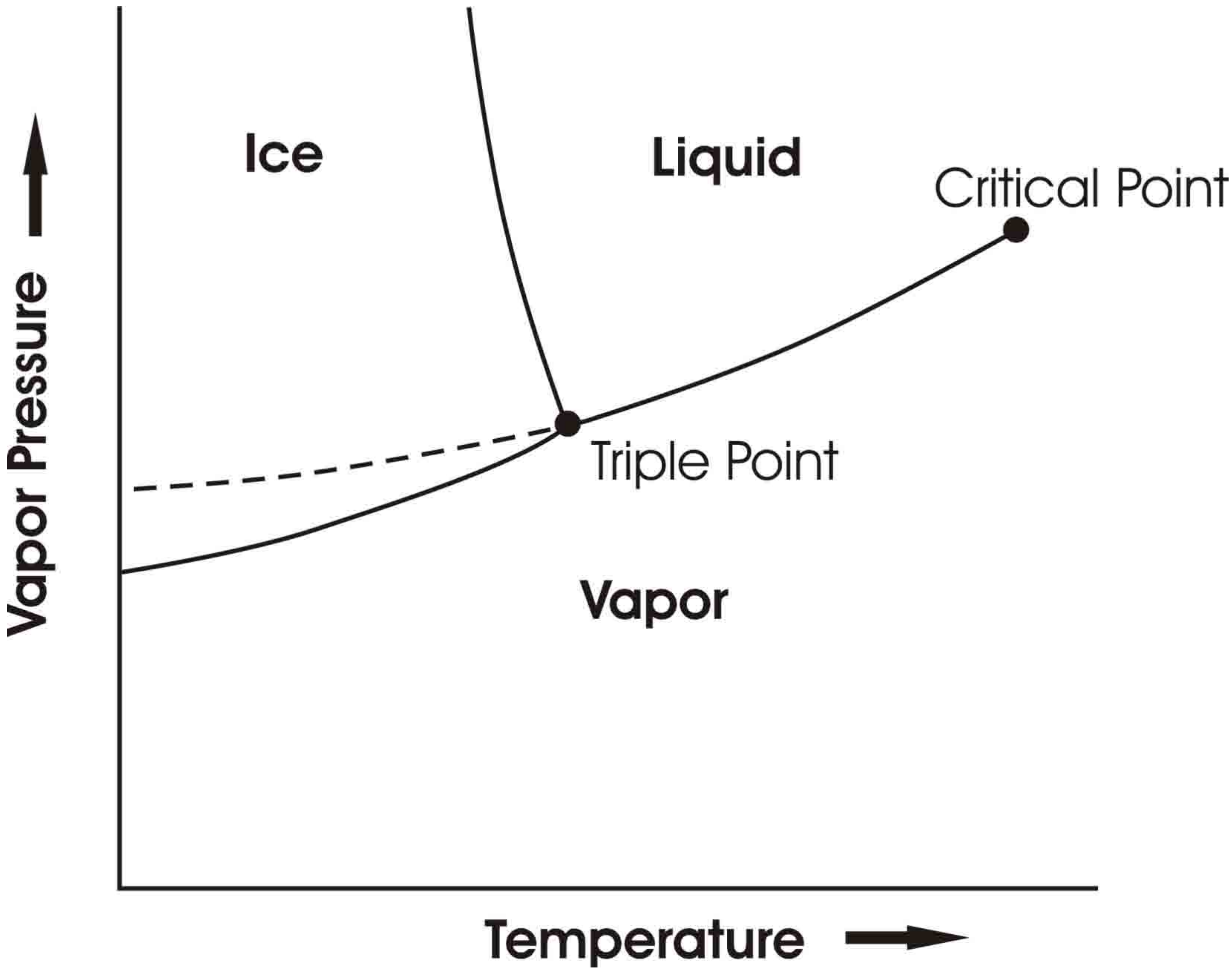
Above a thin boundary layer, most atmospheric convection involves phase change of water:

# Moist Convection

# Moist Convection

- Significant heating owing to phase changes of water
- Redistribution of water vapor – most important greenhouse gas
- Significant contributor to stratiform cloudiness – albedo and longwave trapping

# Phase Equilibria



# When Saturation Occurs…

- Heterogeneous Nucleation
- Supersaturations very small in atmosphere
- Drop size distribution sensitive to size distribution of cloud condensation nuclei

This image is from public domain (released by the United States Navy).

# Precipitation Formation

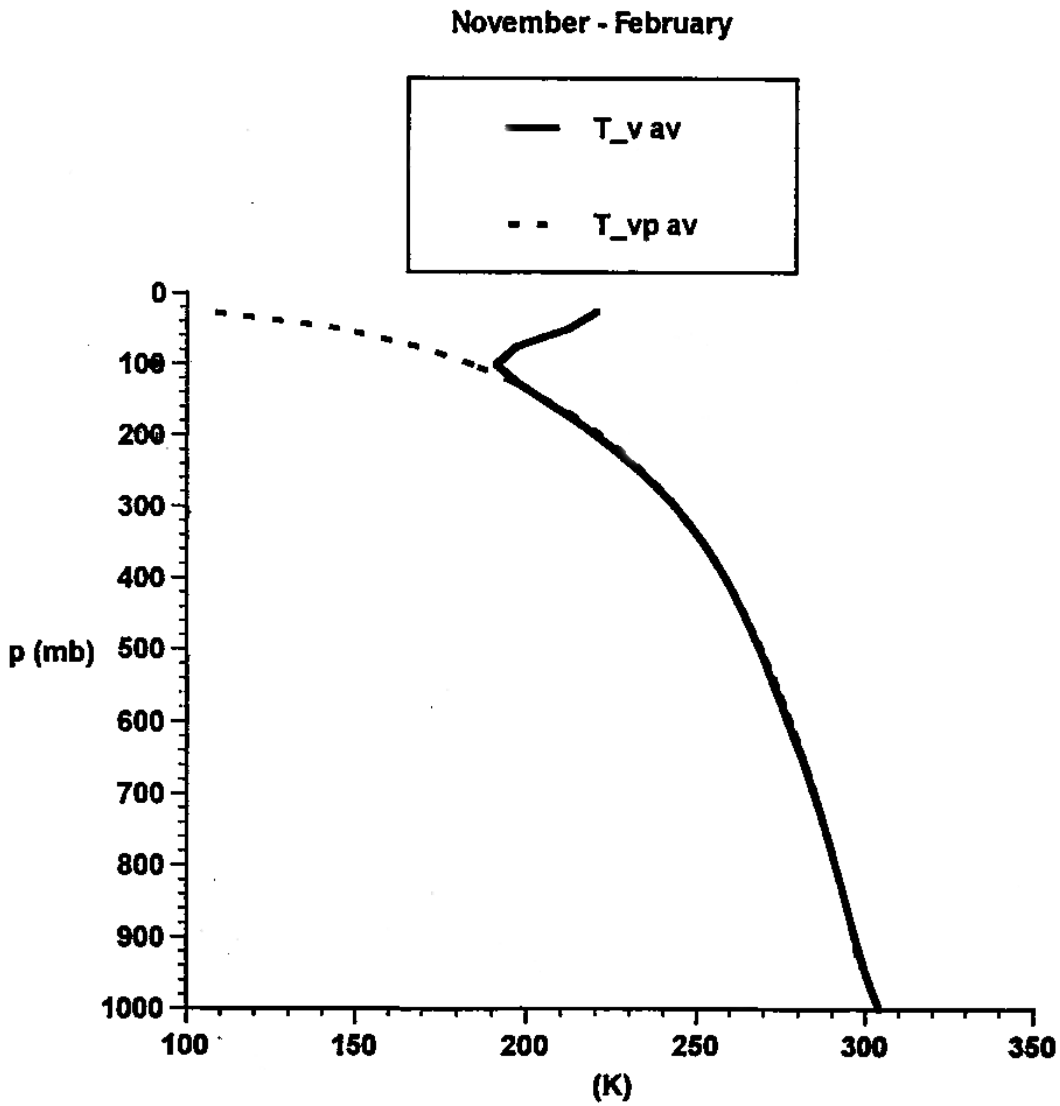
- Stochastic coalescence (sensitive to drop size distributions)
- Bergeron-Findeisen Process
- Strongly nonlinear function of cloud water concentration
- Time scale of precipitation formation ~10-30 minutes

