SOES 6006 Climate Dynamics

The Greenhouse Effect and Radiative-Convective Models

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Vertical atmospheric processes

- ♦ The vertical is an important dimension, because there are ...
  - Strong gradients (of temperature, humidity, etc)
  - Significant ***flux divergences*** (=> heating/cooling)
    - (NB: zonal fluxes are large, but divergences are small)
- ♦ The most important vertical processes are :
  - ***Convection***
    - **large-scale ascent & descent** => meridional circulation (Hadley/Ferrell circulation etc)
    - **small-scale turbulent overturning & mixing** (=> unstable stratification)
  - ***radiation***
    - absorption and re-emission (some SW, but especially LW)

Vertical temperature structure of the atmosphere

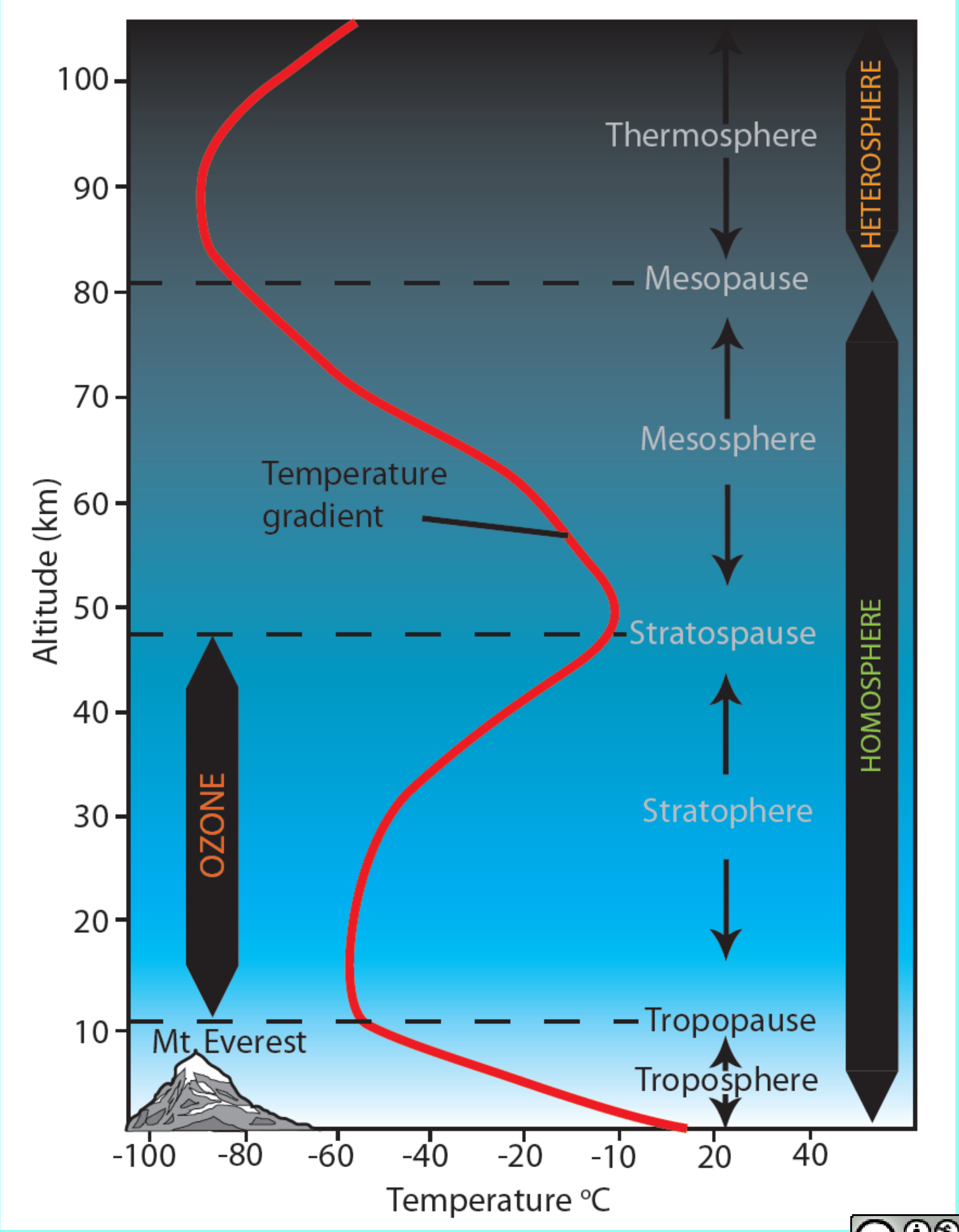
Temperature ***falls linearly*** with altitude in the troposphere, i.e. up to ~10km at mid-latitudes (but NB it is higher at the equator, and lower at the poles)

[This ***lapse rate*** is due to convective mixing]

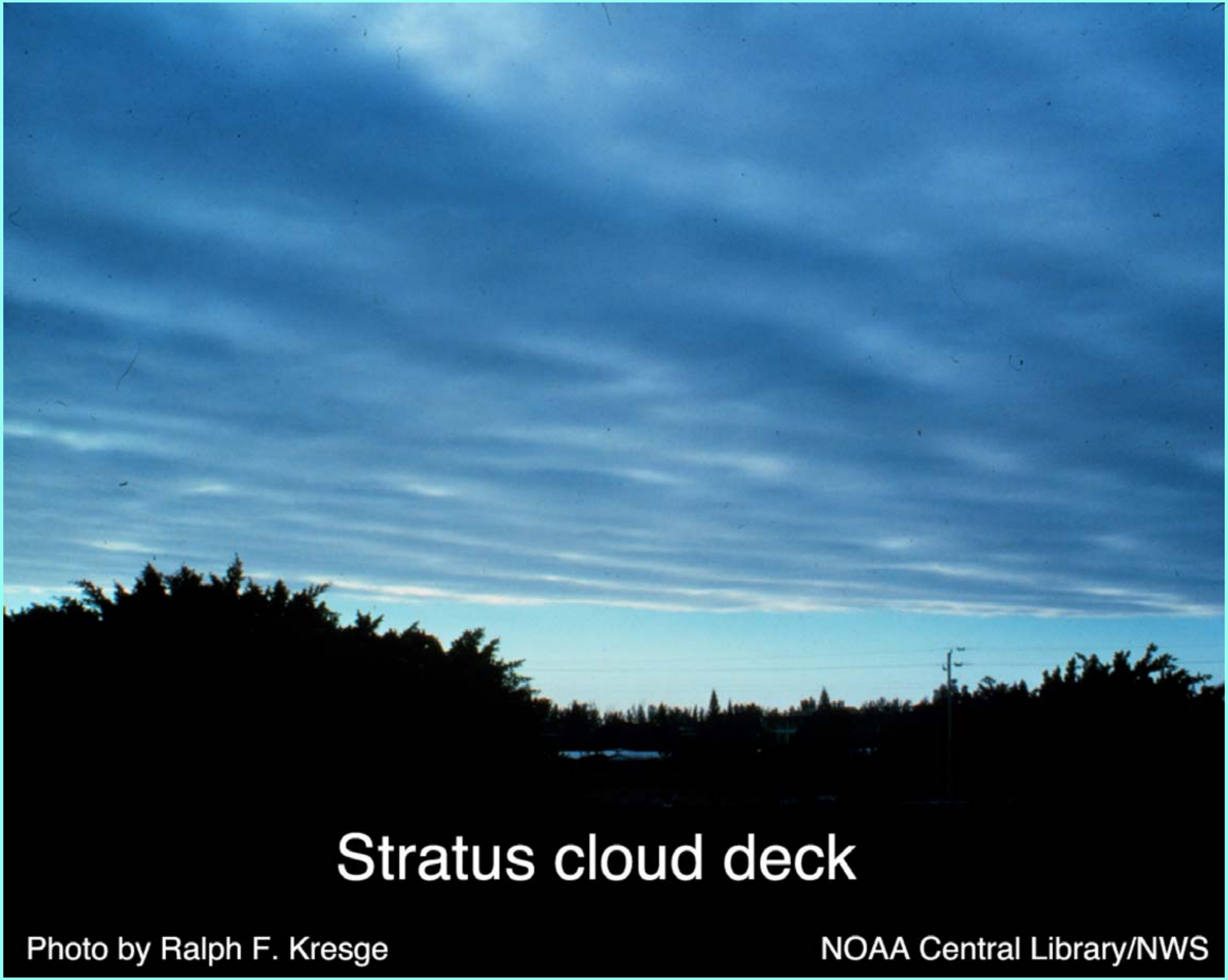
It then increases again above the tropopause, in the stratosphere

[This is due to absorption of UV radiation by ozone.]

