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

Variability of the atmosphere: Vertical (z) ≫ Meridional (y) ≫ Zonal (x)

↑ gravity; ↑ solar radiation, ↑ Coriolis parameter; ↑ topography

solar radiation: stronger diurnal ⟷ weaker annual

Meridional structure (geographic): tropics, temperate, frigid

Coriolis parameter: 0 ⟷ stronger

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

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

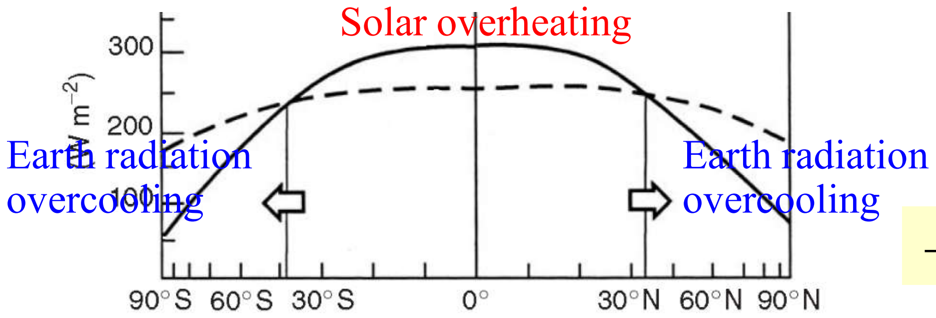


Figure 7 Annual-mean net incoming solar radiation (solid line) and outgoing terrestrial radiation (dashed line) as a function of latitude, expressed in units of W m^{-2}. Distance on the latitude scale is proportional to area on the Earth's surface. (Diagram provided by Socorro Medina.)

→ Poleward atmospheric and oceanic heat transport

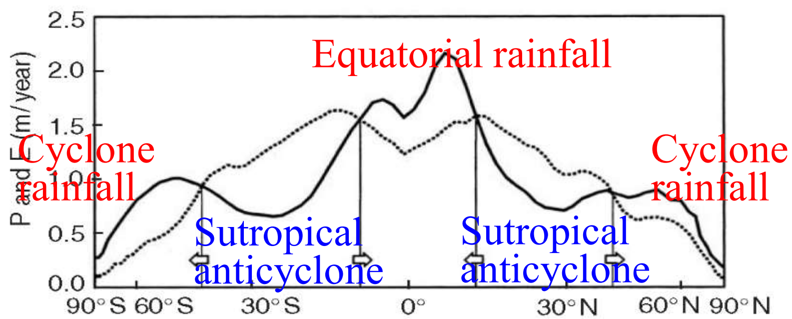
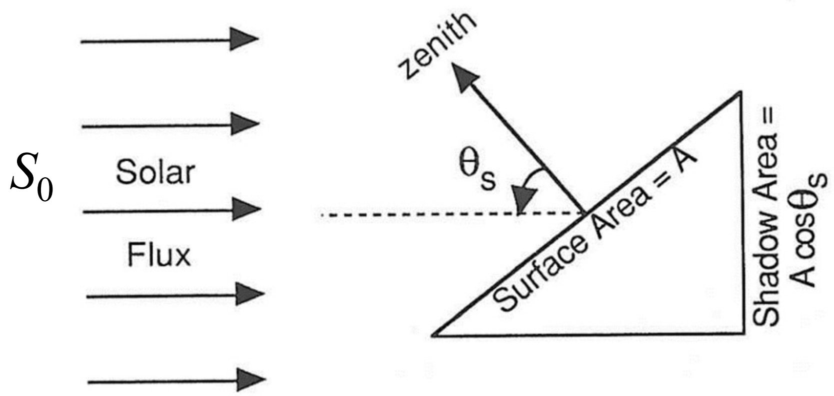


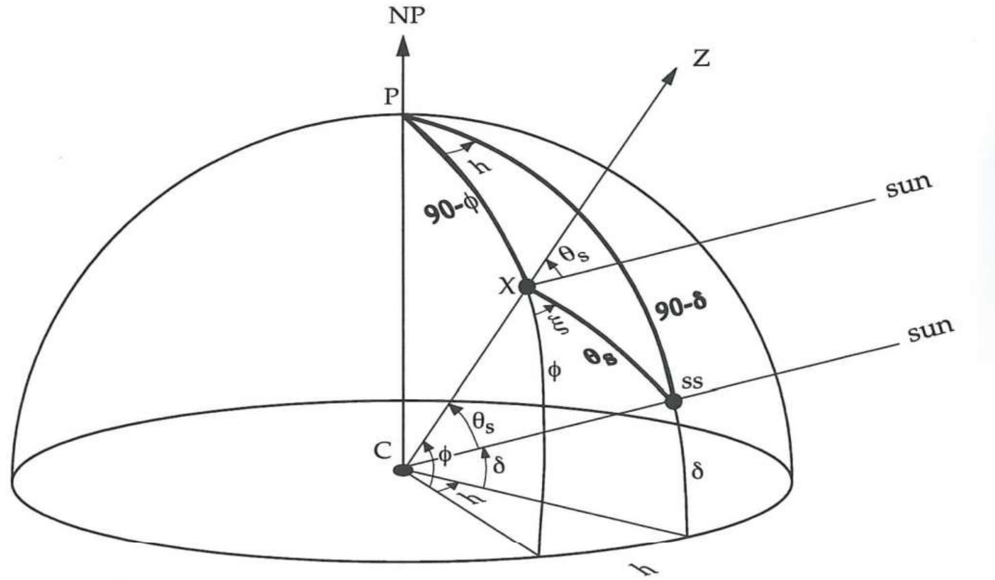
Figure 10 Annual-mean precipitation (solid) and evaporation (dashed) as a function of latitude, expressed in units of meters per year. Distance on the latitude scale is proportional to area on the Earth's surface. Based on NCEP/NCAR Reanalyses for the period 1958–1997. (Diagram provided by Socorro Medina.)

→ 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)

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

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

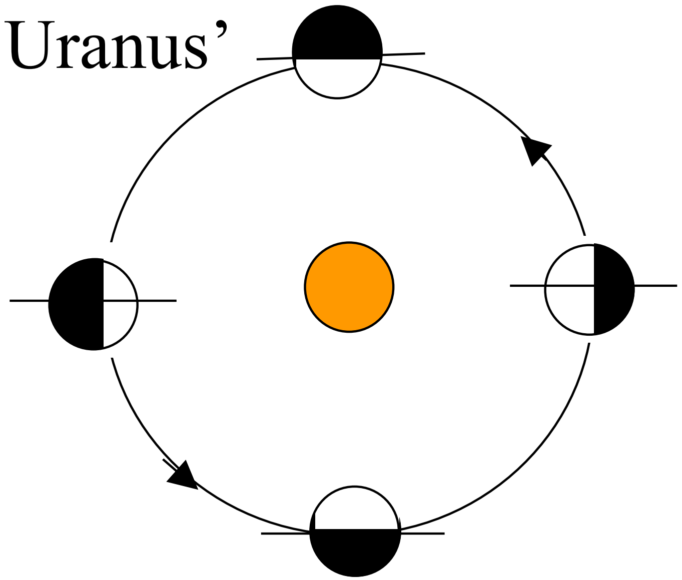
$$\cos\ h_0 = -\tan\ \phi\ \tan\ \delta$$

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

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

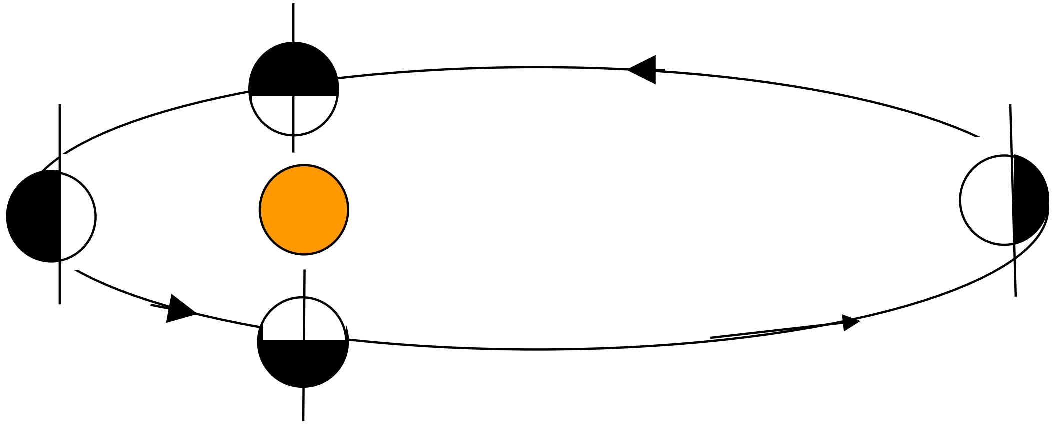
Two extreme cases of seasonal cycle forcing

'Uranus'

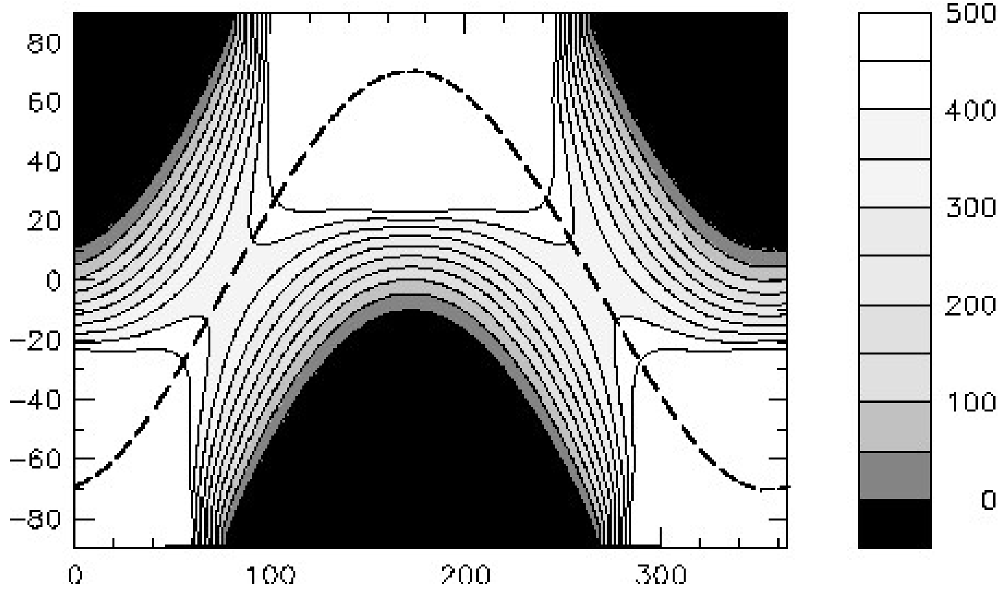


Rotation-axis obliquity

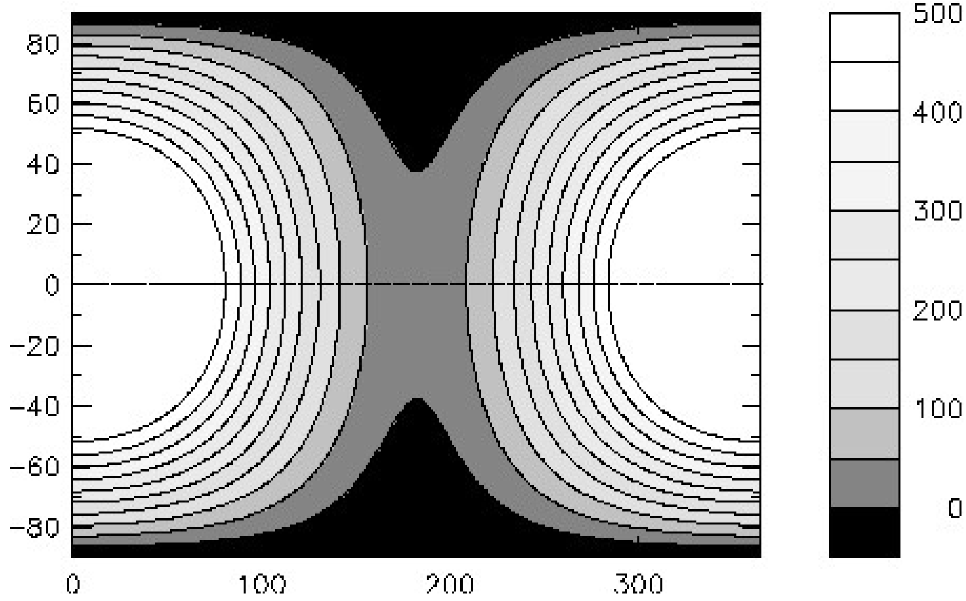
'a type of extra-solar planet'



Orbital eccentricity

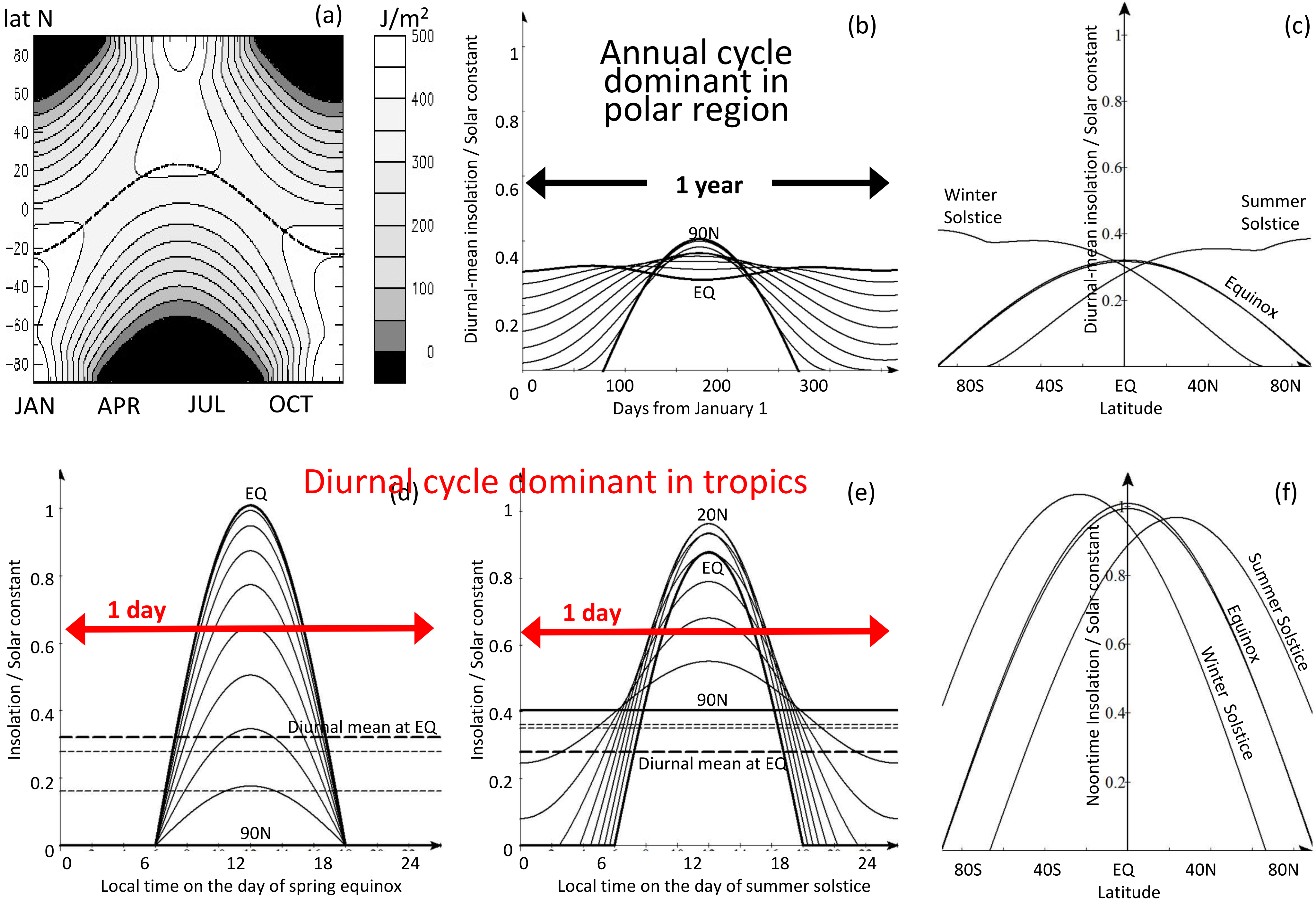


Hemispherically anti-phase



Hemispherically in-phase

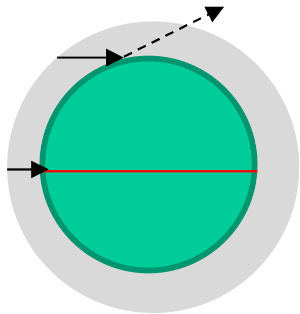
Solar heating on earth with revolution and rotation



Why tropics is tropics?

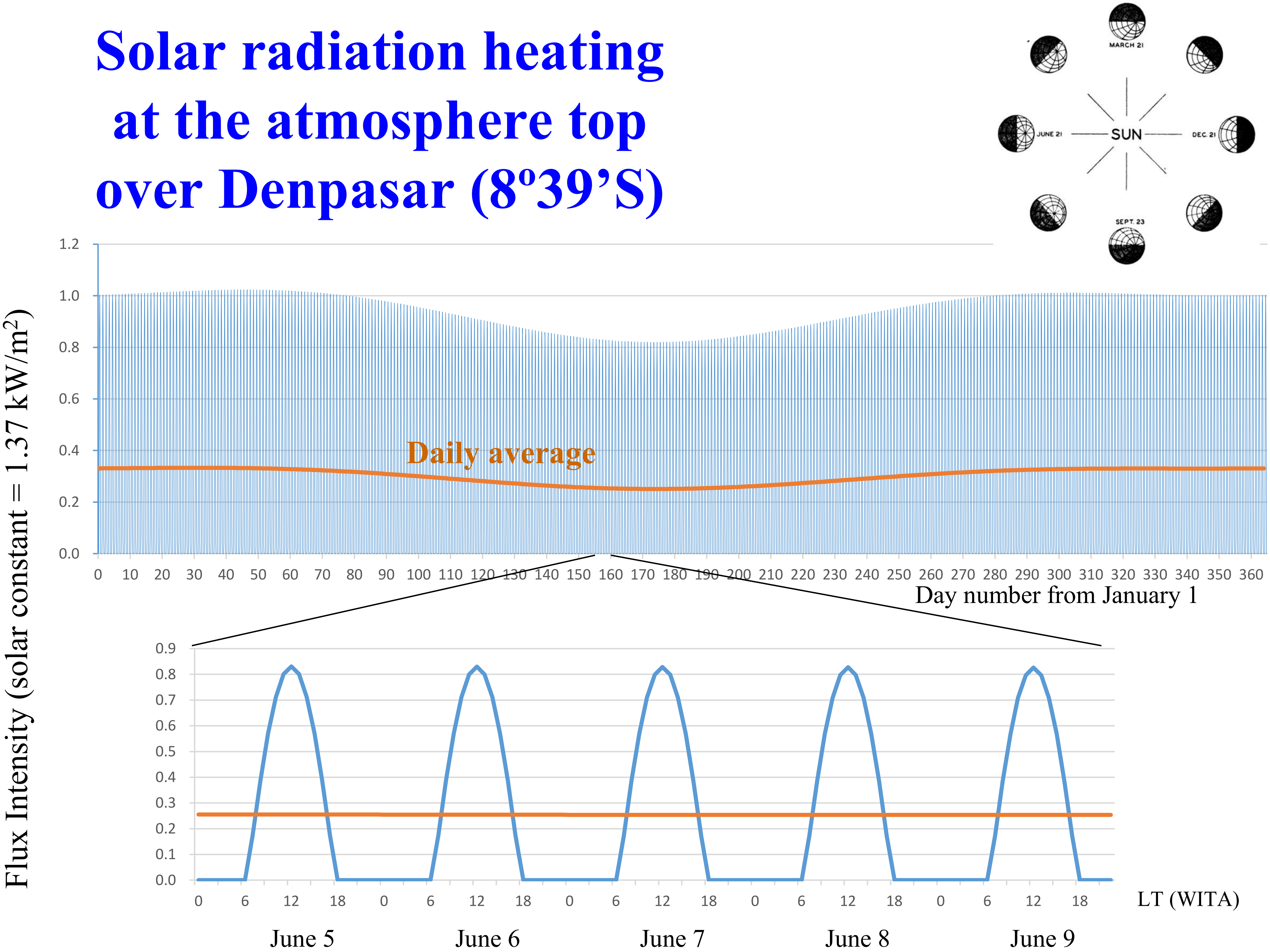
- High latitudes: Low solar angle
  - Large reflection (strong albedo)
  - Large refraction (long optical depth)
  - → Low temperature → Cryosphere/Clouds

