Cours climat

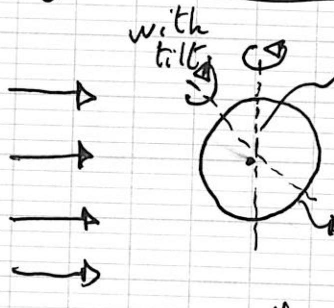
I] Constante solaire:

the sun shines light with a power distributed on a spherical surface. At distance D from the center of the sun this power per unit of surface is $\mathcal{G}_s = \dfrac{P}{4\pi D^2}$ by mere geometrical effect.

P from the blackbody law is given by $P = 4\pi R_\odot^2 \sigma T_\odot^4$ surface temperature

$R_\odot \simeq 7 \cdot 10^5$ km
$T_\odot \simeq 5\,780$ K
$\sigma \simeq 5.67\ 10^{-8}\ W m^{-2} K^{-4}$

geometrical interception by the Earth



disk $S_\oplus = \pi R_\oplus^2$

distributed over surface $\Sigma_\oplus = 4\pi R_\oplus^2$

so the average power from sun by unit of surface is

$$\frac{S_\oplus}{\Sigma_\oplus}\mathcal{G}_s = \frac{P}{4\pi D^2}\,\frac{1}{4} = \boxed{\frac{\mathcal{G}_s}{4} \simeq 342\ W m^{-2} = \mathcal{G}_s'}$$

Average albedo of the Earth: $A_b \simeq 0{,}3$

Flux on surface of Earth: $\Phi_\odot = \mathcal{G}_s'(1 - A_b) \simeq \boxed{239\ W m^{-2}}$

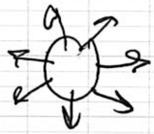
it is an <u>average</u>: the actual value fluctuates factor: $1\ W m^{-2} = 0{,}024\ kWh/m^2/day$

III Radiative balance: Greenhouse effect

equivalent temperature: (zero couche)

$\Phi_{in} = 4\pi R_\oplus^2\, \Phi_0$ received

$\Phi_{out} = 4\pi R_\oplus^2\, \sigma T_{eq}^4$ emits in all directions



at équilibrium: $\Phi_{in} = \Phi_{out}$

$$\Rightarrow \sigma T_{eq}^4 = \mathcal{F}_s'(1-A_b)$$

or $$\boxed{T_{eq} = \left(\frac{\mathcal{F}_s'(1-A_b)}{\sigma}\right)^{1/4}}$$ (plot table for planets)

A.N.: Earth: $-18°C$! (254 K)

Greenhouse effect, model with one shell of atmosphere

[Question: why not reemission of visible light?]

Balance: in / out

out / in

space: $\mathcal{F}_s' = \mathcal{F}_s' A_b + (1-\varepsilon)\sigma T_s^4 + \varepsilon\sigma T_a^4$

stratosphere: $\mathcal{F}_s' + \sigma T_s^4 = \mathcal{F}_s'(1-A_b)(1-\alpha) + \mathcal{F}_s' A_b + (1-\varepsilon)\sigma T_s^4 + 2\varepsilon\sigma T_a^4$

surface: $\mathcal{F}_s'(1-A_b)(1-\alpha) + \underbrace{\varepsilon\sigma T_a^4}_{\text{key ingredient}} = \sigma T_s^4$

key ingredient $\Rightarrow$ feedback

Rk: $T_s \neq T_a \Rightarrow$ radiative effect allows for setting a gradient of temperature between the high atmosphere and the surface.

we are looking for T_s, only two independent equation

second line using first

$$\mathcal{F}_s' + \sigma T_s^4 = \mathcal{F}_s'(1-A_b)(1-\alpha) + \overbrace{\mathcal{F}_s' A_b + (1-\varepsilon)\sigma T_s^4 + \varepsilon\sigma T_a^4}^{\mathcal{F}_s'} + \varepsilon\sigma T_a^4$$

... gives back the third one

$$\mathcal{F}_s'(1-A_b) = \underbrace{(1-\varepsilon)\sigma T_s^4 + \sigma T_s^4}_{(2-\varepsilon)\sigma T_s^4} - \mathcal{F}_s'(1-A_b)(1-\alpha)$$

$$\mathcal{F}_s'(1-A_b)(1+1-\alpha) = (2-\varepsilon)\sigma T_s^4 \Rightarrow \sigma T_s^4 = \frac{1-\alpha/2}{1-\varepsilon/2}\mathcal{F}_s'(1-A_b)$$

or $$\boxed{T_s = \left(\frac{1-\alpha/2}{1-\varepsilon/2}\right)^{1/4} T_{eq}}$$

Rk: i) we could have put $\varepsilon_s \sigma T_s^4$ for the emission of the Earth (in practice $\varepsilon_s \simeq 0{,}95$)

ii) if $\left|\begin{array}{l}\varepsilon = 1 \\ \alpha = 0\end{array}\right.$: fully absorbing atmosphere $T_s = \sqrt[4]{2}\, T_{eq} > T_{eq}$

more effect of adding a piece of glass!

if $\alpha \nearrow$, $T_s \searrow$

if $\varepsilon \nearrow$, $T_s \nearrow$ (increases absorption in IR $\Rightarrow$ greenhouse effect!)

