Global Energy and Water Budgets
Modeling the Climate System

(Check to see the process in detail)

Includes the Atmosphere, Land, Oceans, Ice, and Biosphere
EARTH'S ENERGY BUDGET

Incoming solar energy 100%

Reflected by atmosphere 6%
Reflected by clouds 20%
Reflected from earth's surface 4%

Radiated to space from clouds and atmosphere 64%
Radiated directly to space from earth 6%

Absorbed by atmosphere 16%
Absorbed by clouds 3%
Conduction and rising air 7%

Radiation absorbed by atmosphere 15%
Carried to clouds and atmosphere by latent heat in water vapor 23%

Absorbed by land and oceans 51%
As the Earth rotates on its axis, fixed points on its face, but the entire troposphere.

As the Earth's surface warms, the latent heat of condensation and the sensible heat flux from the surface to the atmosphere are quite small, as illustrated in the following exercise. The thin Martian atmosphere is constrained not to exceed the dry adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve).

The atmosphere above it and the underlying surface are heated more strongly by the absorption of ultraviolet solar radiation by ozone, which enables it to dispose of the solar energy absorbed by greenhouse gases (mainly CO$_2$) and O$_3$ while emitting longwave radiation at a lower temperature.

Increasing the emissivity of stratospheric air, thereby increasing the net heating rate (Fig. 4.29) is very close to the radiative equilibrium. Heating due to the absorption of ultraviolet solar radiation by ozone is equal to the rate of energy loss divided by the heat capacity of the atmosphere (per m$^2$).

Solutions:

- Using a pure radiative equilibrium assumption, the Earth's atmospheric tide increases the emissivity of stratospheric air, thereby enabling it to dispose of the solar energy absorbed by greenhouse gases (mainly CO$_2$) and O$_3$ while emitting longwave radiation at a lower temperature.

- Raising the concentration of atmospheric CO$_2$ by the presence of CO$_2$ while emitting longwave radiation at a lower temperature.

- Over land, the response to the alternating heating and cooling of the underlying surface produces diurnal temperature variations within the free atmosphere. During the daylight hours is lost as the point rotates through the sunlit, day hemisphere, the atmosphere above it and the underlying surface are heated more strongly by the absorption of ultraviolet solar radiation by ozone, which enables it to dispose of the solar energy absorbed by greenhouse gases (mainly CO$_2$) and O$_3$ while emitting longwave radiation at a lower temperature.

- Hence, if the Earth's atmosphere emitted radiative convective equilibrium, the net heating rate (Fig. 4.29) is very close to the dry adiabatic value.

- The Earth's atmospheric tides are quite small, as illustrated in the following exercise. The thin Martian atmosphere is constrained not to exceed the dry adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve).

- The gravitational attraction of the moon and sun also induce atmospheric tides, but these gravitational tides are much weaker than the atmospheric tides.

- The thin Martian atmosphere is constrained not to exceed the dry adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve).

- The observed lapse-rate throughout the tropics is close to the saturated adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve) and the observed global-mean tropospheric lapse rate (blue curve).

- In contrast to the troposphere, the stratosphere is cooled.

- The thin Martian atmosphere is constrained not to exceed the dry adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve).

- The observed lapse-rate throughout the tropics is close to the saturated adiabatic value (dashed black curve) and the observed global-mean tropospheric lapse rate (blue curve) and the observed global-mean tropospheric lapse rate (blue curve) and the observed global-mean tropospheric lapse rate (blue curve).
sensible and latent heat from the underlying surface, some time within the boundary layer, absorbing incoming radiation over outgoing radiation. [Adapted from Dennis L. Hartmann, Global Physical Climatology, p. 31 (Copyright 1994), with permission from Elsevier.]

The photosphere marks the transition from a lower, optically dense layer in which convection is the dominant mechanism for transferring heat outward from the nuclear furnace in the sun's core to a higher, optically thin layer in which radiative transfer is the dominant energy transfer mechanism. Like the tropopause in planetary atmospheres, the photosphere is marked by a decrease in the optical depth for outgoing longwave radiation. Below the 10-km level that defines the tropopause (Fig. 1.9) corresponds roughly to the level of unit absorptivity for outgoing longwave radiation. Annual average flux density of absorbed solar radiation as a function of latitude in Fig. 10.2.

Because the tropospheric lapse rate is determined not by the radiative-convective equilibrium as they descend much more slowly in clear air. But rather by the radiative-convective equilibrium maintained mainly by latent heat release and, to a lesser extent, by the absorption of solar radiation. The pronounced temperature minimum near the 10-km level that defines the tropopause in planetary atmospheres is a result of the dome of cold air that forms because of the sinking of cold air, also contributing to the stable lapse rate. As the air descends much more slowly in clear air. It is possible to mimic these effects in the simplest stratification. It is possible to mimic these effects in the simplest stratification. It is possible to mimic these effects in the simplest stratification. It is possible to mimic these effects in the simplest stratification.
Illustration of Cumulus Processes

- **updraft**
- **downdraft**
- **entrainment**
- **detrainment**
- **compensating subsidence**

boundary layer
Input
Temperature, Humidity

$Z_r$ (Buoyancy free level)

Detrainment (Only cloud top)

Change of environmental field by detrainment

Subsidence heating

Entrainment

Cloud mass flux

Precipitation calculated

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

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.)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Cloud-Free</th>
<th>Cloud Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLR</td>
<td>240</td>
<td>266</td>
<td>+26</td>
</tr>
<tr>
<td>Absorbed Solar Radiation</td>
<td>240</td>
<td>288</td>
<td>−47</td>
</tr>
<tr>
<td>Net Radiation</td>
<td>+0.56</td>
<td>+22</td>
<td>−21</td>
</tr>
<tr>
<td>Albedo</td>
<td>29%</td>
<td>15%</td>
<td>+14%</td>
</tr>
</tbody>
</table>
$S_0$: solar constant (incoming solar flux, 1367 W m$^{-2}$).

