Generalized dynamics of monsoon and sea-land breeze circulations

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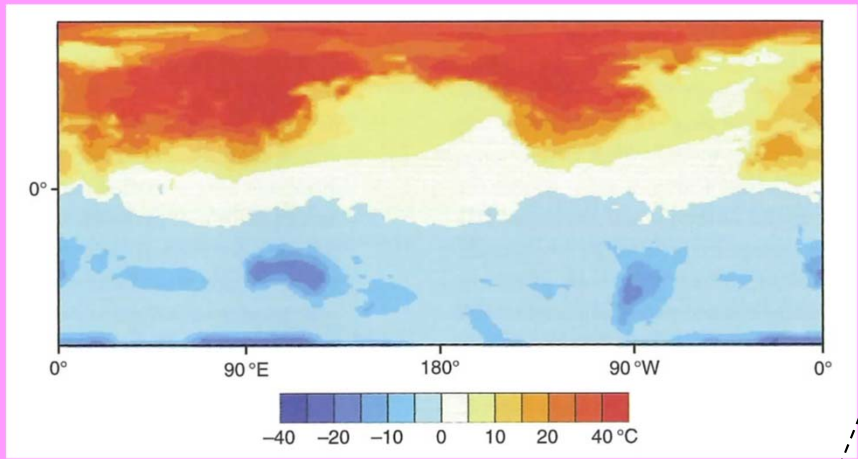
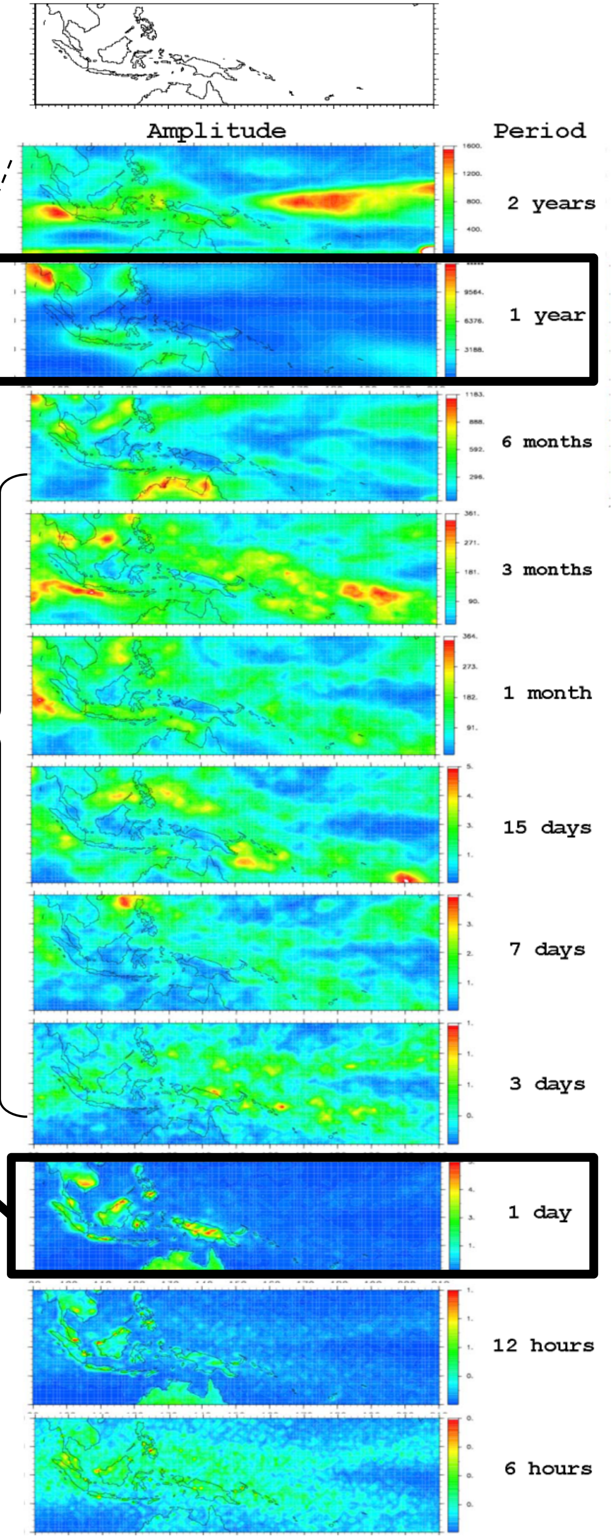
"Find the continents" game
July – January
(Wallace & Hobbs, 2006; original by Mitchel)



Spectral distribution of GMS cloud height

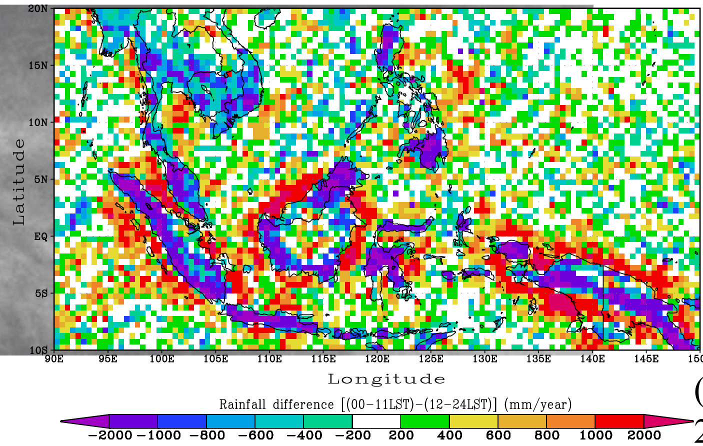
Interannual & intraseasonal variations over oceans

Annual & Diurnal cycles around lands



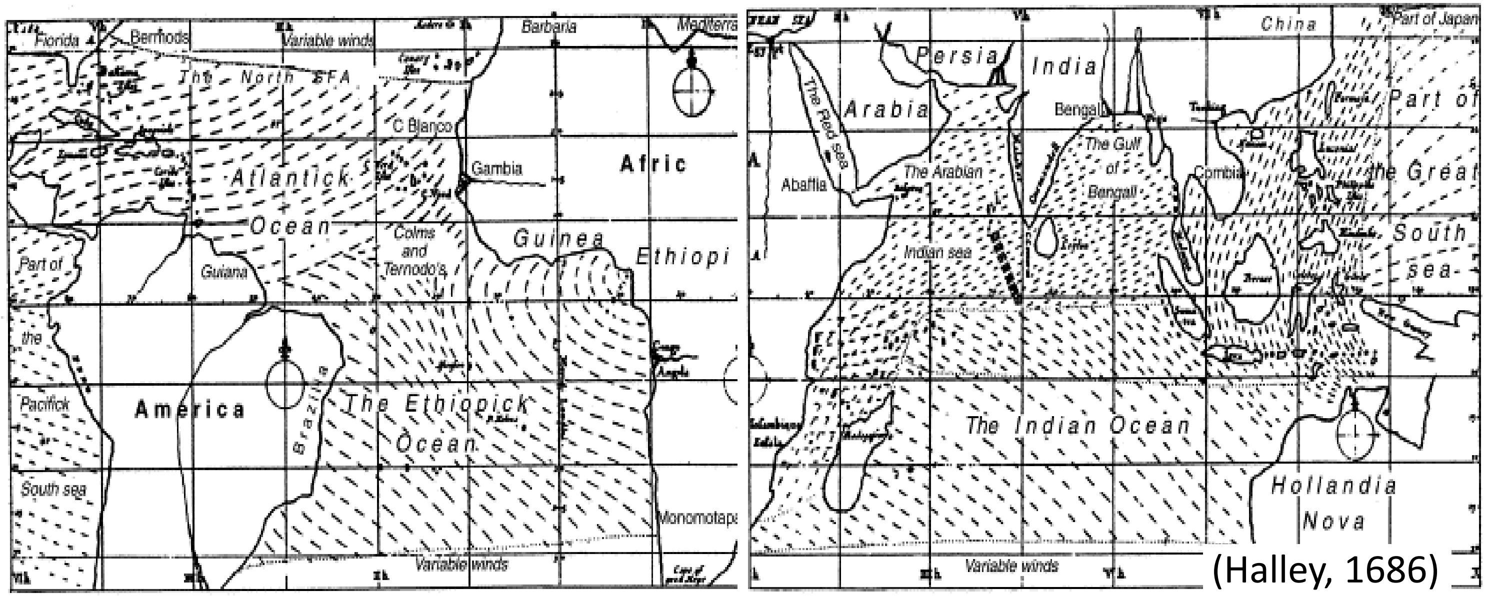
Mon. mean GMS clouds

TRMM Morning − Evening Rain

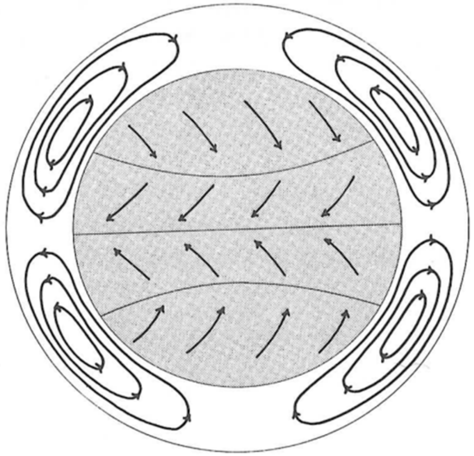


(Mori et al., 2004)

