GEOPHYSICA NORVEGICA . VOL. 31 . NO. 3 . PAGES 1-5 . 1976
UNIVERSITETSFORLAGET

Geophysica Norvegica

GEOFYSISKE PUBLIKASJONE

INGOLF KANESTRØM

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VOL. 31 NO. 3 . 1976
UNIVERSITETSFORLAGET

Geophysica Norvegica

is a journal of geophysics, issued under the auspices of the Norwegian Academy of Science and Letters

PUBLISHER

Universitetsforlaget: P. O. Box 7508, Skillebekk, Oslo 2, Norway
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CO_2: Greenhouse or atmospheric effect

INGOLF KANESTRØM
Institute of Geophysics, University of Oslo

Kanestrøm, I. CO_2: Greenhouse or atmospheric effect. *Geophysica Norvegica*, Vol. 31, No. 3, 1976.

The heating in a greenhouse is studied in a theoretical model with two different house covers: (1) the greenhouse is made of glass that absorbs the longwave radiation; (2) the cover consists of a substance (for instance rock salt) transparent to longwave radiation. Also the turbulent transport of sensible heat is taken into account. With the assumptions made, the model shows that the ratio between the surface temperature inside these houses depends strongly on the shortwave radiation and the strength of the turbulent heat transfer (given by the Nusselt and Rayleigh numbers).

I. Kanestrøm, Institute of Geophysics, University of Oslo, P.O. Box 1022, Blindern, Oslo 3, Norway

1. INTRODUCTION

In several articles (Fleagle and Businger (1963), Lee (1973), Businger (1975)) it is claimed that the so-called radiation 'greenhouse' effect is a misnomer. While the concept is useful in describing what occurs in the earth's atmosphere, it is invalid for cryptoclimates created when a space is enclosed with glass, e.g. in greenhouse and solar energy collectors. Specifically, elevated temperatures observed under glass cannot be traced to spectral absorptivity of glass.

The experiment carried out by Wood in 1909 is quoted as a proof (Wood (1909)). Wood performed the experiment with two small model greenhouses, of which one was covered with glass and the other with rock salt. Rock salt is transparent for both short- and long-wave radiation and therefore does not 'trap' the radiation. Both greenhouse models reached about the same high temperatures. Consequently, the effectiveness of greenhouse in growing plants should not be a result of absorption of longwave radiation by glass. Greenhouses reach much higher temperatures than the surrounding air because the glass cover of the greenhouse prevents the warm air from rising and removing heat from the greenhouse. This effect, Fleagle and Businger claim, is four to five times as important as the absorption of longwave radiation by glass.

2. MODELS

Lee (1973) gives the equation for the net flux of radiation energy R_n (in ly min^{-1}) at the surface. At steady conditions we have

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

where R is the incident shortwave flux and $C_a = 7.61 \times 10^{-16}$ ly min^{-1} K^{-6}. The second term on the right side is the Swinbank estimate of longwave radiation at the surface under clear skies at screen temperature T_a (Swinbank (1963)). Finally σT_s^4 is the emitted longwave flux from the surface at temperature T_s.

Under a glass cover with shortwave transmissivity t and with unit absorptivity to longwave radiation, the net flux at surface is given by

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

where T_g is the glass temperature and T_{sg} the surface temperature.

According to Lee (1973) the difference,

$$R_{ng} - R_n = (t-1)R + [\sigma T_g^4 - C_a T_a^6] + \sigma[T_s^4 - T_{sg}^4], \tag{3}$$

is the effect of the glass, i.e. the radiation 'greenhouse' effect. However, in the case of radiation

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This paper was submitted to the Norwegian Academy of Science and Letters, 10th September 1976.

equilibrium, these differences will always be equal to zero. Eq. (3) can therefore not generally be taken as a measure of the greenhouse effect.

