EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY

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Reliable empirical determination of climate sensitivity is limited by uncertainties in the observations [1] as well as in climate theory. *A fortiori,* reliable numerical determination of sensitivity by general-circulation models is hindered not only by these uncertainties but also by difficulties inherent in modeling the coupled, non-linear, mathematically-chaotic climate object [2-4]. Of the ten papers [5-14] cited in [1] as attempting to determine climate sensitivity empirically as opposed to numerically, four concur with the Intergovernmental Panel on Climate Change [4] in finding sensitivity high: in [5], for instance, it is suggested that sensitivities >10 K cannot be ruled out. Two of the ten papers [13, 14] are criticisms of [7, 12], implying high sensitivity. The remaining four papers [7, 10-12] argue for low sensitivity: typically ~1 K per CO2 doubling, implying net-negative temperature feedbacks.

In this lively debate, further papers explicitly finding sensitivity low are [15], which found that sensitivities over various recent and paleoclimatic periods cohere at 1-1.7 K if an amplification of solar forcing owing to cosmic-ray displacement is posited, but not otherwise; [16], where a reanalysis of the NCEP tropospheric humidity data showed significantly negative zonal annual mean specific humidity at all altitudes >850 hPa, implying that the long-term water-vapor feedback is negative and that equilibrium sensitivity is ~1 K; and [17], where the observed rate of decrease in aerosol optical depth, particularly in the United States and Europe, was found to have contributed a strong positive forcing, requiring that canonical equilibrium climate sensitivity be halved to 1-1.8 K.

In [15-17] the sensitivities ~1 K were declared explicitly. However, several papers contain internal, unstated evidence for low climate sensitivity. For instance, [18] displays a flow-diagram for the energy budget of the Earth and its atmosphere, such that incoming and outgoing fluxes are shown to balance at the surface. The diagram shows surface radiation as 390 $\mathrm{W\ m^{-2}}$, corresponding to a blackbody emission at 288 K, equivalent to today's mean surface temperature 15 °C. If the surface radiative flux were indeed the blackbody flux of 390 $\mathrm{W\ m^{-2}}$, then by differentiation of the fundamental equation of radiative transfer the implicit value of the Planck parameter λ_0 would be $\Delta T / \Delta F = T/4(390+78+24) = 0.15\ \mathrm{K\ W^{-1}\ m^2}$ (after including 78 $\mathrm{W\ m^{-2}}$ for evapo-transpiration and 24 $\mathrm{W\ m^{-2}}$ for thermal convection), whereupon, assuming feedbacks summing to the IPCC's implicit central estimate 2.1 $\mathrm{W\ m^{-2}\ K^{-1}}$, equilibrium climate sensitivity $\Delta T_{2x} = \Delta F_{2x}\,\lambda_0\,(1 - 2.1\,\lambda_0)^{-1} = 3.7(0.15)(1.5) = 0.8$ K.

There is a further, and important, indication of low climate sensitivity in [18], where the total radiative forcing from the five principal greenhouse gases (H2O, CO2, CH4, O3, and N2O) in the entire atmosphere is given as 125 W m^{-2} in clear skies and 86 W m^{-2} in cloudy skies, giving ~101 W m^{-2} forcing overall. Holding insolation and albedo constant *ad experimentum*, the difference between surface temperatures with and without the atmosphere is readily established as 288 – 255 = 33 K, so that, assuming that any other forcings are comparatively insignificant, the climate sensitivity of the whole atmosphere is simply 3.7(33/101) = 1.2 K.
Much has been written [e.g. 33-35] of the discrepancy between modeled and observed rates of warming in the tropical mid-troposphere. The theory of the moist adiabat, supported by the models, holds that there should be 2.5-3 times as much warming in the tropical mid-troposphere as at the surface. However, [19], cited with approval in [4], regards the existence of the tropical mid-troposphere "hot-spot" as a fingerprint of anthropogenic warming. If so, in all but one of the dozen radiosonde and satellite datasets of tropical mid-troposphere temperature, the fingerprint is absent, indicating that the IPCC's current central estimate of climate sensitivity should be divided by 2.5-3, giving an equilibrium sensitivity ~1 K.

