STATUS REPORT: DETECTION AND ATTRIBUTION OF ANTHROPOGENIC CLIMATE SIGNAL

BY THE INTERNATIONAL AD HOC DETECTION AND ATTRIBUTION GROUP

External influence on global climate has been detected by several groups using different data and techniques at confidence levels better than 5%. Observed climate changes in the atmosphere, oceans and cryosphere cannot reasonably be attributed to internal climate variability, while natural drivers such as solar variability or volcanic activity are at most partially responsible for the large-scale temperature changes observed over the past century. Most of the global warming over the past 50 years is likely due to the anthropogenic increase in greenhouse gas levels.

Given this strong evidence for a substantial human influence on global climate, it seems imperative that we now try to determine just what the changes will be on a regional scale for variables that impact society, i.e. what will the coming changes mean to the next generation and their way of life? Without such information, it is not possible to make rational policy choices nor is it possible to develop realistic mitigation and/or adaptation strategies.

1. Introduction
It is now widely recognised that human activities, if continued unregulated, will produce long lasting, major changes in the climate of the earth. The growing public and political acceptance of the climate change problem has been driven by the mounting evidence that the anthropogenic climate change predicted by computer models is becoming discernible, with high statistical confidence, in observations from the oceans, the atmosphere and cyrosphere. Despite the models being far from perfect and some “loose ends” in detection of their predicted signals, especially with regard to regional impacts, there seems no way to avoid the conclusion that the greenhouse signal has been found in real world, global-scale data with high statistical confidence. This statement is based on results of the International ad hoc Detection and Attribution Group (IDAG for short) given in Barnett et al. (1999), plus results reported by the Intergovernmental Panel on Climate Change (IPCC, 1990, 1996 and 2001). The case for detection and attribution has been strengthened by recent results from the IDAG reported in this article. We summarize these newer results below and conclude with a list of areas that need further research to further sharpen detection statements.

Given that the probability of having detected anthropogenic changes in the global climate system is so high, it seems imperative that steps be taken now to see how these changes will affect the World’s population. We call for a comprehensive program to estimate the regional changes expected from increased anthropogenic pollution. Failure to actively push such an effort is simply irresponsible, for without knowledge of what is likely to happen in the future, it is impossible to make rational policy decisions or to plan mitigation/adaptation strategies.
Background
In the last decade, significant advances in the detection and attribution (D&A) problem have been achieved. This is documented in detail in the first three assessment reports of the IPCC noted above and the earlier review article of this group (Barnett et al., 1999). The first IPCC report concluded that the observed changes in climate could not be attributed to human influences with reasonable statistical confidence. The second IPCC report stated that “the balance of evidence suggests a discernible human influence on climate”, while the wording of the third IPCC report was still more affirmative. The recent review of the IDAG (all of whose members contributed in some form to the IPCC reports) arrived at similar conclusions, although more emphasis was given in that report to the many uncertainties and open questions.

Why have we become more confident now in our D&A statements than we were just a few years ago? The answer lies in a number of parallel developments listed below and expanded on in new results from the IDAG in following sections:

1) More comprehensive and detailed analyses of the climate history of the last millennium, using various sources of proxy data, have yielded improved estimates of natural climate variability on the time scales relevant for D&A. **Proxy data indicate the change in Earth’s climate in the last century is unprecedented in the context of the last 1000 years.** However there still remain considerable uncertainties in the true level of climate variability inferred from proxy data (cf. Esper et al., 2002 and Osborn and Briffa, 2002) and the appropriate way to use proxy error. Further note that the early 20th century warming may be also unprecedented in the proxy record and is likely to be largely natural in origin (Tett et al., 2002a).

2) Increasing greenhouse gas emissions and the resultant global warming have led to a continual enhancement in the strength of the anthropogenic climate change signal compared with natural climate variability (five of the seven warmest years since 1861 have occurred since 1997). Although incomplete, 2002 will be the warmest or second warmest year in the record. **We can now rigorously detect the predicted signal in the oceans, the atmosphere and the cyrosphere** (Vinnikov et al., 1999), while also finding good qualitative agreement between model predictions and observations of key hydrological parameters (e.g. Stewart et al., 2002).

3) **Many more scenario simulations**, carried out by an increasing number of climate institutions, applying various combinations of greenhouse-gas, aerosol and natural forcings, **have enhanced the confidence in model simulations**, at the same time providing **also a better understanding of their limitations**.

4) More sophisticated, multivariate statistical analyses have provided improved estimates of signal-to-noise ratios and significance levels for both D&A of recent climate change to anthropogenic and natural forcings. **Assuming the simulated climate variability is an adequate representation of reality, the formal significance levels attributed to detection statements now exceed 95% in most cases.**

In the following sections, we discuss the current status of the D&A problem in more detail, summarizing the advances achieved since the most recent IPCC assessment. Our conclusions and the priority issues/questions still attending the D&A of anthropogenic warming are summarized in the final section.

2. Pre-instrumental data

2.1 The last millennium

Both instrumental measurements and proxy data can be used to investigate climate change and climate variability of Earth’s recent past. Instrumental data are more accurate, but can be used only to investigate climate change since the mid-19th century. Instrumental temperatures (Section 3) indicate a warming of 0.61 ± 0.16°C between 1861 and 2000. Prior to the mid-19th century, only European instrumental data are adequate to extend series back to about 1750.

Before 1750 over Europe (and 1850 elsewhere) it is necessary to use proxy records to estimate temperatures in earlier periods. Although the proxy evidence will be less reliable than instrumental data (e.g. Esper et al., 2002), estimates for earlier centuries (particularly the last millennium) are vital as they enable the last 140 years to be placed in a longer context. These records also provide the likely range of variability on decadal to century time scales that can occur naturally due to external forcing from solar output changes and explosive volcanism and to internal factors.