Low latitude:
High solar angle
Short path length



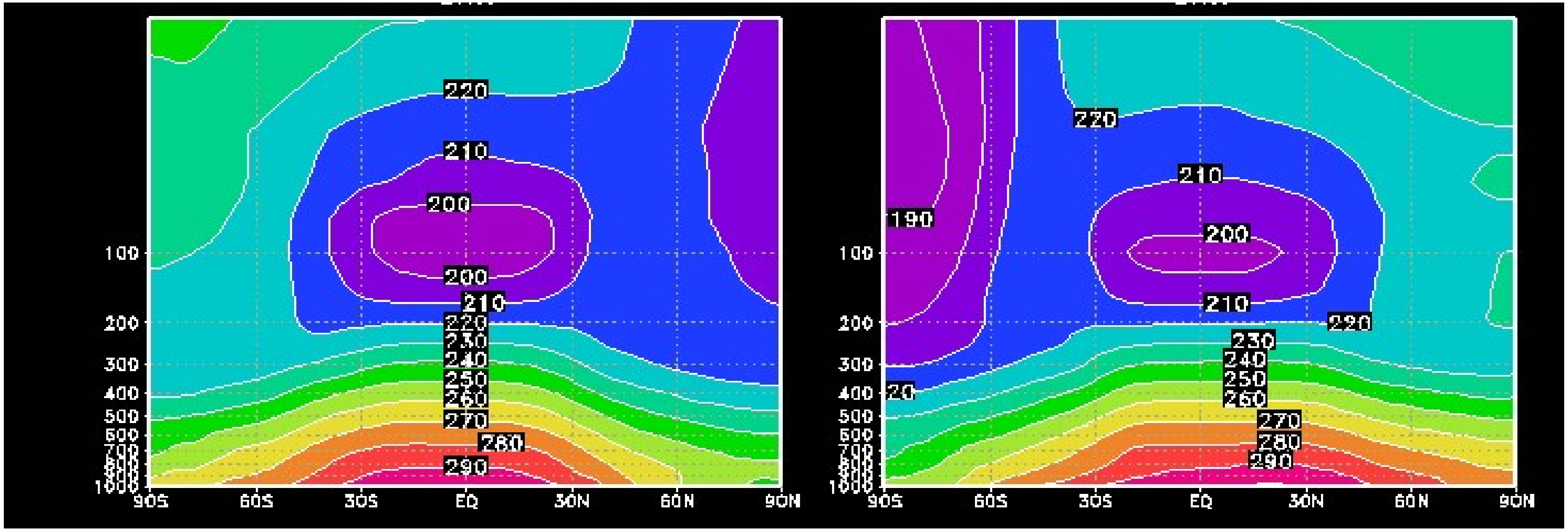
- Rapid rotation &
  Slow circular revolution
  - Zonal homogeneity
  - Weak hemispheric anti-symmetry

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



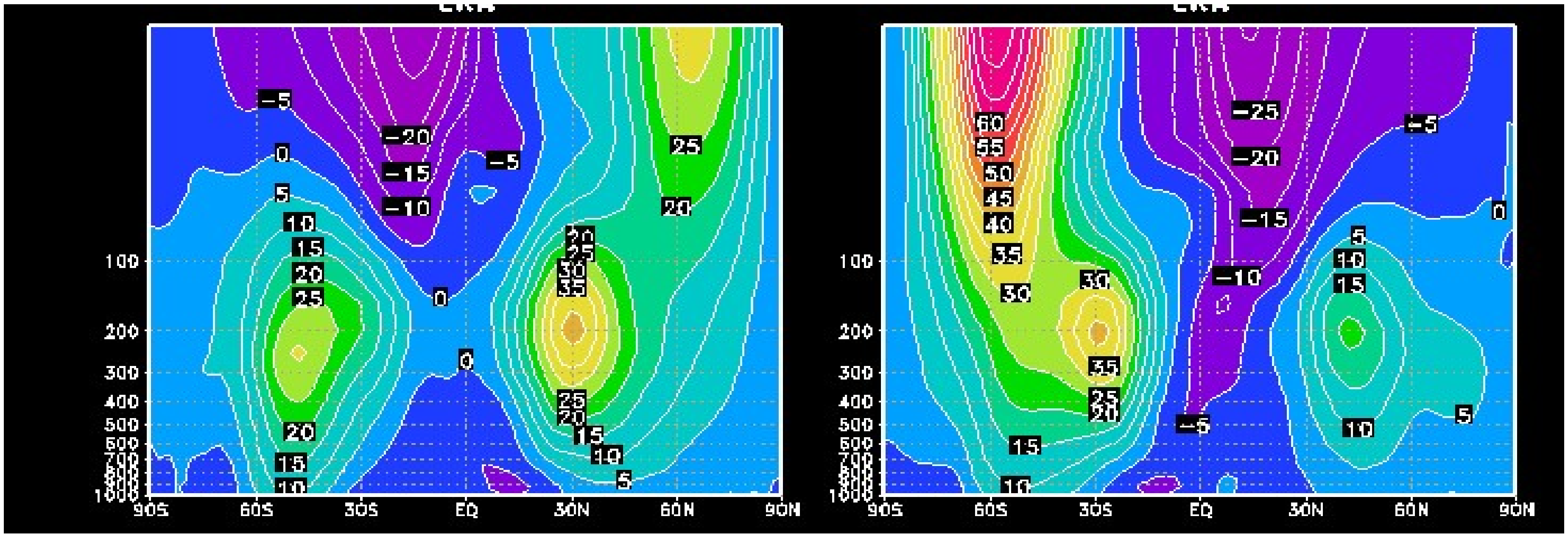
4.1-c Trade wind (Equatorial easterly & mid-latitude westerly)

DJF $\overline{T}$



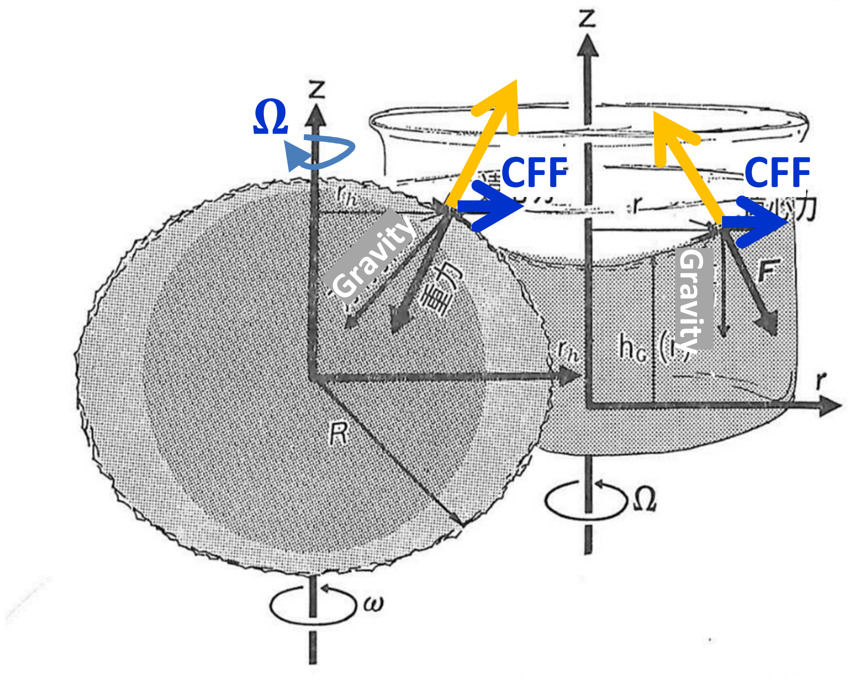
JJA $\overline{T}$

DJF $\overline{u}$

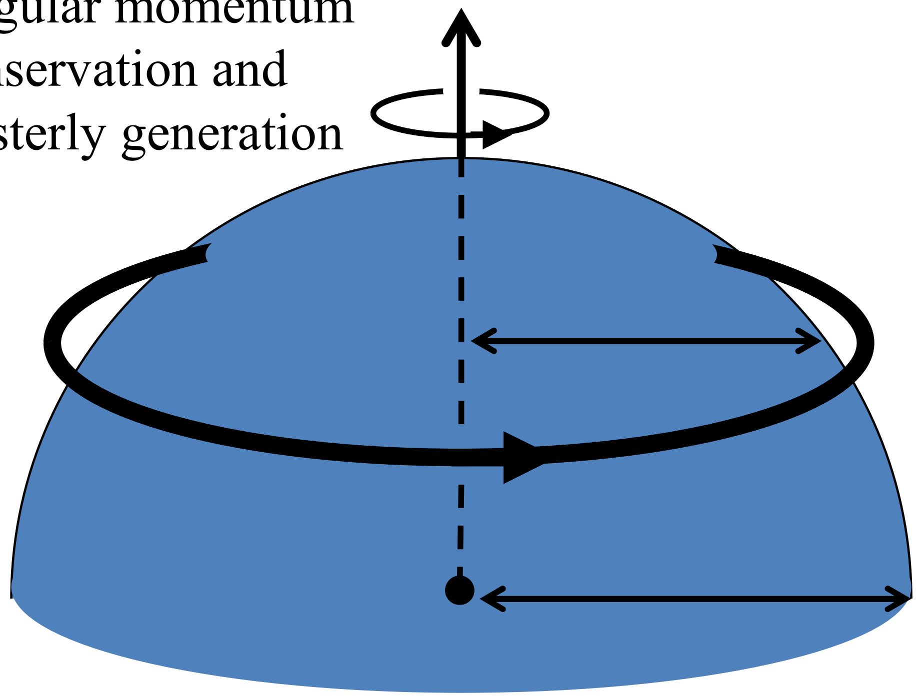


JJA $\overline{u}$

Rotating fluid and centrifugal/Coriolis forces



Angular momentum conservation and westerly generation



“Thermal wind” equilibrium

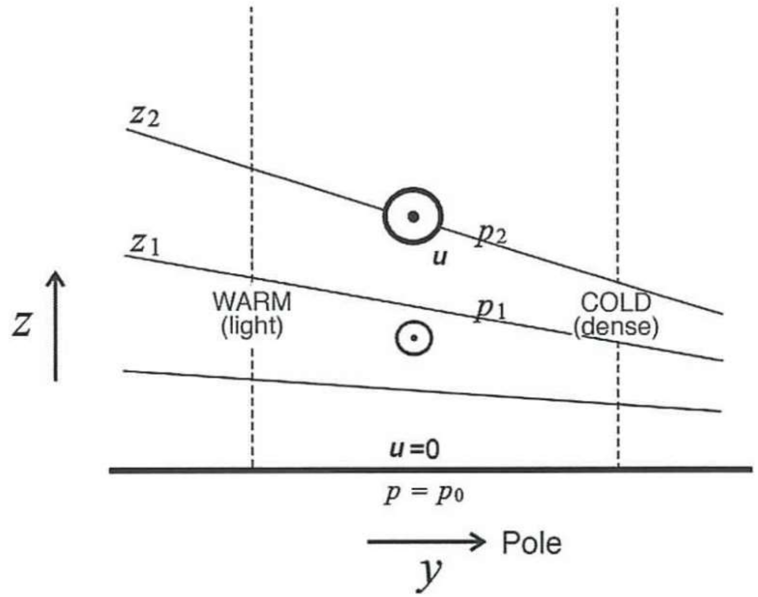


FIGURE 5.14. Warm columns of air expand, cold columns contract, leading to a tilt of pressure surfaces, a tilt which typically increases with height in the troposphere. In Section 7.3, we will see that the corresponding winds are out of the paper, as marked by ⊙ in the figure.

(Marshall & Plumb, 2009)

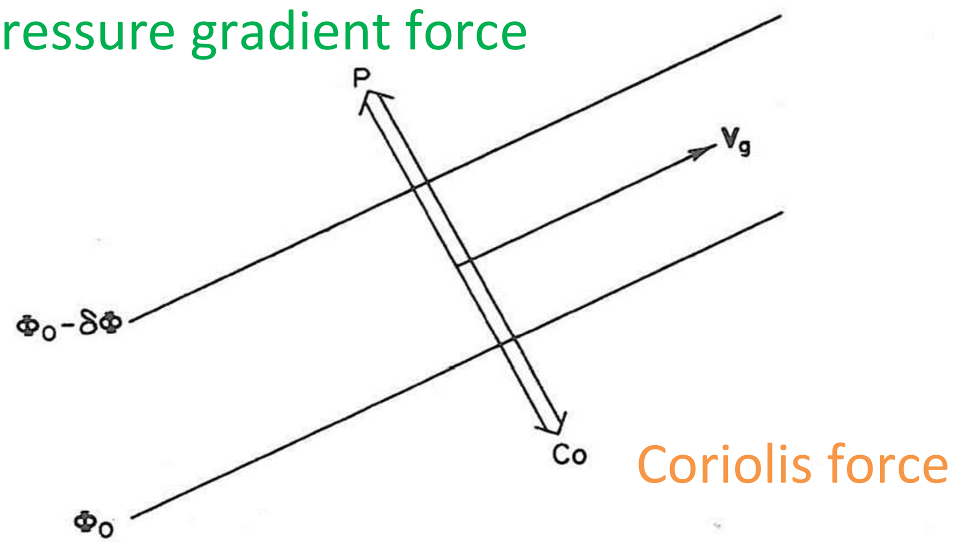


Fig. 3.2 Balance of forces for geostrophic equilibrium. The pressure gradient force is designated by P and the Coriolis force by Co.

(Holton, 1972)

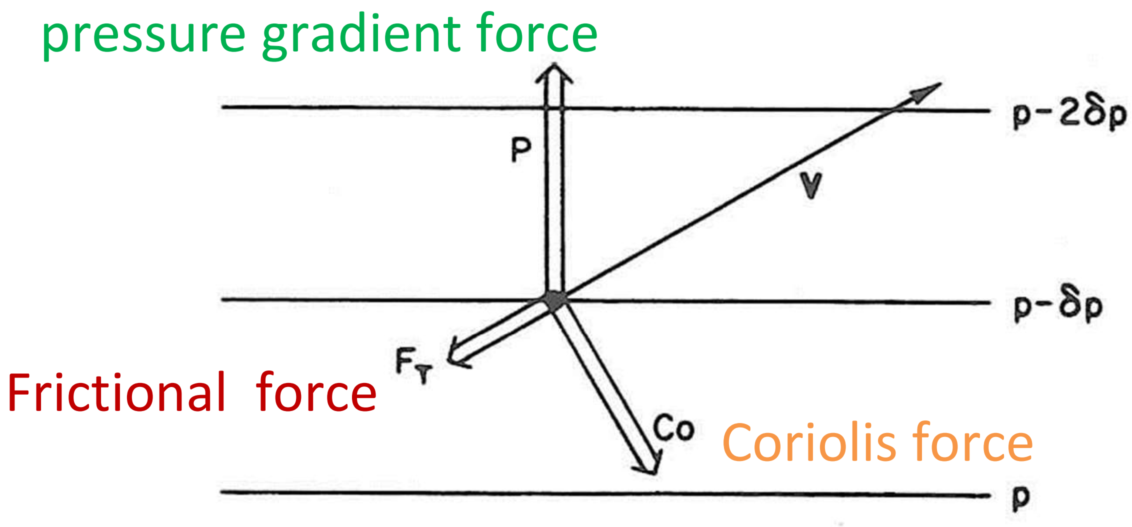


Fig. 5.3 Balance of forces in the well-mixed planetary boundary layer: P designat gradient force, Co the Coriolis force, and F_T the turbulent drag.

Upper ocean
(Marshall & Plumb, 2008)

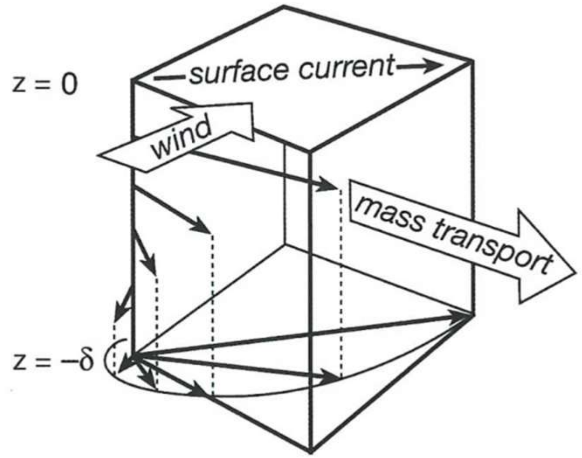
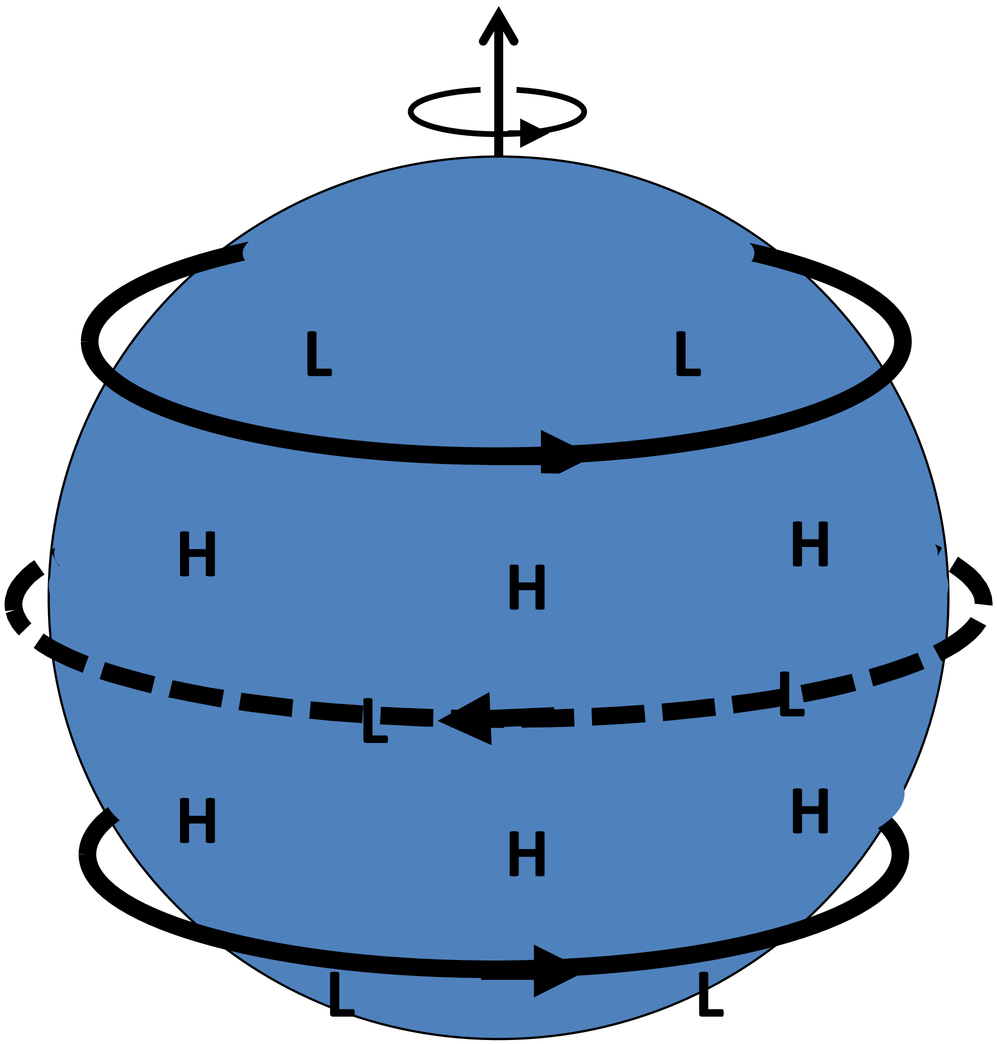
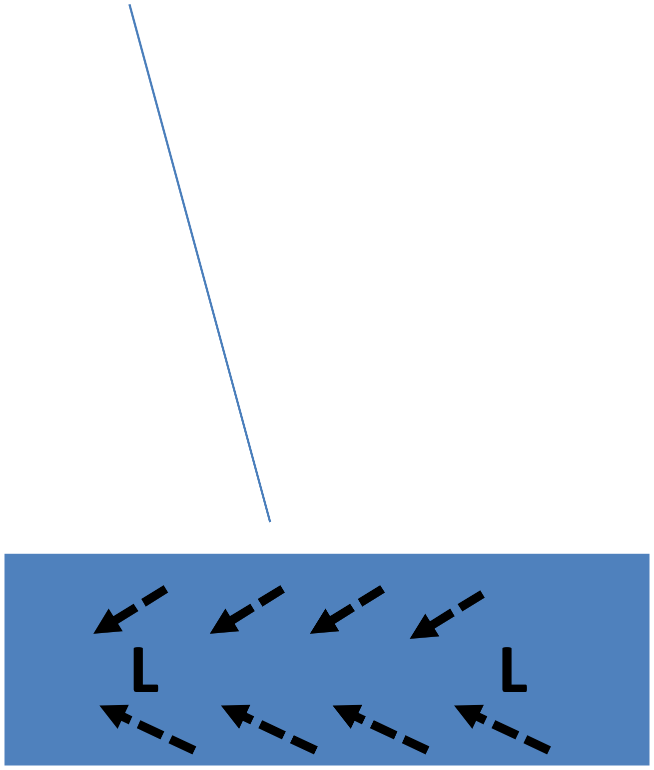


FIGURE 10.5. The mass transport of the Ekman layer is directed to the right of the wind in the northern hemisphere (see Eq. 10-5). Theory suggests that horizontal currents, u_{ag}, within the Ekman layer spiral with depth as shown.

