4. Mean zonal-meridional circulations: 4.1-a. Differential heating

Variability of the atmosphere: $\boxed{\text{Vertical } (z) \gg \text{Meridional } (y)} \gg \text{Zonal } (x)$

$\uparrow$ gravity — $\uparrow$ solar radiation, $\uparrow$ Coriolis parameter — $\uparrow$ topography

stronger diurnal $\longleftrightarrow$ weaker annual

Meridional structure (geographic): tropics, temperate, frigid

0 $\longleftrightarrow$ stronger

(Eulerian-) zonal mean and disturbance: (λ: longitude, $a = 6.37 \times 10^6$ m: Earth's radius)

$$\overline{(\quad)} \equiv \frac{1}{2\pi}\int_0^{2\pi} (\quad) d\lambda = \frac{1}{2\pi a}\int_0^{2\pi a} (\quad) dx\,, \qquad (\quad)' \equiv (\quad) - \overline{(\quad)} \tag{22}$$

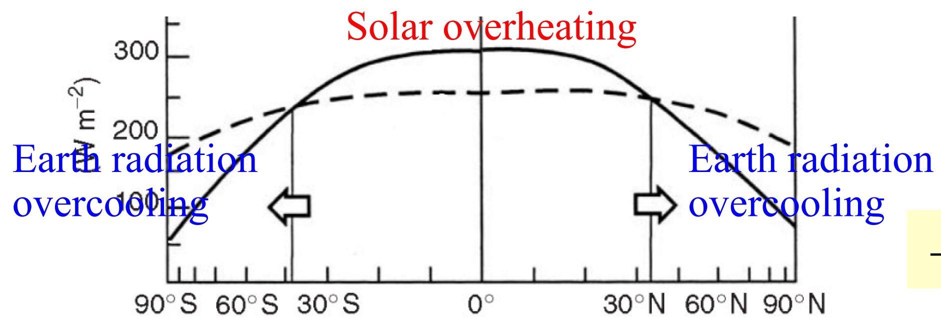


Figure 7 Annual-mean net incoming solar radiation (solid line) and outgoing terrestrial radiation (dashed line) as a function of latitude, expressed in units of W m^{-2}. Distance on the latitude scale is proportional to area on the Earth's surface. (Diagram provided by Socorro Medina.)

→ Poleward atmospheric and oceanic heat transport

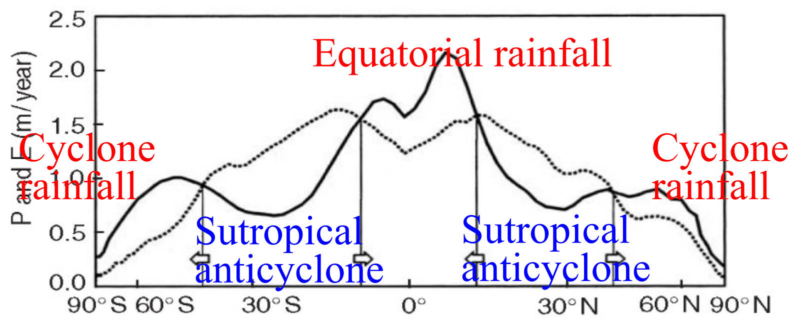
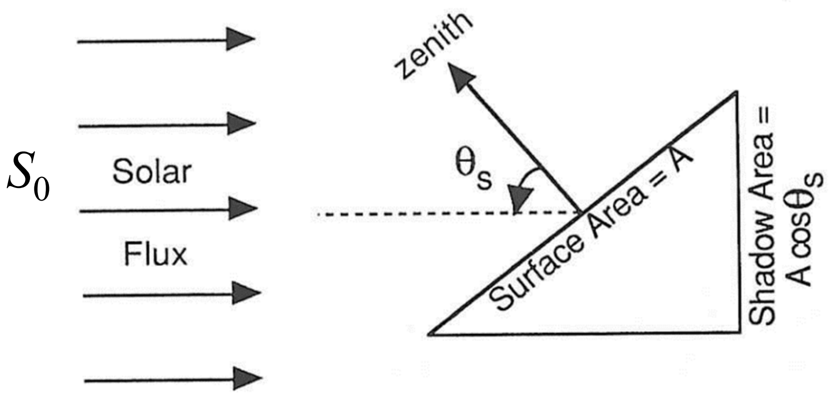


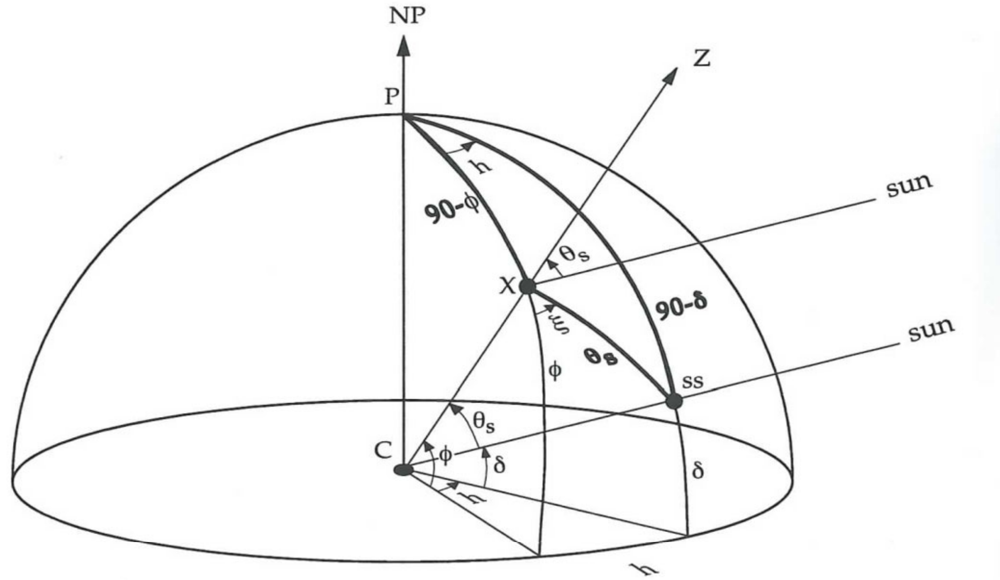
Figure 10 Annual-mean precipitation (solid) and evaporation (dashed) as a function of latitude, expressed in units of meters per year. Distance on the latitude scale is proportional to area on the Earth's surface. Based on NCEP/NCAR Reanalyses for the period 1958–1997. (Diagram provided by Socorro Medina.)

→ Equatorward water vepor transport

(Wallace, 2005)

2-dimensional climate: Meridional-seasonal





$$Q = S_0 \left(\frac{\bar{d}}{d} \right)^2 \cos \theta_s$$

$$\cos\theta_s = \cos(90-\phi)\cos(90-\delta) + \sin(90-\phi)\sin(90-\delta)\cos h$$

(d: Solar distance, given by Kepler' s eqation)

$$\cos \theta_s = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h$$

$$\frac{\sin(180-\xi)}{\sin(90-\delta)} = \frac{\sin h}{\sin \theta_s}$$

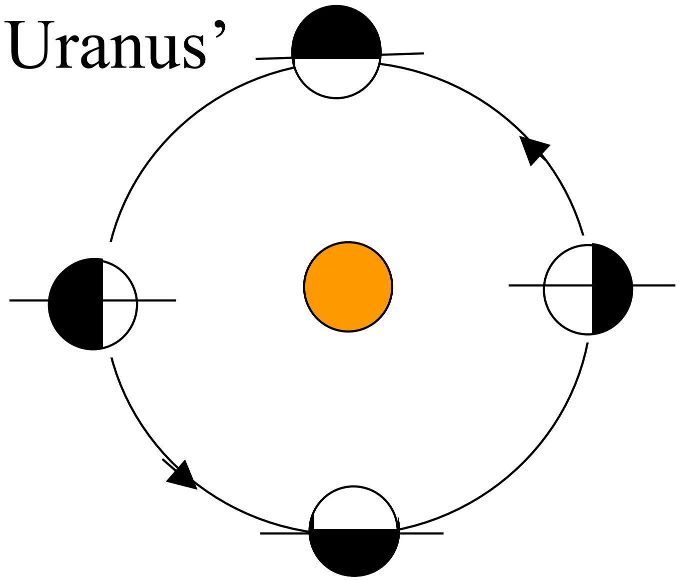
$$\cos h_0 = -\tan \phi \tan \delta$$

$$\sin \xi = \frac{\cos\delta \sin h}{\sin \theta_s}$$

$$\boxed{\overline{Q}^{\,\mathrm{day}} = \frac{S_0}{\pi} \left(\frac{\bar{d}}{d} \right)^2 \left[h_0 \sin\phi \sin\delta + \cos\phi\cos\delta \sin h_0 \right]}$$

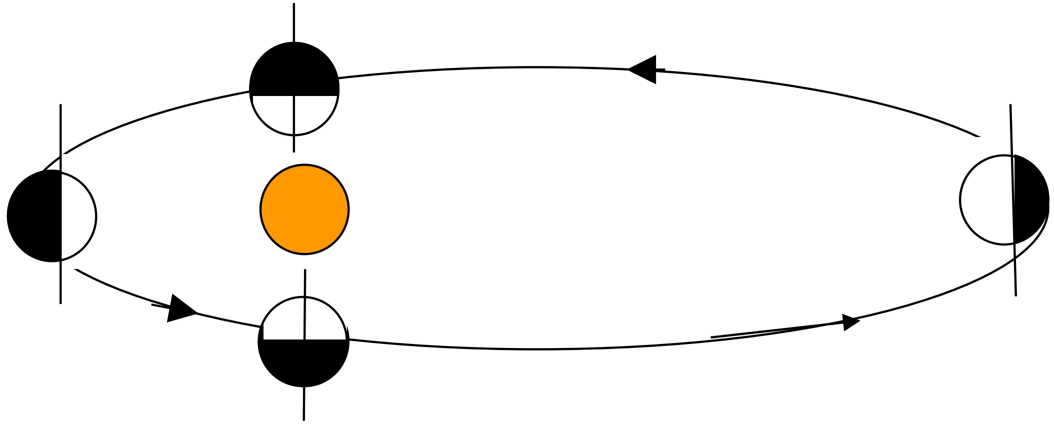
Two extreme cases of seasonal cycle forcing

'Uranus'

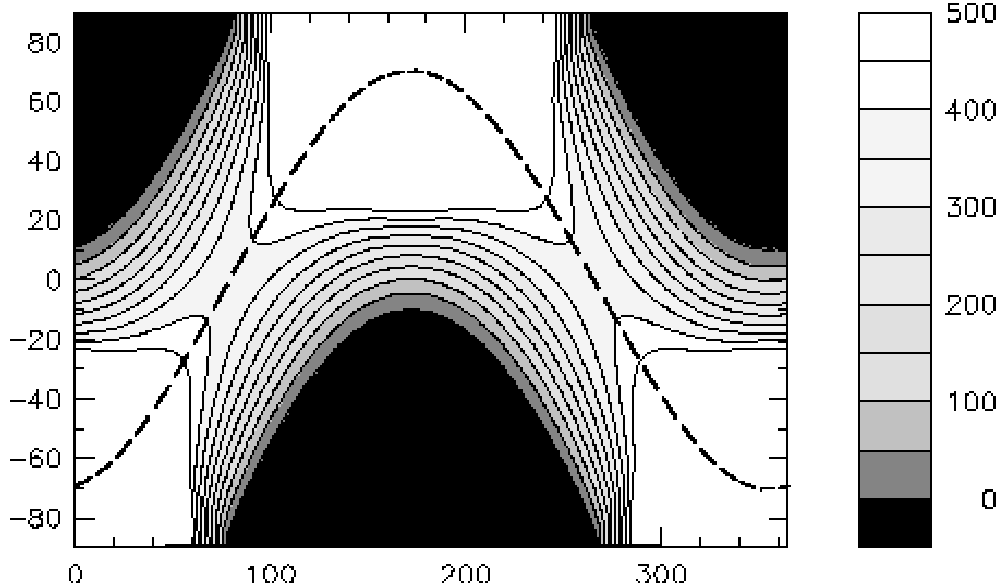


Rotation-axis obliquity

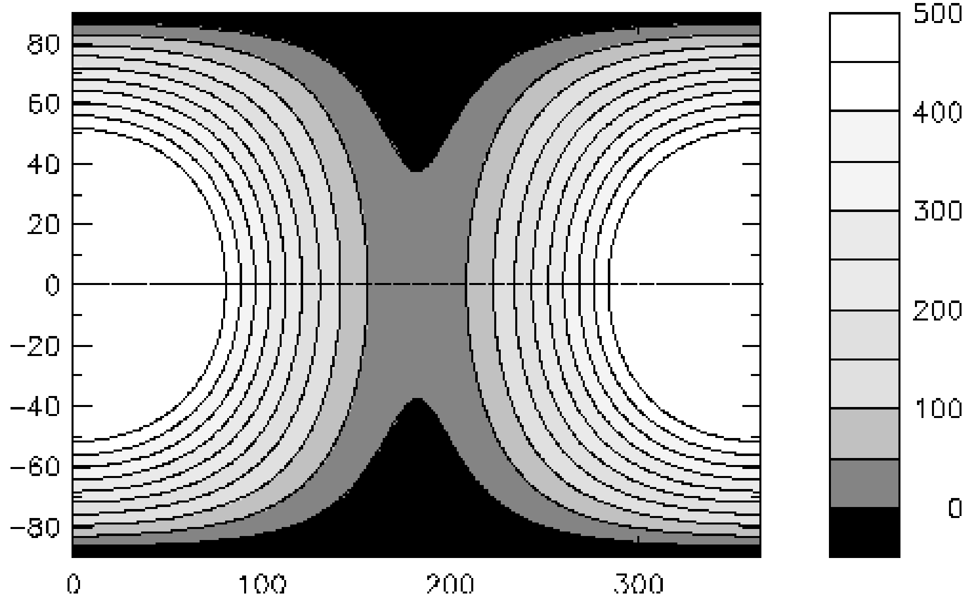
'a type of extra-solar planet'



Orbital eccentricity

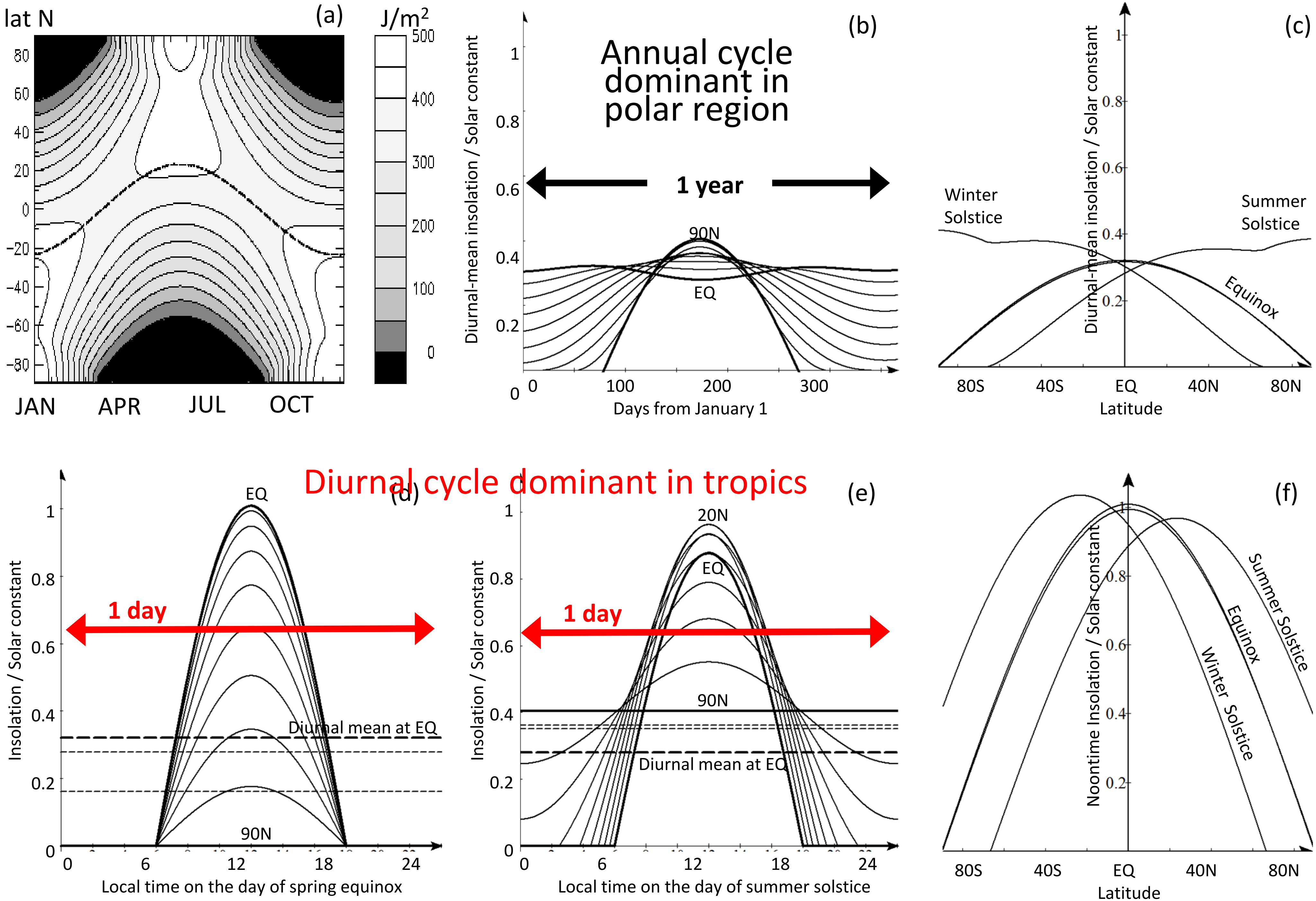


Hemispherically anti-phase



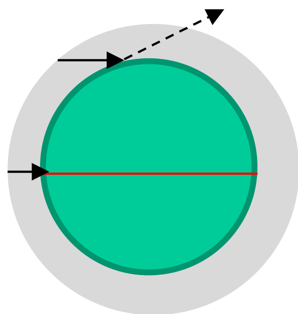
Hemispherically in-phase

Solar heating on earth with revolution and rotation



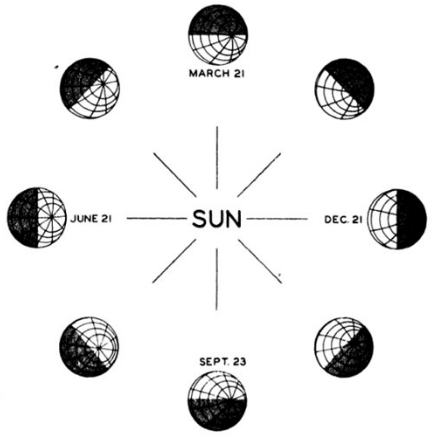
Why tropics is tropics?

