3.3 SIMULATING THE RECENT HOLOCENE

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Abstract

A climate simulation of the last 500 years, with natural (orbital, solar and volcanic) forcings alone, is generally stable on multi-century timescales despite considerable forced multi-decadal variability. Simulated natural forcing increases large scale precipitation and temperature variability relative to internal variability with decadal-mean temperature variability in the tropics being enhanced by a factor of two. However, it has no significant impact on the variability of the North Atlantic Oscillation or the meridional overturning circulation.

A second simulation using both anthropogenic (well-mixed greenhouse gases, ozone, sulphate aerosol and land-surface) and natural forcings from 1750 to 2000 has been carried out. Comparing this simulation with the natural-only simulations suggests that anthropogenic forcings have had a significant impact on climate during the entire 20$^{\text{th}}$ century, and on the southern hemisphere during the 19$^{\text{th}}$ century. Comparison of recent observed trends with those simulated using natural forcings suggests that recent changes are outside the range of natural variability over large regions of Eurasia and the Indian Ocean. Thus it is likely that anthropogenic climate change has already affected natural systems in these regions.

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1 Introduction

Collins *et al* (2002) found that there were significant differences between temperature variability simulated by the control simulation of HadCM3(Pope *et al*, 2000; Gordon *et al*, 2000) and proxy reconstructions of past variability. Collins *et al* (2002) suggested that the discrepancy could be explained by lack of external natural forcing. To support this they used an ensemble of simulations driven by natural forcings alone. However the simulations only covered the period 1850 to 1999(Tett *et al*, 2002) and so the results were not definitive.

In this paper we explore the extent to which natural and anthropogenic forcings impact decadal-centinial time-scale climate variability for a several important climate variables. We do this by comparison between the control simulation of HadCM3 and two new simulations. One driven by natural forcings from 1492 to 2000 (NATURAL500) and another driven by natural and anthropogenic forcings from 1750 to 2000 (ALL250). The anthropogenic forcings used are an evolution of those used by Stott *et al* (2000). We do not compare with paleo reconstructions as current reconstructions are likely to underestimate multi-decadal climate variability(von Storch *et al*, 2004). Once techniques have been developed that take full account of calibration uncertainty we will apply them to the simulations described in this paper.

NATURAL500 was started using initial conditions from year 1000 of CONTROL – the control simulation of HadCM3 (Collins *et al*, 2001). The start date for NATURAL500 was 1/12/1491. The forcings used to drive this simulation are:

Volcanic Annual-mean aerosol loading was estimated from sulphate in the Arctic and Antarctic ice-caps. The aerosol loading was estimated by regressing the Sato *et al* (1993) optical depth against ice-cap sulphate for the period 1900 to 1961. Where possible, historical records were used to identify the particular volcano and then to reconstruct forcing in four equal-area bands (90°N-30°N, 30°N- equator, equator - 30°S and 30°S-90°S). See Crowley *et al* (2003) for more details.

To convert from annual-mean to monthly-mean aerosol depth all volcanoes were assumed to follow the same optical-depth time profile as Pinatubo did. If the eruption is known then the date of the eruption is used. Otherwise the eruption is assumed to occur in January.

Orbital forcing Changes in the orbital parameters following Berger (1978) were used.

Solar Forcing The Lean *et al* (1995) reconstruction of solar irradiance was spliced with a reconstruction of solar irradiance changes using ^{10}Be (Crowley, 2000).

Vegetation Forcing Vegetation fields for the year 1750 were used throughout this simulation. See the description of changing vegetation forcings used in ALL250 for details.

Well-Mixed Greenhouse Gases Volume mixing ratios of well-mixed greenhouse gases were set to pre-industrial values: CO_2=277.5 ppmv, CH_4=790 ppbv[1] and N_2O=270 ppbv.

The ALL250 simulation started in 1749 using initial conditions from NATURAL500. In addition to the forcings used above the ALL250 simulation also used:

Well-mixed greenhouse gases Changes in these were as Johns *et al* (2003) with linear interpolation used from the pre-industrial values used in NATURAL500 till the 1860 values of Johns *et al* (2003). In addition to changes in trace gases listed above changes the simulation also include changes in six different (H)(C)FCs.