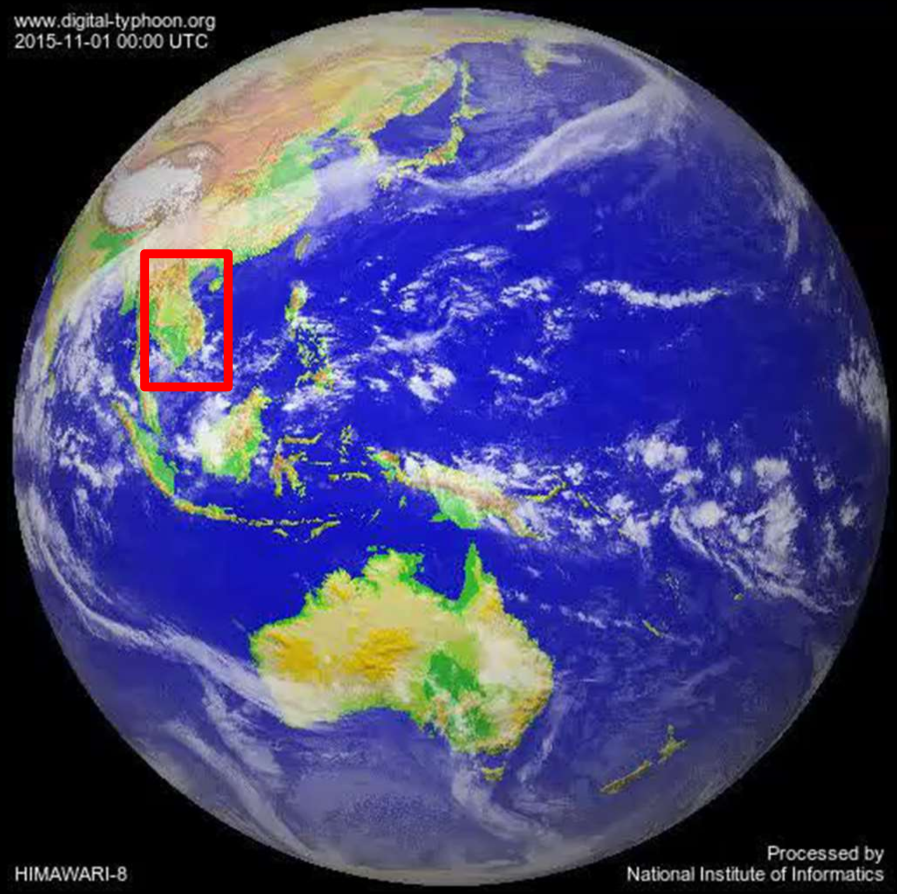
Geostrophic and surface (frictional) flow



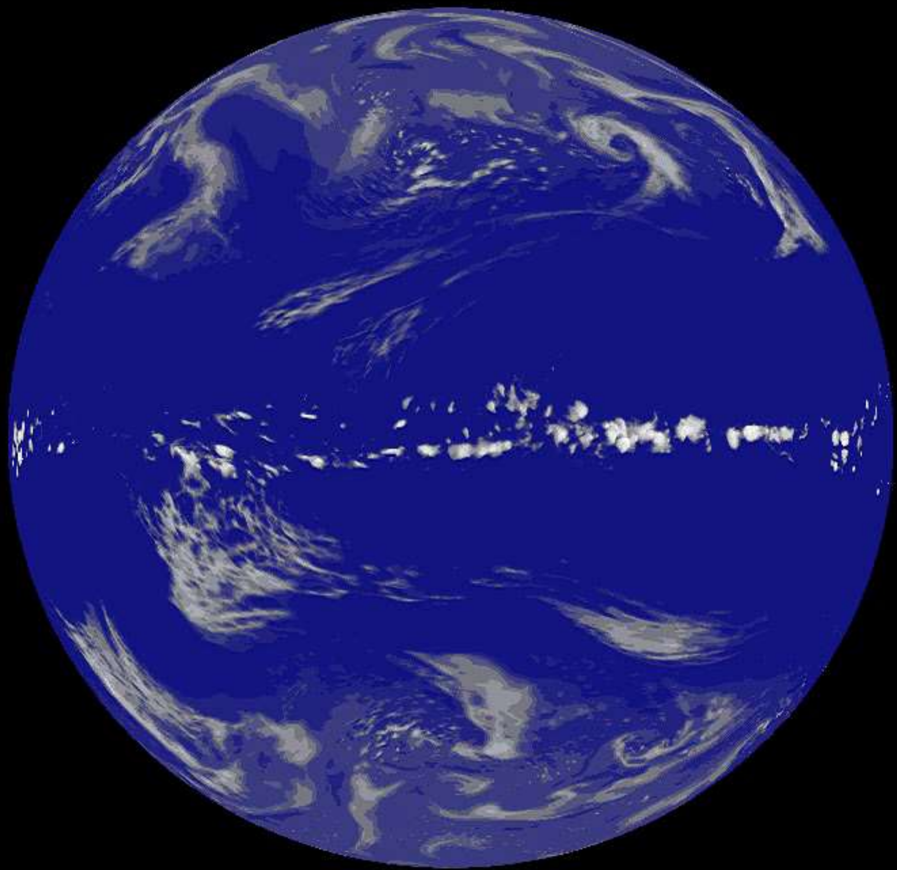


“convergence”

Earth ≠ "Aqua-Planet"

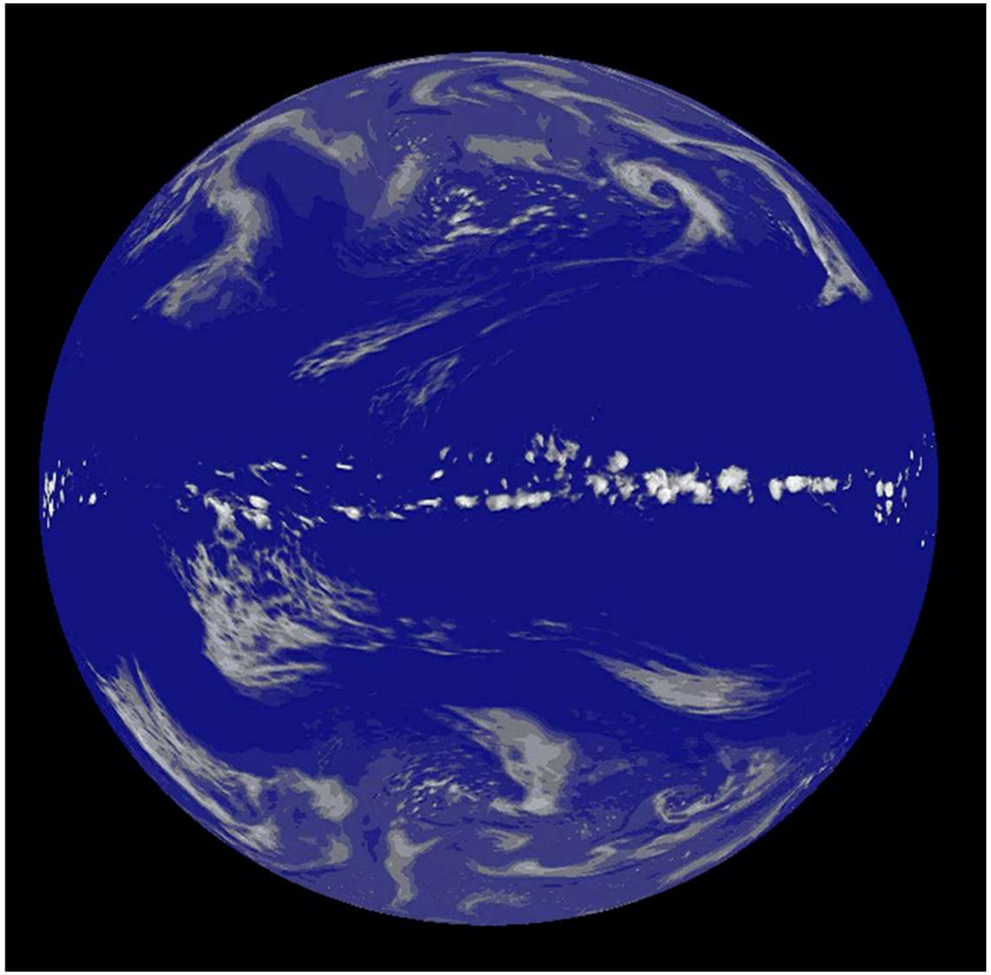


Himawari-8/JMA (1-30 Nov 2015)



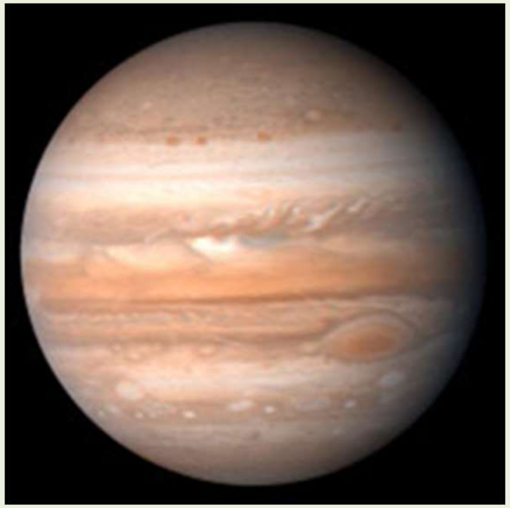
NICAM/JAMSTEC (Satoh et al., 2008)

"Virtual Earth" (Aqua-Planet) by the Earth Simulator

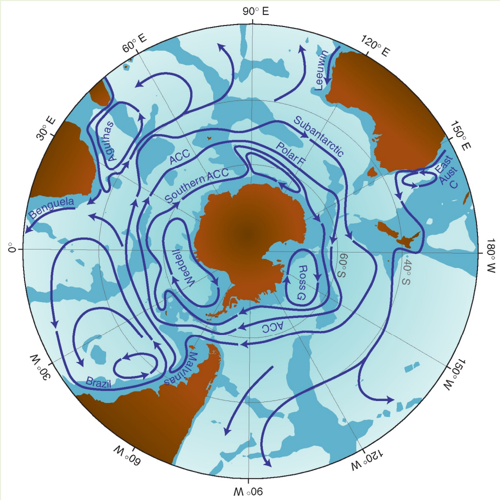


- Imagine the Earth is a complete sphere, then the liquid water covers the whole Earth, that is so-called an "aqua-planet".
- In such a case the oceanic circulation should be almost zonal (as appeared in stripe patterns of dense atmospheres of Jupiter and Saturn).
- The atmosphere circulation must have meridional circulations dependent on differential solar heating
- Updraft and cloud are generated along the equator, which is observed over open oceans of the actual Earth and called inter-tropical convergence zone (ITCZ).
- More striking feature is induced by ocean-atmosphere interactions, which is so-called intraseasonal variations (ISVs) or super cloud clusters moving eastward with periods of 1-2 months and zonal scales of a few thousand kilometers as observed actually over Indian and Pacific Oceans.

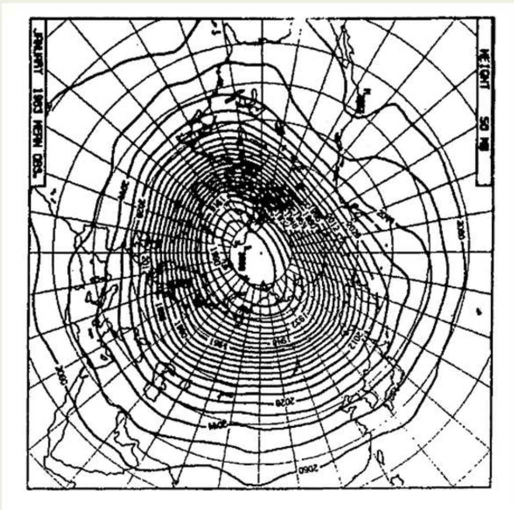
"stripes" of deep atmosphere of Jupiter



circumpolar ocean current around Antarctica

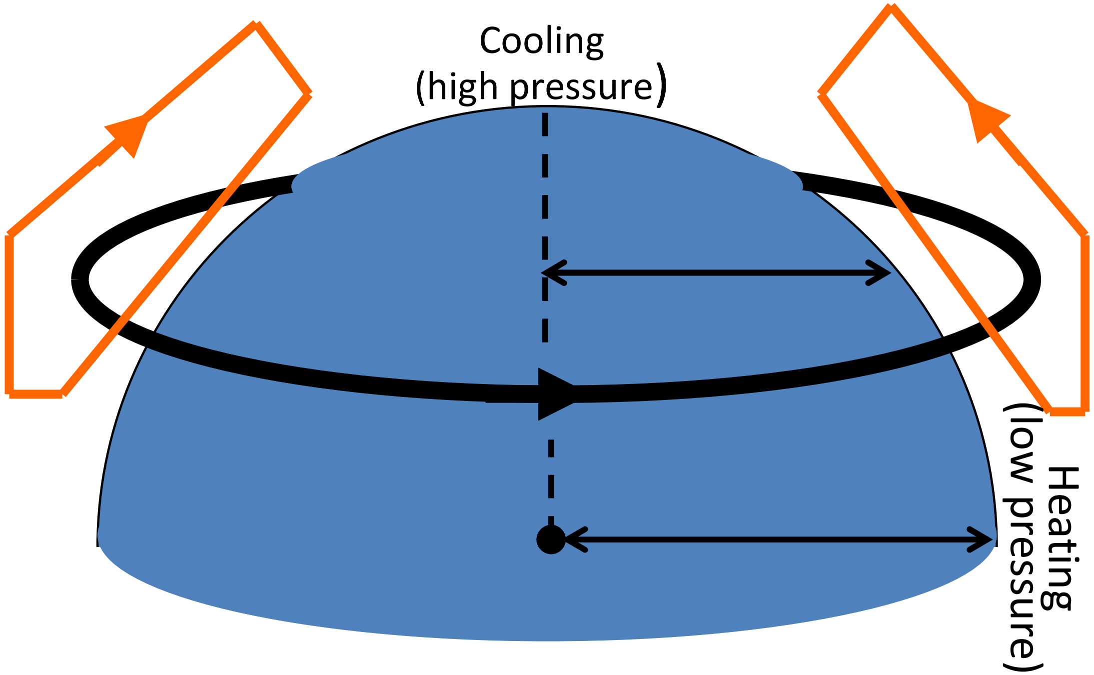


Arctic anticyclone in summer stratosphere



"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) : $\Gamma\,w = \alpha'\Delta T$)

Hermann Ludwig Ferdinand von Helmholtz (1821 – 1894)

Quasi-2D (horizontal) flow velocity:

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

(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)

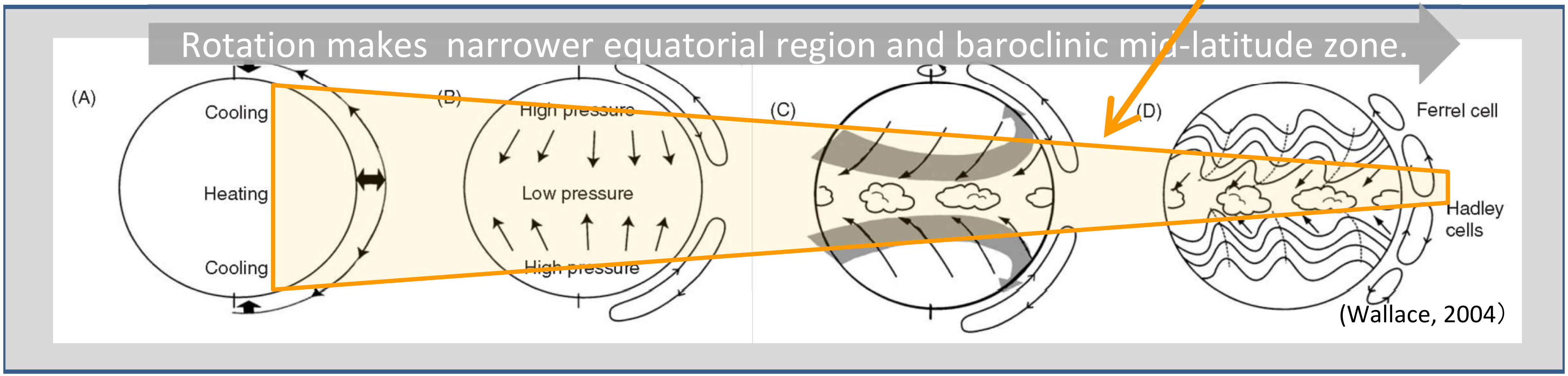
↓

Weather maps

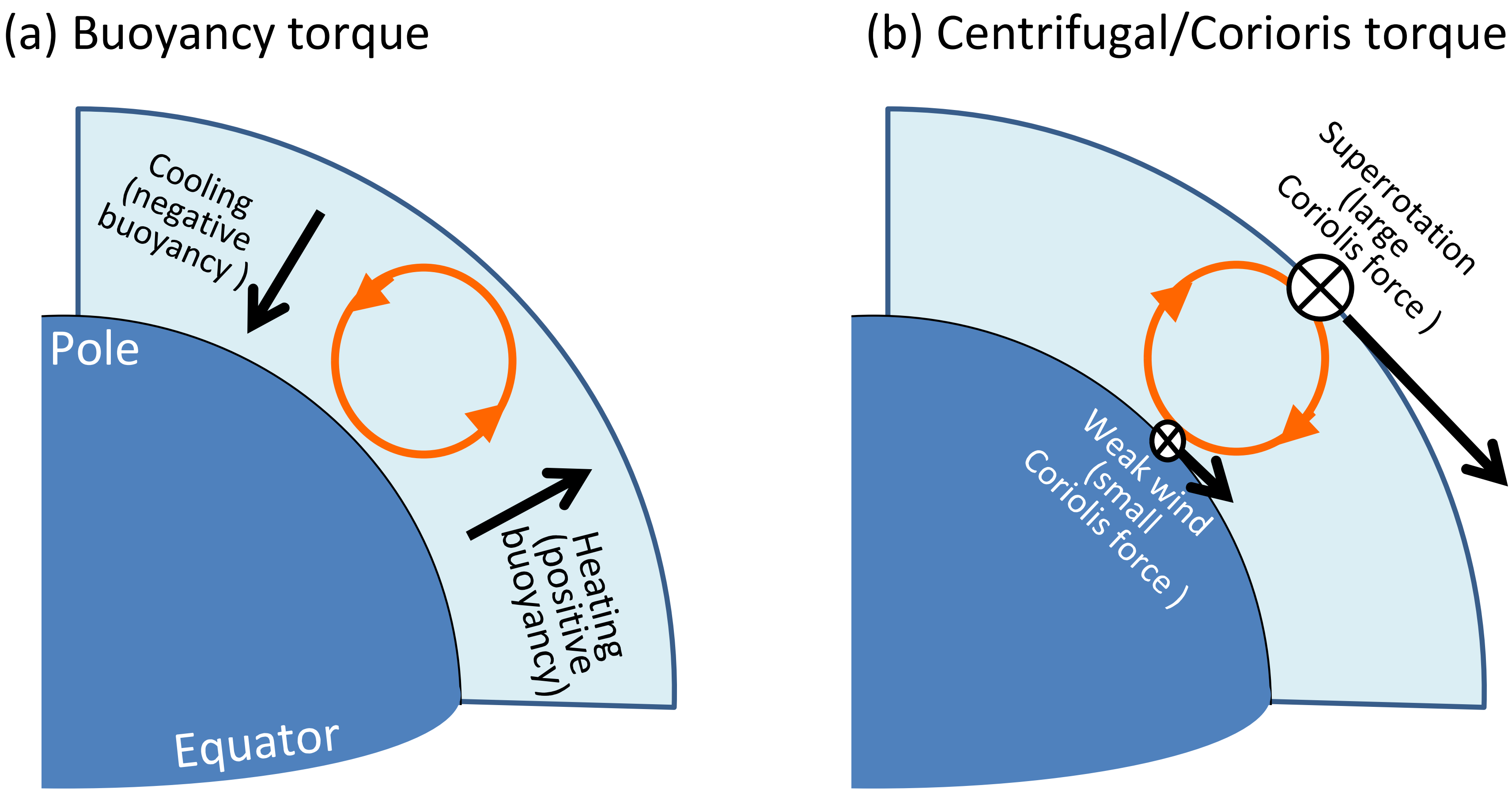
$$\nabla \times (-\nabla \chi) = 0$$

irrotational

"**convection**" on vertical plane



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

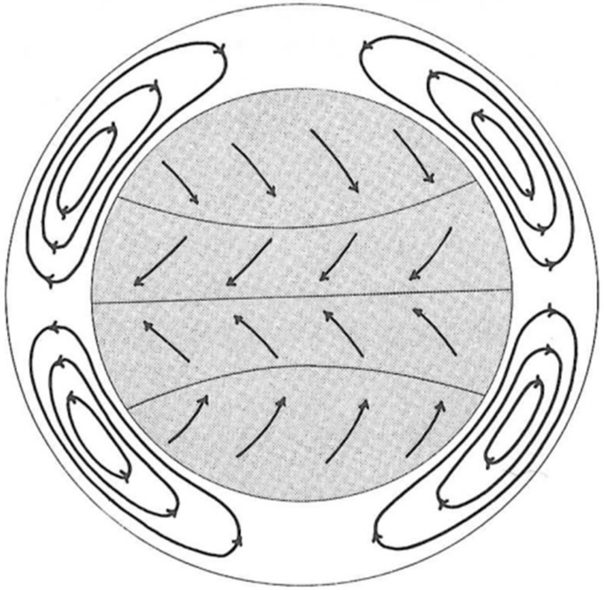


(adapted from Matsuda & Yoden, 1985)

