Clouds & Radiation:

From a cloud particle to the Earth Radiative Budget

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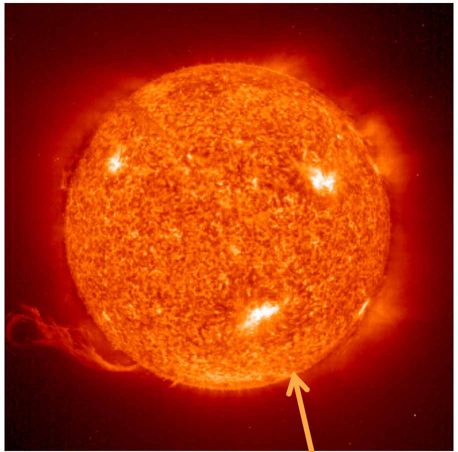
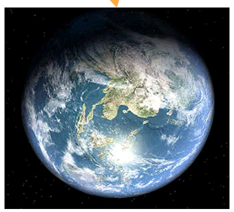
Background



Sun Radius :
695 500 km

Distance Earth-Sun:
150 000 000 km

Earth Radius:
6 378 km

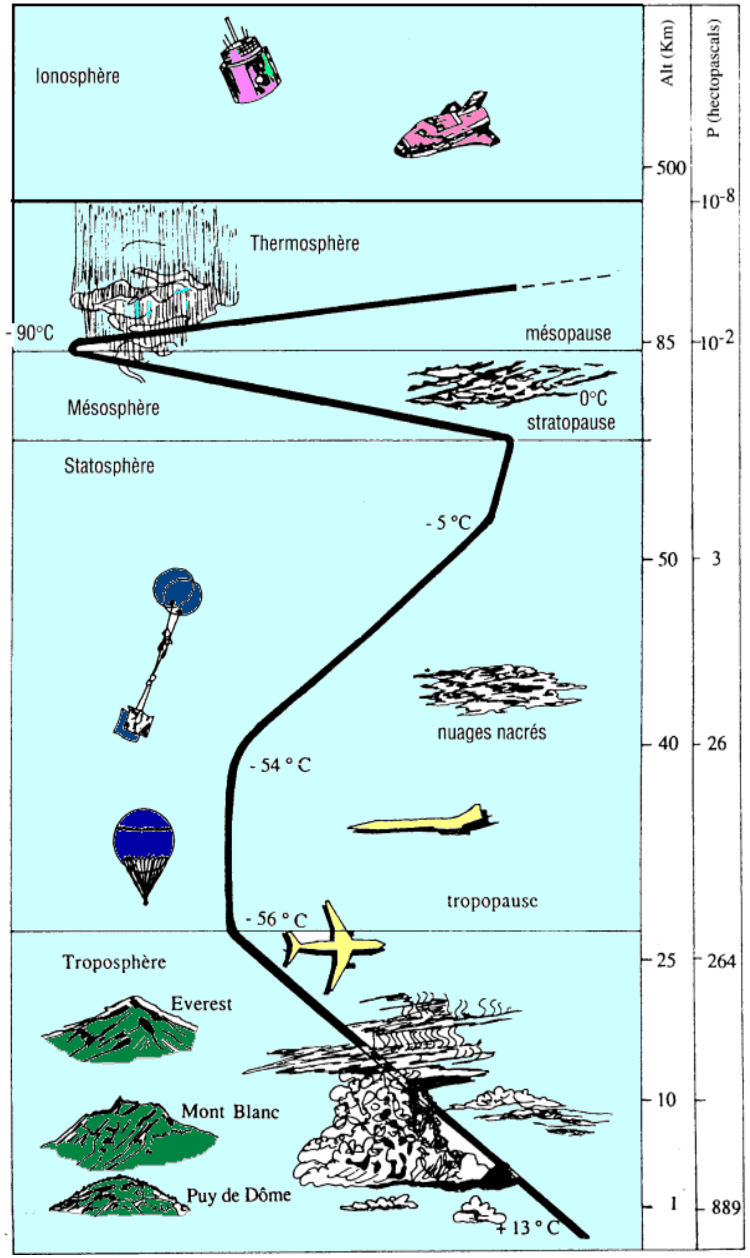


The Earth Atmosphere:

its weight is concentrated in about *20 km* of thickness.

1360 W/m2
Solar radiation received at the top of the atmosphere through a surface of 1m x 1m perpendicular to the Earth-Sun direction

340 W/m2 for one day all over the globe

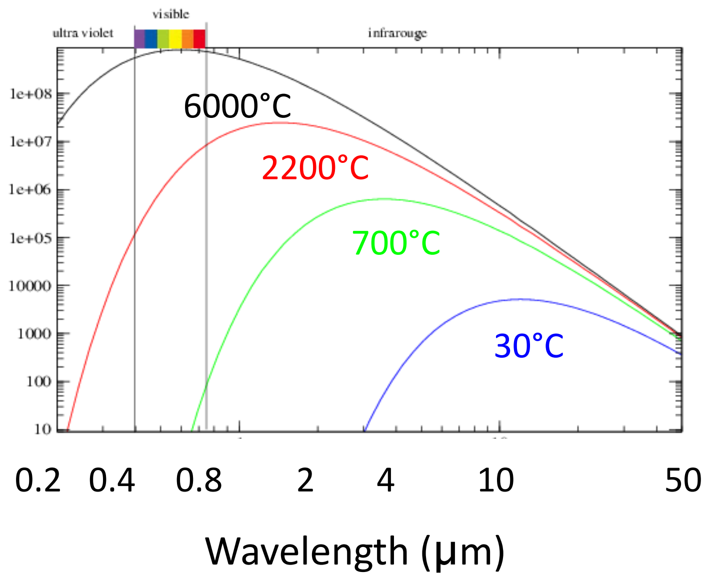


Background (cont'd)

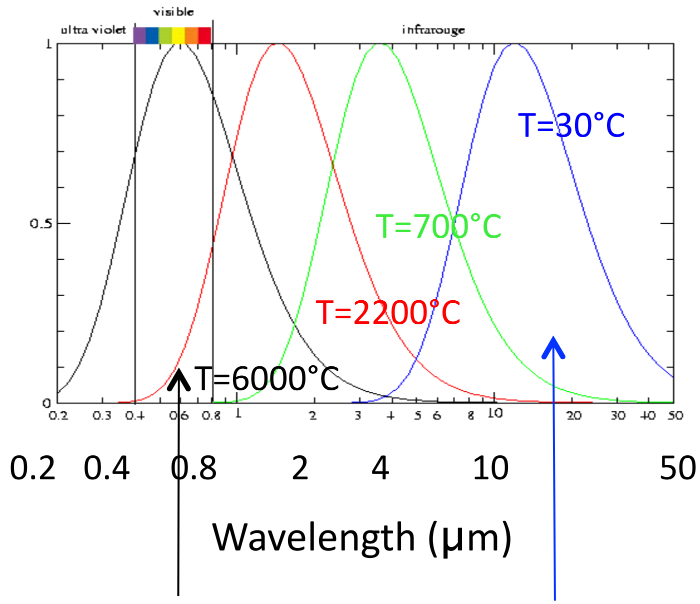
1) Radiation in radiance L ($W.m^{-2}.sr^{-1}$) or Flux ($W.\ m^{-2}$)

2) All bodies emit radiation its intensity and wavelength depend on the body temperature

Emitted Energy



Normalized Emitted Energy



Sun (about 6000°C)
Light bulb (2200°C)
Volcano lava (700°C)
Earth (about 30°C) Clouds (-30°C)

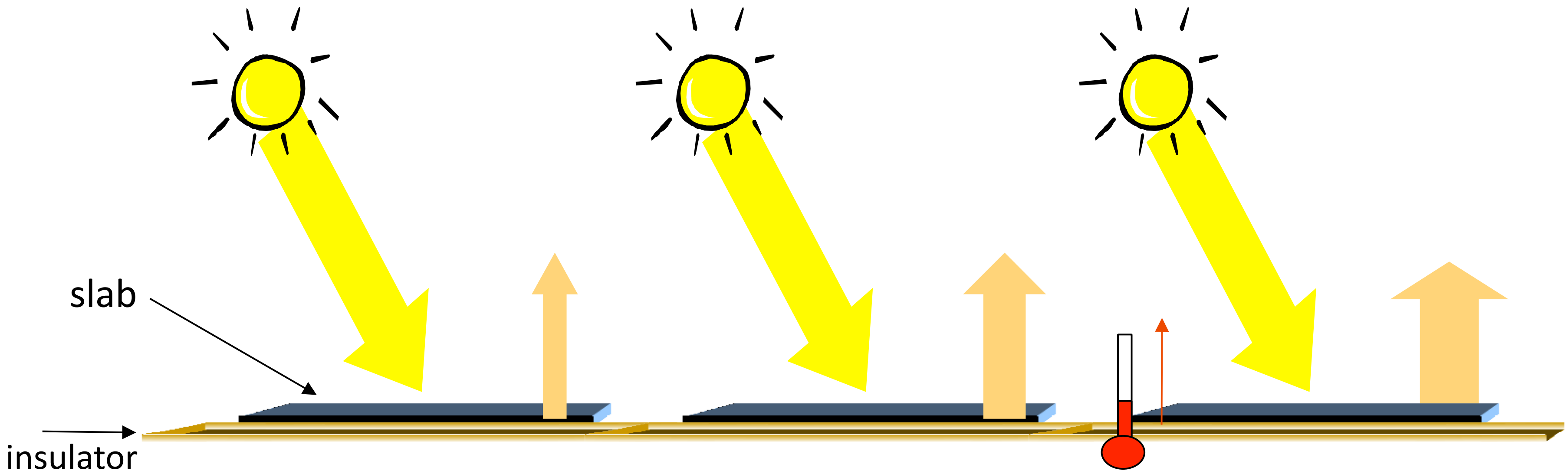
Separation of emission spectrum
Sun emission: Max in the Visible
Earth emission: mostly the Infrared

Stefan Bolzmann Law: $M = \sigma T^4$ and Planck's Law: $B_{\lambda}(T)$
Wien Law: $\lambda_{max}T$ = constant

Fig. JL Dufresne

Background (cont'd)

3) Temperature of equilibrium :



4) Interaction between radiation and a media by:

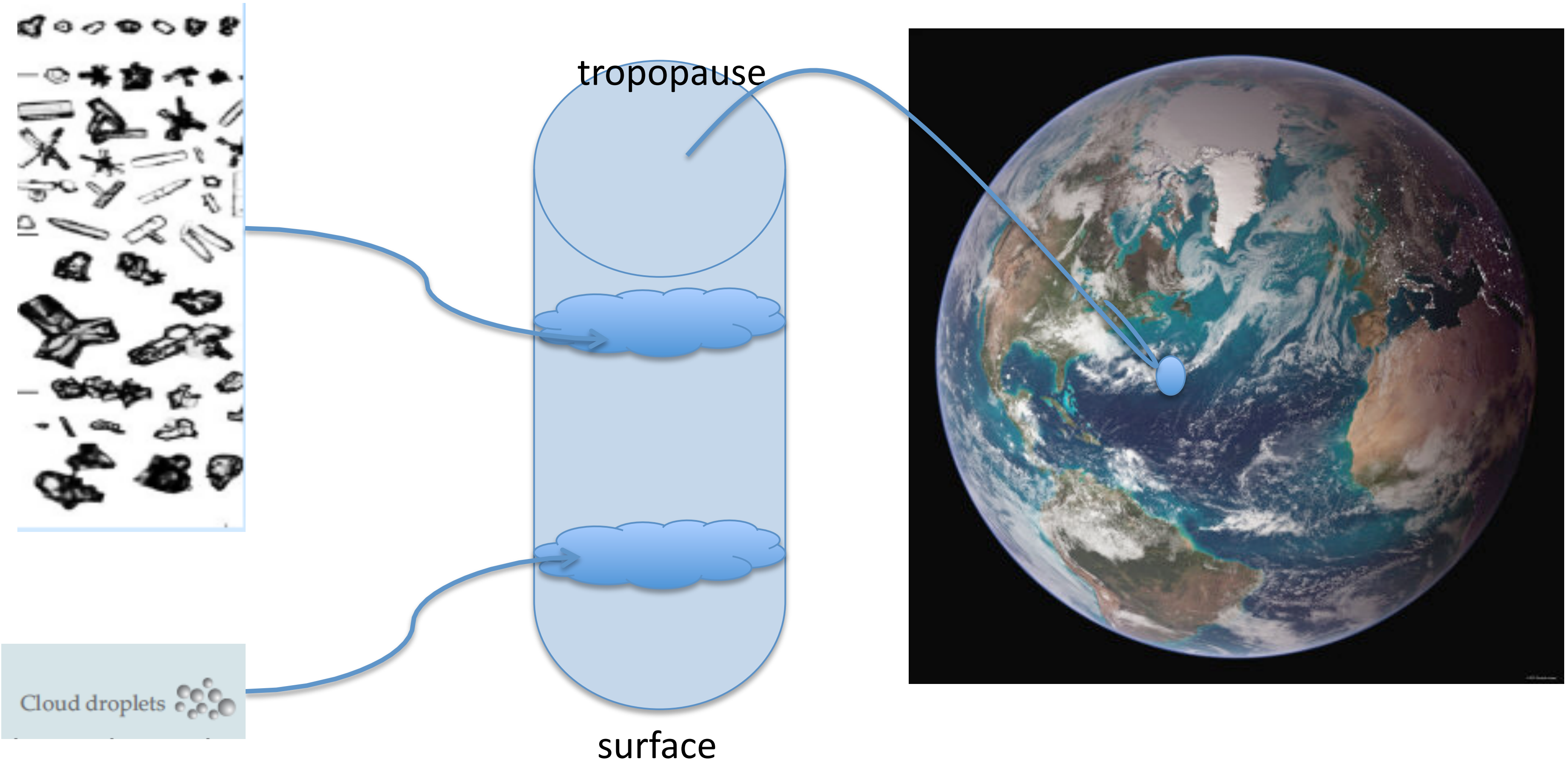
absorption / emission and-or scattering

Cloud - radiation interactions

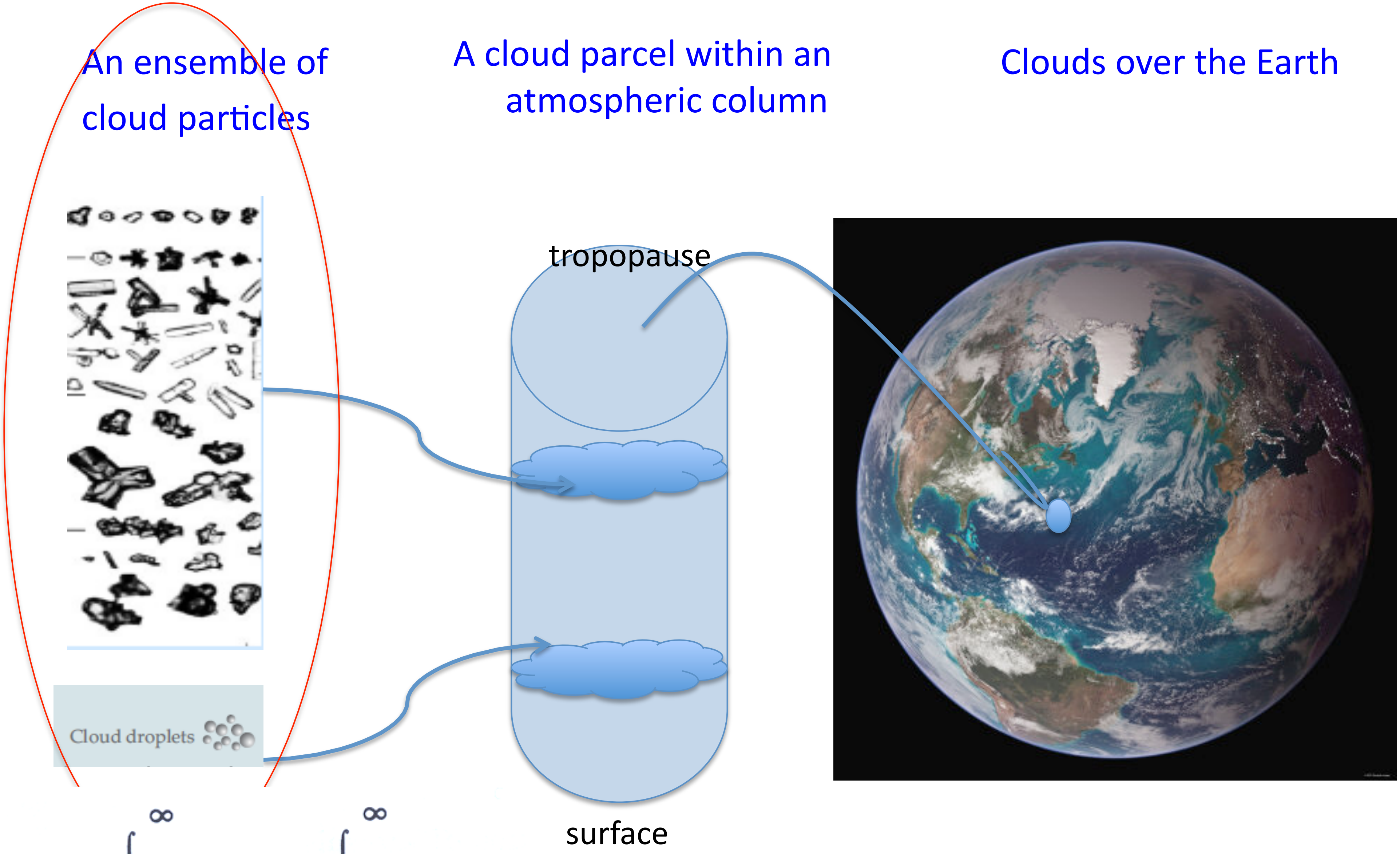
An ensemble of cloud particles

A cloud parcel within an atmospheric column

Clouds over the Earth



Cloud - radiation interactions

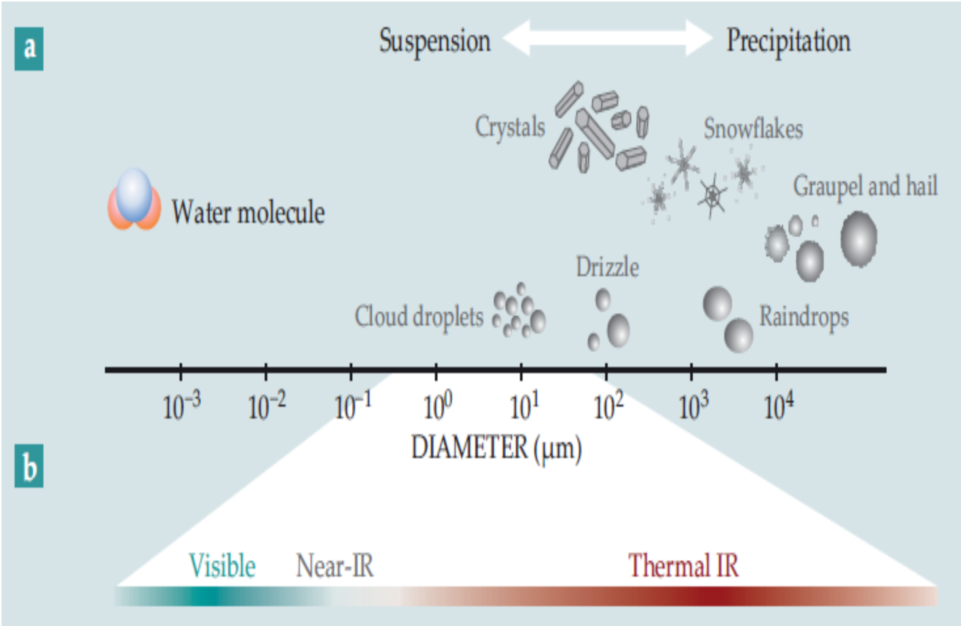


$$r_{\text{eff}} = \int_0^\infty r^3 n(r)\, dr \Big/ \int_0^\infty r^2 n(r)\, dr$$

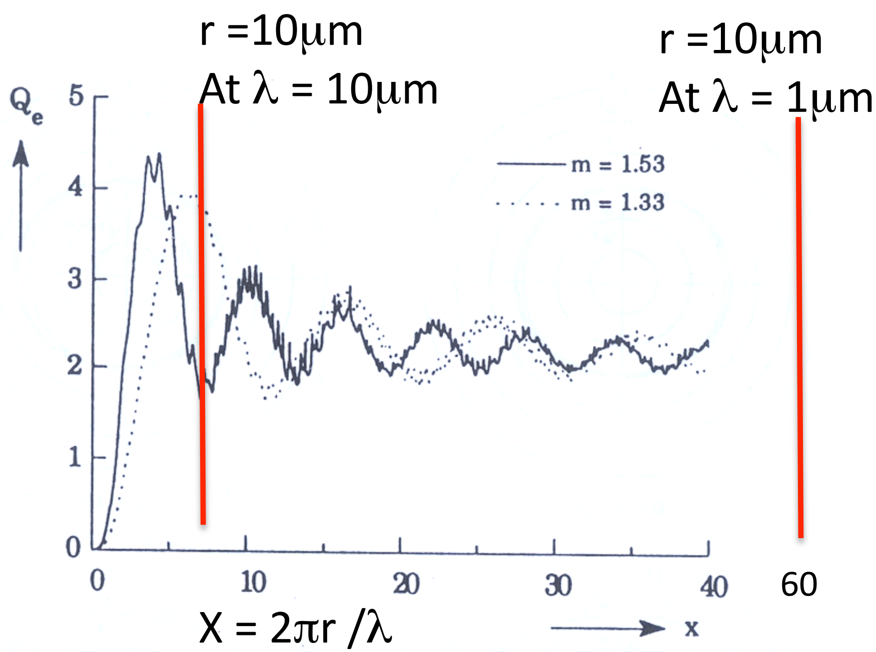
What drives interactions between an ensemble of cloud particles and radiation?

1) When do an ensemble of cloud particles and radiation interact?

=> Particle size .vs. Wavelength: the extinction efficiency



Stevens, Bony



⇒The particle cross section (1 particle) at λ : Cext = Qext.π. r^2 [m^2]

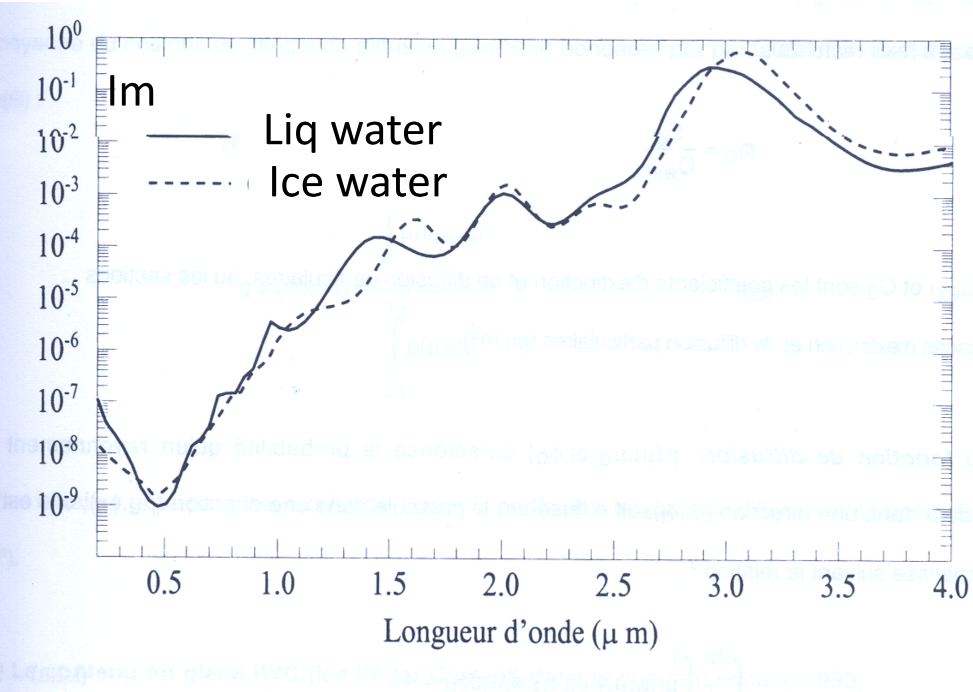
For a cloud particle, usually : Qext = 2 in the visible domain

⇒ Extinction coefficient (ensemble of particles) : $\sigma_{ext,\lambda} = \int C_{ext,\lambda}(r)n(r)dr$ [m^{-1}]

What drives interactions between an ensemble of cloud particles and radiation?

2) Absorption or scattering?

Index of refraction of liquid and ice, function of the wavelength



The extinction coefficient at λ [m^{-1}]:

$$\sigma_{ext} = \sigma_{sca} + \sigma_{abs}$$

The single scattering albedo (wo) at λ :

$$\omega_0 = \frac{\sigma_{sca}}{\sigma_{ext}}$$

Consequences for cloud particles :

Scattering dominates the visible domain : wo(vis) = 1

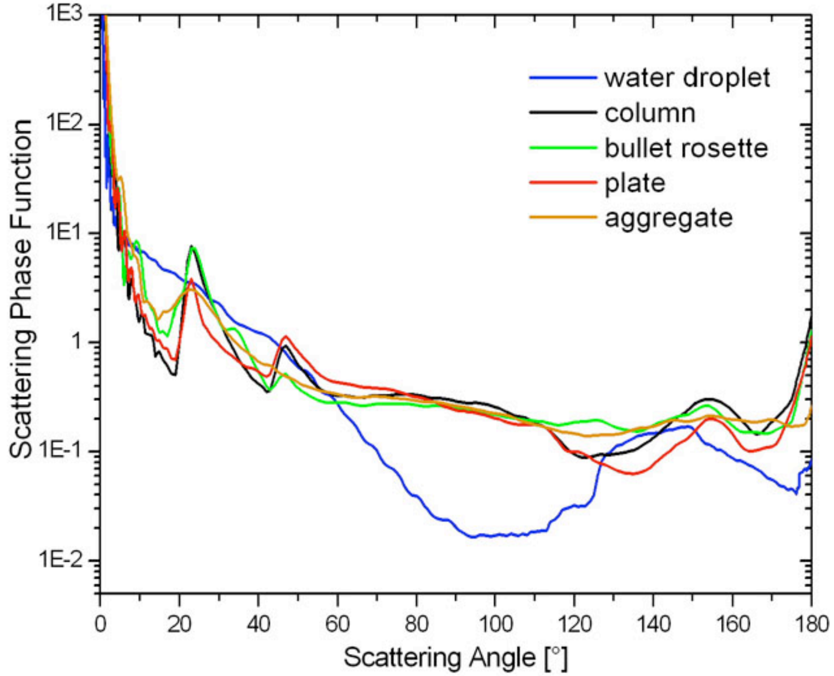
Absorption/emission dominate the thermal IR(but scattering also occurs): wo(IR) =0

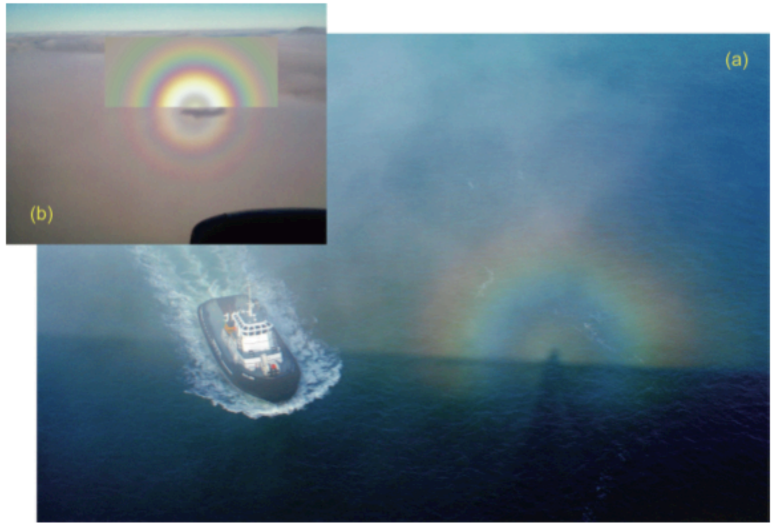
What drives interactions between an ensemble of cloud particles and radiation ?

