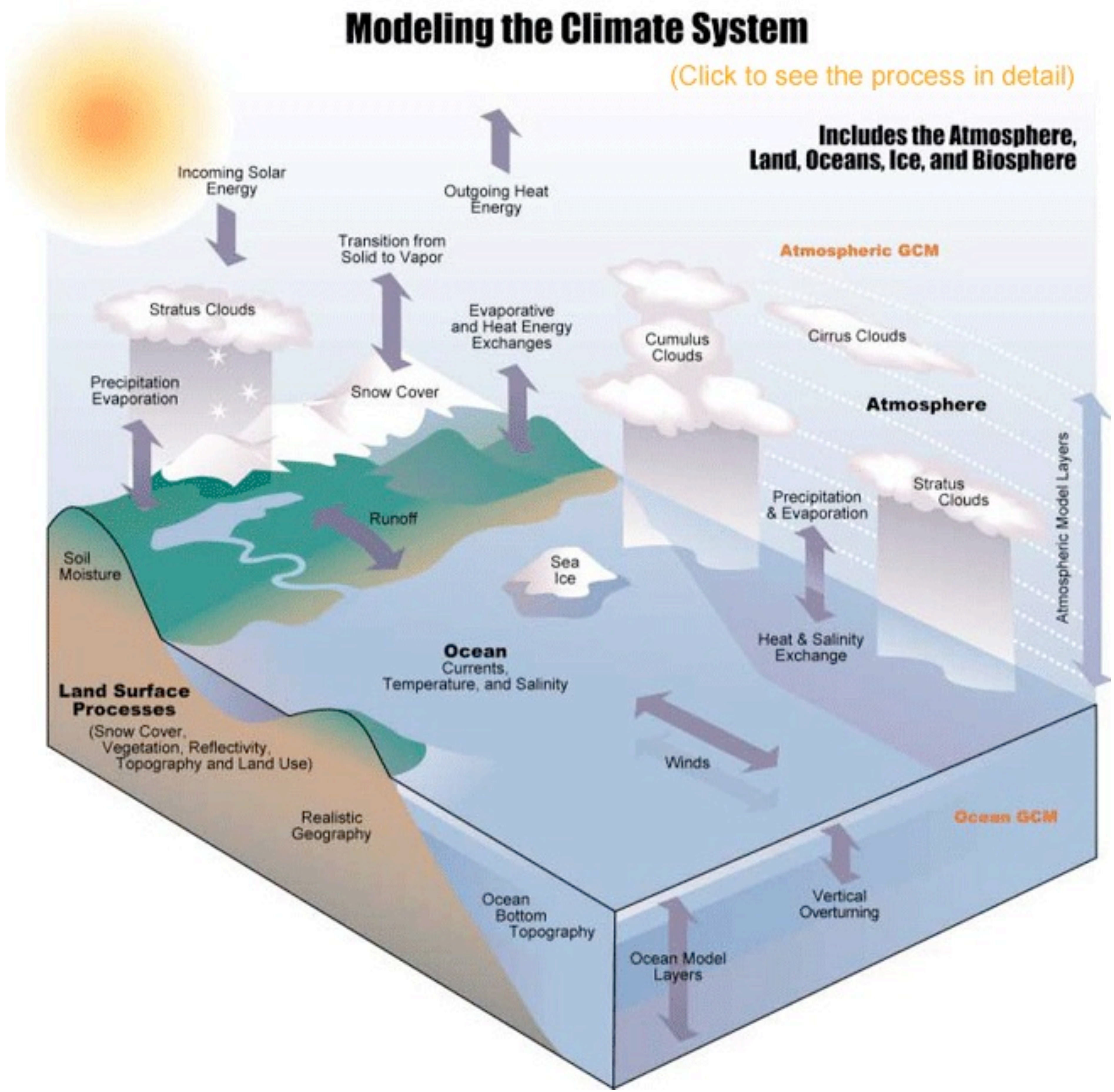
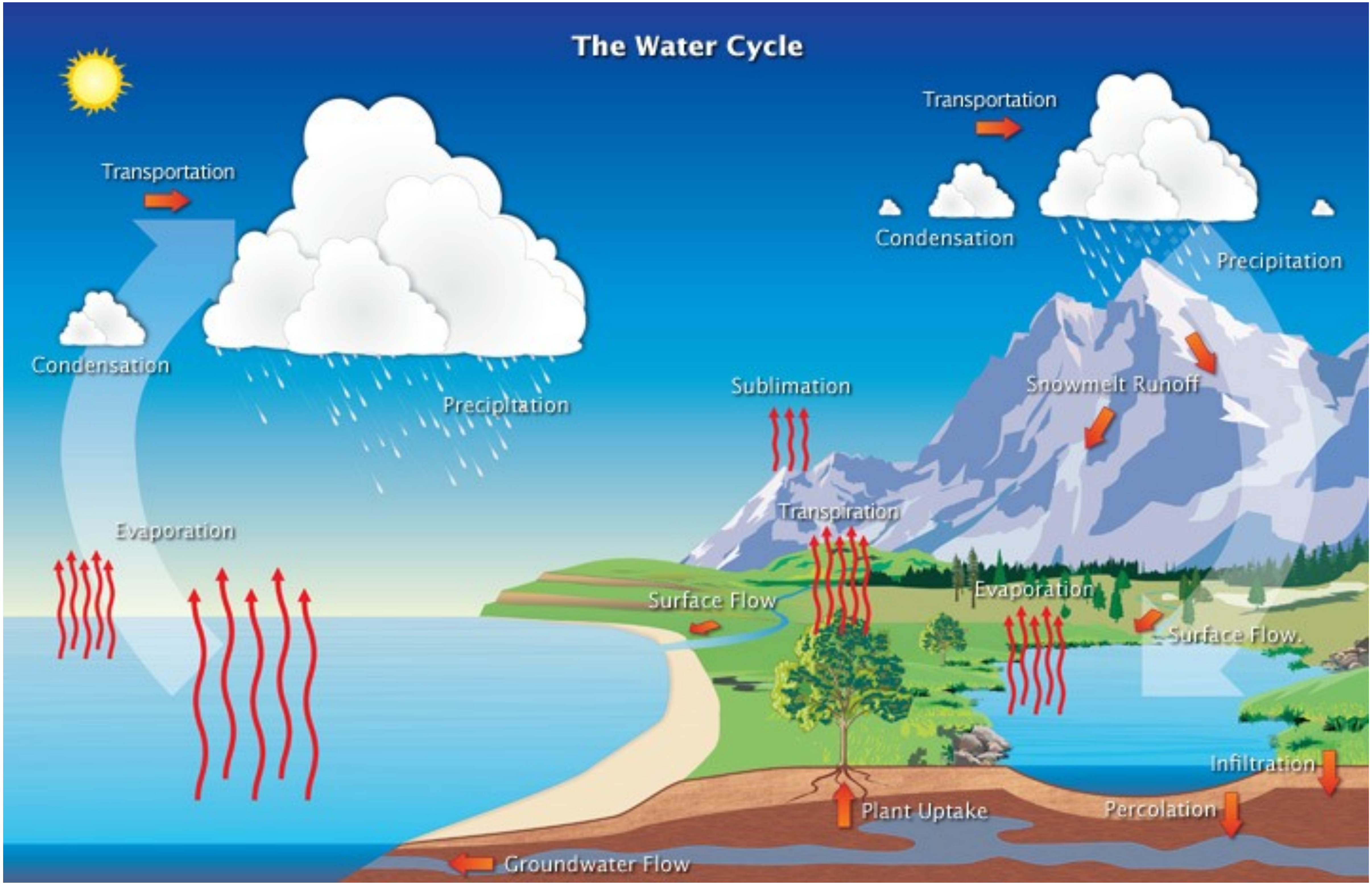
Global Energy and Water Budgets

Modeling the Climate System

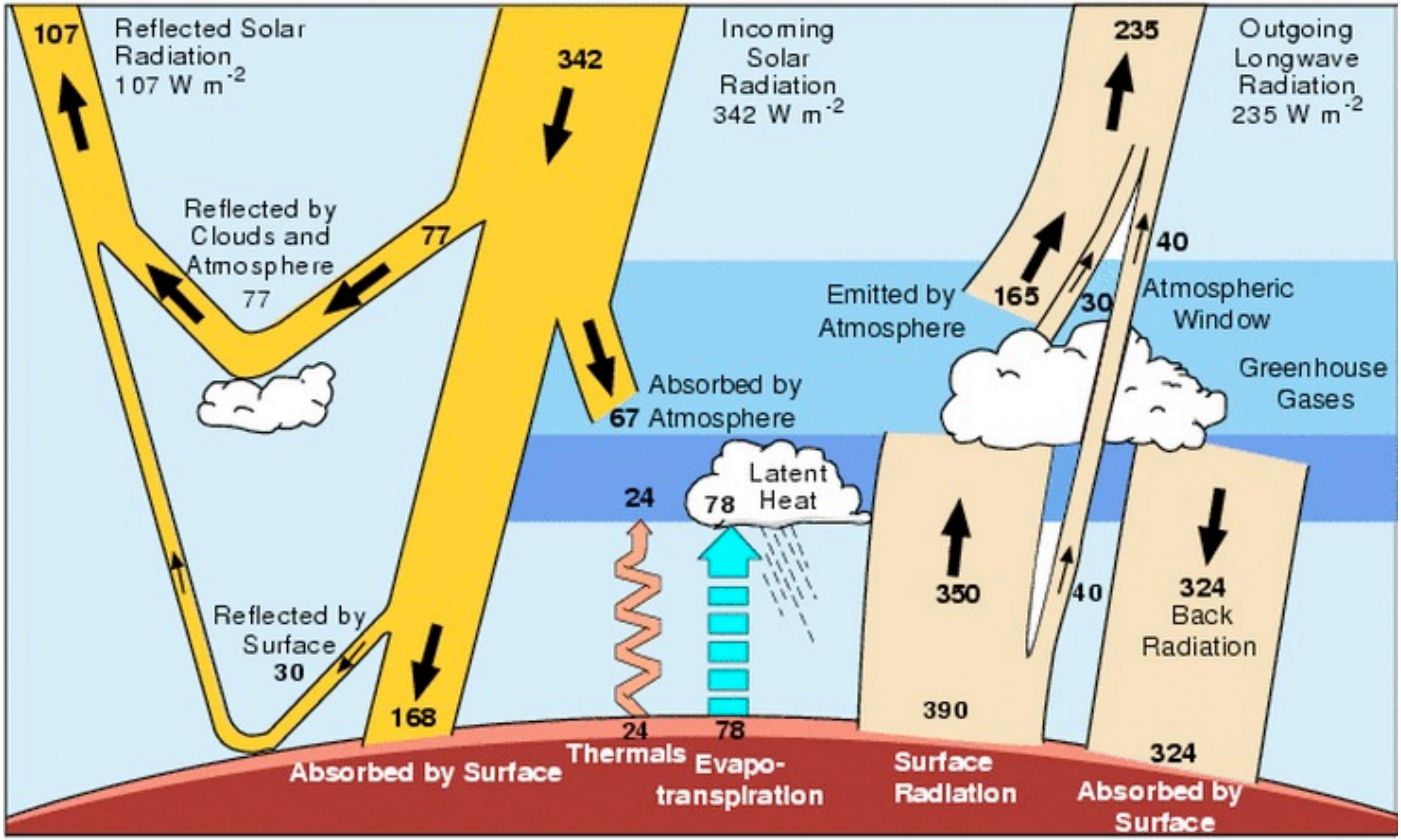
(Click to see the process in detail)