# Stability

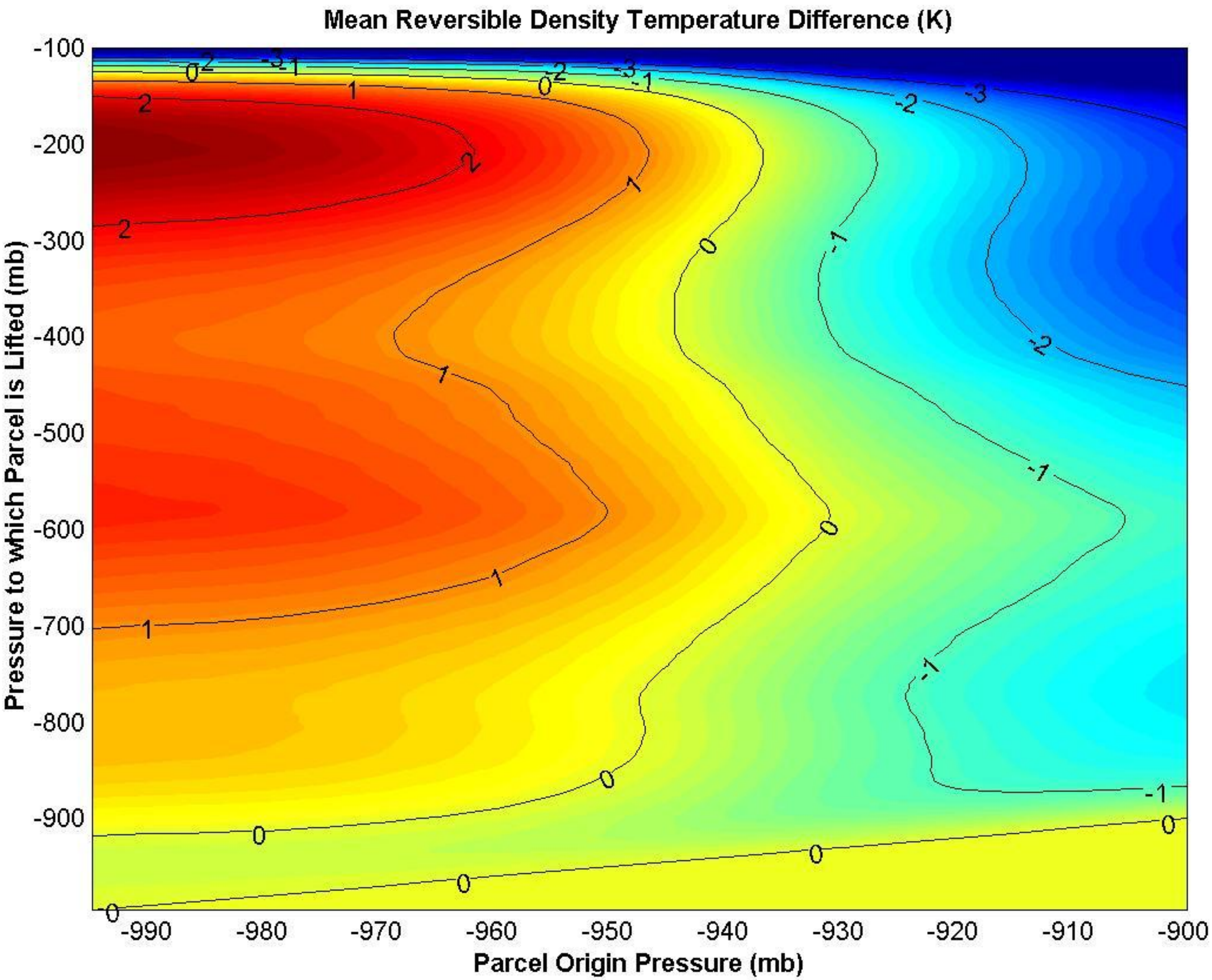
No simple criterion based on entropy. But air inside ascending cumulus turrets has roughly the same density as that of it environment. It can be shown that neutral stability corresponds to the constancy of the *saturation entropy* s*:

$$s^* = c_p \ln\left(\frac{T}{T_0}\right) - R_d \ln\left(\frac{p}{p_0}\right) + L_v \frac{q^*(T,p)}{T}$$

