Simple Climate Models

Lecture 3

One-dimensional (vertical) radiative-convective models

Vertical atmospheric processes

- The vertical is the second important dimension, because there are...
  - Strong gradients (of temperature, humidity, etc)
  - Significant flux divergences
    - (zonal fluxes are large, but their divergences are quite small)
- The most important vertical processes are
  - ***convection***
    - large-scale ascent & descent (subsidence) : meridional circulation
    - small-scale turbulent overturning & mixing (unstable stratification)
  - ***radiation***
    - absorption and re-emission (some SW, but especially LW)

Convection & Atmospheric lapse rates

- The troposphere is (on average) just stable
  - but there are major differences between regions of ascent (active convection) and descent (subsidence)
- in ascending regions (small) : slightly unstable
  - mostly saturated with water vapour (condensation)
  - lapse rates tend to **moist adiabatic,** i.e. $\Gamma < 6$ °C/km
- in descending regions (large) : slightly stable
  - under-saturated (because the air has been dried out)
  - lapse rate tends to **dry adiabatic,** i.e. $\Gamma \approx 10$ °C/km
- large-scale average lapse rates are actually close to 6.5 °C/km everywhere (due to lateral mixing, etc)

Relative Humidity

- ♦ High (≈100%) in ascending air (condensation)
- ♦ Low (< 60%) in descending (dry) air
  - over the sea, evaporation causes RH to increase rapidly (to ≈ 85%)
  - over land, humidification depends on P-E
  - high in tropics, and near ± 60 ° latitude
  - low around ± 30 ° latitude (subsidence)
    - (which is why there are deserts there...)
- ♦ Overall, RH ≈ 80 ± 15 % almost everywhere
    - (NB "almost everywhere" is over the sea !!)

A very basic description of the atmosphere

- ♦ The "US standard" atmosphere
  - lapse rate = -6.5 °C/km
  - RH = 75 %
- ♦ Ascent (and excess precipitation)
  - near the equator (in the ITCZ)
  - around ± 60 ° latitude
- ♦ Subsidence (and excess evaporation)
  - near the poles
  - around ± 30 ° latitude
- ♦ Hadley and Ferrel circulation cells

Radiative equilibrium

two-stream approximation, "grey" atmosphere

- ♦ Static medium (no convection etc)
- ♦ Energy balance, due to radiation **only**
- ♦ Partial absorption, independent of wavelength
  - the "grey" atmosphere
- ♦ Simple case : consider upwelling and downwelling thermal infra-red only...
- ♦ Deduce temperature gradient (and T_s)
- ♦ Consider optical thickness $\Delta\tau$ of many layers...
  - See M.L. Salby (in Trenberth, 1992)
  - also J.T. Houghton, "The Physics of Atmospheres", second edition, CUP (1997)

Recommended proto-book

- **A First Course in Climate : *Earth and Elsewhere***
- **Volume I: Thermodynamics and radiation**
- **Volume II: Dynamics of the Atmosphere**
  - (with just enough oceanography to get by)
  - R. T. Pierrehumbert
    - Department of Geophysical Sciences
    - University of Chicago
    - Chicago, IL
- http://geosci.uchicago.edu/~rtp1/geo232/Notes.pdf

See also my attempt (less abstract)…

- **"Simple but very useful models of the atmosphere"**
- *Rad-Conv Text.pdf* (on course web-site)
- N.B. not yet complete….

Radiative (equilibrium) processes (1)

using the two-stream approximation
and a "grey" atmosphere

Divide atmosphere into thin layers, of optical thickness $\Delta\tau$

where $\tau = \int \rho \; a \; dz \quad \approx (a/g)\, p$, and $p =$ pressure....

if upward IR flux is F_{up} , and downward IR flux is F_{dn}

net IR flux $F = F_{up} - F_{dn}$, and at equil'm, $dF/dz = 0$

and $\therefore \; F = const = F_0$ (net upward IR flux at TOA)

Radiative (equilibrium) processes (2)

but $dF_{up}/d\tau = F_{up} - B(\tau)$, and $-dF_{dn}/d\tau = F_{dn} - B(\tau)$

where $B(\tau) = \sigma T^4$ (black-body radiation)

$\therefore dF/d\tau = F_{tot} - 2B(\tau) = 0 \quad \therefore F_{tot} = 2B(\tau)$

but also $dF_{tot}/d\tau = F_{up} - F_{dn} = F_0$

$\therefore F_{tot} = F_0 \int d\tau = F_0\tau + const = F_0(\tau + 1) = 2B(\tau)$

$\therefore B(\tau) = \frac{F_0}{2}(\tau + 1)$, and $F_{tot} = 2B(\tau) = F_0(\tau + 1)$

Radiative (equilibrium) processes (3)

But, since $B(\tau) = \frac{F_0}{2}(\tau + 1)$, $B(1) = F_0$.

