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A simple-model toolbox for understanding global warming

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Within a single conceptual framework, I develop answers to fundamental questions about global warming such as: Why does the stratosphere cool under CO2 increase? Why does the surface keep warming even after a rising CO2 concentration has stabilized (commitment warming)? Why has land-ice melt consumed only 1% of the Earth's energy imbalance over the past 50 years yet has contributed 40% to sea-level rise? I develop a 5-layer horizontal-global-mean energy balance model, with one layer each for the stratosphere, the troposphere, the ocean surface mixed layer, the ocean thermocline, and the deep ocean. The stratosphere is in radiative balance (zero heat capacity); all other layers have realistic heat capacities. Mixed layer and thermocline are advectively coupled by Ekman pumping and suction; thermocline and deep ocean are advectively coupled by the vertical branches of the meridional overturning circulation. The model allows for accurate approximate analytical solution and readily interpretable numerical solution; the solutions yield immediate and explicit answers to the questions formulated above. Stratospheric cooling is caused by CO2 increase in roughly equal measure through two effects: First, enhanced opacity of the troposphere prevents longwave radiation welling up from the surface from reaching the stratosphere; this is a transient effect that vanishes when the Earth again attains energy balance. Second, while both longwave emission and absorption in the stratosphere increase linearly with the concentration of CO2, total absorption increases less than linearly because of a constant contribution from shortwave absorption by ozone. Thus, as CO2 concentration increases, stratospheric emission increases more strongly than does stratospheric absorption; the stratosphere cools, which is a permanent effect. The advective coupling between the mixed layer and the thermocline reduces by a factor of four both the timescale and the amplitude of the short-term (first decade) adjustment of the mixed layer to a switch-on in radiative forcing. After the first decade, the mixed layer temperature is "slaved" to that of the thermocline and further warms alongside. Conversely, the coupling to the mixed layer implies that the thermocline responds to the switch-on in radiative forcing on a timescale that is enhanced by a factor of four compared to a naÔve estimate of the thermocline thermal adjustment timescale. It takes 200 years for the surface to realize about 75% of the steady-state warming implied by radiative forcing and climate sensitivity. Consistent with the results of a comprehensive climate model, the steady-state warming is the same in all ocean layers. The efficiency of land-ice melt in raising sea level is explained through a thought experiment in which Earth's energy imbalance is either used entirely for land-ice melt or used entirely for ocean warming and hence expansion. We can express the ratio of sea-level rise caused by land-ice melt to that caused by ocean warming with a single dimensionless number, (heat capacity of water per unit volume) divided by (thermal expansion coefficient of water times latent heat of ice melt). This number is about 90, which explains the large energetic efficiency of land-ice melt in raising sea level, but which also indicates that when simulating explicitly the contribution of land-ice melt to sea-level rise, exquisite care must be taken that the land-ice melt is apportioned the correct amount of energy imbalance.