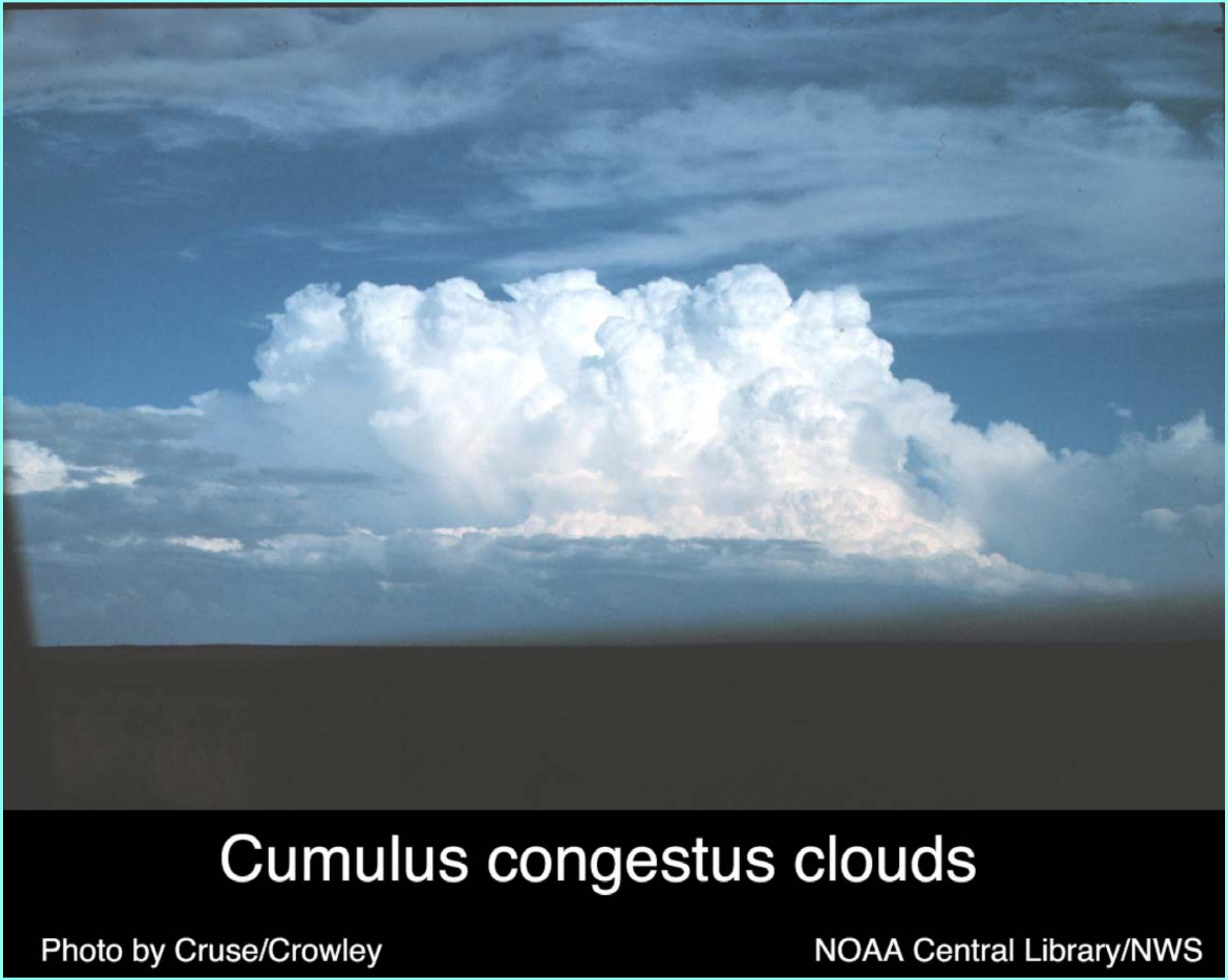
- “Tropo” comes from Greek root for “turning” (as in “turning over”)
- “Strato..” refers to stratification



Stably stratified atmosphere

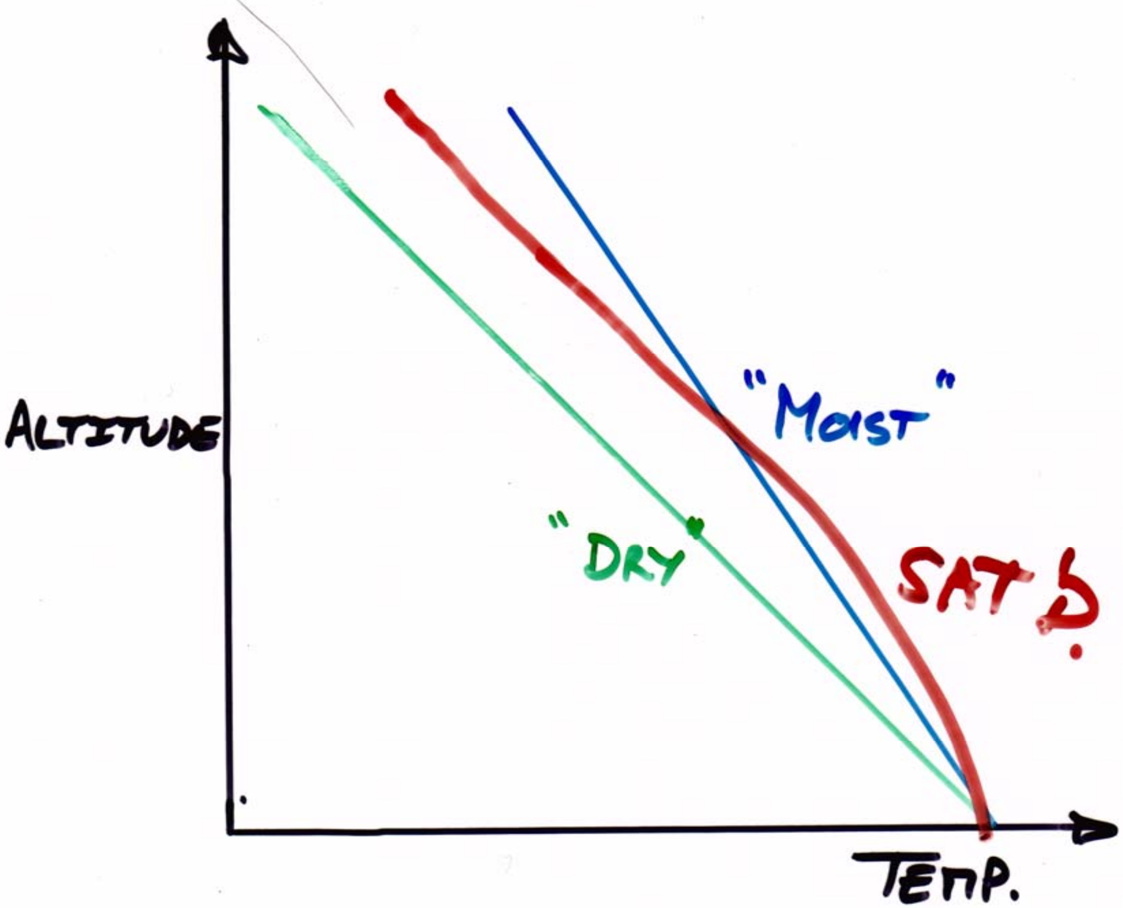


Convectively unstable atmosphere



Convection & Atmospheric lapse rates

- The troposphere is (on average) just stable
  - but there are major differences between regions of ***ascent*** (active convection) & ***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 quite close to 6.5 °C/km almost everywhere
  - due to lateral mixing, etc

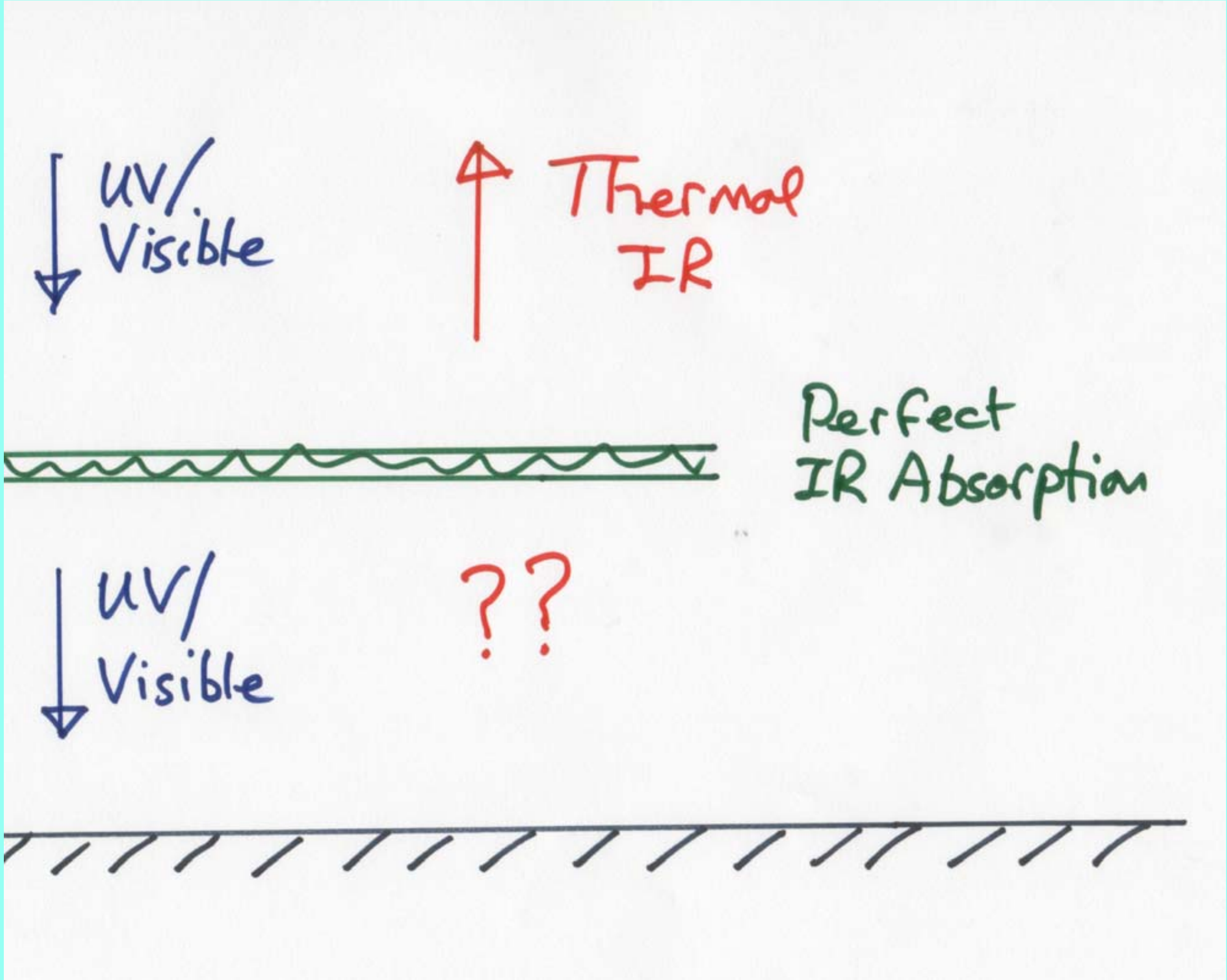


ADIABATIC LAPSE RATES

"MOIST" (SATURATED) ≲ 6.5 °C/km

"DRY" ~ 10 °C/km

Outgoing (Thermal IR) Radiation and the Greenhouse Effect (1)



