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Interactive Comment

Interactive comment on "Greenhouse effect dependence on atmospheric concentrations of greenhouse substances and the nature of climate stability on Earth" *by* V. G. Gorshkov and A. M. Makarieva

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The main statement of Dr. Harrison's review is that, while deriving our major conclusion that an Earth-type climate with liquid hydrosphere cannot be physically stable, we did not take into consideration some important climatic characteristics. In order to obtain a scientifically sound conclusion on climate stability, one needs first to identify major factors that determine the stable or unstable state of climate. Then, on the basis of quantitative estimates, it is necessary to show that those factors that were neglected or taken into consideration in an approximate form do not influence the major conclusion. We believe that this is the only way to obtain a physically transparent result that can be checked by the scientific community. This is what we aimed at in our paper.

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In order to show that our major conclusion on physical instability of modern climate is wrong, it would be necessary to show that some climatic factor that we neglected or took into account only approximately, is in fact the deciding one. So that when it is taken into account, the result changes, i.e. the climate with liquid hydrosphere becomes stable. Dr. Harrison did not state that our result is wrong. From our side, we can say that all the climatic factors evaluated by Dr. Harrison as neglected by us, were in fact taken into account through a quantitative estimate of their potential impact on climate stability.

We now turn to specific comments made by Dr. Harrison.

In the first paragraph of the review, Dr. Harrison states that we use a one-dimensional model which contains empirical coefficients that are evaluated by comparison with a more exact radiative transfer equation. In fact, we did not consider the one-dimensional case (where thermal photons may only propagate along z-axis up or down). In the 1D case the equation derived by us, in its continuous form, completely coincides with the traditional radiative transfer equation. This can be immediately checked putting in Eqs. (3.3b) and (3.3c) (p. 300) $\mu = 1$, which corresponds to transition to the one-dimensional case. Then $J^{\pm}(\tau) = H^{\pm}(\tau)$ $(H^{+}/H \equiv f)$ and equations (3.3d) coincide with those derived by us, see (2.7) and (2.8), given the boundary conditions in the continuous form are correctly chosen.

In our paper we considered the real three-dimensional case, which corresponds to stratified atmosphere after global averaging. If one takes any 3D global circulation model and performs its global averaging, one also arrives to a stratified atmosphere with altitude z as the single variable. However, the dynamic processes of vertical convection (which we do take into account) are several orders of magnitude more powerful than the dynamic proccesses of advection by the oceans and winds (which one can therefore neglect). All the dynamic processes arise due to formation of a temperature gradient. They would disappear if the temperatures of the atmosphere and ocean were the same in the whole atmosphere and in the whole ocean. Convective processes

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arise due to the vertical temperature difference, which is of the order of 30 degrees Kelvin and corresponds to the vertical distance of about 10 km. Processes of horizontal advection arise due to the temperature difference between the equator and the poles, which is also of the order of 30 K, but arises over a distance of several thousand kilometers. Thus, the global average temperature gradient of advective processes are thousand times less than those of convection processes. An account of the Coriolis forces that are due to Earth's rotation and lead to interaction between the advective and convective processes does not change the statement that the most important dynamic processes are those of vertical convection.

Dr. Harrison further states that we neglect clouds, oceans and polar caps. However, such a statement is clearly a misunderstanding, because our main result owes itself to a very large degree namely to the account of cloudiness, see pp. 296, 310, 319 and the data of Stephens and Greenwald (1991) for cloudy sky. Most part of atmospheric water evaporates from the oceanic surfaces, and it is the presence of a large hydrosphere (oceans) that is responsible for climate instability. Finally, we take into account polar caps and their possible behavior in our formula for the albedo (5.12), p. 314.

What is referred to in the review as the alpha-theorem is in fact a simple consequence of the law of energy conservation: thermal energy may leave the Earth system only in the form of thermal radiation. All upward convective dynamic fluxes of energy must finally convert to thermal radiation. Obviously, this condition must be satisfied in any model.