if $A_b \nearrow$, $T_s \searrow$

III/ Geostrophic wind formula:

$$f\,\vec{k}\wedge\vec{V_g} = -\frac{1}{\rho}\begin{pmatrix}\partial_x P\\ \partial_y P\end{pmatrix}$$

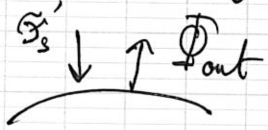
$$f\left(\vec{k}\wedge\left(\vec{k}\wedge\vec{V_g}\right)\right) = f\left(\overset{0}{\overset{\shortparallel}{(\vec{k}\cdot\vec{V_g})}}\,\vec{k} - \overset{1}{\overset{\shortparallel}{\vec{k}^2}}\,\vec{V_g}\right) = -\frac{1}{\rho}\,\vec{k}\wedge\vec{\nabla}P$$

$$= -\frac{1}{\rho}\begin{pmatrix}0\\0\\1\end{pmatrix}\wedge\begin{pmatrix}\partial_x P\\ \partial_y P\\ 0\end{pmatrix} = -\frac{1}{\rho}\begin{pmatrix}-\partial_y P\\ \partial_x P\\ 0\end{pmatrix}$$

$$\Rightarrow \quad \boxed{\vec{V_g} = +\frac{1}{\rho f}\begin{pmatrix}-\partial_y P\\ \partial_x P\end{pmatrix}}$$

IV/ Radiative forcing and feedbacks

We look at the equation at the top of the troposphere:



$$N = \mathcal{F}_s' - \Phi_{out}$$

at equilibrium $N = 0$ (radiative balance)
Now $N(\vec{E}, \vec{I}, T_s)$ is a function of external parameters $\vec{E}$, internal parameters $\vec{I}$ that are dependent on T_s and of T_s. An elementary variation of ΔN writes

$$\Delta N = \underbrace{\sum_i \frac{\partial N}{\partial E_i}\Delta E_i}_{\Delta F_i} + \underbrace{\left(\frac{\partial N}{\partial T_s} + \sum_j \frac{\partial N}{\partial I_j}\cdot\frac{\partial I_j}{\partial T_s}\right)\Delta T_s}_{\text{variation of flux due to climate system response}}$$

$\hookrightarrow$ radiative forcing

total forcing is $\Delta F = \sum_i \Delta F_i$
↳ independent contribution

in the end, at equilibrium $\Delta N = 0$ and the climate system changes its surface temperature by ΔT_s given by

$$\boxed{\Delta T_s = G \, \Delta F}$$

↳ in $W m^{-2}$

G is the <u>gain of the system</u> in $K W^{-1} m^2$

We observe that

$$G^{-1} = \underbrace{-\frac{\partial N}{\partial T_s}}_{G_0^{-1}} \underbrace{- \sum_j \frac{\partial N}{\partial I_j} \cdot \frac{\partial I_j}{\partial T_s}}_{R}$$

<u>interpretation:</u>

* G_0 corresponds to the bare gain of the system if all internal parameters are kept constant I_j in the presence of ΔF, i.e. there is no feedback

$$\Delta T_s^{(0)} = G_0 \, \Delta F \quad \text{in this hypothetic situation}$$

<u>Example:</u> in the equivalent temperature model

$$N = \mathcal{F}_s' - \mathcal{F}_s' A_b - \sigma T_s^4$$

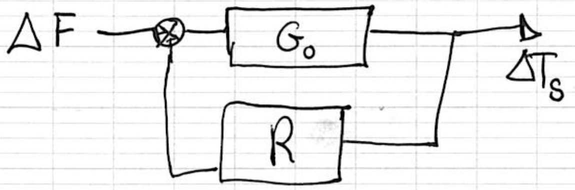
$$\frac{\partial N}{\partial T_s} = -4\sigma T_s^3 \Rightarrow \boxed{G_0 = (4\sigma T_s^3)^{-1}}$$

* R is a feedback term showing that changing T_s to a new equilibrium value modify the I_j which in turn modifies ΔN.

$$\boxed{G = \frac{1}{G_0^{-1} - R} = \frac{G_0}{1 - G_0 R}}$$

↳ amplification term

It has the following interpretation as in electronic circuits:



$$\Delta T_s = G_0\left(\Delta F + \underbrace{R\,\Delta T_s}_{\text{feedback amplification terme}}\right)$$

$$\Leftrightarrow \quad \Delta T_s = \frac{G_0}{1 - G_0 R}\,\Delta F$$

Example: same model as before

$$N = \mathcal{F}_s'(1 - A_b) - \sigma T_s^4$$

consider that ΔT_s affect albedo $A_b(T_s)$, then

$$\boxed{R = \underbrace{\frac{\partial N}{\partial A_b}}_{"-\mathcal{F}_s'"}\frac{\partial A_b}{\partial T_s} = -\mathcal{F}_s'\frac{\partial A_b}{\partial T_s}}$$

if $T_s \nearrow$ induces $\frac{\partial A_b}{\partial T_s} < 0$ (less ice sea decreases albedo)

then $R > 0 \Rightarrow$ positive retroaction (increase temperature)

$$\Delta T_s = \frac{G_0}{1 - G_0 R}\,\Delta F > G_0 \Delta F = \Delta T_s^{(0)}$$

$R > 0$: positive feedback.
$R < 0$: negative feedback.