Aerosols Emission histories of aerosol were used. From 1830 to 1860 a growth rate of 5%/year compounded in sulphate emissions was assumed and the 1860 emission estimates fields of Johns *et al* (2003) scaled by this factor. After this point the same fields of sulphur emissions as Johns *et al* (2003) were used. The sulphur cycle model used in this experiment includes many improvements on the earlier version used in previous HadCM3 experiments (Johns *et al*, 2003; Tett *et al*, 2002). Several of these improvements concern the wet deposition of sulphur dioxide and sulphate particles, and in general lead to a greater sulphate loading per unit mass of emissions. A parameterization of particle coagulation has also been introduced: this strengthens the direct forcing per unit mass of sulphate by shifting mass into the more efficiently scattering accumulation mode. The reaction rates used for the oxidation of sulphur dioxide have been amended. Also, 1 % of the anthropogenic sulphur emissions are now assumed to occur in particulate form instead of as sulphur dioxide. The same crude parametrisation of the indirect effect of aerosol on cloud optical properties was used as in Johns *et al* (2003). However as aerosols concentrations differ from earlier experiments due to the changes in the sulphur cycle model then the indirect forcing will also differ.

Land Surface Changes Changes in land surface were prescribed from 1750 to 2000. Changes in crop history were from Ramankutty and Foley (1999) with pasture changes from Goldewijk (2001). These changes were used to modify the land-surface data set of Wilson and Henderson-Sellers (1985). The radiative forcing is due to the albedo change from forest to grassland or pasture. This is greatest when snow is present (Betts, 2000).

Ozone Changes in both tropospheric ozone were used following Johns *et al* (2003); Tett *et al* (2002). Following the discovery of an error in the stratospheric ozone used in Tett *et al* (2002); Johns *et al* (2003); Stott *et al* (2000) the stratospheric ozone was corrected. The error was due to a miscalculation in the level thicknesses and its approximate effect was to double the rate of ozone loss over that specified in Randel and Wu (1999). We applied the correct values in this simulation with values post 1999 calculated as outlined in Johns *et al* (2003).

As CONTROL drifts we make the assumption

[1] This value is in error due to use of the CONTROL value rather than the correct pre-industrial value of 700 ppbv. The consequent error in radiative forcing is about +0.05 W/m^2 and thus negligible.

that the forced simulations will show the same drift. We correct for this drift by fitting a second order polynomial to Control and removing the fitted values from two forced simulations. For global-mean temperature, over about 2200 years, this cooling is small and is about 0.2K with about 0.15K cooling occurring during the first 1000 years of the control. Internal variability is computed from Control after removal of the drift.

Radiative forcing is often used to quantitatively compare the effects of different forcing factors. In this paper all forcing have been adjusted for stratospheric temperature changes (See Appendix A of Tett *et al* (2002) for details). The global-mean radiative forcing from Natural500, relative to Control, is about $-0.25\mathrm{W/m^2}$ with an initial value of about $-0.3\mathrm{W/m^2}$. In the remainder of this paper we quote forcings relative to the average for 1700–1749. This period is a reasonable representative of "pre-industrial" conditions and has a mean offset from Control of -0.18 $\mathrm{W/m^2}$. The forcing timeseries is punctuated by many volcanic eruptions with the largest being -4.75 $\mathrm{W/m^2}$ following the Tambora eruption of 1816 (Fig. 1(a)). Also apparent are the slower changes in forcing due to secular changes in solar irradiance.

On fifty-year timescales volcanic eruptions are a larger source of forcing variability than are changes in solar irradiance (Fig. 1(b)). Minimum forcing occurs around the time of Tambora in the early nineteenth century. Low-frequency forcing declines till the early 18^{th} century, then rises, and is stable till the early 19^{th} century after which it falls then recovers. This recovery continues till the mid-20^{th} century until another period of volcanic activity at the end of this century leads to a small positive forcing resulting from a near-cancellation of positive solar forcing and negative volcanic forcing(Fig. 1(b)).

The radiative forcing diagnosed in the All250 simulation shows large differences from the Natural500 from the mid-19^{th} century(Fig. 1(b)). By the late 19^{th} century All250 forcing is about 0.25 $\mathrm{W/m^2}$ larger than that in Natural500. By the last half of the twentieth century the total anthropogenic forcing is about 0.7 $\mathrm{W/m^2}$ with a small positive contribution from natural forcing. In 1999 total annual-mean anthropogenic forcing is about 1.1 $\mathrm{W/m^2}$.