Discovery of monsoon and Hadley circulations

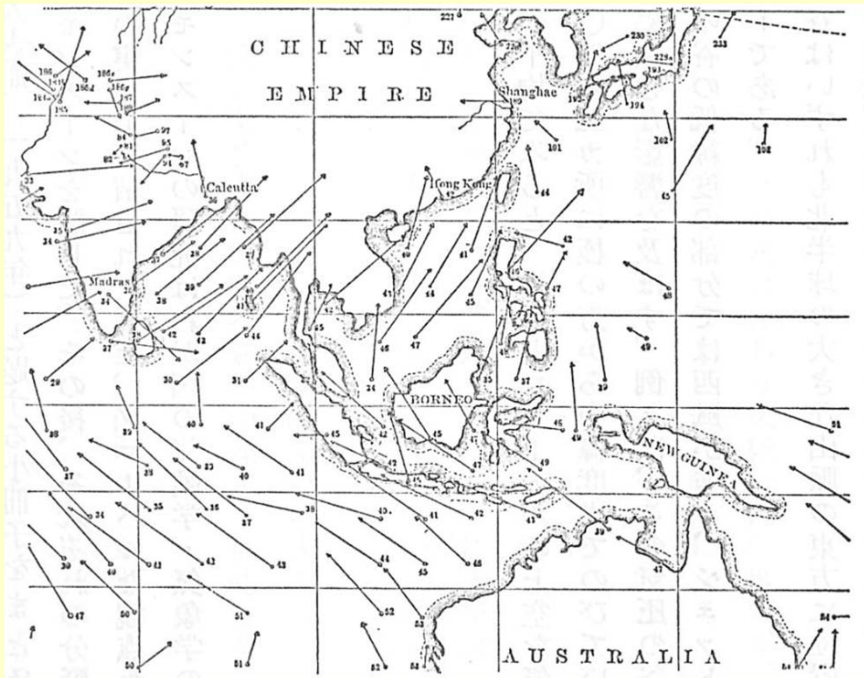


(Halley, 1686)

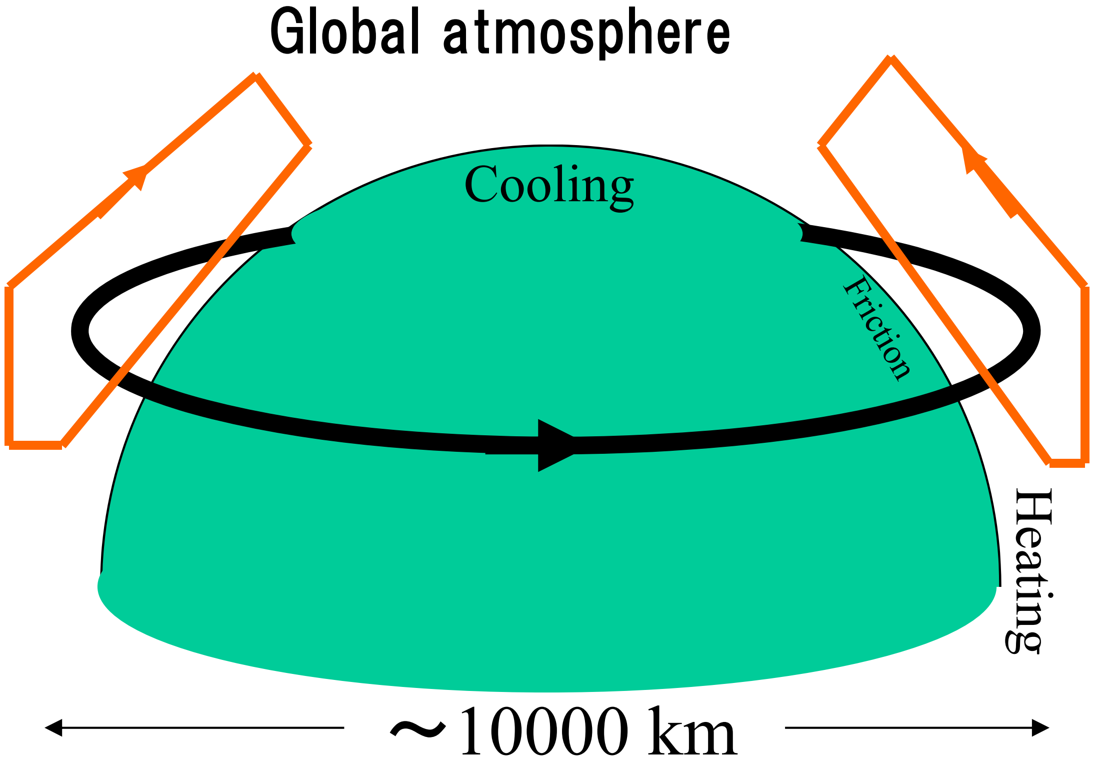


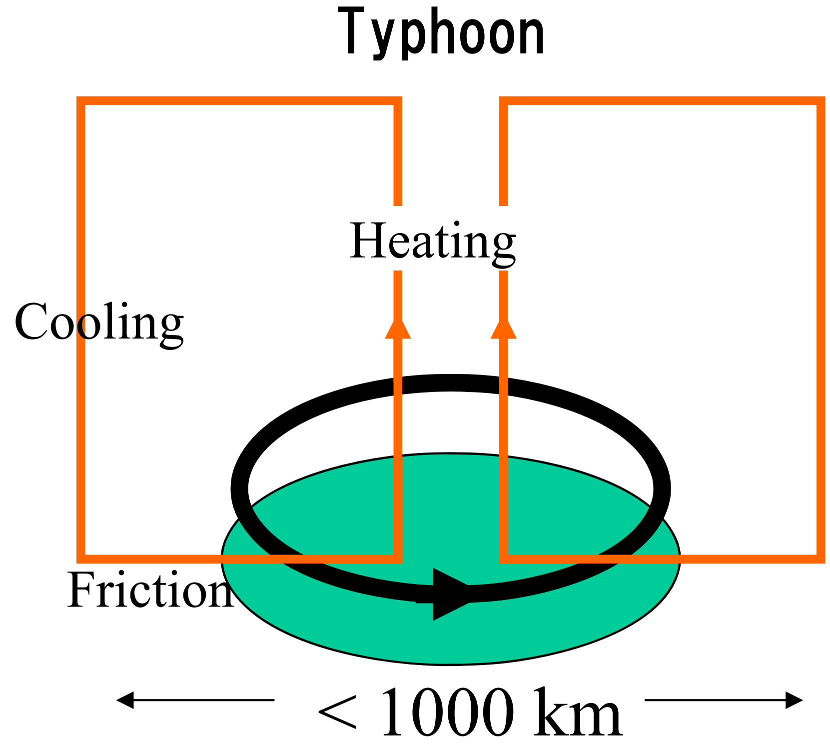
(Hadley, 1735;
reproduced by Lorenz, 1967)

(Coffin, 1876;
Copied by
Yoshino, 1989)



Geofluid motion = Vortex + Convection



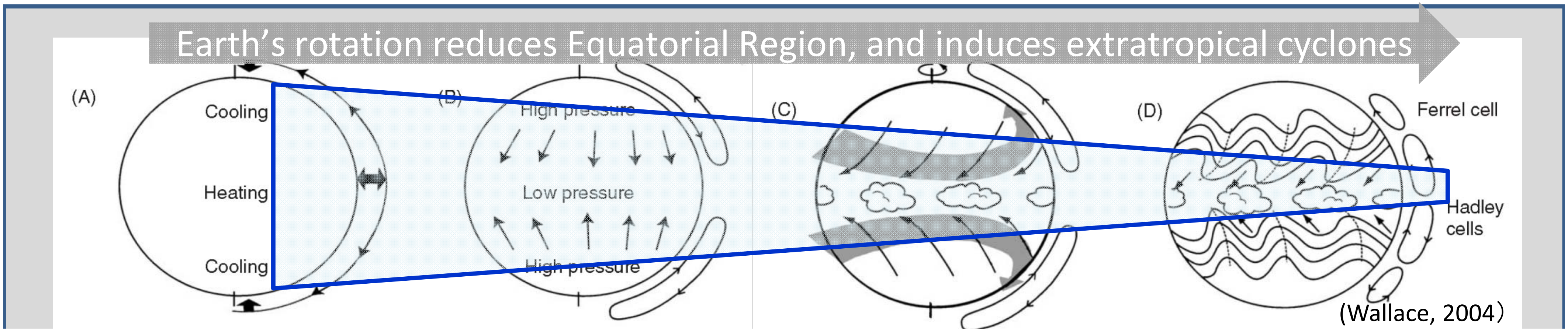


Zonal geostrophic flow (**Coriolis**/centrifugal force) ⇔ Meridional pressure gradient