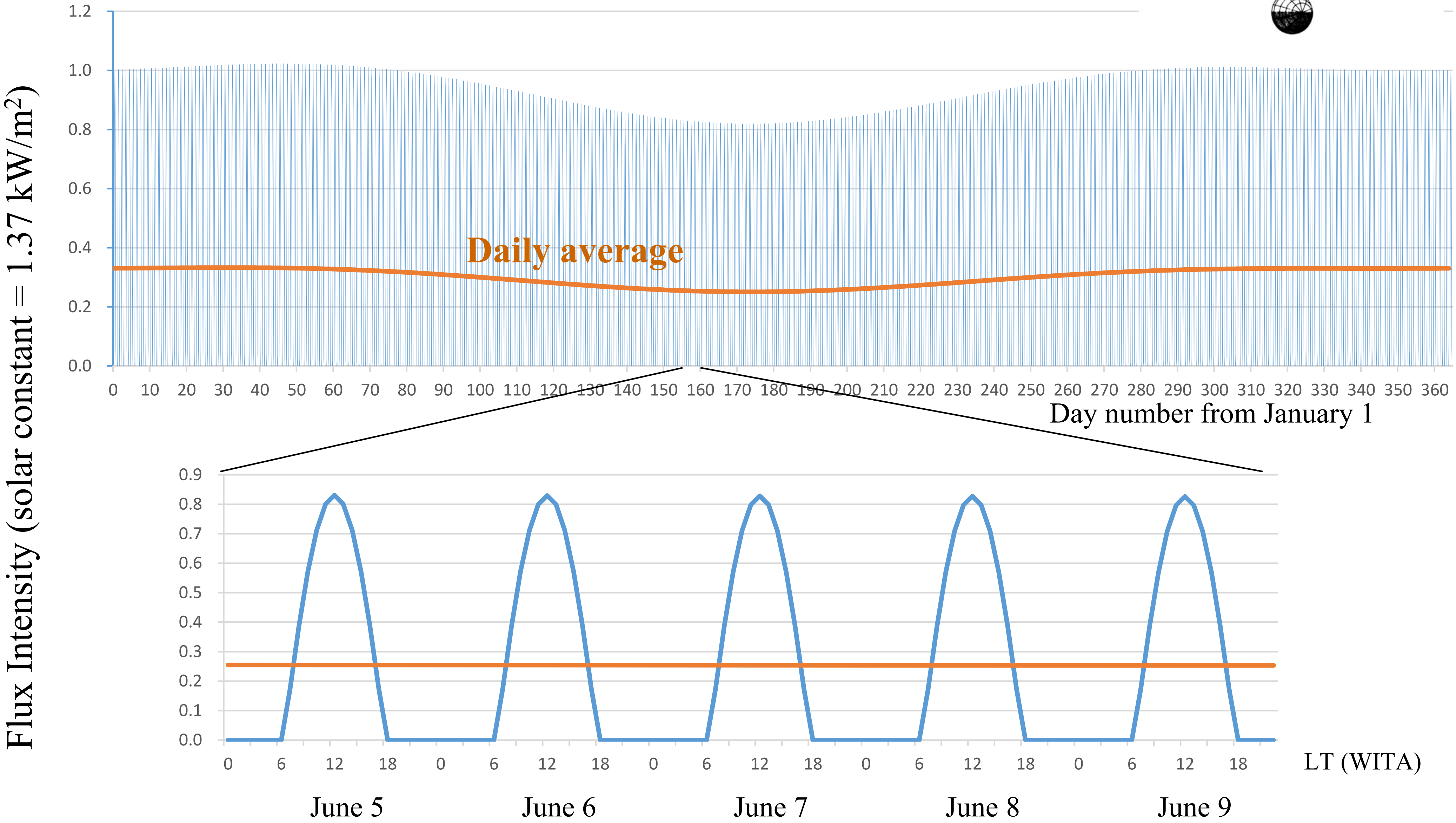
- High latitudes: Low solar angle
  - Large reflection (strong albedo)
  - Large refraction (long optical depth)
  - → Low temperature → Cryosphere/Clouds



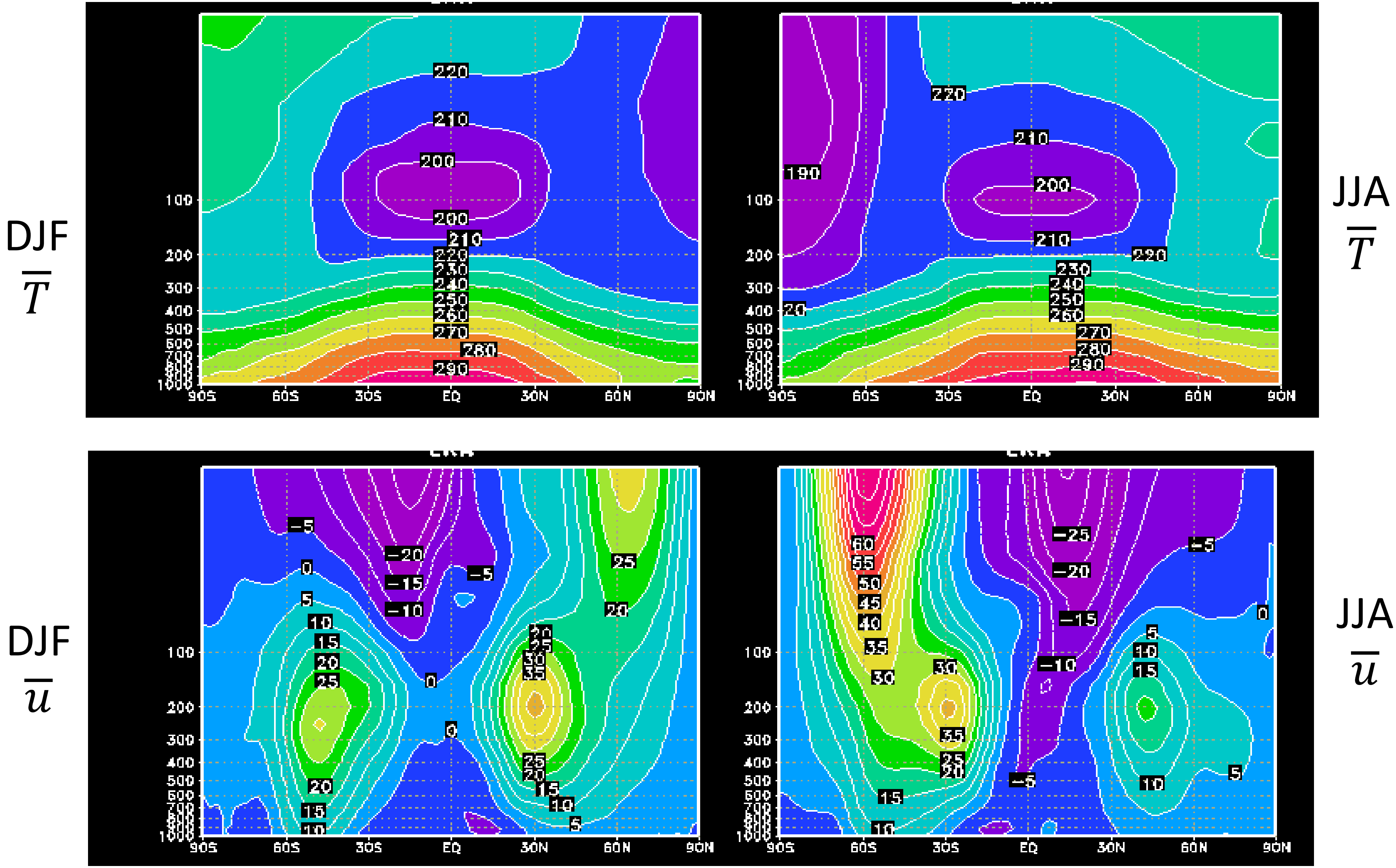
- Rapid rotation &
  Slow circular revolution
  - Zonal homogeneity
  - Weak hemispheric anti-symmetry

Solar radiation heating at the atmosphere top over Denpasar (8º39’S)

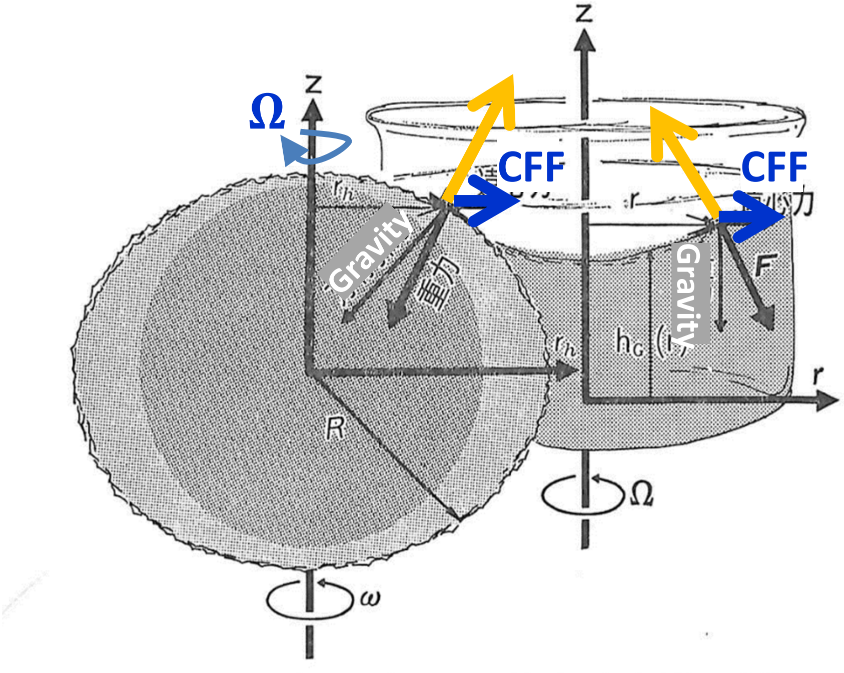




4.1-c Trade wind (Equatorial easterly & mid-latitude westerly)



Rotating fluid and centrifugal/Coriolis forces



"Thermal wind" equilibrium

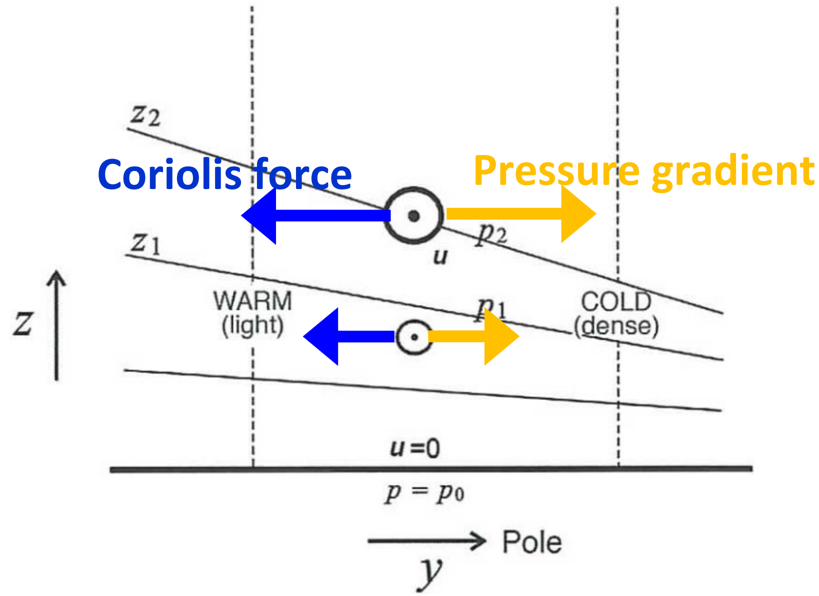
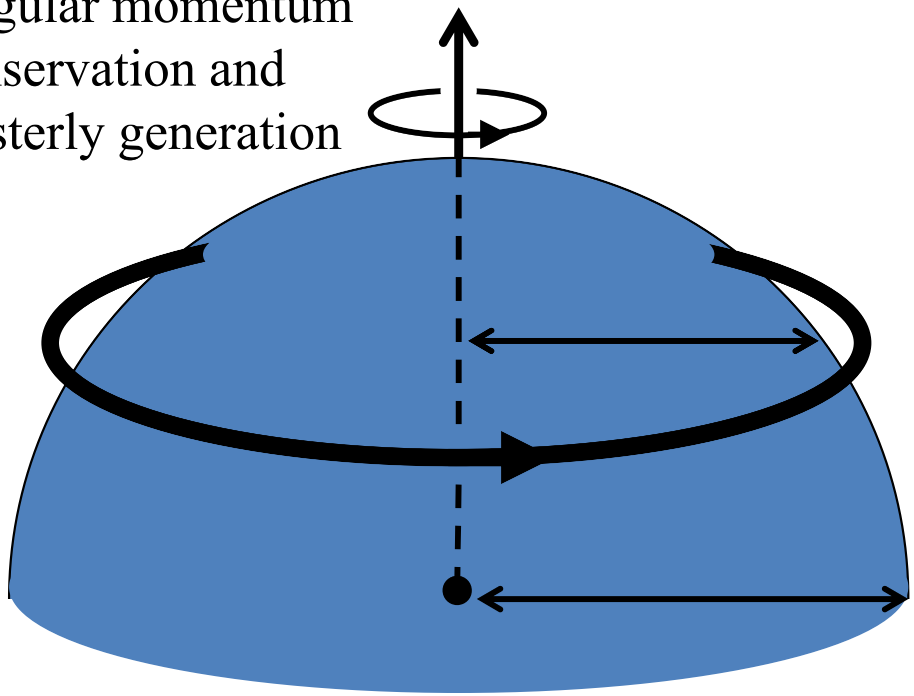


FIGURE 5.14. Warm columns of air expand, cold columns contract, leading to a tilt of pressure surfaces, a tilt which typically increases with height in the troposphere. In Section 7.3, we will see that the corresponding winds are out of the paper, as marked by ⊙ in the figure. (Marshall & Plumb, 2009)

Angular momentum conservation and westerly generation



"Keirin" circuit

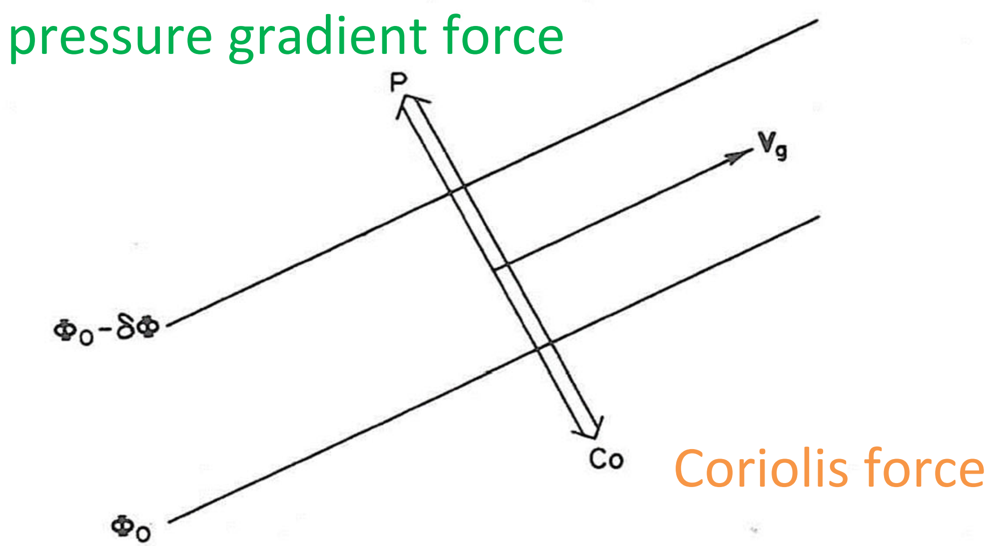


Fig. 3.2 Balance of forces for geostrophic equilibrium. The pressure gradient force is designated by *P* and the Coriolis force by *Co*.

(Holton, 1972)

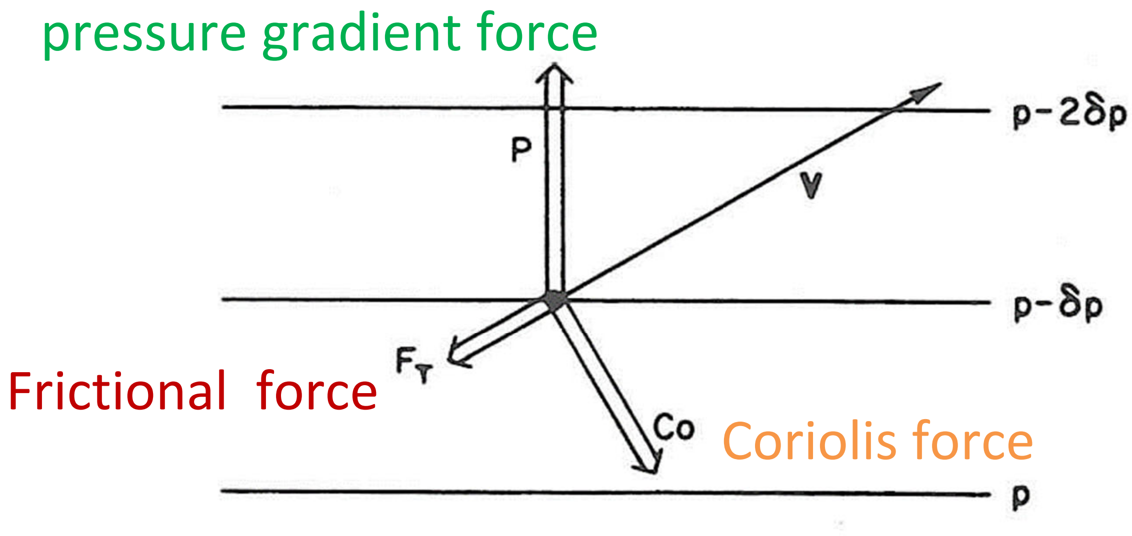


Fig. 5.3 Balance of forces in the well-mixed planetary boundary layer: *P* designat gradient force, Co the Coriolis force, and F_T the turbulent drag.

Upper ocean
(Marshall & Plumb, 2008)

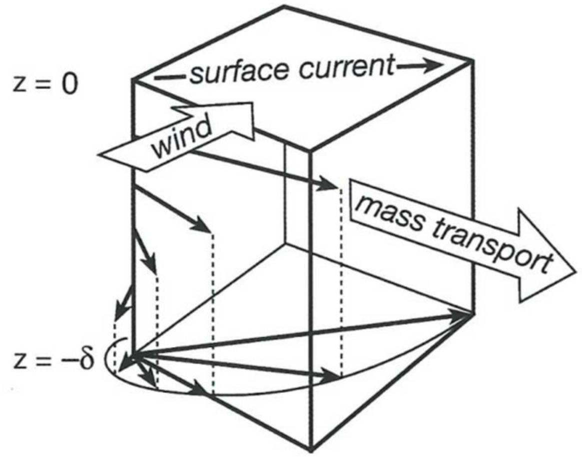
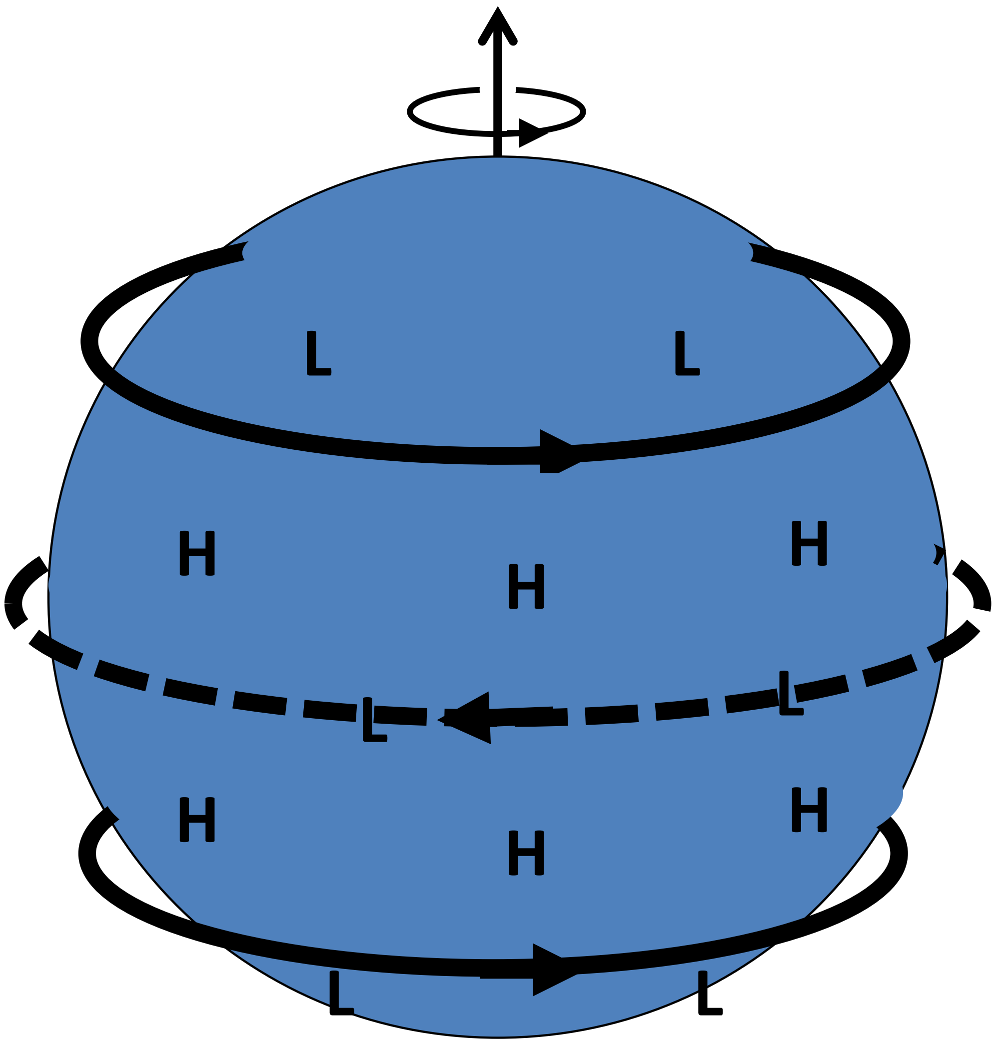
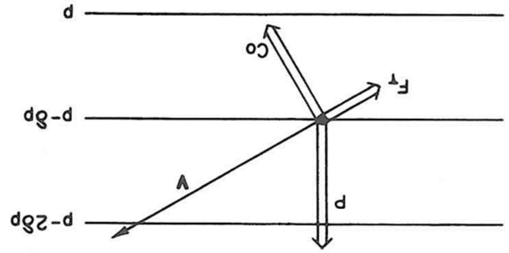


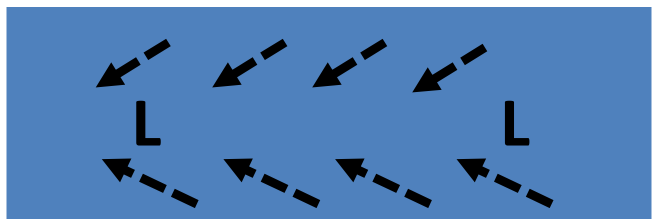
FIGURE 10.5. The mass transport of the Ekman layer is directed to the right of the wind in the northern hemisphere (see Eq. 10-5). Theory suggests that horizontal currents, u_{ag}, within the Ekman layer spiral with depth as shown.

