

# **The King's Foot**

[Editorial]

**Stephen E. Schwartz**

**Atmospheric Sciences Division, Brookhaven National Laboratory**

**Upton NY 11973**

**ses@bnl.gov**

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*Diverse weights and diverse measures are an abomination unto the Lord.*

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Way back in ancient history the world was a place of diverse weights and diverse measures, but gradually, as measurement science has progressed, the scientific community has settled upon a mutually agreed to universal set of measures, the so-called International System of Units (SI). Over my career I have measured gas pressure in pounds per square inch, millimeters of mercury, torr (ever so slightly different), atmosphere, bar (1.325% different), newtons per square meter, and pascals (thankfully, the same). Over time definitions became refined – density of mercury corrected to a temperature 0 C; gravitational acceleration corrected to 9.80665 m s<sup>-2</sup>. Epicycles upon epicycles. How many countless hours were spent in converting from one unit to another? How many times did data tabulated in "old torr" have to be converted to "standard torr"? And how many years did it take to become internally "calibrated" with a sense of the magnitude of a familiar quantity in an unfamiliar unit? Fortunately, in science, those days are mostly over, although as an American I still have trouble, without doing some mental arithmetic, "knowing" whether a height of 185 cm is tall or short for a man. A further, tremendous, advantage of systematic units is the ability to calculate quantities of interest, for example the energy change on expansion of a gas as  $\Delta(PV)$ , without having to convert units along the way.

Despite the universally recognized advantage of systematic units, in climate science we are still back in the day of the King's Foot, the length of which differed from one realm to the next, and even with time as the king was succeeded by his son. "Oh, no," you say, "we are beyond that stage. We all use hectopascals and watts per square meter." And so we do. Mostly.

One big exception turns out to be the unit that is used to quantify Earth's equilibrium climate sensitivity, a measure of the susceptibility of planetary temperature to a sustained change in the radiative balance and thus a quantity that is of great practical interest as well as a key geophysical property of Earth's climate system. Here is as authoritative a definition of the climate sensitivity that one might hope to find, from the IPCC Fourth Assessment Report (Hegerl et al., 2007 p. 718):

‘Equilibrium climate sensitivity’ (ECS) is the equilibrium annual global mean temperature response to a doubling of equivalent atmospheric CO<sub>2</sub> from pre-industrial levels and is thus a measure of the strength of the climate system’s eventual response to greenhouse gas forcing.

It is clear from this definition that this measure of equilibrium climate sensitivity is particularized to a change in the radiation budget that results from a specific change in radiative budget, namely that resulting from "a doubling of equivalent atmospheric CO<sub>2</sub>." Note as a consequence the requirement, implicit in "equivalent" that forcings (changes in radiation budget) due to changes in amounts of other atmospheric substances or other changes (solar luminosity, surface reflectance) must be in some way normalized to a doubling of atmospheric CO<sub>2</sub>. Is this beginning to sound like millimeters of mercury? Note further the implicit assumption that the forcing that results from the doubling of CO<sub>2</sub> is more or less independent of the initial mixing ratio ("preindustrial levels" not precisely specified); that is, the assumption that the forcing depends exactly on the logarithm of the CO<sub>2</sub> mixing ratio. Is this beginning to sound like millimeters of mercury corrected to 0 °C and gravitational acceleration 9.80665 m s<sup>-2</sup>? Actually, although qualitatively similar, quantitatively the situation is much worse because of the large uncertainties associated with the pertinent properties of CO<sub>2</sub>.