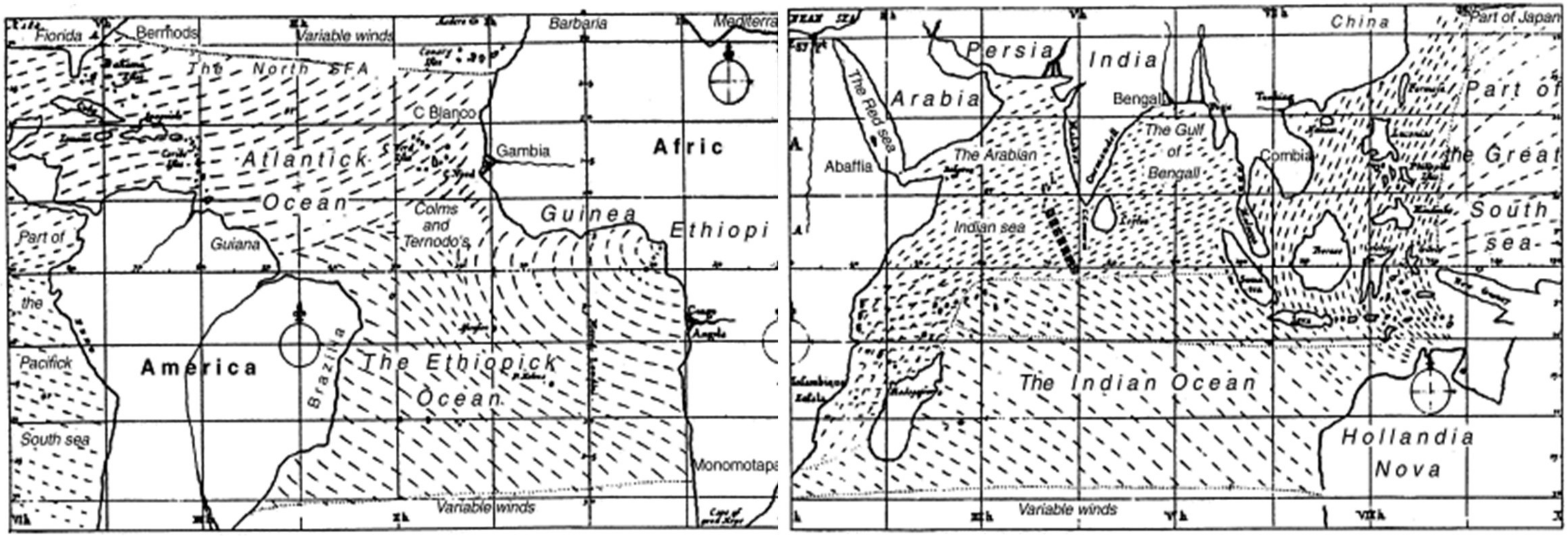
Edmond Halley (1656 –1742)

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

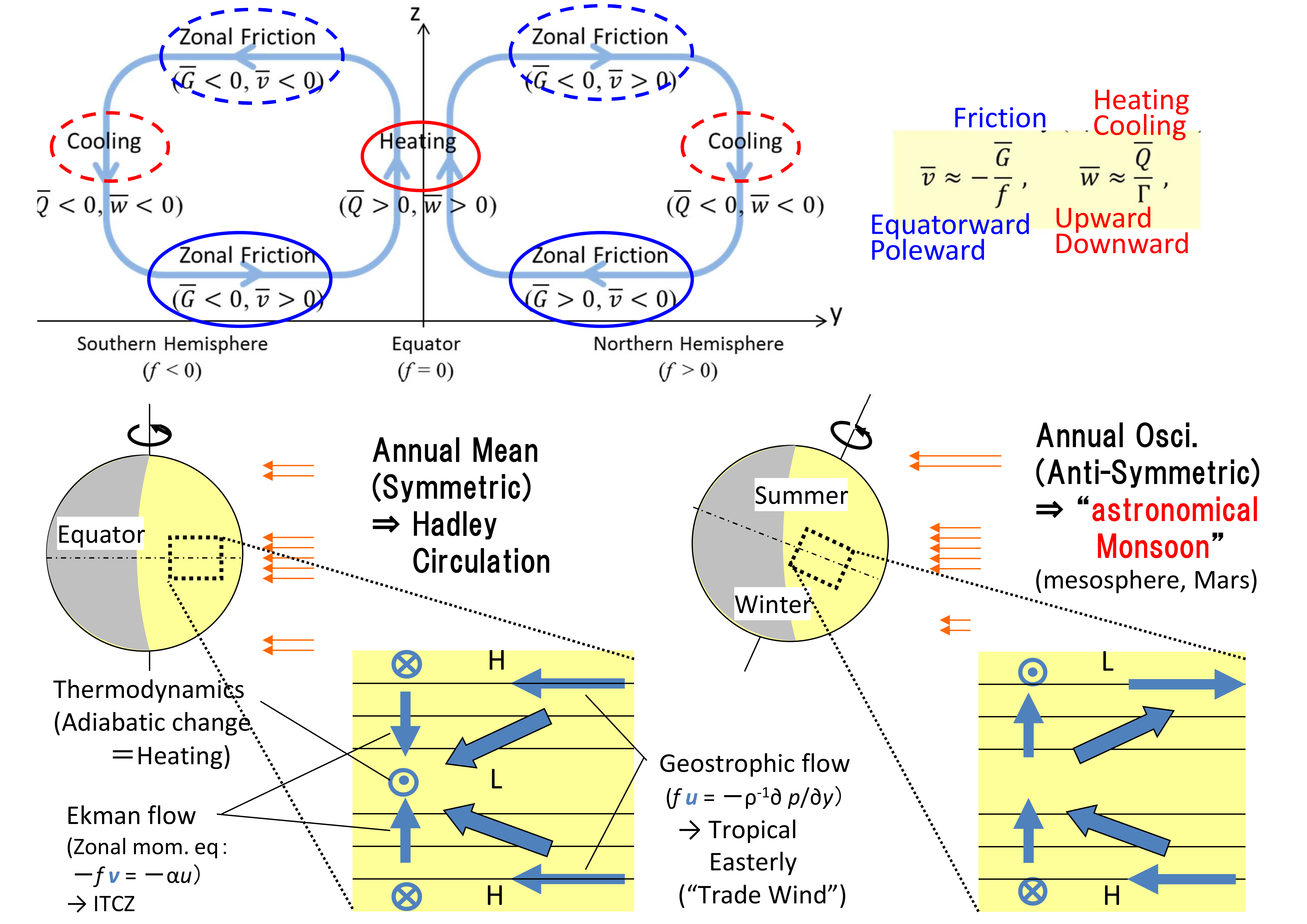
George Hadley (1685 – 1768)



(Hadley, 1735; reproduced by Lorenz, 1967)



(Halley, 1686)



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")

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**)

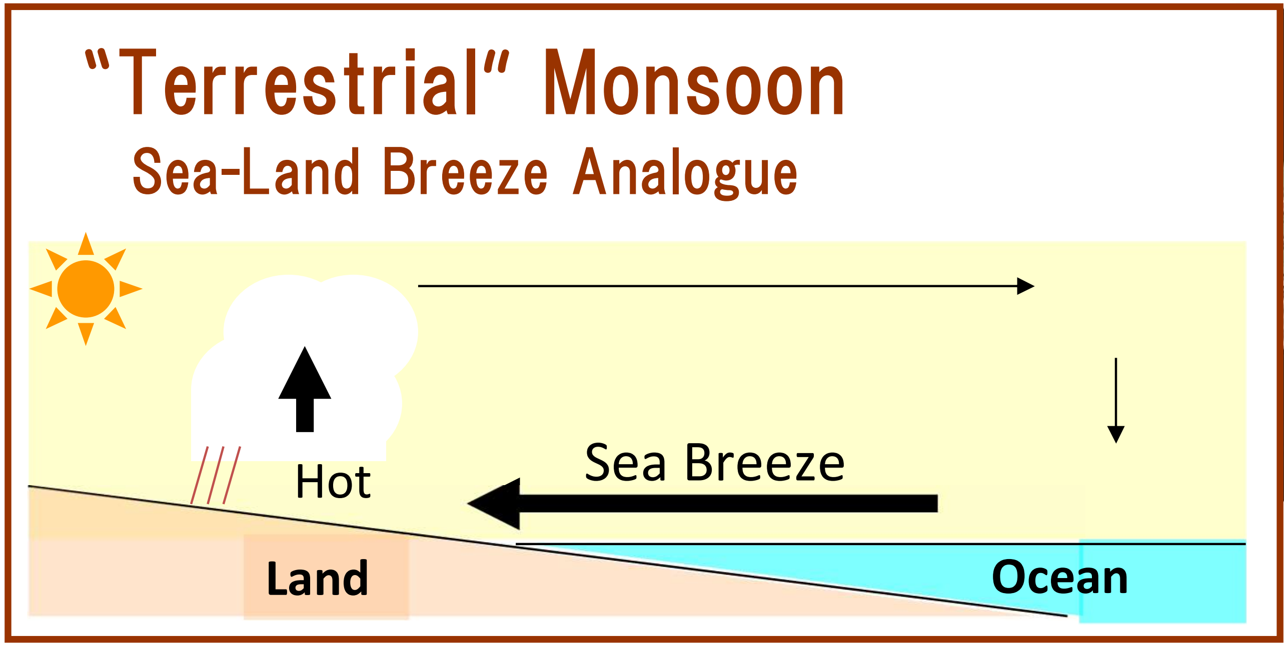
Monsoon is a seasonal cycle of wind, generated by the solar radiation through the following two reasons:

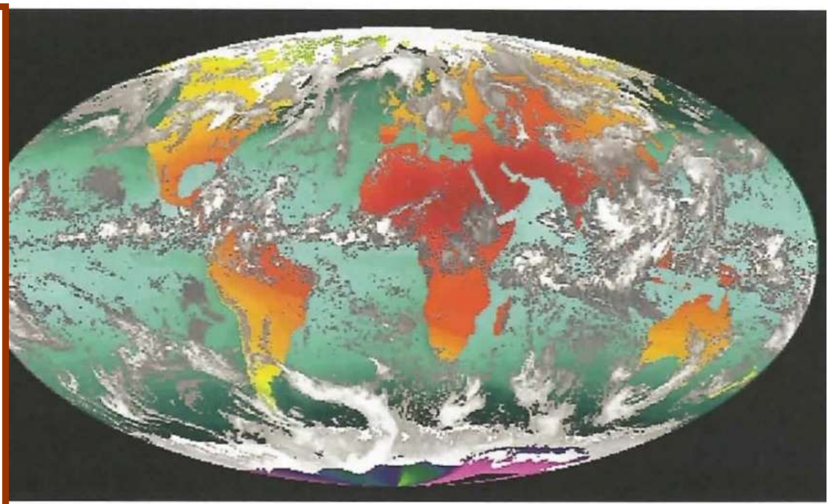
(i) Astronomical (planetological): Hemispheric differential heating, driving a global meridional circulation.
The dominat component of solar heating is equatorially symmetric, which drives the Hadley circulation.
Seasonal variation of solar radiation on a planet is generated by the following two reasons:
- 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.

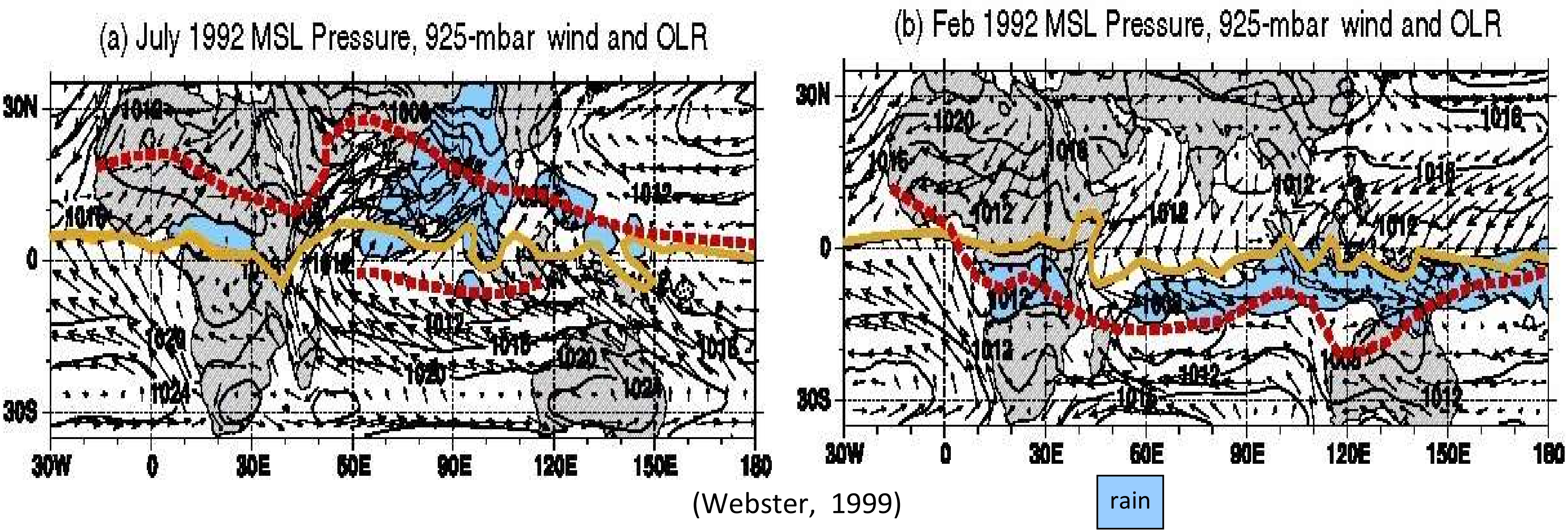
(ii) Geographical (terrestrial) : Continent-ocean differential heating, driving a flow crossing the coastline.
Land (solid) – sea (liquid) heat capacity contrast, generating a diurnal cycle of sea-land breeze circulation.
Integration (residue) of diurnal cycle generates the seasonal cycle and thus the 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.

Ocean-Land Contrasts and Monsoon

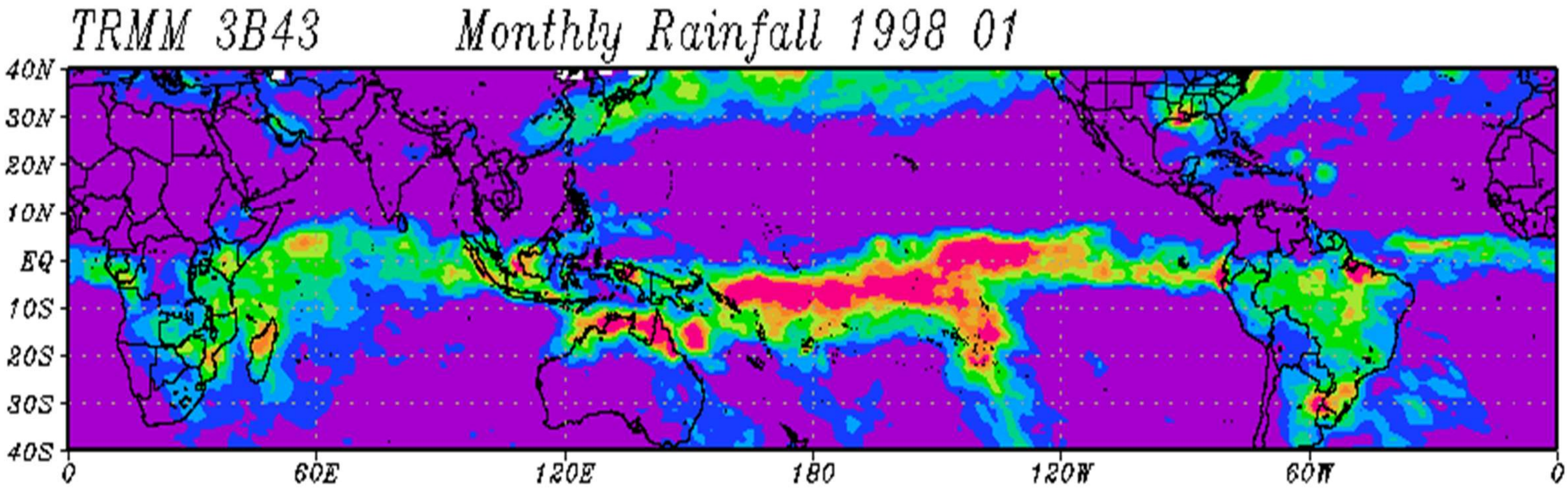


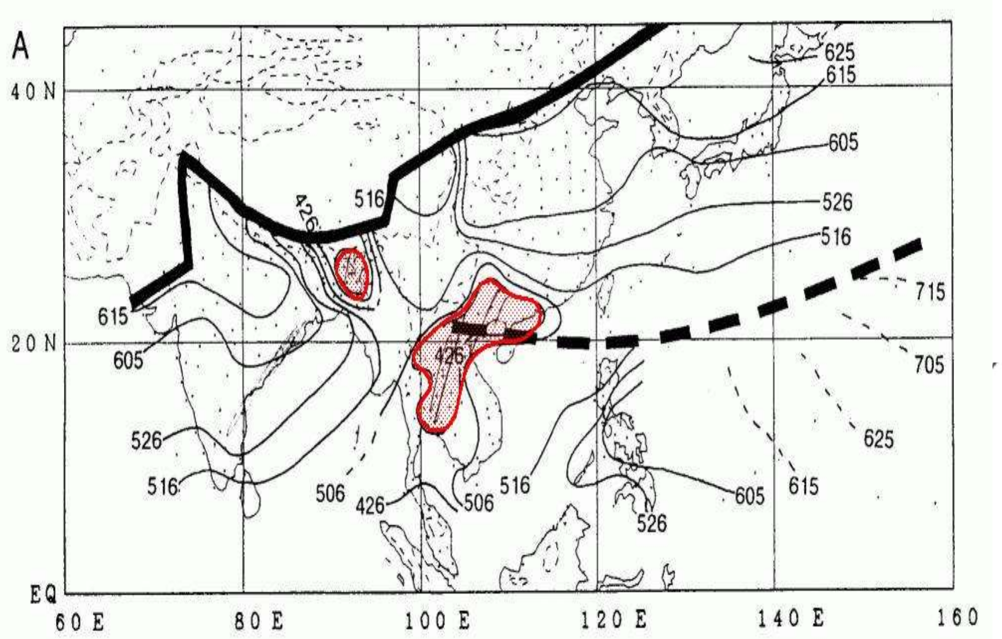


(Wallace & Hobbs, 2006; originally from UWSSEC)