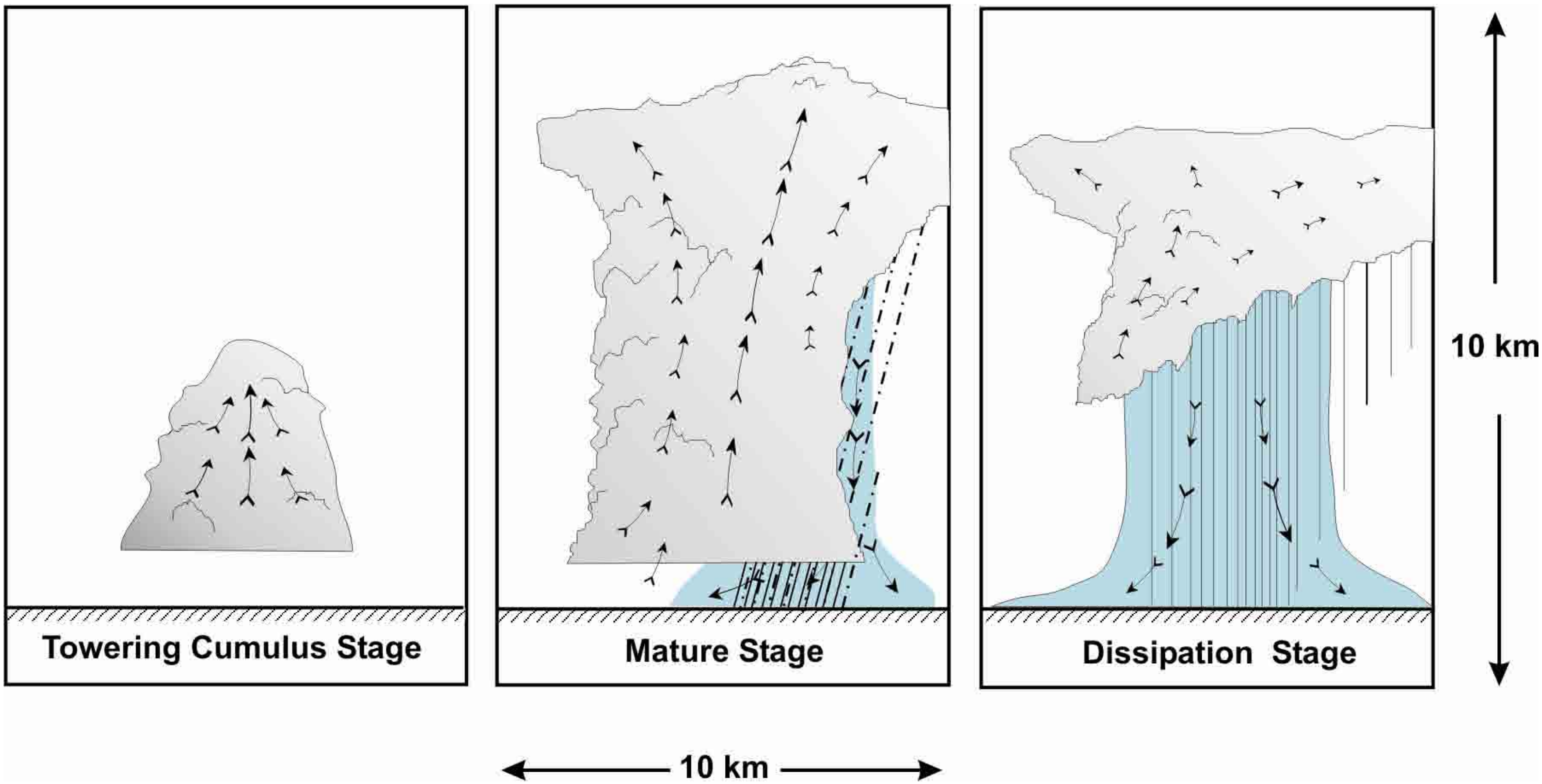
# Tropical Soundings



# Average density difference between reversibly lifted parcels and their environments, deep Tropics



# "Air-Mass" Showers:



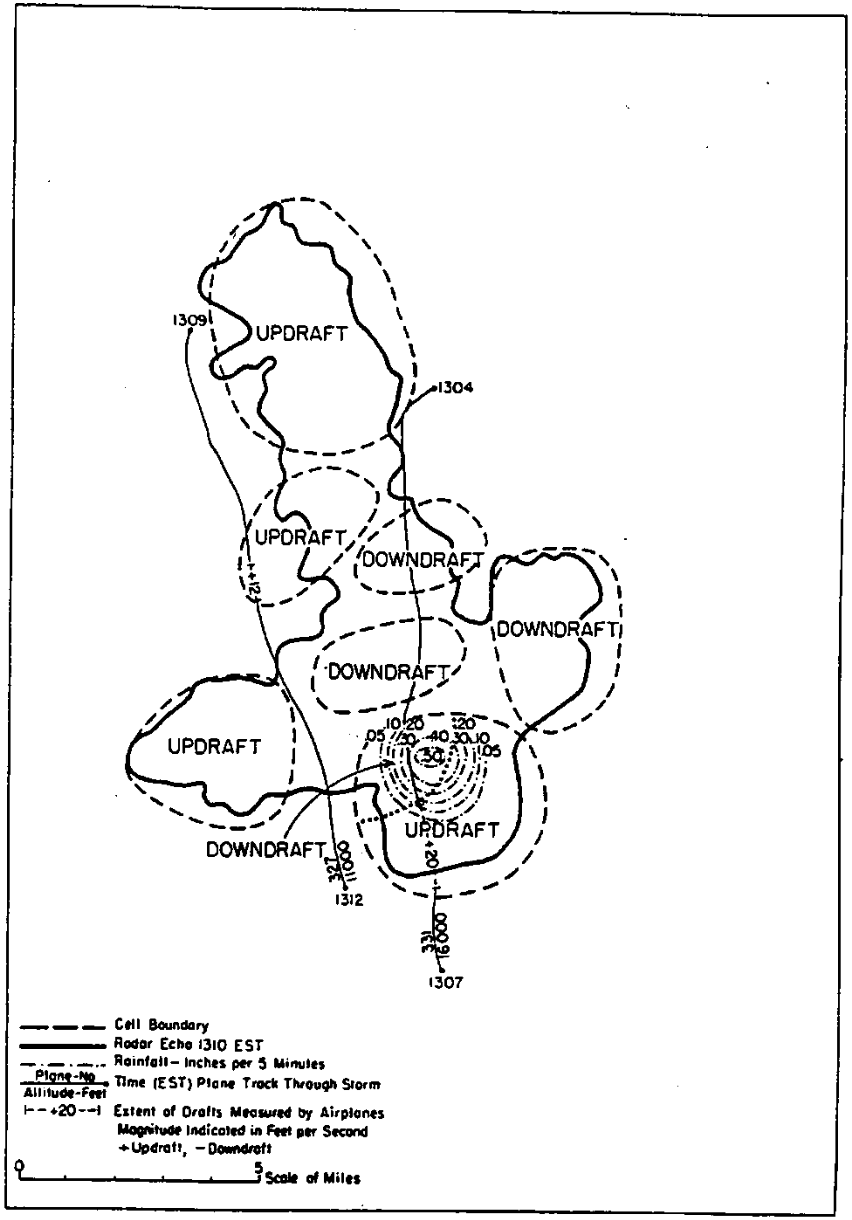



FIG. 15. Radar echo, plane paths, measured draft data, and cell outlines, 1310 EST 9 July 1946.

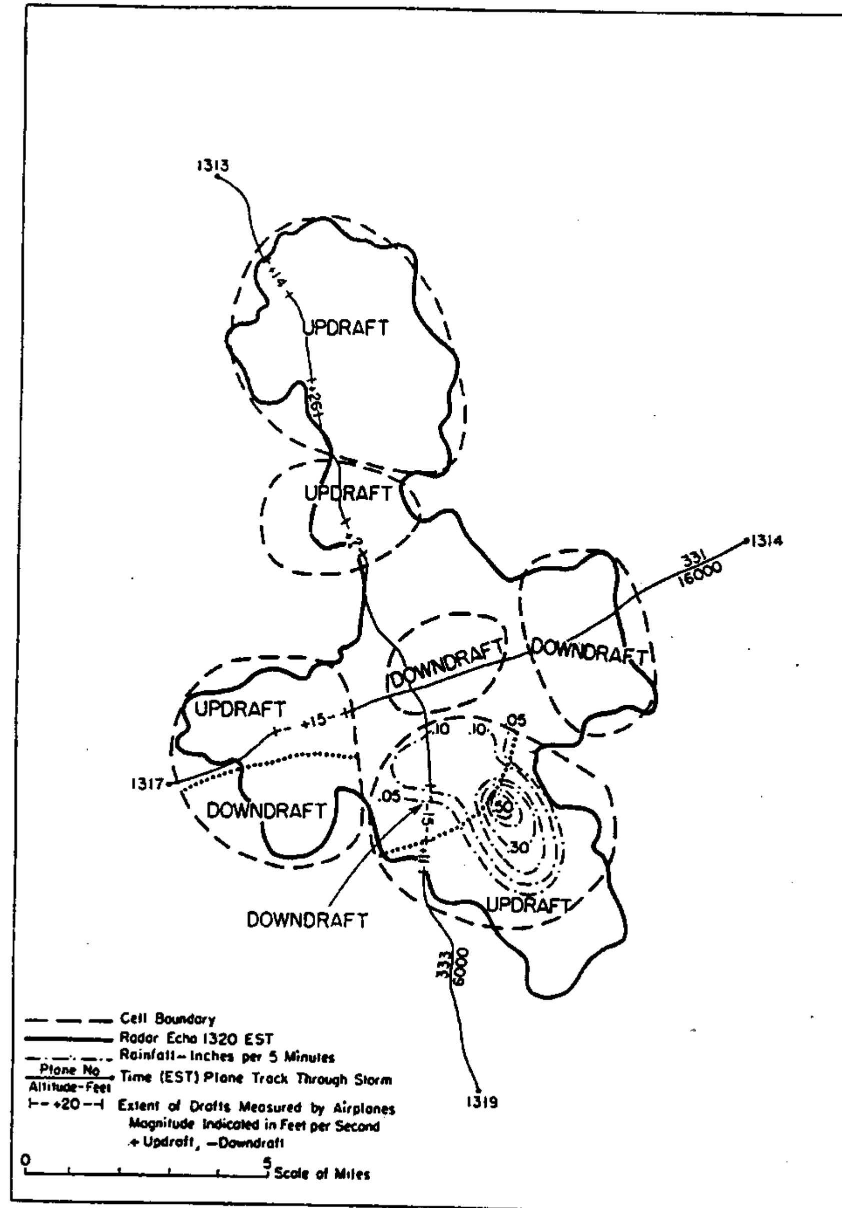
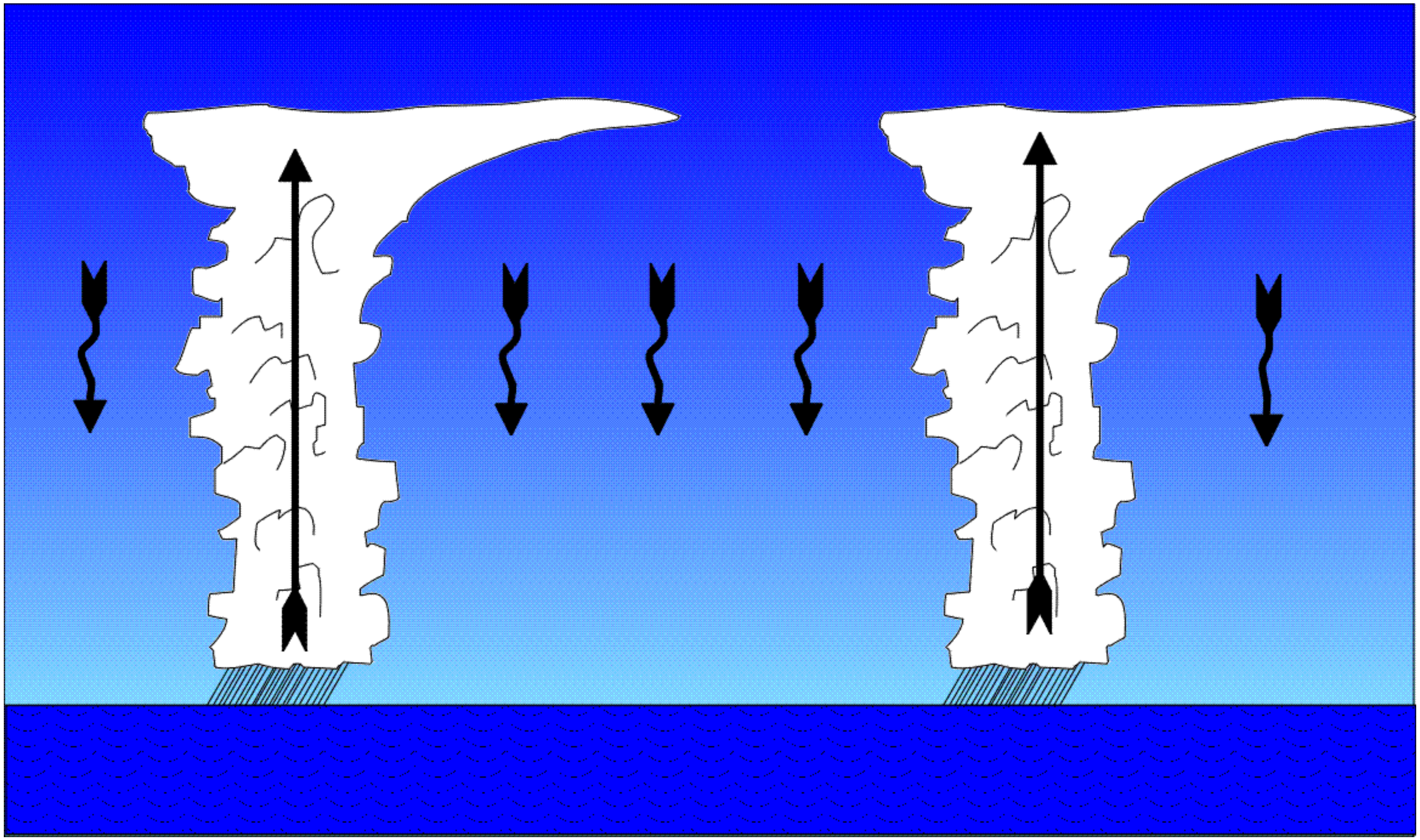



FIG. 16. Radar echo, plane paths, measured draft data, and cell outlines, 1320 EST 9 July 1946.

