

5. Atmospheric waves

- Horizontal (in particular, zonal) homogeneity
 - waves/oscillations (with sufficiently small amplitudes and zero zonal mean)
- Quasi-periodic forcings: solar annual/diurnal cycles, continental distribution (with IMC)
- Small amplitude → Equation linearization
 - Orthonormal (Fourier-Laplace, cylindrical, spherical) expansions
 - Normal (one-dimensional) differential or algebraic equations
 - General (fundamental) solutions and wave dispersion relations (classification)
- Merits of linear wave theory application to atmospheric/oceanic phenomena:
 - Predictability (period, wavelength)
 - Energy/momentum budget

$$\begin{pmatrix} u' \\ v' \\ \phi' \end{pmatrix} \equiv e^{z/2H} \cdot \Re \left[\begin{pmatrix} \bar{u}(y) \\ \bar{v}(y) \\ \bar{\phi}(y) \end{pmatrix} \exp\{i(kx + mz - \omega t)\} \right] \cos(kx + mz - \omega t)$$

Governing equations → Wave solutions

→ Dispersion relations (of frequency & wavenumbers)

Polarization relations (of amplitudes of u , v , w , T , ϕ)

5.1. Classification of waves in geophysical fluids near equator

5.2. Zonal-vertical (Walker) circulation

5.3. Atmosphere-ocean interaction: ENSO (and IOD)

5.4. Wave-mean flow interaction: QBO (and SAO)

Variabilities of climate and weather

- Annual mean – Vertical/Meridional dependencies

- Shorter/smaller-scale variabilities

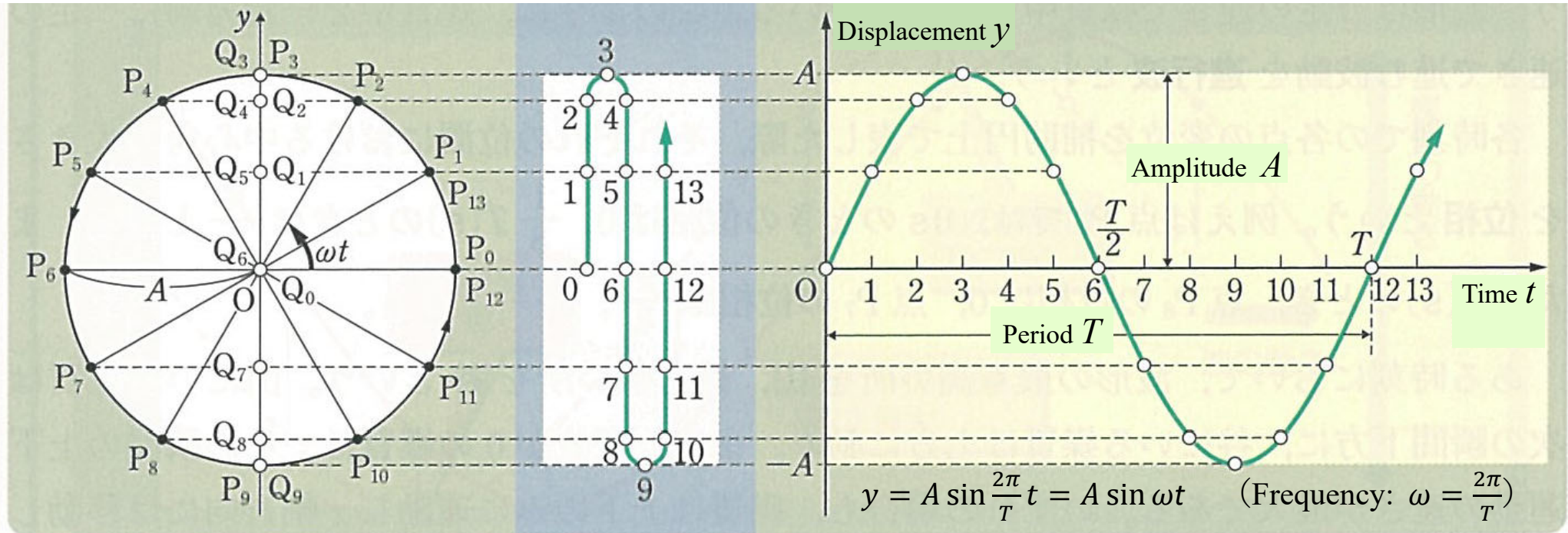
- Waves and convections/clouds
narrow meaning of “waves”

- Longer/larger-scale variabilities

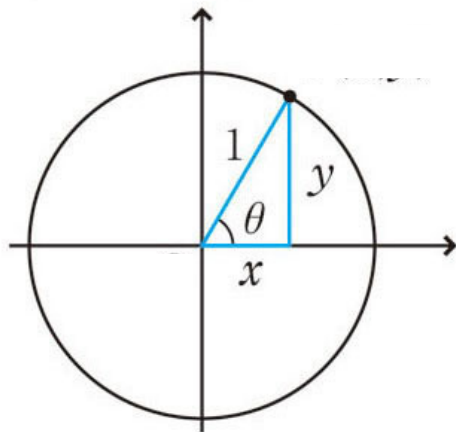
- Annual/Interannual variations

Broader meaning of “waves” : including convections and longer/larger variabilities

Periodical phenomena: Circular motion, Pendulum oscillation, Waves



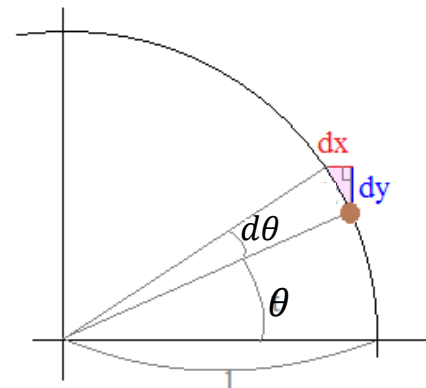
Unit circle and trigonometric functions



$$\sin \theta = \frac{y}{1} = y$$

$$\cos \theta = \frac{x}{1} = x$$

$\cos \theta$ is $\sin \theta$ with an angular shift $\frac{\pi}{2}$ (time delay $\frac{T}{4}$)



Twice differentiation of trigonometric function is the original function with opposite sign.

$$\frac{d \sin \theta}{d \theta} = \frac{dy}{d \theta} = \cos \theta$$

$$\frac{d \cos \theta}{d \theta} = \frac{dx}{d \theta} = -\sin \theta$$

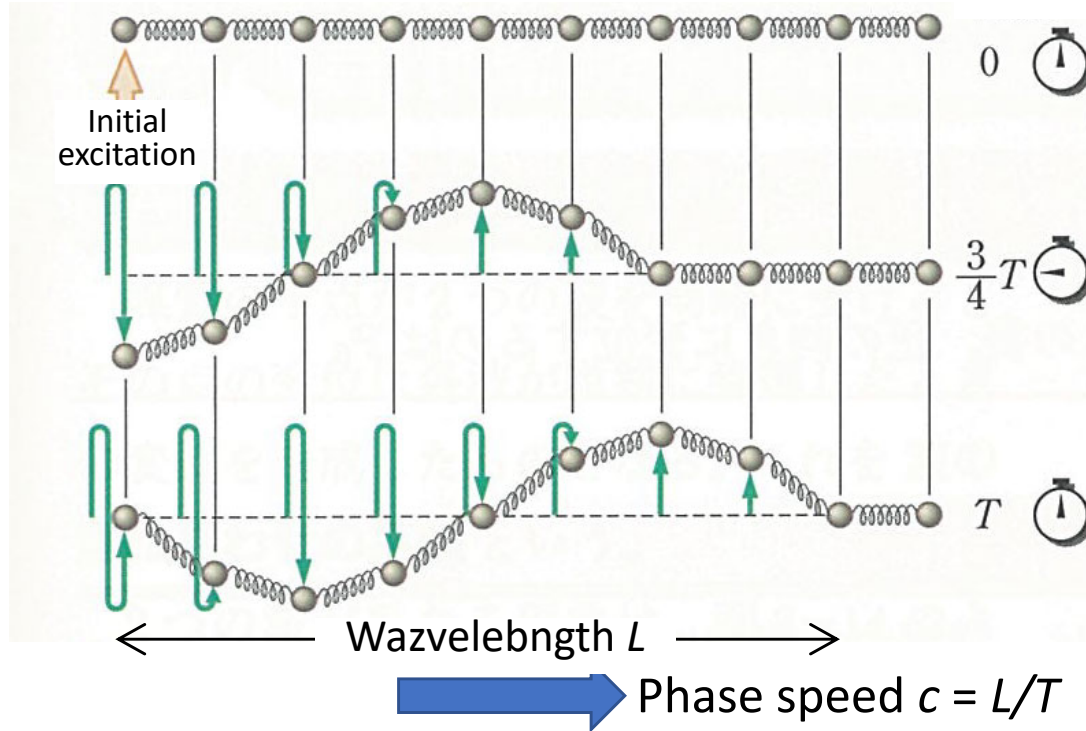
$$\frac{d^2 \sin \theta}{d \theta^2} = \frac{d^2 y}{d \theta^2} = -\sin \theta$$

$$\frac{d^2 y}{d \theta^2} + y = 0$$

“Oscillation equation”

Waves: Oscillations both in time and in space

$$\theta = k(x - ct)$$



$$\begin{aligned}\sin\theta &= \sin(kx - kct) \\ &= \sin kx \cos kct - \cos kx \sin kct\end{aligned}$$

$$\frac{d^2 \sin \theta}{d\theta^2} = \frac{d^2 y}{d\theta^2} = -\sin \theta$$

$$\frac{d^2 \sin kx}{dx^2} = \frac{d^2 y}{dx^2} = -k^2 \sin \theta$$

$$\frac{\partial^2 \sin k(x - ct)}{\partial t^2} = \frac{\partial^2 y}{\partial t^2} = -k^2 c^2 \sin \theta$$

“Wave equation”

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial x^2}$$

“Wave equation” has the wave solution $A(x, t)$:

$$\frac{\partial^2 A}{\partial t^2} = c^2 \frac{\partial^2 A}{\partial x^2}$$

“Dispersion relation” by substituting

$$A = \mathcal{A} \exp\{i(kx - \omega t)\}$$

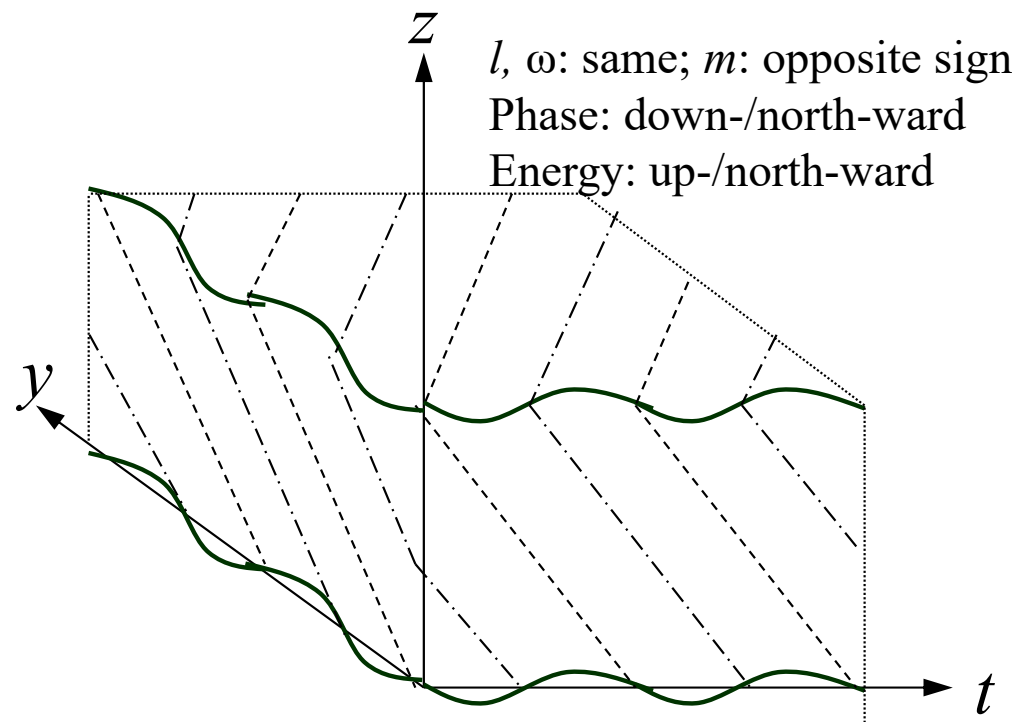
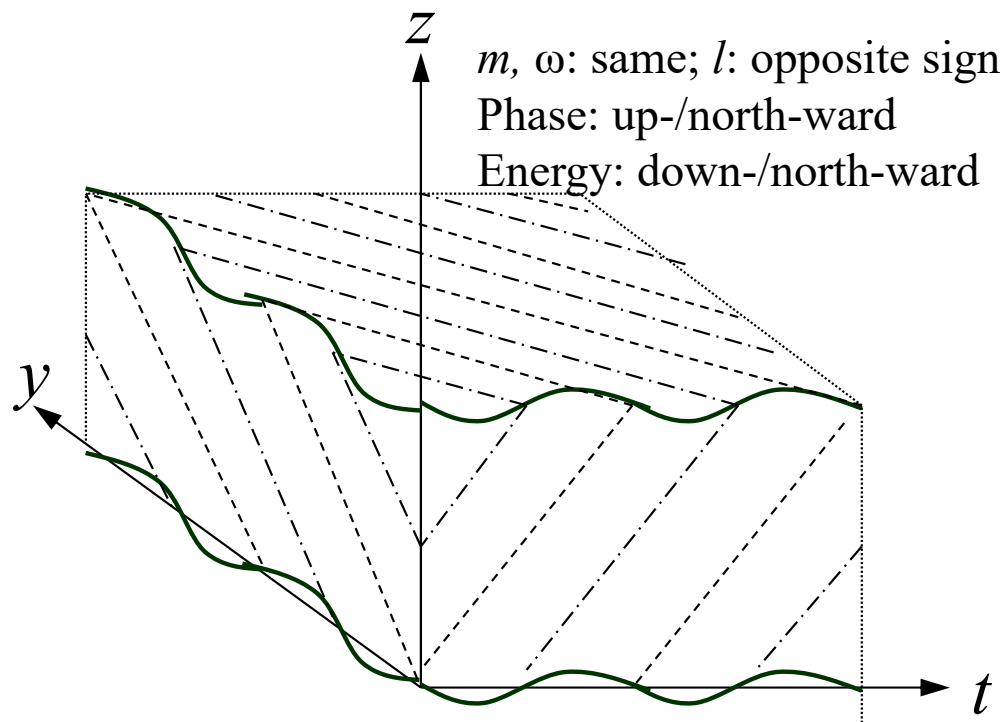
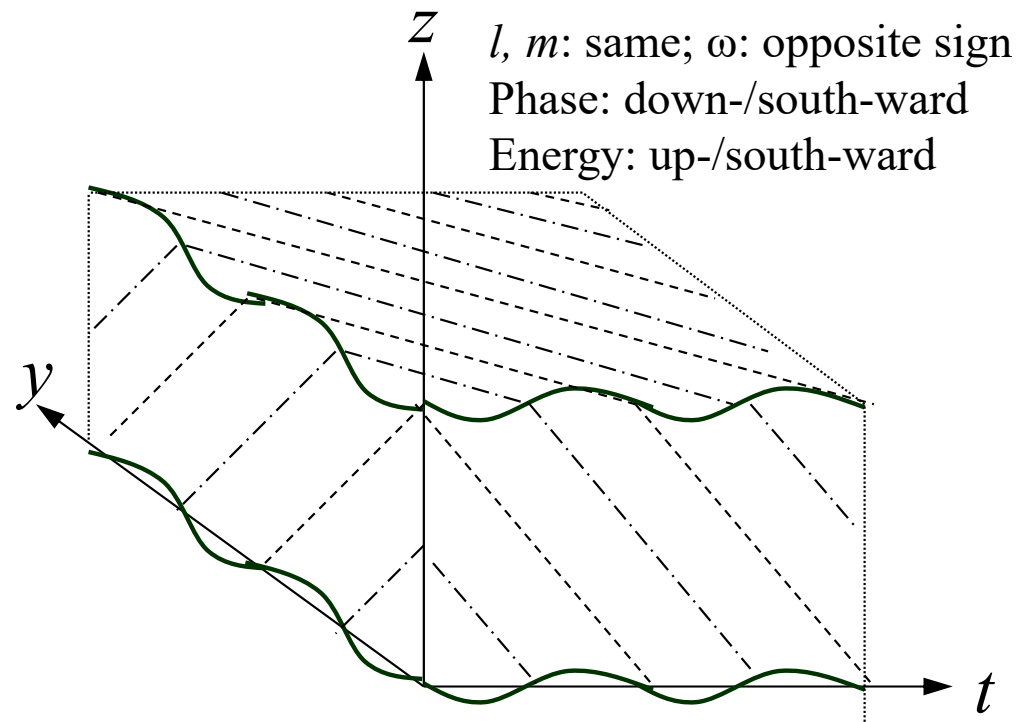
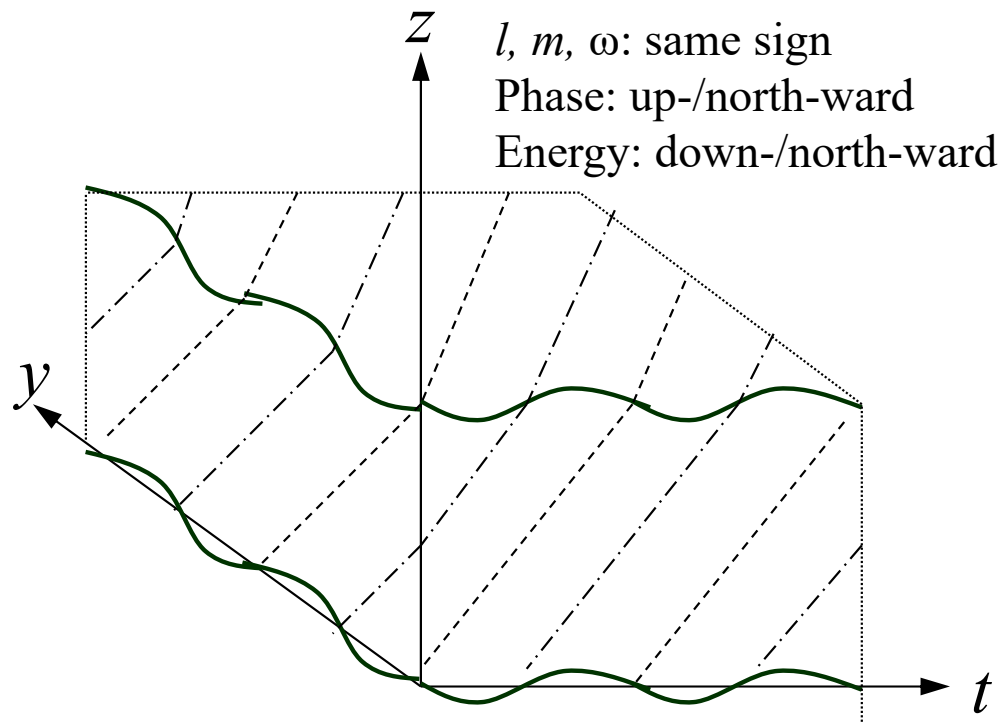
into the wave equation:

$$\omega^2 = c^2 k^2$$

“Fourier expansion”:

Any data may be expressed by waves

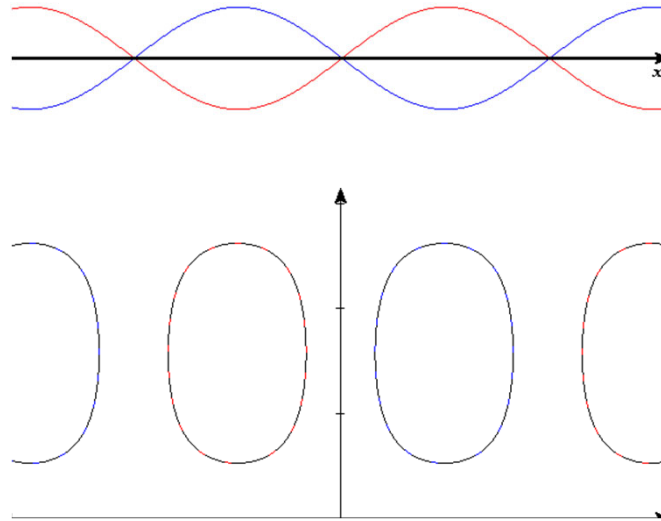




Stationary convection ($|Westward| = |Eastward|$)

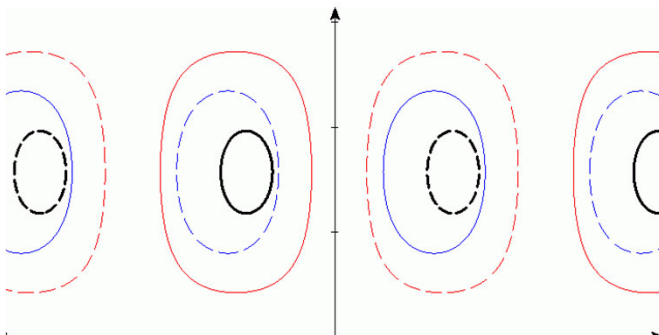
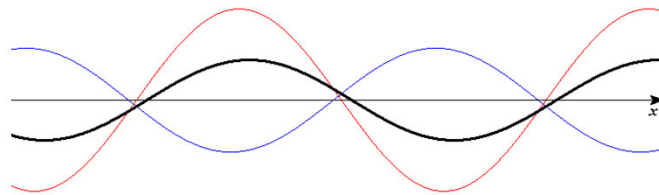
Westward component
 $\psi = \cos(kx + mz + \omega t)$
 $-\cos(kx + mz + \omega t)$
 $= -2 \sin(kx + \omega t) \sin mz$

Eastward component
 $\psi = \cos(kx + mz - \omega t)$
 $-\cos(kx + mz - \omega t)$
 $= -2 \sin(kx - \omega t) \sin mz$



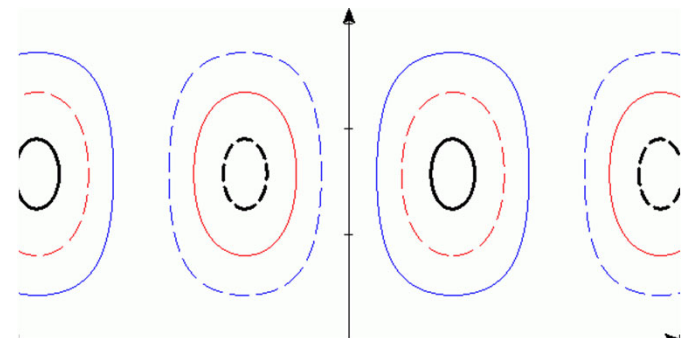
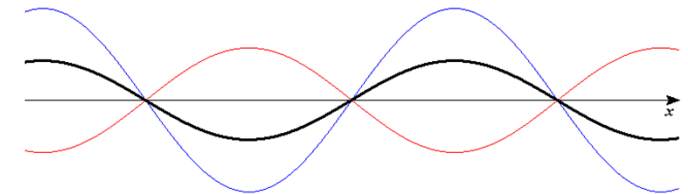
Westward traveling convection

($|Westward| > |Eastward|$)



Eastward traveling convection

$|Westward| < |Eastward|$



Fourier expansion:

Any fluctuations are the sum of waves

Many software applications: MATLAB, EXCEL, etc.



