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Objective estimation of the probability density function for climate sensitivity

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Abstract. The size and impacts of anthropogenically induced climate change (AICC) strongly depend on the climate sensitivity, ΔT_{2x}. If ΔT_{2x} is less than the lower bound given by the Intergovernmental Panel on Climate Change (IPCC), 1.5°C, then AICC may not be a serious problem for humanity. If ΔT_{2x} is greater than the upper bound given by the IPCC, 4.5°C, then AICC may be one of the most severe problems of the 21st century. Here we use a simple climate/ocean model, the observed near-surface temperature record, and a bootstrap technique to objectively estimate the probability density function for ΔT_{2x}. We find that as a result of natural variability and uncertainty in the climatic radiative forcing, the 90% confidence interval for ΔT_{2x} is 1.0°C to 9.3°C. Consequently, there is a 54% likelihood that ΔT_{2x} lies outside the IPCC range.

1. Introduction

The earliest estimate of ΔT_{2x} was made by Arrhenius [1896], using an energy balance model [*Schlesinger et al.,* 1997] which yielded ΔT_{2x} = 5.4°C. Subsequent estimates by such models, radiative-convective models and general circulation models [*Schlesinger et al.,* 1997], gave estimates of 0.24°C [*Newell and Dopplick,* 1979] to 9.6°C [*Möller,* 1963], 0.48°C [*Somerville and Remer,* 1984] to 4.2°C [*Wang and Stone,* 1980], and 1.3°C [*Washington and Meehl,* 1983] to 5.2°C [*Wilson and Mitchell,* 1987]. On the basis of studies with general circulation models, the Intergovernmental Panel on Climate Change (IPCC) estimated the range of climate sensitivity to be 1.5°C to 4.5°C [*Houghton et al.,* 1990, 1996, 2001]. ΔT_{2x} estimates based on paleoclimatic and instrumental temperature data range from 1.3°C [*Hoffert and Covey,* 1992] to 5.8°C [*Barron,* 1994] and from 0.7 to 10.0°C [*Schlesinger and Ramankutty,* 1992], respectively. None of these estimates provided probability density functions (pdf's) for ΔT_{2x}. An expert elicitation [*Morgan and Keith,* 1995] provided subjective pdf's for 16 experts whose 90% confidence intervals ranged from 0.1°C – 0.5°C to 0.1°C – 8°C. Most recently, subjective estimates of the ΔT_{2x} pdf were obtained from the instrumental temperature record using Bayesian updating [*Tol and Vos,* 1998], with the result that the posterior pdf depended strongly on the assumed prior (initial) pdf. Here we obtain an objective estimate of the ΔT_{2x} pdf using a simple climate/ocean model to perform Monte Carlo simulations of the instrumental temperature record.

2. Simple Climate/Ocean Model

The simple climate/ocean model [Schlesinger et al., 1997] determines the changes in the temperatures of the atmosphere and ocean, the latter as a function of depth from the surface to the ocean floor. The model ocean is divided vertically into 40 layers and horizontally into a polar region, where bottom water is formed, and a nonpolar region, where there is upwelling. The atmosphere in each hemisphere is subdivided into the atmosphere over the ocean and the atmosphere over land, with heat exchange between them. In contrast to a general circulation model, ΔT_{2x} is prescribed in the simple model rather than calculated. This simple model has been used for several physical studies [Bretherton et al., 1990; Schlesinger et al., 1992; Schlesinger and Ramankutty, 1992, 1994; Andronova and Schlesinger, 2000] and policy studies [Hammitt et al., 1992; Lempert et al., 1994, 1996, 2000; Mendelsohn et al., 2000; Schlesinger, 1993; Schlesinger and Williams, 1997; Yohe and Schlesinger, 1998]. As used here, the model's parameters other than ΔT_{2x} were calibrated against the observed annual cycle of near-surface temperature.

3. Radiative Forcing Models

The radiative forcing for hemisphere i used by the simple model is

$$\Delta F_i(t) = \Delta F_{\mathrm{GHG}}(t) + 2\beta_i\,[\mu_{\mathrm{ASA}}\Delta F_{\mathrm{ASA}}(t) + \mu_{\mathrm{TRO3}}\Delta F_{\mathrm{TRO3}}(t)] + \mu_{\mathrm{Sun}}\Delta F_{\mathrm{Sun}}(t) + \mu_{\mathrm{Vol}}\Delta F_{\mathrm{Vol},i}(t) \quad i = N, S,$$

where $\Delta F_{\mathrm{GHG}}(t)$ is the radiative forcing by all greenhouse gases other than tropospheric ozone (CO_2, methane, nitrous oxide, and the chlorofluorocarbons) based on the IPCC/97 report [*Harvey et al.,* 1997] but updated to *Myhre et al.* [1998]. $\beta_N = \alpha$ (= 0.8) and $\beta_S = 1-\alpha$ are the fractions of the anthropogenic sulfate aerosol (ASA) and tropospheric ozone (TRO3) radiative forcing that occur in the Northern and Southern Hemispheres, respectively. By choosing the values of the four μ_i's to be either zero or unity, we consider 16 radiative forcing models.