The reference of Dr. Harrison to the principle of work of lasers is not relevant to this discussion. Lasers work at the expense of other ordered processes that perform laser energy "pumping", i.e. excitation of the upper energy level of the radiator molecules. A considerable part of this external pumping energy may release into heat or other non-laser "waste" energy fluxes. That is, the efficiency of energy conversion in laser is naturally less than unity. Thus, for laser (as well as for any other energy generator) the sum of the alpha coefficients is less than unity. However, for the planetary system there is no way for energy release other than thermal radiation. In this sense the planet represents a "laser" with 100% efficiency, converting all "pumping" energy of the dynamic processes into radiation. This corresponds to unity for the sum of the alpha coefficients.

A more important and less trivial statement is the positive sign of coefficients α that describe conversion of the convective dynamic energy into thermal radiation. Indeed, this is the consequence of the second law of thermodynamics. The energy of thermal radiation is characterized by the highest entropy, exceeding the entropy of any convective dynamic processes. Thus, the positiveness of signs of α corresponds to the increase of entropy. We note that heat flow from the warmer to the colder medium is also associated with entropy increase and can therefore be considered as one of the consequences of the second law of thermodynamics, despite that this process was known well before the opening of the second law.

Dr. Harrison further disagrees with our statement that convection itself arises only due to the presence of a non-zero greenhouse effect. He states that "convection may also arise from latent heat release and from heat transfer from eddy-diffusive effects." Dr. Harrison considers our statement as rejection of any physics that "our model does not accomodate". We assert that our statement is correct, following unambiguously from the law of energy conservation. Undoubtedly, convection may arise from latent heat release and from heat transfer from eddy-diffusive effects. However, both these energy fluxes may exist only in the situation of a non-zero greenhouse effect. If the greenhouse effect is absent, there could be no vertical temperature gradient. The atmosphere would have a uniform temperature coinciding with that of the Earth's surface. In such a case all vertical dynamic physical fluxes of energy (including latent heat fluxes and eddy heat fluxes) ceased to exist.

It is easy to show that the existence of vertical dynamic processes in the atmosphere in the absence of the greenhouse effect corresponds to the perpetuum mobile of the first type. Absence of greenhouse effect is equivalent to the absence of interaction between air molecules and thermal photons. If this is the case, all thermal radiation that leaves the planet into space, is emitted from the Earth's surface (not from the atmosphere). In the stationary case (after global averaging over longitude, latitude and seasonal and diurnal oscillations) the flux of thermal radiation of Earth's surface into space is equal to the flux of solar radiation absorbed by the Earth's surface. Thus, the energy balance is closed. In the stationary case there are no energy sources that could lead to formation of any dynamic energy fluxes in the atmosphere (fluxes of sensible or latent heat).

If the dynamic processes do arise, which is possible under conditions of deviations from stationarity, the energy of these processes cannot dissipate into thermal radiation due to the assumed absence of interaction between air molecules and thermal radiation. The energy of the dynamic processes may thus be only converted into the energy of thermal motion of air molecules, heating the air. Such heating will proceed until the temperature of the atmosphere becomes uniform throughout the entire atmospheric column and coincides with that of the Earth's surface. After that, any dynamic processes become impossible.

It is clear from this consideration that in the absence of the greenhouse effect the adiabatic temperature gradient associated with the gravitational field of the Earth may not arise either. Otherwise it would be possible to organize dynamic processes at the expense of this gradient (and, consequently, at the expense of the gravitational field) without external energy supply, because all the energy coming in the form of solar photons must leave the planet in the form of thermal radiation without interaction with the atmosphere.

The statement of Dr. Harrison about our overestimation of the biotic effects does not correspond to the content of our paper. In our paper we only assert that we do not envisage any explanation of the observed climate stability other than climate control by the natural biota. A detailed account of our position on this topic may be found in our book Gorshkov et al. (2000). We do not claim anywhere in the paper that transpiration by the biota is more powerful than regular evaporation from the global oceanic surface.