**Jean-Baptiste Joseph
Fourier (1768 – 1830)**

Lagrangian motion associated with Eulerian wave

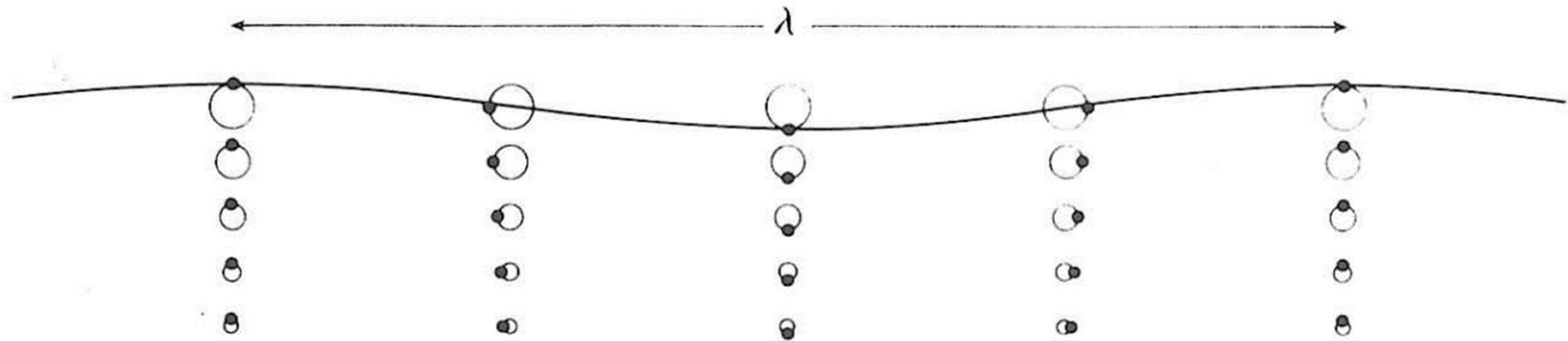


Figure 50. Motion of fluid particles (on linear theory) in a sinusoidal wave of length λ travelling from left to right on deep water. The maximum surface elevation is 0.02λ , and particles on the surface describe circles of this radius. The particles shown at mean depths 0.05λ , 0.1λ , 0.15λ and 0.20λ describe circles of radius 0.0146λ , 0.0106λ , 0.0078λ and 0.0057λ respectively. In each case the particle's instantaneous position on its circular path is shown. (Lighthill, 1978)



Kelvin-Helmholtz (shear) Instability and Wavebreaking

(Klaassen and Peltier, 1985)

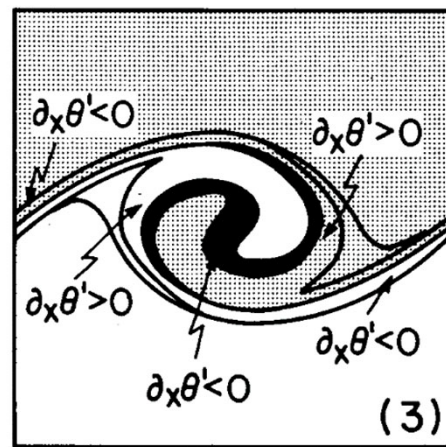
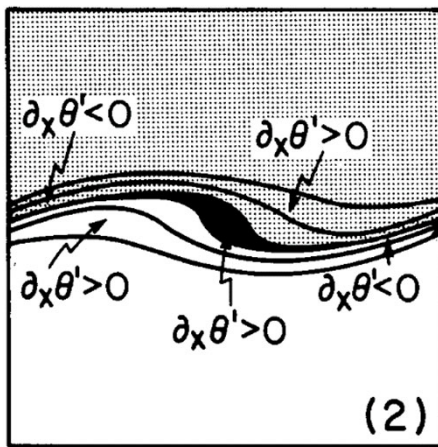
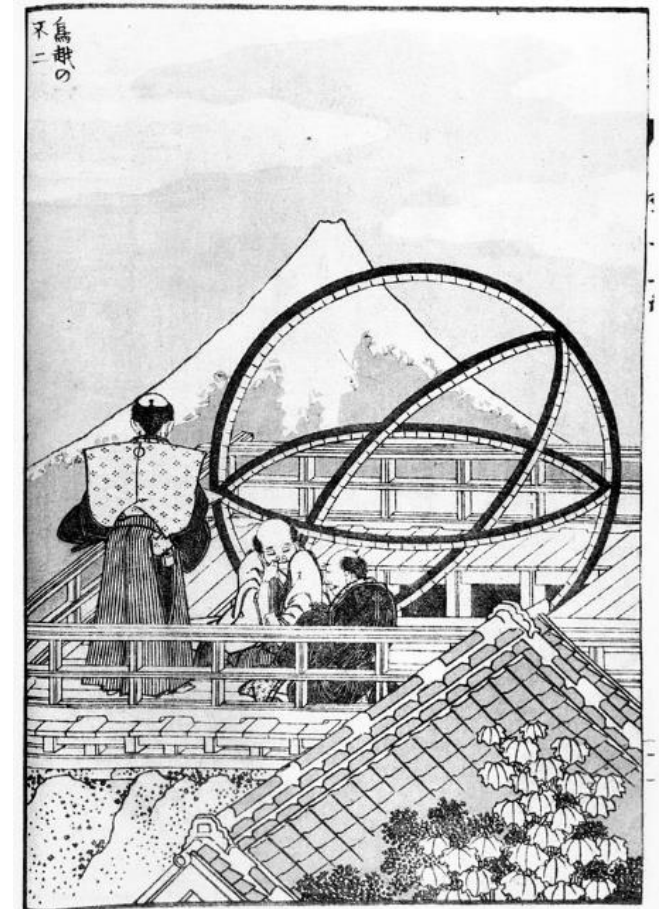


FIG. 4. Sketches of potential temperature field illustrating baroclinic sources and sinks of vorticity for a typical KH wave at key times (2) and (3) in the energy cycle. Median contour interval has been shaded darkly; regions with potential temperatures greater than the median value have been shaded lightly. Regions of baroclinic generation of vorticity ($\partial_x \theta' < 0$) are found in the braids; regions of baroclinic destruction ($\partial_x \theta' > 0$) are found at the right and left edges of the core.



(Hokusai Katsushika, 1833)

Quasi-Geostrophic Motions in the Equatorial Area*

By Taroh Matsuno

Geophysical Institute, Tokyo University, Tokyo

(Manuscript received 15 November 1965, in revised form 11 January 1966)

Abstract

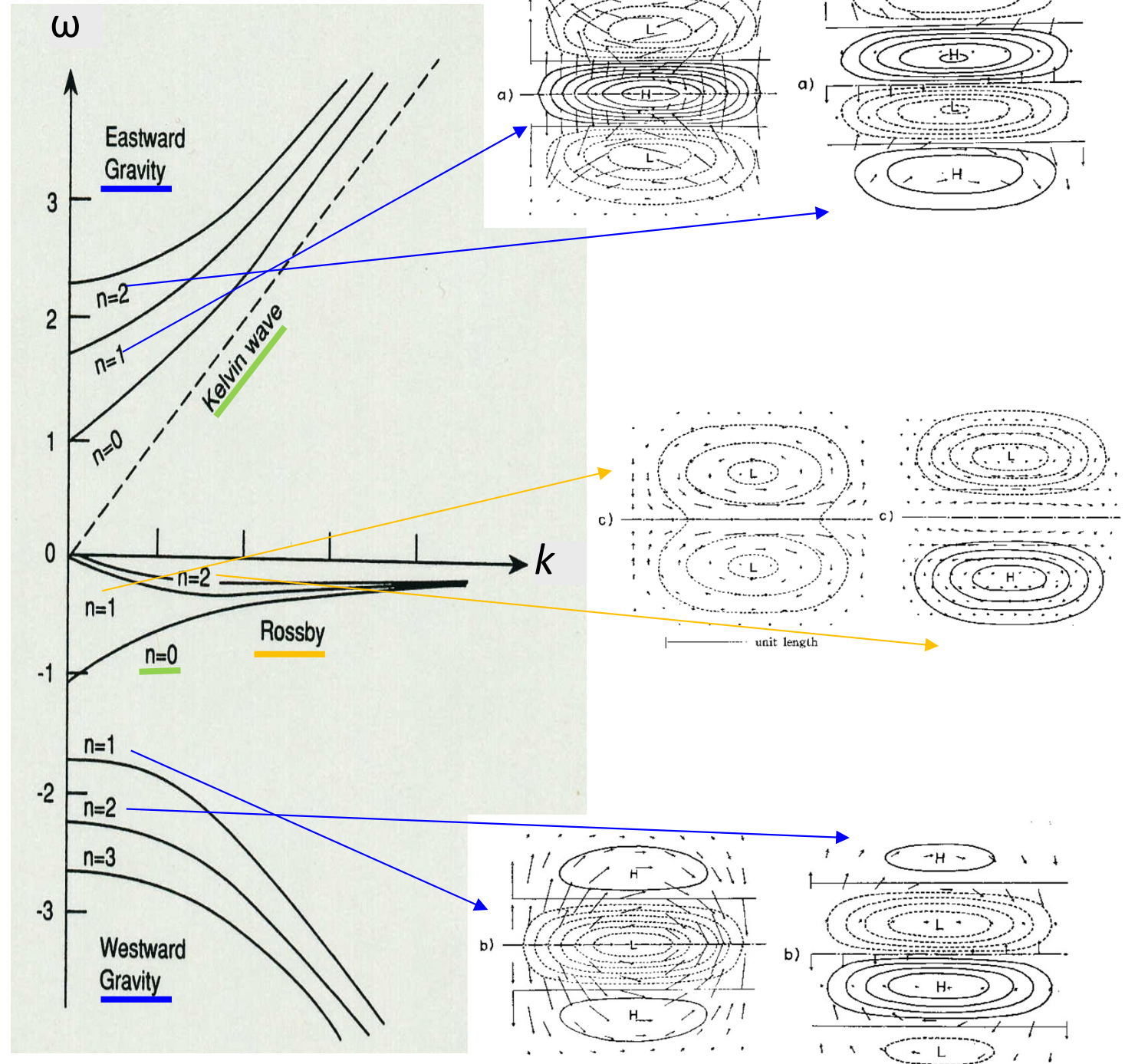
Quasi-horizontal wave motions in the equatorial area are discussed. A single layer of homogeneous incompressible fluid with free surface is treated. The Coriolis parameter is assumed to be proportional to the latitude. In general, waves of two different types are obtained as solutions, one being the inertio-gravity wave and the other Rossby wave. They are distinguished from each other by the difference of frequencies and by the relationships between pressure and velocity fields.

For the solutions of the lowest mode (waves confined near the equator), however, the distinction between the Rossby and the inertio-gravity waves is not clear. The wave moves westward and the frequency of this wave is compared to that of the gravity wave, if wave length is large. With the increase of the wave number the frequency decreases and approaches to that of the Rossby type wave. The pressure and wind fields of this wave show somewhat mixed character of the two types, and change continuously with the wave number. In this connection it seems impossible to "filter out" gravity waves from large scale motions.

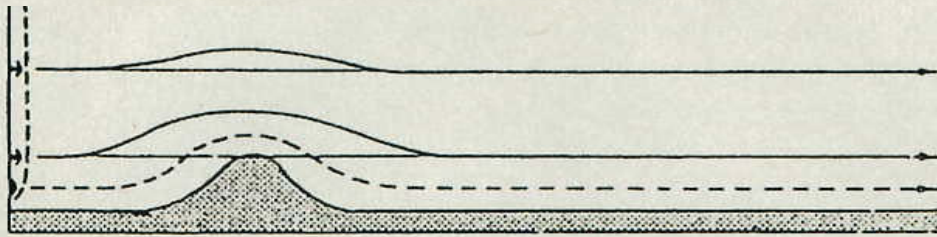
Another interesting feature of the equatorial disturbances is that the low frequency waves are trapped near the equator. It is shown that the both waves of inertio-gravity type and of the Rossby type have appreciable amplitude only near the equator. The characteristic north-south extent of the waves is $(c/\beta)^{1/2}$, where c is the velocity of long gravity waves and β is the Rossby parameter. This expression is identical with that derived by Bretherton (1964) for inertio-gravity oscillations in a meridional plane.

Wave types and characteristics

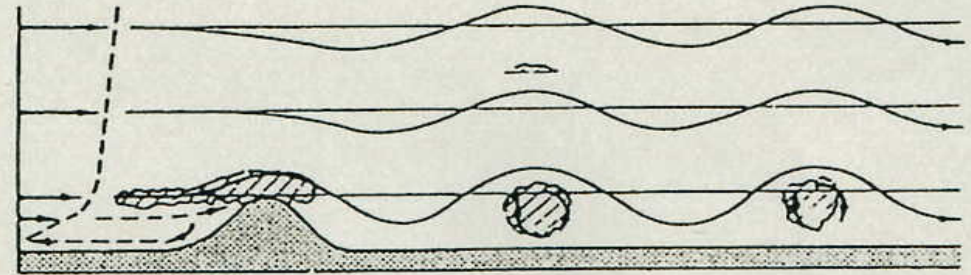
- **Rossby waves** are longer period
- **Gravity waves** are shorter period (filtered out under extratropical quasi-geostrophic approximation)
- **Equatorial (Kelvin and Rossby-gravity) waves** (mentioned later)
- Sound waves have been filtered from basic equations (Boussinesq or anelastic approximations)



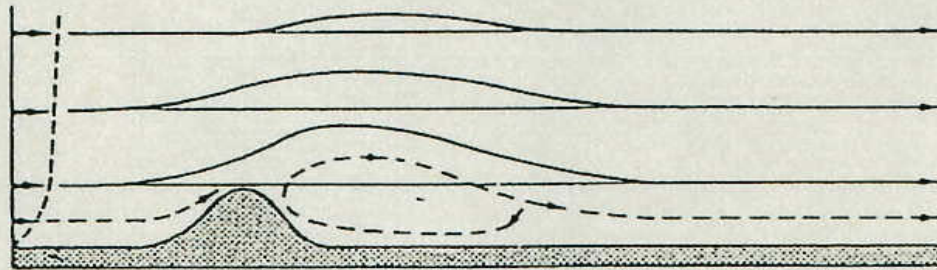
Internal Gravity Waves (negligible rotation)



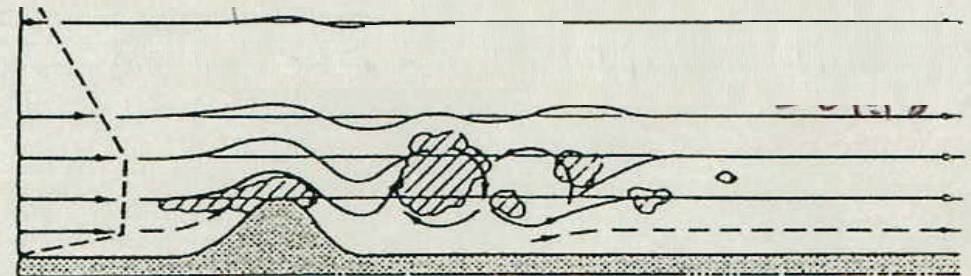
Almost no shear



Lee waves and in a shear flow

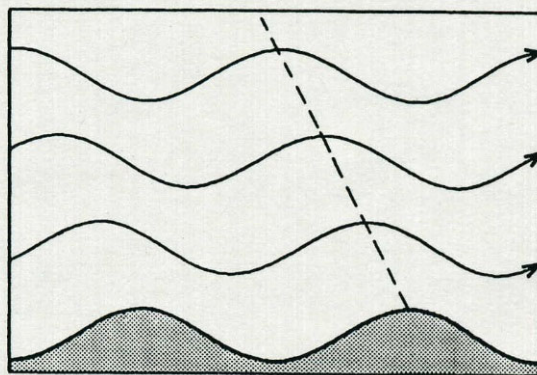


Low-level weak shear



Breaking lee waves and in a low-level jet

(Corby, 1954)



(b)

broad ridge case (b). The dashed line in (b) shows the phase of maximum upward displacement. (After Durran, 1990.)

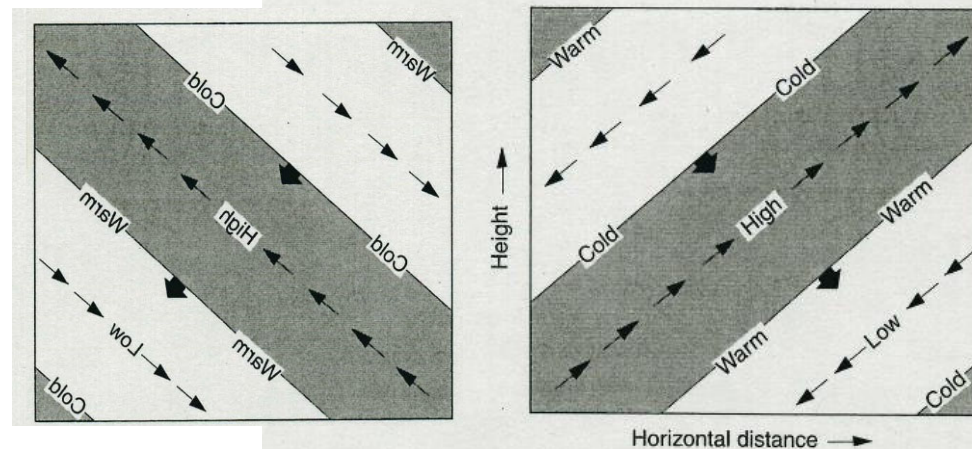


Fig. 7.9 Idealized cross section showing phases of pressure, temperature, and velocity perturbations for an internal gravity wave. Thin arrows indicate the perturbation velocity field, blunt solid arrows the phase velocity. Shading shows regions of upward motion.

Inertia-gravity waves

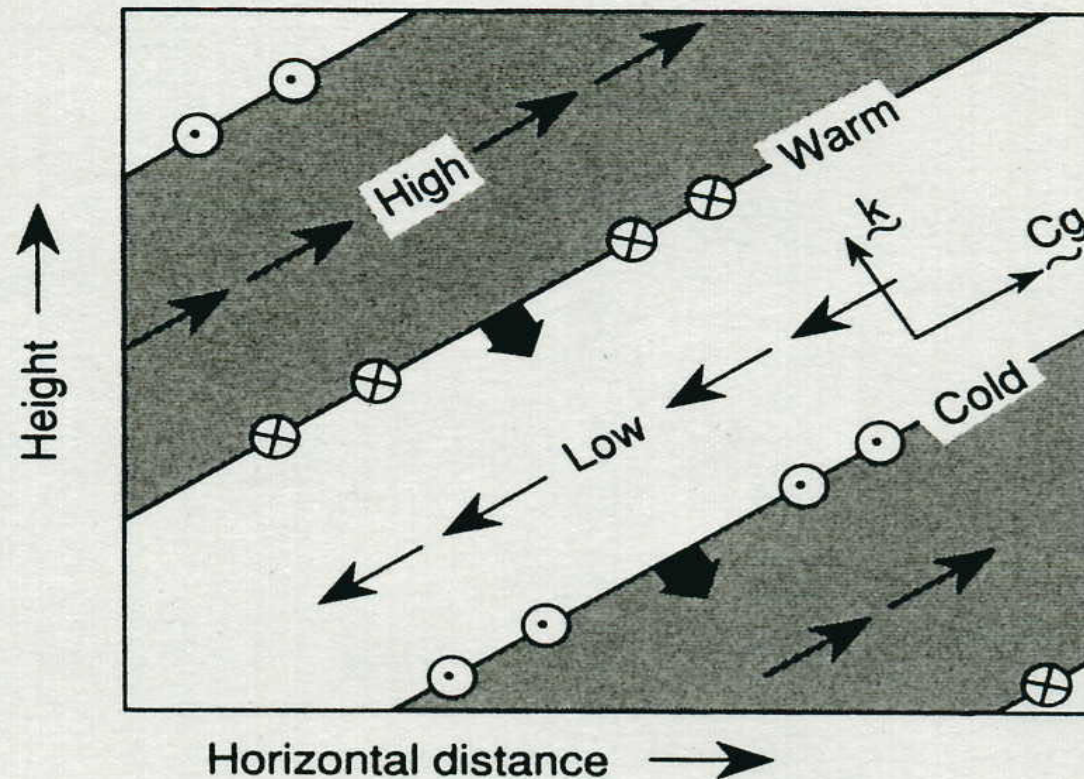


Fig. 7.12 Vertical section in a plane containing the wave vector k showing the phase relationships among velocity, geopotential, and temperature fluctuations in an upward propagating inertia-gravity wave with $m < 0$, $\nu > 0$, and $f > 0$ (Northern Hemisphere). Thin sloping lines denote the surfaces of constant phase (perpendicular to the wave vector), and thick arrows show the direction of phase propagation. Thin arrows show the perturbation zonal and vertical velocity fields. Meridional wind perturbations are shown by arrows pointed into the page (northward) and out of the page (southward). Note that the perturbation wind vector turns clockwise (anticyclonically) with height. (After Andrews et al., 1987.)

Intensive radiosonde observations of internal (inertio-)gravity waves

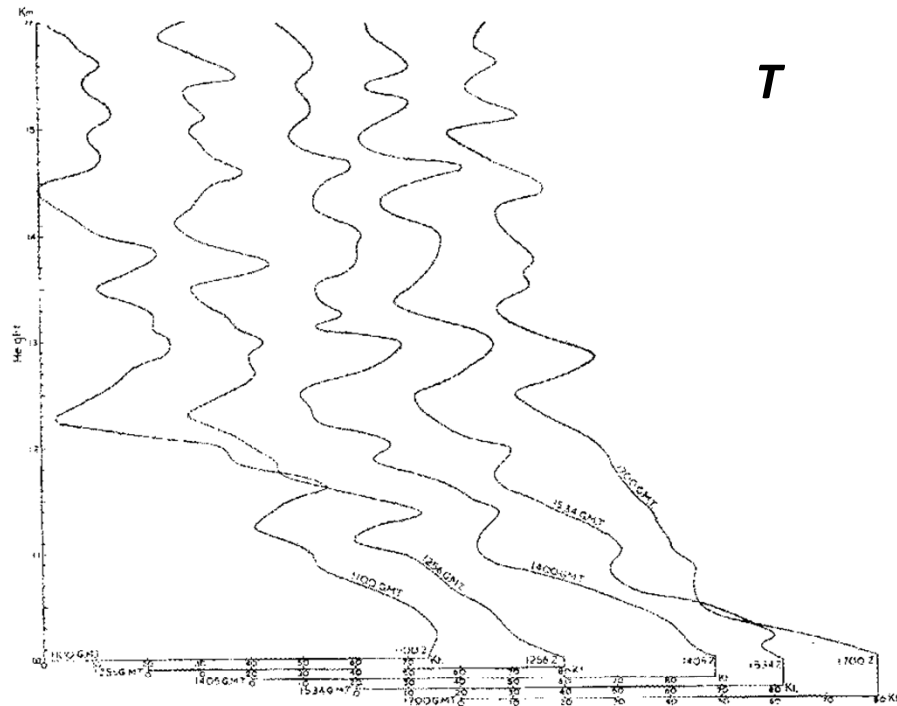


Figure 3. Northward component of velocity on five successive soundings on 24 March 1959.

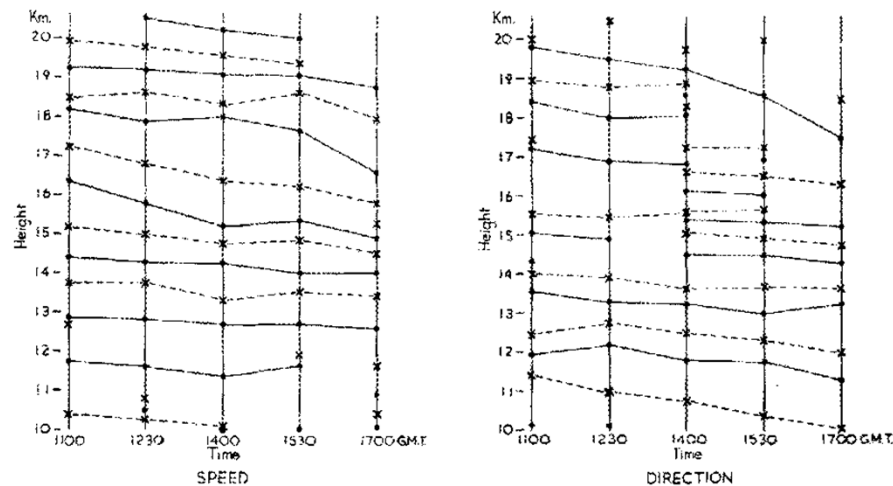


Figure 4. Heights of maxima and minima of wind velocity and extremes of wind direction on five successive soundings on 19 March 1959 (Maxima are indicated by $\bullet$ and joined by continuous lines where appropriate; minima are indicated by $\times$ and joined by broken lines).

