HOW TURBULENCE AND CUMULUS CLOUDS CARRY ENERGY UPWARD

Princeton primers in climate: Atmosphere, Clouds, and Climate.

Radiative deficit of the atmosphere

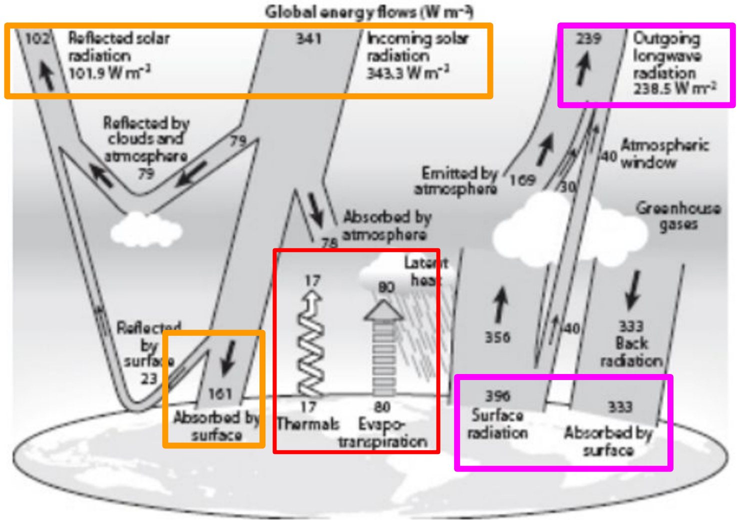


Figure 1.3. An overview of the flow of energy in the climate system.
The global annual mean Earth's energy budget for the March 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.
Source: Based on a figure in Trenberth et al. (2009).

Table 2.2
The globally and annually averaged surface radiative energy budget of the atmosphere. A positive sign means that the atmosphere is warmed.

Absorbed solar radiation (239 – 161)	78 W m^{-2}
Net emitted terrestrial radiation (–239 + 63)	-176 W m^{-2}
Net radiative heating	-98 W m^{-2}

The deficit is compensated in great part by latent heat release.

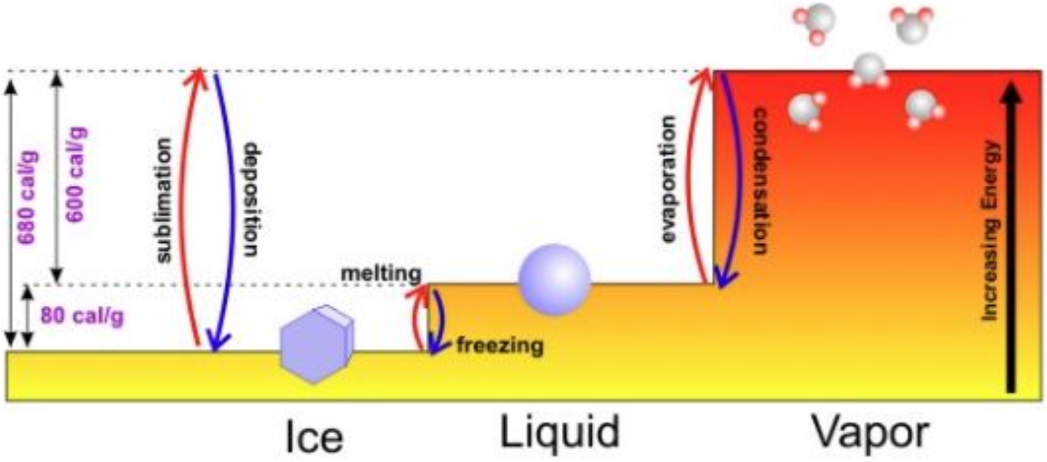
Radiative surplus of the surface (98-103 W/m2)
How is it handled?

Ocean water accumulates much more energy than soil because of two reasons: what are the two reasons?

Ocean currents can transport absorbed radiative energy great distances.

Locally there can be both positive or negative net flow.

Radiative surplus of the surface (98-103 W/m2)
How is it handled?



https://www.e-education.psu.edu/meteo3/l4_p3.html

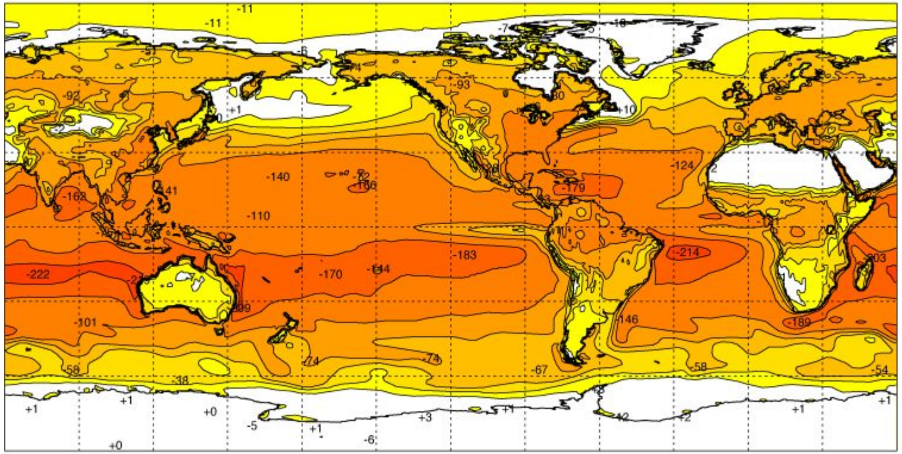
Evaporation (cooling of the surface): mostly over oceans but also inland.

Condensation (warming of the troposphere)

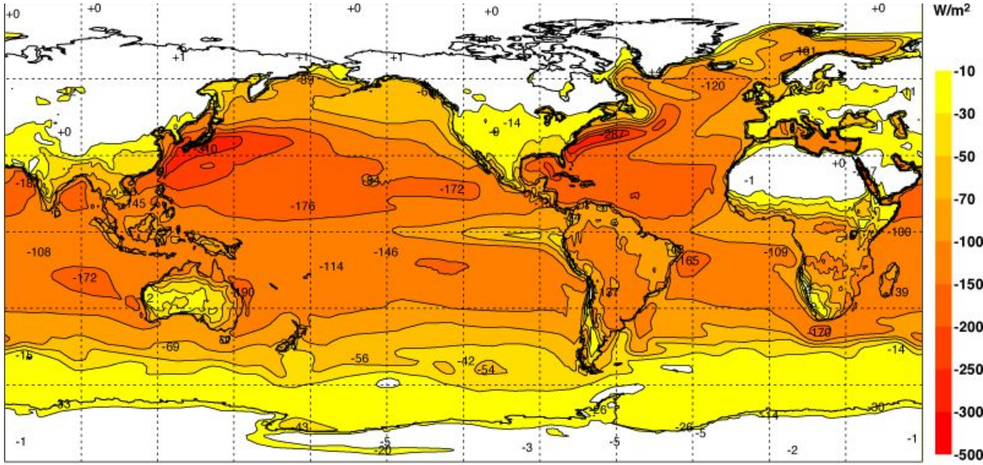
What are two exceptions?

