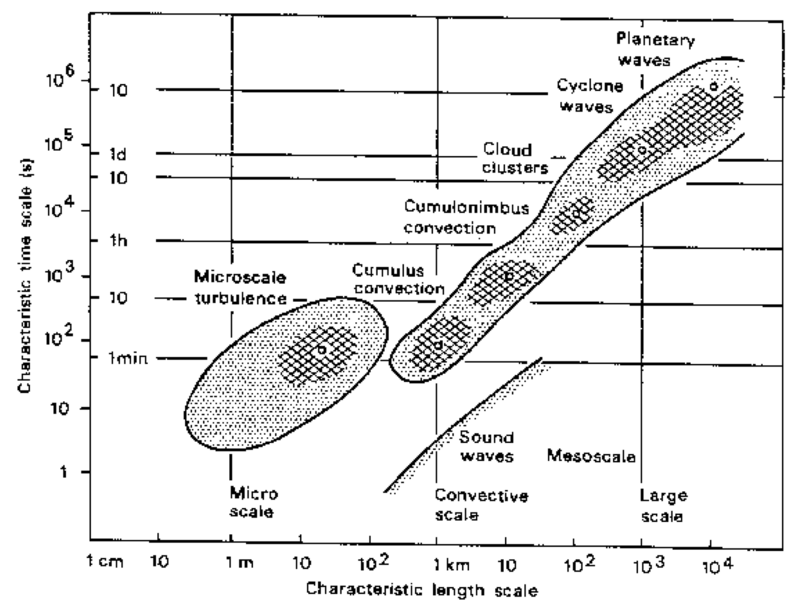
The Problem of Parameterization in Numerical Models

Outline

- What is physical parameterization and why we need physical parameterization?
- What processes should be parameterized?
- How do we do parameterization in models?
- Example: Cumulus convection parameterization
- The problems in parameterization
- Summary

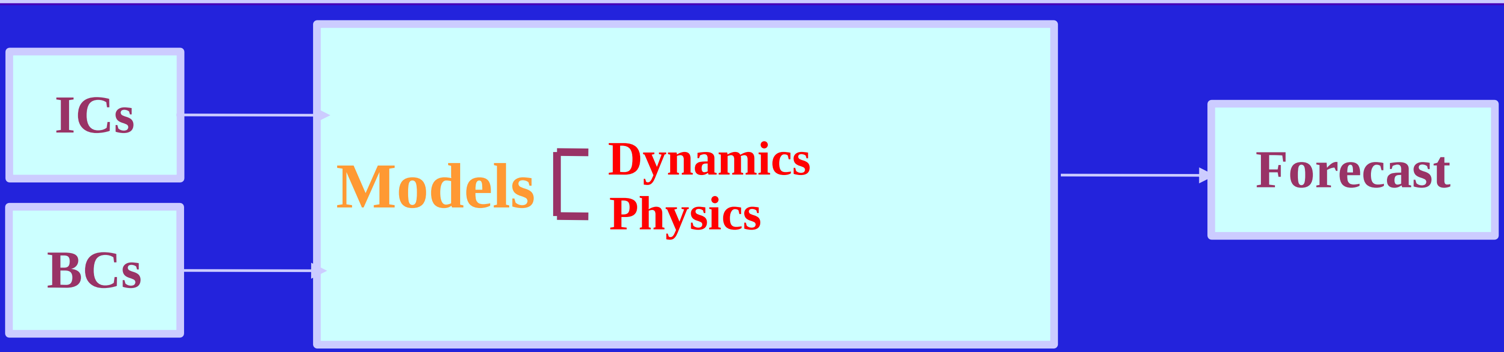
What is physical parameterization?



Characteristic scales of atmospheric processes

- **Atmospheric motions have different scales.**
- **Climate model resolutions:**
  Regional: 50 km
  Global: 100~200 km
- **Sub-grid scale processes:** Atmospheric processes with scales can not be explicitly resolved by models.
- **Physical parameterization:** To represent the effect of sub-grid processes by using resolvable scale fields.

Why do we need physical parameterization?



- Dynamic core of models

$$\frac{d\vec{V}}{dt} = -\alpha\nabla p - \nabla\Phi + \vec{F} - 2\Omega\times\vec{V}$$

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\vec{V})$$

$$p\alpha = RT$$

$$Q = C_p\frac{dT}{dt} - \alpha\frac{dp}{dt}$$

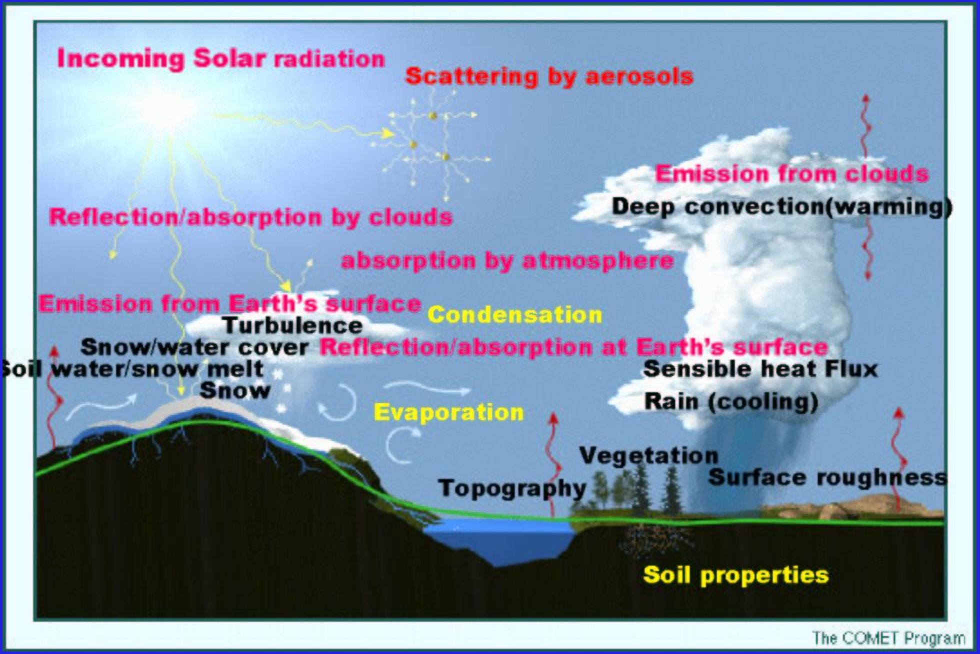
$$\frac{\partial\rho q}{\partial t} = -\nabla\cdot(\rho\vec{V}q) + \rho(E - C)$$

- Model physics:
  - Processes such as phase change of the water are in too small scale and too complex.
  - Processes such as cloud microphysics are poorly understood.
  - Computer is not powerful enough.

What should be parameterized ?

Model Physics include:

- Radiation transfer.
- Surface processes.
- Vertical turbulent processes.
- Clouds and large-scale condensation.
- Cumulus convection.
- Gravity wave drag.



16 major physical processes in climate system. (from http://www.meted.ucar.edu/nwp/pcu1/ic4/frameset.htm)

How do we do parameterization in numerical models?