(Sawyer, 1961; Crawley, UK; 51.1°N)

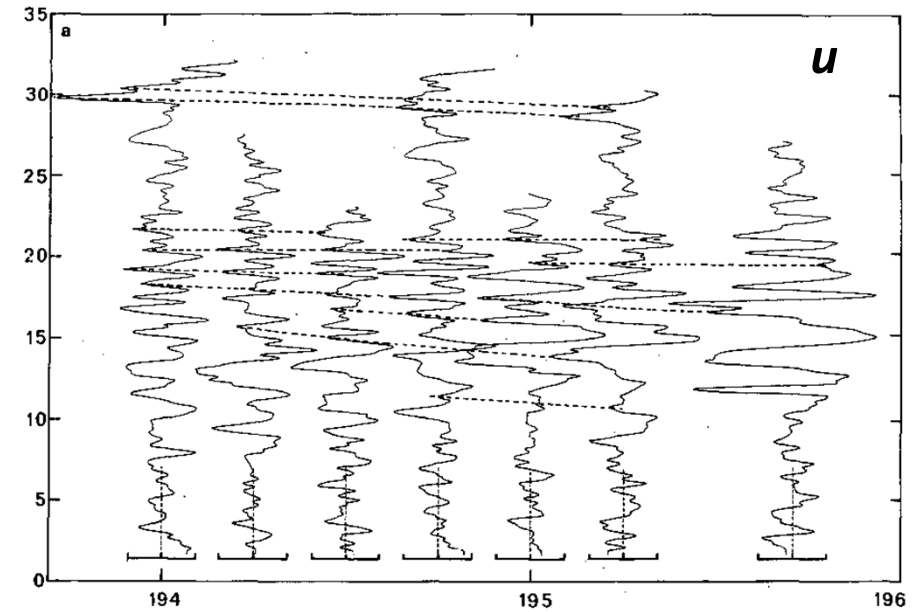


FIG. 8a. Sequence of vertical profiles of the u component in the vertical wavelength band 200-1500 m. Phase 1. The abscissa for each time is shifted so that the origin is indicated by vertical dashed lines. Time is in Julian Days.

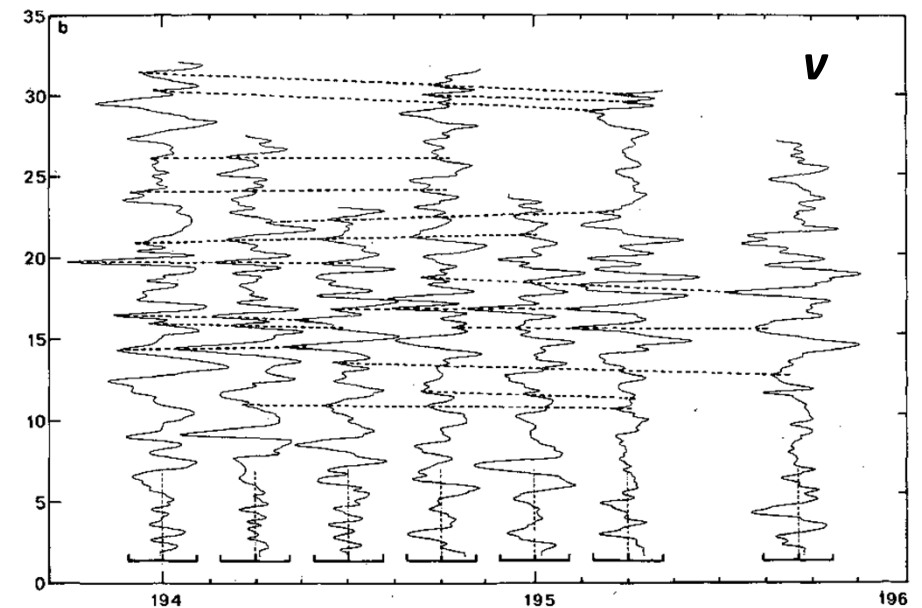
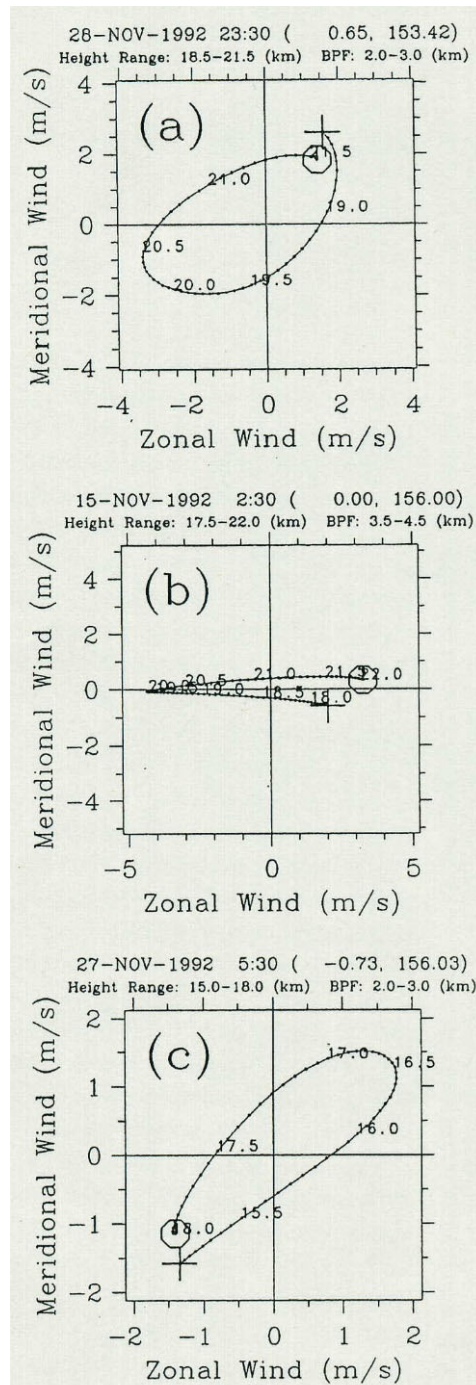
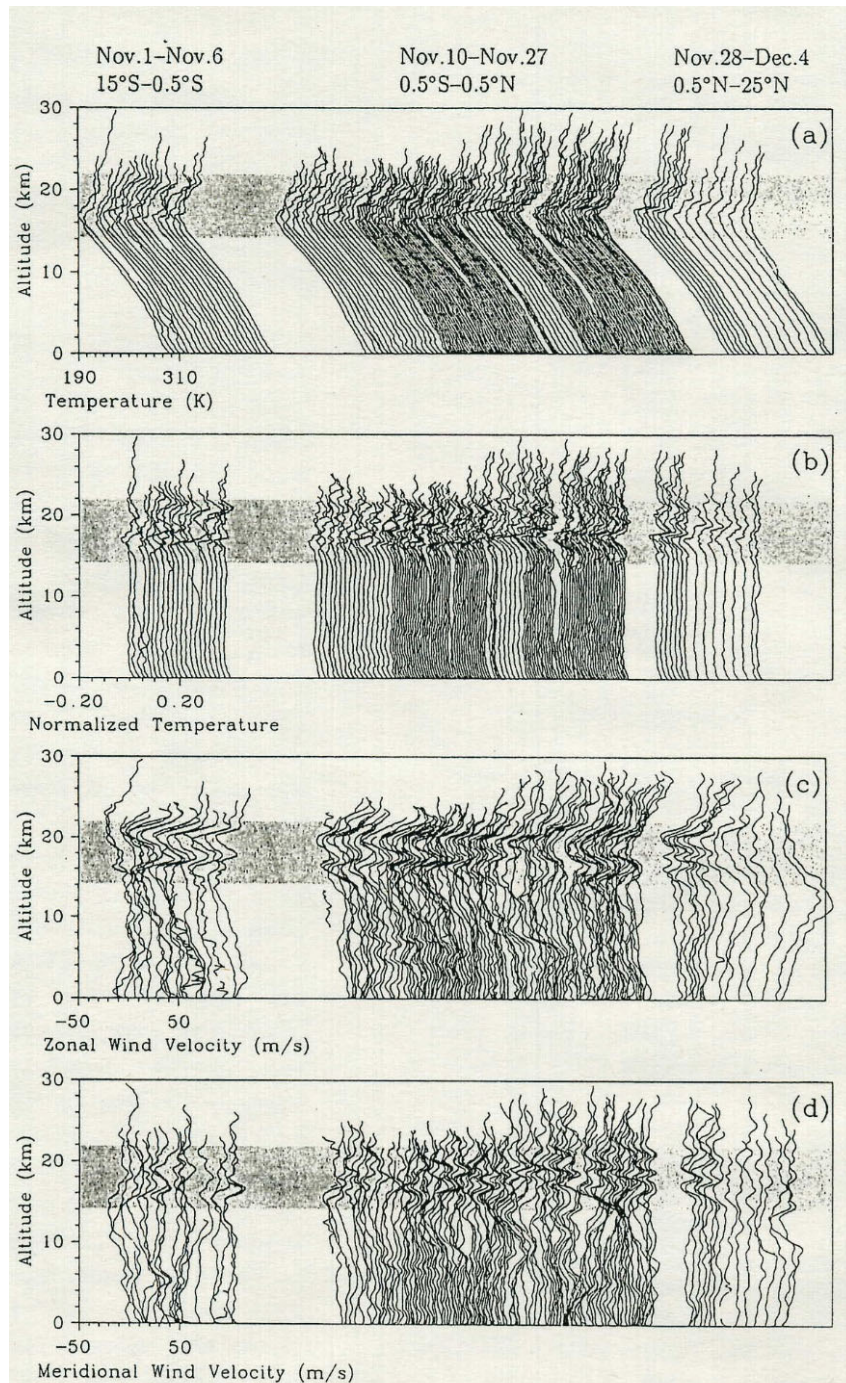


FIG. 8b. Sequence of vertical profiles of the v component in the vertical wavelength band 200-1500 m. Phase 1.

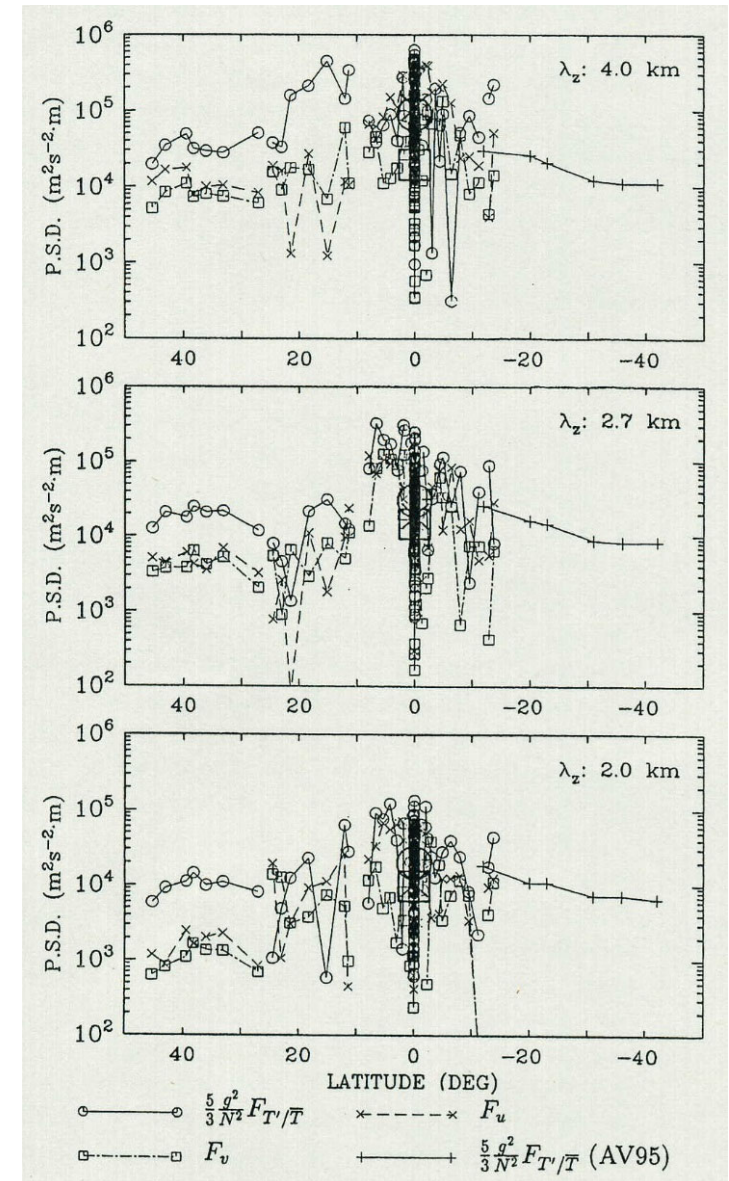
(Cadet & Teitelbaum, 1979; USNS-R/V Vanguard at 8.5°N over the Atlantic)

Example of Inertio-Gravity Waves (2)



Equatorial Pacific rawinsonde obs from res.vessel "Hakuohomaru"

(Ogino et al., 1995)





MU radar (1984)



JMA-WINDAS (2000)

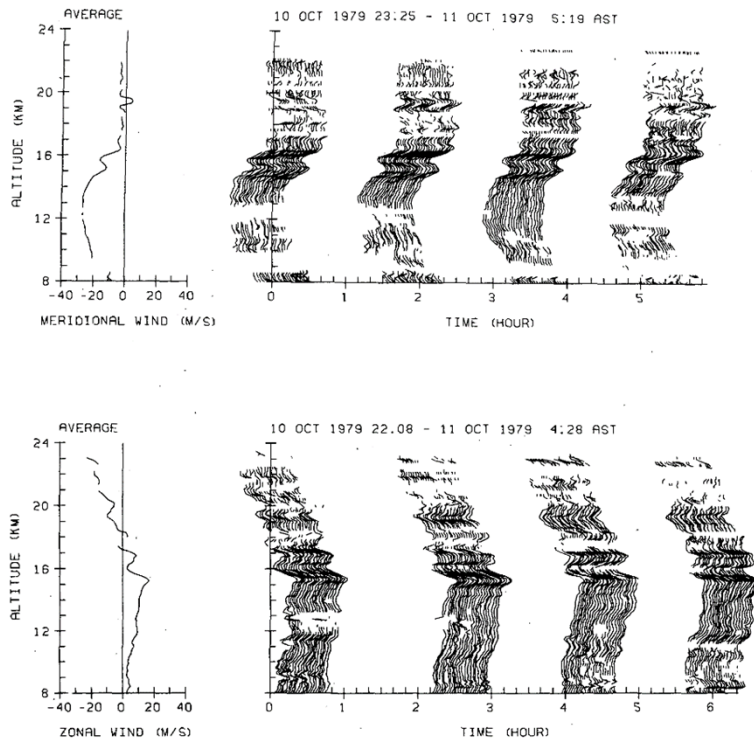
33 stations



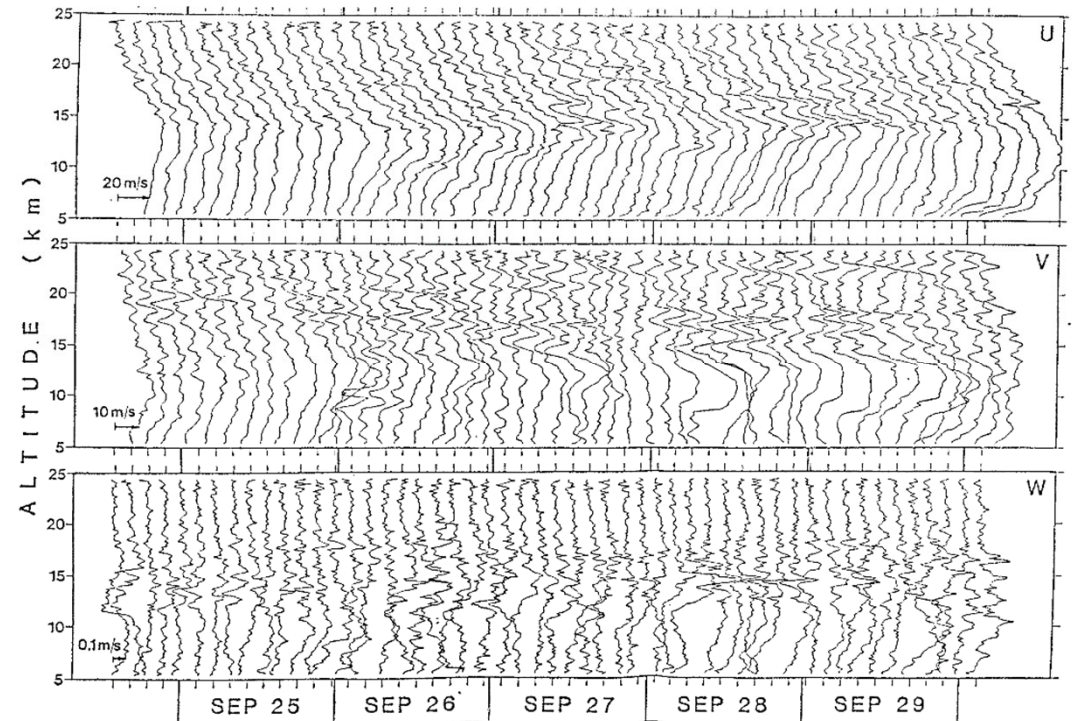
Serpong MWR/BLR (1992); Kototabang BLR (1998) EAR (2001)
(Kyoto U, BPPT, BMKG, LAPAN)

Profilers vs balloons

- High time resolution, continuity ⇔ High vertical resolution, up to stratopause
- Almost vertical sounding ⇔ Possible quasi-Lagrangian sounding
- RASS T_v , turbulence parameters ⇔ Direct p , T , q ; instrumental gondoras
- Almost unmanned operation ⇔ Low cost, transportable

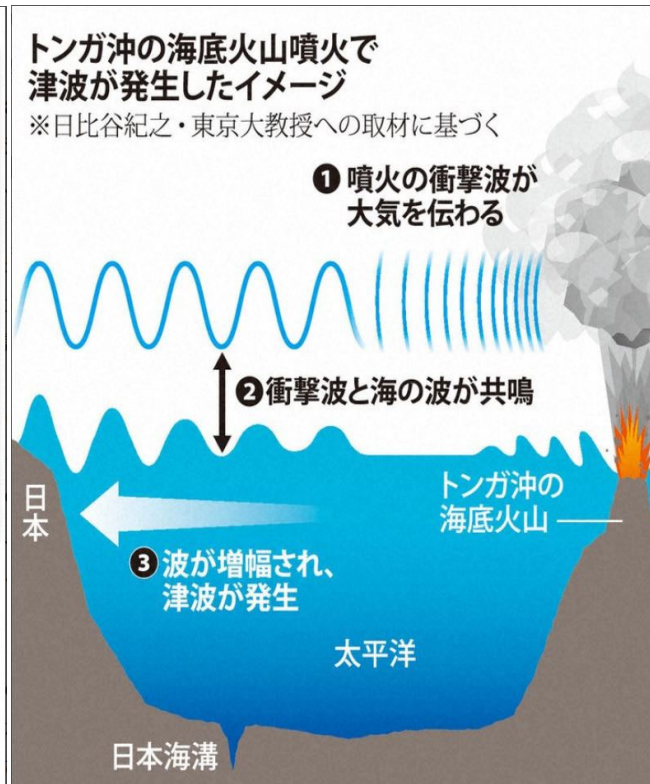
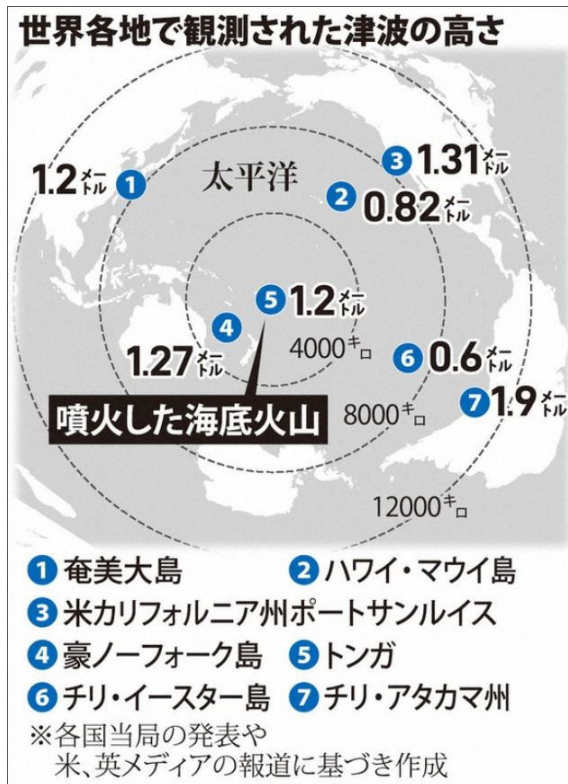


(First gravity wave observations with a UHF (430 MHz) radar at Arecibo, Puerto Rico (18.3°N) in 1979, analyzed by Sato & Woodman, 1980)



(First one-week continuous operation of Kyoto University's MU radar (VHF, 46.5 MHz) at Shigaraki, Japan (34.9°N) in 1985 (Yamanaka, 1987), Detailed analysis published finally by Ushimaru & Tanaka, 1990)

2022年1月15日 南太平洋トンガ付近の海底火山噴火による海洋・大気波動



トンガ海底火山噴火（直後の衛星動画）

https://twitter.com/Takki_Sapporo/status/1482381947548897286

トンガ海底火山噴火（朝日新聞）

<https://www.youtube.com/watch?v=bsXO4NXoOGI>

大気中の波（ラム波）の伝播（理化学研究所）

<https://www.yomiuri.co.jp/stream/article/19346/>

他の火山・海底火山噴火動画等（国立情報学研究所）

<http://agora.ex.nii.ac.jp/digital-typhoon/volcano-eruption/>

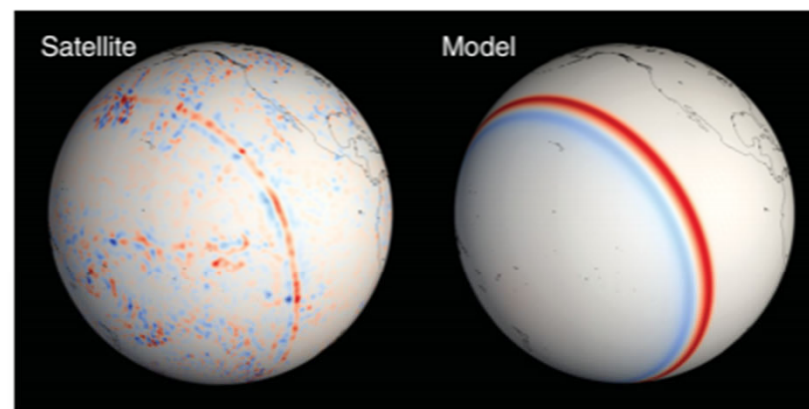


Figure 2.18 The atmospheric acoustic-gravity wave excited by the explosive Tonga eruption January 15, 2022, shown 6 hours after the time of the excitation of the wave. (Left) Infrared imagery in the water vapor channel, highpass filtered in the frequency domain to isolate the fast-moving waves. At these high frequencies the variations in the infrared radiances reveal the temperature perturbations induced by adiabatic compression and expansion as the wave passes. (Right) The corresponding pressure perturbations (the same phase at all levels, but amplifying exponentially with height) in a numerical simulation based on the shallow water wave equations, which will be introduced in Chapter 10. The pressure and temperature perturbations are in phase. The wave is propagating toward the antipodal point with a phase speed of 318 m s^{-1} . Courtesy of Mathew Barlow, simulations provided by Nedjeljka Žagar. The corresponding animations can be viewed on the companion web page.

