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Earth's Energy Imbalance: Confirmation and Implications

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Our climate model, driven mainly by increasing human-made greenhouse gases and aerosols among other forcings, calculates that Earth is now absorbing 0.85 ± 0.15 W/m^2 more energy from the Sun than it is emitting to space. This imbalance is confirmed by precise measurements of increasing ocean heat content over the past 10 years. Implications include: (i) expectation of additional global warming of about 0.6°C without further change of atmospheric composition; (ii) confirmation of the climate system's lag in responding to forcings, implying the need for anticipatory actions to avoid any specified level of climate change; and (iii) likelihood of acceleration of ice sheet disintegration and sea level rise.

Earth's climate system has considerable thermal inertia. This point is of critical importance to policy and decision-makers who seek to mitigate the effects of undesirable anthropogenic climate change. The effect of the inertia is to delay Earth's response to climate forcings, i.e., changes of the planet's energy balance that tend to alter global temperature. This delay provides an opportunity to reduce the magnitude of anthropogenic climate change before it is fully realized, if appropriate action is taken. On the other hand, if we wait for more overwhelming empirical evidence of climate change, the inertia implies that still greater climate change will be in store, which may be difficult or impossible to avoid.

The primary symptom of Earth's thermal inertia, in the presence of an increasing climate forcing, is an imbalance between the energy absorbed and emitted by the planet. This imbalance provides an invaluable measure of the net climate forcing acting on Earth. Improved ocean temperature measurements in the past decade, along with high precision satellite altimetry measurements of the ocean surface, permit an indirect but precise quantification of Earth's energy imbalance. We compare observed ocean heat storage with simulations of global climate change driven by estimated climate forcings, thus obtaining a check on the climate model's ability to simulate the planetary energy imbalance.

The lag in the climate response to a forcing is a sensitive function of equilibrium climate sensitivity, varying approximately as the square of the sensitivity (*1*), and it depends on the rate of heat exchange between the ocean's surface mixed layer and the deeper ocean (*2*–*4*). The lag could be as short as a decade, if climate sensitivity is as small as ¼°C per W/m^2 of forcing, but it is a century or longer if climate sensitivity is 1°C per W/m^2 or larger (*1*, *3*). Evidence from Earth's history (*3*–*6*) and climate models (*7*) suggests that climate sensitivity is ¾ ± ¼ °C per W/m^2, implying that 25-50 years are needed for Earth's surface temperature to reach 60 percent of its equilibrium response (*1*).

We investigate Earth's energy balance via computations with the current global climate model of the NASA Goddard Institute for Space Studies (GISS). The model and its simulated climatology have been documented (*8*), as has its response to a wide variety of climate forcing mechanisms (*9*). The climate model's equilibrium sensitivity to doubled CO_2 is 2.7°C (~2/3°C per W/m^2). The climate simulations for 1880-2003 used here will be included in the Intergovernmental Panel on Climate Change (IPCC) 2007 report and are available with other IPCC runs at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php or via www.giss.nasa.gov/data/imbalance.

Climate forcings. Figure 1A summarizes the forcings that drive the simulated 1880-2003 climate change. Among alternative definitions of climate forcing (*9*), we use the effective forcing, F_e. F_e differs from conventional climate forcing definitions (*10*) by accounting for the fact that some forcing mechanisms have a lesser or greater "efficacy" in altering global temperature than an equal forcing by CO_2 (*9*). F_e is an energy flux change arising in response to an imposed forcing agent. It is constant throughout the atmosphere, as it is evaluated after atmospheric temperature has been allowed to adjust to the presence of the forcing agent.

The largest forcing is due to well-mixed greenhouse gases, CO_2, CH_4, N_2O, CFCs (chlorofluorocarbons) and other trace gases, totaling 2.75 W/m^2 in 2003 relative to 1880 (Table 1). Ozone (O_3) and stratospheric H_2O from oxidation of increasing CH_4 make the total greenhouse gas (GHG) forcing 3.05 W/m^2 (*9*). Estimated uncertainty in the total GHG forcing is ~15% (*10*, *11*).

