Key outcomes/non technical summary

The first objective of this contract was to solidify results concerning large scale temperature changes and to extend these studies to other variables and to regional scales. Highlights include:

- The development of a detection methodology that explicitly takes account of error in the climate model, allowing multi-model studies. This new methodology was applied to surface temperature and precipitation (featuring in the IPCC AR4 report).
- The development of variants of the standard attribution methodology to deal with incomplete ensembles of simulations. These were applied to the IPCC AR4 ensemble of climate model simulations (featuring in the IPCC AR4 report).
- The extension of temperature attribution studies to regional scales (featuring in the IPCC AR4 report, including one figure provisionally designated for both the Summary for Policy Makers and the Technical Summary).
- The transfer of the optimal detection code to the NIES group in Japan and the application to their many simulations performed on the Earth Simulator.
- The release of a supported public version of the existing optimal detection code.

This second objective of this contract was to develop a methodology which would produce quantitative statements about the extent to which human influence is responsible for the risk of specific regional weather events. Highlights include:

- The development of a methodology for attributing the risk of single weather events.
- The application of this methodology to the summer 2003 European heatwave. This study found that anthropogenic emissions had very likely at least doubled the likelihood of such summers, a result which has generated much public interest (featuring in the IPCC AR4 report).
- The launch of a public distributed computing project using the climate*prediction*.net framework which will allow the application of this methodology to the record wet autumn of 2000 in the U.K.

Associated publications

- 16 peer-reviewed publications from work assisted by this contract (see Section 3).
- Public supported release of detection and attribution code developed previously.

Press interest

- A great deal of press interest was associated with the work on the attribution of the summer 2003 European heatwave.
  Television: BBC News World Edition, CNN (USA), BBC (Newsnight, 6 O'Clock News), News 24, RTL (Germany)
  Radio: at least 6 shows in 4 countries
  Newspapers: at least 22 in 9 countries
  Online news sources: at least 38 in 13 countries
- There will be considerable press interest in the release of the IPCC AR4 report in February 2007 (one of the figures likely to feature in the Summary for Policy Makers was developed under this contract).
- Publicity for the autumn 2000 UK floods project on the World Wildlife Fund for Nature website.

1 Report on status

This contract had the first objective of solidifying the conclusions related to large scale temperature changes and of extending these studies to other variables including precipitation as well as to more regional scales. Several investigations toward this end have been conducted under this contract or by other groups with assistance from the recipients of this contract. The results are set to feature prominently in the upcoming IPCC Fourth Assessment Report, including one summary regional detection figure prepared under this contract that is provisionally designated to feature in the Summary for Policy Makers.

The first detection and attribution studies naturally concentrated on large scale global temperature changes, but these have limited direct impact on any individual stakeholder. Consequently, the second objective of this contract was to develop a methodology which would produce quantitative statements about the extent to which human influence is responsible for specific regional weather events, with a focus on Northwest European weather events. This methodology has been developed and applied in a very public study on the hot summer of 2003 in Europe which has generated much public interest in this field.

A detailed report on completed activities is given below in Section 2 under the headings of the deliverables stated in the contract. Current publications and other outcomes are listed at the end of this document in Section 3.

2 Progress on deliverables

2.1 Extension of Total Least Squares detection code to accommodate an explicit representation of model error

- Developed methodology to take account of model error in optimal detection; applied to surface temperature and precipitation (featuring in the IPCC AR4 report).
- Compared two different methods for constraining predictions (not an original deliverable).
- Compared response patterns to anthropogenic sulphate emissions across climate models.

At the start of this contract, the state-of-the-art detection methodology compared an observed climate variable with the same variable from simulations of a climate model. This methodology allowed for the possibility that the amplitude of the pattern of change produced by the model may be incorrect, but assumed that the model was producing the pattern correctly. Under this contract, the detection methodology was extended to allow for uncertainty in this pattern and applied to large scale temperature changes using many climate models (Huntingford et al. 2006, Figure 1) and similarly applied to global land precipitation changes (Lambert et al. 2005).