Also $F_{up} = \frac{1}{2}(F_0 + F_{tot}) = F_0(1 + \tau/2)$

$\{\therefore \varepsilon = F_0/F_{up}(\tau) = 1/(1 + \tau/2)\}$

and $B(T_g) = F_{up}(\tau) = F_0(1 + \tau/2) = \sigma T_g^4$

Since $F_0 = \sigma T_{eff}^4 \quad T_g^4 = T_{eff}^4(1 + \tau/2)$

Radiative (equilibrium) processes (4)

$\therefore T_g = T_{eff}(1 + \tau/2)^{1/4}$

and $\tau = 2(T_g^4/T_{eff}^4 - 1)$

with $T_g = 288$ K, $T_{eff} = 255$ K, $\tau = 1.254$

$\Rightarrow H_{eff} = (1/1.254) \times 1000$ mbar ≈ 800 mbar

but NB also $T_g - T_{eff} = 33$ K

and a lapse-rate of 6.5 K/km

$\Rightarrow H_{eff} = 5$ km $\cong 600$ mbar

These results are *inconsistent*

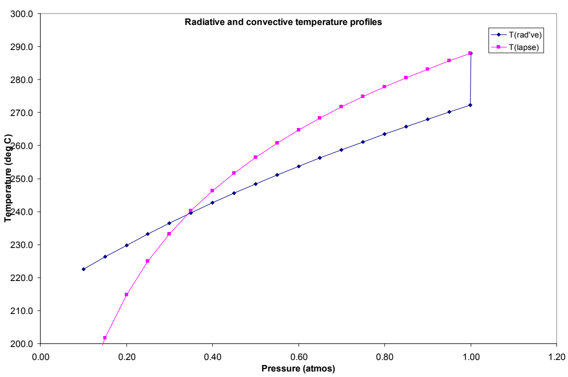
$\Rightarrow$ there is a problem here...

The problem is due to…

- Development of a near-ground temperature "discontinuity"
- Which makes the temperature stratification ***statically unstable***
- Causing vertical convection
- Which carries a significant heat flux
- So the assumptions of a static atmosphere, and heat transport by radiation only are untenable
- We need to allow for convection, and so need a ***radiative-convective*** model

Instability of pure radiative equilibrium

[H=7 km, tau=1.6, ΔT= 15.8°C]

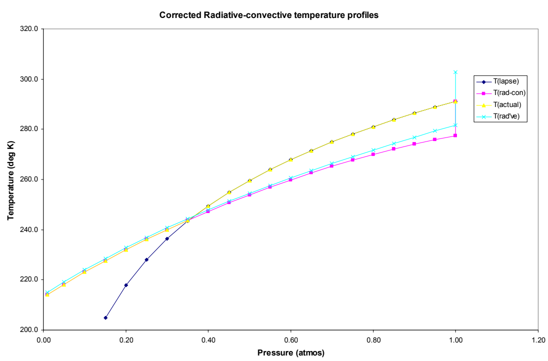


The near-ground temperature "discontinuity"

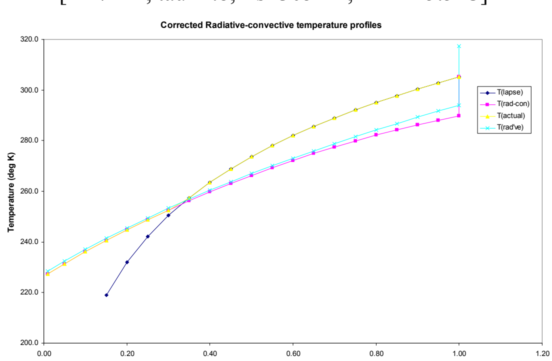
Convective adjustment:
(time-dependent calculation)