Atmospheric aerosols cause climate forcings by reflecting and absorbing radiation, as well as via indirect effects on cloud cover and cloud albedo (*10*). The aerosol scenario in our model uses estimated anthropogenic emissions from fuel use statistics and includes temporal changes in fossil fuel use technologies (*12*). Our parameterization of aerosol indirect effects (*13*, *9*) is constrained by empirical evidence that the aerosol indirect forcing is ~ -1 W/m^2 (*9*). The effective aerosol forcing in 2003 relative to 1880, including positive forcing by absorbing black carbon (BC) aerosols, is –1.39 W/m^2, with subjective estimated uncertainty ~ 50%.

Stratospheric aerosols from volcanoes cause a sporadically large negative forcing, with an uncertainty that increases with age from 15% for 1991 Mount Pinatubo to 50% for 1883 Krakatau (*9*). Land use and snow albedo forcings are small on global average and uncertain by about a factor of two (*9*). Solar irradiance is taken as increasing by 0.22 W/m^2 between 1880 and 2003, with estimated uncertainty a factor of two (*9*). All of these partly subjective uncertainties are intended as 2σ error bars. The net change of effective forcing between 1880 and 2003 is +1.8 W/m^2, with formal uncertainty ±0.85 W/m^2 due almost entirely to aerosols (Table 1).

Climate simulations. The global mean temperature simulated by the GISS model driven by this forcing agrees well with observations (Fig. 1B). An ensemble of five simulations was obtained by using initial conditions at intervals of 25 years of the climate model control run, thus revealing the model's inherent unforced variability. The spatial distribution of the simulated warming (see fig. S1) is slightly excessive in the tropics, as much as a few tenths of a degree, and on average the simulated warming is a few tenths of a degree less than observed in middle latitudes of the Northern Hemisphere, but there is substantial variation from one model run to another (fig. S1).

Discrepancy in the spatial distribution of warming may be partly a result of the uncertain aerosol distribution, specifically the division of aerosols between fossil fuel and biomass burning aerosols (*9*). However, excessive tropical warming in our model is primarily in the Pacific Ocean, where our primitive ocean model is unable to simulate climate variations associated with ENSO processes.

The planetary energy imbalance in our model (Fig. 1C) did not exceed a few tenths of 1 W/m^2 prior to the 1960s. Since then, except for a few years following each large volcanic eruption, the simulated planetary energy imbalance has grown steadily. According to the model, Earth is now absorbing 0.85 ± 0.15 W/m^2 more solar energy than it radiates to space as heat.

Ocean heat storage. Confirmation of the planetary energy imbalance can be obtained by measuring the heat content of the ocean, which must be the principal reservoir for excess energy (*3*, *14*). Levitus *et al*. (*14*) compiled ocean temperature data that yielded increased ocean heat content of about 10 W yr m^{-2}, averaged over the Earth's surface, during 1955-1998 [1 W yr/m^2 over the full Earth ~ 1.61×10^{22} joules; see table S1 for conversion factors of land, air, water and ice temperature changes and melting to global energy units]. Total ocean heat storage in that period is consistent with climate model simulations (*15–18*), but the models do not reproduce reported decadal fluctuations. The fluctuations may be a result of variability of ocean dynamics (*16*) or, at least in part, an artifact of incomplete sampling of a dynamically variable ocean (*17*, *18*).

Improved definition of Earth's energy balance is possible for the past decade. First, the predicted energy imbalance due to increasing greenhouse gases has grown to 0.85 ± 0.15 W/m^2 and the past decade has been uninterrupted by any large volcanic eruption (Fig. 1). Second, more complete ocean temperature data is available, including more profiling floats and precise satellite altimetry that permits improved estimates in data sparse regions (*19*).

