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Net-exchange analysis of the Earth greenhouse effect increase

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Abstract. In this paper, we propose an analysis of the greenhouse effect on the basis of a net-exchange formulation for clear sky atmospheres. This formulation allows access to exchanges beetwen the differents elements of the atmosphere (gas layers, the ground and space). When the greenhouse gas concentration increases, we first use a simple configuration to analyse the variations of analytic monochromatic net exchange rates. The same type of analysis is then applied to the Earth atmosphere for a clear-sky middle latitude summer configuration with an increase in water vapour of 20% at all altitudes.

Keywords: Net-Exchange Rate (NER), greenhouse effect, radiative transfert
PACS: 92.60.Vb, 42.68.Ay, 92.70.Cp

DESCRIPTION OF THE NET-EXCHANGE FORMULATION

The net-exchange formulation is based on the Net Exchange Rates (NER) $\Psi_{i,j}$ between all pairs of elements (either surfaces or volume elements) i and j, which is defined as the difference between the energy rate emitted from the element i and absorbed by the element j, and the energy rate emitted from the element j and absorbed by the element i. This formulation was first proposed by Green [1], and then to optimize Monte Carlo algorithm [3, 5, 6, 7, 8, 10], to analyse the radiative exchanges on Earth [11] and to develop parametrisations for Mars [4] and Venus [9].

With this formulation, the Net Radiative Budget Ψ_i of a gas layer i is the sum of the Net Exchange Rates (NER) between layer i and all the other elements j : $\Psi_i = \sum_j \Psi_{i,j}$. These net exchanges may be show as a matrix (Fig. 1). The intersection between the line i and the column j shows the NER between the two elements i and j. The sign of this NER depends of the temperature gradient between i and j. Generally speaking, a gas layer in the troposphere is cooled by the atmosphere above, which is colder, and warmed by the atmosphere below, which is warmer. Thanks to this formulation, the net exchange between any pair of element i, j may be analyzed independently from all the other elements. The formulation was presented in some details in previous papers [4, 11]. Although the results presented here was computed with a full 3D geometry, we present the expressions of monochromatic NERs in a simple case, where only one direction of photon propagation is considered, without scattering and we assume that the layer thickness are elemental ($\Delta z_i = \delta z_i$). $B_\nu(T(z))$ is the Planck function at the frequency ν and temperature $T(z)$.

The monochromatic NERs between the ground and space $\Psi_\nu^{s,s}$, between the ground and an elemental gas layer i centered on z_i $\Psi_\nu^{s,\nu}$, between two elemental gas layers i, j centered on z_i and z_j $\Psi_\nu^{\nu,\nu}$ may be written as:

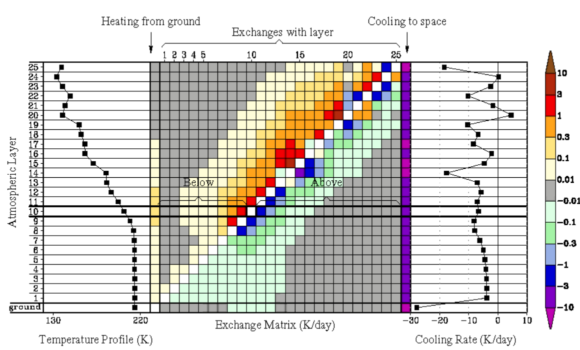

FIGURE 1. Vertical temperature profile (K, left), Net Exchange matrix(K/day, center) and heating rate (K/day, right) for a typical atmospheric profil on Mars [4].

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$$\Psi_{\nu}^{s,s} = (B_{\nu}(T_g) - B_{\nu}(T_s))\mathfrak{T}_{\nu}(z_g, z_s) \quad (1)$$

$$\Psi_{\nu}^{s,v} = (B_{\nu}(T_g) - B_{\nu}(T_i))\left|\frac{\partial \mathfrak{T}_{\nu}(z_g, z)}{\partial z}\right|_{z=z_i} \delta z_i \quad (2)$$

$$\Psi_{\nu}^{v,v} = (B_{\nu}(T_i) - B_{\nu}(T_j))\left|\frac{\partial^2 \mathfrak{T}_{\nu}(z_1, z_2)}{\partial z_1 \partial z_2}\right|_{z_i, z_j} \delta z_i \delta z_j \quad (3)$$