- calculate radiative fluxes
  - (divergence => heating or cooling)
- update temperature profile
- if unstable w.r.t. chosen lapse rate
- apply convective mixing → desired lapse rate
  - (conserve heat, water, etc)
  - → implied convective heat flux...
- repeat → radiative-convective equilibrium
- → tropo-pause & (unrealistic) stratosphere

Radiative-convective equilibrium (global average)
[H=7 km, tau=2.0, Ts=291 °K, ΔT= 13.8°C]

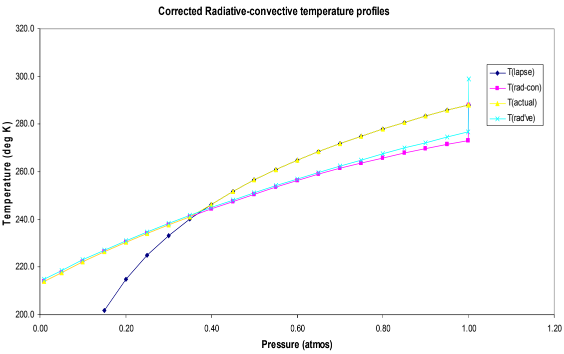


Radiative-convective equilibrium (equator)
[H=7 km, tau=1.8, Ts=305 °K, ΔT= 15.5°C]



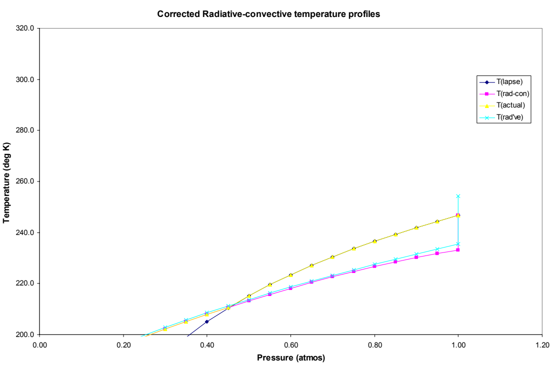
Radiative-convective equilibrium (mid-latitude)

[H=7 km, tau=1.8, Ts=288 °K, ΔT= 15.0°C]



Radiative-convective equilibrium (polar)

[H=7 km, tau=1.8, Ts=247 °K, ΔT= 13.5°C]

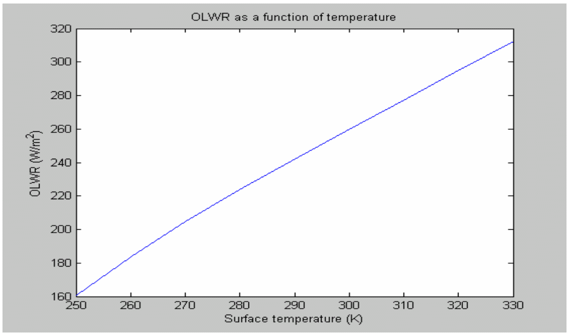


Grey Atmosphere Radiative Convective Model

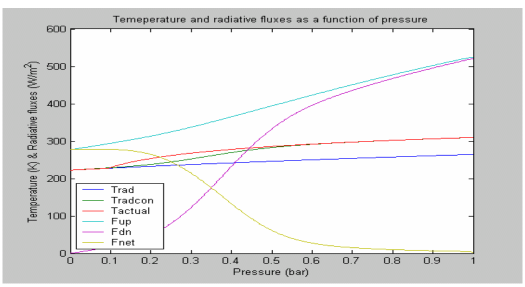
100% saturated, lapse-rate = 5 C/km

[including water-vapour/altitude relationship]

