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Manabe's Radiative–Convective Equilibrium

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ABSTRACT: Syukoro (Suki) Manabe's Nobel Prize in Physics was awarded largely for his early work on one-dimensional models of "radiative–convective equilibrium" (RCE), which produced the first credible estimates of Earth's climate sensitivity. This article reviews that work and tries to identify those aspects that make it so distinctive. We argue that Manabe's model of RCE contained three crucial ingredients. These are (i) a tight convective coupling of the surface to the troposphere, (ii) an assumption of fixed relative humidity rather than fixed absolute humidity, and (iii) a sufficiently realistic representation of greenhouse gas radiative transfer. Previous studies had separately identified these key ingredients, but none had properly combined them. We then discuss each of these ingredients in turn, highlighting how subsequent research in the intervening decades has only cemented their importance for understanding global climate change. We close by reflecting on the elegance of Manabe's approach and its lasting value.

KEYWORDS: Convective adjustment; Climate change; Climate sensitivity; Feedback; Radiative transfer

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The selection of Syukoro (Suki) Manabe for a Nobel Prize in Physics is a source of pride for all who know him and for the climate modeling community as a whole. It also provides motivation to reexamine some aspects of Suki's research and why it is so foundational.

The widely acknowledged starting point for Suki's climate research trajectory are his papers on radiative–convective equilibrium (RCE) in the 1960s: Manabe and Strickler (1964, hereafter MS64) and Manabe and Wetherald (1967, hereafter MW67). Joe Smagorinsky had earlier hired Manabe to be a member of a group constituted to create and study global climate models, a group that was later to become the core of the Geophysical Fluid Dynamics Laboratory and that included associate scientists like Strickler and Wetherald (Lewis 2008). Suki's initial assignment was the development of an atmospheric radiative transfer module, a foundation for any climate model. Suki designed his single column RCE model to simulate the globally averaged atmospheric thermal structure, along with the capability to address the sensitivity of this structure to CO_2—all while exercising the radiation module for its primary application to global climate modeling.

Suki wrote no other papers explicitly using the RCE framework, although he did mention the results from an improved radiative transfer computation in a workshop report (Manabe 1971). Rather he proceeded directly to focus on three-dimensional (3D) global climate modeling, leading to the first CO_2 sensitivity study with such a model (Manabe and Wetherald 1975) and also to coupling to a dynamic World Ocean, which provided path-breaking results on the transient climate response and its spatial structure (Manabe 1969; Manabe et al. 1975, part of a remarkable long-term collaboration with Kirk Bryan). The result of these labors was a blueprint for global modeling that is still discernible today, with many of the insights emerging from these simulations still embodied in the comprehensive CMIP-class models used today in support of the IPCC process. While Manabe's RCE studies were preparatory to these much more comprehensive 3D modeling studies, the MW67 results have stood the test of time as providing the first physically sound estimates of equilibrium climate sensitivity to CO_2.

What is it about Manabe's RCE work, and MW67 in particular, that gives it such prominence in the development of our understanding of climate sensitivity? We argue here that its distinctiveness is due to its incorporation of three ingredients within a single model:

1) non-radiative–convective energy fluxes that strongly couple surface temperature to tropospheric temperatures and constrain the tropospheric lapse rate, turning the focus away from the surface energy balance and toward the energy balance at the top of the atmosphere (TOA);[1]
2) a sufficiently realistic representation of H_2O, O_3, and CO_2 radiative transfer, which allows the model to simultaneously simulate tropospheric and stratospheric responses to perturbations; and

[1] When diagnosing the response to CO_2 in terms of forcing and feedback, it is important to distinguish between the energy balance at the TOA and at the tropopause. But when one is comparing two equilibrium states in both of which the stratosphere is in radiative equilibrium there is no need for this distinction, so we simply refer to the TOA energy balance throughout this essay. Note that MW67 does not directly present a forcing–feedback decomposition of the response, even though it laid the groundwork for this idea.

3) the assumption of fixed tropospheric *relative* humidity (RH) as the appropriate starting point for studies of the strength of the water vapor feedback.

