Supporting Online Material

Figure S1 provides global maps of observed and simulated surface temperature changes based on local linear trends for three periods: 1880-2003, 1900-2003, and 1950-2003. Observations are based on surface air measurements at meteorological stations and sea surface temperatures over ocean areas (21). The mean for the five model runs is shown in the bottom row.

Figure S2 shows the decadal rate of change of heat content in the upper 750 m of ocean during 1993-2003 in our five climate model runs and in the observational analysis of Willis et al. (19).

The effective forcings, F_e, that drove the climate changes in Figs. 1, 2, 3, S1 and S2 are summarized in Table 1. These effective forcings are obtained from 5-run ensembles of climate simulations carried out for the individual forcings for the assumed 1880-2000 changes of the forcing mechanisms and a 5-run ensemble with all forcing mechanisms acting at once (9). The GHG and solar forcings in Table 1 for 1880-2003 are based on the assumption that the effective forcing F_e is proportional to the adjusted forcing F_a, the latter computed precisely for both 1880-2000 and 1880-2003. The 2000-2003 change of GHG forcing is +0.11 W/m^2, while the 2000-2003 change of the solar forcing is –0.06 W/m^2. Thus the 2000-2003 change of the sum of all individual forcings is +0.05 W/m^2, as is the assumed 2000-2003 change for all forcings acting at once. The sum of all of the 1880-2003 effective forcings is not identical to the effective forcing for all forcing mechanisms operating at once because of non-linearity in the combination of all forcings and because of the unforced variability in the climate model response to any forcing mechanism.

All of the results in the present paper are from an extensive set of simulations carried out in 2004, submitted to the Intergovernmental Panel on Climate Change (IPCC) in 2004 for inclusion in the 2007 IPCC report, and made available to the scientific community from http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php. The stratospheric ozone change in these simulations during 1979-1997 was inadvertently only 5/9 as large as the stratospheric ozone change recommended by Randel and Wu (S1) for that period. A subset of the simulations for IPCC was rerun in 2005 using the Randel and Wu ozone change and is available at the same web site indicated in this paragraph. The effect of this ozone correction is to change the global ozone forcing by –0.02 W/m^2 for the period 1979-1997 and the total climate forcing for the period 1880-2003 by –0.02 W/m^2, i.e., the total forcing is reduced from 1.80 to 1.78 W/m^2. This change has a detectable effect on stratospheric temperature, increasing the lower stratospheric cooling by about 0.2°C over the 1979-1997 period and over the entire 1880-2003 period. However, as expected, this small forcing change has little effect on the troposphere, the climate changes there being less than the variability among ensemble members with the same forcings.

Thus conclusions derived from observed ocean heat storage are not significantly dependent on such small uncertainties in the climate forcings. However, because the net 1880-2003 forcing is estimated as only ~1.8 W/m^2, it is apparent that feasible changes of the aerosol direct and indirect forcings could significantly alter the net forcing and heat storage. As discussed in the main text, if the net forcing were reduced, both global warming and heat storage would be reduced, and the opposite would be true if the forcings were increased.

Table S1 provides conversion factors that allow the planetary heat storage to be estimated for specified changes of global temperature or ice amount. For example, the planetary heat imbalance required to yield 1.5 cm eustatic sea level rise by melting ice is 0.015 x 9.4 W yrs ~ 0.14 W yrs. An atmospheric warming rate typical of the last 25 years, ~0.2°C/decade requires 0.2 x 0.32 W yrs ~ 0.064 W yrs. Actual decadal rate of sea ice thickness change is highly uncertain, but a 5% reduction in sea ice mass requires 0.05 x 1.3 W yrs ~ 0.065 W yrs. Warming of the land surface by 0.2°C in a decade requires about 0.2 x 0.23 W yrs ~ 0.046 W yrs.

Supplementary References

S1. W.J. Randel, F. Wu, *Geophys. Res. Lett.* **26**, 3089 (1999).

Fig. S1. Observed and modeled surface temperature change for 1880-2003, 1900-2003 and 1950-2003. Reliability and accuracy of observations increases with the successively more recent periods. The five climate model runs are each driven by the forcings in Fig. 1.

Fig. S2. Maps of 10-year change of heat content in upper 750 meters of ocean in our climate model simulations and in observations (19).