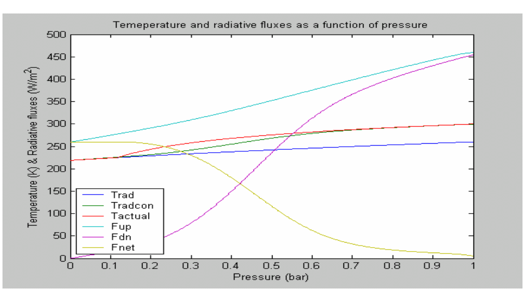
OLWR versus Temperature



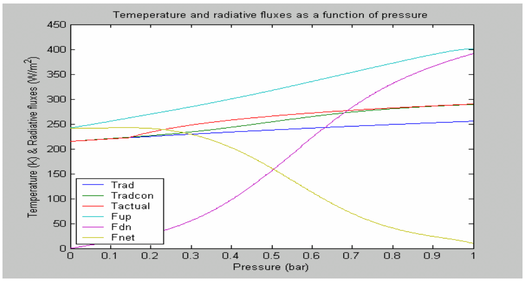
T_s=310 K



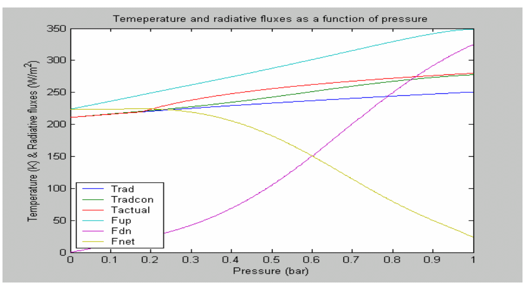
T_s=300 K



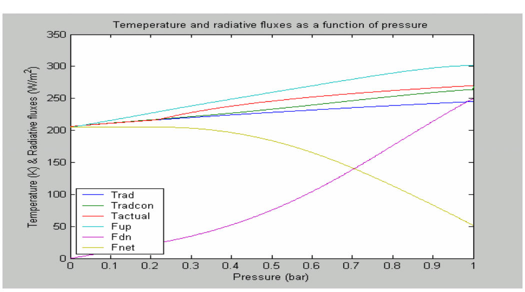
T_s=290 K



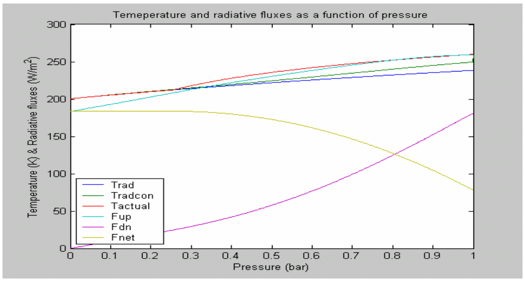
T_s=280 K



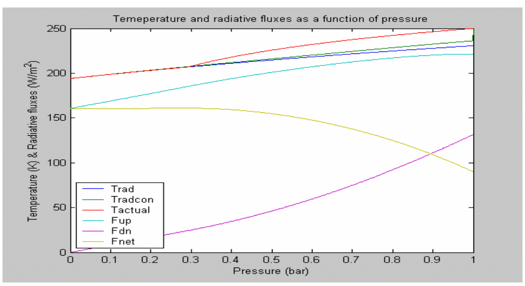
T_s=270 K



T_s=260 K



T_s=250 K



1-D Radiative-Convective models : features

- ♦ Can include various radiatively active gases
  - (water vapour, ozone, CO_2, methane etc...)
  - better representation of stratosphere c.f. troposphere..
- ♦ Allow direct estimation of GH effects
  - (and thus climate sensitivity)
  - Can estimate OLWR as a function of T_s
  - Can calculate troposphere height c.f. latitude
- ♦ Can include clouds : e.g. if RH > $RH_{crit} \approx 90$ %
  - specify albedo (≈ 0.5) or estimate (diffuse scattering)
  - specify cloud height & depth
    - fixed cloud top height, or temperature (?)
  - several cloud layers ? (how to model ?)

1-D Radiative-Convective models : in practice

- Need to consider
  - many (≈ 20) layers
  - many radiatively active “species” (gases etc)
  - integration over many spectral lines and bands, and over a continuum (8 to 13 μm)
  - both UV/Visible and IR radiation
  - Also particulate scattering...
- Complex and time-consuming calculations...!
- Essentially = radiation code of a GCM
  - N.B. Computational demand of radiation code may exceed that of fluid flow, in GCM’s

1-D Radiative-Convective Models Overview

- Are valid only locally (isolated, pointwise), or as a global mean
- but the results vary with latitude/insolation
  - → latitudinal variation of tropo-pause height, etc
- but ⇒ inconsistency : adjacent columns are not compatible (have different temperature profiles)
- So one needs to allow for lateral transports
- ⇒ need for 2-D (meridional/vertical) models (at least)