Compilations of proxy records developed during the last few years clearly show that the planet has warmed rapidly in the last 100 or so years (see review by Jones et al., 2001). Although there is increasing uncertainty for earlier centuries in the millennium, there is surprising agreement between the temperature time series developed by different authors (Figure 1a). Average temperatures during the last two decades were likely the warmest of the last millennium (0.2°C warmer than the 1961 to 1990 average), about 0.2°C warmer than warm decadal periods in the 11th and 12th centuries. The first half of the millennium was generally cooler than the last 20 years, but milder (0.2°C below the 1961-90 average) than the 1500 to 1900 period. The coolest century was the 17th followed by the 19th, separated by a milder 18th century. The inter-century range, estimated by all compilations, is of
the order 0.5°C, implying that the 20th Century temperature increase encompasses slightly more change than experienced in all of the previous nine centuries. So, the proxy-derived series show that 20th century warming is unique in the last millennium both for its size and rapidity. It is probable, however, that the early 20th century warming is largely natural in origin (Tett et al., 2002a) suggesting that natural temperature variability can be as large as that due to anthropogenic forcings.

This view of temperature change over the last 500 years has been challenged recently by reconstructions of past surface temperatures derived from boreholes (see Huang et al., 2000 for a discussion of the results, reconstruction techniques and the myriad of confounding influences). Boreholes only provide centennial timescale information and suggest that surface temperatures have warmed by over 1°C since 1500, compared to the conventional proxy estimate of about 0.5 ± 0.2°C (Figure 1a). Part of the discrepancy is due to the seasonal differences in the response of different proxy series. Conventional proxies mainly respond to the growing season (Figure 1b) while boreholes respond to the entire year.

Knowledge of past inter-century temperature variability is a vital factor in constraining the estimate of climate sensitivity (ΔT2x). The conventional proxy temperature change is compatible with a value for ΔT2x of about 2-3°C (based on estimates of the forcing by solar variability and volcanoes (Crowley, 2000, see Section 2.2). If the borehole estimate of change since 1500 is correct, a much higher climate sensitivity is required to explain the course of millennial change.

Reconciling conventional and borehole proxies is therefore important in reducing uncertainties in D&A studies. Areal weighting of the 453 Northern Hemisphere borehole series, rather than simple averaging as in Huang et al. (2000), reduces the warming since 1500 by 0.2°C; a result due solely to signal processing. Other reassessments of borehole records further reduce any discrepancy (Mann et al., 2002).

At this time, most evidence points to the conventional proxy (as opposed to the boreholes) view of the last millennium as being nearer reality.

Although the full significance of the borehole/conventional proxy difference has only been realized by a few, it has served paleoclimatology well by forcing a reassessment of exactly what part of the year a proxy represents.

For each proxy, the response ‘season’ needs to be more clearly defined. Greater realization of the seasonal limitations of all proxy reconstructions is required in the future; a lesson the apparent borehole/paleo proxy contradiction brings home clearly.

### 2.2 Paleoclimate forcing and modelling studies

Substantial progress has been made over the last few years in refining paleo-proxy forcing time series and applying them to simple energy balance climate models (EBMs). Based on a comparison of EBM simulations and proxy reconstructions, Crowley (2000) estimated that about 50% of the decadal averaged pre-anthropogenic Northern Hemisphere temperature variance can be attributed to a direct response to solar and volcanic variability. The results of that study have been updated and assessed in three different ways. First, a homogeneous millennial proxy time series has been developed for the mid-high latitude (30-90N) and calibrated against the Jones et al. (1999) instrumental record. Second, the proxy forcing time series have been updated, with the volcano forcing improved to include more data and validation with the results broken into four equal-area strips so that it can be used for both GCM studies and EBM calculations. Finally, a new 2.5D EBM has been developed that includes geography, the seasonal cycle, and upwelling-diffusive coupling to the deep ocean. This approach allows the model output to be subsampled over the same domain represented by the paleo data.

Comparisons of the new model results against the new paleo data reconstruction, and against the Briffa et al. (2001) reconstruction of Northern...
Hemisphere summer temperature changes over land (Figure 2), confirm the previous conclusions by Crowley (2000). They also suggest a proportionately larger role for volcanism and a lesser role for solar variability, but this depends on the length of time series and data being analysed. Solar variability at present can explain only ~0-10% of the pre-anthropogenic variance, while volcanic forcing explains nearly 50% (a small additional amount of variance is explained by the small CO₂ drop in the Little Ice Age). Almost 70% of the decadally-scaled variance can be explained in the whole proxy record (1005-1995). This study also clearly indicates that only greenhouse gas forcing can explain the late 20th century temperature increase.

Multiple regression can also be used to attribute climate variability in the last millennium to solar, volcanic and greenhouse gas (plus sulfate aerosol for the 20th century) forcing. A range of reconstructions have been compared with the respective seasonal and hemispherically-averaged data from the EBM simulations. The results indicate that the response to volcanism and greenhouse gases can be clearly detected in most records (Briffa et al., 2001; Crowley et al., in prep; Mann et al., 1999) with only small differences in results for different records. Simulations with a climate sensitivity of 2.5 yield results that are consistent with the reconstructions (Figure 3; Hegerl et al., in prep). The response to solar forcing cannot be detected, although the EBM simulation of solar forcing is not inconsistent with the record. The uncertainties in estimates of solar response are too large to be detected, since the forcing is rather small and is dominated by very-low-frequency variability. Also, errors in the forcing history, particularly early in the record, might obscure the solar signal (Lean et al., 2002).

Comparing simulations with varying climate sensitivities, ocean-heat uptake and aerosol forcing to the observations can help reduce the uncertainty in the estimation of climate sensitivity. First results from this modelling effort are in broad agreement with results using 20th century instrumental data only (Forest et al., 2000, 2002), which indicate a 10-90% range on climate sensitivity of 1.8-6.5K (Allen and Ingram, 2002). Inclusion of palaeodata reduces the upper bound of this uncertainty range closer to 4.5K (Hegerl et al., in prep).

Further work using the post-1400 part of the forcing time series (where Antarctic ice cores can be used to estimate global changes in radiative forcing from volcanism) can be used to estimate global changes in ocean heat storage (Figure 4). Using the best-fit model comparison against the surface proxy data set, we estimate substantial changes in ocean-heat storage during the Little Ice Age and a warming that commenced in the mid-19th century. The end of the record agrees very
well with the Levitus et al. (2001) reconstruction of ocean heat storage changes. The first phase of the ocean-heat storage increase represents a relaxation towards a warmer background state after the intense phase of volcanism in the early 19th century. The more recent increases in ocean heat content (and associated sea level rise) are driven mostly by the greenhouse gas increases. Even though greenhouse forcing was much greater in the second half of the 20th century, its effect on ocean-heat storage has been damped by both the increasing tropospheric aerosol effect and the resurgence of volcanism in the last four decades. Three of the largest ten eruptions in the last 600 years have occurred during this time.