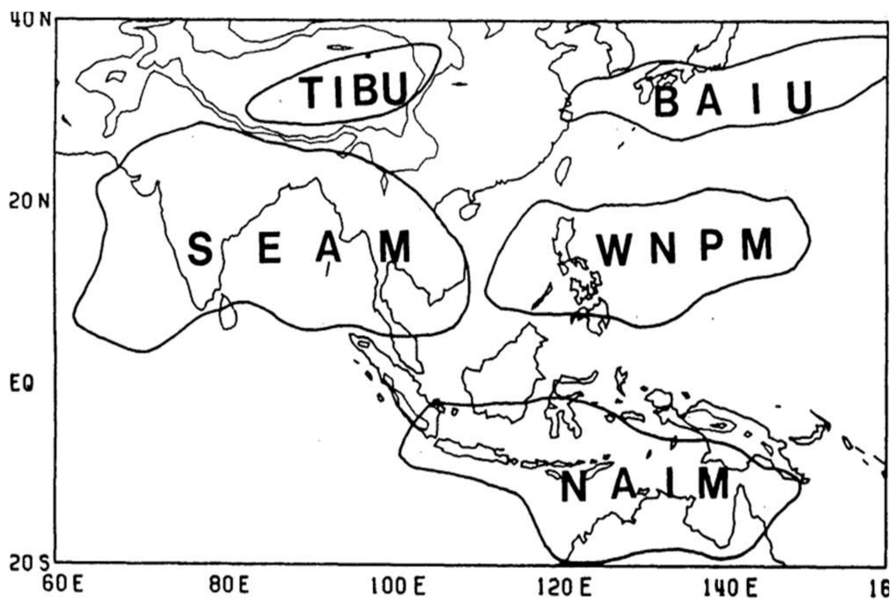


(Webster, 1999)

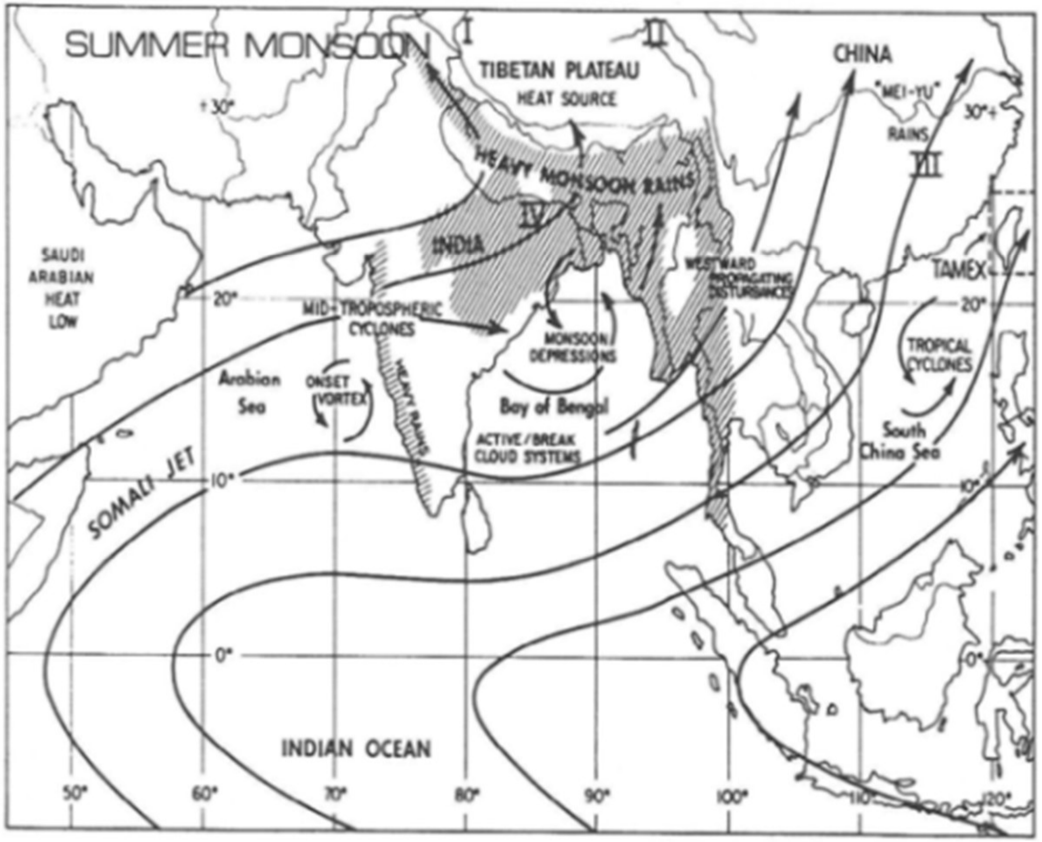
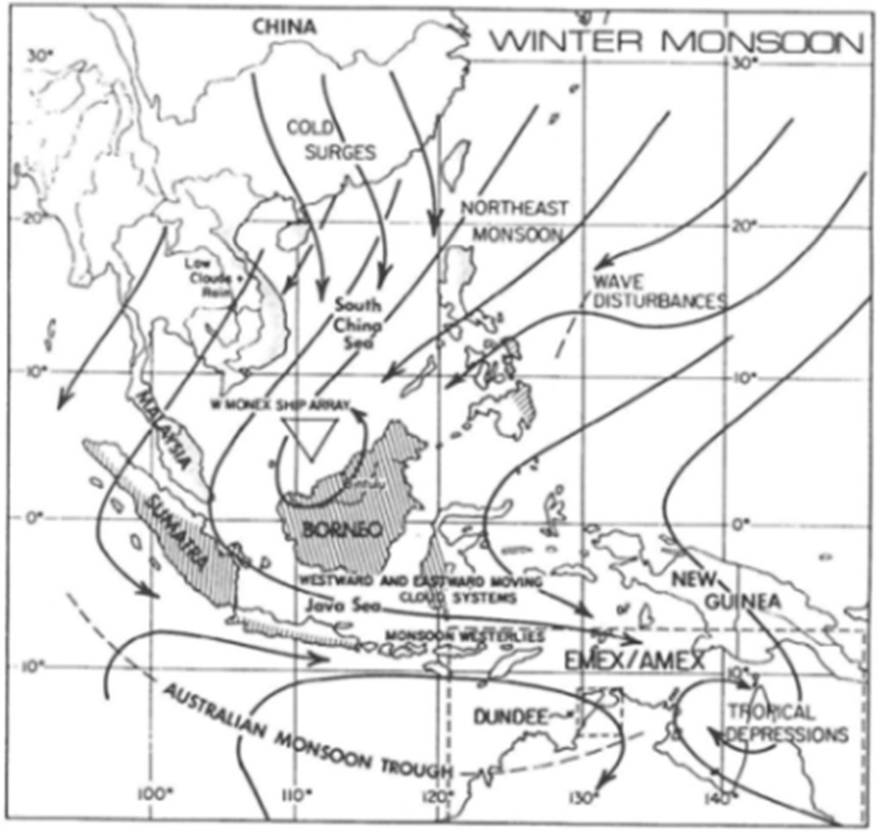
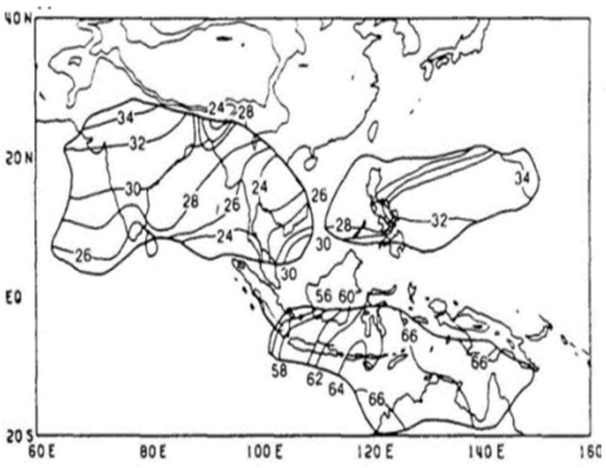
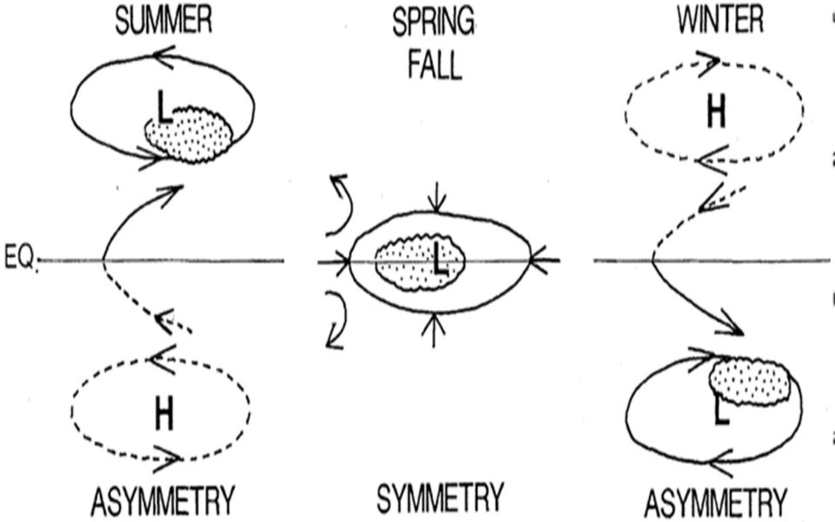
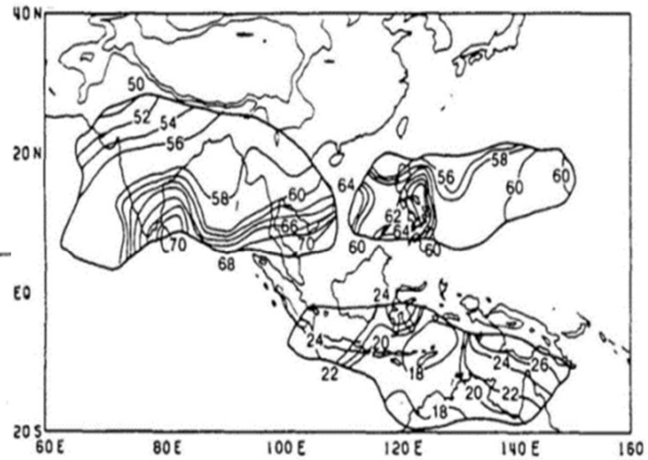




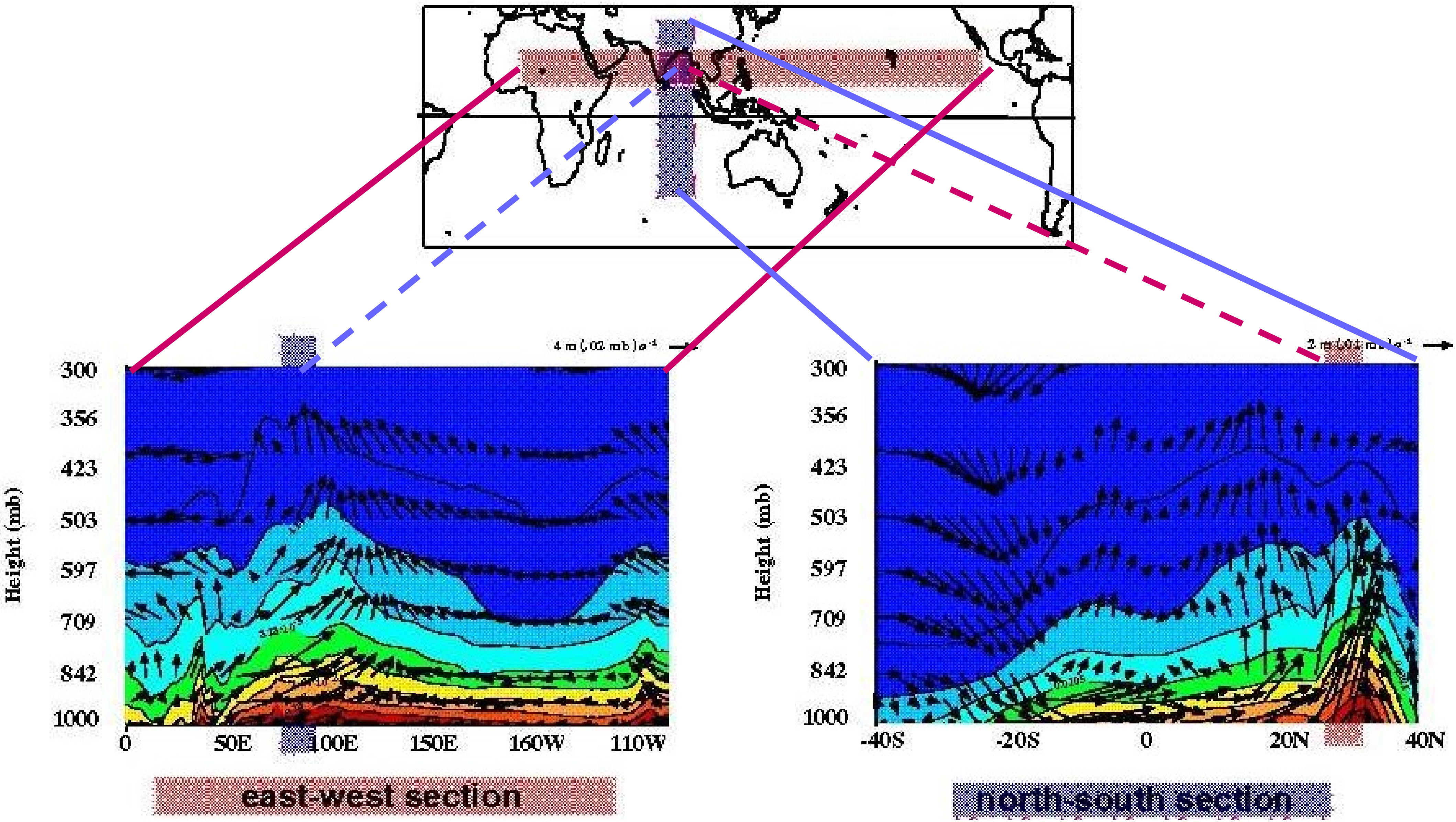
(Matsumoto and Murakami, 1992)



(Murakami and Matsumoto, 1994)

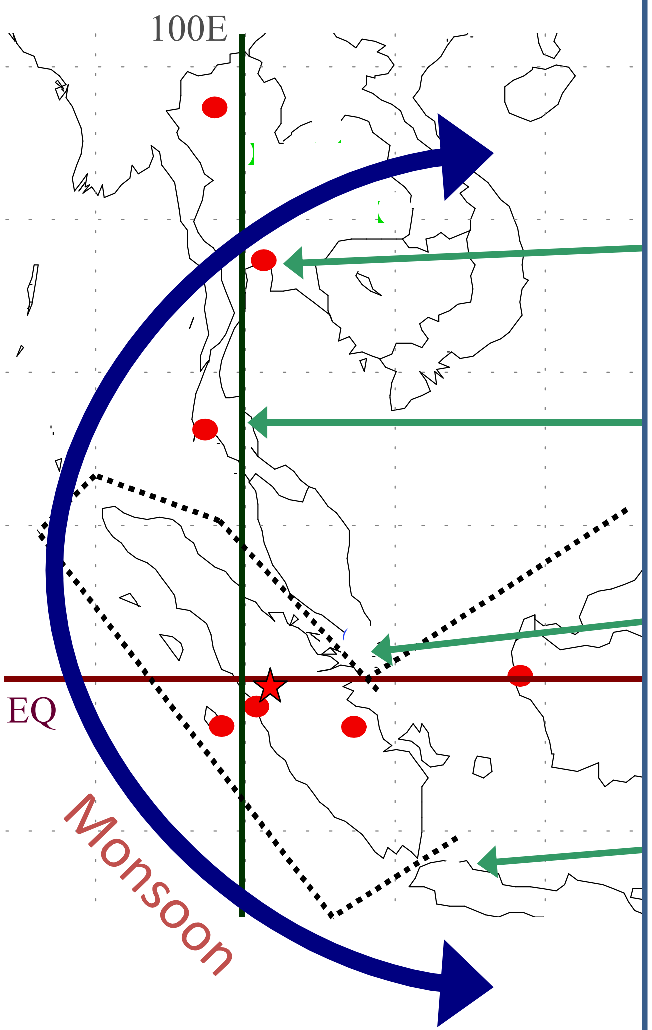

SUMMER MONSOON
TIBETAN PLATEAU
HEAT SOURCE
CHINA
"MEI-YU"
RAINS
HEAVY MONSOON RAINS
INDIA
SAUDI ARABIAN HEAT LOW
MID-TROPOSPHERIC CYCLONES
WESTWARD PROPAGATING DISTURBANCES
TAMEX
MONSOON DEPRESSIONS
TROPICAL CYCLONES
Arabian Sea
ONSET VORTEX
HEAVY RAINS
Bay of Bengal
ACTIVE/BREAK CLOUD SYSTEMS
South China Sea
SOMALI JET
INDIAN OCEAN
I
II
III
IV
30°
20°
10°
0°
50°
60°
70°
80°
90°
100°
110°
120°

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
NEW GUINEA
MONSOON WESTERLIES
EMEX/AMEX
DUNDEE
TROPICAL DEPRESSIONS
AUSTRALIAN MONSOON TROUGH
30°
20°
10°
0°
100°
110°
120°
130°
140°

40N
20N
EQ
20S
60E
80E
100E
120E
140E
160

SUMMER
L
H
ASYMMETRY
SPRING
FALL
EQ.
L
SYMMETRY
WINTER
H
L
ASYMMETRY

40N
20N
EQ
20S
60E
80E
100E
120E
140E
160

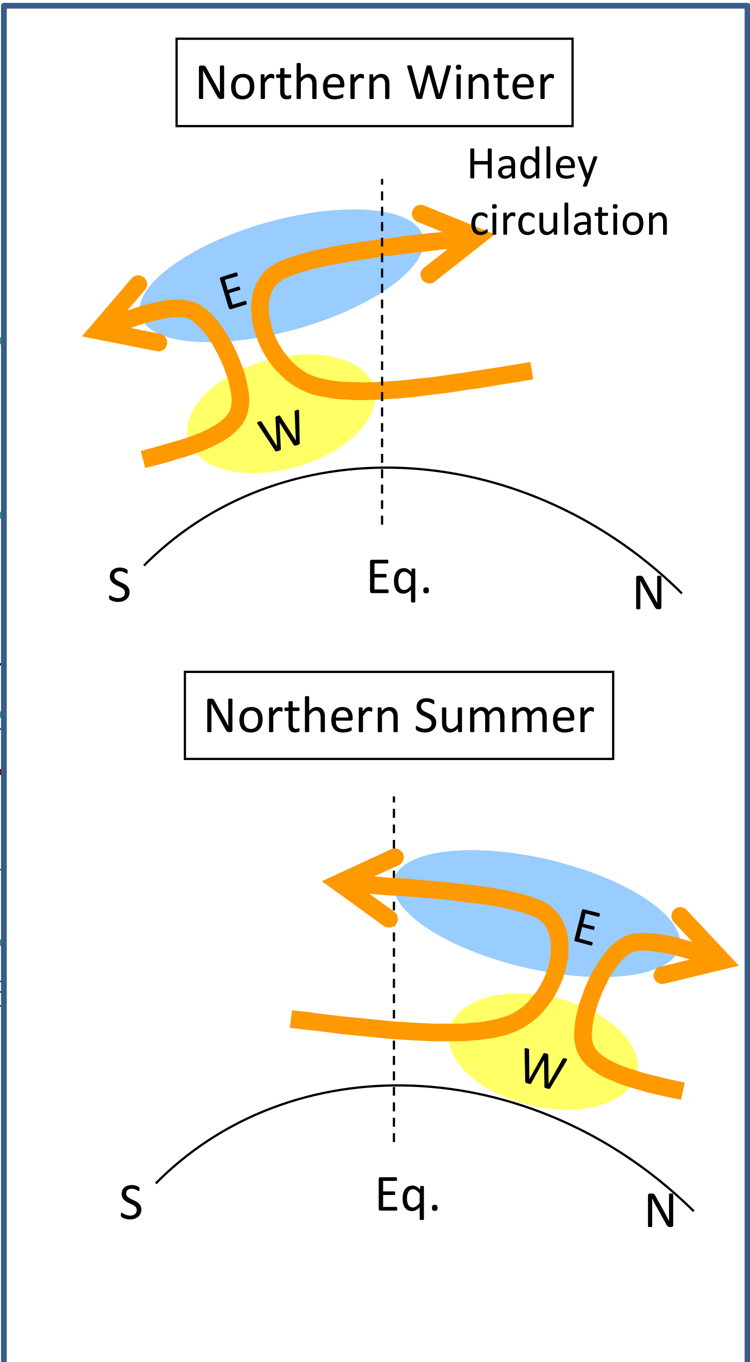
Longitudinal / latitudinal sections in NH Summer

