5.3 CLIMATE CHANGE DETECTION AND ATTRIBUTION IN THE UPPER AIR

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1. INTRODUCTION

Since the Third Assessment Report of the IPCC, improvement has been made in the general agreement between models' forecasts of trends in the global average surface air temperature. When the evolution of the temperature field is examined in any more detail, though, it is clear that substantial disagreement remains. A vast disparity remains in predictions of regional surface air temperature trends. Considering that previous climate signal detection change and attribution studies have relied on horizontal patterns of surface air temperature change (e.g., Tott et al. 2001), the inter-model disagreement in the horizontal patterns leads to some doubt as to the robustness of these studies.

Observing temperature trends in the upper air may prove a more reliable method of detection and attribution of climate change because of its relative insensitivity to surface influences and because it is more easily interpreted in terms of bulk atmospheric structure. To date, the only extensive data set on the upper air comes from radiosondes and the Microwave Sounding Units. Both have suffered from calibration problems: there is uncertainty regarding whether global warming in upper tropospheric air has even been detected by radiosondes, and rates of upper tropospheric warming remain nearly unconstrained in MSU data (Seidel et al. 2004).

Radio occultation using the transmitters of the Global Positioning System (GPS) does not suffer from such calibration issues. Its calibration is directly tied to atomic clocks, which are precise to at least 1 part in 10^{12} (Kursinski et al. 1997). Its observable is the microwave refractivity, profiled with ~100 m vertical resolution, which is proportional to atmospheric density above the tropical lower troposphere and to a combination of density and humidity in the tropical lower troposphere. It also contains all of the information necessary to measure the geopotential heights of constant pressure surfaces directly from space (Leroy 1997). GPS occultation proof-of-concept missions have been flying since 1995 and have met with great success. In early 2006 the COSMIC project will fly a constellation of six occultation receivers.

We survey the changes in upper air temperature as predicted by the climate models participating in the Climate Model Evaluation Project for the IPCC Fourth Assessment Report (IPCC AR4) when subjected to the SRES A1B radiative forcing scenario. In this study we focus on those aspects of the climate which are most robustly predicted, and determine how long it will take to confirm the models' common predictions using GPS occultation data.

2. PATTERNS OF UPPER AIR CHANGE

2.1. Temperature

The global average surface air temperature predictions of the CMEP models, when subjected to SRES A1B radiative forcing, shows better overall agreement than in the Third Assessment Report. This agreement hides substantial disagreements at continental scales. For example, Siberia is predicted to see surface air temperature changes ranging from -1 to +1 K decade^{-1}.

In contrast, the patterns of upper air temperature change among the IPCC AR4 models shows qualitatively better agreement. The most prominent pattern is of synchronized warming of the tropical upper tropospheric air. Warming in the tropical surface air is accompanied by 40% more rapid warming at 200 hPa, as is expected given maintenance of a moist adiabat. Some models show a rapid increase in north polar surface air temperature, most likely the result of a large ice-albedo feedback, but this pattern is regionally isolated. All models predict a rapidly cooling stratosphere, but the rate and patterns of cooling differ substantially from model to model, most likely a result of differing implementations of ozone evolution. Trends in geopotential height are interpretable as thermal expansion of the troposphere: changes in the distribution of atmospheric mass have relatively little influence on the dynamic forcing of the atmosphere.

2.2. GPS Occultation Dry Pressure

Trends in "dry pressure" as might be measured by GPS radio occultation are nearly identical to trends in geopotential height at constant pressure (Leroy 1997, Leroy and Anderson 2006). The observable of GPS radio occultation is microwave refractivity N, the departure of the microwave index of refraction from unity in parts per million. Empirically it is given by

$$N = a\ p/T + b\ p_W/T^2 \qquad (1)$$

where p is pressure, T temperature, p_w water vapor pressure, and the constants a and b are 77.6 K hPa^{-1} and 373×10^3 K^2 hPa^{-1} (Smith and Weintraub 1953). Dry pressure is the integral of the refractivity N in geopotential height from the top of the atmosphere downward and multiplied by 4.402×10^{-4} hPa m^{-1}. It is the same as atmospheric pressure everywhere except where the second term on the right of equation 1 is significant, namely in the tropical lower troposphere.