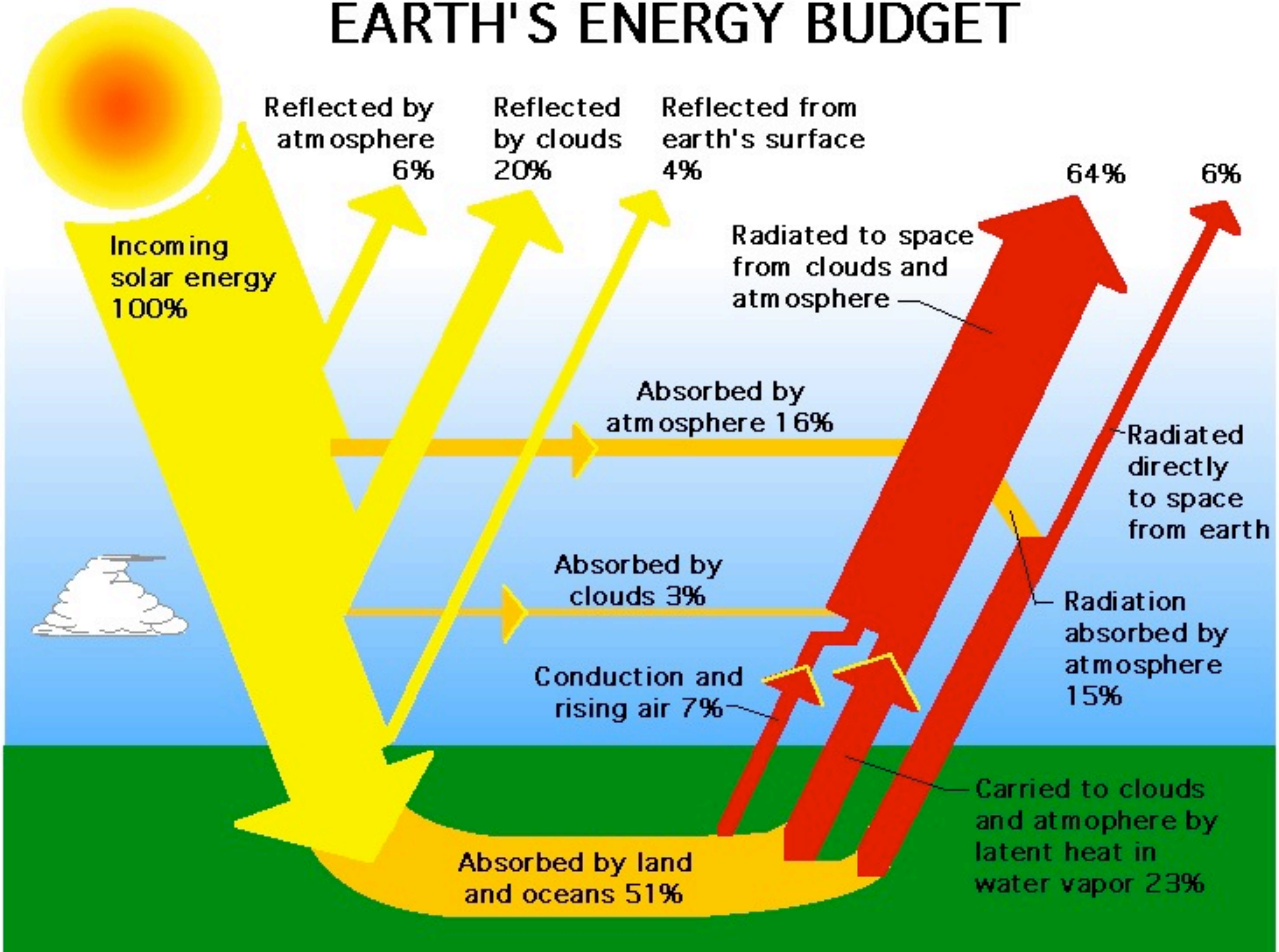
The Water Cycle
Transportation
Condensation
Precipitation
Evaporation
Transportation
Condensation
Precipitation
Sublimation
Snowmelt Runoff
Transpiration
Surface Flow
Evaporation
Surface Flow
Infiltration
Plant Uptake
Percolation
Groundwater Flow