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2.**

Land surface warming by 1°C: The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

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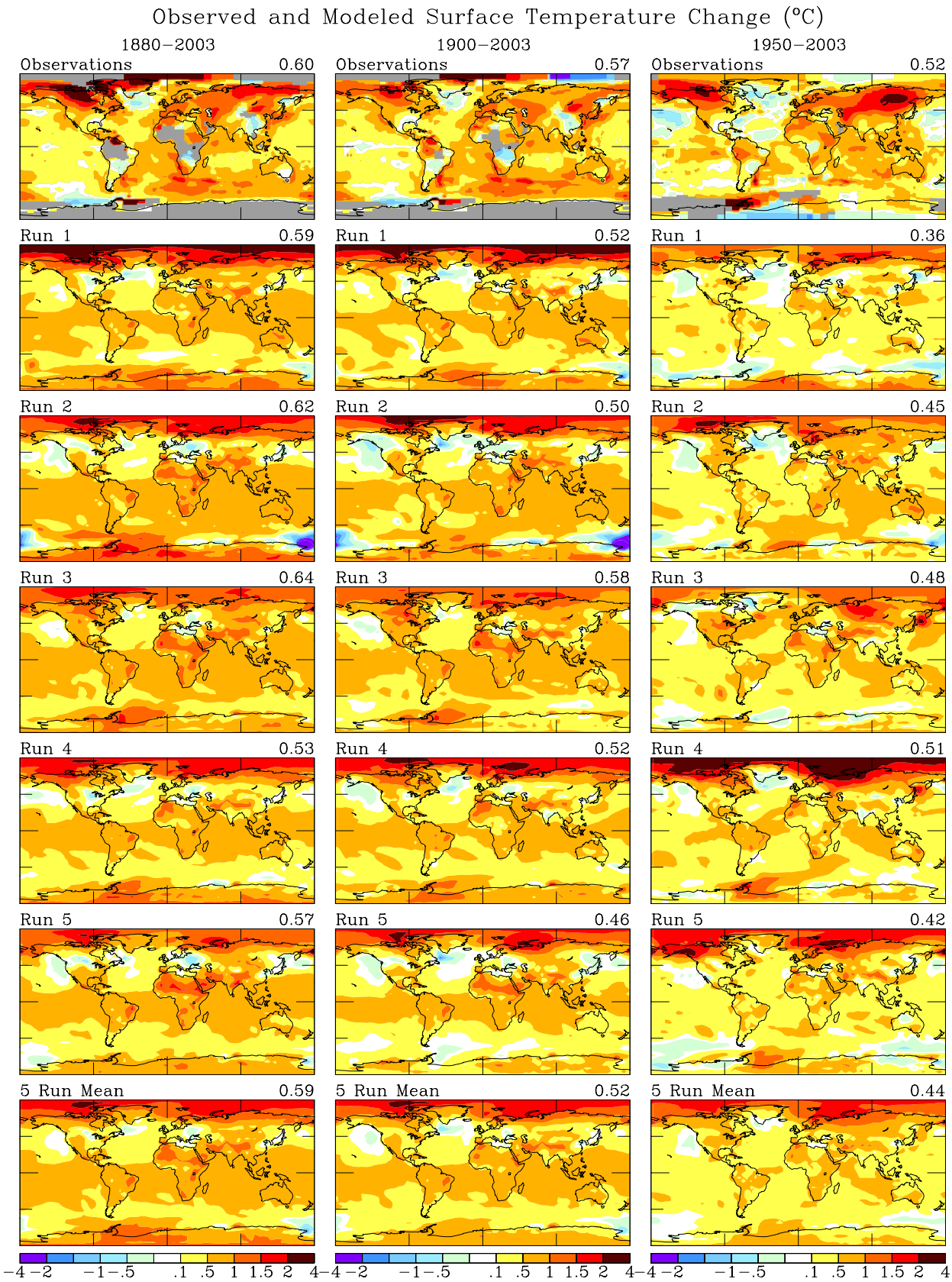
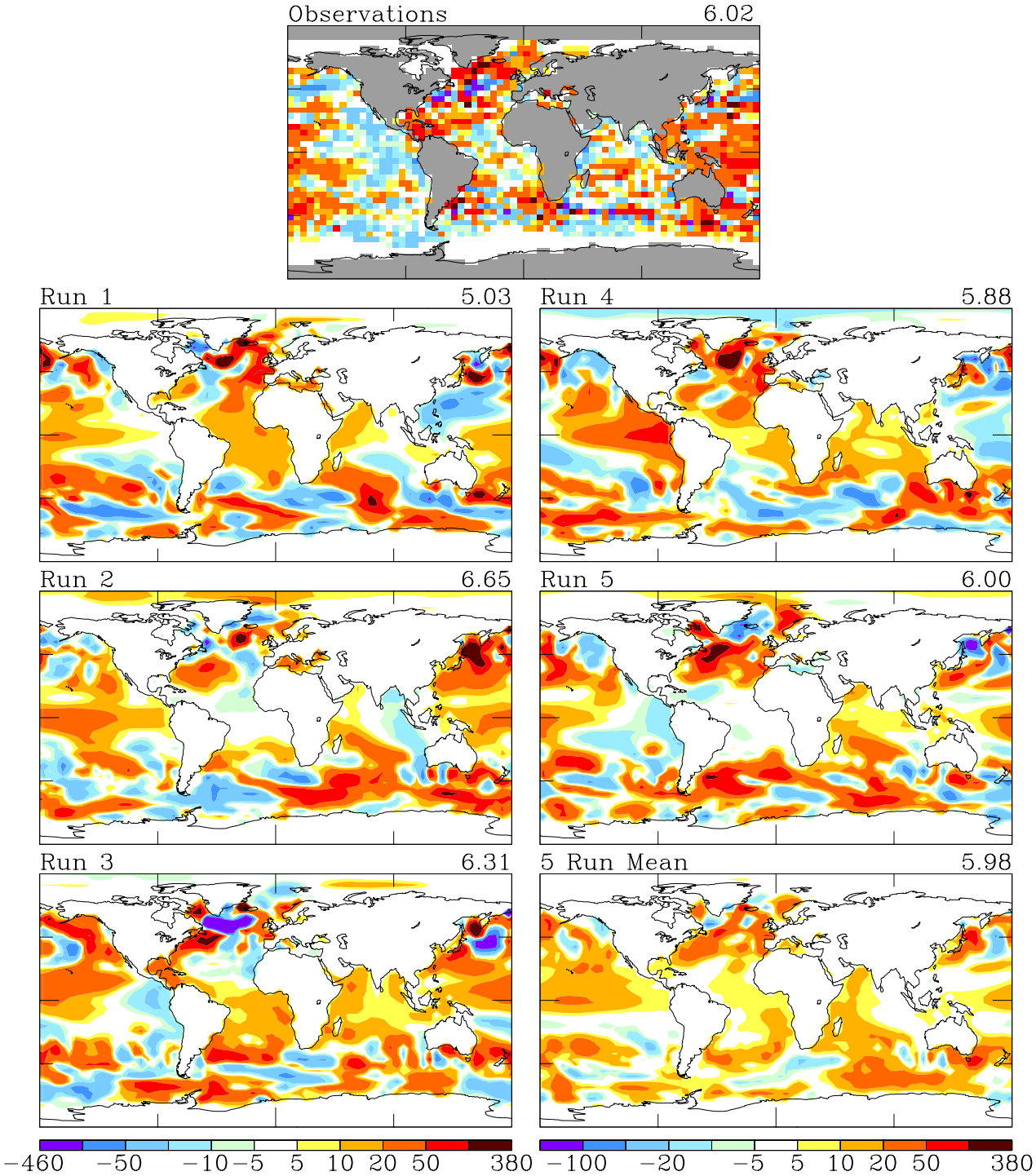
[1]Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.


Observed and Modeled Surface Temperature Change (°C)
1880–2003
1900–2003
1950–2003
Observations 0.60
Observations 0.57
Observations 0.52
Run 1 0.59
Run 1 0.52
Run 1 0.36
Run 2 0.62
Run 2 0.50
Run 2 0.45
Run 3 0.64
Run 3 0.58
Run 3 0.48
Run 4 0.53
Run 4 0.52
Run 4 0.51
Run 5 0.57
Run 5 0.46
Run 5 0.42
5 Run Mean 0.59
5 Run Mean 0.52
5 Run Mean 0.44
−4 −2 −1 −.5 .1 .5 1 1.5 2 4

Ocean Heat Content Change (W yr/m^2) in upper 750 meters