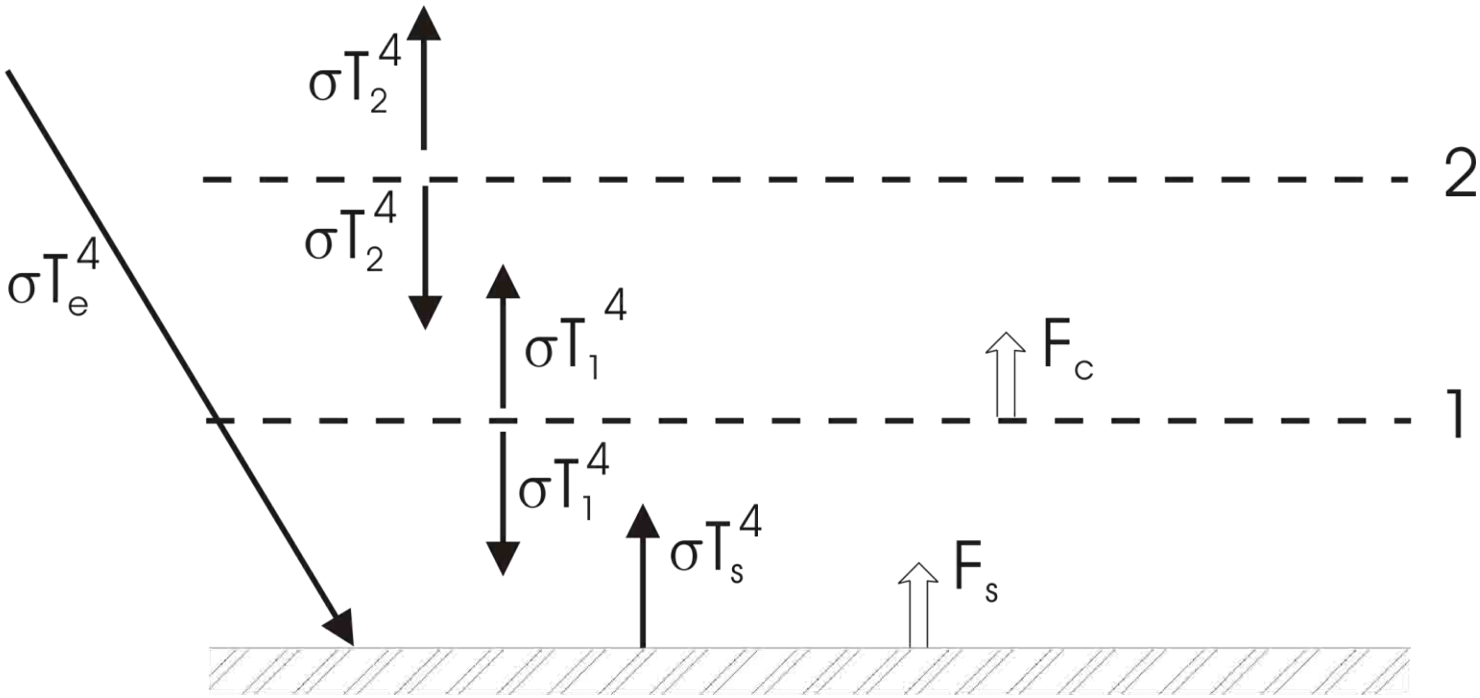
# Precipitating Convection favors Widely Spaced Clouds (Bjerknes, 1938)



# Properties of Moist Convection

- Convective updrafts widely spaced
- Surface enthalpy flux equal to vertically integrated radiative cooling
- $$M \frac{c_p T}{\theta} \frac{\partial \theta}{\partial z} = -\dot{Q}$$
- Precipitation = Evaporation = Radiative Cooling
- Radiation and convection *highly* interactive

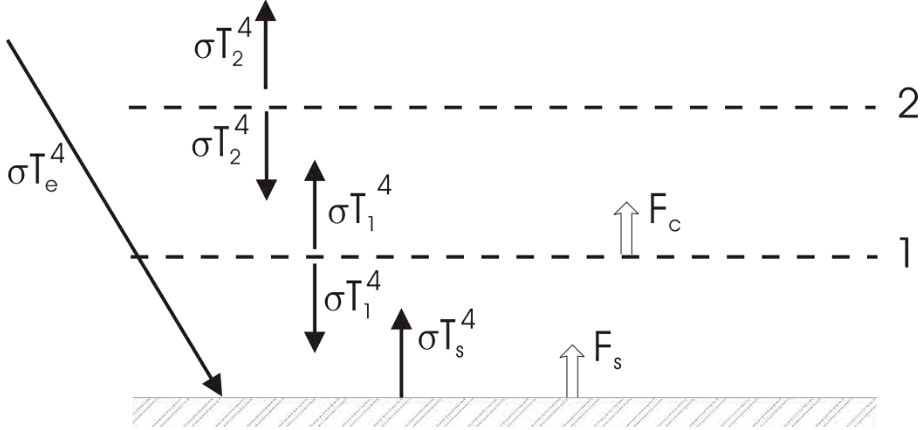
# Simple Radiative-Convective Model




Enforce convective neutrality:

$$T_1 = T_2 + \Delta T,$$

$$T_s = T_2 + 2\Delta T$$




$$TOA: \quad T_2 = T_e \rightarrow T_1 = T_e + \Delta T, \quad T_s = T_e + 2\Delta T$$

$$Surface: \quad F_s + \sigma T_s^{\,4} = \sigma T_e^{\,4} + \sigma T_1^{\,4}$$

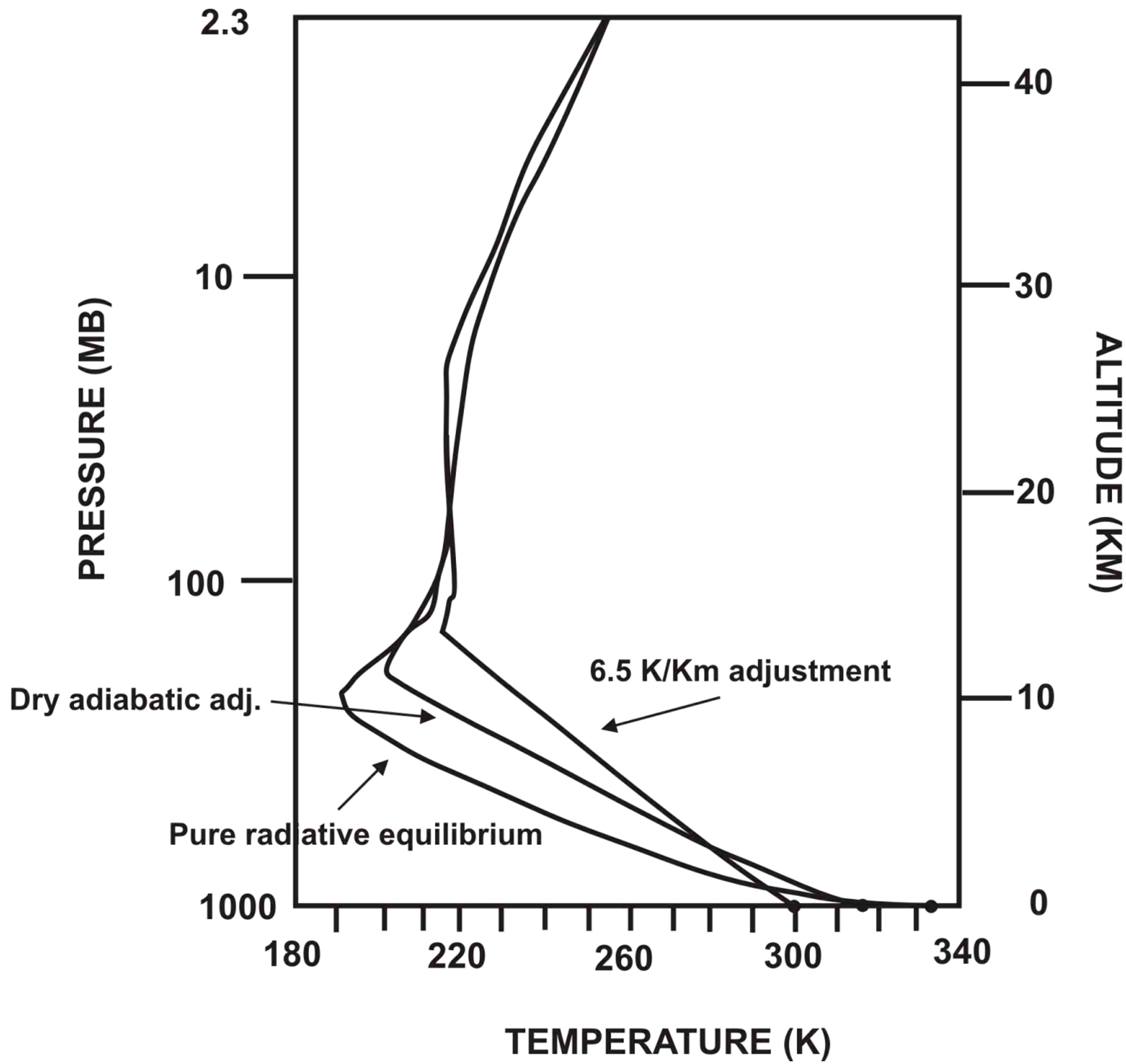
$$Layer\ 2: \quad 2\sigma T_e^{\,4} = \sigma T_1^{\,4} + F_c$$