One benefit of such attribution results is to provide constraints on the climate response which can be used to produce predictions of future changes. Separate work in the U.S. has developed a different probabilistic method of climate forecasting that uses Bayesian techniques for weighting model ensemble means (Tebaldi, 2003) rather than the method of using attribution based constraints derived from the attribution framework underlying the research in this contract (Stott and Kettleborough, 2002). A detailed comparison of these two methods has been performed with input from this contract (Lopez et al. 2006), which has helped reveal the origins of very substantial differences between the two, particularly in their estimates of uncertainty. Attribution-based estimates of uncertainty, being primarily driven by observational data, provide generally more conservative, but also more robust, probabilistic climate forecasts than Bayesian weighted model ensembles, so they provide an essential complementary approach.

Finally, the application of the traditional optimal fingerprinting approach was applied in order to further investigate the nature of climate responses to various forcings. In particular, the response patterns to changing burdens of tropospheric sulphate aerosols were compared across models in Stott et al. (2006b). Such multi-model

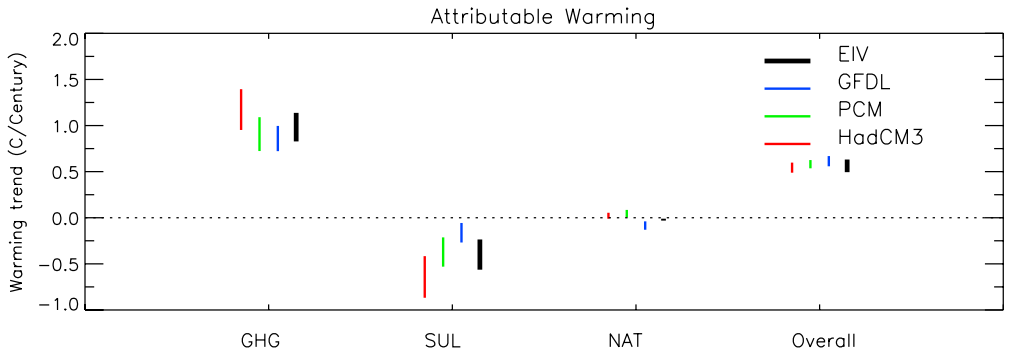

Figure 1: Twentieth century attributable temperature trends estimated from each model individually using the standard optimal detection methodology and from all three models combined (EIV) using the new methodology that allows for uncertainty in the response pattern. From (Huntingford et al. 2006)

studies were summarised in the IDAG (2005) review in which MA and PS participated. Optimal fingerprinting results were then used to produce observationally constrained estimates of future regional climate change (Stott et al. 2006a).

2.2 Development of basic methodology to account for selection effects in the application of detection and attribution algorithms to one-off events

- Developed methodology for attributing risk of single weather events and applied to 2003 European heatwave (featuring in the IPCC AR4 report).
- Launched new methodology for attribution of U.K. rainfall and floods through climate*prediction*.net framework.

It is not large scale climate changes but rather local weather events that generally impact specific individuals. Thus, a main aim of this contract was to transfer a methodology for attributing changes in the risk of damaging events from the epidemiological sciences to the climate change problem (Stone and Allen 2005b). This technique was applied to the unusually hot summer over Europe in 2003, with the finding that human activities have very likely at least doubled the risk of such summers (Stott et al. 2004, Figure 2). Conclusions like this provide a scientific basis upon which legal action could be taken in response to damages (Allen and Lord 2004).

Most climate variables do not follow such predictable behaviour patterns as does temperature, so the mainly statistical approach used on the summer of 2003 problem is not valid. Such problems require a full ensemble modelling approach. For instance, changes in the frequency or intensity of droughts or floods are potentially of larger concern to the British agricultural industry and to property owners because of the very direct impact of these hydrological events, yet representing these events requires explicit modelling of the relevant processes. A full ensemble modelling approach that can deal with such events was developed by PP using the services of the climate*prediction*.net project. The damaging floods that occurred in Britain during the autumn of 2000, the wettest autumn on record, is being used as a case study (Figure 3). Modelling output from this experiment will also be used to examine other events that occurred in 2000, such as the dry winter over the Washington State area and glacier retreat in Nepal, in collaboration with other research centres. The public launch of this modelling project occurred in early March. This project constitutes an extension to the objectives of the original contract.