- Ignore some processes (in simple models).
- Simplifications of complex processes based on some assumptions.
- Statistical/empirical relationships and approximations based on observations.
- **Nested models and super-parameterization:** Embed a cloud model as a parameterization into climate models.

Clouds effects in the climate system

- **Clouds radiaton effects:** modifying the absorption, scattering, emission.
- **Clouds influence PBL:** the vertical transport of heat, moisture and momentum.
- **Clouds hydrological effects:** condensation,evaporation and precipitation.

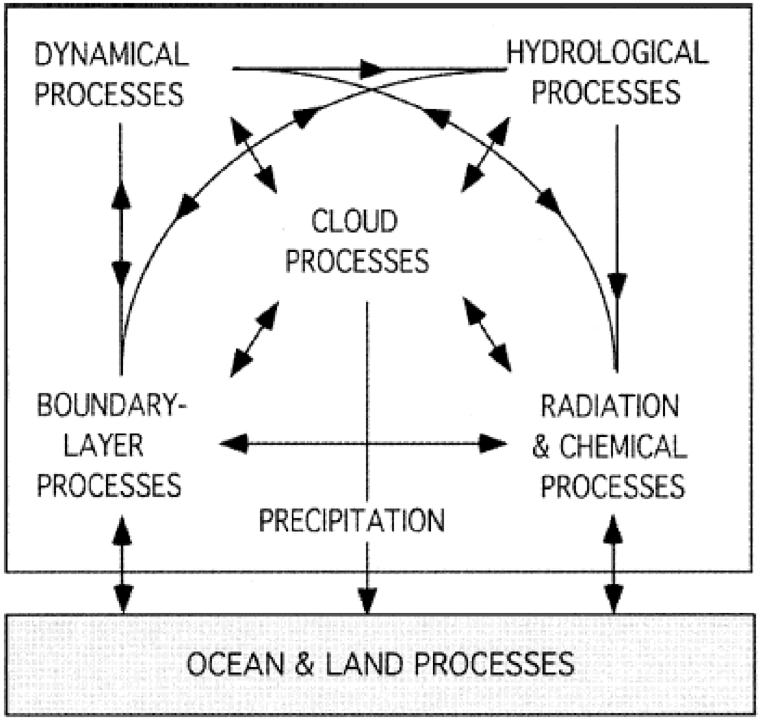


FIG. 1. Interactions between various processes in the climate system.

Physical processes and interactions.
(from Arakawa, 2004)

Cumulus convective Parameterization schemes

- Arakawa – Schubert scheme.
- Betts – Miller scheme.
- Kuo scheme.

Early stage of cumulus development.

Mature stage of cumulus development.

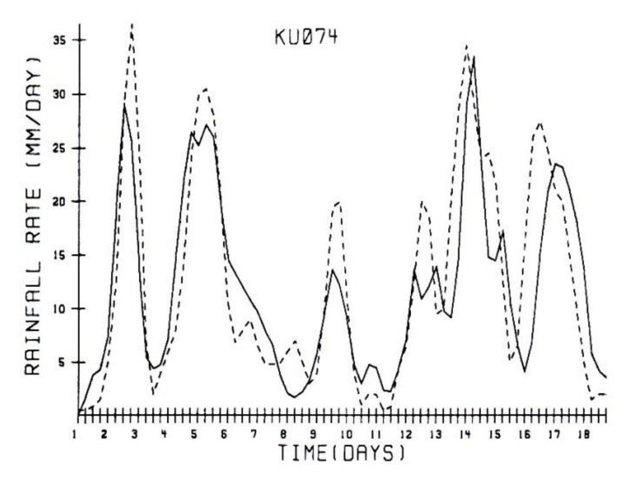
This storm has reached an upper-level inversion, forming an anvil-shape to the cloud.

2. Kuo scheme

- **Simple scheme from Kuo(1965, 1974)**
- **Widely used in GCMs for deep convection.**
- **Basic idea:**
  - The rate of precipitation is balanced by the rate of horizontal convergence of moisture and surface evaporation.

$$P = \frac{F_s - \int_0^{p_s} (\nabla \cdot Vq) dp / g}{1+b}$$

- **Limitations:**
  - Too simple, can not represent the realistic physical behavior of convection.
  - Can not represent shallow convection
  - *b* is a constant.



Radar observed rainfall(dashed line) and rainfall diagnosed from Kuo scheme(solid line) for a period of 18 days during GATE. (From Krishnamurti et al. (1980))

3. Betts – Miller scheme

- **Betts 1986, Betts and Miller 1986**
- **Basic idea:**
- To relax temperature and mixing ratio profile back to reference profiles in the unstable layer.
- $$\boxed{\frac{\partial T}{\partial t}=\frac{T_R-T}{\tau} \qquad \frac{\partial q}{\partial t}=\frac{q_R-q}{\tau}}$$ *R* represent reference profile, τ is relaxation
- time scale.
- Deep convection and shallow convection are considered separately:

→ Deep convection: if the depth of the convective layer exceeds a specified value. The reference profile are empirically determined from observations.

→ Shallow convection: when the depth of the convective layer is less than the value, it will not produce precipitation.

- **Limitations:**
- A fixed reference profile of RH may cause problems in climate models.
- Changes below cloud base have no influence.

4 Arakawa – Schubert scheme

- **Complex scheme from Arakawa and Schubert 1974.**
- **Basic idea:**

- Assume convection can be represented as an ensemble of entraining plumes with different height and entrainment rates. Convection keeps the atmosphere nearly neutral.
- Cloud work function measure of moist convective instability of each type of cloud.

$$A_i = \int_{Z_b}^{Z_{Di}} e^{\lambda_i (Z - Z_b)} B_i \, dZ$$

- Quasi-equilibrium assumption:

  Convective tendencies are very fast.

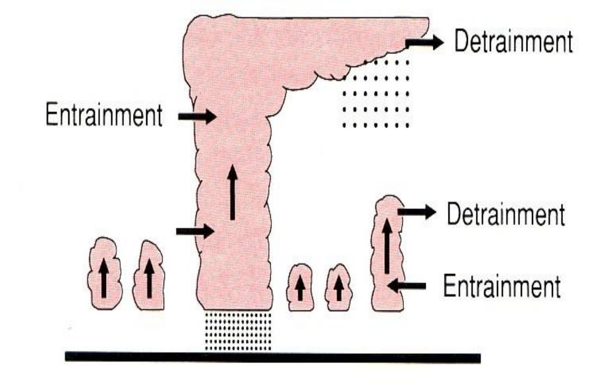
  So large scale tendencies approximately

  balances the convective tendencies.

$$-\left(\frac{dA_i}{dt}\right)_{LS} = \sum_j M_{b_j} K(\lambda_i, \lambda_j)$$

- **Limitations:**

- Complexity, take longer time
- Requires detailed cloud ensemble model



Schematic of an ensemble of cumulus clouds.
(from Trenberth, 1992)