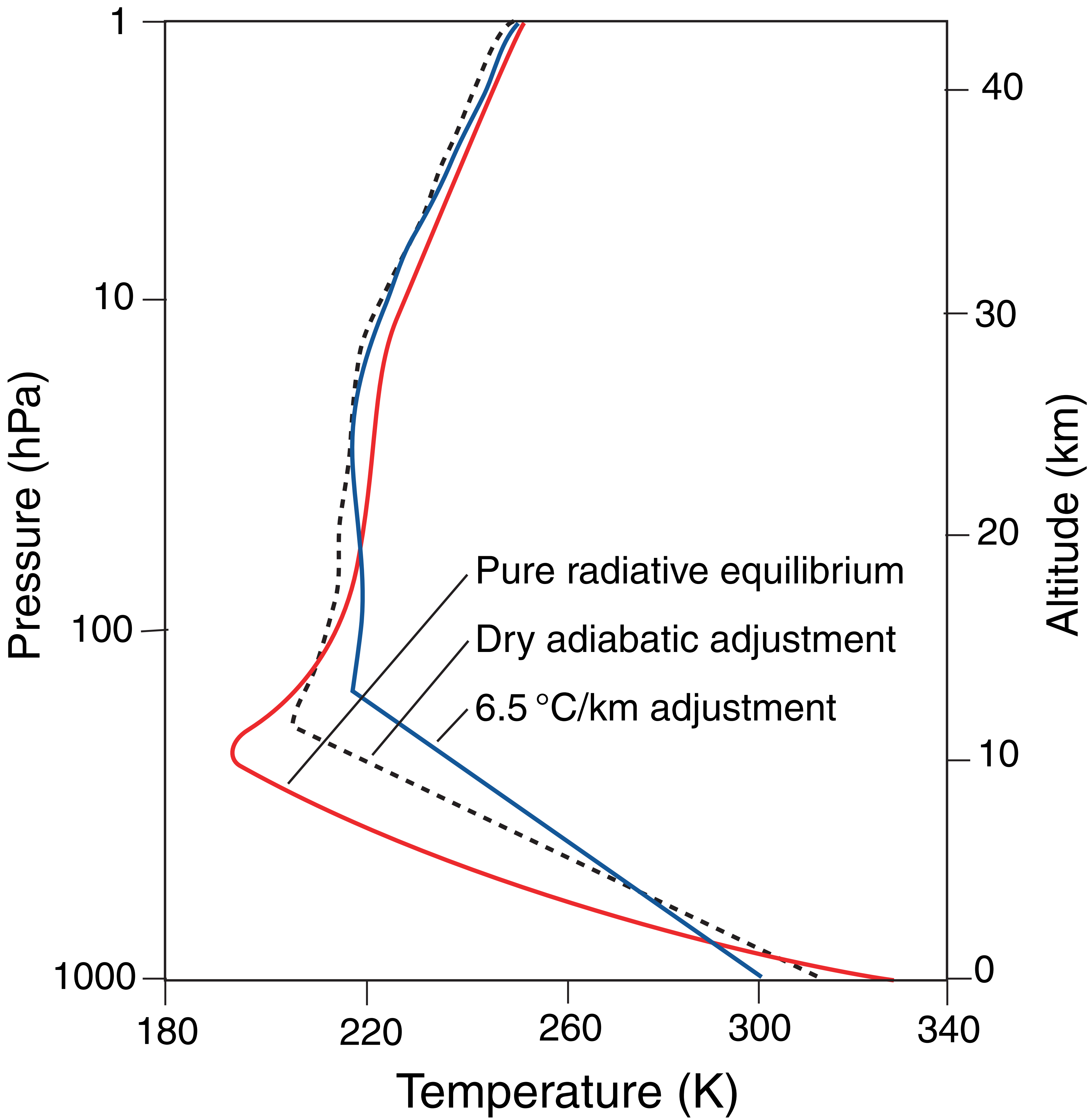
Global Heat Flows



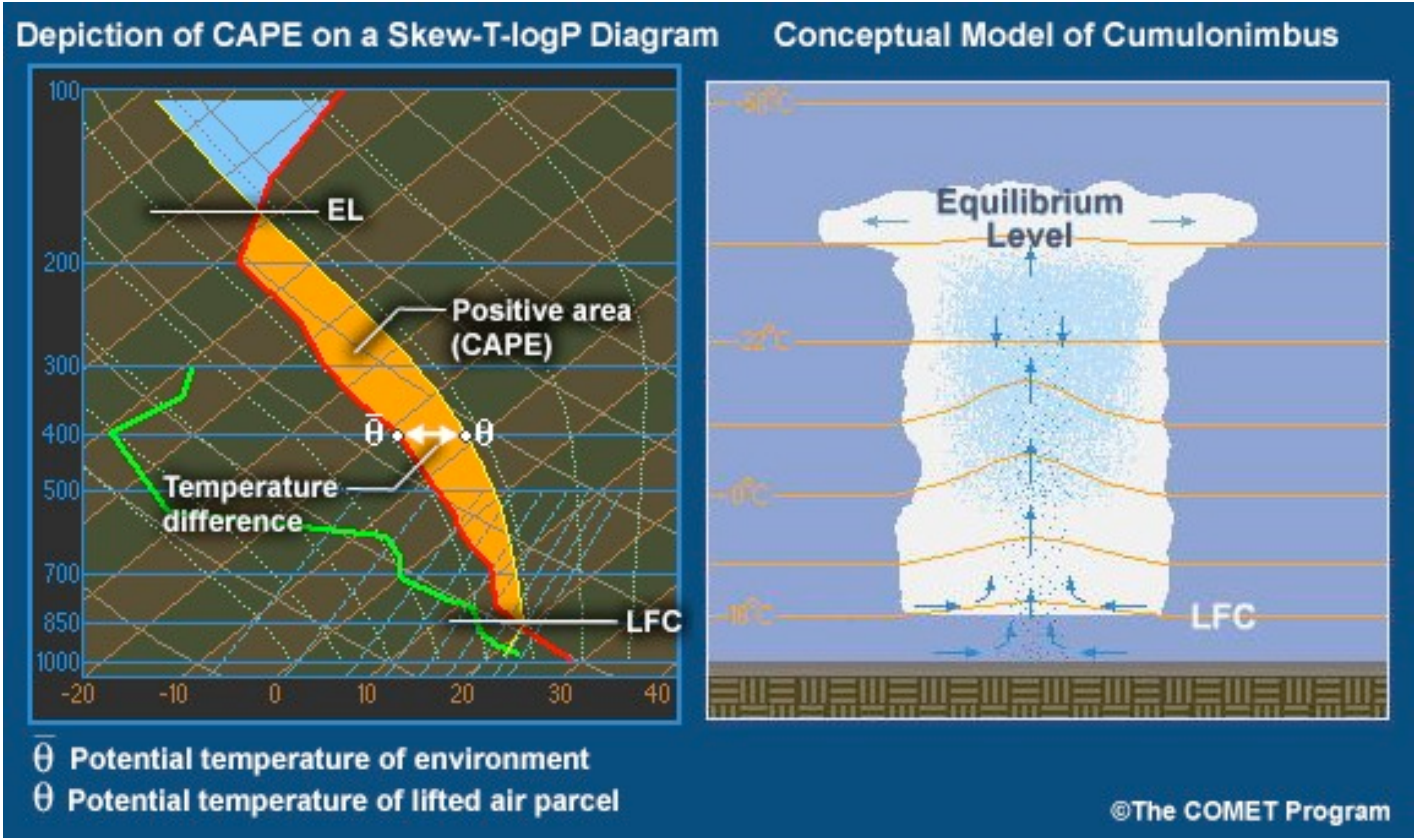
Kiehl and Trenberth 1997

EARTH'S ENERGY BUDGET





Pressure (hPa)
1
10
100
1000
Altitude (km)
40
30
20
10
0
Pure radiative equilibrium
Dry adiabatic adjustment
6.5 °C/km adjustment
180
220
260
300
340
Temperature (K)



Depiction of CAPE on a Skew-T-logP Diagram
Conceptual Model of Cumulonimbus
100
200
300
400
500
700
850
1000
-20
-10
0
10
20
30
40
EL
Positive area (CAPE)
$\bar{\theta}$
θ
Temperature difference
LFC
Equilibrium Level
LFC
$\bar{\theta}$ Potential temperature of environment
θ Potential temperature of lifted air parcel
©The COMET Program

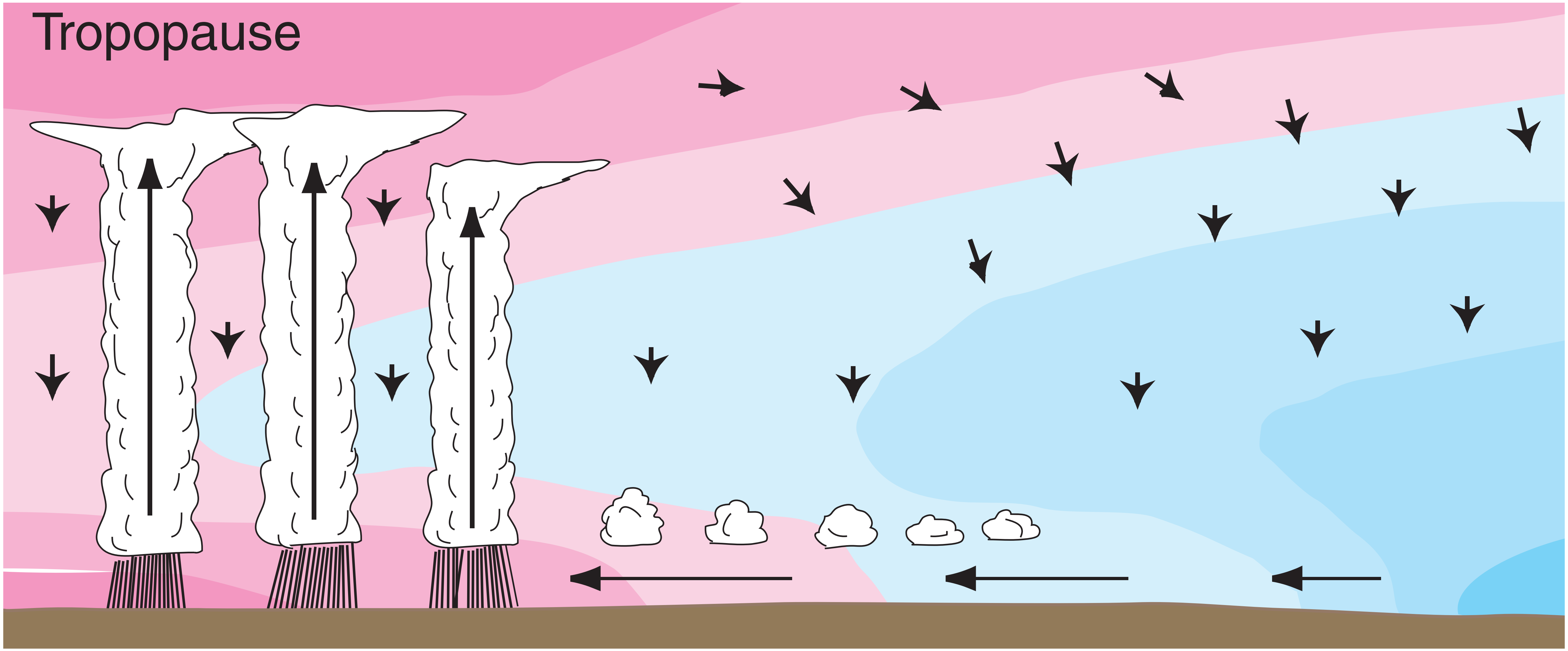
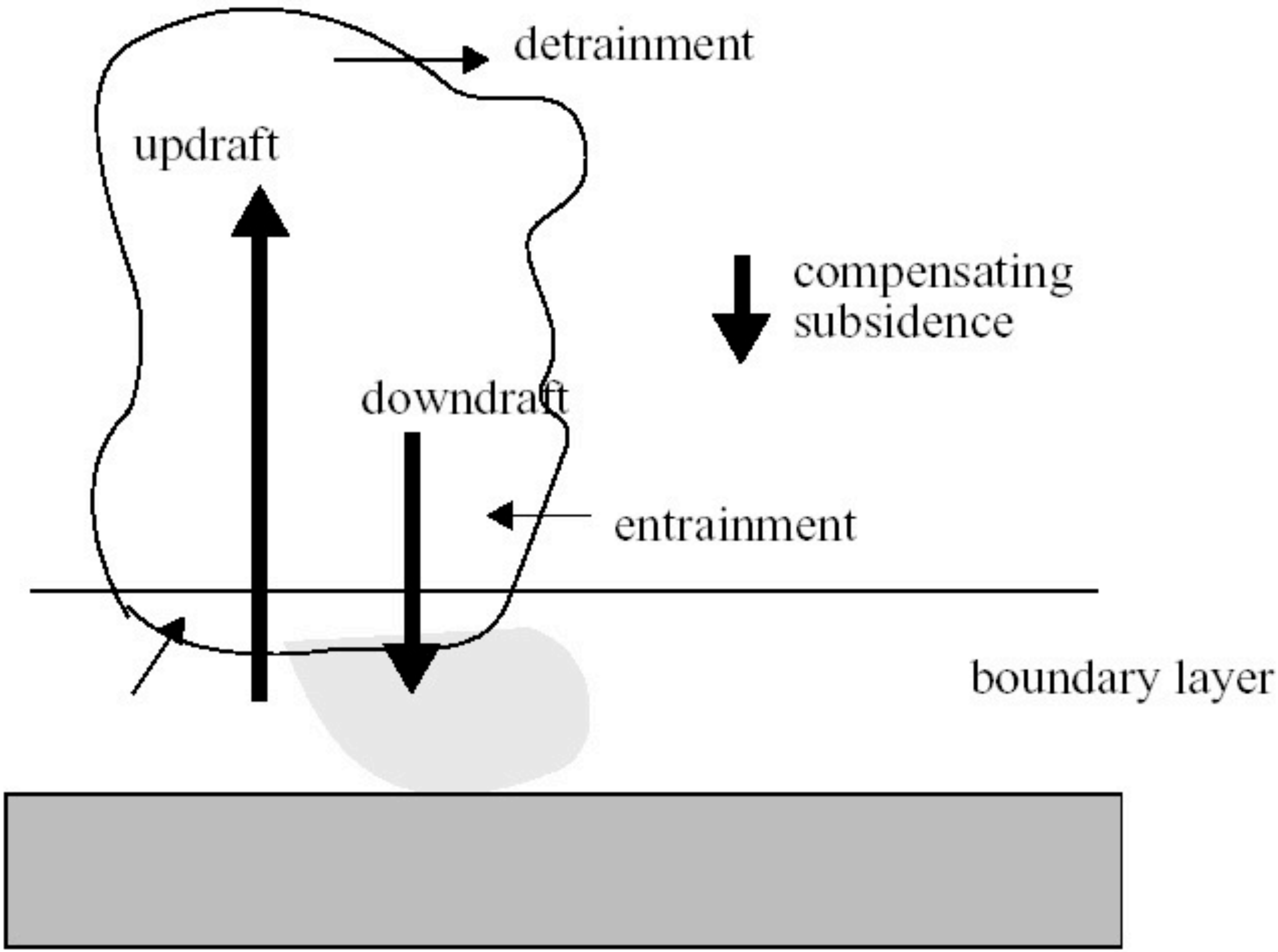
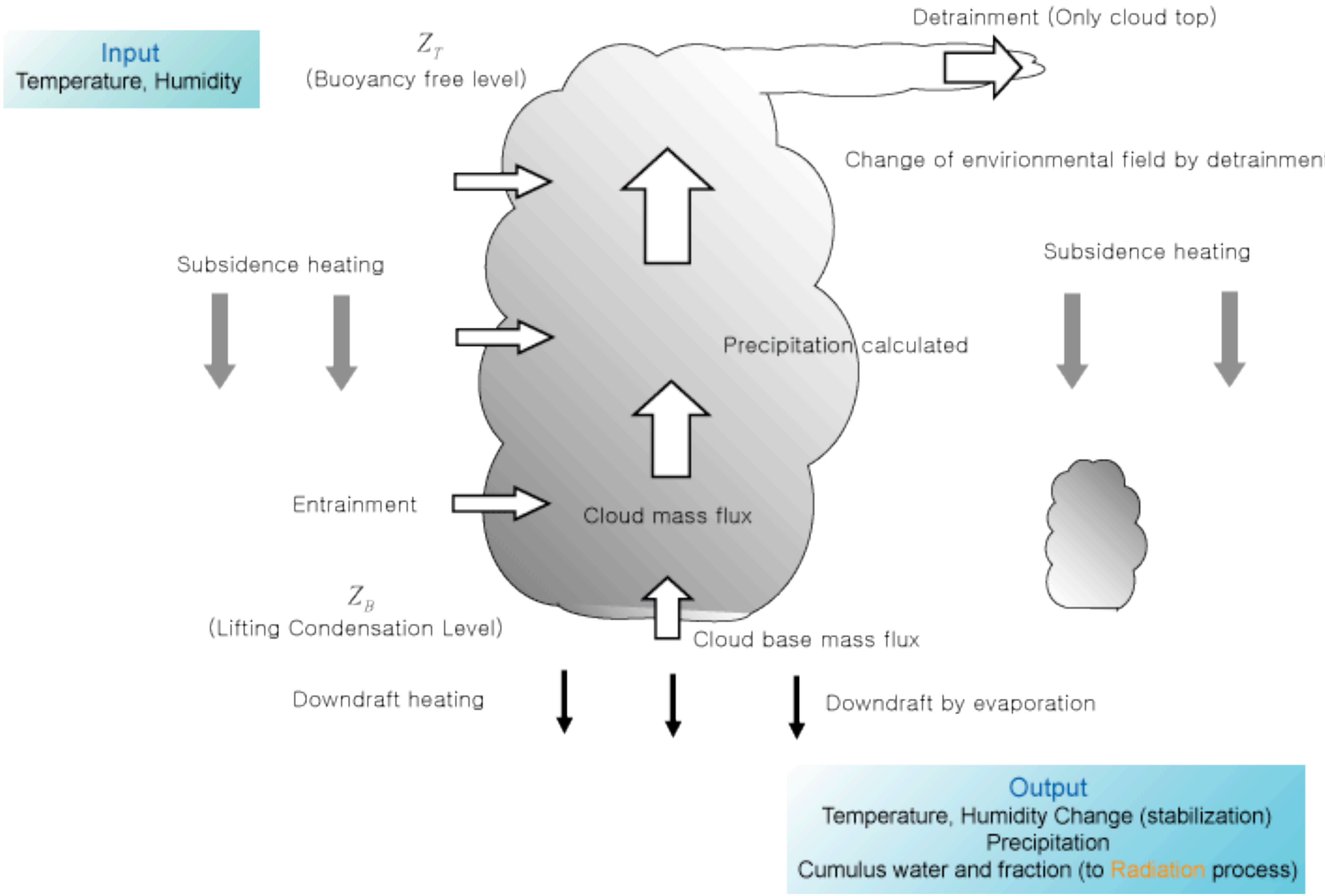