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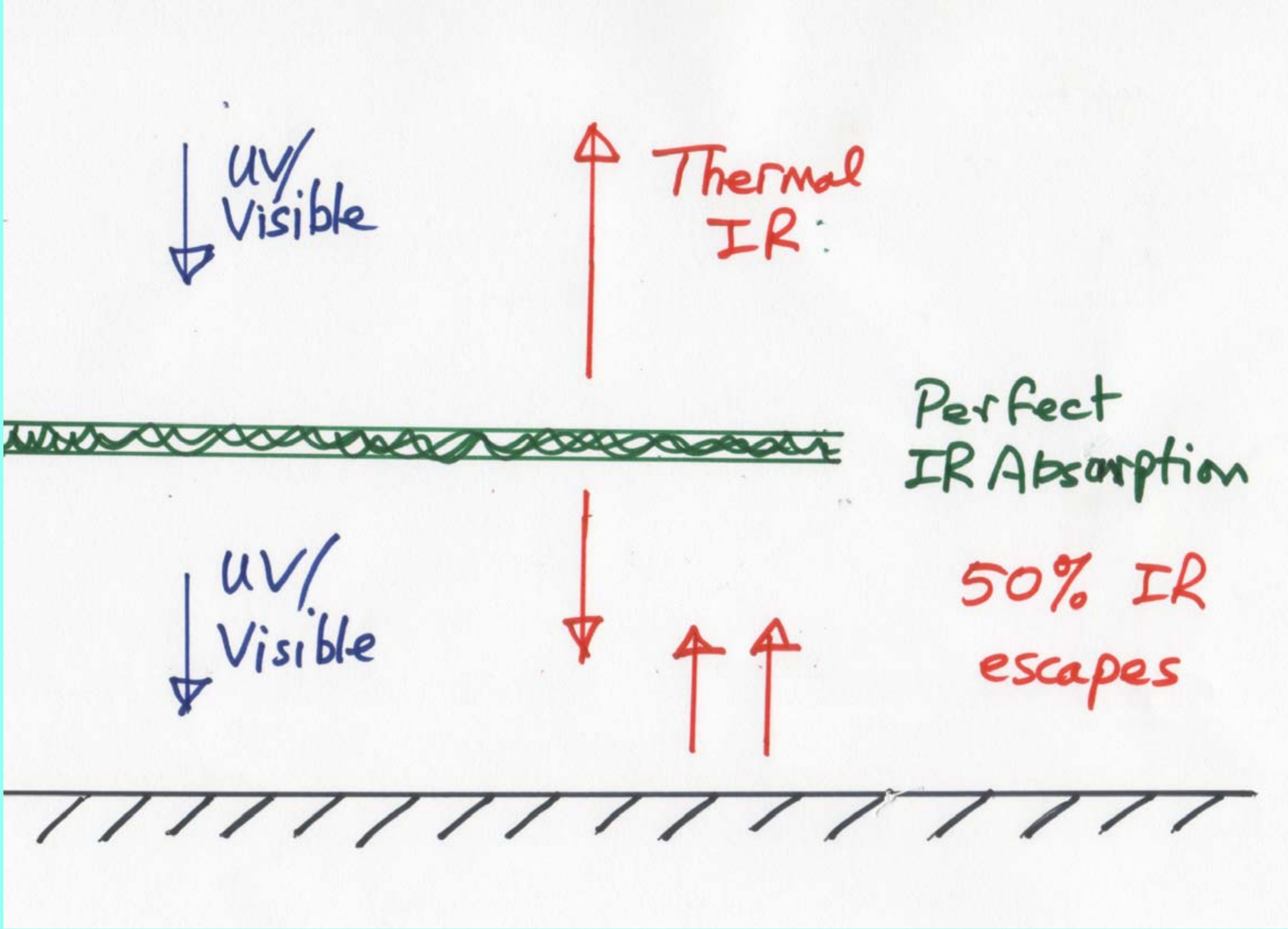
Outgoing (Thermal IR) Radiation and the Greenhouse Effect (2)



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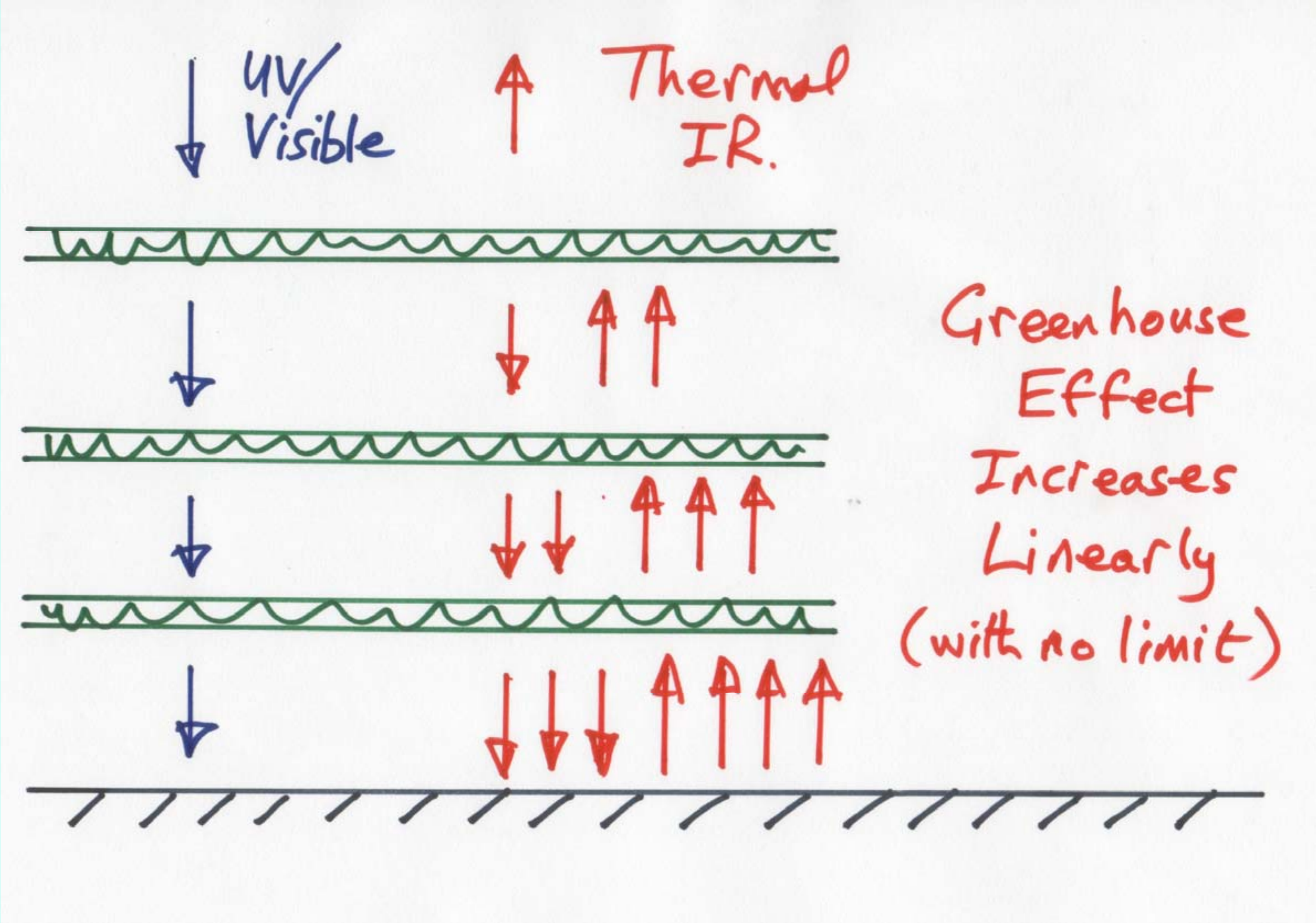
Outgoing (Thermal IR) Radiation and the Greenhouse Effect (3)



