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ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
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Solar Influences on Climate - I

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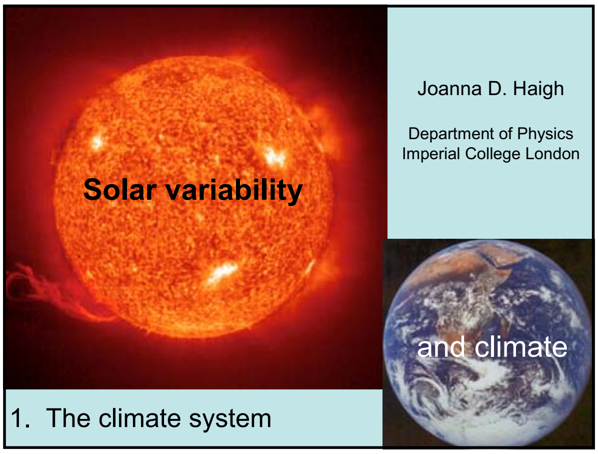

Solar variability

and climate

Joanna D. Haigh

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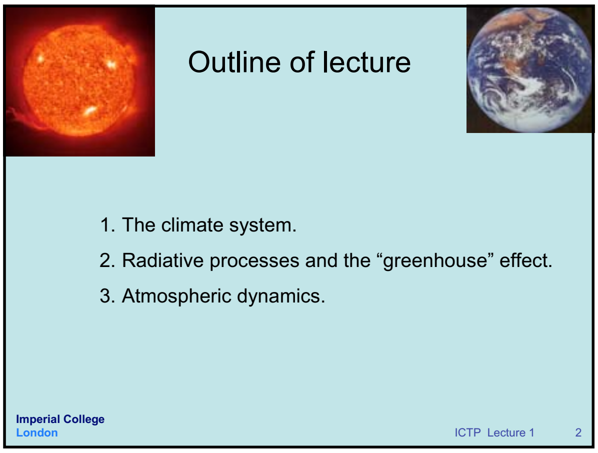
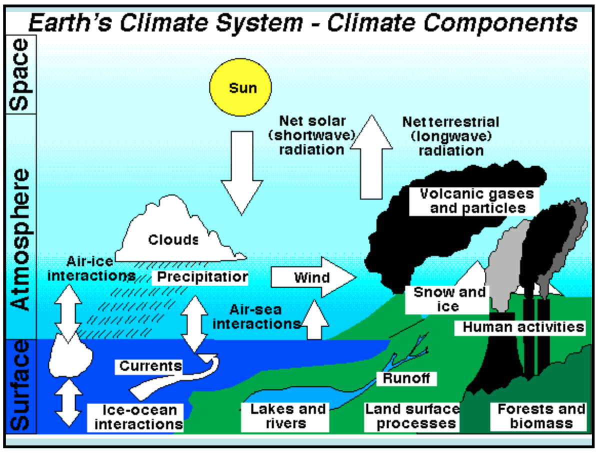
1. The climate system

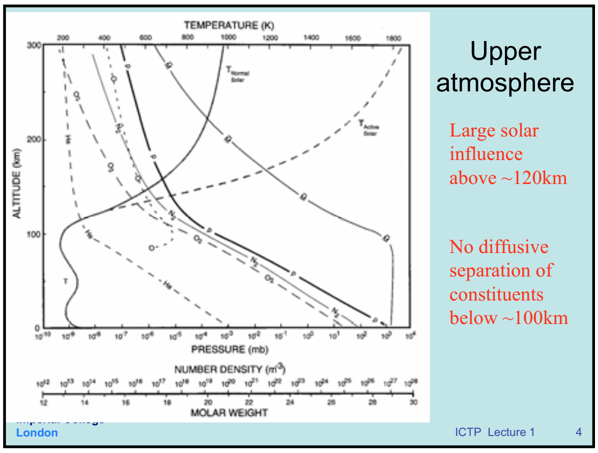


Outline of lecture

1. The climate system.
2. Radiative processes and the “greenhouse” effect.
3. Atmospheric dynamics.



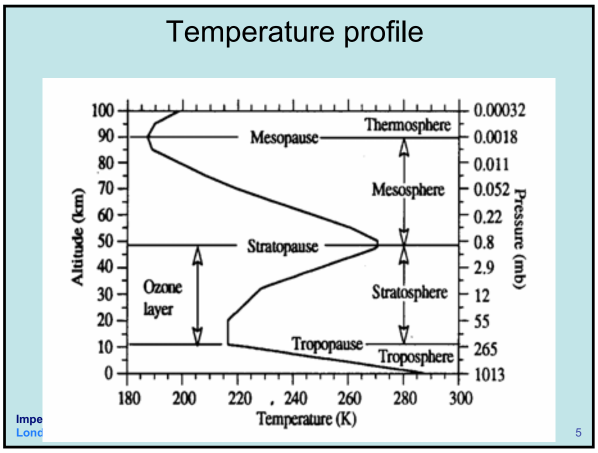
Earth’s Climate System - Climate Components



