ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Earth System modelling School 2009

3-7 August 2009, Helsinki, Finland

Atmosphere in the Earth system

heikki.jarvinen@fmi.fi

NASA

Outline ::

- **Role of the atmosphere in the Earth system**

1. **Interaction with the surrounding Universe**
   - Upper boundary condition of the Earth system
2. **Interaction with the underlying surface**
   - Lower boundary condition of the atmosphere
   - Non-linear interaction with other Earth system components
3. **Internal dynamics**

1. Interaction with the surrounding Universe

- **Solar wind of high energy particles + cosmic rays**
- **Lunar interaction through gravitation (ocean tides)**
- **Solar irradiance**

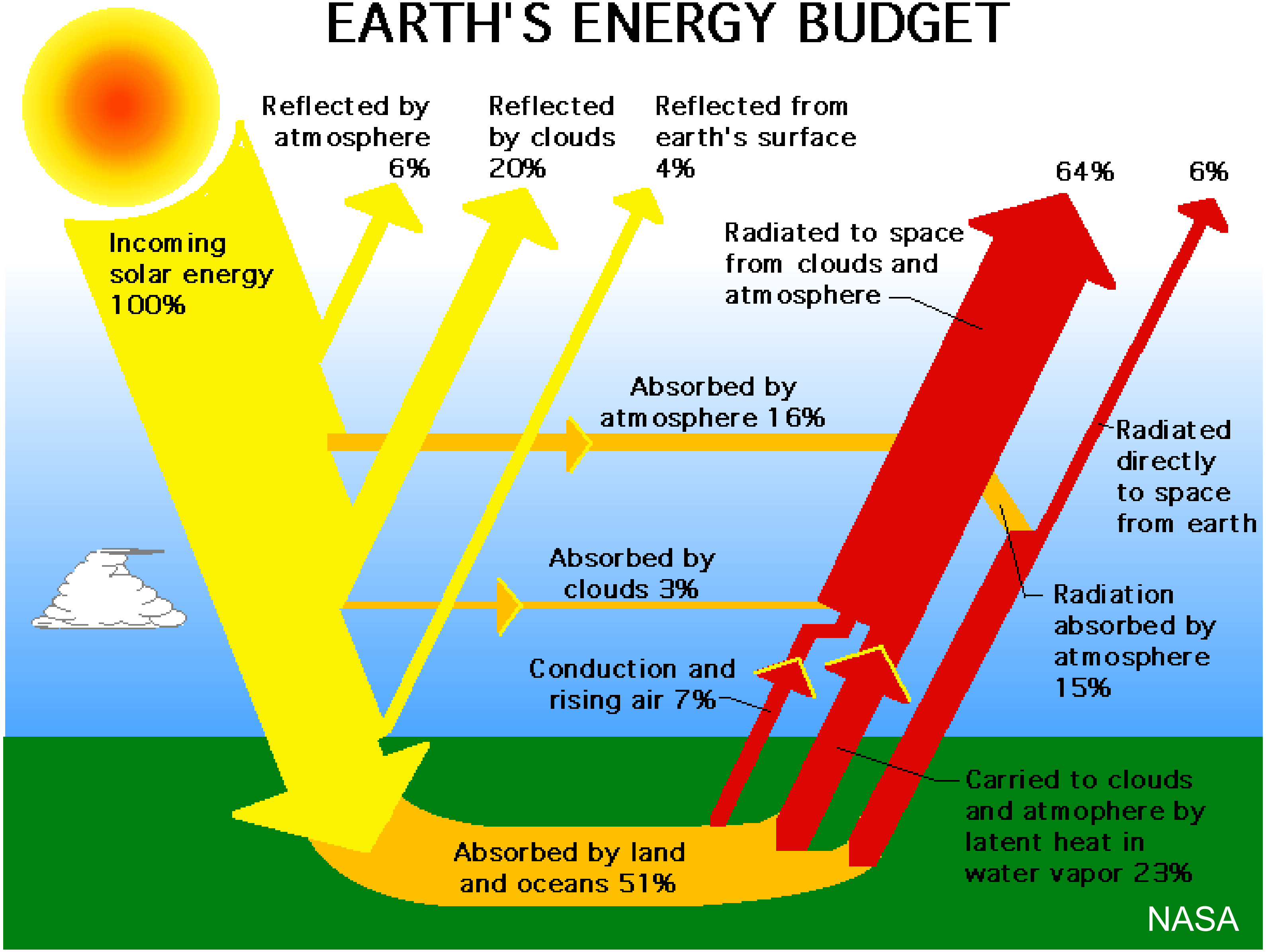
1. Interaction with the surrounding Universe

- Solar wind of high energy particles + cosmic rays
- Lunar interaction through gravitation (ocean tides)
- **Solar irradiance**

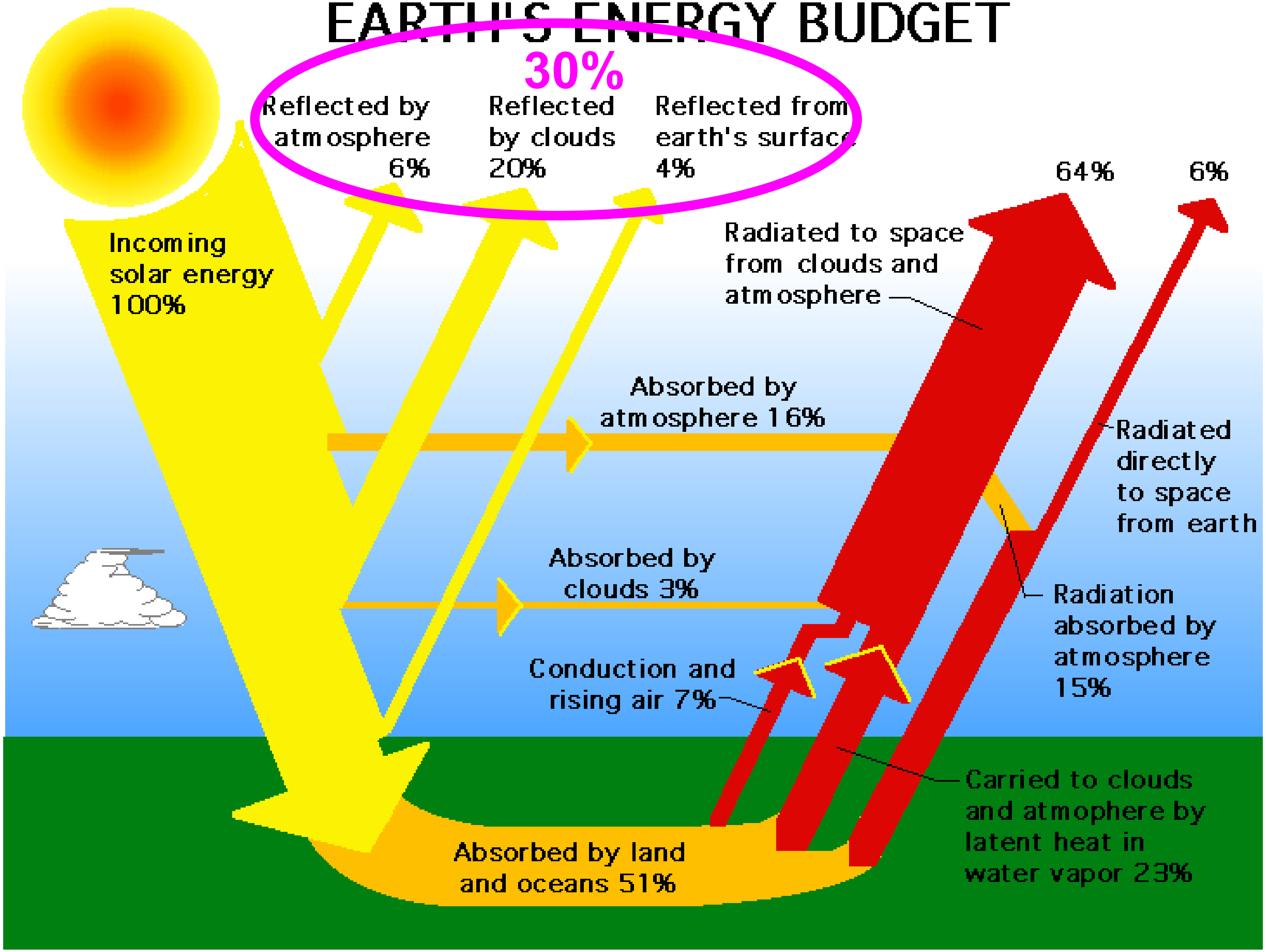
Radiation budget of the Earth

- **incoming (shortwave) radiation from the Sun**
- **reflected (shortwave) radiation from the Earth**
- **outgoing thermal (longwave) from the Earth**