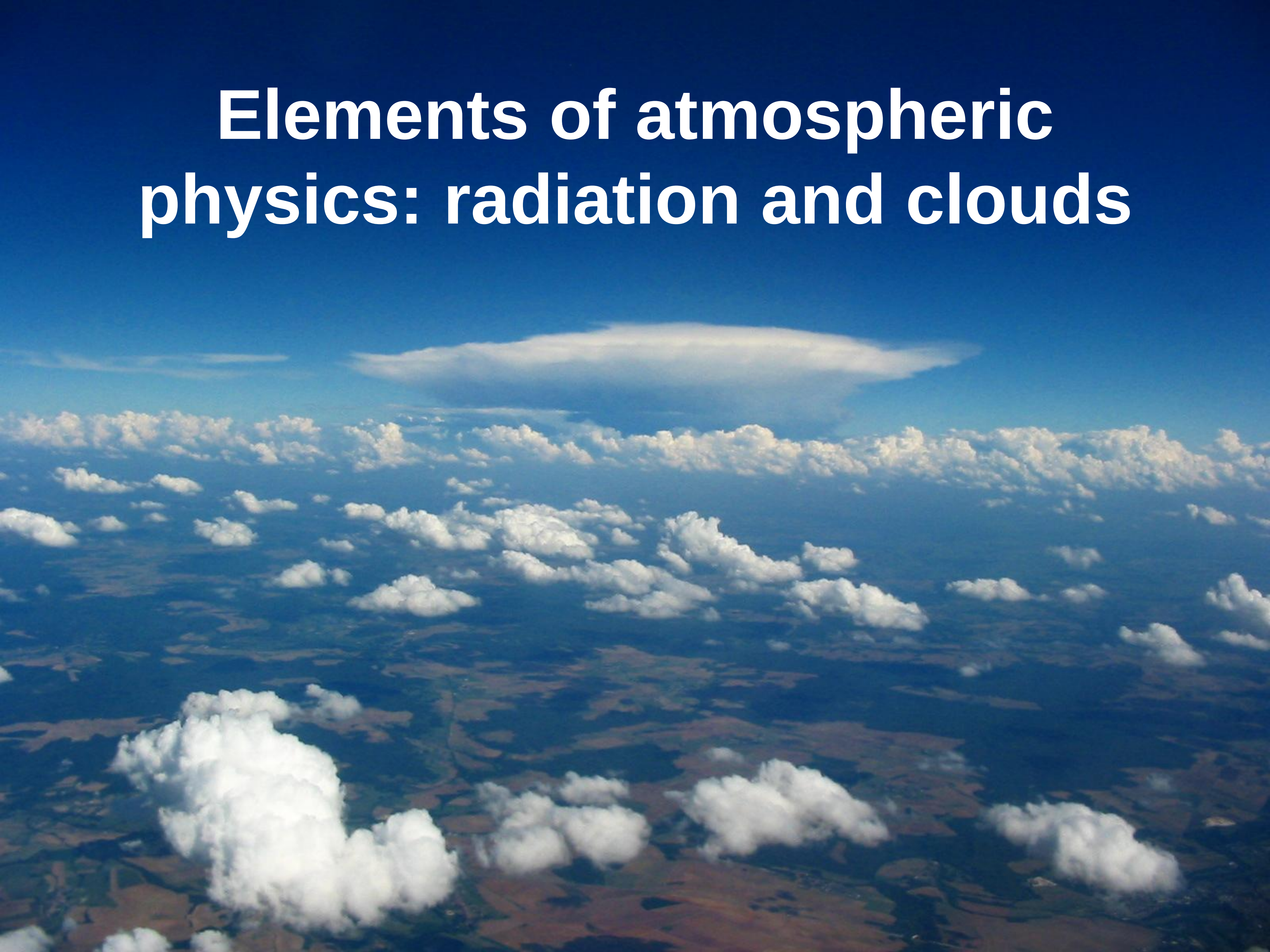
The problems in parameterization

- **The current parameterization schemes are too simple to describe the nature of the processes.**
- **Our knowledge about physical processes and feedback mechanism limits the improvement of parameterization.**
- **Superparameterization seems to be a better way to represent of physical processes comparing with conventional parameterization.**
- **It is only used in cloud processes (CRM).**
- **Computational costs are very expensive, about 100 ~ 1000 times more than the conventional parameterization.**

Summary

- Parameterization is a method to represent the effects of physical processes which are too small or too complex or poorly understood.
- The importance of parameterization for weather and climate prediction has been well recognized and a lot of works have been done to improve physical parameterization. But, parameterization has not been a mature subject till now.
- The best way to improve parameterization is to understand the physical processes better by observations and high resolution simulations .

Elements of atmospheric physics: radiation and clouds



Outline

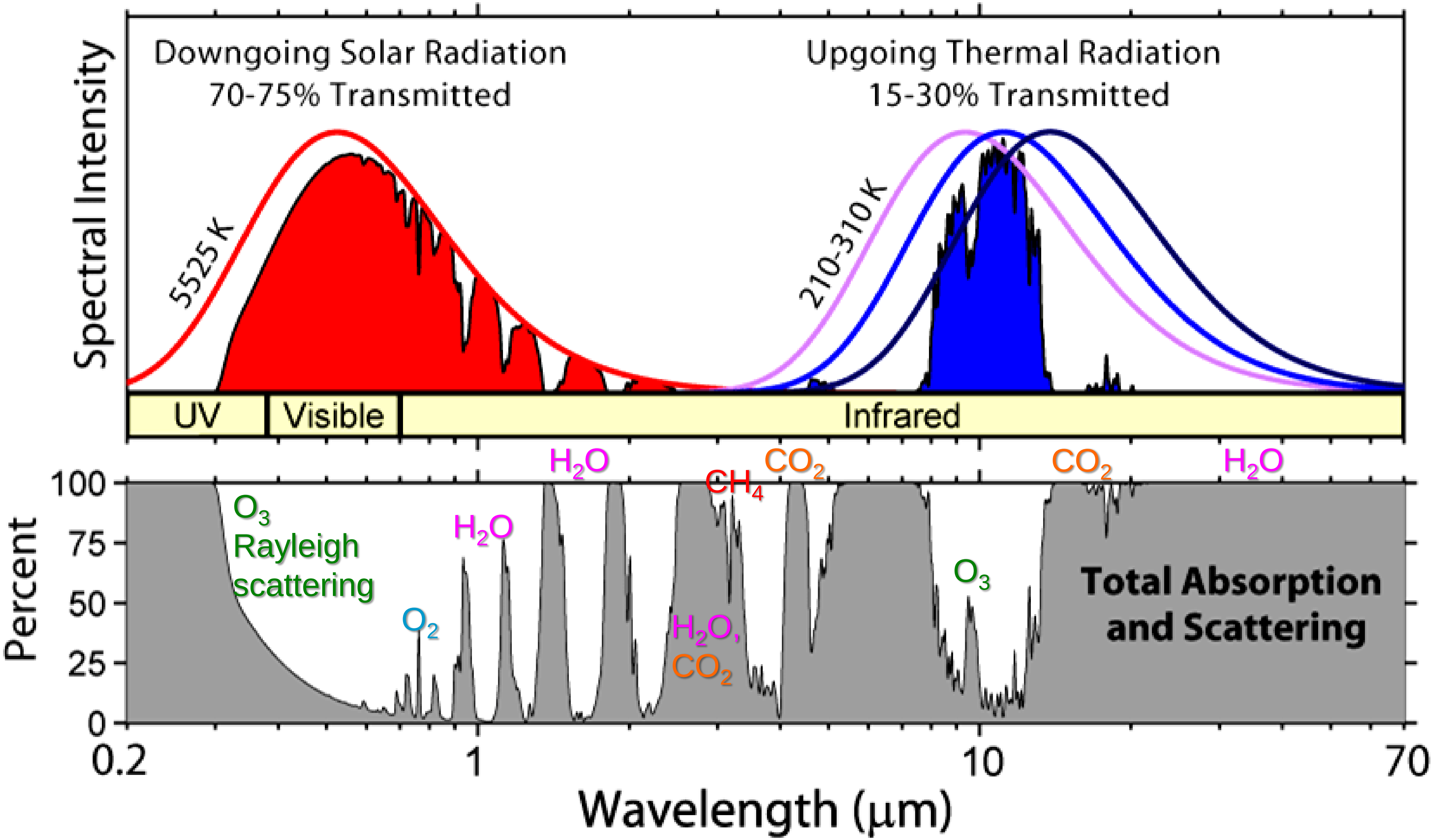
- Introduction: radiation and climate
- Physics parametrizations
  - Boundary layer
  - Convection
  - Gravity wave drag
  - Clouds
  - Precipitation
  - Radiation
- What do we still need to know?