$$Define \quad x \equiv {\Delta T}/{T_e},$$

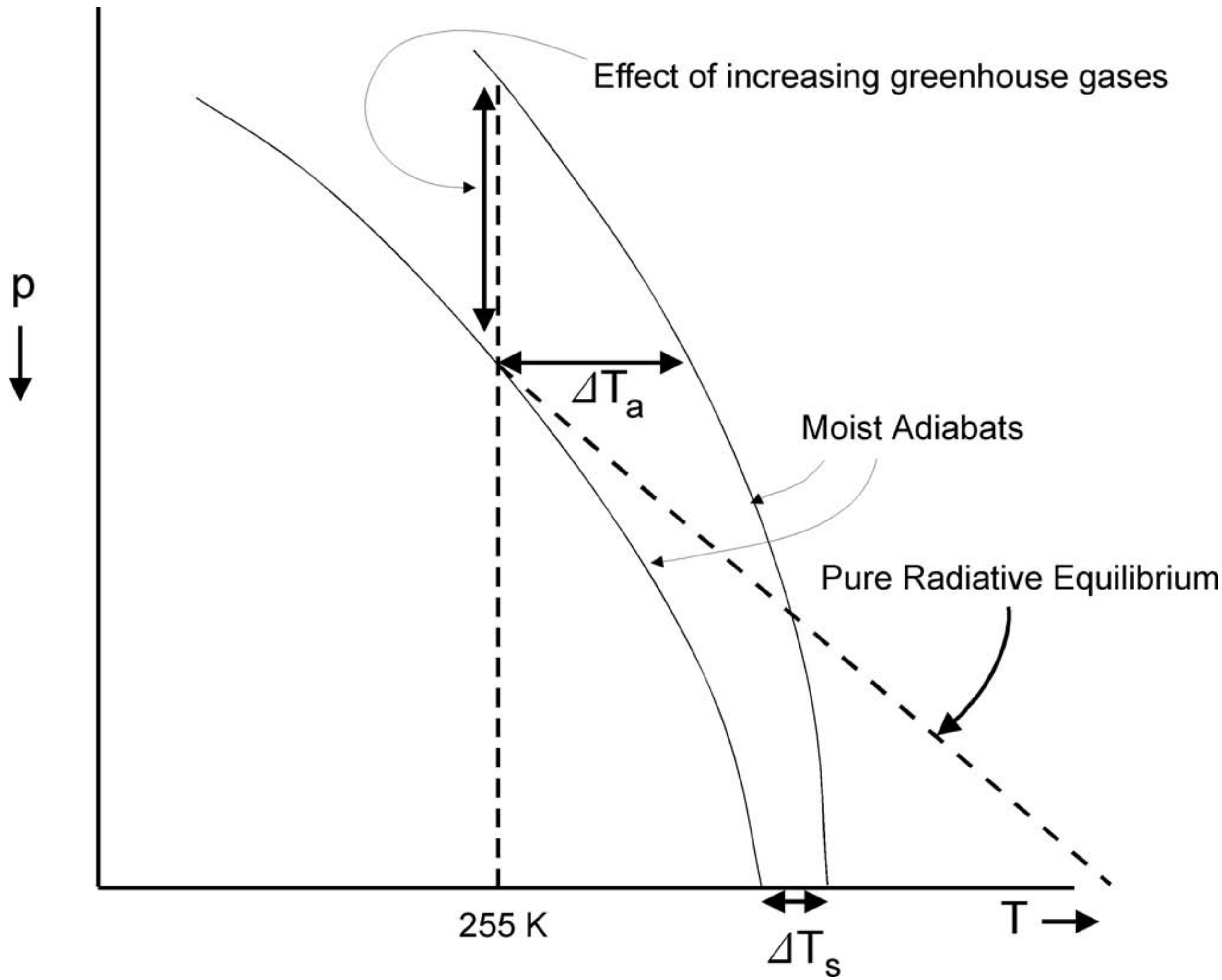
$$F_s = \sigma T_e^{\,4}\left[1 + (1+x)^4 - (1+2x)^4\right],$$

$$F_c = \sigma T_e^{\,4}\left[2 - (1+x)^4\right]$$

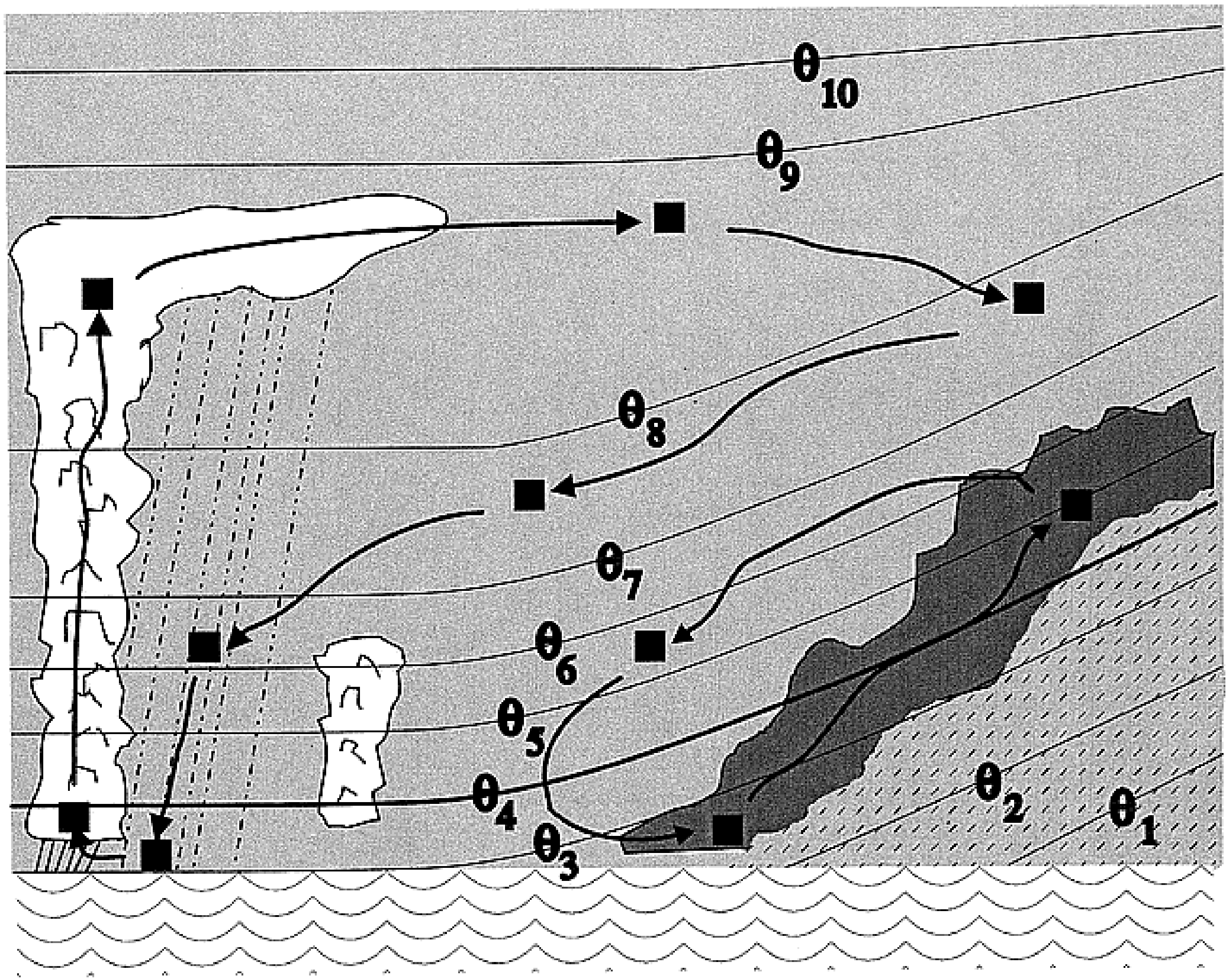
# Manabe and Strickler 1964 calculation:



# Effect of Moist Convective Adjustment on Climate Sensitivity



# Flux of water by convection makes real problem complex



This image has been removed due to copyright restrictions.