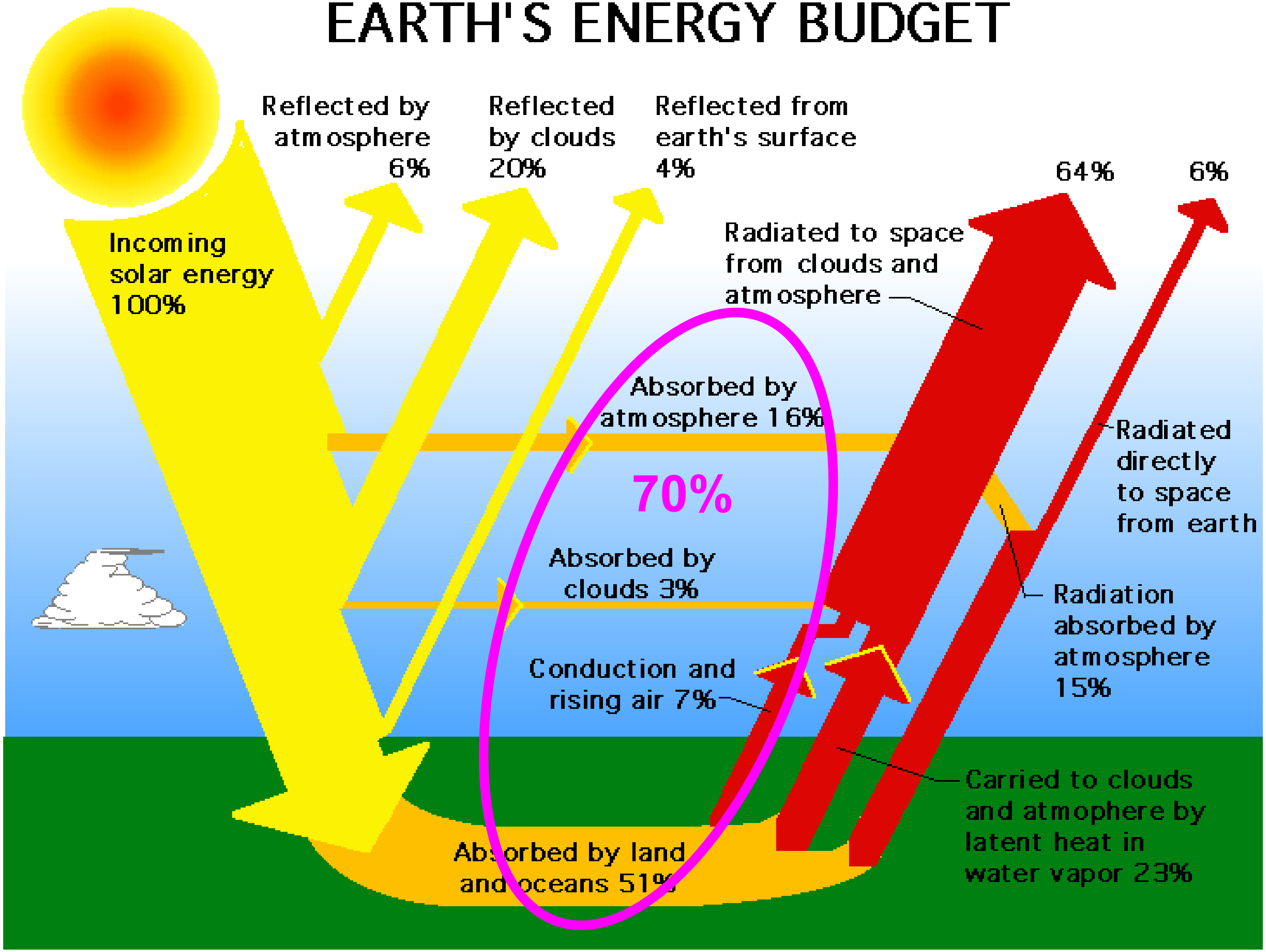
EARTH'S ENERGY BUDGET



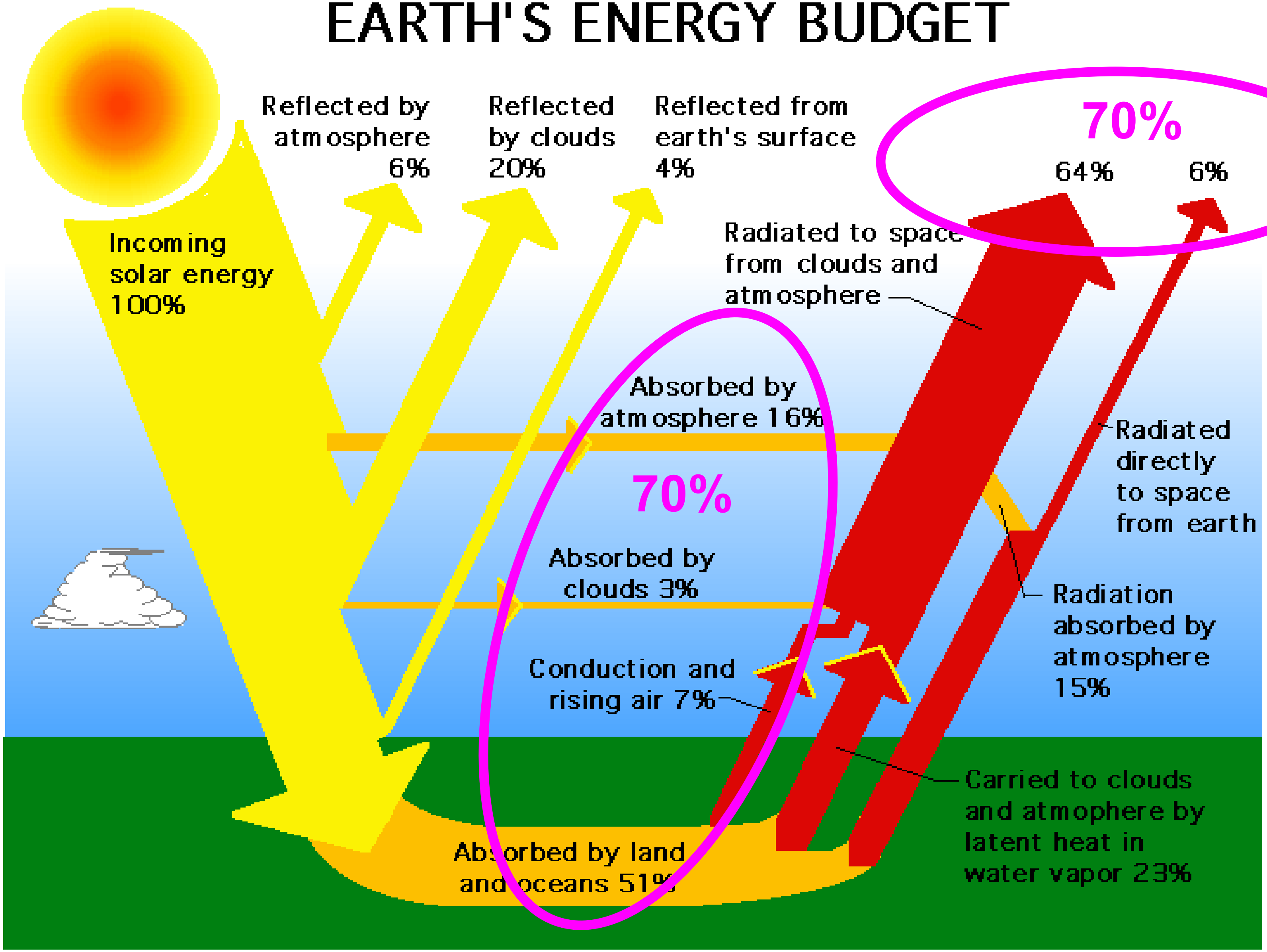
EARTH'S ENERGY BUDGET



EARTH'S ENERGY BUDGET



EARTH'S ENERGY BUDGET



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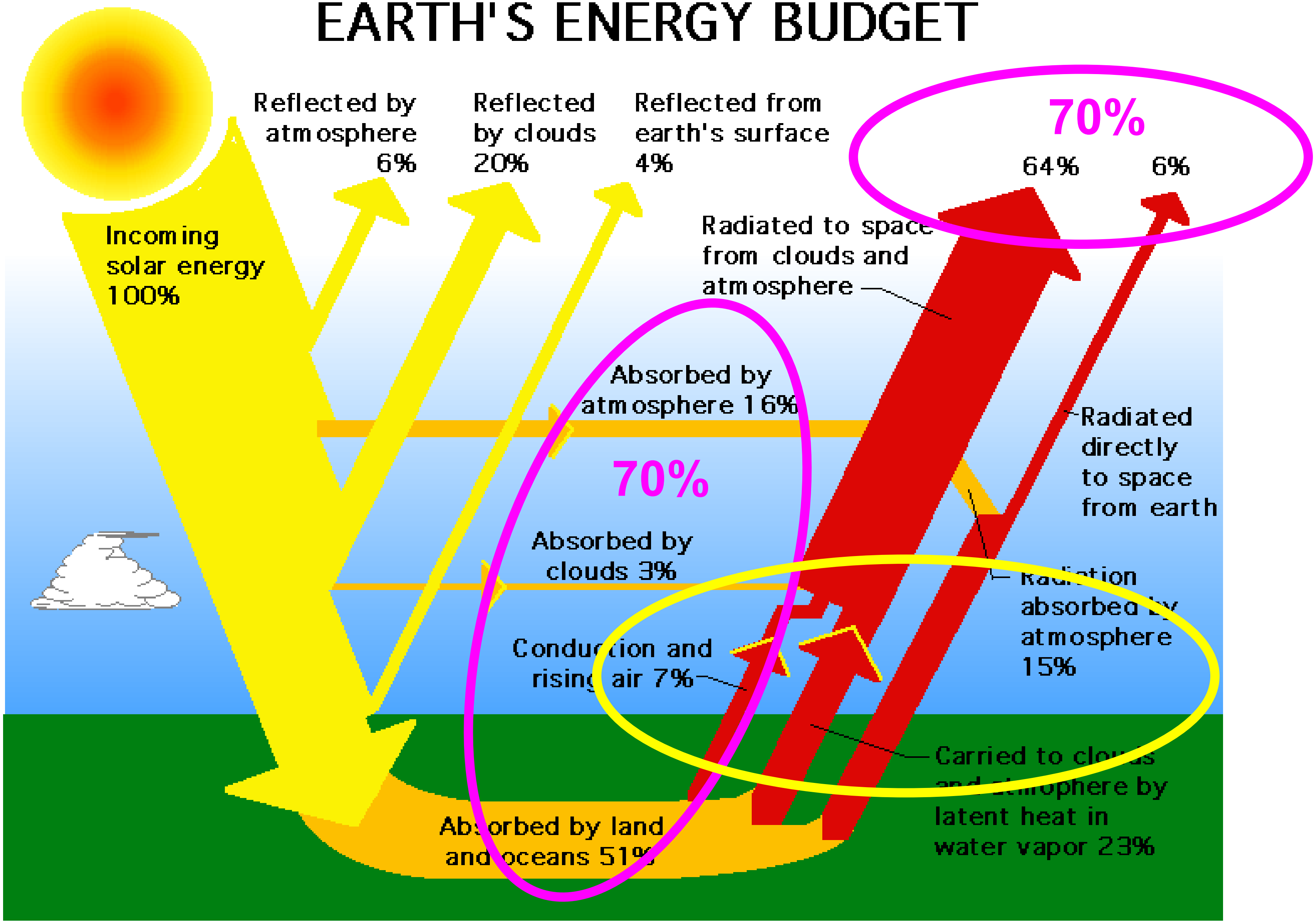

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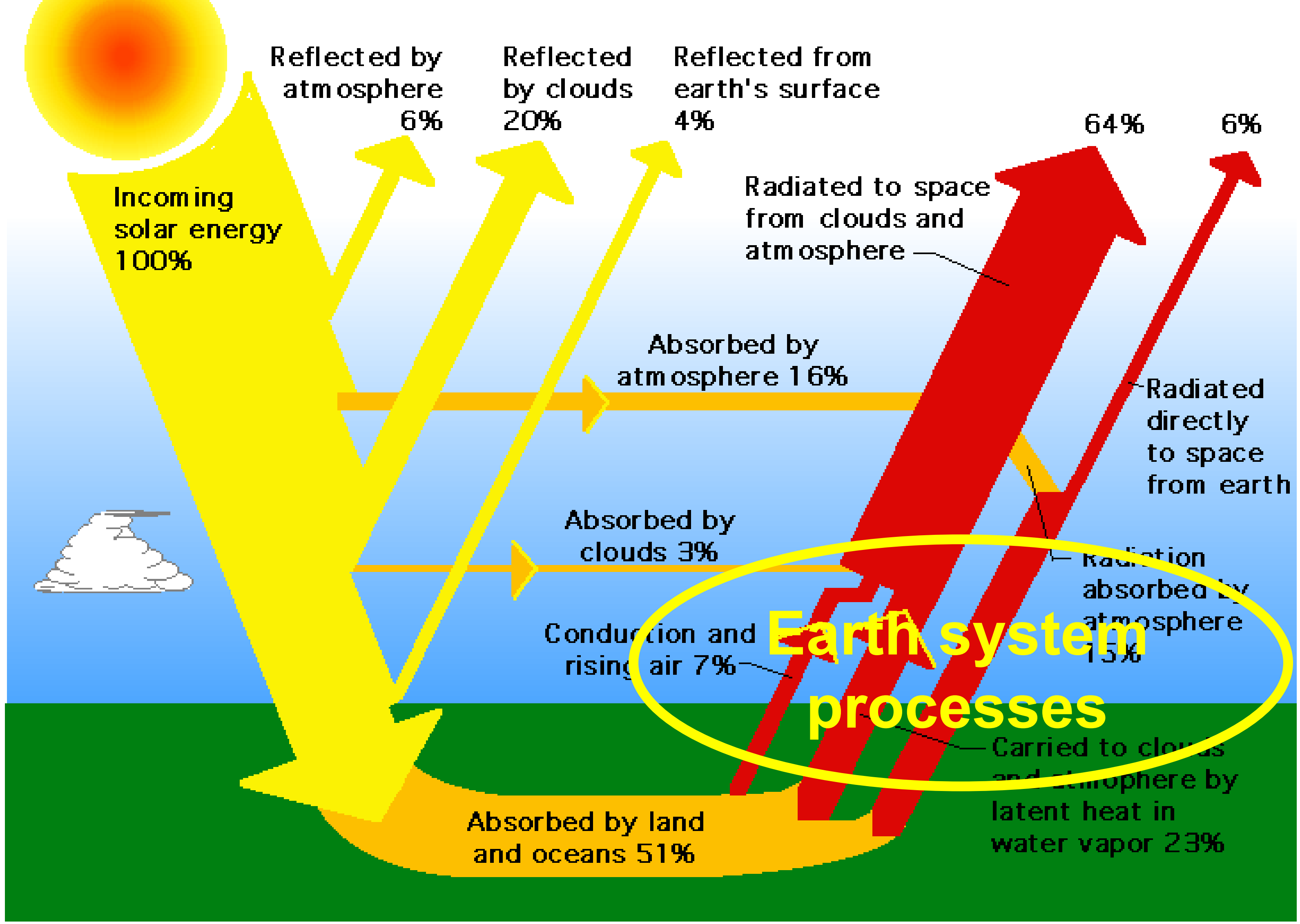
EARTH'S ENERGY BUDGET

