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Solution to Problem #4

(10 pts)

Balanced Energy Budget:
The Earth's Average Surface Temperature without Greenhouse Gases

Consider **Figure 3.31** in Lab Activity #5: "Long-Term Average Heat Budgets for the Earth's Atmosphere and Surface", which shows a complete, long-term, global average energy budget diagram for the earth's atmosphere and surface. Suppose that all gases that absorb terrestrial radiation (notably water vapor and carbon dioxide, but other, less important ones, too, such as ozone) were removed from the atmosphere. Removing water vapor would also mean that no clouds could be present, either, which would reduce the atmosphere's (and hence the earth's) albedo. There would be other changes as well, such as less absorption of solar radiation in the atmosphere.

(a) Estimate the size of the various terms in the heat budgets for the atmosphere and the earth's surface under these conditions, assuming that the budgets balance. (You can simply list them by name with their new values, or you can sketch a budget diagram and label them on the diagram.) *For each term, explain your reasoning*.

To keep things simpler, make the following assumptions:

i. ignore the sensible heat flux from the surface into the atmosphere (for reasons that I can explain in person if you want, though you might figure it out yourself!);
ii. the albedo of the earth's surface that you estimated in Question 2(c) in Lab Activity #5 remains the same for the surface; and
iii. since there is no water vapor (or clouds) in the revised atmosphere, ignore the latent heat flux from the surface into the atmosphere (due to evaporation and sublimation).

<u>Revised Budget Terms</u> (see figure at the end of this document)

Solar Radiation

<u>Atmosphere</u>

•*Absorption of solar radiation by "air" ≅ 0.* Solar absorption is normally due to ozone (absorbing ultraviolet radiation) and, secondarily, water vapor (absorbing near-infrared radiation), with minor contributions from carbon dioxide and other greenhouse gases. In contrast, nitrogen, oxygen, and argon don't absorb significant amounts of solar radiation. (See Question #1(a) in Lab Activity #5: Long-Term Average Heat Budgets for the Earth's Atmosphere and Surface.)

Ultraviolet radiation constitutes about 10% of all solar radiation, and almost all of that is absorbed in the atmosphere (mostly by ozone) before reaching the surface. This constitutes the majority of the 16 units (normalized) of solar energy absorbed by the atmosphere. (Most of the rest is near-IR radiation absorbed mostly by water vapor.)

Hence, removing greenhouse gases eliminates virtually all of the absorption of solar radiation by "air".

•*Absorption of solar radiation by clouds = 0.* Removing water vapor removes the source of water to make clouds, so clouds will be absent and won't absorb any solar radiation.

Hence, without greenhouse gases and clouds, *the atmosphere would absorb essentially no solar radiation*!

<u>Surface</u>

•The solar radiation normally absorbed by "air" and by clouds (16 + 4 = 20 normalized units total) will now reach the surface, as will solar radiation normally reflected back to space by clouds (20 units), for a total of 40 units.

Removing greenhouse gases removes only about 1% of all air molecules (water vapor constitutes only about 1% of all air molecules, on the average, and the other greenhouse gases represent much smaller concentrations than that). What's left are nitrogen, oxygen, and argon, which constitute about 99% of all air molecules. Hence, air will continue to scatter and reflect about 6 units of solar radiation back to space.

In summary, in addition to the 54 units of solar radiation that reach the surface today, 40 more units of solar energy will reach the surface in the absence of greenhouse gases and clouds, for a total of 54 + 40 = 94 units.

The surface doesn't absorb all 94 units of solar radiation reaching it, though, because it reflects part of it back to space. The albedo of the surface, according to our calculations in Question #2(c) in Lab Activity #5, is 4/54 = 0.074 (or 7.4%). Hence, the surface will reflect 0.074 × 94 units = 7 units of solar radiation back to space and absorb the rest:

Absorption of solar radiation by the earth's surface = 94 units arriving – 7 units reflected = 87 units.

This is considerably more than what the surface absorbs today (50 units).

<u>Planet as a Whole</u>

Without greenhouse gases and clouds, the atmosphere absorbs virtually no solar radiation, while the surface absorbs 87 units. Hence, the planet as a whole absorbs 87 units and reflects the other 6 units (by air) + 7 units (by the surface) = 13 units back to space.