An intriguing discrepancy between modeled and observed rates of evaporation from the surface was reported by [20]. The models predict evaporation $\Delta E/\Delta T$ = 1-3% per Kelvin of surface warming: observations, however, indicate that the true value is close to 6%. The equilibrium-sensitivity parameter λ is directly determinable from the rate of change in evaporation expressed as a percentage per Kelvin of surface warming, thus: $\lambda = (0.8\ \Delta E/\Delta T)^{-1}$. This result, from [21], may be verified by plugging the model-projected 1-3% K^{-1} into the equation, yielding λ on [0.42, 1.25] and consequently a climate sensitivity on [1.5, 4.5] K, precisely the model-derived values that the IPCC projects. However, the measured 5.7% K^{-1} indicates λ = 0.22 and equilibrium sensitivity 0.8 K.

It is sometimes said that we are conducting an experiment on the only planet we have. We have been conducting that experiment with increasing vigor for a quarter of a millennium. Some results are by now available. In [22], an assessment of all greenhouse-gas forcings since 1750 was presented. The total is 3.1 W m^{-2}. From this, the net-negative non-greenhouse-gas forcings of 1.1 W m^{-2} given in [4] are deducted to give a net forcing from all sources of ~2 W m^{-2} over the period. Warming from 1750-1984 was 0.5 K [23], with another 0.3 K since then [24], making 0.8 K in all, not inconsistent with the 0.9 K indicated in [25-27]. Then the climate sensitivity over the period, long enough for feedbacks to have acted, is (5.35 ln 2)(0.8/2) = 1.5 K, on the assumption that all the warming over the period was anthropogenic. A similar analysis applied to the data since 1950 produces a further sensitivity ~1 K.

More simply still, the most rapid supra-decadal rate of warming since the global instrumental record [23] began was equivalent to 0.16 K/decade. This rate was observed from 1860-1880, 1910-1940, and 1976-2001, since when there has been no warming. There are no statistically-significant differences between the warming rates over these three periods, which between them account for half of the record. On the assumption that in the next nine decades what has been the maximum supra-decadal warming rate becomes the mean rate, climate warming to 2100 will be 1.4 K.

Another simple method is merely to project to 2100 the linear warming rate since 1950, when greenhouse-gas emissions first became significant. This is legitimate, since [4] expects CO2 concentration to rise near-exponentially, but the consequent forcing is logarithmic. In that event, once again the centennial warming will be 1.2 K.

These four sensitivities ~ 1 K derived from the temperature record are of course transient sensitivities: but, since equilibrium will not be reached for 1000-3000 years [28], it is only the transient sensitivity that is policy-relevant. In any event, on the assumption that approaching half of the warming since 1750 may have been natural, equilibrium sensitivities ~1 K are indicated.

Resolution of the startling discrepancy between the low-sensitivity and high-sensitivity cases is of the first importance. The literature contains much explicit and implicit evidence for low as well as high sensitivity, and the observed record of temperature change – to date, at any rate – coheres remarkably with the low-sensitivity findings. Until long enough periods of reliable data are available both to the empiricists and to the modelers, neither group will be able to provide a definitive, widely-accepted interval for climate sensitivity.

Two conclusions follow. First, given the uncertainties in the empirical method and the still greater uncertainties inherent in the numerical method, a theoretical approach should be considered. Climate sensitivity to any forcing is the product of three parameters: the forcing itself, the Planck sensitivity parameter λ_0, and the overall feedback gain factor [29]. Though the CO2 forcing cannot be quantified directly by measurement in the laboratory, where it is difficult to simulate non-radiative transports, the current value 5.35 times the logarithm of the proportionate change in CO2 concentration, or 3.7 W m^{-2} (some 15% below the value in [30]), is generally accepted as likely to be correct. Likewise, the value of λ_0 is clear: it is the first differential of the fundamental equation of radiative transfer at the characteristic-emission altitude, where incoming and outgoing radiative fluxes are by definition identical, augmented by ~17% to allow for latitudinal variation.