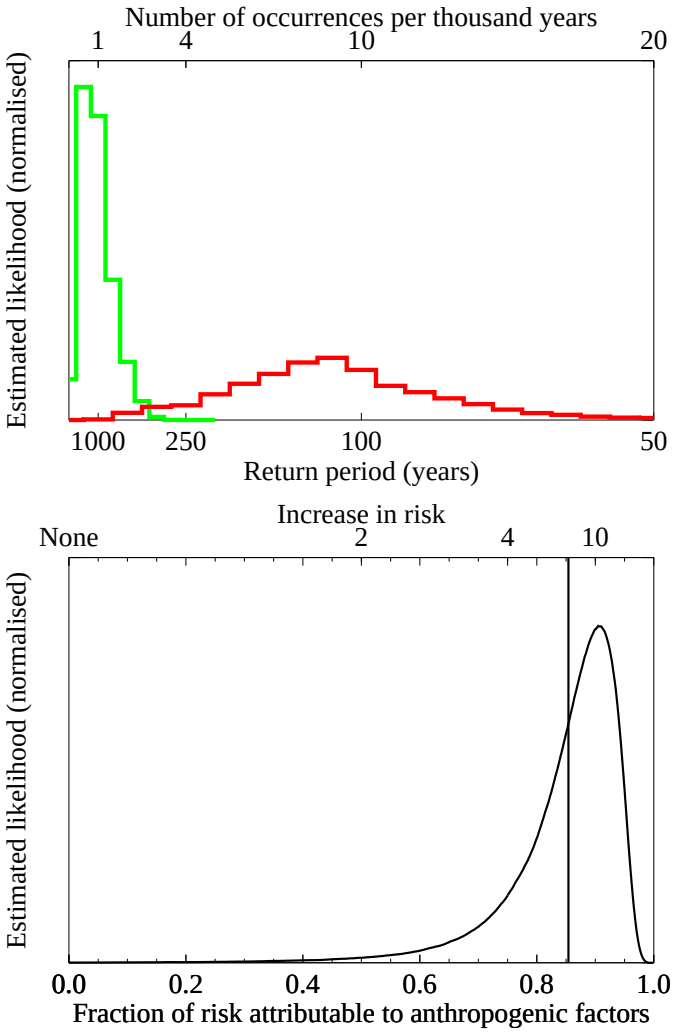

Figure 2: The change in risk of mean European summer temperatures exceeding the 1.6 K threshold. Top: histograms of instantaneous return periods under late twentieth century conditions with (red) and without (green) anthropogenic climate change included in the climate model simulations. Bottom: the probability function of the fraction of the risk of such warm summers being attributable to anthropogenic emissions, with the best guess marked as a vertical line. From Stott et al. (2004).

