be qualitatively reliable.
- Such projections should account for current human influences, which may have very long term effects on atmospheric composition and surface boundary conditions (ice, vegetation, etc.).
- Reliability of and confidence in the realism of GCM climate change projections would be increased by the use of more than one model, and intercomparing results from different models.
- Because of the uncertainties, projections should be thought of as scenarios that, if carefully designed, can span the range of possible future climates.

SUMMARY: 2

- On spatial scales of order 100km or less, GCM-based precipitation change estimates must be treated with caution.
- Statistical downscaling methods forced by GCM-derived circulation change information may be necessary to obtain such small scale details—but even these methods are of unknown quality on scales of less than 10km.
- The best approach would be to use a judicious synthesis of GCM data, statistical downscaling methods and stochastic simulation techniques.