Tropopause

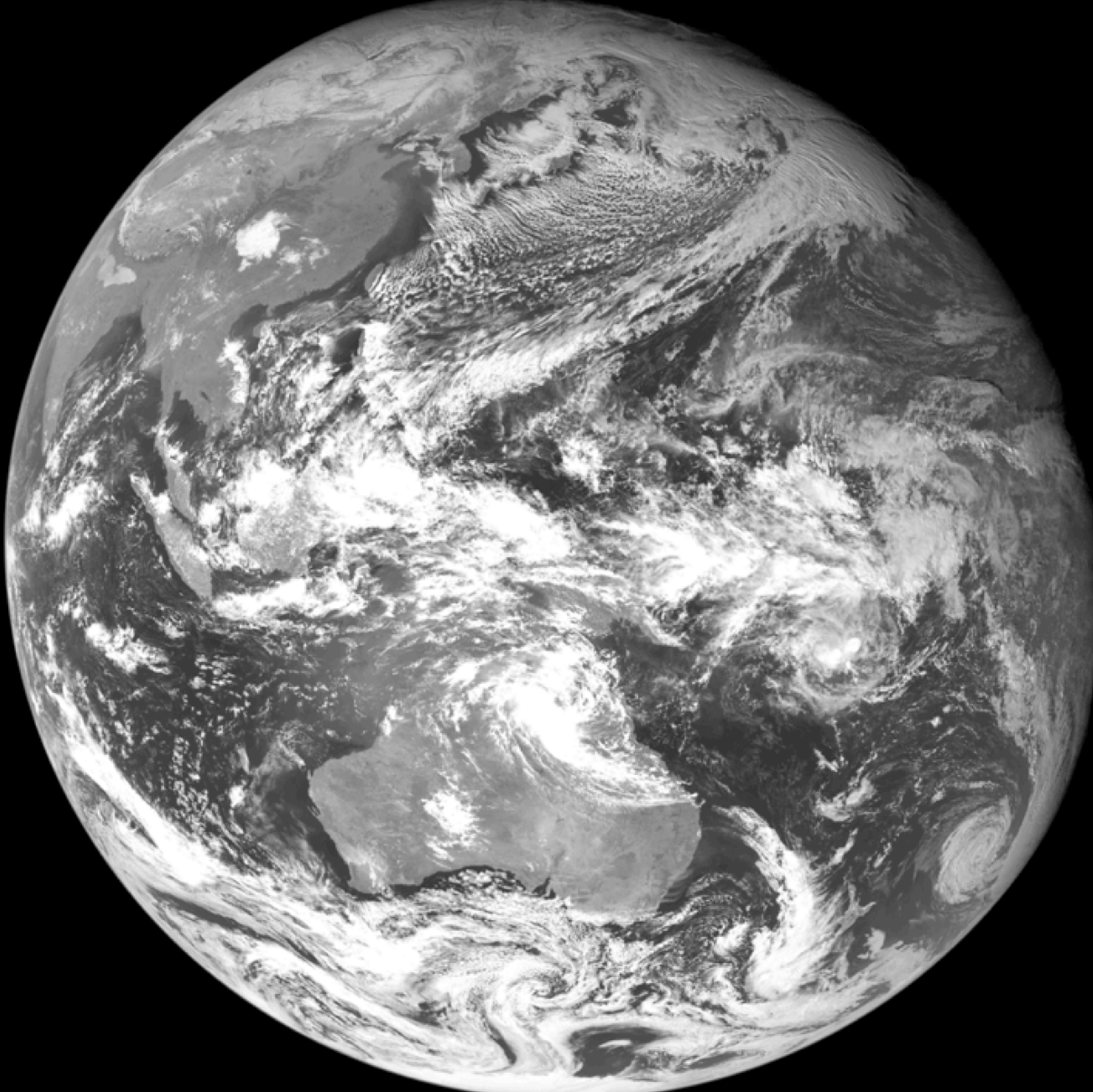
Illustration of Cumulus Processes





Input
Temperature, Humidity
Z_T
(Buoyancy free level)
Detrainment (Only cloud top)
Change of envirionmental field by detrainment
Subsidence heating
Subsidence heating
Precipitation calculated
Entrainment
Cloud mass flux
Z_B
(Lifting Condensation Level)
Cloud base mass flux
Downdraft heating
Downdraft by evaporation
Output
Temperature, Humidity Change (stabilization)
Precipitation
Cumulus water and fraction (to Radiation process)

Cloud Radiative Effects



https://www.atmos.washington.edu/~dennis/321/

Global Physical Climatology by Dennis Hartmann

Cloud Radiative Effects

Table 3.2 Cloud radiative effect on the top-of-atmosphere global energy balance as estimated from satellite measurements. Irradiances are given in W m^{-2} and albedo in percent. (From CERES data as described in Loeb et al. 2009.)

	Average	Cloud-Free	Cloud Effect
OLR	240	266	+26
Absorbed Solar Radiation	240	288	–47
Net Radiation	+0.56	+22	–21
Albedo	29%	15%	+14%

S_0: solar constant (incoming solar flux, 1367 W m^{-2}).

α_p: planetary albedo (0.30).

$F^{\uparrow}(\infty)$: outgoing longwave (IR) radiation at TOA (234 W m^{-2}).

Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

- TOA Energy Balance

$$R_{\mathrm{TOA}} = \frac{S_0}{4}(1-\alpha_p) - F^{\uparrow}(\infty)$$

$$\Delta R_{\mathrm{TOA}} = R_{\mathrm{cloudy}} - R_{\mathrm{clear}} = \Delta Q_{\mathrm{abs}} - \Delta F^{\uparrow}(\infty)$$

- Cloud Radiative Effect – Add Clouds, what changes?

$$\Delta Q_{\mathrm{abs}} = \frac{S_0}{4}(1-\alpha_{\mathrm{cloudy}}) - \frac{S_0}{4}(1-\alpha_{\mathrm{clear}})$$

$$= \frac{S_0}{4}(\alpha_{\mathrm{cloudy}} - \alpha_{\mathrm{clear}}) = -\frac{S_0}{4}\Delta\alpha_p$$

Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

- Cloud Radiative Effect – Add Clouds, what changes?

$$\Delta R_{\mathrm{TOA}} = R_{\mathrm{cloudy}} - R_{\mathrm{clear}} = \Delta Q_{\mathrm{abs}} - \Delta F^{\uparrow}(\infty)$$

- Shortwave bit

$$\Delta Q_{\mathrm{abs}} = \frac{S_0}{4}(1-\alpha_{\mathrm{cloudy}}) - \frac{S_0}{4}(1-\alpha_{\mathrm{clear}})$$

$$= \frac{S_0}{4}(\alpha_{\mathrm{cloudy}} - \alpha_{\mathrm{clear}}) = -\frac{S_0}{4}\Delta\alpha_p$$

- Longwave bit

$$\Delta F^{\uparrow}(\infty) = F^{\uparrow}_{\mathrm{cloudy}}(\infty) - F^{\uparrow}_{\mathrm{clear}}(\infty)$$

Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

- Longwave bit

$$\Delta F^{\uparrow}(\infty) = F^{\uparrow}_{\text{cloudy}}(\infty) - F^{\uparrow}_{\text{clear}}(\infty)$$

- Expand using grey absorption integral equations

$$\Delta F^{\uparrow}(\infty) = \sigma T_{z_{\text{ct}}}^{4} \mathscr{T}\{z_{\text{ct}},\infty\} - \sigma T_{s}^{4} \mathscr{T}\{z_{s},\infty\} - \int_{\mathscr{T}\{z_s,\infty\}}^{\mathscr{T}\{z_{\text{ct}},\infty\}} \sigma T(z')^4 \, d\mathscr{T}\{z',\infty\}$$