Geostrophic and surface (frictional) flow

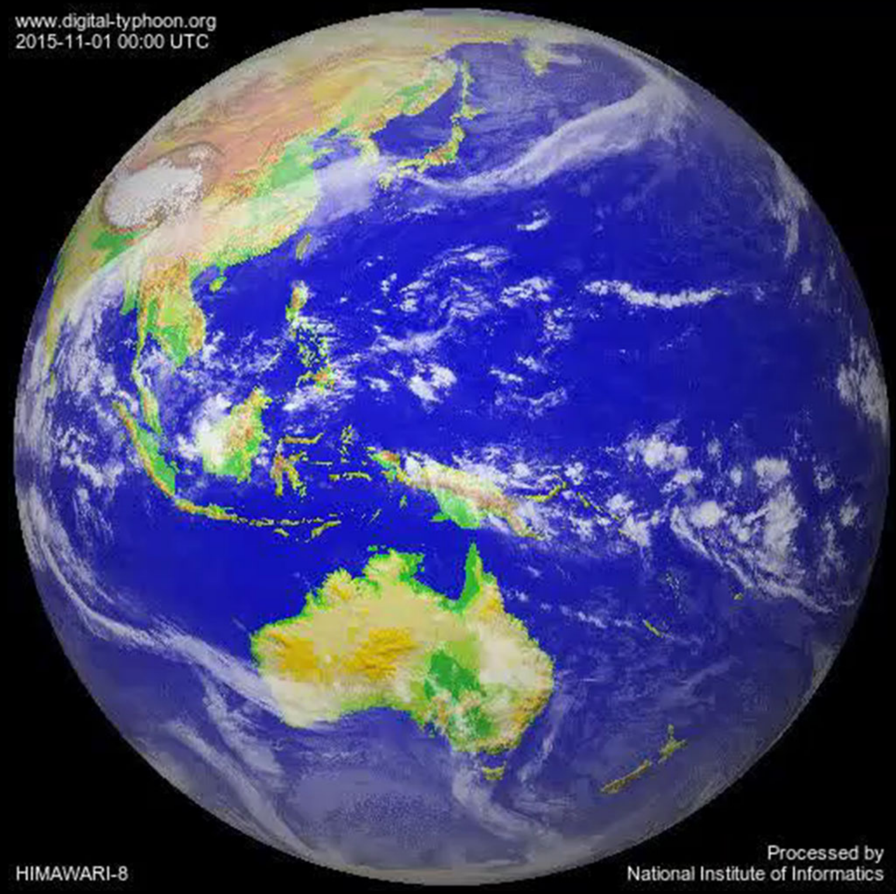




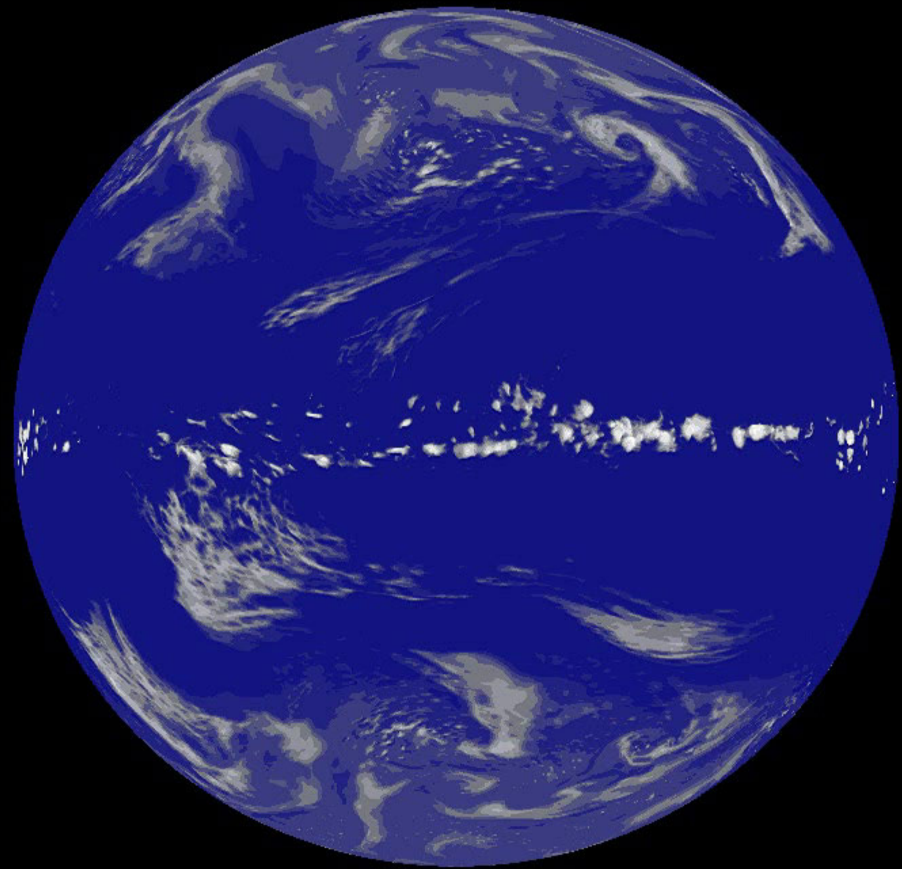
“convergence”



Earth ≠ “Aqua-Planet”



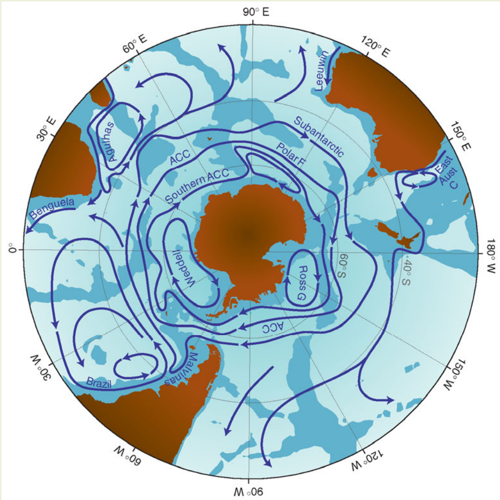
Himawari-8/JMA (1-30 Nov 2015)



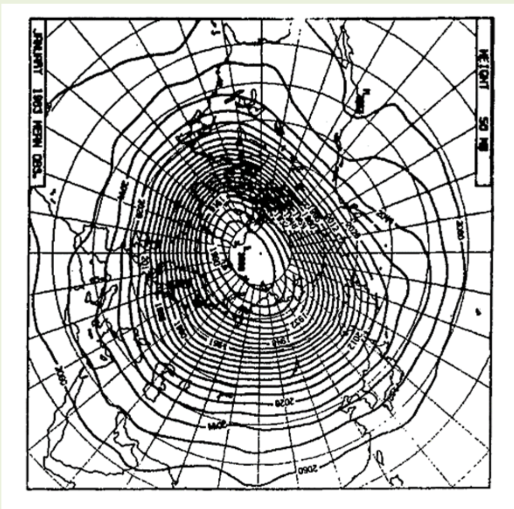
NICAM/JAMSTEC (Satoh et al., 2008)

“stripes” of deep atmosphere of Jupiter

circumpolar ocean current around Antarctica

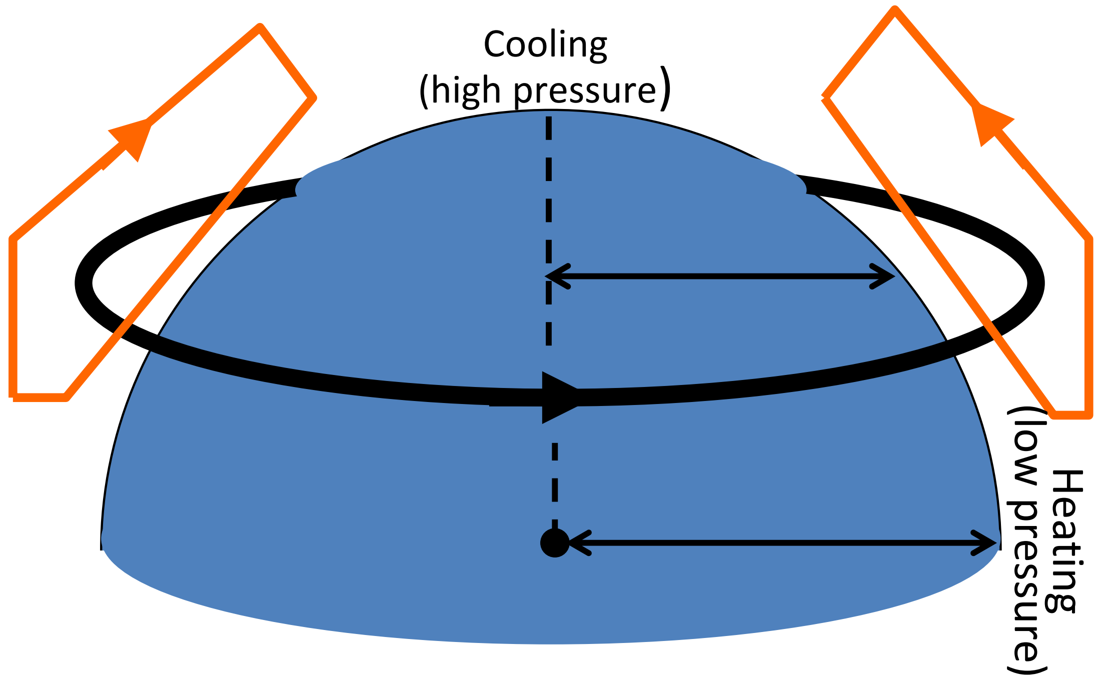


Arctic anticyclone in summer stratosphere



“Aqua-planet” zonal vortex

with differential heating



Zonal flow (u) ⇔ Meridional (y) pressure gradient

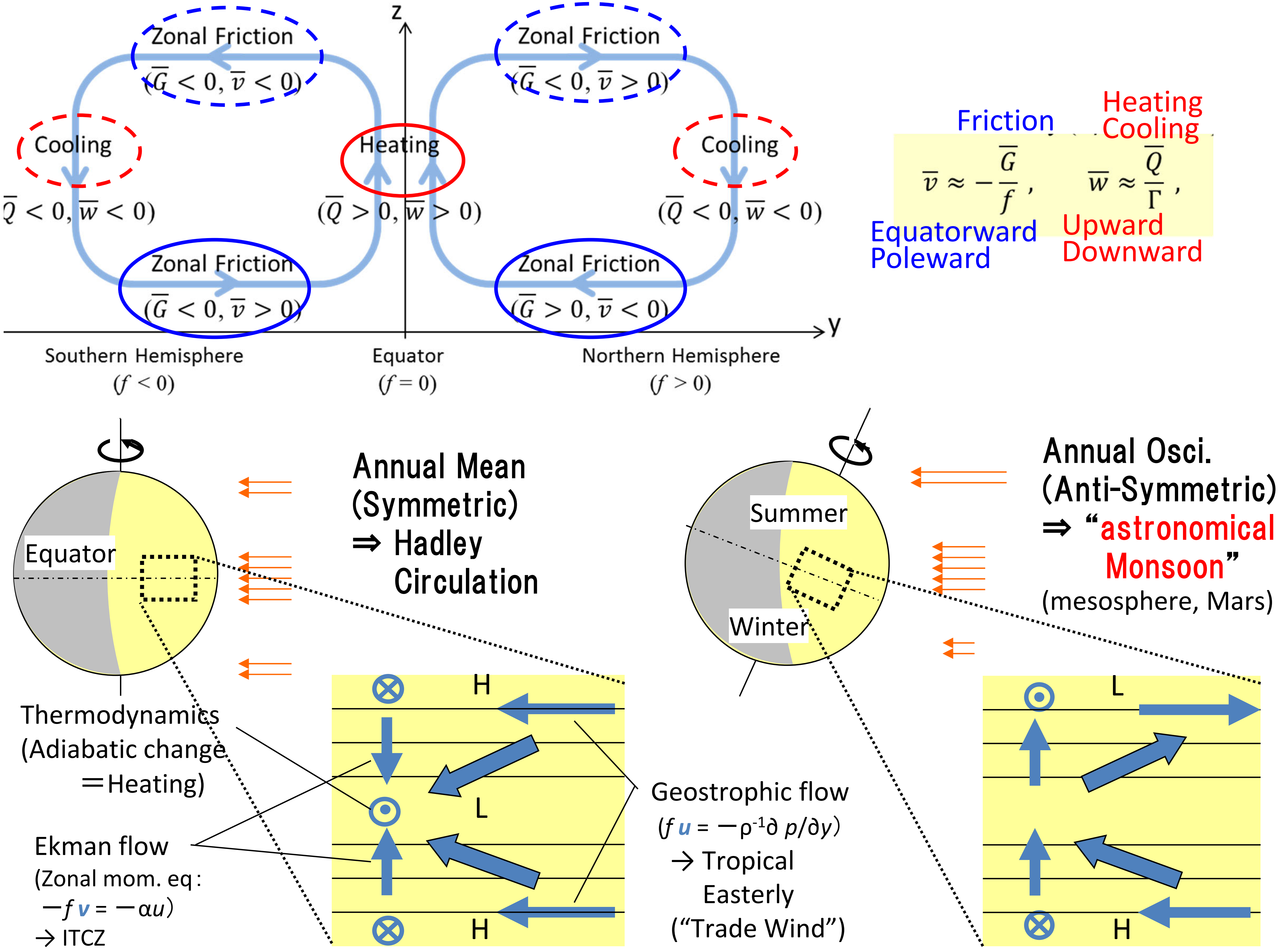
(y-momentum eq. (geostrophic) : $f\,u = -\rho^{-1}\partial p/\partial y$)

Meridional flow (v) ⇔ Zonal (x) friction/drag

(x-momentum eq. (Ekman) : $-f\,v = -\alpha u$)

Vertical flow (w) ⇔ Radiative/Latent heating

(thermodynamic eq. (pseudoadiabatic) : $\Gamma\,w = \alpha'\Delta T$)


z
Zonal Friction
$(\overline{G} < 0, \overline{v} < 0)$
Zonal Friction
$(\overline{G} < 0, \overline{v} > 0)$
Cooling
$(\overline{Q} < 0, \overline{w} < 0)$
Heating
$(\overline{Q} > 0, \overline{w} > 0)$
Cooling
$(\overline{Q} < 0, \overline{w} < 0)$
Zonal Friction
$(\overline{G} < 0, \overline{v} > 0)$
Zonal Friction
$(\overline{G} > 0, \overline{v} < 0)$
y
Southern Hemisphere
$(f < 0)$
Equator
$(f = 0)$
Northern Hemisphere
$(f > 0)$
Friction
Heating
Cooling
$\overline{v} \approx -\frac{\overline{G}}{f}, \qquad \overline{w} \approx \frac{\overline{Q}}{\Gamma},$
Equatorward
Poleward
Upward
Downward
Equator
Annual Mean
(Symmetric)
⇒ Hadley
Circulation
Summer
Winter
Annual Osci.
(Anti-Symmetric)
⇒ “astronomical
Monsoon”
(mesosphere, Mars)
H
L
H
L
H
Thermodynamics
(Adiabatic change
＝Heating)
Ekman flow
(Zonal mom. eq :
$-f\,v = -\alpha u$)
→ ITCZ
Geostrophic flow
$(f\,u = -\rho^{-1}\partial p/\partial y)$
→ Tropical
Easterly
(“Trade Wind”)

Hermann Ludwig Ferdinand von Helmholtz (1821 – 1894)

Quasi-2D (horizontal) flow velocity:

$$\boldsymbol{u} = \boxed{\nabla \times (0,0,\phi)} \boxed{- \nabla \chi}$$

(ϕ: stream function; χ: velocity potential)

$\nabla \cdot (\phi_y, -\phi_x, 0) = 0$

non-divergent (solenoidal)

"**vortex**" on (quasi-)horizontal plane

$\phi \sim$ geopotential (geostrophic)

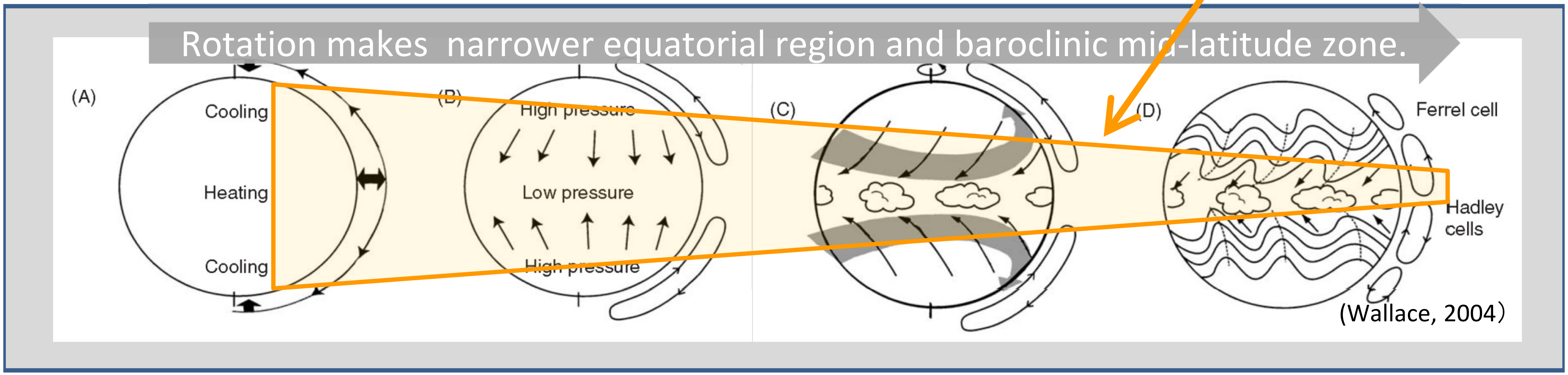
↓

Weather maps

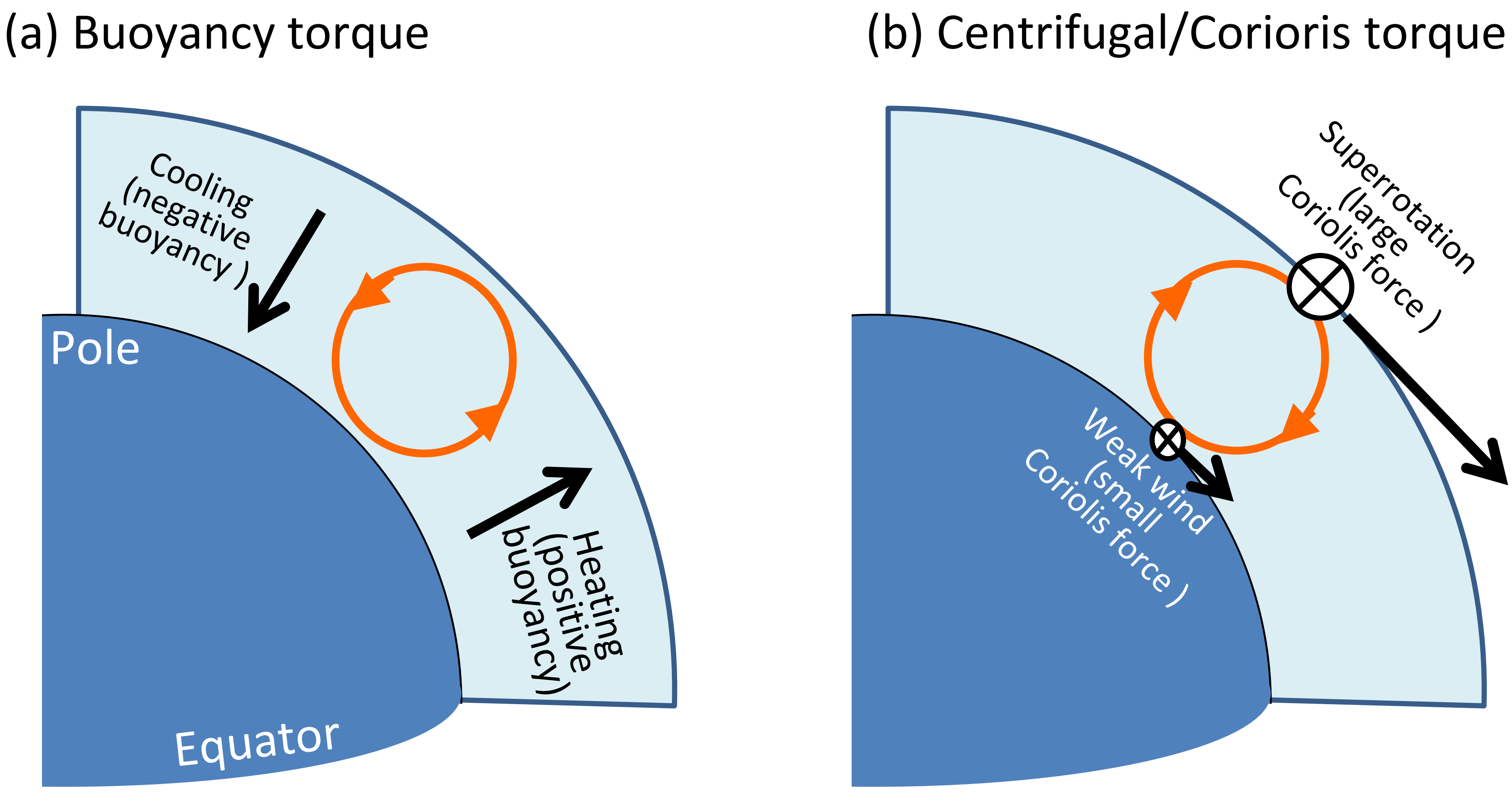
$\nabla \times (-\nabla \chi) = 0$

irrotational

"**convection**" on vertical plane



Direct / indirect circulations due to differential heating / shear satisfying by meridional temperature gradient