Figure 2 shows that the modeled increase of heat content in the past decade in the upper 750 m of the ocean is 6.0 ± 0.95 (std. dev.) W yr/m^2, averaged over the surface of Earth, varying from 5.0 to 7.15 W yr/m^2 among the five simulations. The observed annual mean rate of ocean heat gain between 1993 and mid 2003 was 0.86 ± 0.12 W/m^2 per year for the 93.4% of the ocean that was analyzed (*19*). Assuming the same rate for the remaining 6.6% of the ocean yields a global mean heat storage rate of 0.7 x 0.86 = 0.60 ± 0.10 W/m^2 per year or 6 ± 1 W yr/m^2 for 10 years, 0.7 being the ocean fraction of Earth's surface. This agrees well with the 5.5 W yr/m^2 in the analysis of Levitus *et al*. (*20*) for the upper 700 meters based only on in situ data.

Figure 3 compares the latitude-depth profile of the observed ocean heat content change with the five climate model runs and the mean of the five runs. There is a large variability among the model runs, revealing the chaotic "ocean weather" fluctuations that occur on such a time scale. This variability is even more apparent in maps of change in ocean heat content (fig. S2). Yet the model runs contain essential features of observations, with deep penetration of heat anomalies at middle to high latitudes and shallower anomalies in the tropics.

The modeled heat gain of ~0.6 W/m^2 per year for the upper 750 meters of the ocean differs from the decadal mean planetary energy imbalance of ~0.75 W/m^2 primarily because of heat storage at greater depths in the ocean. 85% of the ocean heat storage occurred above 750 meters on average for the five simulations, with the range from 78% to 91%. The mean heat gain below 750 m was ~0.11 W/m^2. The remaining 0.04 W/m^2 warmed the atmosphere and land and melted sea ice and land ice (see supplementary information).

Earth's energy imbalance. We infer from the consistency of observed and modeled planetary energy gains that the forcing still driving climate change, i.e., the forcing not yet responded to, averaged ~ 0.75 W/m^2 in the past decade and was ~ 0.85 ± 0.15 W/m^2 in 2003 (Fig. 1C). This imbalance is consistent with the total forcing ~1.8 W/m^2 relative to 1880 and climate sensitivity ~2/3°C per W/m^2. The observed 1880-2003 global warming is 0.6-0.7°C (*10*, *21*), which is the full response to nearly 1 W/m^2 of forcing. 0.85 W/m^2 of the 1.8 W/m^2 forcing remains, i.e., additional global warming of 0.85 x 2/3 ~ 0.6°C is "in the pipeline" and will occur in the future even if atmospheric composition and other climate forcings remain fixed at today's values (*3*, *4*, *22*).

The present planetary energy imbalance is large by standards of Earth's history. For example, an imbalance of 1 W/m^2 maintained for the last 10,000 years of the Holocene is sufficient to melt ice equivalent to 1 km of sea level (if there were that much ice), or raise the temperature of the ocean above the thermocline by more than 100°C (table S1). Clearly on long time scales the planet has been in energy balance to within a small fraction of 1 W/m^2.

An alternative interpretation of the observed present high rate of ocean heat storage might be that it results, not from climate forcings, but from unforced atmosphere-ocean fluctuations. However, if a fluctuation had brought cool water to the ocean surface, as needed to decrease outgoing heat flux, the ocean surface would have cooled, while in fact it warmed (*21*). A positive climate forcing, anticipated independently, is the more viable interpretation.

The present 0.85 W/m^2 planetary energy imbalance, its consistency with estimated growth of climate forcings over the past century (Fig. 1A), and its consistency with the temporal development of global warming based on a realistic climate sensitivity for doubled CO_2 (Fig. 1B) offer strong support for the inference that the planet is out of energy balance because of positive climate forcings. If climate sensitivity, climate forcings, and ocean mixing are taken as arbitrary parameters (*23*), one may find other combinations that yield warming comparable to that of the past century, but (1) climate sensitivity is constrained by empirical data, (2) our simulated depth of penetration of ocean warming anomalies is consistent with observations (fig. S2), thus supporting the modeled rate of ocean mixing, and (3) despite ignorance about aerosol changes, there is sufficient knowledge to constrain estimates of climate forcings (*9*).