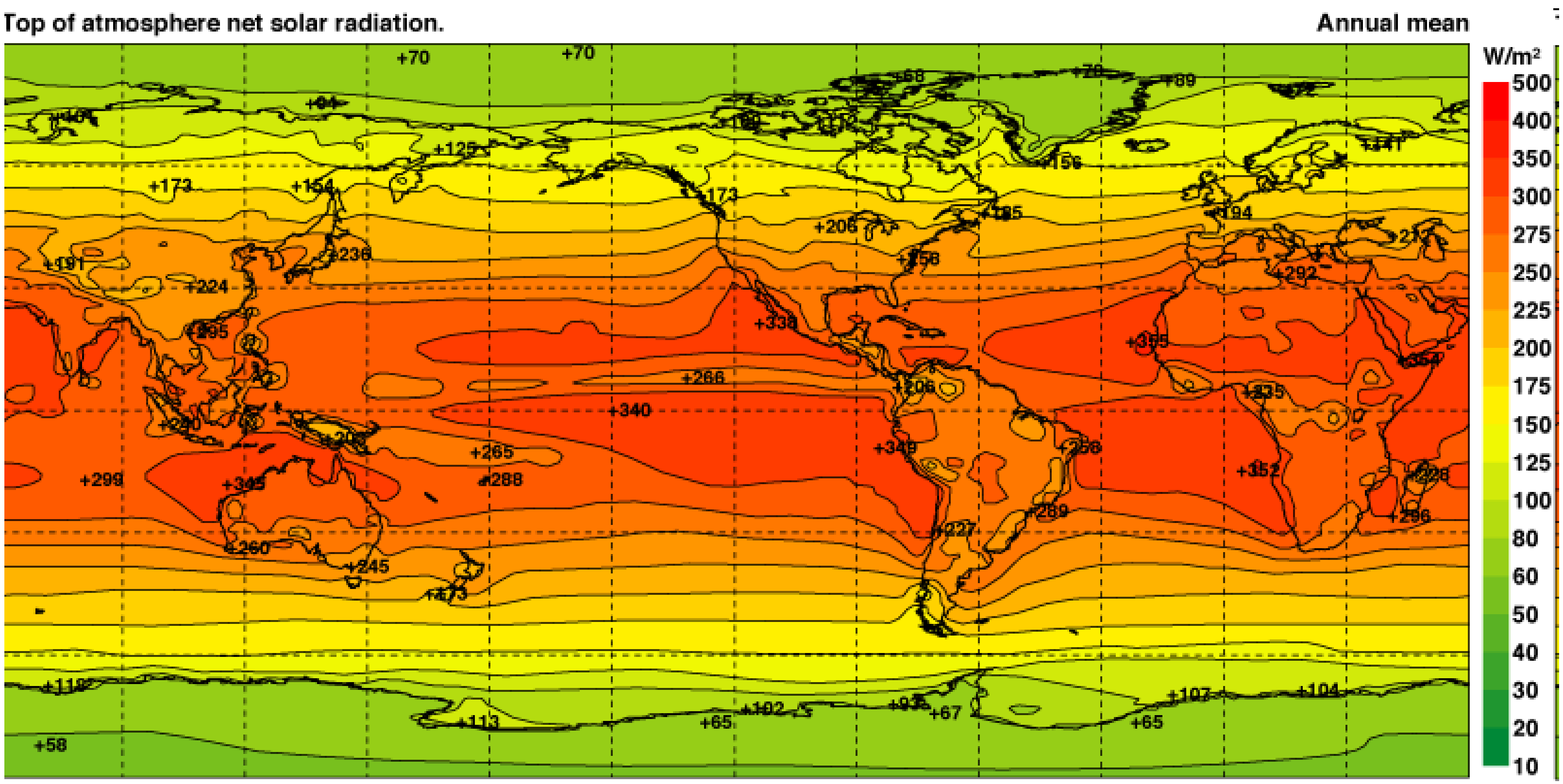


Upper boundary condition

- **purely radiative**

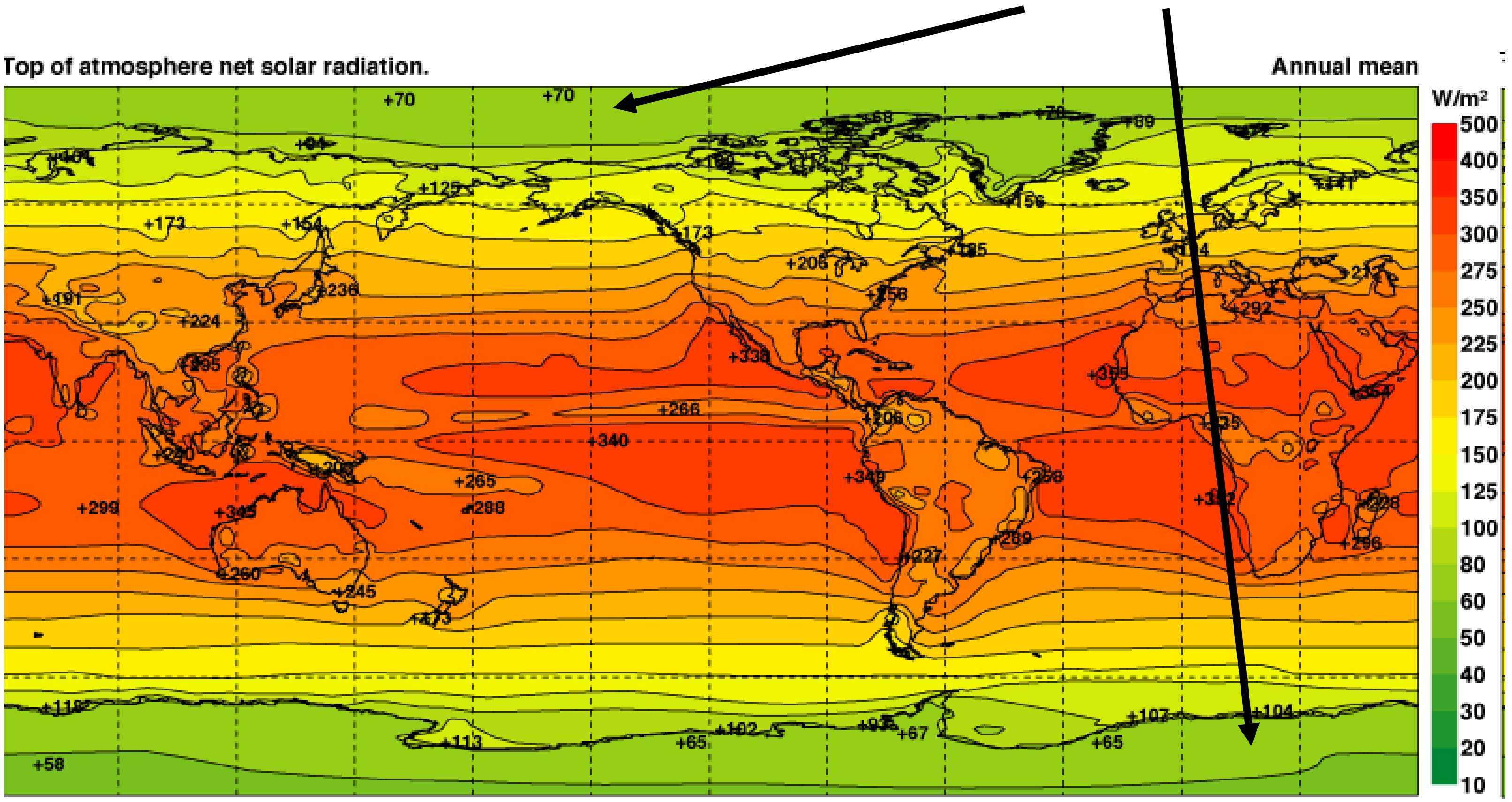
- **Next: net shortwave and longwave radiation (distribution at the top of the atmosphere)**

Incoming net solar radiation (absorbed)



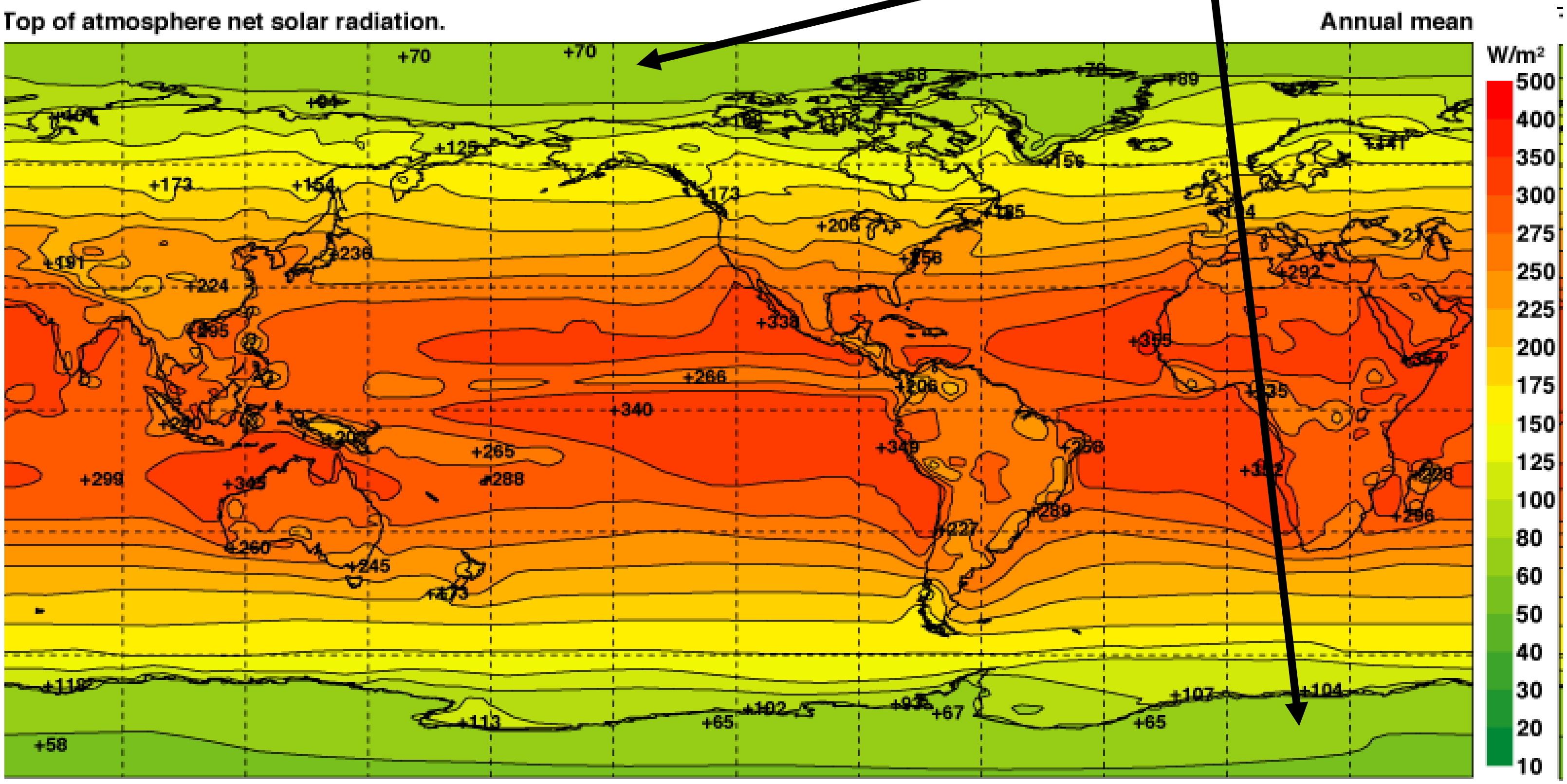
ECMWF, ERA40

Average solar zenith angle large in polar regions



ECMWF, ERA40

High albedo due to … low cloud and snow



ECMWF, ERA40

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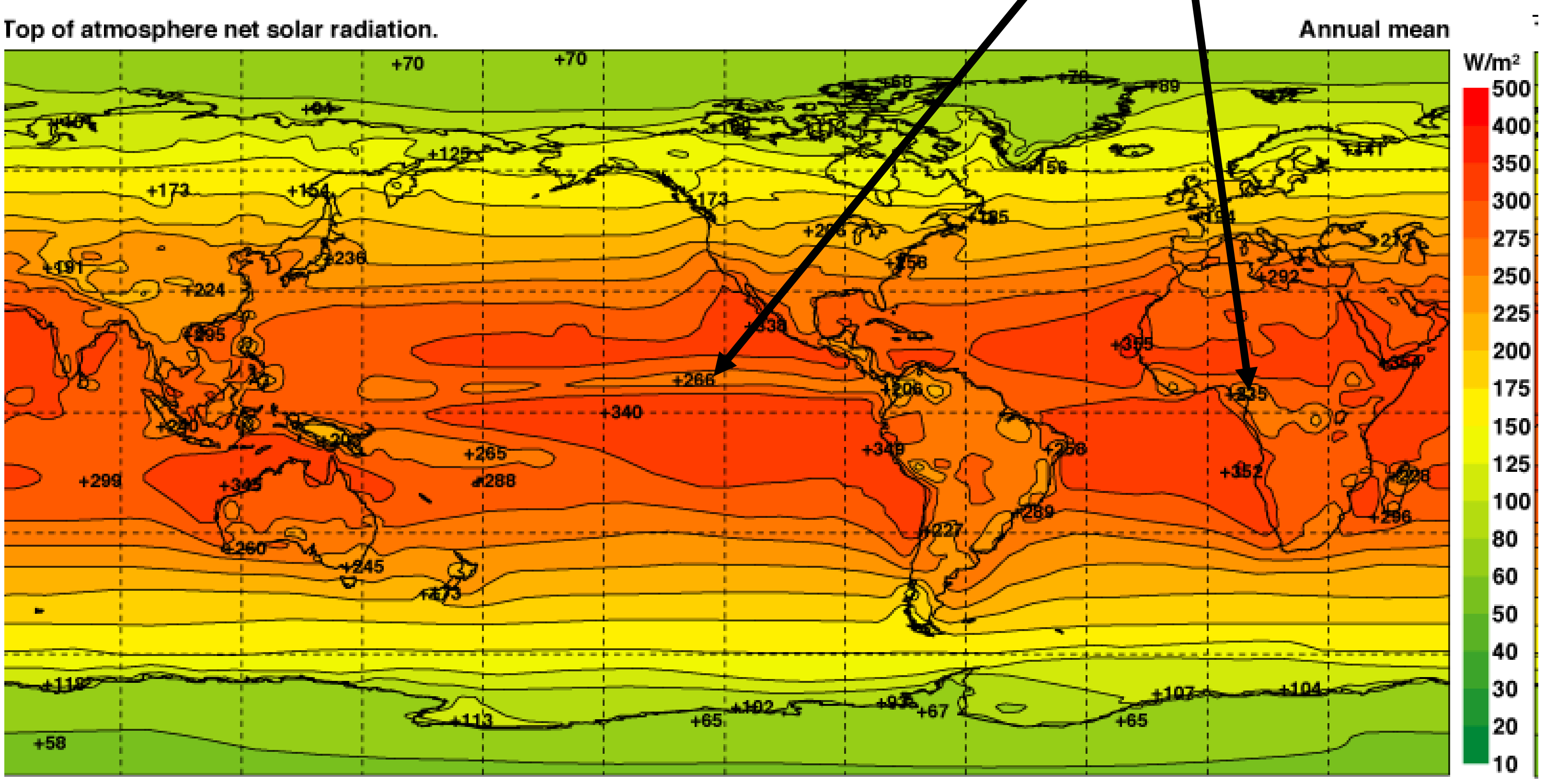
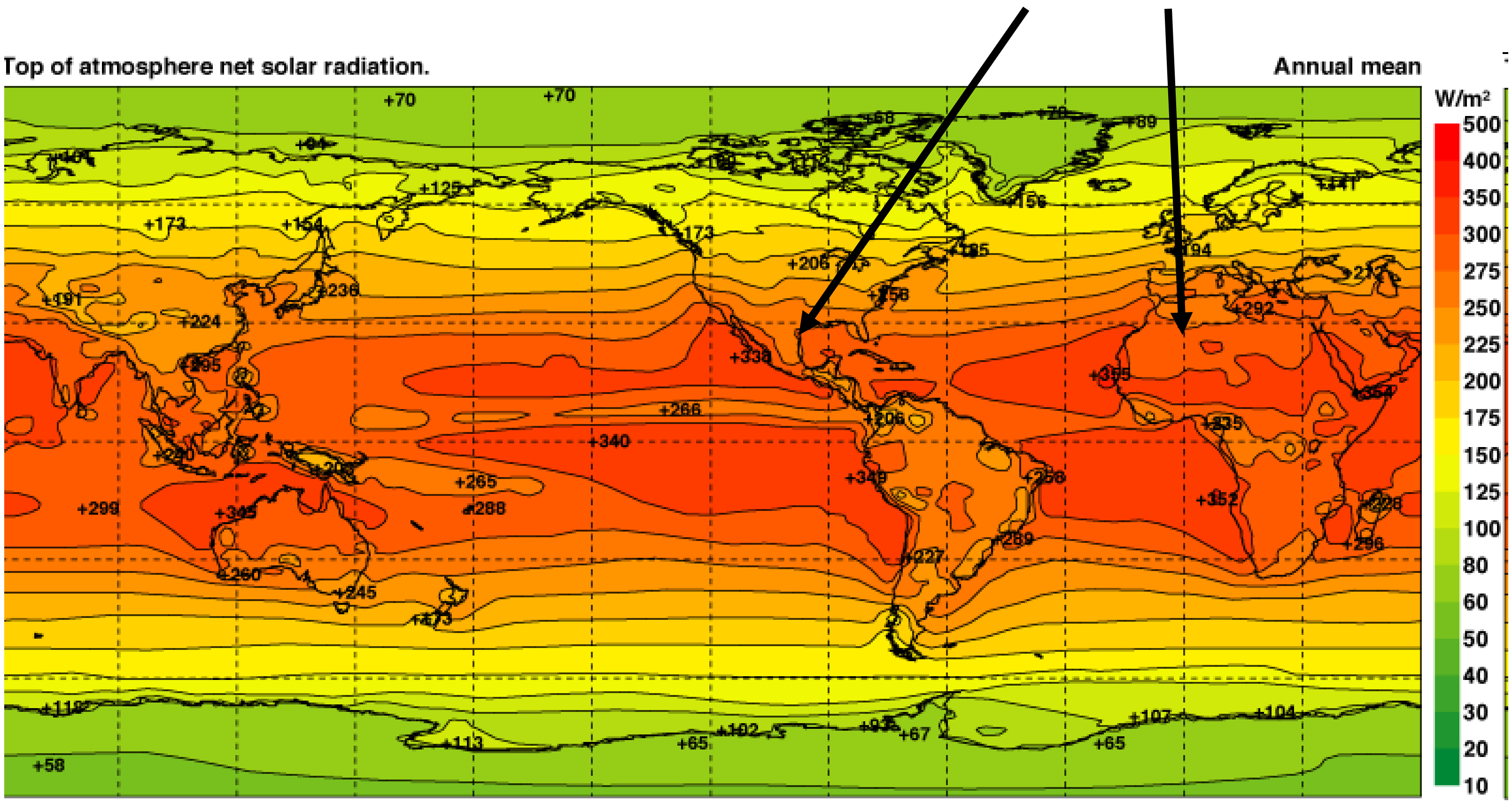
High albedo due to … persistent high clouds