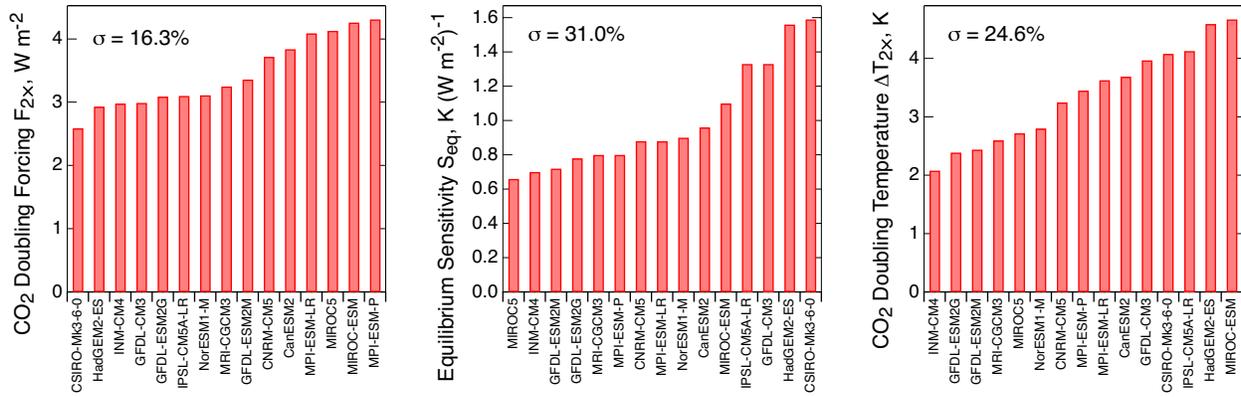
Recently Andrews et al (2012) compared the forcings and response coefficients of 15 atmosphere-ocean general circulation models (GCMs) that participated in the CMIP-5 model intercomparison. Forcing and response coefficient were inferred from the output of the model runs respectively as intercept and slope of a graph of net top-of-atmosphere energy flux versus global mean temperature anomaly subsequent to a step-function quadrupling of atmospheric CO<sub>2</sub>. (Because the model experiments examined response to a quadrupling of CO<sub>2</sub>, rather than a doubling, the intercept had to be divided by 2 to obtain the forcing pertinent to doubled CO<sub>2</sub>). The forcing is interpreted as an "adjusted forcing" that includes rapid adjustments, mainly of atmospheric structure, that modify the TOA radiative flux on time scales shorter than a year or so. According to the planetary energy conservation equation the response coefficient,  $\lambda$ , units W m<sup>-2</sup> K<sup>-1</sup>, would be equal to the inverse of what I denote as equilibrium climate sensitivity  $S_{eq}$ , in systematic units K (W m<sup>-2</sup>)<sup>-1</sup> that would characterize the change in global mean surface temperature that would ultimately result from a sustained forcing, ratioed to that forcing, under assumption that the

steady-state increase in temperature is linearly proportional to the applied forcing. The Andrews et al. study also reported for each model the quantity, denoted here  $\Delta T_{2\times}$ , the so-called CO<sub>2</sub> doubling temperature, unit K, (and commonly denoted "equilibrium climate sensitivity") evaluated as

$$\Delta T_{2\times} = F_{2\times} S_{\text{eq}}, \quad (1)$$

where  $F_{2\times}$  is the forcing associated with doubled CO<sub>2</sub> for that model.

A key finding of the Andrews et al. study is the spread of values of  $F_{2\times}$  exhibited by the different GCMs, Figure 1. The spread in the forcings for the different models is 16%, 1- $\sigma$  (spreads are expressed here as the fractional standard deviations relative to the mean and are given throughout as 1- $\sigma$  except where otherwise specified), but perhaps a better perception of the spread in the forcing relative to that in other quantities is given by the distribution of this quantity across the several GCMs. The spread in forcing is a consequence of differing treatments of the radiation transfer in the several models as well as different treatments of clouds that interact with radiation. As the forcing inferred from the analysis of Andrews et al. is an adjusted forcing, it also reflects differences among the models in rapid ( $\lesssim 1$  yr) response of atmospheric structure to the imposed forcing. This spread in forcings inferred from the climate model runs is substantially greater than the uncertainty that is frequently associated with forcing by long-lived greenhouse gases in general and CO<sub>2</sub> in particular, for which the IPCC Fourth Assessment Report (Forster et al., 2007 p. 131) gives a 5-95% confidence range ( $\pm 1.64 \sigma$ ) of  $\pm 10\%$ ; i.e., 1- $\sigma$  uncertainty 6.1%. That there is such a difference in the range of  $F_{2\times}$  as calculated by GCMs and radiative transfer models should not come as much of a surprise. For example, although the Radiative Transfer Model Intercomparison Project (Collins et al., 2006) reported a 1- $\sigma$  spread in longwave forcing at 200 hPa among the GCMs compared of only 8.5%, that study was restricted to cloud-free atmospheres, with the reason given that "the introduction of clouds would greatly complicate the intercomparison exercise," from which one infers that the spread of forcing in a model with clouds would greatly exceed that in an idealized cloud-free model. Hence the finding of a spread of some 16% in the forcings is likely an accurate assessment not only of current capability of calculating  $F_{2\times}$  in GCMs but also of the maximum level of confidence that can be placed in this quantity more generally, at least at present. As a consequence, the ruler that is used to measure climate sensitivity as  $\Delta T_{2\times}$  would seem to be uncertain by at least  $\pm 16\%$  (1- $\sigma$ ). One would therefore expect the spread in  $F_{2\times}$  to propagate into spread in  $\Delta T_{2\times}$ , as that quantity depends on  $F_{2\times}$ .