where $\mathfrak{T}_{\nu}(z_1, z_2) = e^{-\tau_{\nu}(z_1, z_2)}$ is the monochromatic transmittivity and $\tau_{\nu}(z_1, z_2)$ the monochromatic optical thickness. In Eq. 1,2 and 3, the different NERs between two elements are the product of the Planck luminance difference between these two elements and an optical exchange factor, which is equal to the transmittivity or its derivatives : $O_{\nu}^{s,s}(z_{s1}, z_{s2}) = \mathfrak{T}_{\nu}(z_{s1}, z_{s2})$, $O_{\nu}^{s,v}(z_s, z_i) = \left|\frac{\partial \mathfrak{T}_{\nu}(z_s, z)}{\partial z}\right|_{z=z_i}$ and $O_{\nu}^{v,v}(z_i, z_j) = \left|\frac{\partial^2 \mathfrak{T}_{\nu}(z_1, z_2)}{\partial z_1 \partial z_2}\right|_{z_i, z_j}$.

SENSITIVITY OF THE OPTICAL EXCHANGE FACTORS TO GAS CONCENTRATION IN AN IDEALIZED CASE

To interpret how the optical exchange factors change with the concentration of greenhouse gas, we first consider a simple case where the absorption coefficient per unit of mass k_{ν} is constant in all the atmosphere. In that case, when the mass of absorbing gas in the atmosphere is multiplied by a factor f, the optical thickness between z_1 and z_2 becomes $\tau_{\nu}(z_1, z_2) = f k_{\nu} M(z_1, z_2)$, where $M(z_1, z_2) = \int_{z_1}^{z_2} \rho(z)\, dz$ is the mass of gas between z_1 and z_2 and $\rho(z)$, the gas density. Around $f = 1$, the sensitivity of the monochromatic optical exchange factor to a change of f reads:

For the ground to space exchange

$$\frac{\partial O_{\nu}^{s,s}(z_s, z_s)}{\partial f} = -\frac{\tau_{\nu}(z_{s1}, z_{s2})}{f}\mathfrak{T}_{\nu}(z_{s1}, z_{s2}) \quad (4)$$

For the gas i to space or the ground exchange

$$\frac{\partial O_{\nu}^{s,v}(z_s, z_i)}{\partial f} = k_{\nu}\,(1 - \tau_{\nu}(z_s, z_i))\mathfrak{T}_{\nu}(z_s, z_i)\,\rho(z_i) \quad (5)$$

For the gas i to the gas j exchange

$$\frac{\partial O_{\nu}^{v,v}(z_i, z_j)}{\partial f} = f k_{\nu}^2 (2 - \tau_{\nu}(z_i, z_j))\mathfrak{T}_{\nu}(z_i, z_j)\rho(z_i)\rho(z_j) \quad (6)$$

As it is well known the intensity of the monochromatic NER $\Psi_{\nu}^{s,s}$ (Eq. 1) between the ground and space always decreases when the optical thickness increases as the derivate $\frac{\partial O_{\nu}^{s,s}(z_g, z_s)}{\partial f}$ is always negative (Eq. 4). For the intensity of the monochromatic NER $\Psi_{\nu}^{s,v}$ between a black body (space or ground) and a gas layer, the intensity may increase or decrease when the optical thickness increases, depending of the optical thickness between the two extremities. If the optical thickness τ_{ν} is less than 1, an increase in greenhouse gas concentration will increase the optical exchange factor (Eq. 5) and thus the absolute value of the NER (Eq. 2). When the optical thickness τ_{ν} is greater than 1, an increase in greenhouse gas concentration will decrease the optical exchange factor and so, the absolute value of the NER (Eq. 2) too. For the intensity of the monochromatic NER between two gas layers $\Psi_{\nu}^{v,v}$ (Eq. 3), the optical exchange factor $O_{\nu}^{v,v}$ increases if the optical thickness τ_{ν} is less than 2 or decreases if the optical exchange factor is higher than 2 (Eq. 6).

APPLICATION TO AN INCREASE OF WATER VAPOUR

In this section, we analyse how net exchanges are affected when the concentration of water vapour changes. We use the same narrow band model as (Eymet & *al* [11]), the same number and the same numbering of narrow bands. The infrared spectrum is divided into 121 narrow bands. The atmosphere we use, is a typical MLS (Middle Latitude Summer Fig 4) with 41 layers as used by Collins & *al* [2].

Global net-exchange rate variations

For an increase in water vapour of 20%, the ground radiative cooling decreases by 12.1 W/m^2 and the atmosphere radiative cooling increases by 8.1 W/m^2, space gets less energy ($-4\,W/m^2$) (Fig. 2-a). So "ground + atmosphere" loses less energy toward space. These results are consistent with those of Collins & *al* [2]. The variations of the exchange beetwen the ground and the rest of the atmosphere are essentially located in the transparency window ($8 - 13\ \mu m$, #65 to 85 index narrow bands) (Fig. 2-a). Except in the ozone absorption band (close to 9.7 µm), the variation of the ground-space NER is more important than the ground-atmosphere NER. For the atmosphere, the warming by the ground decreases and its cooling by space increases (Fig. 2-b). Finally, the space-ground NER decreases and the space-atmosphere NER increases (Fig. 2-c). With this two effects, the net exchange between "ground + atmosphere" and space increases slightly.