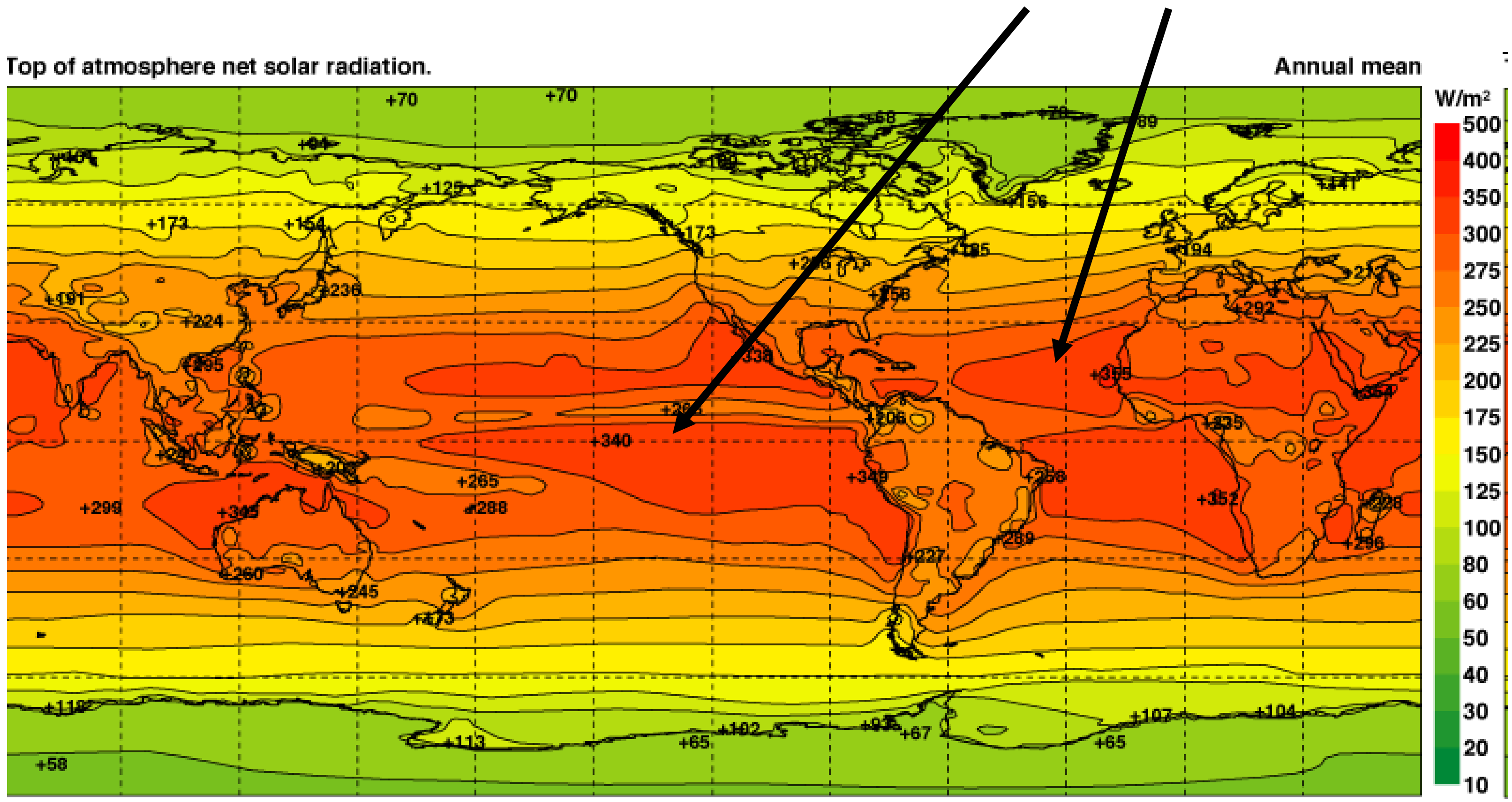
ECMWF, ERA40

High albedo due to … bright surfaces



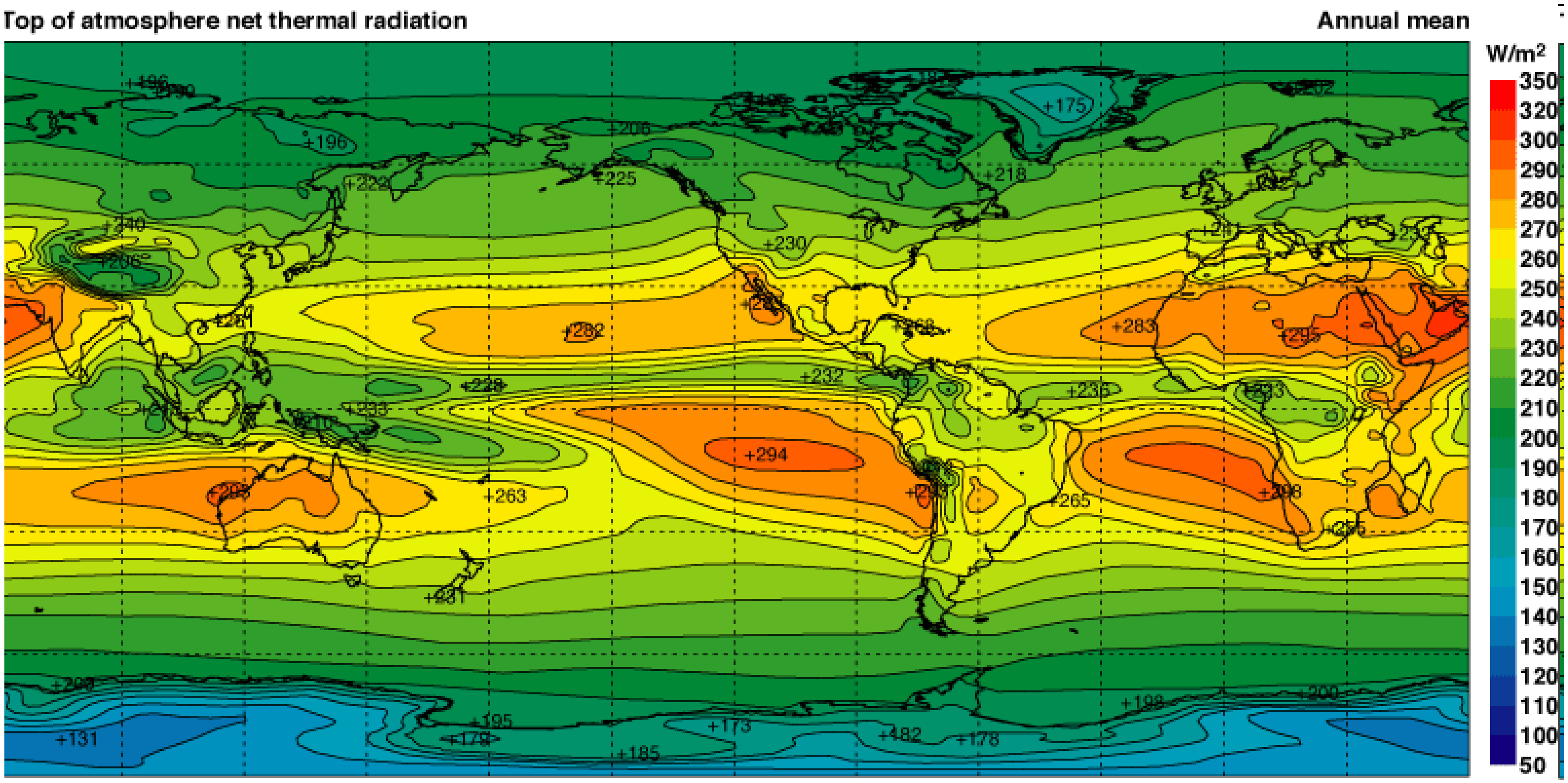
ECMWF, ERA40

Intrinsically low albedo of ocean surfaces



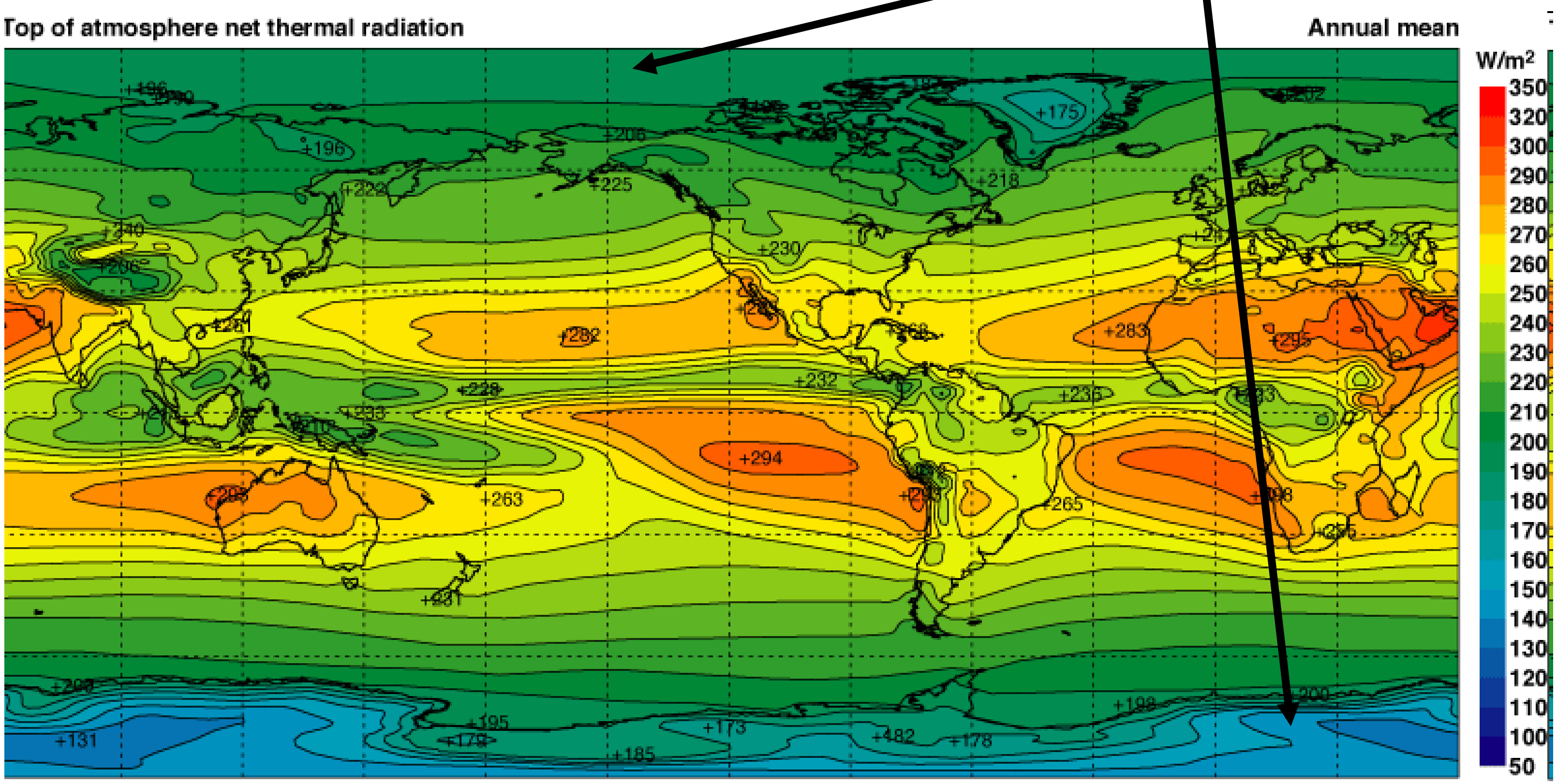
ECMWF, ERA40

Outgoing longwave radiation (emitted)