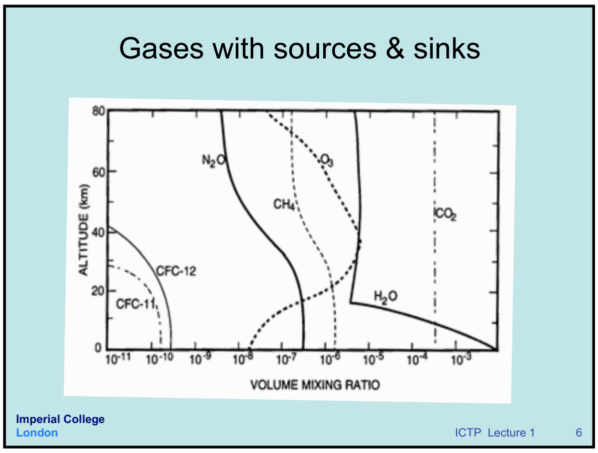
Upper atmosphere

Large solar influence above ~120km

No diffusive separation of constituents below ~100km

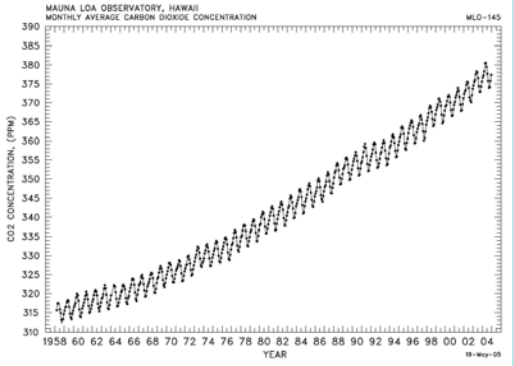


Temperature profile

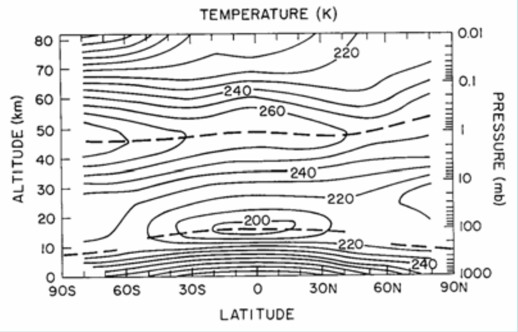


Gases with sources & sinks

Carbon dioxide

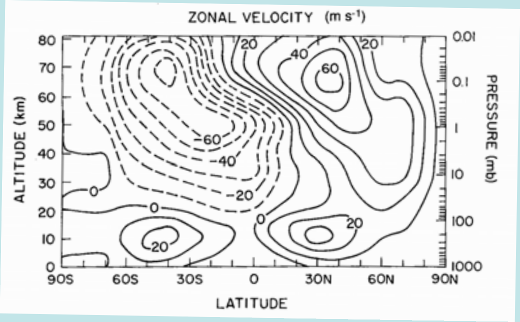


Temperature: meridional structure



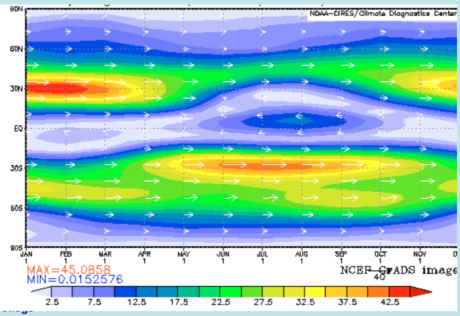
December

Zonal wind: meridional structure



December

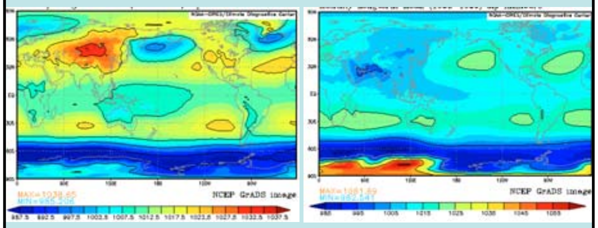
Wind at ~12km, vectors and amplitudes: seasonal variation



Mean sea level pressure

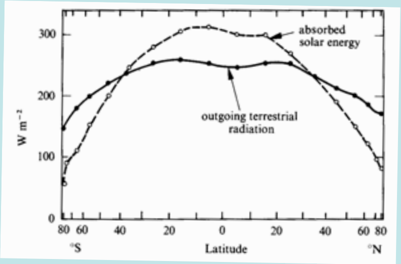
DJF

JJA



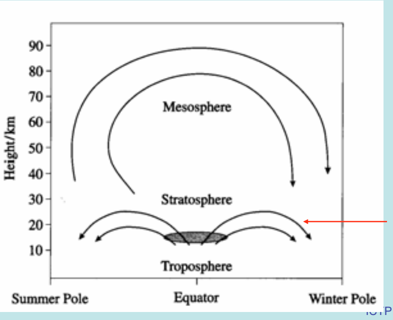
(hPa)