We start by reviewing the lay of the land prior to MW67. Earlier estimates of sensitivity to CO_2 prior to MW67 have been covered in some detail elsewhere, the recent account in Manabe and Broccoli (2020) providing an especially valuable discussion (see also Archer and Pierrehumbert 2011). So our discussion here of this context is brief, instead emphasizing how one or two of the ingredients listed above had been incorporated in studies prior to MW67, but never all three. We then discuss each of these ingredients in turn, focusing on how the physical assumptions incorporated in this RCE model have stood the test of time, even through the dramatic growth in both observational and modeling studies in the intervening years.

Prior to MW67

The key ingredients of MW67 largely predated it, in some cases by decades, but were reported only sporadically in earlier papers, none of which contained all three ingredients (Table 1; note that ingredient 1 is split into a convective constraint and TOA balance, components that were independent in other models but tightly coupled in MW67, as discussed below). For instance, the early work of Hulburt (1931) incorporated the effects of convection (for perhaps the first time), but the treatment of radiation was inadequate: Hulburt's spectroscopic data, as well as his "windowed-gray" representation of the frequency dependence of radiative transfer, were too crude to provide a reliable estimate of climate sensitivity, and he did not model the radiative interaction between CO_2 and O_3 in the stratosphere in any detail. Conversely, the works of both Callendar (1938) and Plass (1956) contained reasonable (i.e., spectral) representations of radiation, but both papers focused on the surface energy balance and neglected convection. Möller (1963) similarly focused on the surface energy budget and overlooked the importance of convection, despite being one of the first papers to quantitatively incorporate a water vapor feedback.

The models of Goody (1949) and Möller and Manabe (1961) (see also Manabe and Möller 1961) also deserve mention as precursors to Manabe's RCE model, even though those works focused on upper-atmospheric structure rather than climate sensitivity. Both models, developed by radiation experts, had realistic radiative transfer incorporating detailed spectroscopy of H_2O, CO_2, and O_3, and also treated the whole atmosphere rather than just the surface. The Goody (1949) model also had convectively constrained tropospheric lapse rates, but crucially was not capable of iterating on the surface/tropospheric temperatures to calculate equilibrium states. Conversely, the model of Möller and Manabe (1961) could be run to equilibrium under TOA energy balance but did not feature a convective constraint, thus producing unrealistic tropospheric and surface temperatures. Overcoming these difficulties required a method for iterating on temperatures while also preserving the convective constraint. The "convective

Table 1. Summary of papers predating MW67. The bold font signifies that MW67 is the only paper in this list to incorporate all of the required ingredients.

Paper	Convective constraint	TOA balance	Gray/spectral	Fixed RH
Hulburt (1931)	Yes	Yes	Windowed gray	No
Callendar (1938)	—	No	Spectral	No
Goody (1949)	Yes	No	Spectral	—
Plass (1956)	—	No	Spectral	No
Möller and Manabe (1961)	No	Yes	Spectral	No
Möller (1963)	—	No	Spectral	Yes
MS64	Yes	Yes	Spectral	N
MW67	**Yes**	**Yes**	**Spectral**	**Yes**

adjustment" of MS64 and MW67 was just such a method, and the resultant coupling of surface and TOA energy balance is the essence of ingredient 1 above.

The three key aspects of MW67 enumerated above are intimately connected in their implications for climate sensitivity, a point that we emphasize as we discuss each of these in turn.

Surface–troposphere coupling

We begin with a qualitative picture of surface–troposphere coupling and the maintenance of the global mean vertical temperature profile. This picture was understood prior to MS64 and MW67, but its importance for estimating climate sensitivity was not widely recognized, as evidenced by the first and second columns of Table 1.

The atmosphere is largely transparent to solar radiation and is, therefore, heated primarily from below by the surface. As a consequence, in pure radiative equilibrium the atmosphere in the global mean is gravitationally unstable in a layer adjacent to the surface. Atmospheric motions transport heat upward to balance the radiative destabilization. The tropopause separates the troposphere, the layer through which heat is predominately distributed by these atmospheric motions, from the stratosphere where radiative equilibrium provides a useful first approximation to the energy balance.

In addition, the surface is very strongly coupled to the near-surface air by turbulent boundary layer fluxes. The strength of this coupling, as measured by the energy fluxes generated when the air–surface temperature difference is increased, is an order of magnitude larger than the energy fluxes generated at the TOA when the surface and troposphere are warmed uniformly by the same amount (e.g., Romps 2020). This means it is very difficult to generate a large air–surface temperature difference, as large fluxes will arise to oppose it. Thus, one cannot, on average, increase climatological surface temperatures without simultaneously increasing tropospheric temperatures, or vice versa. Therefore, *the surface and troposphere must be considered as a unit to first approximation*.