There is a small positive trend in forcing over the 500 years of Natural500 (Table 1) and a larger trend in All250. The trend in All250 was computed by concatenating the forcing timeseries from 1499 to 1749 from Natural500 with the forcing timeseries of All250. The naturally forced trend is not due to orbital changes but due to increased vulcanism in the 16^{th} and 17^{th} centuries relative to the 20^{th} century and a modest increase in solar forcing in the 20^{th} century. The increased trend in All250 results, unsurprisingly, from large changes in anthropogenic forcing.

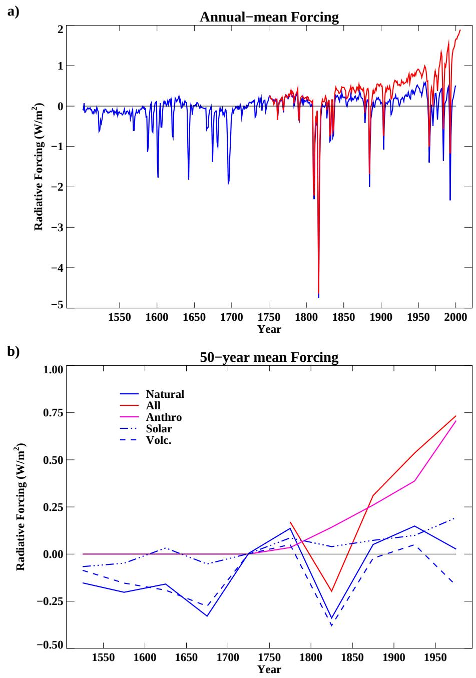

Figure 1: Forcing Timeseries

a: annual mean global-mean adjusted radiative forcings from Natural500 (blue) and All250 (red) simulations. All values are relative to 1700-1749 average from Natural500.
b: as a) but for 50-year average with the addition of Anthropogenic (pink), Solar (blue dash-dot-dot) and Volcanic (blue dashed). Solar forcing was computed from inward shortwave divided by mean albedo and so will include a small orbital component. Volcanic forcing was computed from difference between Natural500 forcing and estimated solar forcing.

2 Simulated response

In this section we look at some aspects of the simulated response. We first focus on temperature timeseries before looking at the stability (or otherwise) of the simulated climate since 1500.

Timeseries of global-mean, northern and southern hemispheric temperature (Fig. 2) in Natu-

Table 1: Trends per 1000 years from forced simulations. Also shown is maximum absolute 500-year trend from CONTROL.

	NATURAL500	ALL250	Max abs. CONTROL
GM forcing (W/m^2)	0.64	1.93	–
NH Temp (K)	0.23	0.83	0.37
SH Temp (K)	-0.013	1.1	0.17
GM Temp (K)	0.10	0.97	0.18
NH Land Temp (K)	0.29	0.90	0.36
NH Land AMJJAS Temp (K)	0.38	0.56	0.27
GM Precip (mm/day)	0.0040	0.019	0.013
NH Land Precip (mm/day)	-0.011	-0.091	0.042
NH MAM ice (10^6 km^2)	0.25	-1.2	0.70
SH SON ice (10^6 km^2)	0.76	-1.7	0.43
NH MAM land snow (10^6 km^2)	-0.0072	1.8	0.94
Atl. Merid. Over. Circ. (Sv)	0.11	1.5	2.0

RAL500 are all very similar. All show cooling of about 0.2K over the first 50-years which is likely a response to the initial forcing imbalance of about 0.3 W/m^2. The period corresponding to the late Maunder minimum (early 17th century) is cool. This is followed by a very warm late 17th century and then a cold early 19th century following the eruption of Tambora. This is qualitatively consistent with that gained from reconstructions of past climates (i.e. Briffa and Osborn (2002)). These temperature changes are quite similar to the changes in forcing discussed earlier (see Fig. 1(b)) which are dominated by changes in volcanic forcing. If the model simulations are approximately correct then it is plausible that the late Maunder minimum cooling is a response to changes in the volcanic eruptions and not due to the relatively small changes in solar irradiance.