Surface latent heat flux (~80 W/m2)

June-August



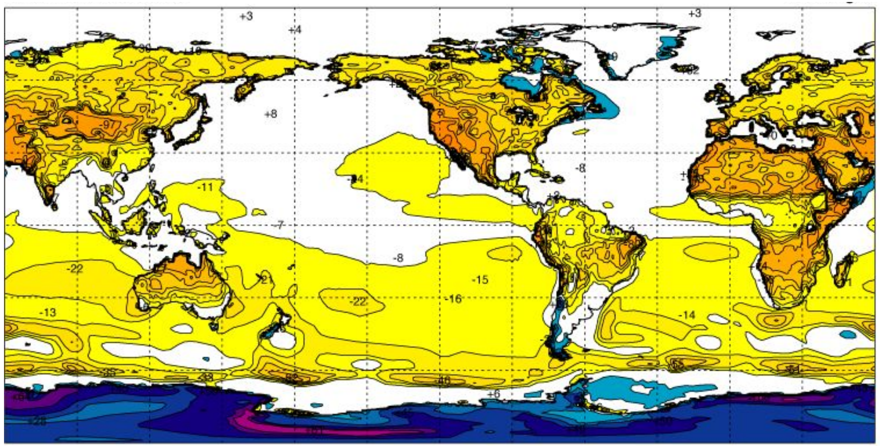
December-February



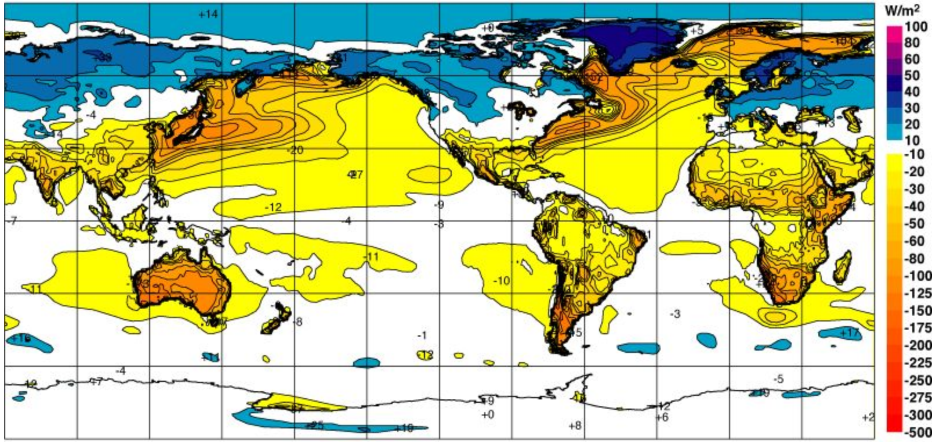
https://sites.ecmwf.int/era/40-atlas/docs/section_B/parameter_sfolhpd.html

Surface sensible heat flux (~17 W/m2)

June-August



December-February



https://sites.ecmwf.int/era/40-atlas/docs/section_B/parameter_sfoshpd.html

The flux is stronger over sun-warmed land during the day. At night IR emission cools the ground quicker than the air, then there is a small (against buoyancy) flux downward.

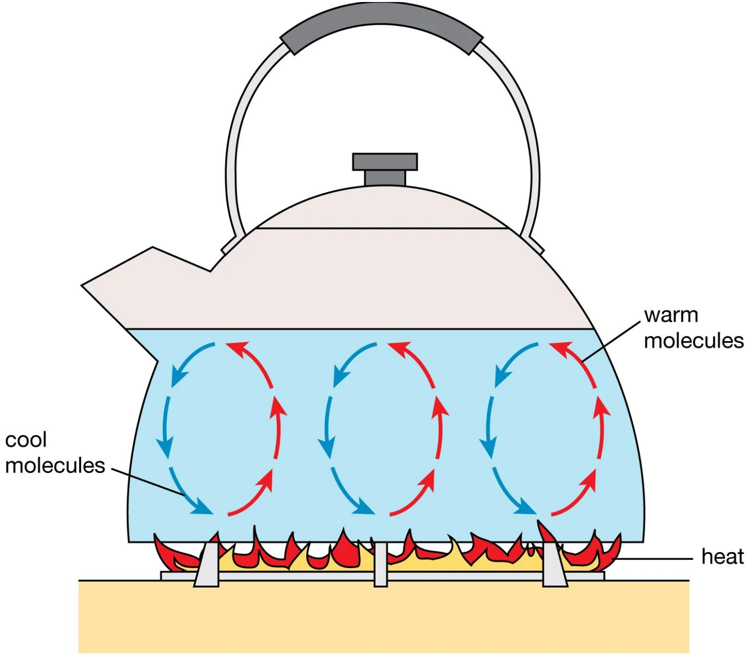
Energy fluxes through the atmosphere:

What happens after the latent or sensible heat is given to the atmosphere?

Advection (from Latin **advectio "act of bringing"*****):*** Horizontal or vertical uniform flow that carries mass from place to place, changing the distribution of temperature and mass from place to place.

Small-scale motions/eddies: *Turbulence in the boundary layer, updrafts and downdrafts associated with cumulus clouds, turbulence above boundary layer in regions of high wind shear, atmospheric waves.*

Eddies



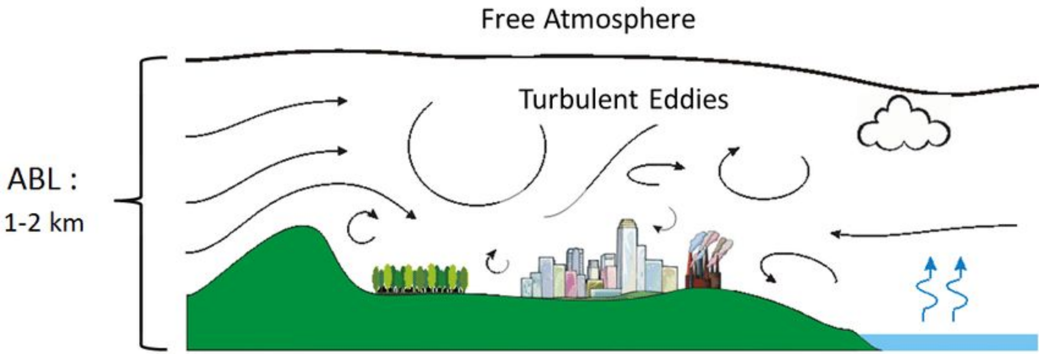
https://www.britannica.com/science/convection

Thermals: High energy molecules ascend and low energy molecules descend.

What is their effect in terms of temperature in the upper and lower water?

Turbulent mixing in the boundary layer

"The energy gradually accumulates in the boundary layer, like water building up behind a dam, waiting for release."



Boundary layer: direct recipient of turbulent latent and sensible heat fluxes.

Turbulent mixing in the boundary layer

Some quantities can be homogenized **(conservative variables)**, such as oxygen, nitrogen, argon, neon, and carbon dioxide (no phase changes).