(adapted from Matsuda & Yoden, 1985)

Solar differential heating and monsoon circulation

	Global differential heating	Local heat capacity contrast
Rotation (Diurnal)	Day-Night circulation (**Tides**)	**Sea-Land** (Mountain-valley) **breeze**
Revolution (Annual)	Summer-winter circulation (hemispheric anti phase) Perihelion-Aphelion (in phase)	Ocean-Continent (**Monsoon**)

Monsoon is a seasonal cycle of wind, generated by the solar radiation through the following two reasons:

(i) Astronomical (planetological): Hemispheric differential heating, driving a global meridional circulation.
The dominat component of solar heating is equatorially symmetric, which drives the Hadley circulation.
Seasonal variation of solar radiation on a planet is generated by the following two reasons:
- Eccentricity if the planetary orbit: globally in-phase, which does not contribute to monsoon.
- Inclination of the planetary rotation axis: anti-phase between the hemispheres, contributing to monsoon.

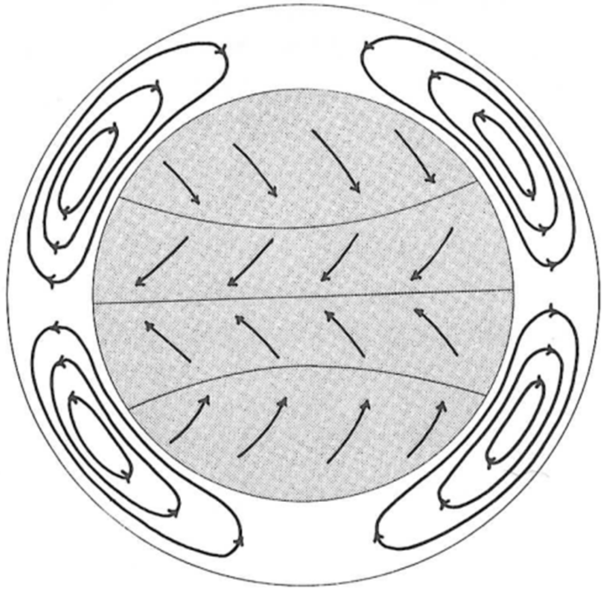
Diurnal cycle of (day-night) hemispheric differential heating of solar radiation may generate thermal tides.

(ii) Geographical (terrestrial) : Continent-ocean differential heating, driving a flow crossing the coastline.
Land (solid) – sea (liquid) heat capacity contrast, generating a diurnal cycle of sea-land breeze circulation.
Integration (residue) of diurnal cycle generates the seasonal cycle and thus the monsoon.
Wind from ocean to continent (in summer hemisphere) brings moisture, and therefore generates rainy season.
The cloud-precipitation water cycle makes latent heat transport, and feedbacks to monsoon enhancement.

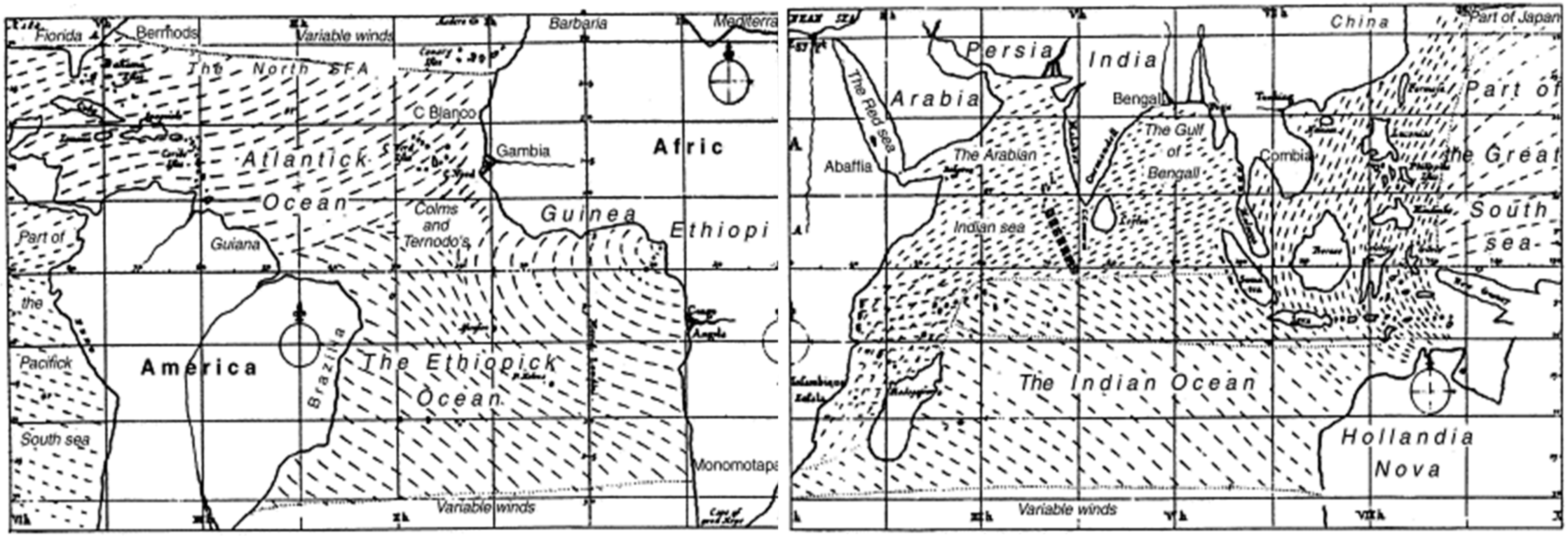
Edmond Halley (1656 –1742)

(http://www.staff.science.uu.nl/~gent0113/astrology/newton.htm)

George Hadley (1685 – 1768)

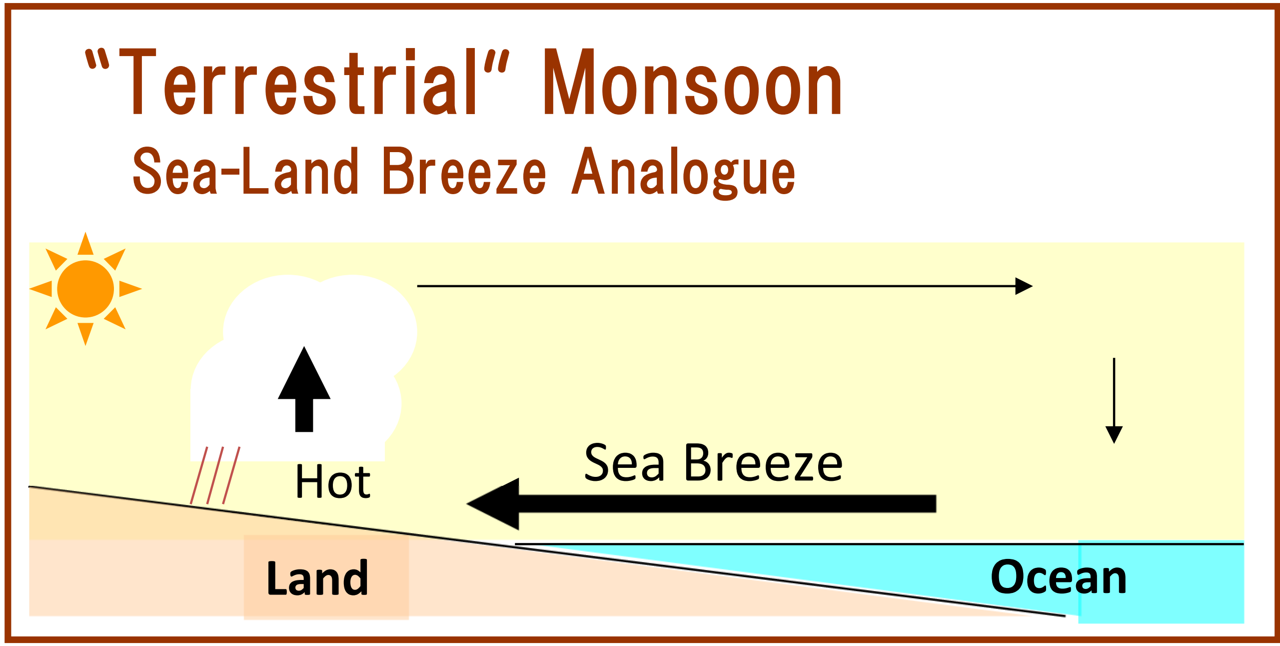


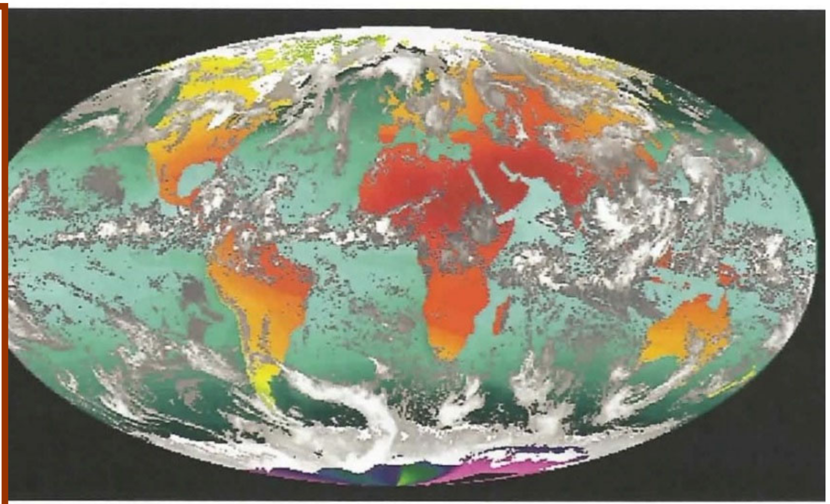
(Hadley, 1735; reproduced by Lorenz, 1967)



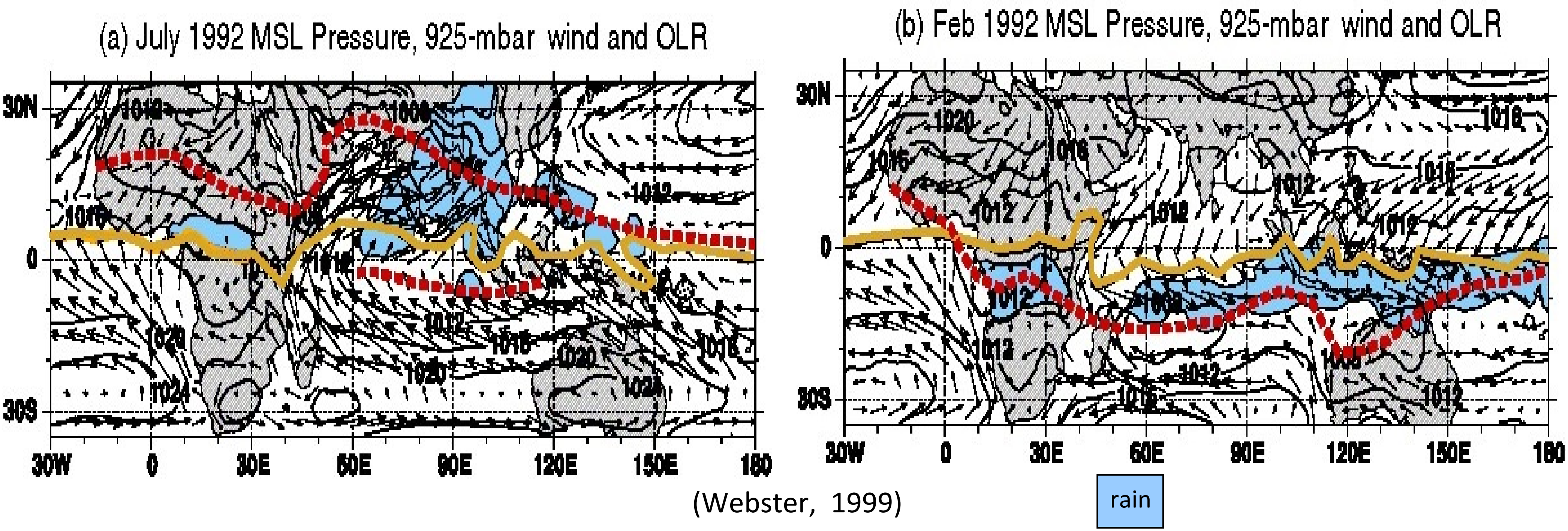
(Halley, 1686)

Ocean-Land Contrasts and Monsoon

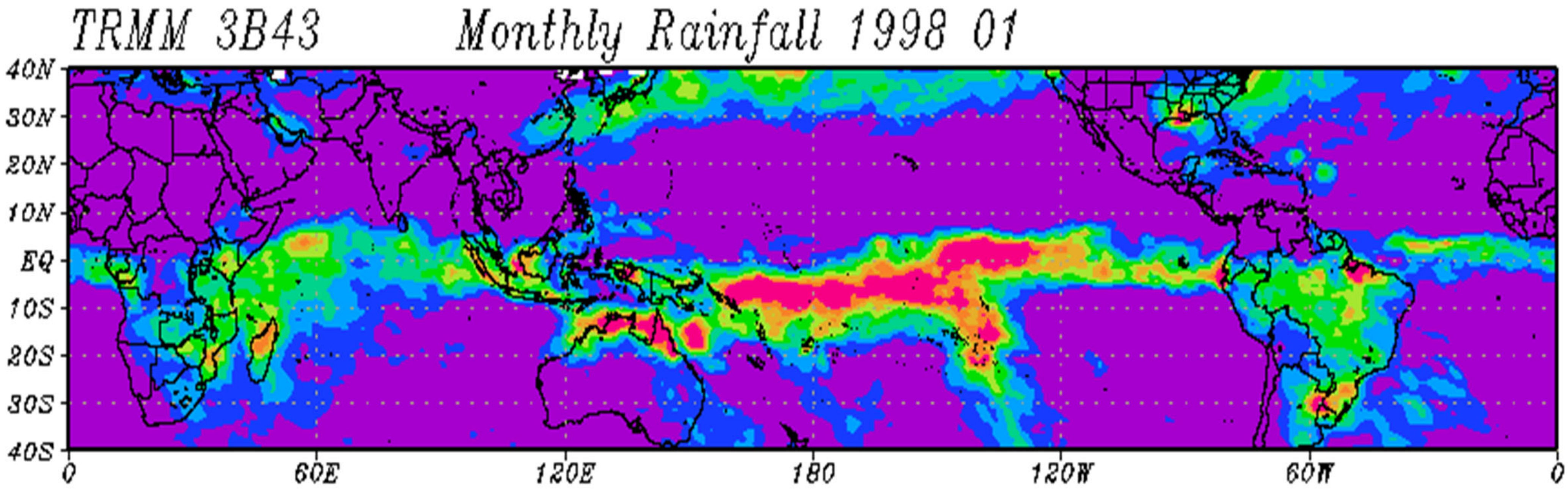


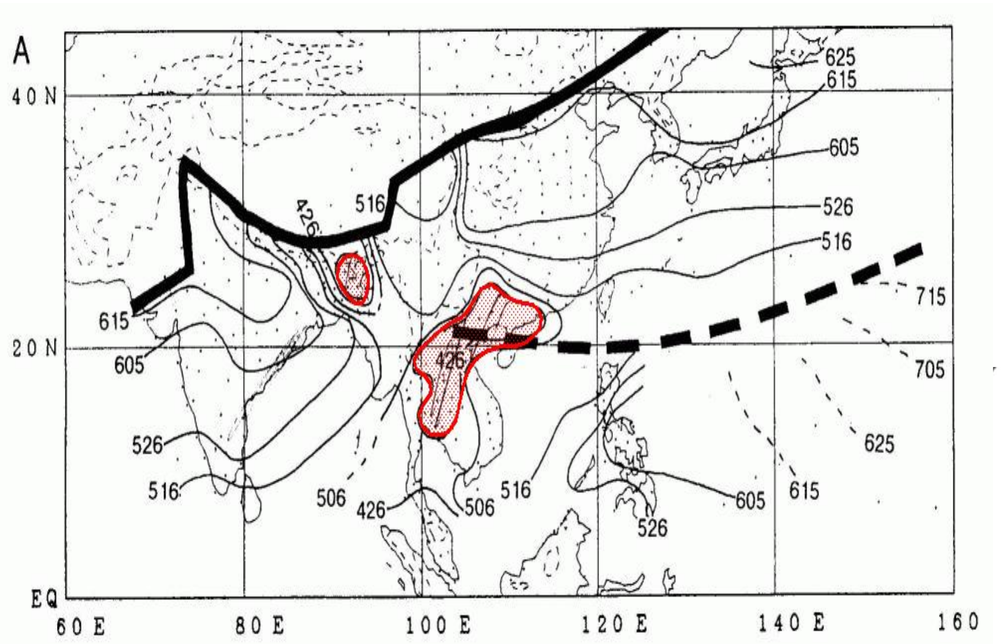


(Wallace & Hobbs, 2006; originally from UWSSEC)

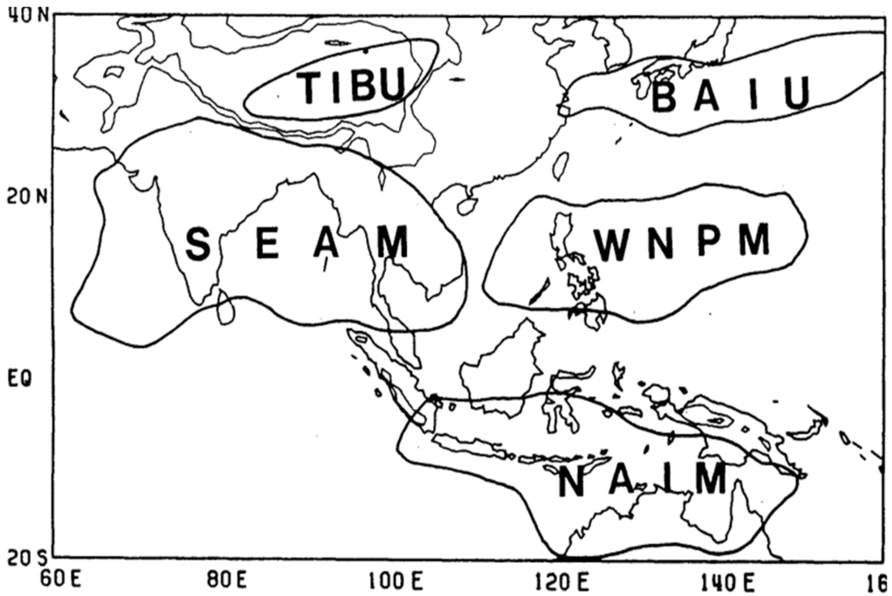


(Webster, 1999)