In this paper, Lee (1973) gives an expression for the change in net radiation caused by temperature differences

$$\Delta(R_{\mathrm{ng}}-R_{\mathrm{n}}) = 0.01(T_{\mathrm{g}}-T_{\mathrm{a}}+T_{\mathrm{s}}-T_{\mathrm{sg}}), \quad (4)$$

with unit (ly min^{-1} K^{-1}). Since $T_{\mathrm{sg}}-T_{\mathrm{s}}$ can be expected to exceed $T_{\mathrm{g}}-T_{\mathrm{a}}$, the radiation 'greenhouse' effect becomes increasingly negative, Lee claims. However, a negative change in the net radiation does not necessarily mean that the radiation 'greenhouse' effect becomes negative, but it is obvious that the net radiation will become less than zero if the surface radiation by any means increases far enough.

We have performed some simple calculations based on two different assumptions: (1) the glass absorbs all longwave radiation and transmits 90% of the shortwave radiation, (2) the glass transmits all thermal radiation and 90% of the shortwave radiation.

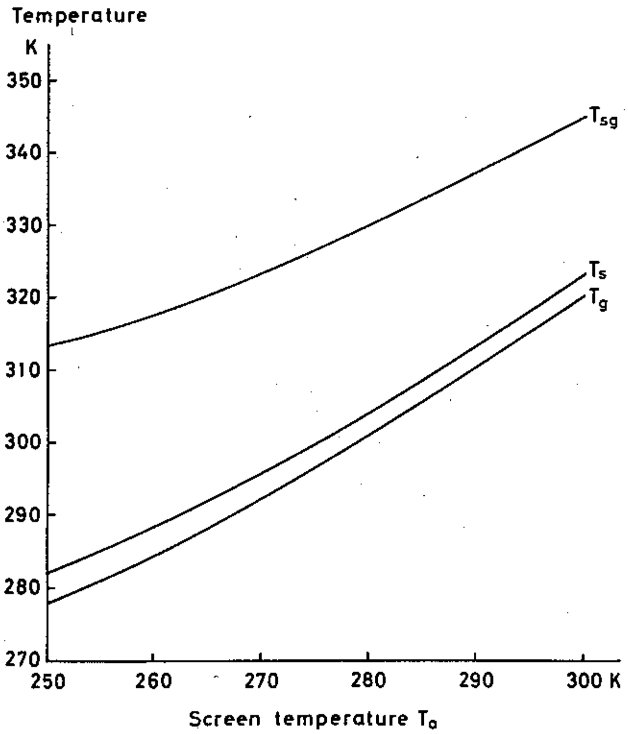

Fig. 1. Calculated surface temperature T_{s} outside and T_{sg} inside the greenhouse and the glass temperature T_{g} as function of the atmospheric temperature T_{a}.

The simplest assumption to make is radiation equilibrium, i.e. no non-radiation heat transport. In this case the surface temperature with and without greenhouse can easily be calculated as a function of the longwave atmospheric radiation at the surface, given by the clear sky screen temperature T_{a}. The results obtained for a shortwave radiation flux, equal to 230 Wm^{-2} (the average insolation over the earth's surface), are given in Fig. 1. As seen, the greenhouse effect decreases as the atmospheric temperature or longwave atmospheric radiation increases. This reflects the fact that the surface radiation increases faster than the black body radiation from the glass. However, using Lee's formula, we find that

$$\Delta(R_{\mathrm{ng}}-R_{\mathrm{n}}) = 0.01(T_{\mathrm{g}}-T_{\mathrm{a}}+T_{\mathrm{s}}-T_{\mathrm{sg}})>0, \quad (5)$$

reflecting the inaccuracy of his formula.

As seen from Fig. 1, the temperature differences between the surface and the glass, surface and atmosphere, and glass and atmosphere, are large. Therefore, the lower airlayer is unstable, and turbulent heat transfer will take place. Consequently, the performed calculations are unrealistic.