Temperature is not conserved (thermodynamic energy equation):

$$\rho \frac{D}{Dt}\boxed{(c_p T)} = \frac{Dp}{Dt} + \boxed{LC + Q_{rad}}$$

Enthalpy

Heating rate

c_p Specific heat of air at constant pressure
L Latent heat of condensation
C Condensation rate
Q_{rad} Radiative heating rate

Pressure fall -> temperature decrease

Turbulent mixing in the boundary layer

Dry static energy:

$$s \equiv \boxed{c_p T} + \boxed{gz.}$$

Enthalpy

Gravitational potential energy

$$\rho \frac{Ds}{Dt} = \boxed{LC + Q_{rad}}.$$

Heating rate

Turbulent mixing in the boundary layer

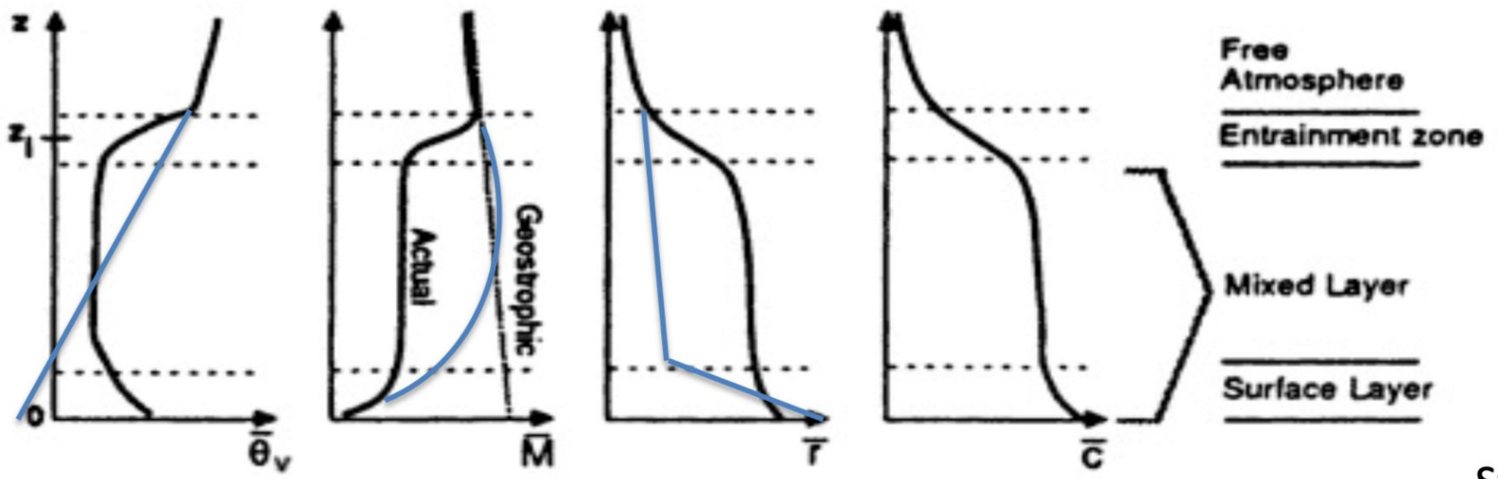
Water vapor:

$$\rho \frac{Dq}{Dt} = -C, \quad q \equiv \rho_{\text{vapor}}/\rho$$

q Specific humidity

"When falling rain **evaporates** into subsaturated air, **C <0**. Where **C = 0**, which basically means **away from clouds**, water vapor is conserved, and it can be **homogenized by mixing."**

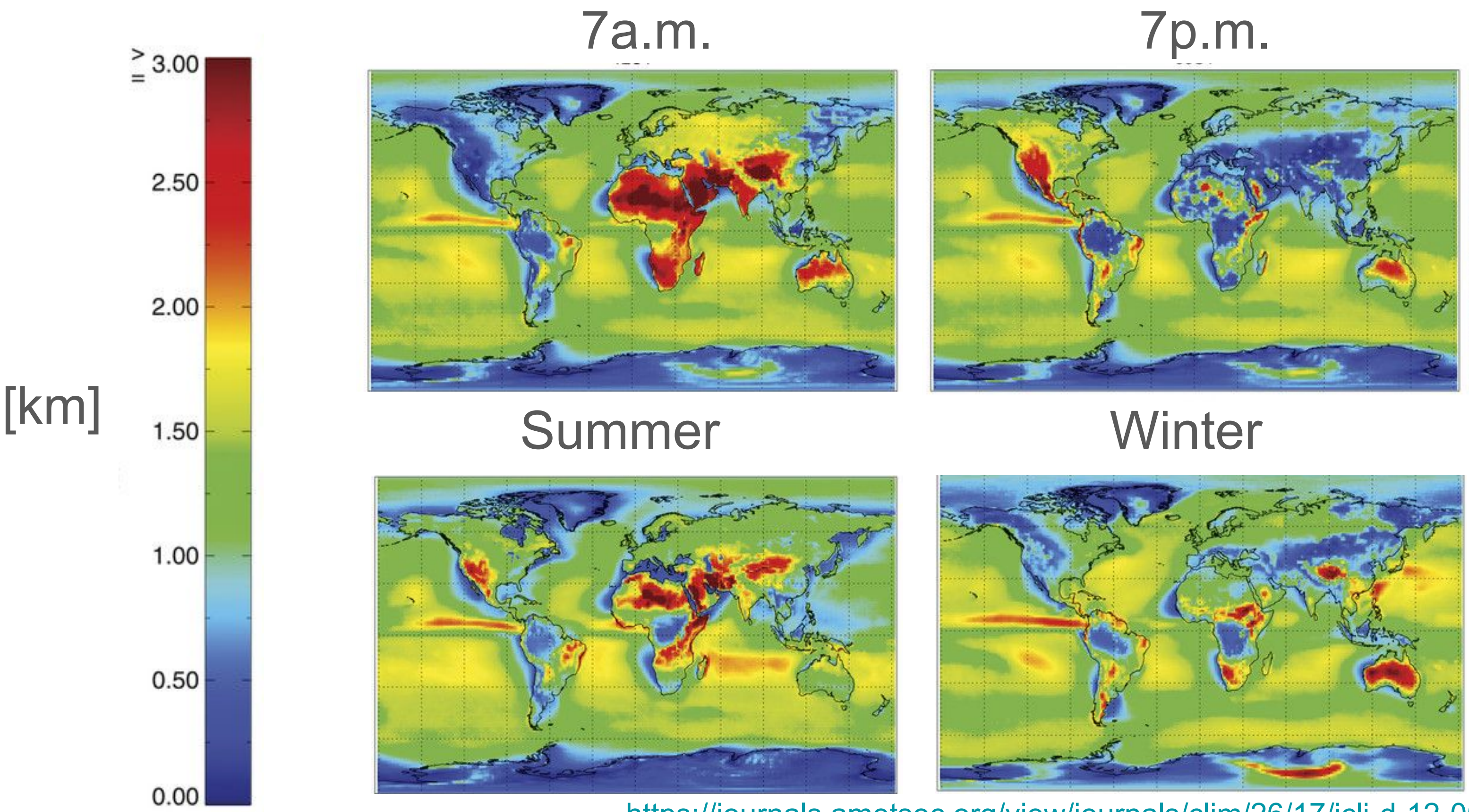
Turbulent mixing in the boundary layer



Stull (1988)

Fig. 1.9 Typical daytime profiles of mean virtual potential temperature $\overline{\theta}_v$, wind speed $\overline{M}$ (where $\overline{M}^2 = \overline{u}^2 + \overline{v}^2$), water vapor mixing ratio $\overline{r}$, and pollutant concentration $\overline{c}$.

