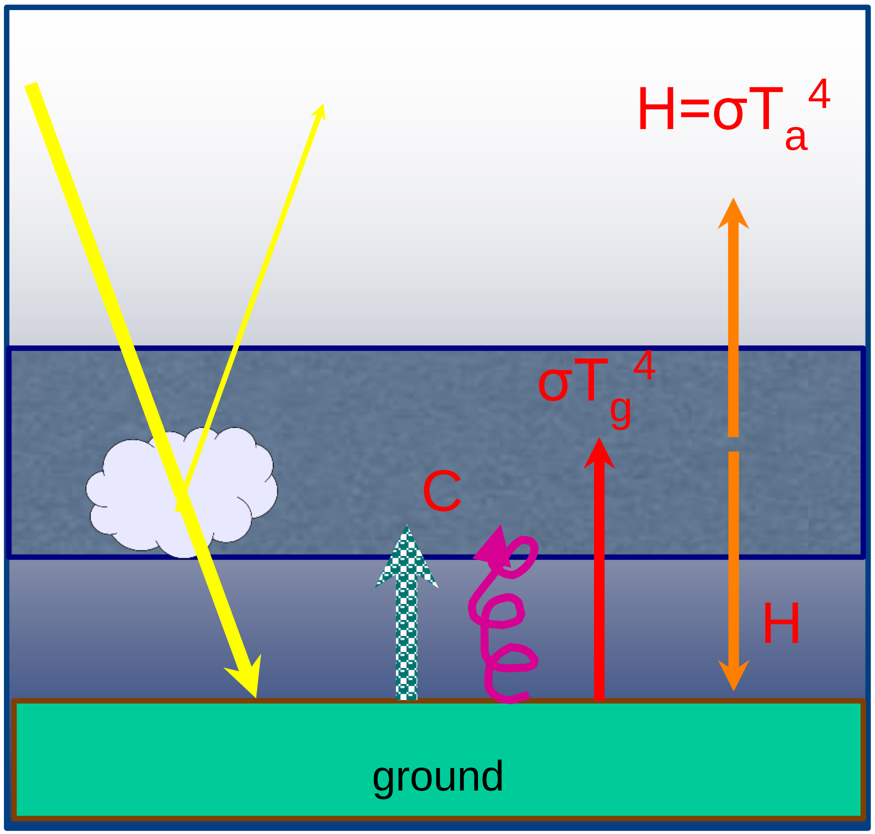
Since radiation makes the surface hotter than the air just above it, the surface looses heat not only through radiation, but also through latent and sensible heat transports (both upwards and polewards).



A few assumptions:

1) A linear temperature dependence: $C=aT_g+b$

$$\sigma T_g^4 + aT_g + b = H + \sigma T_a^4$$

2) A bulk flux formulation- $C=a(T_a-T_g)$

3) Radiative-convective adjustment: set $(Tg-Ta)/z=\Gamma$ when unstable

This yields colder T_g than with pure radiative surface cooling

Radiative convective equilibrium…
Manabe and Strickler, 1964

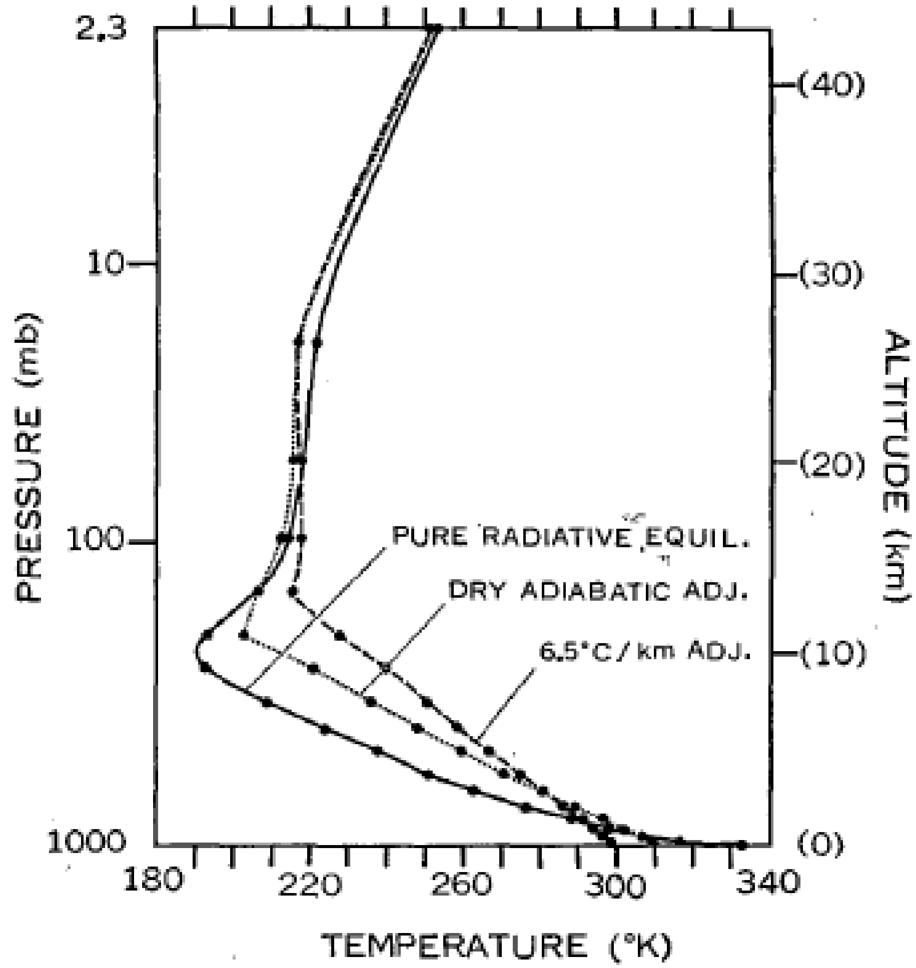


FIG. 4. The dashed, dotted, and solid lines show the thermal equilibrium with a critical lapse rate of 6.5 deg km^{-1}, a dry-adiabatic critical lapse rate (10 deg km^{-1}), and pure radiative equilibrium.

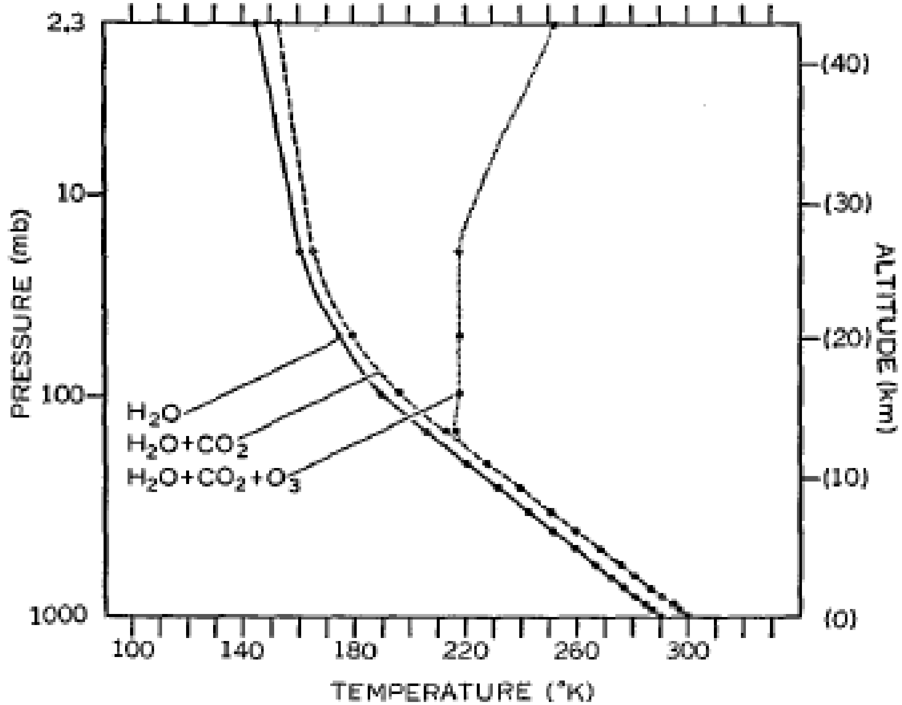
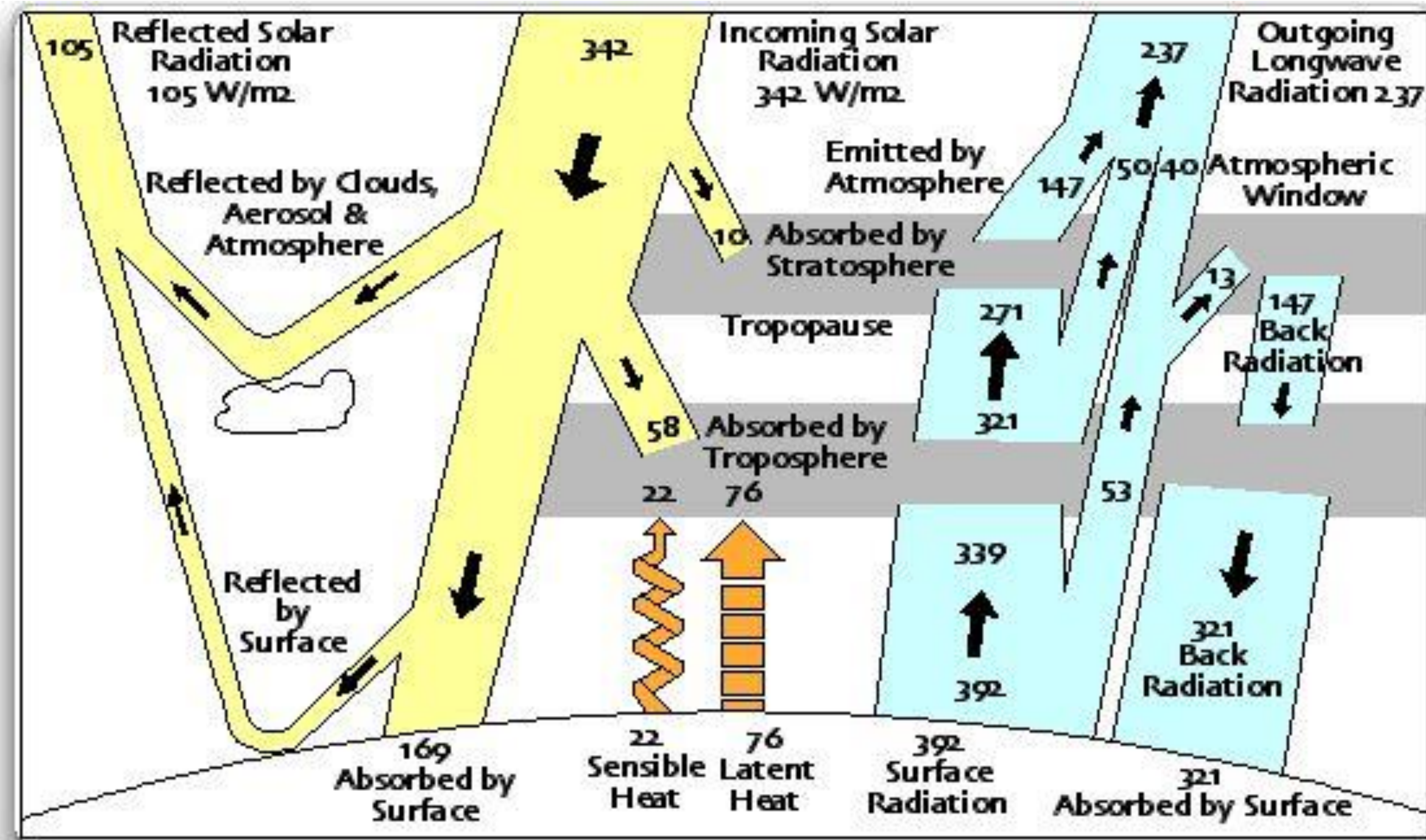
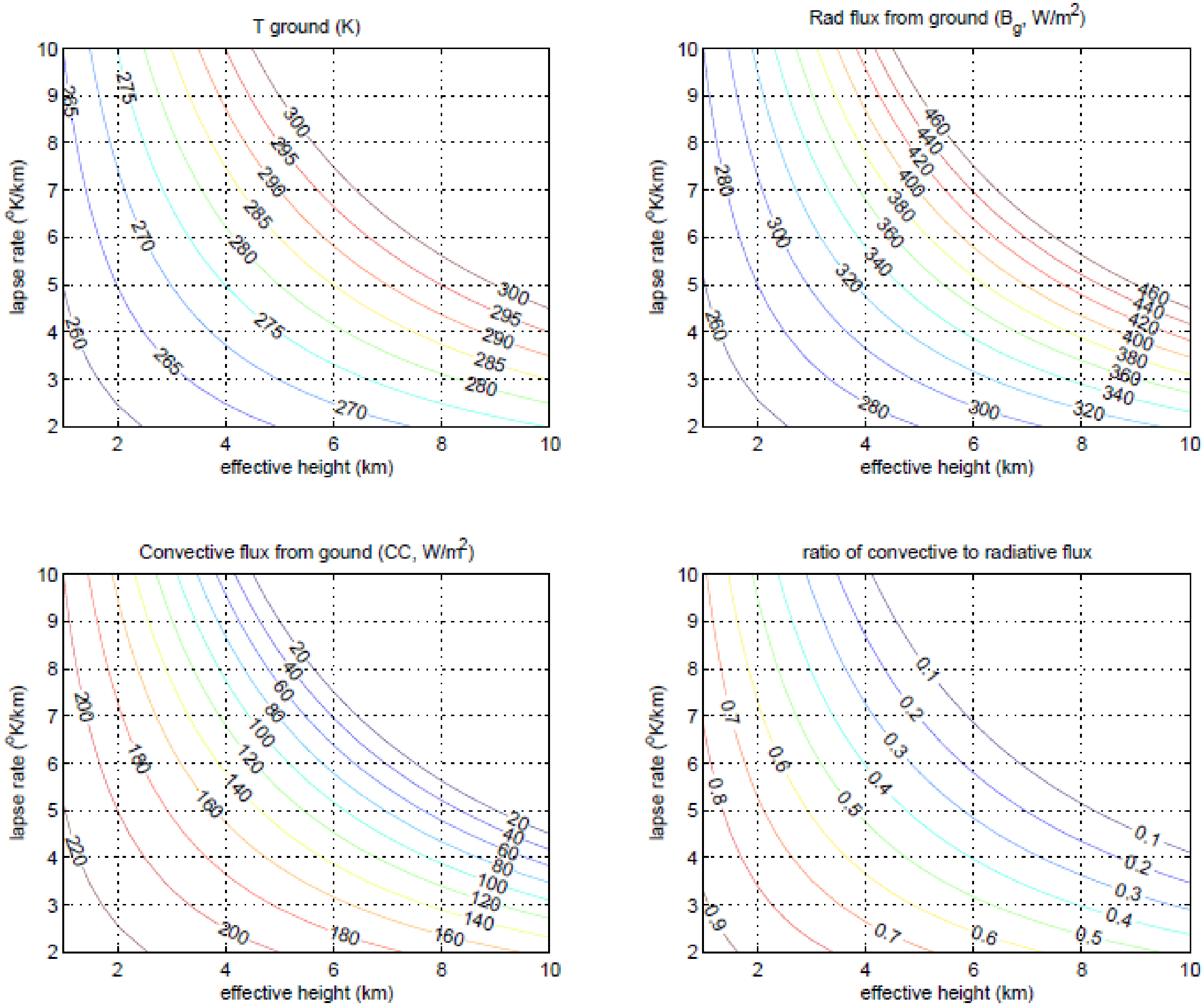