Comparative planetology

Planet	Distance from sun (Earth = 1)	Mean surface temperature (K)	Surface pressure (Earth = 1)	Atmospheric composition	Absorbed solar radiation (Wm^{-2})
Mercury	0.387	103-623	~ 0	-	2000
Venus	0.723	750	92	> 96% CO_2	150
Earth	1	293	1	78% N_2, etc	235
Mars	1.524	186-268	0.007 - 0.009	96% CO_2	125

Conclusion: the composition of the atmosphere and the magnitude of the greenhouse effect are crucial factors for regulating the surface temperatures of the planets

Spectral distribution of radiation



- **Shortwave: atmosphere is mostly transparent**
- **Longwave: atmosphere is mostly opaque**

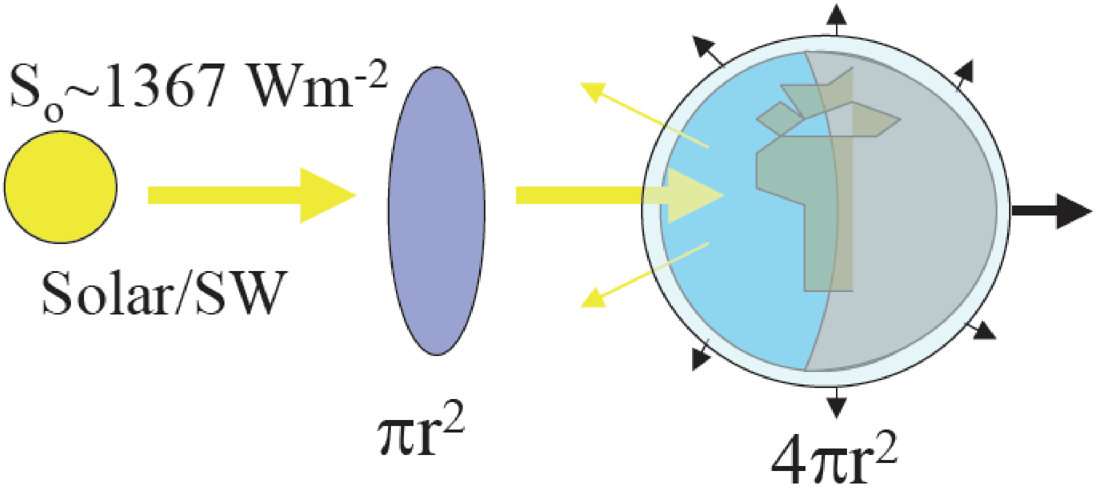
Composition of the Earth’s atmosphere

Gas	Parts by volume	Interaction
Nitrogen (N_2)	780,840 ppmv (78.084%)	**SW (Rayleigh)**
Oxygen (O_2)	209,460 ppmv (20.946%)	**SW (Ray+abs)**
Water vapour (H_2O)	~0.40% full atmosphere, surface ~1%-4%	**LW**, **SW (abs)**
Argon (Ar)	9,340 ppmv (0.9340%)	
Carbon dioxide (CO_2)	390 ppmv (0.039%) *rising*	**LW**, **SW (abs)**
Neon (Ne)	18.18 ppmv (0.001818%)	
Helium (He)	5.24 ppmv (0.000524%)	
Methane (CH_4)	1.79 ppmv (0.000179%) *rising*	**LW**
Krypton (Kr)	1.14 ppmv (0.000114%)	
Hydrogen (H_2)	0.55 ppmv (0.000055%)	
Nitrous oxide (N_2O)	0.319 ppmv (0.00003%) *rising*	**LW**
Carbon monoxide (CO)	0.1 ppmv (0.00001%)	
Xenon (Xe)	0.09 ppmv (9×10^{-6}%) (0.000009%)	
Ozone (O_3)	0.0 to 0.07 ppmv (0 to 7×10^{-6}%)	**LW**, **SW (abs)**

SW “shortwave” solar radiation: Rayleigh scattering (blue sky) or absorption

LW “longwave” terrestrial infrared radiation: absorbing greenhouse gases

Earth’s radiation balance



S_o~1367 Wm^{-2}

Solar/SW

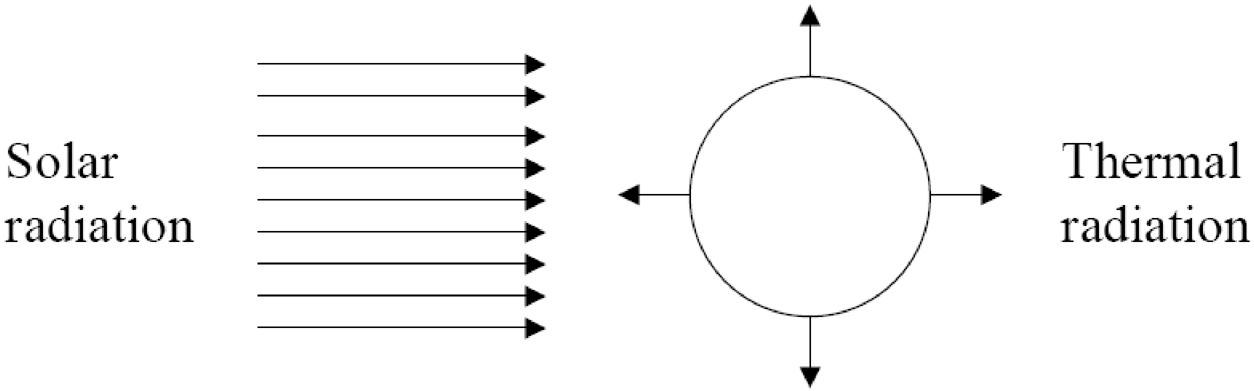
πr^2

$4\pi r^2$

Thermal or outgoing longwave radiation (OLR)

- In equilibrium, the net absorption of solar radiation is balanced by the emission of thermal radiation back to space
- The thermal emission is controlled by the strength of the greenhouse effect
- If there is an increase in the concentrations of greenhouse gases, such as carbon dioxide, then the system warms as it tries to reach a new equilibrium