3) Does the radiation change direction because of the interaction with cloud particles ?

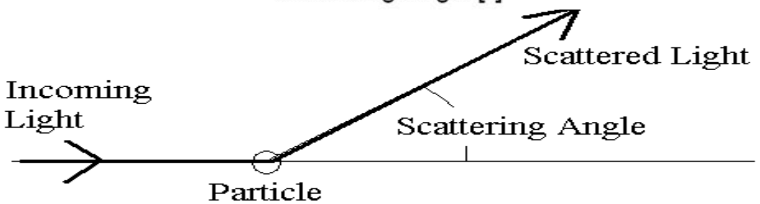
Absorption / Emission (IR) => isotropic
Scattering (VIS) => non isotropic

The particle scattering phase function P(Θ)[no unit]





autiful glory photographed from San Francisco's Golden Gate Bridge and by swirling fog above cold water (photograph courtesy of L. Zinkova). (b) Full-merical Mie simulation of scattering of sunlight from 4.8-μm-radius water drops posed on the photograph of a glory taken from a commercial aircraft (image of P. Laven).



The asymmetry factor : $g = \langle \cos \theta \rangle = \dfrac{\int_{-1}^{+1} \mu \, p(\mu) \, d\mu}{\int_{-1}^{+1} p(\mu) \, d\mu}$.

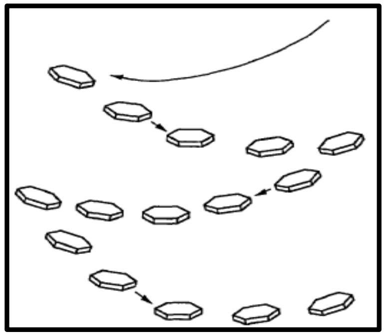
For cloud particles 0.7 < g< 0.99
depends on the shape and size

What drives interactions between an ensemble of cloud particles and radiation ?

4) What happens when cloud particles contain a significant amount of non –water component ?

⇒Absorption can occur in the VIS: the single scattering albedo decreases in the VIS (wo< 1)

5) Does the particle orientation in space (when non spherical) impact the interactions between radiation and cloud particles ?



⇒Change the Phase function P(Θ)

⇒ the Asymmetry factor : g decreases

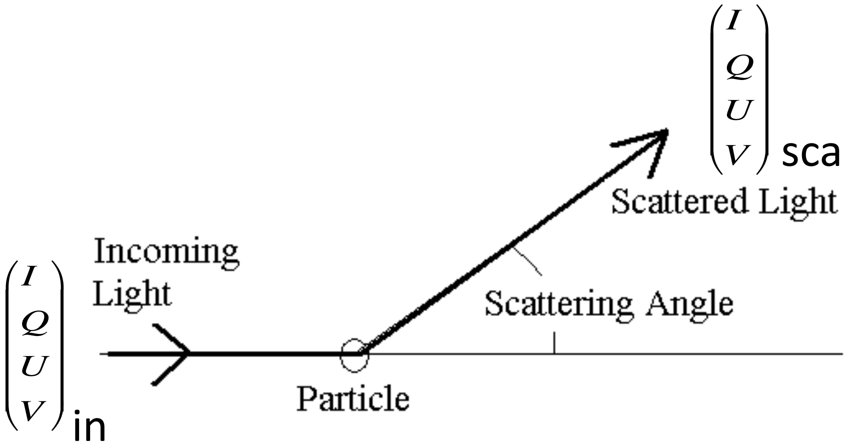
What drives interactions between an ensemble of cloud particles and radiation ?

6) Radiation is not only intensity, but also a state of polarization:

The state of polarization of the light changes because of the interaction with cloud particles

Stokes vector

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \qquad \begin{aligned} I &= E_l.E_l^* + E_r E_r^* \\ Q &= E_l.E_l^* - E_r E_r^* \\ U &= E_l.E_r^* + E_r E_l^* \\ V &= i\,(E_l.E_r^* - E_r.E_l^*) \end{aligned}$$



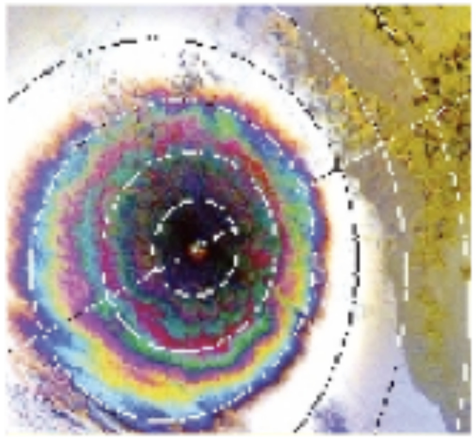
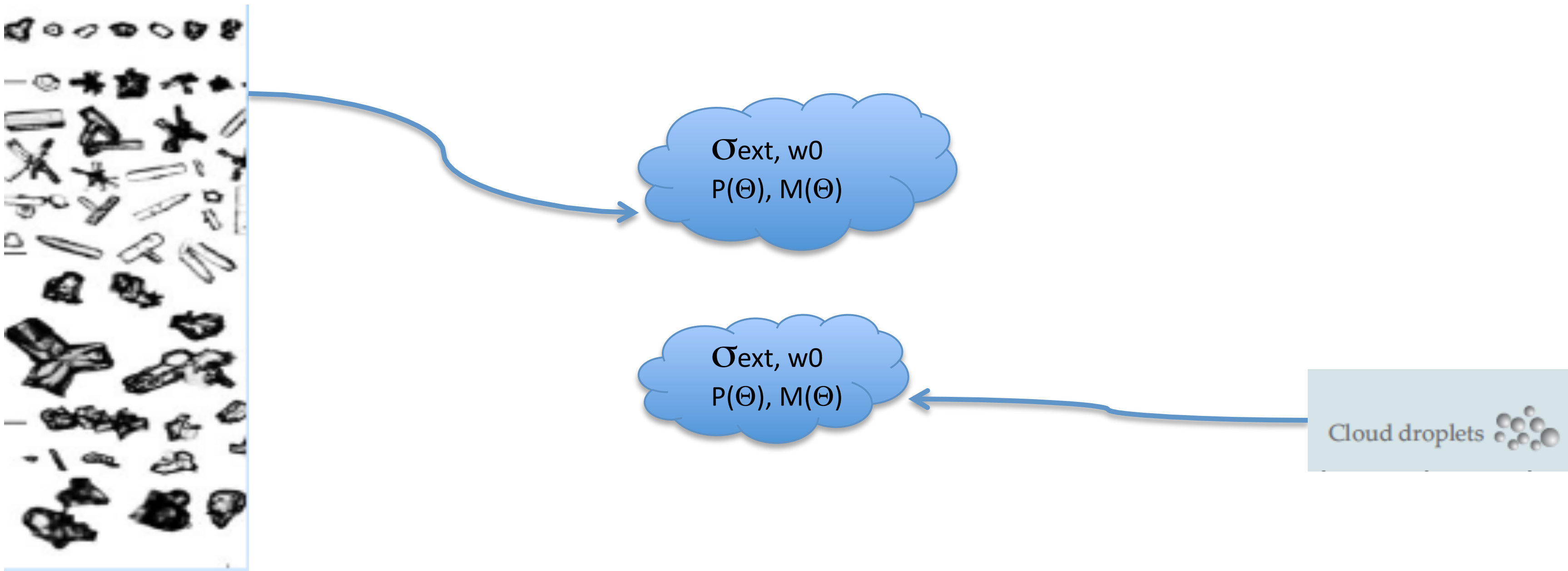


Figure 3: POLDER image showing polarization arcs observed in a cloud field off the coast of Africa.

Interactions between an ensemble of cloud particles and radiation: What formalism do we use to describe these processes?

The **cloud optical properties** defined, at a given wavelength, as

- Extinction coefficient(σ_{ext}) and single scattering albedo (wo)
- Scattering phase function P(Θ) and asymmetry factor (g)
- Scattering matrix (for describing the state of polarization) M(Θ)



Interactions between an ensemble of cloud particles and radiation

The cloud optical properties depend on coupling between wavelength and cloud microphysics: particle size (distribution), composition, shape, orientation in space

The cloud optical properties are critical because they link the cloud microphysical properties and its radiative properties

!! (σext, w0, P(Θ), M(Θ)) do NOT depend on the total amount of condensed water in the cloud

!! whereas « cloud radiative properties » depend on the total amount of condensed water in the cloud

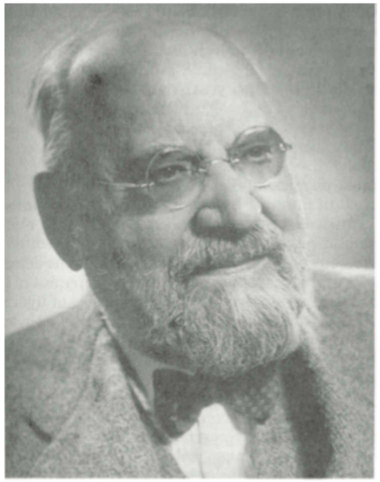
Interactions between an ensemble of cloud particles and radiation:
How do we estimate (or compute) the cloud optical properties ?

By solving the Maxwell equations,

With a realistic assumption :
« the independent or incoherent scattering »:
cloud particles are separated by distance much larger than their size; therefore there is no systematic relation between the phases of the waves scattered by the different particules, and the scattered intensity can be simply added

And some simplifications:
properties of symmetry of the « cloud medium »

A « simple » case: spherical homogeneous particles adapted to liquid clouds particles



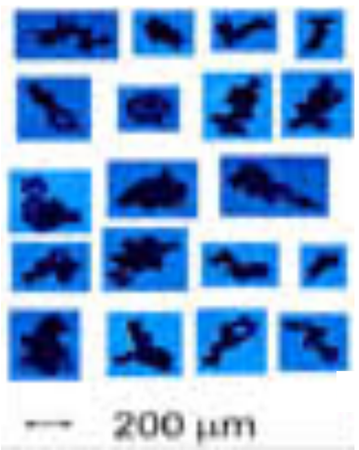
Gustav Mie

Ann. Phys. **1908,** *25*, 377	Contributions to the optics of turbid media, especially colloidal metal suspensions

Interactions between an ensemble of cloud particles and radiation:
How do we estimate (or compute) the cloud optical properties ? (cont'd)

More complex cases: non spherical particles, less symmetric

Formes réelles

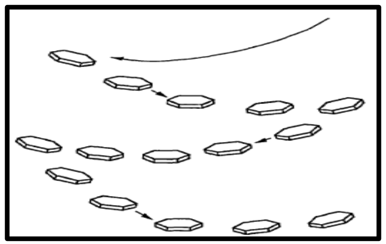


Formes modélisées

Approaches:
Geometrical Optic
Finite differential Time domain
Discrete Dipole Approximation…

Authors:
Van de Hulst
Eg. Mishchenko, P. Yang

Even more complex cases: non spherical particles, not randomly oriented in space



Van de Hulst
Y. Takano, V. Noel

Another complexity : cloud particles containing significant amount of non water component

Eg.A. Macke, or L. Labonnote

Interactions between an ensemble of cloud particles and radiation

Since Mie, a large scientific community has been studying particles optical properties for more than one century