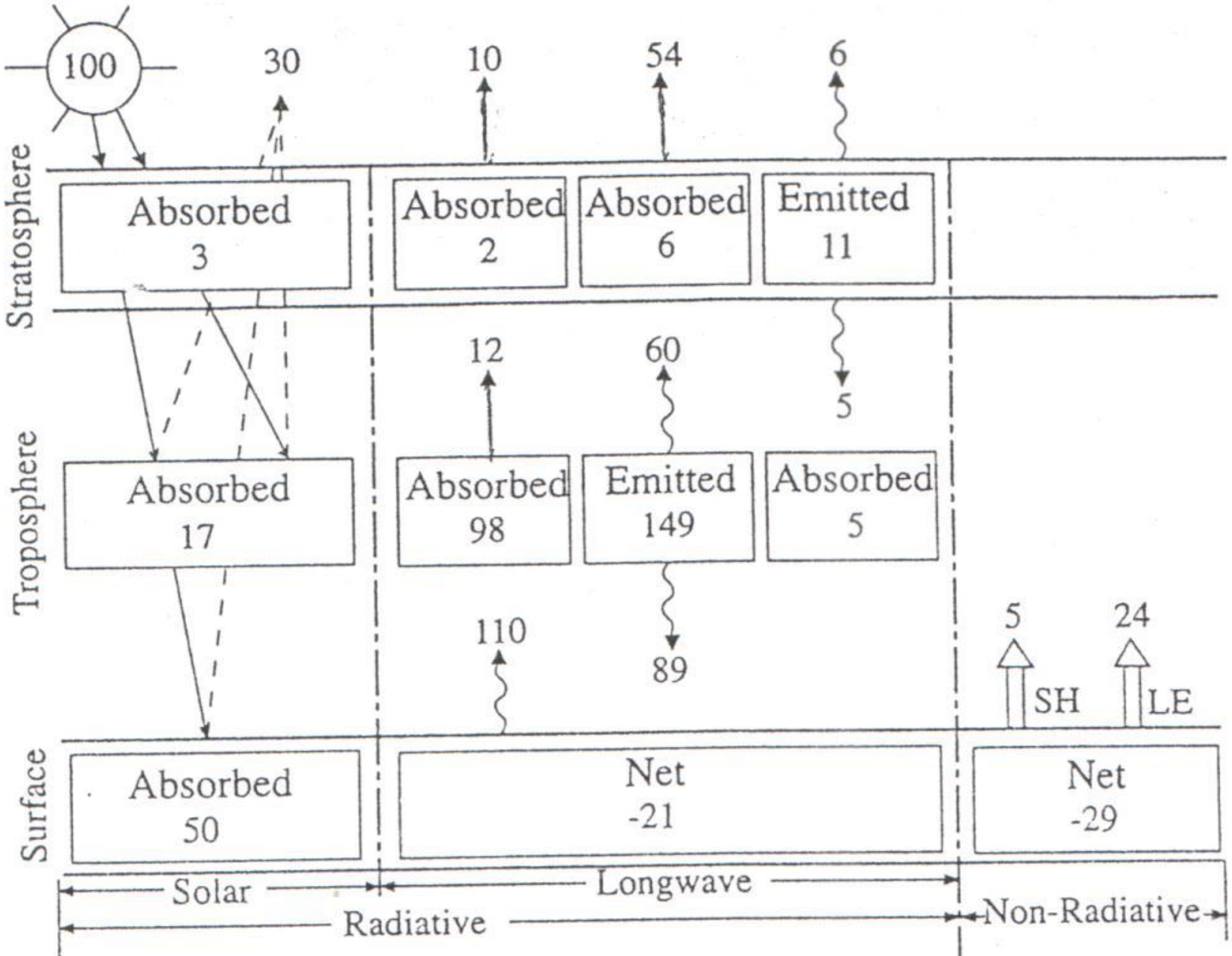
FIG. 6c. Thermal equilibrium of various atmospheres which have a critical lapse rate of 6.5 deg km^{-1}. Vertical distributions of gaseous absorbers at 35N, April, were used. $S_c=2$ ly min^{-1}, $\cos\bar{\zeta}=0.5$, $r=0.5$, no clouds.



Overall, we get a surface temperature of $T_g=(390/\sigma)^{1/4}=288°K=15^\circ C$



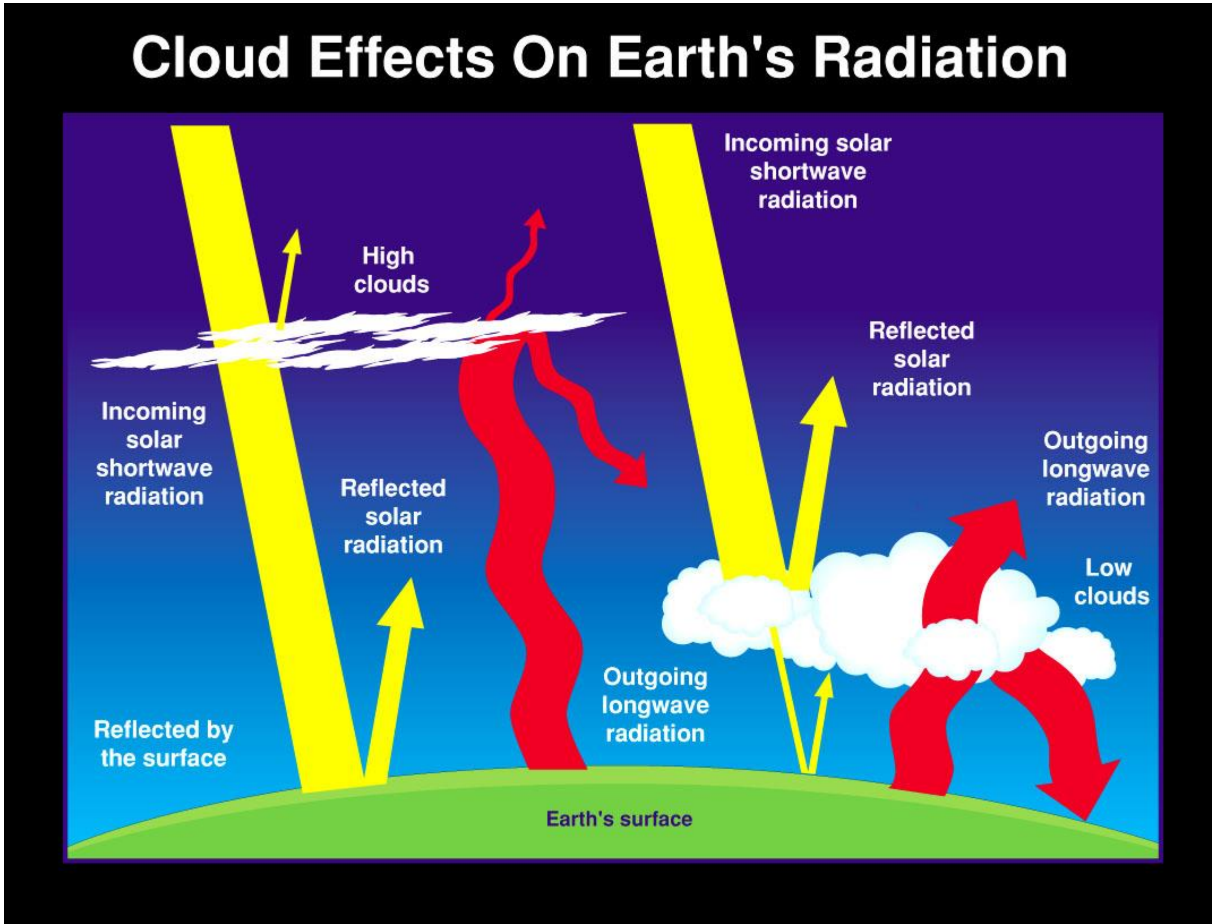
Surface temperature decreases, the larger C is. C is largest for lowest emission heights- makes sense since in this model T1 and Tg are fixed, so lapse rate larger, the smaller the emission height.


100
30
10
54
6
Stratosphere
Absorbed 3
Absorbed 2
Absorbed 6
Emitted 11
12
60
5
Troposphere
Absorbed 17
Absorbed 98
Emitted 149
Absorbed 5
110
89
5
24
SH
LE
Surface
Absorbed 50
Net -21
Net -29
Solar
Longwave
Radiative
Non-Radiative

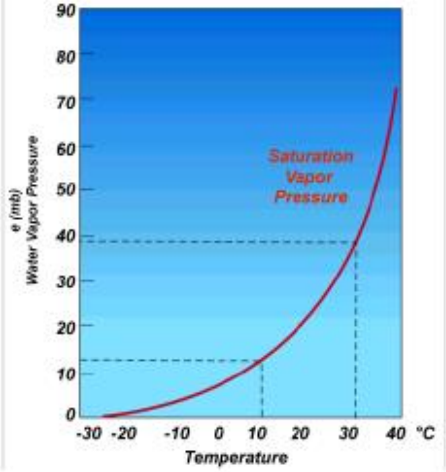
Clouds complicate the picture:

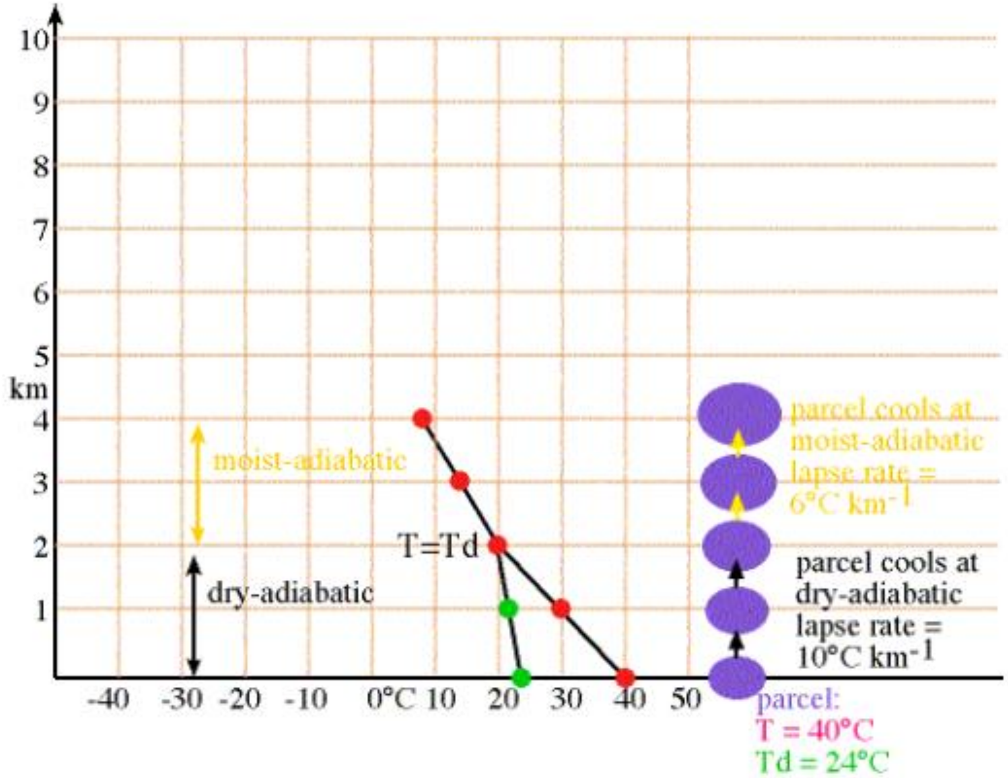
Clouds affect short wave by reflecting it, and long wave by absorbing it. These are opposing effects on surface energy budget.

Different cloud types – high, middle and low. Thick and thin. Each has a different net effect.



$e_s = 6.11\exp(0.0067T)$ hPa (T in degrees C)