The central uncertainty in the debate about climate sensitivity, therefore, resides in the value of the last of the three parameters – the overall feedback gain factor $G = (1 - \lambda_0 f)^{-1}$, where f is the sum of all individual positive and negative feedbacks and $g = \lambda_0 f$ is the closed-loop gain. Process engineers designing electronic circuits customarily constrain g to a maximum value +0.01 to ensure that conditions leading to runaway feedback do not occur. Above 0.01, or at maximum 0.1, there is a danger that defective components, errors in assembly, and the circumstances of use can conspire to cause runaway feedback that damages or even destroys the circuit.

The climate is an object on which feedbacks operate. Yet in the past 750 Ma [31] absolute mean global surface temperature has not varied by more than 8 K, or 3%, either side of the long-run mean. Similar results were separately obtained for the past 65 Ma [32]. It is most unlikely, therefore, that the loop gain g in the climate object exceeds 0.1. However, the IPCC's interval of climate sensitivities, [2, 6.4] K, implies a loop gain on [0.4, 0.8], an interval so far above 0.1 that runaway feedback would have occurred at some point in the geological record. Yet there is no sign that any such event has ever occurred. Given this significant theoretical constraint on g, equilibrium climate sensitivity cannot in any event exceed 1.2 K.

The second conclusion is related to the first. It is that, in accordance with the fundamental constraint that theory dictates, climate sensitivities attained by a variety of methods appear to cohere at ~1 K per CO2 doubling, not the far higher values offered by the high-sensitivity community. As we have seen, in five papers [11-12, 15-17], climate sensitivity is explicitly stated to be ~1 K; in a further three [18-20], by four distinct methods, implicit sensitivity is found to be ~1 K; by four further methods applied to the recent global temperature record, sensitivity seems to be ~1 K; and the coherence of these results tends to confirm the theoretical argument that the feedback loop gain, and therefore climate sensitivity, cannot be strongly positive, providing a 15th and definitive indication that sensitivity is ~1 K.

Since no single method is likely to find favor with all, a coherence of multiple empirical and theoretical methods such as that which has been sketched here may eventually decide the vexed climate-sensitivity question. *Remote Sensing,* therefore, was right to publish [12], authored by two of the world's foremost experts on the design and operation of satellite remote-sensing systems and on the interpretation of the results. The authors stand in a long and respectable tradition of reassessing not only the values of individual temperature feedbacks but of their mutually-amplified aggregate. Their results suggest that temperature feedbacks are somewhat net-negative, implying climate sensitivity ~1 K. In the context of the wider evidence considered in outline here, they may be right.

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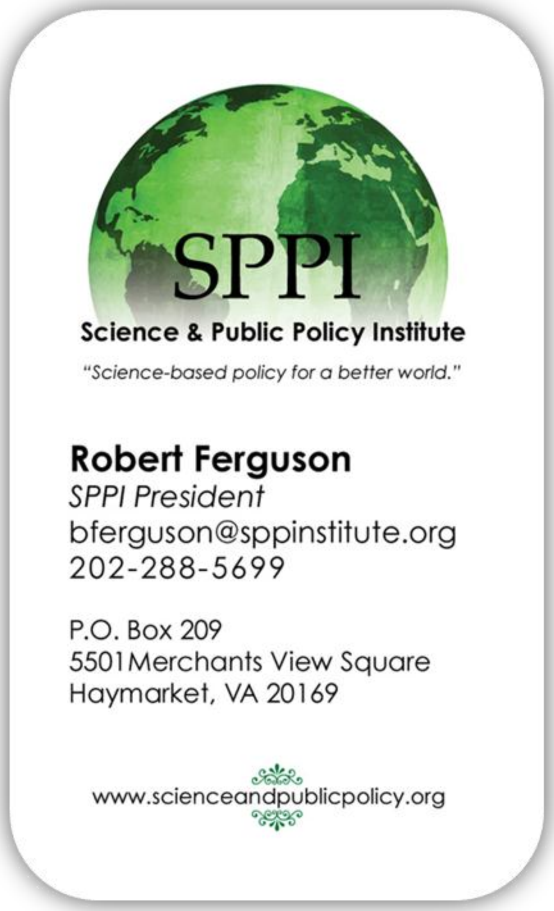

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