The addition of anthropogenic forcings to give ALL250, as in earlier work(Tett *et al*, 2002), warms the planet. Relative to the naturally forced simulation we find that significant warming occurs in the early 19$^{\text{th}}$ century in the Southern Hemisphere. In the Northern Hemisphere significant warming does not occur till the early 20$^{\text{th}}$ century. During the 19$^{\text{th}}$ century this simulation is cooler, but not significantly so, than the simulation forced with natural forcings only. This reflects the general cooling from sulphate aerosols and land-surface changes both of which are concentrated in the Northern Hemisphere land.

Using these simulations we can ask how stable would late Holocene climate have been without anthropogenic forcings. We do this by computing least-squares trends for the 500-year period 1499 to 1999. We concatenated data from ALL250 onto data from NATURAL500 for the period 1499-1749. We assess significance by comparison with the max-

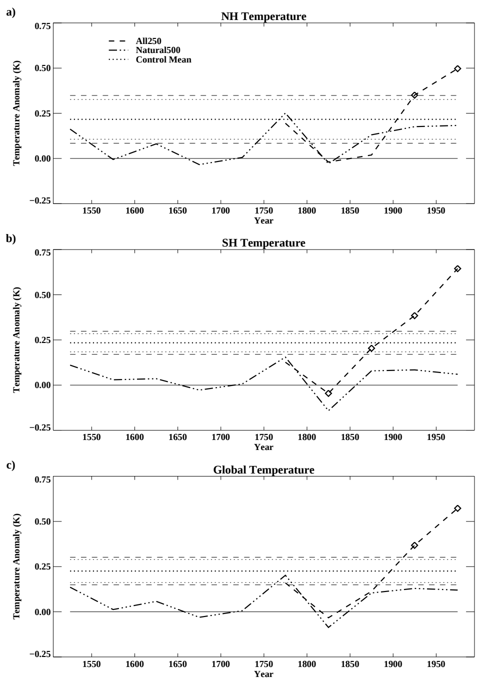

Figure 2: Temperature Timeseries

Fifty-year average temperature for northern hemisphere (a), southern hemisphere (b) and global mean (c). All values are relative to 1700-1749 average from NATURAL500. Thick dotted line shows Control values. Thin dotted (dashed) lines denote uncertainty ranges for ALL250 (NATURAL500). Diamonds show where ALL250 and NATURAL500 are significantly different. All uncertainties were estimated using 50-year averages from CONTROL after removal of the slow drift.

imum absolute trend in the 2200 years of CONTROL available to us. If the trend is outside this range we conclude it is significantly non-zero. Though we compute 500-year trends from segments offset by 10 years there are only 4 independent 500-year trends in the 2200 years. Thus the maximim absolute trend will correspond to approximately the 10% signifance level(Allen and Tett, 1999).

As discussed above NATURAL500 shows a positive trend in forcing. However, for almost all the climate variables that we considered (Table 1) trends from NATURAL500 are not significantly different from zero. Northern Hemispheric growing season (April to September) shows a significantly positive trend. This is likely a consequence of the increase in forcing (0.6W/m^2/1000 years) and that land summar temperatures respond rapidly to external forcings. The only other variable with significant trend is ice cover during austral spring southern hemisphere which shows a significant increase. This is probably due to slow adjustment in the the southern ocean to the initial forcing imbalance.

In the simulation with both anthropogenic and natural forcings we find that, in general, that there are significant 500-year trends. For temperature and global-mean precipitation these are, as expected, a significant increase. We also find decreases in sea-ice area but no significant change in the Atlantic Meridional Overturning Circulation (AMOC). Unexpectedly we find significant decreases in Northern Hemispheric land precipitation. More detailed analyses (not shown) shows this is due to a reduction in precipitation in the tropics rather than the extra-tropics. Northern hemisphere spring snow cover increases. This is due to an increase of snow in regions of deforestation which generates locally cooler conditions as snow covered grassland has higher albedo than forest. This causes some positive feedback as snow cover can then persist for longer in the colder conditions.