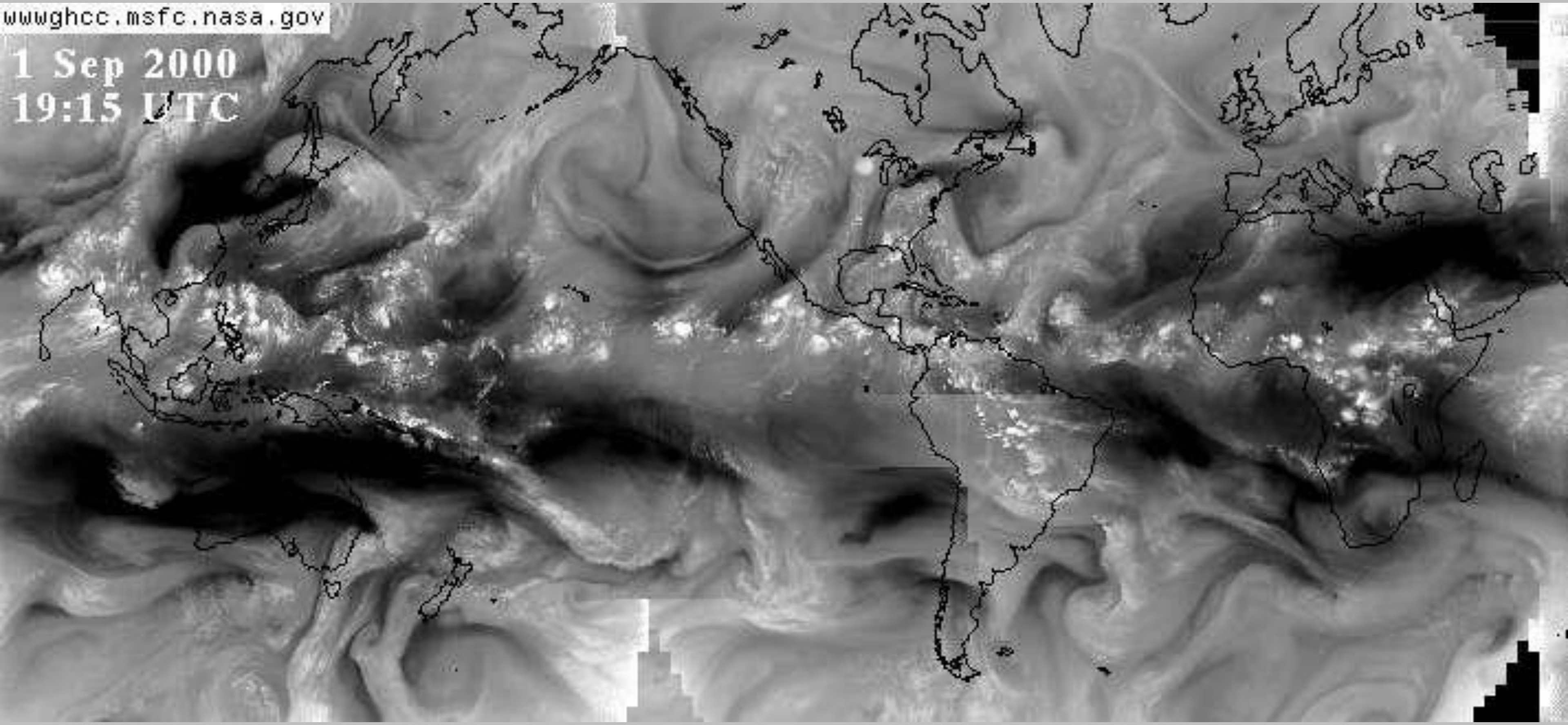
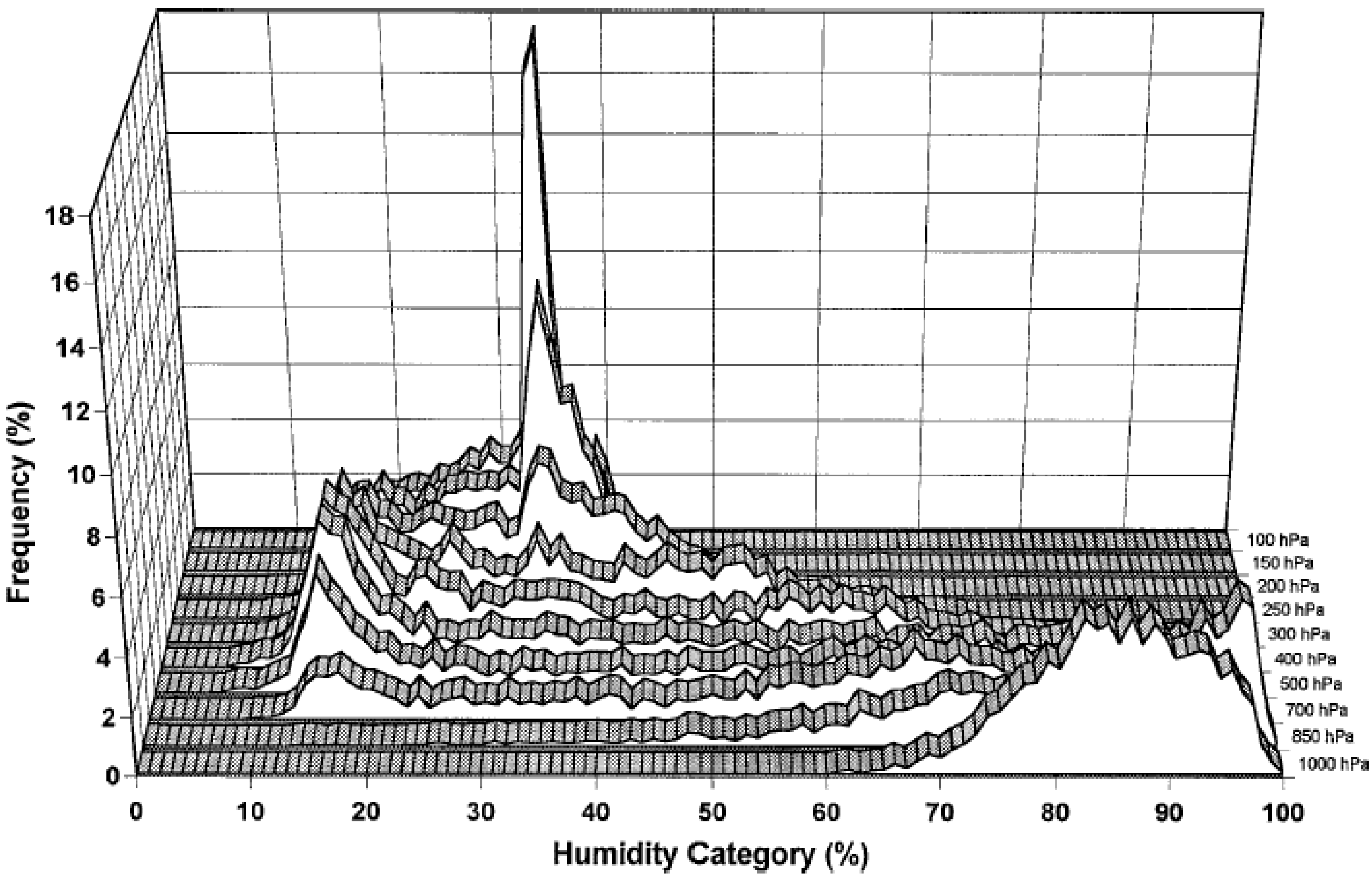



Image courtesy of NASA.