$\Delta F_{\mathrm{ASA}}(t)$ is the sum of the direct and indirect radiative forcing by anthropogenic and natural sulfate aerosols,

$$\Delta F_{\mathrm{ASA}}(t) = \Delta F_{\mathrm{ASA}}^{\mathrm{dir}}(1990)\,\frac{E(t)}{E(1990)} + \Delta F_{\mathrm{ASA}}^{\mathrm{ind}}(1990)\,\frac{\log(1+E(t)/E_{\mathrm{nat}})}{\log(1+E(1990)/E_{\mathrm{nat}})}\ ,$$

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where $E(t)$ is the global anthropogenic emission rate of sulfur in the form of SO_2, $E(1990)$ = 72.6 TgS yr^{-1}, E_{nat} = 22.0 TgS yr^{-1}, and $\Delta F^{dir}_{ASA}(1990)$ and $\Delta F^{ind}_{ASA}(1990)$ are the unknown direct and indirect sulfate forcings in 1990, respectively. We take $\Delta F^{ind}_{ASA}(1990)/\Delta F^{dir}_{ASA}(1990) = 0.8/0.3$ as given by *Harvey et al.* [1997]. Our tests with the model showed that the total sulfate radiative forcing in 1990 is insensitive within 2% to values of the ratio $\Delta F^{ind}_{ASA}(1990)/\Delta F^{dir}_{ASA}(1990)$, at least within the range of 0 to 10. The ASA radiative forcing begins in 1857.

$\Delta F_{TRO3}(t)$ is the radiative forcing by tropospheric ozone. Because tropospheric ozone is the indirect result of industrial activity, as is ASA, we take the hemispheric partitioning of the tropospheric-ozone radiative forcing to be the same as that for ASA. Annual values of the tropospheric ozone forcing are interpolation of the data presented by *Stevenson et al.* [1998] and begins in 1860. Stratospheric-ozone forcing due to ozone depletion is ignored here as it is small [*Forster,* 1999].

$\Delta F_{Vol,i}(t)$ is the radiative forcing by volcanoes in hemisphere i,

$$\Delta F_{Vol,i}(t) = \Delta F^{LW}_{Vol,i}(t) + \Delta F^{SW}_{Vol,i}(t) \quad i = N, S,$$

where $\Delta F^{LW}_{Vol,i}(t)$ and $\Delta F^{SW}_{Vol,i}(t)$ are the hemispheric-mean changes in the adjusted longwave and shortwave radiation at the tropopause due to volcanic aerosol, respectively, obtained by *Andronova et al.* [1999]. The volcanic hemispheric radiative forcing begins in 1850.

For the solar irradiance forcing, $\Delta F_{Sun}(t)$, we have chosen the model of solar irradiance variation proposed by *Lean et al.* [1995], $S_{LN}(t)$, and use it as the solar radiative forcing at the tropopause. We take $\Delta F_{Sun}(t)$ to be

$$\Delta F_{Sun}(t) = \frac{1-\alpha_p}{4}[S_{LN}(t) - S_{LN}(1610)] \quad 1610 \le t \le 1994,$$

where $S_{LN}(1610)$ = 1365.7 W m^{-2}, α_p = 0.3 is the planetary albedo, and the factor 4 accounts for the ratio of the area of emission of terrestrial (longwave) radiation to the area for the absorption of solar radiation. For the period 1978-1998, when satellite observations of the solar irradiance exist, we updated the solar model to the data of *Fröhlich and Lean* [1998]. The radiative forcing components are displayed in *Andronova and Schlesinger* [2000].

We consider 16 radiative forcing models (RFMs), each including greenhouse gas (GHG) forcing and denoted by a mnemonic such as GTASV, in which G, T, A, S, and V represent the radiative forcing by GHGs, tropospheric ozone, anthropogenic sulfate aerosol, the Sun, and volcanoes, respectively. The cases without ASA forcing represent the end-member of no net aerosol radiative forcing. We have included these cases because there may be positive radiative forcing due to carbonaceous aerosols that is not included here which partly or largely cancels the negative ASA forcing [*Schwartz and Buseck,* 2000]. The cases without volcanoes represent the end-member of no net volcanic radiative forcing. We have included these cases because the large differences between the simulated and observed temperature changes following the Krakatoa (1883) and Pinatubo (1991) eruptions [*Andronova and Schlesinger,* 2000] indicate that