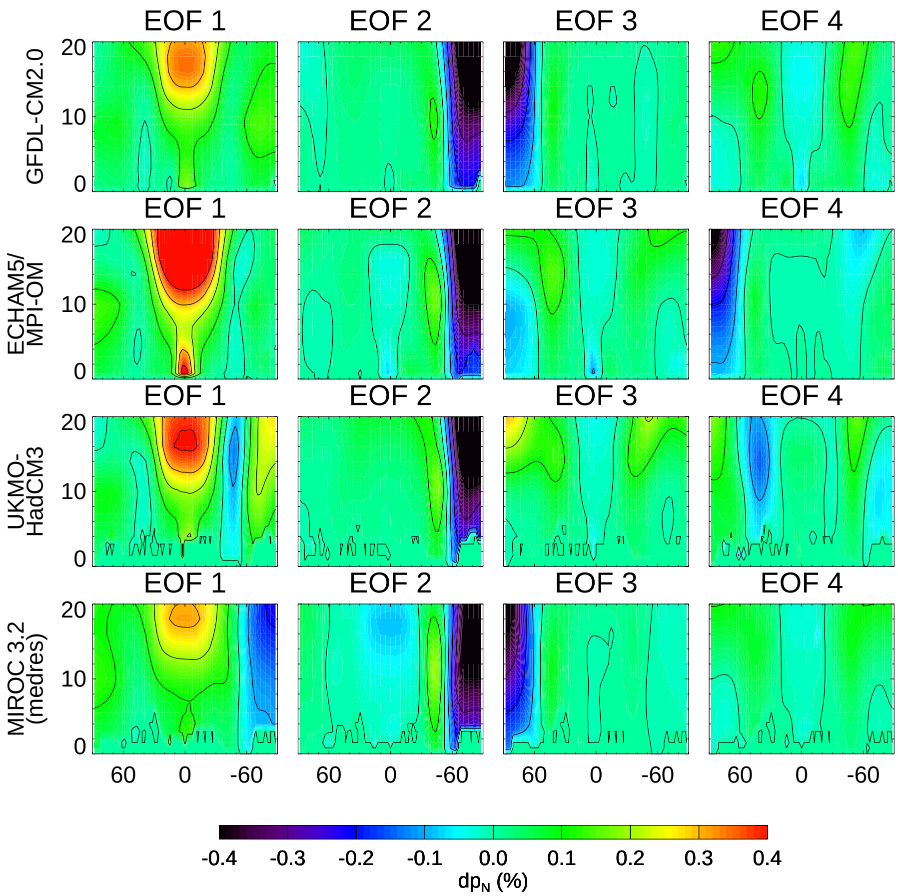

Figure 1. Empirical orthogonal functions of interannual variability of GPS radio occultation "dry pressure." The first four EOFs of the interannual variability of the log of zonal average dry pressure was computed from long pre-industrial control runs contributed by four models of the IPCC AR4. In each case the first EOF corresponds to ENSO, the second to the Southern Annular Mode, and the third and fourth to the Northern Annular mode and a newly identified symmetric jet migration EOF. The ordinate is latitude and the abscissa is geopotential height in km.

3. CLIMATE SIGNAL DETECTION

We use optimal methods to estimate how long it would take to detect and attribute anthropogenic warming in the tropospheric upper air using GPS radio occultation data. In optimal fingerprinting, specific patterns of temperature change are assumed to uniquely identify specific causes of change (Hasselmann 1993, North et al. 1995). They are sought out in such a way that they are perfectly distinguished from other causes of climate change and distinguished from natural variability to the greatest degree possible. It is accomplished by decomposing fingerprints according to the EOFs of natural variability and preferentially weighting toward those components of variability which have relatively large ratios of signal projections to natural variance. It has been shown to be the most optimal detection strategy of detecting trends against a background of naturally occurring variability.

3.1. Natural Interannual Variability

We first determined the EOFs of interannual variability of zonal average dry pressure in the troposphere using pre-industrial control runs of four independent climate models of the IPCC AR4 ensemble: GFDL-CM2.0, ECHAM5/MPI-OM, UKMO-HadCM3, and MIROC 3.2 (medres). See Fig. 1. We weighted by mass. In every case, the first EOF of interannual variability corresponds to warming/cooling of the tropics and is closely associated with ENSO. Also, in every case the second EOF corresponds to the Southern Annular Mode (SAM), reflecting a simultaneous poleward shift of the southern eddy-driven jet and a net mass migration from the south polar region (Thompson and Wallace 1998, 2000). The third and fourth EOFs correspond to the Northern Annular Mode (NAM) and a symmetric jet migration EOF, and not necessarily in that order. While migration of the eddy-driven jet streams is a defining requirement of the annular modes, the annular modes do not explain all of the variability associated with migration of those jets. The symmetric jet migration