- Assume cloud top is above most of water vapor, then OLR is emission from top of cloud

$$\mathscr{T}\{z_{\text{ct}},\infty\} \approx 1.0$$

$$\Delta F^{\uparrow}(\infty) = \sigma T_{z_{\text{ct}}}^{4} - \sigma T_{s}^{4} \mathscr{T}\{z_{s},\infty\} - \int_{\mathscr{T}\{z_s,\infty\}}^{1} \sigma T(z')^4 \, d\mathscr{T}\{z',\infty\}$$

$$\Delta F^{\uparrow}(\infty) = \sigma T_{z_{\text{ct}}}^{4} - F^{\uparrow}_{\text{clear}}(\infty)$$

Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

- Putting the pieces together,

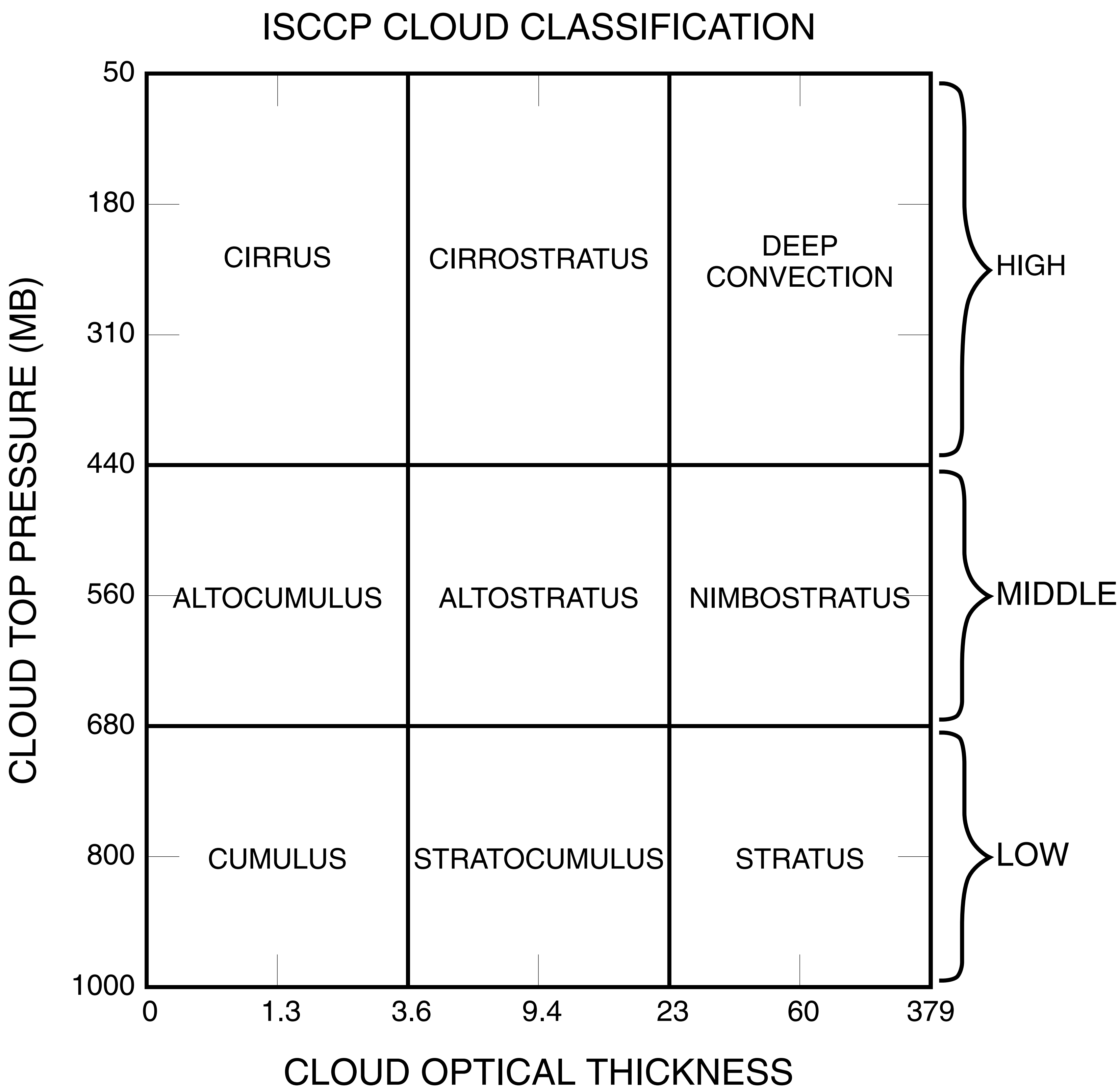
$$\Delta R_{\mathrm{TOA}} = R_{\mathrm{cloudy}} - R_{\mathrm{clear}} = \Delta Q_{\mathrm{abs}} - \Delta F^{\uparrow}(\infty)$$

- becomes

$$\Delta R_{\mathrm{TOA}} = -\frac{S_0}{4}\Delta\alpha_p + F^{\uparrow}_{\mathrm{clear}}(\infty) - \sigma T^4_{z_{\mathrm{ct}}}$$

- The solar and longwave parts tend to be of opposite sign and we can calculate the cloud top temperature at which they will exactly cancel.

$$T_{z_{\mathrm{ct}}} = \left\{\frac{-(S_0/4)\Delta\alpha_p + F^{\downarrow}_{\mathrm{clear}}(\infty)}{\sigma}\right\}^{1/4}$$


ISCCP CLOUD CLASSIFICATION
50
180
310
440
560
680
800
1000
CLOUD TOP PRESSURE (MB)
CIRRUS
CIRROSTRATUS
DEEP CONVECTION
ALTOCUMULUS
ALTOSTRATUS
NIMBOSTRATUS
CUMULUS
STRATOCUMULUS
STRATUS
HIGH
MIDDLE
LOW
0
1.3
3.6
9.4
23
60
379
CLOUD OPTICAL THICKNESS