3 Variability Enhancement

In this section we quantify the impact that external forcing has on variance on annual-mean, decadal-mean and fifty year timescales. We use the same variables that we computed trends. Our aim is to see how important external forcing is to climate variability. We compare ratios of standard deviations from the forced simulations with the control simulation for the same variables that we computed 500-year trends for (see above). As before we combine data from years 1499-1749 from NATURAL500 with data from ALL250.

For the naturally forced simulation we find that the standard deviations of large-scale temperature and global-mean precipitation (Table 2) are significantly enhanced relative to CONTROL. Enhancement is largest on 50-year timescales and on global scales. Southern Hemispheric ice cover has enhanced variance relative to CONTROL even on decadal time scales suggesting that Antarctic spring ice-cover is sensitive to external forcings. Northern hemispheric snow cover has significantly less variance than CONTROL. This is probably because of the reduction in snow cover in NATURAL500 relative to CONTROL discussed earlier. There is no evidence of any enhanced variability for either the AMOC or the winter North Atlantic Oscillation (NAO).

In the simulation driven by anthropogenic and natural forcings we find significant enhancements in variability for almost all variables considered. The only exceptions are northern hemisphere spring snow cover which is likely to be for the same reasons we discussed in NATURAL500. We find no significant change in the NAO. However we do find changes in the AMOC suggesting an anthropogenic influence on the AMOC.

We have shown that large scale temperature variability is enhanced by natural and anthropogenic forcings. What about the role of natural forcing on small-scale variability? To examine this question we computed the standard deviation ratio between NATURAL500 and CONTROL for fields of decadal-mean near-surface temperature (Fig. 3(a)). This shows significant enhancements in *gridpoint* temperature variability across most of the tropics and sub-tropics. Largest increases occur over the Indian Ocean and tropical Africa. Examining changes in zonal-mean temperature standard deviation we can see a significant enhancement throughout the tropics and sub-tropics (Fig. 3(b)). However there is less evidence of enhanced variability on decadal timescales in extra-tropical regions. The implications of this are that studies into tropical decadal variability (and its teleconnections) need to consider natural forcings as an important driver of climate variability. It also suggests that a small number of sites in the tropics may be sufficient to look at the forced response of the climate system to external forcings.

4 20th Century Changes

We have shown that external forcings enhance decadal climate variability on both both global and continental scales. We use 50-year trends from NATURAL500 to evaluate recent *observed* trends in surface temperature. 50-year trends for each $5^\circ \times 5^\circ$