Rossby Waves (Planetary Waves)

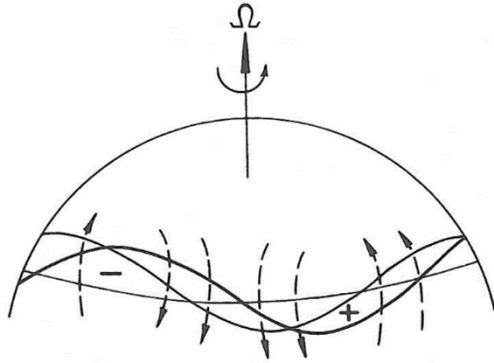


Fig. 7.14 Perturbation vorticity field and induced velocity field (dashed arrows) for a meridionally displaced chain of fluid parcels. Heavy wavy line shows original perturbation position; light line shows westward displacement of the pattern due to advection by the induced velocity.

(Holton's textbook)



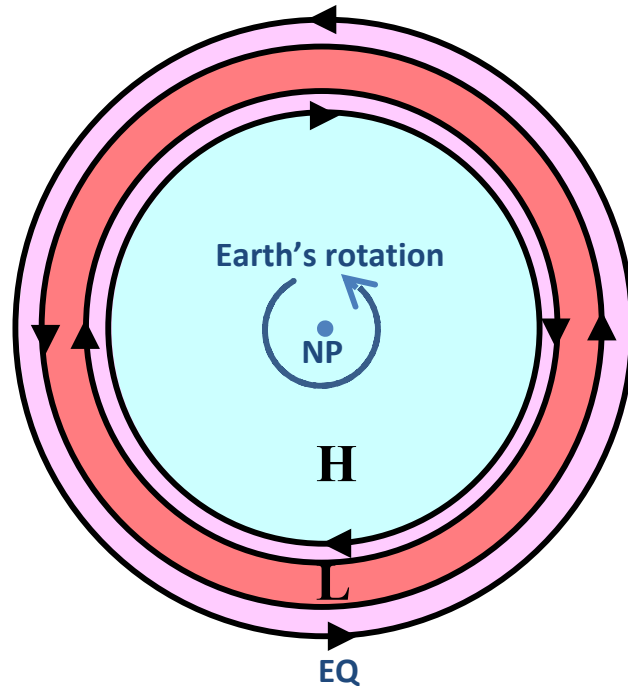
Figure 2 (A) Streamlines (solid) and absolute vorticity, $\bar{\zeta} + f$, averaged at the 300 hPa level in the upper troposphere (figure from Lau NC, *Journal of the Atmospheric Sciences*, 36: 996–1016, 1979). The deviation of the streamlines from circles is a wave pattern analogous to **Figure 1**. If this were simply barotropic Rossby waves, the dashed and full lines would coincide. Continents are shown with dotted curves; North America is at the bottom of the figure.

(Rhines' overview)

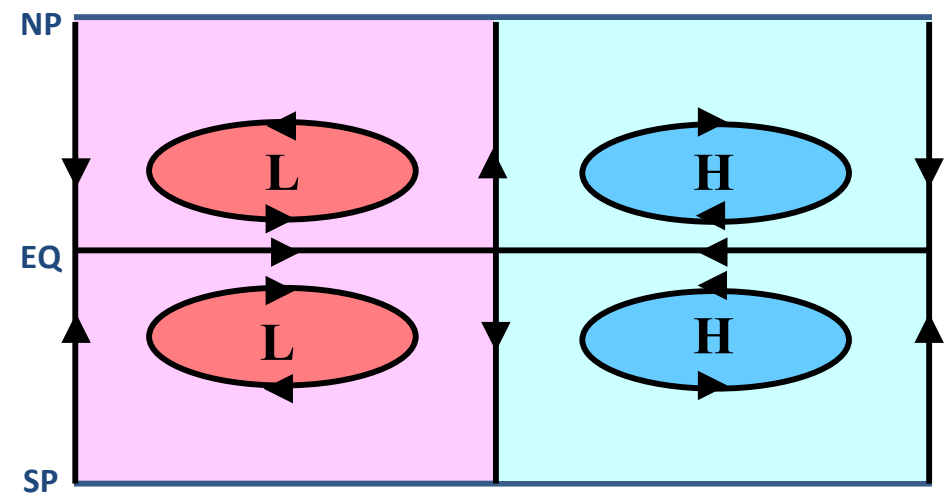
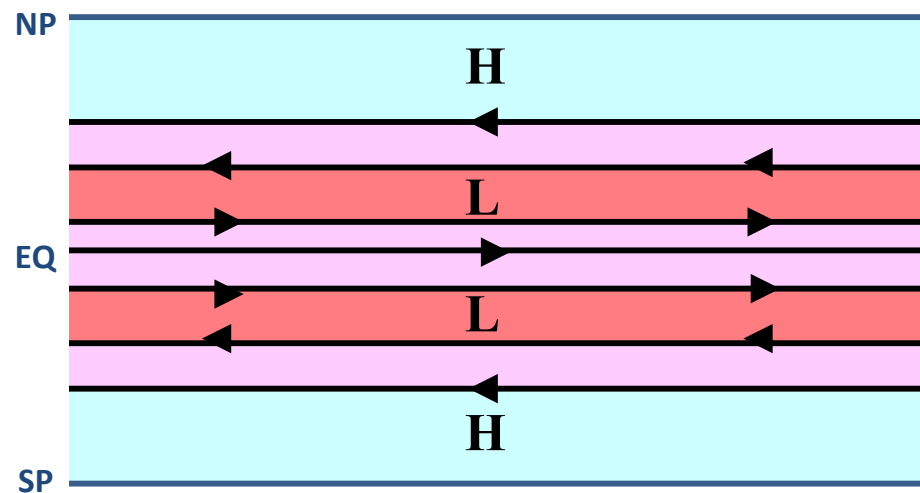
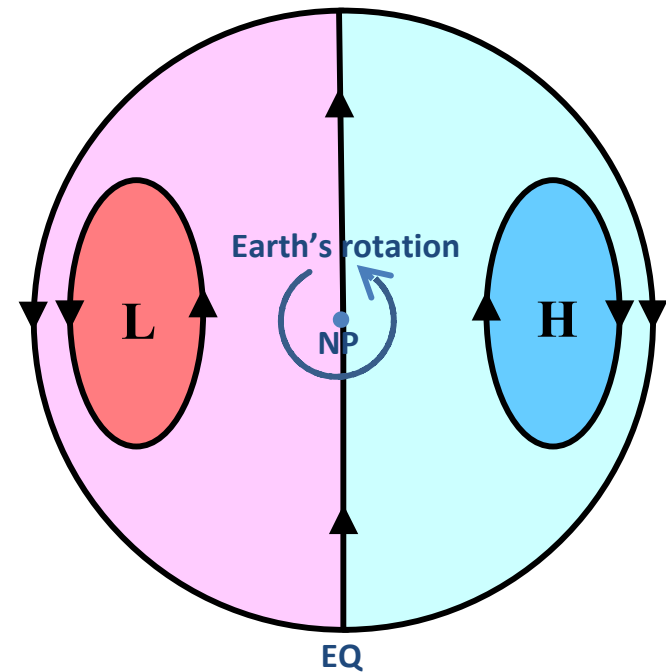
Note: In the mid-latitude troposphere, baroclinic instability (extratropical cyclones) is dominant

Planetary (Rossby) waves (equatorially trapped)

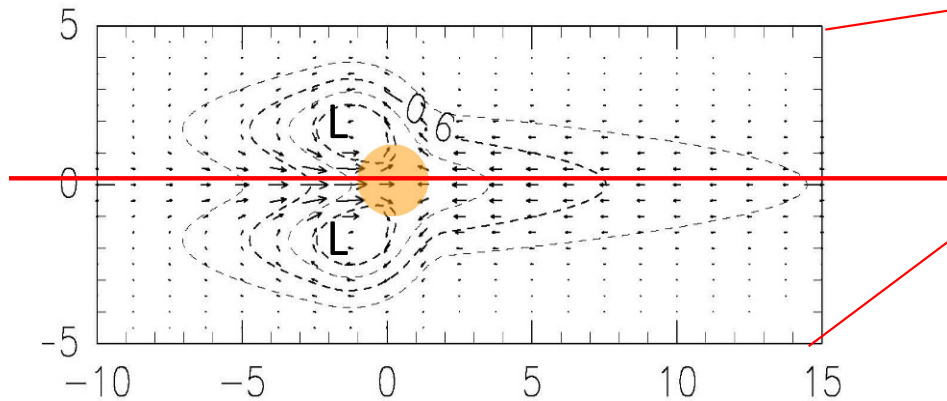
Zonal wavenumber = 0
(stationary)



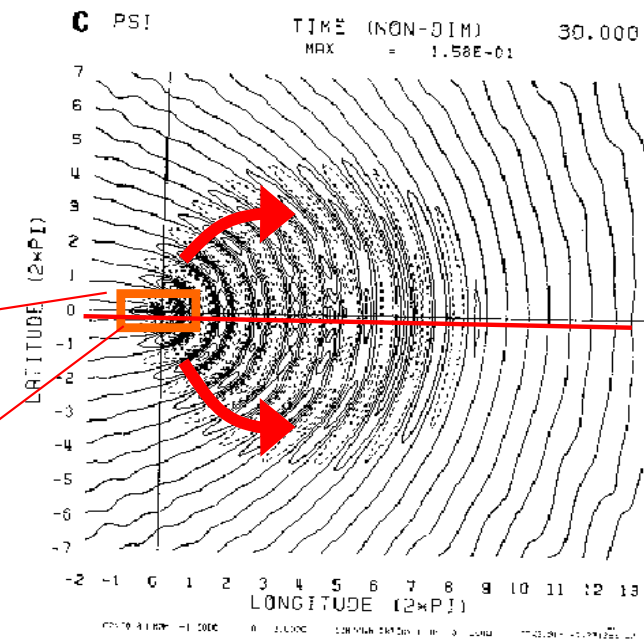
Zonal wavenumber = 1
(westward propagation)



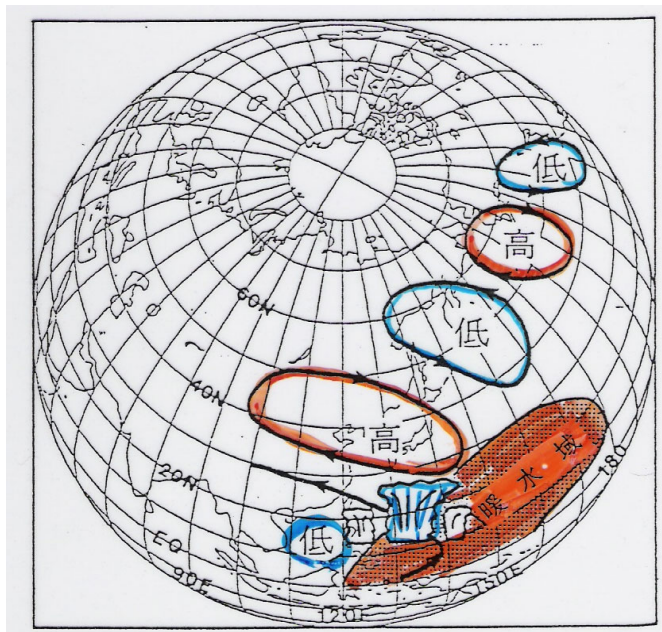
Global abnormal weather due to Rossby wave propagation forced at the equator (“Teleconnection”)



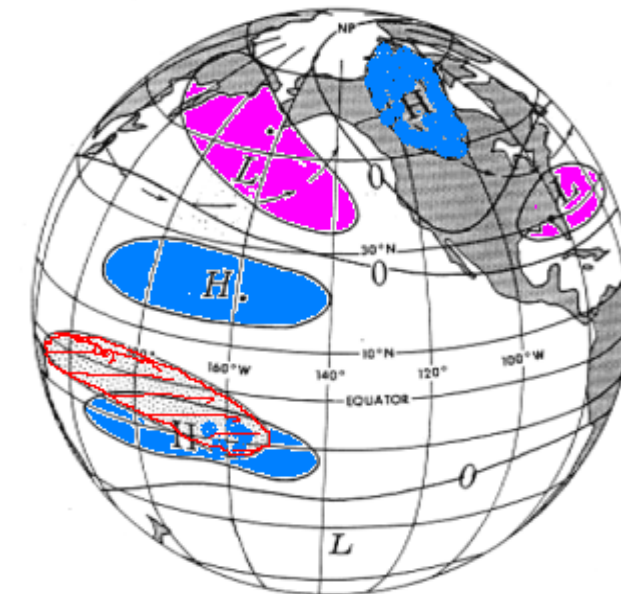
(Gill, 1980)



(Hayashi, 1987)



(Nitta, 1987)



(Wallace, 1981)

Equatorial (Kelvin and Rossby-Gravity) Waves

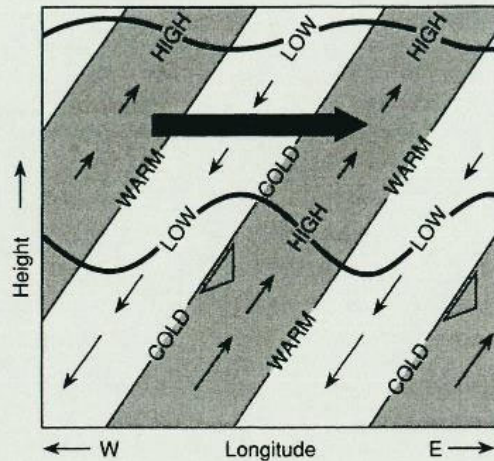


Fig. 12.12 Longitude-height section along the equator showing pressure, temperature, and wind perturbations for a thermally damped Kelvin wave. Heavy wavy lines indicate material lines; short blunt arrows show phase propagation. Areas of high pressure are shaded. Length of the small thin arrows is proportional to the wave amplitude, which decreases with height due to damping. The large shaded arrow indicates the net mean flow acceleration due to the wave stress divergence.

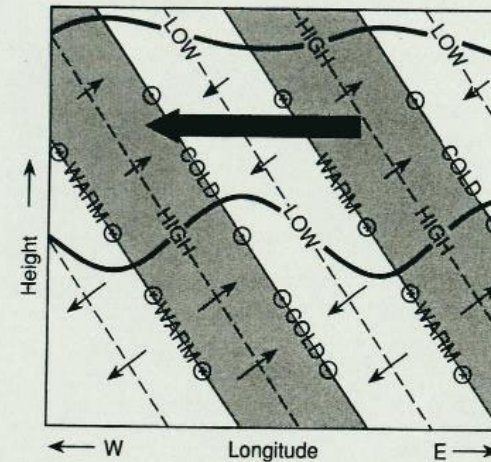


Fig. 12.13 Longitude-height section along a latitude circle north of the equator showing pressure, temperature, and wind perturbations for a thermally damped Rossby-gravity wave. Areas of high pressure are shaded. Small arrows indicate zonal and vertical wind perturbations with length proportional to the wave amplitude. Meridional wind perturbations are shown by arrows pointed into the page (northward) and out of the page (southward). The large shaded arrow indicates the net mean flow acceleration due to the wave stress divergence.

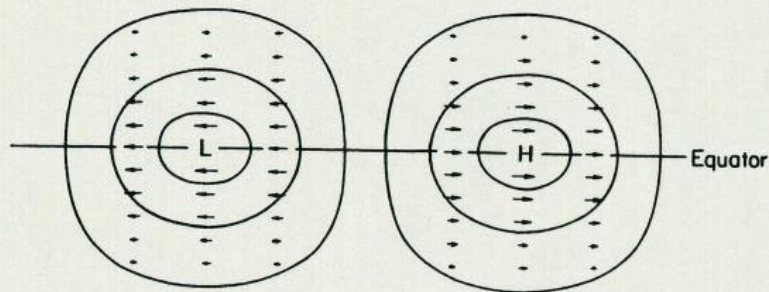


Fig. 11.15 Plan view of horizontal velocity and height perturbations associated with an equatorial Kelvin wave. (Adapted from Matsuno, 1966.)

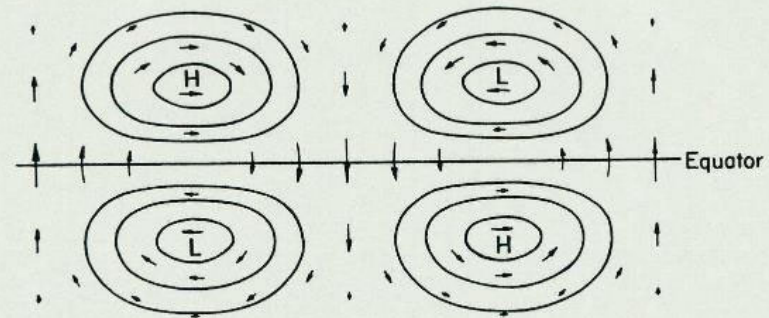
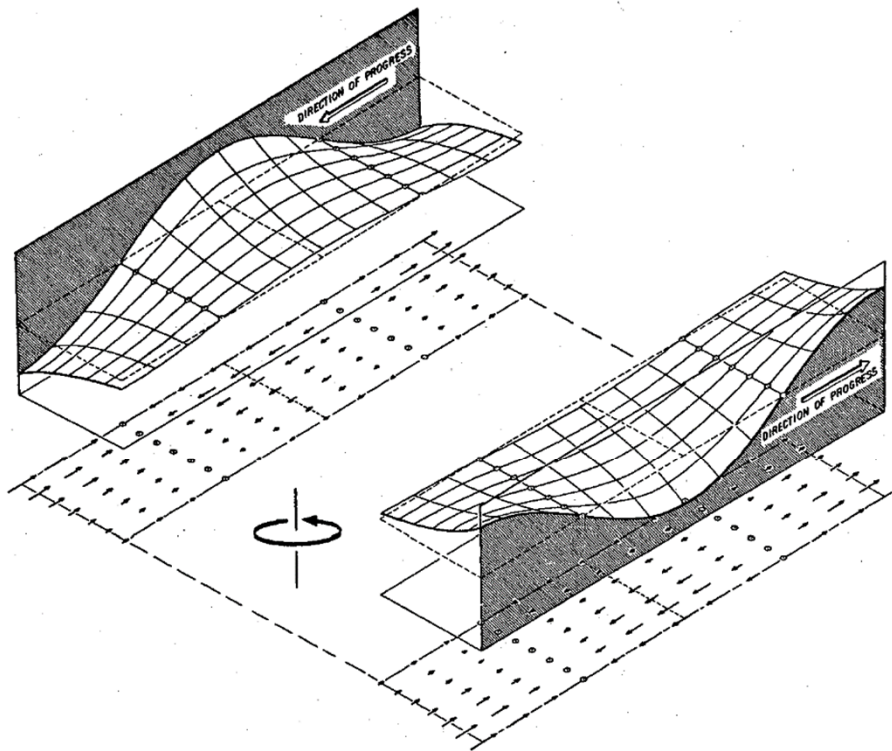


Fig. 11.13 Plan view of horizontal velocity and height perturbations associated with an equatorial Rossby-gravity wave. (Adapted from Matsuno, 1966.)

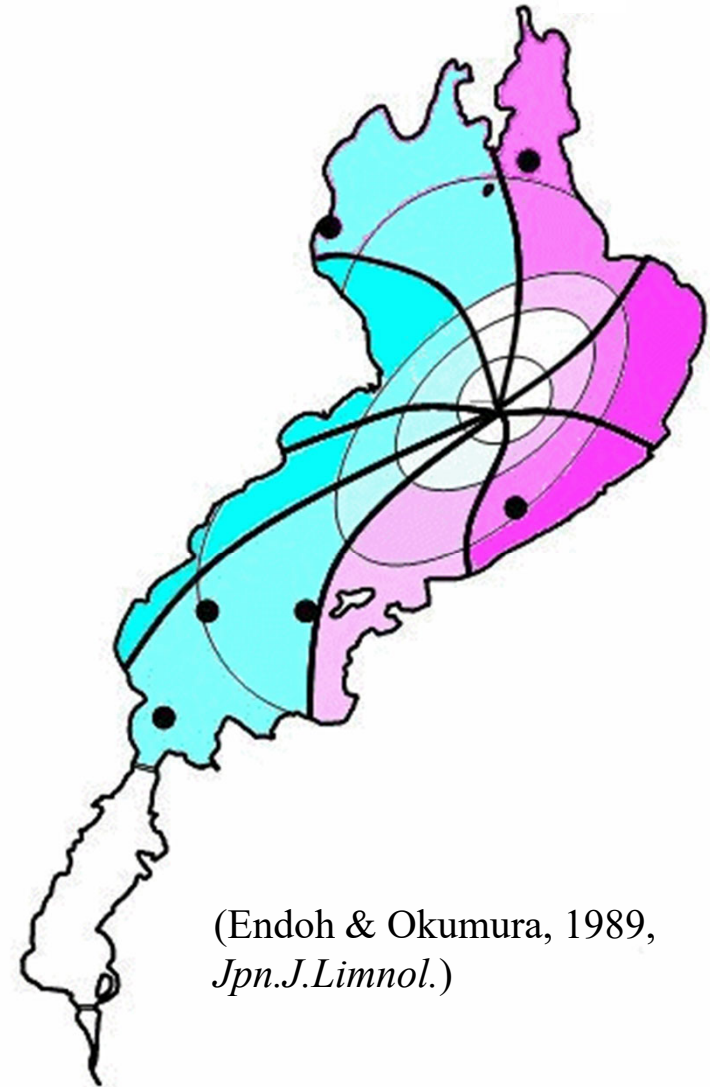
XVI. *On Gravitational Oscillations of Rotating Water.*
By Sir WILLIAM THOMSON.*

THIS is really Laplace's subject in his Dynamical Theory of the Tides; where it is dealt with in its utmost generality except one important restriction—the motion of each particle to be infinitely nearly horizontal, and the velocity to be always equal for all particles in the same vertical. This implies that the greatest depth must be small in comparison with the distance that has to be travelled to find the deviation from levelness of the water-surface altered by a sensible fraction of its maximum amount. In the present short communication I

* From the Proceedings of the Royal Society of Edinburgh, March 17, 1879. Communicated by the Author. (reprinted in *Philos. Mag.*, 1880)