Latitudinal radiation budget



Atmosphere and oceans transport heat from low to high latitudes

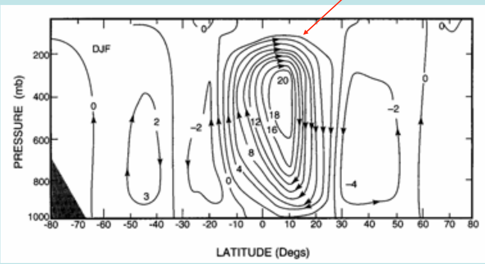
Mean meridional circulation (middle atmosphere)



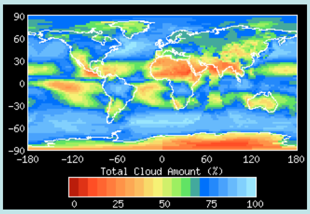
Brewer-Dobson circulation

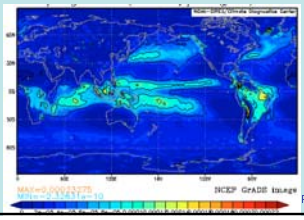
Mean meridional circulation, December (troposphere)

Winter Hadley cell

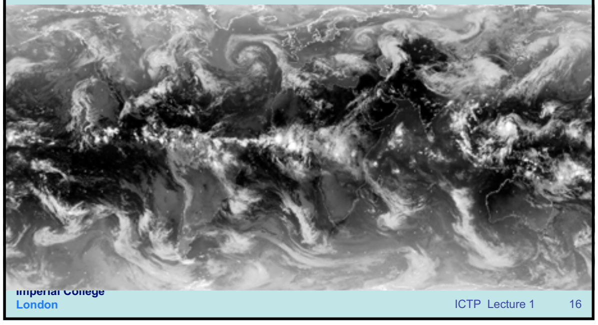


DJF cloud and precipitation





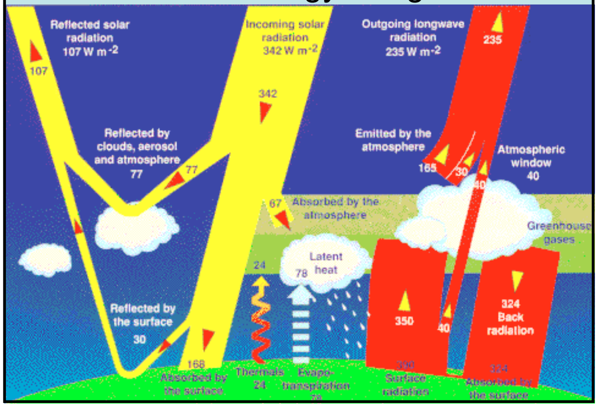
Composite of infrared images from geostationary satellites 11/05/06



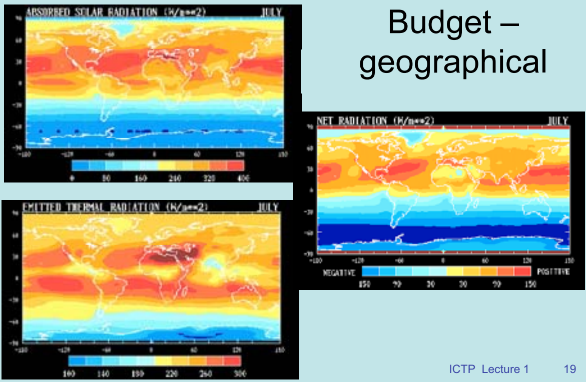
Radiative processes

- Earth energy budget.
- Top of atmosphere radiation components.
- The “greenhouse” effect.
- Radiative forcing of climate change.
- Atmospheric heating rates.

Earth Energy Budget



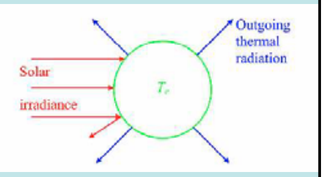
Earth Radiation Budget – geographical



Radiative equilibrium temperature

In equilibrium:

absorption solar radiation = emission infrared radiation:

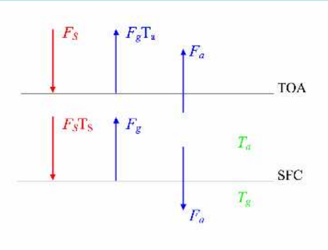


$$\pi R^2(1-\alpha)S = 4\pi R^2\sigma T_e^4$$

$$\sigma T_e^4 = (1-\alpha)S/4 = F_s$$

$$S = 1370 \quad Wm^{-2} \quad F_s = 240 \quad Wm^{-2} \quad T_e = 255 \quad K$$

Greenhouse effect



$$\mathrm{TOA}: F_S = \mathrm{T}_L F_g + F_a$$

$$\mathrm{SFC}: F_S\mathrm{T}_S = F_g - F_a$$

$$\therefore F_g = \frac{(1+\mathrm{T}_S)}{(1+\mathrm{T}_L)}F_S$$

$$\text{i.e. } T_g^4 = \frac{(1+\mathrm{T}_S)}{(1+\mathrm{T}_L)}T_e^4$$

$$\therefore \text{If } \mathrm{T}_S > \mathrm{T}_L \text{ then } T_g > T_e$$

Factors which affect T_g

T_e	S Solar irradiance
T_e	α Albedo: surface, cloud, aerosol, O_3
T_S	O_3, H_2O, NO_2, ……………
T_L	H_2O, CO_2, CH_4, N_2O, O_3, CFCs, …(GHGs)

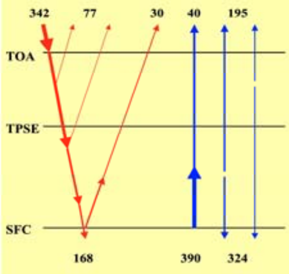
Radiation budget, atmospheric transmittance and radiative forcing

$\mathrm{T}_S = 0.49$ $\mathrm{T}_L = 0.10$

→ T_g = 275 K

(using simple model)

Global annual average radiation budget (Wm^{-2})



Radiative forcing is a measure of the perturbation to the net radiative flux due to a change in the radiative properties of the atmosphere or surface, or the solar input.

Radiative forcing

Net downward flux at TOA is:

$$\begin{aligned} F_N^{\downarrow} &= F_S - \mathrm{T}_L F_g - F_a \\ &= \sigma T_e^4 - \mathrm{T}_L\sigma T_g^4 - (1-\mathrm{T}_L)\sigma T_a^4 \\ &= \sigma\left[T_e^4 - \left(T_g^4 - T_a^4\right)\mathrm{T}_L - T_a^4\right] \\ &= 0 \text{ in equilibrium} \end{aligned}$$

For given T_g, T_a perturbations to T_e or T_L give $F_N^{\downarrow} \neq 0$

Define radiative forcing RF = $\Delta F_N^{\downarrow}$

Why is radiative forcing a useful concept?

Because GCMs, & limited observational studies, suggest that the perturbation to global average, equilibrium surface temperature, T_g, is related to radiative forcing, *RF*, by:

$$\Delta T_g = \lambda \, RF$$

where λ, the climate sensitivity parameter, is independent of the nature of the forcing.

$\lambda \sim 0.6$ K (W m^{-2})$^{-1}$ [$0.3 < \lambda < 1.0$]

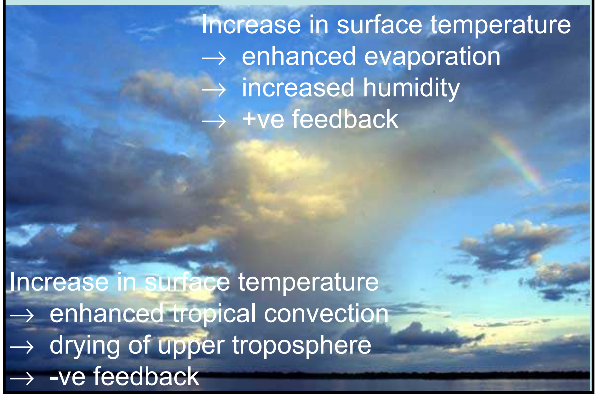
Total solar irradiance (TSI) and radiative forcing

As in equilibrium temperature calculation:

$$RF = \frac{1}{4}(1-\alpha)\Delta TSI$$

$$\text{i.e. } RF \simeq \frac{1}{6}\Delta TSI$$

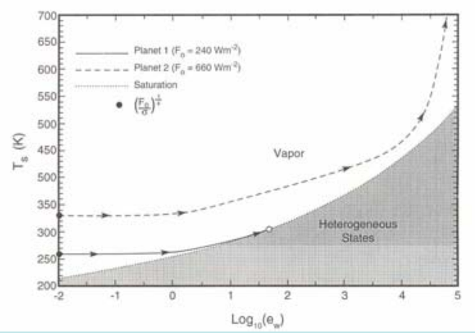
Water vapour feedback

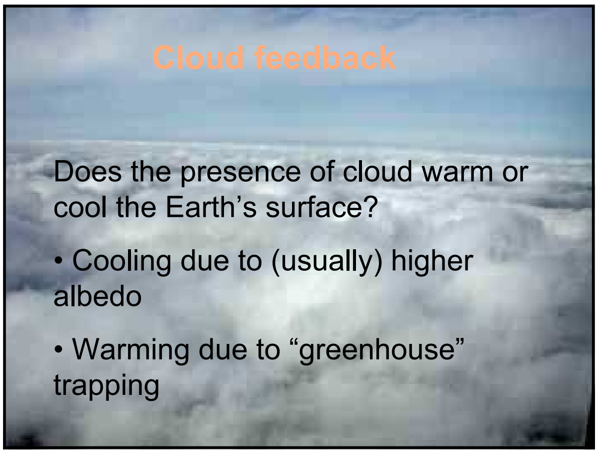


Increase in surface temperature
→ enhanced evaporation
→ increased humidity
→ +ve feedback

Increase in surface temperature
→ enhanced tropical convection
→ drying of upper troposphere
→ -ve feedback

Water vapour and the “runaway greenhouse effect”

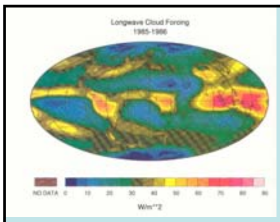


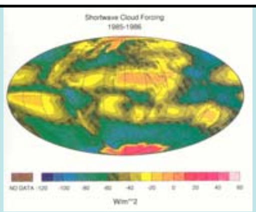


Cloud feedback

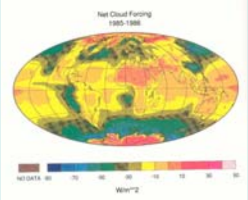
Does the presence of cloud warm or cool the Earth’s surface?

- Cooling due to (usually) higher albedo
- Warming due to “greenhouse” trapping





ERBE cloud forcing



Ice-albedo feedback

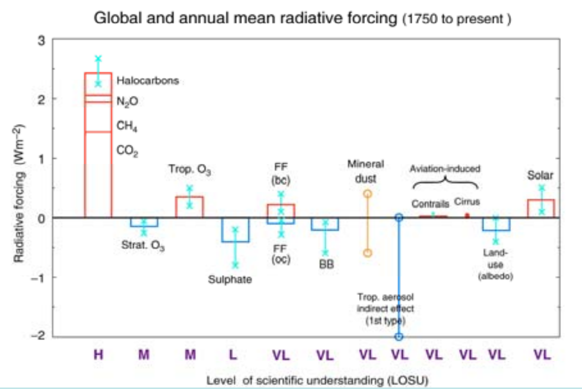
Increase in surface temperature →
melting of polar ice →
reduction in albedo →
+ve feedback

Water vapour, cloud & ice feedbacks

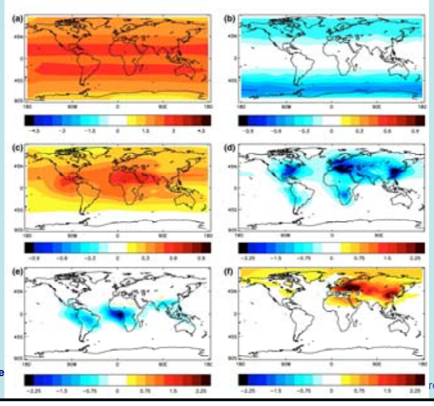
Very important but implicitly included in definition of λ so they:

- are a major cause of uncertainty in the value of λ but
- do not affect the concept of RF or values of RF components

IPCC radiative forcing estimates



Geographical distribution of RF (I)



GHGs

strat O_3

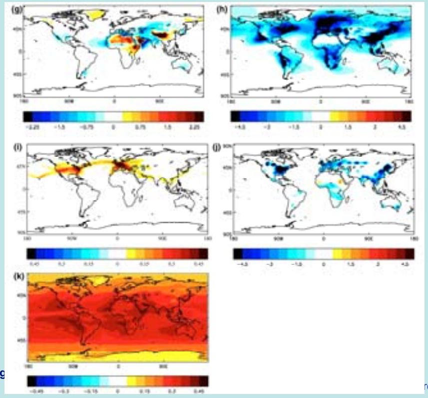
trop O_3

SO_4

bio C

fuel C

Geographical distribution of RF (II)