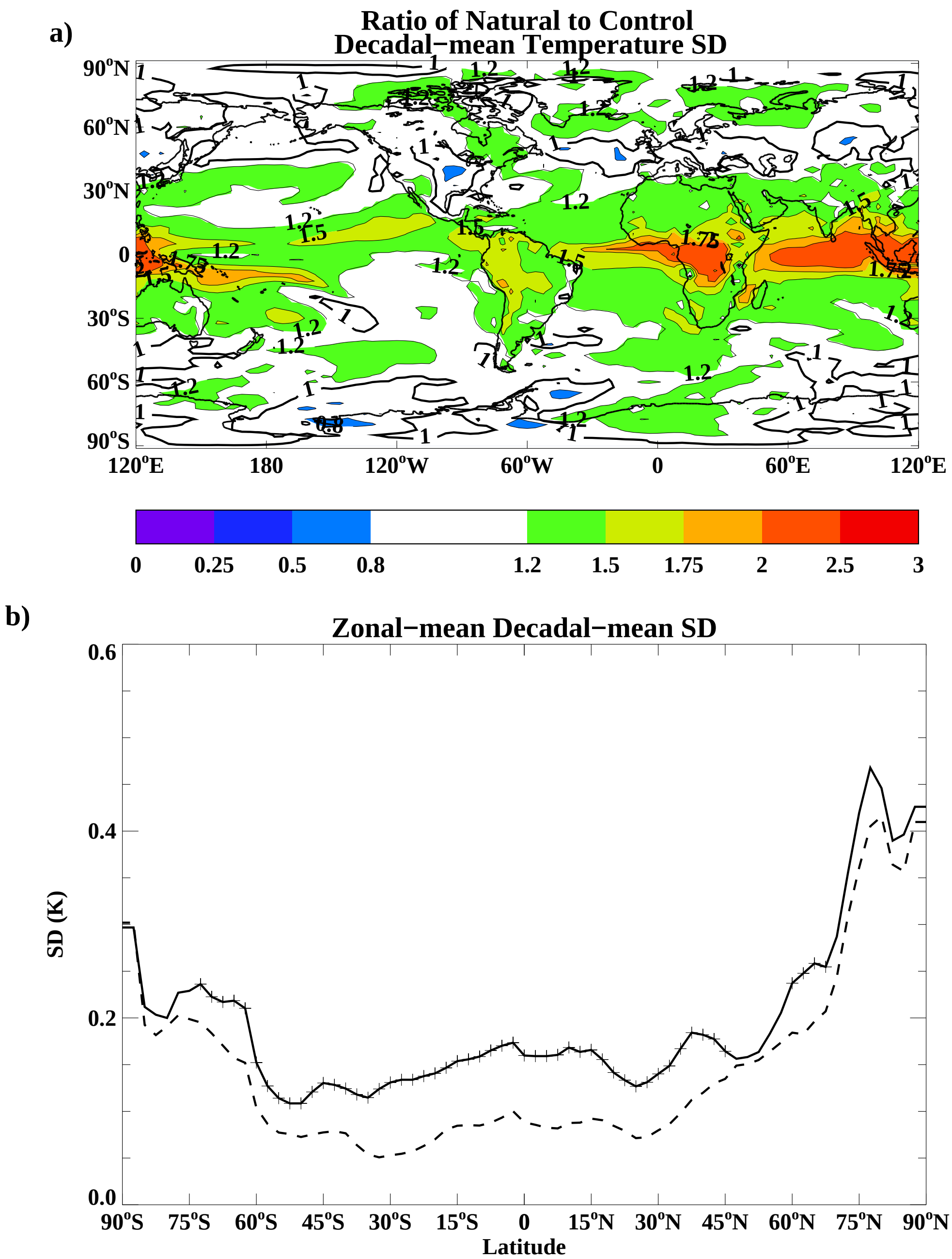

Figure 3: Temperature standard deviation
a: Map of ratio of NATURAL500 to CONTROL standard deviations for decadal-mean temperature. Values greater (less) than 1.2 (0.80) are where NATURAL500 has significantly (95 % level) greater (less) variability than CONTROL and are colour-filled. The 1.0 contour is drawn bold.
b: Plot of standard deviations of zonal-mean decadal-mean temperature for NATURAL500 (solid) and CONTROL (dashed). Where NATURAL500 has a significantly (95 % level) higher standard deviation than CONTROL pluses are marked. Uncertainties were computed assuming all decades are independent.

Table 2: Ratio of standard deviations between forced and control simulations
⋆shows where ratios are not significantly larger than one, at the 95% level, assuming all data is independent. †shows where ratios are significantly less than one.

	NATURAL500			ALL250		
	Annual	10-year	50-year	Annual	10-year	50-year
NH Temp	1.35	1.67	1.87	1.92	2.34	3.25
SH Temp	1.31	2.34	3.28	2.00	4.28	8.65
GM Temp	1.44	2.32	2.79	2.20	3.78	6.10
NH Land Temp	1.34	1.83	2.07	1.76	2.32	3.23
NH Land AMJJAS Temp	1.25	1.74	2.17	1.48	1.70	2.07
GM Precip	1.40	2.52	2.74	1.51	2.64	3.25
NH Land Precip	0.98 ⋆	1.05 ⋆	1.04 ⋆	1.10	1.59	2.50
NH MAM ice	–	1.09 ⋆	1.16 ⋆	–	1.46	2.24
SH SON ice	–	1.30	2.25	–	1.85	4.14
NH MAM land snow	0.90 †	0.88 ⋆	0.79 ⋆	0.96 †	1.36	2.02
AMOC	–	0.96 ⋆	0.70 ⋆	–	1.13	1.38
DJF NAO	0.99 ⋆	1.12 ⋆	0.75 ⋆	0.96 ⋆	1.05 ⋆	0.92 ⋆

gridbox, for 1952–2002, from HadCRUT2 (Jones and Moberg, 2003) are generally positive (Fig. 4) with large parts of Asia having trends greater than 0.3K/decade. The global-average of these trends is 0.11K/decade.