Coastal Kelvin Waves in oceans, lakes and channels



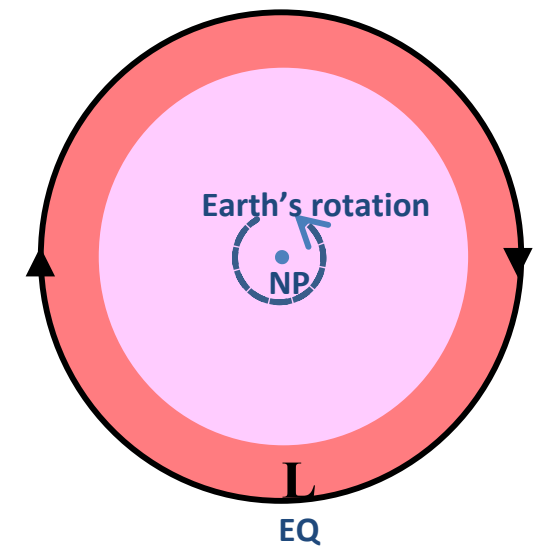
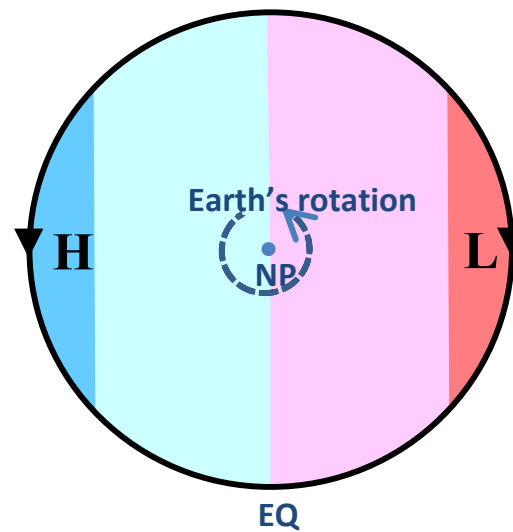
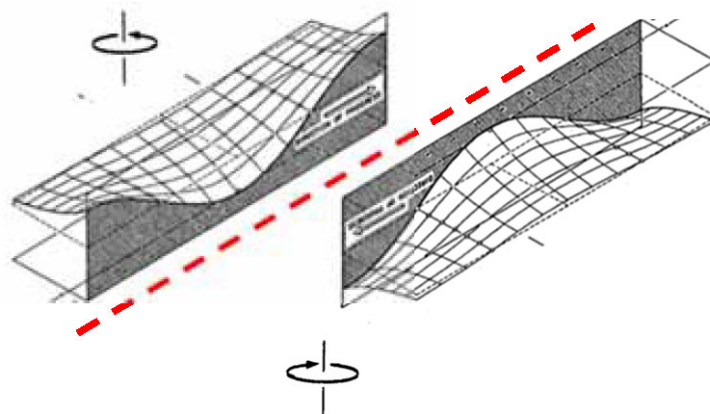
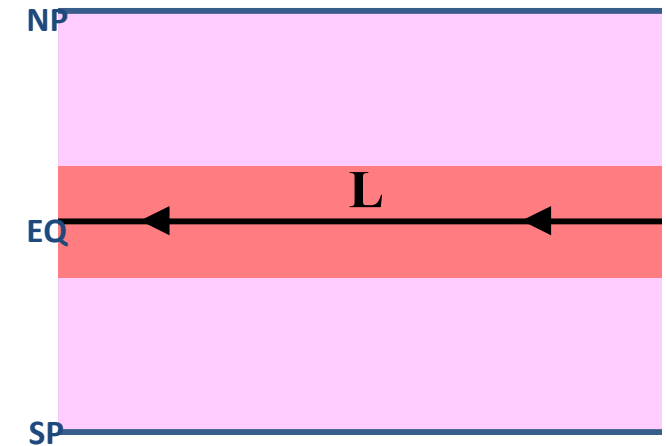
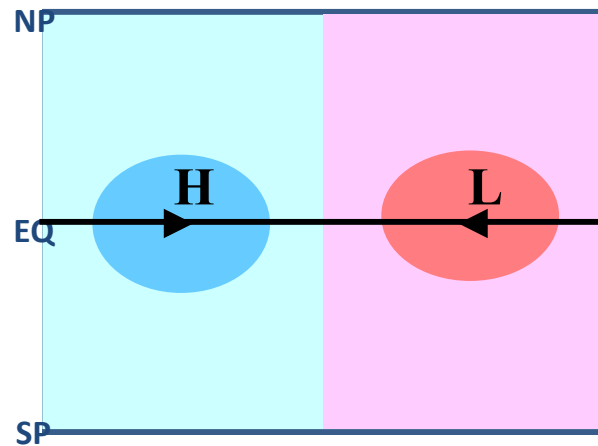
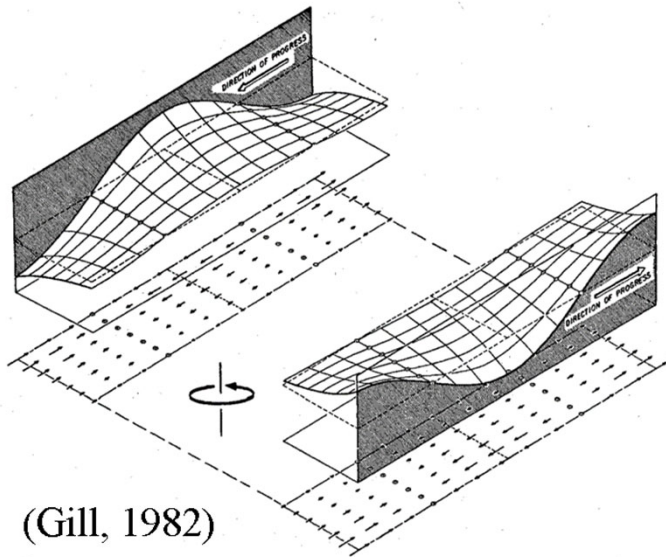
(Endoh & Okumura, 1989,
Jpn.J.Limnol.)

Fig. 10.3. Northern hemisphere Kelvin waves on opposite sides of a channel that is wide compared with the Rossby radius. In each vertical plane parallel to the coast, the currents (shown by arrows) are entirely within the plane and are exactly the same as those for a long gravity wave in a nonrotating channel. However, the surface elevation varies exponentially with distance from the coast in order to give a geostrophic balance. This means Kelvin waves move with the coast on their right in the northern hemisphere and on their left in the southern hemisphere. [From Mortimer (1977).]

Kelvin waves: Coastal & Equatorial

Zonal
wavenumber = 1
(eastward
propagation)

Zonal
wavenumber = 0
(stationary)



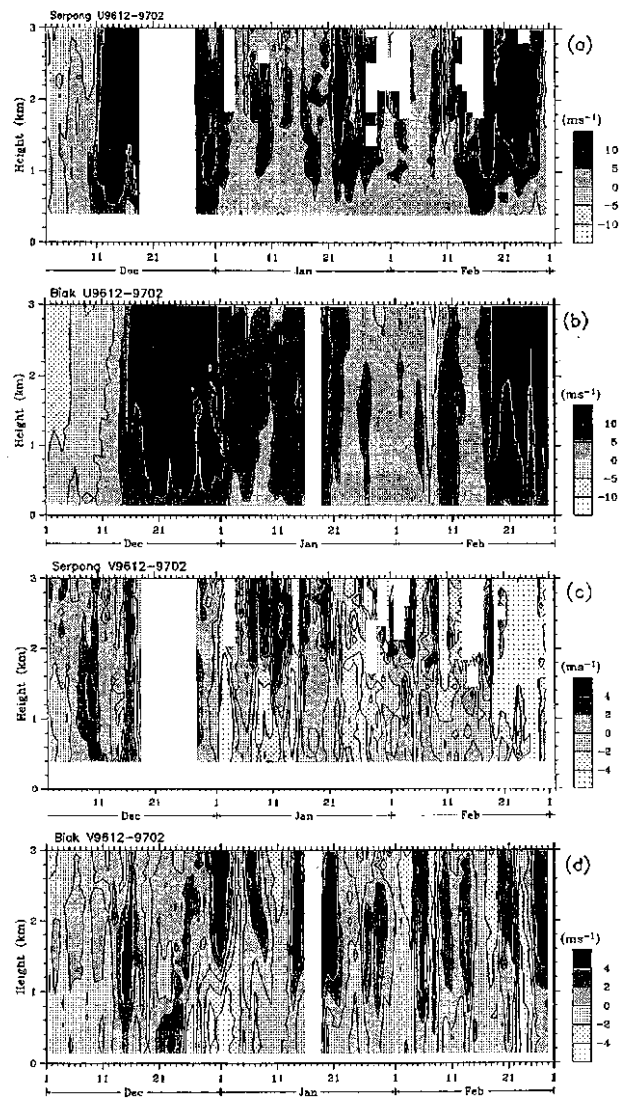


図 1.5: インドネシア東西 2 地点でのプロファイラ高分解能観測による下部対流圏内の西風 (a) (b)・南風 (c) (d) 各成分風速の時間・高度変化。約 3200 km 離れた Serpong (Jakarta 郊外; 6°S, 107°E) (a) (c) および Biak (Papua 島の属島; 1°S, 136°E) (b) (d) における観測結果。Widiyatmi *et al.* (2001) による。

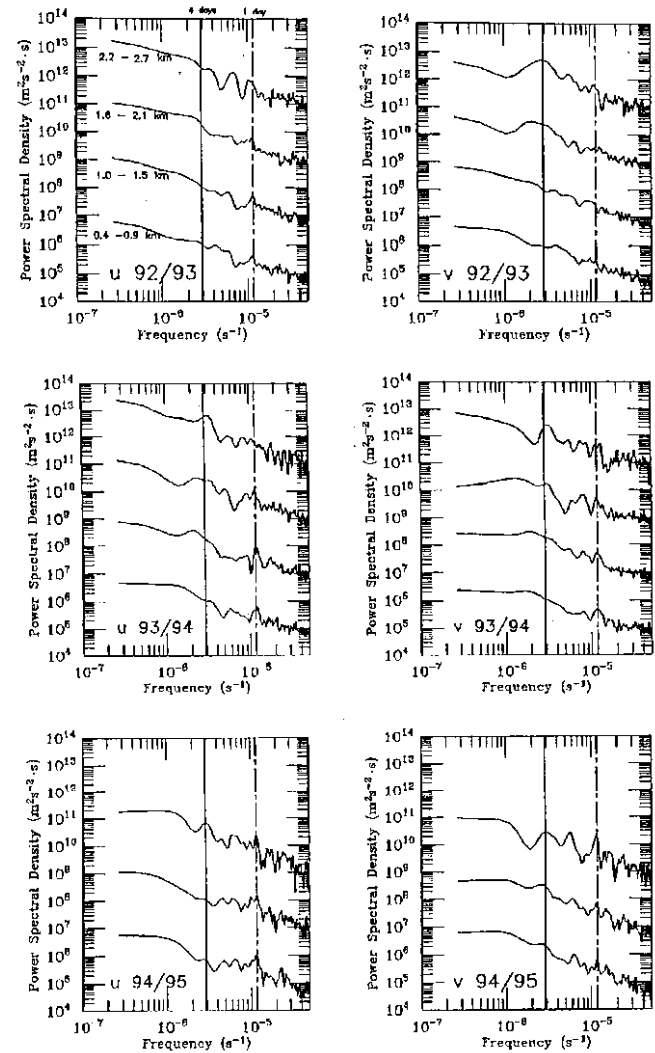


図 1.6: インドネシアの雨季における風速変動の周波数スペクトル。Serpong (6°S, 107°E) における 1992 ~ 93 (上), 93 ~ 94 (中), 94 ~ 95 (下) の 11 ~ 2 月のプロファイラ観測による西風 (左)・南風 (右) 各成分風速データから作成。各図の 4 本の曲線は 0.4 ~ 0.9, 1.0 ~ 1.5, 1.6 ~ 2.1, 2.2 ~ 2.7 km の各高度領域 (100 m ごとの結果を 6 個ずつ平均) における結果を、後 3 者はそれぞれ 10^2 , 10^4 , 10^6 倍したもの。縦直線は 4 日 (実線) および 1 日 (点線) 周期を示す。Widiyatmi *et al.* (1999) による。



Carl-Gustaf Arvid Rossby
(1898 – 1957)

(http://sok.riksarkivet.se/sbl/bilder/6953_7_030_00000575_0.jpg)



Michio Yanai (柳井迪雄)
(1934 – 2010)

(<http://web.atmos.ucla.edu/~yanai/>)

Equatorial Forcing and Atmospheric Response

- Stationary modes (**Kelvin+Rossby**)
 - Zonally uniform ($k=0$ or Zonal mean)
 - Symmetric $\Rightarrow$ zonal **Hadley cells (ITCZ)**
 - Anti-symmetric $\Rightarrow$ “**Monsoon**”
 - Cyclic/isolated
 - $\Rightarrow$ Zonal (Walker) circulations
 - (**Matsuno-Gill patterns**)
 - Teleconnections
 - Rossby-wave propagation
- Traveling modes (**Kelvin+Rossby**)
 - Eastward along equator (Kelvin)
 - $\Rightarrow$ **IntraSeasonal variations**
 - (Madden-Julian Oscillation, etc.)
- Regional/Local modes (**gravity waves**)
 - $\Rightarrow$ Sea-Land (Mountain-Valley) breeze circulations

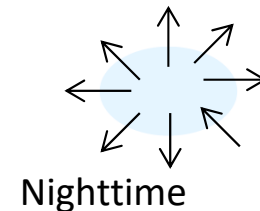
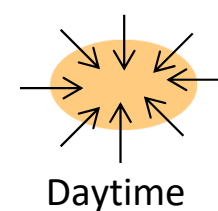
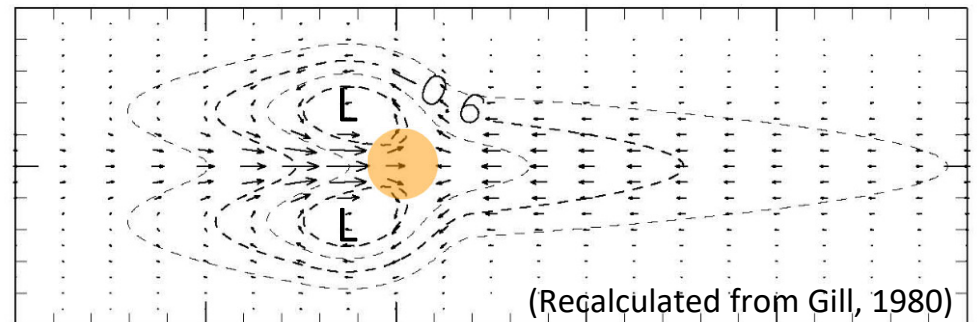
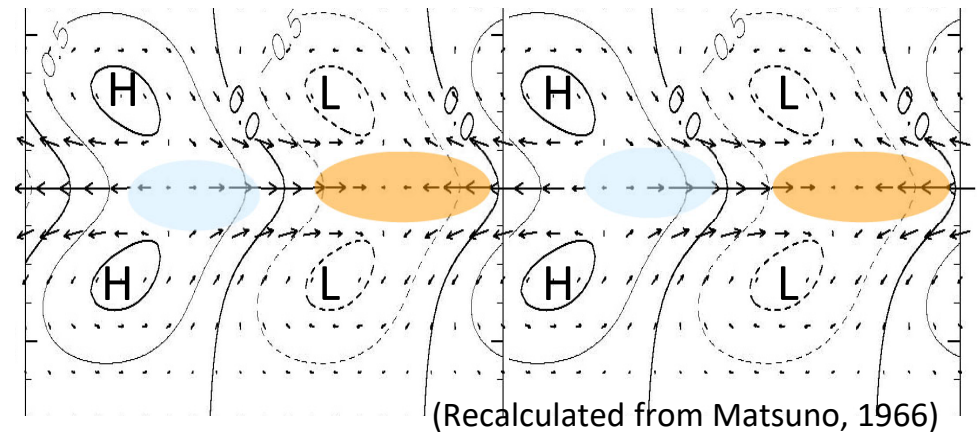
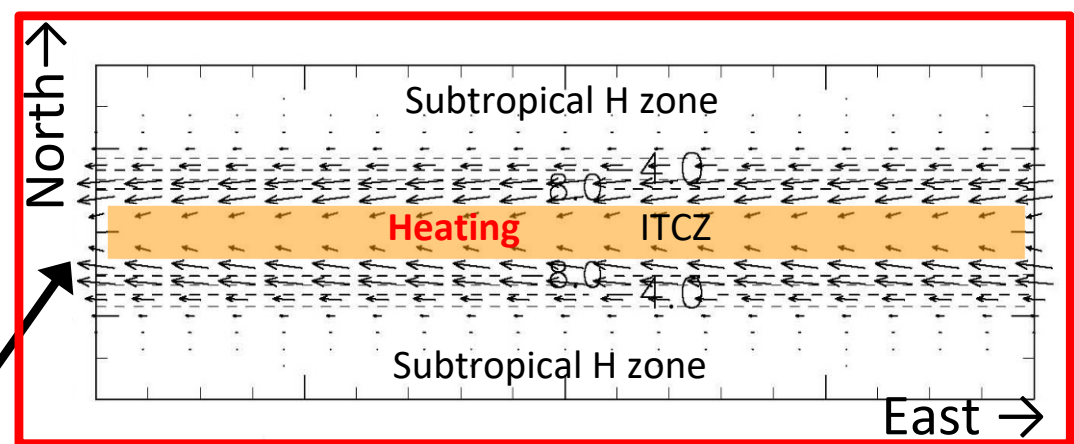
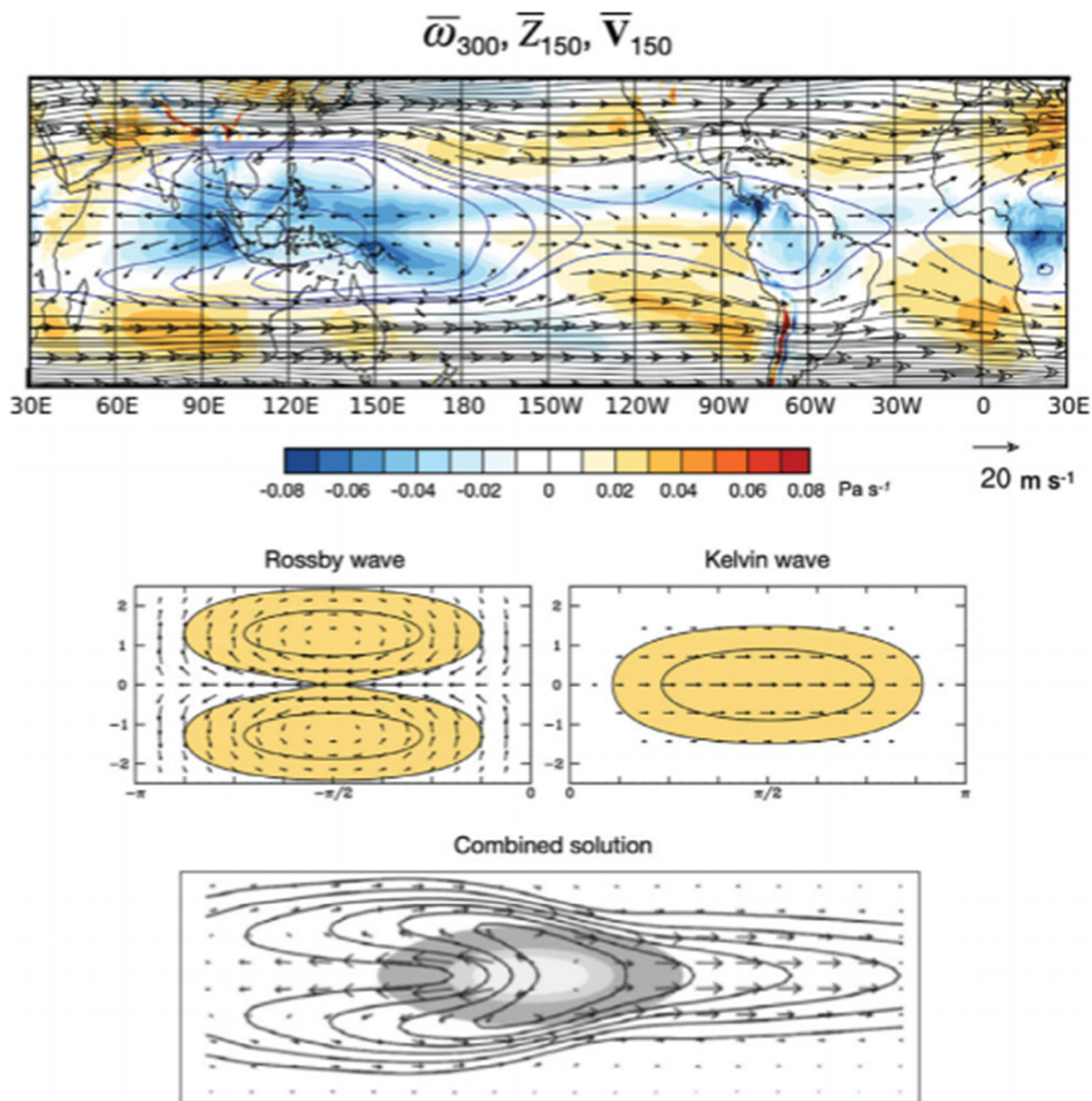
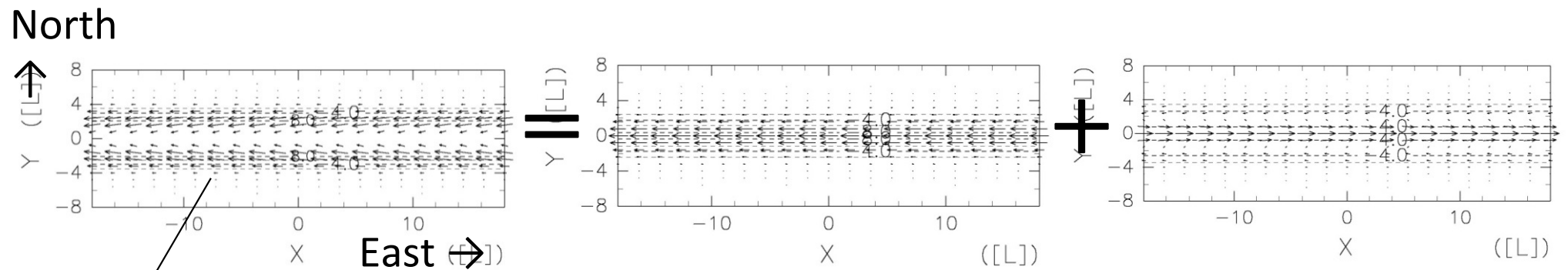
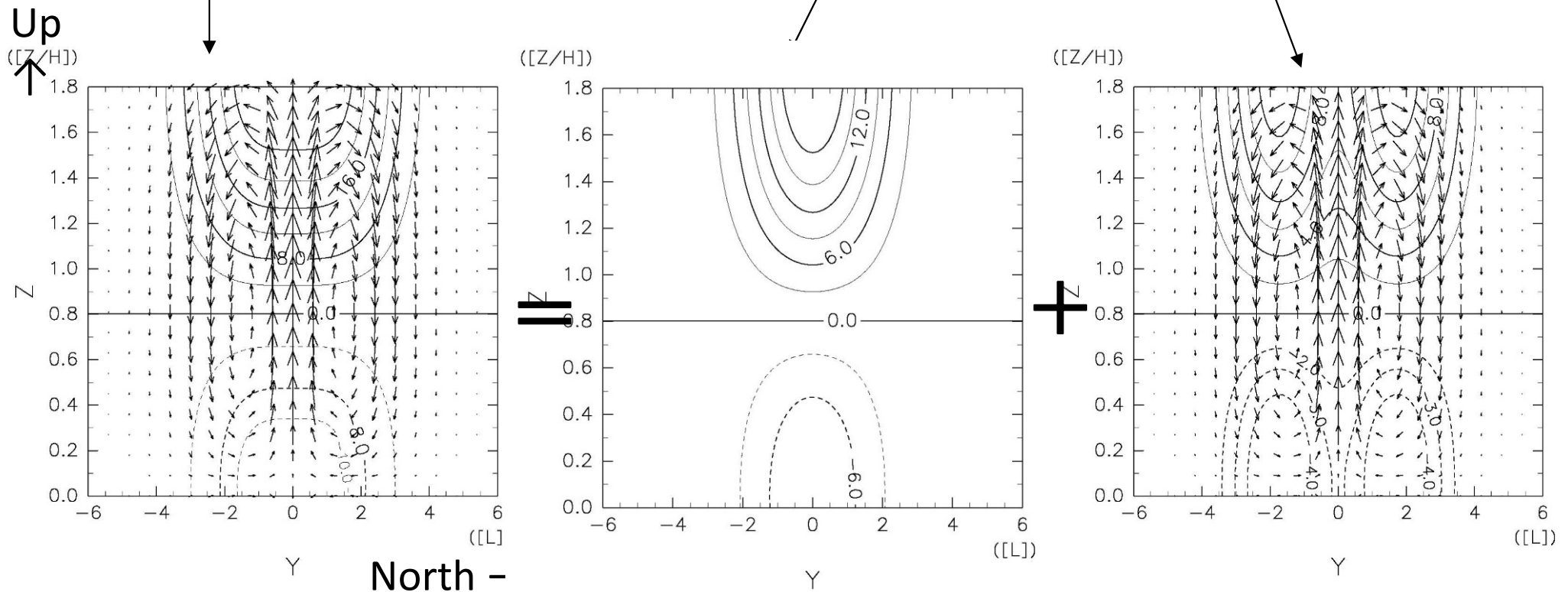


Figure 14.4 (Top) Annual mean vertical velocity ω at the 300 hPa level (colored shading), superimposed on 150 hPa wind vectors (scale at bottom right) and geopotential height (contour interval 100 m for the black contours and 20 m for the blue contours; the lowest of the blue contours corresponds to 14 200 m). (Middle panels) Geopotential and horizontal wind extending over a half cycle in (left) the equatorially trapped $n = 1$ Rossby wave and (right) the $n = -1$ Kelvin wave. (Bottom) The Gill (1980) solution for the response to an isolated heat source located on the equator, indicated by the shading, which consists of a superposition of the wave solutions, with a Rossby wave to the west of the heat source and a Kelvin wave to the east of it.