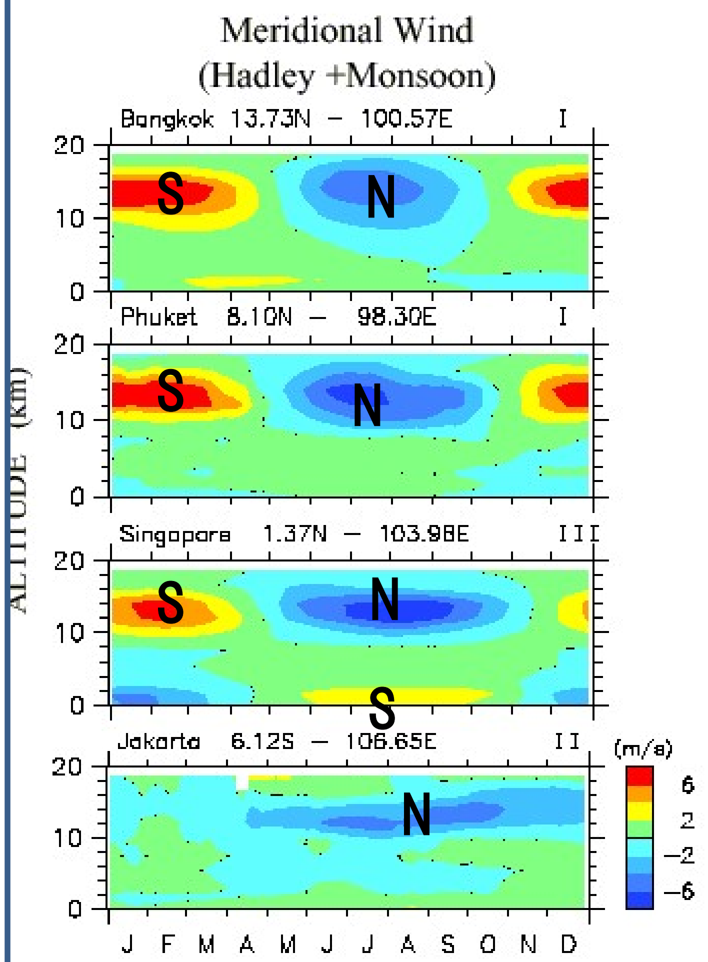


(Webester, 1999)

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







(Okamoto et al., 2004)

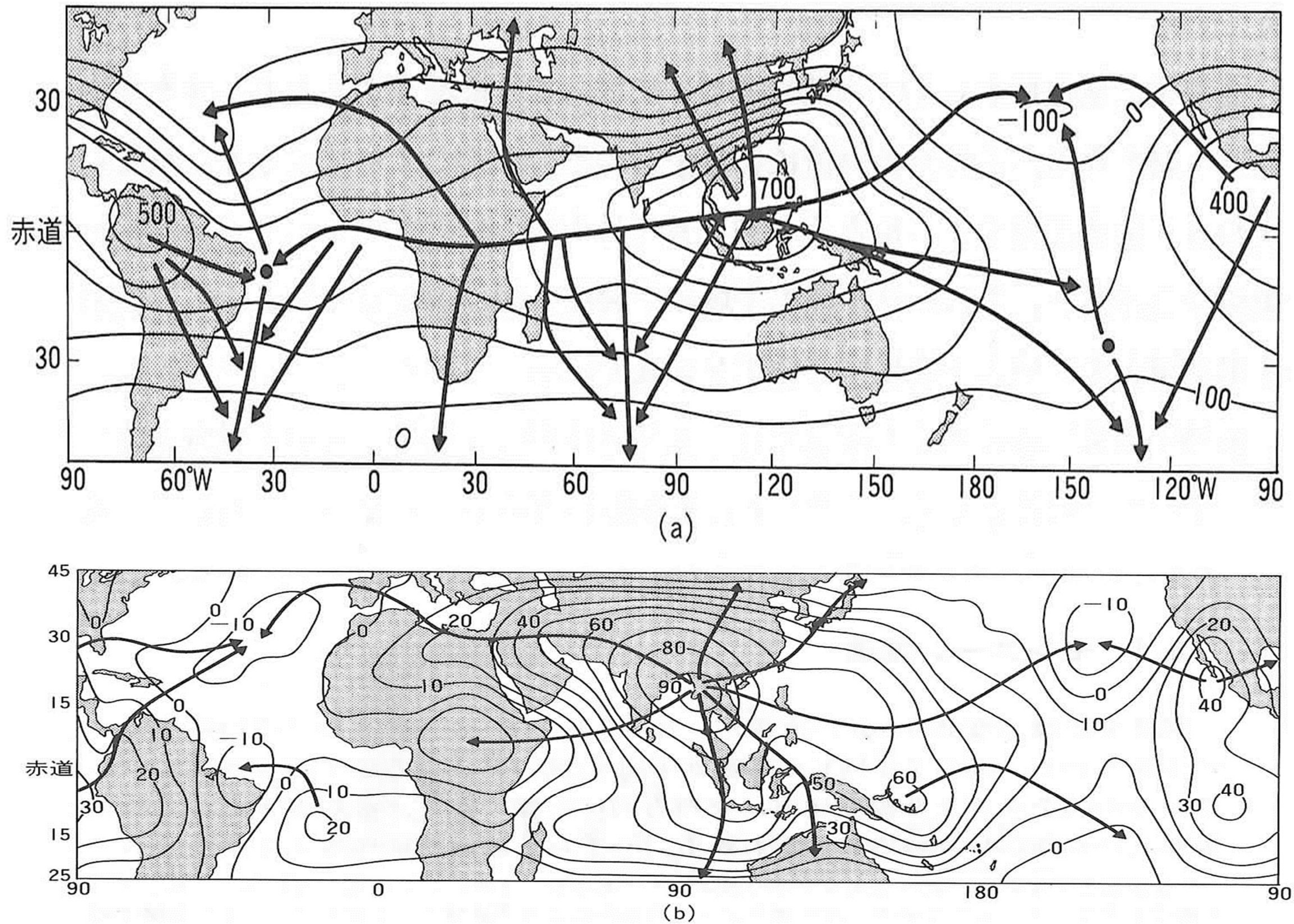
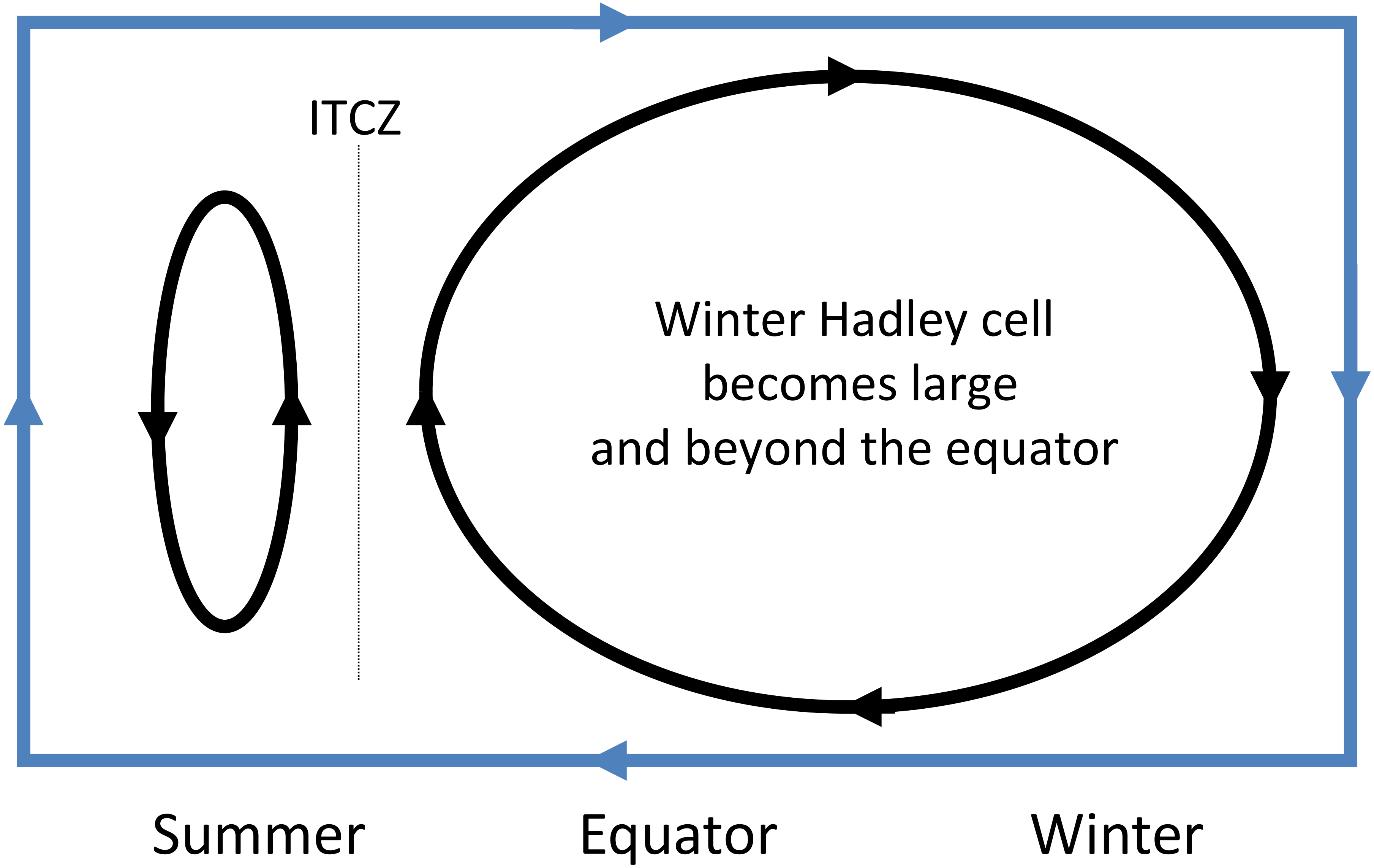
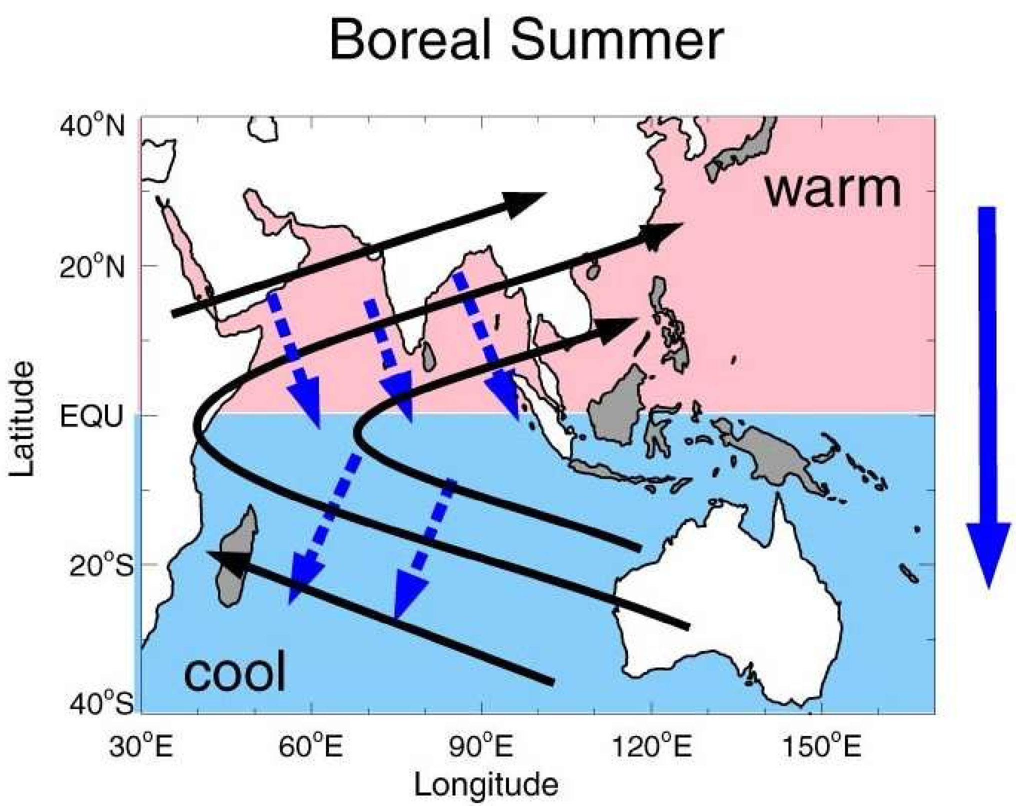


図 5.7 高度 200mb の準定常発散場と速度ポテンシャル χ の分布（発散風は χ に垂直な方向に吹く）. (a)12〜2 月の図 (Krishnamurti *et al.*, 1973), (b)6〜8 月の図 (Krishnamurti, 1971).

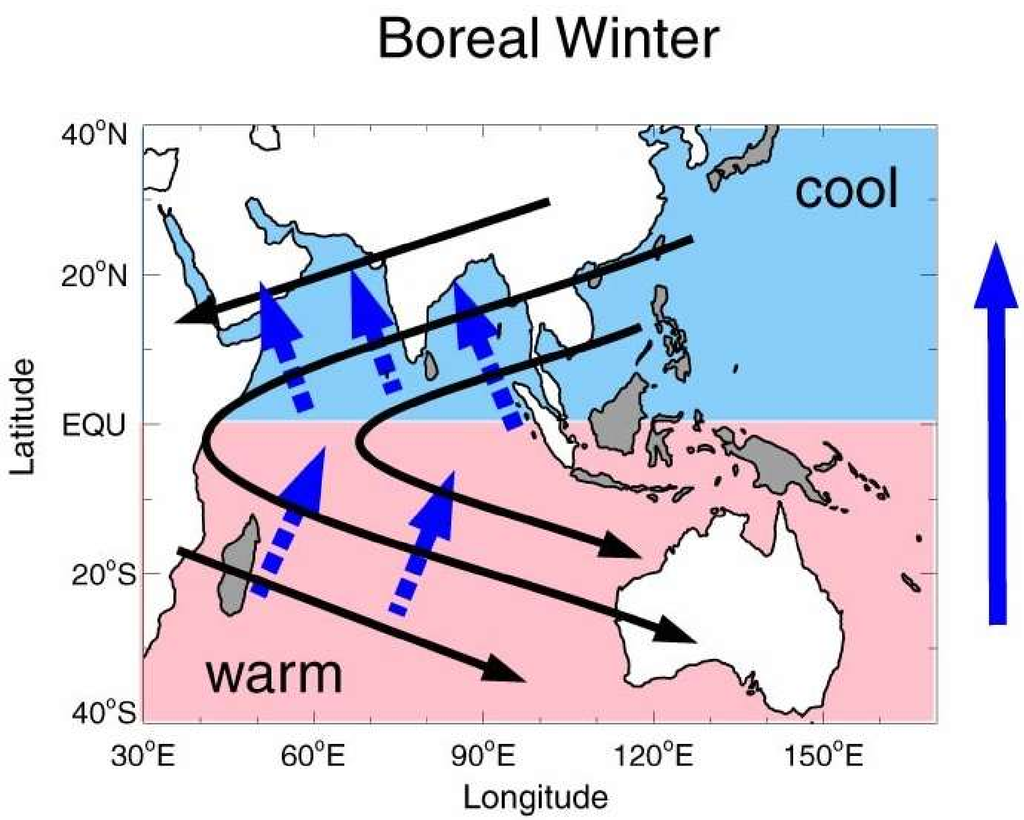
Superimposing Monsoon and Hadley circulations



Monsoon-Induced Ocean Heat Transport

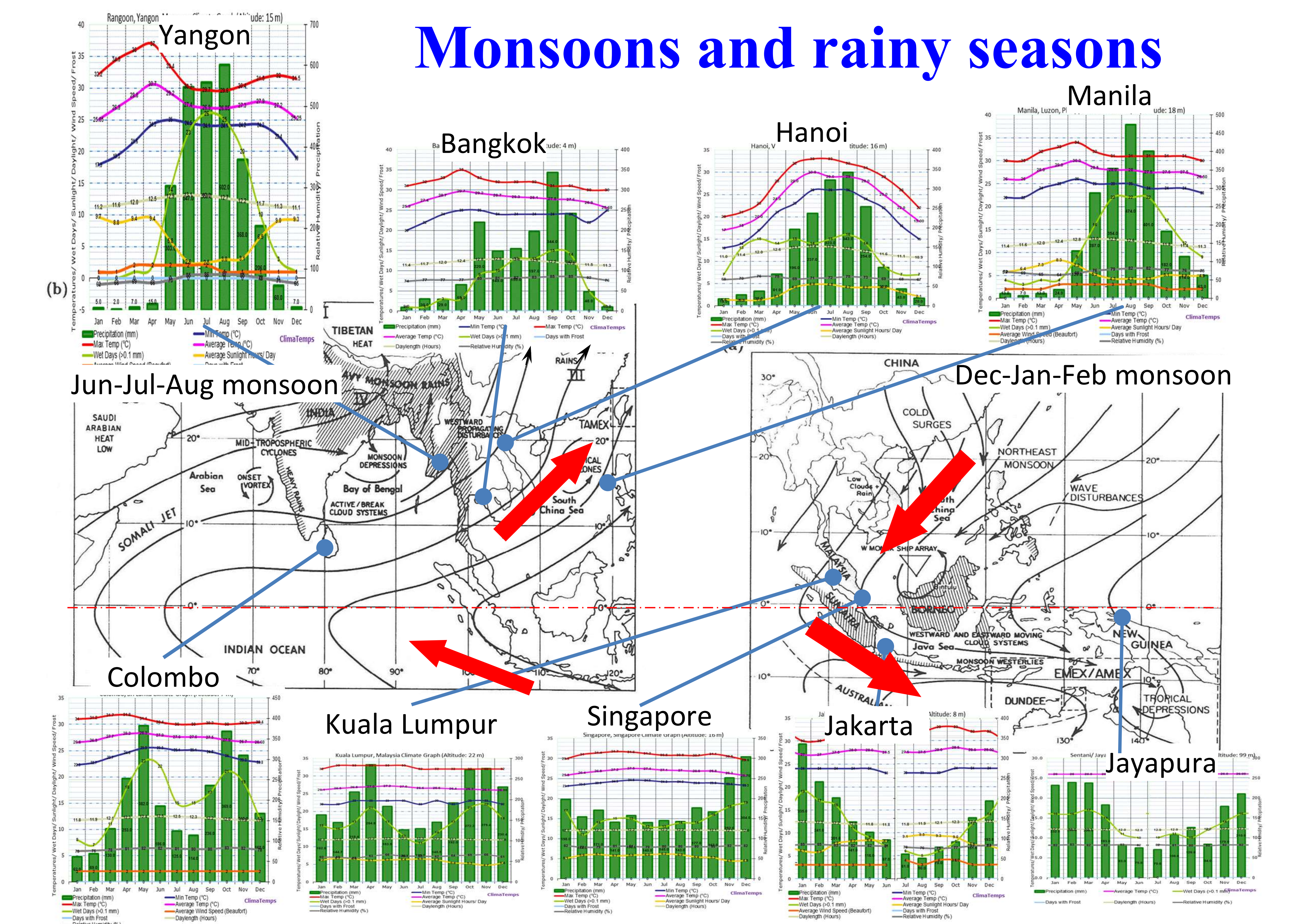


Southward ocean heat transport of 1.5 PW
(cools NIO while warming SIO)