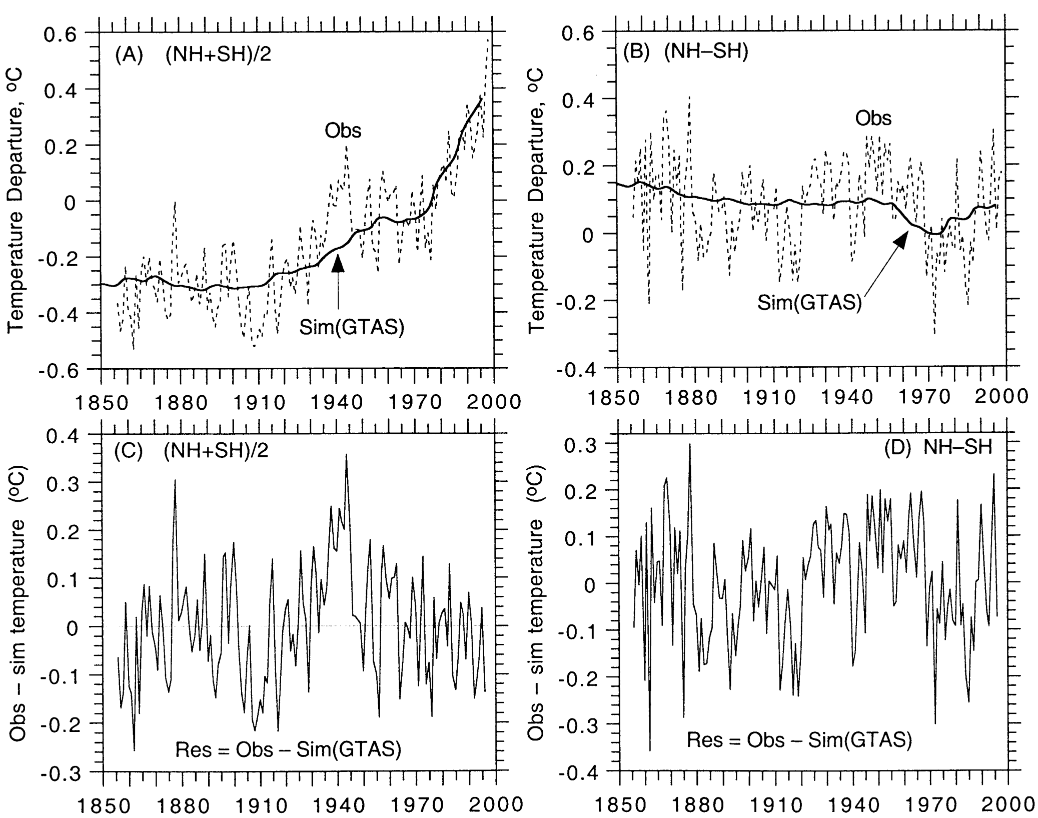

Figure 1. (a) Simulated global-mean temperature ((NH+SH)/2) and (b) interhemispheric temperature difference (NH–SH) for the GTAS radiative forcing model (RFM) in comparison with the observations. (c and d) Corresponding observed-minus-simulated temperature residuals. For the GTAS case, ΔT_{2x} = 2.7°C [Andronova and Schlesinger, 2000].

