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THE DETECTION OF ANTHROPOGENIC CLIMATE CHANGE

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1. INTRODUCTION

The U.S. Department of Energy (DOE) has initiated a project to develop a methodology and plan of research for detecting climate change due to greenhouse gas emissions and other anthropogenic perturbations to the global climate system. This methodology has been developed by a panel of experts in climate change detection and related scientific disciplines. The methodology provides a technical plan for assessing the anthropogenic contribution to global climate change -- the data requirements, the analysis methods to be used, the modeling work needed to guide and support the analysis, and the research needed to develop and improve techniques for detecting changes in the Earth's climate and attributing any changes to their source.

This paper describes the basic elements of the climate change detection methodology. At the core of the methodology are four interactive activities:

- Modeling -- the work needed to determine what the human-induced climate change signal should look like.
- Data Analysis -- the work needed to identify and assemble quality assured observations and analyses of the climate variables most likely to contain the expected signal.
- Methodology Development -- the development of improved procedures for identifying the expected anthropogenic signal in the observational record.
- Methodology Application -- the application of procedures for determining if the anthropogenic climate signal has occurred in the observations.

2. PREVIOUS WORK ON DETECTION

Serious attempts to examine anthropogenic effects on climate began in the late 1970s and early 1980s. Initial attempts were based on trend analyses of the most obvious climate variables, such as surface temperature. The approach was to determine whether trends in the measurements of these variables were consistent with predictions of the effects of rising concentrations of greenhouse gases that were beginning to be made by global climate models. Although these analyses indicated that a general warming had occurred over the past century, they could not exclude the possibility that these trends were the product of natural causes or of an inherent, low-frequency variability in the climate system (Wigley and Barnett, 1990).

In order to resolve this ambiguity, thinking began to shift to strategies that would look for temporal or spatial patterns in the climate variables unique to anthropogenic forcing -- patterns that could be used as climate change "fingerprints". MacCracken and Moses (1982) and MacCracken and Kukla (1985) were among the first to outline the essential elements of a fingerprint approach to climate change detection, and their ideas have been extended (but never completely or systematically implemented) by several investigators. Essentially, the approach entails the simulation of the anthropogenic forcing and climatic response by means