The planetary energy imbalance and implied warming "in the pipeline" complicate the task of avoiding any specified level of global warming. For example, it has been argued, based on sea level during prior warm periods, that global warming of more than 1°C above the level of 2000 would constitute "dangerous anthropogenic interference" with climate (*24*, *25*). With 0.6°C global warming in the pipeline and moderate growth of non-CO_2 forcings, a 1°C limit on further warming limits peak CO_2 to about 440 ppm (*11*). Given current CO_2 ~378 ppm, annual growth ~1.9 ppm (*11*), and a still expanding worldwide fossil fuel energy infrastructure, it may be impractical to avoid 440 ppm CO_2. A conceivable, though difficult, reduction of non-CO_2 forcings could increase the peak CO_2 limit for 1°C warming to a more feasible 520 ppm (*11*). This example illustrates that the 0.6°C unrealized warming associated with the planet's energy imbalance implies the need for near-term anticipatory actions, if a low limit on climate change is to be achieved.

Sea level. Sea level change includes steric (mainly thermal expansion) and eustatic (mainly changes of continental ice and other continental water storage) components. Observed temperature change in the upper 700-750 m yield a steric sea level rise of 1.4-1.6 cm (*19*, *20*). The full ocean temperature changes in our five simulations yield a mean steric 10-year sea level increase 1.6 cm. Our climate model does not include ice sheet dynamics, so we cannot calculate eustatic sea level change directly. Sea level measured by satellite altimeters since 1993 increased 2.8 ± 0.4 cm/decade (*26*), but as a measure of the volume change (steric + eustatic) of ocean water this must be increased ~0.3 cm to account for the effect of global isostatic adjustment (*27*). We thus infer a eustatic contribution to sea level rise of ~1.5 cm in the past decade.

Both the total sea level rise in the past decade and the eustatic component, which is a critical metric for ice melt, are accelerations over the rate of the preceding century. IPCC (*10*) estimated sea level rise of the past century as 1.5 ± 0.5 cm/decade, with a central estimate of only 0.2 cm/decade for the eustatic component, albeit with large uncertainty. Decadal variability limits the significance of sea level change in a single decade (*27*, *28*). However, we suggest that both the steric and eustatic increases are a product of the large, unusual, persistent planetary energy imbalance that overwhelms normal variability and as such may be a harbinger of accelerating sea level change (*25*).

The estimated ~1.5 cm eustatic sea level rise in the past decade, even if entirely ice melt, required only 2% of the Earth's present energy imbalance (table S1). Much more rapid melt is possible if iceberg discharge is accelerating, as some recent observations suggest (*29*, *30*) and has occurred in past cases of sharp sea level rise that accompanied rapid global warming (*31*). Unlike ice sheet growth, which is limited by the snowfall rate in cold dry regions, ice sheet disintegration can be a wet process fed by multiple radiative and dynamical feedbacks (*25*). Thus the portion of the planetary energy imbalance used for melting is likely to rise as the planet continues to warm, summer melt increases, and melt-water lubricates and softens the ice sheets. Other positive feedbacks include reduced ice sheet albedo, a lowering of the ice sheet surface, and rising sea level (*25*).

Implications. The thermal inertia of the ocean, with resulting unrealized warming "in the pipeline", combines with ice sheet inertia and multiple positive feedbacks during ice sheet disintegration to create the possibility that the climate system could reach a point where large sea level change is practically impossible to avoid. If the ice sheet response time is millennia, the ocean thermal inertia and ice sheet dynamical inertia are relatively independent matters. However, it has been suggested, based on the saw-toothed shape of glacial-interglacial global temperature and qualitative arguments about positive feedbacks, that substantial ice sheet change could occur on the time scale of a century (*25*).

The destabilizing impact of comparable ocean and ice sheet response times is apparent. Say initial stages of ice sheet disintegration are detected. Before action to counter this trend could be effective it would be necessary to eliminate the positive planetary energy imbalance, now ~0.85 W/m^2, which exists due to the ocean's thermal inertia. Given energy infrastructure inertia and trends in energy use, that task could require of order a century. If the time for significant ice response is as short as a century, the positive ice-climate feedbacks imply the possibility of a system out of our control.