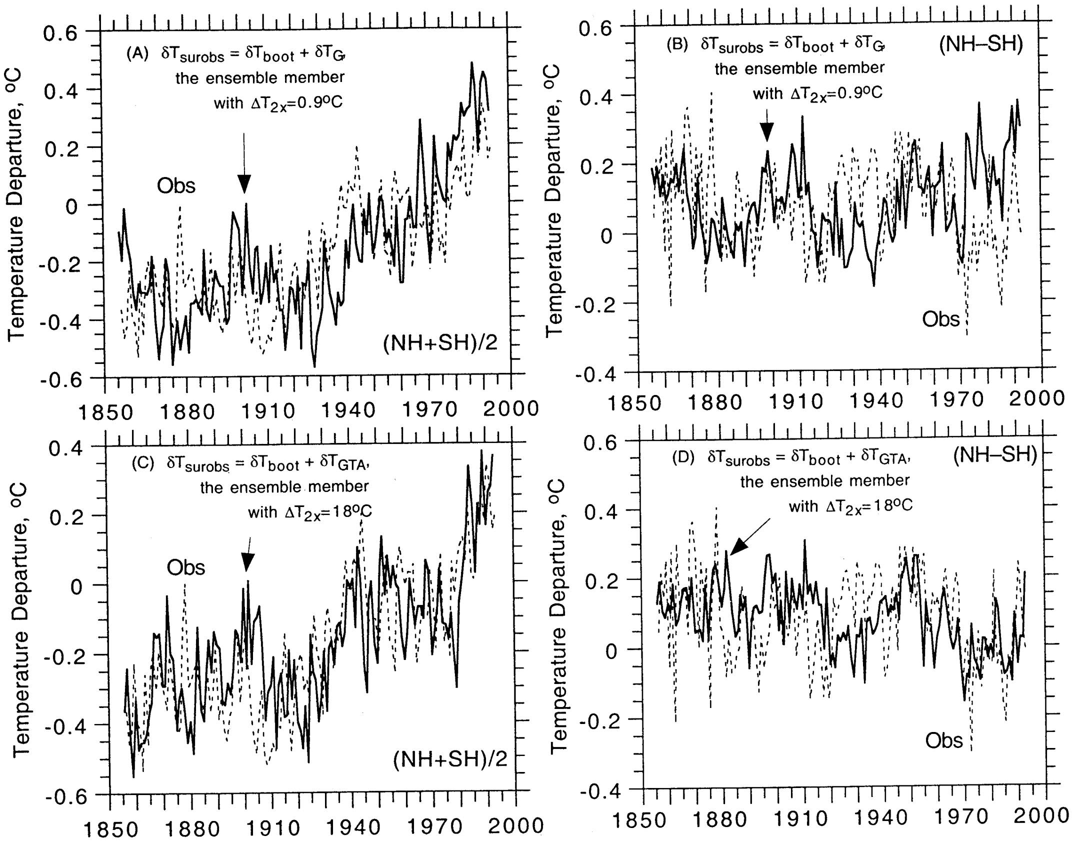

Figure 2. One realization of the 5000-member ensemble for each of two radiative forcing models: (a and b) G and GTA (c and d) for the global-mean temperature ((NH+SH)/2) (Figures 2a and 2c) and the interhemispheric temperature difference (NH–SH) (Figures 2b and 2d). Dotted line shows the corresponding observational record..

either their estimated radiative forcings are too large or factors other than volcanos, such as El Niño, contributed warming to the observed temperatures near the times of these volcanic eruptions [*Andronova et al.*, 1999]. For a similar reason, we have included cases without tropospheric ozone forcing as the end-member of no net tropospheric ozone radiative forcing. Lastly, we have included cases with and without solar irradiance forcing, as it is not known whether such forcing actually occurred.

4. Estimation Method and Results

For each radiative forcing model the changes in global-mean ((NH+SH)/2) near-surface temperature, $\Delta T_{GL}^{\text{sim}}(t)$, and in the interhemispheric (NH–SH) near-surface temperature difference, $\Delta T_{HD}^{\text{sim}}(t)$, were calculated from 1765 through 1997 by the simple model for many prescribed values of ΔT_{2x} and the direct (clear sky) ASA radiative forcing in reference year 1990, $\Delta F_{\text{ASA}}^{\text{dir}}(1990)$. The simulated departures in global-mean near-surface temperature, $\delta T_{GL}^{\text{sim}}(t) = \Delta T_{GL}^{\text{sim}}(t) + C_{GL}$, and in the interhemispheric near-surface temperature difference, $\delta T_{HD}^{\text{sim}}(t) = \Delta T_{HD}^{\text{sim}}(t) + C_{HD}$, were compared with the corresponding observed temperature departures from the 1961-1990 means [*Jones et al.*, 1999], $\delta T_{GL}^{\text{obs}}(t)$ and $\delta T_{HD}^{\text{obs}}(t)$, from 1856 through 1997, with the constants, C_{GL} and C_{HD}, determined to minimize the individual root-mean-square (RMS) differences between $\delta T_{GL}^{\text{sim}}(t)$ and $\delta T_{GL}^{\text{obs}}(t)$, and $\delta T_{HD}^{\text{sim}}(t)$ and $\delta T_{HD}^{\text{obs}}(t)$ [*Schlesinger et al.*, 1992; *Schlesinger and Ramankutty,* 1992]. Maximum-likelihood values of ΔT_{2x} and $\Delta F_{\text{ASA}}^{\text{dir}}(1990)$, hence the total (all sky) ASA radiative forcing $\Delta F_{\text{ASA}}(1990) = 3.67\ \Delta F_{\text{ASA}}^{\text{dir}}(1990)$ [*Harvey et al.*, 1997], were determined by simultaneously minimizing the RMS difference between $\delta T_{GL}^{\text{sim}}(t)$ and $\delta T_{GL}^{\text{obs}}$ and between $\delta T_{HD}^{\text{sim}}(t)$ and $\delta T_{HD}^{\text{obs}}(t)$. This was done separately for monthly and annual observed temperatures, with negligible differences in the results. Figure 1 illustrates the simulated temperatures for the GTAS RFM in comparison with the observations.