min dust

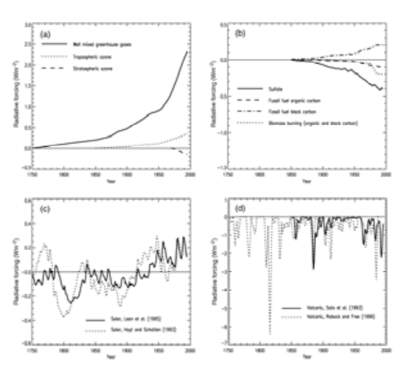
indirect SO_4

contrails

land use

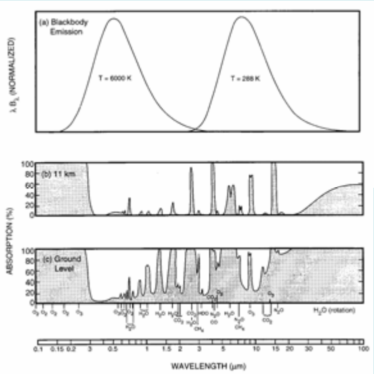
solar

Time evolution of RF components

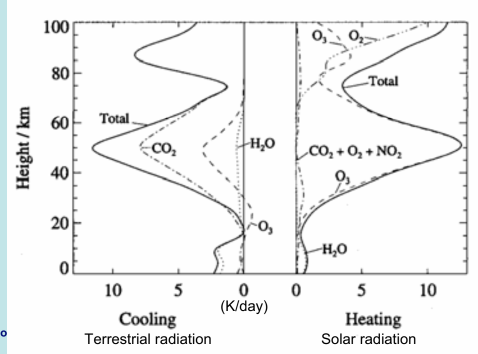


N.B. Cannot use these directly to give the evolution of T_s.

Atmospheric absorption



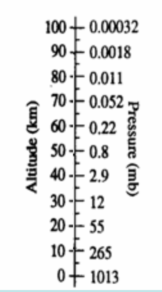
Atmospheric heating rate profiles



Atmospheric Dynamics

- Brief introduction to the physical laws determining the (thermo-) dynamical structure of the atmosphere.
- Waves and large scale modes of variability of the lower atmosphere.

Pressure and altitude



$$\frac{\partial p}{\partial z} = -g\rho \qquad pM = \rho RT$$

$$\frac{\partial \ln p}{\partial z} = \frac{gM}{RT}$$

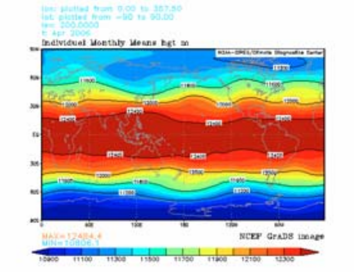
$$p(z) = p_0 \exp\left(-\int_0^z \frac{gM}{RT}\,dz'\right)$$

$$p(z) = p_0 \exp(-z/H) \quad \text{where scale height} \quad H = \frac{R\overline{T}}{Mg} \simeq 7.5\ \text{km}$$

pressure decays exponentially with altitude

Scale height and geopotential height

$$p(z) = p_0 \exp(-z/H) \qquad \text{Geopotential height} \quad Z_i = H \ln\left(\frac{p_0}{p_i}\right)$$



Z_i gives a measure of the mean temperature between p_0 and p_i

e.g. height of 200 hPa surface April 2006

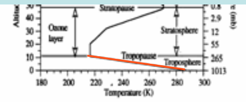
Adiabatic lapse rate

1st Law of thermodynamics: $dQ \equiv dW + dU$

Adiabatic: $dQ = 0$ so $0 = pdV + C_V dT$

Ideal Gas Law: $pV = RT$ so $pdV + Vdp = RdT$

Thus $0 = -Vdp + (C_V + R)dT$



$$\frac{dT}{Vdp} = \frac{1}{C_p}$$

$$\frac{dT}{dz} = -\frac{g}{C_p} = -\Gamma_d \qquad \text{For moist air:} \quad \frac{dT}{dz} = \frac{-\Gamma_d}{\left(1 + \frac{1}{C_p}\frac{\partial r_c}{dT}\right)}$$

$$\simeq -10\ \text{K/km} \qquad\qquad \simeq -6.5\ \text{K/km}$$

The temperature gradient in the troposphere is determined by convective not radiative processes.

Fundamental GFD equations for dry air

Newton's 2nd Law:

$$\frac{D\boldsymbol{u}}{Dt} = \boldsymbol{g} - \frac{1}{\rho}\nabla p - 2\boldsymbol{\Omega}\times\boldsymbol{u} + \boldsymbol{F}$$

Pressure gradient force Coriolis force Friction

Conservation of Mass:

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla.\boldsymbol{u} = 0$$

Thermodynamic Equation:

$$\frac{DT}{Dt} = Q + \frac{1}{\rho C_p}\frac{Dp}{Dt}$$

Diabatic heating Adiabatic compression

Ideal Gas Law:

$$pM = \rho RT$$

6 equations in 6 unknowns: velocity **u**, pressure p, density ρ, temperature T (given Q, F)

General circulation models (GCMs)