To look further into the problem, we shall perform calculations where the turbulent heat transfer is taken into account. As our knowledge of turbulent heat transfer is still incomplete, the heat transport will be included in a very simple manner.

Inside the greenhouse, experimental results on the heat transfer in various liquids will be used (Chandrasekhar 1961). From such experiments the Nusselt number

$$Nu = Q/(k\Delta T/d), \quad (6)$$

is plotted against the Rayleigh number

$$Ra = g\alpha\Delta t d^3/(H\nu), \quad (7)$$

where Q is the heat transfer through the layer, k the coefficient of heat conduction, g the acceleration due to gravity, α, H, and ν the coefficients of volume expansion, thermometric conductivity, and kinematic viscosity, respectively. The quantity ΔT is the temperature difference over the layer with depth d. Chandrasekhar (1961) has given the experimental results for Rayleigh number in the interval 10^2 to 10^7. By extrapolating the results to Rayleigh number of order 10^{10}, the heat transfer can be computed as a function of the temperature difference between the surface and the glass.

This method is inadequate outside the house, and the heat transfer is difficult to compute without performing a minute calculation of the temperature profile. Assuming that the process of turbulent diffusion is similar to that of molecular diffusion, the formula obtained for the vertical turbulent heat flux in the airlayer near the ground is

$$Q = -\varrho c_p k_1 \frac{\partial \theta}{\partial z}, \tag{8}$$

where ϱ is the air density, c_p the heat capacity, k_1 the coefficient of turbulent exchange, and $\partial\theta/\partial z$ the vertical temperature gradient. From this equation Budyko (1958) derived

$$Q = 0.0085 \varrho c_p \Delta T \Delta u \left\{1 + a \frac{\Delta T}{(\Delta u)^2}\right], \tag{9}$$

where $a = 0.059\ \mathrm{m^2\ s^{-2}\ K^{-1}}$, and ΔT and Δu are the differences in temperature and wind speed between the surface and the upper boundary of the air layer considered.

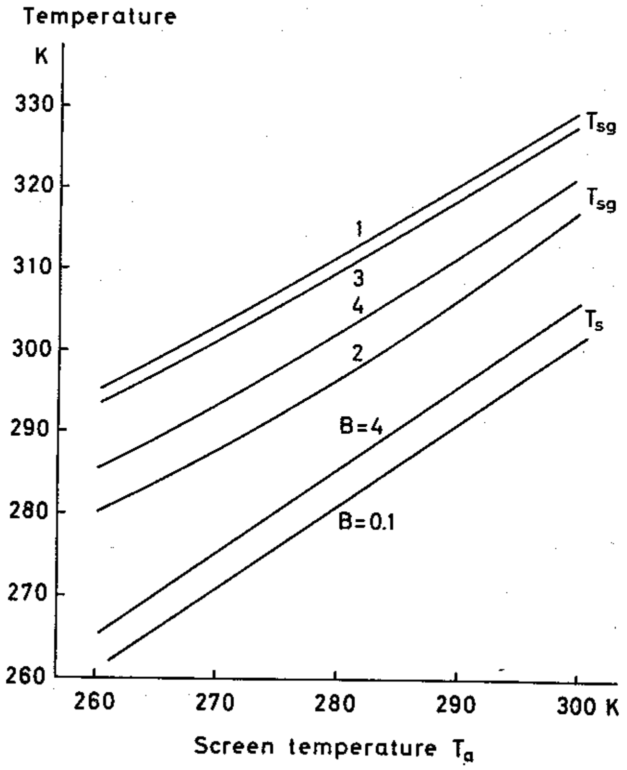

Fig. 2. Calculated temperatures as function of the atmospheric temperature. The surface temperature outside the greenhouse is given for two values of the Bowen ratio, $B = 0.1$ and $B = 4.0$. Curve 1: all longwave radiation absorbed by the glass. Curve 2: all longwave radiation transmitted. Curve 3: the glass is transparent for the turbulent heat flux. Curve 4: the glas absorbs and emits radiation as a grey body with half the intensity of a black body.