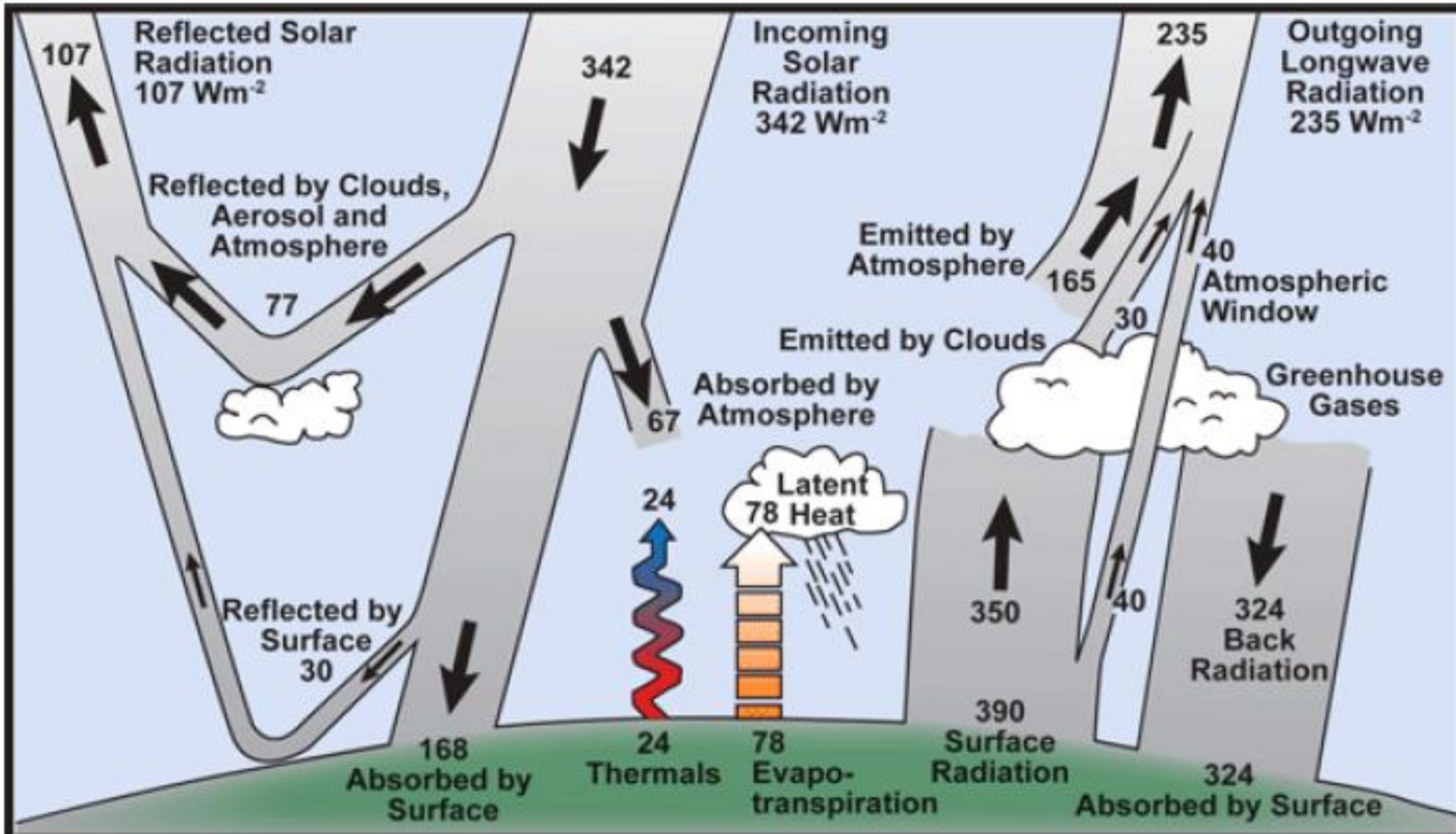
**Frequency histogram of rawindsonde relative humidities from 1600 ascents at the tropical Pacific islands of Yap, Koror, Ponape and Majuro, January-May, 1994-95. Spencer and Braswell, *Bull. Amer. Meteor. Soc.,* 1997.**



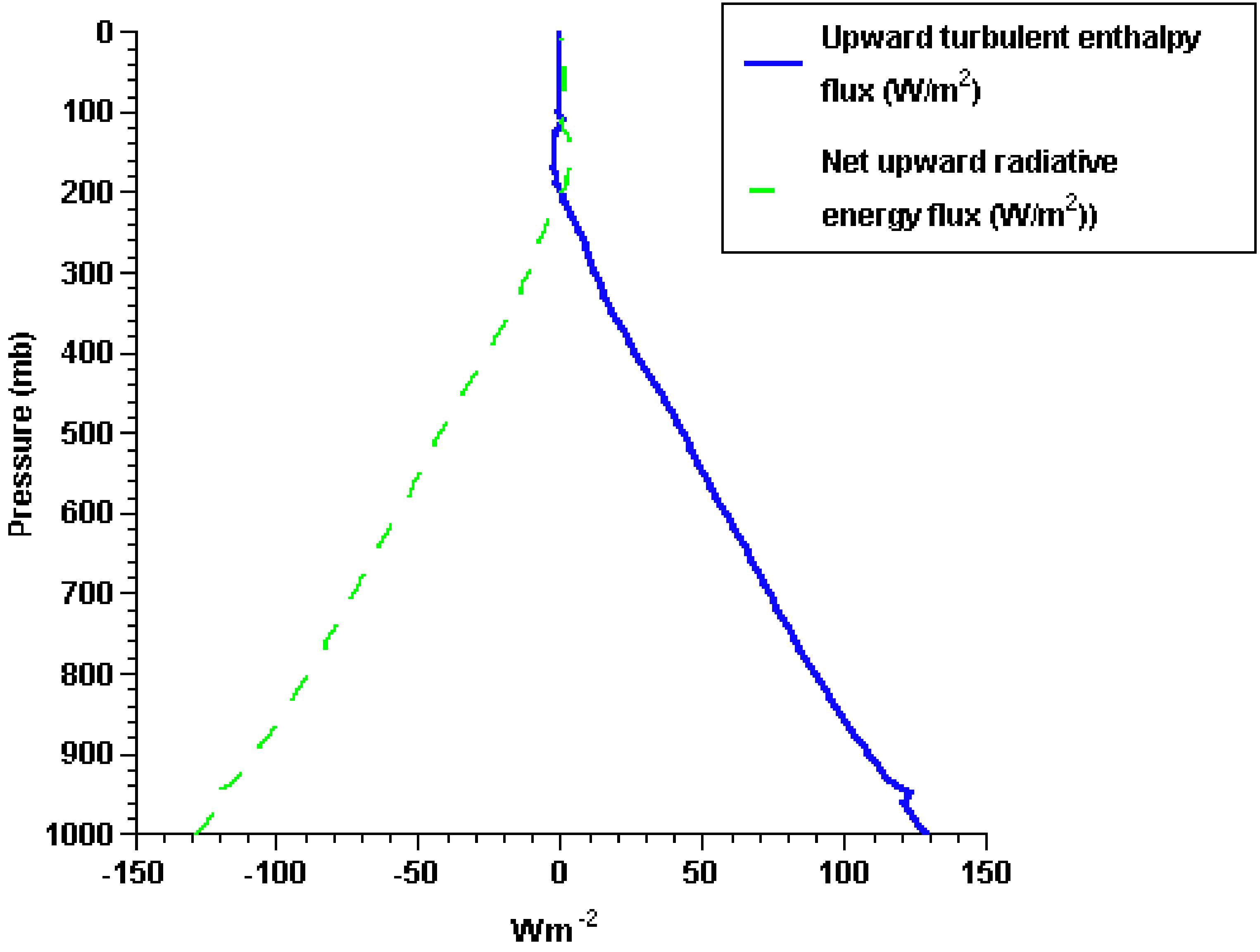
# Effects of Clouds on Radiative Transfer

- Responsible for much of Earth's albedo
- Important greenhouse effect from longwave absorption and re-emission

# Globally Averaged Energy Balance




Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, FAQ 1.1, Figure 1. Cambridge University Press. Used with permission.