3. Instrumental Data

3.1 Surface Temperature

Averaged globally, surface temperature has warmed 0.61°C since 1861. Assessments, including all known systematic and sampling errors in the basic land and marine data, indicate that this trend has an uncertainty of ±0.16°C (Folland et al., 2001). The current land surface temperature database has recently been enhanced by Jones and Moberg (2002), because the raw land and marine temperature data are not a static resource. Attempts are underway in many countries to improve data quality and extend data availability. Unfortunately, most efforts are concentrated in developed countries when they would be better deployed in Central and South America, Africa and southern Asia. In these regions many more data series await rehabilitation. For ocean areas, improvements in data availability are expected in the next few years for the 19th century and the two world war periods (Diaz et al., 2002). Despite these efforts and the potential recovery of new data in less developed regions of the world, it is unlikely that the warming trend (global) will be significantly altered and uncertainties associated with its estimation only marginally reduced. Emphasis in observational climatology should also be placed on other variables (e.g. pressure, precipitation and cloudiness/sunshine) in order to gain a more complete picture of instrumental climate change (from the mid-19th century onwards) than currently available from just temperature.

3.2. Variability and extreme events

Anthropogenic climate change should not only affect the climatic mean state, but also modes of climate variability (e.g. Palmer, 1999) and climatic extremes (IPCC, 2001). Such changes are expected to have a much stronger societal impact than changes in the mean and, therefore, need to be monitored rigorously.

An example of the state of the art, is the recent tendency of the AO/NAO (also called Northern Annular Mode) to linger in its positive state (Thompson and Wallace, 1998, Thompson et al., 2000, Gillett et al., 2002a). This has been attributed by some to anthropogenic greenhouse gas increases and/or ozone forcing (Shindell et al., 2001 and Fyfe et al., 1999). But although all anthropogenically forced models consistently produce a strengthening of the pressure gradient between the Mediterranean and the Arctic, regional details are not consistent between models (Gillett et al., 2002c and Osborn, 2002). Natural variability of the NAO/AO cannot be fully eliminated as longer episodes showing similar changes have occurred in the early 20th century and earlier centuries (from paleo reconstructions, Luterbacher et al., 2002) and recent winters have seen a decline in the NAO back to more average levels of the 1951-80 period. The change in the NAO is more unusual with respect to the observed earlier variability than that in the NAO index (Thompson et al., 2000), but the AO index early in the 20th century suffers from data uncertainty. Therefore the attribution of the observed AO/NAO trend to human influences is uncertain (Osborn, 2002, Gillett, et al., 2002c). Note, however, that anthropogenic temperature change is detectable even if AO-induced warming is removed (Gillett et al., 2000c; see also Zwiers and Zhang, 2002).

Evidence for observed changes in climatic extremes is generally ambiguous and attribution attempts are therefore premature. The evidence seems to depend on the region considered and the
analysis method (IPCC, 2001). So far, only a few global analyses have been performed, mainly due to the poor availability of daily station data. This situation is rapidly improving since indices for temperature and precipitation extremes are becoming available, including regions where daily station data are not readily available (Frich et al., 2002). A first analysis of a subset of indices suggests detectable signals for temperature extremes, but poor agreement between modeled and observed changes in rainfall and drought extremes (Kiktev et al., 2002). Significant increases in extreme precipitation over the United States have been reported (e.g. Karl and Knight, 1998; Groisman, et al., 1999), the average increase is similar to changes expected for greenhouse warming (for example, Semenov and Bengtsson, 2002). Tendencies in the frequency of extratropical storms and hurricanes generally depend on the analysis methods, the region considered, and the definition of the events considered; results are therefore ambiguous (for example, Lambert, 1996). Widely reported increases in hurricane damage are to a large part attributable to increased vulnerability rather than changes in events (Landsea et al., 1999). In short, anthropogenic changes in extreme events have not yet been rigorously detected, and may not be easily detectable given data and model uncertainty.

Studies based on model data alone can be used to determine suitable approaches for the early detection of changes in climate extremes. For example, model results suggest that precipitation extremes change generally stronger than mean precipitation (Groisman et al., 1999 for observations; Wehner, 2002; Semenov and Bengtsson, 2002; Hegerl et al., 2003 for models). Simulated changes in temperature extremes cannot be explained by a shift in the temperature distribution alone, either (Hegerl et al., 2003). Therefore, daily data cannot be substituted by monthly or seasonal data to record and detect changes in extremes.

Simulated changes in global average annual and extreme precipitation appear to be quite consistent between models and follow physical principles (Allen and Ingram, 2002). However, the spatial pattern of precipitation changes is very different between models. The latter makes changes in annual mean precipitation difficult to detect in data from another model, and probably also in observations. A model-model study, where fingerprints from one model were attempted to detect in simulations from another suggests, that changes in intermediately extreme precipitation may be more robustly detectable (Figure 5, Hegerl et al., 2003). This is mainly because precipitation extremes increase over a large fraction of the globe, making detection results less sensitive to the spatial pattern of change.

3.3 Radiosonde and satellite data

A persistent criticism of studies that claim to have identified human effects on global climate is that the models used in such studies cannot simulate the recent behavior of tropospheric temperature (Singer, 1999, 2001). This criticism
relies on observational records of tropospheric temperature change derived from radiosondes and the satellite-based Microwave Sounding Unit (MSU). Both records appear to show little or no warming of the troposphere since operational MSU temperature measurements began in 1979 (Parker et al., 1997 and Christy et al., 1998). In contrast, model simulations of the response to anthropogenic forcing often show pronounced tropospheric warming over this period (e.g., Santer et al., 2001 and Tett et al., 2002).