Overall energy balance of the Earth



$$(1-\alpha)\, S_o\, \pi\, r^2 = 4\, \pi\, r^2\, \sigma\, T^4_{eff}$$

Simplifying, we find that;

$$\sigma\, T^4_{eff} = (1-\alpha)\, S_o/4$$

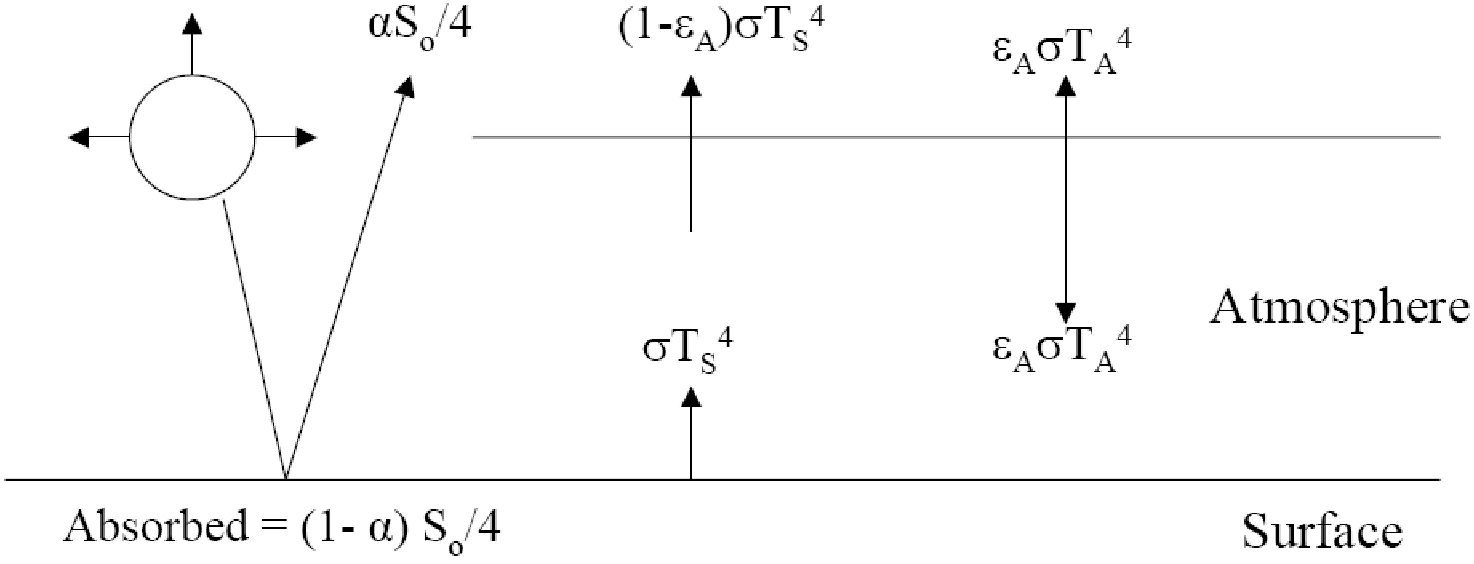
and hence

$$T_{eff} \approx 255\ \mathrm{K}$$

where α is the planetary or system albedo, *S* is the solar constant (1370 w m^{-2}) and σ is the Stefan – Boltzmann constant (5.67x10^{-8} W$m^{-2}$$K^{-4}$).

The total energy received from the sun per unit time is π*R*^{2}*S* where *R* is the radius of the Earth. The total area of the Earth is, however, 4π*R*^{2}*.* Therefore the time averaged energy input rate is *S*/4 over the whole Earth. Hence,

Overall energy balance including the greenhouse effect



Consider the equilibrium of the atmosphere and then of the surface;

$$\varepsilon_A \sigma T_S^4 = 2\varepsilon_A \sigma T_A^4 \tag{4}$$

$$(1-\alpha)S_o/4 + \varepsilon_A \sigma T_A^4 = \sigma T_S^4 \tag{5}$$

Hence

$$\sigma T_S^{\,4} = \{(1-\alpha)S_o/4\} \,/\, (1 - \varepsilon_A/2) \tag{6}$$

and

$$T_A = T_S/2^{1/4} \tag{7}$$

Note that T_S is larger than T_{eff} given by (2), because of the additional downward thermal emission from the atmosphere. So, the greenhouse effect ensures that the surface is warmer with an atmosphere than without. Secondly, the atmosphere is colder than the surface and slightly colder than T_{eff}.

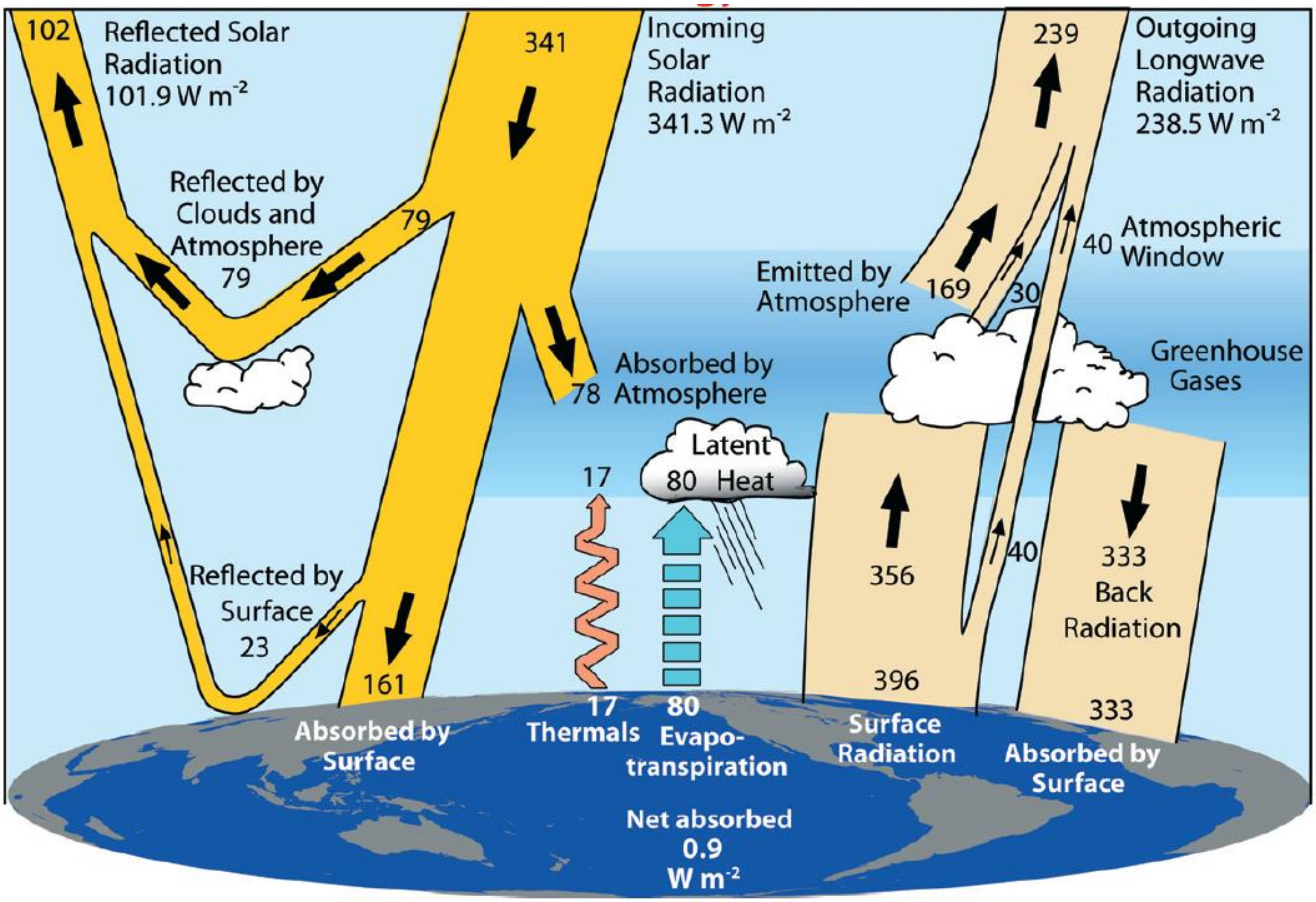
If we assume that $\alpha = 0.3$ and $\varepsilon_A = 0.8$ then we find that;