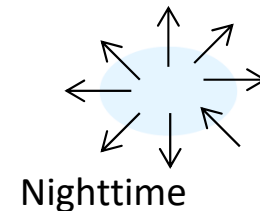
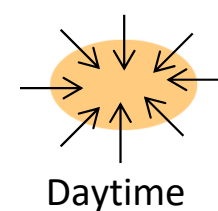
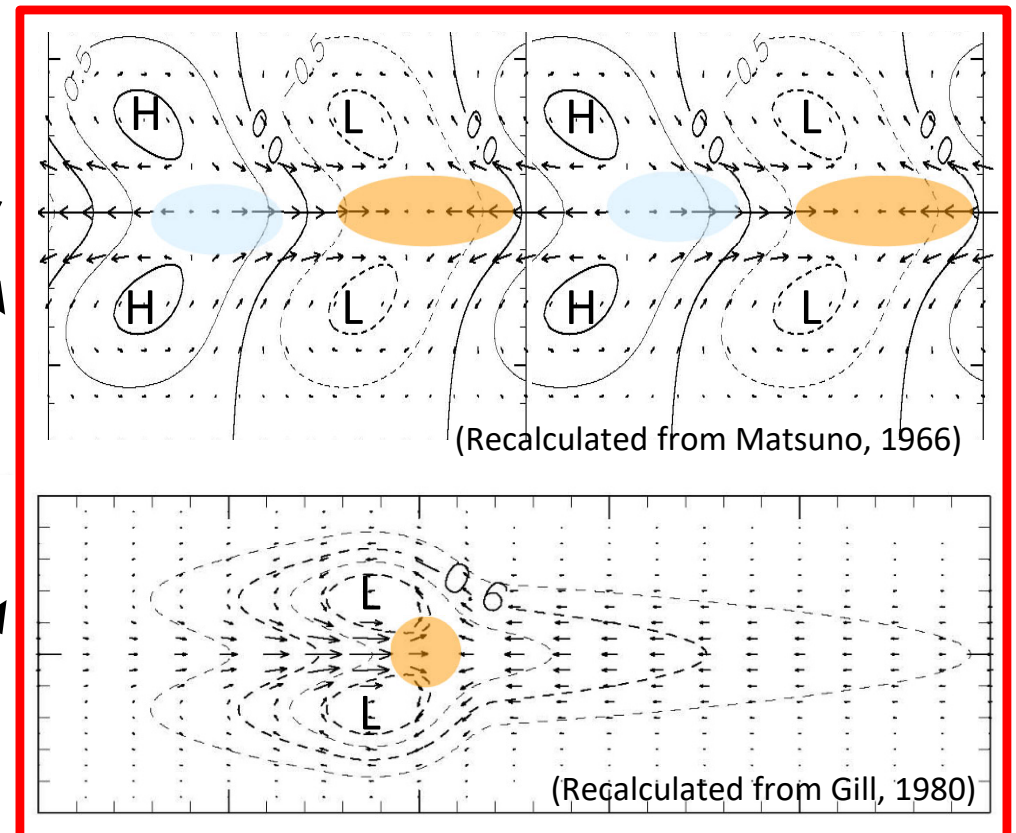
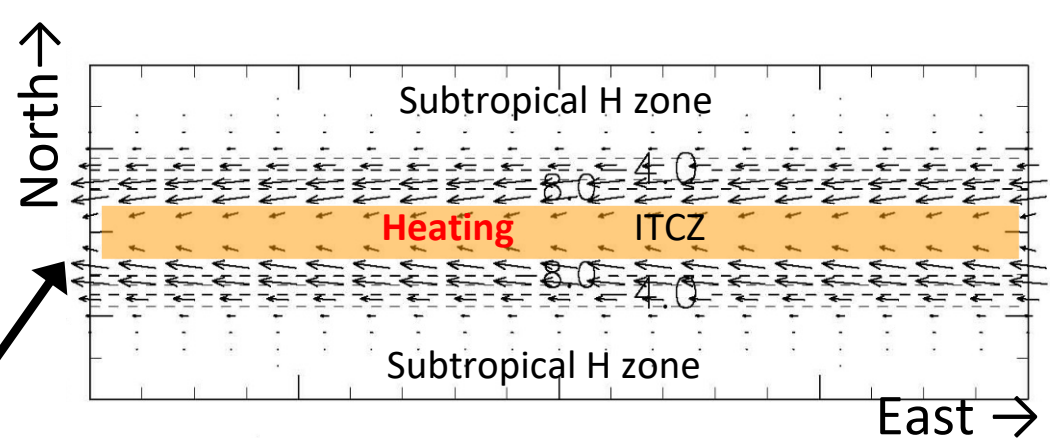
Hadley cell by zero-zwn Kelvin and Rossby waves



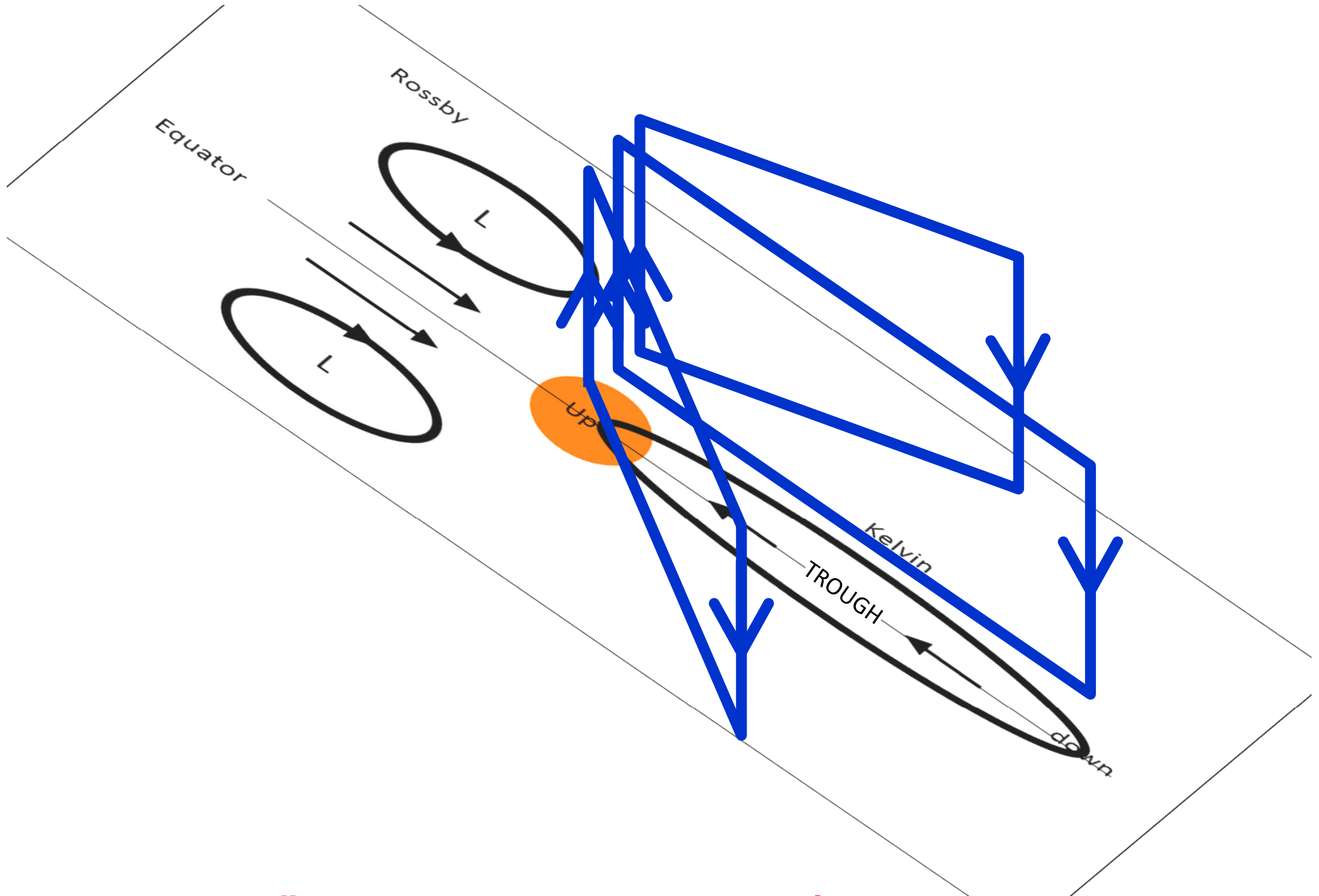
Trade wind zones are separated in the both sides of ITCZ.

Equatorial Forcing and Atmospheric Response

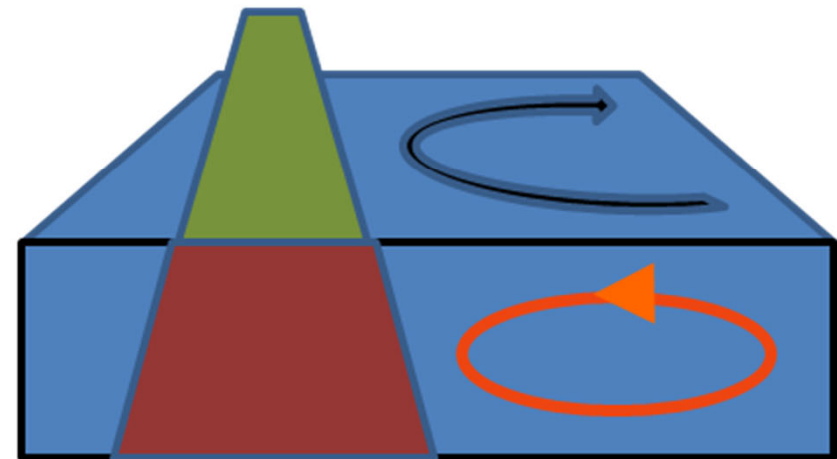
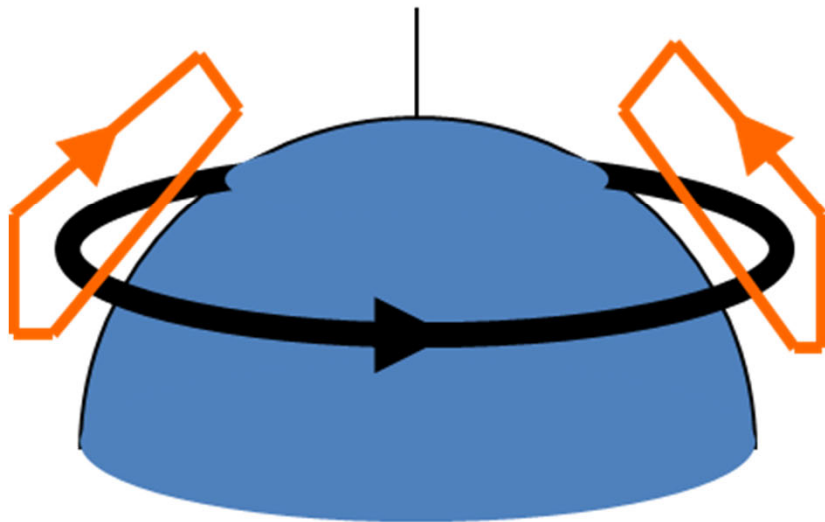
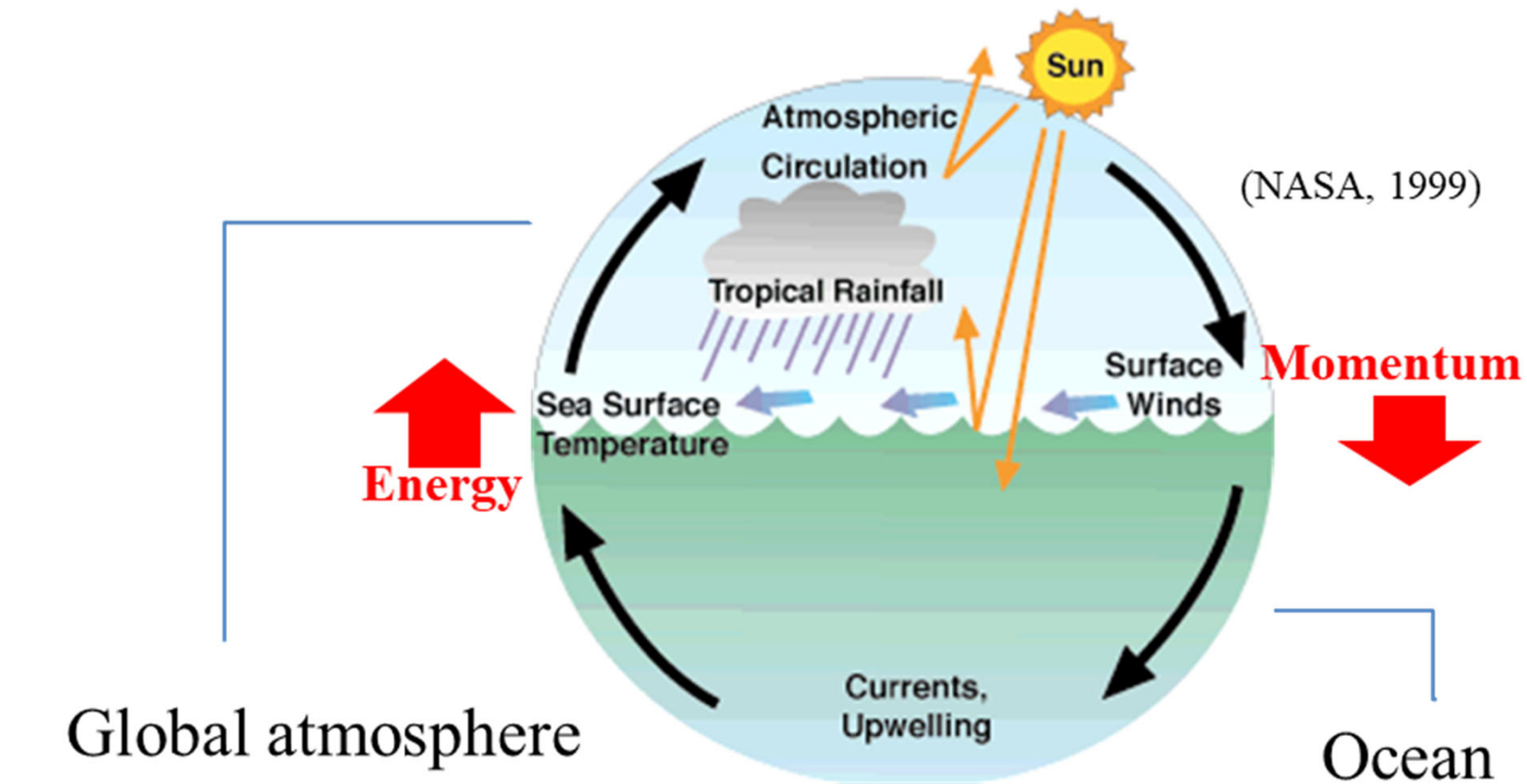
- Stationary modes (**Kelvin+Rossby**)
 - Zonally uniform ($k=0$ or Zonal mean)
 - Symmetric $\Rightarrow$ zonal **Hadley cells (ITCZ)**
 - Anti-symmetric $\Rightarrow$ **"Monsoon"**
 - Cyclic/isolated
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 - Teleconnections
 - Rossby-wave propagation
- Traveling modes (**Kelvin+Rossby**)
 - Eastward along equator (Kelvin)
 - $\Rightarrow$ **IntraSeasonal variations**
 - (Madden-Julian Oscillation, etc.)
- Regional/Local modes (**gravity waves**)
 - $\Rightarrow$ Sea-Land (Mountain-Valley) breeze circulations



Matsuno-Gill pattern and Hadley-Walker circulations

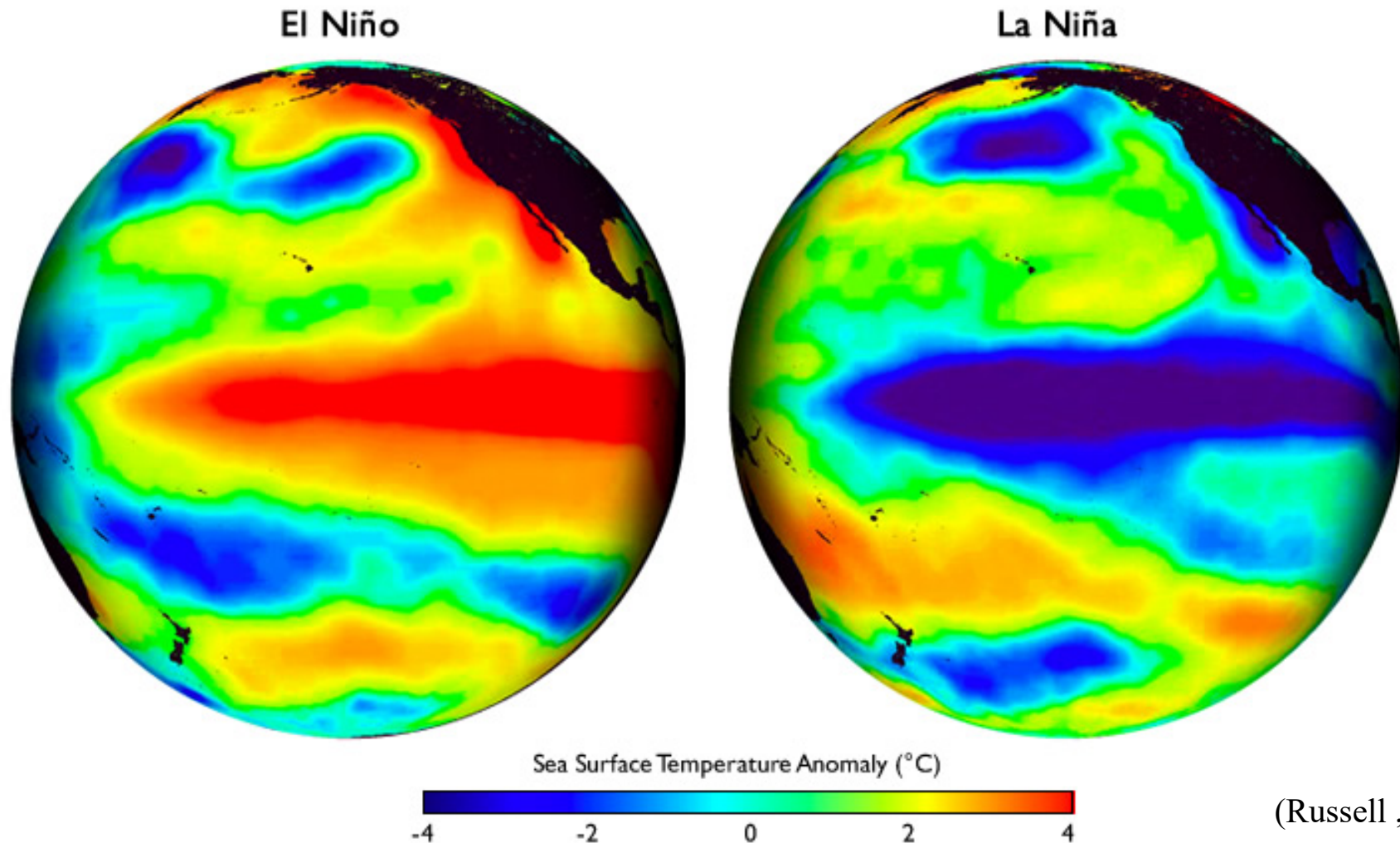


5.3. Atmosphere-ocean interaction and El Niño-southern oscillation (ENSO)



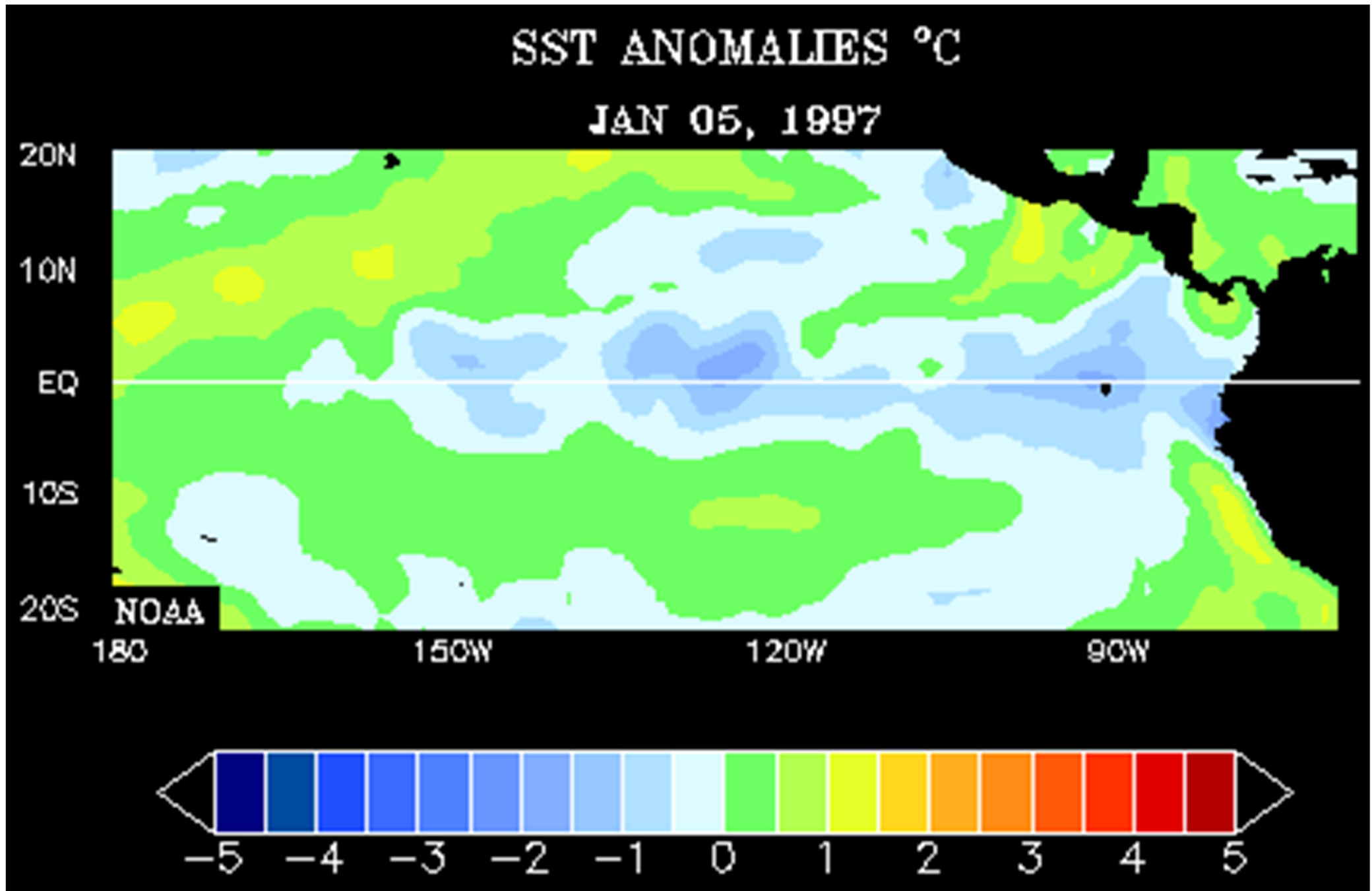
Atmosphere-ocean interaction and El Niño-southern oscillation (ENSO)