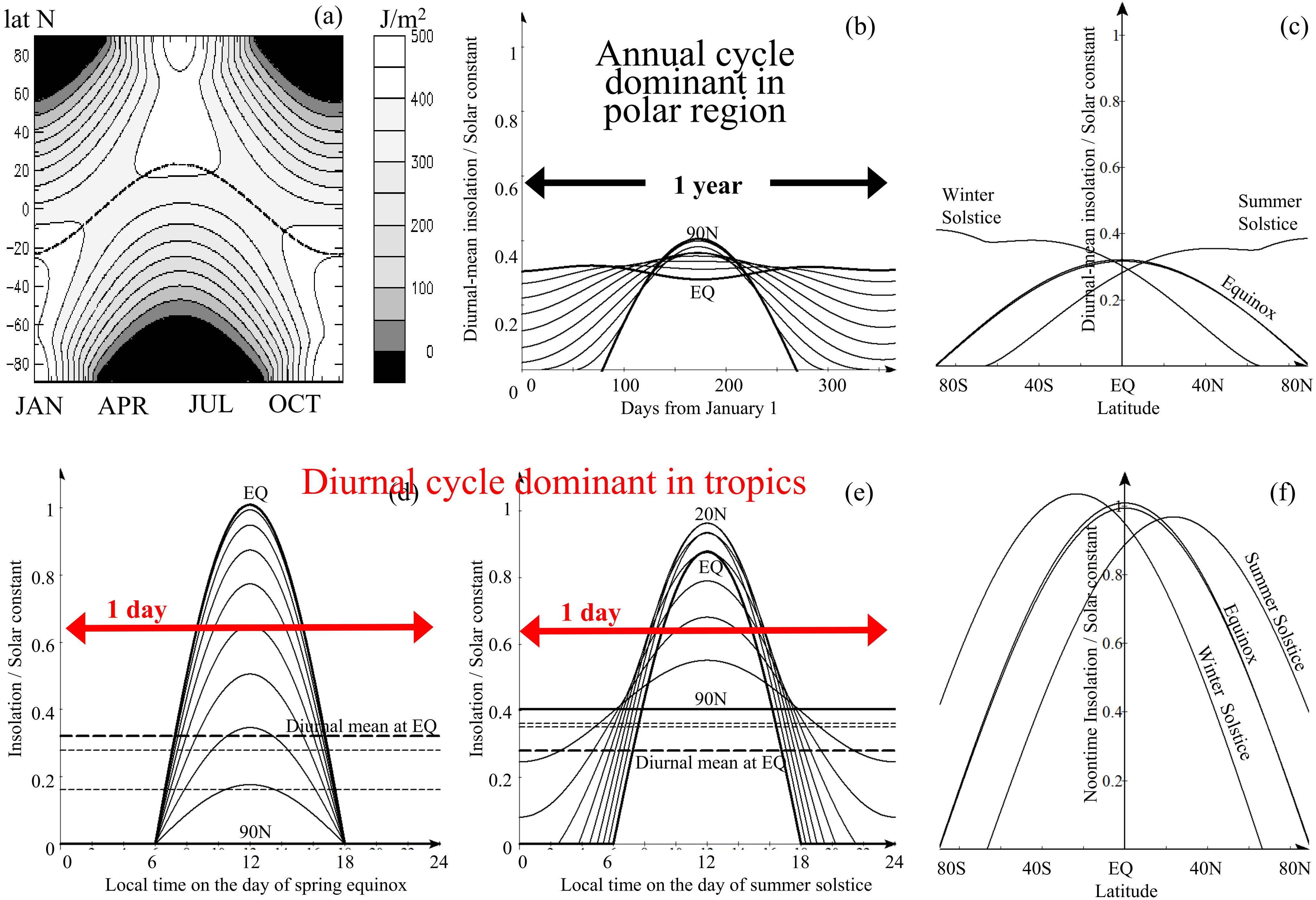
Meridional flow ⇔ (zonal) Friction (Surface, turbulence)

Vertical flow ⇔ Heating/cooling (radiation, clouds, …)

Diurnal/Annual

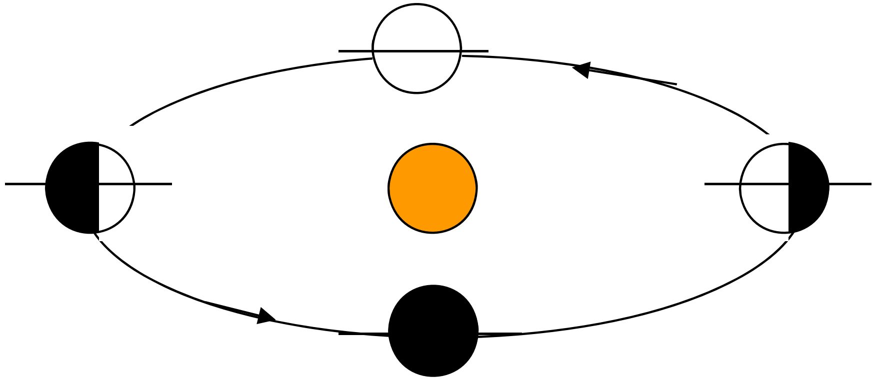


Solar heating on earth with revolution and rotation



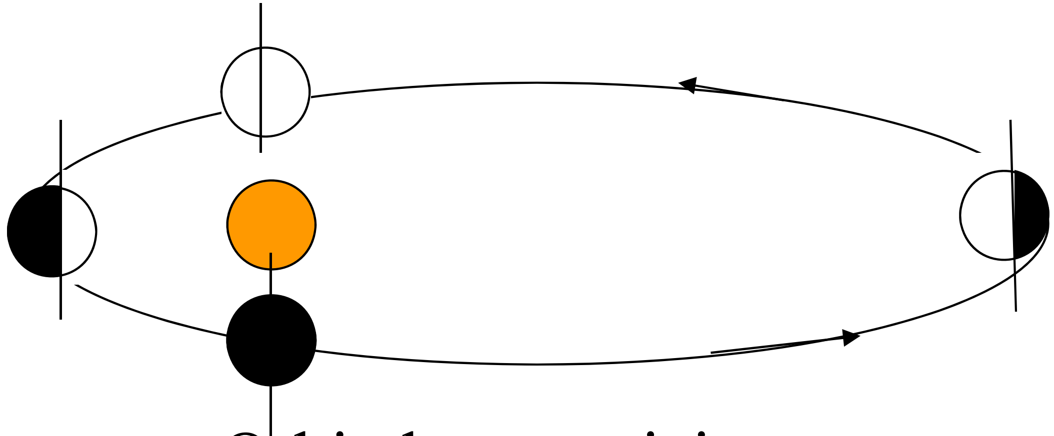
Two limited cases of seasonal cycle forcing

‘Uranus’

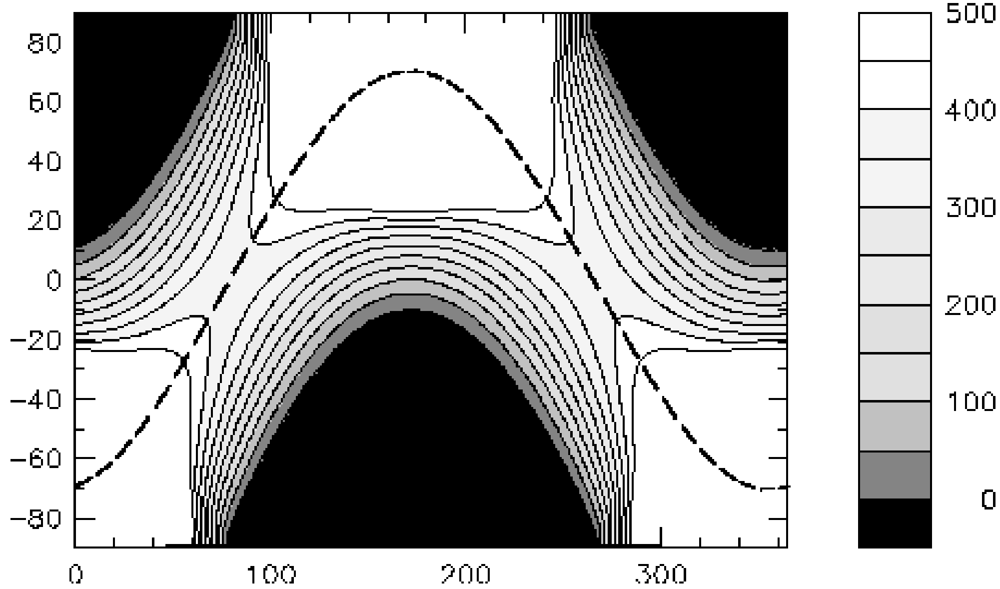


Rotation-axis inclination

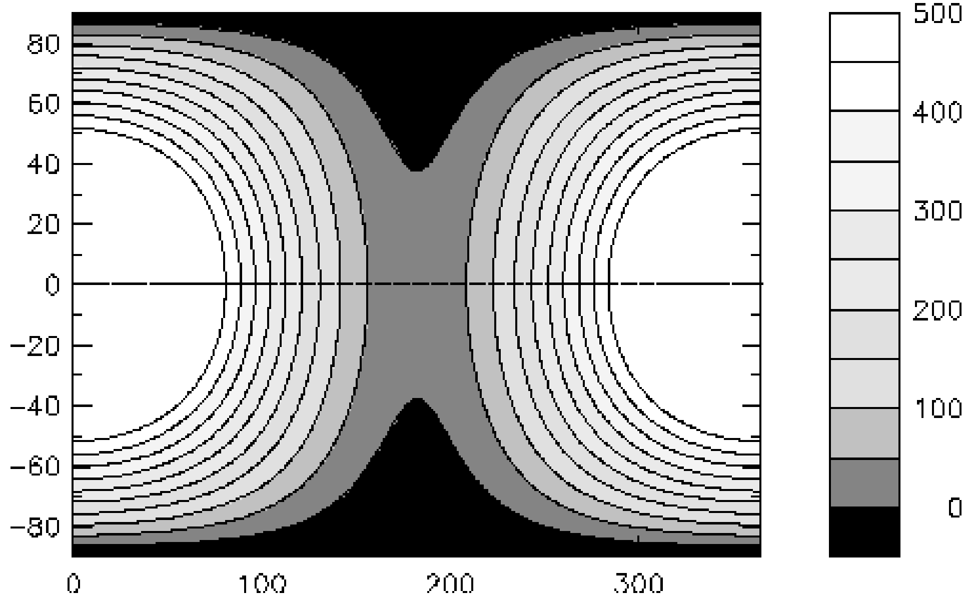
‘a type of extra-solar planet’