Radiative equilibrium theory

"two-stream" approximation, "grey" atmosphere

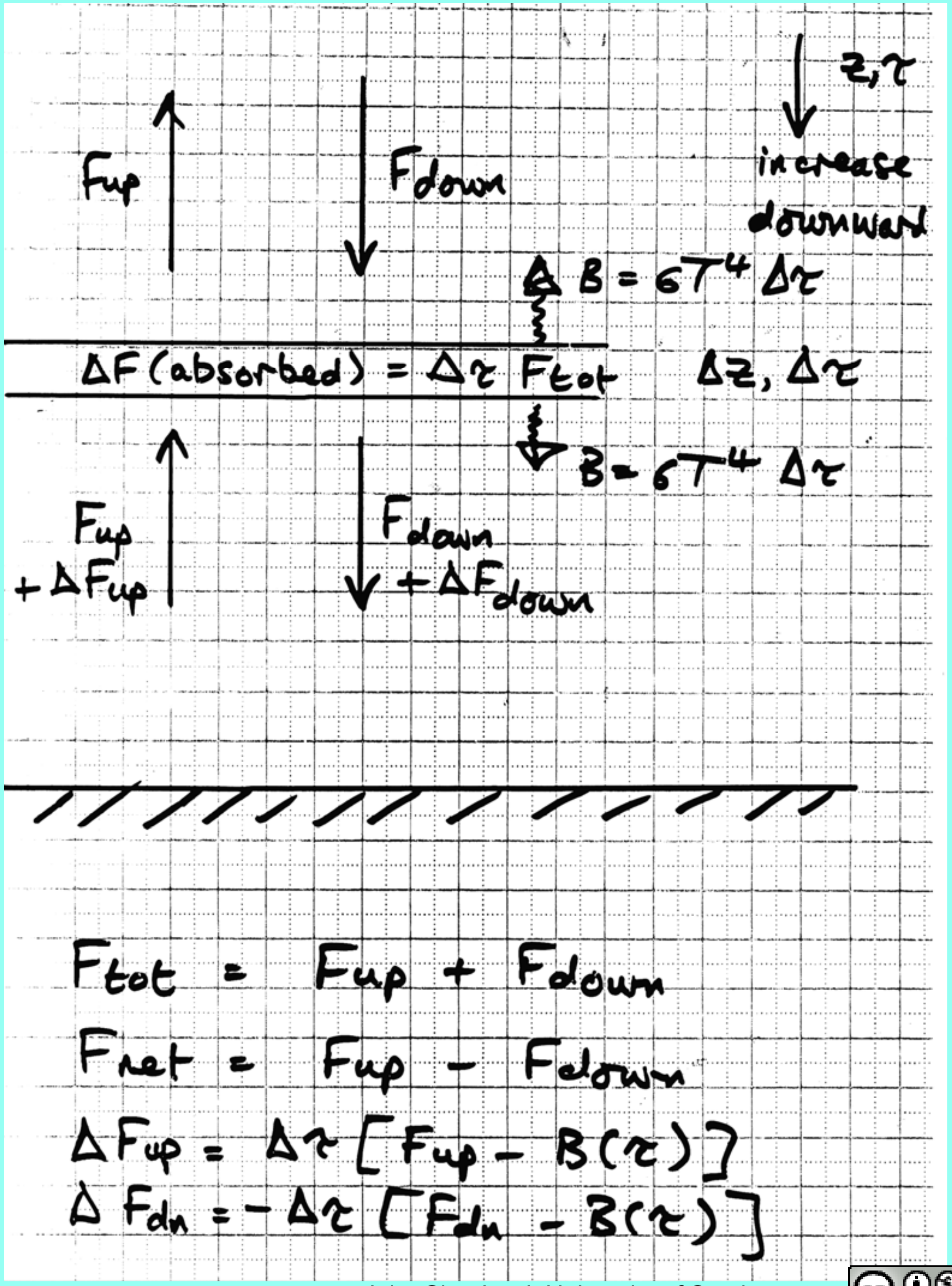
- ***Static*** medium (no convection, etc.)
- Energy balance, due to radiation **only**
- ***Partial*** absorption, independent of wavelength
  - the "grey" atmosphere (absorbs ***some*** radiation)
- Simplest case : consider upwelling and downwelling of *thermal infra-red radiation* only ...
- Deduce temperature gradient (and hence estimate surface temperature 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)

Radiative equilibrium model

Schematic & basic equations for LW balance in a "grey" atmospheric layer

N.B. $\sigma T^4 \Delta\tau$ is like $\varepsilon\sigma T^4$ (from 0-D EBM yesterday) - represents LW absorption (& re-emission) in a single layer of the atmosphere

ΔF_{up}, ΔF_{dn} account for partial absorption of incoming radiation (F_{up},F_{dn}) + re-emission (B), sign convention according to net gain (+ve) or loss (-ve) by the layer



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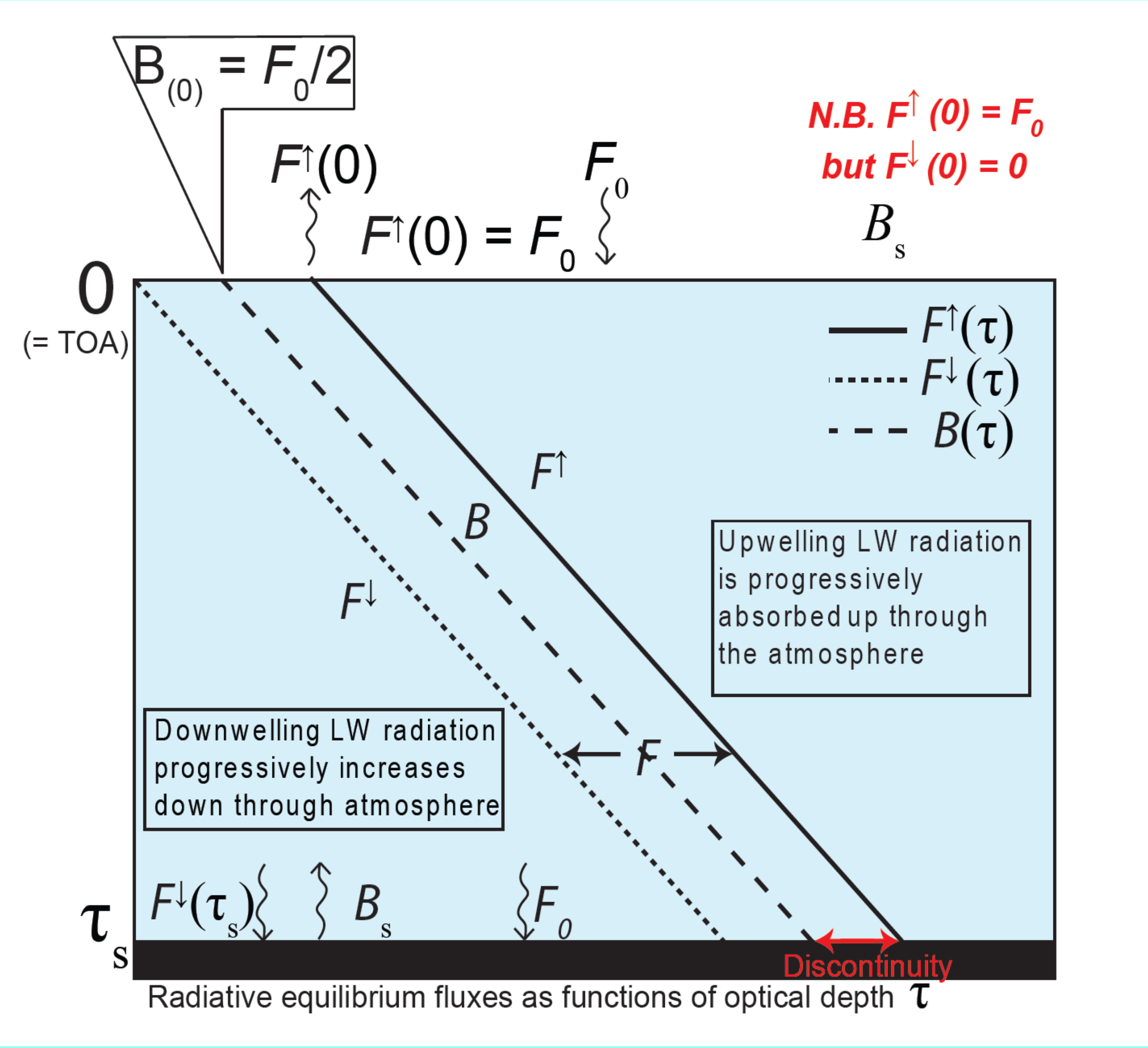
Radiative Equilibrium Solution

NB: there is an implied temperature discontinuity just above ground (where it is suddenly warmer)



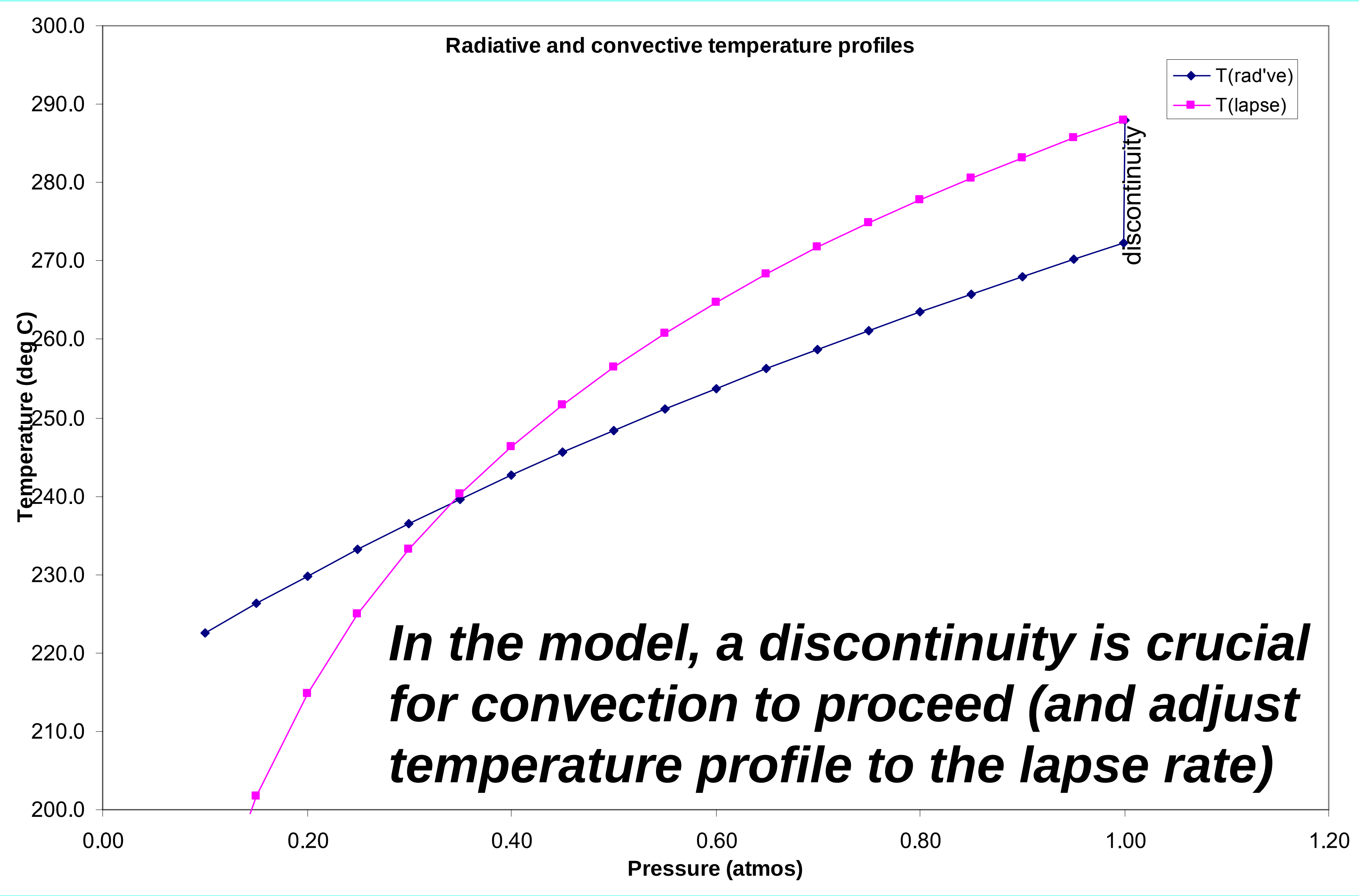
Redrawn and modified from Salby, M., 1992, Fundamentals of Atmospheric Physics, Academic Press, 627p.