The demonstration in MS64 and MW67 of the power of a 1D radiative–convective model, which, by incorporating a conceptually simple "convective adjustment" was able to encapsulate this basic picture, resulted in its universal acceptance for essentially all work that followed in this 1D framework. MS64 and MW67 used a time integration to equilibrate their radiative transfer model, after adding a local adjustment to a lapse rate of 6.5 K km^{-1} whenever adjacent layers became more unstable than this value. Similarly, the surface temperature was adjusted to avoid a supercritical lapse rate between the surface and lowest model layer. The details of the adjustment scheme differed among the papers that followed, but the essence remained the same—namely, a final state in energy balance at the TOA, a stratosphere in radiative equilibrium, a troposphere with prescribed lapse rate (either uniform or moist adiabatic), continuity of temperature at the tropopause, and a temperature jump at the surface that is either ignored or changes only slightly in response to climate change.

The strong coupling between surface and troposphere implies that the energy balance at the TOA, rather than at the surface, is critical for the analysis of climate sensitivity: changes in the surface energy balance are dominated by changes in convective fluxes that are *constrained* to take on values consistent with a small air–surface temperature jump. Much of the historical confusion regarding the sensitivity of temperature to CO_2 has resulted from failing to consider this constraint, and assuming that convective fluxes will instead remain invariant under climate change (see, e.g., www.realclimate.org/index.php/archives/2010/01/plass-and-the-surface-budget-fallacy/#more-2652). Today, the strongly coupled surface–troposphere perspective serves as a basis for the ubiquitous forcing–feedback decomposition underlying much of our current understanding of sensitivity and our ability to relate the climate responses to different forcing agents (e.g., Sherwood et al. 2020). As an important example, the effects of high cirrus cloud and of boundary layer stratocumulus feedbacks on surface temperature can both be measured by their effects on the TOA energy balance. There is no need for a detailed understanding of the distinctive pathways through which high- and low-cloud radiative effects are transmitted to the surface; the constraint on the lapse rate and on the surface–air temperature difference provides a simple model for the end effect of these cloud–radiation interactions.

The distinction between the TOA and surface energy budgets is particularly profound when considering changes in atmospheric absorption of sunlight. For example, one might intuitively expect the effect of increased near-infrared absorption by water vapor with warming to be a negative feedback at the surface. But from the perspective of the surface–troposphere system as a whole, this absorption removes radiation that would otherwise be reflected back to space by the surface or by clouds, and reduced reflection results in net energy input at the TOA and, therefore, surface/troposphere *warming*. The effect due to absorbing aerosols such as black carbon is similar: one must understand the change in reflection of sunlight at TOA, rather than the reduction in solar absorption at the surface, to estimate the effect on the surface/troposphere as a whole.

This strongly coupled surface–troposphere paradigm operates throughout MW67, as Manabe tests the sensitivity of the model to all of its input parameters, including assumed RH, surface albedo, and cloudiness. At the same time, however, this strongly coupled paradigm is not always valid. Perhaps the most dramatic exception to this rule is the "nuclear winter" scenario (Turco et al. 1983), in which the aerosol absorption described above is sufficiently strong as to stabilize the atmosphere to nearly all convection, thus decoupling the surface from the region of atmospheric absorption (Ramaswamy and Kiehl 1985). More prosaic exceptions to the strongly coupled paradigm include high-latitude winters and tropical regions of ocean upwelling, where surface temperatures are suppressed by lack of sunlight or upwelling of cold waters, and the overlying atmosphere is heated nonlocally by horizontal heat transport (via, e.g., midlatitude eddies or convectively generated gravity waves). Such climate regimes exhibit little to no convection, as well as strongly stable stratifications which manifest as temperature inversions, a telltale sign of surface–atmosphere decoupling (Cronin and Jansen 2016; Mauritsen 2016). These real world exceptions to the strongly coupled paradigm imply that equivalent TOA forcings from different forcing agents may not produce equivalent warming, leading to the notion of "efficacy" for different forcing agents (Hansen et al. 2005).