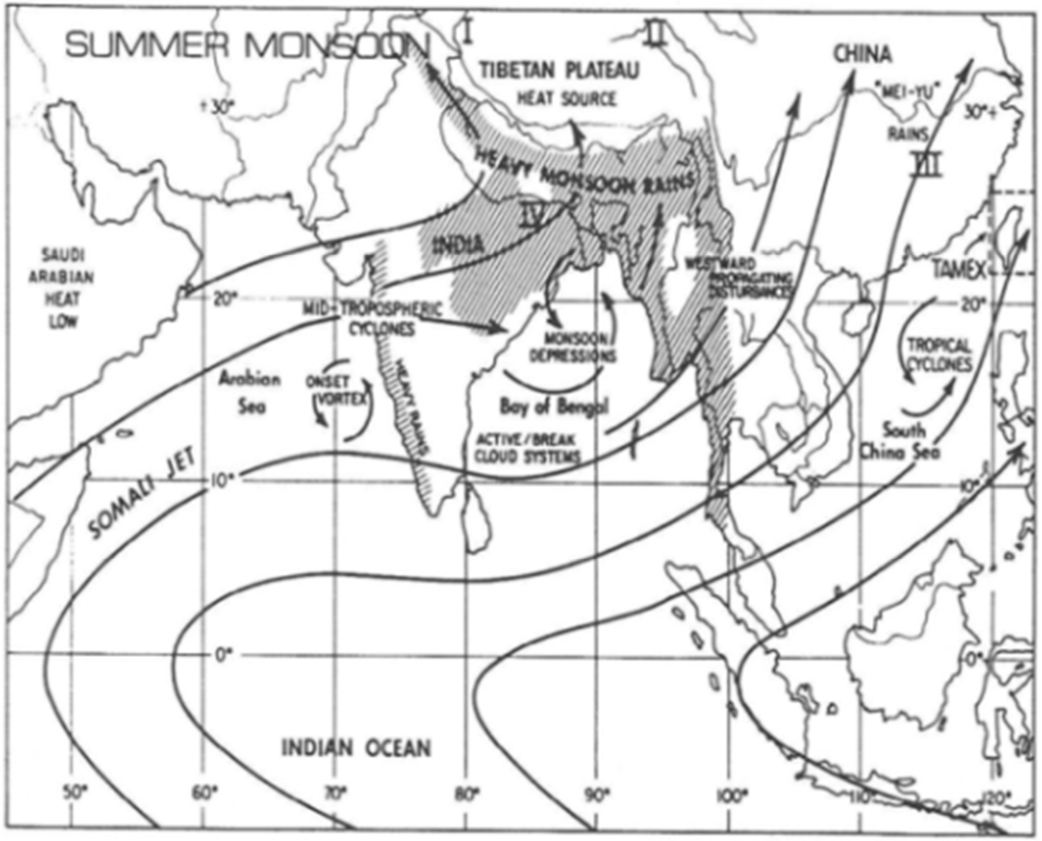


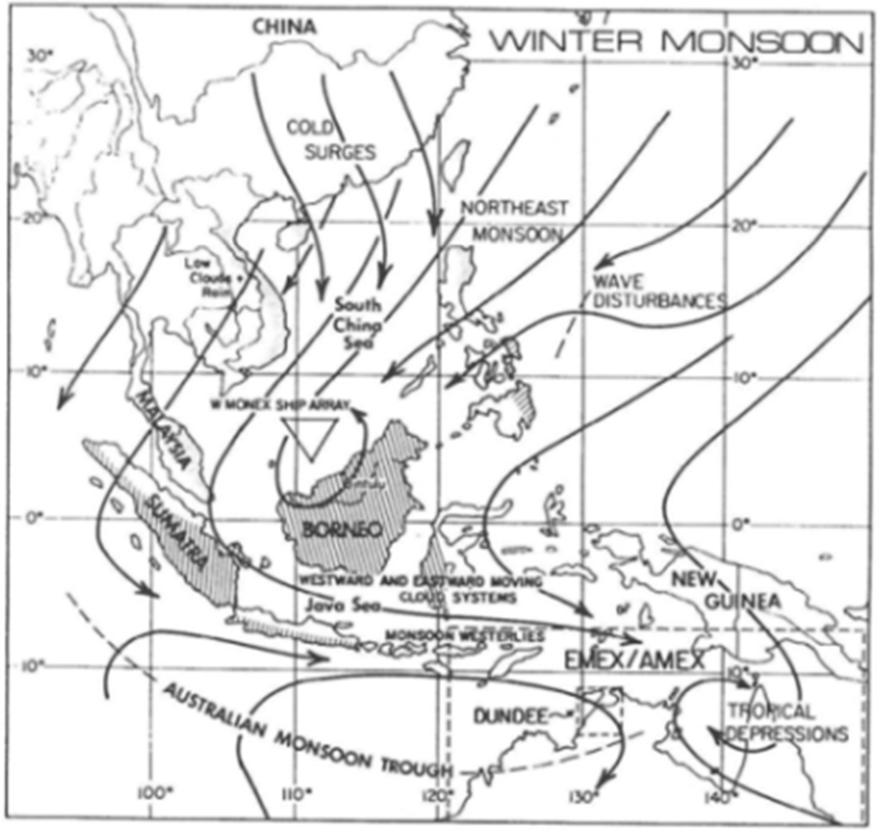


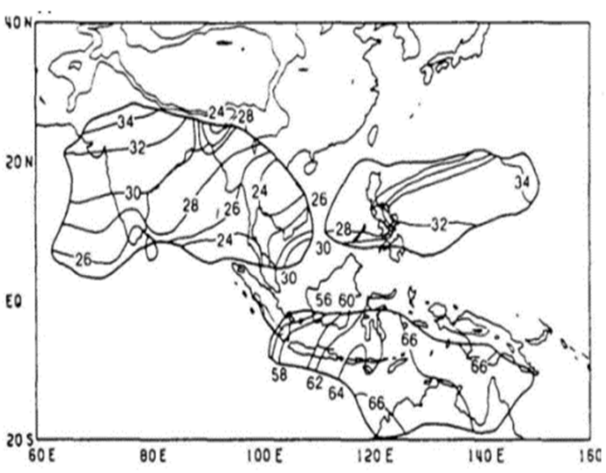
(Matsumoto and Murakami, 1992)

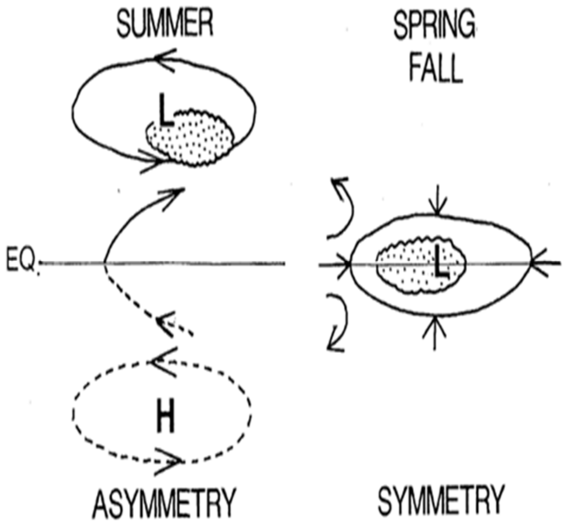


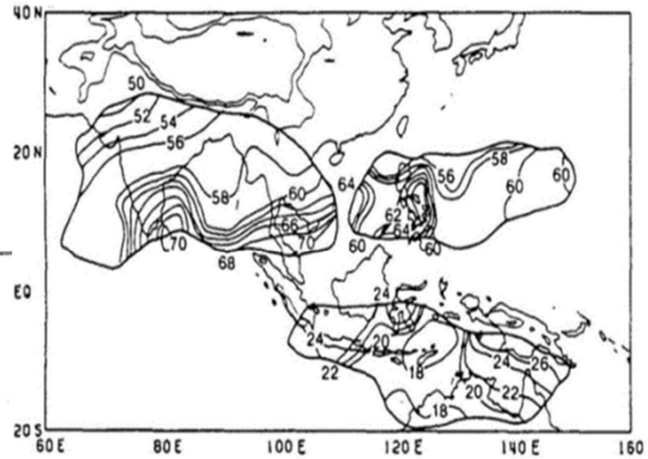
(Murakami and Matsumoto, 1994)


SUMMER MONSOON
TIBETAN PLATEAU
HEAT SOURCE
CHINA
"MEI-YU"
RAINS
HEAVY MONSOON RAINS
INDIA
SAUDI
ARABIAN
HEAT
LOW
MID-TROPOSPHERIC
CYCLONES
MONSOON
DEPRESSIONS
WESTWARD
PROPAGATING
DISTURBANCES
TAMEX
TROPICAL
CYCLONES
Arabian
Sea
ONSET
VORTEX
HEAVY RAINS
Bay of Bengal
ACTIVE/BREAK
CLOUD SYSTEMS
South
China Sea
SOMALI JET
INDIAN OCEAN

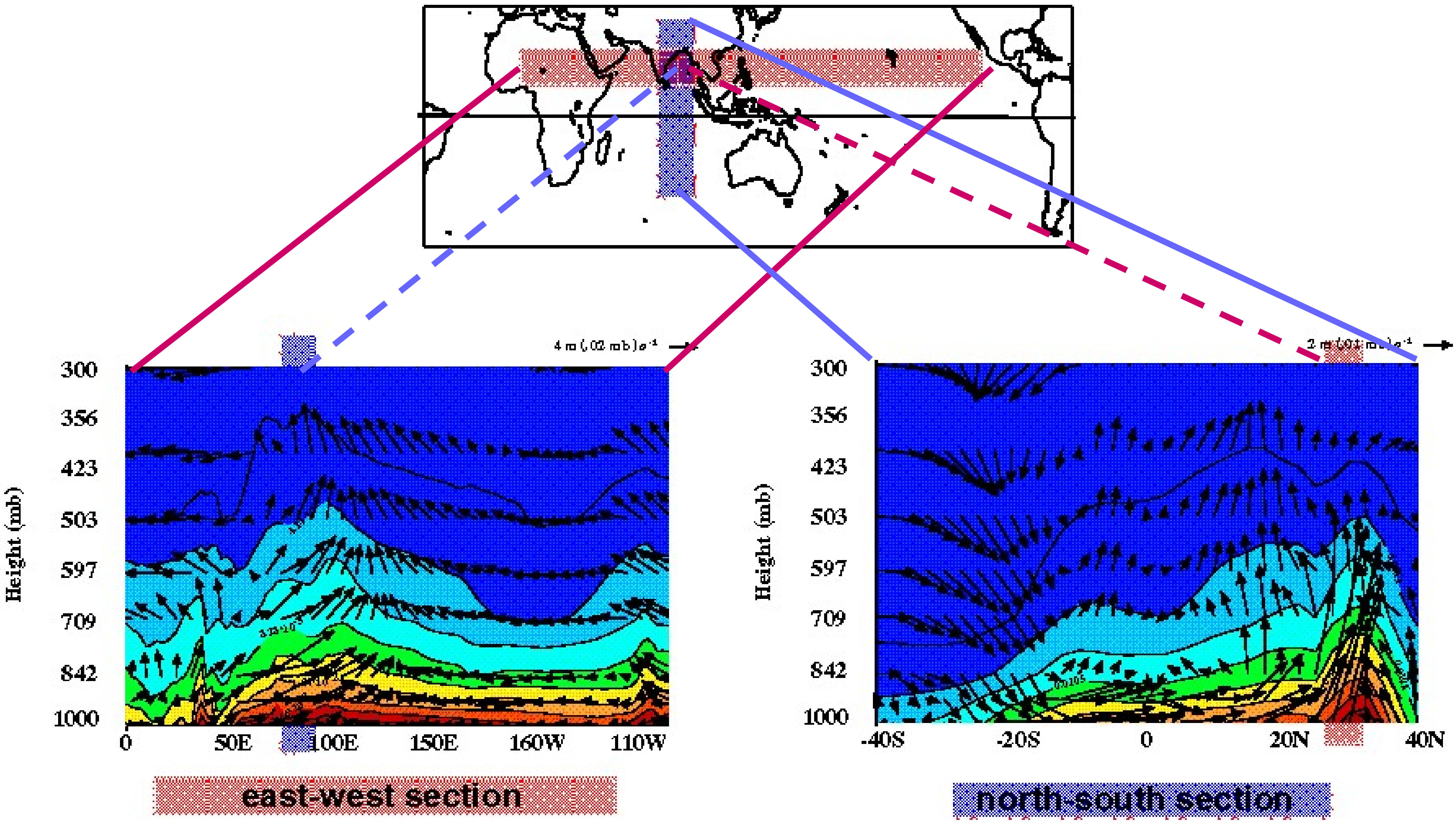

CHINA
WINTER MONSOON
COLD
SURGES
NORTHEAST
MONSOON
Low
Clouds +
Rain
South
China
Sea
WAVE
DISTURBANCES
W MONEX SHIP ARRAY
MALAYSIA
SUMATRA
BORNEO
WESTWARD AND EASTWARD MOVING
CLOUD SYSTEMS
Java Sea
MONSOON WESTERLIES
NEW
GUINEA
EMEX/AMEX
DUNDEE
AUSTRALIAN MONSOON TROUGH
TROPICAL
DEPRESSIONS




SUMMER
SPRING
FALL
WINTER
L
H
EQ.
ASYMMETRY
SYMMETRY
ASYMMETRY

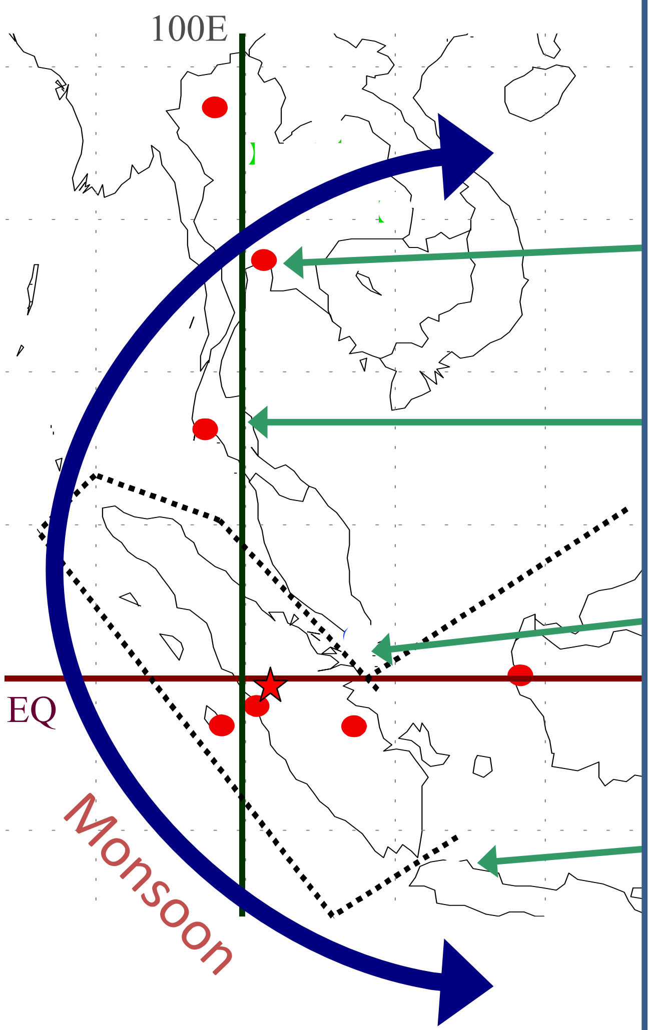


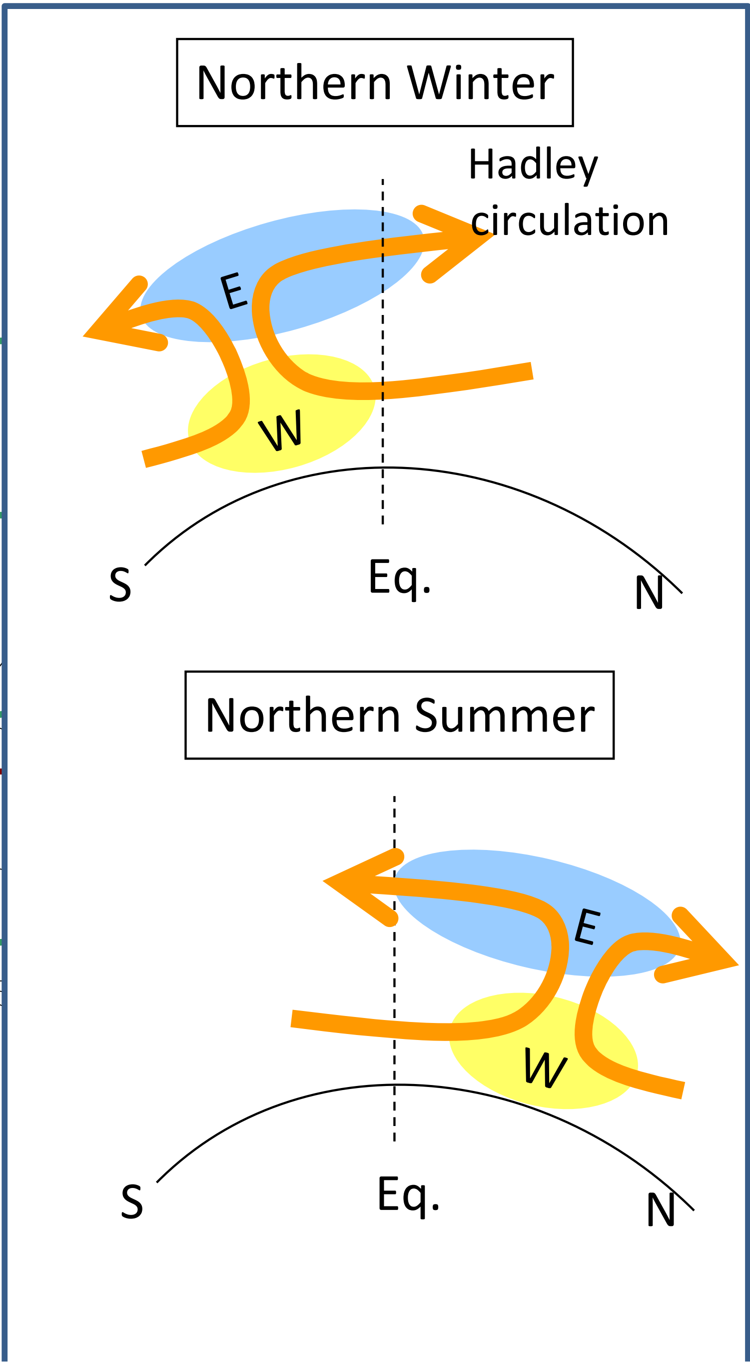
Longitudinal / latitudinal sections in NH Summer

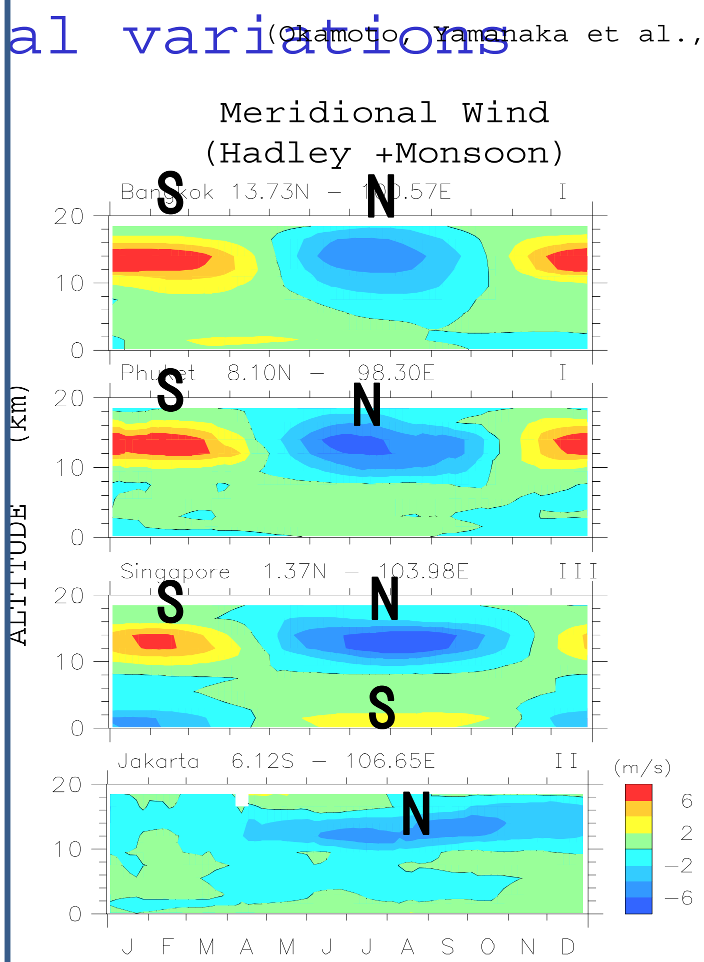


(Webester, 1999)

100E meridian (Sumatera-Malay-Thailand) obs.