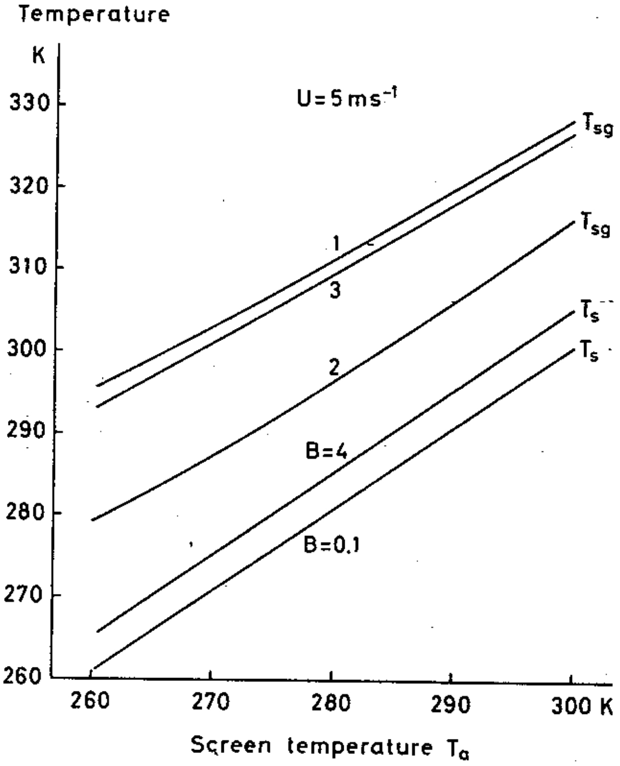

Fig. 3. The same as Fig. 2, using eq. (11) instead of eq. (10) for the sensible heat transfer.

Investigations of the relationship between vertical gradient of temperature and wind speed show that for moderate wind speeds, at superadiabatic temperature gradients, the values of the turbulent heat flux change only slightly with the change in wind speed. From experiments, one can obtain an approximate equation for turbulent sensible heat exchange

$$Q = \text{const.} \times (\Delta T)^{1.2} \tag{10}$$

The calculation is performed for a value of the constant equal to $11.2\ \mathrm{Wm^{-2}\ K^{-1.2}}$. In order to calculate the equilibrium surface temperature outside the house, the transport of both latent and sensible heat has to be considered. This is done by using different values of the Bowen ratio.

At steady state conditions, an attempt to solve the heat equation with the Newton–Ralphson method was performed. However, the method failed, and therefore the set of equations was solved by tabulating the functions with the temperatures as variable parameters. The results are shown in Fig. 2. The surface temperature outside the house is calculated for two different values of the Bowen ratio. As seen, the non-radiation heat transfer is very important, and it reduces the surface temperature outside the house by about 15 °C. The surface temperature within the house is calculated with a different assumption. Curve 1 shows the temperature obtained if all longwave radiations were absorbed by the glass, curve 2 if all longwave radiations were transmitted. Curve 3 shows the unphysical situation that the turbulent heat transfer inside the house is determined by the temperature difference between the surface and the glass, but the heat is not stopped by the glass. Curve 4 shows the temperature when the glass absorbs and emits radiation as a grey body with $\sigma' = 0.5\sigma$. These simple calculations indicate that the trapping of the longwave radiation by the glass has an important effect on the greenhouse temperature.