Radiative transfer

In contrast to the simplicity of the convective-adjustment framework, the treatment of radiation in MS64 and MW67 was relatively comprehensive. Spectral calculations of both infrared and solar radiative transfer, involving H_2O, CO_2, and O_3, were made using the most up-to-date laboratory measurements and analytical techniques, including consideration of H_2O–CO_2 overlap. One sees a precedent for this comprehensive treatment of radiation in the lesser known papers of Möller and Manabe (1961) and Manabe and Möller (1961), which calculated radiative equilibria only and focused on the stratosphere. These papers demonstrated the sensitivity of the stratosphere and tropopause to greenhouse gas composition and distribution, suggesting that these must be modeled fairly realistically to obtain reasonable results, in contrast to convection.

This comprehensive treatment of radiation paid off in MW67's discovery of stratospheric cooling in response to CO_2 doubling (Fig. 1). This cooling, which results from enhanced CO_2 emission to space from the upper stratosphere (Jeevanjee et al. 2021b), is a distinctive aspect of CO_2-induced global warming and has been replicated in virtually every subsequent simulation of anthropogenic warming, as well as observed in the satellite and instrumental record (Ramaswamy et al. 2001; Shine et al. 2003; note that the observed cooling also reflects a decrease in ozone concentrations, which dominate in the lower stratosphere). This cooling of the stratosphere also modifies the forcing felt by the surface–troposphere system (the so-called stratospheric adjustment), which turns out to be key for accurately estimating climate sensitivity (Houghton et al. 1994; Hansen et al. 1997). Manabe's careful treatment of the stratosphere, rooted in his earlier work, thus paid off in ways that were difficult to imagine beforehand. This also includes realistic responses to changes in the assumed O_3 and stratospheric H_2O profiles, which MW67 also explore.

The careful treatment of radiative transfer in MW67 also meant that their quantitative calculations of the surface temperature response to a doubling of CO_2, a quantity later known as the equilibrium climate sensitivity (ECS), have largely held up despite continuing advances in spectroscopic data, in situ measurement, and radiative transfer methodology (Table 5 of MW67, reproduced here as Fig. 2).[2] As seen in Fig. 2, however, calculations of ECS depend strongly on the assumed distribution of water vapor in a changing climate. Identifying this sensitivity, and clarifying the fixed relative humidity assumption as the most natural one, was yet another key achievement of the MW67 model, to which we turn next.

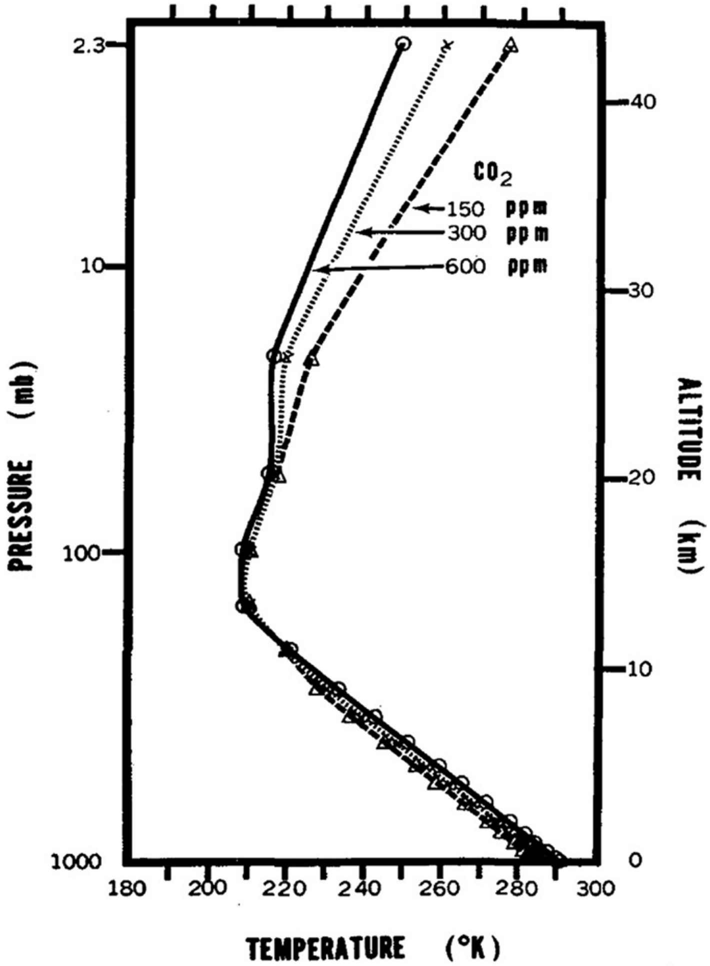

Fig. 1. Stratospheric cooling and tropospheric warming from CO_2 doubling. Figure from MW67.