The apparent failure of the troposphere to warm over the past 23 years has also been used to question the recent warming of the Earth’s surface (Singer, 1999), which is estimated to range from 0.15 to 0.20°C/decade. The reality of recent surface warming has been confirmed by numerous investigations (see, e.g., Jones et al., 1999; National Research Council, 2000), although there are some concerns that it may have been overestimated in the equatorial Pacific (Christy et al., 2001).

The best observational evidence currently available indicates that the rates of surface and tropospheric warming have evolved in a complex way over the past 40 years. Gaffen et al. (2000) showed that the tropical troposphere warmed relative to the surface over 1960-1978, and thereafter cooled relative to the surface. Similar multi-decadal changes in lapse rate have been noted by Brown et al. (2000) and Hegerl and Wallace (2002). Over the period 1959-1998, Angell (2000) found no discrepancy between the overall warming rates at the surface and in the lower troposphere. These results clearly illustrate that our perspective on interpretation of observed lapse-rate changes should not be limited to the MSU era.

A number of recent studies have sought to understand the possible causes of differential surface and tropospheric warming rates in both models and observations. This work has focussed on the effects of:

**Spatial coverage differences between satellite data and surface observations**

While the Christy et al. (2000) MSU 2LT data have global coverage, the surface data are spatially incomplete (Jones et al., 1999) and undersample some of the muted warming of the Southern Ocean that occurred during the satellite era. These differences in spatial coverage could explain up to one-third of the difference between surface and lower tropospheric temperature (2LT) trends over 1979-1999 (Santer et al., 2000).

**External forcing (primarily explosive volcanic eruptions and stratospheric ozone depletion)**

External forcing also helps to reconcile some of the differential warming. Model results from Bengtsson et al. (1999), Hansen et al. (1997), and Santer et al. (2000) strongly suggest that both volcanic eruptions and stratospheric ozone depletion may have cooled the troposphere by more than the surface over the last several decades (see Section 2.2 also). Observational studies by Santer et al. (2001) and Free and Angell (2002) yield similar conclusions. There are, however, uncertainties in quantifying the differential cooling caused by these forcings, both in models and observations. These arise from uncertainties in the volcanic and ozone forcings, from errors in the model responses to these forcings, from the short length of the MSU 2LT record, and from difficulties in deconvolving the temperature effects of volcanoes and ozone depletion from the effects of ENSO variability.

**Modes of natural internal variability**

Several recent investigations have assessed the differential effects of natural modes of variability on observed surface and tropospheric temperatures. They find that ENSO has probably made only minor contributions to overall differences in observed surface and tropospheric warming rates (Santer et al., 2001; Hegerl and Wallace, 2002). The same applies to the AO and to other modes of natural internal variability (Hegerl and Wallace, 2002).

There are two main messages from this body of work. The first is that accounting for coverage differences, volcanic and ozone forcing, and natural internal variability helps to explain some but not all of the apparent differential warming of the surface and lower troposphere in the observations (Santer et al., 2001; Hegerl and Wallace, 2002). The second is that accounting for differences in some of these factors in models and observations generally improves the correspondence between modeled and observed temperature trends, but cannot reconcile models and observations completely.

One can interpret these results in at least two ways. In the first interpretation, the observational estimates of surface and tropospheric temperature are taken at face value, assuming that remaining uncertainties are very small. If this is the case, the recent differential warming of the surface and lower troposphere is real, and we do not fully understand why it exists in the observations, or what factors control its behavior on multi-decadal timescales (Gaffen et al., 2000; Hegerl and Wallace, 2002: Figure 6). Nor can we simulate this differential warming with fidelity in coupled model experiments with combined anthropogenic and natural forcings. Under this interpretation, we would conclude that our inability to reliably simulate the observed differential warming was due
to a combination of model error and missing or inaccurately-specified external forcings.

The second interpretation focuses on observational errors as the explanation for the remaining discrepancy. There is some recent evidence to support this interpretation. A complete reprocessing of the MSU channel 2 temperature data by Wentz et al. (2001) yields a markedly different result, with warming of +0.142°C/decade over 1979-2000. Anomalies in both data sets are defined relative to their respective climatological monthly means over 1979-1997.

Figure 6: Changes in global-mean monthly-mean mid- to upper tropospheric temperatures (MSU channel 2) over 1979 to 2000. The Christy et al. (2000) version of the MSU channel 2 data shows virtually no overall warming (+0.014°C/decade). Independent reprocessing of the raw channel 2 radiances by Wentz et al. (2001) yields a markedly different result, with warming of +0.142°C/decade over 1979-2000. Anomalies in both data sets are defined relative to their respective climatological monthly means over 1979-1997.

Explain. Coupled with the effects of coverage differences, external forcing, and internal variability, residual errors in the observations might fully resolve the apparent discrepancy between surface and tropospheric warming rates. Under this second interpretation, there is no serious inconsistency between modeled and observed tropospheric temperature trends (Santer et al., 2002a; Figure 7).

The truth probably lies somewhere between these two interpretations. However, our group’s work on MSU-related issues highlights the importance of reducing uncertainties in satellite- and radiosonde-based estimates of recent tropospheric temperature changes. For example, one view of the MSU data suggests “close correspondence” with greenhouse driven model results, while the other interpretation suggests there is a “fundamental inconsistency” between the models and observations. The resulting impact on claims that MSU data do or do not support increased warming are huge (c.f. Figure 7). This is an unsatisfactory situation for climate-change D&A studies. The differing results of Wentz et al. and Christy et al. need to be reconciled.

3.4 Ocean warming

The oceans, because of their large heat storage capacity, are the thermal flywheel of the planetary climate system. They store most of the heat and, along with the atmosphere, redistribute it to maintain the climate system, as we know it today. As global warming effects increase, it is critical to know just how oceanic heat storage will be affected.

Recent work by Levitus et al. (2001) has made it possible to document changes in oceanic heat content over the last 45 years. These have been evaluated on an ocean-by-ocean basis by Barnett et al. (2001). They found that the heat content in the upper 3000m of each of the world’s oceans has been increasing since 1955, the beginning of the Levitus data set (and apparently well before that, Section 2.2), and further that the model had the same levels of decadal variability as the observations. These observed changes were compared with similar changes predicted by five different realizations from a global climate model forced with observed anthropogenic pollutants over the same time period. The model predictions and observations were submitted to a rigorous D&A analysis (c.f. Hegerl et al., 1997; Allen and Tett, 1999). The results showed that the model results could not be distinguished from the observations at the 5% confidence level, i.e. the probability of the model producing the observed signal by chance was less than 5%. In other words, the model and observational data on increases in the oceans’ heat content over the last 50 years were statistically identical. Similar results have been
reported by Reichert et al. (2002) for a different climate model.