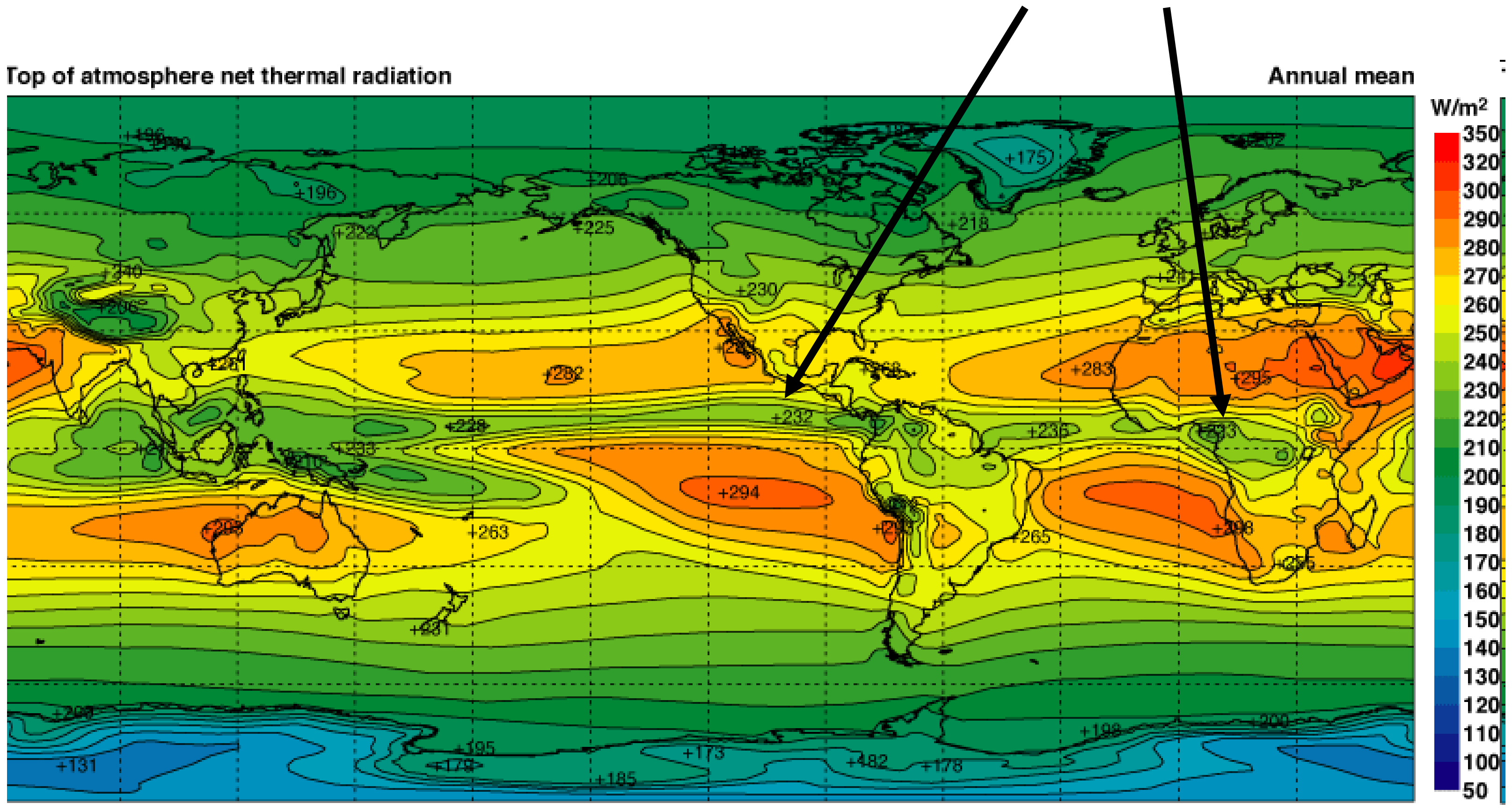
ECMWF, ERA40

Cold surface and atmosphere



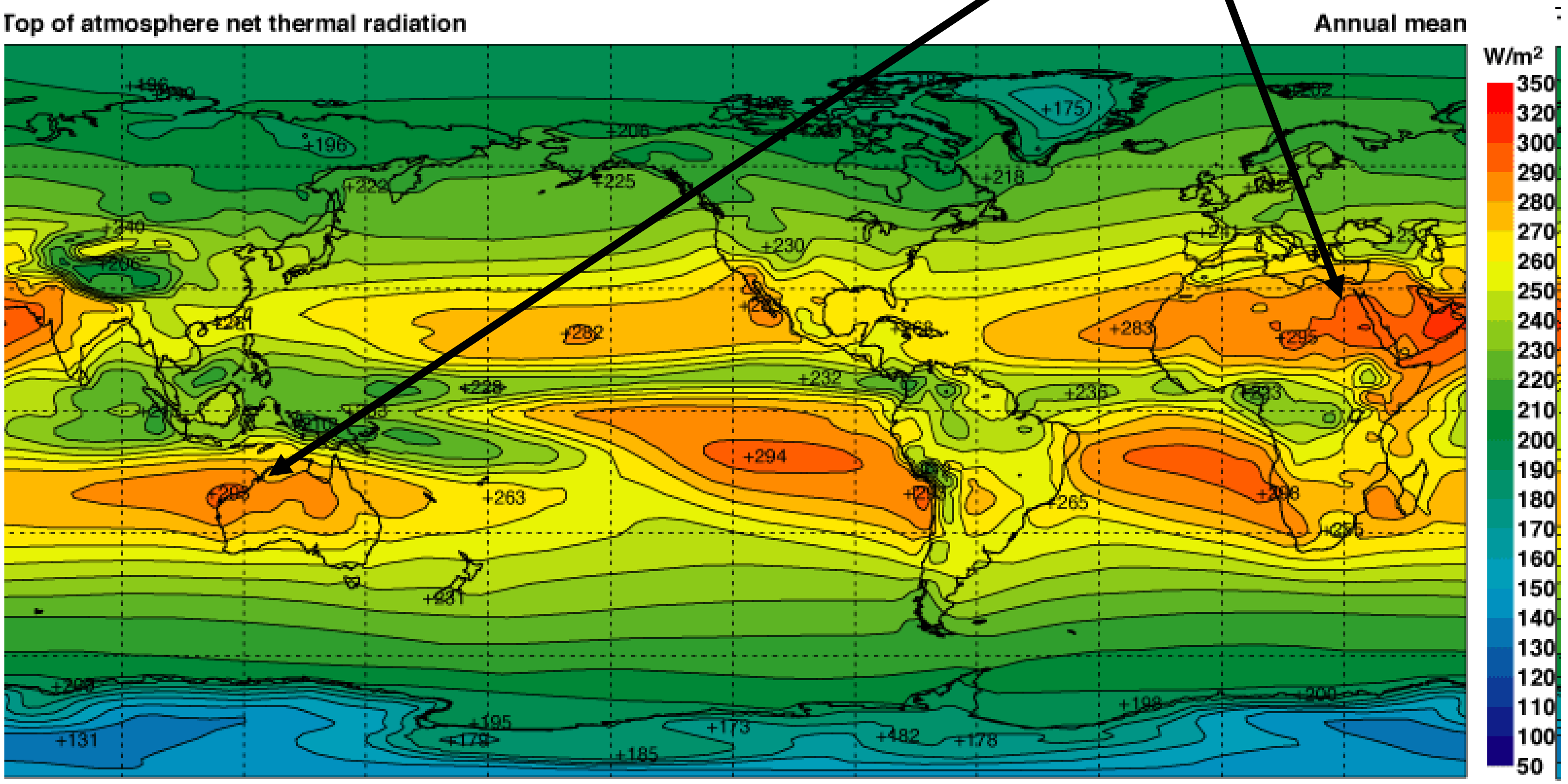
ECMWF, ERA40

Persistent high level clouds



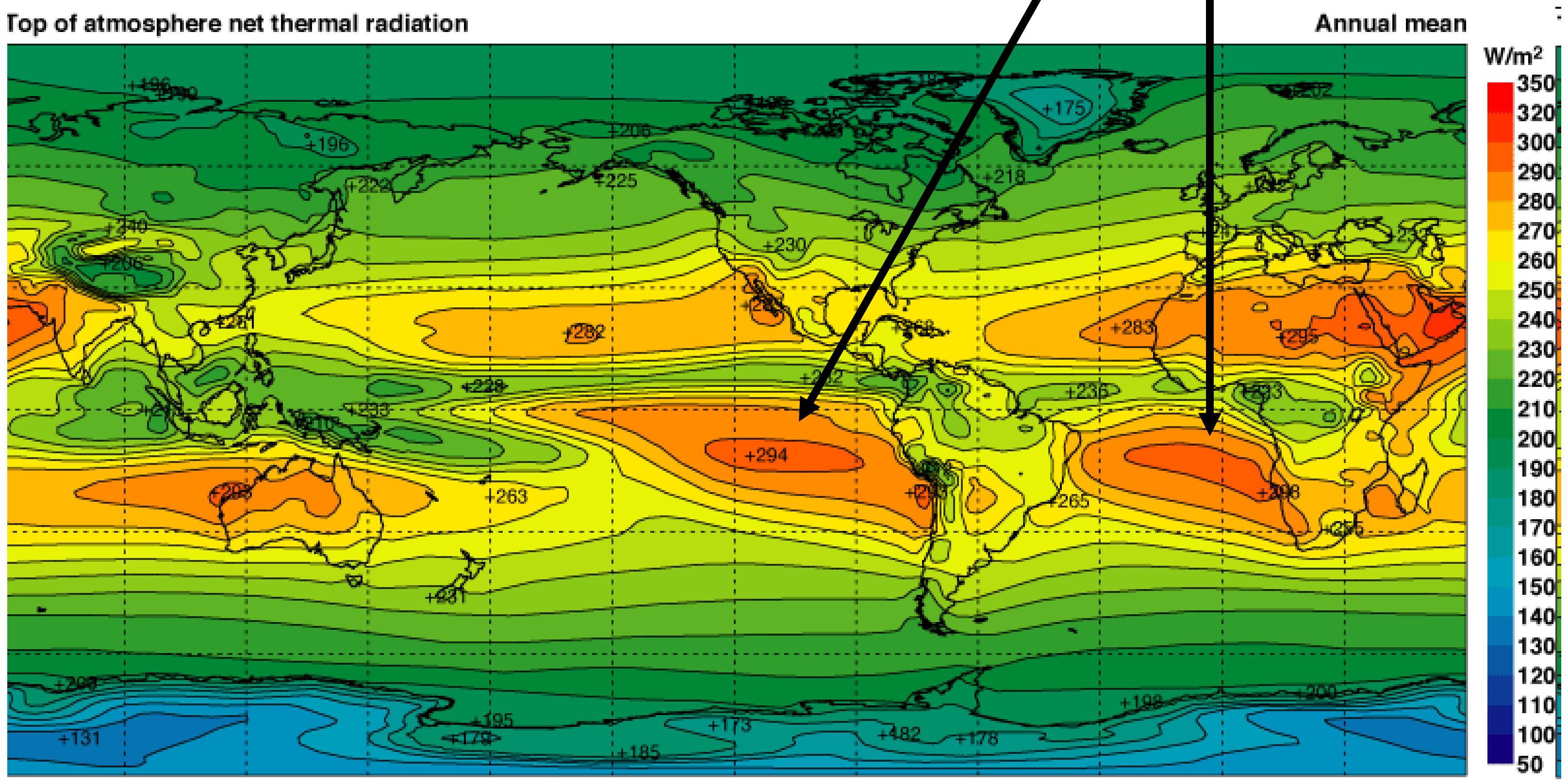
ECMWF, ERA40

Warm surface, dry atmosphere



ECMWF, ERA40

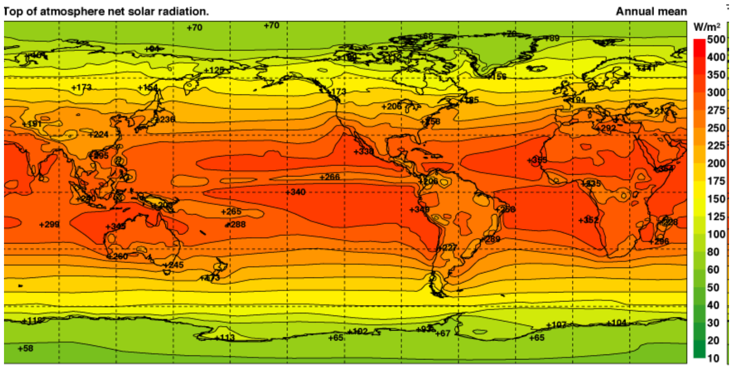
Tropical oceans, low cloudiness

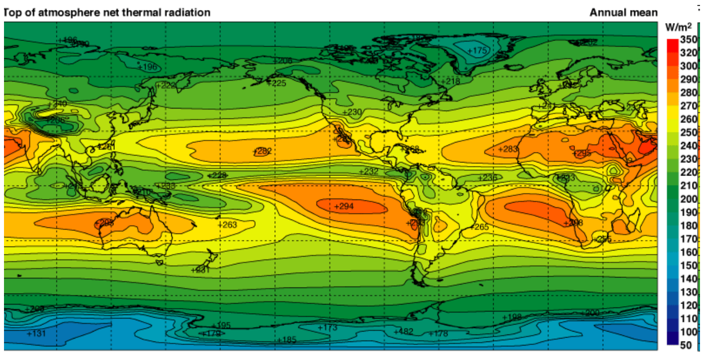


ECMWF, ERA40

Net incoming radiation

Absorbed solar … minus … emitted longwave





… and take average over latitude circles

Net incoming radiation

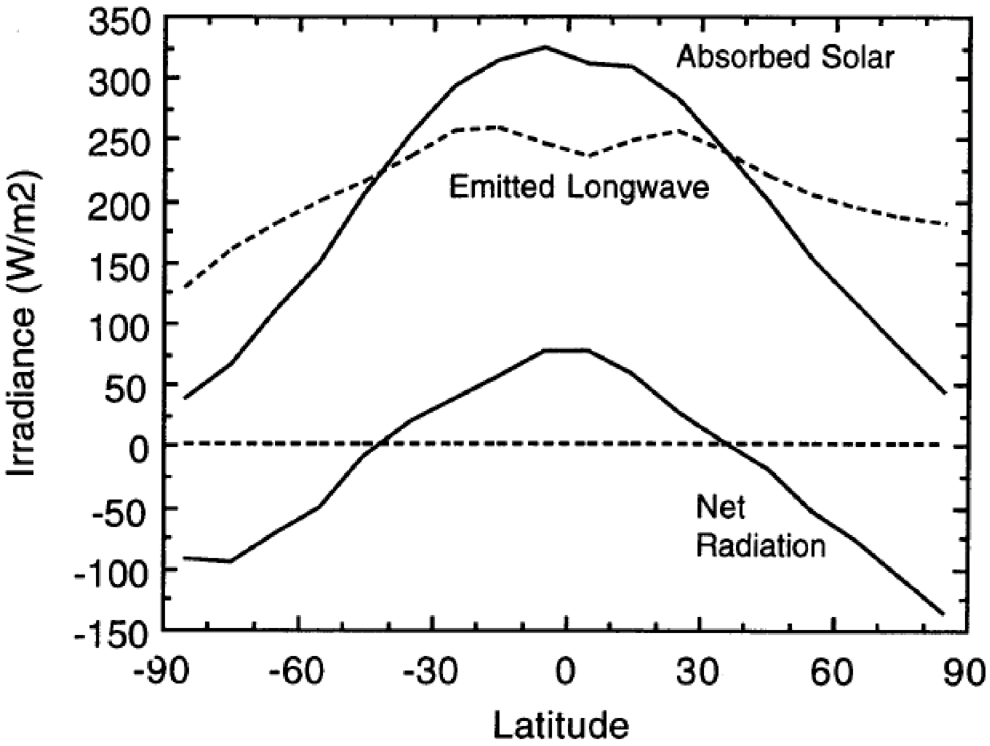


Fig. 2.12 Graphs of annual-mean absorbed solar radiation, OLR, and net radiation averaged around latitude circles.

Hartmann, 1994

Net incoming radiation

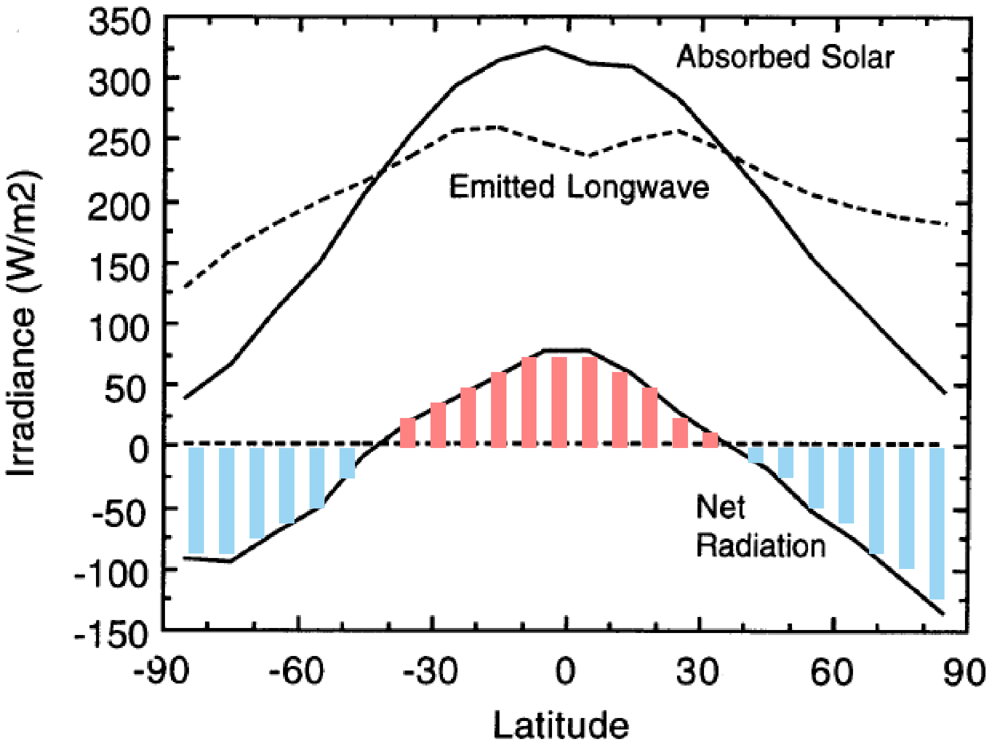


Fig. 2.12 Graphs of annual-mean absorbed solar radiation, OLR, and net radiation averaged around latitude circles.