$$T_S = 289 \text{ K}$$

$$T_A = 243 \text{ K}$$

Which are reasonable values for the global mean surface and atmospheric temperatures.

Global energy flows



- Trenberth et al. (2009); modification of Kiehl & Trenberth (1997)

Radiative-convective equilibrium

If we assume that only radiative processes are operating, the equilibrium surface temperature is very high, tropospheric temperatures very low and the profile is strongly superadiabatic.

In reality, convection removes heat from the surface, warms the atmosphere and adjusts the lapse-rate towards that observed.

From the classic paper by Manabe and Wetherald, JAS, 1967

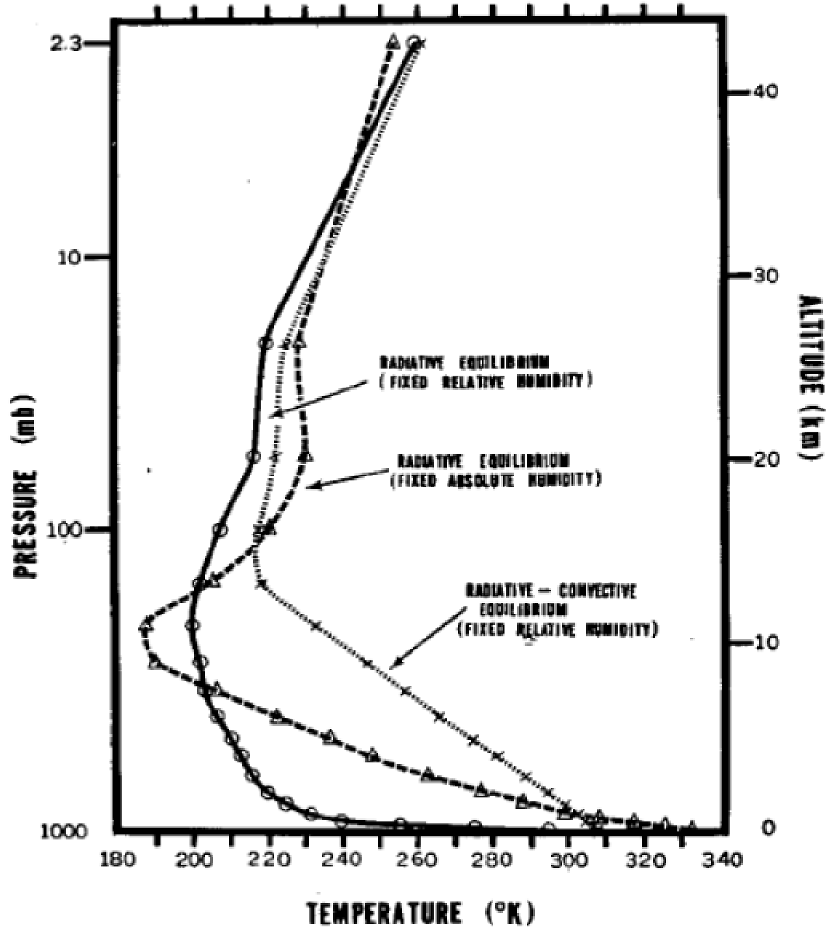
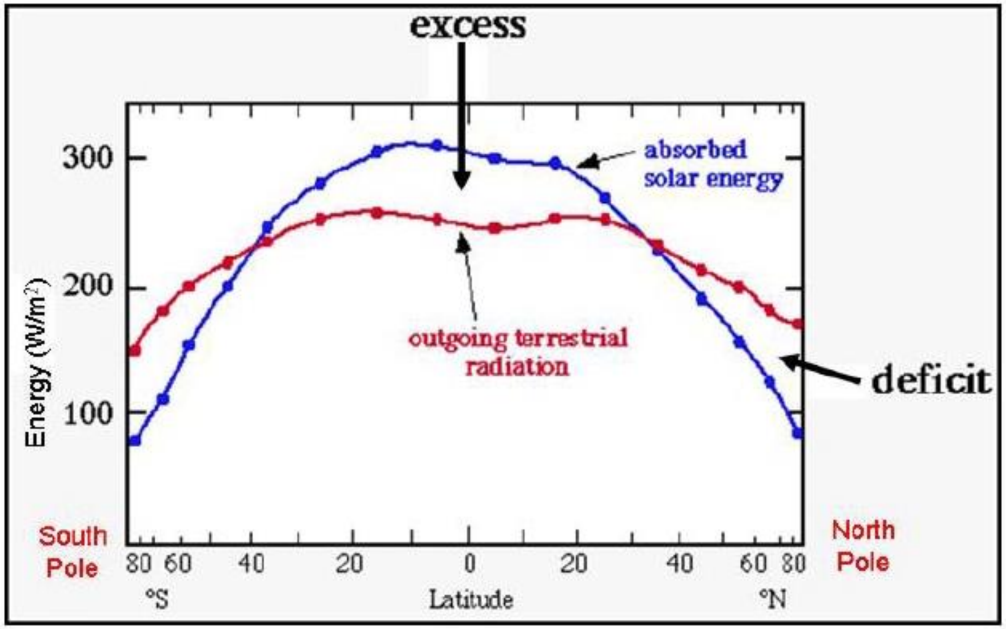
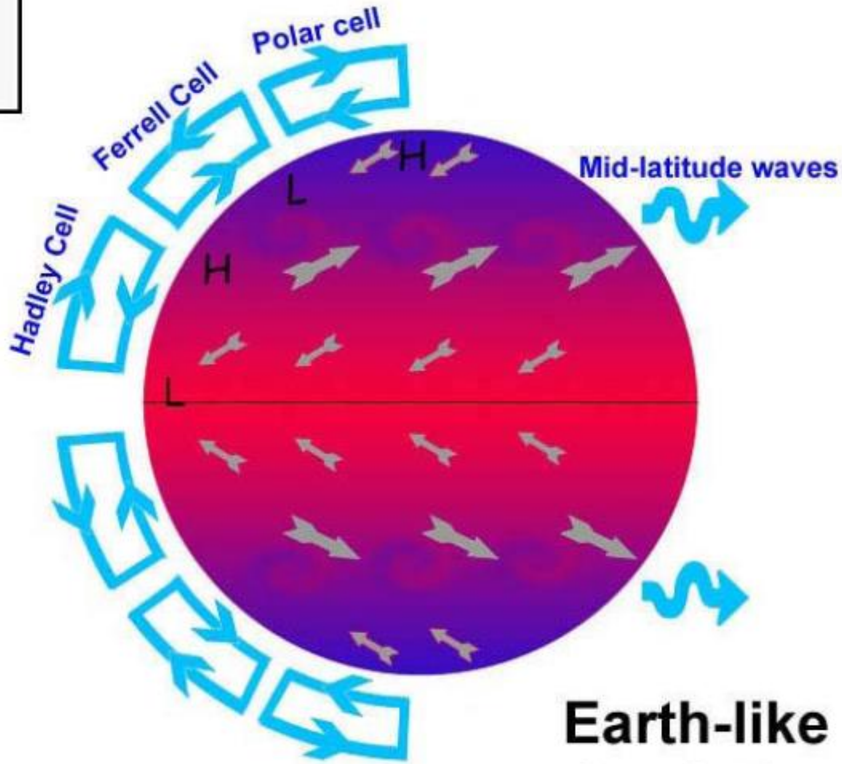