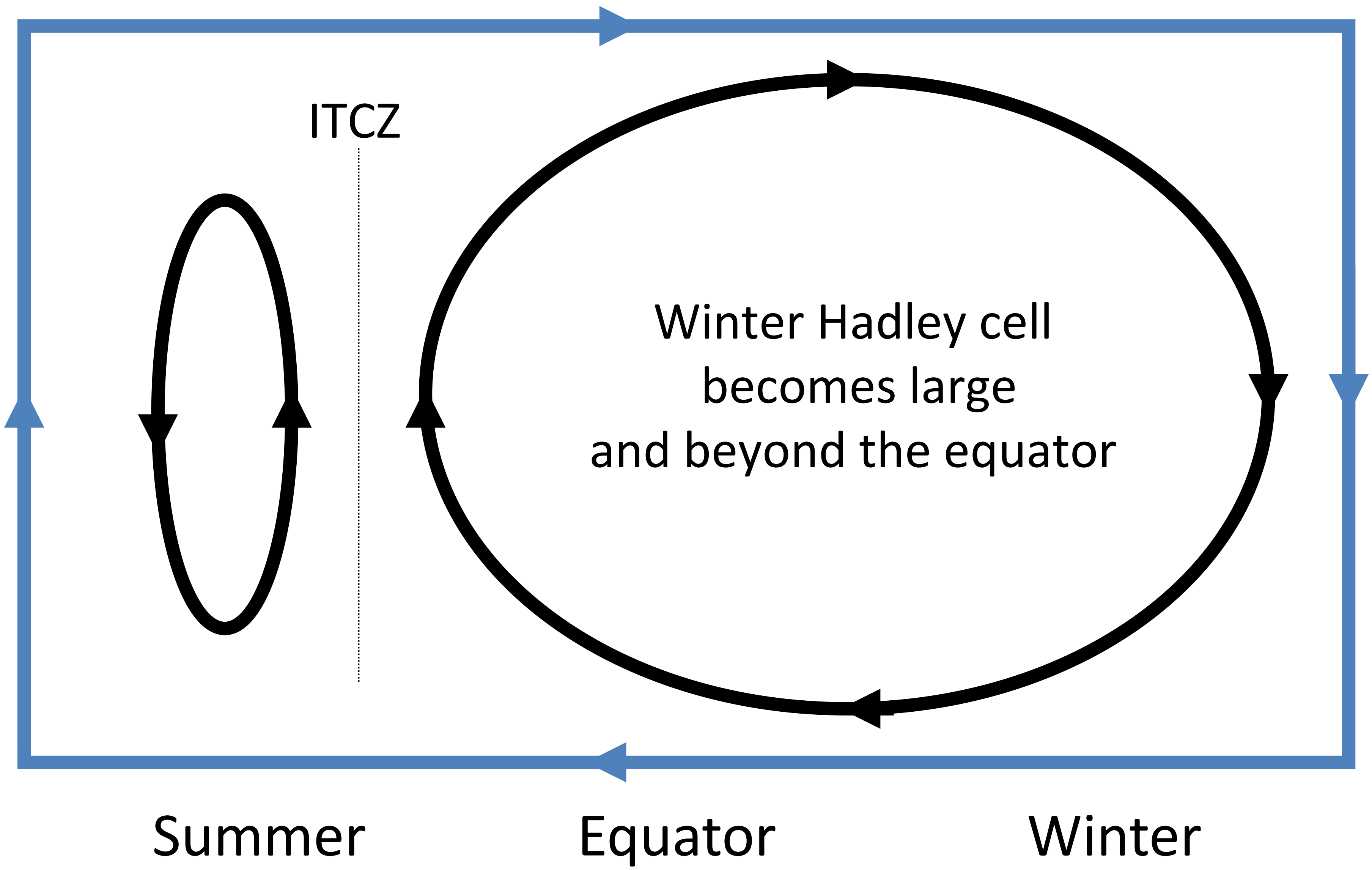






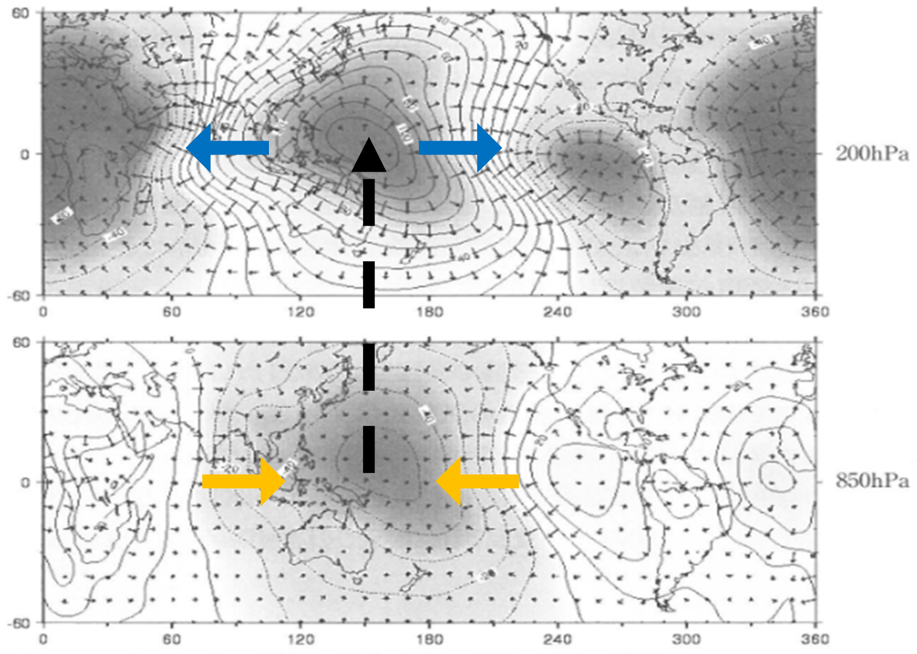
(Okamoto et al., 2004)

Superimposing Monsoon and Hadley circulations



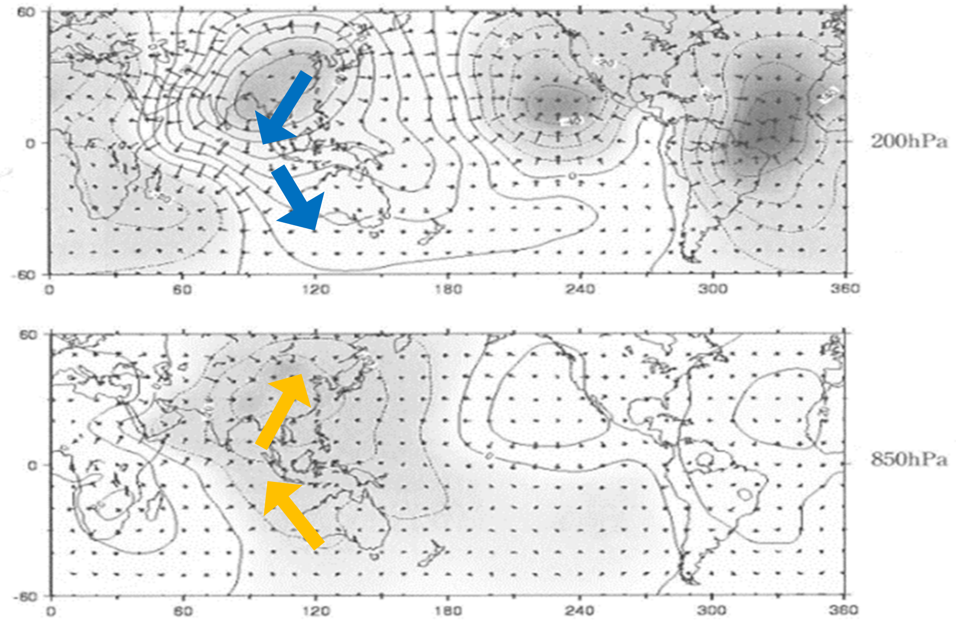
Heating-induced zonal (Walker) and Summer-Winter (Monsoon) circulations

Walker circulation

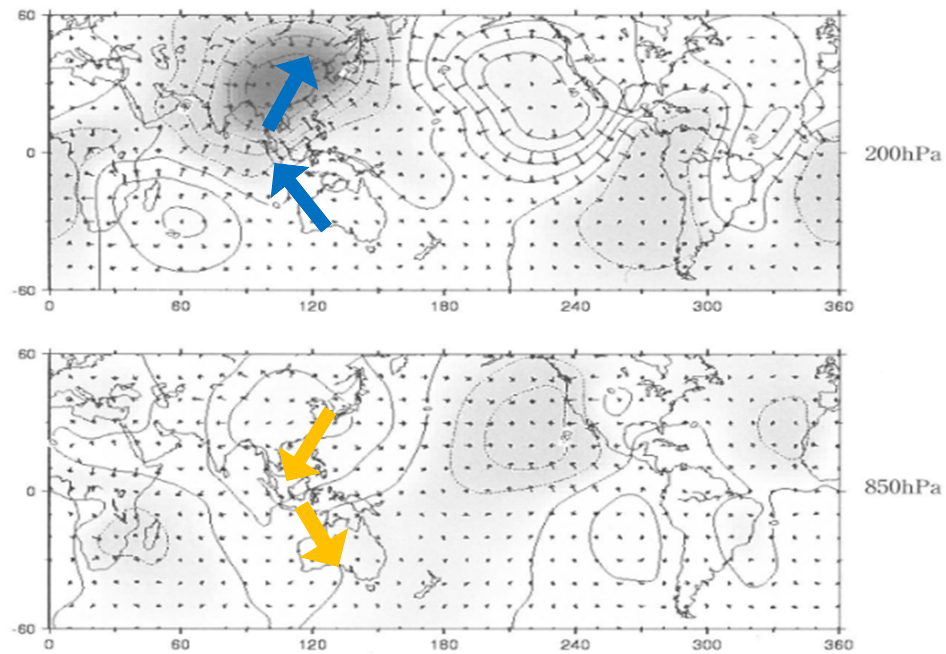


(Tanaka, 2015)

June-July-August Monsoon circulation



December-January-Februaryt Monsoon circulation



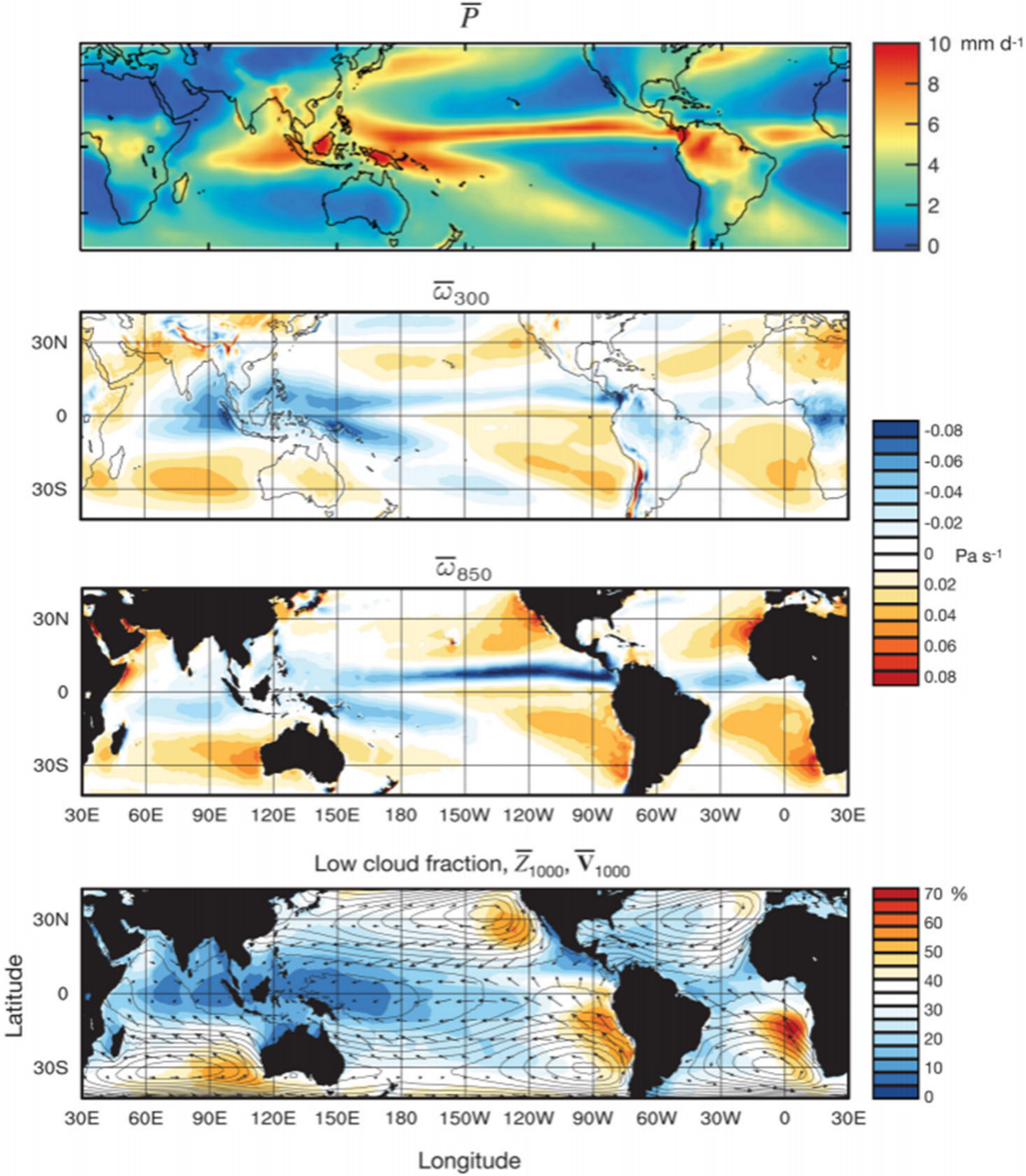
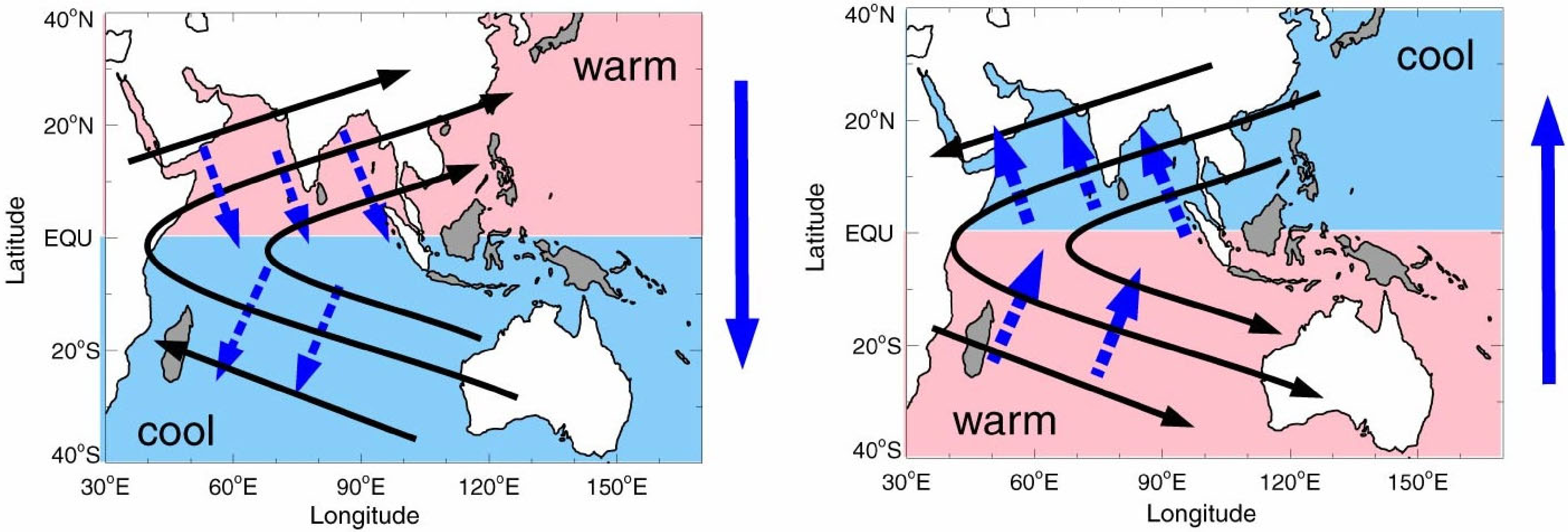


Figure 14.1 Annual mean maps: (top) rain rate; (second) vertical velocity at the 300 hPa level; (third) vertical velocity at the 850 hPa level; and (bottom) the percentage of the sky covered by low clouds, superposed on the 1000 hPa wind vectors and geopotential height (contour interval 10 m). Note that positive values of ω indicate descent.