Pure radiative model is inadequate …

- Development of a near-ground temperature "discontinuity", ΔT
- Which makes the temperature stratification ***statically unstable***
- Causing vertical ***convection,*** i.e. motion…
- 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, τ = 1.6, ΔT = 15.8°C]



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Structure of a typical radiative-convective model (from McGuffie & Henderson-Sellars, Chapter 4)

Non-dimensional vertical coordinate:

$$\sigma = \frac{p - p_T}{p_s - p_T};$$

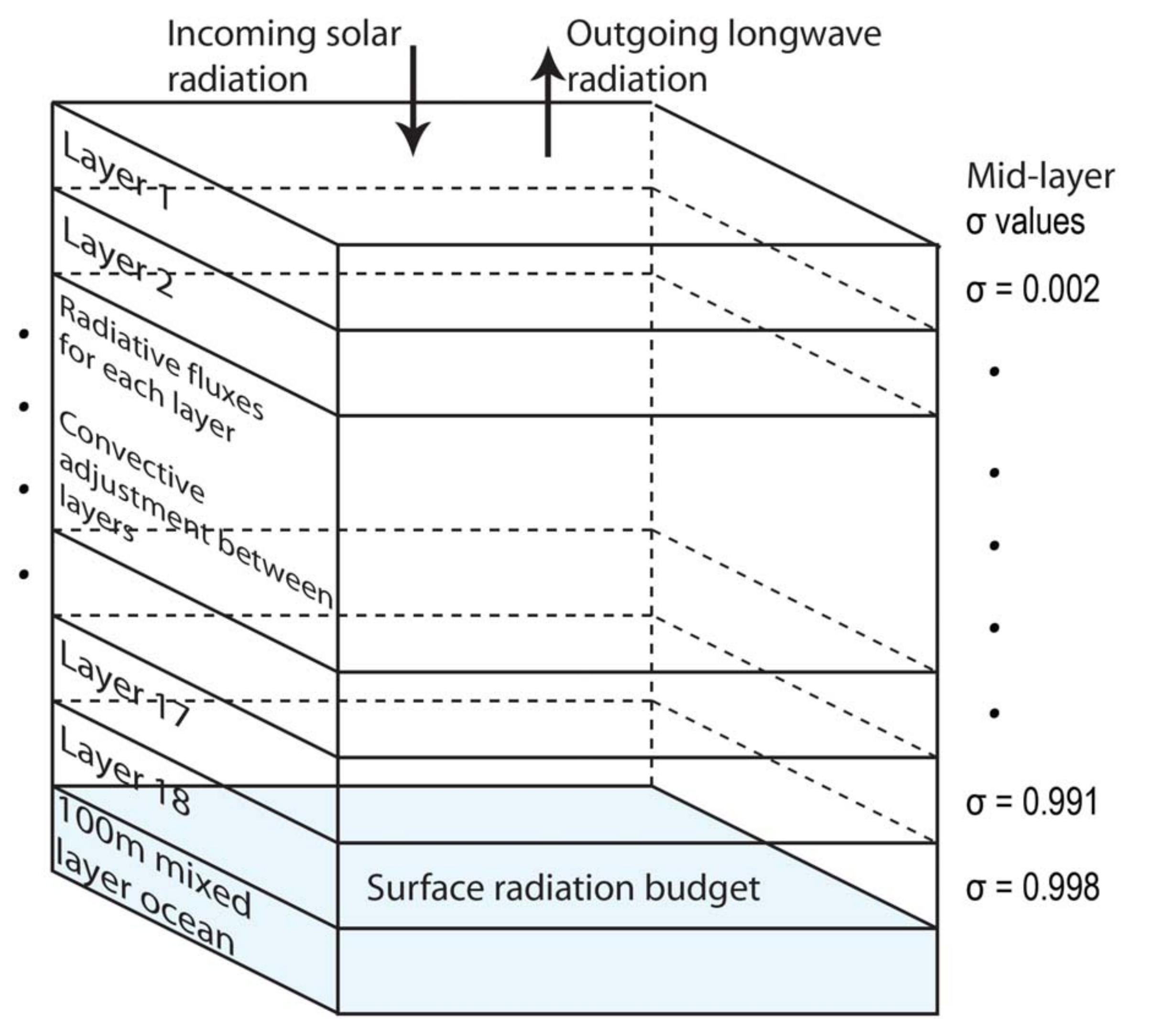
$p =$ pressure at height z

$p_T = p$ at upper level

$p_s = p$ at ground level

Radiation balance is solved in detail

Convection = iterative adjustment of the vertical temperature profile

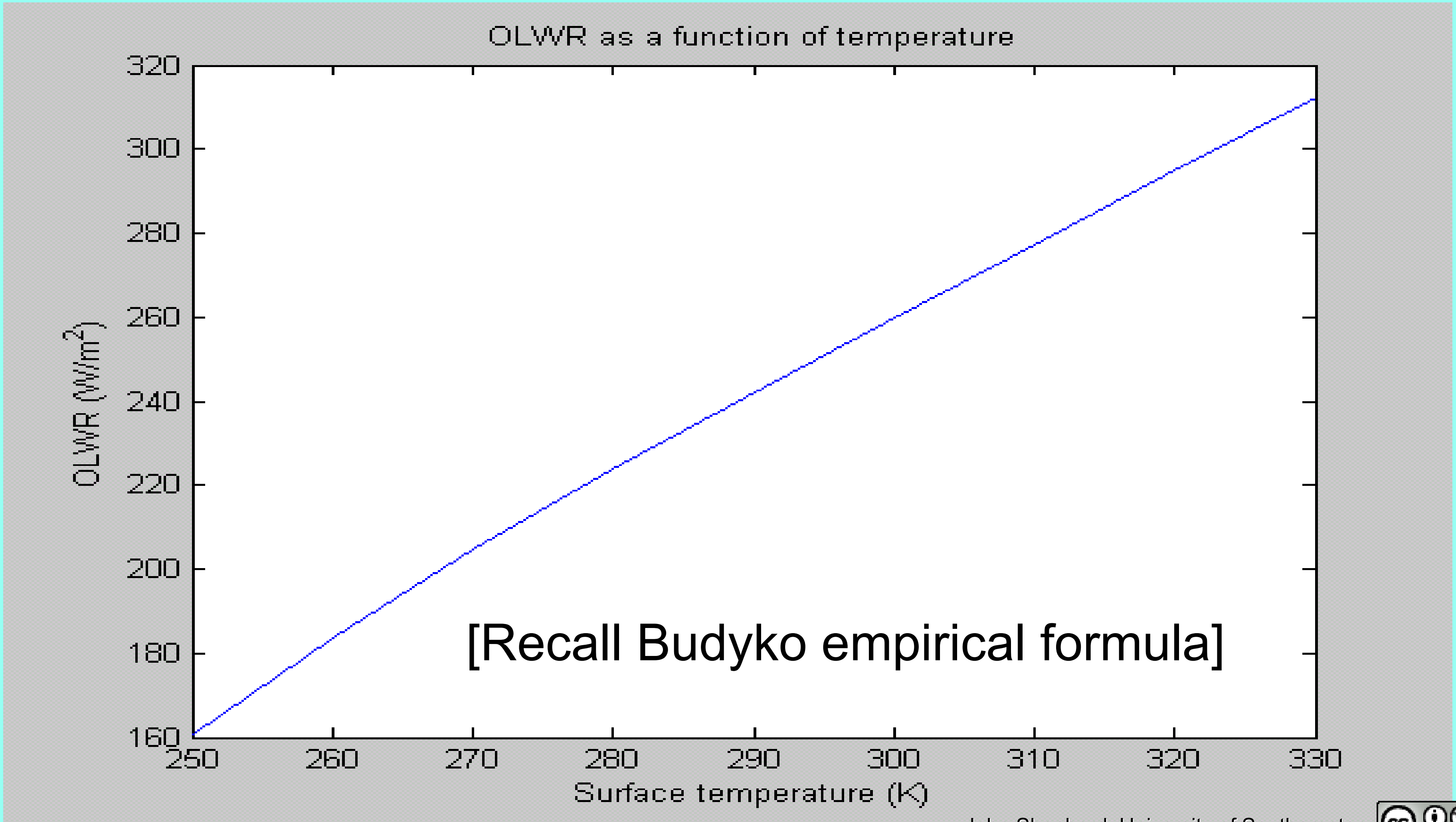


Radiative-Convective adjustment: (time-dependent numerical calculation)