We have investigated the dependence of our estimates of ΔT_{2x} and $\Delta F_{\text{ASA}}^{\text{dir}}(1990)$ on the year t_b in which we begin to compare the simulated temperature departures with the observed temperature departures. As t_b is varied between 1856 and 1885, ΔT_{2x} varies on average over the 16 RFMs from –9% to 14% of its respective 1856-1885 mean, while $\Delta F_{\text{ASA}}^{\text{dir}}(1990)$ varies from –8% to 7%. Thus the uncertainty in ΔT_{2x} due to t_b before 1885 is much smaller than the uncertainty due to the different RFMs, as is shown below. Accordingly, henceforth we use t_b= 1856.

In addition to the uncertainty in the estimate of ΔT_{2x} due to the uncertainty in the radiative forcing models, there is uncertainty due to the natural variability in the instrumental temperature record. This can be illustrated by the residual temperature change, $\delta T_{\text{res}}^{i}(t) = \delta T_{\text{obs}}^{i}(t) - \delta T_{\text{sim}}^{i}(t)$, $i = N, S$, where $\delta T_{\text{obs}}^{i}(t)$ and $\delta T_{\text{sim}}^{i}(t)$ are the observed and simulated temperature departures at time t for hemisphere i, the latter for any RFM. Figure 1 presents $0.5\,[\delta T_{\text{res}}^{N}(t) + \delta T_{\text{res}}^{S}(t)]$ and $[\delta T_{\text{res}}^{N}(t) - \delta T_{\text{res}}^{S}(t)]$ for the GTAS RFM. While we cannot state with certitude that there is not a part of the residuals that may be due to unknown external forcing, it is seen that the

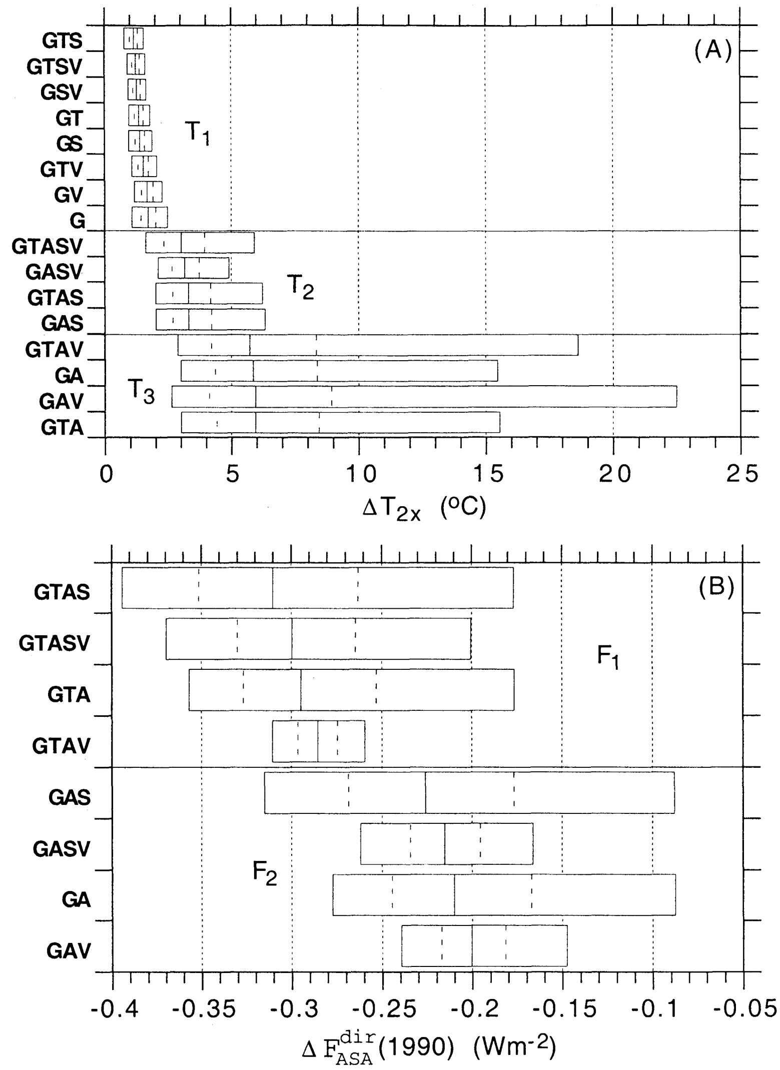

Figure 3. Distributions of ΔT_{2x} and $\Delta F^{\text{dir}}_{\text{ASA}}(1990)$ for each of the 16 radiative forcing models (RFMs). Each box displays the 5, 25, 50, 75, and 95 percentiles of the 5000 estimates.

residuals nevertheless have the appearance of noise, that is, natural variability. The observed temperature record is but a single realization of the natural variability, and our estimation of ΔT_{2x} and $\Delta F^{\text{dir}}_{\text{ASA}}(1990)$ is influenced by this single realization. If we were to estimate ΔT_{2x} and $\Delta F^{\text{dir}}_{\text{ASA}}(1990)$ for multiple observational records, each with a different realization of the natural variability but with the same simulated temperature departure, we would obtain a range of estimates for ΔT_{2x} and $\Delta F^{\text{dir}}_{\text{ASA}}(1990)$.