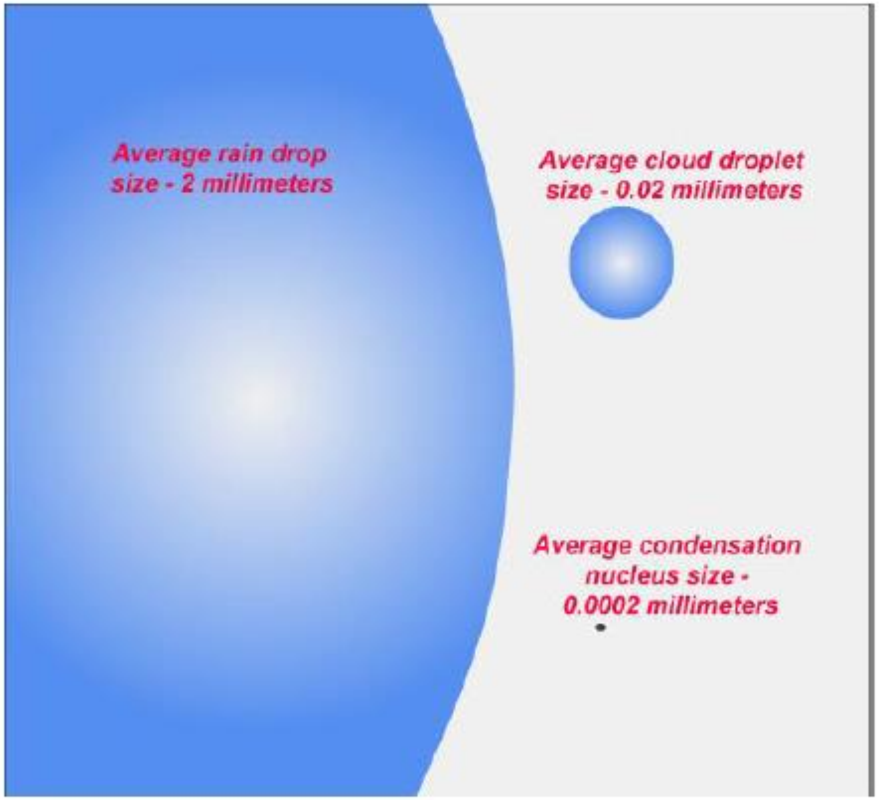




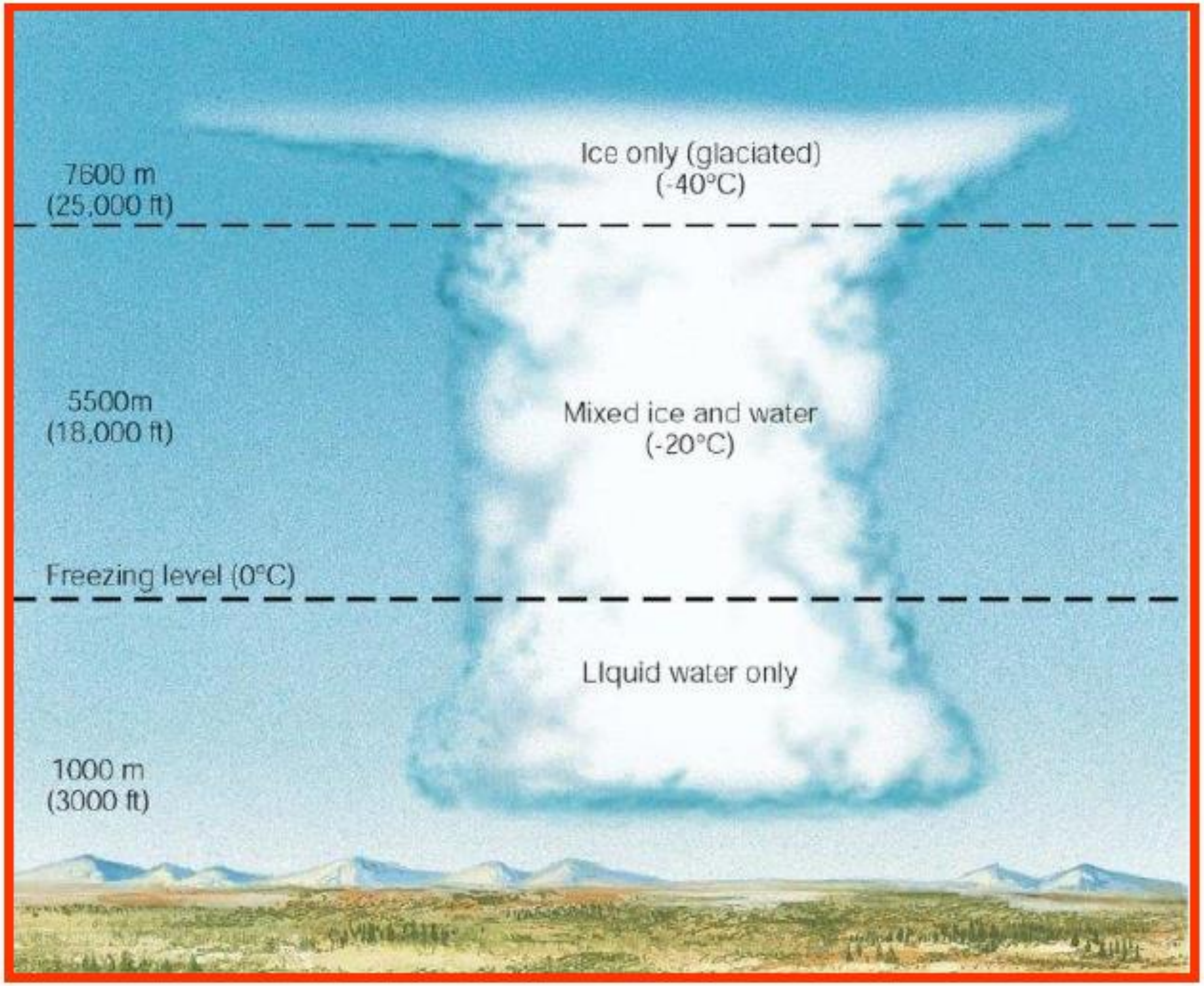
Typical sizes of cloud droplets

- Formation of droplets depends on availability of Cloud Condensation Nuclei (CCN)

- Pure water will condensate at relative humidity of about 1000%
- Ice crystals will form at temperature of -40C.



Water and ice in a cloud



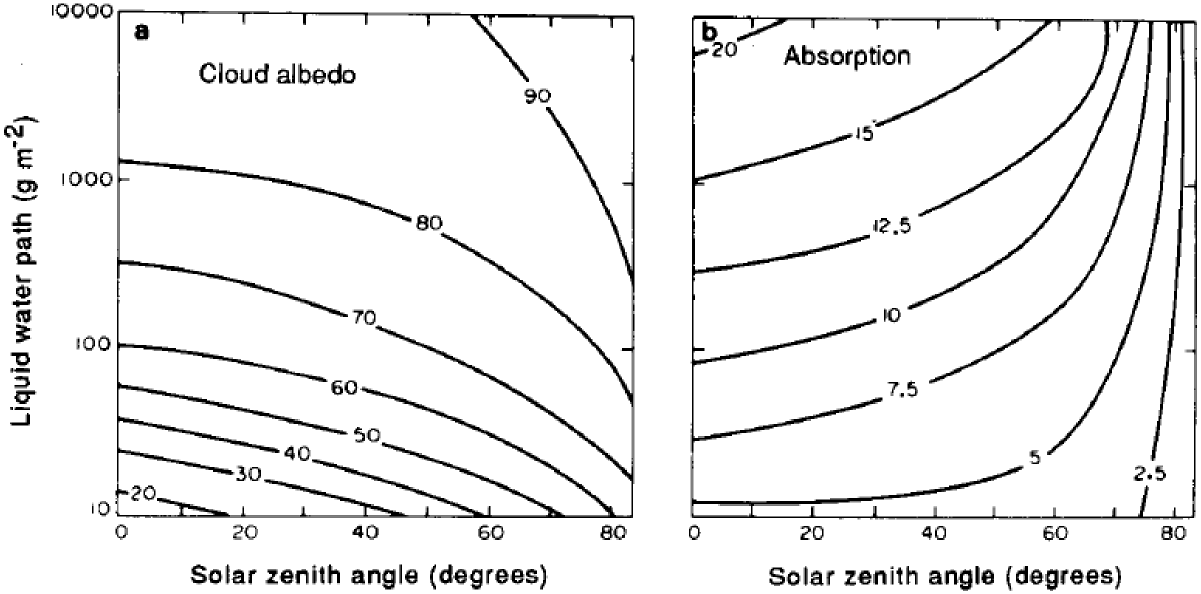


Fig. 3.13 The dependence of (a) cloud albedo and (b) cloud absorption on cloud liquid water path and solar zenith angle. Values are given in percent. [From Stephens (1978). Reprinted with permission from the American Meteorological Society.]

Effects of clouds on solar radiation – for idealized plane-parallel clouds: depends on solar zenith angle, liquid water content, and droplet size distribution.
LWC- effect saturates at high LWC, esp. at high SZA. More small drops reflects more.

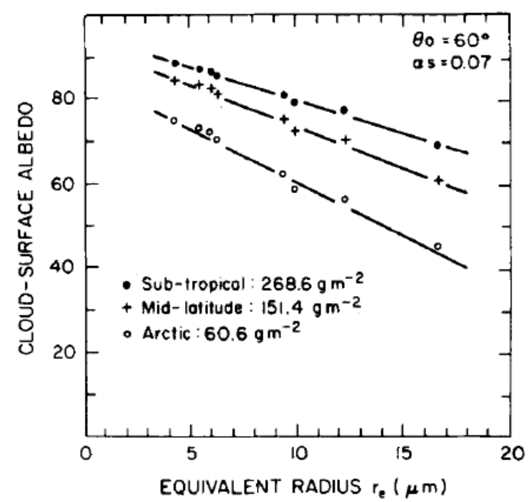


Fig. 3.14 The dependence of planetary albedo on the size of cloud droplets. [From Slingo and Schrecker (1982). Reprinted with permission from the Royal Meteorological Society.]

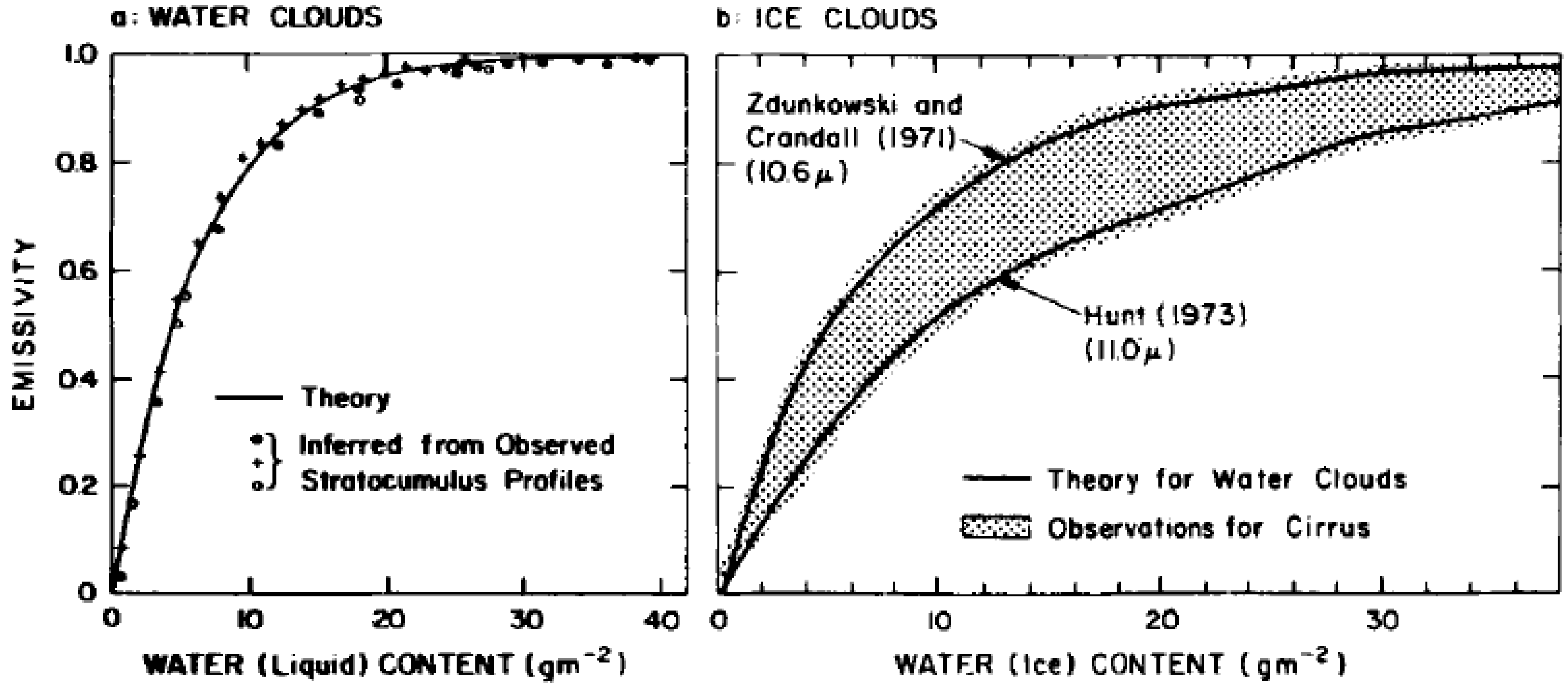


Fig. 3.15 The dependence of the longwave emissivity on (a) liquid water content [from Slingo *et al.* (1982); reprinted with permission from the Royal Meteorological Society] and (b) ice content [from Griffith *et al.* (1980); reprinted with permission from the American Meteorological Society].

Effects of clouds on long wave radiation – depends on liquid water content – for quite small values fully absorbing and can be treated as black body

Saturation with LWC for LW occurs much before it occurs for SW

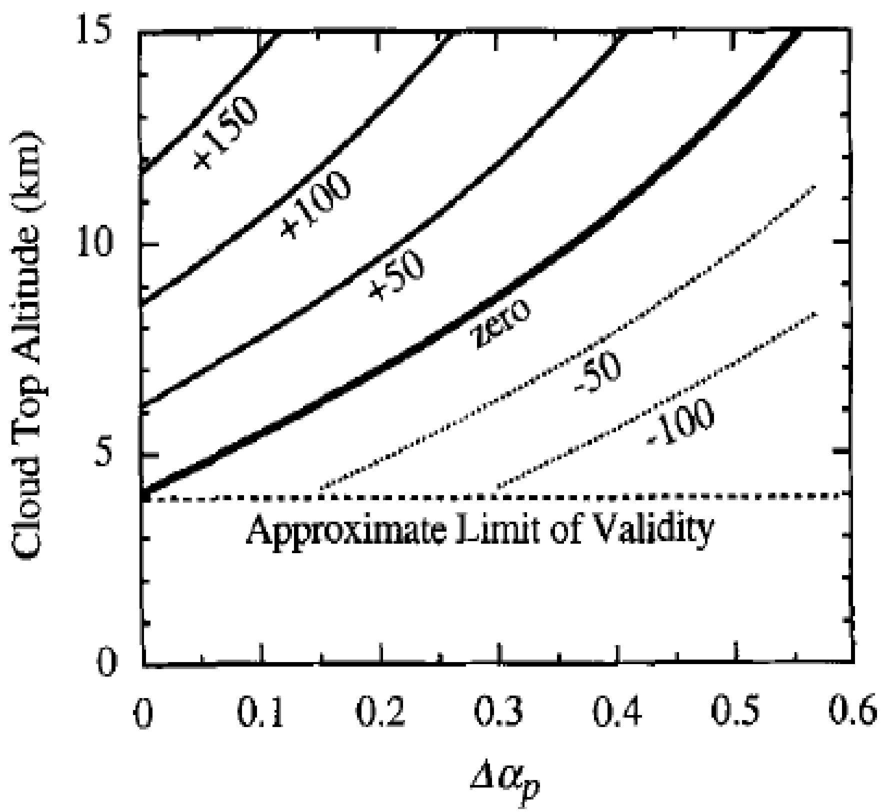


Fig. 3.20 Contours of change in net radiation at the top of the atmosphere caused by the insertion of a cloud into a clear atmosphere, plotted against cloud top altitude and the planetary albedo contrast between cloudy and clear conditions. The net radiation changes are calculated with the approximate model described in Section 3.8 that is invalid for clouds with tops lower than about 4 km. Contours from -100 to $+150$ W m^{-2} are shown at an interval of 50 W m^{-2}. The zero contour where the cloud has no net effect on the radiation budget at the top of the atmosphere is bold and negative contours are dashed.