- For any specified initial temperature profile …
- calculate radiative fluxes
  - vertical divergence => heating or cooling
  - update temperature profile
- if unstable w.r.t. chosen lapse rate …
- apply convective mixing:
  - returning temperature profile to desired lapse rate
  - conserving heat, water, etc.
  - NB this involves an ***implied*** convective heat flux
- repeat until radiative-convective equilibrium obtained
- Simulates troposphere & gives tropopause with an (unrealistic) stratosphere (no UV/Vis absorption)

RC Model result: OLWR versus Temperature

Grey Atmosphere "moist" Radiative-Convective Model
100% saturated, lapse-rate = 5°C/km
[including water-vapor/altitude relationship]



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OLWR as a function of humidity & temperature

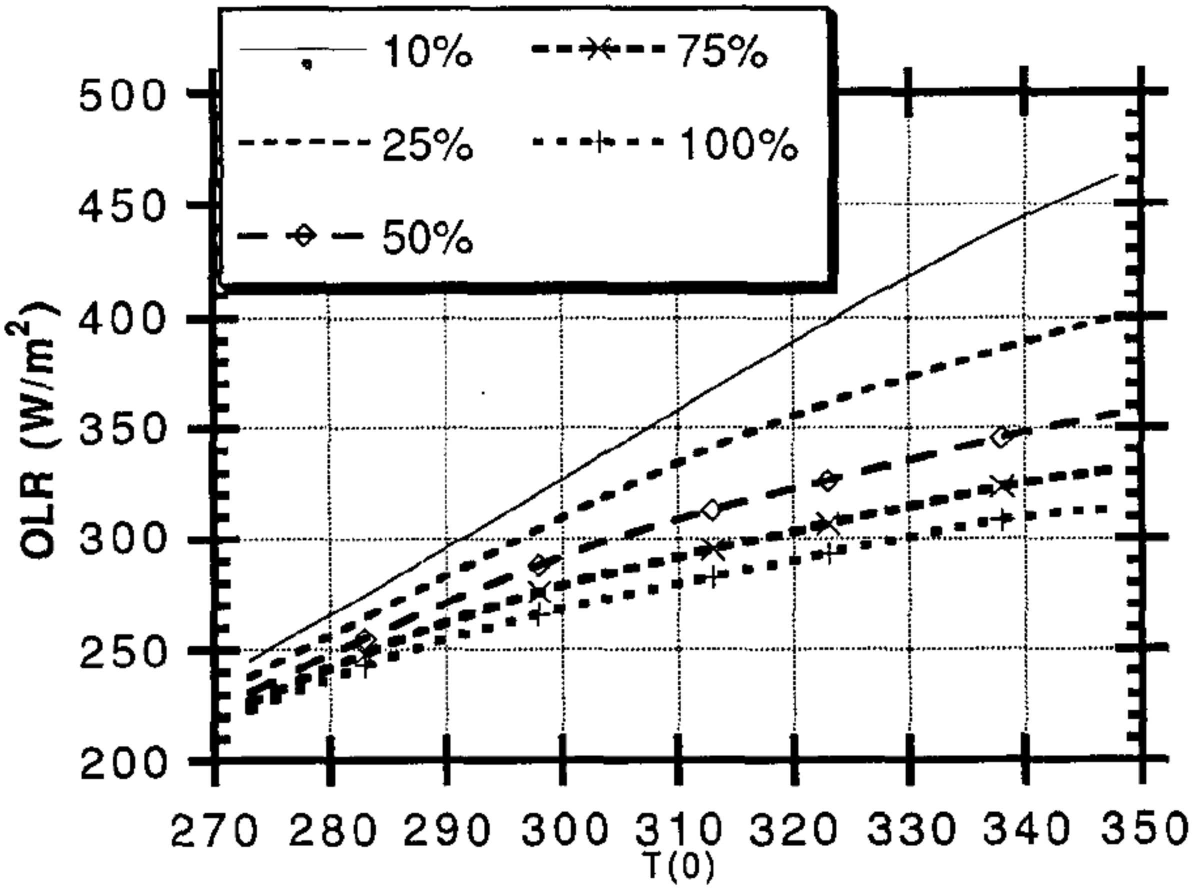


FIG. 2. Clear-sky OLR computed for various relative humidities, using the NCAR CCM radiation code and present-day CO_2. Results are shown as a function of low-level air temperature $T(0)$. See text for details concerning the temperature profile.

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 ?)

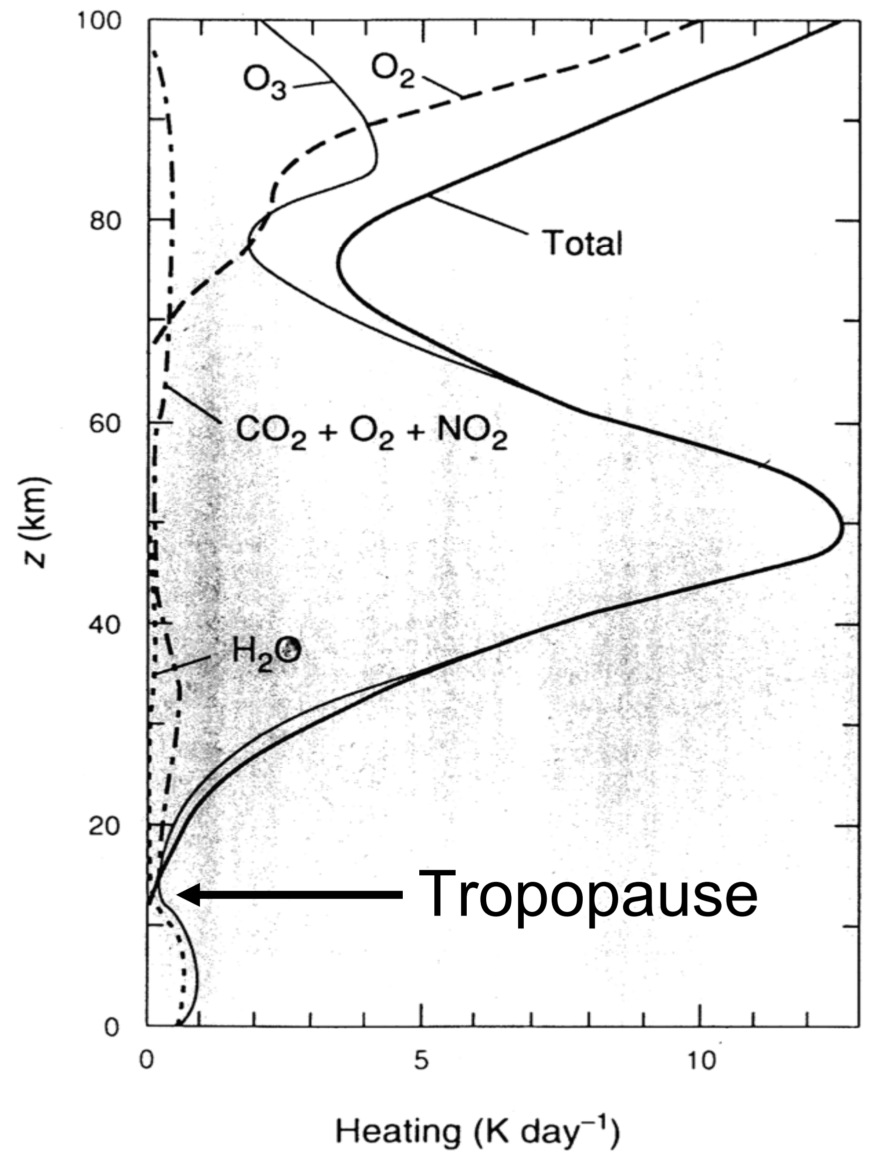
1-D Radiative-Convective models: in practice

- ♦ 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 GCMs

Real-world Complications:

Absorption of ISWR by the atmosphere

(from Trenberth 1992)