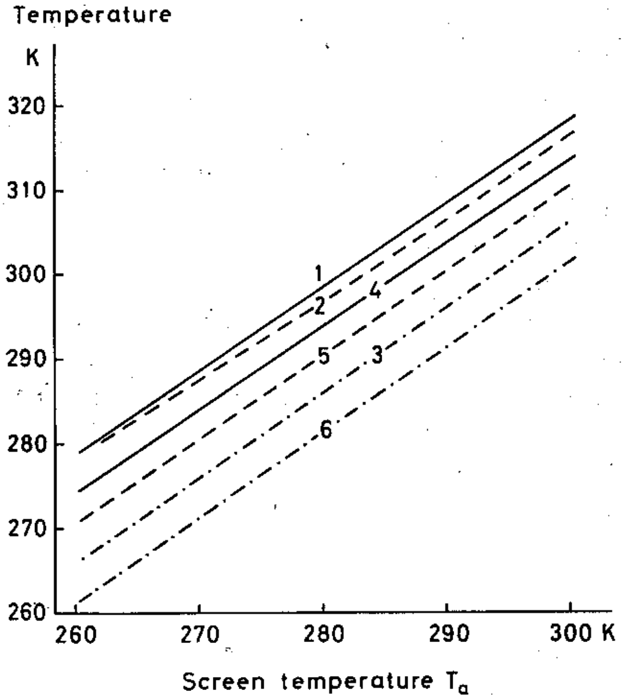

Fig. 4. Calculated temperatures as function of the atmospheric temperature, with shortwave insolation equal to 230 $\mathrm{Wm^{-2}}$. Curve 1 and 2 show the surface temperatures inside the house with absorption and nonabsorption of the longwave radiation by the glass, and curve 3 the surface temperature outside the house with a Bowen ratio equal to 4.0, all with enhanced turbulent heat transfer by a factor 10 inside the house. The corresponding temperatures when the turbulent heat transfer outside the house also is increased by a factor 10, are given by curves 4, 5, and 6.

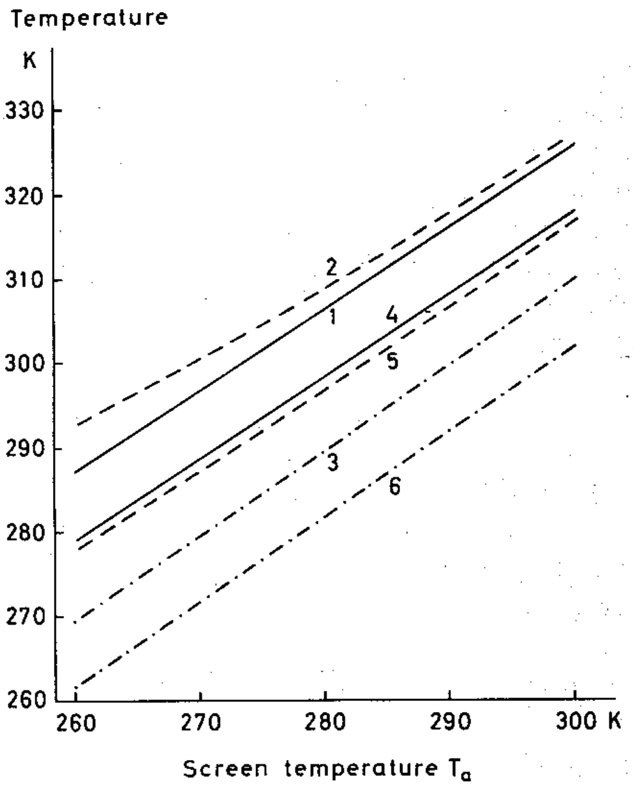

Fig. 5. The same as Fig. 4 with shortwave insolation equal to 345 $\mathrm{Wm^{-2}}$.

Similar calculations are also carried out using a sensible heat transfer, proportional to the surface wind speed u (Haltiner 1971, Priestley 1959)

$$Q = \varrho C_D u \Delta T_1 \qquad (11)$$

where C_D is the drag coefficient taken equal to 2.5 $\mathrm{m^2\,s^{-2}\,K^{-1}}$. The results for $u = 5\ \mathrm{ms^{-1}}$ are shown in Fig. 3. As seen, the result is about the same as for the sensible heat transfer, calculated from the Budykos formula. Calculations also show that the greenhouse temperature is nearly independent of the wind speed in the range 5–15 $\mathrm{ms^{-1}}$, while the surface temperature outside the house decreases with increasing wind speed.

