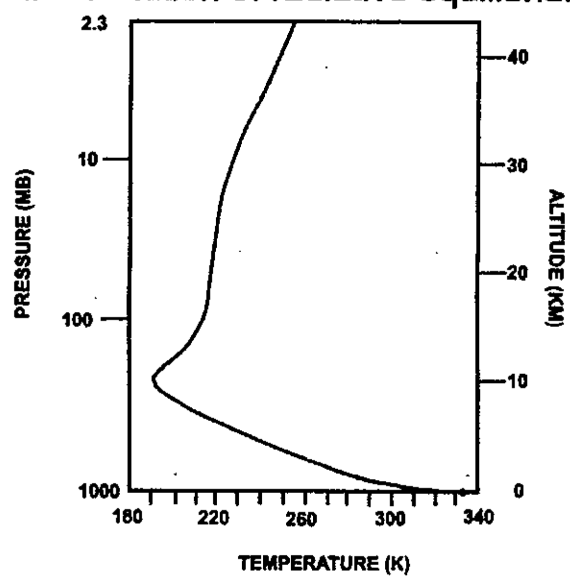
1. **The Earth's Energy budget (地球的能量收支)**
Let's consider the energy balance at the top of the atmosphere and calculate the emission temperature of the Earth.
(a) Assuming the solar constant is S, the Earth's planetary albedo is α, and the Earth is a blackbody. Please write down the energy balance at the top of the atmosphere. (4 pts)
(b) The solar luminosity is 3.9×10^{26} W. The mean distance between the Earth and the sun is 1.5×10^{11}m. Please calculate the solar constant, the energy flux density of the solar emission at the mean distance of Earth from the sun (the answer will be in W/m^2) (3 pts)
(c) Assume the Earth's planetary albedo α is 30%. Please calculate the emission temperature of the Earth (i.e., the blackbody emission temperature the Earth requires to balance the solar energy it absorbs). (3 pts)

2. **A simple radiative equilibrium model (簡化的輻射模型)**
In addition to the balance at the top of the atmosphere (or a 1-layer model), let's now consider the vertical structure.
Figure 1 (on the right) is a result from a radiative equilibrium model. It is a one-dimensional model (considering global mean) that accounts for all of the radiative processes to the best of our knowledge – the atmosphere is divided into many thin layers, allows for the presence of clouds, treats each wavelength separately, allows for atmospheric absorption layer-by-layer – which depends on the vertical distribution of absorbers (H_2O, CO_2, and O_3…). It also assumes radiation is the only process affecting temperature (there is no atmospheric motion).

Full calculation of radiative equilibrium:



(a) Please describe how temperature change with height below 10km. Please also describe factors and mechanisms determining the temperature in the troposphere in this radiative model. (5pts)
(b) Is the equilibrium surface temperature in the model higher or lower than the emission temperature calculated in question 1(c)? Why? (5 pts)
(c) Is the equilibrium surface temperature in the model higher or lower than the observed annual mean global mean surface temperature? Why? (5 pts)
(d) Please describe how increasing CO_2 would affect the equilibrium temperature profile in Figure 1 (please describe how surface temperature, the temperature in the troposphere, and the temperature in the stratosphere would change). Why? (Please explain your reasons in detail.) (10 pts).

3. **Changes in temperature and rainfall under a warmer climate (暖化下氣溫與降雨之變化)**

(a) Under anthropogenic climate changes, the atmospheric temperature changes variously as shown in panels (a) to (c) of Figure 2. Please illustrate what you see on those temperature changes in panels (a) to (c). (10 pts)

(b) The rainfall intensity changes under the warmer climate have the tendency of "wet-get-wetter and dry-get-drier", as shown in panel (d) of Figure 2. Please illustrate the potential physical mechanisms in such rainfall changes. (Note you can start from more water vapor in the atmosphere because of the warmer atmospheric temperature) (10 pts)