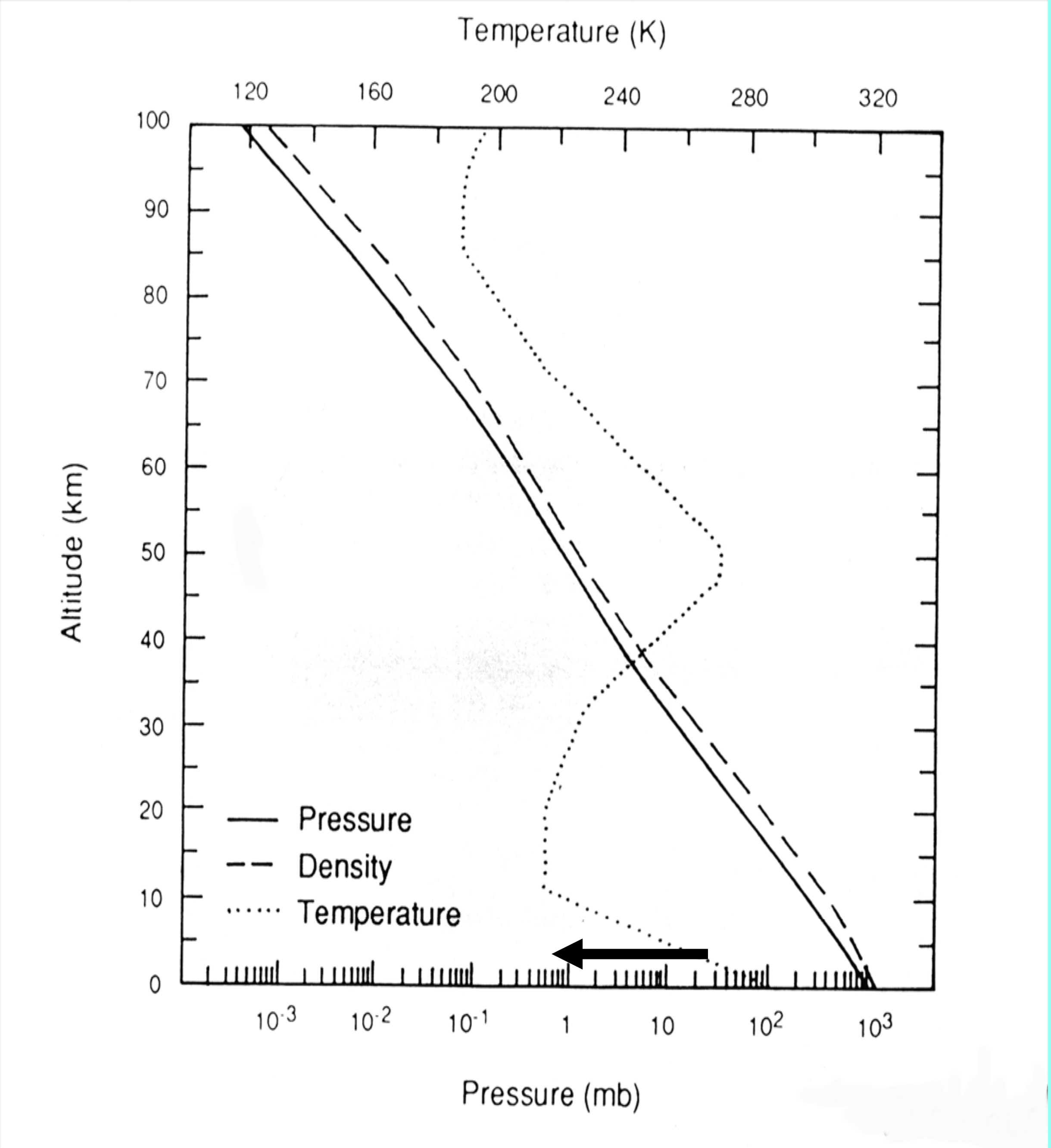


Vertical profile of radiative solar heating K day^{-1} for various atmospheric constituents.

From: London, J., 1980 Radiative Energy Sources and Sinks in the Stratosphere and Mesosphere. Proceedings of the NATO Advanced study institute on Atmosphere Ozone: Its variations and Human Influences, Reports FAA-EE-80-20 A.C., Aikin (ed.), p. 703-721

The real atmosphere

(from Trenberth 1992)

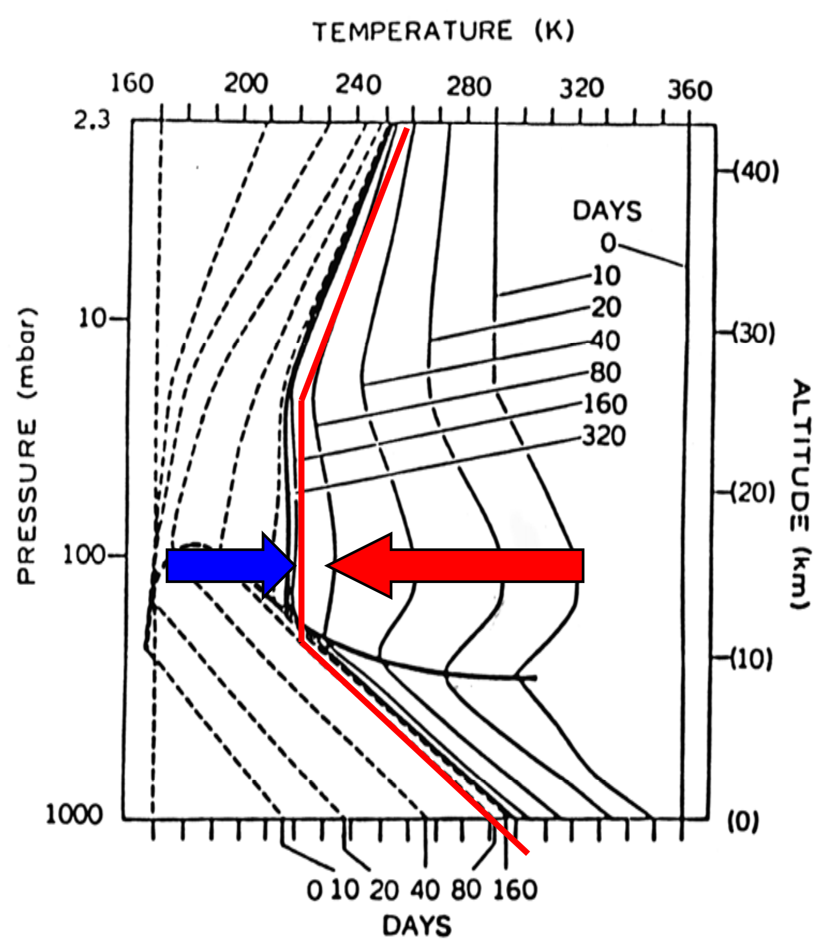


Radiative-convective models in practice

(Manabe & Strickler 1964)

- Same RC model is started from 2 different initial temp. profiles
- After nearly 1 model year, both simulated T-profiles convergence on some "truth"

INTRODUCTION TO CLIMATE MODELS



Simulation of vertical atmospheric temperature structure as it equilibrates from two originally isothermal conditions. Temperature (abscissa) versus altitude (shown as pressure on the left and height in km on the right) as a function of time for two cases in a radiative convective model simulation. The rightmost sequence is started from a vertically isothermal condition of 360°K with profiles shown for different times (days) after the model starts to integrate. Dashed profiles on the left are the same type of sequence for a very cold isothermal initial condition

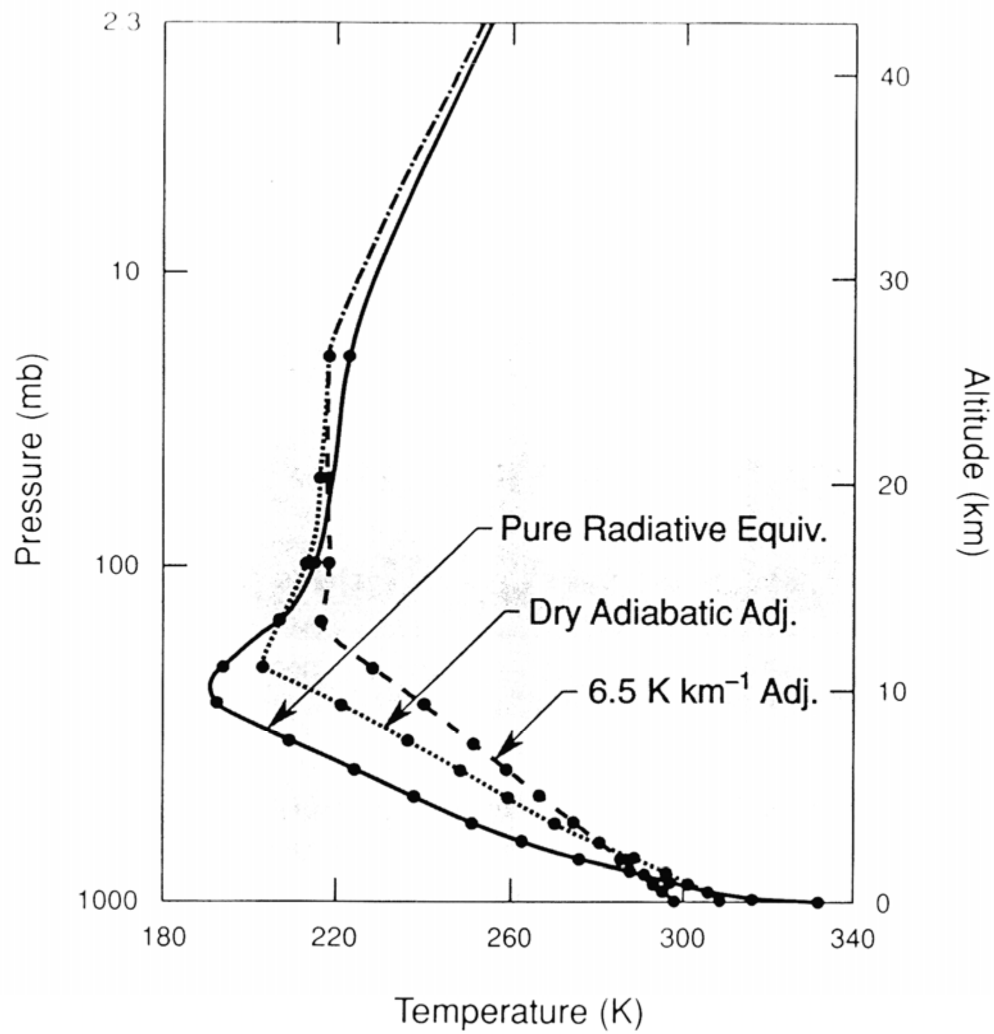
Radiative-convective models in practice

(Manabe & Strickler 1964)