Fig. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

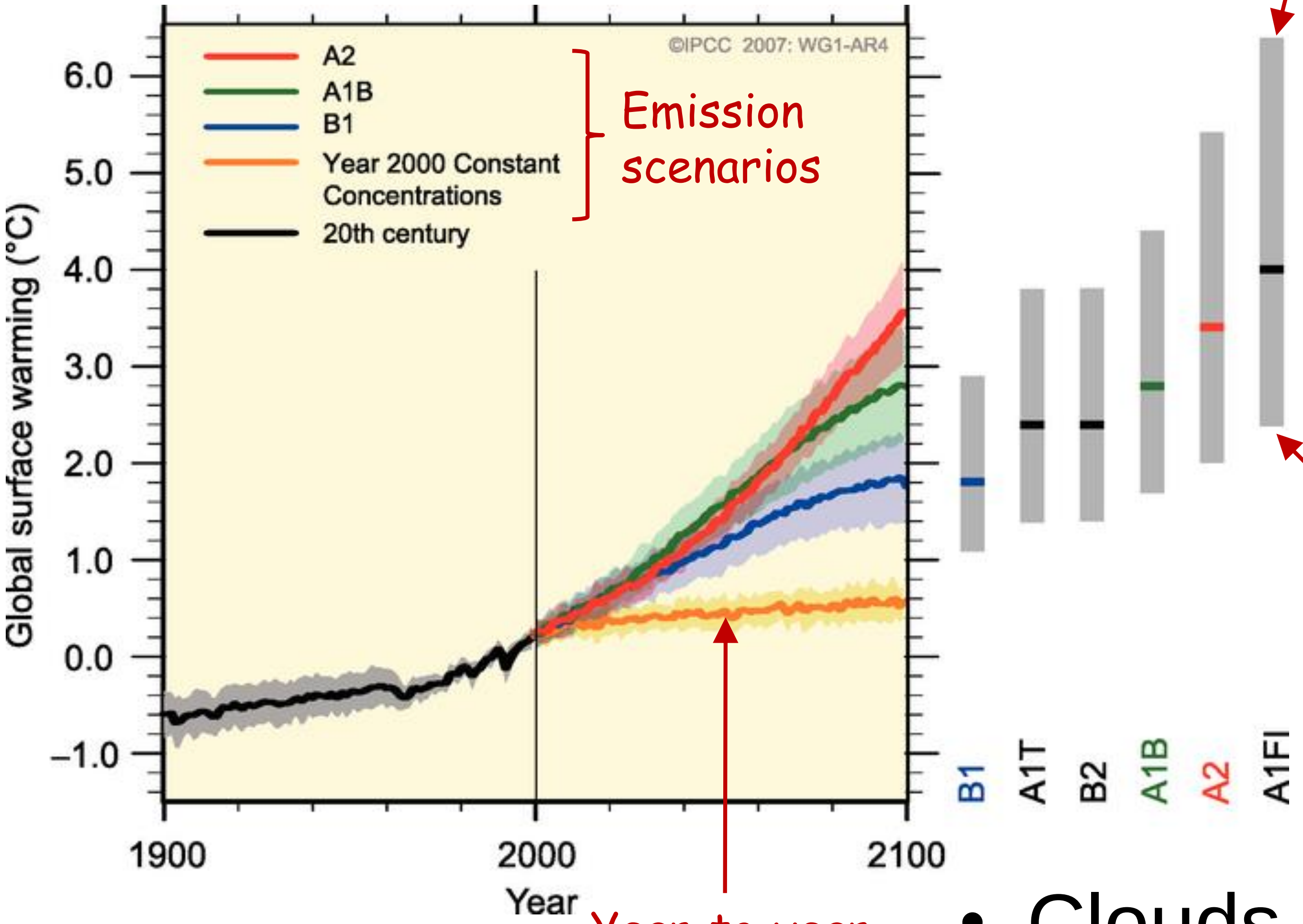


Radiative imbalances between the surface and the atmosphere, and between the tropics and polar regions, together with the planet's rotation, drive convection and the general circulations of the atmosphere and oceans



Earth-like circulation

What about climate *prediction*?



Emission scenarios

Models with a strong positive cloud radiative feedback (e.g. cloud cover decreases in a warmer climate)

Spread between models

Models with a near-zero cloud feedback (clouds stay about the same)

Year-to-year variability

- Clouds and radiation are key to

Conservation equations for gridbox-mean quantities in a model

- Mass

$$\nabla \cdot (\rho \bar{\mathbf{u}}) = 0$$

- Thermodynamic energy

$$\frac{D\bar{\theta}}{Dt} = \boxed{F_\theta}$$

  - Radiation
  - Latent heat release
  - *Transport by turbulence*
  - *Transport by deep convection*

- Water vapour

$$\frac{D\bar{q}}{Dt} = \boxed{F_q}$$

  - Condensation/evaporation
  - Precipitation
  - *Transport by turbulence*
  - *Transport by deep convection*

- Momentum (acceleration = force per unit mass)