Table 3.2

Values of Cloud Shortwave Reflectivity and Absorptivity and Fractional Area Coverage Assumed in Manabe and Strickler (1964)

Type	SW reflectivity	SW absorptivity	% of area
High (cirrus)	0.21	0.005	0.228
Medium (cumulus)	0.48	0.020	0.090
Low (stratus)	0.69	0.035	0.313

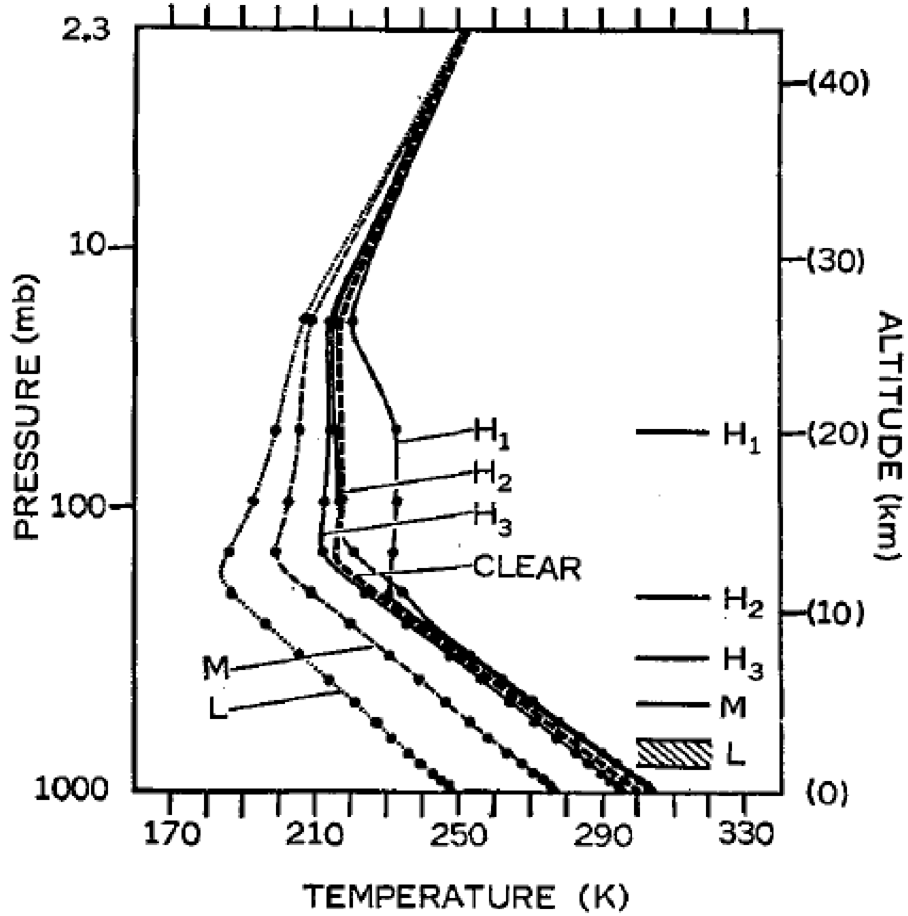


Fig. 3.19 Thermal equilibrium temperature profiles for atmospheres with various cloud distributions. The cloud heights corresponding to each type of cloud are shown on the right (L = low, M = medium, and H = high cloud). The heavy dashed line shows the equilibrium profile for clear skies. [From Manabe and Strickler (1964). Reprinted with permission from the American Meteorological Society.]

Table 3.3

Cloud Radiative Forcing as Estimated from Satellite Measurements

	Average	Cloud-free	Cloud forcing
OLR	234	266	+31
Absorbed solar radiation	239	288	−48
Net radiation	+5	+22	−17
Albedo	30%	15%	+15%

Radiative flux densities are given in W m^{-2} and albedo in percent. [From Harrison *et al.* (1990), © American Geophysical Union.]

Observed cloud fractions

High Clouds (p<440mb) | Low Clouds (p > 680mb)

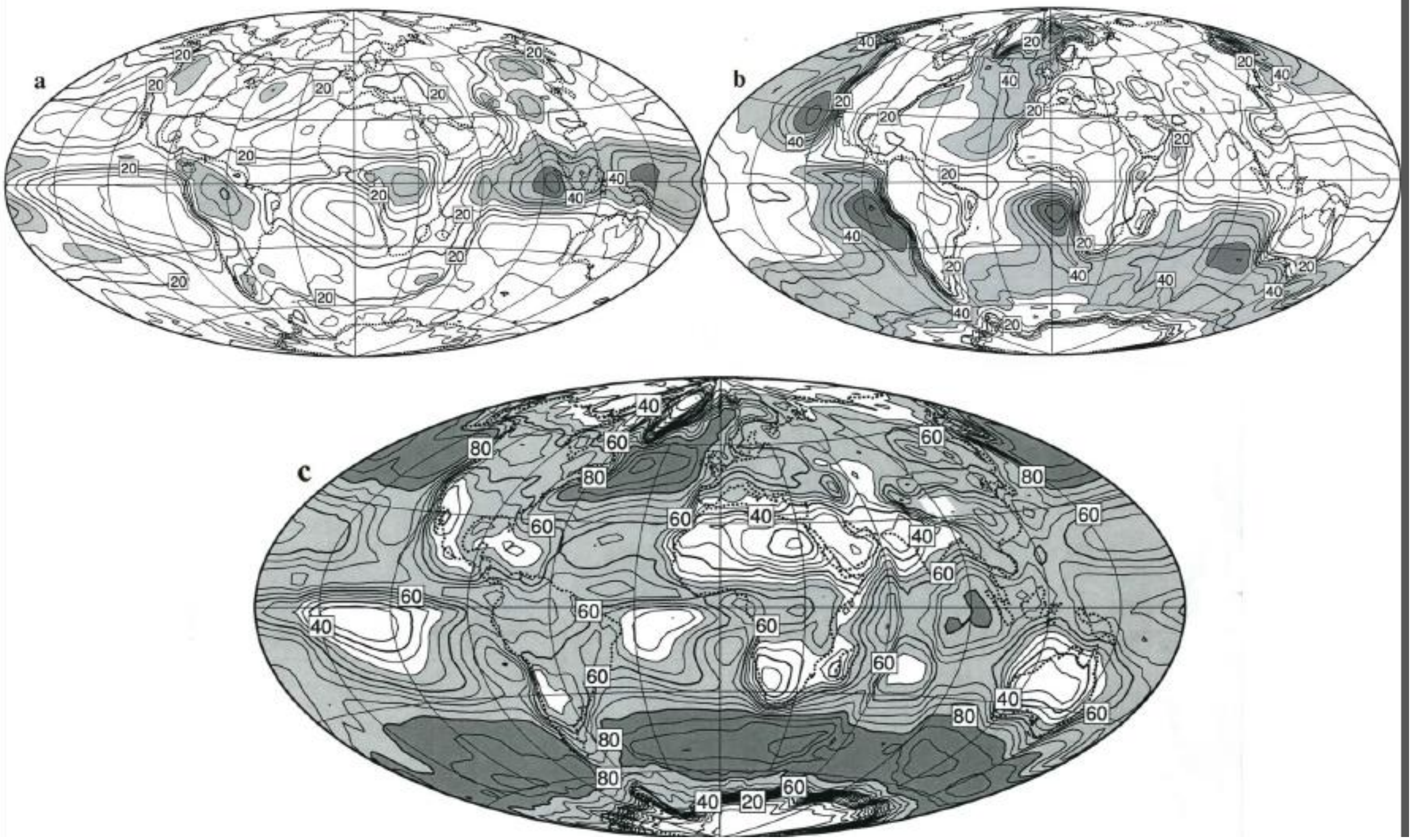
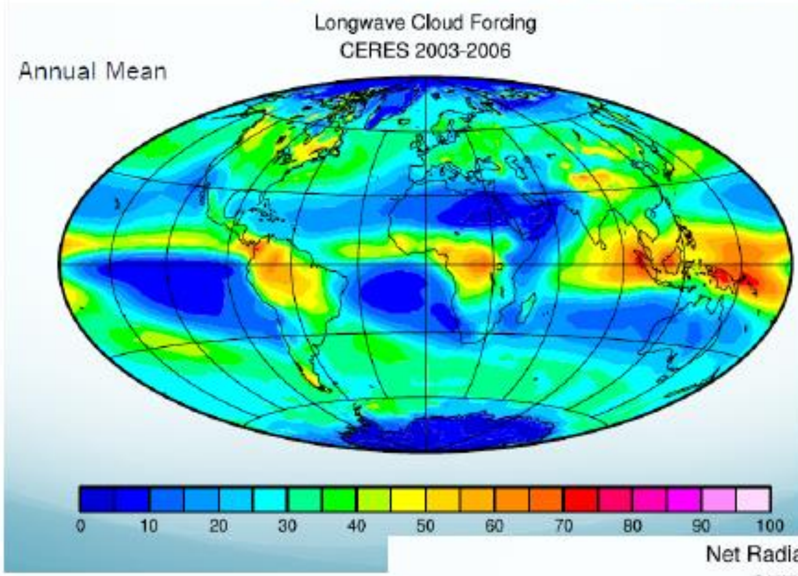
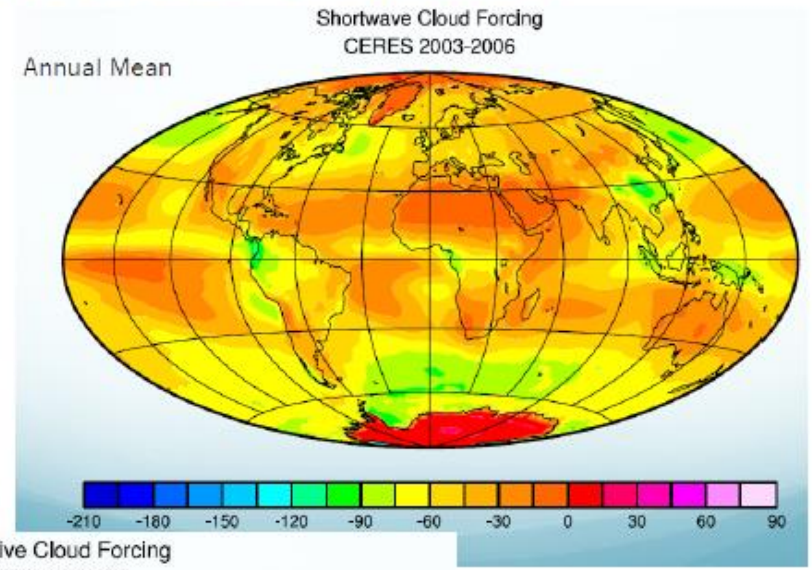
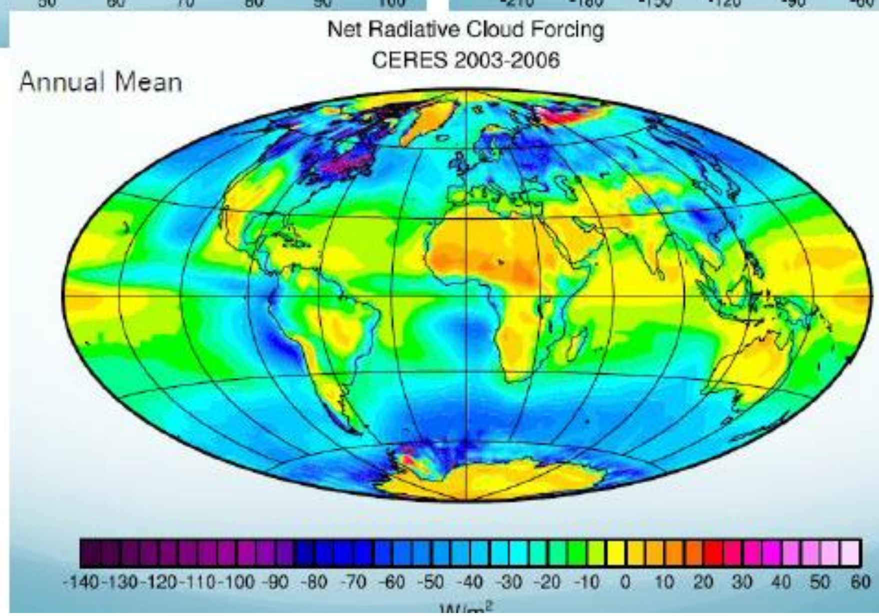


Fig. 3.21 Annual average cloud fractional area coverage in percent estimated from satellite data under the International Satellite Cloud Climatology Project [ISCCP, Rossow and Schiffer (1991)]. (a) Clouds with tops higher than 440 mb, (b) clouds with tops lower than 680 mb, and (c) all clouds. In (a) and (b) the contour interval is 5%, with values greater than 30% lightly shaded, and greater than 50% heavily shaded. In (c) the contour interval is also 5%, but light shading is applied for values greater than 50% and heavy shading for values greater than 80%.