Radiative balance

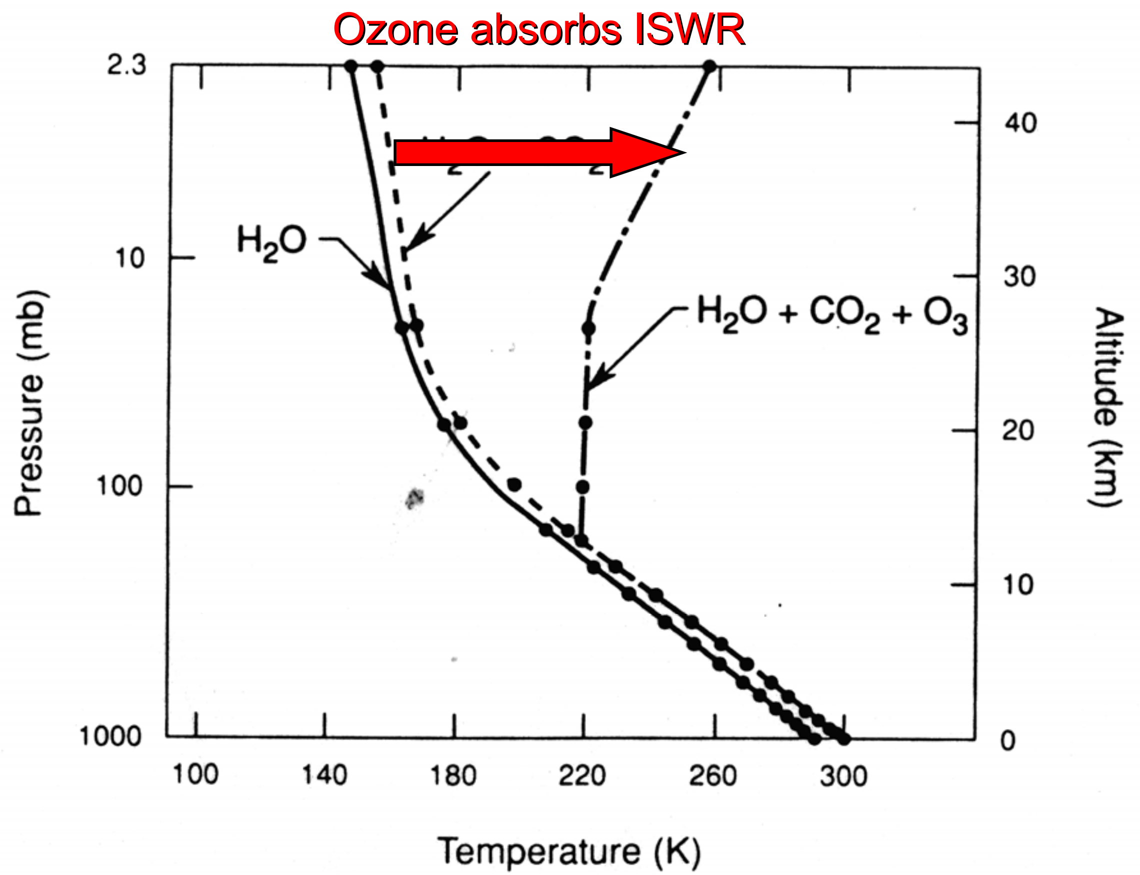
+ convection

+ moisture



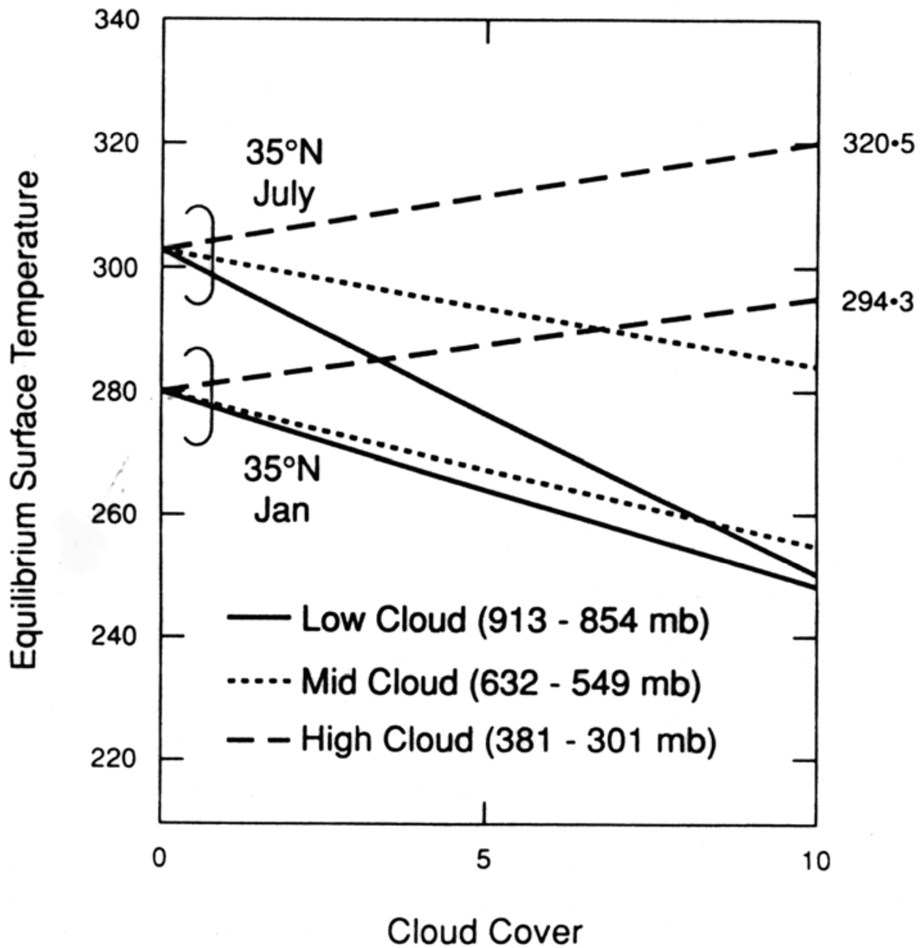
Vertical temperature profile obtained from the one-dimensional radiative-convective model of Manabe and Strickler (1964). Shown are temperature profiles for the pure radiative equilibrium case, convectively adjusting to a dry adiabat and a lapse rate of 6.5 K km^{-1}.

Radiative-convective models in practice : The effect of absorption of ISWR by Ozone
(Manabe & Strickler 1964, from Trenberth 1992)



Vertical temperature profile for the case of a
Pure H_2O.H_2O, and $H_2O + CO_2 + O_3$ atmosphere

The radiative effects of clouds (in RC models)



Surface temperature obtained from a one-dimensional radiative-convective model versus fractional cloud cover. Results are shown for low, mid-level and high cloud cover.

Reproduced by permission of American Meterological Society: Stophens, G.L., Webster, P.J., (1981) Clouds and Climate: Sensitivity of Simple Systems, J. Atmos. Sci, v. 38, p. 235-247.

1-D Radiative-Convective Models : Overview & Where Next?

- Are valid only locally (isolated, pointwise), or as a global mean …
- but the results vary with latitude/insolation
  - $\rightarrow$ latitudinal variation of tropopause height, etc
- This leads to inconsistency : adjacent columns are not compatible (have different temperature profiles)
- So one needs to allow for lateral transports
- $\Rightarrow$ need for 2-D (meridional/vertical) models (at least) for greater realism
- But R-C models allow conceptual understanding of greenhouse effect, reasonable estimates for OLWR
  - compared with Budyko's empirical approximation

Summary (1)

- ♦ Focus on the vertical dimension:
- ♦ Consider models of radiative equilibrium based on:
  - Upwelling & downwelling ***Thermal IR fluxes***
  - Consider vertical ***flux divergences***
  - Solutions imply temperature discontinuity of ~15°C at ground level
  - due to the assumption of static atmosphere & pure radiative balance
- ♦ Resolve inconsistency by allowing for convection (vertical mixing of heat between layers):
  - => Radiative-convective model
  - An iterative (numerical) model procedure
  - Repeated convective adjustment (and radiation balance) so that model temperature conforms to “standard” lapse rate

Summary (2)

- ♦ Radiative-convective equilibria:
  - => Temperature vs. Pressure profiles
  - Global-mean and/or by latitude (Equator; Mid-latitudes; Poles)
  - Convection extents vertically to tropopause (where ambient air becomes warmer than radiative-convective T-profile)
- ♦ Predictions of 1-D Radiative-Convective model:
  - Tropopause = convective lid on lower atmosphere
  - Tropopause height decreases towards poles
  - Can estimate OLWR as function of T_s which approximates the Budyko empirical approximation

Summary (3)

- Elaborating Radiative-Convective models:
  - Include moist processes (changes lapse rate)
  - Predict OLWR as function of temperature ***& relative humidity***
  - Include various greenhouse gases & aerosols
  - Include clouds (scattering, albedo effects)
  - Predict ***radiative forcing*** due to change in trace gas such as CO_2
  - Predict ***climate sensitivity*** (change in global-mean surface temperature as a consequence …)
- Radiative-Convective models in practice:
  - many-layered radiative-convective schemes are computationally costly
  - may be simplified / rationalized for use in AGCMs
  - atmosphere absorbs some SW radiation (varies with altitude, but mostly attributed to Ozone in the stratosphere)
  - Observed temperature profile through troposphere & stratosphere can nevertheless be predicted with fully elaborated R-C models

Recommended additional notes

- **Chapter 4, McGuffie & Henderson-Sellers**

- **"A First Course in Climate : *Earth and Elsewhere*"**

  by R. T. Pierrehumbert, Dept. Geophysical Sciences, University of Chicago

  http://geosci.uchicago.edu/~rtp1/geo232/Notes.pdf

Climate Sensitivity for R-C models
(NB: no ice-albedo feedback)

Equilibrium surface temperature increase due to doubled CO2 (300-600 ppmv): results from a suite of one-dimensional model sensitivity experiments (Redrawn from Hansen et al., 1981).

Model*	Description	ΔT (K)	Feedback factors + f	Feedback factors + λ_{TOTAL}
1	Fixed absolute humidity, 6.5 K km^{-1}, fixed cloud altitude	1.22	1	3.75
2	Fixed relative humidity, 6.5 K km^{-1}, fixed cloud altitude	1.94	1.6	2.34
3	Same as model 2, except moist adiabatic lapse rate replaces 6.5 K km^{-1}	1.37	0.7	5.36
4	Same as model 2, except fixed cloud temperature replaces fixed cloud altitude	2.78	1.4	2.68

* Model 1 has no feedbacks affecting the atmospheres radiative properties. + The feedback factors *f* (dimentionless) and λ_{TOTAL} ($W\ m^{-2}\ K^{-1}$) are two commonly used methods of representing the effect of each added process on model sensitivity to doubled CO_2.

- Note important influence of clouds on climate sensitivity

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