Analysis of the variations of net-exchange rate

The net exchange between space and the atmosphere is negative because the temperature of the atmosphere is higher than space. In the transparency window, the optical thickness between space to the ground is less than 1, so an increase in H_2O concentration rises the energy exchange between the gas layers and space (Fig. 3-b), therefore the atmosphere get colder. For the other narrow bands : in the upper part of the atmosphere, the optical thicknesses beetwen gas layers and space are less than 1. Consequently the intensity of NER increases when the water vapour concentration increases, and so the radiative cooling too. In the rest of the atmosphere, it's the opposite effect, the optical thicknesses beetwen gas layers and space are greater than 1, so the radiative cooling decreases. Close to the ground, the optical thicknesses are so important that NERs beetwen space and gas layers are weak.

For the ground-atmosphere NER (Fig. 3-c), we use the same argument, the temperature of the ground is higher than the atmosphere. In H_2O bands, the optical thicknesses between the ground and gas layers increase strongly with the altitude and are greater than 1. Therefore, the increase in H_2O concentration decreases the NER between the ground and the atmosphere. In the transparency window, the optical thicknesses between the ground and gas layers in the lower part of the atmosphere are less than 1, so the intensity of the NER between the ground and the lower part of the atmosphere increases. In the upper part of the atmosphere, the optical thicknesses between the ground and gas layers become important, the sign of the derivate of optical factor (Eq. 5) change when the H_2O concentration increases. The global net budget rate variation (Fig. 3- right) of gas layer is dominated by the NER between space and gas layers. However, exchanges in the atmosphere are not negligible.

Analysis of the variations of net exchange rate in the atmosphere

In the atmosphere, the reference NER matrix (Fig. 4-a) shows the NER between gas layers. The change of NER signs follows the temperature gradient, as explain in the first paragraphe. The sign changes two times, at the tropopause (close to the layer #15) and at the stratopause (close to the layer #32) (Fig. 4).

We separate the transparency window and strong absorption bands. When the water vapour increases, in the transparency window, the sign of the NER (Fig. 4-c) changes as the same as the sign of the reference NER matrix (Fig. 4-a). Optical thickness between gas layers are less than 2. So an increase in H_2O concentration rises exchange between gas layers. In the lower part of the atmosphere, the warming by gas layers above rises and, symmetrically, the cooling by gas layers below rises too. In the upper part of the atmosphere, optical thickness between gas layers are so weak, NER variations are closed to 0.

In the H_2O band, above the layer #12, NER sign (Fig. 4-d) changes like the reference NER matrix. In this section, optical thickness between gas layers are less than 1 and so an increase in H_2O concentration augments the intensity of NER. Below the #12 gas layer, NER signs (Fig. 4-d) are opposite to the reference NER matrix (Fig. 4-a). An increase in H_2O concentration induces a decrease in the intensity of NER between gas layers.

Over infrared spectrum, NER signs which are in the lower part of the atmosphere, are governed by the exchange in the transparency window. In the lower part of the atmosphere, NER signs are governed by the exchange in the strong optical thickness band.

CONCLUSION

Thanks to the net exchange formulation, we can analyse the effect of an increase in H_2O concentration between the different elements in the atmosphere. The gas-gas net exchange rates in the lower part of the atmosphere are governed by the net exchange in the transparency window, whereas gas-gas net exchange rates in the upper of the atmosphere are governed by the net exchange in H_2O absorption bands.

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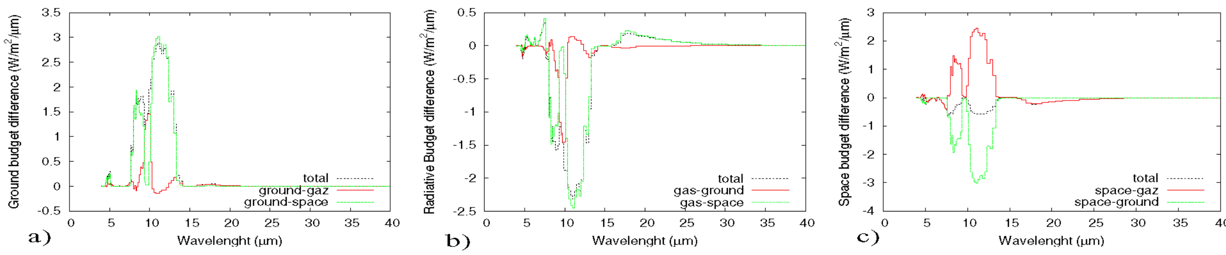

FIGURE 2. Variation of the different monochromatic radiative budget ($W/m^2.\mu m^{-1}$) (a- Ground, b- atmosphere, c- space) after an increase in water vapour gas of 20% .