Cloud Radiative Forcing

A_i = cloud amount for cloud type i

A = total cloud amount

A = A_i • I

OvcCRF_i = ovc CRF for cloud type i

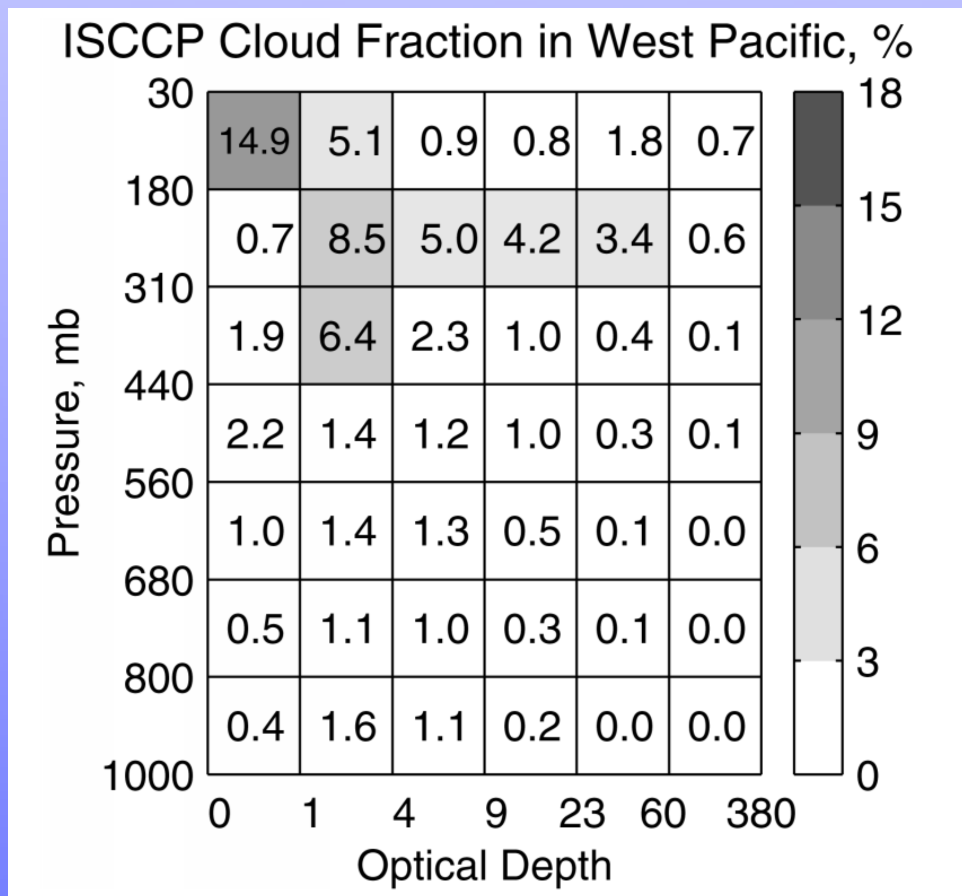
CRF_i = avg CRF for cloud type i

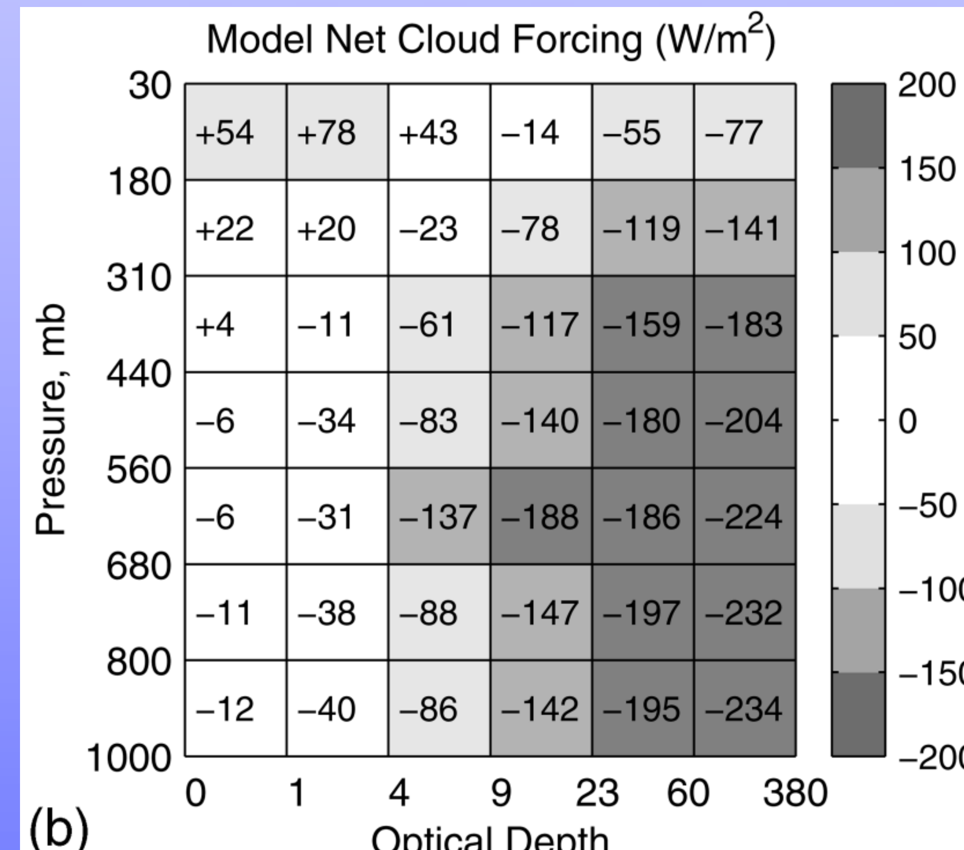
CRF = total avg CRF

CRF_i = A_i * OvcCRF_i

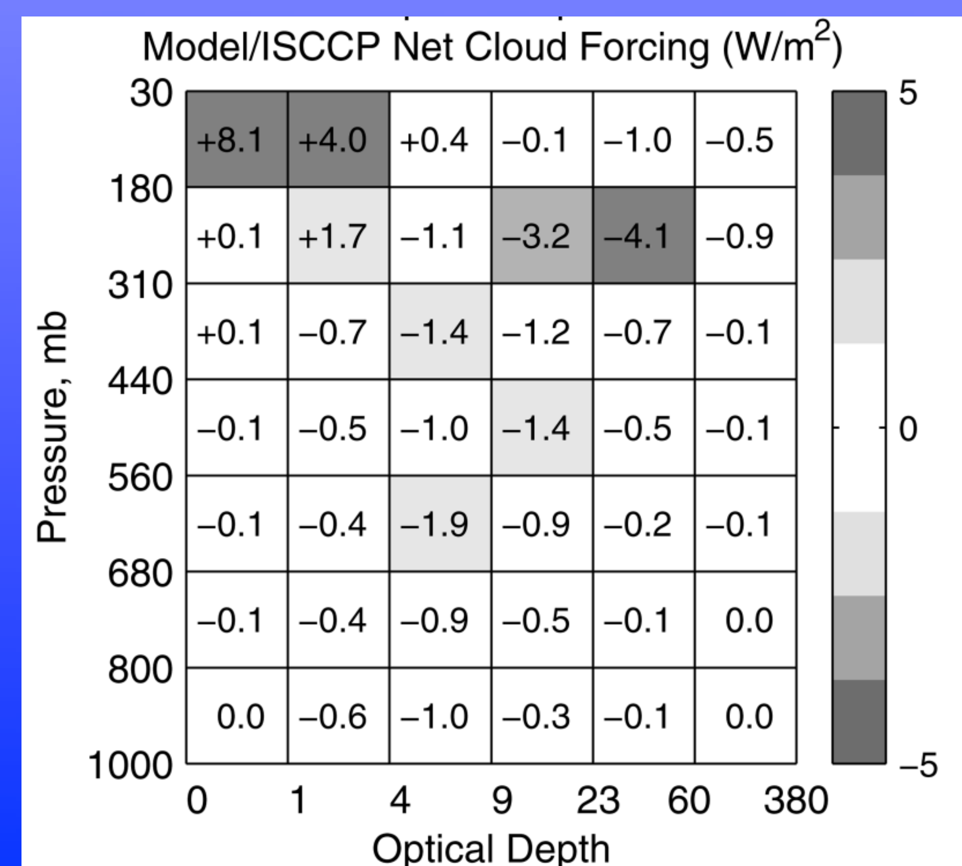
CRF = A_i • CRF_i = OvcCRF_i • I

A_i * OvcCRF_i





= CRF_i



from Hartmann, Moy, and Fu 2001

There is good agreement between modeled radiative fluxes (using *observed* cloud type frequencices) and observed (ERBE) radiative fluxes.

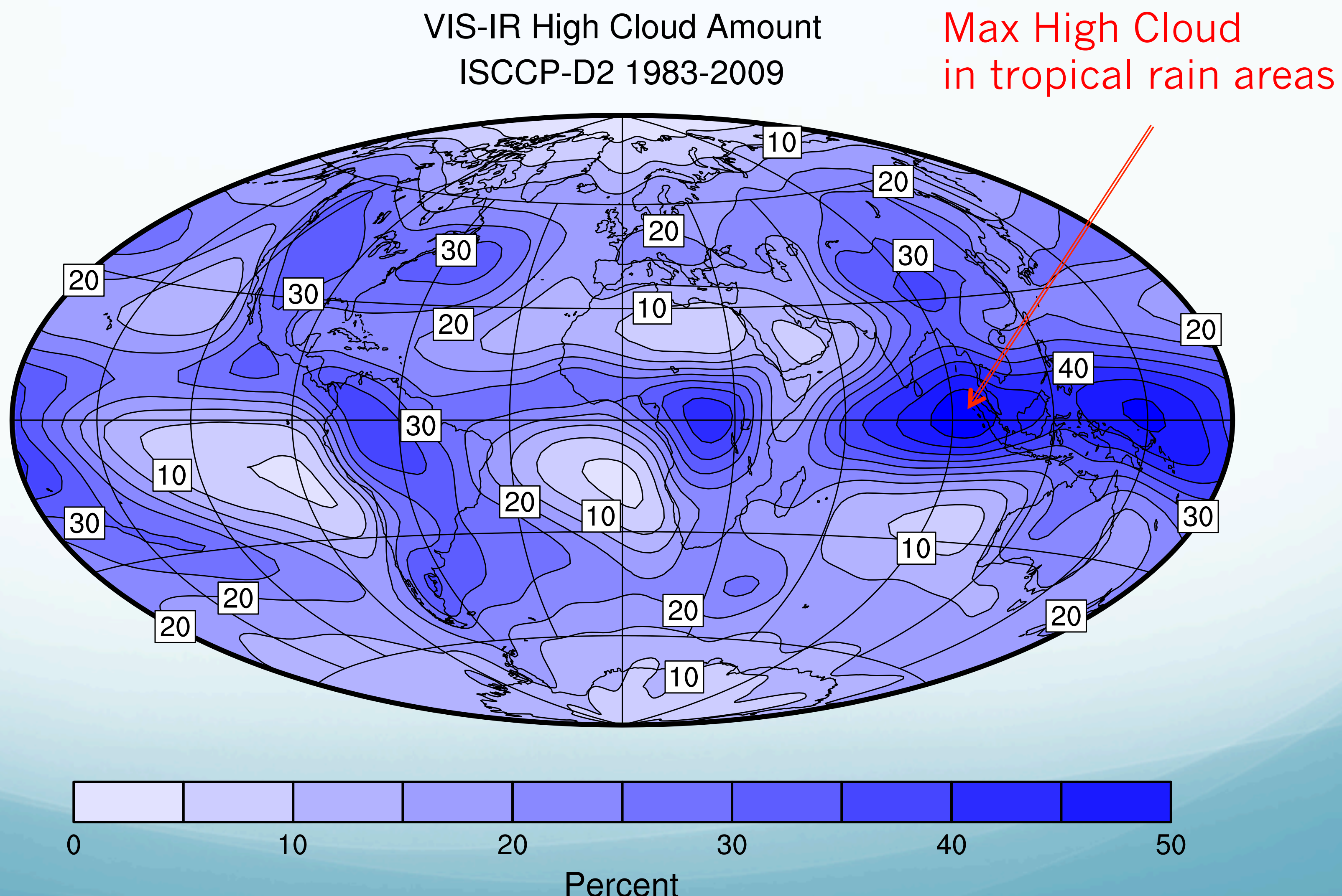
TABLE 1. ERBE and modeled radiation balance components for the west Pacific convective region 0°–15°N, 120°–150°E (W m^{-2}).

	Longwave		Shortwave		Net radiation	
	ERBE	Model	ERBE	Model	ERBE	Model
Average sky	211	213	117	119	96	92
Clear sky	280	278	40	42	103	103
Cloud forcing	70	65	−77	−77	−7	−11