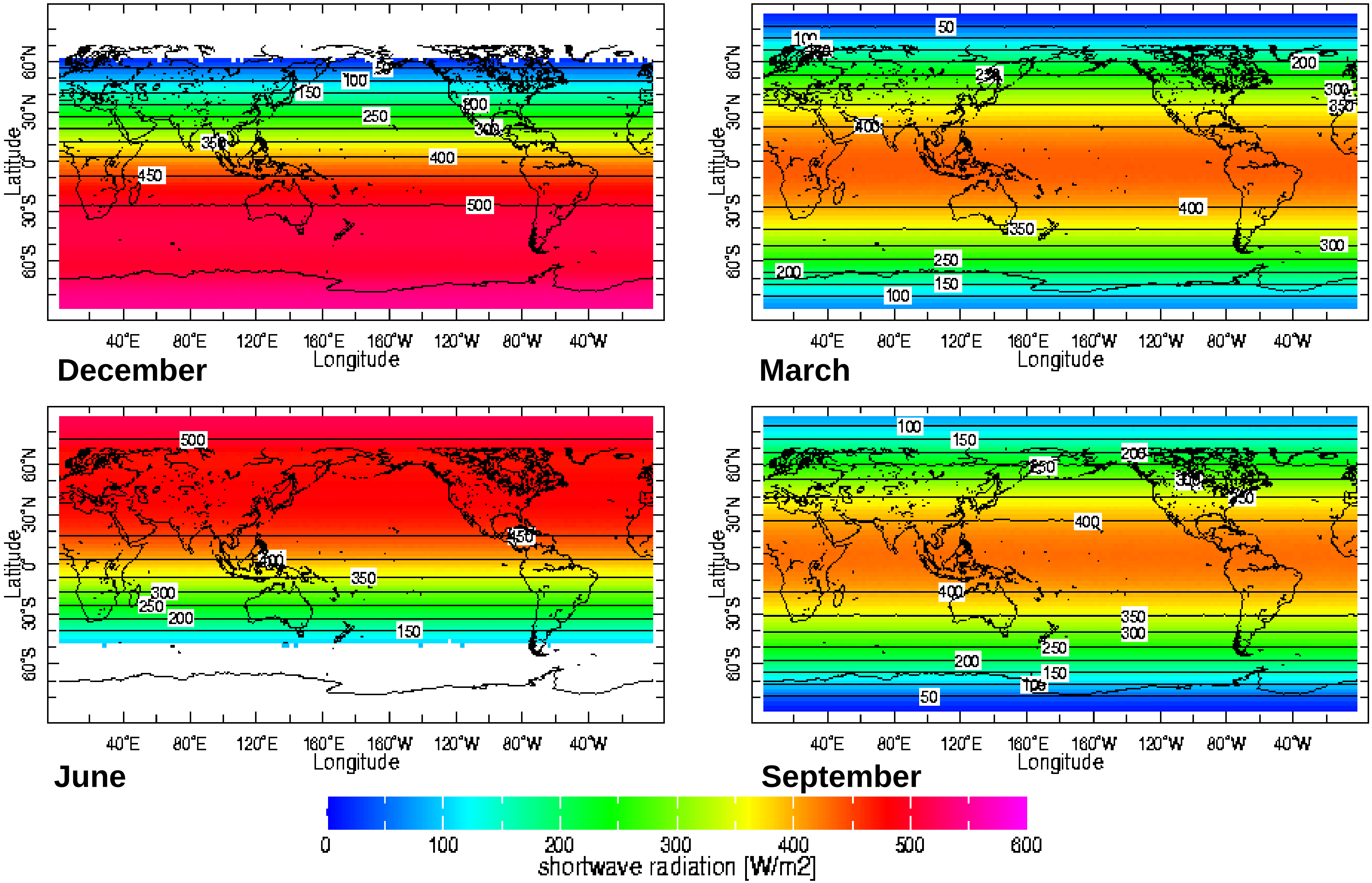
Observed cloud effect on radiation





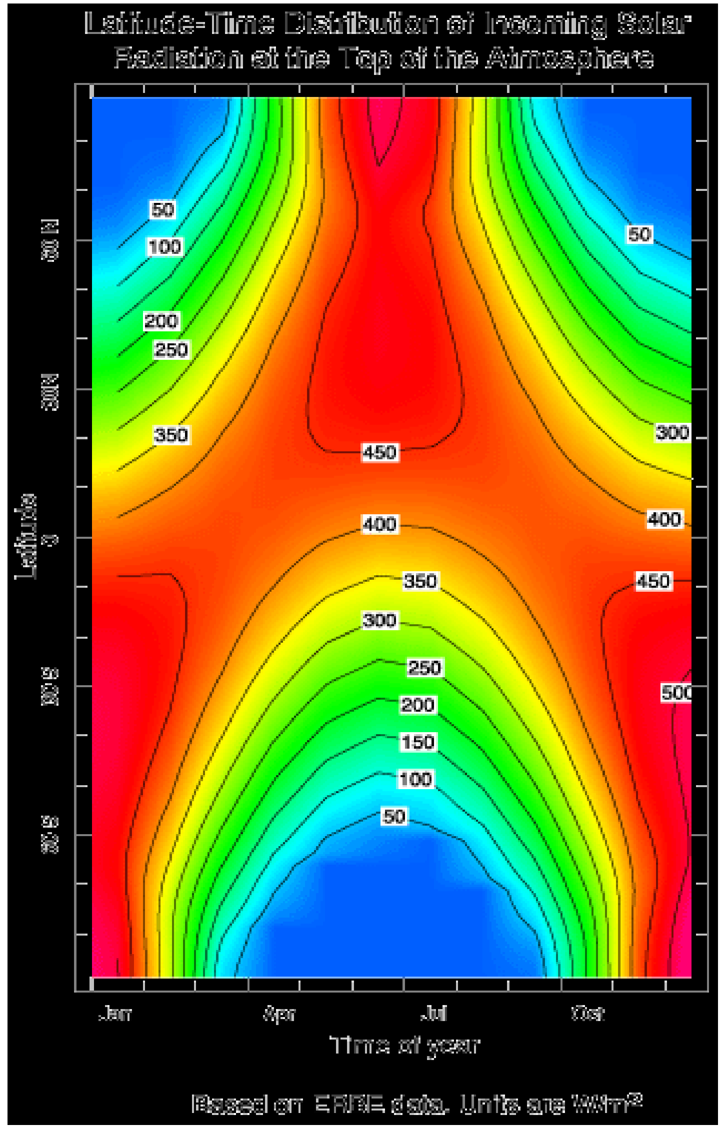


Incoming Solar (Shortwave) at TOA



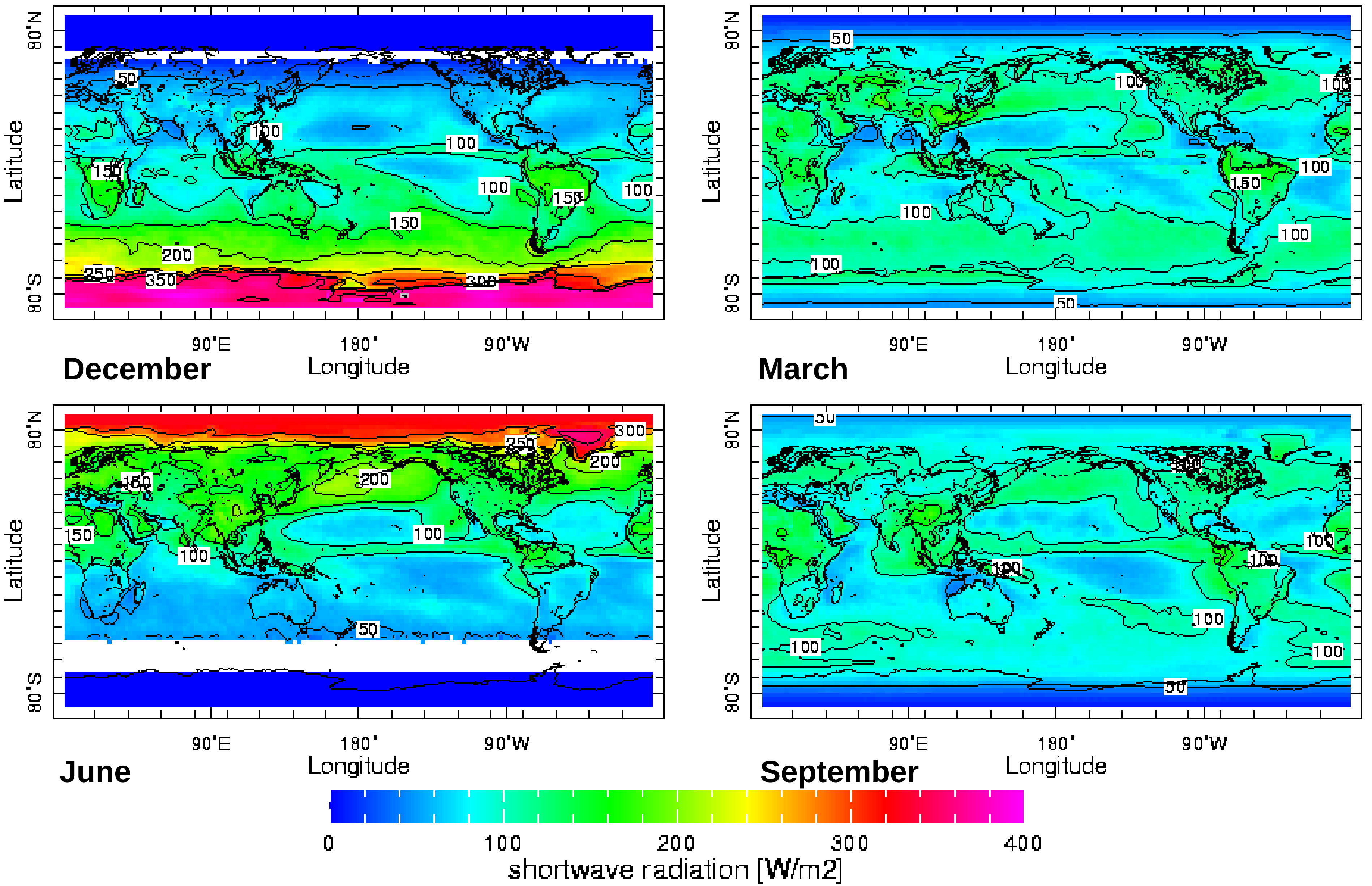
Daily mean incoming solar radiation at top of the atmosphere (W/m^2)

Latitude



Based on ERBE data Time of year

Reflected Solar at TOA



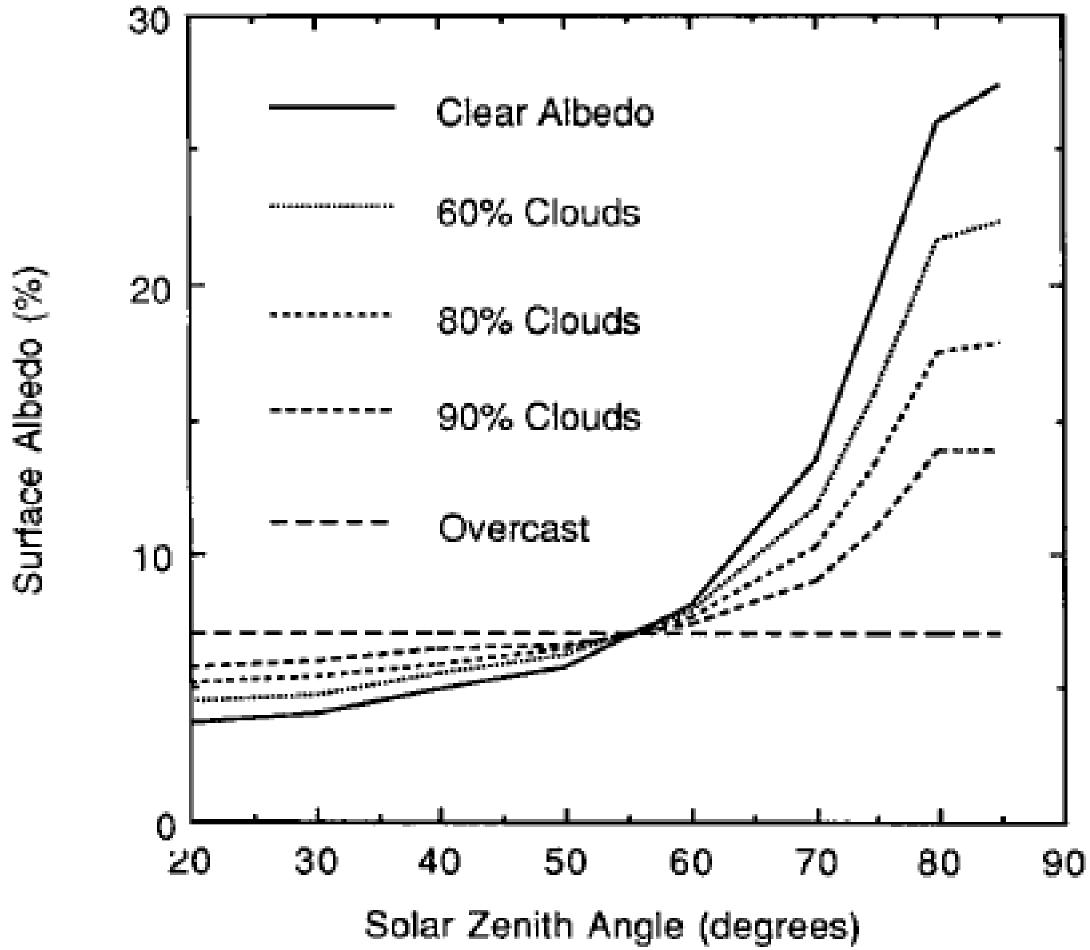


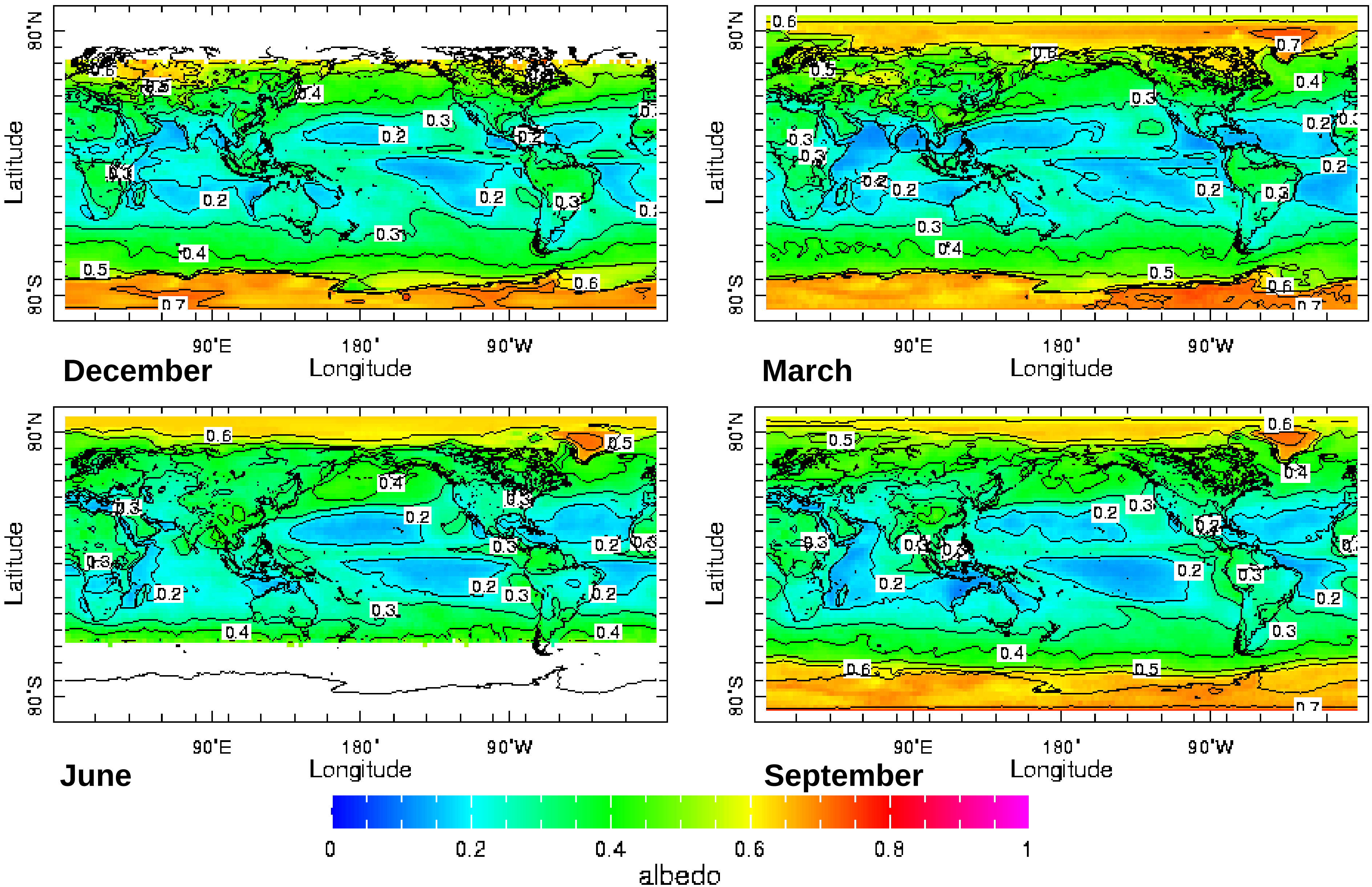
Fig. 4.4 Dependence of the albedo of a water surface on solar zenith angle and cloud cover. [Data from Mirinova (1973).]