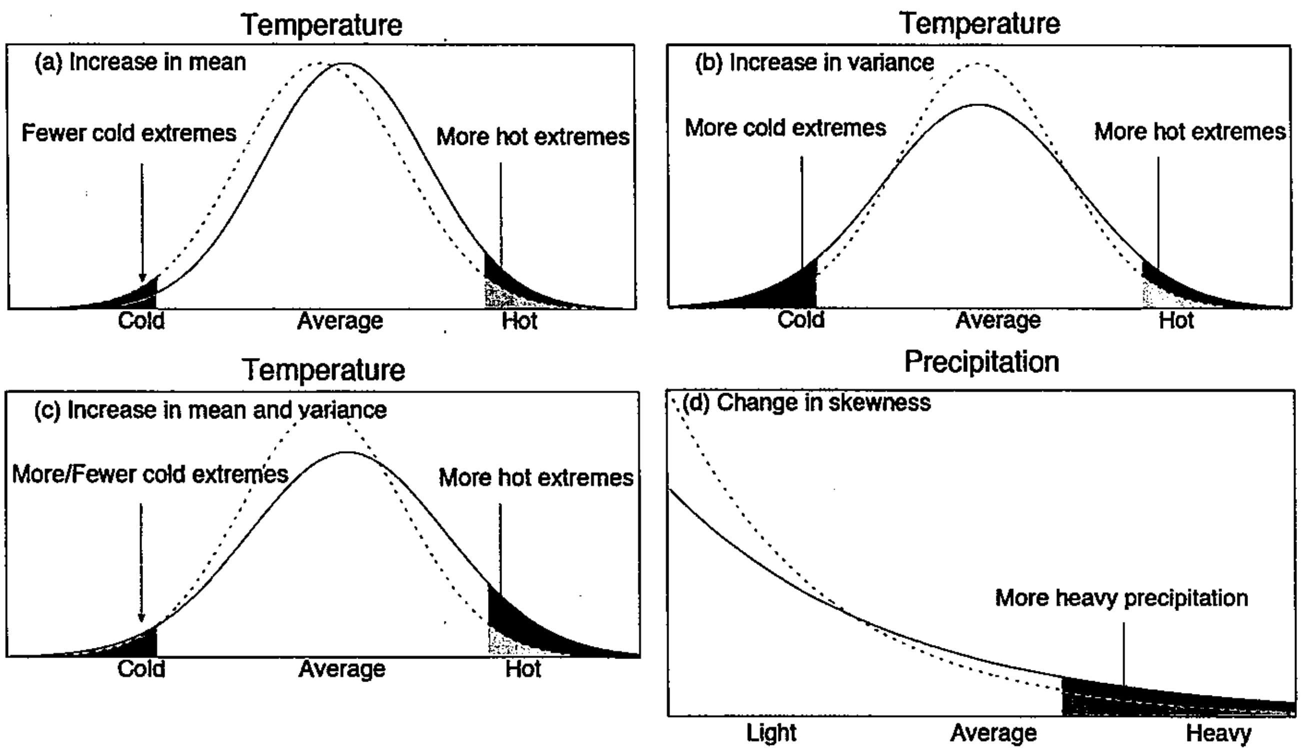


Figure 2. Taken from IPCC report, Figure 1.8, 134, Cubasch et al. [2013].

(c) More heatwaves were observed under warmer atmospheric temperature scenarios. In addition, the land use change may increase the probability of heatwave occurrences. Please illustrate how the land use changes affect the local land surface water and energy cycles as well as its impacts on the heatwave occurrences. (10 pts)

4. <u>The Jet Stream (西風噴流)</u>

The subtropical jet stream is a belt of strong upper-level westerlies at around 30 degrees (in the subtropics).

How is the subtropical jet maintained? (In other words, please describe the force/momentum balance of the subtropical jet or factors that can affect the strength of the subtropics jet.) (10 pts)

5. <u>Changes in monsoons in a warming climate (暖化下季風的改變)</u>

(a) Global climate models' projections of monsoon changes are highly uncertain. Please explain why it is challenging to predict changes in monsoon circulation. What factors and mechanisms may lead to the intensification of monsoon circulation in the future? And what factors and mechanisms may lead to the weakening of monsoons? (15 pts)

(Hint: You may find the paragraphs below Question(b) helpful, and it is okay to make a guess. Please use your own words when answering the questions.)