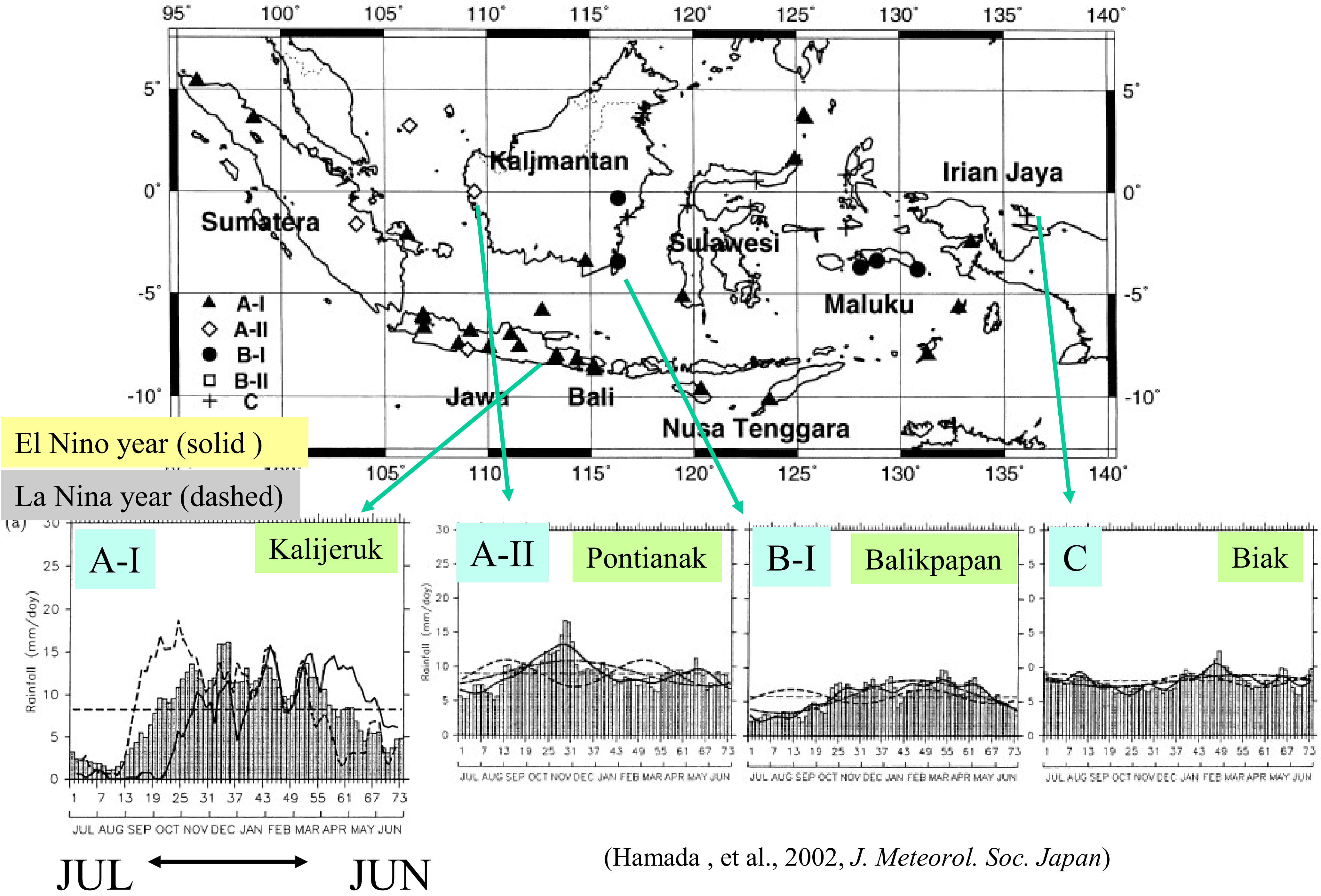
Northward ocean heat transport of 1.5 PW
(cools SIO while warming NIO)

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 (Webster, 1999)



Monsoons and rainy seasons
Yangon
Bangkok
Hanoi
Manila
Jun-Jul-Aug monsoon
Dec-Jan-Feb monsoon
Colombo
Kuala Lumpur
Singapore
Jakarta
Jayapura
TIBETAN HEAT
SAUDI ARABIAN HEAT LOW
MID-TROPOSPHERIC CYCLONES
MONSOON DEPRESSIONS
Arabian Sea
ONSET VORTEX
Bay of Bengal
ACTIVE/BREAK CLOUD SYSTEMS
SOMALI JET
INDIAN OCEAN
WESTWARD PROPAGATING DISTURBANCES
TAMEX
South China Sea
RAINS
CHINA
COLD SURGES
NORTHEAST MONSOON
WAVE DISTURBANCES
Low Clouds + Rain
MALAYSIA
SUMATRA
BORNEO
WESTWARD AND EASTWARD MOVING CLOUD SYSTEMS
Java Sea
MONSOON WESTERLIES
EMEX/AMEX
NEW GUINEA
DUNDEE
TROPICAL DEPRESSIONS
AUSTRALIA
ClimaTemps

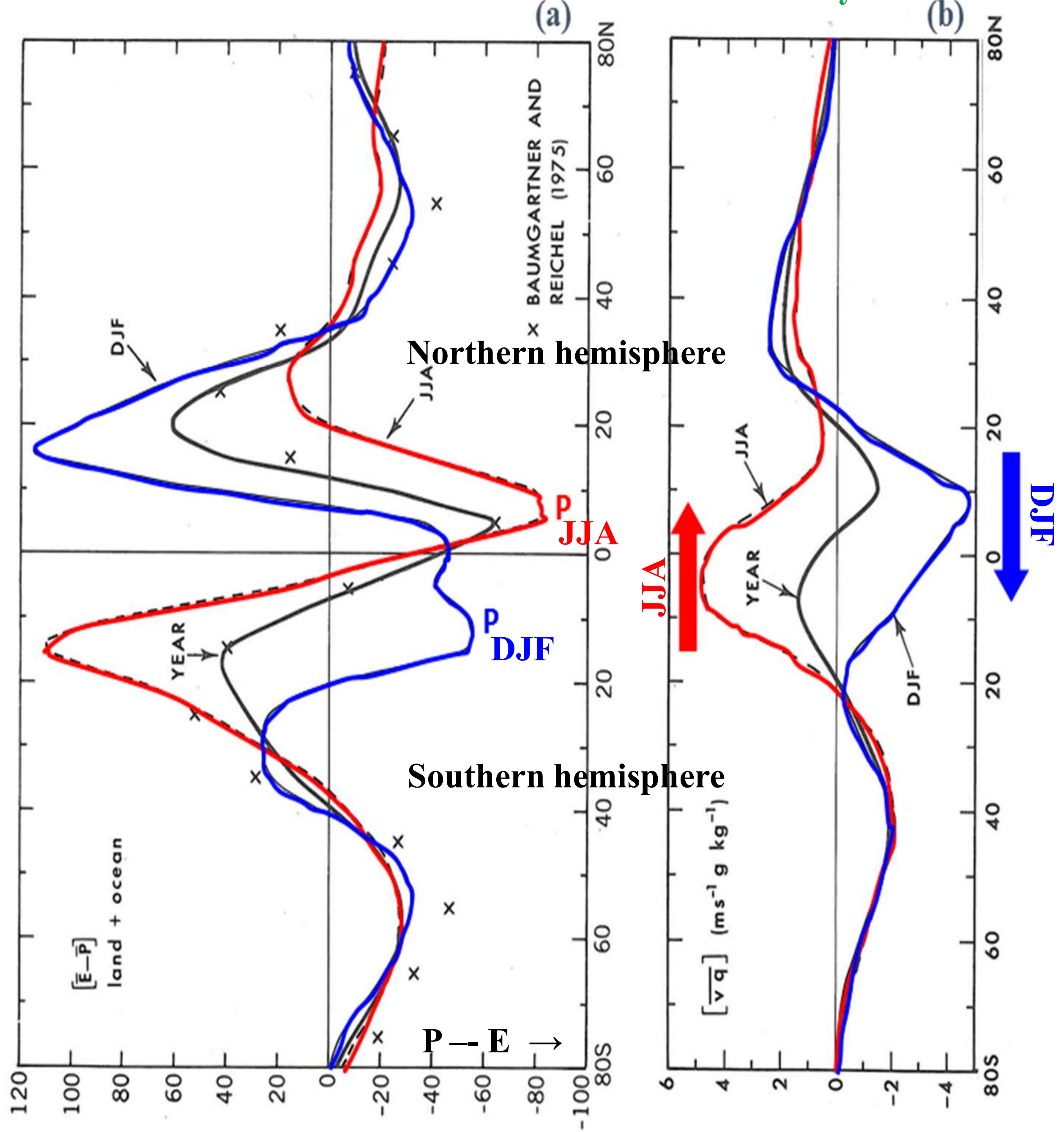
Seasonal and interannual variations



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

Equatorial annual-cycle dehydrator

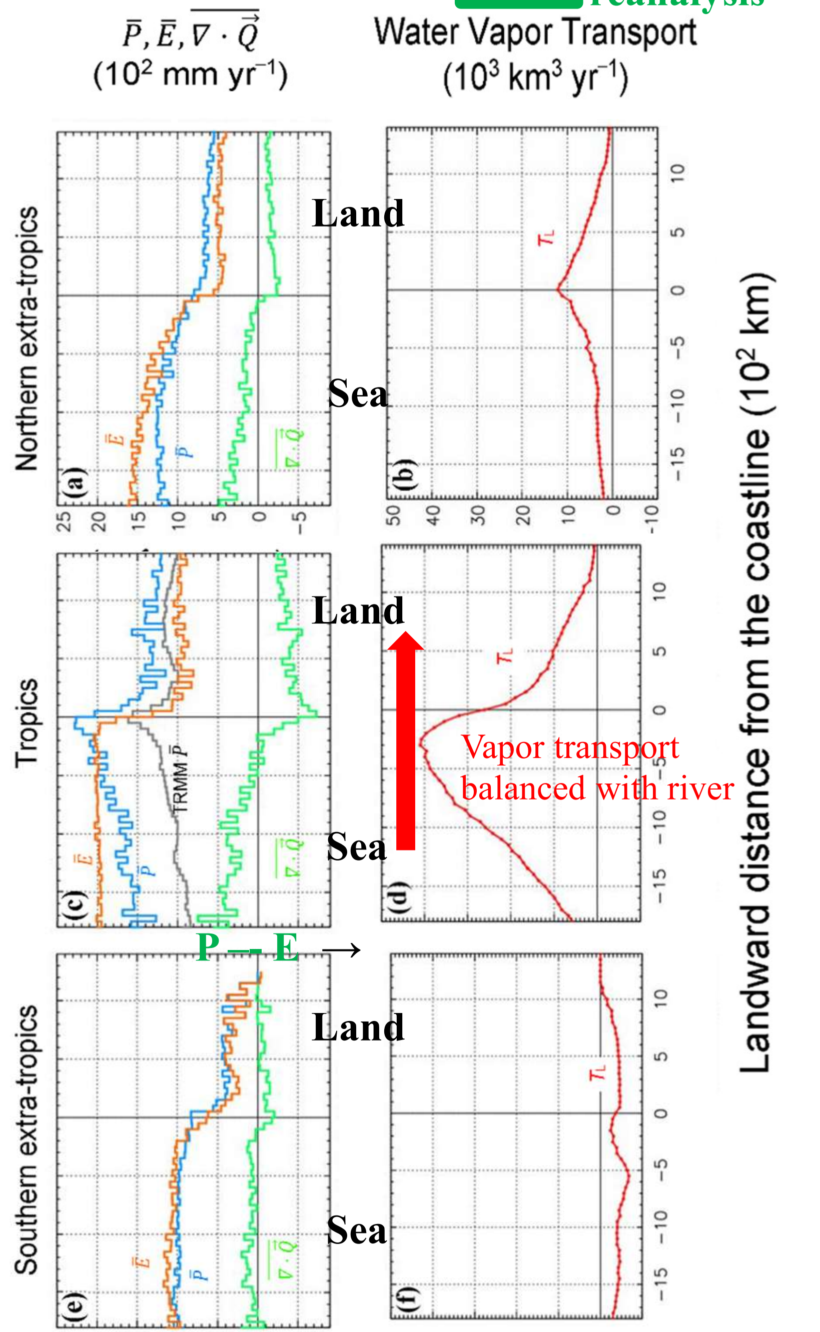
(1963-1973, based on 1000 stations) **Subjective analysis**



(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*)

Contribution of tropical rainfall to global climate balance

Global mean rainfall ≈ 1,100 mm/year × 0.7 (ocean) + 700 mm/year × 0.3 (land)
≈ 1,000 mm/year

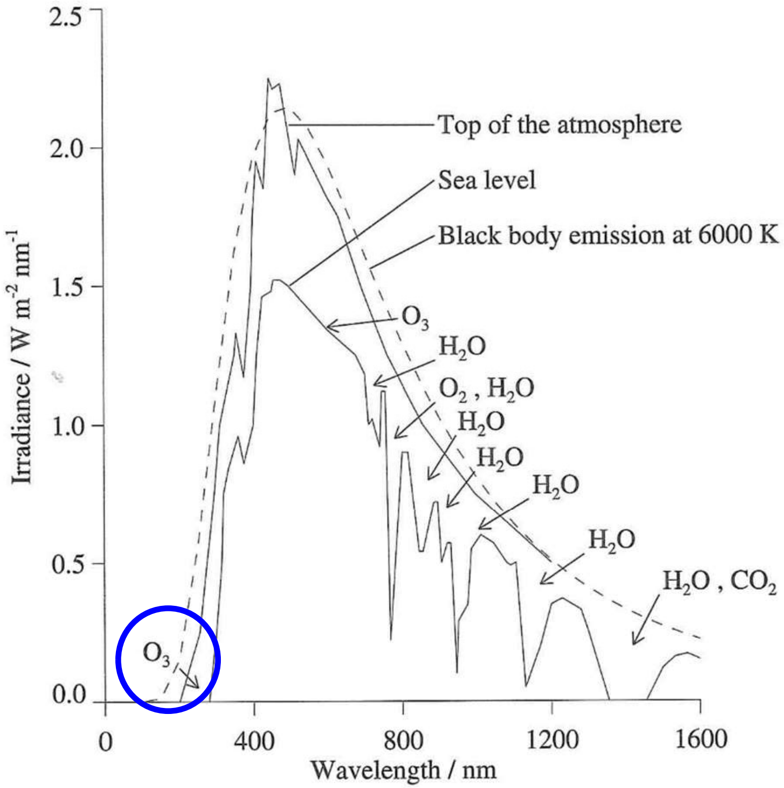
(Multiplying water density 1,000 kg/m^3)
→ Water mass precipitating per unit area ≈ 1 × 10^3 kg/m^2/year

(Multiplying latent heat ≈ 600 cal/g ≈ 2.5 × 10^6 J/kg)
(Dividing the result by 1 year ≈ 3.15 × 10^{7}s)
→ Heating atmosphere per unit mass and unit time ≈ 80 W/m^2
(about 1/3 of the green house (IR heating) effect)

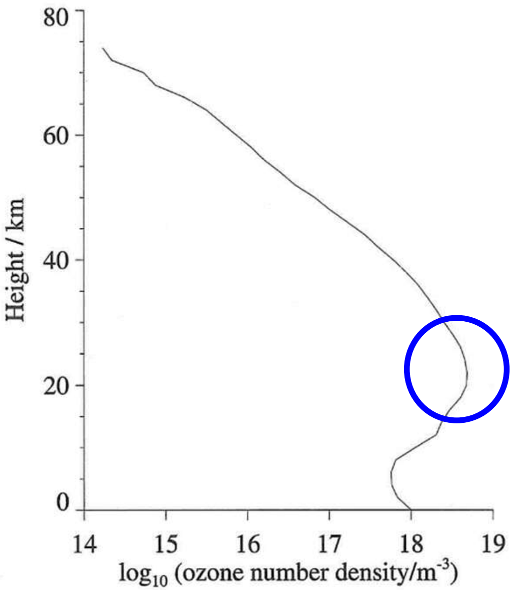
Tropical rainfall: largest over the globe (2,000 mm/year near the equator)

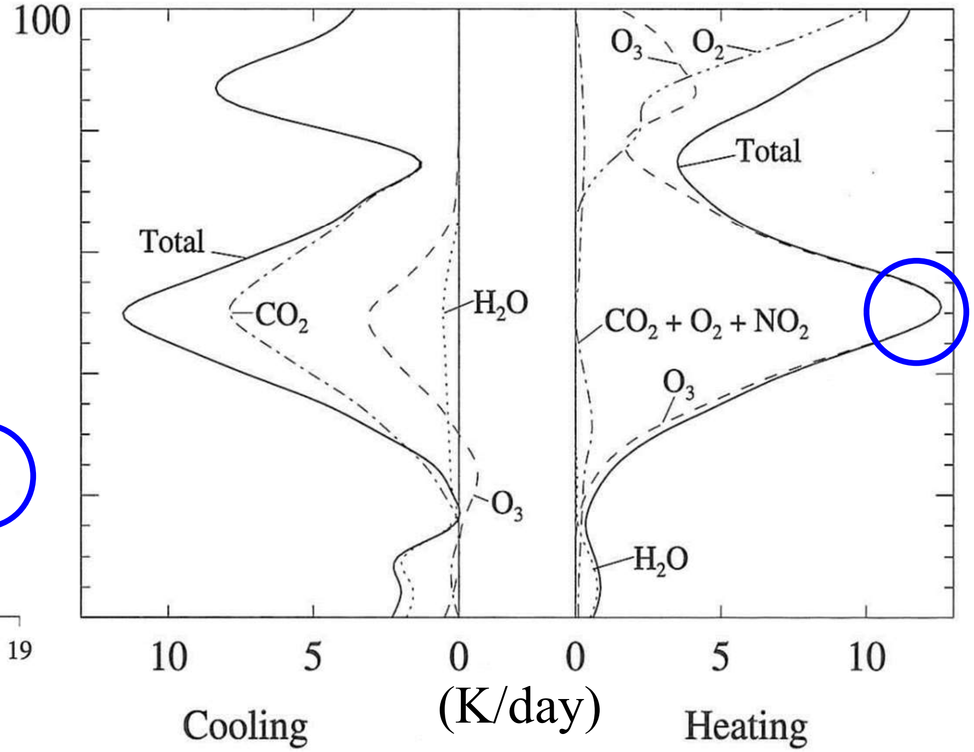
Southeast Asian rainfall: largest in the tropics (2,500 mm/year in average)
→ about 2.5 times of the global mean
→ Maritime-continent rainfall variations affect the global climate greatly.