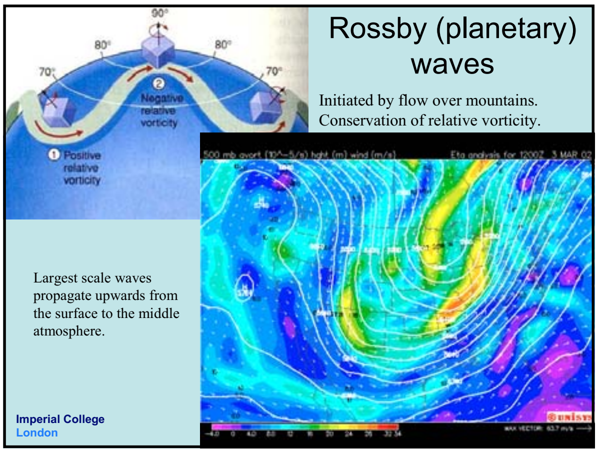
Numerical representation of "primitive equations"

Scientific considerations:
- fluid dynamics
- radiative transfer
- water phase
- surface effects
- chemistry

Computational considerations:
- discrete representation
- sub-grid-scale processes
- advection
- cpu / memory limitations

Can simplify – depending on application

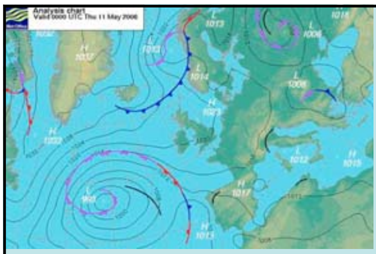
Waves in the atmosphere



Rossby (planetary) waves

Initiated by flow over mountains.
Conservation of relative vorticity.

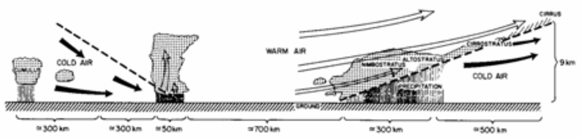
Largest scale waves propagate upwards from the surface to the middle atmosphere.

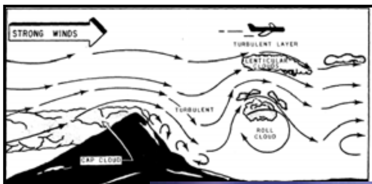


Baroclinic waves

Covert potential energy available from 3D temperature structure into kinetic energy of wave.

Section through mid-latitude cyclone

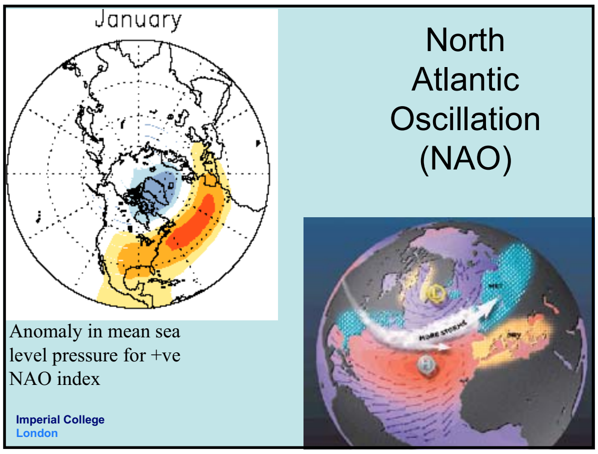




Lee (mountain) waves

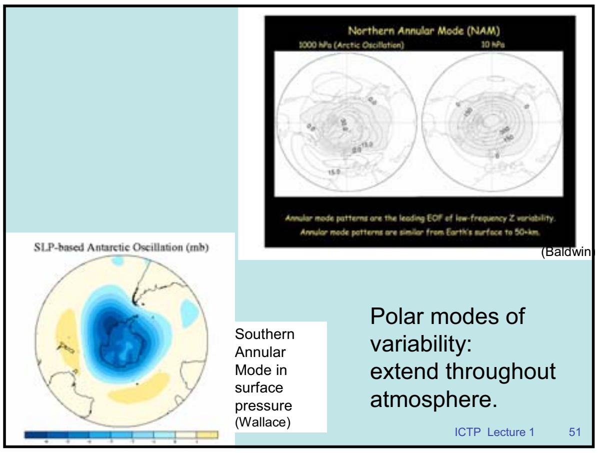
Restoring force is buoyancy. Example of atmospheric "gravity waves"

Modes of variability of the atmosphere



North Atlantic Oscillation (NAO)

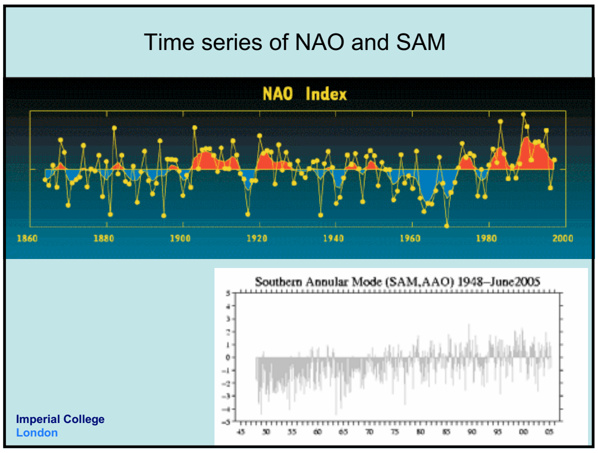
Anomaly in mean sea level pressure for +ve NAO index