A caveat accompanying our analysis concerns the uncertainty in climate forcings. Good fit of observed and modeled temperatures (Fig. 1) also could be attained with smaller forcing and larger climate sensitivity, or with the converse. If climate sensitivity were higher (and forcings smaller), the rate of ocean heat storage and warming "in the pipeline" or "committed" would be greater, e.g., models with sensitivity 4.2-4.5°C for doubled CO_2 yield ~1°C "committed" global warming (*3*, *4*). Conversely, smaller sensitivity and larger forcing yields lesser committed warming and ocean heat storage. The agreement between modeled and observed heat storage (Fig. 2) favors an intermediate climate sensitivity, as in our model. This test provided by ocean heat storage will become more useful as the period with large energy imbalance continues.

Even if the net forcing is confirmed by continued measurement of ocean heat storage, there will remain much room for trade-offs among different forcings. Aerosol direct and indirect forcings are the most uncertain. The net aerosol forcing that we estimate, -1.39 W/m^2, includes a large positive forcing by black carbon and a negative aerosol indirect forcing. Both of these aerosol forcings reduce sunlight reaching the surface, and may be the prime cause of observed "global dimming" (*32*) and reduced pan evaporation (*33*).

Given the unusual magnitude of the current planetary energy imbalance and uncertainty about its implications, careful monitoring of key metrics is needed. Continuation of the ocean temperature and altimetry measurements is needed to confirm that the energy imbalance is not a fluctuation and determine the net climate forcing acting on the planet. The latter is a measure of the changes that will be needed to stabilize climate. Understanding of the forcings that give rise to the imbalance requires more precise information on aerosols (*34*). The high rate of recent eustatic sea level rise that we infer suggests positive contributions from Greenland, alpine glaciers, and West Antarctica. Quantification of these sources is possible using precise satellite altimetry and gravity measurements as initiated by the IceSat (*35*) and GRACE satellites (*36*), which warrant follow-on missions.

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Supporting Online Material
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SOM Text
Figs. S1 and S2
Table S1
References

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Fig. 1. (**A**) Forcings (*9*) used to drive global climate simulations. (**B**) Simulated and observed temperature change; prior to 1900 the observed curve is based on observations at meteorological stations and the model is sampled at the same points, while after 1900 the observations include SSTs for the ocean area and the model is the true global mean (*21*). (**C**) Net radiation at the top of the atmosphere in the climate simulations. Five climate simulations are carried out differing only in initial conditions.

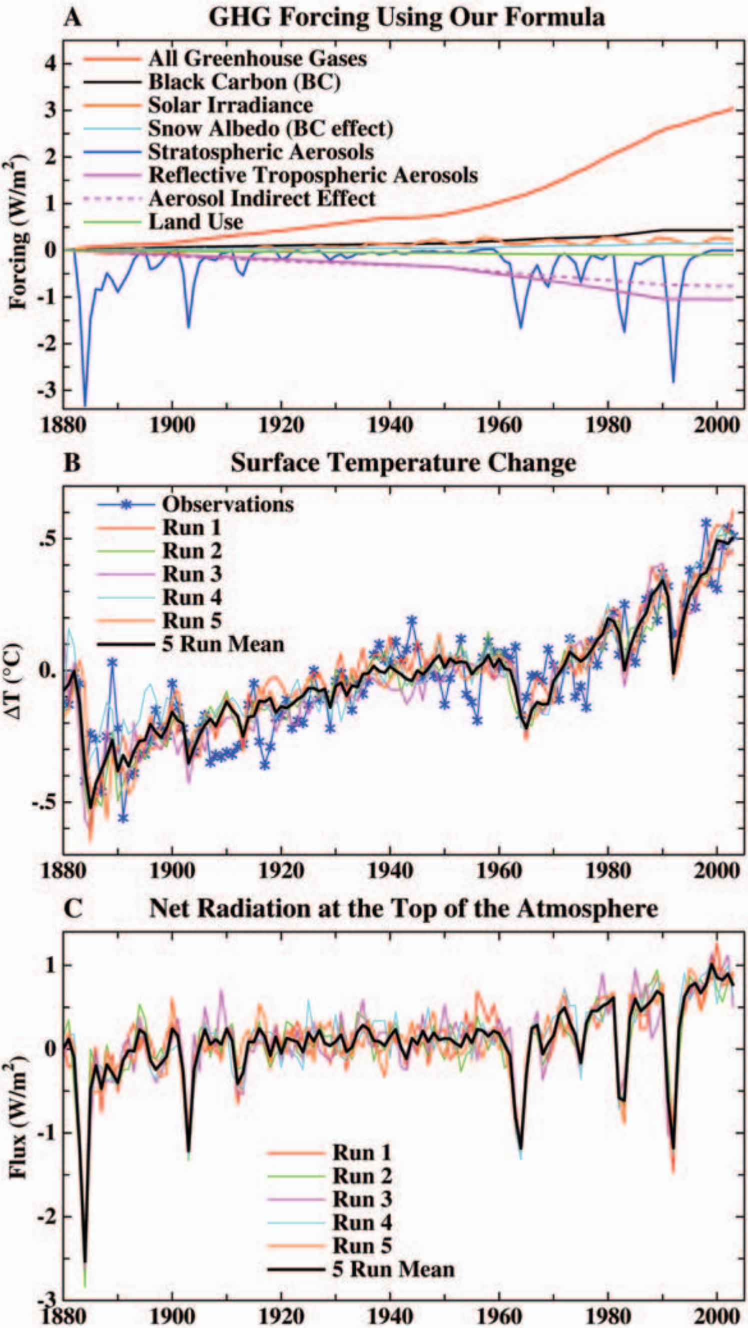
Fig. 2. Ocean heat content change between 1993 and 2003 in top 750m of world ocean. Observations are from (*19*). Five model runs are for the GISS coupled dynamical ocean-atmosphere model (*8*, *9*).