- South-American fishermen: Bad fishery in Christmas season → El Niño
- Walker (1920s) : Interannual pressure/monsoon variation → Southern oscillation
- Oceanographers, ichthyologists: Water temperature warming → plankton extinction
- Bjerknes (1969) : Atmosphere-ocean interaction → El Niño-southern oscillation (ENSO)
- Convection center/warm water shift: 1/4 equatorial circle (IMC → central Pacific)

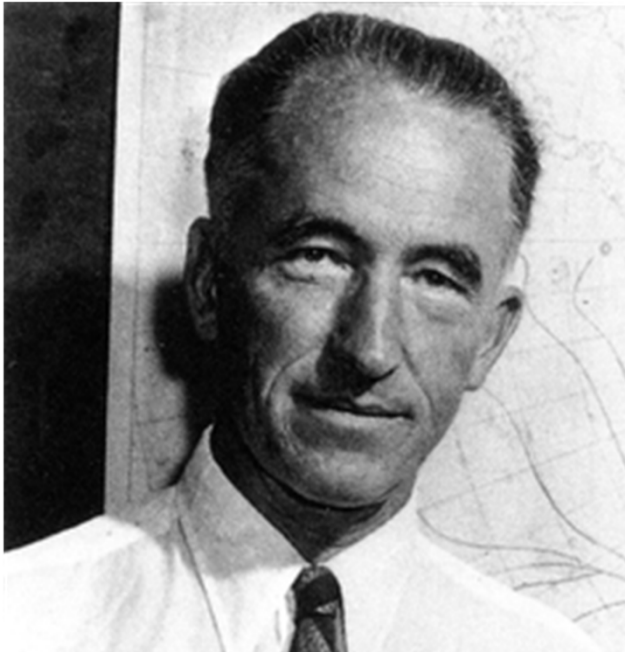


(Russell , 2004)

Strongest (1997–98) El Niño so far observed



Jacob Aall Bonnevie Bjerknes (1897 – 1975)



(http://docs.lib.noaa.gov/rescue/Bibliographies/Bjerknes/Bjerknes_July_2004.htm)

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VOLUME 87 NUMBER 2

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MARCH 1969

UDC 551.513:551.509.338:551.465.6(265)(267)

ATMOSPHERIC TELECONNECTIONS FROM THE EQUATORIAL PACIFIC¹

J. BJERKNES

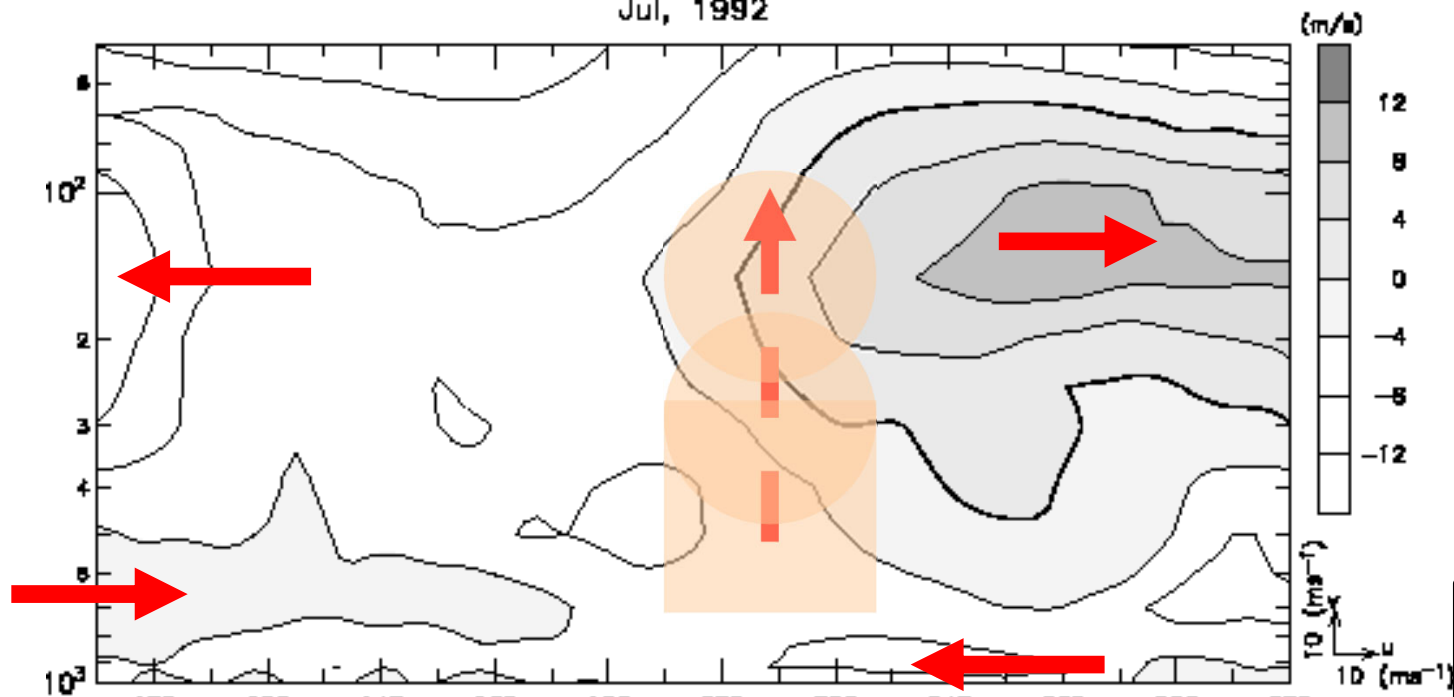
Department of Meteorology, University of California, Los Angeles, Calif.

ABSTRACT

The “high index” response of the northeast Pacific westerlies to big positive anomalies of equatorial sea temperature, observed in the winter of 1957–58, has been found to repeat during the major equatorial sea temperature maxima in the winters of 1963–64 and 1965–66. The 1963 positive temperature anomaly started early enough to exert the analogous effect on the atmosphere of the south Indian Ocean during its winter season.

The maxima of the sea temperature in the eastern and central equatorial Pacific occur as a result of anomalous weakening of the trade winds of the Southern Hemisphere with inherent weakening of the equatorial upwelling. These anomalies are shown to be closely tied to the “Southern Oscillation” of Sir Gilbert Walker.

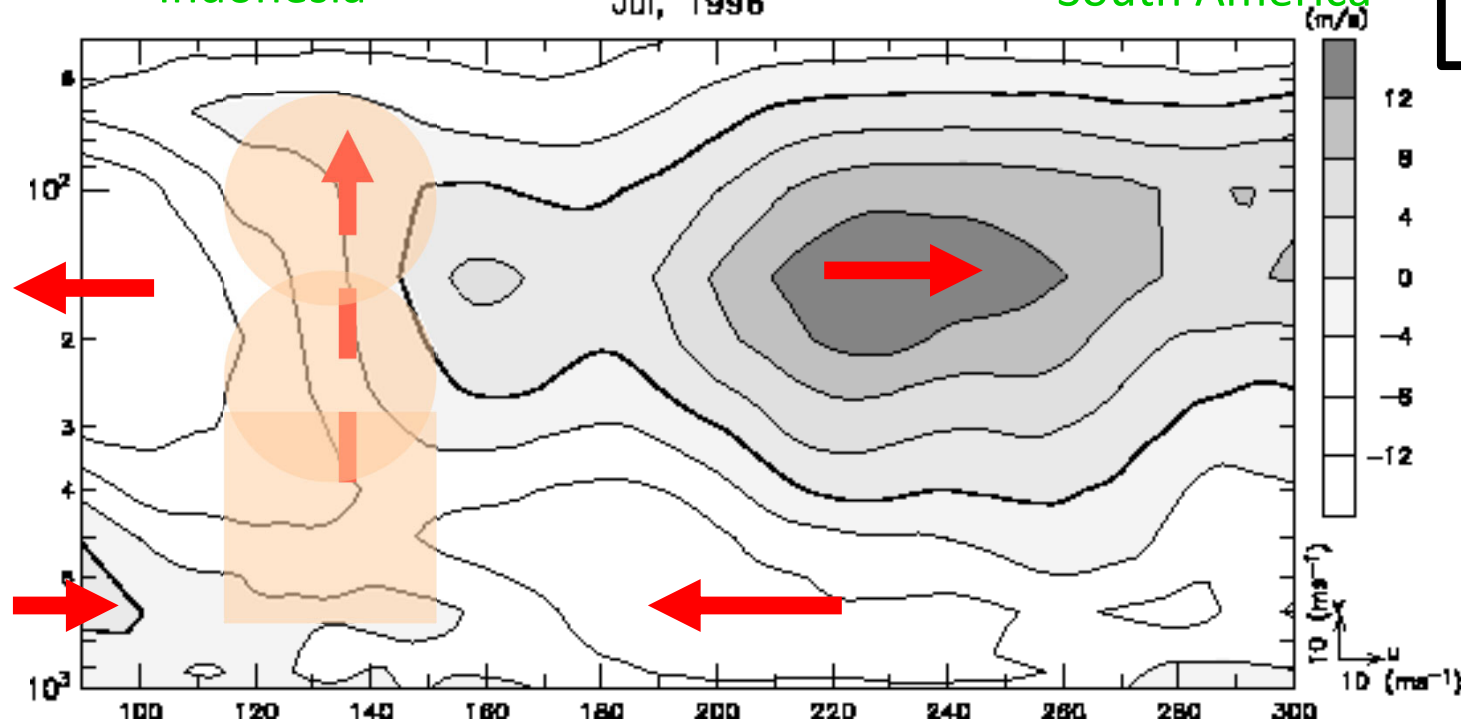
Jul, 1992



Indonesia

South America

Jul, 1996



El Nino

Interannual Variation
of Walker Circulation

La Nina

Note:
Based on NCEP reanalysis with
almost **no Indonesian data**.

Oceanic wave propagation and ENSO

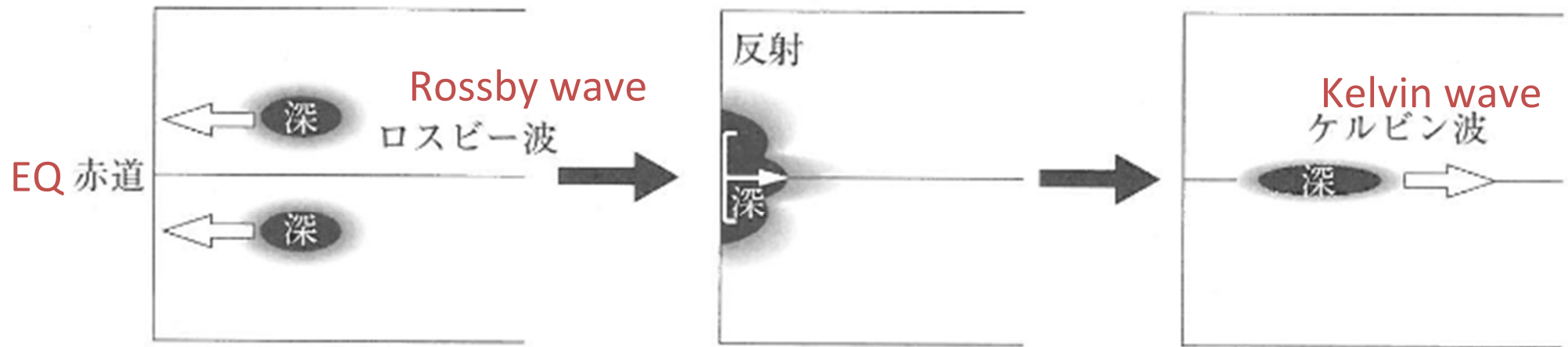
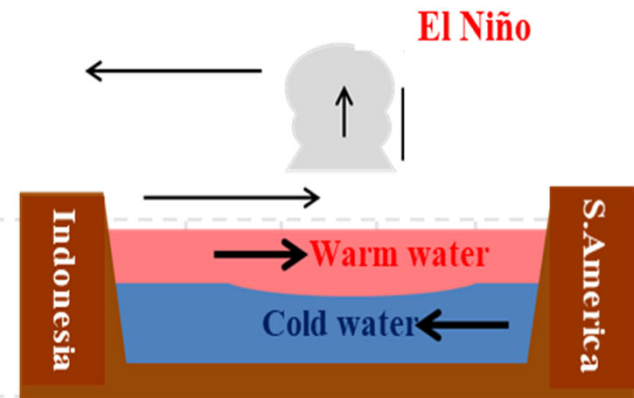
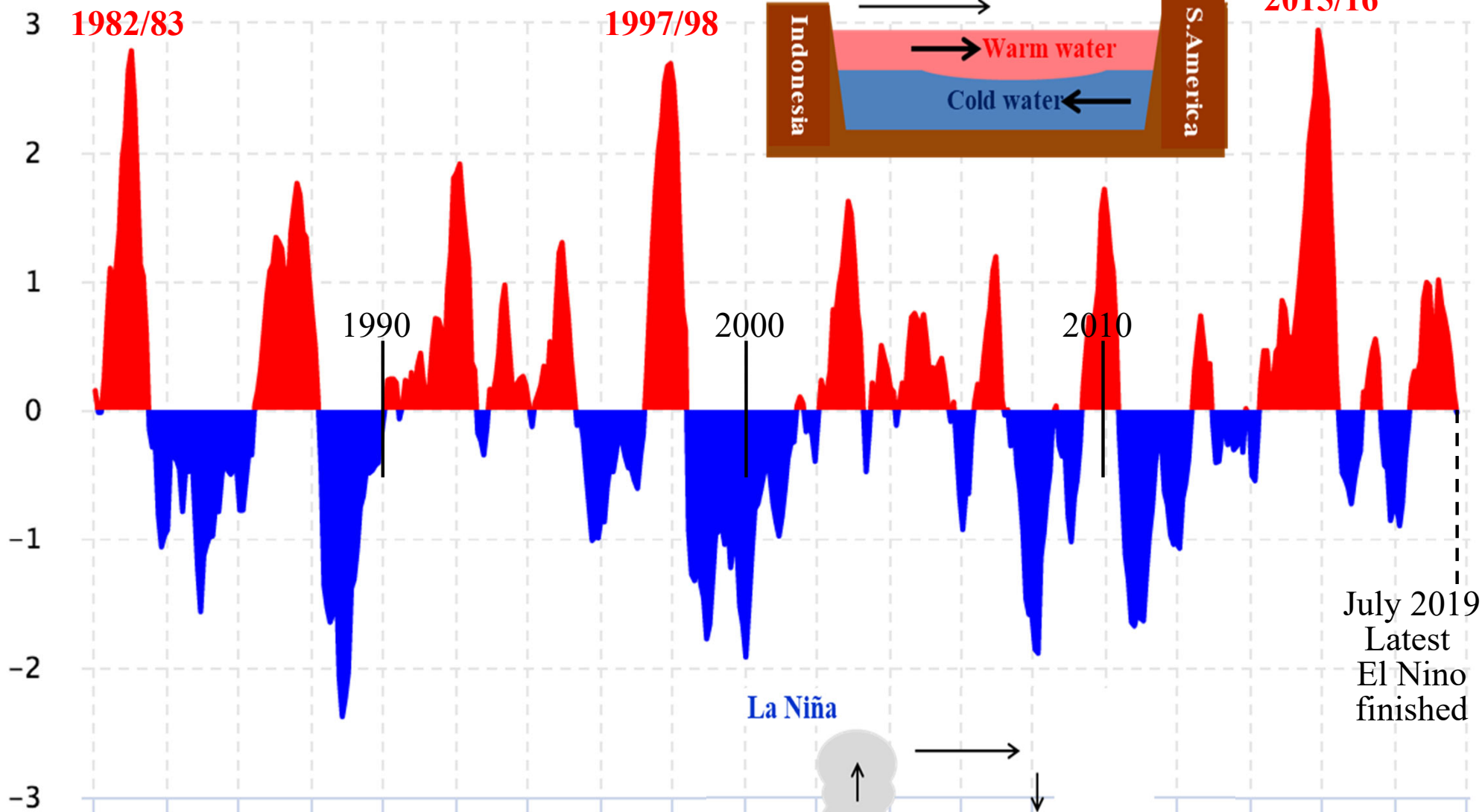
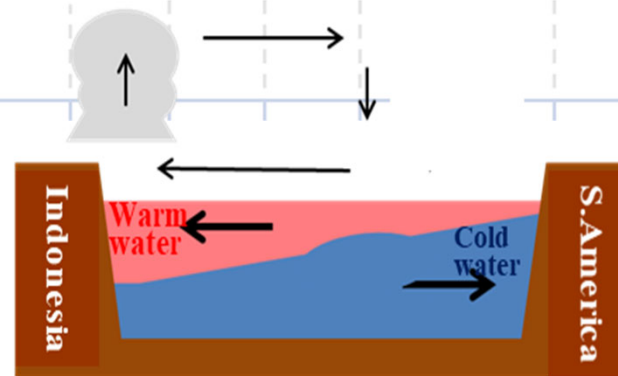


図 14-7 遅延振動子による ENSO のメカニズムの考察 (木村・新野, 2010)^{2) 4)}

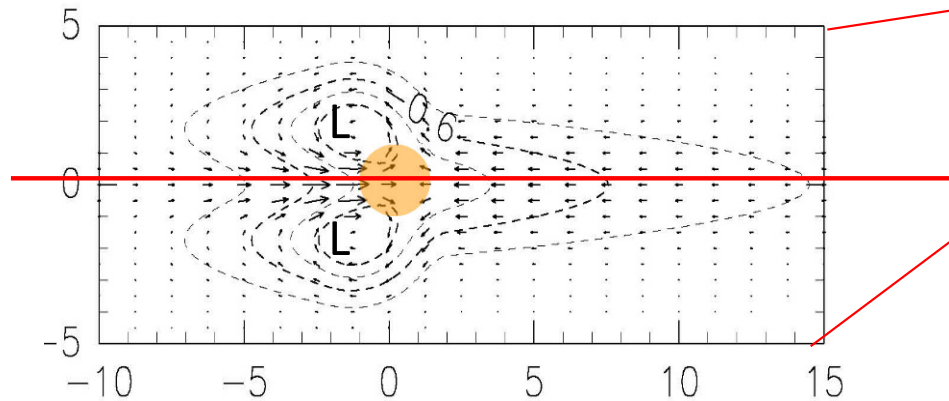
Sea surface temperature anomaly of eastern equatorial pacific (°C)



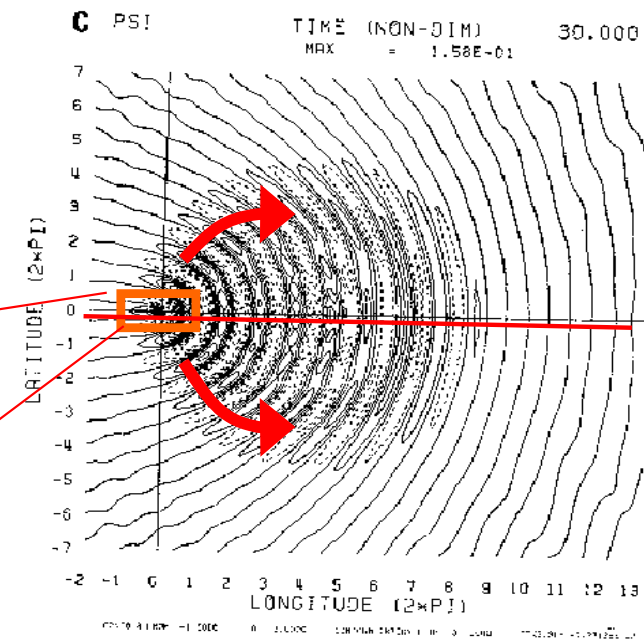
La Niña



Global abnormal weather due to Rossby wave propagation forced at the equator ("Teleconnection")

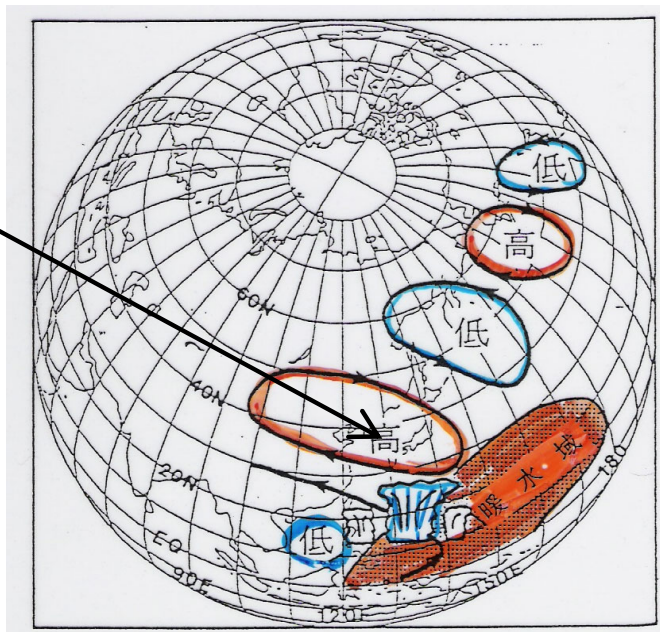


(Gill, 1966)

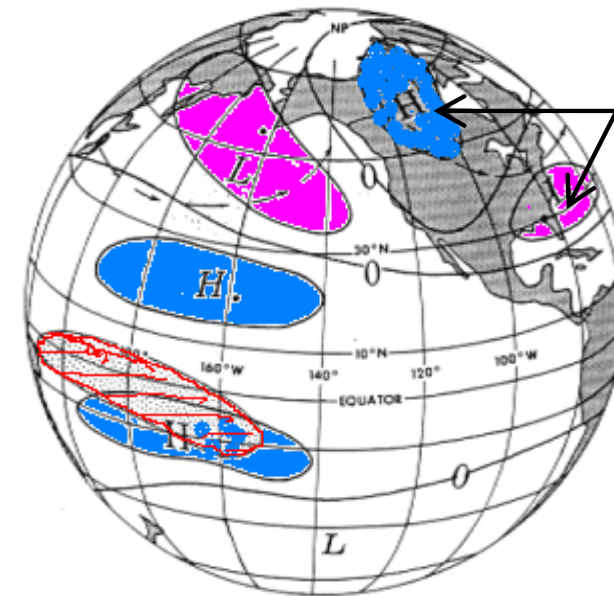


(Hayashi, 1987)

Intensified
Pacific high
inducing
hot summer
in Japan



(Nitta, 1987)