[2] While Manabe's clear-sky ECS is indeed close to today's central estimate of 3 K (Sherwood et al. 2020; Forster et al. 2021), some compensating errors should be noted. In particular, MW67's clear-sky estimate neglects positive cloud and surface albedo feedbacks, but also contains radiation errors which were later corrected (Manabe 1971) and which offset the absence of these feedbacks.

Fixed relative humidity

The realization that the assumption of fixed relative rather than specific humidity was a more appropriate starting point for estimating climate sensitivity can be traced back to Arrenhius (1896) and Chamberlin (1899). As indicated by the title of the Chamberlin paper ("An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis"), explaining ice ages was the central issue facing these pioneering climate sensitivity analyses. But fixing the specific humidity makes no physical sense as the climate cools, since regions of climatological supersaturation would arise. So it should be no surprise

Table 5. Change of equilibrium temperature of the earth's surface corresponding to various changes of CO_2 content of the atmosphere.

Change of CO_2 content (ppm)	Fixed absolute humidity		Fixed relative humidity	
	Average cloudiness	Clear	Average cloudiness	Clear
300 → 150	−1.25	−1.30	−2.28	−2.80
300 → 600	+1.33	+1.36	+2.36	2.92

Fig. 2. Table 5 from MW67.

that these authors gravitated to the equally simple but far more plausible assumption of fixing *relative* humidity. The same argument cannot be applied to a warming climate, but making the fixed specific humidity assumption on the warming side and not the cooling side is difficult to justify: it is far more natural to stick with the "Copernican principle"—that there is nothing special about the present climate.

MW67 pointed to the modest changes in relative humidity in the seasonal cycle, reproduced here as Fig. 3, as observational support for fixing the relative humidity when perturbing their model. The relative humidity distribution is a consequence of atmospheric motions that create saturation and precipitation when parcels are cooled and subsequent subsaturation when these parcels are warmed. Though these motions exhibit large seasonal changes, Fig. 3 hints at how hard it is for these changes to create substantial changes in relative humidity. An exception to this, of course, is stratospheric water vapor, which is better thought of as controlled by the flow of air from the troposphere through the cold point overlying the equatorial tropopause. Recognizing this, MW67 (and many other subsequent RCE models) simply specify a stratospheric mixing ratio.

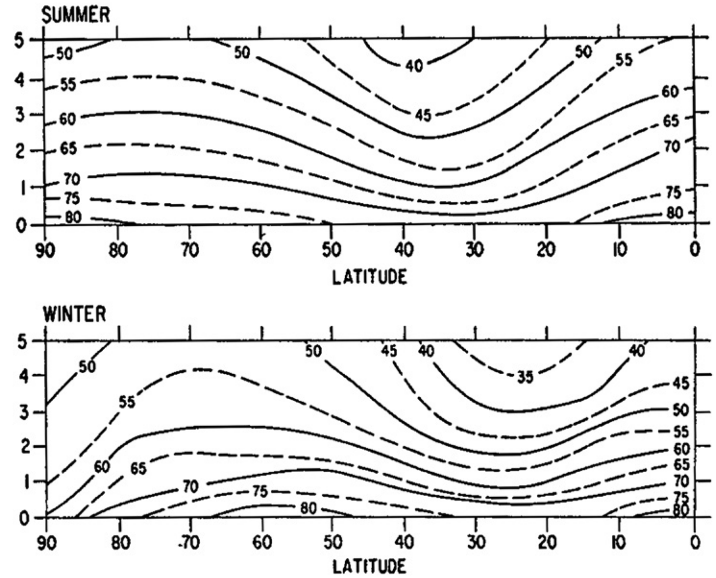

Fig. 3. Latitude–height distribution of relative humidity for (top) summer and (bottom) winter. Figure from MW67.