from Hartmann, Moy, and Fu 2001

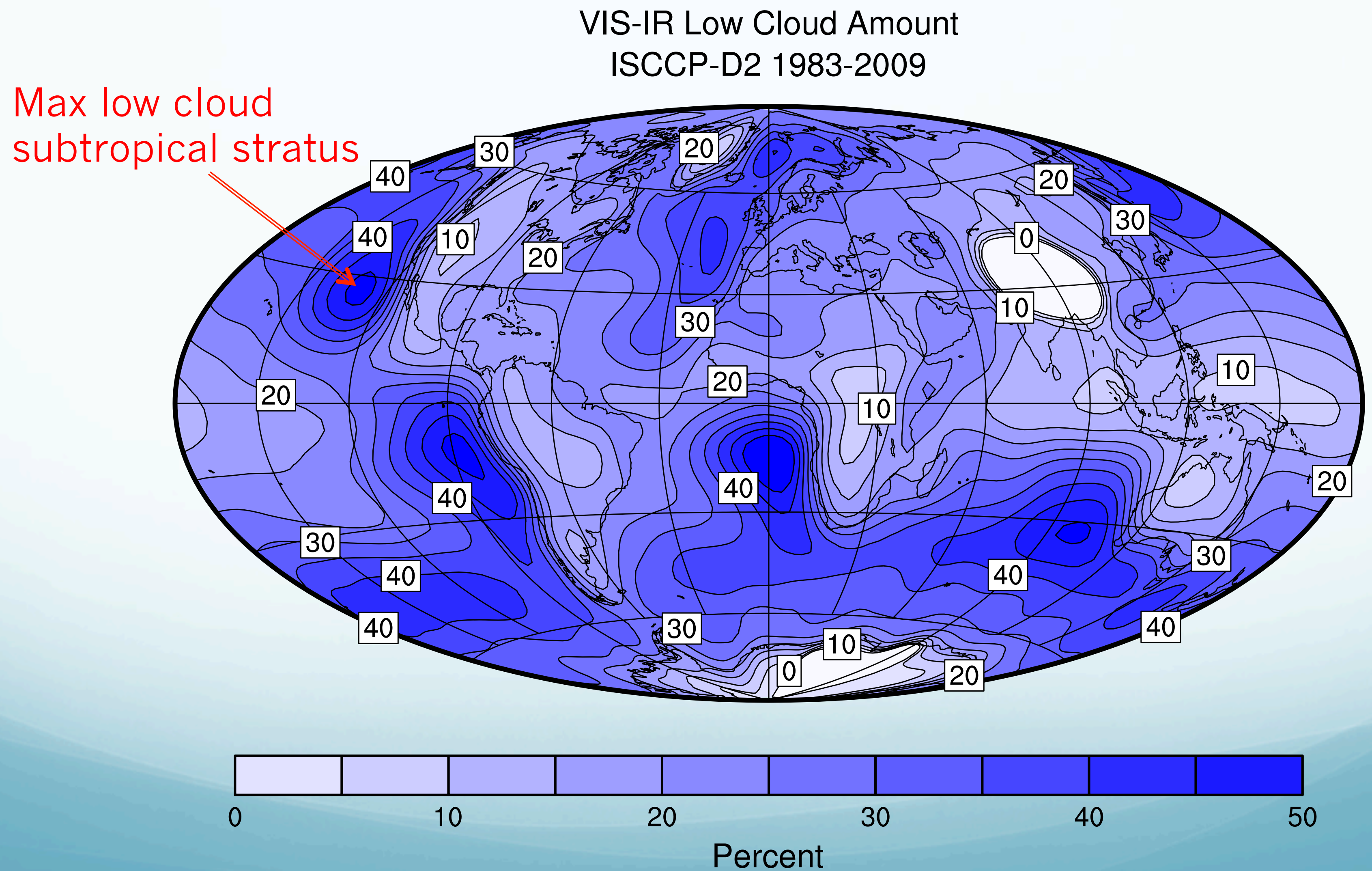
Observed Cloud Fractions

- High Clouds (p<440mb)

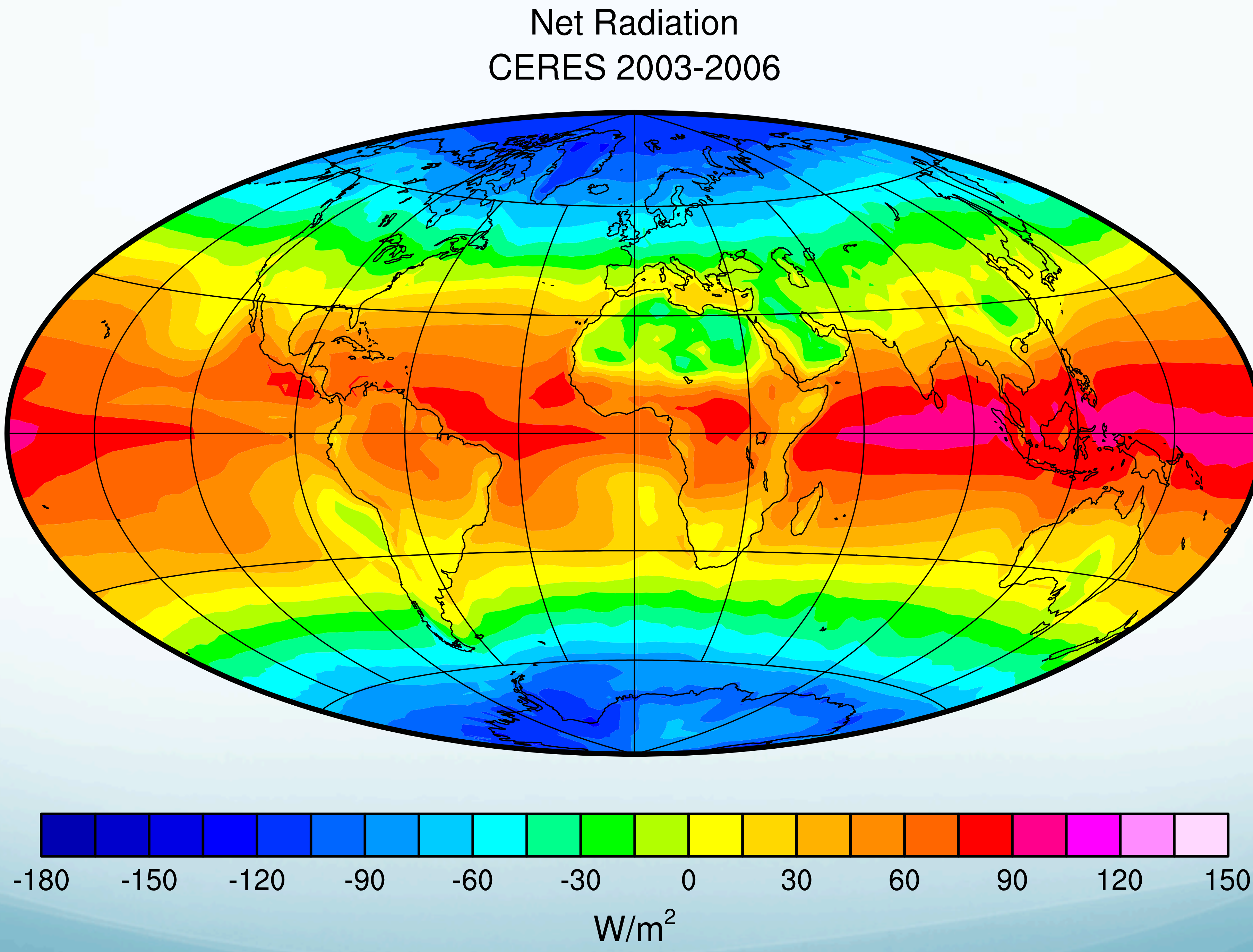


Observed Cloud Fractions

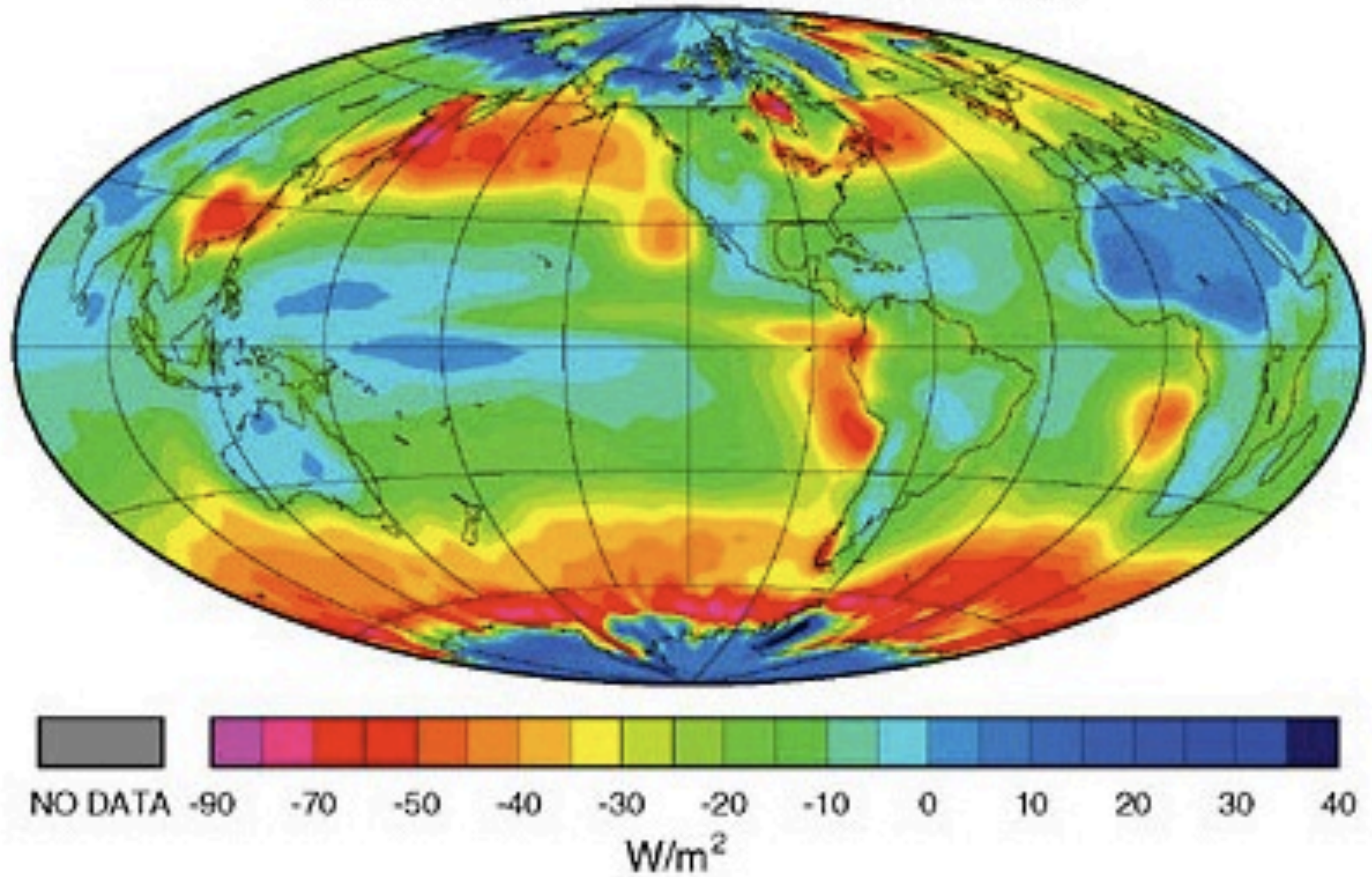
- Low Clouds (p > 680mb)