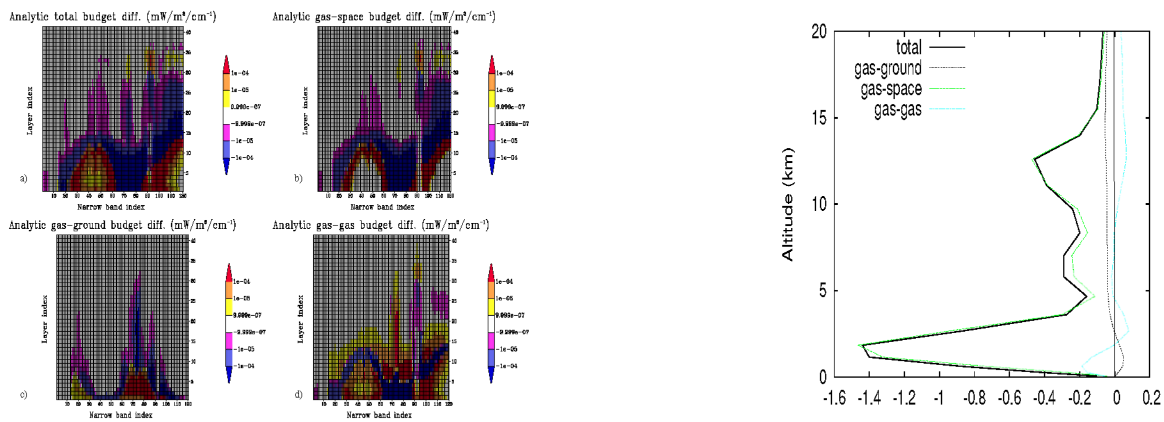

FIGURE 3. Left : Variations of the net budget rate (a), of gas layers - space NER (b), of gas layers - ground NER (c), according to narrow bands and index layers (bottom : ground, top : space). Right : Variations according to the altitude of the net budget rate, exchanges with the ground, with space and with the atmosphere (K/day).

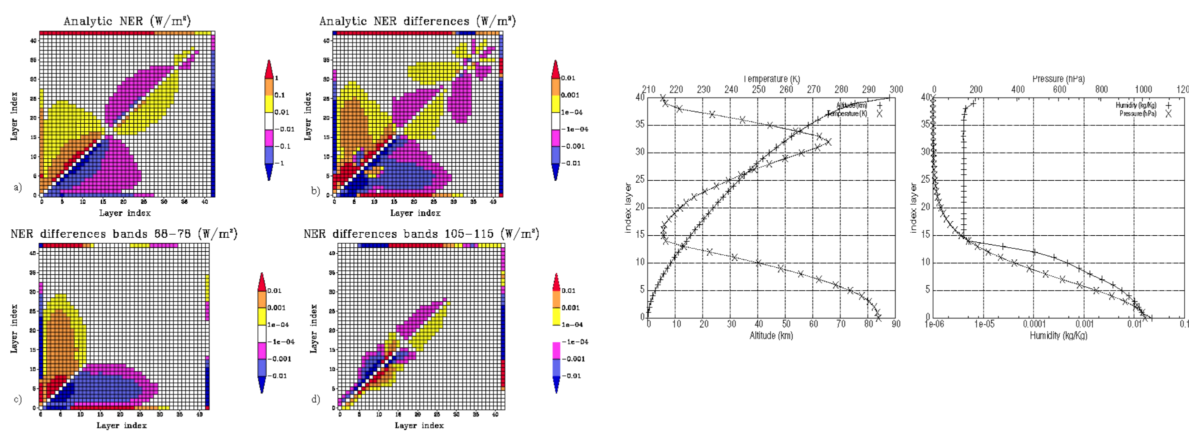

FIGURE 4. Left : Reference NER matrix (a), variation of this matrix after an increase in H_2O concentration (20%) over infrared spectrum (b), in the transparency window (c) and in the H_2O absorption band (d, 105 to 115 index narrow band). Right : profils of temperature and level according to altitude. On the right, profils of humidity and pressure, corresponding to the MLS profil.