3. DISCUSSION

The results presented so far indicate that the effect of trapping the longwave radiation in the glass is important for the greenhouse temperature. Glass, transparent to longwave radiation, will also originate an increase in the temperature, but only about one half of the first one.

The thermal conductivity of glass used in our calculation is 1.05 $Wm^{-1} K^{-1}$. If the thermal conductivity of the glass transparent to longwave radiation is considerably greater, the greenhouse temperature will be higher than the calculated one. However, the thermal conductivity of a NaCl crystal is one order of magnitude higher than for glass, and cannot explain the discrepancy between calculated and observed temperature.

As mentioned in section 2, our knowledge of turbulent heat transfer is still incomplete. Therefore calculations are performed where the turbulent heat transfer for a given temperature difference is increased by a factor 10. The results are given in Figs. 4–6, for a shortwave radiation flux equal to 230, 345, and 460 Wm^{-2}, respectively. Curves 1 and 2 give the surface temperature inside the greenhouse, when the turbulent heat transfer inside the house is increased by a factor 10, and curve 3 gives the surface temperature outside the house. Curves 4, 5, and 6, in the same order, indicate the temperature if the turbulent heat transfer outside the house given with eq. (10) is also increased by a factor 10. Our model shows that the difference between the surface greenhouse temperature with rock salt and glass depends strongly on the turbulent heat transfer and the shortwave insolation. The experimental results obtained by Wood (1909) can be understood if the turbulent heat transfer outside the house is of the same order of magnitude as given by eq. (10), and the heat transfer inside the house is considerably larger than obtained from the experiments, as reported by Chandrasekhar (1961). According to our model, with reinforced turbulent heat transfer, the equilibrium temperature of the rock salt is higher than for the glass. Thereby a higher surface greenhouse temperature is obtained.

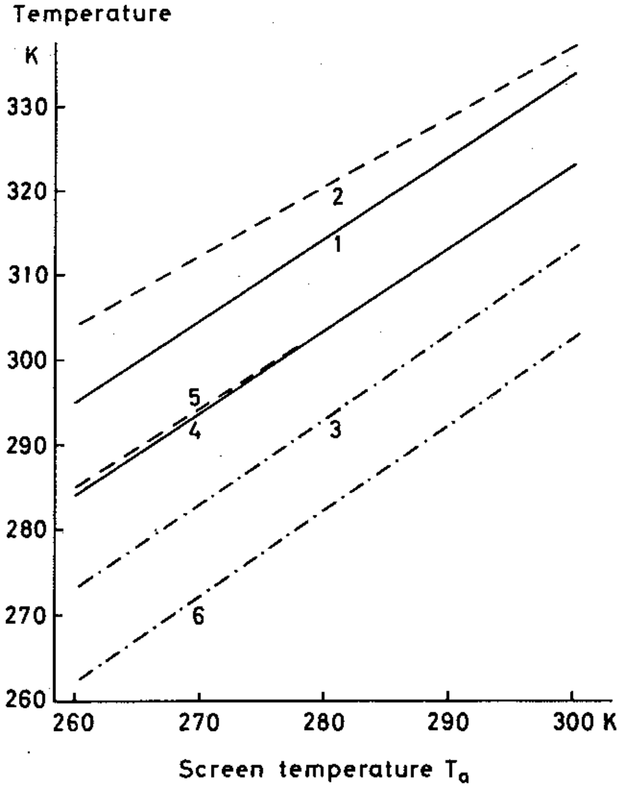

Fig. 6. The same as Fig. 4 with shortwave insolation equal to 460 Wm^{-2}.

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