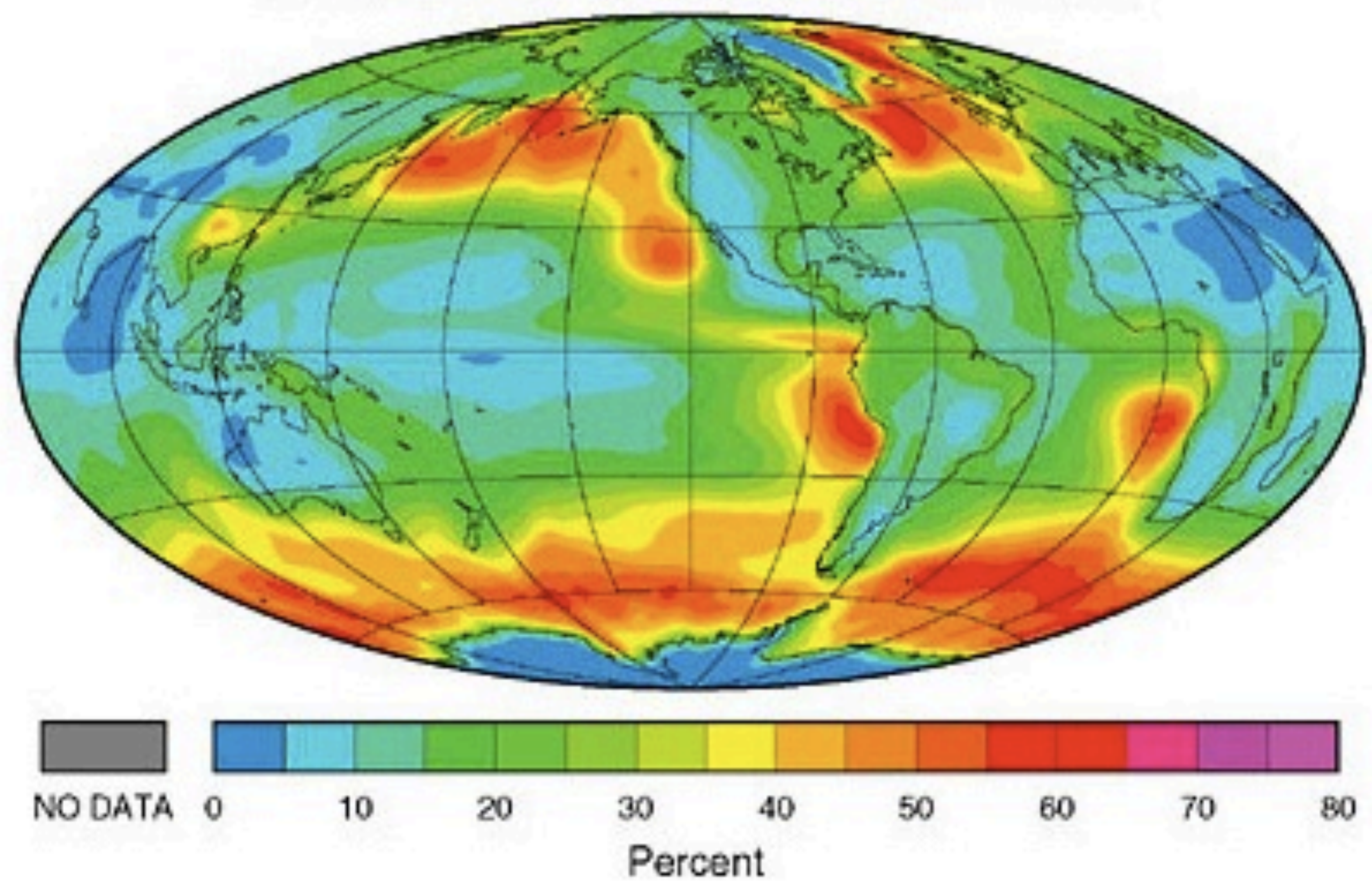
Net Radiation – Annual Mean



Annual ERBE Net Radiative Cloud Forcing

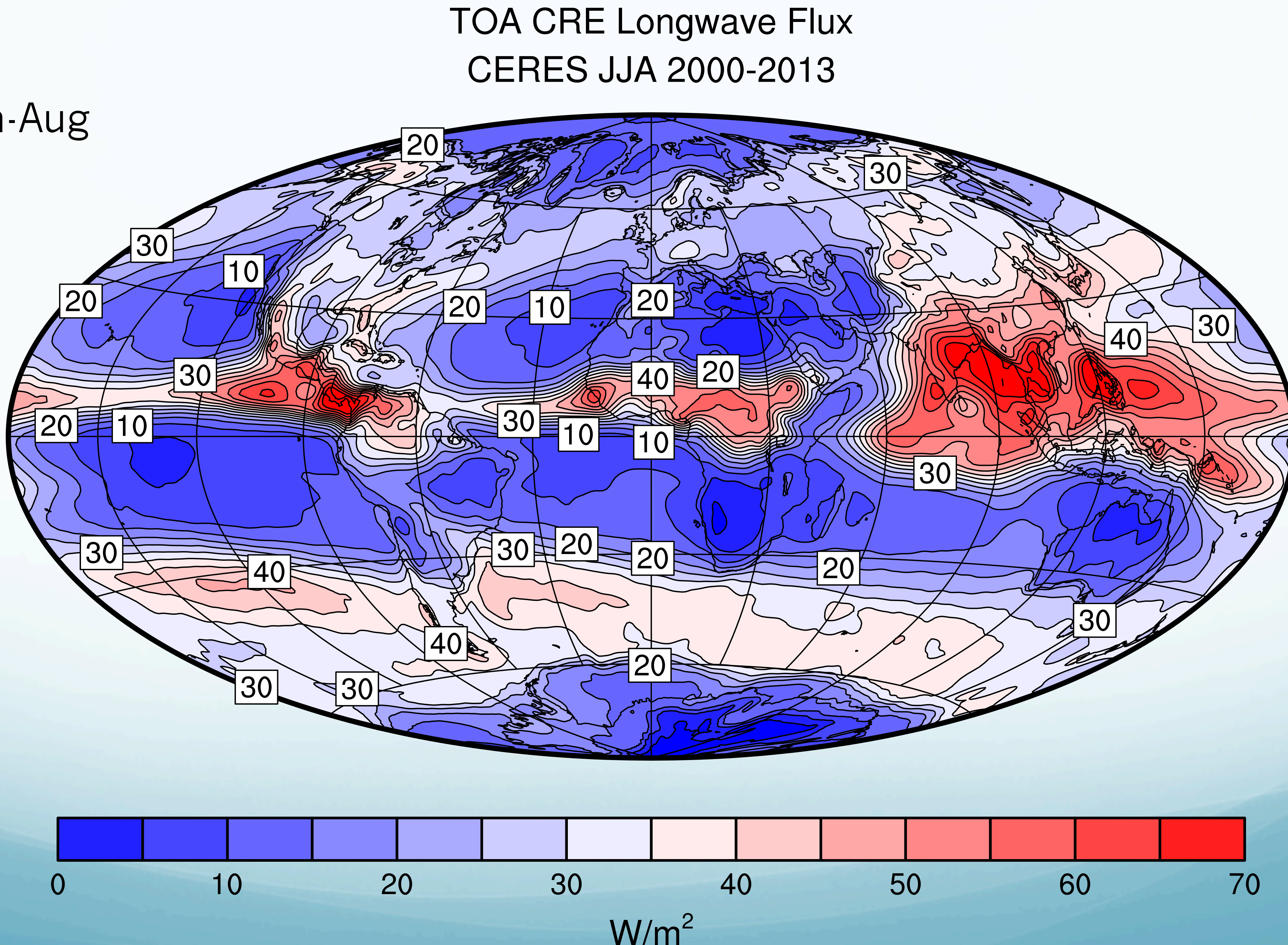


Annual ISCCP C² Inferred Stratus Cloud Amount

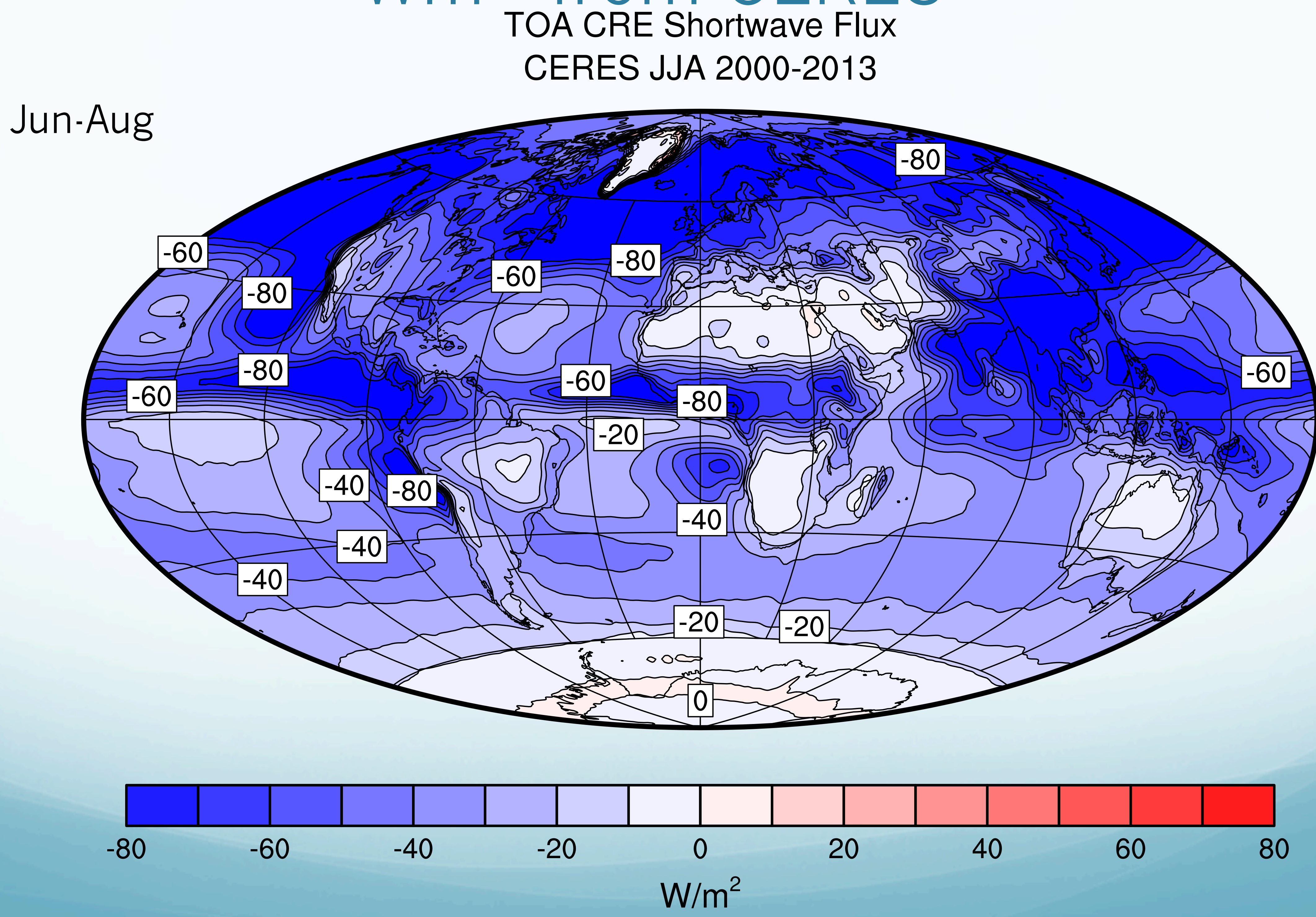


Observed Cloud Radiative Effects in Wm^{-2} from CERES

Jun-Aug



Observed Cloud Radiative Effects in Wm^{-2} from CERES



Observed Cloud Radiative Effects in Wm^{-2} from CERES

July-Aug