Other potential sources of the observed ocean warming have since been investigated. Changes in various measures of solar luminosity, which have been monitored in detail for over 20 years, could explain only a few percent of the observed changes. Geothermal heat escaping to the oceans from the great rifts could explain perhaps 15% of the observed change: the seafloor heating is unlikely to be a major factor. By contrast, greenhouse-driven warming explains the observed oceanic warming completely.

Future efforts must seek to evaluate the heat input into the oceans, and their response, on a full three dimensional basis. Such information will be valuable for checking the validity of global climate models. Regional ocean information will also be necessary for regional response studies and biological impacts analyses.

3.5 Sea Level

Changes in sea level have been measured at a surprising number of locations around the world since before 1900. Several studies conducted over the last 20 years have suggested a linear rise of sea level of approximately 18 cm over the last century (IPCC, 2001), a value that has substantial uncertainty attached to it. A continued rise associated with anthropogenically-induced ocean warming (steric effects) and reduction of land ice could have potentially large impacts on low lying regions of the Earth such as the Gulf Coast of the United States, the world’s main deltaic regions and assorted island chains (e.g. the Maldives). But how much of the observed rise to date can be attributed to anthropogenic causes?

It has recently been possible to begin to partition the observed increase in sea level to various physical mechanisms (cf. Munk, 2002). The global ocean temperature data provided by Levitus et al. (2000, 2001) referred to above, shows a rise of 3 cm due to greenhouse warming. The IPCC attributes 6 cm/century to melting of land-bound ice and other eustatic processes. This raises a serious problem as noted by Munk (2002), since there remains about 50% of sea level rise to account for: the observed sea level rise starts too early, is too linear and is far too large to be due to...
anthropogenic effects alone. Munk notes that the differential might be explained by melting of the polar caps, but observed changes in the Earth’s rotation characteristics only partially support such conjecture.

Future work needs to be directed at resolving this important ‘enigma’ as Munk calls it. The results of Section 2.2 show that a substantial part of the unexplained difference could be due to ‘rebound’ from strong volcanic episodes, although this needs to be verified with a more sophisticated ocean model. But Munk (2002) notes other possibilities abound. Are current estimates of sea level rise accurate enough to claim the unexplained difference is real? Could estimates of heat storage in the oceans be wrong, especially in the deep ocean where there are few observations? Or perhaps, the astronomical observations from the late 19th and early 20th centuries have enough uncertainty to better support the polar melting idea.

In summary, there are large uncertainties in observed sea level rise over the last 100 years, a rise we cannot adequately explain at this time. But it seems clear that global warming will almost certainly cause a significant change in the level of the world’s oceans. The problem is that estimates of future sea level changes are attended by large uncertainties so that the signal-to-noise ratio for the anthropogenic sea level rise is currently small.

### 3.6 Tropopause height

The tropopause marks the transition between the turbulently-mixed troposphere and the more stably-stratified stratosphere. It can be defined in a variety of ways, based on thermal, dynamical, and chemical properties of the atmosphere (Seidel et al., 2001). Measurements from radiosondes indicate that the height of the tropopause has increased in recent decades (Ramaswamy et al. 2001; Seidel et al., 2001). Reanalysis products show similar changes (Randel et al., 2000; Santer et al., 2002b). Superimposed on these decadal-scale increases in tropopause height are decreases associated with major volcanic eruptions.

Until recently, no attempt has been made to identify model-predicted tropopause height signals in observational data. Preliminary evidence suggests that changes in tropopause height may be a useful fingerprint of human-induced climate change. Its behavior is an integrated response to temperature changes in both the troposphere and stratosphere, leading to signal-to-noise (S/N) characteristics that are markedly different from those of atmospheric temperatures in discrete layers. Other properties that are useful from a detection standpoint include high S/N ratios in model data (Santer et al., 2002c) and filtering of variability on ENSO time scales.

Model results show that the observed decadal-scale increase in tropopause height is largely driven by the GHG-induced warming of the troposphere and the ozone-induced cooling of the stratosphere, and that natural variability alone (internal, solar, and volcanic) cannot explain this increase. Even without optimization, the model fingerprints of anthropogenically-forced tropopause height change are readily detectable in reanalysis data (Santer et al., 2002c). Further work is necessary to determine whether the behavior of the tropopause can be used to constrain existing uncertainties in our estimates of observed tropospheric temperature changes (Section 3.3).

### 3.7 Other climate indices

In addition to the climate change data discussed above, a number of qualitative climate change indices (see below) have been investigated for potential evidence of anthropogenic signal. Most of these studies are fraught with uncertainties, for the natural variability of the indices is unknown. Such knowledge is a necessary factor for conventional statistical D&A analysis. For this reason, detection of an anthropogenic signal in these indices was not considered in detail by the IDAG. However, we plan to incorporate these indices in a generalised, comprehensive Bayesian D&A analysis (see also Section 4.2).

We note it is important that the high-visibility climate indices be subjected to Bayesian analysis soon, for some of these indices suggest major shifts in global climate. Examples include: Arctic sea ice extent and thickness, which show progressive decline in the last three decades; glaciers, which have been retreating world-wide for more than a century; ice shelves in the Antarctic, of which large sections have broken off recently; coral reefs, which have been extensively affected following recent El Niños and the frequency of extreme events, which have increased in some regions (such as storms in the North Atlantic, extreme precipitation events, etc). All are discussed in the latest IPCC (2001) report. The attribution of changes in these indices to anthropogenic global warming rather than internal climate variability is in most cases speculative, but the variables represent high impact outcomes of climate change and have accordingly received considerable public attention. A further clarification of the origin of these changes, and the inclusion of existing subjective judgements of the likely causes of the changes within an overall Bayesian D&A analysis, therefore appears desirable at the earliest possible date.