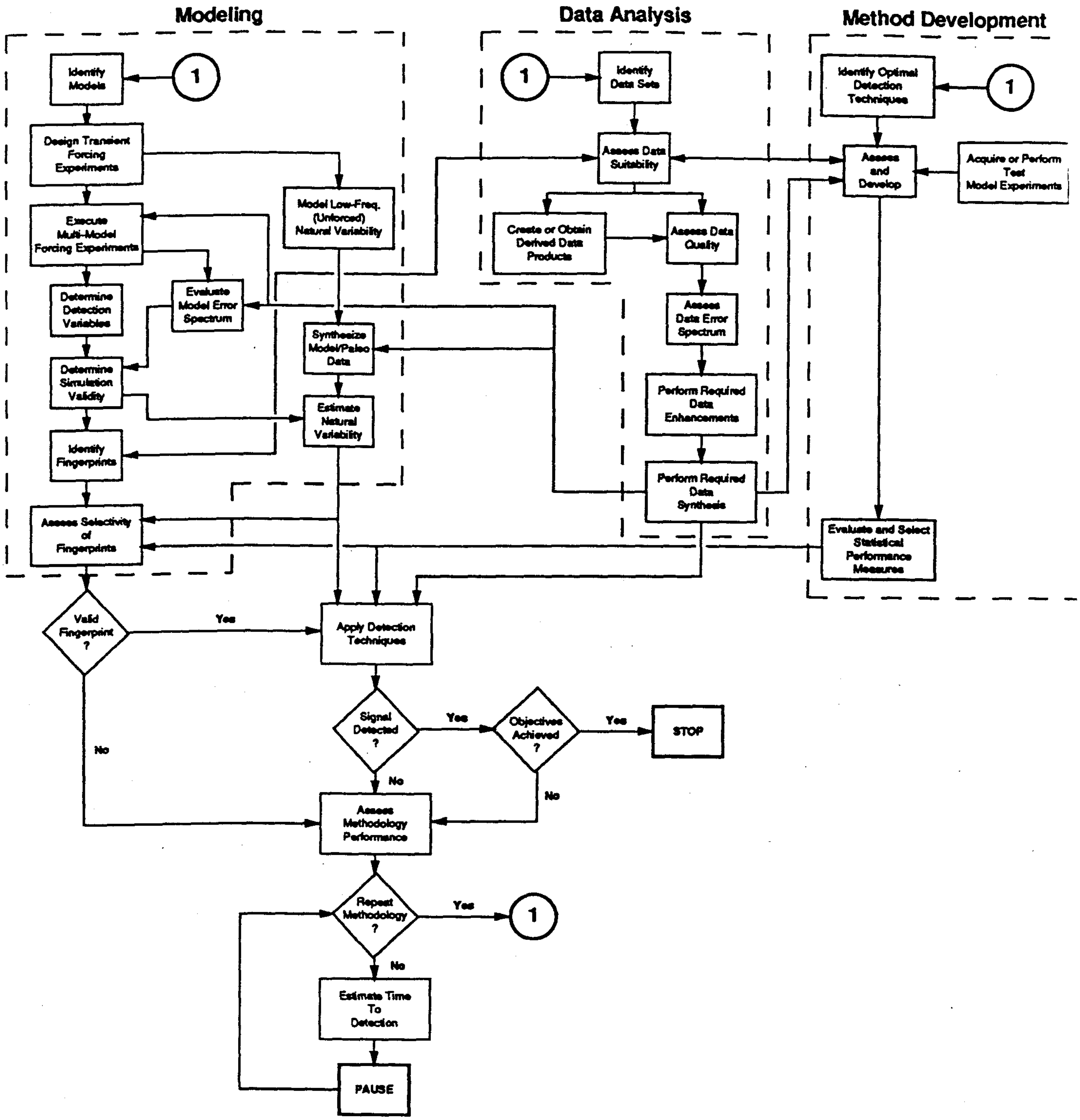

Figure 1. Task sequences and linkages for achieving detection and attribution of human induced climate change

In addition to these multi-model forcing experiments, long control runs (spanning several centuries) are required to determine the natural variability of the models at very low frequencies. Hasselmann (1992), for example, has shown that the low-frequency noise component can have a very strong impact on the definition of the optimal set of variables that can be used to separate the forcing signal from the noise. Multi-century simulations, combined with information from the paleoclimate record, will also provide the best hope for obtaining an estimate of the century-scale variability of the climate system itself.

Once the forcing experiments have been completed, candidate detection-variables are selected by comparing simulations for the type of forcing in question, which defines the expected signal, with an unforced control run covering the same period of time, which defines the noise. Those variables or combinations of variables with the highest signal to noise ratio offer the best prospects for climate change detection and attribution (Barnett et al., 1991; Santer et al., 1992a). However, these variables must be accurately simulated by the models, and they must be among the climate state parameters recorded by the climate observing system.

Determining how accurately each model simulates the various candidate detection-variables for today's climate is the purpose of the next step of the modeling activity. A key step in this evaluation is defining the error spectrum for each model. Such a spectrum will be created for each variable of interest, and it will be used to define the space-time structure of their error field (simulation minus observation). Given the model error spectrum, it is possible to determine the time and space scales (and portions of the modeled domain) for which the model best represents the current climate -- subject to the temporal and spatial limitations of the existing data. Presumably, these scales and regions would also be the ones best simulated in the longer transient forcing and natural variability runs.

Variables that are accurately simulated can then be combined to form multivariate fingerprints whose spatial and temporal behavior might be indicative of anthropogenic climate forcing. Some criteria for the selection of fingerprints include:

- the variable or variables comprising a fingerprint must be generally available in the observational data,
- fingerprints must be specific to anthropogenic forcing -- their patterns should be easily distinguished from patterns generated by other types of forcing or natural variability, and
- fingerprints must consistent from model to model and not sensitive to reasonable model perturbations -- they must be robust.

4.2 Data Analysis Activities

Data are required to document both the physical state of the climate system and the critical external forcing factors (e.g., radiatively active atmospheric trace gases, solar variability, volcanic activity) that drive it. Ideally, these data should:

- span a period of time long enough to establish the relationship between the forcing in question and the hypothesized climate signal and to define the natural variability on the time-scale of interest
- span the spatial and temporal domain over which the hypothesized climate signal has a favorable signal to noise ratio
- represent real, not artificial, climate variations and change
- include the parameters that can be most reliably simulated by a climate model.