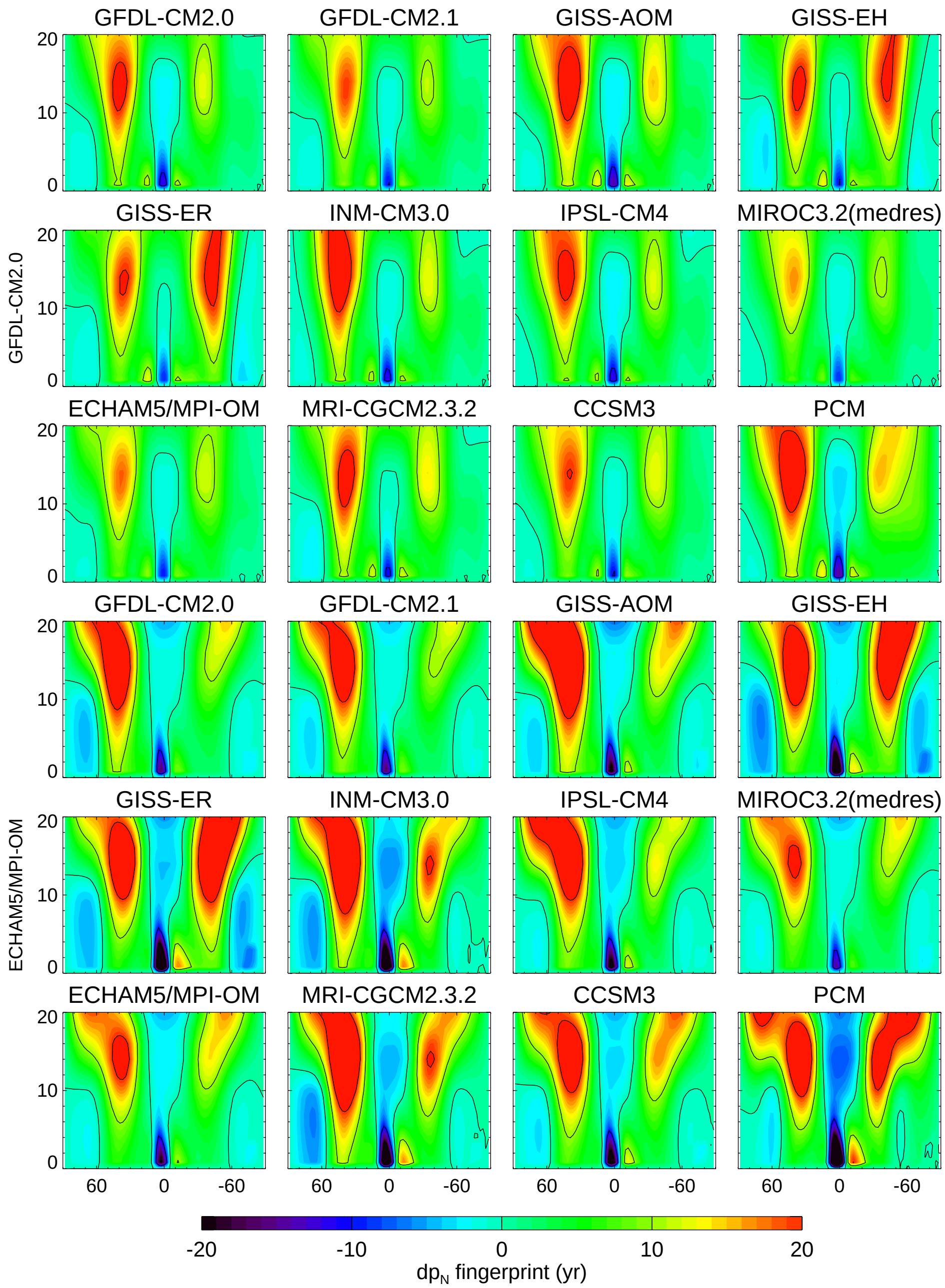

Figure 2. Optimal fingerprints of climate signal detection as applied to GPS occultation dry pressure. An optimal fingerprint is the map of coefficients used to multiply trends in data in order to come with an optimal estimate for the strength of a signal against a background of natural variability. We show optimal fingerprints for two different prescription of natural variaibility (GFDL-CM2.0 and ECHAM5/MPI-OM; the first twelve and the second twelve respectively) and twelve prescriptions for the global change signal expected to emerge. The amplitude of the coefficients is directly proportional to the amount of time expected for a significant detection to be obtained. Axes as in Figure 1.

EOF explains poleward motion of both the northern and southern mid-latitude jets, and, while statistically degenerate with an antisymmetric jet migration EOF, still leads the antisymmetric EOF in the pre-industrial control runs of the four independent IPCC AR4 climate models listed above. The symmetric jet migration EOF is characterized by ~10 m anomalies in geopotential height at 200 hPa centered at 45° north and south latitude with full widths at half maximum of 30°.