**Figure 1.** Distributions of CO<sub>2</sub> doubling forcing  $F_{2x}$ , equilibrium sensitivity in systematic units  $S_{eq}$ , and CO<sub>2</sub> doubling temperature  $\Delta T_{2x}$  as inferred from response of global mean surface temperature to step function quadrupling of CO<sub>2</sub> in 15 coupled atmosphere-ocean GCMs by Andrews et al. (2012).

To examine the influence of spread in  $F_{2x}$  on  $\Delta T_{2x}$  I also show in Figure 1 distributions and fractional standard deviation in  $S_{eq}$  (calculated as the inverse of the values of climate response coefficient  $\lambda$  reported by Andrews et al., denoted  $\alpha$  by those investigators) and in  $\Delta T_{2x}$  (calculated by Eq 1 from values of  $F_{2x}$  and  $S_{eq}$  inferred for each GCM). Here one observes first that the spread in both measures of climate sensitivity are substantially greater than in the forcings. This is to be expected, given that the climate sensitivity in a GCM (as in the real world) depends on the response of the entire climate system to the forcing and hence that differences in the modeled sensitivity must reflect differences in treatments of the processes governing climate sensitivity that are represented in the several GCMs. As the CO<sub>2</sub> doubling temperature  $\Delta T_{2x}$  is the product of  $S_{eq}$  and  $F_{2x}$ , one would expect, if the two quantities were uncorrelated across models, that the spread in values of  $F_{2x}$  would propagate into a spread in  $\Delta T_{2x}$  that exceeds that in  $S_{eq}$ , specifically that the spreads would add in quadrature resulting in an spread in  $\Delta T_{2x}$  of 35%, rather than the value 25% found in the Andrews et al. results that is less even than the spread in  $S_{eq}$ . As noted by Andrews et al., this situation implies a negative correlation between  $F_{2x}$  and  $S_{eq}$  across the models, a result that is somewhat surprising given that forcing and response in GCMs (as in the real world) depend on very different processes. This situation has the effect of diminishing the apparent spread in modeled climate sensitivity across the several models when that sensitivity is reported as  $\Delta T_{2x}$  rather than  $S_{eq}$ . In any event it is clear that the range of forcings in the models substantially affects the spread in climate sensitivity across the models when reported as doubling temperature  $\Delta T_{2x}$ .

Another instance in which CO<sub>2</sub> is used as a ruler in climate science is in the definition, evaluation, and application of so-called global warming potentials (GWPs) of radiation influencing substances other than CO<sub>2</sub>. The GWP of a substance is a measure of the global-average forcing commitment that would

result from introduction of a given mass of the substance into the atmosphere, the forcing integrated over a specified period of time (time horizon) per mass of emitted material. Conventionally the GWPs of substances other than CO<sub>2</sub> are ratioed to the GWP of CO<sub>2</sub>, and therein lies the rub. In fact the term "global warming potential" conventionally refers to the ratio, with the un-ratioed quantity being denoted "absolute global warming potential," AGWP. Interestingly when the GWP concept was introduced in the IPCC first assessment report (Shine et al., 1990) several "problems" associated with evaluating GWPs were explicitly noted, namely the estimation of atmospheric lifetimes of gases (and in particular CO<sub>2</sub>), the dependence of forcing of a gas on its concentration and the concentrations of other gases, indirect (chemical) effects, and specification of the most appropriate time horizon. However absent from this list of problems was the problem of specifying the forcing of CO<sub>2</sub> itself. The report explicitly acknowledged that presentation of GWP relative to CO<sub>2</sub> "may not be the ideal choice" because of uncertainty associated with the atmospheric lifetime of CO<sub>2</sub>, which is certainly correct, but does not similarly note the consequence of uncertainty in forcing by a given incremental amount of atmospheric CO<sub>2</sub>. Despite these recognized problems, global warming potentials continue to be reported as ratios to that for CO<sub>2</sub>.