Table 4.2

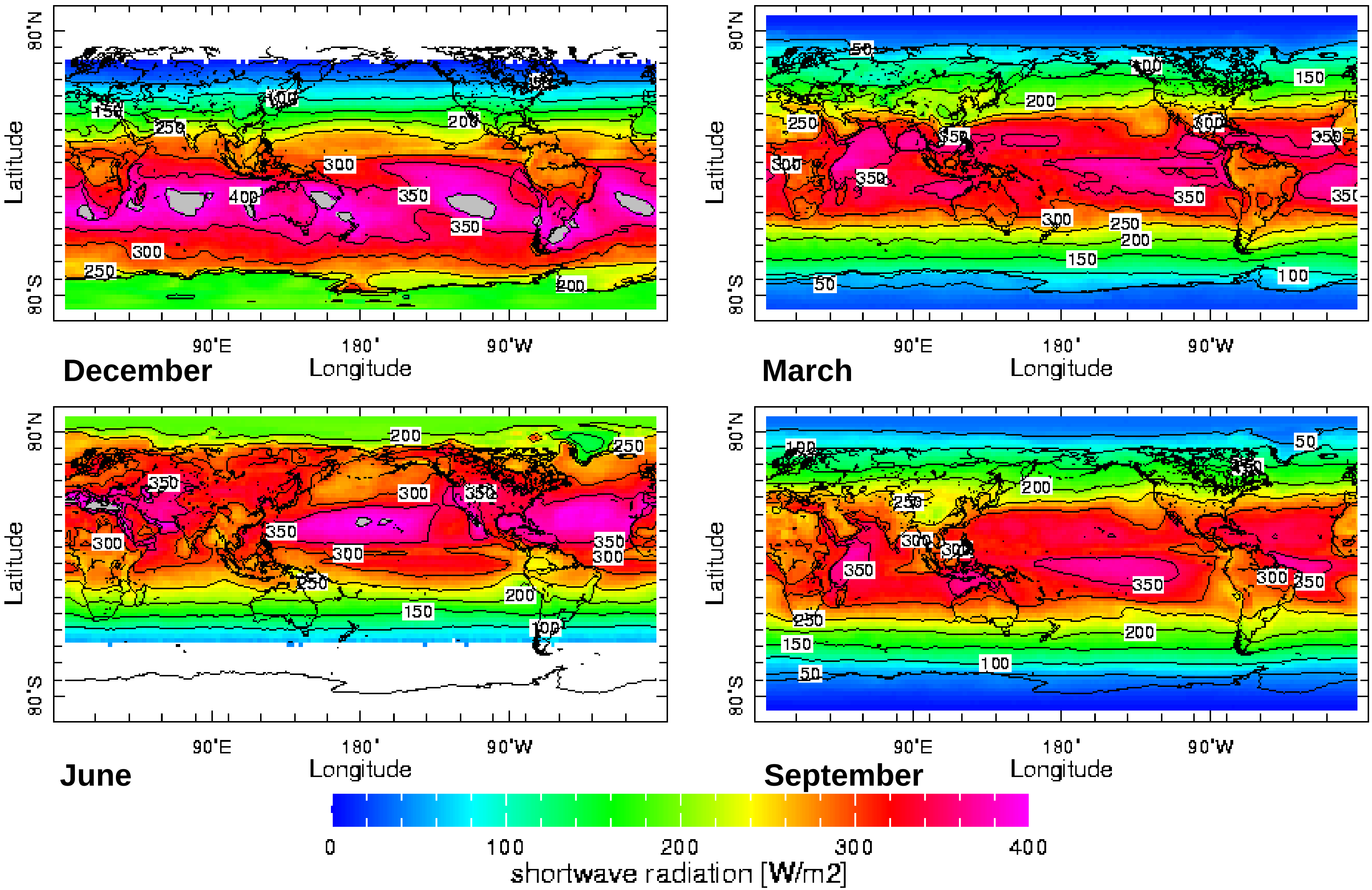
Albedos for Various Surfaces in Percent

Surface type	Range	Typical value
Water		
Deep water: low wind, low altitude	5–10	7
Deep water: high wind, high altitude	10–20	12
Bare surfaces		
Moist dark soil, high humus	5–15	10
Moist gray soil	10–20	15
Dry soil, desert	20–35	30
Wet sand	20–30	25
Dry light sand	30–40	35
Asphalt pavement	5–10	7
Concrete pavement	15–35	20
Vegetation		
Short green vegetation	10–20	17
Dry vegetation	20–30	25
Coniferous forest	10–15	12
Deciduous forest	15–25	17
Snow and ice		
Forest with surface snowcover	20–35	25
Sea ice, no snowcover	25–40	30
Old, melting snow	35–65	50
Dry, cold snow	60–75	70
Fresh, dry snow	70–90	80

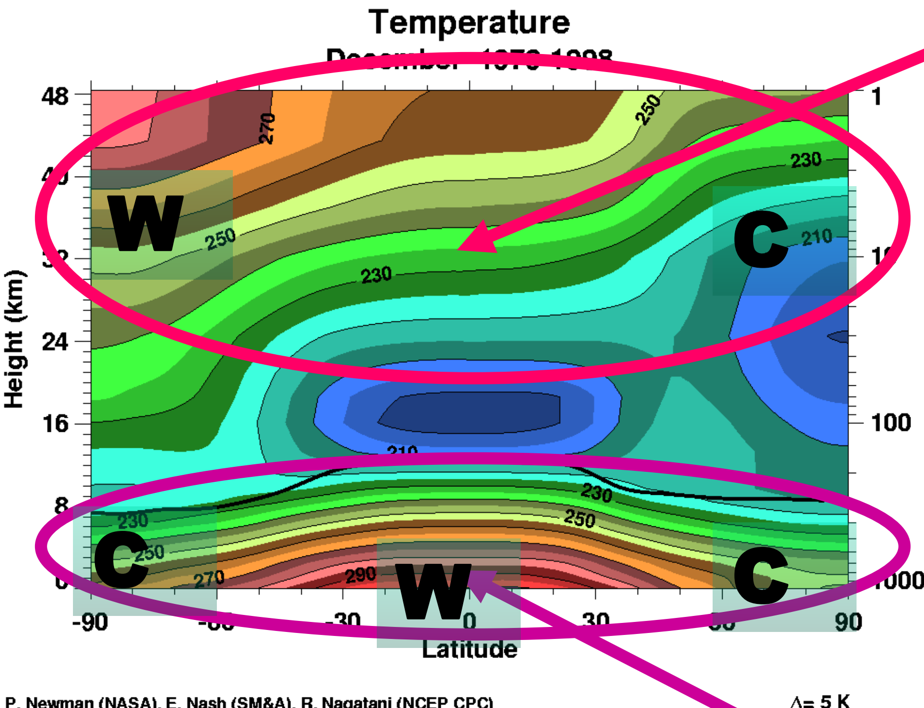
Planetary Albedo



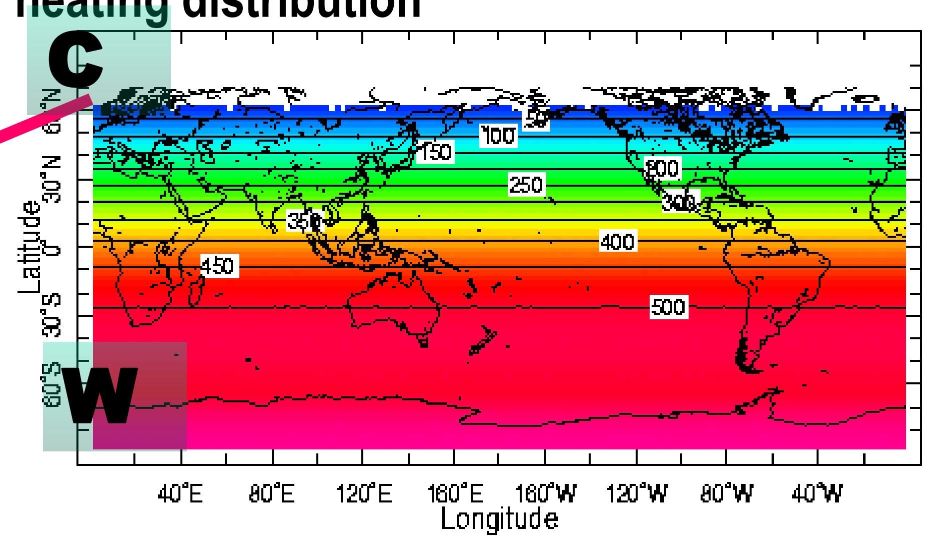
Net Shortwave (Solar) Radiation



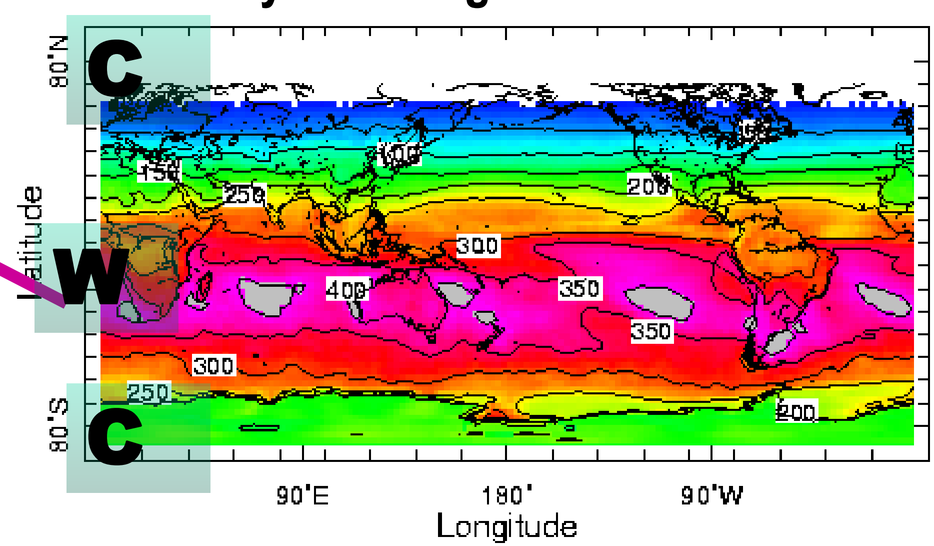
Latitude-height zonal mean temperature structure



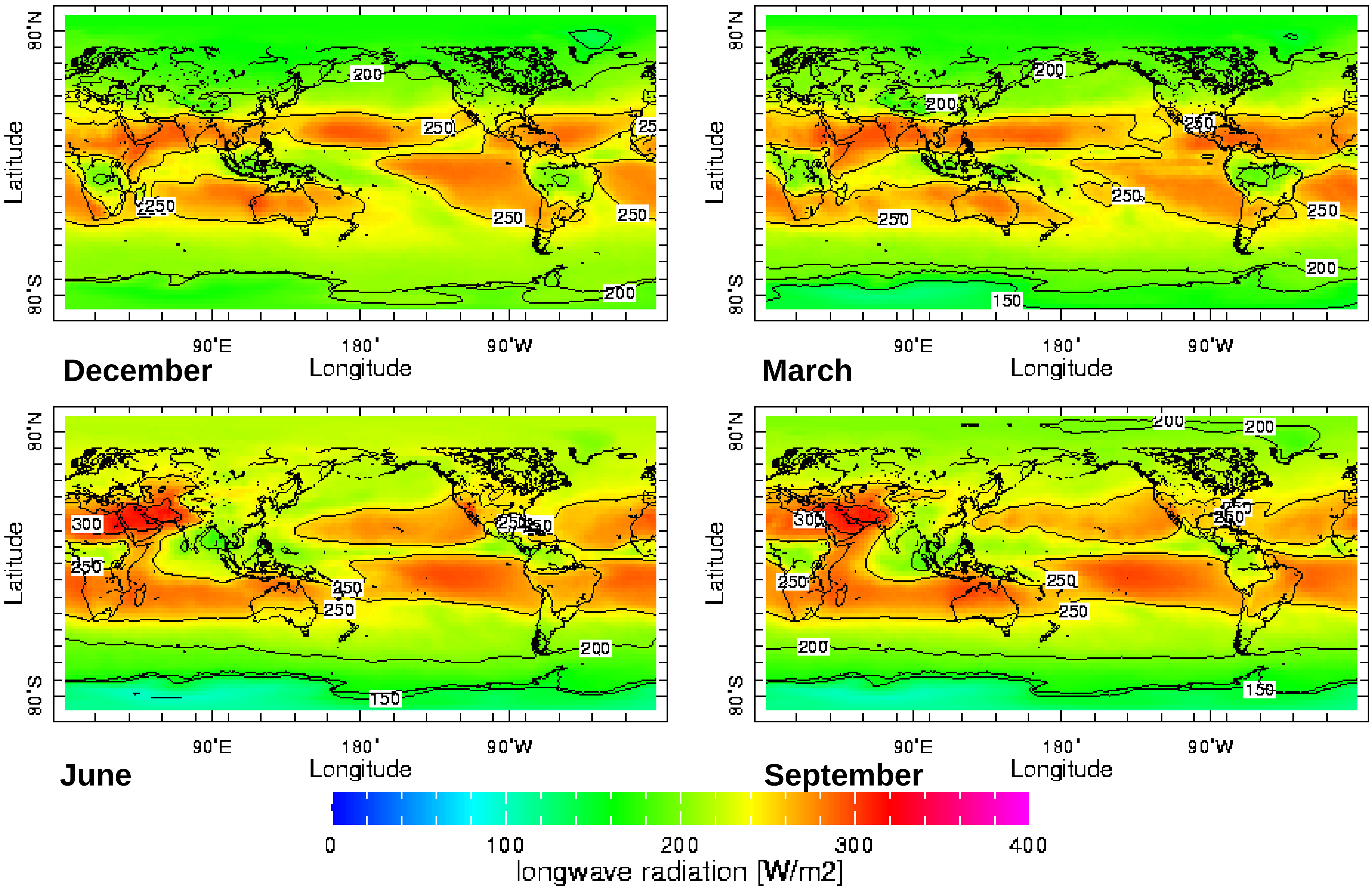
Daily incoming radiation at top of atmosphere during December – ozone heating distribution