To measure the "variability-induced" uncertainty, included in $\delta T_{\text{res}}(t)$, we used the bootstrap resampling method for correlated data developed by *Solow* [1985] to generate 5000 realizations of "natural variability," $\delta T^{i}_{\text{boot}}(t)$, each realization is of n = 142 years duration. The bootstrap method is based on the same principle as Monte Carlo simulation, with the only difference being that the bootstrap uses the empirical distribution of the sample itself from which to resample. Each bootstrap sample is chosen by sampling n values at random with replacement from the original observations. The basic idea of the bootstrap resampling method for correlated data involves transforming the original correlated data to uncorrelated quantities, forming a bootstrap sample from these quantities, and then transforming back to a quasi bootstrap sample from the original data without destroying the pattern of autocorrelation exhibited by the original sample.

We construct an ensemble of 5000 surrogate observational temperature records for each hemisphere by $\delta T^{i}_{\text{surobs}}(t) = \delta T^{i}_{\text{boot}}(t) + \delta T^{i}_{\text{sim}}(t)$, $i = N, S$, one ensemble for each of the 16 RFMs, and $\delta T^{i}_{\text{boot}}(t)$ is a bootstrap sample of $\delta T^{i}_{\text{res}}(t)$. By definition of the bootstrap technique, the range of each surrogate observational temperature departure at any time during the 142-year period does not exceed the difference between the absolute maximum and absolute minimum of the residual temperature departures over the 142-year period. For each ensemble member we used the same procedure to estimate ΔT_{2x} and $\Delta F_{\text{ASA}}(1990)$ that we did for the single real observational record. As an example, Figure 2 shows one realization of the 5000-member ensemble for each of two radiative forcing models, one for G, which corresponds to the low climate sensitivity estimation, ΔT_{2x} = 0.9°C, and the other for GTA, which corresponds to the high climate sensitivity