### 4. Theoretical analysis

#### 4.1 Conventional D&A analysis

The reliable D&A of climate change requires, first, a demonstration that a climate change has occurred that cannot be attributed solely to internal climate variability (detection) and, second, the identification of the external forcing responsible for the observed climate change
Optimal D&A methods are generalised regression methods that are particularly suitable for attributing observed climate changes to externally-forced climate change signals (Hasselmann, 1979; Hasselmann et al., 1997, Allen and Tett, 1999). Applications of these methods to observed large-scale surface temperature change during the 20th century (Hegerl et al., 1996, 1997, 2001; Tett et al., 1999, Stott et al., 2001, Allen et al., 2002, Barnett et al. 2001) showed that significant warming has been observed that can not be explained by natural external influences, i.e. the warming is due to anthropogenic causes. Even though natural climate influences such as volcanoes and changes in solar radiation can be detected, they cannot explain the major part of the observed warming. Anthropogenic climate change is also clearly detected in changes in ocean heat content over the last 50 years (Barnett et al., 2001), Arctic sea ice extent (Vinnikov et al., 1999), changes in the diurnal cycle of surface air temperature (Schur, in prep) and changes in tropospheric height (Santer et al., 2002b). In summary, the predicted global warming signal has been rigorously detected with high statistical significance by several methods in key climatic fields.

Small differences between the D&A results can be explained by the use of stepwise versus multiple regression (Hegerl and Allen, 2002) and data-treatment methods. The latter include the season over which temperatures were averaged, the length of the climatology from which anomalies were taken and the use of a time-evolving signal pattern as opposed to a spatial pattern of temperature trends (Gillett et al., 2002a). This demonstration of consistency and robustness of results increases our confidence in the detection of anthropogenic climate change.

The comparison of results in combination with application of the time-space detection algorithm to data from a broad range of climate models (Allen et al., 2002) shows that estimates of the warming attributable to anthropogenic greenhouse-gas increases vary from model to model (Figure 8). However, all model-estimates of large-scale warming indicate that a substantial fraction of the observed warming has been caused by greenhouse gases. In many cases the estimate of the greenhouse-gas-induced warming is larger than the observed warming, since it is countered by sulfate aerosol cooling. This led to the IPCC statement that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (IPCC, 2001).

Despite the qualitative similarity in detection results, estimated contributions of individual forcing agents to the observed warming are sensitive to which model was used to estimate the climate change signal and climate variability. The sensitivity is partly due to differences in forcing and response to sulfate aerosols and to forcing mechanisms that may be in some models, but not others. It can be shown that the sulfate aerosol signal is mainly responsible for reported significant differences between a number of climate model simulations and observations that were reported in Barnett et al. (1999) (Figure 8, Hegerl and Allen, 2002). Part of this problem is due to the uncertainty in our understanding of sulfate aerosol forcing, particularly the contribution by indirect sulfate aerosol forcing, and the forcing by non-sulfate aerosols, soot, biomass burning etc. (see e.g. Sateesh and Ramanathan, 2000 and IPCC 2001).

Even if forced with nearly identical sulfate aerosol forcing, two different models can show substantial differences in their response, which influences their detection results (Hegerl et al., 2000). Attributed responses to natural climate forcing are also model sensitive (Allen et al., 2002). Therefore, a rigorous treatment of model uncertainty within the detection framework is a necessary next step in D&A research (Barnett et al., 2000).

A first attempt to estimate model uncertainty has been based on inter-model differences. Detection results from five models (HadCM2, HadCM3, CGCM1, CGCM2 and ECHAM3) were synthesised using the mean response patterns as fingerprints in a detection of greenhouse gas and sulfate aerosol influence, including an estimate of model uncertainty (Gillett et al., 2002b). Preliminary results indicate that the inter-model differences do not greatly increase D&A uncertainties as applied to temperature data and that averaging fingerprints actually improves detection results. This statement does not preclude the possibility that systematic errors common to all models may still be important, and intermodel differences may be much more important in the detection and attribution of either regional temperature changes or changes in precipitation (Allen and Ingram, 2002).

The impact of global warming on society is largely determined by spatial scales far smaller than those associated with D&A studies to date. But can the D&A studies done to date tell us anything about these more critical regional scales? We answered this question by repeating a D&A study on a global data set from which we systematically deleted global mean information. The result is shown in Figure 9a-c (after Allen et al., 2002). The detection diagram with full global mean information is shown in Figure 9a (corresponding to Figure 12.12 in the most recent IPCC report). Virtually all of the models considered are seen to produce a highly significant D&A result. Removing the linear trend in the global mean (Figure 9b) still gives a significant signal, although the confidence levels are
somewhat wider. Removing all global mean information (Figure 9c) produces even wider confidence limits, and now only about half of the models produce a significant result. But, given the high confidence levels with which we are working, this still represents a strong endorsement for significant D&A; the joint likelihood of this many models producing 95% significant results is minuscule simply as a result of a chance modelling artefact is minuscule (although it must be emphasised that these studies all rely on the same set of observations, and so are not fully independent). This later result also rules out the possibility that the models were tuned to give the desired answer, for tuning a CGCM to this level of space-time detail is beyond current capabilities.

The reduced signal-to-noise ratio shown in Figure 9c for sub-global scale information is expected. However, some of the models appear to be able to capture more of the regional signal correctly than others. This suggests that a full scale evaluation of current CGCMs’ ability to simulate regional climate changes associated with anthropogenic warming is critical and needs to be begun immediately.

**4.2 Bayesian analysis**

As mentioned in Section 3.7, some of the evidence of anthropogenic climate change is circumstantial and, through lack of an adequate statistical data base, cannot be quantified within the framework of the conventional D&A analysis described in the previous sub-section. It would nonetheless be useful to incorporate this form of evidence within a comprehensive D&A assessment of climate change. This requires, however, consideration of the necessarily divergent subjective assessments of the relative probabilities of alternative explanations of observed climate change. The tools for this approach are available in the form of Bayesian statistics (e.g. Earman, 1992).
The basic Bayesian approach to the D&A of climate change has been described in Hasselmann (1998) and Risbey et al. (2000). We have developed an optimal filtering technique appropriate for the Bayesian method (Schnur and Hasselmann, 2002). In the conventional D&A approach, optimal filters (optimal fingerprints) are introduced to maximize the signal-to-noise ratio with respect to the natural variability noise. In the Bayesian approach, in contrast, the goal is to maximize the impact of the observations (the "evidence") on the probability that the hypothesis of an anthropogenic origin of climate change is true. In the conventional approach, the optimal filter is critically dependent on the model specifics, whereas in the Bayesian approach, the model error structure is included in the analysis.