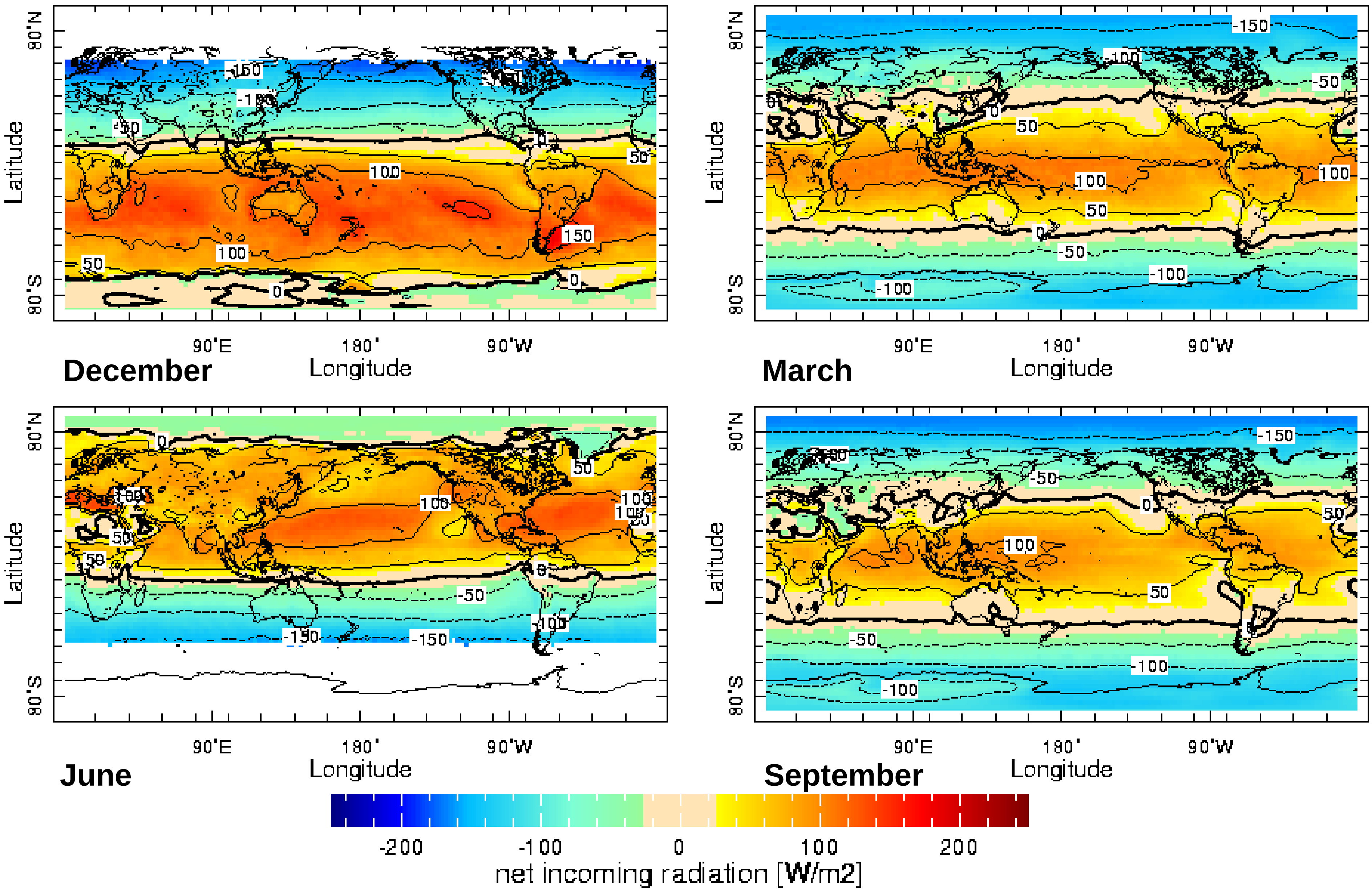
Net daily incoming solar radiation



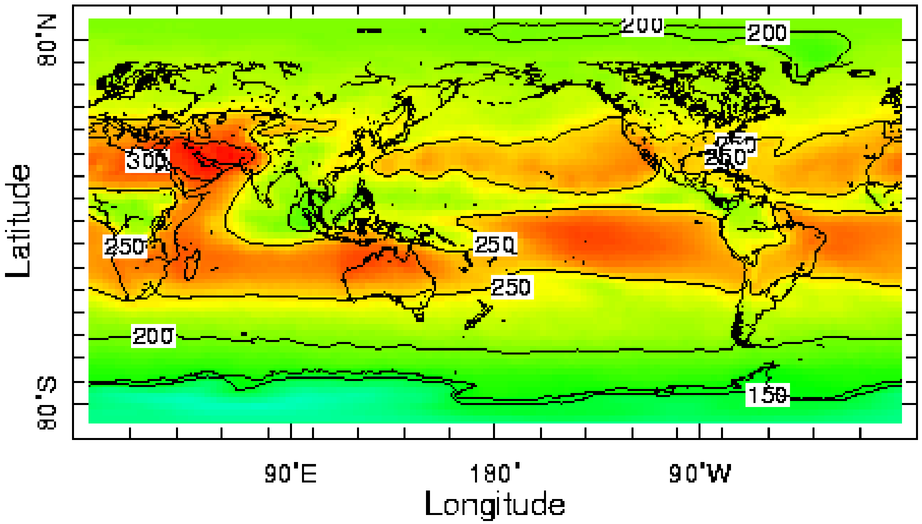
Outgoing Longwave (IR) at TOA



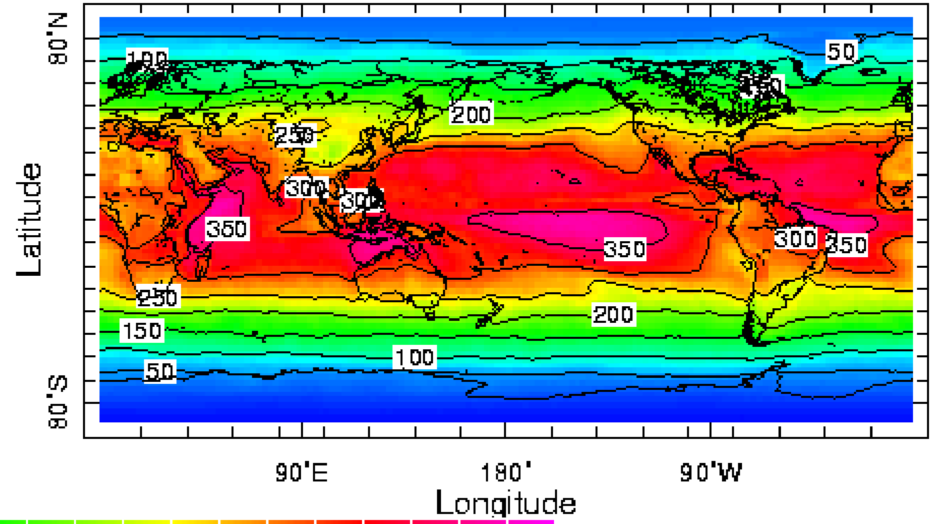
Net Incoming Radiation (LW and SW)

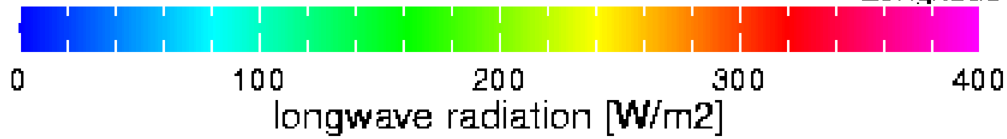


Outgoing longwave radiation (OLR)

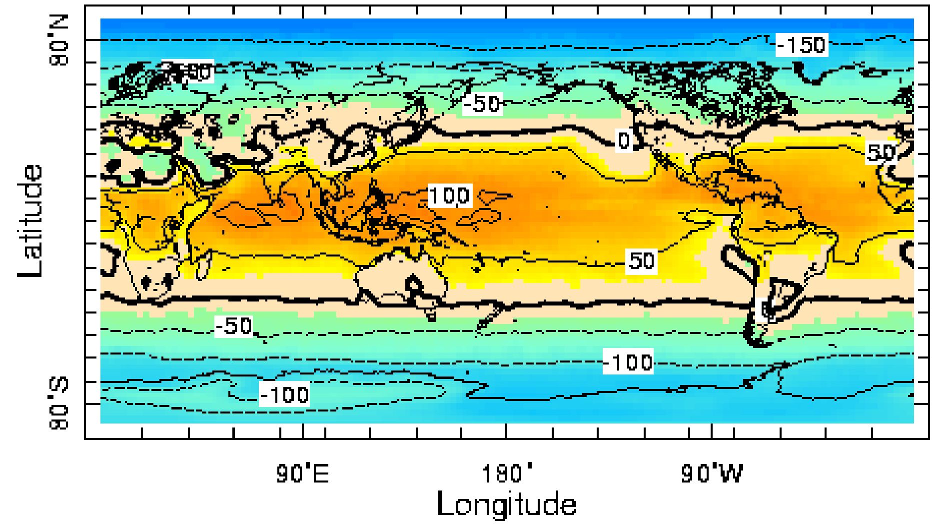


Net Shortwave (Solar) Radiation

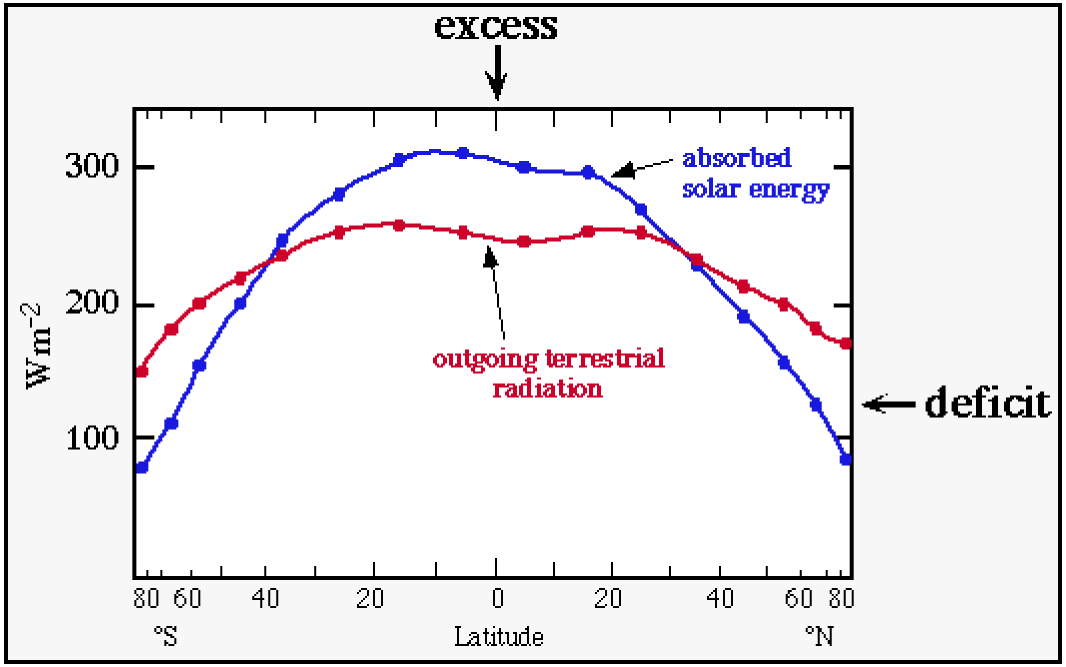


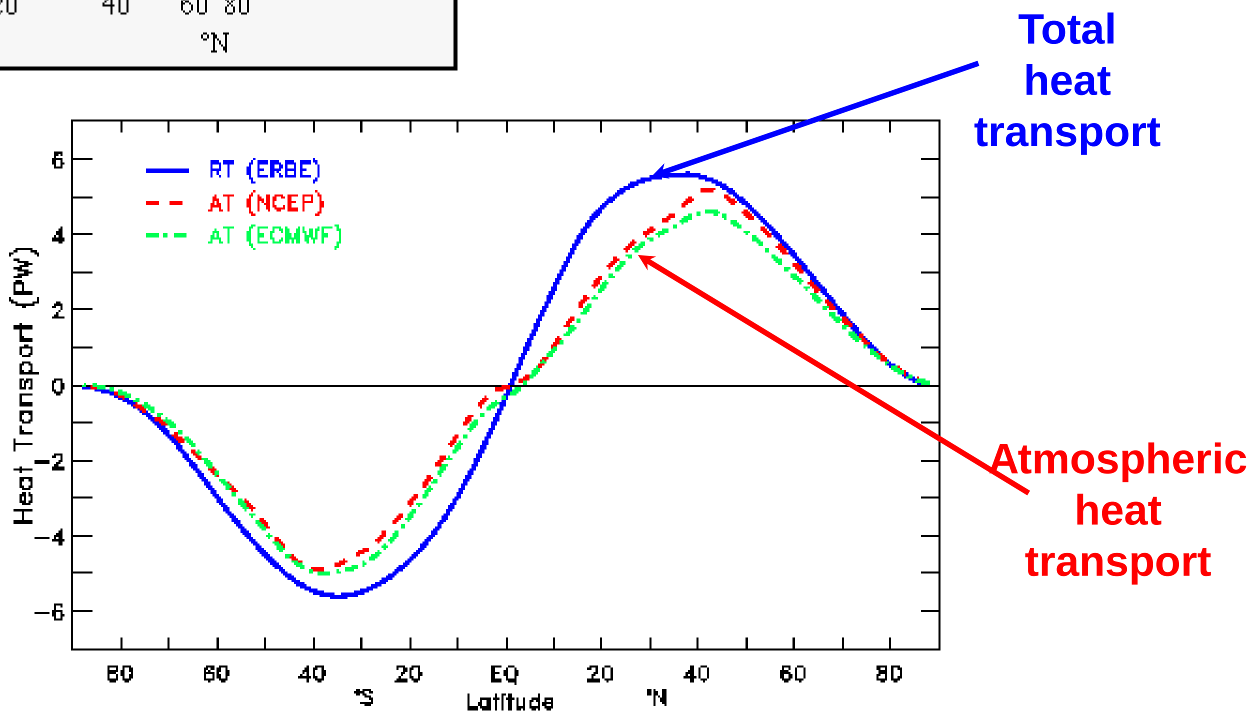


Net incoming Radiation (SW-LW)



Latitudinal Radiation Imbalance





adapted from Trenberth and Caron (2001)

PW=10^{15} W

Meridional heat transport

Trenberth and Caron (2001)

