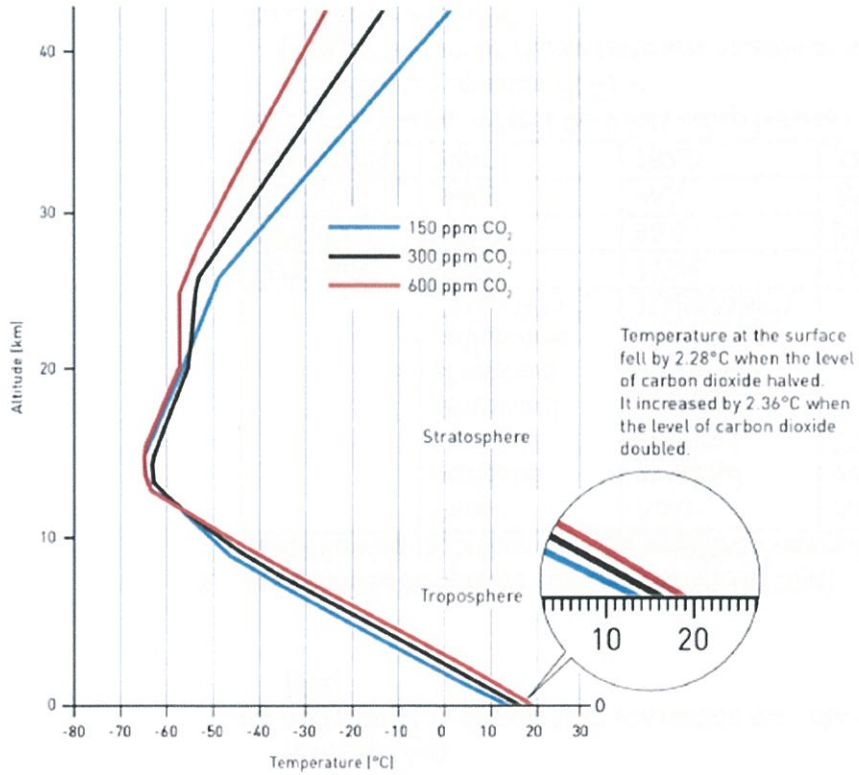
1. The radiative convective equilibrium [20pt]
As an attempt of understanding mechanisms maintaining the atmospheric energy balance, Dr. Syukuro Manabe and his colleagues developed a simplified model called "radiative convective equilibrium" in 1960s. They used the model to make the first reliable and quantitative estimation of the influence of anthropogenic greenhouse gas on global mean temperature (as illustrated in the figure below).



(a) Please describe how the model simulates the steady state vertical temperature profile. *(Hint: How they calculate the heating tendency as it approaches equilibrium? What are the assumptions? What factors need to be prescribed?)* [8pt]

(b) In steady state, the net longwave radiative effect of CO_2 is to cool the atmosphere. One may guess an increase in CO_2 would lead to larger cooling. Why does the tropospheric temperature increase when CO_2 doubled? *(Hint: In other words, please describe the fundamental mechanisms of global warming.)* [7pt]

(c) In the state of the art global climate models (i.e. those that are used in the IPCC report), they also simulate cooling in the stratosphere and warming in the troposphere under increasing CO_2 (consistent with the figure above). In addition, all of these models project larger warming at upper troposphere than at the surface. This robust feature isn't simulated in Manabe's model. Assuming a fixed relative humidity, please provide a physical explanation for the amplified warming aloft. [5pt]

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2. The convection-environment interactions [20pt]
   (a) Sketch the vertical structure that represents the environment of the deep convection in the tropics in terms of moist static energy (h), saturation moist static energy (h*), and dry static energy (s) from the surface to the bottom of the stratosphere. Be careful about the detailed relationship between the state variables and their quantitative values (in terms of temperature [K]) [6pt]
   (b) Following (a) explains how condensation happens inside the cumulus cloud to affect the large-scale environment [5pt].
   (c) Following (b), explain the role of convection in terms of temperature and moisture (you need to provide the vertical structure of both profiles) [4pt]
   (d) Following (c), discuss how convection may change under the global warming scenario. (Discuss one potential mechanism in detail). [5pt]

3. Atmospheric circulation and energy budget [20pt]
   The following table lists the area-weighted averaged radiation at the top of the atmosphere (TOA).

	Area-weighted averaged downward shortwave radiation at TOA (W/m^2)	Area-weighted averaged upward shortwave radiation at TOA (W/m^2)	Area-weighted averaged outgoing longwave radiation at TOA (W/m^2)
90°S~60°S	201.9	119.4	181.3
60°S~EQ	361.8	96.6	249.0
EQ~30°N	398.9	96.7	258.4
30°N~90°N	280.7	102.0	224.1

   (a) In steady state, what is the relationship between net downward flux at TOA and meridional (northward) energy transport? Please complete the equation $F(\phi) =$
   ($F(\phi)$is the sum of atmospheric and oceanic energy transport at latitude ϕ) [8%]
   (b) Calculate F at 30N°
   (hint: be careful about the direction of each flux. The mean radius of the earth is 6.36×10^6 m*)* [7pt]
   (c) Hadley Cell plays the main role of transporting the energy poleward in the tropics. Many global climate models project weakened Hadley Cell in warming climate. Why? *(Question 1(c) may give you some hints.)* [5pt]

接次頁

4. Atmospheric circulation and momentum budget [20pt]
   (a) Calculate the zonal velocity of an air parcel at 30°N, if it has conserved angular momentum while moving to 30°N from 7°N, where it was initially at the rest relative to the surface. [8pt]
   (b) During El Nino years, the equatorial region tends to be warmer. Do you think zonal wind at 30°N would be stronger or weaker during El Nino years? Why? [7pt]
   (c) Assume everything else being the same, how would the anomalous subtropical jet during El Nino years affect the critical latitude (where phase speed c = background zonal wind u) of southward propagating Rossby waves and the associated precipitation. [5pt]

5. Terrestrial water/energy cycles [20pt]
   Dr. Manabe developed the 1st generation land surface model for the climate models in the 1960s, called the "bucket model". While it was simple, the bucket model concept can estimate the land surface water budget.

   (a) Please illustrate the concept of the bucket model and why Dr. Manabe developed this model in the 1960s? Why do we need more sophisticated models for land-surface processes? [10pt]

   Under global warming, the hydrological cycle may intensify, which may affect the resident time of the water vapor. Please answer the below questions.
   (b) Please calculate the resident time of the water vapor (you will need to make necessary and reasonable assumptions to solve it). [6pt]
   (c) How may the resident time of the water vapor change under a warmer climate? [4pt]

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