Variability of the boundary layer height



https://journals.ametsoc.org/view/journals/clim/26/17/jcli-d-12-00385.1.xml

Convection and cumulus clouds

Convection: General buoyancy-driven overturning of the air.

Figure 3.1. Top panel: A group of small and large cumulus clouds.
Rapidly rising moist air forms the cloudy towers. The air around the towers is slowly sinking. Some of the larger towers have flat cloud layers near their tops. These are regions where the air has stopped rising and is flowing out to the sides.
Source: This beautiful photo was taken by Marco Lillini, an airline pilot, and is used with his kind permission. His web site is here: http://www.lillini.com/.

http://www.lillini.com/sito/sito2010/html/7catalogo/catalog/content/l08_large.html
http://www.lillini.com/sito/sito2010/html/7catalogo/catalog/content/r08_large.html

How does convection develop after “loading” the boundary layer with energy?

Humid air breaks away from the boundary layer, and floats upward under the influence of the positive buoyancy generated through the release of latent heat.

The rising, humid air forms a cloudy tower, which can sometimes be many kilometers tall.

A tall cumulus cloud precipitates, and sometimes generates lightning and thunder.

Stratified troposphere

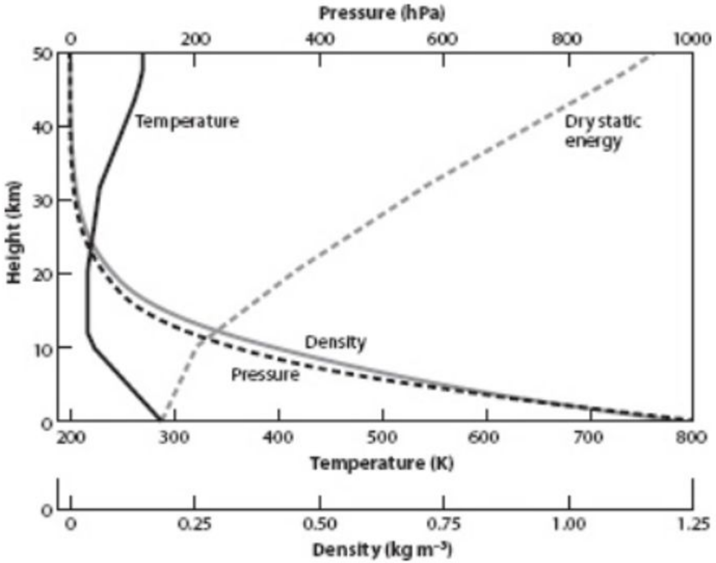


Figure 3.2. Like Figure 1.1, but with an added curve for the dry static energy, divided by c_p to give units of temperature, and with a modified temperature scale to accommodate the large values of s/c_p in the stratosphere.

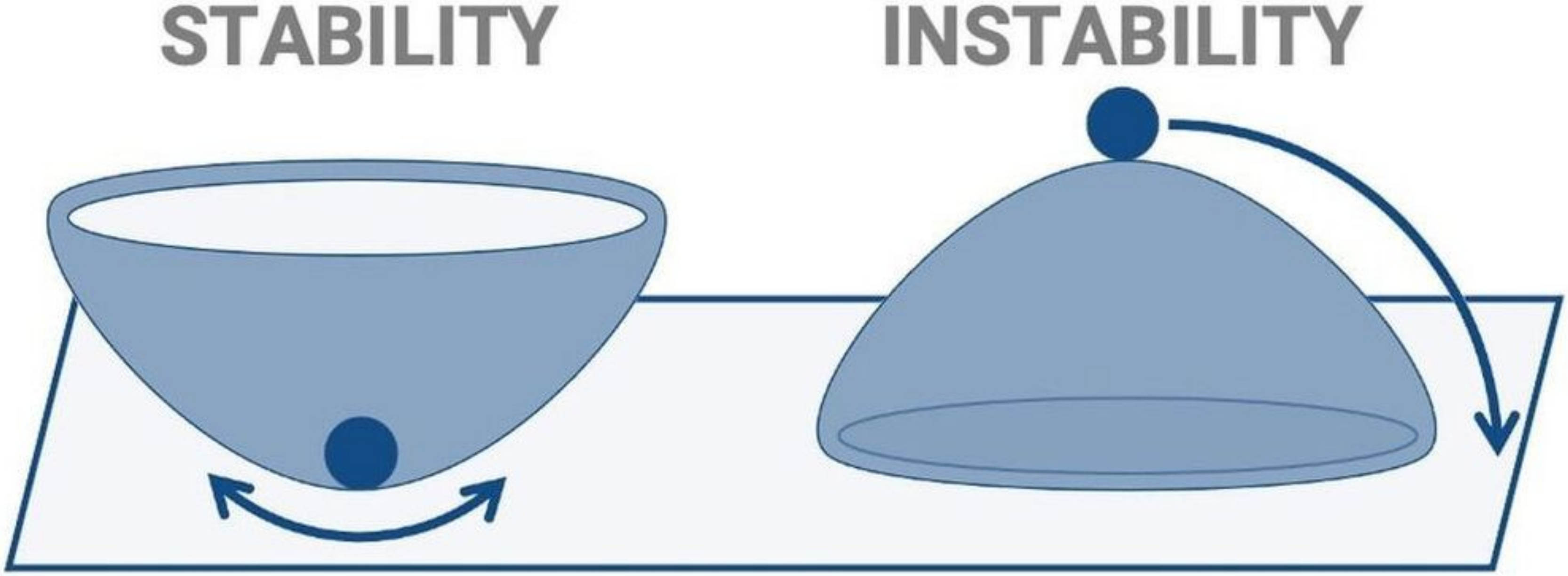
The dry static energy increases upward through most of the troposphere, and it increases even more strongly upward in the stratosphere. The figure is based on the U.S. Standard Atmosphere.

“Because the turbulence is weak, mixing is overwhelmed by **heating** and other processes, and even conservative variables can change rapidly with height.”

Why is the dry static energy so high in the upper-troposphere / stratosphere?

Static stability and instability of dry air

How is the system’s response to small perturbations?



Static stability and instability of dry air

"There is a tendency for parcels to maintain their relative vertical positions in a stratified column of air"

Basic state: The temperature of every parcel is the same as the temperature of the neighboring parcels at the same height.

The parcel displacements are opposed by buoyancy.