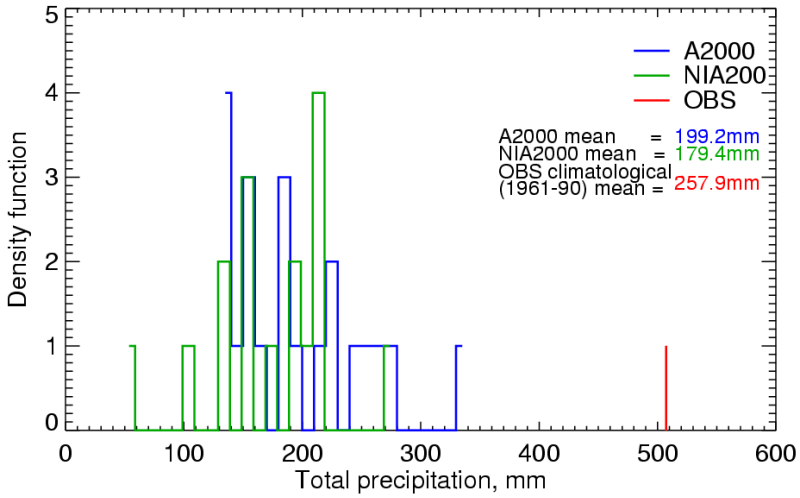

Figure 3: Histograms of England-Wales total autumn 2000 precipitation from beta test simulations of the distributed computing project concerning the risk of the autumn 2000 floods in the U.K. The red histogram is from autumn 2000 simulations, while the green histogram is from simulations of a hypothetical autumn 2000 in which humans had never emitted any greenhouse gases. The blue line marks the extreme amount of precipitation received in the actual autumn of 2000. See http://attribution.cpdn.org/ for updates.

2.3 Application of conventional detection and attribution methodology to global and regional rainfall data and atmospheric circulation diagnostics

- Applied standard and new detection and attribution methods to precipitation (featuring in the IPCC AR4 report).
- Participated in writing of an international review paper covering climate change detection including of non-temperature variables.

At the start of this contract, detection and attribution studies had focused on surface temperature changes. With assistance from this contract, the standard and new (see Deliverable 2.1) methodologies were applied to land precipitation changes (Lambert et al. 2004; 2005, Figure 4). These results were particularly interesting in highlighting that the climate system appears to respond quite differently to certain forcings, for instance the effects of aerosols in the stratosphere from volcanic eruptions versus the effects of greenhouse gases. These results will feature prominently in the upcoming IPCC Fourth Assessment Report. MA and PS were also authors on the IDAG (2005) review of climate change detection, intended to provide information for the IPCC and others on the status of the field, including the detection of changes in non-temperature variables.

2.4 Extension of generalised detection and attribution methodology to accommodate non-traditional climate modelling experimental designs

- Released documented public version of optimal detection code.
- Transferred optimal detection code to NIES (Japan) group and applied it to their many simulations from the Earth Simulator.
- Developed variants of standard detection and attribution method to deal with incomplete ensembles and applied to IPCC ensemble for IPCC AR4 (featuring in the IPCC AR4 report).

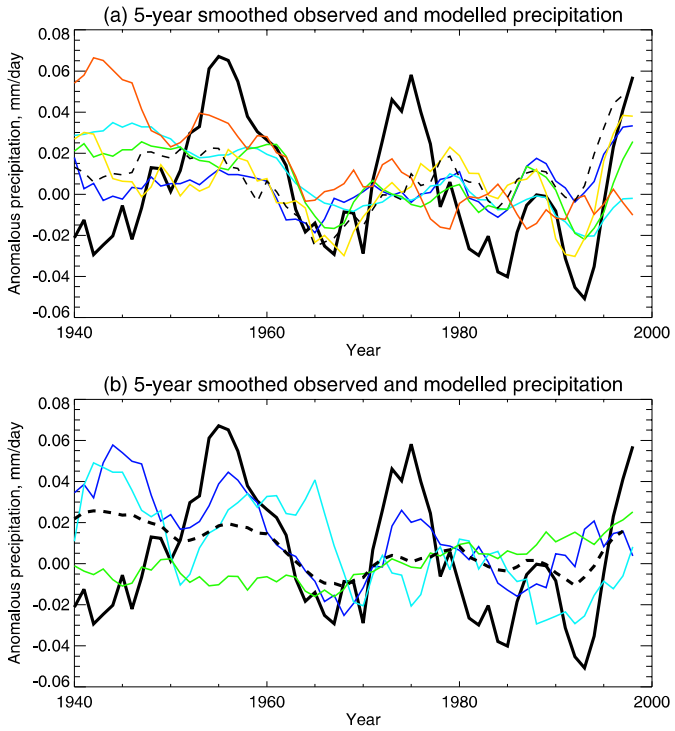

Figure 4: Smoothed time series of mean global land precipitation anomalies from the 1961-1990 climatology. In both plots the solid black line represents the observations. The coloured lines are averages from ensembles of historical simulations performed with climate models. The dashed black line is the average across all model simulations. From Lambert et al. (2005).