Fig. 3. Trend of zonally averaged temperature versus depth and latitude. Observations are from (*19*). Five model runs are as in Fig. 2.

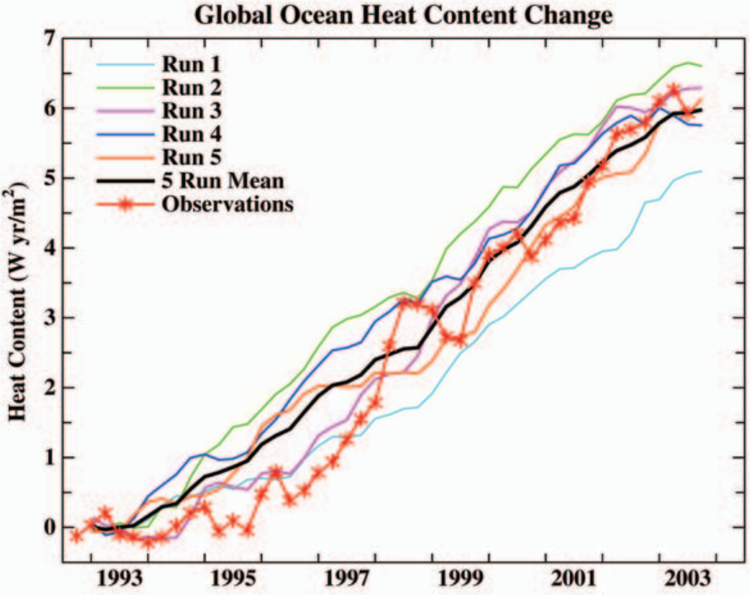
Table 1. Effective climate forcings (W/m^2) used to drive the 1880-2003 simulated climate change in the GISS climate model (*9*).

Forcing Agent*	Forcing (W/m^2)	
Greenhouse Gases (GHGs)	–	–
Well-Mixed GHGs	2.75	–
Ozone[¶§]	0.24	–
CH_4–Derived Stratospheric H_2O	0.06	–
Total: GHGs		3.05 ± 0.4
Solar Irradiance		0.22 (x2)
Land Use		–0.09 (x2)
Snow Albedo		0.14 (x2)
Aerosols		
Volcanic Aerosols	0.00	–
Black Carbon[§]	0.43	–
Reflective Tropospheric Aerosols	–1.05	–
Aerosol Indirect Effect	–0.77	–
Total: Aerosols	–	–1.39 ± 0.7
Sum of Individual Forcings	–	1.93
All Forcings at Once	–	1.80 ± 0.85