Orbital eccentricity



Hemispherically anti-phase



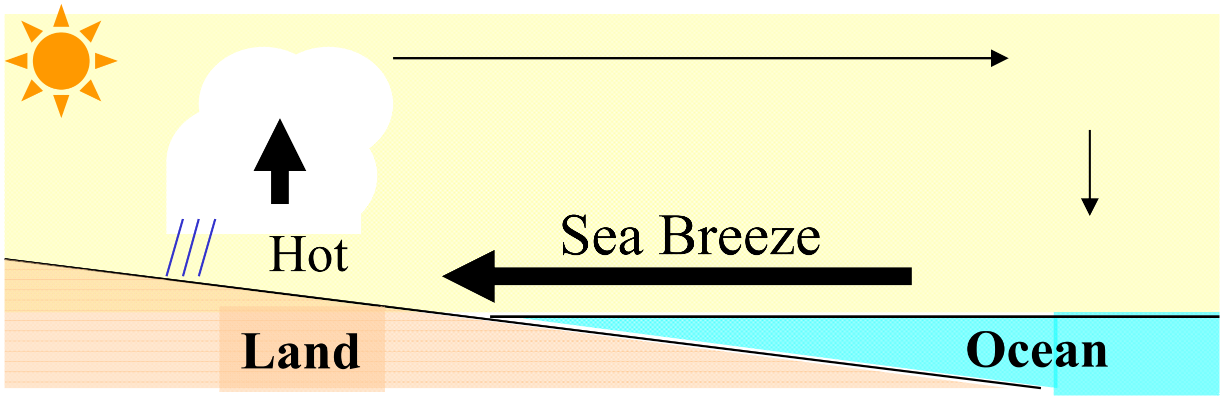
Hemispherically in-phase

"Planetological" Monsoon

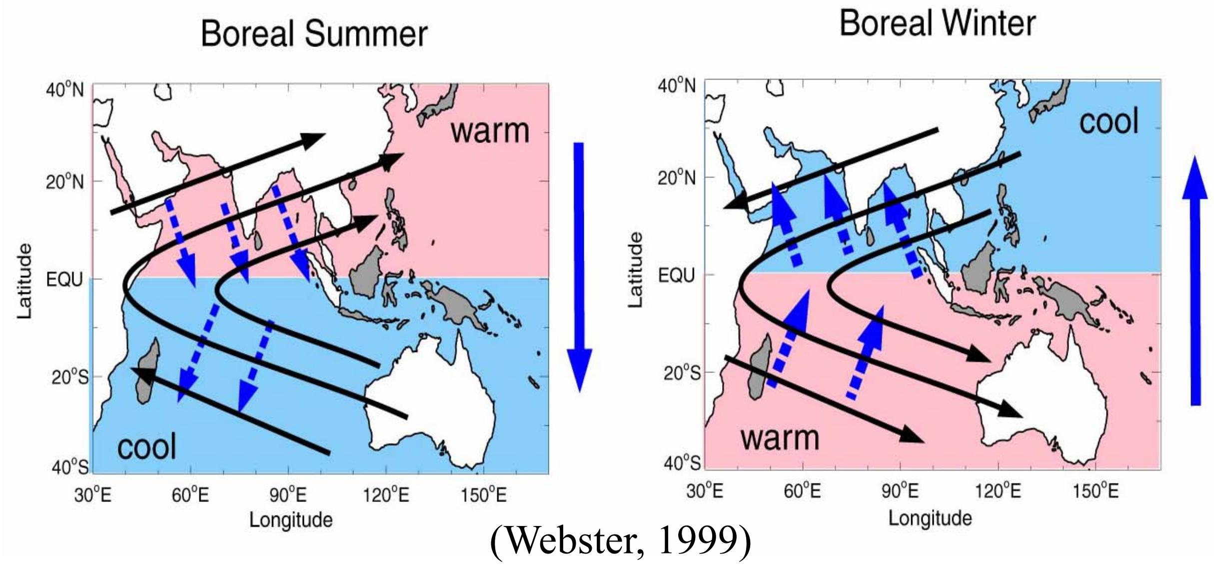
Axi-Symmetric Meridional Circulation due to Differential Solar Heating

"Terrestrial" Monsoon

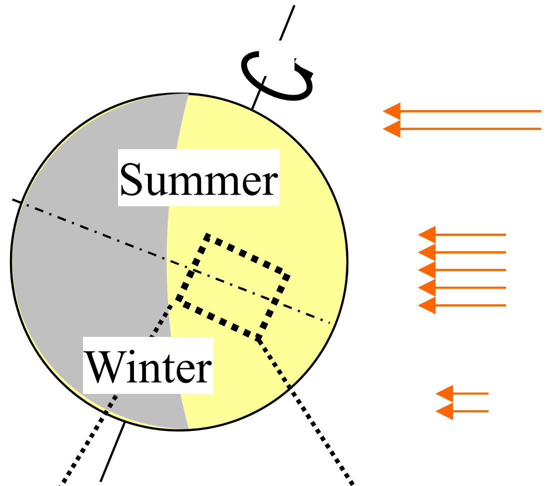
Sea-Land Breeze Analogue



Monsoon-driven Seasonal Ocean Current

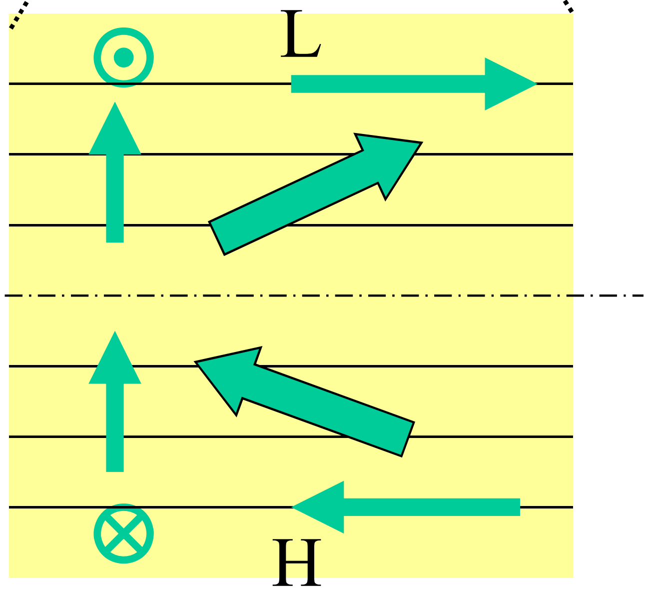


(Webster, 1999)



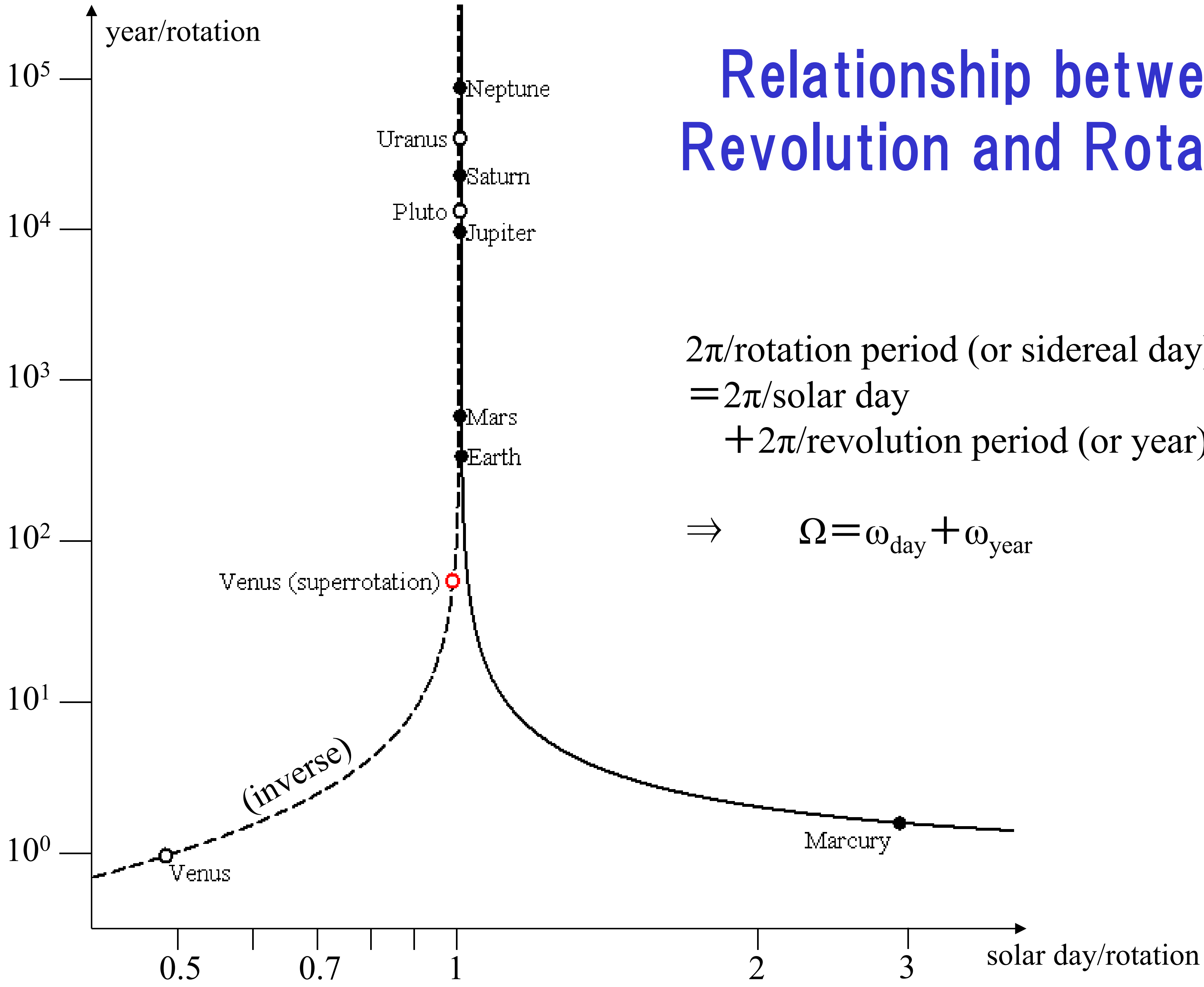
Annual Osci. (Eq. Anti-Symmetric)