Monsoon-Induced Ocean Heat Transport



Southward ocean heat transport of 1.5 PW (cools NIO while warming SIO)

(Webster, 1999)

Northward ocean heat transport of 1.5 PW (cools SIO while warming NIO)

Overall impact of wind-driven Ekman ocean heat transport is to cool the summer hemisphere and warm the winter hemisphere thus reducing the cross-equatorial SST gradient and minimizing seasonal extremes in the monsoon

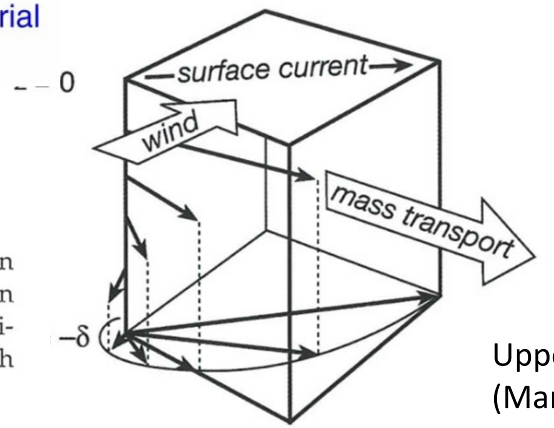
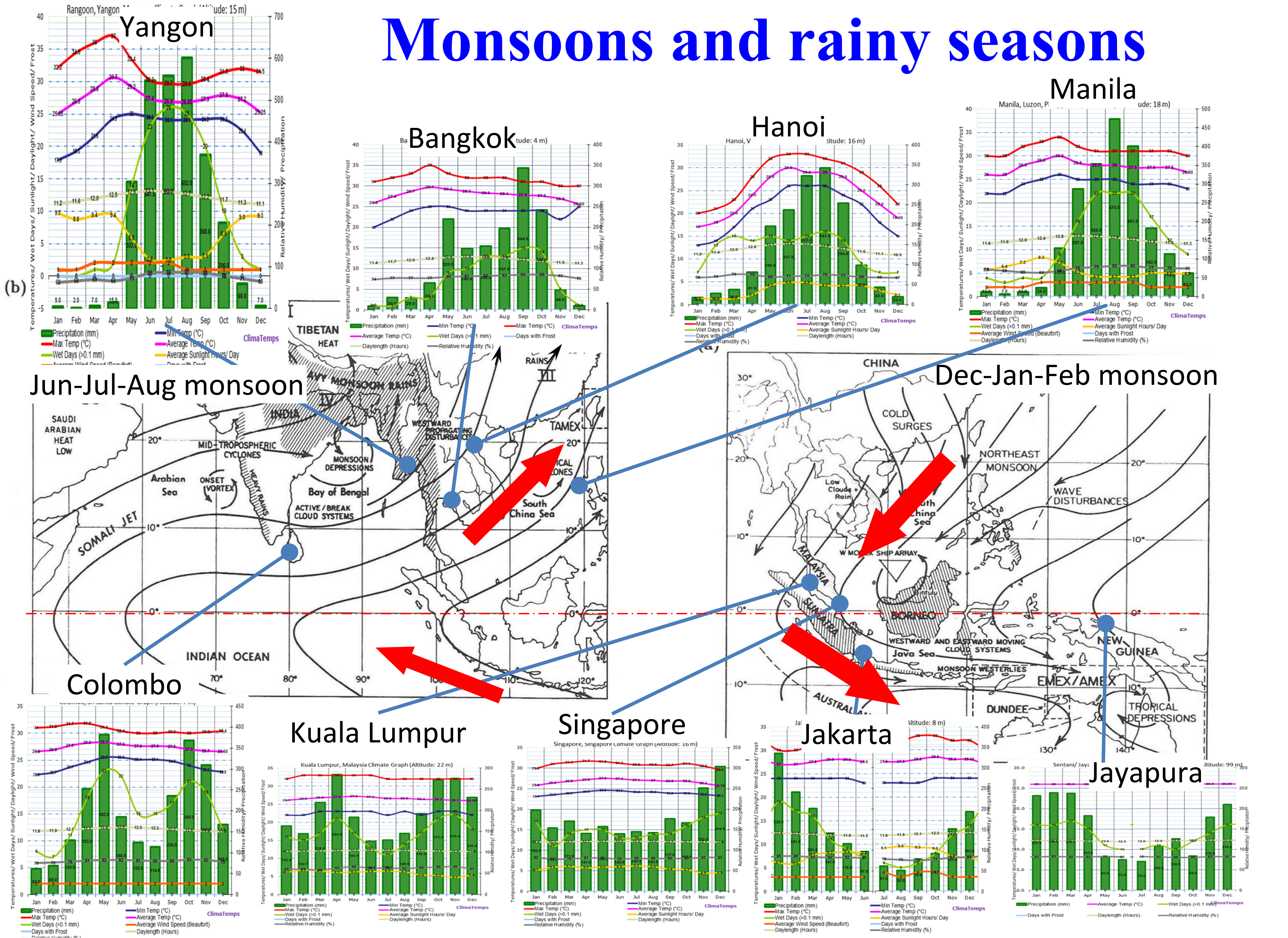


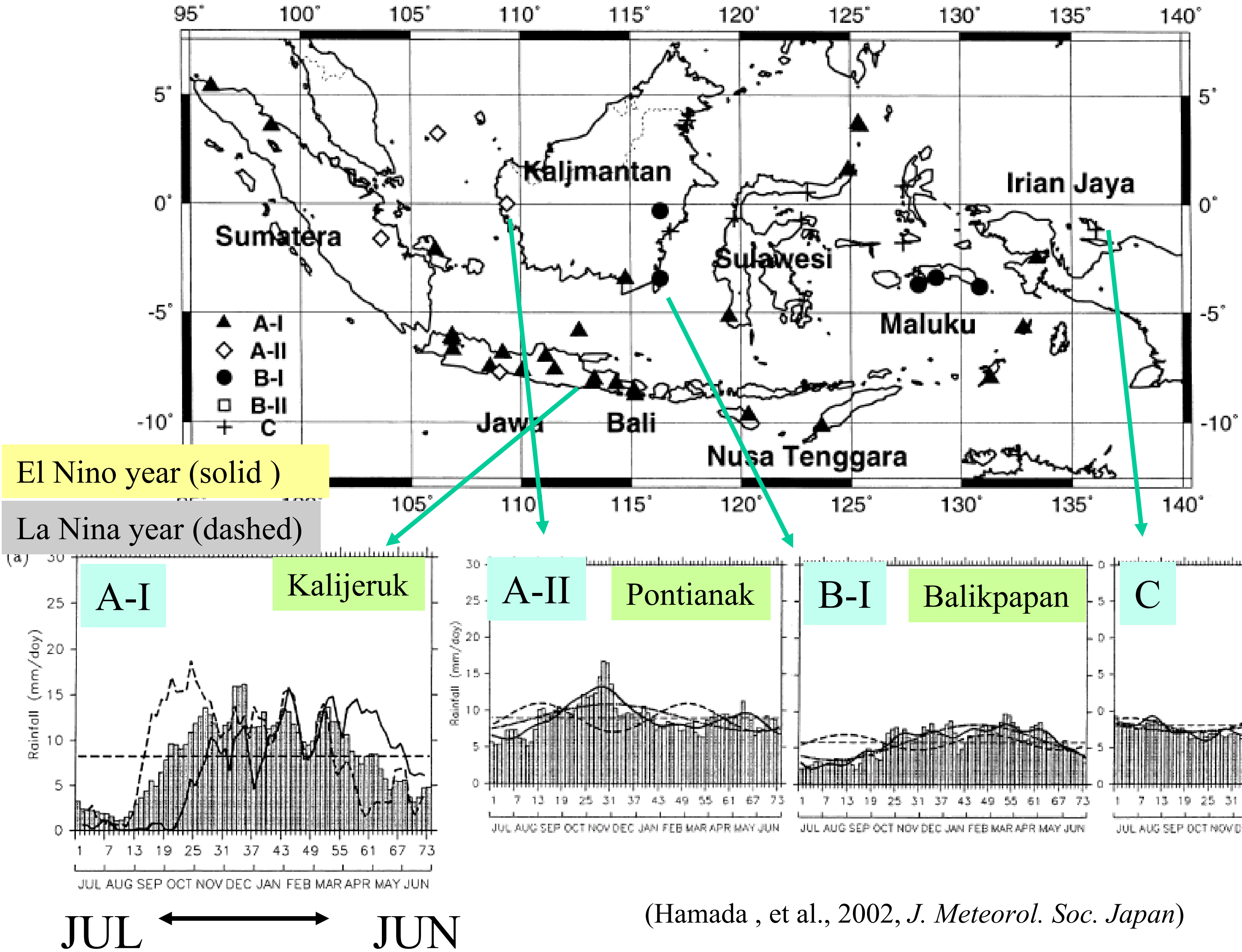
FIGURE 10.5. The mass transport of the Ekman layer is directed to the right of the wind in the northern hemisphere (see Eq. 10-5). Theory suggests that horizontal currents, u_{ag}, within the Ekman layer spiral with depth as shown.

Upper ocean
(Marshall & Plumb, 2008)

Monsoons and rainy seasons

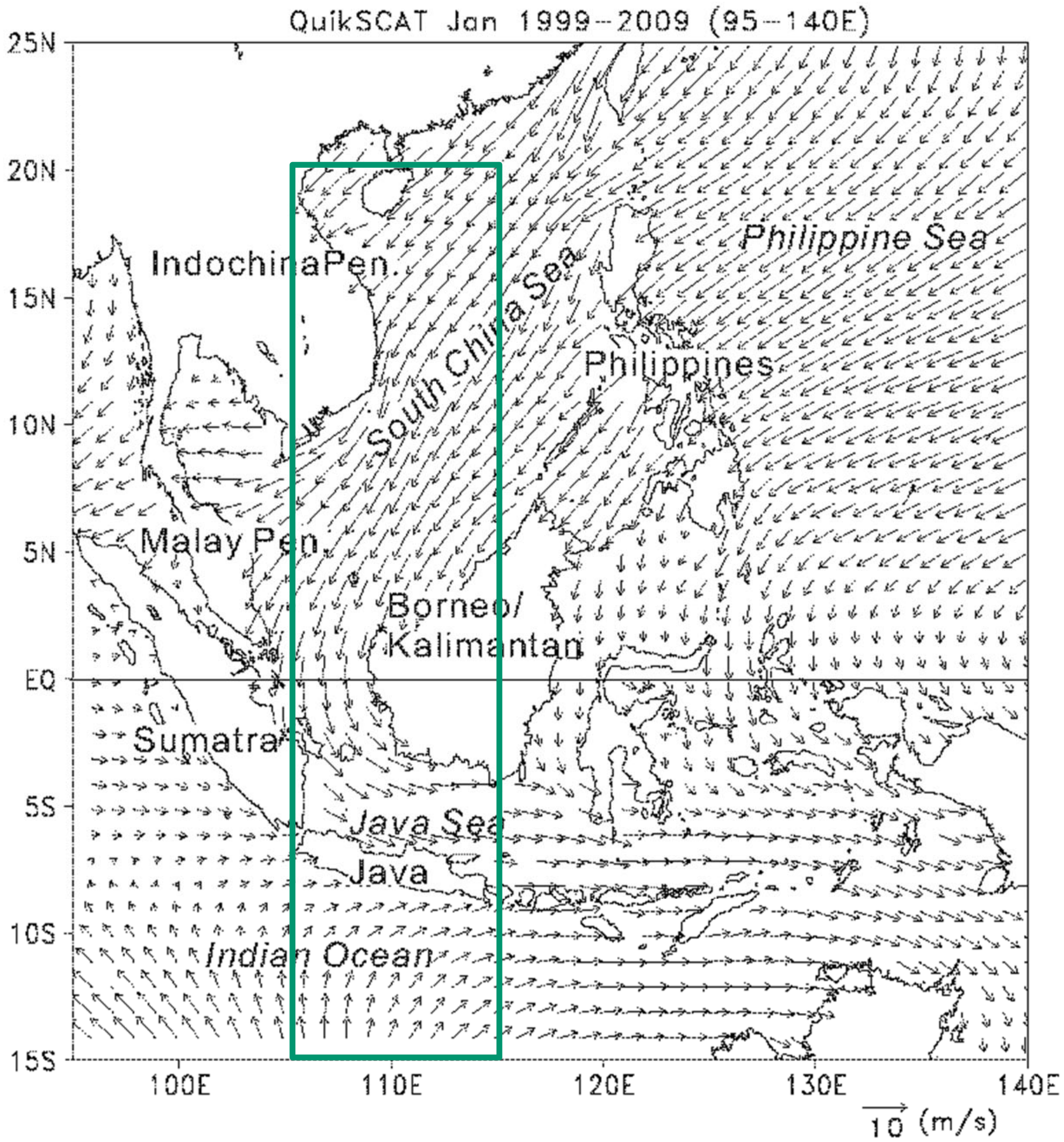


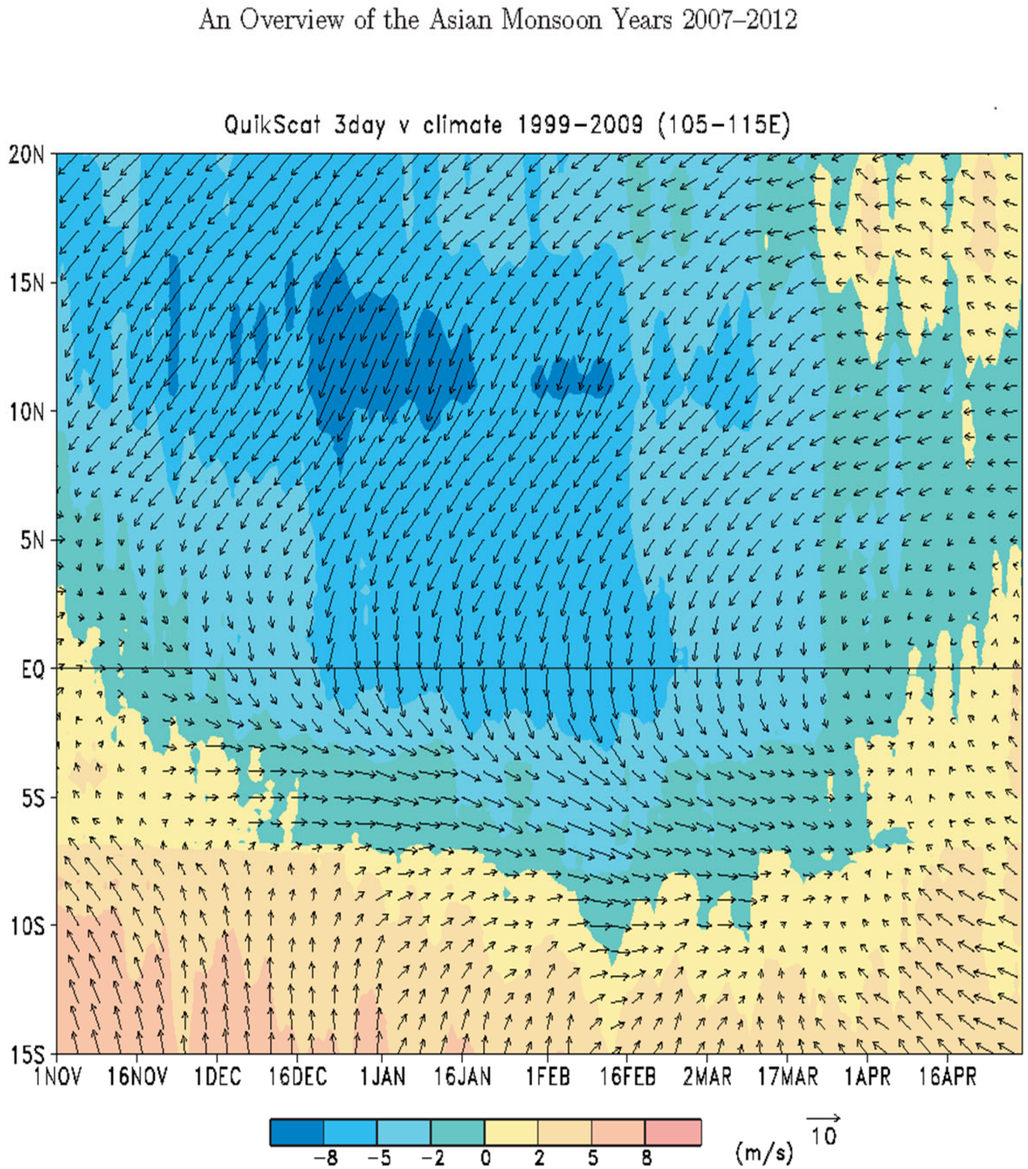
Seasonal and interannual variations



(Hamada , et al., 2002, *J. Meteorol. Soc. Japan*)

Cold surge climatology

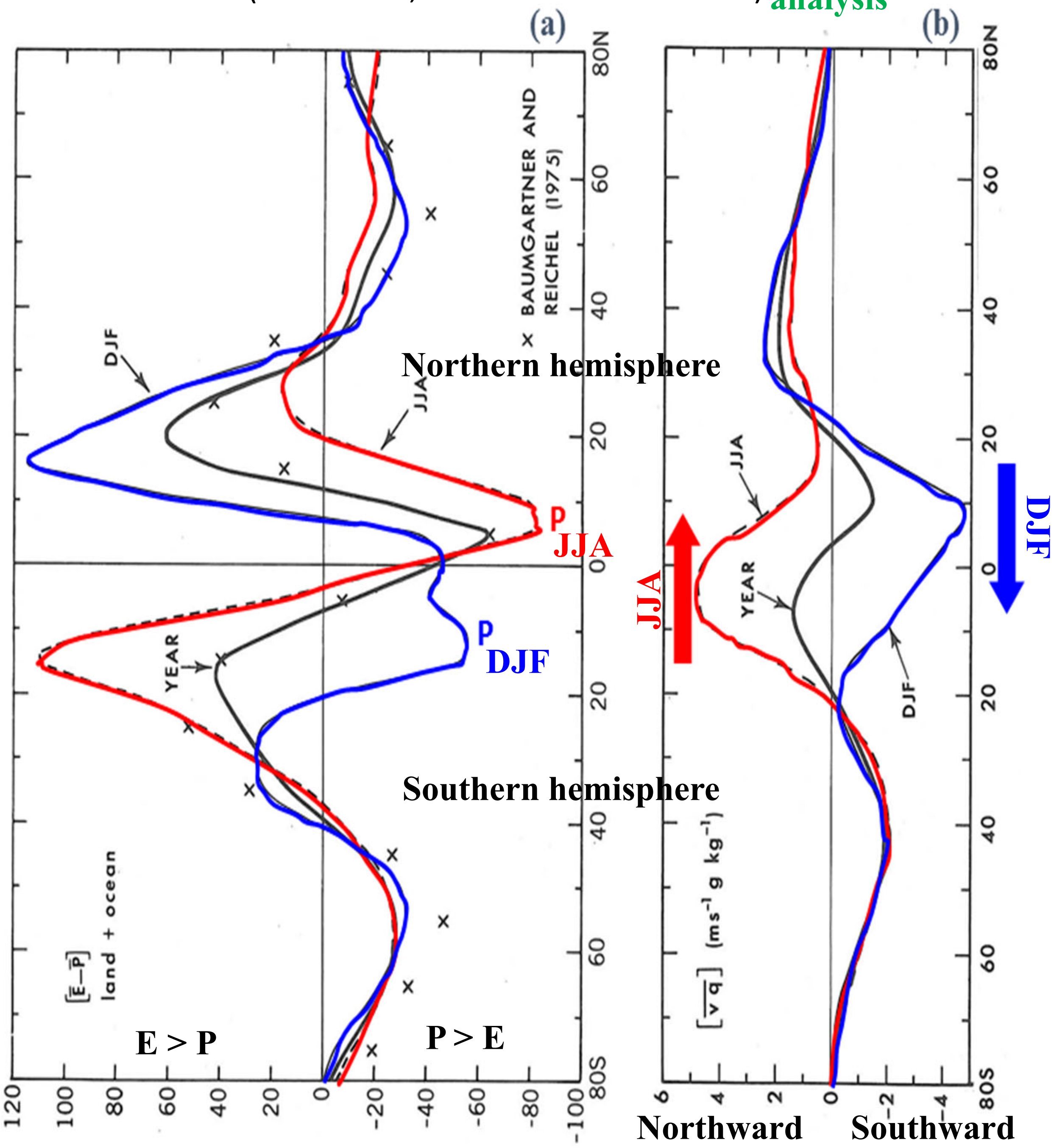




(Hattori et al., 2011; Matsumoto et al., 2017)

Equatorial annual-cycle dehydrator

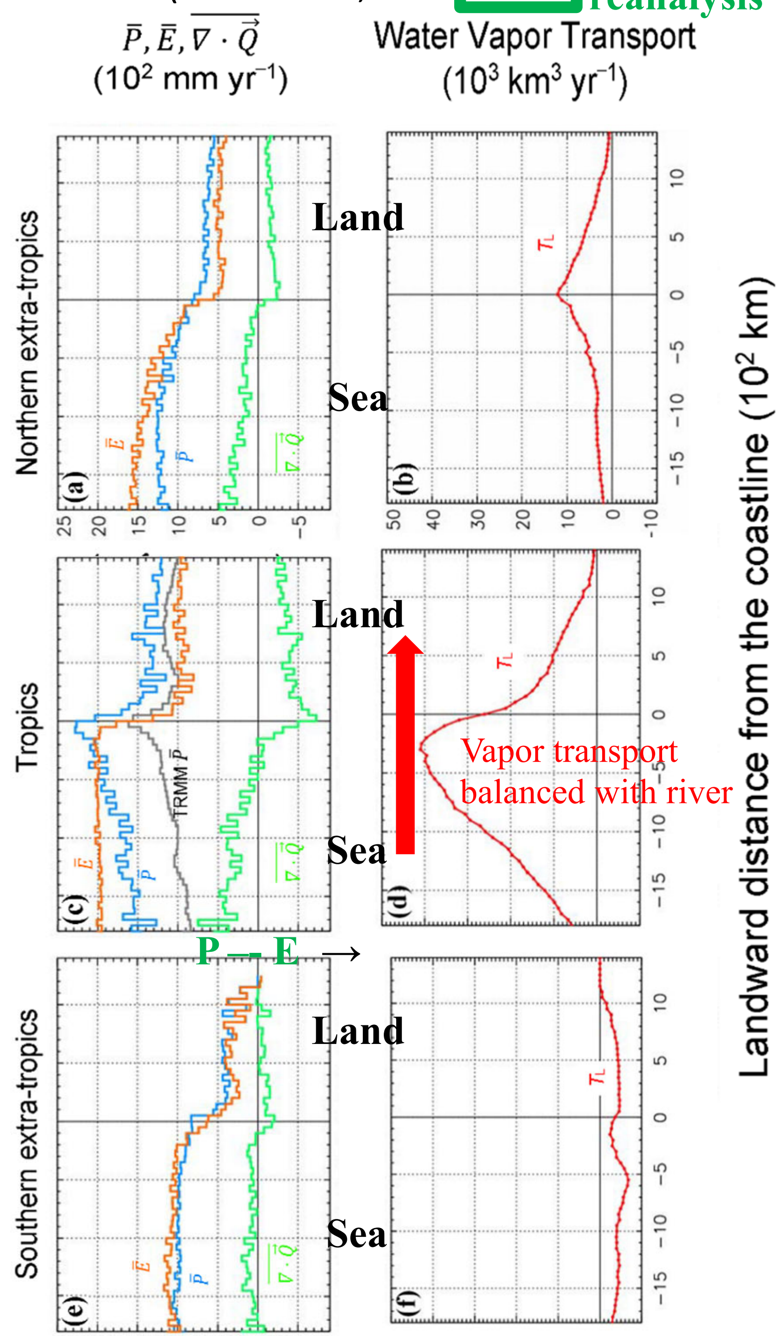
(1963-1973, based on 1000 stations) Subjective analysis