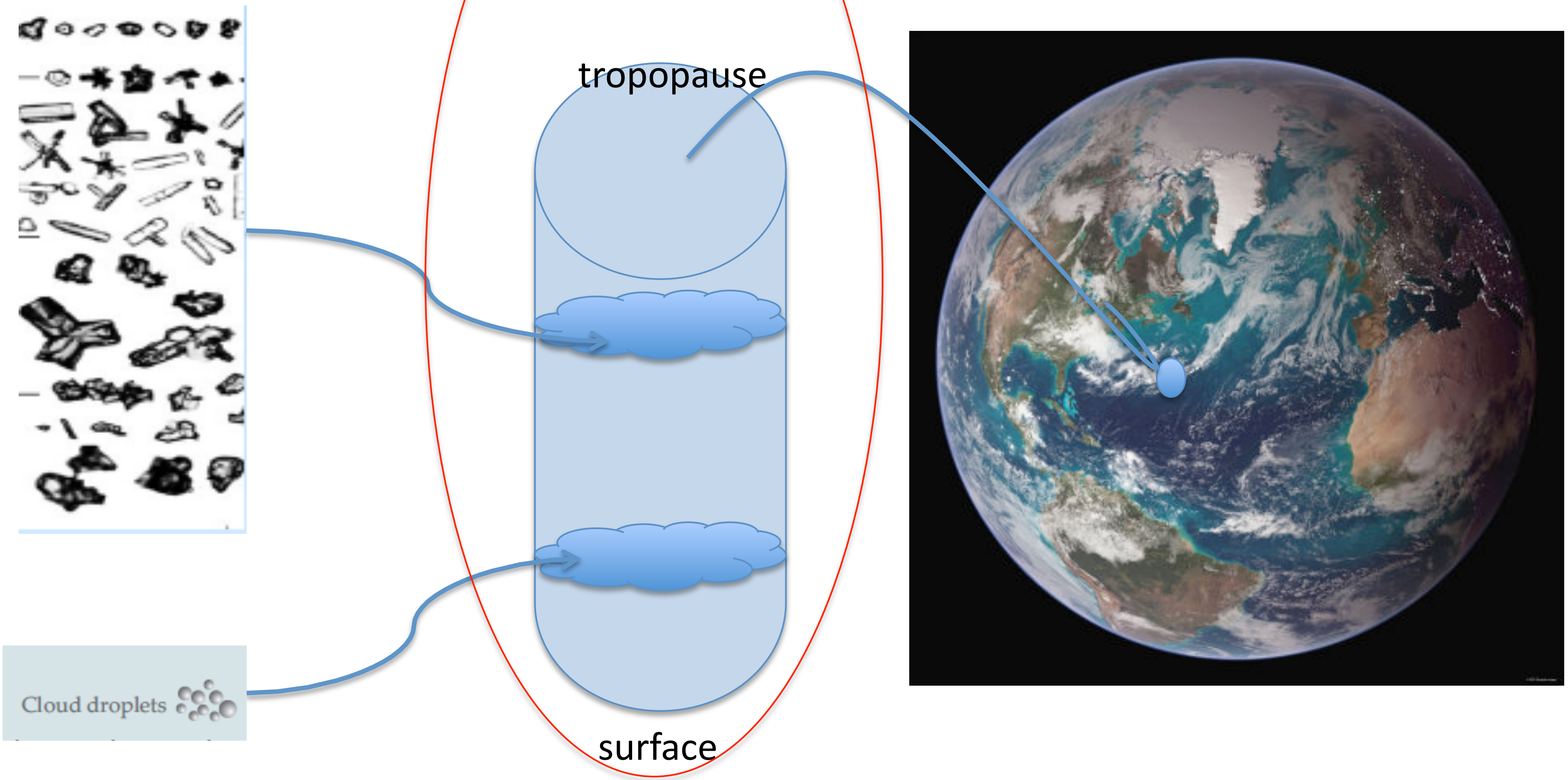
=> the results are easy to use for cloud spherical particles, for cloud non spherical particles, and for non pure liquid particles

Cloud - radiations interactions

An ensemble of cloud particles

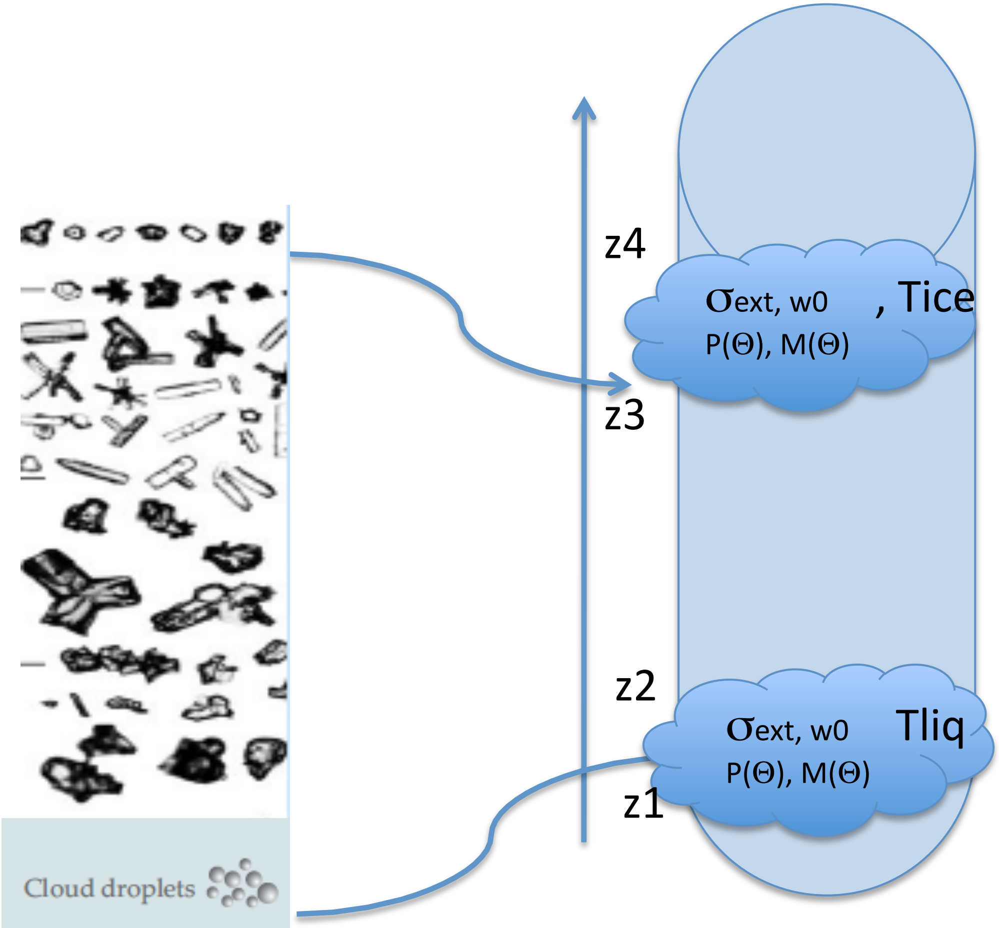
A cloud parcel within an atmospheric column

Clouds over the Earth



An ensemble of particles (or cloud parcel) within an atmospheric column

Hypothesis : At a given altitude level the composition of the column is homogeneous; fully clear or fully cloudy with constant optical properties



= >Ice water content:

IWC = $\rho\ 4/3.\ \pi r_{i,eff}^3\ .N$ [g.m-3]

⇒Ice cloud layer optical thickness:

$\tau_{\lambda\iota} = \sigma_{\lambda,ext}.\ \Delta z$ [no unit]

= > Liquid Water Content: LWC

LWC = $\rho\ 4/3.\ \pi r_{l,eff}^3\ .N$ [g.m-3]

=>Liquid cloud layer optical thickness:

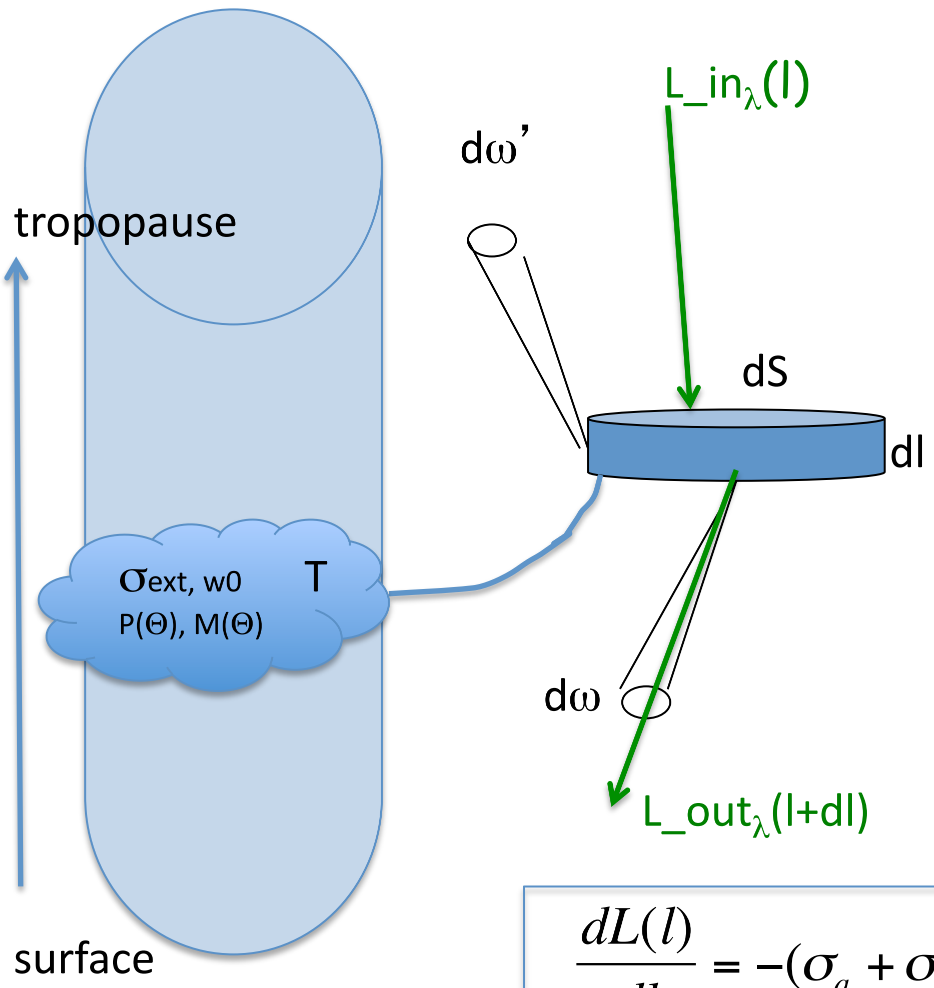
$\tau_{\lambda l} = \sigma_{\lambda,ext}.\ \Delta z$ [no unit]

=> $\tau_{\lambda} = 3\ LWC\ .Q_{\lambda,ext}.\ \Delta z./(4\rho\ r_{l,eff})$

Total column optical thickness: $\tau_{\lambda,}$_column = $\tau_{\lambda\iota} + \tau_{\lambda i}$

How do we describe the interactions between radiations and the element composing the atmospheric column (including clouds) ?

with the radiative transfer equation



At λ fixed:

$dL\_abs = -\sigma_a L_\lambda(l)dl$

$dL\_sca = -\sigma_{sca} L_\lambda(l)dl$

$$dL\_sca(d\omega' \rightarrow d\omega) = \sigma_{sca}\, dl. \iint_{espace} \frac{1}{4\pi} L_\lambda(M')P(M' \rightarrow M)$$

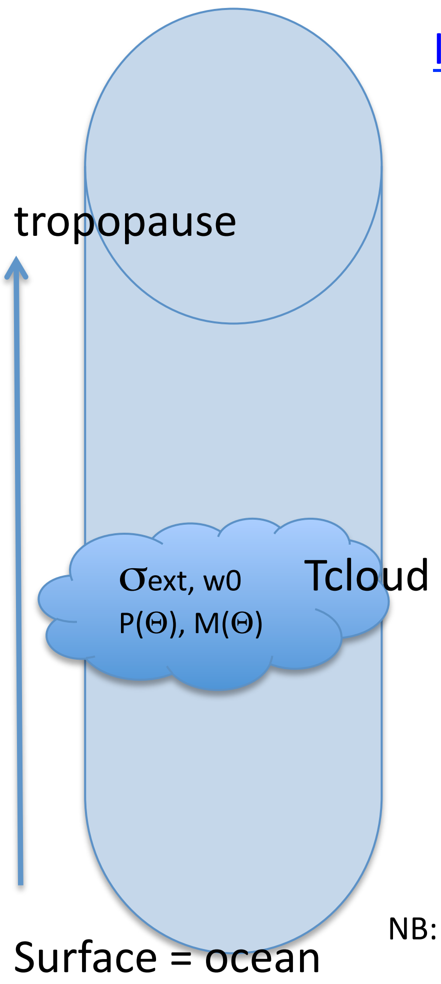
$dL\_emis = \sigma_a . B_\lambda(T)dl$

$$\frac{dL(l)}{dl} = -(\sigma_a + \sigma_{sca})L(l) + B(T)\sigma_a + \frac{\sigma_{sca}}{4\pi} \iint_{espace} P(l' \rightarrow l)L(l')d\omega'$$

Which cloud properties drive the radiances and fluxes within the atmospheric column ?