Upward turbulent enthalpy flux (W/m2)
Net upward radiative energy flux (W/m2))
Pressure (mb)
0
100
200
300
400
500
600
700
800
900
1000
-150
-100
-50
0
50
100
150
Wm -2

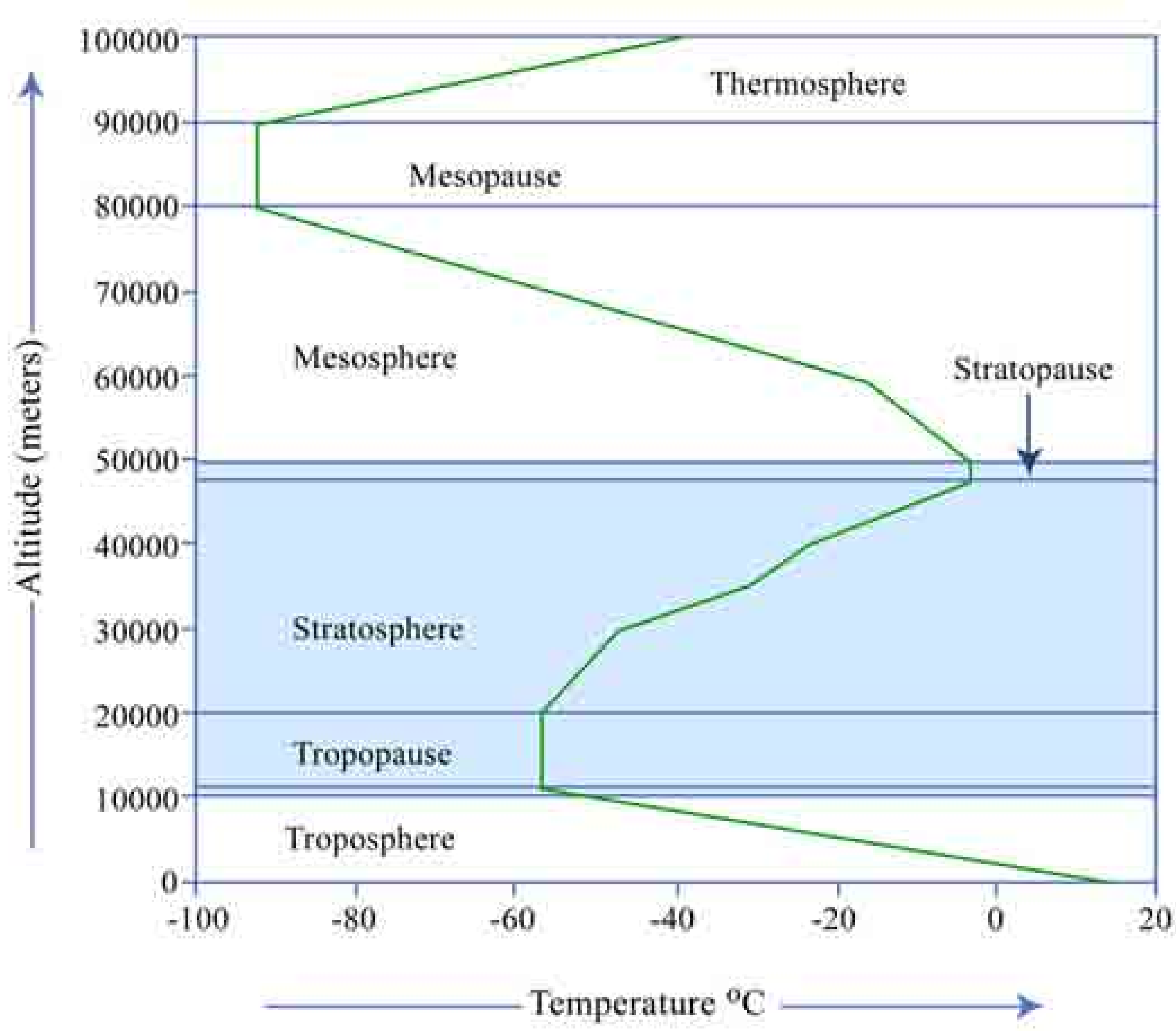
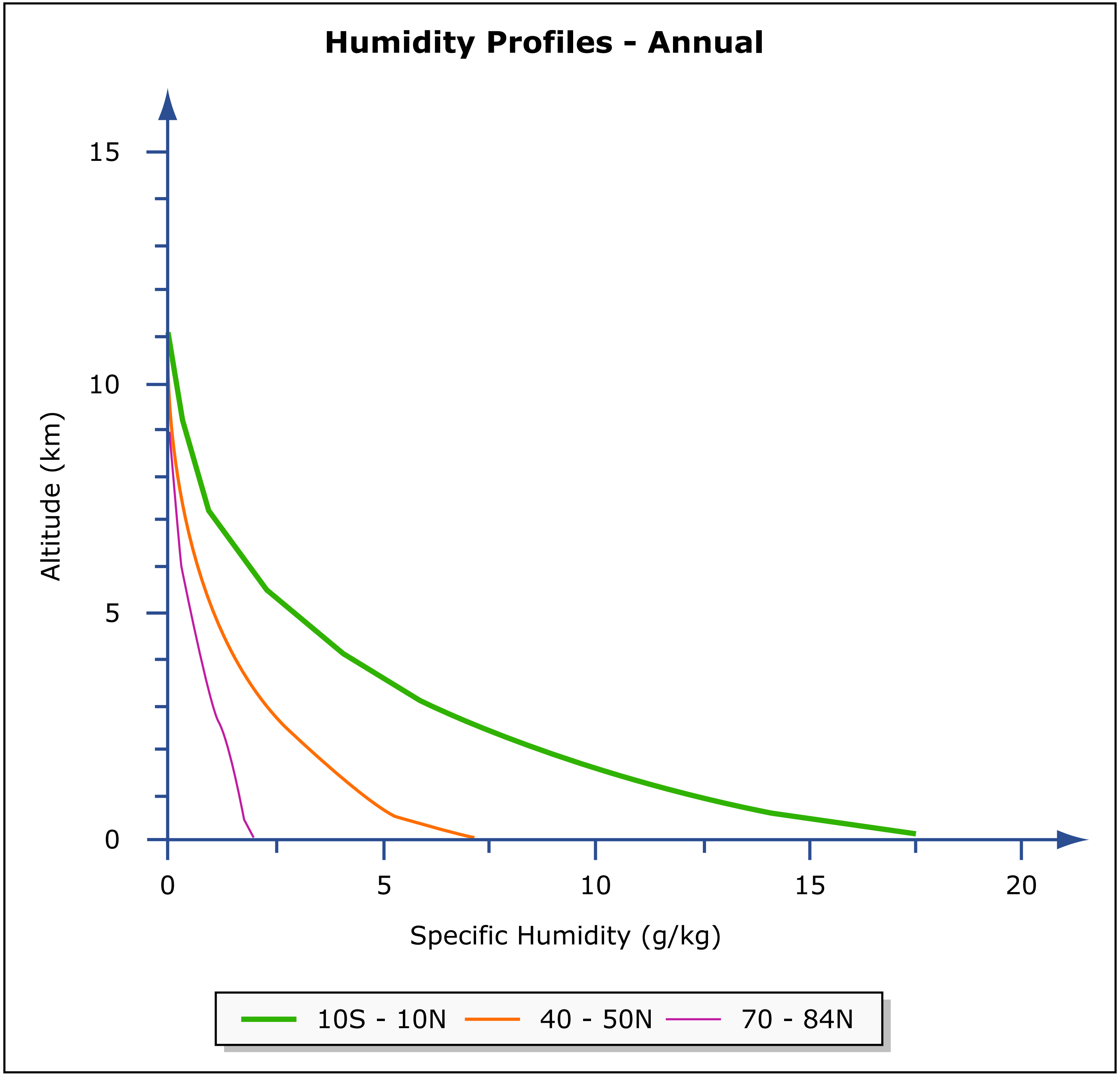



Figure by MIT OpenCourseWare.


Humidity Profiles - Annual
15
10
5
0
Altitude (km)
0
5
10
15
20
Specific Humidity (g/kg)
10S - 10N
40 - 50N
70 - 84N

# Radiative-Convective Model

- Band-averaged radiation
- Radiation interacts with $H_20$, $CO_2$, $O_3$, clouds
- Two-stream approximation: radiation assumed to travel vertically
- Moist convection whenever instability exists
- Convection transports $H_20$, enthalpy
- Representation of layered clouds

# Open MATLAB
# Type “run_model”

- 1) Restart from last run? [n]
- 2) Interactive radiation? [y]
- 3) Interactive clouds? [y]
- 4) Interactive surface temp? [n]
- 5) Time-dependent radiation? [n]
- 6) Date-dependent radiation? [n]
- 7) Diurnal-average radiation? [n]
- 8) Annual-average radiation? [y]
- 9) Surface albedo [0.32]
- 10) Amount of CO2 [360 ppm]
- 11) End time of integration [100 days]
- 12) Graphics averaging time [1 days]
- 13) Frequency of radiation calls [3 hours]
- 14) Frequency of graphics output [2 hours]

- 0) Run model with current configuration.

# Suggested Experiments

- Annual cycle: Average results over 365 days, run for 5x365=1825 days; repeat with double $CO_2$. Allow interactive surface temperature
- Do same but without interactive clouds
- Same as first bullet above, but test sensitivity to surface albedo
- Same as above, but without interactive clouds