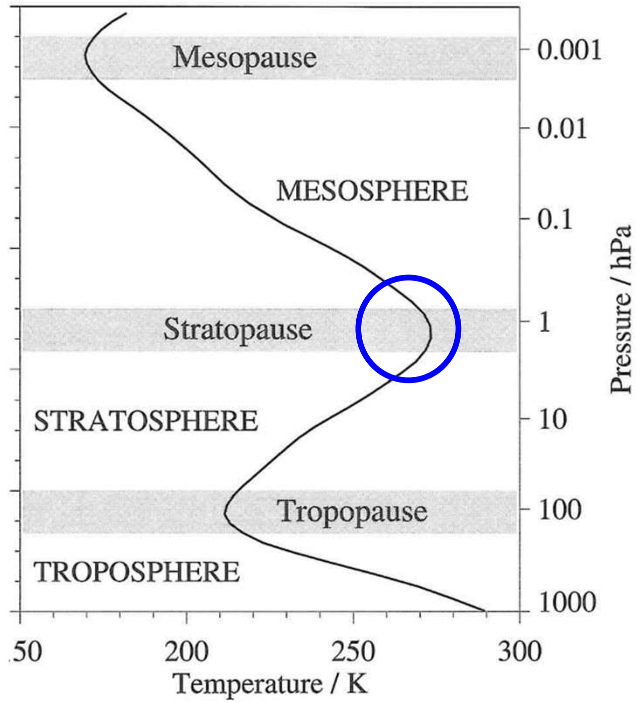
Ozone UV heating
and
Middle Atmosphere
(Mesosphere & Stratosphere)



(Brasseur & Solomon, 1986)



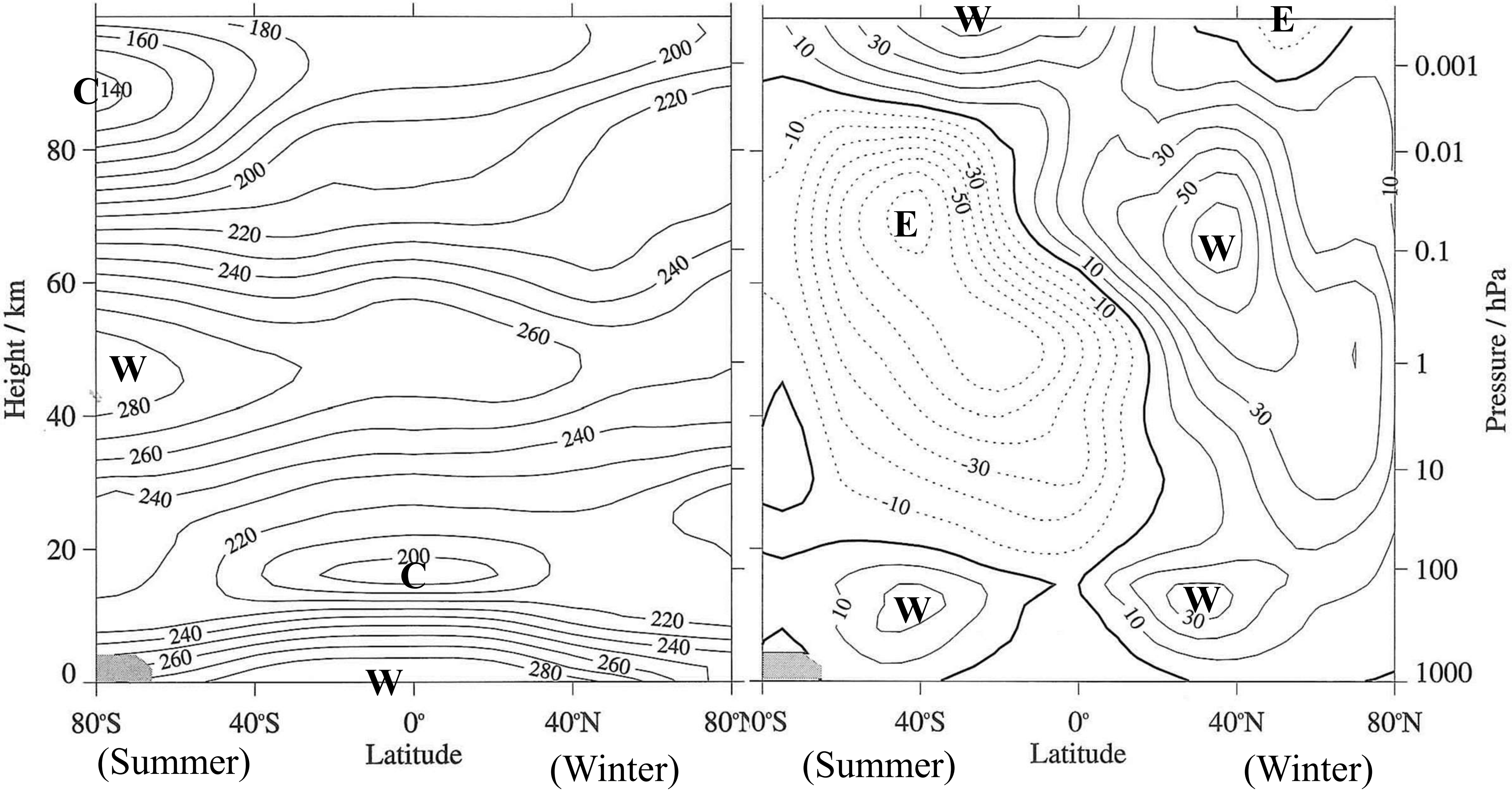


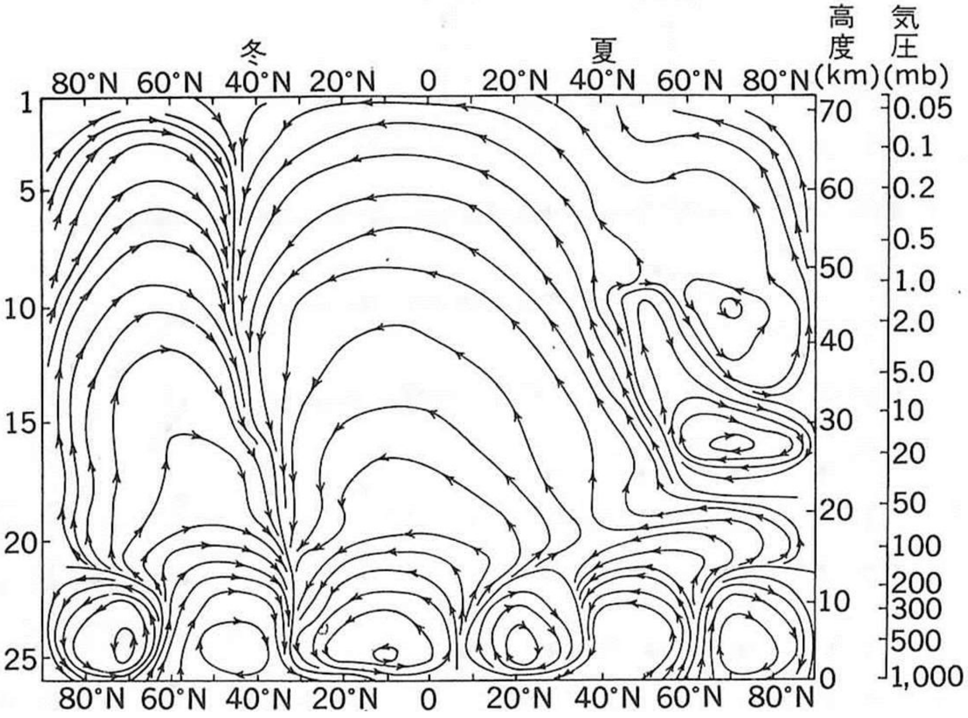


(CIRA1986)

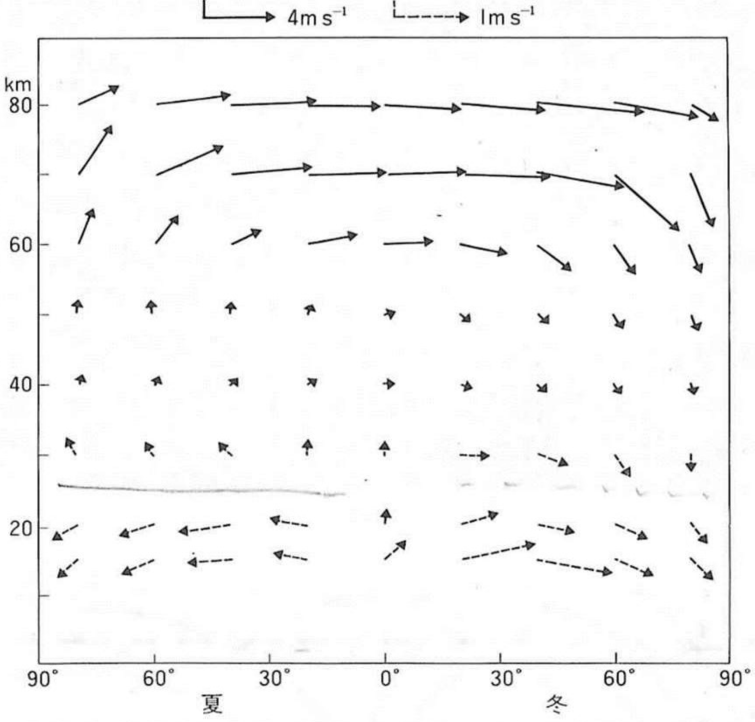
Meridional distribution of Temperature and Zonal Wind

(January, CIRA1986)

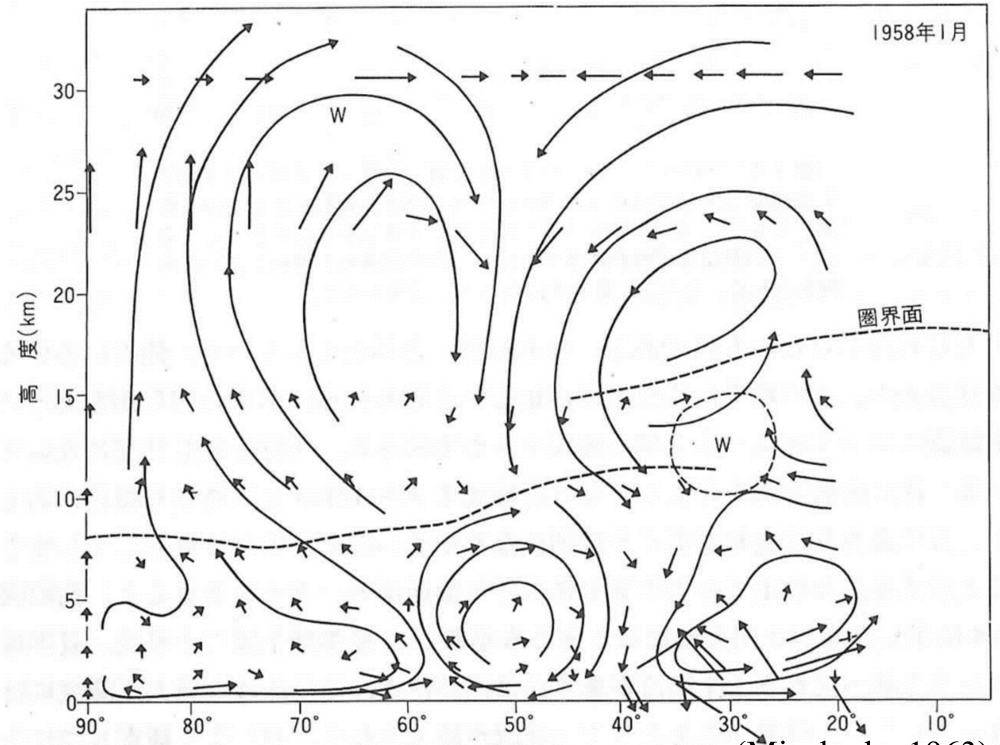




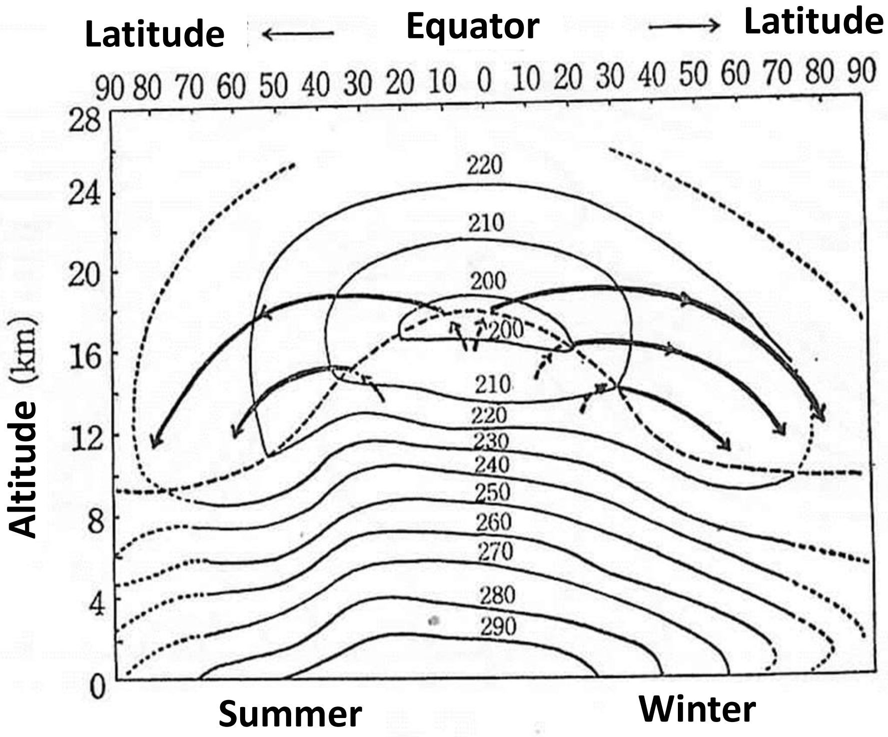
(Cunnold et al., 1975)



(Murgatroyd & Singleton, 1961)

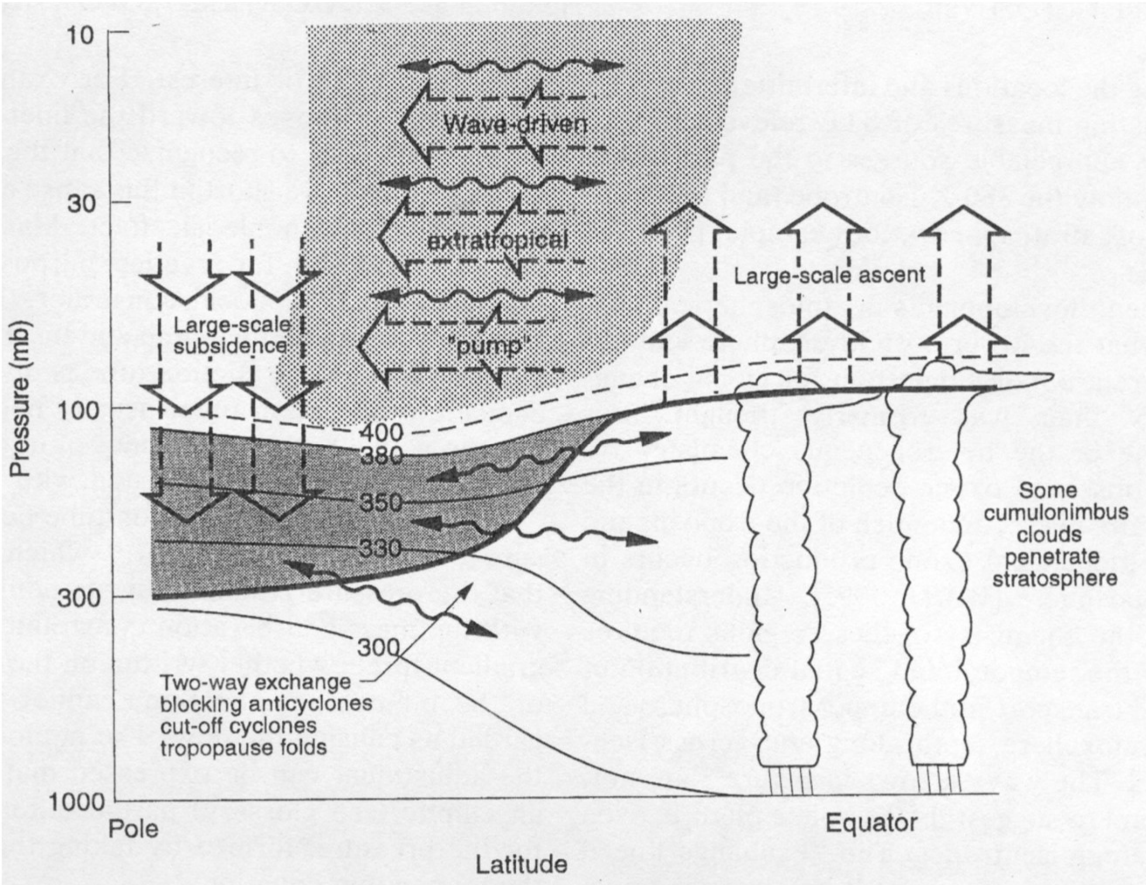


(Miyakoda, 1963)



(Brewer, 1949)

Stratospheric response to tropospheric convection



(Holton, 1995)

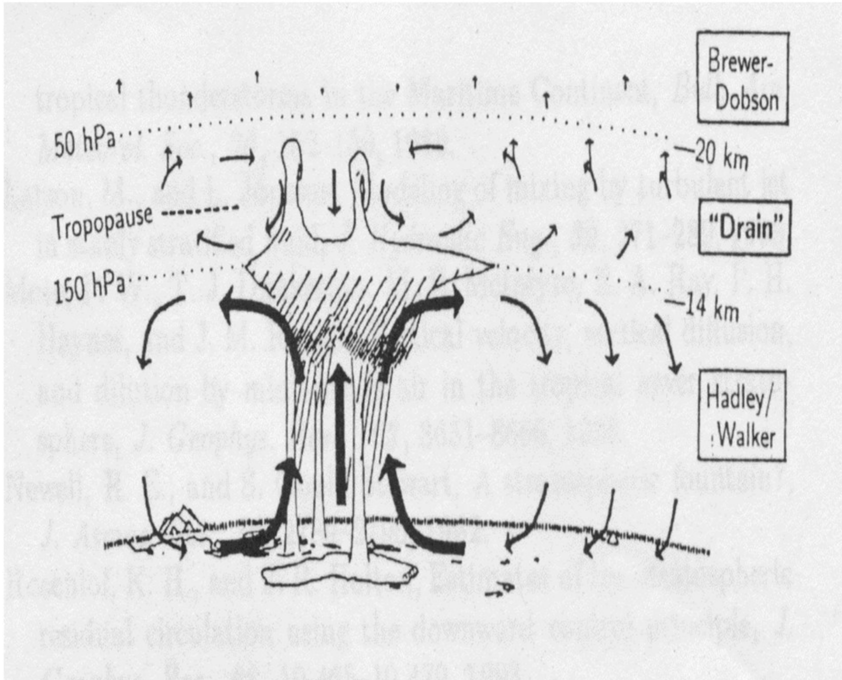


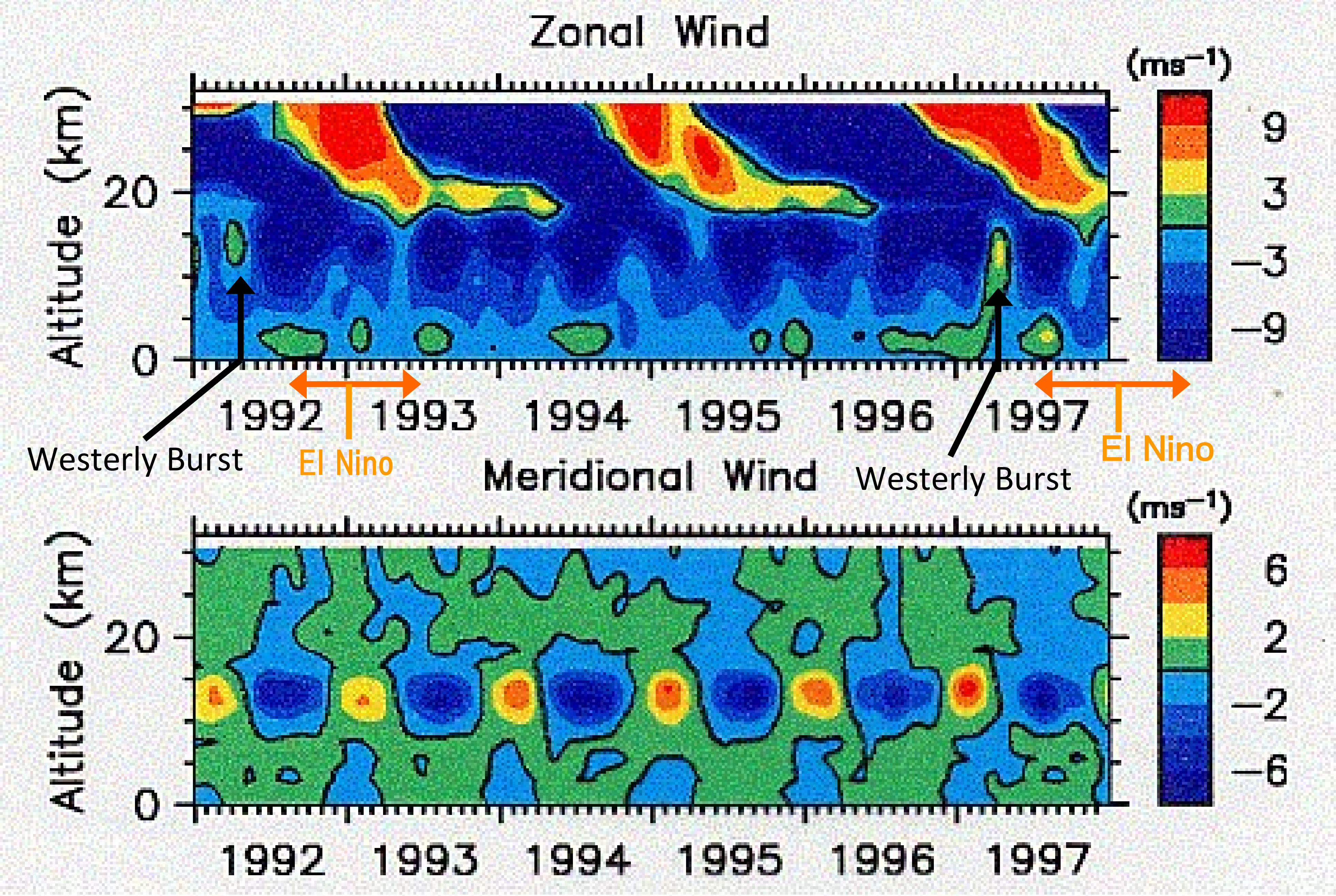
Figure 4. Illustration of the diabatic mean flow (arrows) and its relationship to the locations of deep convection and convective outflows.

(Sherwood, 2000)

cf. Ogino's ozone observations at Hanoi

Interannual Variations of Wind over Indonesia

(Okamoto, Yamanaka et al., 2003b)



Variabilities of climate and weather

- Annual mean – Vertical/Meridional dependencies

- Shorter/smaller-scale variabilities
  – Waves and convections/clouds

- Longer/larger-scale variabilities
  – Interannual variations