In stratified atmosphere, at a given λ, over ocean (no surface reflection)

$$L(\tau) = L(\tau o).\exp(-(\tau-\tau o)) + \int_{\tau o}^{\tau} d\tau'.\exp(-\tau')\left\{(1-\omega_0(\tau'))B(T(\tau')) + \frac{\omega_0(\tau')}{4\pi}\iint P(\tau',\theta)L(\tau')d\omega'\right\}$$



In the IR, no scattering in cloud particles (wo = 0) => τ and Tcloud drive L_IR

$$L_{IR,down}(\tau) = \int_0^{\tau} d\tau'.\exp(-\tau')\{B(T(\tau'))\}$$

$$L_{IR,up}(\tau) = L_{IR,surf}.\exp(-\tau) + \int_0^{\tau} d\tau'.\exp(-\tau')\{B(T(\tau'))\}$$

Approximation for opaque clouds: $\tau >> 1$ => L_{IR} is close to emission by a black body

$$L_{IR,down}(\tau) = L_{IR,up}(\tau) = B(Tcloud)$$

Approximation for optically thin clouds: $\tau << 1$

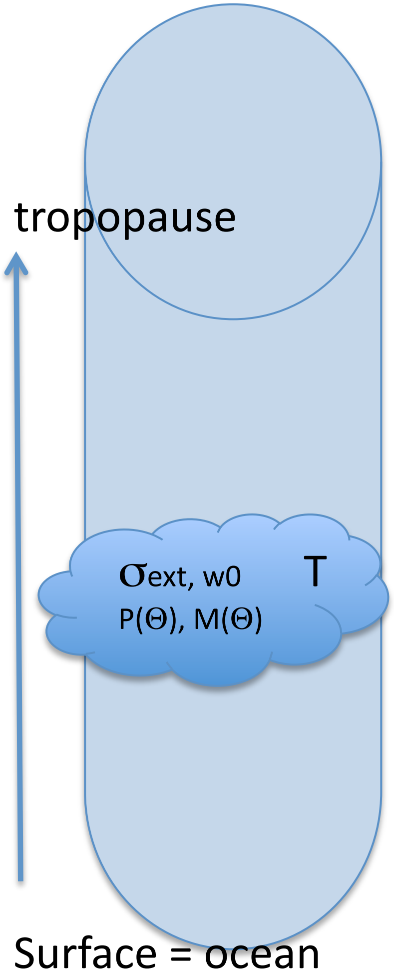
$$L_{IR,up}(\tau) \approx L_{IR,surf} + \tau.\left(B(Tcloud) - L_{IR,surf}\right)$$

NB: In the IR we can also use cloud émissivity (ε) instead of cloud IR optical thickness: $\varepsilon + \exp(-\tau_{IR}) = 1$

Which cloud properties drive the radiances and fluxes within the atmospheric column ?

In stratified atmosphere, at λ fixed, over ocean (no surface reflection)

$$L(\tau) = L(\tau o).\exp(-(\tau - \tau o)) + \int_{\tau o}^{\tau} d\tau'.\exp(-\tau')\left\{(1-\omega_0(\tau'))B(T(\tau') + \frac{\omega_0(\tau')}{4\pi}\iint P(\tau',\theta)L(\tau')d\omega'\right\}$$



In the VIS, no absorption in cloud particles (wo = 1)=> τ and P(Θ) drive Lvis

$$L_{vs,down}(\tau) = L_{vis,sun}.\exp(-\tau) + \int_0^{\tau} d\tau'.\exp(-\tau')\left\{\frac{1}{4\pi}\iint P(\tau',\theta)L(\tau')d\omega'\right\}$$

$$L_{vis,up}(\tau) = \int_0^{\tau} d\tau'.\exp(-\tau')\left\{\frac{1}{4\pi}\iint P(\tau',\theta)L(\tau')d\omega'\right\}$$

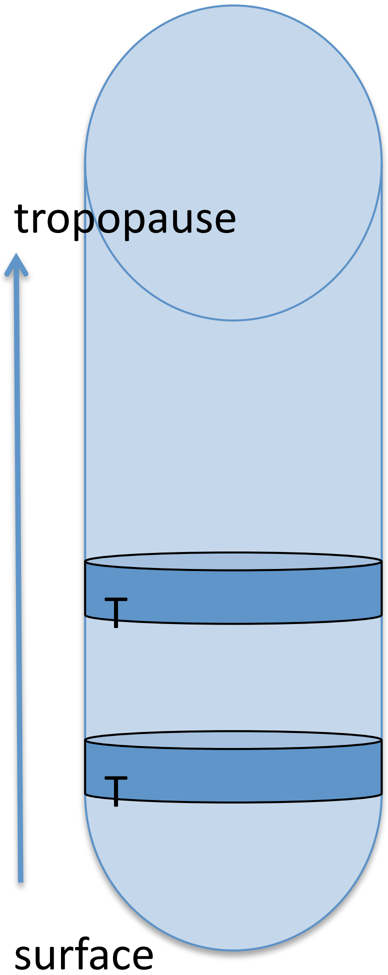
Approximation for opaque clouds: τ >> 1 => L_{sw} becomes isotropic because of multiple scattering

$$L_{vis,up}(\tau) = L_{vis,down}(\tau) = \int_0^{\tau} d\tau'.\exp(-\tau')\left\{\frac{1}{4\pi}\iint P(\tau',\theta)L(\tau')d\omega'\right\}$$

Approximation for optically thin clouds: τ << 1 => close to single scattering

$$L_{vis,up}(\tau) \propto\approx (1-g)\tau$$

How do we estimate (compute) the radiative transfer in a cloudy column ?



Resolving the Radiative transfert Equation to estimate the radiances and fluxes at all levels in the atmosphere: computing the radiances, and integrating it over directions to obtain fluxes

Main constrains for clouds: Anisotropic in the SW & Clouds can be optically thick

Several methods:

various analytical formulation, and numerical computations

Ex; Successive ordre of scattering
Ex; Discrete ordinate method
Ex; Doubling adding method => POWERFUL for OPTICALLY THICK CLOUDS
Ex; Monte Carlo
Ex; approximate two streams (Eddington method) and four streams methods for fluxes

The results of these computations depend significantly on the amount of condensed water in the cloud, the cloud temperature and the cloud optical properties

In the above mentioned methods, the atmosphere is assumed to be plane-parallel infinite.

Uncertainties on the computation of radiative transfer in a cloudy column ?

- The uncertainty is small within « the plane parallel infinite approximation »

Intercomparison exercises: http://circ.gsfc.nasa.gov/CIRC_publications.html

NB: Do not misunderstand uncertainty in the radiative transfer computation with uncertainty in the optical properties: the cloud optical properties are very variable

- But in reality: clouds are not necessarily plane paralle infinite

The importance of this effect depends on the scale studied

Intercomparison exercises for 3D effects
http://i3rc.gsfc.nasa.gov/I3RC-intro.html

Barker. 2012

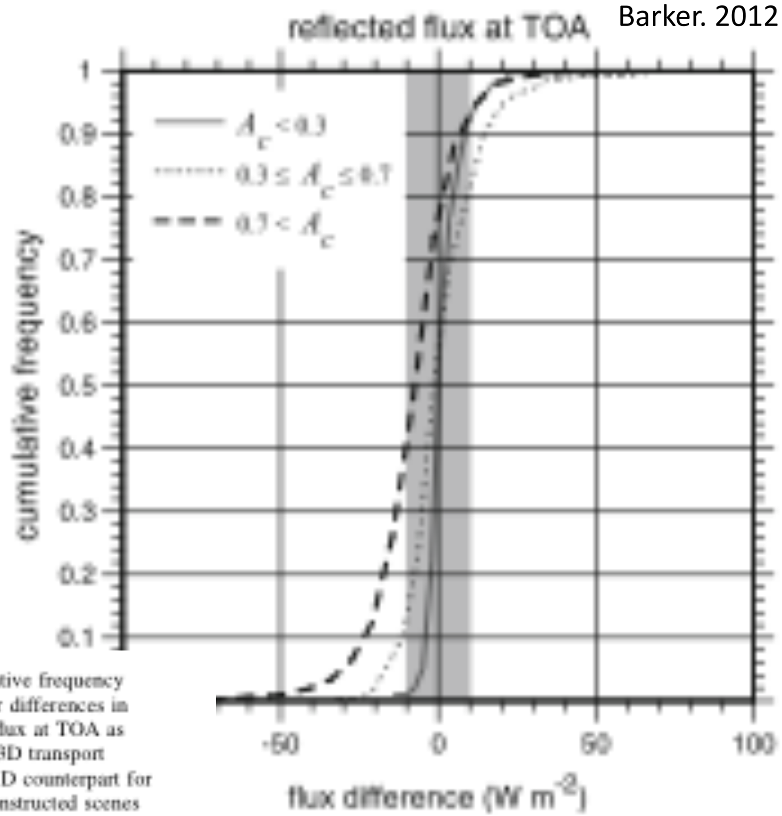


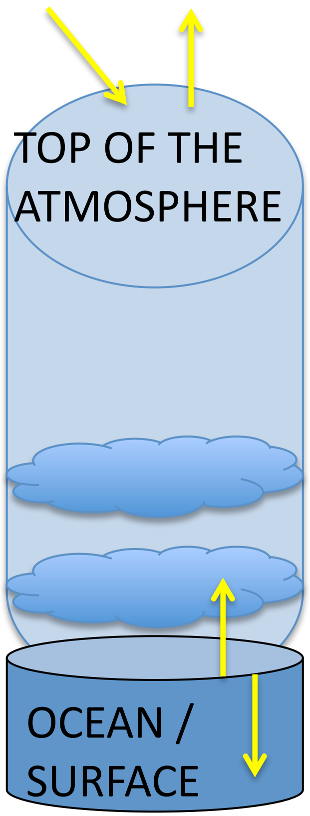
Fig. 9 Cumulative frequency distributions for differences in reflected solar flux at TOA as predicted by a 3D transport model and its 1D counterpart for 50 × 50 km constructed scenes

Is the column (atm + surf) warmed or cooled by radiative exchanges ? the Net downward Flux (Fnet)

Fnet = F in – F out

Fnet > 0 => the column warms

Fnet < 0 => the column cools



Fnet_TOA indicates how the entire column (atmosphere+surf) warms/cools

Fnet_Atmosphere indicates how the atmosphere warms/cools:

Fnet_Atmosphere = Fnet_TOA – Fnet_Surface

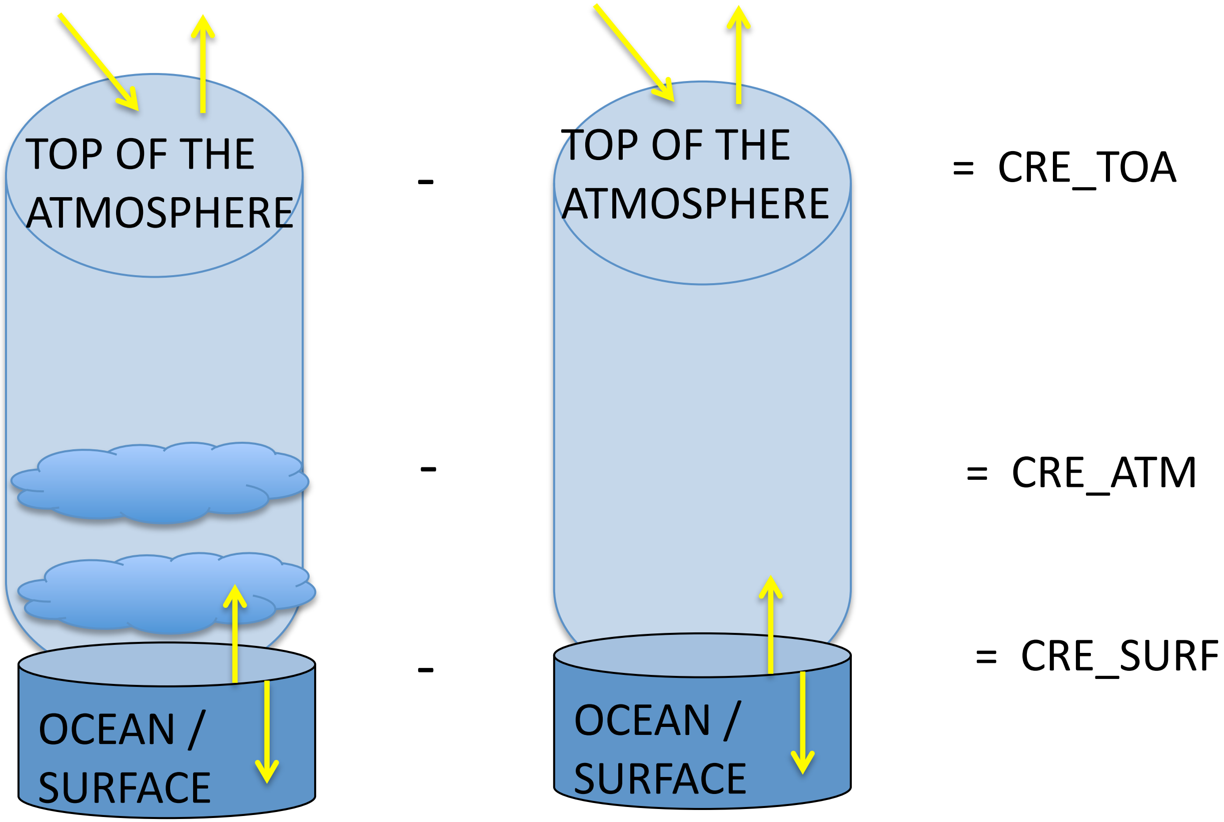
Fnet_Surface indicates how the ocean and surface warms/cools

Do clouds contribute to warm or cool the column (atm + surf) ?
the Cloud Radiative Effect (CRE)