⇒ Monsoon Circulation



(cf. Mesosphere, Mars)

Relationship between Revolution and Rotation



2π/rotation period (or sidereal day)
$= 2\pi$/solar day
$\quad + 2\pi$/revolution period (or year)

$\Rightarrow \qquad \Omega = \omega_{day} + \omega_{year}$

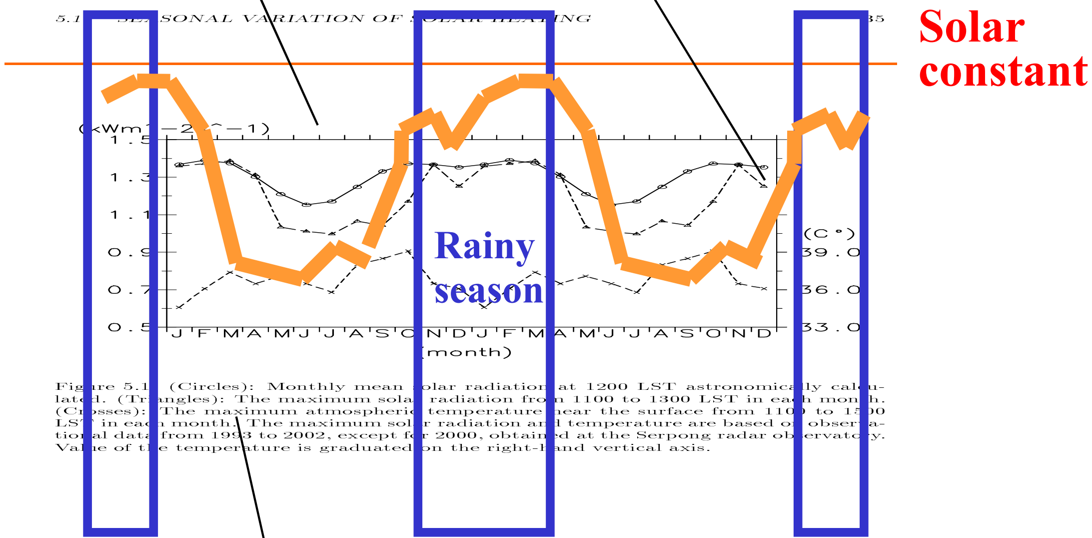
Mechanism of Seasonal and Diurnal Cycles

Strong solar radiation in the morning of "rainy season"

Solar radiation at Serpong11-13LT (1993-2002)

Astronomical calculation

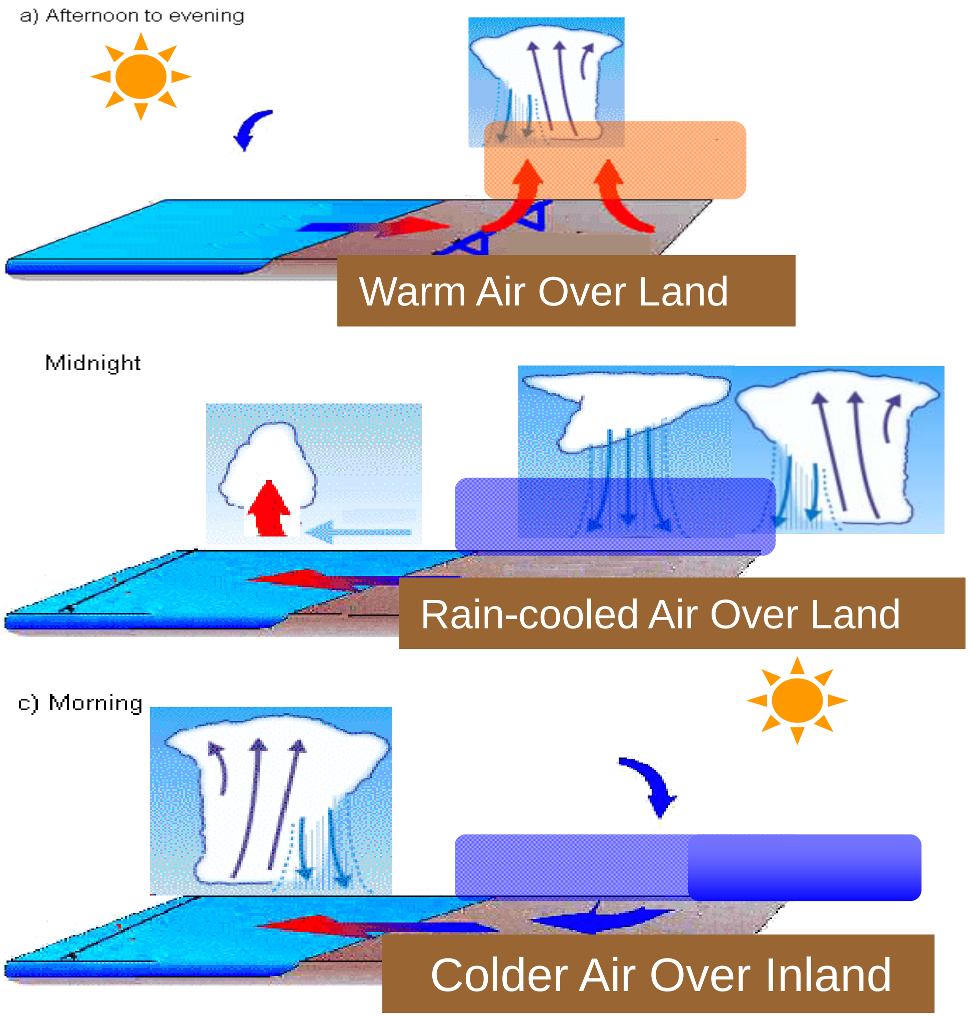
Maximum observed solar radiation



Maximum temperature

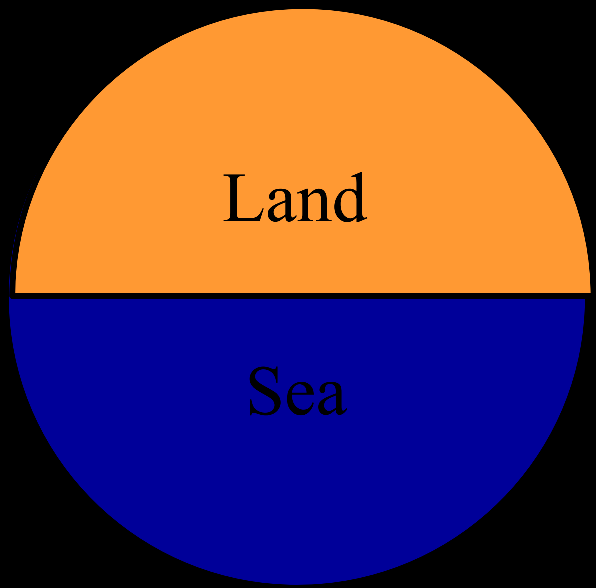
(Araki et al., 2007)

Sea-Land Breeze circulation with cloud "sprinkler" effect

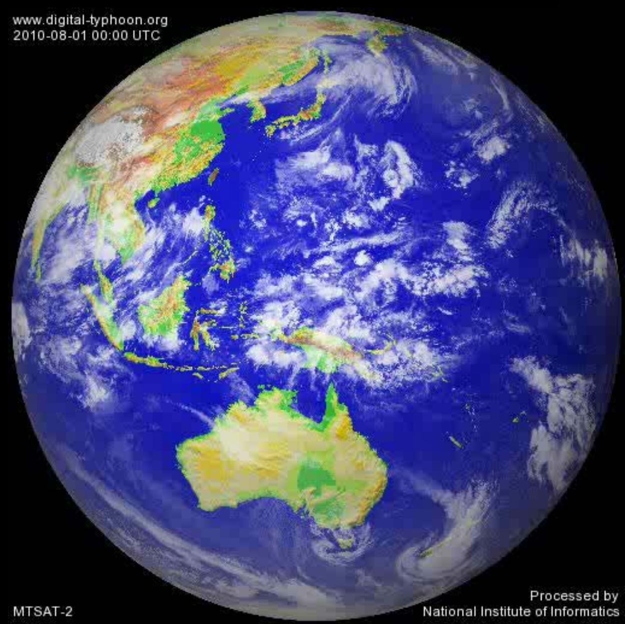


(Wu, Yamanaka & Matsumoto., 2008)

Land-Sea planet

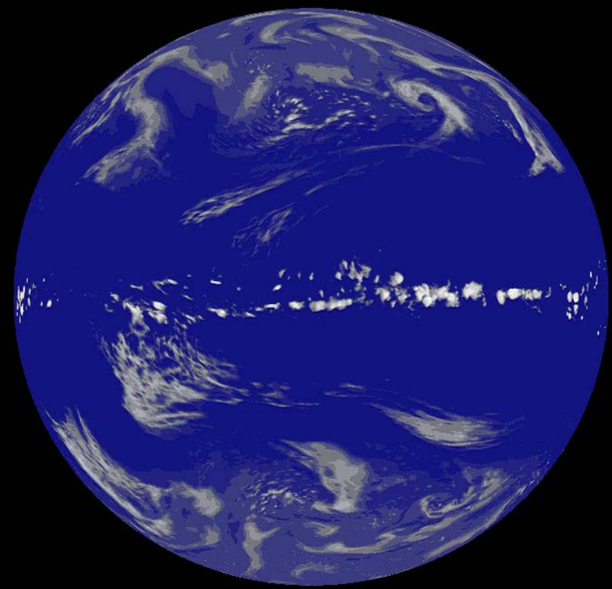


Earth



MTSAT-IR (August 2010)