As can be seen from the above, the comments made by Dr. Harrison do not disprove our main statement about the non-physical nature of the observed stability of the modern climate. Major characteristics of the potential pit describing this stability (Fig. 8, p. 337) were retrieved by us from the available empirical data. In support of the usefulness of the results obtained in our paper, we consider below some implications of our major result to the broadly debated problem of global warming.

In contrast to water vapor, the atmospheric concentration of CO_2 is largely independent of temperature and increases due to anthropogenic activities. According to the available estimates (e.g. Kiehl and Dickinson, 1987) the logarithmic collisional broadening of the main absorption band of CO_2 (15 μm) in response to CO_2 doubling results in an increase of the thermal flux at the Earth's surface by $\Delta F \approx 4.4$ W m^{-2} and surface temperature by $\Delta T \approx 1$ K.

According to our formulae (5.4) and (5.5), even if the atmospheric CO_2 concentration grows infinitely ($\widetilde{m}_{\mathrm{CO_2}} \to \infty$), the transmissivity b diminishes and the relative greenhouse effect $(F_s - F)/F_s = 1 - b$ increases by $\delta_{\mathrm{CO_2}} = 19\%$. The outgoing flux F_{out} will decrease by the same magnitude, see (5.1). Given that the incoming energy flux F_{in} remains constant, the condition of energy balance will lead to the shift of the unstable physical point of intersection of the curves F_{out} and F_{in} in Fig. 6 to the region of lower, not higher, temperatures.

Given that there are certain forces (irrespective of their physical or biotic nature) responsible for the formation of the stable potential pit of the modern climate, the stable point 2 of intersection of the curves F_{out} and F_{in} in Fig. 7b may retain its position on the temperature axis. This would physically mean that the impact of the excessive atmospheric CO_2 was compensated by changing atmospheric composition of the other greenhouse substances, first of all, atmospheric water. The excessive CO_2 will then play the role of an additional disturbance factor for the climatic system. This can be manifested as the increase in temperature *fluctuations* with the mean global surface temperature remaining unchanged.

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If the mechanism of climate stability (again irrespective of its nature) is instantly destroyed, the climate will inevitably drive, via ever increasing temperature fluctuations, towards one of the two stable lifeless states, 1 or 3, irrespectively of the magnitude of CO_2 concentration in the atmosphere. Due to the shift of the unstable equilibrium towards lower temperatures in the case of large increases of atmospheric CO_2 concentration, the modern climate will find itself on the slope leading to state 3 (complete evaporation of the atmosphere), which makes this transition more probable.

We also note that at constant atmospheric water content ($\widetilde{m}_{\mathrm{H_2O}} = \mathrm{const}$ and $\widetilde{m}_0 = \mathrm{const}$) and increasing CO_2 concentration, the logarithmic change of transmissivity b (caused by collisional broadening of the absorption band of CO_2 and corresponding increase in the value of $\delta_{\mathrm{CO_2}}$ in (5.5)) becomes more essential than the respective change due to the linear increase in $\widetilde{m}_{\mathrm{CO_2}}$ only when $\widetilde{m}_{\mathrm{CO_2}} > 5$, which is 2.5 times higher than the modern value of $\widetilde{m}_{\mathrm{CO_2}} = 1.9$, see (5.7). For $\widetilde{m}_{\mathrm{CO_2}} < 5$, a linear-fractional (5.4), not logarithmic, mode of transmissivity b and relative greenhouse effect $1 - b$ changes with increasing CO_2 concentration is expected to dominate.

Thus, without analyzing and identifying the mechanisms responsible for climatic stability on Earth, it is impossible to make any predictions (even in the zeroth approximation) with respect to the magnitude of changes of the stationary mean surface temperature of the Earth's surface.

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