In reality, the available climate data base falls significantly short of these stringent requirements. Much of these data were acquired or derived for other purposes, such as weather forecasting, and are of operational rather than research quality. Any climate change detection methodology must, therefore, adopt a strategy that reflects the realities and limitations of the data. Achieving this strategy requires that the data analysis activities be tightly coordinated with the modeling and methodology development elements of the program. Both of these activities must be congruent with the realities of the observations.

Figure 1 provides an overview of the chief data analysis activities of the methodology, and it indicates the principal linkages between data analysis and the other tasks. The obvious first step in the procedure is to identify the data sets that are available for detection studies. These data include instrumental records, derived data products, and proxy data (e.g., climatic inferences from ice cores, tree rings and pollen records). Next, the data must be evaluated in terms of their suitability for detection and attribution. This is a significant and continuing interactive activity with the modeling element -- fingerprints are only valuable if constructed from variables for which there is a suitable climatic record.

Once the potential data record has been screened for suitability, a series of data assessment and analysis activities are required. Derived data sets must either be obtained or created. These data could include such things as simple time series, averages over a given area, or a complete field analysis that provides estimates on a regular grid. Gridded analyses, in turn, might be based on empirical/statistical techniques, or they might be derived from four-dimensional data assimilation procedures. Within the derived data sets, estimates of the climatic variables might be obtained from instrument-based observations, or they could result from proxy reconstructions of climate parameters.

As indicated in the Figure, data quality assessments will be required for both the instrumental records and the derived data products. Two activities of particular importance to this assessment are a critical evaluation of the manner in which the observed data were taken (instrumental bias can masquerade as a low frequency climate signal) and an evaluation of the effect of spatial inhomogeneities in the observations (particularly changes in spatial coverage with time) on derived fields and spatial averages.

Flowing from the assessment and analysis activities will be data error spectra (similar to the model error spectra discussed previously), data enhancements or bias corrections that may be identified as necessary to improve data quality, and the necessary data synthesis and fusion activities required to support the modeling, methodology development, and methodology application activities.

An especially important product of the planned data synthesis activities will be a reconstruction of the behavior of the Earth's climate over the past millennium using the available proxy data. As mentioned in the previous section, this analysis will be combined with model simulations to obtain an estimate of the natural variability of the climate system on the decade to century time scale -- an estimate of the low frequency variability of this system for a period not influenced by large-scale human activity.

4.3 Methodology Development

Figure 1 shows the key activities in methodology development to be the identification, assessment and improvement of optimal detection techniques. The methodology used to achieve detection and attribution must be multi-pronged and subject to a program of continuous reexamination and refinement. Estimation of the climatic effects of anthropogenic forcing and the associated statistical uncertainties cannot rely on a single approach or a restricted use of the available data. A broad attack, even to the point of some redundancy, is necessary to ensure that any conclusions regarding the detection of climate change and the attribution to its root cause or causes result from a comprehensive scientific foundation.

With a few exceptions, past work on climate change detection has concentrated on pattern correlation methods -- determining whether or not the pattern predicted by a model is apparent in an independent set of observations (e.g., Barnett, 1986; Barnett and Schlesinger, 1987; Santer et al., 1992b). Although these techniques are attractive and will continue to be used, the development, testing and application of alternative approaches will be encouraged in this program.

One possible alternative approach involves adapting the methods of classical signal processing theory to the problem (Hasselmann, 1979 and 1992; Bell, 1982 and 1986; North et al., 1992). The main idea is to construct an "estimator" of the signal, which is in essence a filter applied to a weighted, space-time integral over the observed data stream. The filter blocks out the natural variability and passes the signal unaltered -- to the maximum extent possible in a least-square error sense. This "optimal" filter depends on the space-time structure of both the predicted signal and the natural variability. The more (or less) one knows about the structure of each of these, the better (or poorer) the performance of the filter. For example, an otherwise high performance filter can be seriously degraded by a data stream that is poorly sampled or of insufficient length. Therefore, the optimal filter approach offers not only a "best" detection scheme in the least-squares sense but also a consistent basis for framing important questions about the quality of the data and the model simulations, alike.