Volcanic eruptions are a major contributor to natural forcings but their impact on climate is asymmetric. They cause rapid cooling then a slower warming recovery to normal conditions. Thus 50-year trends from NATURAL500 are asymmetric with large negative trends being more frequent than large positive trends. In order to evaluate recent change we compare the observed trends with both the maximum trend and largest absolute trend simulated in the 508 years of NATURAL500. Trends larger than the maximum (maximum absolute) are when observed rates of warming (temperature change) are likely to be outside the range of *natural* climate variability. Impacts on natural systems are most likely in such regions especially where the rate of temperature change is outside natural ranges.

Approximately 40% (Fig. 4) of the observed trends (Asia, Canada, Alaska, the Indian Ocean and Indonesia) are outside the range of simulated warming trends as is the global-average observed trend. About 27% of the observed trends are outside the absolute range of warming trends. Regions which do not show unprecedented trends are largely the Atlantic, Pacific and most of the United States. Thus if the simulated variability is correct then recent observed changes are outside natural variability.

5 Summary

We have carried out two new simulations of HadCM3. One driven by natural forcings alone and an other by natural and anthropogenic forcings. We found that natural forcings were dominated by volcanic forcings and the simulations showed cooling in the late 17th century. Over the 500 years of the simulation there is a positive trend in forcing which appears to drive an increase in land growing season temperatures. The only other variable which shows a significant trend is southern hemisphere sea-ice during spring. However this shows an increase so is likely part of a slow adjustment in the Southern Ocean to the initial forcing inbalance. Of the other variables consider none show any significant trends. In contrast there are many significant trends in the simulation forced with natural and anthropogenic forcings. We found a significant simulated anthropogenic effect on climate in the 19th century in the southern hemisphere and throughout all of the 20th century in the northern hemisphere.

Large scale temperature and precipitation variability was significantly enhanced in the naturally forced simulation relative to the control simulation of HadCM3. Decadal-mean temperature variability was strongly enhanced throughout most of the tropics. This suggests that studies into natural variability should consider external forcings as well as modes of internal variability.

Finally we found that observed temperature trends from 1952 to 2002 were outside the range of simulated natural climate variability over several regions of the world.

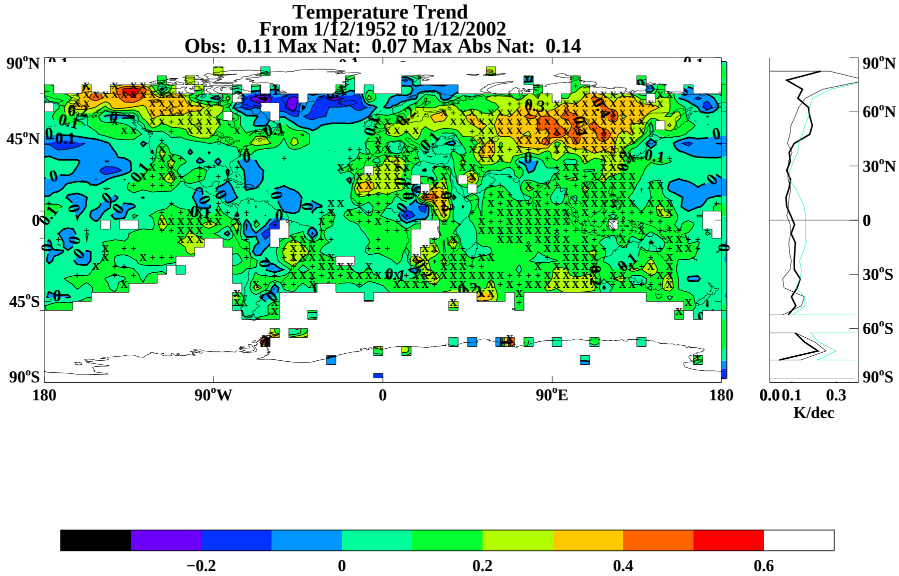

Figure 4: Observed changes relative to Natural variability

Observed 50-year trends from HadCRUT2 (K/decade) with a contour interval of 0.2K/decade. Where observed trends are greater than the largest simulated trend an "+" is plotted. Where observed trends are greater than the largest absolute simulated trend an "X" is plotted. About 40% (27%) of observed gridded trends are greater than the largest (absolute) simulated trend from NATURAL500. The area-weighted average of the observed trend (0.11K/decade) is greater than the largest 50-year trend (0.11K/decade) but not the largest absolute value (0.14K/decade) from NATURAL500.
To the right is shown the zonal-mean observed temperature-trend (solid), the maximum zonal-mean trend from NATURAL500 (thin black line) and the maximum absolute zonal-mean trend from NATURAL500 (thin green line).