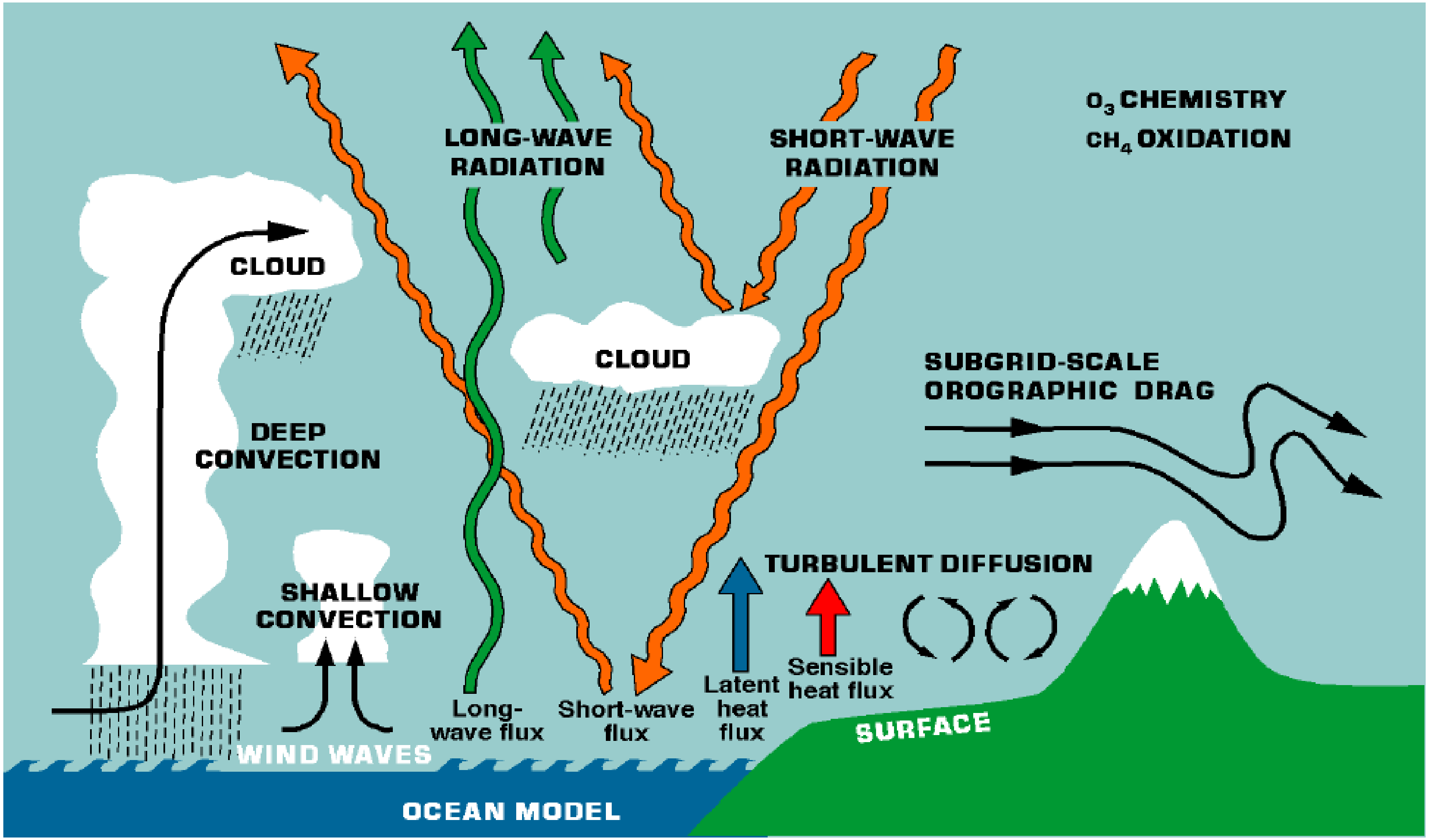
$$\frac{D\bar{\mathbf{u}}}{Dt} + f\hat{\mathbf{k}} \times \bar{\mathbf{u}} + \frac{1}{\rho}\nabla p + \hat{\mathbf{k}} g = \boxed{\mathbf{F}_{\mathbf{u}}}$$

  - *Gravity wave drag*
  - *Transport by turbulence*
  - *Transport by deep convection*

Old fashioned division: terms on the left are "dynamics", terms on the right are "physics"

Processes in italics are purely due to unresolved processes: would be unnecessary in a high resolution model (e.g. 100 m)

Processes to be parametrized



- These processes transport energy, water and momentum vertically much faster than the resolved winds

3 types of physical parametrization in atmospheric models

1. Processes occurring at scales smaller than the grid-scale so not explicitly represented
    - Convection, boundary-layer turbulent transport, gravity wave drag
    - Anything carried by the wind is transported (momentum, heat, water, chemicals, aerosols)
2. Processes that contribute to internal heating (diabatic)
    - Radiative transfer and latent heat release
    - Both strongly affected by the cloud representation
3. Process that involve additional prognostic model variables (i.e. solve an equation for *d/dt* of the variable)
    - Carbon cycle, chemistry, aerosols etc.
    - Land surface processes (ice, soil, vegetation, urban areas)

This talk covers only the first two

How does sub-grid motion affect the mean flow?

- Consider equation for any quantity *q (could be u, v, θ etc)*

$$\frac{Dq}{Dt} = 0 \quad \text{where} \quad \frac{Dq}{Dt} = \frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + w\frac{\partial q}{\partial z}$$

$$q = \bar{q} + q', u = \bar{u} + u' \text{ etc.}$$

- Substituting *Reynolds averaged quantities*

$$\frac{D\bar{q}}{Dt} = -\frac{\partial \boxed{\overline{q'w'}}}{\partial z}$$

Vertical flux of *q* due to sub-grid deviations of wind from its gridbox-mean value

- and averaging leads to vertical transport by eddies

Boundary layer transports

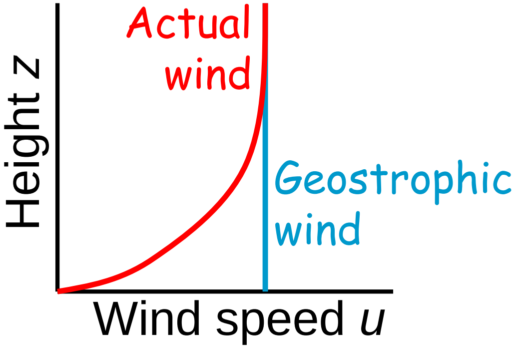
- Simplest approach: flux is proportional to gradient

$$\overline{q'w'} \approx -K\frac{\partial \overline{q}}{\partial z} \quad \text{so} \quad \frac{\partial \overline{q'w'}}{\partial z} \approx \frac{\partial}{\partial z}\left(-K\frac{\partial \overline{q}}{\partial z}\right) \approx -K\frac{\partial^2 \overline{q}}{\partial z^2}$$

- A diffusion-like term where *K* is the *eddy diffusivity*
- If can parametrize *K* then have a *closed* set of equations
- Three main sources of turbulence in boundary layer:
  - Wind shear, particularly near the surface
  - Convective instability due to surface shortwave heating
  - Convective instability due to cloud-top longwave cooling

Shear-induced mixing

- Wind goes to zero at the surface
- Hence must be shear in the boundary layer
- Shear instability governed by the *Richardson number*:



$$R_i = \frac{\dfrac{g}{\overline{\theta}}\dfrac{\partial\overline{\theta}}{\partial z}}{\left(\dfrac{\partial\overline{u}}{\partial z}\right)^2 + \left(\dfrac{\partial\overline{v}}{\partial z}\right)^2}$$

- Typical diffusivity parametrization:
- λ_m is *neutral mixing length* (0-50m)

$$K_m = \begin{cases} \text{nonlocal scheme} & R_i < 0 \\ \lambda_m^2 (1 - 5R_i)^2 \, \partial\overline{u} / \partial z & 0 < R_i < 0.2 \\ 0 & R_i > 0.2 \end{cases}$$