As a first step towards the planned application of the Bayesian approach to the complete set of available climate change data, the method has been illustrated in Schnur and Hasselmann (2002) using four observed and simulated data sets with two different external forcing hypotheses: greenhouse gases alone (GHG) and a superposition of greenhouse gas and sulfate aerosol forcing (GS). Significantly more response patterns could be retained in the Bayesian analysis than in the conventional analysis (Figure 10a).

The results of the Bayesian analysis are summarized in Figure 10b in terms of the prior and posterior probabilities for each variable and hypothesis, including the net posterior for using all four variables simultaneously as evidence. We assumed uninformed (i.e. equal) priors, in which case the ratio of posteriors for the two hypotheses $H_1$ and $H_2$ represents the posterior odds of $H_1$ over $H_2$, or the impact of the evidence (observations) on the prior odds. For temperature, the odds of hypotheses GHG and GS against the natural-variability hypothesis are seen to be very large, i.e. the GHG and GS signals are clearly detected in the observations. The odds of GS over GHG is only 2, however, which does not represent decisive evidence for one hypothesis over the other. For diurnal temperature range (DTR) and precipitation, detection is not achieved, since the posterior for the natural-variability hypothesis is higher than the posteriors for either GHG or GS. In the net result, GHG and GS are still both detected, with the odds of GS over GHG being only slightly larger than one. In the Bayesian analysis, the inclusion of the model error structure leads to a downgrading of the information on the impact of sulfate forcing, in comparison to conventional detection analyses. Thus, through the inclusion of model errors, the Bayesian analysis automatically quantifies the effect of the differences in the impact of sulfate forcing found by different models in the conventional analysis.

It is planned to apply the Bayesian method to the complete set of climate change observations that have been considered in the past as possible evidence of anthropogenic climate change. This
requires (subjective) assessments of the natural variability and predicted climate change signals for all relevant climate indices (including model errors, and inter-index correlations of natural variability and model errors). Work on collecting this information from various sources is in progress.

5. Conclusions and Recommendations

5.1 Conclusions

The conclusions of the Detection and Attribution Group are in accordance with the general consensus expressed in the recent IPCC report (IPCC, 2001), namely that climate change has been detected today by several groups using different data and techniques at significance levels above 95%. The observed global warming over the past 50 years cannot reasonably be attributed to internal natural variability alone or to external natural forcings such as solar variability or volcanic activity. Its most likely dominant cause is anthropogenic in origin.

We also conclude that we are not now in a position to estimate the accuracy of estimates of regional climate change from anthropogenic forcing. The problem here is one of neglect, not scientific inability. It is the regional changes that will affect our society, so discussion of changes in global averages is irrelevant in this regard. We call for an immediate and all out effort to determine, in detail, just what kind of world anthropogenic forces are creating for our heirs. In particular, models should be applied to produce rigorous, coordinated regional predictions of variables important to society, such as rainfall, snow pack, drought indices, and variability of critical climate indices. This will be a long term effort, beginning with crude results but eventually producing the information decision makers require.

Foremost among the questions to be addressed by such a program is the impact of anthropogenic climate change on regional climate features such as El Niño and the North Atlantic Oscillation, and extreme events, such as floods, droughts and storms. For the practical implications of climate change, a better understanding of these impacts, and the early detection of changes in these climate features induced by human activities, are more relevant than the demonstration that the global mean temperature, for example, has increased through greenhouse warming. Serious scientific questions attend each of these areas, from model predictions of the changes in the climate indices induced by human activities, to estimates of the natural variability levels against which the predicted climate change signals must be compared. Fortunately, however, the tools exist in the form of nested high-resolution models, statistical downscaling methods and appropriate D&A analysis methods to begin to redress these

Figure 10: Optimal Bayesian detection and attribution analysis for annual means of surface temperature (TAS) and precipitation (PREC), and summer (JJA) and winter (DJF) means of diurnal temperature range (DTR). (a) The number of EOFs retained from the ECHAM3/LSG control run (forming the initial basis), and the number of optimal patterns forming the detection phase space in the Bayesian and conventional detection and attribution analysis, respectively. (b) The prior and posterior probabilities for each of the climate change hypotheses (climate change can be explained by natural variability (“Natural”), greenhouse gases alone (“GHG”), greenhouse gases plus sulfate aerosols (“GHG+S”)). Uniform priors were assumed giving each hypotheses probability 1/3. The net posteriors refer to the posterior probabilities if evidence from all four variables is considered simultaneously. The two small values for “Natural” are actually almost zero and have been inflated for display purposes only.
shortcomings through a coordinated, directed research program.

Without the knowledge provided by the regionalization of the climate studies called for above, it is impossible to develop a rational national energy and climate policy. Negotiations on international mitigation efforts will similarly be carried out in a vacuum. The same applies for any attempts at adaptation. Essentially, one cannot develop an effective, rational policy without the information from a detailed regional climate impacts program on what to expect in the future world.

5.2 Required Research

Despite the advances and new findings reported in this paper, there remain a number of important open questions, which are detailed, in no particular order, in the following. We suggest they would be good priorities for the NOAA/DOE Climate Change Data and Detection (CCDDD) program and other programs concerned with estimating human impacts on the Earth.

1) A more accurate evaluation of the statistical uncertainties associated with D&A estimates, while the climate change signal is still emerging from the noise, is particularly desirable for the timely assessment of risks associated with the formulation and timing of climate adaptation and mitigation policies. The general consensus is that changes in climate induced by human activities have become detectable against the general background noise of internal natural climate variability. Positive detection implies only a high but finite estimated statistical signal-to-noise level. The precise statistical significance level will necessarily remain open to debate as long as the magnitude of the predicted anthropogenic climate change remains comparable, as today, with the level of natural climate variability. On the other hand, if we wait until the anthropogenic signal is so much larger than the natural variability noise that the anthropogenic climate change can be identified beyond all doubt, it will be too late to undertake remedial action.

