Comments on "The Greenhouse Effect"

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Lee (1973) suggests that the so-called greenhouse effect for a real greenhouse is not primarily a result of the radiation imbalance caused by the spectral absorptivity of the glass but rather the difference in the convective losses for the glass-enclosed space. The purpose of these comments is to indicate a possible error in Lee's analysis and to show that the radiation greenhouse effect is indeed a result of the spectral properties of the glass.

Using the same assumptions as Lee, namely an opaque ground surface with zero reflectivity, unit shortwave absorptivity and unit longwave emissivity, and glass with a shortwave transmissivity t and unit longwave absorptivity, we concur with Lee's Eqs. (1) and (2) which are as follows:

$$R_n = R + \alpha T_a^6 - \sigma T_s^4, \tag{1}$$

$$R_{nu} = tR + \sigma T_g^4 - \sigma T_{su}^4, \tag{2}$$

where

- R_n net flux of radiant energy entering the ground outside the greenhouse
- R_{nu} net flux of radiant energy entering the ground inside the greenhouse
- R incident shortwave flux
- α $[=7.61\times10^{-16}$ ly min^{-1} (°K)$^{-6}]$
- σ $[=0.817\times10^{-10}$ ly min^{-1} (°K)$^{-4}]$
- T_a screen temperature under clear skies
- T_g glass temperature
- T_s ground temperature outside the greenhouse
- T_{su} ground temperature inside the greenhouse.

Lee then calculates the difference $R_{nu}-R_n$ as a measure of the greenhouse effect. This appears to be in error, however, as the proper theoretical measure of the greenhouse effect is under equilibrium conditions where both R_{nu} and R_n, and therefore their difference, are identically zero.

We propose to measure the greenhouse effect by the difference $T_{su}-T_s$ under radiative equilibrium. To complete the set of equations we need the radiation balance equation for the glass

$$R_{ng} = (1-t)R + \alpha T_a^6 + \sigma T_{su}^4 - 2\sigma T_g^4, \tag{3}$$

where R_{ng} is the flux of radiant energy entering the glass.

Because it is not central to the main issue in either Lee's or this analysis, we assume for simplicity that the reflectivity of the glass is the same as that assumed by Lee for the ground, namely zero.

Assuming, first, a vacuum, we set $R_n = R_{nu} = R_{ng} = 0$ for equilibrium and subtract (3) from (1) to get

$$0 = tR - \sigma T_s^4 - \sigma T_{su}^4 + 2\sigma T_g^4, \tag{4}$$

and (4) from (2) to get

$$0 = -\sigma T_g^4 + \sigma T_s^4, \tag{5}$$

from which we conclude

$$T_g = T_s. \tag{6}$$

This is to be expected under the stated assumptions since the sky sees both the ground and the glass as an opaque surface where radiation balance must be satisfied independently of the physical processes taking place below the glass.

We now add (5) to (2) to get

$$\sigma T_{su}^4 = \sigma T_s^4 + tR, \tag{7}$$

where we see that the greenhouse effect raises the temperature T_{su} of the ground in the greenhouse above the temperature T_s of the ground outside the greenhouse according to the amount of shortwave radiation transmitted by the glass. Beginning with Lee's numbers, $T_a=300\text{K}$, $R=1.00$ and 1.20 ly min^{-1}, we can evaluate the greenhouse effect. For the better perspective we solve here also for the case $R=0$.

First, from (1) and (6) we find

$$T_s=T_g=288\text{K, for } R=0, \quad (8a)$$
$$=372\text{K, for } R=1.0, \quad (8b)$$
$$=384\text{K, for } R=1.2. \quad (8c)$$

Second, from (7) we have

$$T_{su}=288\text{K, for } R=0, \quad (9a)$$
$$=416\text{K, for } R=1.0, \quad (9b)$$
$$=433\text{K, for } R=1.2. \quad (9c)$$

Thus,

$$T_{su}-T_s=0\text{K, for } R=0, \quad (10a)$$
$$=44\text{K, for } R=1.0, \quad (10b)$$
$$=49\text{K, for } R=1.2. \quad (10c)$$

We see that the glass indeed causes a rise in the temperature of the ground below it and that this temperature rise is clearly important. Furthermore, the temperature differences (10) are increasingly positive as the temperatures [(8) and (9)] rise (contrary to the conclusion of Lee). This, of course, follows directly from (1), (2) and (7) which show T_s, T_{su} and $T_{su}-T_s$ increasing with R. Also, except for the case $R=0$, the above evaluations indicate that $T_{su}-T_s$ is less than T_g-T_a, again contradicting the expectation of Lee.