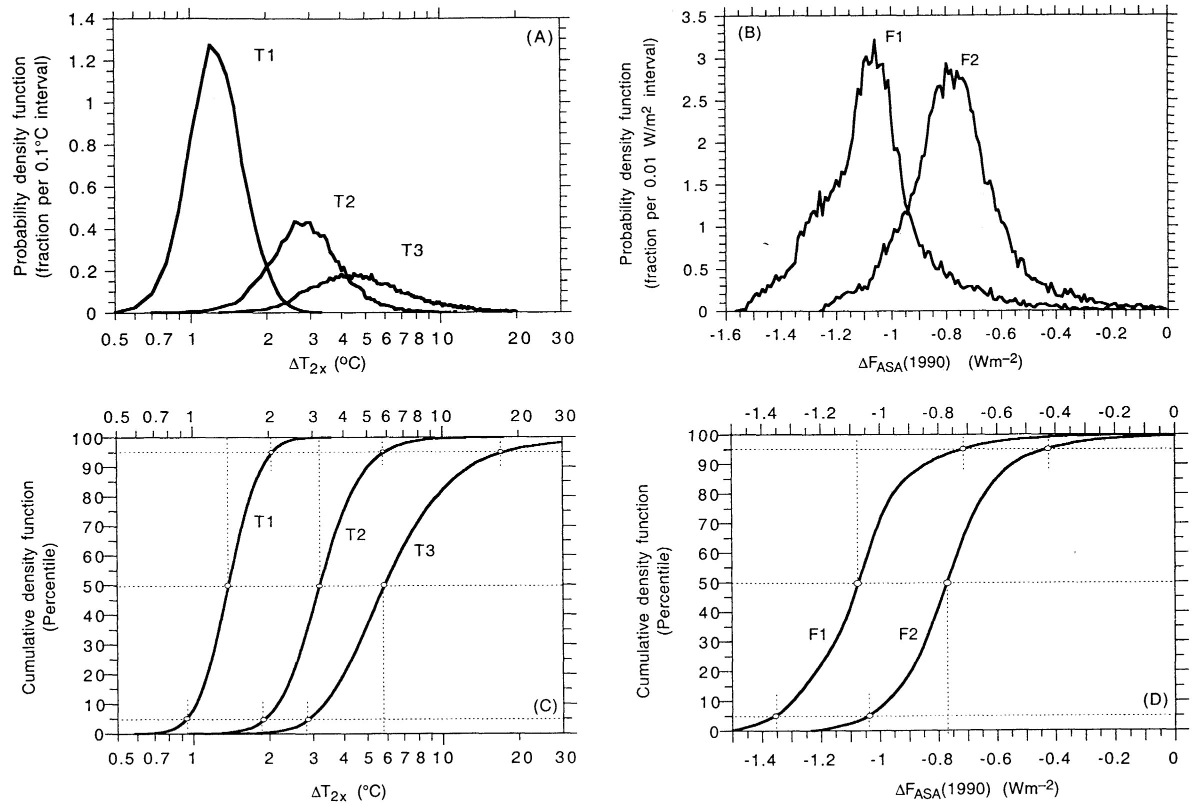

Figure 4. (a and c) Probability density function (pdf) and corresponding cumulative density function (cdf) for ΔT_{2x} and (b and d) $\Delta F_{\mathrm{ASA}}(1990)$ for each of the five groups identified in Figure 2.

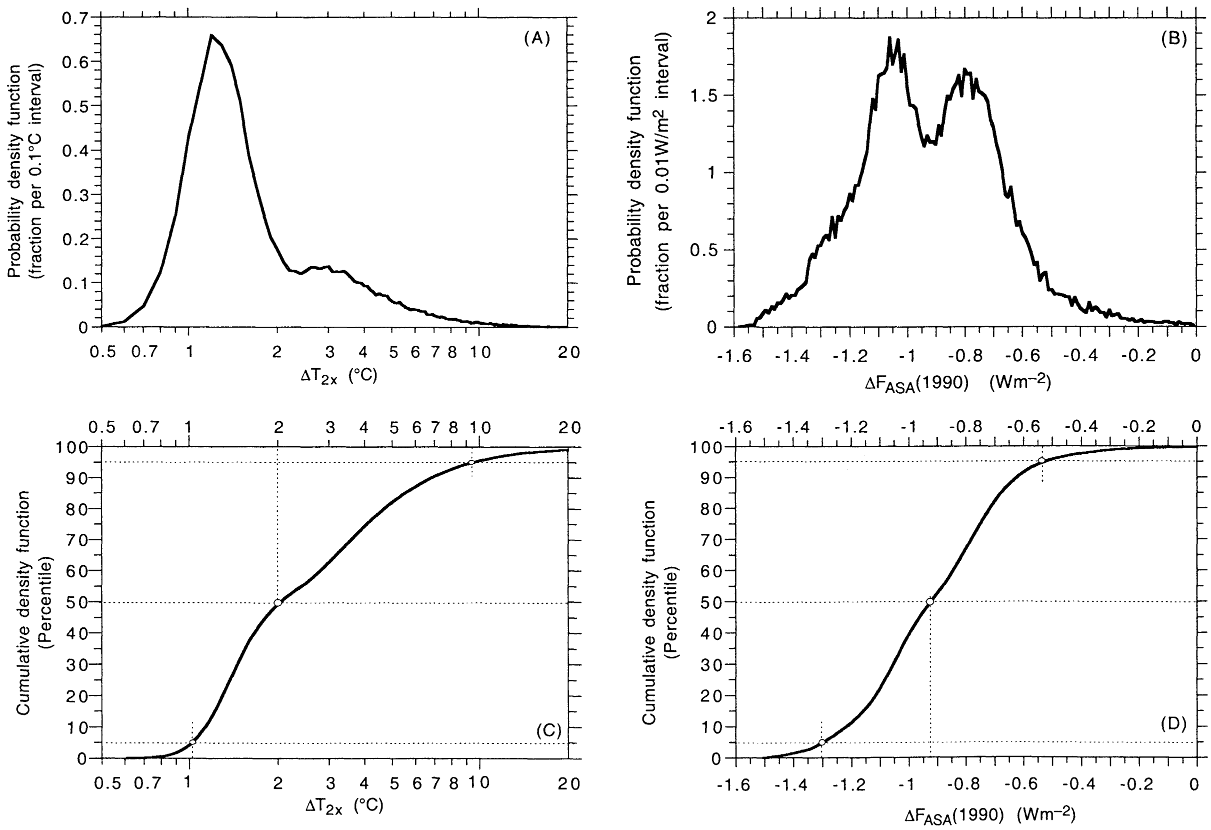

Figure 5. (a and c) Single pdf and cumulative density function (cdf) pair for ΔT_{2x} and (b and d) $\Delta F_{\mathrm{ASA}}(1990)$ obtained by combining all the 80,000 cases for each.

estimation, ΔT_{2x} = 18°C. As is shown later, these values are close to the values of ΔT_{2x} that correspond to the 5 and 90% confidence intervals for its cumulative density function.