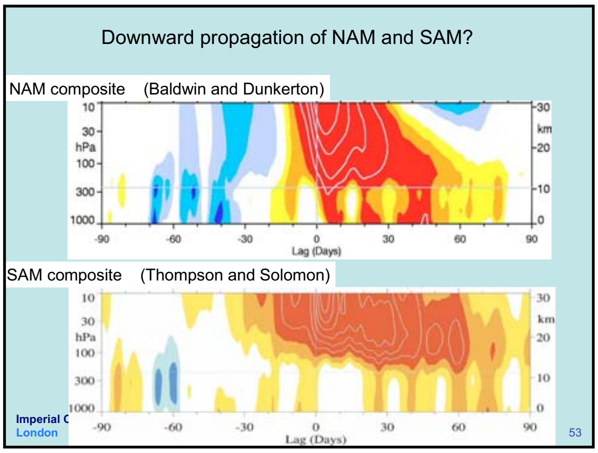
(Baldwin)

Southern Annular Mode in surface pressure (Wallace)

Polar modes of variability:
extend throughout atmosphere.



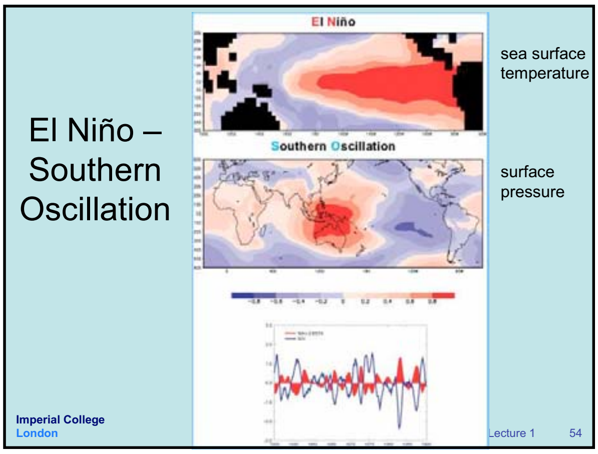
Time series of NAO and SAM



Downward propagation of NAM and SAM?

NAM composite (Baldwin and Dunkerton)

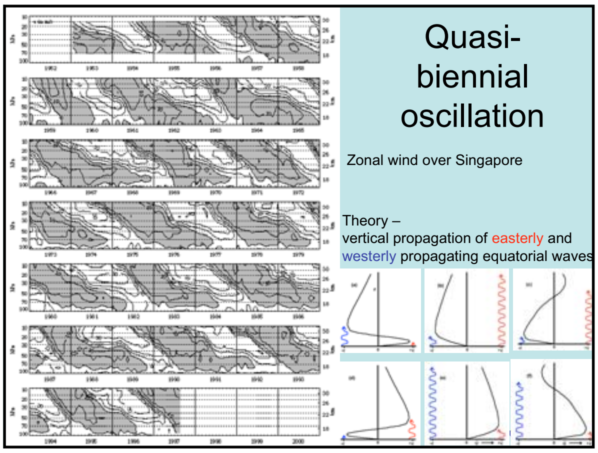
SAM composite (Thompson and Solomon)



El Niño – Southern Oscillation

sea surface temperature

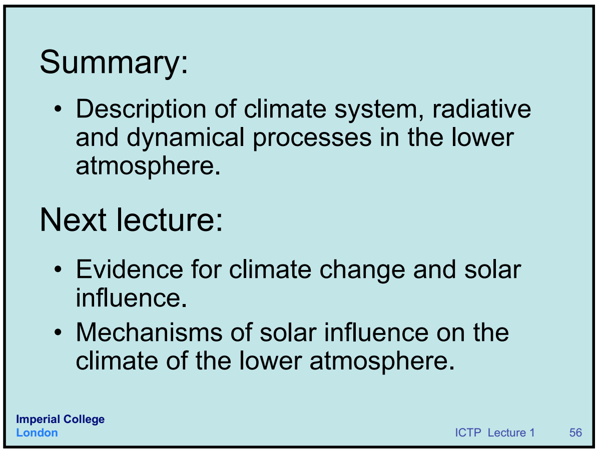
surface pressure



Quasi-biennial oscillation

Zonal wind over Singapore

Theory –
vertical propagation of easterly and westerly propagating equatorial waves



Summary:

- Description of climate system, radiative and dynamical processes in the lower atmosphere.

Next lecture:

- Evidence for climate change and solar influence.
- Mechanisms of solar influence on the climate of the lower atmosphere.

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