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References

Allen, M. R., and S. F. B. Tett, 1999: Checking for model consistency in optimal finger printing. *Climate Dynamics*, **15**, 419–434.

Berger, A. L., 1978: Long-term variations of daily insolation and quaternary climatic. *J. Atmos. Sci.*, **35**.

Betts, R. A., 2000: Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature*, **408**, 187–190.

Briffa, K. R., and T. J. Osborn, 2002: PALEOCLIMATE: Blowing Hot and Cold. *Science*, **295**, 2227–2228.

Collins, M., S. F. B. Tett, and C. Cooper, 2001: The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dyn.*, **17**, 61–81.

——, T. J. Osborn, S. F. B. Tett, K. R. Briffa, and F. H. Schweingruber, 2002: A comparison of the variability of a climate model with a network of tree-ring densities. *J. Climate.*, **15**(13), 1497–1515.

Crowley, T. J., S. K. Baum, K.-Y. Kim, G. C. Hegerl, and W. T. Hyde, 2003: Modeling ocean heat content changes during the last millennium. *Geophys. Res. Let.*, **30**(18), doi:10.1029/2003GL017801.

——, 2000: Causes of climate change over the past 1000 years. *Science*, **289**, 270–277.

Goldewijk, K. K., 2001: Estimating global land use change over the past 300 years: The HYDE database. *Global Biogeochem. Cycles*, **15**(2), 417–433.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dyn.*, **16**, 147–168.

Johns, T. C., J. M. Gregory, W. J. Ingram, C. E. Johnson, A. Jones, J. A. Lowe, J. F. B. Mitchell, D. L. Roberts, D. M. H. Sexton, D. S. Stevenson, S. F. B. Tett, and M. J. Woodage, 2003: Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. *Clim. Dyn.*, **20**, 583–612, doi 10.1007/s00382–002–0296–y.

Jones, P. D., and A. Moberg, 2003: Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Climate.*, **16**, 206–223.

Lean, J., J. Beer, and R. Bradley, 1995: Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophys Res Lett*, **22**, 3195–3198.

Pope, V. D., M. L. Gallani, P. R. Rowntree, and R. A. Stratton, 2000: The impact of new physical parametrizations in the Hadley Centre climate model – HadAM3. *Climate Dyn.*, **16**, 123–146.

Ramankutty, N., and J. A. Foley, 1999: Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochem. Cycles*, **13**, 997–1027.

Randel, W. J., and F. Wu, 1999: A stratospheric ozone trends data set for global modelling studies. *Geophys. Res. Let.*, **26**, 3089–3092.

Sato, M., J. E. Hansen, M. P. McCormick, and J. B. Pollack, 1993: Stratospheric aerosol optical depths (1850–1990). *J. Geophys. Res.*, **98**(D12), 22,987–22,994.

Stott, P. A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins, 2000: External control of twentieth century temperature by natural and anthropogenic causes. *Science*, **290**, 2133–2137.

Tett, S. F. B., G. S. Jones, P. A. Stott, D. C. Hill, J. F. B. Mitchell, M. R. Allen, W. J. Ingram, T. C. Johns, C. E. Johnson, A. Jones, D. L. Roberts, D. M. H. Sexton, and M. J. Woodage, 2002: Estimation of natural and anthropogenic contributions to 20^{th} century temperature change. *J. Geophys. Res.*, **107**, doi 10.1029/2000JD000028.

von Storch, H., E. Zorita, J. M. Jones, Y. Dimitriev, F. González-Rouco, and S. F. B. Tett, 2004: Reconstructing past climate from noisy data. *Science*, **306**, 679–682.

Wilson, M. F., and A. Henderson-Sellers, 1985: A global archive of land cover and soils data for use in general circulation climate models. *Journal of Climatology*, **5**, 119–143.