CRE = Fnet_allsky – Fnet_cloudfreesky

CRE > 0 => the clouds contribute to warm

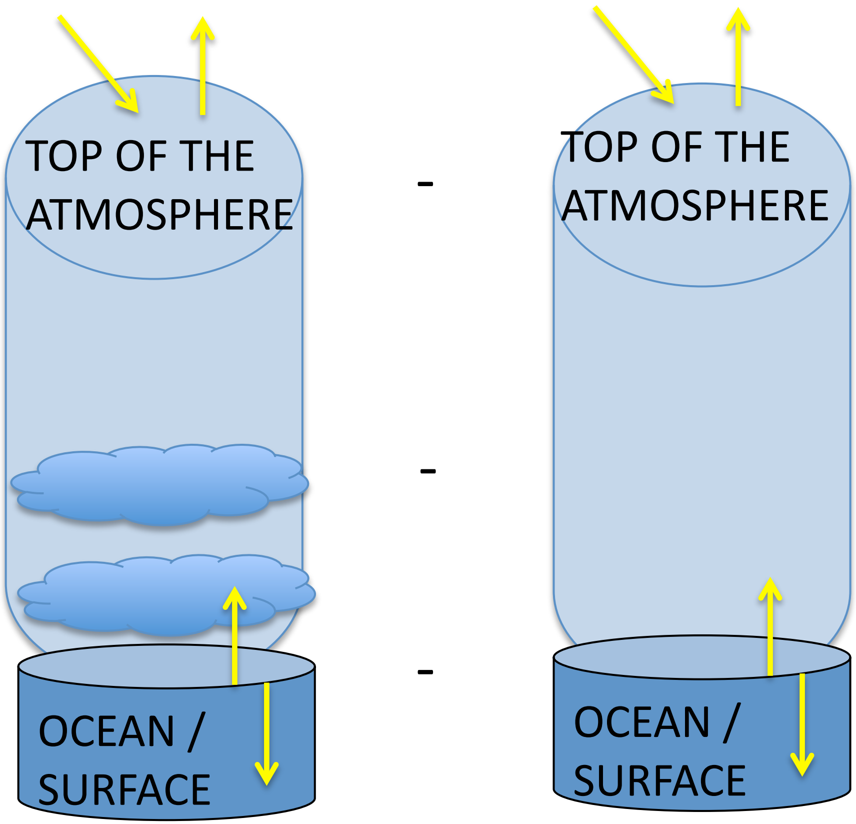
CRE < 0 => the clouds contribute to cool



Do clouds contributes to warm or cool the column (atm + surf) ?

$$CRE = CRE\_SW + CRE\_LW$$

$$= (Fnet\_allsky - Fnet\_cloudfreesky)_{SW} + (Fnet\_allsky - Fnet\_cloudfreesky)_{LW}$$

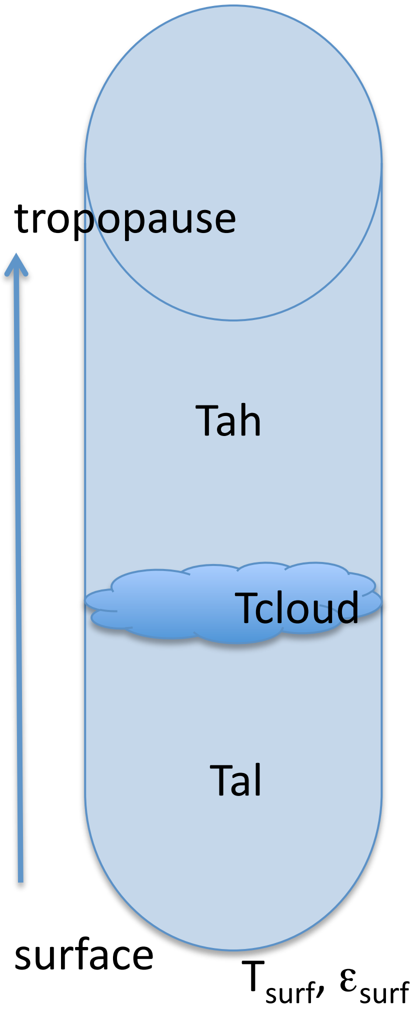


= CRE_TOA
= CRE_TOA_LW + CRE_TOA_SW

= CRE_ATM
= CRE_ATM_LW + CRE_TOA_SW

= CRE_SURF
= CRE_SURF_LW + CRE_SURF_SW

Does this mean cloud warm or cool the entire column ? The surface ? The Atmosphere ?



Fsw Lvis, depends on clouds : $\tau_{vis,cloud}$ (and g) with τ_{vis} ➔LWC/r
and on the surface

Flw Llw depends on clouds: Tcloud and τ_{ir_cloud} (or ε_{cloud}) ➔LWC.Qext/.r
and on the surface
(and on atmospheric gazes, T(z))

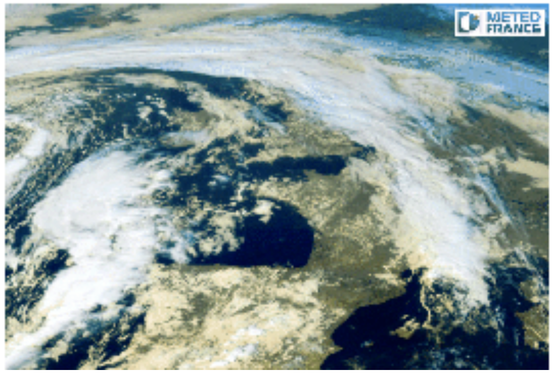
3 atmospheric layers + surface

Does this mean cloud warm or cool the entire column ?
The surface ? The Atmosphere ?

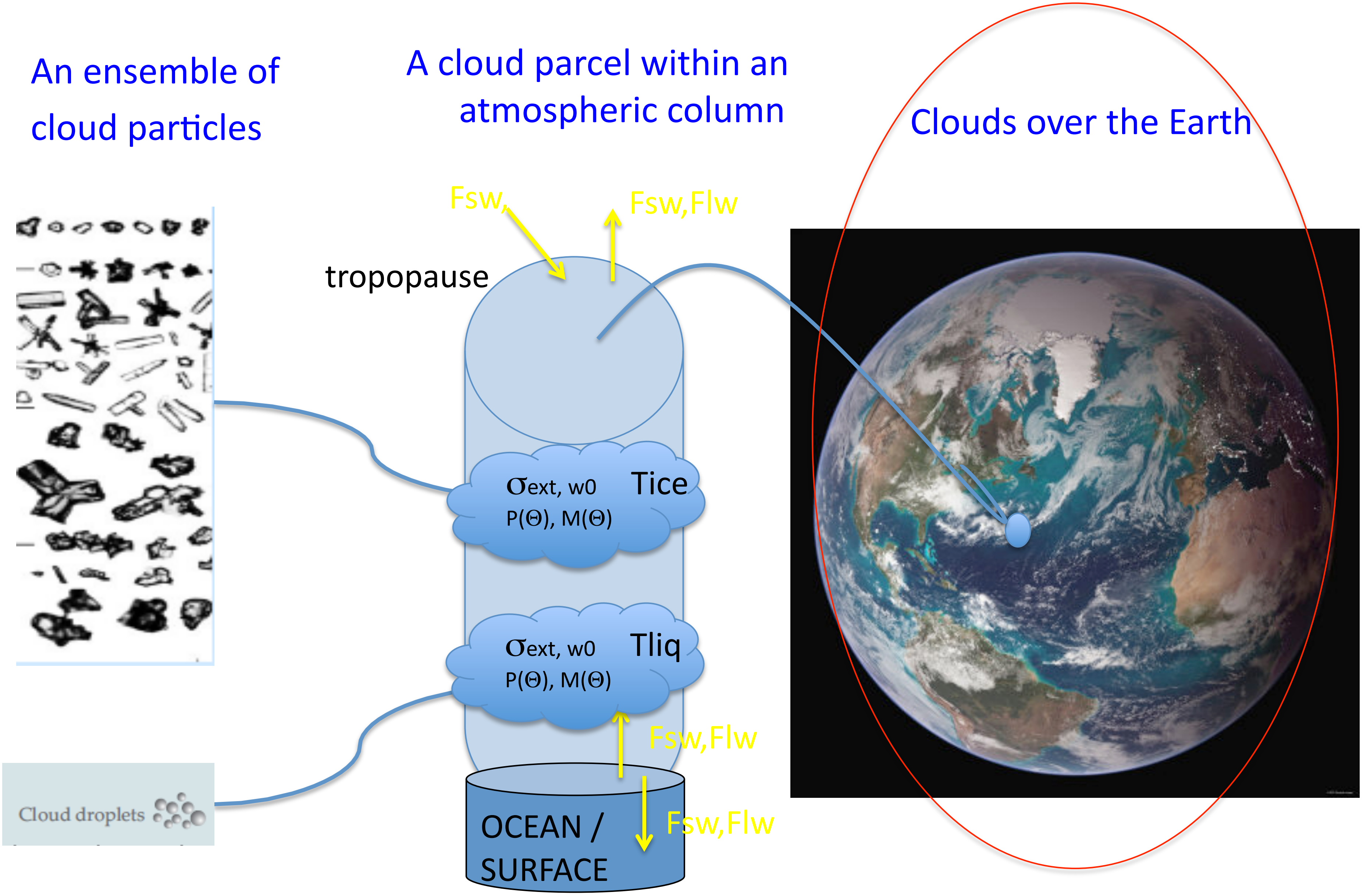
OVER OCEAN

OVER ICE or SNOW

More complex cases:



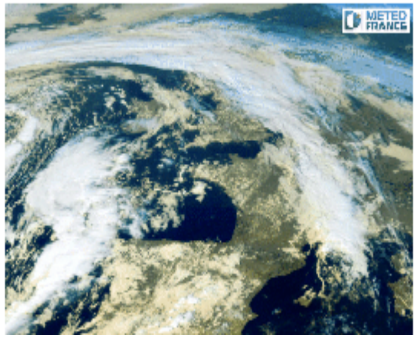
Cloud - radiation interactions

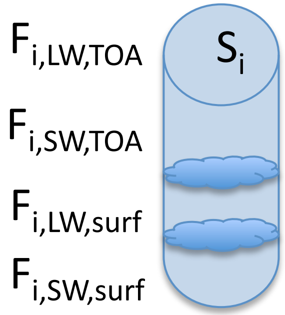


Clouds & radiation at global scale

Hypothesis: The Atmosphere = a sum of n independent atmospheric « homogeneous columns* » with small (and not constant) horizontal extents (S_i)

* At a given altitude level the composition of the column is homogeneous fully clear or fully cloudy with constant optical properties





The global flux : $F = \sum_{i=1}^{n} C_i F_i$ n = the total nb of columns

C_i is the cover of 1 column (i) : $C_i = \dfrac{S_i}{S_{Earth}}$ => $\sum_{i=1}^{n} C_i = 1$

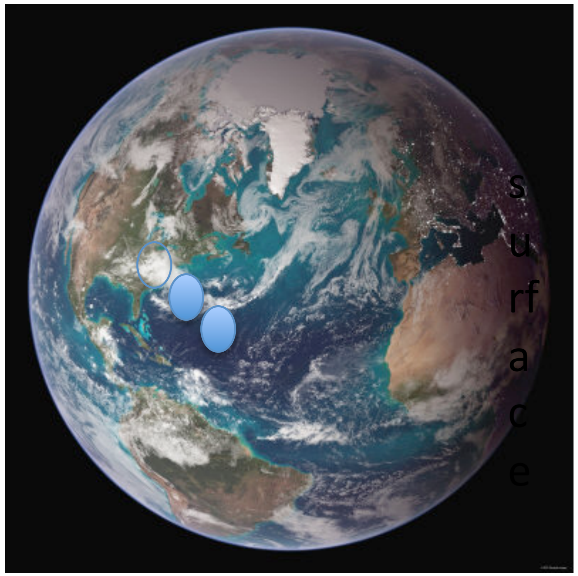
F_i is the flux for 1 homogeneous column (i)

$$F = C_{clear}F_{clear} + C_{aerosols}F_{aerosols} + \sum_{cloudtype=1}^{k} C_{cloudtype}F_{cloudtype}$$