$\alpha_p$: 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

\[ R_{\text{TOA}} = \frac{S_0}{4} (1 - \alpha_p) - F^\uparrow(\infty) \]

\[ \Delta R_{\text{TOA}} = R_{\text{cloudy}} - R_{\text{clear}} = \Delta Q_{\text{abs}} - \Delta F^\uparrow(\infty) \]

- Cloud Radiative Effect – Add Clouds, what changes?

\[ \Delta Q_{\text{abs}} = \frac{S_0}{4} (1 - \alpha_{\text{cloudy}}) - \frac{S_0}{4} (1 - \alpha_{\text{clear}}) \]

\[ = \frac{S_0}{4} (\alpha_{\text{cloudy}} - \alpha_{\text{clear}}) = -\frac{S_0}{4} \Delta \alpha_p \]
Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

• Cloud Radiative Effect – Add Clouds, what changes?

\[ \Delta R_{\text{TOA}} = R_{\text{cloudy}} - R_{\text{clear}} = \Delta Q_{\text{abs}} - \Delta F^{\uparrow}(\infty) \]

• Shortwave bit

\[ \Delta Q_{\text{abs}} = \frac{S_0}{4} (1 - \alpha_{\text{cloudy}}) - \frac{S_0}{4} (1 - \alpha_{\text{clear}}) = \frac{S_0}{4} (\alpha_{\text{cloudy}} - \alpha_{\text{clear}}) = -\frac{S_0}{4} \Delta \alpha_p \]

• Longwave bit

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

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

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

\[ \mathcal{T}\{z_{\text{ct}},\infty\} \approx 1.0 \]

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

\[ \Delta F^\uparrow(\infty) = \sigma T_{z_{\text{ct}}}^4 - F^\uparrow_{\text{clear}}(\infty) \]
Heuristic Model of Cloud Radiative Effect (CRE) a.k.a. Cloud Forcing

• Putting the pieces together,

\[ \Delta R_{\text{TOA}} = R_{\text{cloudy}} - R_{\text{clear}} = \Delta Q_{\text{abs}} - \Delta F^\uparrow(\infty) \]

• becomes

\[ \Delta R_{\text{TOA}} = -\frac{S_0}{4} \Delta \alpha_p + F_{\text{clear}}^\uparrow(\infty) - \sigma T_{z_{\text{ct}}}^4 \]

• 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.

\[ T_{z_{\text{ct}}} = \left\{ \frac{-(S_0 / 4) \Delta \alpha_p + F_{\text{clear}}^\uparrow(\infty)}{\sigma} \right\}^{1/4} \]
Figure 2.5. ISCCP Radiometric cloud classification.

ISCCP CLOUD CLASSIFICATION

CLOUD TOP PRESSURE (MB)

CLOUD OPTICAL THICKNESS

HIGH

MIDDLE

LOW

CIRRUS
CIRROSTRATUS
DEEP CONVECTION

ALTOCUMULUS
ALTOSTRATUS
NIMBOSTRATUS

CUMULUS
STRATOCUMULUS
STRATUS

0 1.3 3.6 9.4 23 60 379
Cloud Radiative Forcing

\[ A_i = \text{cloud amount for cloud type } i \]
\[ A = \text{total cloud amount} \]
\[ A = A_i \cdot I \]

\[ \text{OvcCRF}_i = \text{ovc CRF for cloud type } i \]
\[ \text{CRF}_i = \text{avg CRF for cloud type } i \]
\[ \text{CRF} = \text{total avg CRF} \]

\[ \text{CRF}_i = A_i \cdot \text{OvcCRF}_i \]
\[ \text{CRF} = A_i \cdot \text{CRF}_i = \text{OvcCRF}_i \cdot I \]
A\_i \ast \text{ISCCP Cloud Fraction in West Pacific, } \% \\

<table>
<thead>
<tr>
<th>Pressure, mb</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Depth</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0.4</td>
<td>1.6</td>
<td>1.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.1</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>1.4</td>
<td>1.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>0.4</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.9</td>
<td>6.4</td>
<td>2.3</td>
<td>1.0</td>
<td>0.4</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.2</td>
<td>1.4</td>
<td>1.2</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>1.4</td>
<td>1.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>8.5</td>
<td>5.0</td>
<td>4.2</td>
<td>3.4</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>8.5</td>
<td>5.0</td>
<td>4.2</td>
<td>3.4</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>14.9</td>
<td>5.1</td>
<td>0.9</td>
<td>0.8</td>
<td>1.8</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

= CRF\_i

\text{from Hartmann, Moy, and Fu 2001}
There is good agreement between modeled radiative fluxes (using observed cloud type frequencies) and observed (ERBE) radiative fluxes.

from Hartmann, Moy, and Fu 2001
Observed Cloud Fractions

- High Clouds ($p<440\text{mb}$)

![Map showing the distribution of high cloud amounts with a maximum in tropical rain areas.](image-url)
Observed Cloud Fractions

- Low Clouds (p > 680mb)

VIS-IR Low Cloud Amount
ISCCP-D2 1983-2009

Max low cloud subtropical stratus
Net Radiation – Annual Mean

Net Radiation
CERES 2003-2006

W/m²
Observed Cloud Radiative Effects in Wm$^{-2}$ from CERES

TOA CRE Longwave Flux
CERES JJA 2000-2013

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

TOA CRE Shortwave Flux
CERES JJA 2000-2013

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

TOA CRE Net Flux
CERES JJA 2000-2013

July-Aug