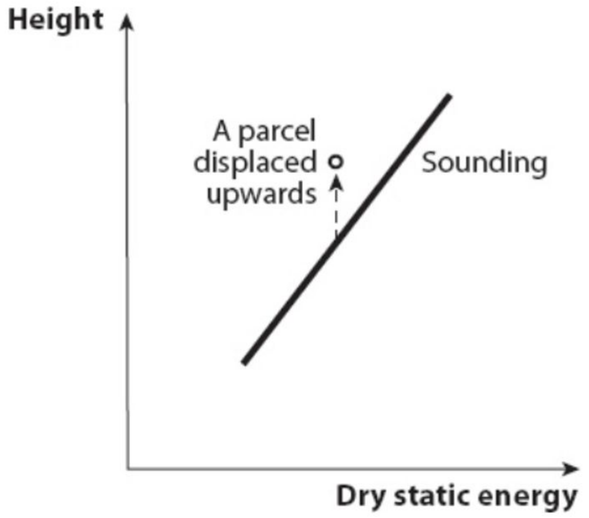


Figure 3.3. Sketch illustrating a parcel that is displaced upward in a statically stable sounding, for which the dry static energy increases upward. The parcel is assumed to conserve its dry static energy.

Static stability and instability of dry air

Gravity waves

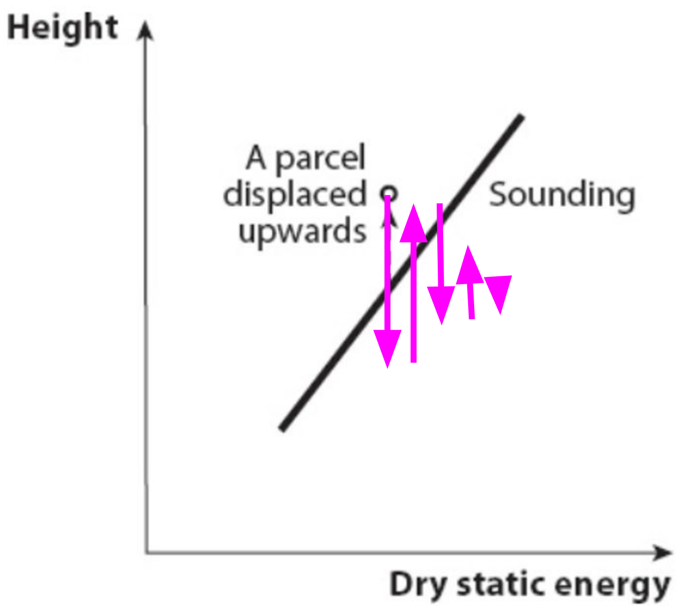


Figure 3.3. Sketch illustrating a parcel that is displaced upward in a statically stable sounding, for which the dry static energy increases upward.
The parcel is assumed to conserve its dry static energy.

Two assumptions:
(a) the dry static energy increases upward in the basic state
(b) the parcel conserves its dry static energy as it moves.

When or how do these assumptions break?

Moist static energy: Let's take into account phase changes of water

Temperature-like variable that is conserved even with phase changes:

Moist static energy

$$h \equiv s + Lq\,.$$

Conservation of moist static energy

$$\rho \frac{Dh}{Dt} = Q_{\mathrm{rad}}\,.$$

Enthalpy of a parcel in the mid troposphere = 250,000 J/kg

Potential energy per unit mass of a parcel near the tropopause = 150,000 J/kg

Latent energy per unit mass of a humid tropical air parcel = 40,000 J/kg

Kinetic energy of a parcel with a wind speed of 15m/s = **112 J/kg**

Cumulus instability

$$s \equiv c_p T + gz.$$

$$h \equiv s + Lq.$$

$$h^* \equiv s + Lq^*.$$

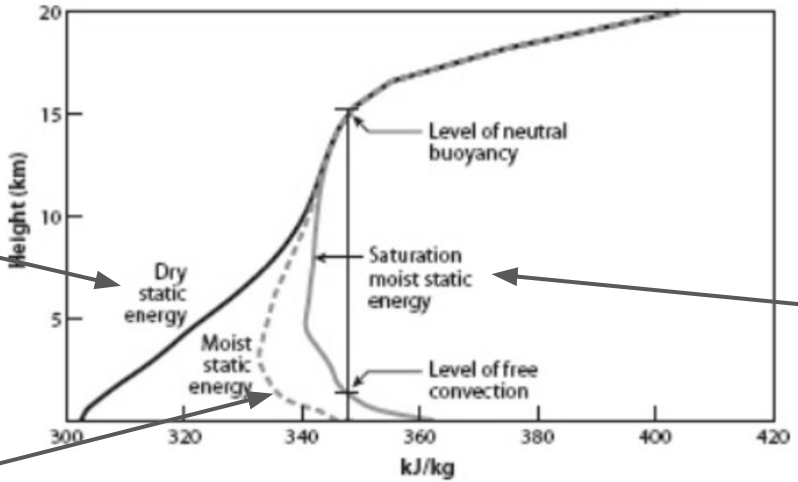
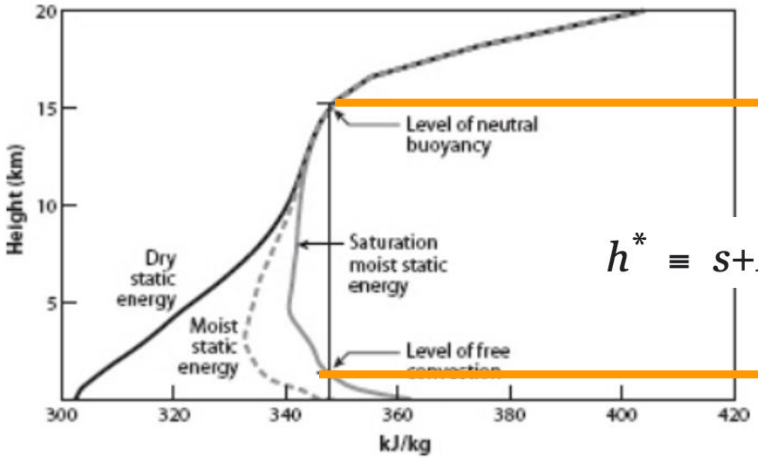


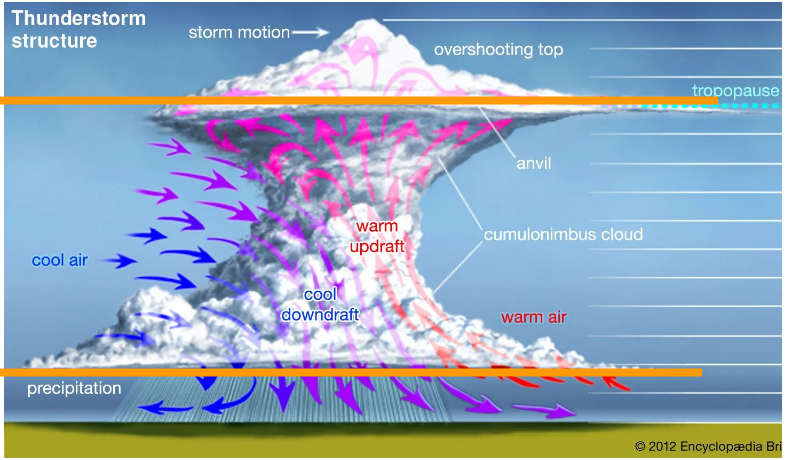
Figure 3.5. The observed vertical distribution of the moist static energy (dashed curve), for January, in kJ kg^{-1}.