$$F_{SW,TOA} = \dots$$

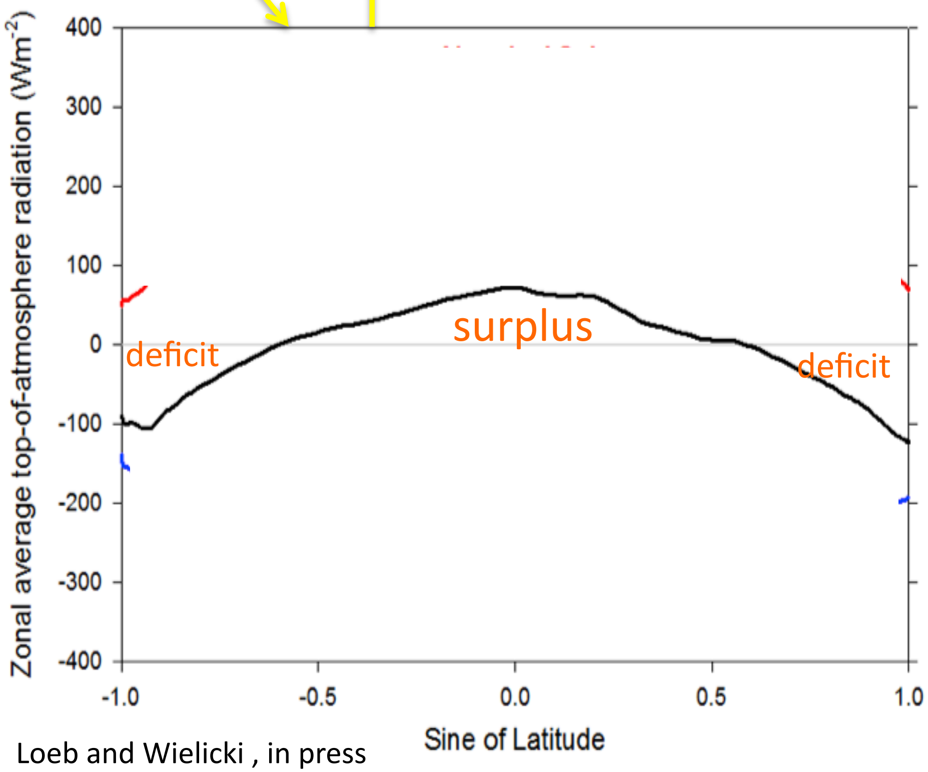
$$F_{LW,TOA} = \dots$$

$$F_{NET,TOA} = \dots$$



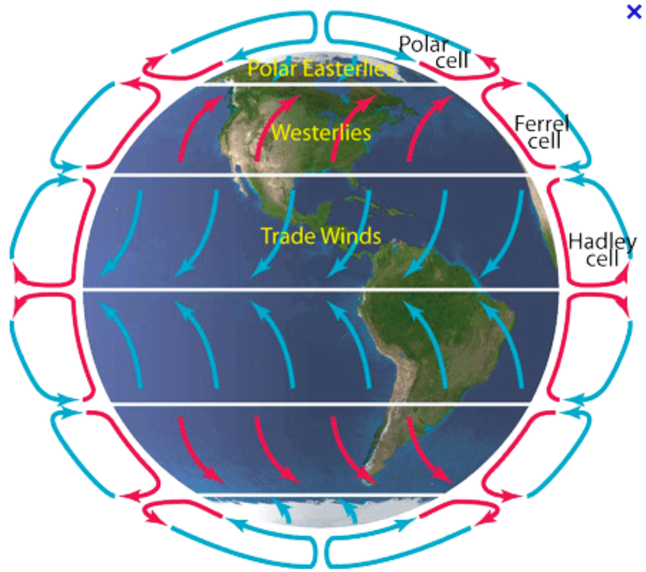
Clouds & radiation <u>at global scale</u>

$F_{NET\_TOA} = F_{in} - F_{out}$ $= F_{NET\_TOA\_SW} + F_{NET\_TOA\_LW}$



Loeb and Wielicki , in press

⇒The Earth's radiation budget :
driver of the atmospheric circulation



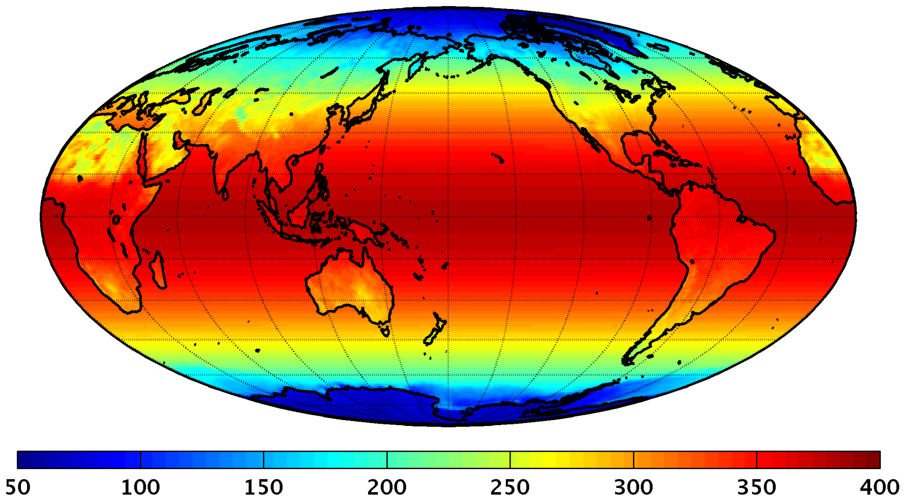
The cloud radiative effect modulates the Earth's radiative budget

Net Downward Shortwave Radiation at Top-of-Atmosphere (CERES)

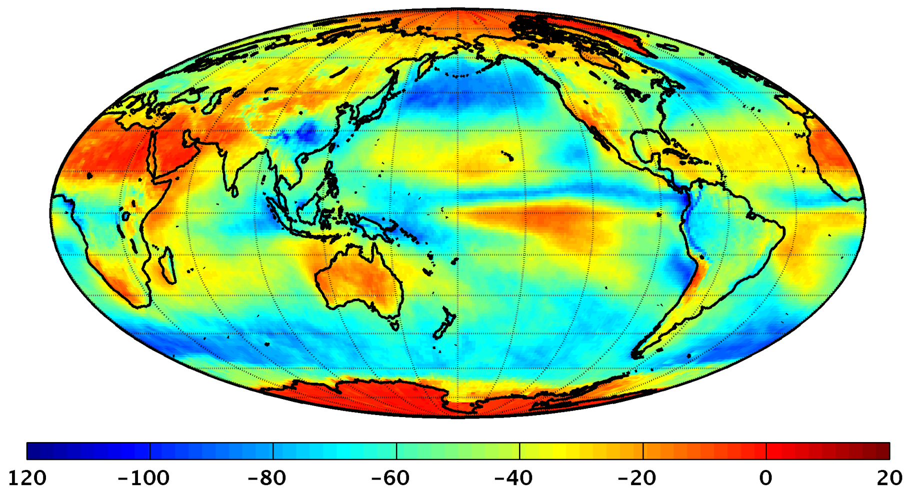
$F_{NET\_TOA} = F_{in} - F_{out}$

$CRE_{TOA} = F_{NET\_TOA\_allsky} - F_{NET\_TOA\_cloudyfreesky}$

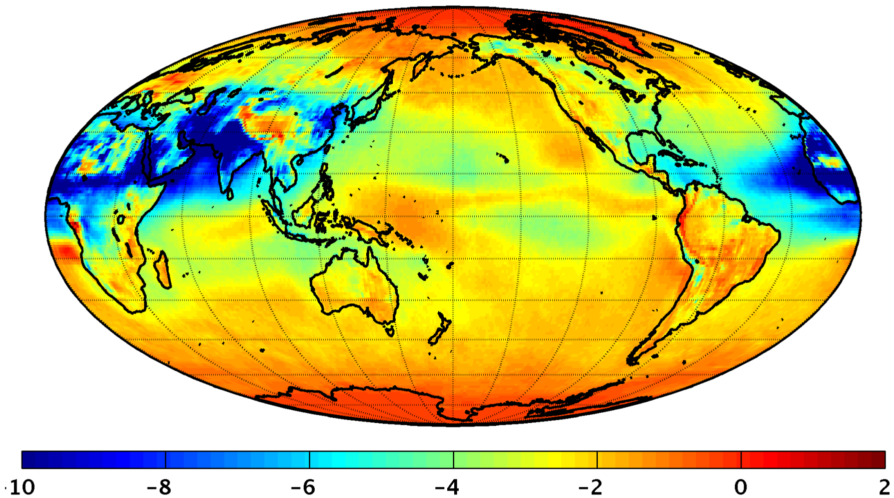
No Aerosols; No Clouds (291 Wm^{-2})



Cloud Radiative Effect (-47 Wm^{-2})

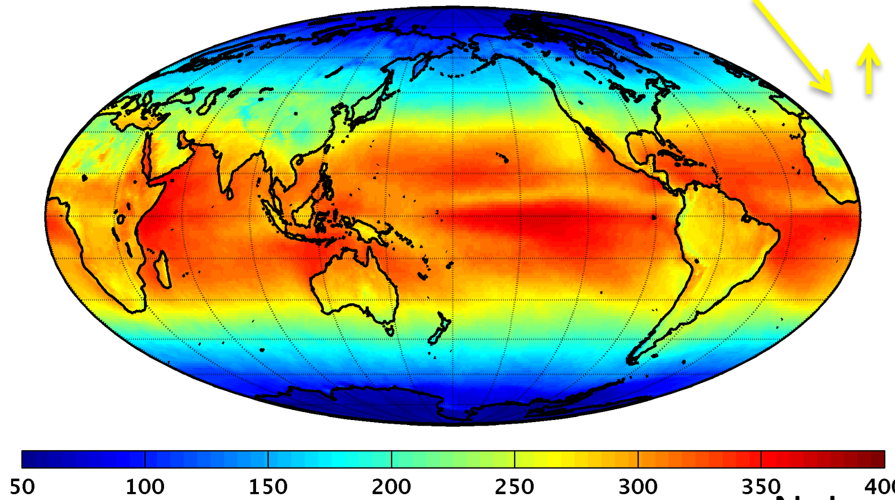


All-Sky Aerosol Direct Radiative Effect (-3 Wm^{-2})



All-Sky (241 Wm^{-2})

$F_{NET\_TOA} = F_{in} - F_{out}$

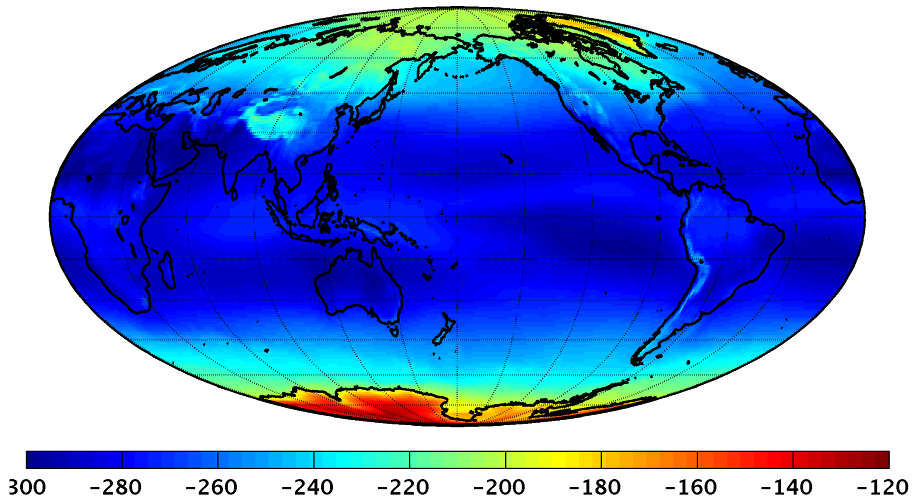


N. Loeb

Net Downward Longwave Radiation at Top-of-Atmosphere (CERES)

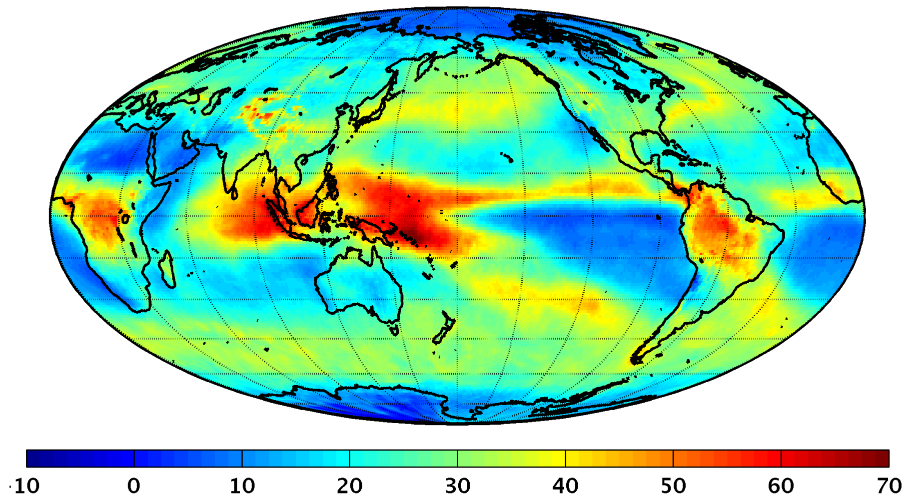
$F_{NET\_TOA} = F_{in} - F_{out}$

No Aerosols; No Clouds (-267 Wm^{-2})

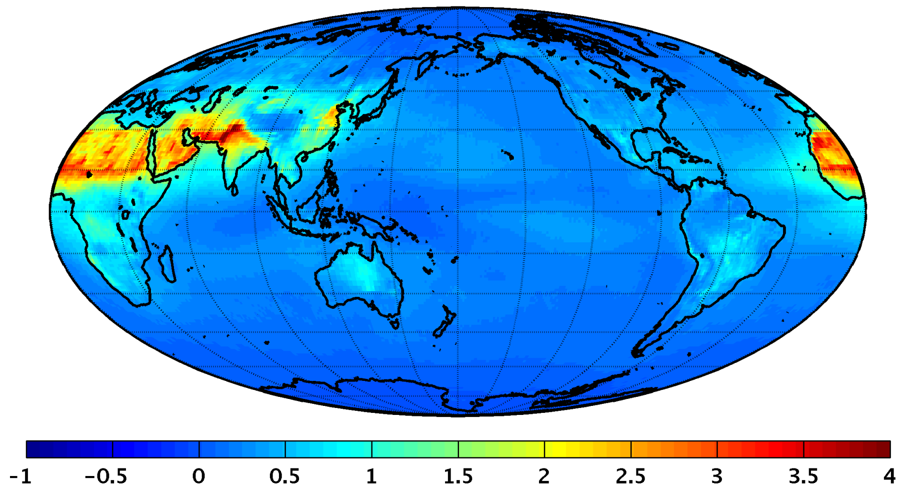


$CRE_{TOA} = F_{NET\_TOA\_allsky} - F_{NET\_TOA—cloudyfreesky}$

Cloud Radiative Effect (27 Wm^{-2})