The validity of this fixed relative humidity approximation has been analyzed repeatedly and has held up well in a variety of modeling setups, including several generations of GCM simulations (Manabe and Wetherald 1975; Sherwood et al. 2010; Zhang et al. 2020), models of RCE with explicit deep moist convection (Held et al. 1993; Tompkins and Craig 1999; Romps 2014), and likely global nonhydrostatic models in the near future (Lang et al. 2021). Observational studies have also supported this assumption, ranging from observational tests that confirm large-scale advection–condensation models (which leave little room for microphysical complications of this simple picture), to studies of the observed responses to Pinatubo, to studies of the observed trends in the tropics. For detailed discussion and further references, see the recent review of Colman and Soden (2021).

The climate implications of the fixed RH assumption are dramatic. Perhaps most significantly, the fixed RH assumption means that the outgoing longwave radiation (OLR) is roughly linear in surface temperature, rather than being quartic as might be expected from the Stefan–Boltzmann law (Fig. 4). The slope of the simulated OLR curves are also noticeably smaller than that of the Stefan–Boltzmann curves for all surface temperatures, so that a larger surface temperature change is required to balance a given TOA forcing. This increase in climate sensitivity is now known as the water vapor feedback.[3]

More quantitatively, when MW67 forced their model by a doubling of CO_2, they obtained their now-famous result that ECS increases by roughly a factor of 2 when relative humidity is fixed, compared to when specific humidity is fixed (cf. Fig. 2). In the presence of other temperature-dependent feedbacks, such as that due to solar reflection by snow and ice, this factor-of-2

[3] This aspect of climate sensitivity has become so fundamental that more recent feedback frameworks actually incorporate it (via a fixed RH assumption) into their default climate responses, so that it longer appears as a "feedback" (Ingram 2013; Held and Shell 2012; Jeevanjee et al. 2021a). In these RH-based frameworks, the slopes of the solid lines in Fig. 4 simply quantify the fixed relative humidity Planck response.

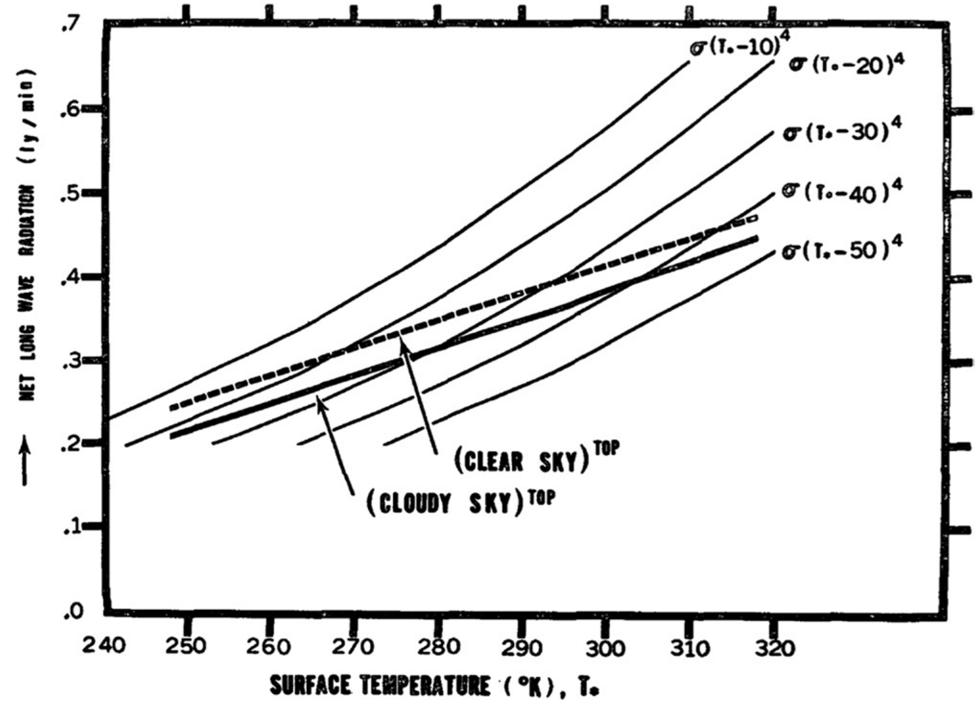

Fig. 4. Outgoing longwave radiation (OLR) as a function of surface temperature T_*. The thick lines show the OLR as calculated from the MW67 RCE model with fixed RH. The thin lines show predictions from the Stefan–Boltzmann law, evaluated at various offsets from the indicated surface temperature. Figure from MW67.