Once a signal has been detected in the observed data that looks something like the signal predicted for a particular type of anthropogenic forcing, how can one assign probabilities to the assertion that the signal is due to the proposed forcing and not to other factors? Furthermore, how can one assign confidence limits to the estimated magnitude of the anthropogenic component of some observed change? Probability statements use assessments of the errors associated with both the models and the observations, as well as the underlying structure of natural variability. Assuming that both of these are known or can be estimated, one will still need to define a statistical framework in which to pose these questions.

Two possible methods for defining a statistical framework are nonparametric and parametric analysis. In the nonparametric approach, the required statistical reference distribution is generated from the available data using the process of data resampling and data permutation (see, for example, Preisendorfer and Barnett, 1983). The drawback to this approach is that care is needed to preserve spatial and temporal coherence in the resampling and permutation methodology. The parametric approach, on the other hand, frames significance questions in the context of parametrically described frequency distributions.

Parametric approaches allow for the use of statistical likelihood-based confidence assessments of attribution hypotheses (e.g., Solow, 1991). Also, the parametric approach may allow full Bayesian analyses in which confidence levels are derived from posterior distributions on parameters of interest.

In addition to these methods, there are other possible approaches to the significance question. As indicated in Figure 1, these alternatives need to be identified and tested in the context of the detection/attribution problem. It is important that these assessments be conducted with the eventual users of the results of this program in mind -- those who will be the stakeholders in any decision on the global warming issue. Any statements regarding detection and attribution, and the uncertainties inherent to these statements, must be accurately framed in a way that is comprehensible to a non specialist.

4.4 Methodology Application

Once the necessary modeling, data analysis, and methodology development activities have been completed, they are brought together to determine if the observed record exhibits the predicted anthropogenic signal. Put another way, a decision is reached as to whether or not the observations indicate that climate is responding to a particular type of forcing in the manner predicted by climate theory.

Figure 1 shows this conclusion as a simple binary decision. In reality, however, the decision process will be considerably more fuzzy. One possible result of the process is a conclusion that the signal can simply not be extracted from the noise, either because the signal is not sufficiently strong or because the signal predicted by the models is incorrect. Another possible result is that detection of the expected signal is indicated but to a level of significance that is judged to be too low. A third possibility is that the signal might be detected in some variables but not in others. Another possibility might be that detection has been achieved in a particularly esoteric fingerprint that might not be viewed as relevant by decision-makers or opinion-leaders.

In any case, a decision on what to do next must be made if the detection/attribution objectives are not achieved. A decision to proceed would have to be justified on the basis of the prospects for improvements. Examples of such improvements could include significant improvements or changes in models, improvements to the data, or improvements in the techniques used to detect the signal.

5. PRIORITIES FOR IMPLEMENTATION

It is clear from Figure 1 and the previous discussion that the climate change detection program will be carried out in a series of phases. The first phase, which is outlined briefly here, is intended to develop and test the methodological framework and to define the level of effort required for the following phases of the program. Although it is not expected that this first phase will result in any definitive conclusions on the detection problem, we do expect that it will result in a significant advance in the science of climate change detection.

The principal tasks to be performed in Phase 1 are listed below. Although a strict numerical ranking is not intended, the ordering of these tasks is more or less by priority -- tasks near the top of the list are thought to be more important than those near the bottom.

Estimating Natural Variability Ignorance of the magnitude, scales and other characteristics of low-frequency natural variability is perhaps the major impediment to achieving successful detection. Consequently, reducing this uncertainty should be the first priority of the program.

Determining the Feasibility of Attribution Although it is the underlying assumption of the program, there has yet to be a complete, systematic test of whether one type of climatic forcing can be discerned from another. Thus, a series of CGCM experiments are needed to estimate the signals associated with a wide range of climate forcings -- forcings that could be confused with the anthropogenic signal of interest.

Test Application of the Methodology It is imperative that the full methodology be tested as soon as possible -- even if some of its key components are known only poorly. Such a test run is needed to determine the weak points or missing steps of the methodology as well as and those parts that are not practical.

As part of this test application, the following tasks or issues need emphasis:

Signal/Noise Ratios We need to determine, as soon as possible, the intersection between the model-predicted signal and the observations. That is, we must focus the modeling and data analysis activities on the variables that will actually be used for detection.

Signal Robustness We need to determine which aspects (if any) of a predicted forcing signal, such as the signal predicted for a greenhouse gas forcing, are largely model independent.