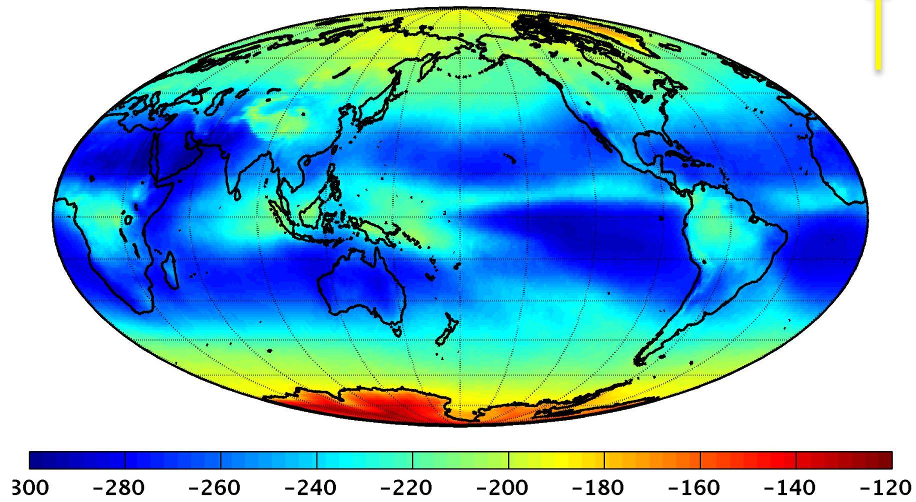


All-Sky Aerosol Direct Radiative Effect (0.4 Wm^{-2})



$F_{NET\_TOA} = F_{in} - F_{out}$

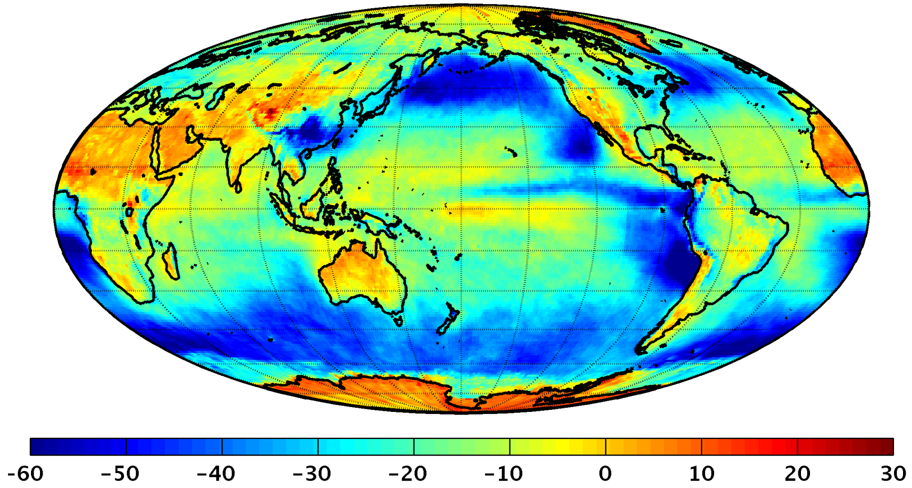
All-Sky (-240 Wm^{-2})



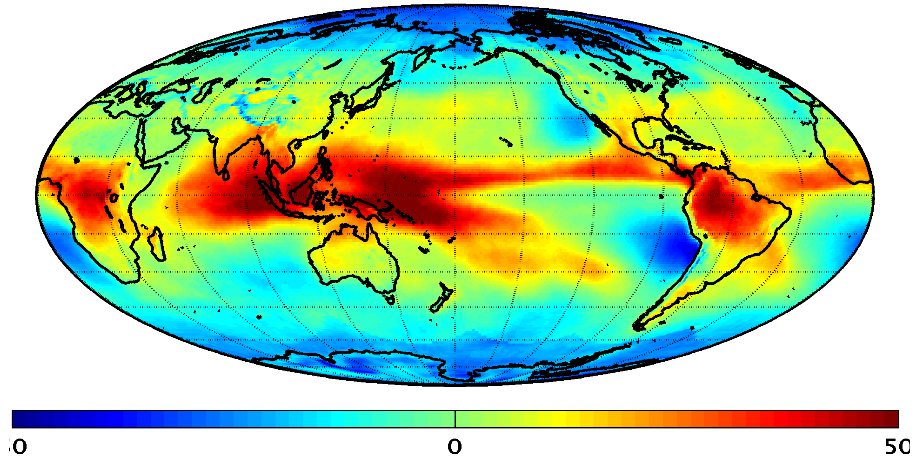
N. Loeb

Net Cloud Radiative Effect (TOA, ATM, SFC) (CERES)

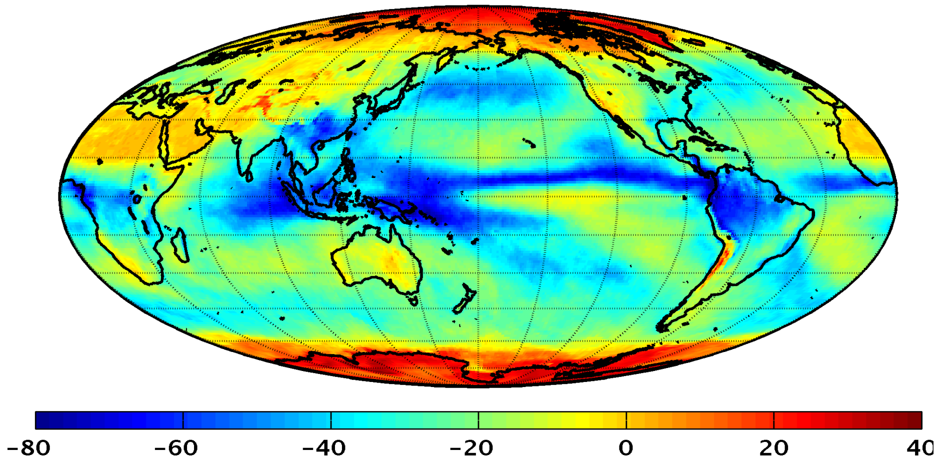
Top-of-Atmosphere (-20.6 Wm^{-2})



Within-Atmosphere (2 Wm^{-2})



Surface (-22.3 Wm^{-2})

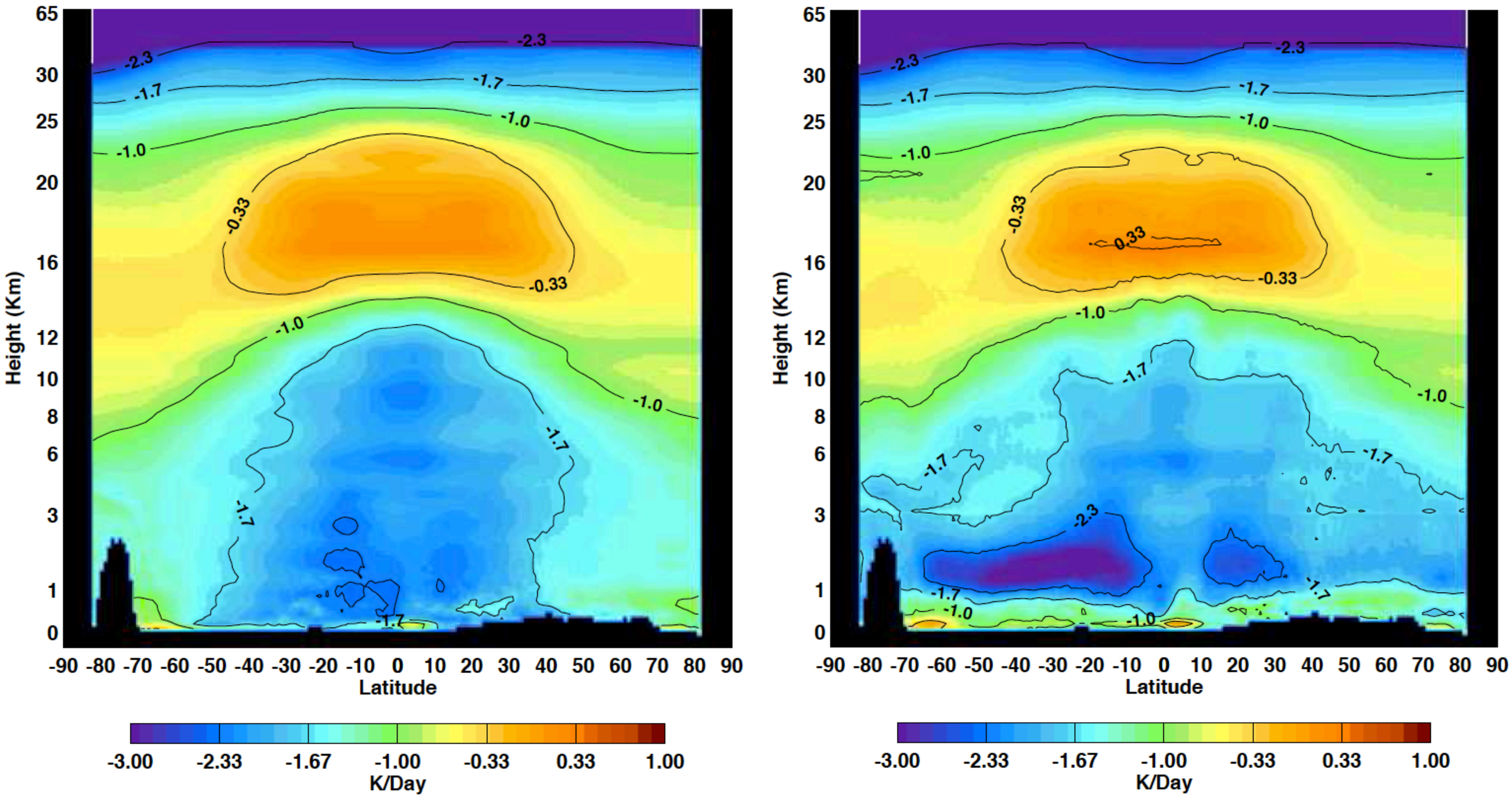


- **High Clouds**
  - SW & LW CRE cancel at TOA (both large).
  - SW CRE (cooling) dominates at SFC.
  - Positive within-atmos net CRE (warming).
- **Low Clouds**
  - SW CRE (cooling) dominates at TOA.
  - SW & LW CRE cancel at SFC (both large).
  - Negative within-atmos net CRE

N. Loeb

Vertical Distribution of Longwave Atmospheric Heating Rate

Clear-Sky / All-sky

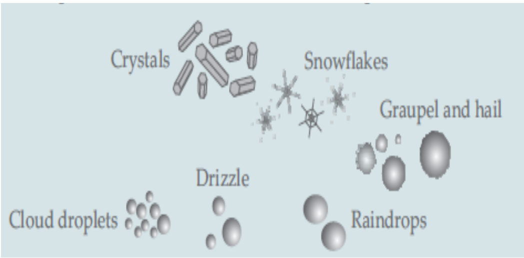


Clouds warm the upper troposhere and cool the lower troposphere

S. Kato

In summary: Clouds and radiation…

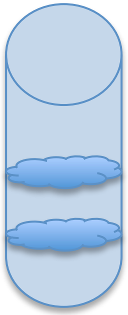
… from a cloud particle …



Key variables, the optical properties: Cext, Csca, wo, P(Θ), g
Sensitive to λ, r_eff, n(r) -- simplified by the composition (water)

Results for spheres (liquid) and non spherical (ice) idealized shapes: typical values and computation codes are available

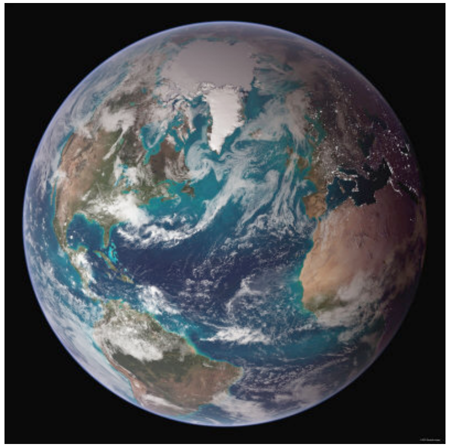
… to a cloud parcel within an atmospheric column…



Key variables: LWC (LWP), IWC(IWP), τ_{vis}, τ_{IR}, $L_{up,SW/LW}$, $L_{down,LW/SW}$, $F_{up,SW/LW}$, $F_{down,LW/SW}$
Sensitive to : the amount and the vertical distribution (T_{cloud}) of condensed water, the optical properties, the surface properties

Solving the radiative transfer equation: results and codes 1D and 3D available
…the simple analytical formulas are valid in very few idealized cases

… to the Earth radiative budget



Key variables: Ci, Fi, Fsw, Flw, Fnet (at TOA, surface and within atmos), the CRE

Sensitive to: all what has been mentionned above

↓

requires to know every time, every where, the state of the atmosphere

Learn to use optical properties

Optimize radiative transfer computations for specific applications (ie. satellite retrievals, or GCMs): time .vs. accurancy

Impact of 3D SW effects , depends on the scale

Radiative transfer is very sensitive to the detailed description of the atmospheric column:

-global scale mean fluxes, Ts estimates