The distributions of ΔT_{2x} and $\Delta F^{\rm dir}_{\rm ASA}(1990)$ for each of the 16 RFMs are presented in Figure 3 in the form of box plots. Each box displays the 5, 25, 50, 75, and 95 percentiles of the 5000 estimates. The results in Figures 3a and 3b are arranged from top to bottom in increasing magnitudes of ΔT_{2x} and $\Delta F^{\rm dir}_{\rm ASA}(1990)$, respectively. It is seen that the estimates of ΔT_{2x} form three groups. Group T1 differs from groups T2 and T3 in that it has no ASA forcing. T2 differs from T3 in that it has putative solar forcing. Accordingly, including ASA forcing increases the estimated ΔT_{2x} and including solar forcing decreases it. This occurs because the ASA forcing reduces the total global radiative forcing (the forcing becomes less positive), and the solar forcing increases it, hence to reproduce the observed global warming, a larger ΔT_{2x} is required with ASA forcing than without, and a smaller ΔT_{2x} is required with solar forcing than without.

Figure 3 also shows that the estimates of $\Delta F^{\rm dir}_{\rm ASA}(1990)$ form two groups. Group F1 differs from group F2 in that it has tropospheric ozone forcing. Accordingly, including this forcing decreases the estimated $\Delta F_{\rm ASA}(1990)$. This occurs because the tropospheric ozone forcing reduces the interhemispheric forcing difference as it is of opposite sign to the ASA forcing; hence, to reproduce the observed interhemispheric temperature difference, a more negative value of $\Delta F^{\rm dir}_{\rm ASA}(1990)$ is required with tropospheric ozone forcing than without.

Figure 4 presents a pdf and the corresponding cumulative density function (cdf) for each of the five groups identified in Figure 2, obtained by first combining all of the estimates that comprise each group, 40,000 for T1 and 20,000 for each of T2, T3, F1, and F2, and then calculating its pdf and cdf. It can be seen that the pdf's and cdf's for T1, T2, and T3 differ considerably both in their central and spread values and 90% confidence intervals, while those for F1 and F2 are much closer to each other. Because T1 has no ASA forcing, its mean (μ = 1.43°C), median (m = 1.38°C), standard deviation (σ = 0.35°C), and skewness (s = 0.80) are small, and its 90% confidence interval, 0.94°C to 2.04°C, is narrower and shifted toward smaller values than the IPCC range of 1.5°C to 4.5°C. With the addition of ASA forcing in T3 the central and spread values (μ = 7.53°C, m = 5.87°C, σ = 5.84°C, s = 3.23) increase dramatically, and the 90% confidence interval, 2.88°C to 17.80°C, becomes much wider and shifted toward much larger values than the IPCC range. With the addition of solar irradiance forcing in T2 the central and spread values (μ = 3.46°C, m = 3.20°C, σ = 1.31°C, s = 1.97) decrease, and the 90% confidence interval, 1.90°C to 6.02°C, is somewhat wider and shifted toward higher values than the IPCC range.

5. Conclusion

Our results show indelibly that the pdf and cdf for ΔT_{2x} very strongly depend on which radiative forcing factors have actually been at work during the period of instrumental temperature measurements. If one were to make a "best estimate" of this, one would likely choose T3 which does include ASA forcing and does not include solar forcing. This is so because it is certain that anthropogenic sulphate aerosols exist in the Earth's atmosphere, but it is very uncertain that solar irradiance variations before the beginning of satellite observations of the sun in 1978 exceeded the variations measured since 1978. In this case it appears that although the value of ΔT_{2x} is most uncertain, there is a 70% chance that it exceeds the maximum IPCC value of 4.5°C. This is a disquieting result.

To diminish the uncertainty of which probability distribution is the appropriate one to use in impact and policy studies will require learning whether the Sun's irradiance actually changed during the past 150 years, and what is the net radiative forcing of all anthropogenic aerosols, not just ASA. For the present we obtain a single pdf, cdf pair separately for ΔT_{2x} and $\Delta F_{\rm ASA}(1990)$ by combining all the 80,000 cases. As shown in Figure 5, the resulting pdf's for ΔT_{2x} and $\Delta F_{\rm ASA}(1990)$ are bimodal with μ = 3.40°C, m = 2.04°C, σ = 3.85°C, s = 4.75; and μ = –0.91 W m^{-2}, m = –0.92 W m^{-2}, σ = 0.24 W m^{-2}, s = 0.32. The corresponding 90% confidence intervals are 1.0°C to 9.3°C and –0.54 W m^{-2} to –1.30 W m^{-2}.

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