amplification due to water vapor feedback is increased further, since one now has to take into account that the water vapor increases and albedo decreases feed on each other, with less ice/snow implying warmer temperatures and more water vapor, etc. The system is, in effect, further sensitized to all other temperature dependent feedbacks (e.g., Fig. 4 in Held and Soden 2000). Values of equilibrium climate sensitivity near 4 K, the high end of the one-sigma range in the Sixth IPCC assessment (2.5–4 K for doubling of CO_2; Forster et al. 2021) would be far less likely in the absence of a water vapor feedback comparable to that obtained by fixing relative humidity. MW67 is thus justly celebrated as laying the foundation for all estimates of the severity of global warming.

Conclusions

This article describes the foundational aspects of Manabe's work on radiative–convective equilibrium. We outlined three key ingredients in the first section, whose implications include the now-ubiquitous forcing–feedback framework, the cooling of the stratosphere in response to increased CO_2, and a doubling of climate sensitivity due to the powerful water vapor feedback, yielding ECS estimates in the neighborhood of 3 K. All of these implications have stood the test of time and have become cornerstones of climate science.

A key to the long-lasting impact of MW67 is that it did not attempt to study phenomena that were not plausibly modeled in 1D, or that require details of atmospheric circulation. For example, the stratosphere is pushed out of radiative equilibrium by the Brewer–Dobson circulation, but this fact cannot easily be incorporated in a 1D model. Similarly, while one can replace the fixed tropospheric lapse rate with a moist adiabat (clearly more appropriate for the tropics), atmospheric profiles in the extratropics are maintained by a more complex interplay of large- and small-scale motions, so changes in global mean lapse rate are once again difficult to meaningfully simulate in 1D. MW67 furthermore make no attempt to model changes in the water vapor or cloud distributions (beyond the fixed RH assumption discussed above), or in the distribution of stratospheric ozone. Three-dimensional global models have subsequently filled many of these gaps, as have high-resolution simulations of RCE in small domains with resolved convection. The good sense to avoid aspects for which the 1D model is not suitable underlies the fact that very little in the MW67 paper is thought of as obsolete, serving instead as a solid and logical foundation for future elaboration. Implicit in MW67's approach is the intuition, borne out by research over the ensuing decades, that results obtained from their RCE model should be robust to the addition of more realism.

The broad appeal and utility of the MW67 model was evident in its adoption by the community for a variety of problems, particularly the sensitivity of climate to not only CO_2 (Schneider 1975), but also aerosols and other trace gases such as ozone and chlorofluorocarbons (Ramanathan and Coakley 1978), and even the nuclear winter problem (Turco et al. 1983; Ramaswamy and Kiehl 1985)—applications not originally considered by MW67. Furthermore, while 3D GCMs later came to dominate as tools of the trade, there has recently been a minor renaissance in 1D RCE modeling, much of it aimed at deepening our understanding of some of the key results first obtained by MW67, including the strength of the water vapor feedback (e.g., Koll and Cronin 2018; Kluft et al. 2019; Seeley and Jeevanjee 2020; Bourdin et al. 2021).

The lasting value of the MW67 model seems to be a result of what Held (2005) referred to as model "elegance"; the quality of capturing a class of phenomenon with minimum complexity or elaboration, unobscured by idiosyncratic modeling choices. The elegance of the MW67 model, and the foundational results it produced, are all the more remarkable given that GCM development was the ultimate goal, with the 1D RCE frameworks of MS64 and MW67 serving as simplified test cases for the radiation module. Key to Manabe's success was systematically testing the sensitivity of the model to each of its assumptions, *one at a time*, to simultaneously understand their role in the climate system as well as build confidence in and understanding of the model itself (Manabe 2022). In this way, Manabe ingeniously wove fundamental scientific inquiry into the course of numerical model development, a prizeworthy approach that should be as enduring as the science it produced.

Data availability statement. No datasets were generated or analyzed for the current study.

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