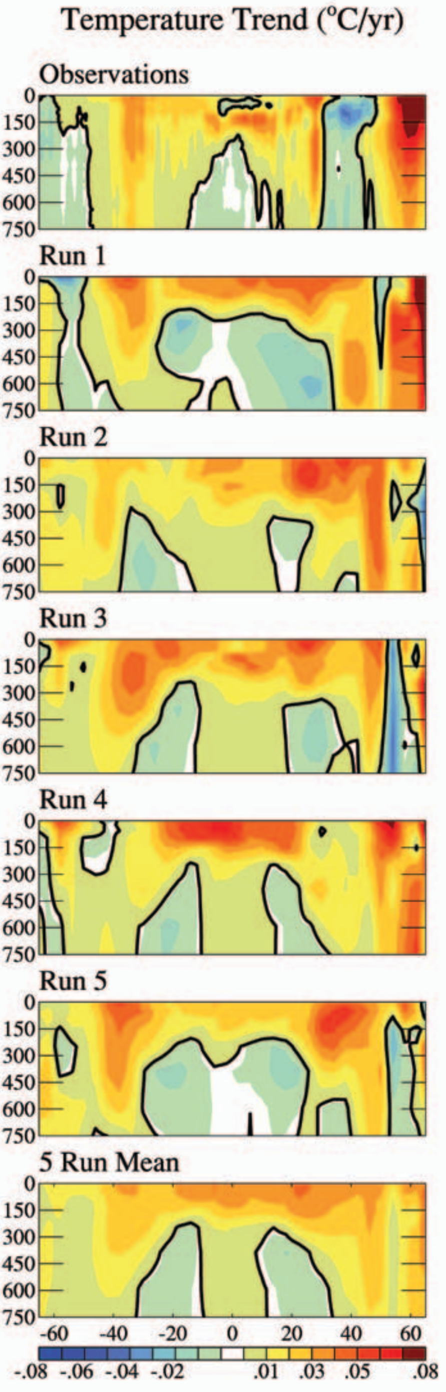
*Effective forcings are derived from 5-member ensembles of 120-year simulations for each individual forcing and for all forcings acting at once (see ref. *9* and Supporting Online Material). The sum of individual forcings differs slightly from all forcings acting at once because on non-linearities in combined forcings and unforced variability in climate simulations. [¶]This is the ozone forcing in our principal IPCC simulations; it decreases from 0.24 to 0.22 W/m^2 when the stratospheric ozone change of Randel and Wu (S1) is employed (see ref. *9* and Supporting Online Material). [§]Ozone and black carbon forcings are less than they would be for conventional forcing definitions (*10*), because their "efficacy" is only ~75% (*9*).



A
GHG Forcing Using Our Formula
All Greenhouse Gases
Black Carbon (BC)
Solar Irradiance
Snow Albedo (BC effect)
Stratospheric Aerosols
Reflective Tropospheric Aerosols
Aerosol Indirect Effect
Land Use
Forcing (W/m2)
4
3
2
1
0
-1
-2
-3
1880
1900
1920
1940
1960
1980
2000
B
Surface Temperature Change
Observations
Run 1
Run 2
Run 3
Run 4
Run 5
5 Run Mean
ΔT (°C)
.5
0.
-.5
1880
1900
1920
1940
1960
1980
2000
C
Net Radiation at the Top of the Atmosphere
Flux (W/m2)
1
0
-1
-2
-3
Run 1
Run 2
Run 3
Run 4
Run 5
5 Run Mean
1880
1900
1920
1940
1960
1980
2000



Global Ocean Heat Content Change
Run 1
Run 2
Run 3
Run 4
Run 5
5 Run Mean
Observations
Heat Content (W yr/m²)
7
6
5
4
3
2
1
0
1993
1995
1997
1999
2001
2003



Temperature Trend (°C/yr)
Observations
Run 1
Run 2
Run 3
Run 4
Run 5
5 Run Mean
0
150
300
450
600
750
-60
-40
-20
0
20
40
60
-.08
-.06
-.04
-.02
.01
.03
.05
.08