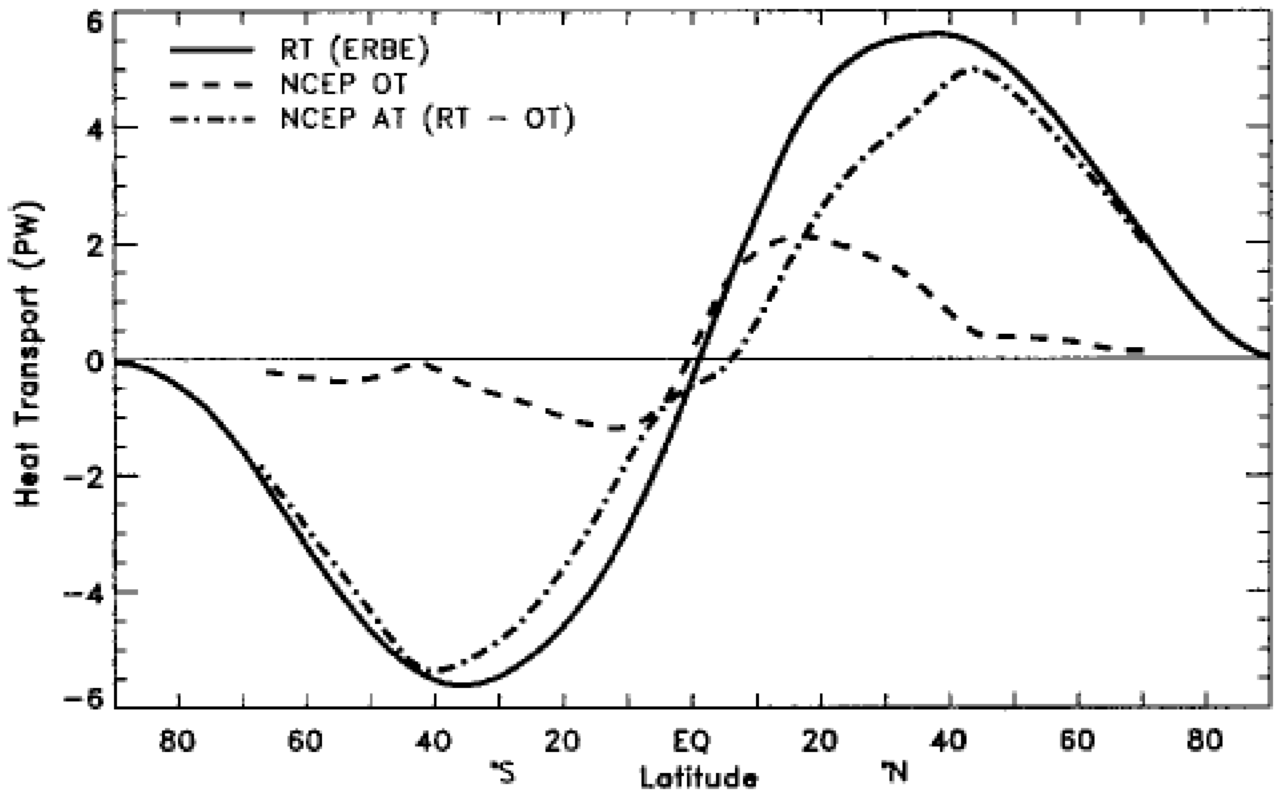
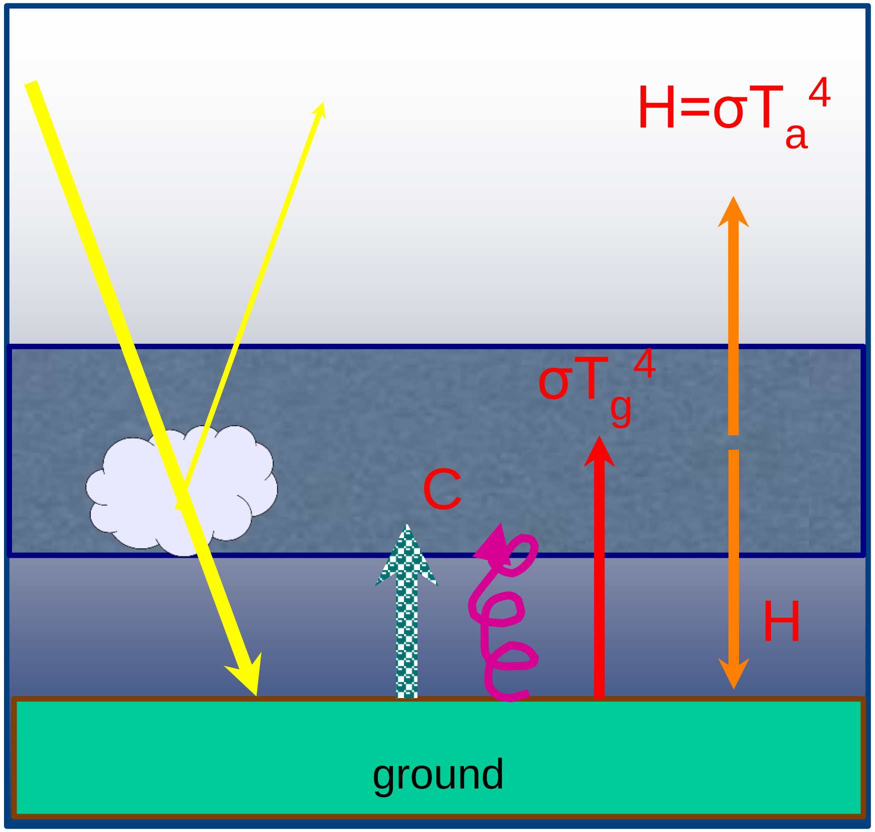


FIG. 7. The required total heat transport from the TOA radiation RT is compared with the derived estimate of the adjusted ocean heat transport OT (dashed) and implied atmospheric transport AT from NCEP reanalyses (PW).

PW=10^{15} W

The surface looses heat through radiation, and latent and sensible heat fluxes.



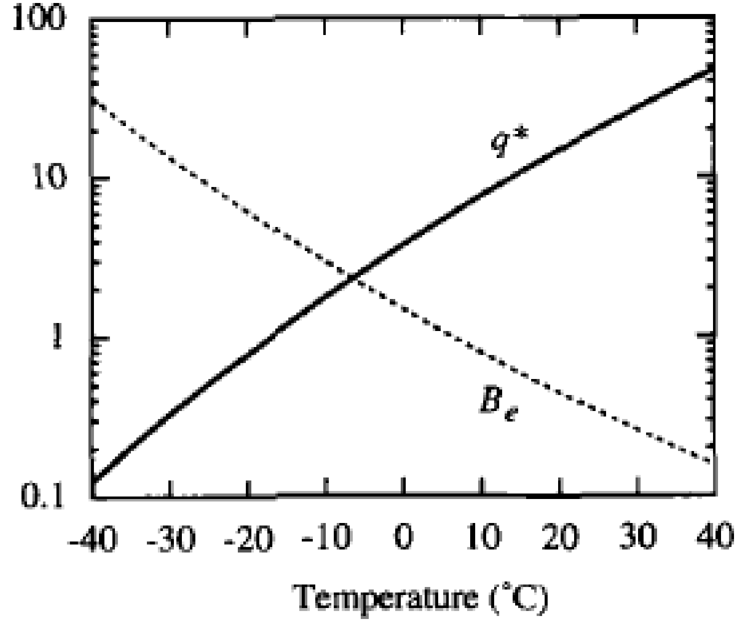
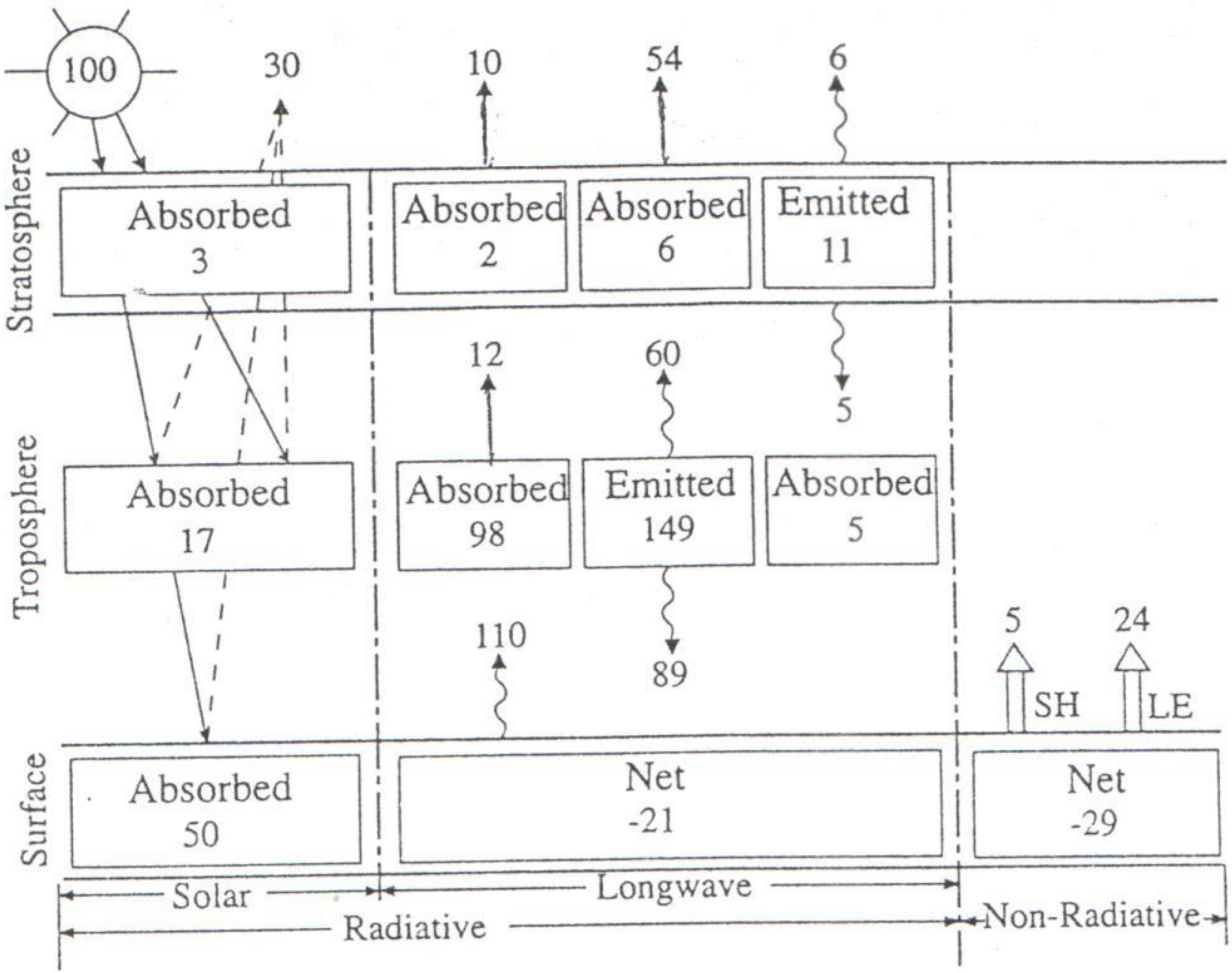


Fig. 4.10 Saturation specific humidity q^* (g kg^{-1}) and equilibrium Bowen ratio B_e, as functions of temperature.



100
30
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54
6
Stratosphere
Absorbed 3
Absorbed 2
Absorbed 6
Emitted 11
12
60
5
Troposphere
Absorbed 17
Absorbed 98
Emitted 149
Absorbed 5
110
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SH
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Surface
Absorbed 50
Net -21
Net -29
Solar
Longwave
Radiative
Non-Radiative

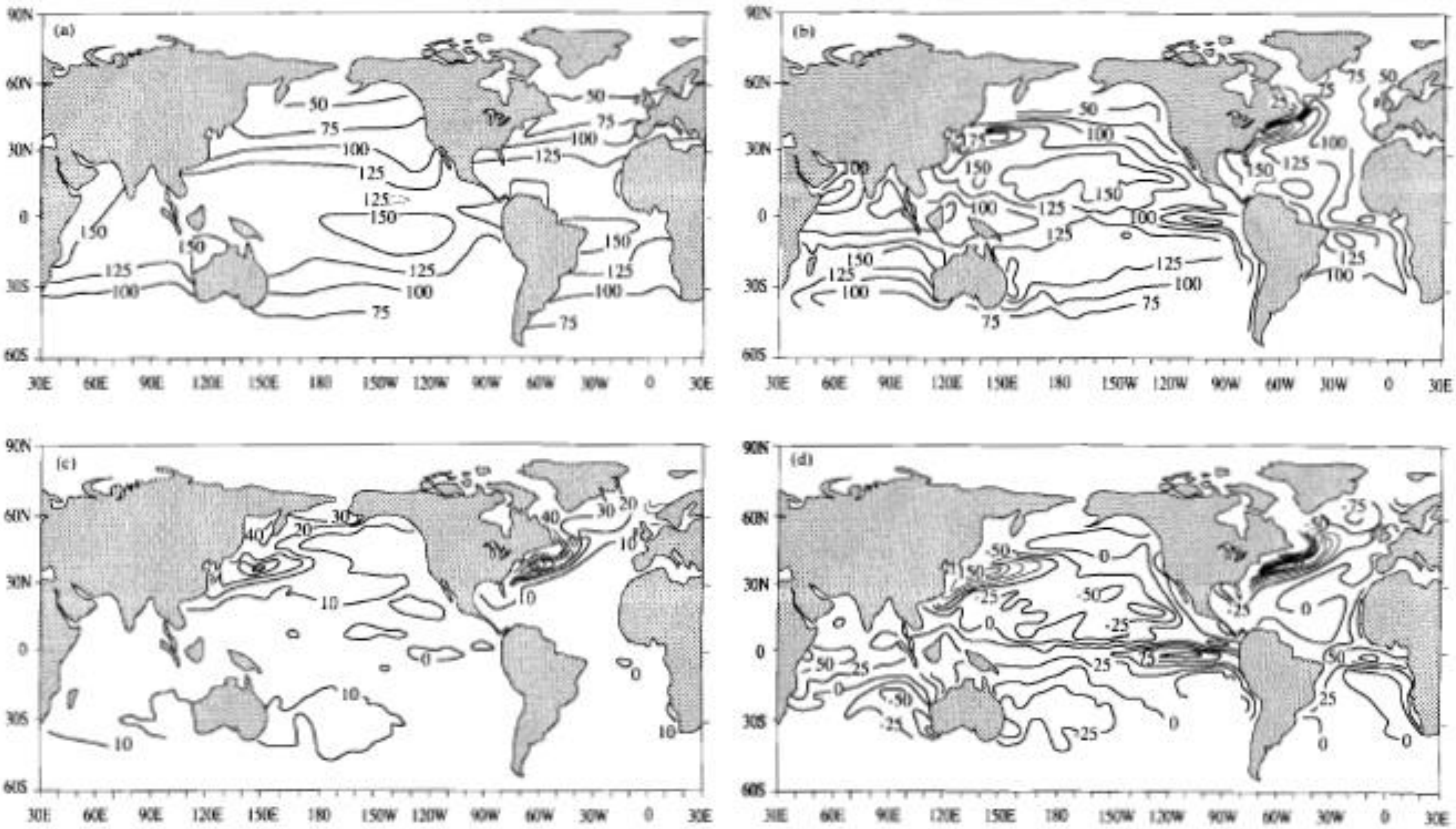

Fig. 4.18 Maps of the annual average energy budget components over the oceans: (a) net radiation; (b) latent heat flux; (c) sensible heat flux; (d) net downward heat flux into the ocean. [From Oberhuber (1988).]