Hartmann, 1994

… Poleward energy flux

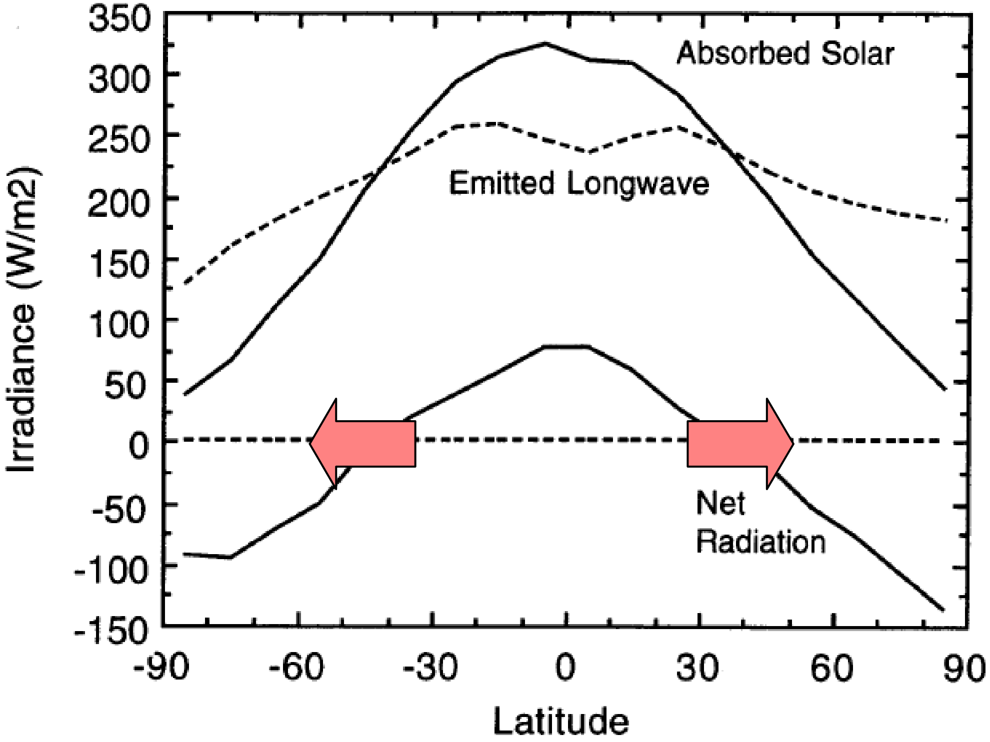


Fig. 2.12 Graphs of annual-mean absorbed solar radiation, OLR, and net radiation averaged around latitude circles.

Hartmann, 1994

Upper boundary condition

- **Conclusion**
  - Purely radiative
  - Relatively straightforward

2. Interaction with the underlying surface

- **Lower boundary condition of the atmosphere**
  - Physical balances of energy, momentum and water
  - Biogeochemical balances of
    - gases and vapours (CO2, VOCs, …)
    - particulate matter (aerosol)
  - Interactions with other Earth system components
  - Highly heterogenous surface properties

- **Next: surface balances of energy and momentum**

2. Surface energy balance

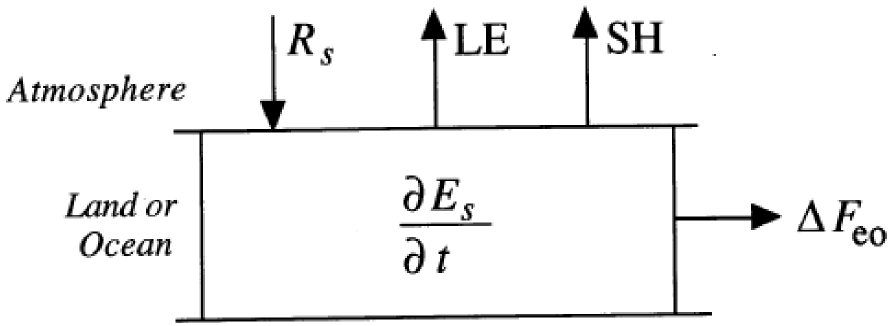
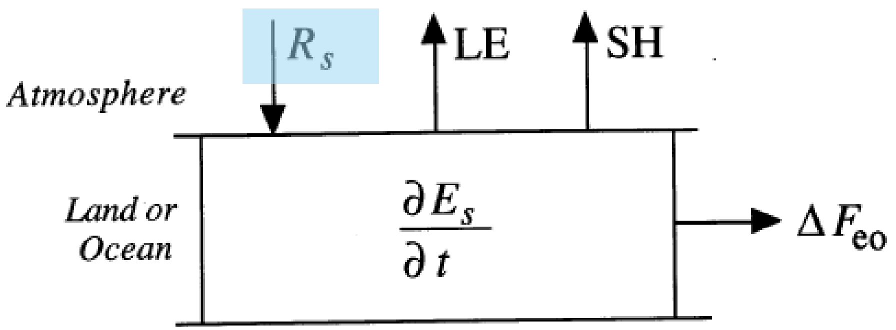


Fig. 4.1 Diagram showing the relationship of the various terms in the surface energy balance (R_s = net radiation, LE = evaporative cooling, SH = sensible cooling, $\partial E_s/\partial t$ = heat storage below the surface, ΔF_{eo} = divergence of horizontal energy flux below the surface).

Hartmann, 1994

2. Surface energy balance

Net radiative flux ↔ surface albedo variations



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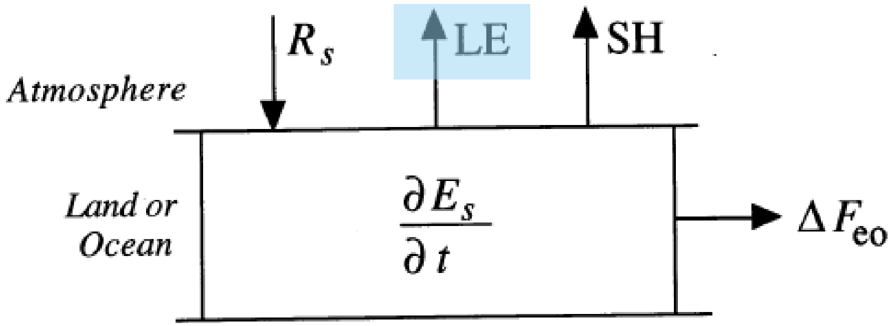
Hartmann, 1994

2. Surface energy balance

Latent heat flux ↔ hydrological cycle



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Hartmann, 1994

2. Surface energy balance

Net radiative flux ↔ **↔ hydrological cycle**

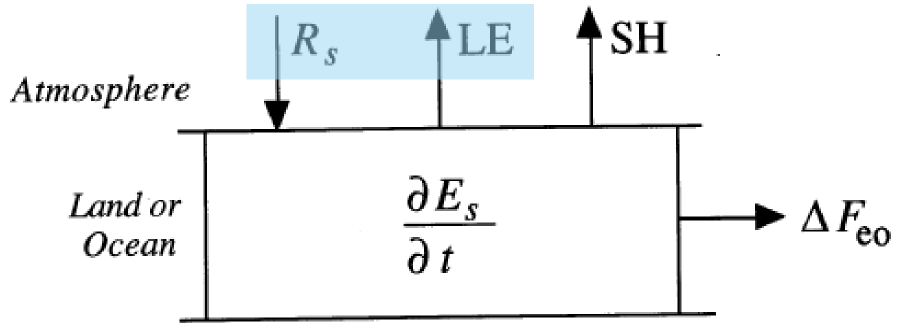


Fig. 4.1 Diagram showing the relationship of the various terms in the surface energy balance (R_s = net radiation, LE = evaporative cooling, SH = sensible cooling, $\partial E_s / \partial t$ = heat storage below the surface, ΔF_{eo} = divergence of horizontal energy flux below the surface).

Hartmann, 1994

2. Surface energy balance

- **Conclusion**
  - important for understanding the climate
  - far more complicated than the energy balance at the upper boundary

Surface momentum balance

Surface momentum balance

- **Angular momentum of the Earth system is conserved**

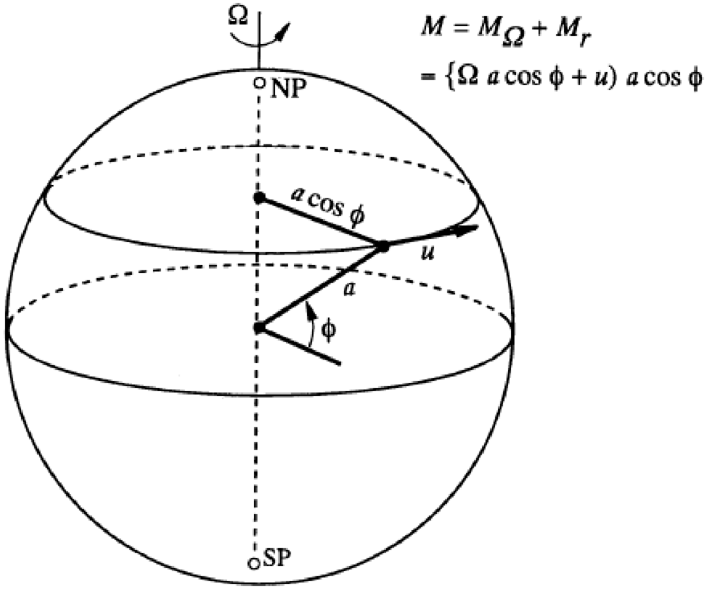


Fig. 6.14 Diagram showing the component of angular momentum about the axis of rotation of Earth. [From Peixóto and Oort (1984). Reprinted with permission from the American Physical Society.]

Conservation of angular momentum

- **No external torque**
- **Transfer of angular momentum to/from atmosphere via frictional forces and pressure forces acting on mountains**
- **Boundary layer processes are important**

Conservation of angular momentum

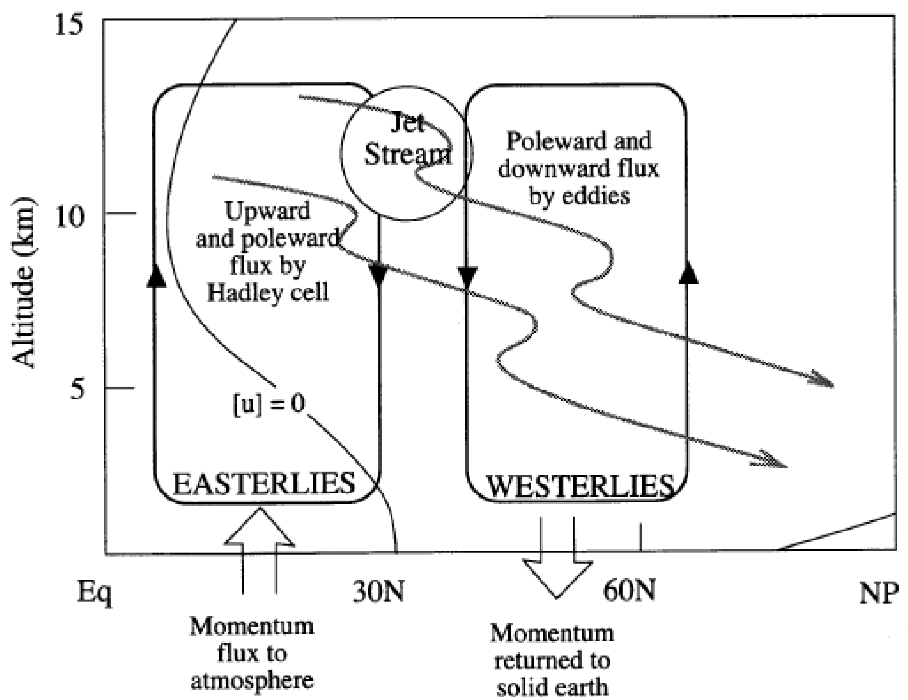


Fig. 6.16 Schematic illustration of the flow of angular momentum from Earth through the atmosphere and back to Earth.