Observational Uncertainties A variety of work is needed to determine the levels of error in the observations and its space-time structure. Issues for resolution include determining the effect of inhomogeneous (and changing) sampling networks on large regional averages or on gridded fields and documentation of biases resulting from changes in instruments, protocols, sampling times, and so forth. Similar analyses must also be conducted for any proxy data used in the methodology.

Establishing Interdisciplinary Communication The success of the program will depend upon the close cooperation between scientists from several disciplines. Early focus will be placed on bringing together modelers and experts on paleo-data (to address the problem of natural variability) as well as models and observationalists (to consider which variables offer the best prospects for signal detection).

6. ACKNOWLEDGEMENT

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7. REFERENCES

Barnett, T.P., 1986: Detection of changes in the global troposphere temperature field induced by greenhouse gases. J. Geophys. Res., **91**, 6659-6667.

Barnett, T.P., and M.E. Schlesinger, 1987: Detecting changes in global climate induced by greenhouse gases. J. Geophys. Res., **92**, 14,772-14,780.

Barnett, T.P., M.E. Schlesinger, Xingjian Jiang, 1991: On greenhouse gas signal detection strategies. In Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations (M.E. Schlesinger, ed.), Elsevier Science Publishers, Amsterdam.

Bell, T.L., 1982: Optimal weighting of data to detect climatic change: Application to the carbon dioxide problem. J. Geophys. Res., **87**, 11,161-11,170.

Bell, T. L., 1986: Theory of optimal weighting of data to detect climatic change. J. Atmos. Sci., **43**, 1694-1710.

Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley, Jr., J.E. Hansen, D.J. Hoffmann, 1992: Climate forcing by anthropogenic aerosols. Science, **255**, 423-430.

Cubasch, U., K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer, and R. Sausen, 1992a: Time dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate Dynamics, In press.

Cubasch U., B.D. Santer, A. Hellbach, H. Höck, E. Maier-Reimer, U. Mikolajewicz, A. Stössel, and R. Voss, 1992b: Monte-Carlo climate forecasts. To be submitted.

Hasselmann, K., 1979: On the signal-to-noise problem in atmospheric response studies. In, Meteorology Over the Tropical Oceans (D. B. Shaw, ed.), Royal Meteorological Society, Bracknell, Berkshire, England.

Hasselmann, K., 1992: Optimal fingerprints for the detection of time dependent climate change. Submitted to Journal of Climate.

MacCracken, M.C., and H. Moses, 1982: The first detection of carbon dioxide effects: Workshop summary 8-10 June 1981, Harpers Ferry, W. Va.. Bull. Am. Meteor. Soc., **63**, 1164-1178.

MacCracken, M.C., and G.J. Kukla, 1985: Detecting the climatic effects of carbon dioxide: Volume summary. In Detecting the Climatic Effects of Increasing Carbon Dioxide (M.C. MacCracken and F.M. Luther, eds.), U.S. Department of Energy, DOE/ER-0235.

North, G.R., K.-Y. Kim, S.S.P. Shen, J.W. Hardin, 1992: Detection of forced climate signals, part I: filter theory. To be submitted to J. Climate.

Preisendorfer, R.W. and T.P. Barnett, 1983: Numerical model-reality intercomparison tests using small-sample statistics. J.Atmos. Sci., **40**, 1884-1896.

Santer, B.D., W. Brüggemann, U. Cubasch, K. Hasselmann, H. Höck, E. Maier-Reimer, and U. Mikolajewicz, 1992a: Orthogonality of signal and noise in time-dependent greenhouse warming experiments. Submitted to Climate Dynamics.

Santer, B.D., T.M.L. Wigley, and P.D. Jones, 1992b: Correlation methods in fingerprint detection studies. Accepted by Climate Dynamics.

Solow, A.R., 1991: On the statistical comparison of climate model output and climate data. In Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations (M.E. Schlesinger, ed.), Elsevier Science Publishers, Amsterdam.

Wang, W.C., M.P. Dudek, and X-Y Liang, 1992: Inadequacy of effective CO_2 as a proxy in assessing the regional climate change due to other radiatively active gases. Geophys. Res. Lett., **19**, 1375-1378.

Wigley, T.M.L. and T.P. Barnett, 1990: Detection of the Greenhouse Effect in the Observations. In Climate Change: The IPCC Assessment (J.T. Houghton, G.L. Jenkins, and J.J. Ephraums, eds.), Cambridge University Press, Cambridge.