“Aqua-Planet”

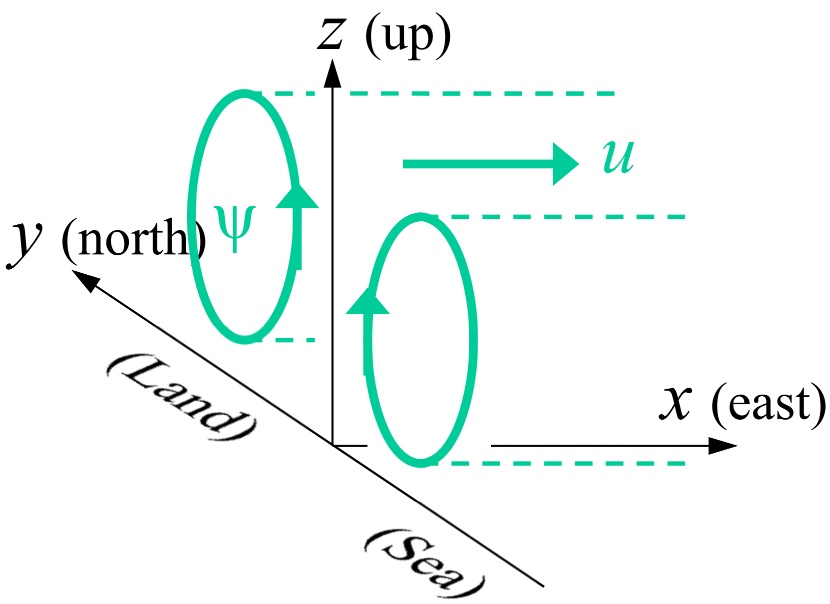


NICAM (M.Sato et al.)

Quasi-2D Boussinesq equations

Momentum, entropy & mass conservation laws: ($\partial/\partial x = 0$, but $u \neq 0$)

$$
\begin{cases}
\dfrac{\partial u}{\partial t} + v\dfrac{\partial u}{\partial y} + w\dfrac{\partial u}{\partial z} - fv = F_x & (0\text{a}) \\[2ex]
\dfrac{\partial v}{\partial t} + v\dfrac{\partial v}{\partial y} + w\dfrac{\partial v}{\partial z} + fu + \dfrac{\partial \phi}{\partial y} = F_y & (0\text{b}) \\[2ex]
\dfrac{\partial w}{\partial t} + v\dfrac{\partial w}{\partial y} + w\dfrac{\partial w}{\partial z} - g\dfrac{\theta}{\theta_0} + \dfrac{\partial \phi}{\partial z} = F_z & (0\text{c}) \\[2ex]
\dfrac{\partial \theta}{\partial t} + v\dfrac{\partial \theta}{\partial y} + w\dfrac{\partial \theta}{\partial z} + \dfrac{\theta_0}{g}N^2 w = Q & (0\text{d}) \\[2ex]
\dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = 0 \Rightarrow v = -\dfrac{\partial \psi}{\partial z}, \quad w = \dfrac{\partial \psi}{\partial y} & (0\text{e})
\end{cases}
$$



(1b), (1c) $\Rightarrow$ x-comp of vorticity eq :

Thermal wind equilibrium

$$
\begin{cases}
\dfrac{\partial \nabla^2 \psi}{\partial t} + \dfrac{\partial(\psi, \nabla^2\psi)}{\partial(y,z)} = \boxed{f\dfrac{\partial u}{\partial z} + \dfrac{g}{\theta_0}\dfrac{\partial \theta}{\partial y}} + \dfrac{\partial F_z}{\partial y} - \dfrac{\partial F_y}{\partial z}, & (1) \\[2ex]
\dfrac{\partial \theta}{\partial t} + \dfrac{\partial(\psi, \theta)}{\partial(y,z)} = -\dfrac{\theta_0}{g}N^2\dfrac{\partial \psi}{\partial y} + Q, & (2\text{a}) \\[2ex]
\dfrac{\partial u}{\partial t} + \dfrac{\partial(\psi, u)}{\partial(y,z)} = -f\dfrac{\partial \psi}{\partial z} + F_x, & (2\text{b})
\end{cases}
$$

$$
\left(\nabla^2 \equiv \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}, \quad \frac{\partial(a,b)}{\partial(y,z)} \equiv \frac{\partial a}{\partial y}\frac{\partial b}{\partial z} - \frac{\partial a}{\partial z}\frac{\partial b}{\partial y} \right)
$$

Horizontal Convection Equations

Zonal mean equations for zonal flow u, meridional stream function ψ and potential temperature θ

$$
\begin{cases}
\dfrac{\partial u}{\partial t} + \dfrac{\partial(\psi,u)}{\partial(y,z)} = -f\dfrac{\partial\psi}{\partial z} + F_x, & \dfrac{\partial(a,b)}{\partial(y,z)} \equiv \dfrac{\partial a}{\partial y}\dfrac{\partial b}{\partial z} - \dfrac{\partial a}{\partial z}\dfrac{\partial b}{\partial y} \quad (3a)\\
\dfrac{\partial\nabla^2\psi}{\partial t} + \dfrac{\partial(\psi,\nabla^2\psi)}{\partial(y,z)} = f\dfrac{\partial u}{\partial z} + \dfrac{g}{\theta_0}\dfrac{\partial\theta}{\partial y} + \dfrac{\partial F_z}{\partial y} - \dfrac{\partial F_y}{\partial z}, & \nabla^2 \equiv \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2} \quad (3b)\\
\dfrac{\partial\theta}{\partial t} + \dfrac{\partial(\psi,\theta)}{\partial(y,z)} = -\dfrac{\theta_0}{g}N^2\dfrac{\partial\psi}{\partial y} + Q & (3c)
\end{cases}
$$

Heating (radiation, condensation)

(o) No motion ($u = v = w = 0$) : $Q = 0$ (Radative (-hydrostatic) equilibrium)

(i) No forcing ($G=0$, $Q=0$): "Thermal-wind" equilibrium without MC

$$\psi = 0, \qquad f\frac{\partial u}{\partial z} + \frac{g}{\theta_0}\frac{\partial\theta}{\partial y} = 0 \qquad \left(\beta\frac{\partial u}{\partial z} + \frac{g}{\theta_0}\frac{\partial^2\theta}{\partial y^2} = 0 \quad \text{for} \quad y \approx 0\right) \qquad (4)$$

(at least inertially stable: Ertel's PV $\overline{P} \equiv (\nabla\times\boldsymbol{u} + \boldsymbol{f})\bullet\nabla\theta$ must have the same sign as f)

(ii) Linear problem for MC [$\partial(\ ,\ )/\partial(y,z)=0$], substituting (3a,c) into ∂(3b)/∂t: (deleting u,θ)

$$\left(\frac{\partial}{\partial t} - K\nabla^2\right)^2\left(\frac{\partial}{\partial t} - K'\nabla^2\right)\nabla^2\psi + N^2\left(\frac{\partial}{\partial t} - K\nabla^2\right)\frac{\partial^2\psi}{\partial y^2} + f^2\left(\frac{\partial}{\partial t} - K'\nabla^2\right)\frac{\partial^2\psi}{\partial z^2} = 0 \qquad (5)''$$

[Quasi-geostrophic case: Replacing (3b) by (4) yields a diagnostic ("omega") equation]

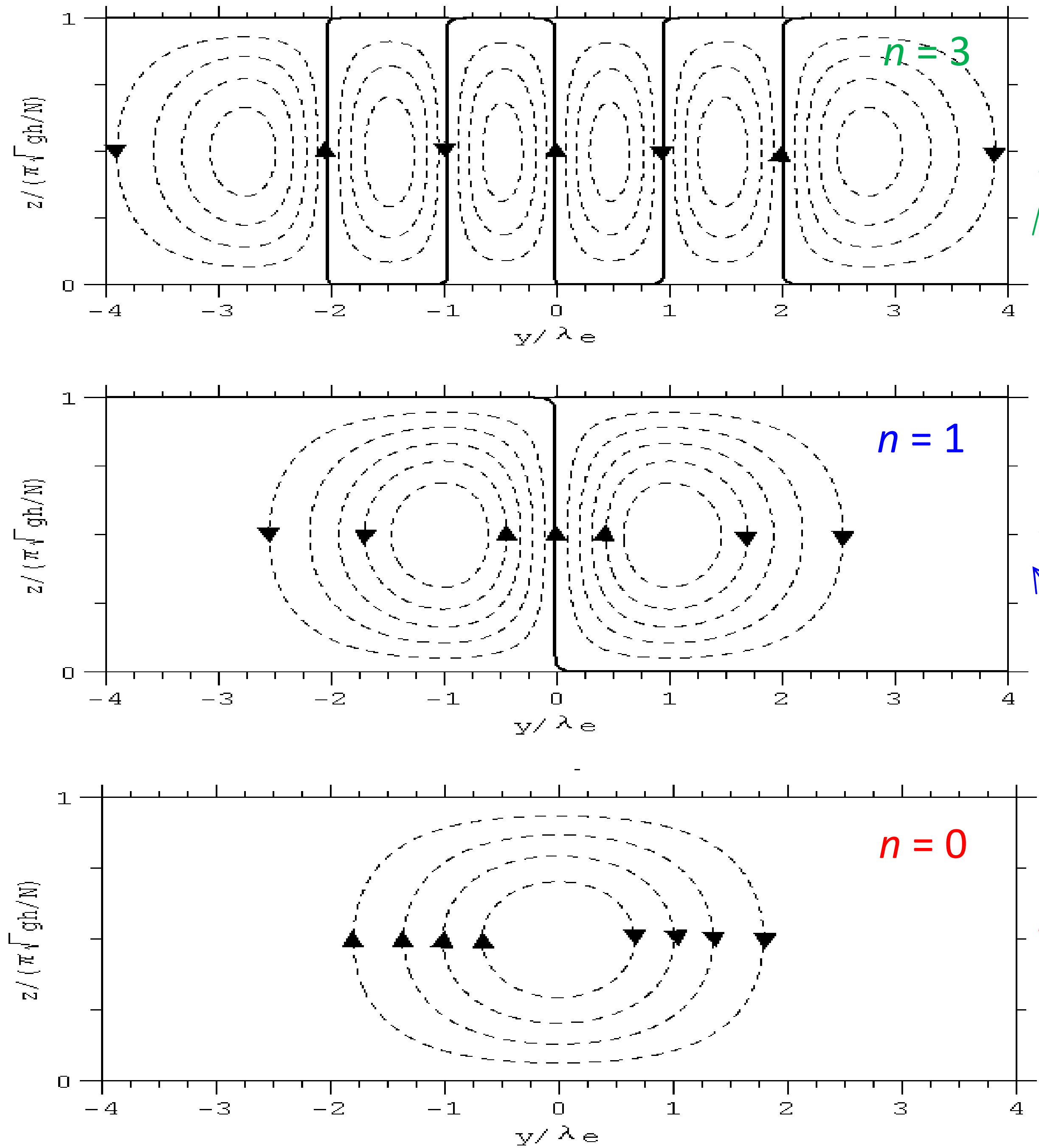
No viscosity ($K=K'=0$) yields "inertio-gravity wave"-like solutions:

$$\overline{\psi} \propto \mathrm{Re}\left[\exp\{i(ly + mz - \omega t)\}\right], \qquad \omega^2\left(l^2 + m^2\right) = l^2N^2 + m^2f^2 \qquad (5)'$$

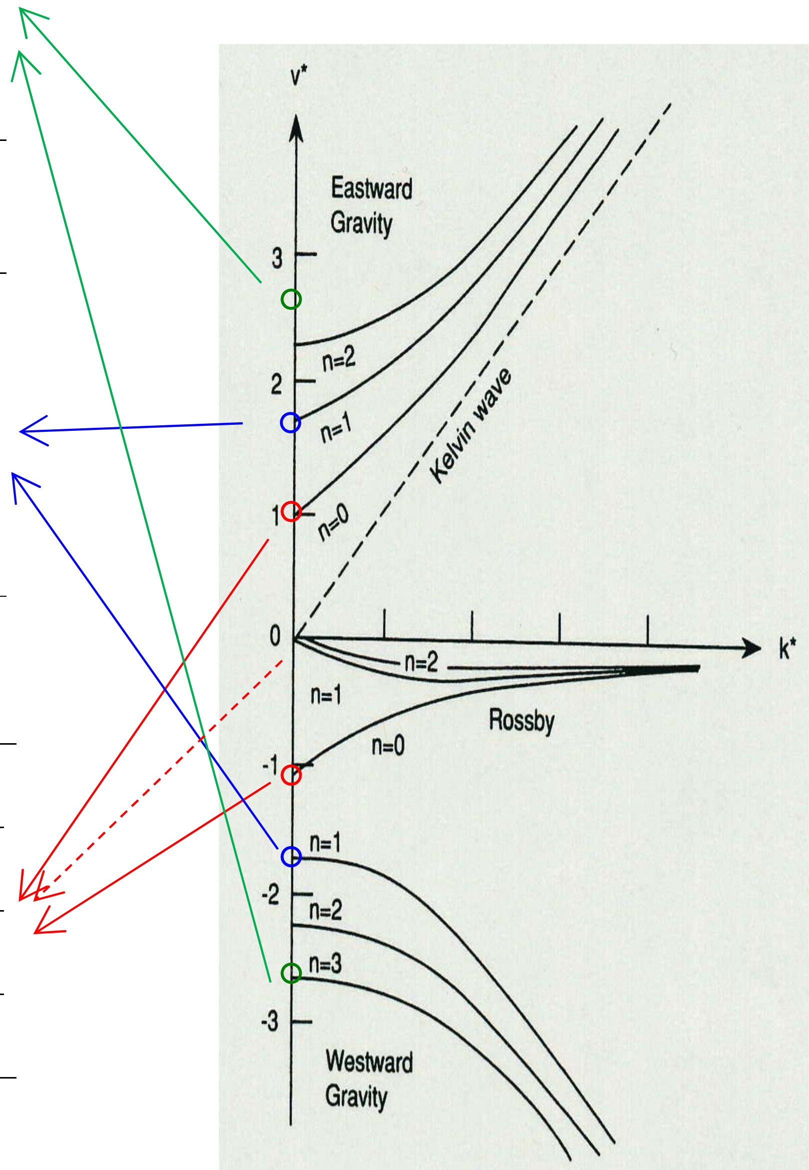
(ω and m may be complex for including transient and vertically decaying solutions)

(iii) Nonlinear cases ⇒ Multiple equilibrium problem (Lorenz).

Horizontal convection or waves trapped along equator or coastline

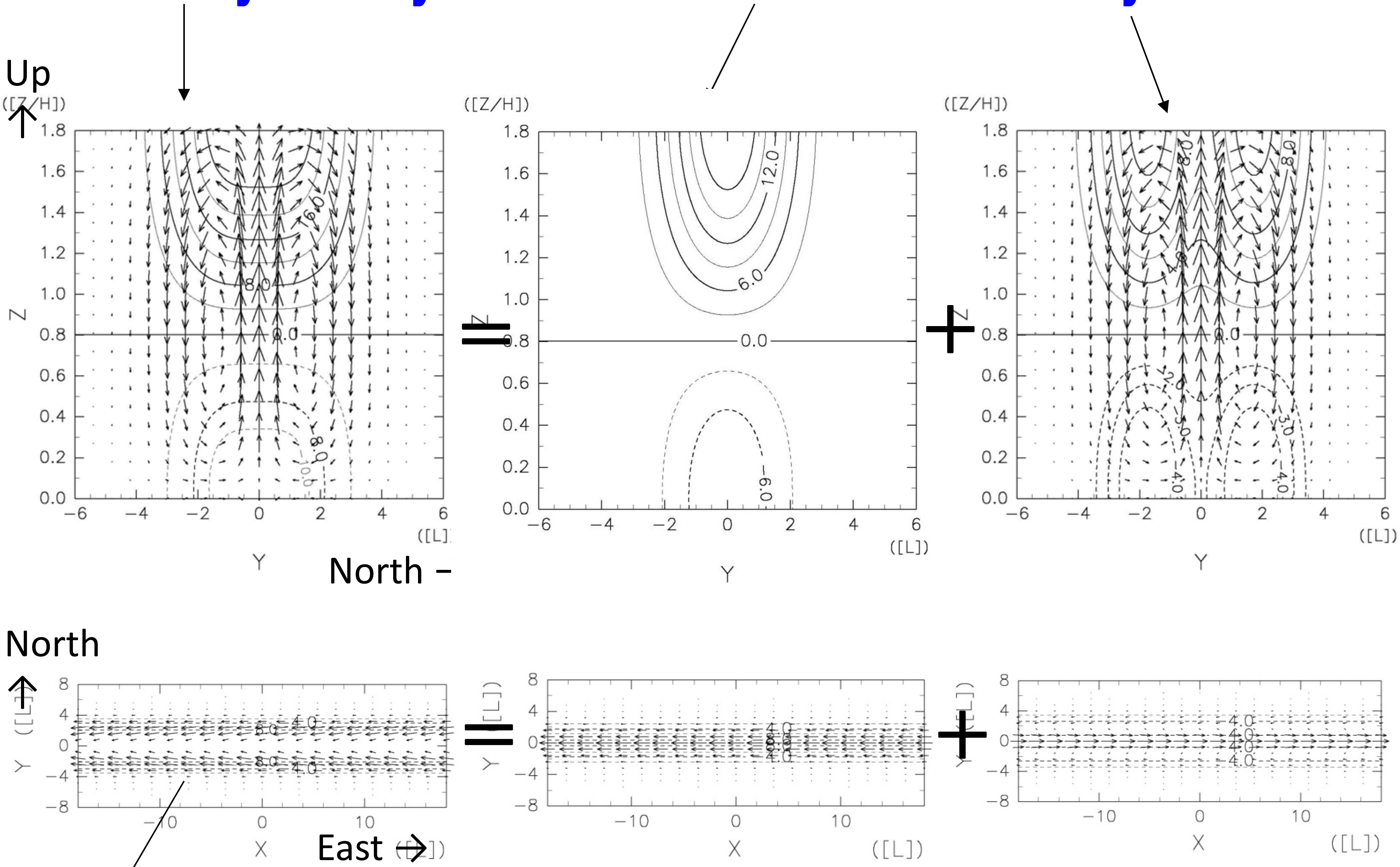


↑
Equator or coastlone



(Matsuno, 1966, for equatorial nonzero zonal wavenumber case)