A minimum occurs in the tropics, about 5 km above the surface. The vertical profiles of the dry static energy (solid black curve) and saturation moist static energy (solid gray curve) are also shown. The thin vertical line represents the moist static energy of a parcel rising moist adiabatically from near the surface, conserving its moist static energy. The parcel is positively buoyant whenever the thin vertical line is to the right of the dashed line, that is, from about 1 km to 15 km above the surface. Further explanation is given in the text. The plots are based on time averages of data collected during a field experiment called TOGA COARE.

Cumulus instability



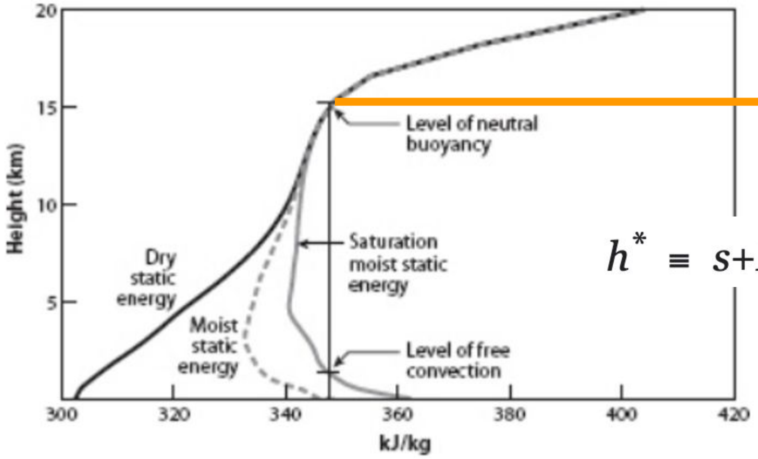
$$h^* \equiv s + Lq^*.$$



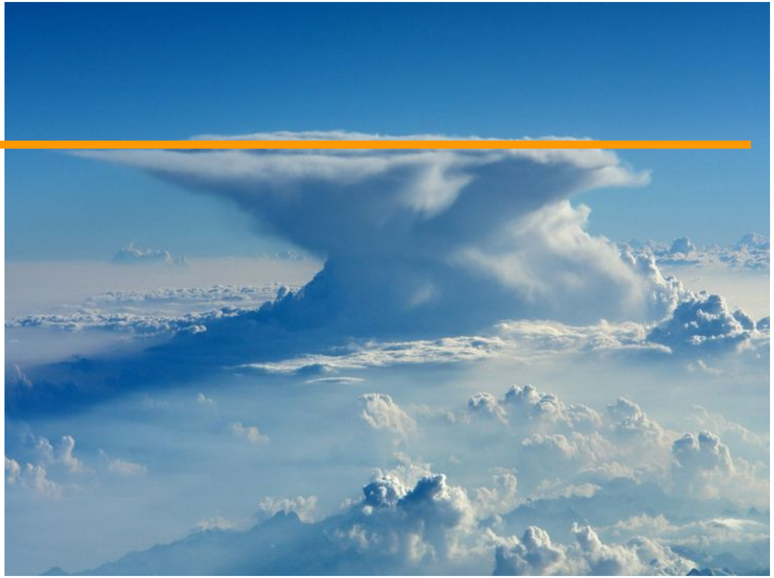
https://www.britannica.com/science/thunderstorm

Strong and organized updrafts. Lifting of moisture, momentum, and chemical species. Precipitation of solid and liquid water.

Cumulus instability: How a cumulus cloud grows



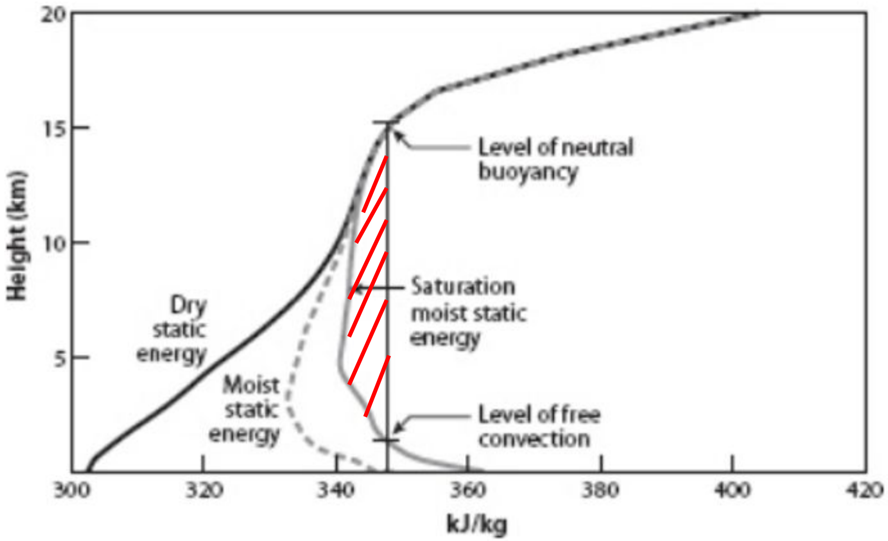
$$h^* \equiv s + Lq^*.$$



https://en.wikipedia.org/wiki/Cumulonimbus_incus

The cumulus cloud top is located at the level of neutral buoyancy: The air cannot go up so it spreads out.

Cumulus instability: How a cumulus cloud grows



Convective available potential energy (CAPE): a measure of the "total" buoyancy of a lifted parcel, integrated over the layer across which the parcel rises.

"Convection converts CAPE into kinetic energy."

Cumulus instability: How a cumulus cloud grows

Conditional instability:

The moist adiabatic lapse rate must be slower to the environmental lapse rate AND the basic state must be sufficiently humid so that condensation will actually occur in a lifted parcel.