Hartmann, 1994

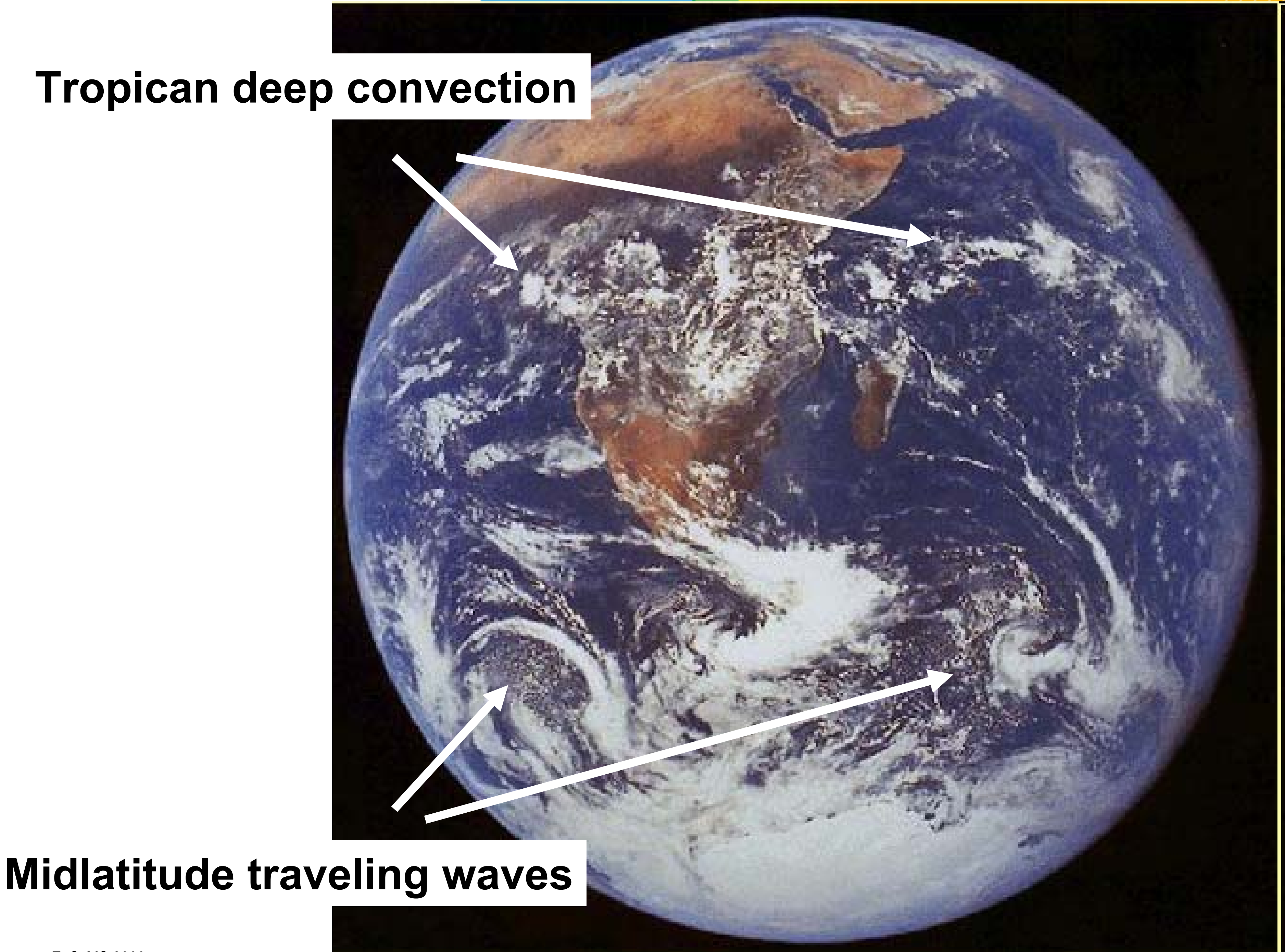
Conservation of angular momentum

- **Poses a strong constraint for the atmospheric general circulation**

  (For instance: westerly winds everywhere would drain the angular momentum of the atmosphere very soon)

3. Internal dynamics

Lee vortices downstream of Jan Mayen Island (NASA)


Tropican deep convection
Midlatitude traveling waves

Governing laws of atmospheric motions

Momentum conservation

$$\frac{\partial U}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial\lambda}+V\cos\theta\frac{\partial U}{\partial\theta}\right\}+\dot{\eta}\frac{\partial U}{\partial\eta}=fV-\frac{1}{a}\left\{\frac{\partial\varphi}{\partial\lambda}+RT_v\frac{\partial}{\partial\lambda}\ln p\right\}+P_u+K_u$$

$$\frac{\partial V}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial\lambda}+V\cos\theta\frac{\partial V}{\partial\theta}+\sin\theta(U^2+V^2)\right\}+\dot{\eta}\frac{\partial V}{\partial\eta}=-fV-\frac{\cos\theta}{a}\left\{\frac{\partial\varphi}{\partial\theta}+RT_v\frac{\partial}{\partial\theta}\ln p\right\}+P_v+K_v$$

Energy conservation

$$\frac{\partial T}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial\lambda}+V\cos\theta\frac{\partial T}{\partial\theta}\right\}+\dot{\eta}\frac{\partial T}{\partial\eta}=\frac{\kappa T_v\omega}{p}+P_T+K_T$$

Mass conservation

$$\frac{\partial}{\partial t}(\ln p_s)=-\frac{1}{p_s}\int_0^1\nabla\cdot\left(\mathbf{v}_h\frac{\partial p}{\partial\eta}\right)d\eta$$

Ideal gas law

$p=\rho RT$

Moisture equation

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial\lambda}+V\cos\theta\frac{\partial q}{\partial\theta}\right\}+\dot{\eta}\frac{\partial q}{\partial\eta}=P_q+K_q$$

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Governing laws of atmospheric motions

Momentum conservation

$$\frac{\partial U}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda}+V\cos\theta\frac{\partial U}{\partial \theta}\right\}+\dot{\eta}\frac{\partial U}{\partial \eta}=fV-\frac{1}{a}\left\{\frac{\partial \varphi}{\partial \lambda}+RT_v\frac{\partial}{\partial \lambda}\ln p\right\}+P_u+K_u$$

$$\frac{\partial V}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda}+V\cos\theta\frac{\partial V}{\partial \theta}+\sin\theta(U^2+V^2)\right\}+\dot{\eta}\frac{\partial V}{\partial \eta}=-fV-\frac{\cos\theta}{a}\left\{\frac{\partial \varphi}{\partial \theta}+RT_v\frac{\partial}{\partial \theta}\ln p\right\}+P_v+K_v$$

Energy conservation

$$\frac{\partial T}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda}+V\cos\theta\frac{\partial T}{\partial \theta}\right\}+\dot{\eta}\frac{\partial T}{\partial \eta}=\frac{\kappa T_v\omega}{p}+P_T+K_T$$

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Moisture equation

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda}+V\cos\theta\frac{\partial q}{\partial \theta}\right\}+\dot{\eta}\frac{\partial q}{\partial \eta}=P_q+K_q$$

Coupled system of Partial differential equations

Governing laws of atmospheric motions

Momentum conservation

$$\frac{\partial U}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda}+V\cos\theta\frac{\partial U}{\partial \theta}\right\}+\dot{\eta}\frac{\partial U}{\partial \eta}=fV-\frac{1}{a}\left\{\frac{\partial \varphi}{\partial \lambda}+RT_v\frac{\partial}{\partial \lambda}\ln p\right\}+P_u+K_u$$

$$\frac{\partial V}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda}+V\cos\theta\frac{\partial V}{\partial \theta}+\sin\theta(U^2+V^2)\right\}+\dot{\eta}\frac{\partial V}{\partial \eta}=-fV-\frac{\cos\theta}{a}\left\{\frac{\partial \varphi}{\partial \theta}+RT_v\frac{\partial}{\partial \theta}\ln p\right\}+P_v+K_v$$

Energy conservation

$$\frac{\partial T}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda}+V\cos\theta\frac{\partial T}{\partial \theta}\right\}+\dot{\eta}\frac{\partial T}{\partial \eta}=\frac{\kappa T_v\omega}{p}+P_T+K_T$$

Mass conservation

$$\frac{\partial}{\partial t}(\ln p_s)=-\frac{1}{p_s}\int_0^1\nabla\cdot\left(\mathbf{v}_h\frac{\partial p}{\partial \eta}\right)d\eta$$

Non-linear

Ideal gas law

$p=\rho RT$

Moisture equation

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda}+V\cos\theta\frac{\partial q}{\partial \theta}\right\}+\dot{\eta}\frac{\partial q}{\partial \eta}=P_q+K_q$$

Governing laws of atmospheric motions

Momentum conservation

$$\frac{\partial U}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial\lambda}+V\cos\theta\frac{\partial U}{\partial\theta}\right\}+\dot{\eta}\frac{\partial U}{\partial\eta}=fV-\frac{1}{a}\left\{\frac{\partial\varphi}{\partial\lambda}+RT_v\frac{\partial}{\partial\lambda}\ln p\right\}+P_u+K_u$$

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Energy conservation

$$\frac{\partial T}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial\lambda}+V\cos\theta\frac{\partial T}{\partial\theta}\right\}+\dot{\eta}\frac{\partial T}{\partial\eta}=\frac{\kappa T_v\omega}{p}+P_T+K_T$$

Mass conservation

$$\frac{\partial}{\partial t}(\ln p_s)=-\frac{1}{p_s}\int_0^1\nabla\cdot\left(\mathbf{v}_h\frac{\partial p}{\partial\eta}\right)d\eta$$

Dissipative

Ideal gas law

$p=\rho RT$

Moisture equation

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial\lambda}+V\cos\theta\frac{\partial q}{\partial\theta}\right\}+\dot{\eta}\frac{\partial q}{\partial\eta}=P_q+K_q$$

Governing laws of atmospheric motions

Momentum conservation

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Energy conservation

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Mass conservation

$$\frac{\partial}{\partial t}(\ln p_s)=-\frac{1}{p_s}\int_0^1\nabla\cdot\left(\mathbf{v}_h\frac{\partial p}{\partial \eta}\right)d\eta$$

Forced

Ideal gas law

$p=\rho RT$

Moisture equation

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda}+V\cos\theta\frac{\partial q}{\partial \theta}\right\}+\dot{\eta}\frac{\partial q}{\partial \eta}=P_q+K_q$$

Governing laws of atmospheric motions

Momentum conservation

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$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2+V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} = -fV - \frac{\cos\theta}{a}\left\{\frac{\partial \varphi}{\partial \theta} + RT_v\frac{\partial}{\partial \theta}\ln p\right\} + P_v + K_v$$

Energy conservation

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \lambda} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} = \frac{\kappa T_v \omega}{p} + P_T + K_T$$

Mass conservation

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Ideal gas law

$p = \rho RT$

Moisture equation

$$\frac{\partial q}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} + \dot{\eta}\frac{\partial q}{\partial \eta} = P_q + K_q$$

Chaotic

=

Deterministic non-periodic flow

… Poleward energy flux

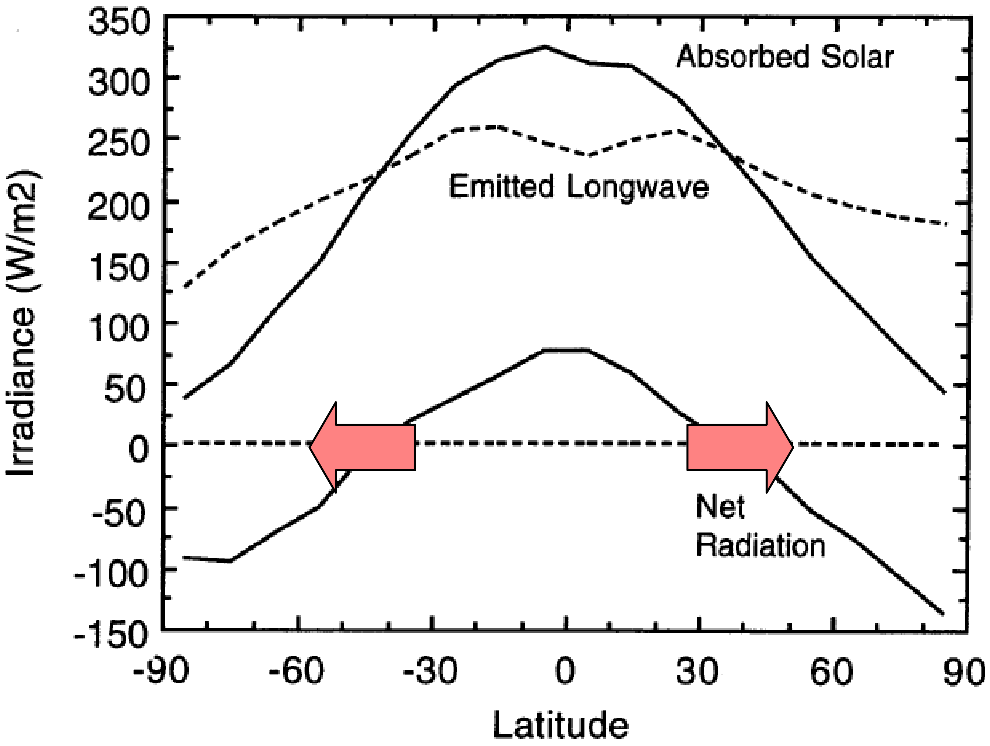


Fig. 2.12 Graphs of annual-mean absorbed solar radiation, OLR, and net radiation averaged around latitude circles.

Hartmann, 1994

… Poleward energy flux

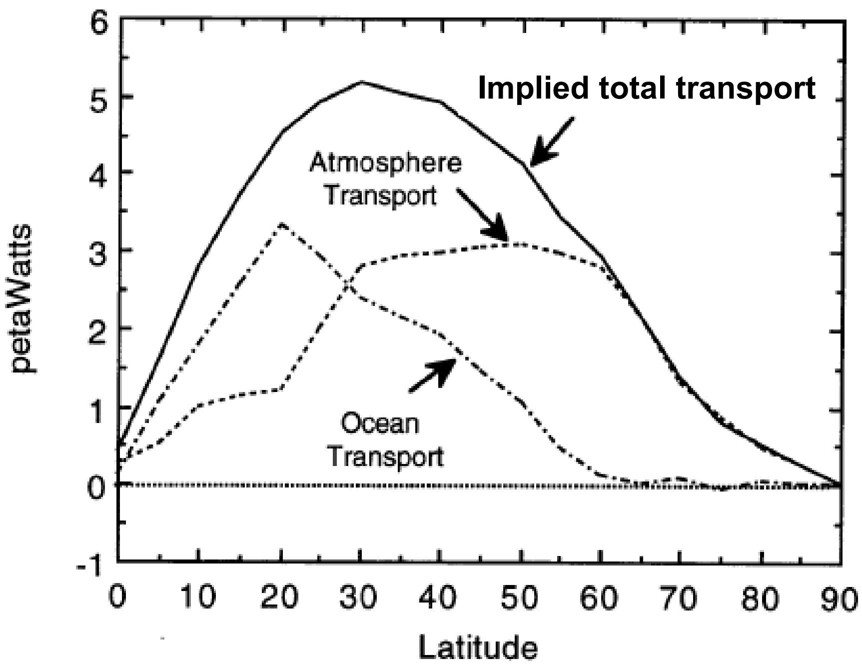


Fig. 2.14 Meridional transport of energy for annual-mean conditions. Net radiation and atmospheric transport are estimated from observations; ocean transport is calculated as a residual in the energy balance. [Adapted from Vonder Haar and Oort (1973). Used with permission from the American Meteorological Society.]