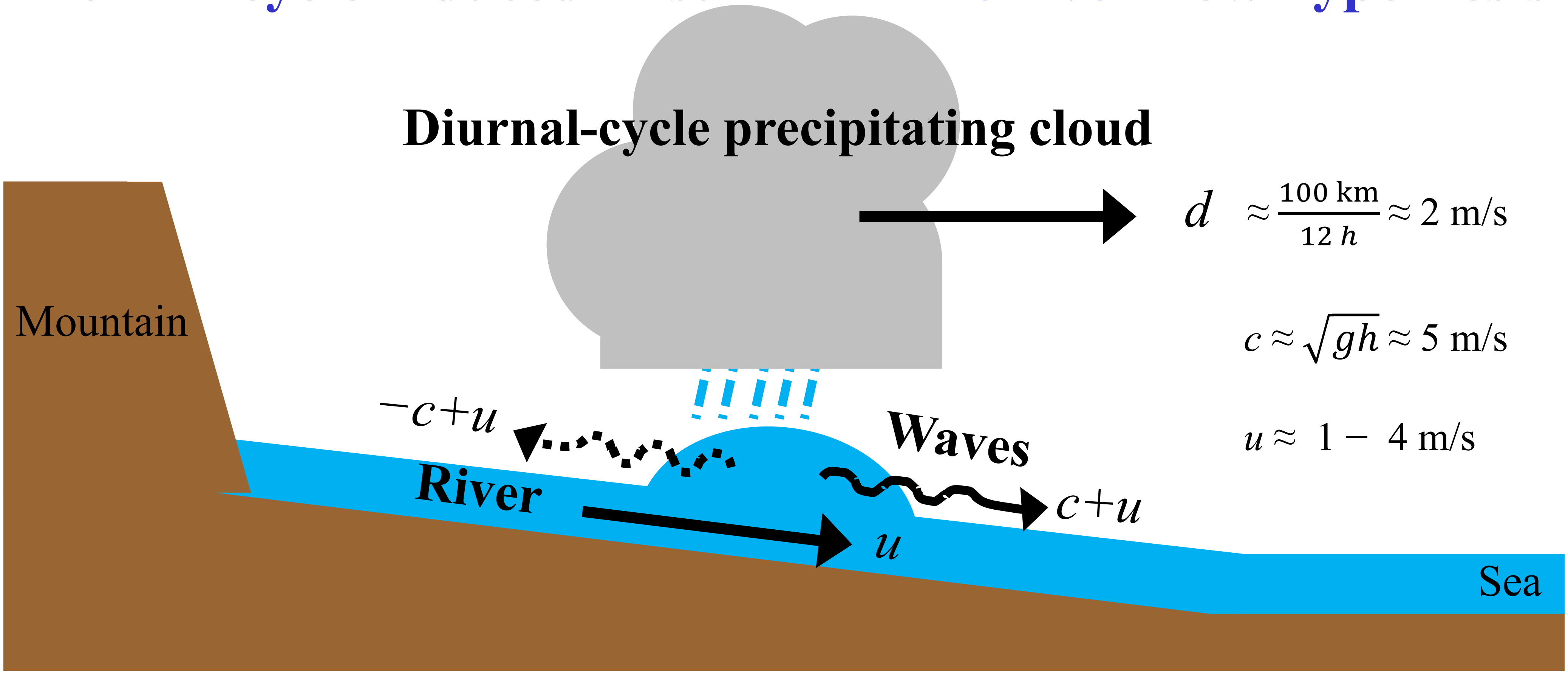
Hadley cell by zero-zwn Kelvin and Rossby waves

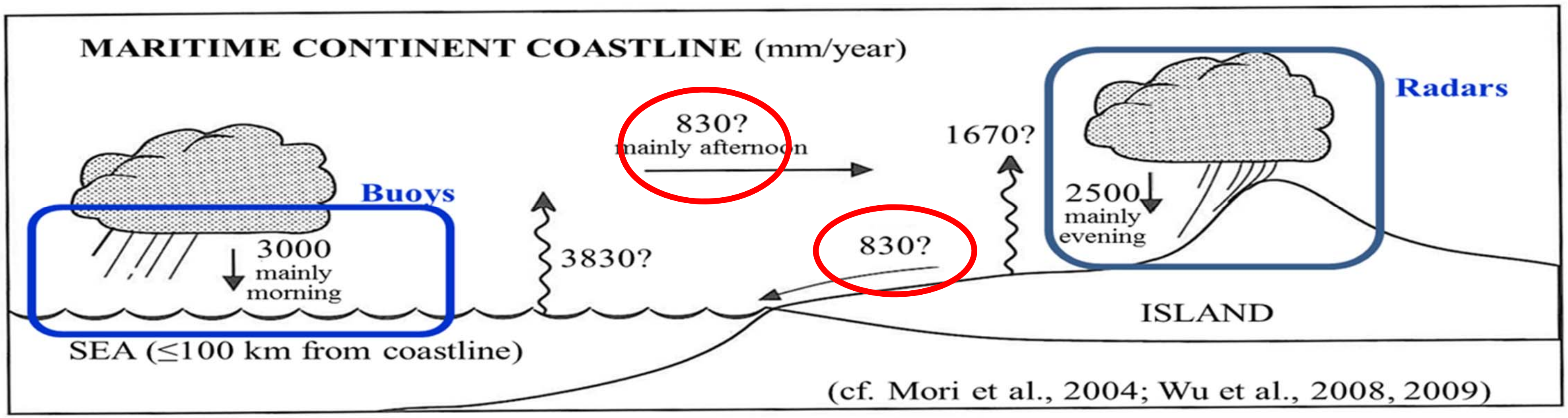


Trade wind zones are separated in the both sides of ITCZ.

Seasonal Variation		Diurnal Variation
Revolution	Planetary motion	Rotation
Latitudinal/Season Continent-Ocean	Diffrential Solar heating	(Longitudinal/LT) Land-Sea, Mt-Valley
(Meridional circ.)		(Thermal Tides)
Monsoon	Horiz. Conv.	**Land-Sea Breezes**
(Planetary waves)	(Waves)	(Gravity waves)
↓ ↑	↓ ↑	↓ ↑
Rainy season	Cloud	Evening shower
Summer＋IMC, etc.	Variety	Sea-wind only, etc.
Year-to-year Interannual	Variability (imbalance)	Day-to-day Intraseasonal

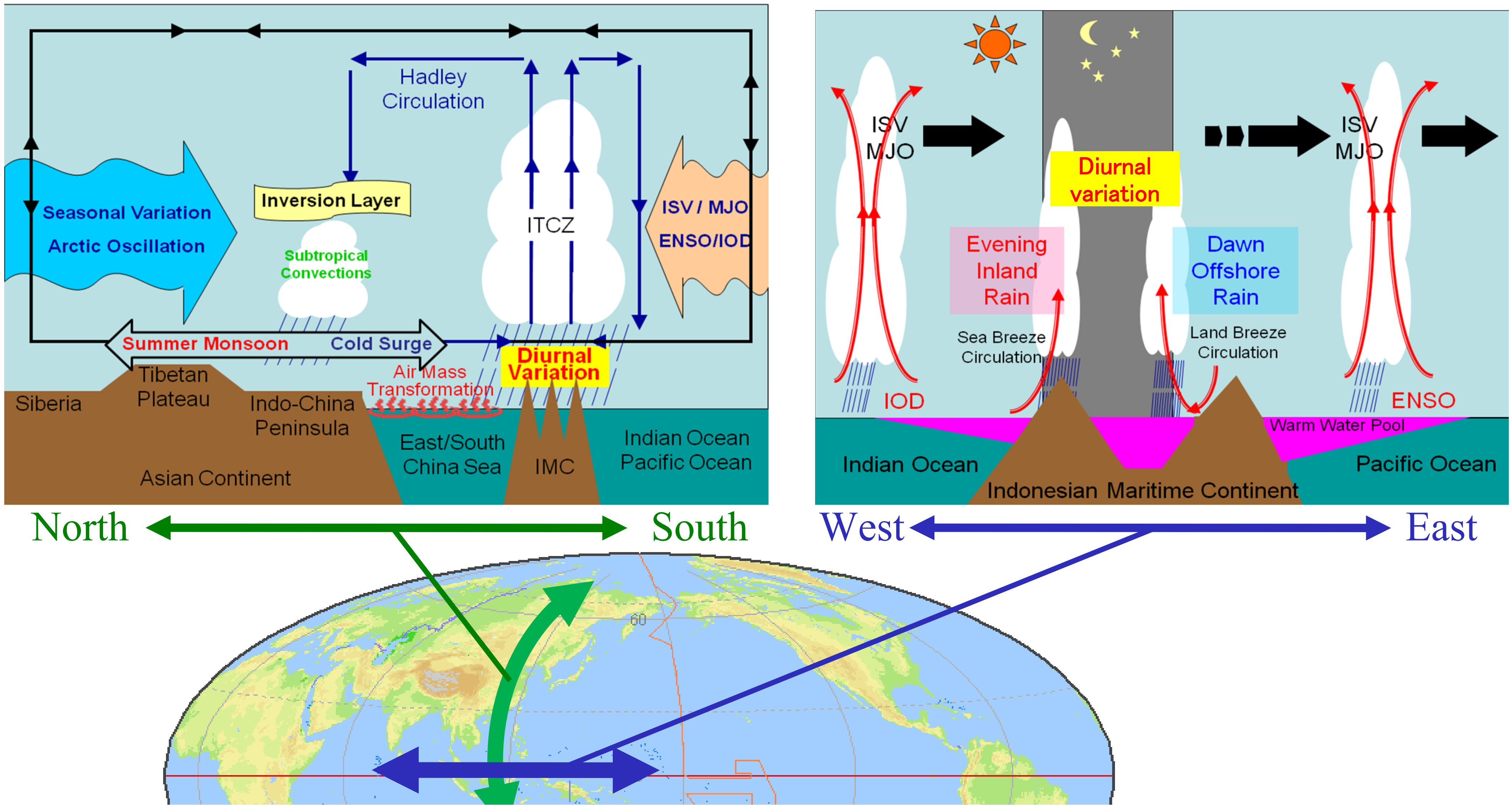
Diurnal-cycle induced "Tsunami"-like river flow hypothesis





Conclusion & scope for further studies

- Land (including anthropogenic)-sea contrast & astronomical forcing
- Horizontal convection as a pair of waves; oceanic & river forcing
- Continental oversea interactions & paleoclimatological application



JEPP-HARIMAU (FY2005-09)

SATREPS-MCCOE Buoy/Radar Network (FY2009-13)