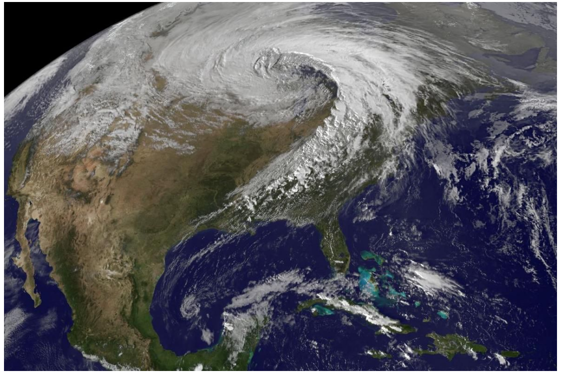
$$\Gamma_d > \Gamma > \Gamma_m.$$

"condensation can create instability for a hydrostatically balanced basic state that would otherwise be gravitationally stable"

Other types of convective systems

Tropical cyclones

https://en.wikipedia.org/wiki/Tropical_cyclone



Extra-tropical cyclones

http://pressbooks-dev.oer.hawaii.edu/atmo/chapter/chapter-13-extratropical-cyclones/

Multicellular mesoscale convective systems

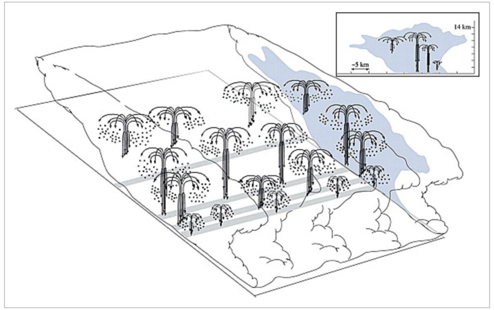
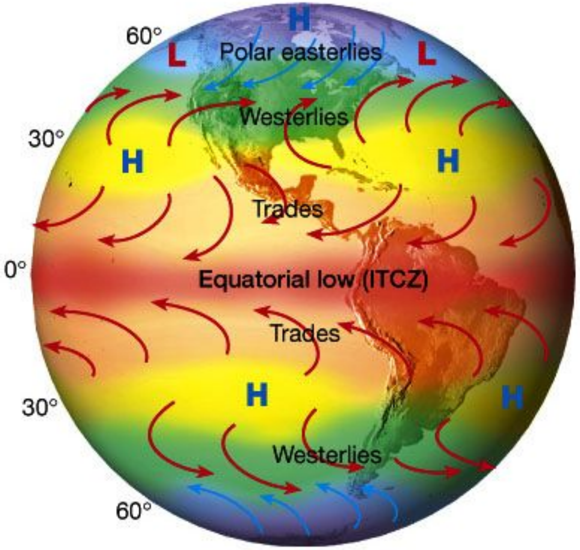


Figure 15 Open in figure viewer | PowerPoint

Conceptual model of an ensemble of particle fountains in a multicellular MCS. Shaded area represents radar reflectivity along a cross section perpendicular to the convective region. Cloud boundary is indicated by the scalloped outline. Inset shows approximate scales and arrangement of the largest particle fountains relative to the radar echo. From *Yuter and Houze* [1995b].

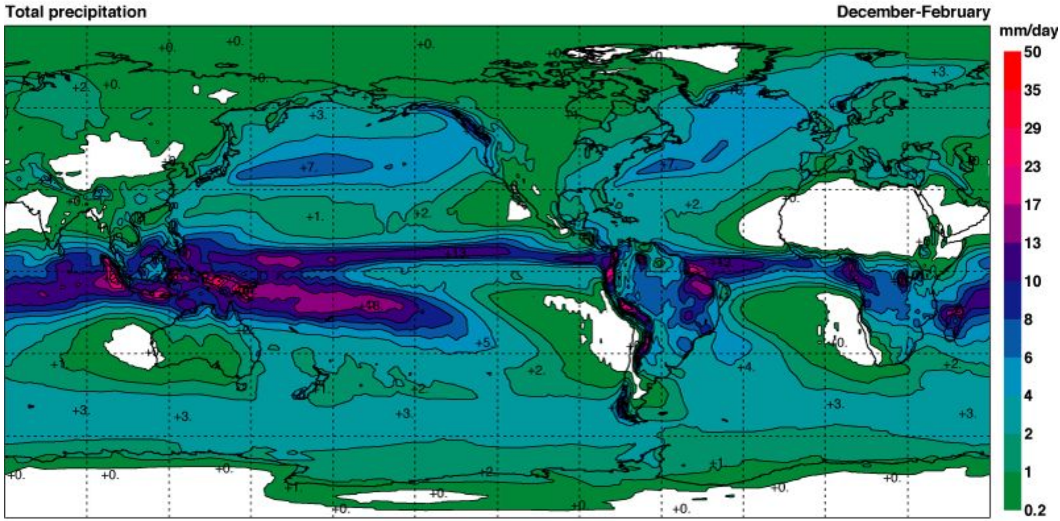
Houze, 2004

The ITCZ

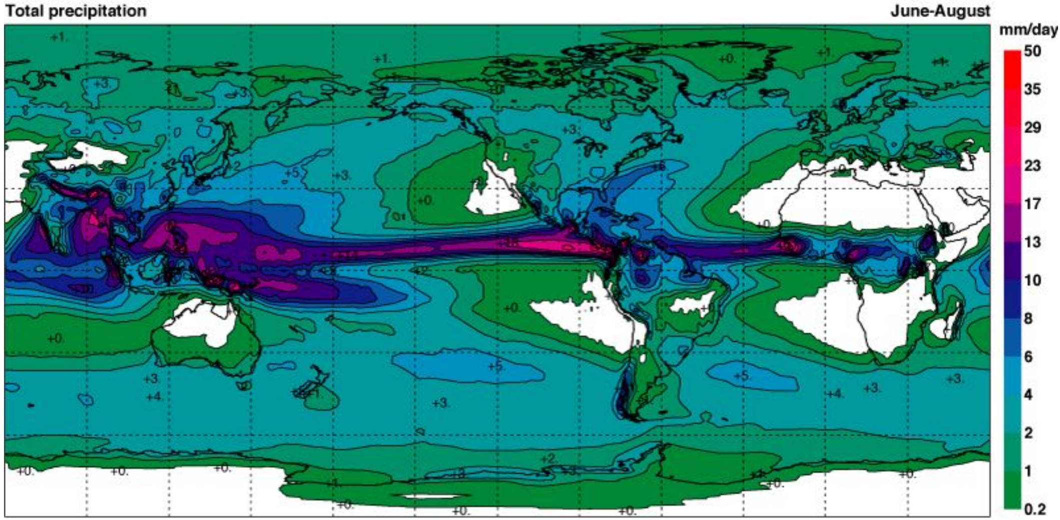


(b)

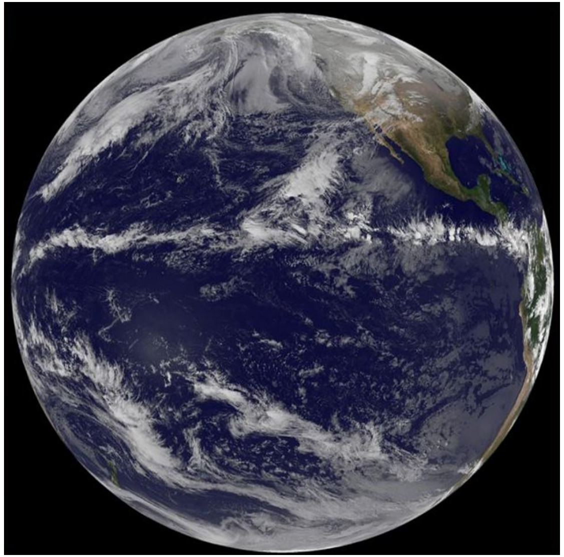
N.H. Winter



N.H. Summer



The Inter-Tropical Convergence Zone



Bottom panel: A full-disk image of the Earth, in visible light, taken on November 24, 2010.