(Peixoto and Oort, 1983, *Variations in the Global Water Budget*)

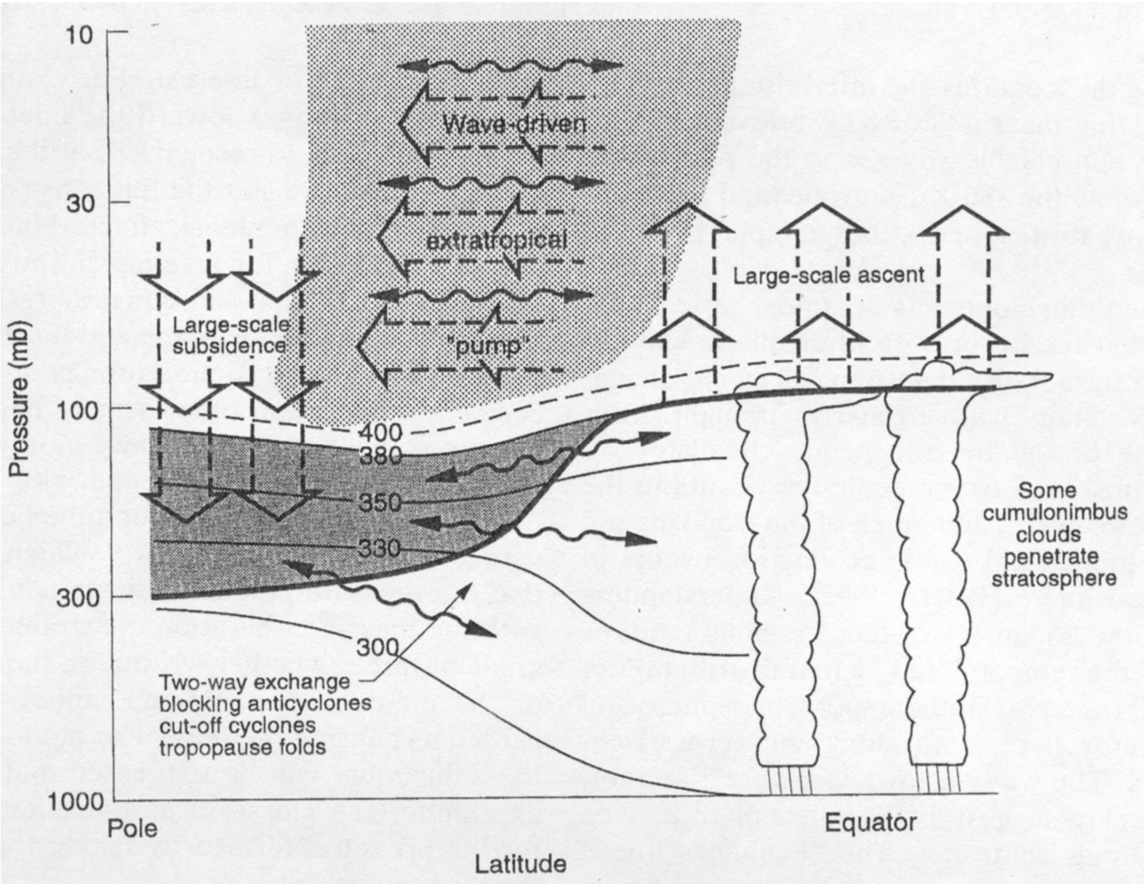
Coastal diurnal-cycle dehydrator

(1981-2010, from JRA55 Operational objective reanalysis



(Ogino et al., 2017, *GRL*)

Stratospheric response to tropospheric convection



(Holton, 1995)

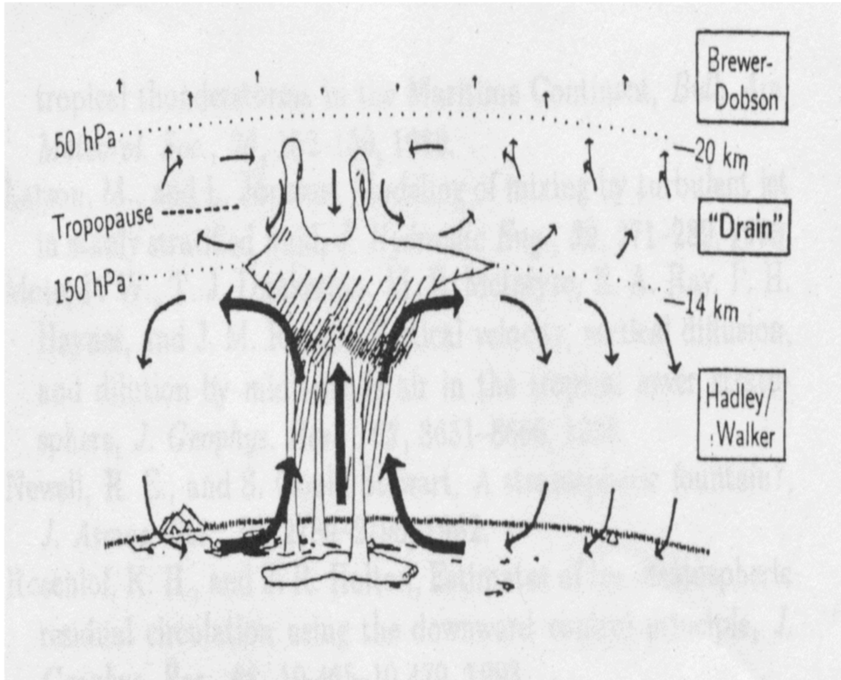
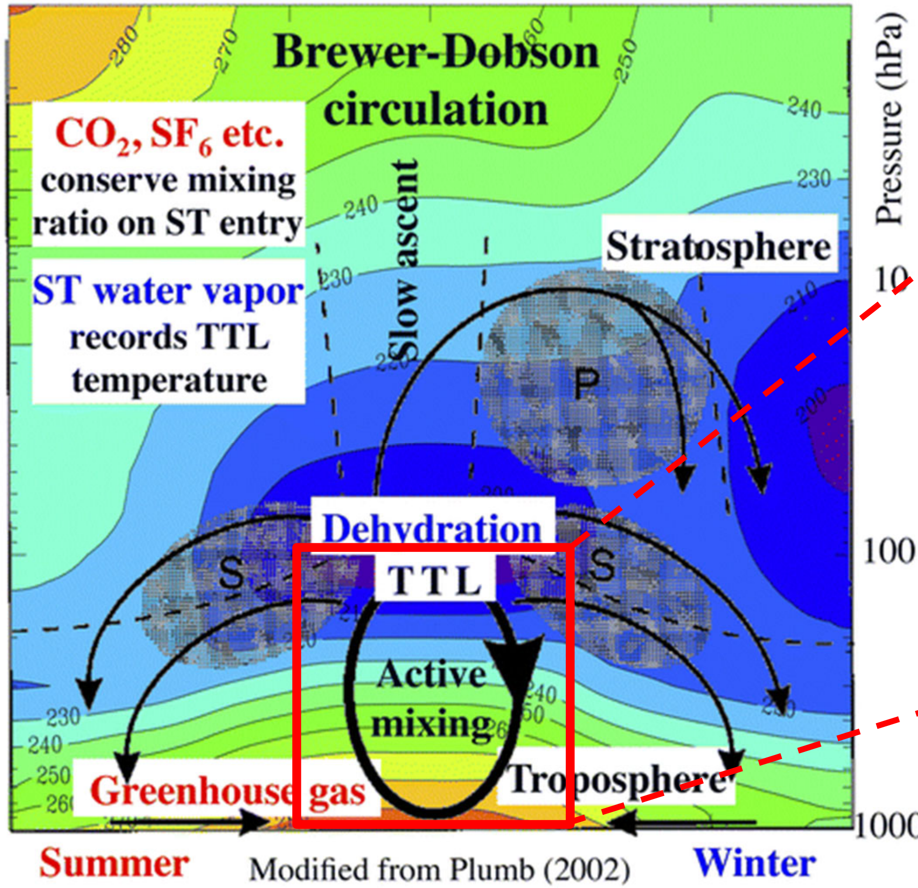


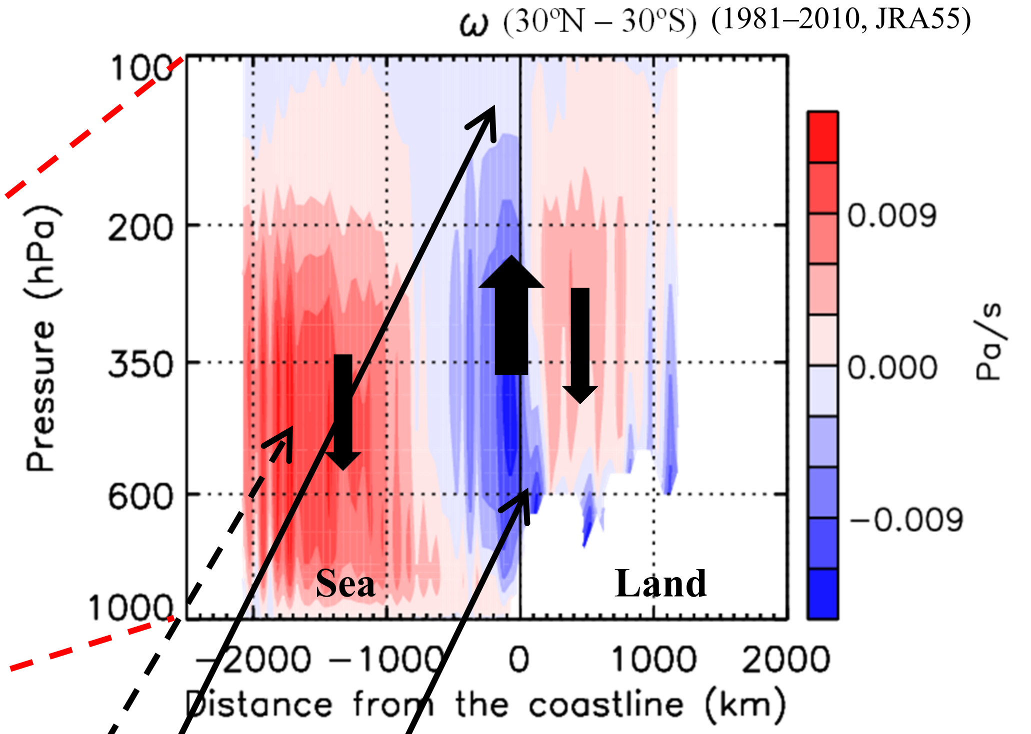
Figure 4. Illustration of the diabatic mean flow (arrows) and its relationship to the locations of deep convection and convective outflows.

(Sherwood, 2000)

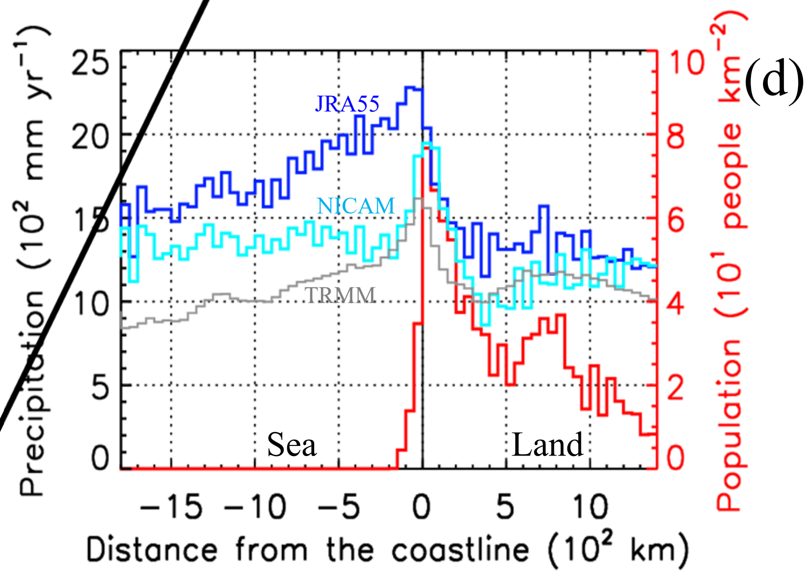
cf. Ogino's ozone observations at Hanoi



(Hasebe et al., 2018, *BAMS*)



(Ogino, Nasuno, et al., 2020, unpublished)



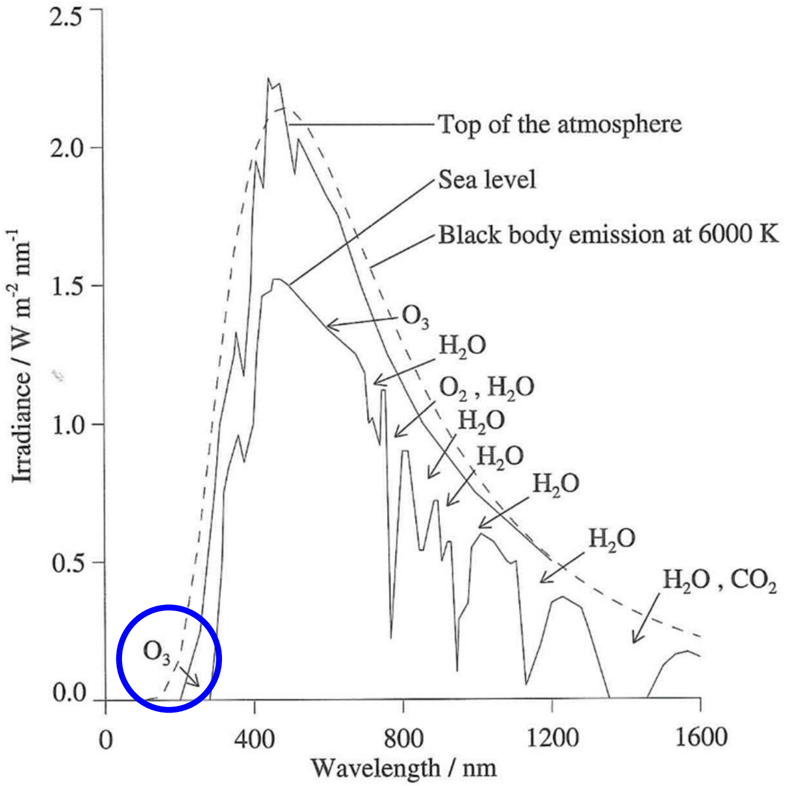
"Stratospheric fountain" and water "cold trap"

Downward, probably due to subtropical anticyclones.

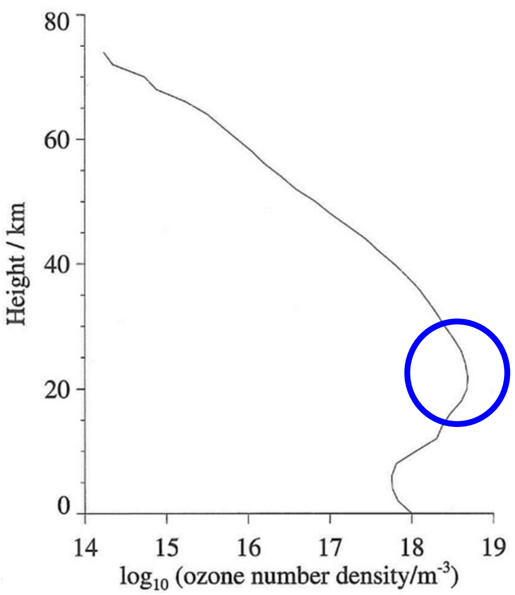
Upward, reaching tropopause, due to morning clouds on sea.

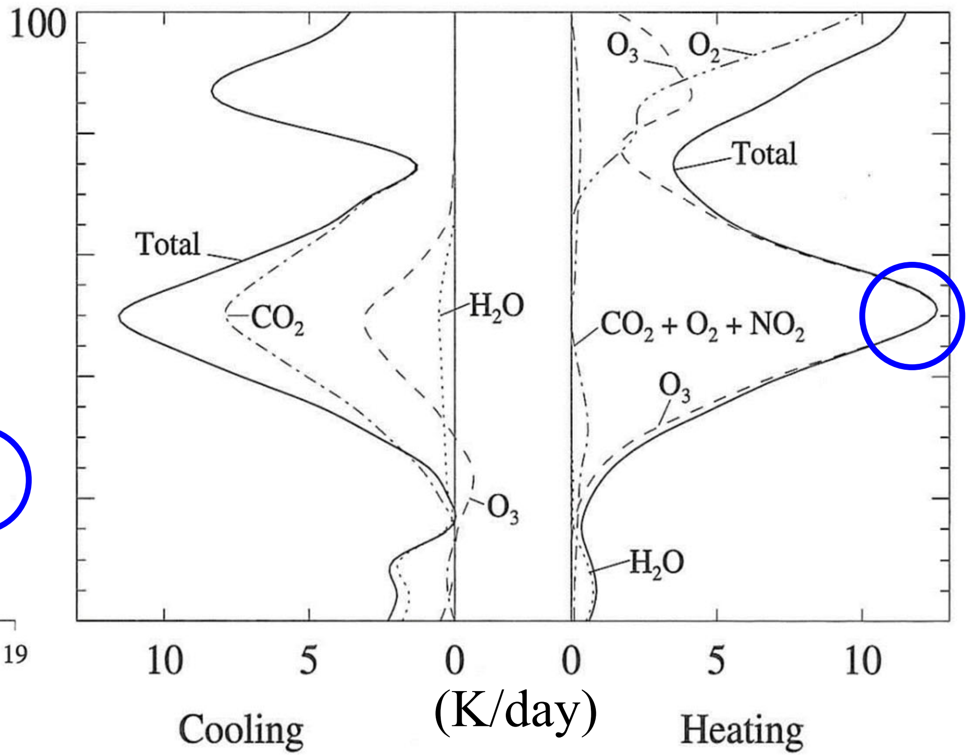
Upward, centered at mid-troposphere due to evening clouds on land.

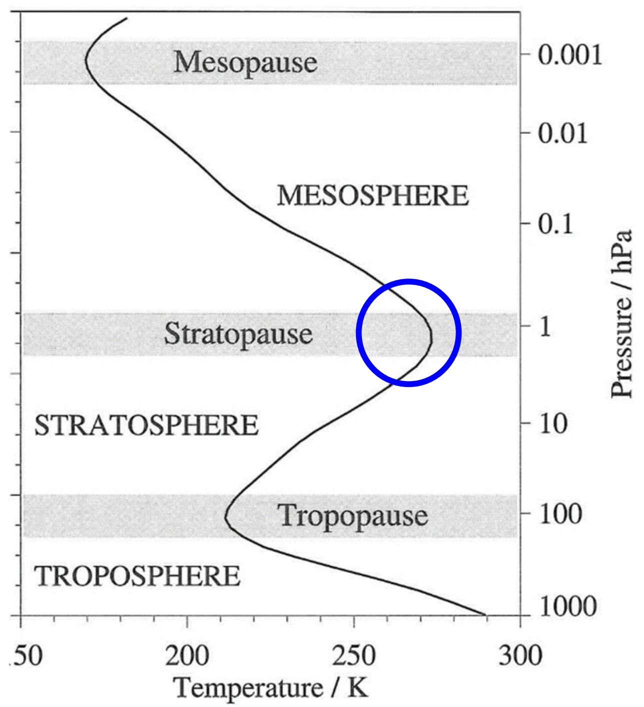
Ozone UV heating and Middle Atmosphere (Mesosphere & Stratosphere)



(Brasseur & Solomon, 1986)







(CIRA1986)

Meridional distribution of Temperature and Zonal Wind

(January, CIRA1986)