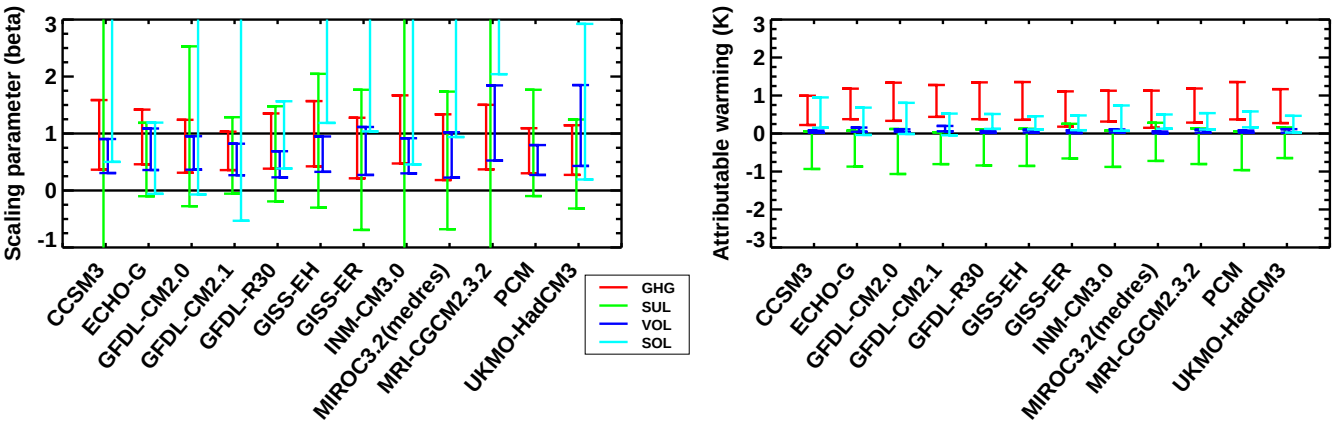

Figure 5: Left: the range of scalings on response patterns for various external forcings and climate models that are consistent with observed surface temperature changes. Right: the derived estimates of twentieth century warming attributable to the various forcings. Note that despite differences in the scalings, the attributable warming estimates are similar across all models, indicating robust response patterns. From Stone et al. (2006b).

- The extension of temperature attribution studies to regional scales using multiple models (featuring in the IPCC AR4 report, including one figure provisionally designated for both the Summary for Policy Makers and the Technical Summary).

Under this contract, the standard detection and attribution techniques were also applied to new simulations from additional models and more recent observations. A public release of the code developed previously and under this contract is now available and being used by several research groups around the world. In particular, a group from the Japanese NIES running a large number of ensembles of climate simulations on the Earth Simulator were keen to apply the optimal detection methodology and so SC visited them at the start of 2005 to instruct them on the application of the methodology. The NIES group have just completed a visit to Oxford to present a staggering number of early results from these simulations and analyses (Nozawa et al. 2006; Nagashima et al. 2006). Amongst these results in the possibility that black carbon emissions have made an important contribution to 20th century climate change.

Furthermore, two variants of the standard detection methodology were developed which can be applied to model simulations not intended for use in detection studies, a common occurrence due to computing limitations (Crooks et al. 2006; Stone et al. 2006a; Stone and Allen 2005a). These techniques were applied to the simulations from the many climate models submitted to the IPCC for the upcoming Fourth Assessment Report and the results will feature prominently in the report (Stone et al. 2006b). A major finding was that the attribution of large scale temperature changes to greenhouse gases is robust and independent of the climate model or method used (Figure 5). These findings also provide observational constraints on future global warming, and it was found that these estimates are now also robust against the model or method used.

A number of modelling groups around the world have now conducted historical climate simulations including natural forcings and variously anthropogenic forcings. These have been combined to produce comparisons between observed climate changes over regions on the order of 1000 km, and simulations including and excluding anthropogenic influences (but crucially always including natural influences). These results are featuring prominently in the IPCC AR4 report, including one figure provisionally designated for the Summary for Policy Makers.