North America can be seen at the upper right. The Equator is directly below the satellite that took the image. The Intertropical Convergence Zone (ITCZ) appears as a "white stripe" that is oriented east-west, slightly north of the Equator. At any given time, the ITCZ contains many thousands of small and large cumulus clouds, comparable to those shown in the upper panel of the figure.

https://eos.org/research-spotlights/tropical-rainfall-intensifies-while-the-doldrums-narrow

"The cumuli collectively lift energy toward the tropopause at the enormous rate of about **3×10^16W**, roughly a third as large as the solar radiation absorbed (or the infrared radiation emitted) by the whole Earth."

Role of the ITCZ on the poleward energy transport

Table 3.1
Net energy transports out of the ITCZ.

Layer	Moist static energy transport out of the ITCZ, in units of 1016 J s-1
Lower troposphere	-3.67
Upper troposphere	3.80

Source: Adapted from Riehl and Malkus (1958).

What type of energy comes in and goes out?

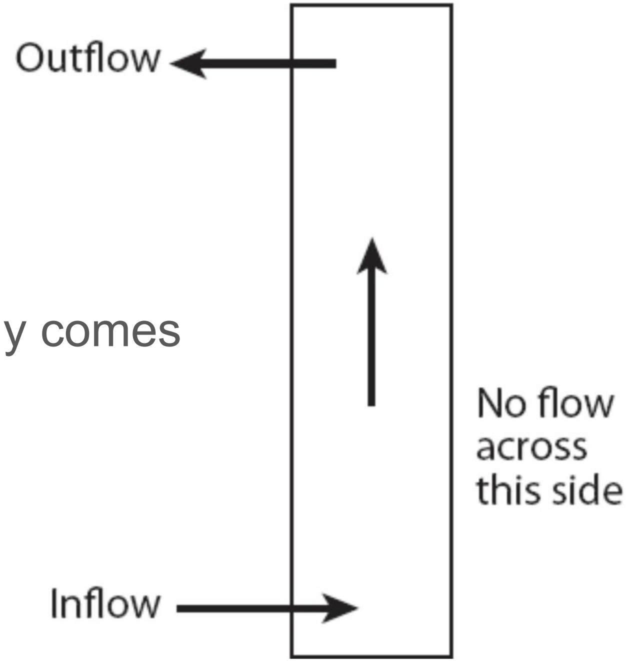
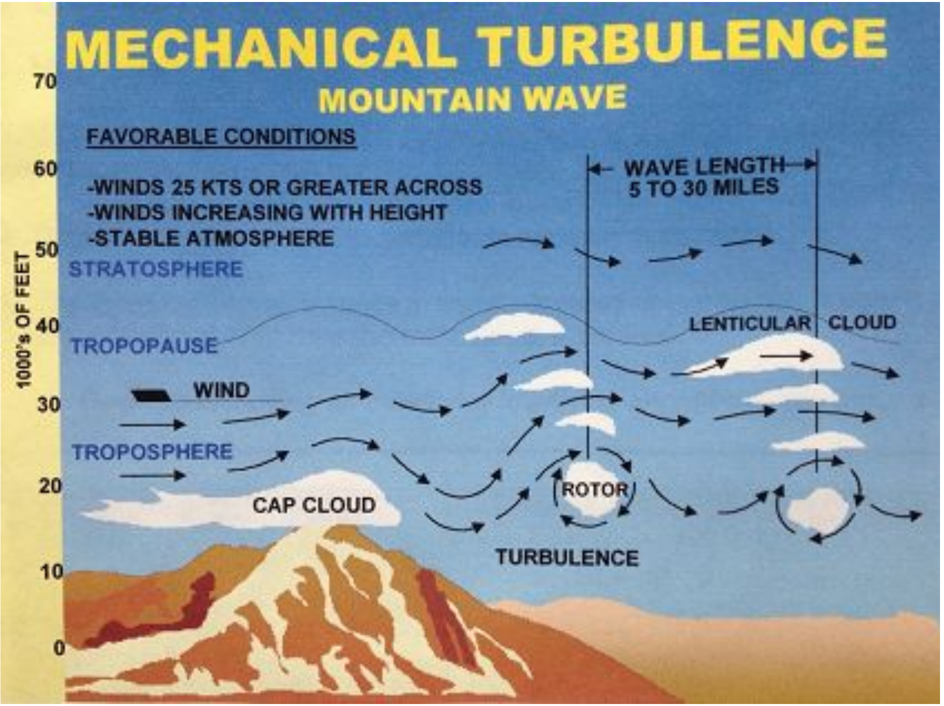


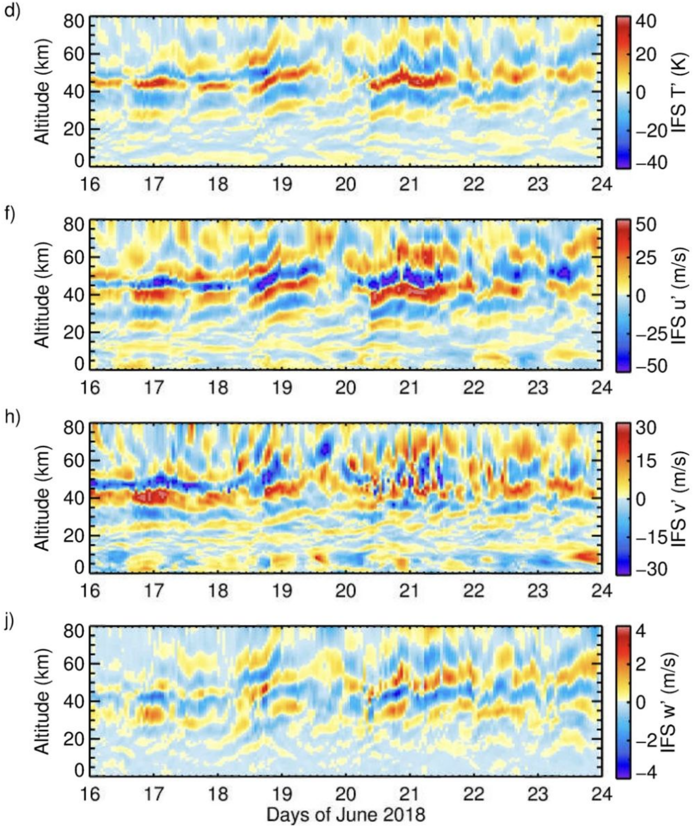
Figure 3.7. The flow through the Intertropical Convergence Zone, as analyzed by Riehl and Malkus.

Mixing due to waves or mechanical turbulence



https://www.weather.gov/source/zhu/ZHU_Training_Page/turbulence_stuff/turbulence/turbulence.htm

Mixing due to waves or mechanical turbulence



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Lidar observations of large-amplitude mountain waves in the stratosphere above Tierra del Fuego, Argentina

N. Kaifler, B. Kaifler, A. Dörnbrack, M. Rapp, J. L. Hormaechea & A. de la Torre

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