Were the glass not transmissible to shortwave radiation then t would be zero and $T_{su}=T_s$ according to (7), and there would be no greenhouse effect.

Convective heat losses would only serve as an additional heat leak in the basic equilibrium equations; thus they cannot affect the direction of the above result but would reduce the calculated temperature differences. Such convection would not obviate the greenhouse effect as the source of the equilibrium temperature T_{su} or as the driving force of the convection.

Since $T_s=T_g$, the ratio of convective losses as considered by Lee above the ground and above the greenhouse is unity. Therefore, T_s will still equal T_g even in the presence of convection (again, assuming similar surface characteristics). But the greenhouse effect concerns what happens at T_{su}. The relationship of T_{su} to the convective trap imposed by the glass is only that this convective trap allows T_{su} to rise higher than the normal limit of atmospheric stability would allow if the glass did not restrict the air motion.

If we rewrite Eqs. (1), (2) and (3) as the net *heat* input (Q_n, Q_{nu}, Q_{ng}) by adding to R_n, R_{nu}, R_{ng}, the convective heat losses of $-A(T_s-T_a)$, $-B(T_{su}-T_g)$ where A and B are convective parameters in the atmosphere and greenhouse, respectively, and $A>B$, the result is the following replacements for (1), (2), (3), (4), (5), (6) and (7):

$$Q_n=R+\alpha T_a^6-\sigma T_s^4-A(T_s-T_a), \quad (1)^*$$

$$Q_{nu}=tR+\sigma T_g^4-\sigma T_{su}^4-B(T_{su}-T_g), \quad (2)^*$$

$$Q_{ng}=(1-t)R+\alpha T_a^6+\sigma T_{su}^4-2\sigma T_g^4 -A(T_g-T_a)+B(T_{su}-T_g), \quad (3)^*$$

$$0=tR-\sigma T_s^4-\sigma T_{su}^4+2\sigma T_g^4 -A(T_s-T_g)-B(T_{su}-T_g), \quad (4)^*$$

$$0=-\sigma T_g^4+\sigma T_s^4+A(T_s-T_g), \quad (5)^*$$

$$T_g=T_s, \quad (6)^*$$

$$\sigma T_{su}^4=\sigma T_s^4+tR-B(T_{su}-T_g), \quad (7)^*$$

where, in parallel with the arguments above, we assume that all surfaces are at their equilibrium temperatures, i.e., $Q_n=Q_{nu}=Q_{ng}=0$. Thus, (6)* in unchanged and and (7)* shows that T_{su} is decreased by convective losses to the glass but still remains greater than T_s and T_g.

The proper way to evaluate the effect of the convective restrictions imposed by the glass is to assume a second greenhouse where the glass does not restrict the air motions. This is equivalent to replacing B by A in the discussion above. When this is done we see that T_g in (6)* will still be equal to T_s but that T_{su} in (7)* will be decreased according to the greater convective parameter A. Owing to the fact that T_s is still equal to T_g, T_{su} must still be greater than T_s and T_g. The convective loss ratio $(T_s-T_a)/(T_g-T_a)$ used by Lee to explain the elevated temperature in the greenhouse is unity and thus provides no explanation at all.

A more complete evaluation of the effect of the glass on restricting convection would require an evaluation of A and B which is beyond the scope of these comments. Suffice it to say that the spectral properties of the glass over a greenhouse are indeed the cause of significant heat storage below the glass, clearly caused by the radiational trapping properties of the glass. The dissipation of this heat is hindered by the restriction the glass imposes on convective losses to the atmosphere. Although it is observed that there is warming at T_{su} due to convective trapping by a cover that has negligible radiation trapping properties, Lee's theoretical analysis does not appear to be adequate to explain this effect.

REFERENCE

Lee, R., 1973: The "greenhouse" effect. *J. Appl. Meteor.*, **12**, 556–557.