3.2. Optimal Fingerprints

In projecting the trends in dry pressure simulated by 12 of the IPCC AR4 models in response to SRES A1B, we find that both trends in the ENSO mode and in the symmetric jet migration EOF are most prominent against a background of natural variability and the most robust predictions of the climate models. There is a wide scatter in the predictions of trends in the northern and southern annular modes between the models, and none of the predictions is large in comparison to the naturally occurring interannual variability in these modes. As a consequence, the fingerprint, or optimal filter, for climate signal detection is dramatically oriented to ENSO and symmetric jet migration, particularly the latter. This is clearly seen in the optimal fingerprints as established by the four independent estimates of natural variability and twelve independent estimates of the climate's response to SRES A1B greenhouse forcing. An optimal fingerprint is the pattern of coefficients by which trends in data are multiplied in order to minimize the influence of natural variability when trying to detect a climate signal and associate it with a unique pattern. See Fig. 2. The first incontrovertible indication of a human influence on climate in tropospheric upper air will be poleward migration of the mid-latitude jets in both hemispheres unassociated with the NAM and the SAM. Moreover, this should be realized in annual average GPS radio occultation data with 95% confidence over a baseline of 7 to 13 years.

4. SUMMARY AND DISCUSSION

While climate models show improved agreement in the response of global average surface air temperature to prescribed greenhouse forcing, the disagreement of the horizontal patterns of temperature trends remains substantial. This casts some doubt not only on climate signal detection and attribution studies that typically rely upon only one climate model, but it also casts doubt on the credibility of climate models as tools for predicting climate change. Hence, it is necessary to implement a regimen of testing climate models using observations of trends in the climate system. We choose to look at observations of the tropospheric upper air because it is both indicative of bulk dynamical trends in the atmosphere and because a new data type which measures the upper air, GPS radio occultation, is absolutely calibrated and ideally suited to the task of testing climate models according to their predictive capability.

We examined how twelve of the IPCC AR4 climate models respond to SRES A1B greenhouse forcing over the next 50 years, particularly in temperature and height. The dominant feature of global change in the tropospheric upper air is tropical warming with maintenance of a moist adiabat up to 200 hPa. The stratosphere cools dramatically in every case.

We apply optimal fingerprinting to estimate how long it would take to detect incontrovertibly the most robust prediction of upper air change as should be measured by GPS radio occultation dry pressure. We find that the most robust and easily detectible trends are in ENSO and poleward migration of the eddy-driven mid-latitude jets. All models agree on both and in each case the predicted trends rapidly exceed the natural variability associated with the mode. The fingerprints of change are mostly reminiscent of the symmetric jet migration EOF. Detection with 95% confidence that natural variability cannot explain an observed trend is estimated to take 7 to 13 years of GPS radio occultation.

The fingerprint patterns illustrated in Fig. 2 have two alternate interpretations. First and most directly, these are the coefficients by which one must multiply trends in data in order to optimally estimate the amount of climate change that has taken place provided that the signal patterns predicted by the relevant models are reliable. Secondly, it shows the pattern of change which will be most readily detectible over the coming decade or two. The fingerprint shows where the climate will change in ways that natural variability cannot explain. Thus, the very first robust detection of climate change in the tropospheric upper air will reveal the eddy-driven mid-latitude jets' migration toward the poles. All models predict the same thing, and the atmosphere does not ordinarily vary in that way.

5. REFERENCES

Hasselmann, K., 1993: Optimal fingerprints for the detection of time-dependent climate change. *J. Climate,* **6**(10), 1957–1971.

Kursinski, E.R., G.A. Hajj, J.T. Schofield, R. Linfield, K. Hardy, 1997: Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System. *J. Geophys. Res.,* **102**(D19), 23,429–23,465.

Leroy, S.S., 1997: Measurement of geopotential heights by GPS occultation. *J. Geophys. Res.,* **102**(D6), 6971–6986.

Leroy, S.S. and J.G. Anderson, 2006: Testing climate models using GPS radio occultation: A sensitivity analysis. *J. Geophys. Res.,* in press.

North, G., K. Kim, S. Shen, and J. Hardin, 1995: Detection of forced climate signals, I: Filter theory. *J. Climate,* **8**(3), 401–408.

Seidel, D. et al., 2004: Uncertainty in signals of large-scale variations in radiosonde and satellite upper-air temperature trends. *J. Climate,* **17**(11), 2225–2240.

Smith, E.K. and S. Weintraub, 1953: The constants in the equation for atmospheric refractive index at radio frequencies. *Proc. I.R.E.,* **41**, 1035–1037.

Stott, P., S. Tett, G. Jones, M. Allen, W. Ingram, and J. Mitchell, 2001: Attribution of twentieth century temperature change to natural and anthropogenic forcings. *Climate Dyn.,* **17**(1), 1–21.

Thompson, D.J., and J.M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential and temperature fields. *Geophys. Res. Lett.,* **25**(9), 1297–1300.

Thompson, D.J., and J.M. Wallace, 2000: Annular modes in the extratropical circulation, Part I: Month-to-month variability. *J. Climate,* **13**(5), 1000–1016.