(b) Despite the uncertainty of changes in monsoon circulation's intensity, most global climate models project increasing monsoon rainfall in the future. Why? (10 pts)

The paragraphs below are quoted from the IPCC report. You may find them helpful for answering the questions above.

"Monsoons are the most important mode of seasonal climate variation in the tropics, and are responsible for a large fraction of the annual rainfall in many regions. Their strength and timing is related to atmospheric moisture content, land–sea temperature contrast, land cover and use, atmospheric aerosol loadings and other factors. Overall, monsoonal rainfall is projected to become more intense in future, and to affect larger areas, because atmospheric moisture content increases with temperature. However, the localized effects of climate change on regional monsoon strength and variability are complex and more uncertain. Monsoon rains fall over all tropical continents: Asia, Australia, the Americas and Africa. The monsoon circulation is driven by the difference in temperature between land and sea, which varies seasonally with the distribution of solar heating. The duration and amount of rainfall depends on the moisture content of the air, and on the configuration and strength of the atmospheric circulation. The regional distribution of land and ocean also plays a rôle, as does topography. For example, the Tibetan Plateau—through variations in its snow cover and surface heating—modulates the strength of the complex Asian monsoon systems. Where moist on-shore winds rise over mountains, as they do in southwest India, monsoon rainfall is intensified. On the lee side of such mountains, it lessens. Since the late 1970s, the East Asian summer monsoon has been weakening and not extending as far north as it used to in earlier times , as a result of changes in the atmospheric circulation. That in turn has led to increasing drought in northern China, but floods in the Yangtze River Valley farther south. In contrast, the Indo-Australian and Western Pacific monsoon systems show no coherent trends since the mid-20th century, but are strongly modulated by the El Niño-Southern Oscillation (ENSO). Similarly, changes observed in the South American monsoon system over the last few decades are strongly related to ENSO variability. Evidence of trends in the North American monsoon system is limited, but a tendency towards heavier rainfalls on the northern side of the main monsoon region has been observed. No systematic long-term trends have been observed in the behaviour of the Indian or the African monsoons. The land surface warms more rapidly than the ocean surface, so that surface temperature contrast is increasing in most regions. The tropical atmospheric overturning circulation, however, slows down on average as the climate warms due to energy balance constraints in the tropical atmosphere. These changes in the atmospheric circulation lead to regional changes in monsoon intensity, area and timing. There are a number of other effects as to how climate change can influence monsoons. Surface heating varies with the intensity of solar radiation absorption, which is itself affected by any land use changes that alter the reflectivity (albedo) of the land surface. Also, changing atmospheric aerosol loadings, such as air pollution, affect how much solar radiation reaches the ground, which can change the monsoon circulation by altering summer solar heating of the land surface. Absorption of solar radiation by aerosols, on the other hand, warms the atmosphere, changing the atmospheric heating distribution. The strongest effect of climate change on the monsoons is the increase in atmospheric moisture associated with warming of the atmosphere, resulting in an increase in total monsoon rainfall even if the strength of the monsoon circulation weakens or does not change. Climate model projections through the 21st century show an increase in total monsoon rainfall, largely due to increasing atmospheric moisture content. The total surface area affected by the monsoons is projected to increase, along with the general poleward expansion

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of the tropical regions. Climate models project from 5% to an approximately 15% increase of global monsoon rainfall depending on scenarios. Though total tropical monsoon rainfall increases, some areas will receive less monsoon rainfall, due to weakening tropical wind circulations. Monsoon onset dates are likely to be early or not to change much and the monsoon retreat dates are likely to delay, resulting in lengthening of the monsoon season. Future regional trends in monsoon intensity and timing remain uncertain in many parts of the world. Year-to-year variations in the monsoons in many tropical regions are affected by ENSO. How ENSO will change in future—and how its effects on monsoon will change—also remain uncertain. However, the projected overall increase in monsoon rainfall indicates a corresponding increase in the risk of extreme rain events in most regions."

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