2) Two factors dominate the uncertainty of estimated signal-to-noise ratios, and they must be addressed to reduce uncertainties: a) the natural climate variability against which the climate change signal must be compared, and the structure of the predicted climate change signal itself must be refined. Natural climate variability can be inferred from pre-instrumental tree ring, ice core, coral, borehole and other proxy data and more recent instrumental data, such as near-surface temperatures and tropospheric temperatures measured with radiosondes and satellite data. Not all of these data sets are mutually consistent, and further work is needed to resolve the discrepancies. Natural climate variability can also be estimated from climate model simulations, but the results from different models also vary relative to one another and the observational data. We need to find out which models are most correct. b) Similarly, the climate change signals predicted by models exhibit differences. These are due largely to poorly understood processes, such as the role of sulfate and sooty aerosols. External forcings other than human activities, such as volcanic eruptions or changes in solar radiation, have also been invoked to explain aspects of the observed recent climate change. Although preliminary model studies and signal detection results suggest that these impacts explain only a fraction of the observed climate change, a number of open questions remain, such as the magnitude of atmospheric response to solar variations or the temporal and seasonal response to volcanic forcing.

3) The reduction of the uncertainties of models and observational data to a level where the observational data on climate change can be applied to verify and improve climate models remains a desirable and realistic long-term goal of D&A investigations. One of the motivations of D&A analysis is to verify climate models against observations with the aim of reducing uncertainty in model-based predictions. This approach has been used to provide objective forecasts of global temperature over the coming decades, using either restrictive assumptions about the nature of model errors (Allen et al., 2000; Stott and Kettleborough, 2002) or heavily simplified models (Forest et al., 2002, Knutti et al., 2002). On the basis of this work, the IPCC concluded that “despite uncertainty in climate sensitivity … anthropogenic warming is likely to lie in the range 0.1 to 0.2°C per decade over the next few decades under the IS92a scenario.” (IPCC, 2001) At present, however, the differences between observations and model predictions, and the uncertainties in both, are still too large to calibrate the full-scale models used for prediction of regional changes and impacts reliably on the basis of observed climate change data. Thus, although the models suggest that part of the observed global climate change is attributable to human activities, the analysis cannot yet be inverted to reduce the present uncertainties in future regional climate change predicted by climate models. Confidence of climate modellers in the predictions of their models is also based on the models’ ability to reproduce the general regional and seasonal properties of our present climate, as well as in the accurate reproduction of the observed changes during, say, the last century, so any programme to use observations to constrain climate predictions should ultimately draw on both sources of information.

Because of the non-linear nature of the system and multiple timescales involved, any systematic approach to using observations to constrain forecasts of future climate change will necessarily
require large ensembles of model integrations (Allen, 1999; Palmer, 2000; Forest et al. 2000; Allen and Stainforth, 2002), spanning not only initial condition uncertainty but also uncertainty in model parameters and model specification. It is important that any climate simulation program contains an element of support for such work even though ensemble experiments cannot be carried out at as high a spatial resolution as individual model runs.

4) The reduction of a number of uncertainties and the removal of inconsistencies in the interpretation of pre-instrumental and instrumental data is required. Although much progress has been made in this regard in recent years, the impact of sulfate, sooty and other aerosols is still highly uncertain. There remain, also, residual inconsistencies between tree-ring and borehole data and between surface, radiosonde and satellite tropospheric temperatures which need to be resolved. In this latter context, we encourage NOAA, possibly in collaboration with other agencies to initiate, as a high priority, a third-party project to assess the present inconsistencies between the Christy et al. and Wenz et al. reconstructions of the MSU satellite data and decide whether the discrepancies can be resolved. The agencies might consider providing some short-term financial support to investigators willing to compile any additional data deemed necessary to support the intercomparison.

5) As in 1999, we call on the modelers to carry out realistic, predictive ensembles of integrations with the full set of currently known atmospheric pollutants. In addition, to reduce the present uncertainties regarding the impact of tropospheric aerosols, we encourage modelers to carry out model sensitivity experiments using extreme ranges of tropospheric aerosol radiative feedback (zero to 2W/m²), and to investigate the impact in regions regarded as particularly sensitive for D&A assessment. Finally, we suggest that the climate modeling community give a high priority to understanding why current climate models’ sensitivity to double CO2 varies by a factor of about TWO between different models. This situation has persisted for over a decade and needs to be resolved if meaningful impact assessments are to be made.

6) Building and rehabilitating data sets for variables that most affect society should be a high priority. This task becomes increasingly important, even mandatory, as we seek to address regional climate changes associated with natural and/or anthropogenic variability. This includes efforts to compile high-density global-scale data sets of daily variables and to produce gridded data which resolve changes in climatic extremes.

7) A joint analysis of all existing climate change data in a comprehensive summary assessment of the D&A issue needs to be carried out. Because of the limitations of objective statistical estimates of the inherent natural variability and model prediction errors of many of the climate variables that have been invoked as possible indicators of anthropogenic climate change, this can be carried through only within a Bayesian statistical analysis framework. The theoretical groundwork for this project has been established, but considerable efforts beyond the resources of the present project will still be required to achieve this goal.

Acknowledgements

The International ad hoc Detection and Attribution Group (IDAG) is a self-organized group of climate experts interested in the problem of D&A of anthropogenic climate signals in the observations. This report, like our others, expresses our collective views and not those of any international or national agency. While most of the Group obtains funding from their normal sources, we wish to acknowledge the Climate Change Detection and Attribution Project, a jointly funded effort by NOAA’s Office of Global Programs and the Department of Energy’s Office of Biological and Environmental Research, for providing the support for meeting and specialized studies of the Group members. We also thank Karen King of Battelle’s Pacific Northwest National Laboratory for handing the Group’s administrative matters.

References


Angell, 2000: Difference in radiosonde temperature...


Diaz, H.F., Folland, C.K., Manabe, T., Parker, D.E., Reynolds, R.W. and


model ensemble. GRL, in press.