3 Outcomes

Publications from work assisted by this contract

Allen, M. R. and R. Lord, 2004: The blame game. *Nature*, **432**, 551–552.

Crooks, S. A., M. R. Allen, and P. A. Stott, 2006: An update on the detection and attribution of observed temperature change - A space-time separable approach. *J. Climate*, submitted.

Huntingford, C., P. A. Stott, M. R. Allen, and F. H. Lambert, 2006: Incorporating model uncertainty into attribution of observed temperature change. *Geophys. Res. Lett.*, **33**(5), L05710, 10.1029/2005GL024831.

IDAG, 2005: Detecting and attributing external influences on the climate system: A review of recent advances. *J. Climate*, **18**, 1291–1314.

Lambert, F. H., N. P. Gillett, D. A. Stone, and C. Huntingford, 2005: Attribution of changes in observed land precipitation with nine coupled models. *Geophys. Res. Lett.*, **32**, L18704, 10.1029/2005GL023654.

Lambert, F. H., P. A. Stott, M. R. Allen, and M. A. Palmer, 2004: Detection and attribution of changes in 20th century land precipitation. *Geophys. Res. Lett.*, **31**, L10203, 10.1029/2004GL019545.

Lopez, A., C. Tebaldi, M. New, D. Stainforth, M. Allen, and J. Kettleborough, 2006: Two approaches to quantifying uncertainty in global temperature changes under different forcing scenarios. *J. Climate*, submitted.

Nagashima, T., H. Shiogama, T. Yokohata, S. A. Crooks, and T. Nozawa, 2006: The effect of carbonaceous aerosols on surface temperature in the mid twentieth century. *Geophys. Res. Lett.*, submitted.

Nozawa, T., T. Nagashima, H. Shiogama, and S. A. Crooks, 2006: Detecting natural influence on surface air temperature change in the early twentieth century. *Geophys. Res. Lett.*, in press.

Stone, D. A. and M. R. Allen, 2005a: Attribution of global surface warming without dynamical models. *Geophys. Res. Lett.*, **32**, L18711, 10.1029/2005GL023682.

—, 2005b: The end-to-end attribution problem: From emissions to impacts. *Clim. Change*, **71**, 303–318.

Stone, D. A., M. R. Allen, F. Selten, M. Kliphuis, and P. A. Stott, 2006a: The detection and attribution of climate change using an ensemble of opportunity. *J. Climate*, accepted.

Stone, D. A., M. R. Allen, and P. A. Stott, 2006b: A multi-model update on the detection and attribution of global surface warming. *J. Climate*, accepted.

Stott, P. A., J. A. Kettleborough, and M. R. Allen, 2006a: Uncertainty in continental-scale temperature predictions. *Geophys. Res. Lett.*, submitted.

Stott, P. A., J. F. B. Mitchell, J. M. Gregory, B. D. Santer, G. A. Meehl, T. L. Delworth, and M. R. Allen, 2006b: Observational constrains on past attributable warming and predictions of future global warming. *J. Climate*, accepted.

Stott, P. A., D. A. Stone, and M. R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610–614.

Other outcomes

- Public release and support of code developed previously and under this contract (http://www.atm.ox.ac.uk/user/stoned/idl_lib/detect/idl_lib.html).
- Supervision of students studying the detection and attribution of climate change at the University of Oxford (2 D.Phil., 3 M.Phys., 2 B.A.).
- Training of two postdoctoral researchers.

4 Future Work

The issue of attributing changes in climate and the risk of weather events has been highlighted by recent increased public interest. There remain pressing issues, however, some of which we plan to examine in the remainder of this contract. Plans include:

- The application of the new multi-model attribution methodology to the perturbed physics ensemble being produced in the climate*prediction*.net project.
- The analysis of results from the U.K. autumn 2000 rainfall/flood event attribution project.
- The incorporation of observational uncertainty into the standard optimal detection methodology.
- The extension of observationally constrained predictions using attribution methods to regional and U.K. scales (application to UKCIP).