Hartmann, 1994

… Poleward energy flux

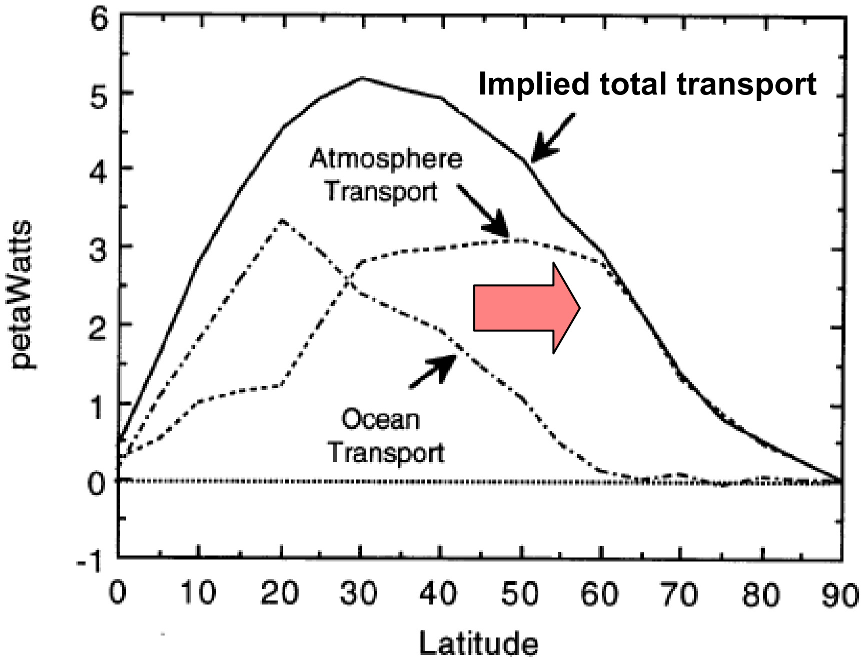
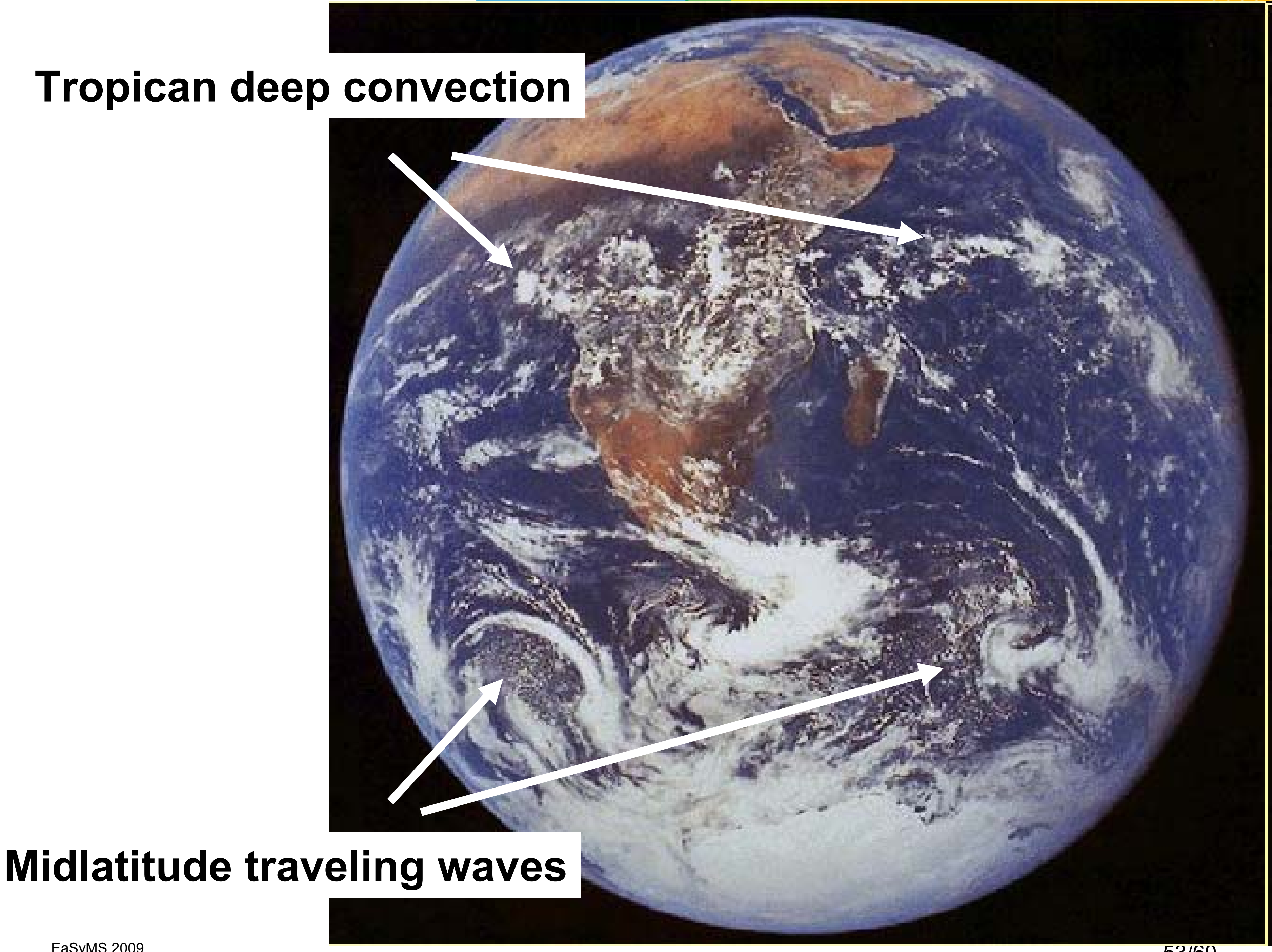


Fig. 2.14 Meridional transport of energy for annual-mean conditions. Net radiation and atmospheric transport are estimated from observations; ocean transport is calculated as a residual in the energy balance. [Adapted from Vonder Haar and Oort (1973). Used with permission from the American Meteorological Society.]

Hartmann, 1994


Tropican deep convection
Midlatitude traveling waves

… Poleward energy flux

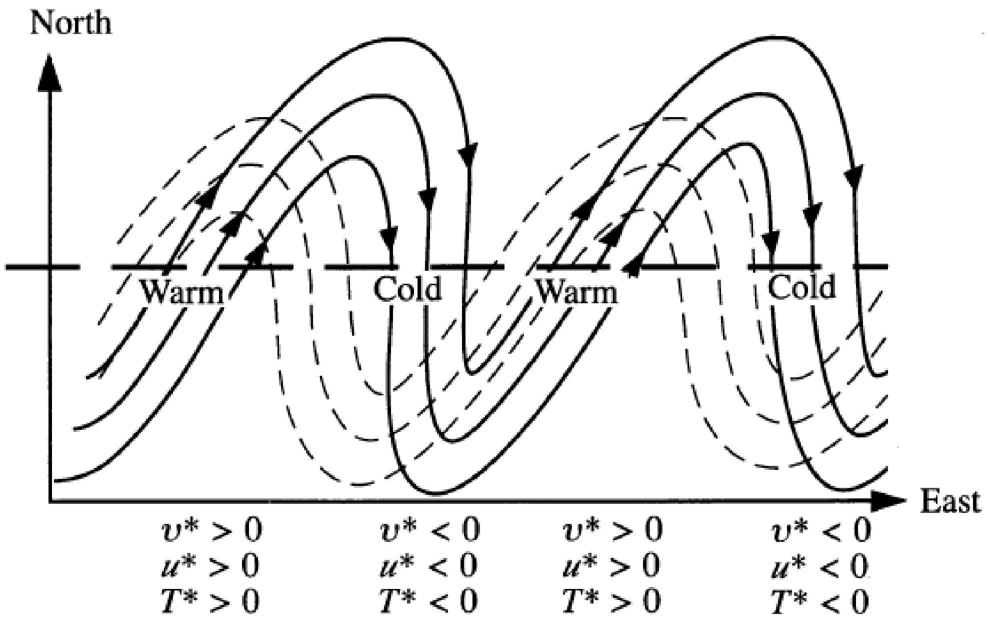
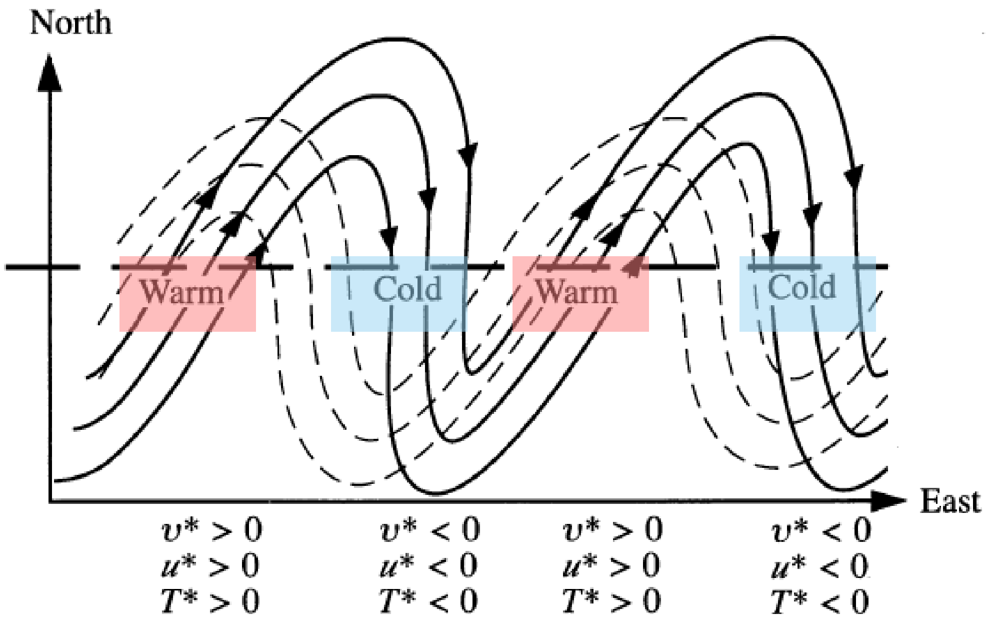


Fig. 6.6 Schematic of the streamlines (solid) and isotherms (dashed) associated with a large-scale atmospheric disturbance in midlatitudes of the Northern Hemisphere. Arrows along the streamline contour indicate the direction of wind velocity. The streamlines correspond approximately to lines of constant pressure, since the winds are nearly geostrophic. The signs of the deviations of the wind components from their zonal-average values are shown to illustrate that the NE–SW tilt of the streamlines indicates a northward zonal momentum transport, and the westward phase shift of the temperature wave relative to the pressure wave gives a northward heat transport.

Hartmann, 1994

… Poleward energy flux



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Hartmann, 1994

… Poleward momentum flux

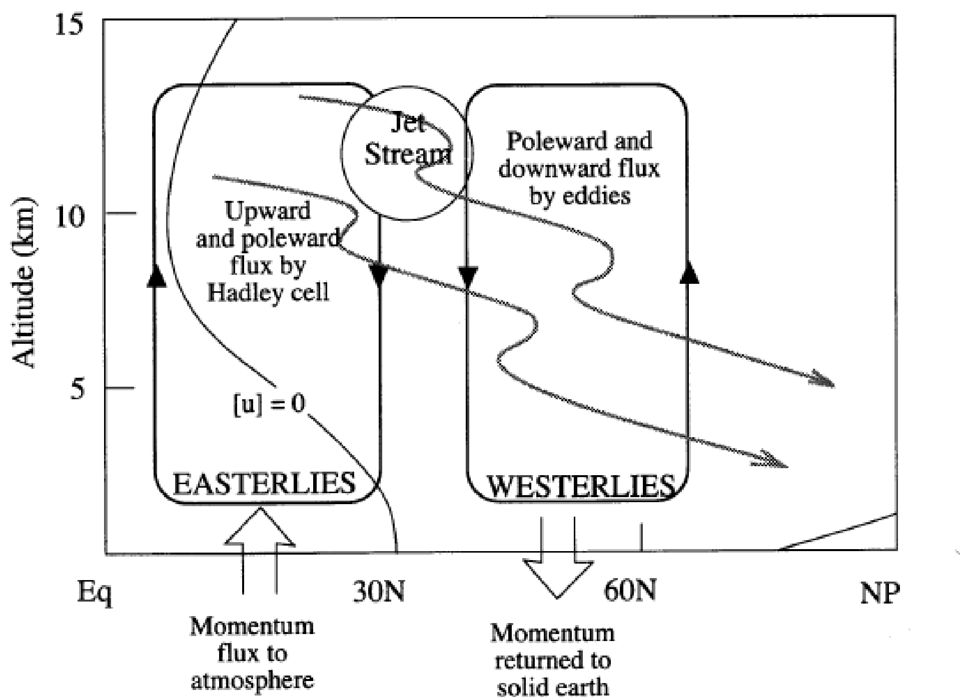


Fig. 6.16 Schematic illustration of the flow of angular momentum from Earth through the atmosphere and back to Earth.

Poleward fluxes of energy and momentum

- **Mid-latitude traveling waves (”depressions”)**
- **Especially in the Southern Hemisphere where stationary waves are weak**

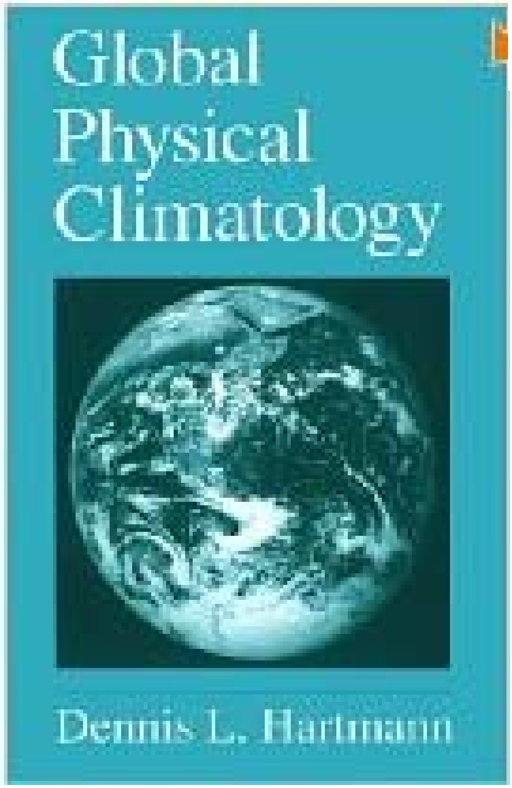
4. Concluding remarks

1. **Interaction with the surrounding Universe**
   - Upper boundary condition for the Earth system
2. **Interaction with the underlying surface**
   - Lower boundary condition for the atmosphere
   - Non-linear interaction with other Earth system components
3. **Internal dynamics**

→ **Approaches for Earth system model validation**

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Reference



ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

heikki.jarvinen@fmi.fi