(Compare this to today's figures, of 70 units of absorption and 30 units of reflection back to space.)

Latent and Sensible Heat Fluxes

<u>Atmosphere</u>

- *Latent heat flux into the atmosphere = 0.* We are not allowing water vapor to exist in the atmosphere, so we won't allow evaporation from the earth's surface, which adds water vapor to the atmosphere. Hence, no condensation of water vapor to form clouds will occur, and hence no transformation of latent heat into heat in the atmosphere.
- *Sensible heat flux from the surface into the atmosphere = 0.* We are told to ignore this, with enlightenment coming to those who ask. (But see Pages 4 and 5.)

<u>Surface</u>

- *Latent heat flux out of the surface = 0.* We are not allowing water vapor to exist in the atmosphere, so we won't allow evaporation from the earth's surface, which means no conversion of sensible heat in the surface into latent heat in water vapor in the atmosphere.
- *Sensible heat flux out of the surface and into the atmosphere = 0.* We are told to ignore this, with enlightenment coming to those who ask. (But see Pages 4 and 5.)

Longwave Infrared (LWIR) Radiation

<u>Atmosphere</u>

•*Absorption of LWIR radiation = 0*. All of the LWIR radiation emitted by the surface that is absorbed in the atmosphere is absorbed by greenhouse gases and clouds. (Nitrogen, oxygen, and argon don't absorb LWIR radiation.) Hence, removing greenhouse gases and clouds means that no LWIR radiation emitted by the surface will be absorbed by the atmosphere, and all of it will escape to space.

•*Emission of LWIR radiation = 0*. A basic law of radiation (Kirchoff's Law) says that an object that absorbs any particular wavelength of radiation is capable of emitting it, too (with intensity that depends on the object's temperature). However, an object that doesn't absorb any particular wavelength can't emit it. Hence, removing all greenhouse gases and clouds removes everything capable of absorbing LWIR and hence everything capable of emitting it. (See Lab Activity #5, Question #5(c).)

<u>Surface</u>

•*Absorption of LWIR radiation emitted by the atmosphere = 0*. This is because, in the absence of greenhouse gases and clouds, the atmosphere lacks anything capable of emitting LWIR radiation.

•*Emission of LWIR radiation = 87 units*. In this exercise, we are trying to determine the sources and sinks of heat for each part of the planet (surface and atmosphere) under a balanced budget scenario in the absence of greenhouse gases and clouds. According to our reasoning and some assumptions made for us, the surface has only one source of heat, absorption of solar radiation (87 units), and it has no sinks other than emission of LWIR radiation. Hence, the surface must emit 87 units of LWIR radiation for its budget to be balanced.

In sum, we see that without greenhouse gases or clouds, the only source or sink of heat for the atmosphere left is the sensible heat flux from the surface. If the atmosphere's heat budget is to be balanced, then this, too must be zero (see Page 5).

The surface gains 87 units by absorption of solar radiation and loses 87 units by emission of LWIR radiation, balancing its budget.

The planet as a whole gains 87 units by absorption of solar radiation (all of it by the surface) and loses 87 units by emission of LWIR radiation (all of it by the surface; all of it escapes directly to space because the atmosphere absorbs none of it). Compare this figure to today's, in which the planet as a whole gains 70 units by absorption of solar radiation and loses 70 units by emission of LWIR radiation, mostly from greenhouse gases and clouds in the atmosphere.

[Suppose we didn't ignore sensible heat flux (that is, conduction) from the surface into the bottom of the atmosphere, which today is 6 units (normalized). In that case, the surface would have to emit only 81 units of LWIR radiation to balance its budget. However, the atmosphere lacks a sink to balance any heat gained by conduction, so its temperature would have to increase. Its temperature would continue to increase until the temperature at the bottom of the atmosphere equaled the earth's surface temperature, at which point conduction would stop (because conduction requires direct contact between two objects or materials at *different* temperatures; heat won't conduct between two objects at the *same* temperature). At that point the atmosphere's heat budget would balance, with no source or sinks, and the surface would have to lose heat (87 units to balance its budget) solely by emission of LWIR radiation to balance its budget. This is the reason why we can neglect sensible heat flux in the first place!]