Defining the absolute global warming potential AGWP of a given gas  $g_i$  over time horizon  $t_h$  as the integrated forcing that results from emission of a unit mass of this gas and denoting this quantity as  $P_{g_i}(t_h)$ , then

$$P_{g_i}(t_h) = \int_0^{t_h} a_{g_i}(c_{g_i}(0), c_{g_{j \neq i}}) I_{g_i}(t) dt \quad (2)$$

where

$a_{g_i}(c_{g_i}(0), c_{g_{j \neq i}})$  is the instantaneous forcing due to an incremental kilogram of gas  $g_i$ , in the global atmosphere, a function of the initial amount of gas in the atmosphere  $c_{g_i}(0)$  and weakly a function of the amounts of other gases in the atmosphere  $c_{g_{j \neq i}}$ , and  $I_{g_i}(t)$  is the fraction of incremental gas  $g_i$  emitted at time 0 that is present in the atmosphere at time  $t$ , the so-called impulse response function of the gas.

The AGWP so defined has systematic units, W yr m<sup>-2</sup> kg<sup>-1</sup>. Although such a unit is not immediately familiar, it has the great strength of allowing one to immediately estimate the integrated forcing that would result from a given past or prospective emission of a substance of interest as a simple product. It might also be noted that by definition the GWP of CO<sub>2</sub> is unity, whereas the AGWP is applicable to CO<sub>2</sub> as well and thus also permits immediate assessment of the integrated forcing that would result from a given emission of that substance.

The GWP as conventionally defined is the ratio of  $P_{g_i}(t_h)$  for the gas of interest to that for CO<sub>2</sub> itself,

$$GWP_{g_i}(t_h) = \frac{P_{g_i}(t_h)}{P_{CO_2}(t_h)} \quad (3)$$

It is clear from (3) that the GWP of a given gas other than CO<sub>2</sub> depends not only on the radiative properties and impulse response function of the gas in question but also on these properties of CO<sub>2</sub>. In contrast the AGWP of a given gas, including CO<sub>2</sub>, depends to first order only on the radiative and persistence properties of the gas in question; there is a slight dependence on the amounts of other gases in the atmosphere because of overlap of spectral lines, but in practice these interactions are hard to apportion and are generally neglected. As a consequence of the first-order dependence of the GWP on  $P_{CO_2}$  any uncertainty in the radiative or persistence properties of CO<sub>2</sub>, or change in values of these properties resulting from improved understanding, would be reflected not in a change in the GWP of CO<sub>2</sub>, which remains unity by definition, but in the GWPs of all other greenhouse gases. This situation is not hypothetical but has actually happened. The table of GWPs in the IPCC Third Assessment Report (Ramaswamy et al., 2001) presents GWPs for several gases that are increased by some 20% relative to those in the corresponding table of the 1994 IPCC Report on Radiative Forcing of Climate Change (Shine et al., 1994), a consequence mainly of the decrease in the forcing of doubled CO<sub>2</sub> used in the two evaluations, from 4.4 to 3.7 W m<sup>-2</sup>. This situation is analogous to the king dying and his son, with a foot 20% shorter than that of his deceased father, ascending to the throne and thereby increasing by 20% the heights of all the inhabitants of the realm.

It is hoped that these two examples serve to demonstrate the concerns that arise from using non-systematic units that are particularized to CO<sub>2</sub> for the expression of quantities that are important to considerations of climate change – climate sensitivity and global warming potentials – and the advantages of expressing these quantities in systematic units rather than values that are hostage to the uncertainties in present estimates of those properties for CO<sub>2</sub> and future changes in these estimates.

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