(b) Based on your revised budget in **(a)**, use the global, long-term average radiative emission flux from the surface to estimate the corresponding effective radiating temperature of the surface. (You'll need to invoke the Stefan-Boltzmann relation. Be sure to convert the emission flux from a percentage figure into an actual energy flux, assuming that the global, long-term average insolation on at the top of the atmosphere is 341.3 W/m^2, calculated using My World's incoming solar radiation data for 1987).

(c) Based on your revised budget in Question (a), what is the effective radiating temperature of the planet as a whole? If it is different from today's value (based on **Figure 3.31** in Lab Activity #5), explain why.

(d) Compare your answer to Question (b) above to today's global, long-term average surface temperature (which is about 288K, or about 15°C, or about 59°F). Based on the Stefan-Boltzmann Law, the assumption of a balanced budget, and the main terms in the budget for the earth's surface with and without greenhouse gases (and clouds), what, at root, accounts for the difference?

Answers:

The budget terms in **Figure 3.31** of Lab Activity #5 are normalized by the long-term, global average insolation at the top of the atmosphere and converted into a percentage by multiplying by 100. If we assume that the long-term, global average insolation at the top of the atmosphere is 341.3 W/m^2, then we can determine the actual fluxes in the revised budget simply by multiplying the normalized fluxes by 341.3 W/m^2 and dividing by 100. Since the LWIR radiative emission flux from the earth's surface without greenhouse gases or clouds would be 87 units (normalized), the actual flux would be 87 units × 341.3 W/m^2/100 = 0.87 × 341.3 W/m^2 = 297.0 W/m^2.

The Stefan-Boltzmann relation says that $E(T) = \sigma T^4$, where $E(T)$ is the emission flux (a function of absolute temperature, T) and σ is the Stefan-Boltzmann constant, a constant of proportionality. Solving this for T gives: $T = \sqrt[1/4]{\frac{E(T)}{\sigma}}$. The Stefan-Boltzmann constant in metric units has a value of 5.67×10^{-8} $(W/m^2)/K^4$, the emission flux we know from above (297.0 W/m^2). Hence, the absolute temperature of the earth's surface (treated as a blackbody, which it effectively is in the LWIR part of the spectrum) would have to be:

$$T = \sqrt[1/4]{\frac{297.0\, W/m^2}{5.67\times10^{-8}\left(W/m^2\right)/K^4}}$$

$$= \sqrt[1/4]{52.4\times10^{8} K^4}$$

$$= 2.690\times10^{2} K = 269.0 K = -4°C = 24.5°F$$

This is about 19 $°C$ (34 $°F$) colder than today's global, long-term average surface temperature of about 15 $°C$ (59 $°F$). Hence, even though the surface would be absorbing quite a bit more solar radiation than it does today, and would no longer be losing heat by conduction or evaporation, the atmosphere would no longer absorb either solar radiation or LWIR radiation emitted by the surface and, more to the point, would no longer emit LWIR radiation, so the surface would no longer absorb any LWIR radiation emitted downward by the atmosphere. The loss of this large source for the surface more than makes up for the increased absorption of solar radiation at the surface and the absence of heat losses by conduction and evaporation from the surface. As a result, the surface would have to be quite a bit colder than it is today for radiative emission to balance the only remaining source, solar absorption.

Note, too, that this temperature is the same one that the planet as a whole would have to have, since all of the planet's radiative emissions would come from the surface. This temperature is actually about $14°C$ ($25°F$) *warmer* than today's effective radiating temperature of the planet! This is because the planet without clouds absorbs more solar radiation (its only source of heat, for all practical purposes) than it does with clouds present, which requires that the planet (in this case, just the surface) emit more radiation if its budget is to balance, which requires that it be warmer overall (according to the Stefan-Boltzmann relation) because radiative emission is the only way for the planet to lose heat.

That is, without greenhouse gases and clouds, the effective radiative temperature of the planet as a whole would be warmer than it is today, but the surface (and the lower atmosphere) would be colder than it is today.

Estimated Long-Term, Global Energy Budget without Greenhouse Gases and Clouds

(Based on Figure 3.31 of Lab Activity #5: Long-Term Average Heat Budgets for the Earth's Atmosphere and Surface)