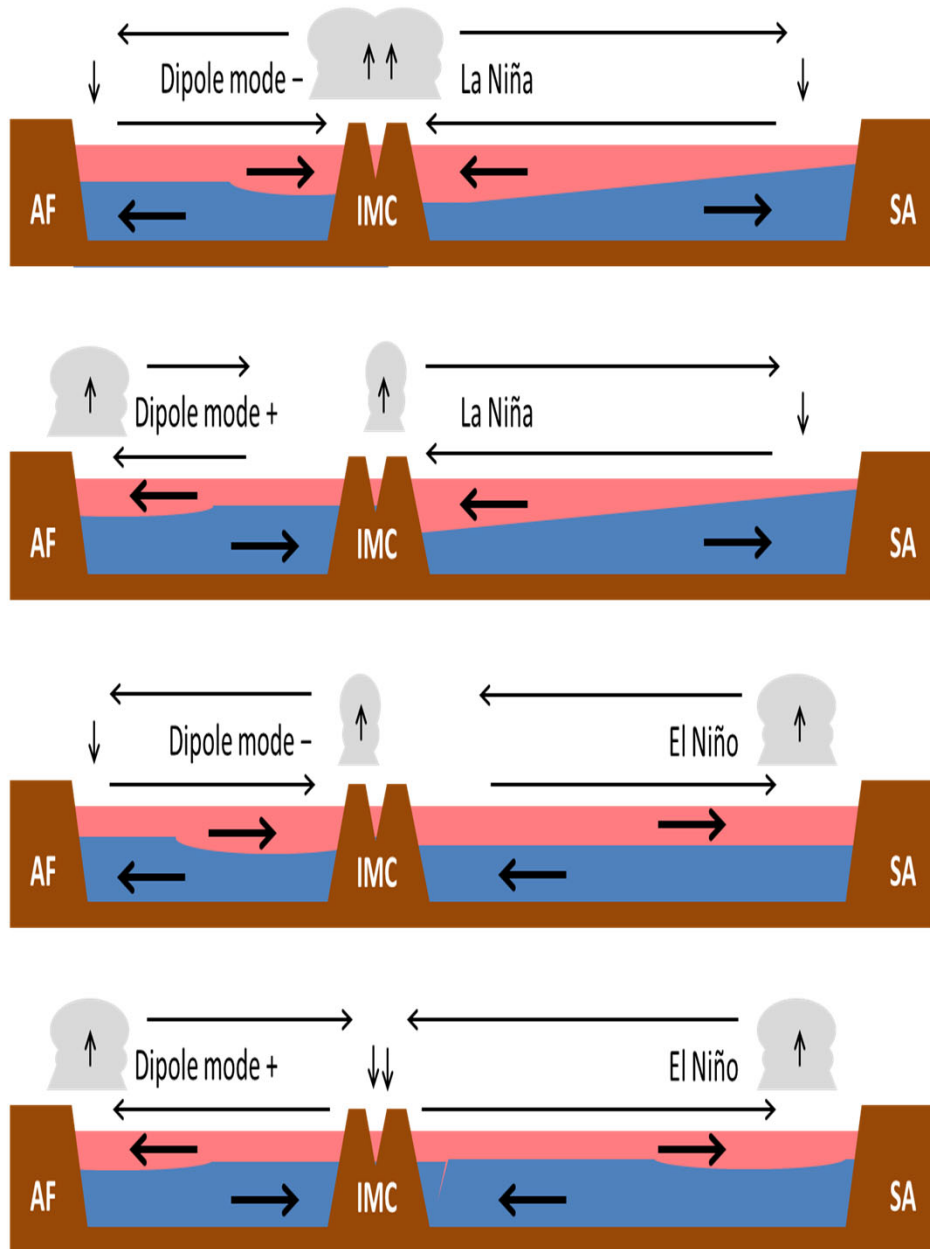


Intensified
high and low
inducing
cold winter
in south US

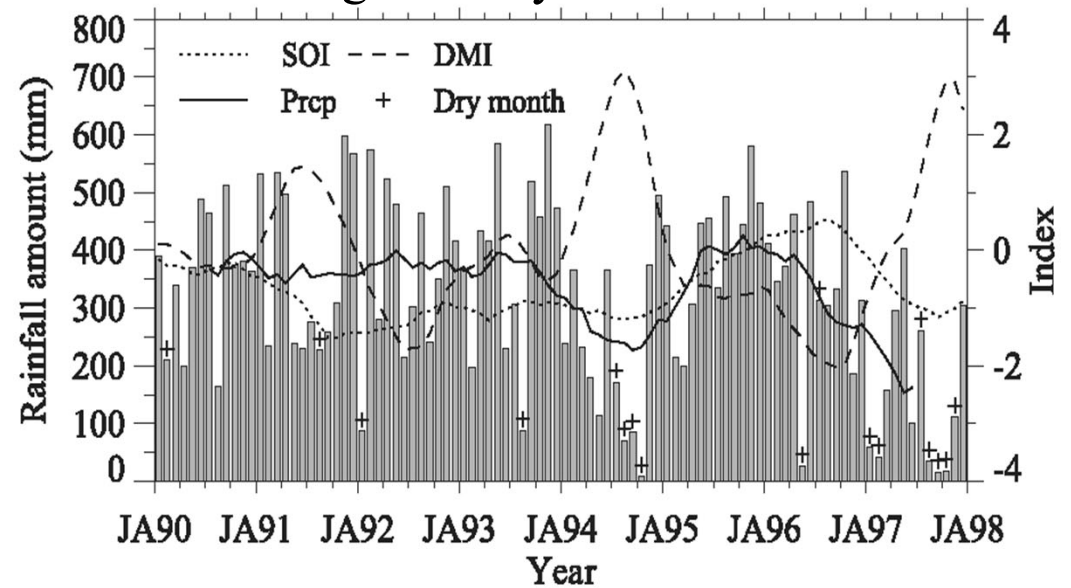
(Wallace, 1981)

Indian Ocean dipole mode (IOD) & El Niño-southern oscillation (ENSO)

Indian Ocean - Indonesia - Pacific Ocean

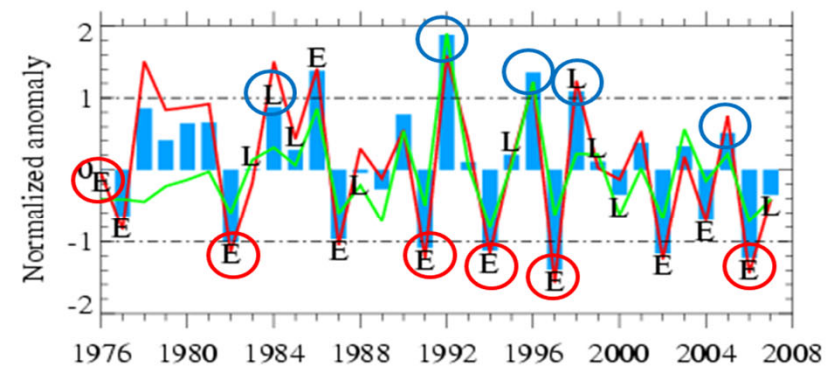


Padang monthly rainfall



(Hamada, Yudi, Tien et al., 2008, *JMSJ*)

Jakarta (9 stations) in the dry season (ASO)



E: El Niño, L: La Niña, Positive IOD, Negative IOD, Rainfall amount, Rainfall days, Heavy rainfall days.

(Hamada, Urip, Sophia et al., 2012, *SOLA*)

A dipole mode in the tropical Indian Ocean

N. H. Saji*, B. N. Goswami†, P. N. Vinayachandran* & T. Yamagata*‡ (1999), *Nature*

* Institute for Global Change Research, SEAVANS N 7F, 1-2-1 Shibaura, Minato-ku, Tokyo 105 6791, Japan

† Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore 560 012, India

‡ Department of Earth and Planetary Physics, Graduate School of Science, The University of Tokyo, Tokyo 113 0033, Japan

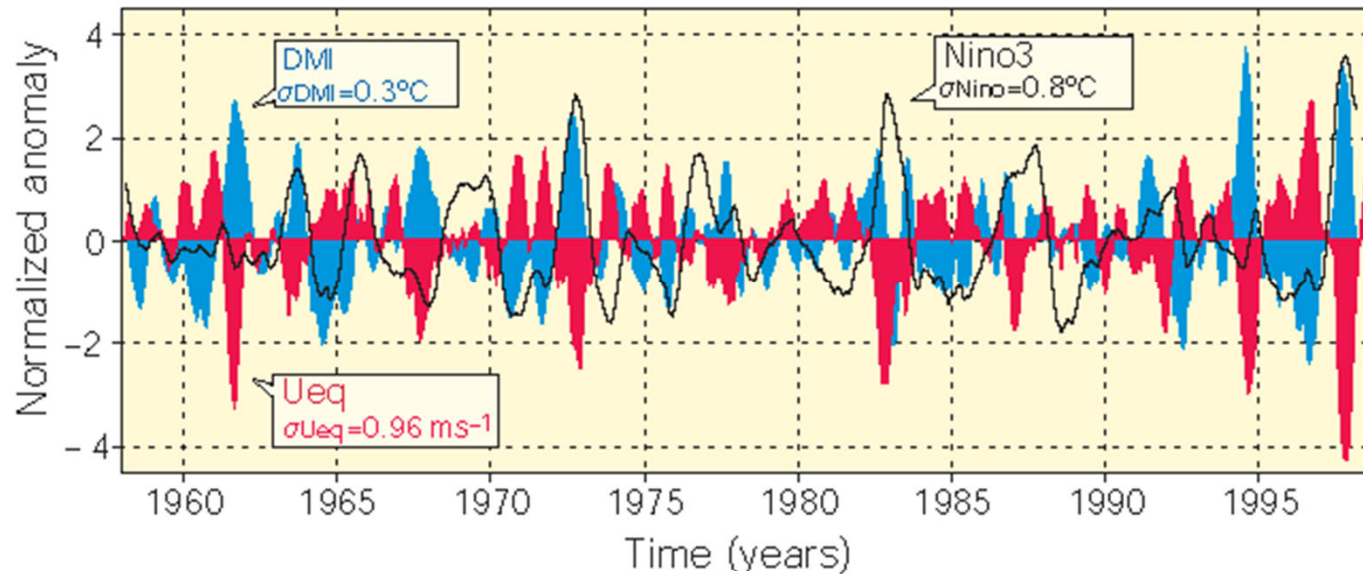
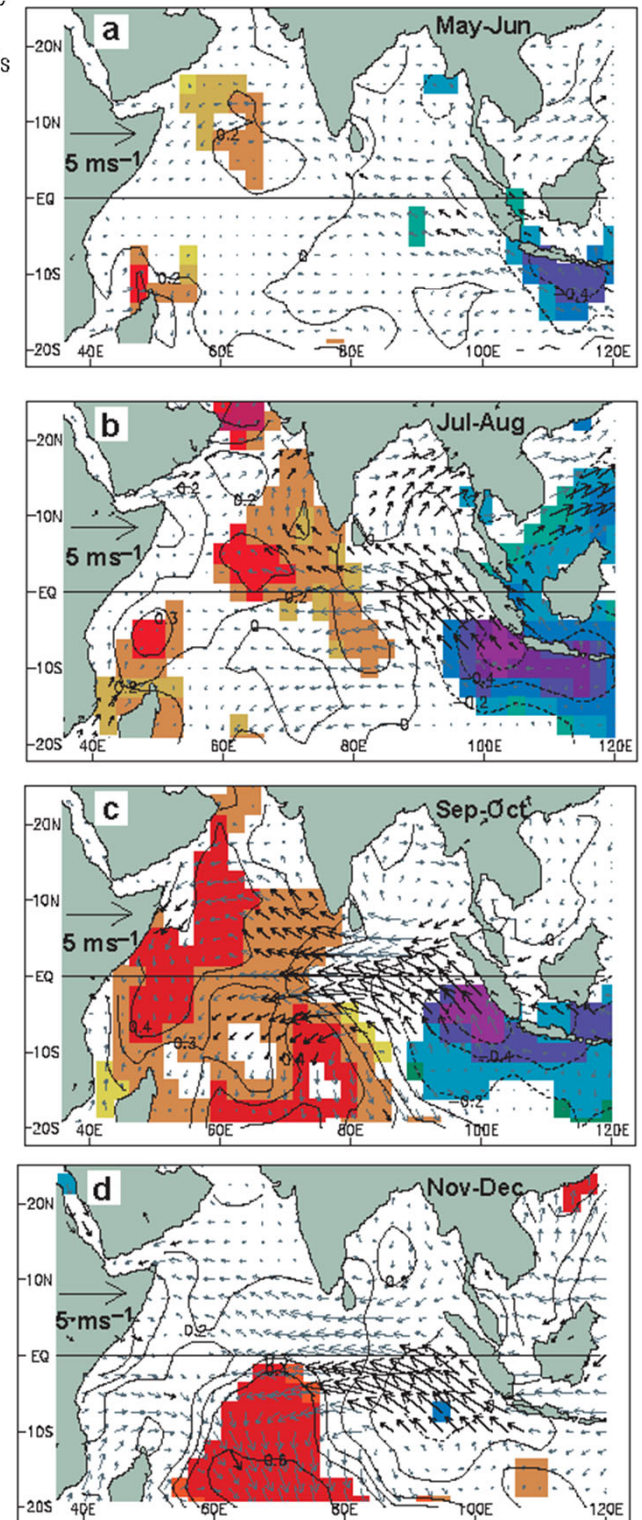
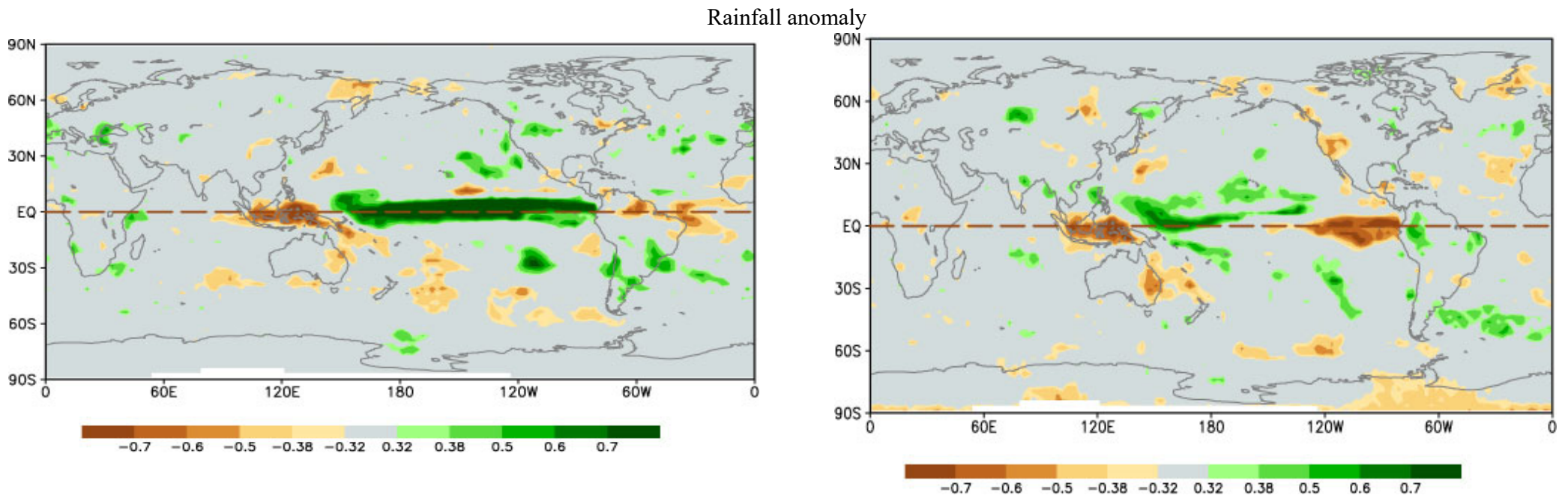
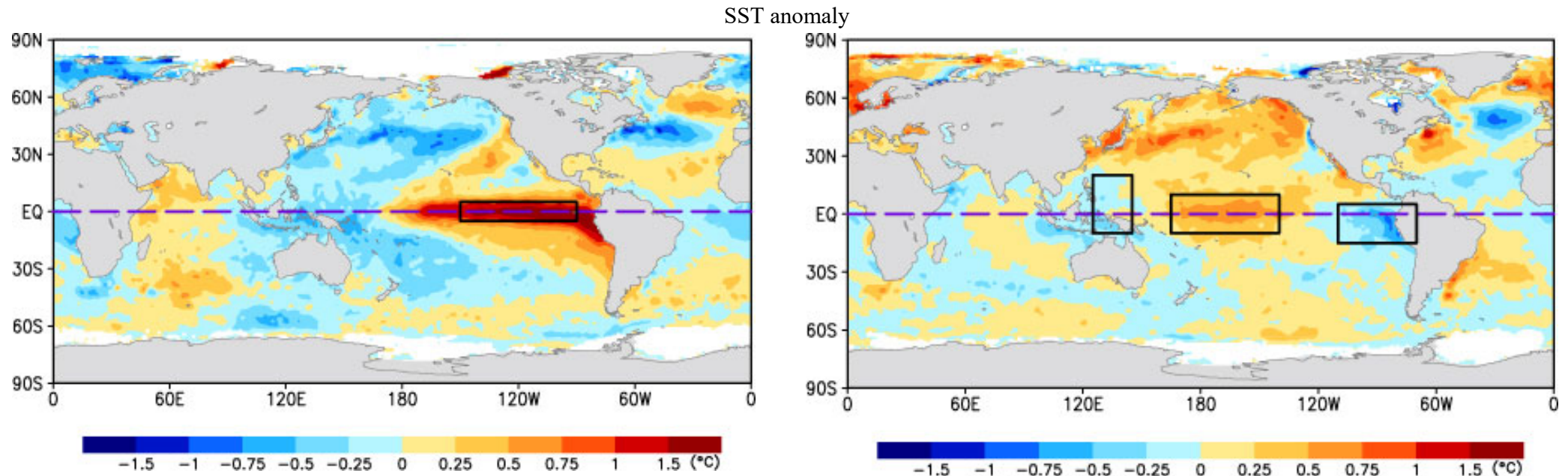


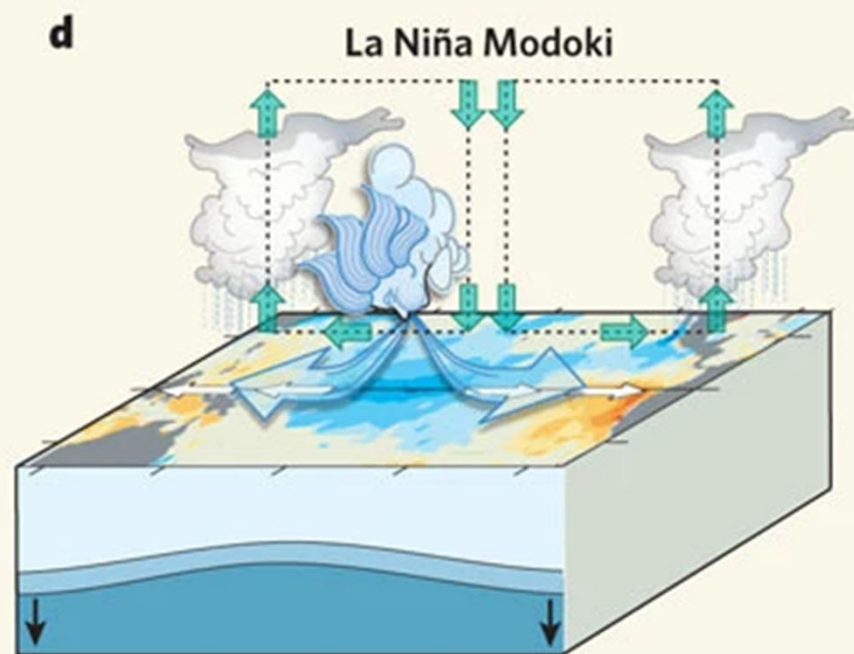
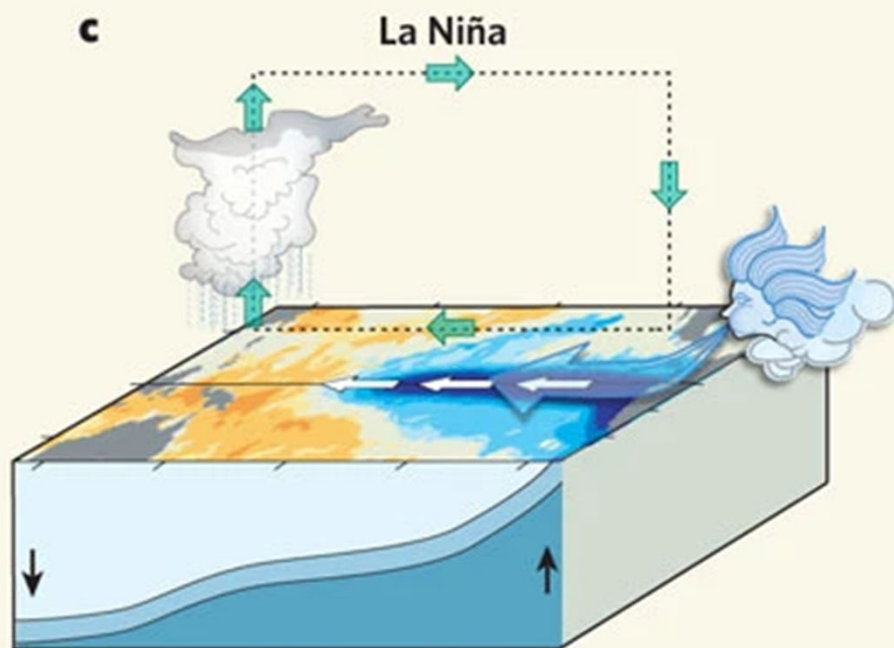
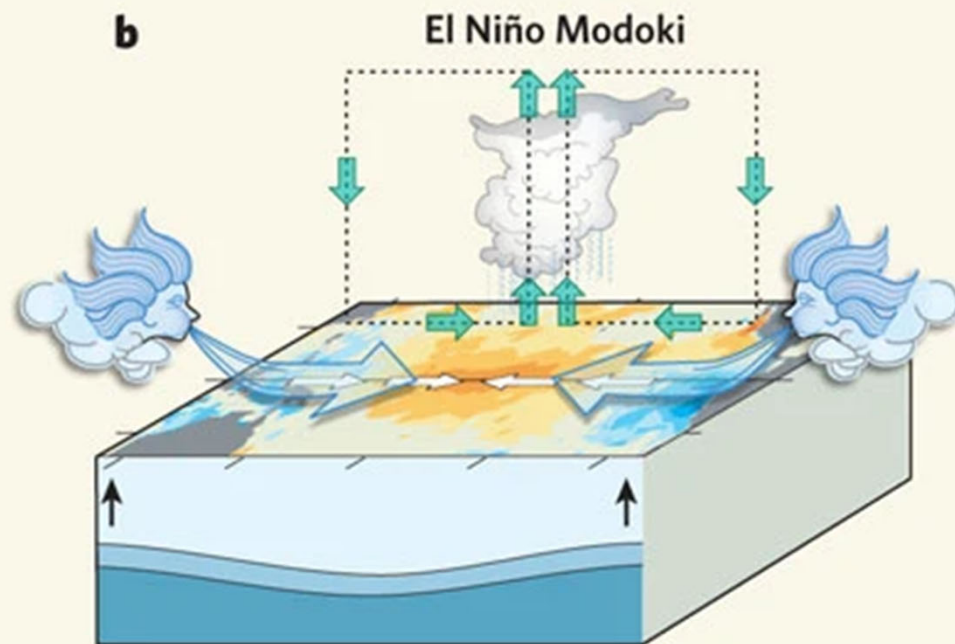
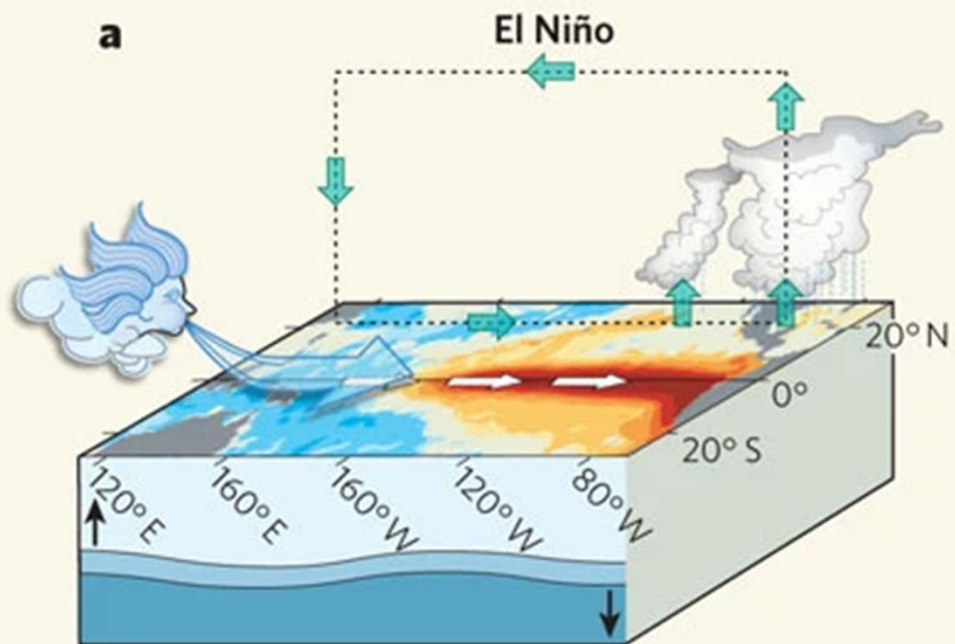
Figure 1 Dipole mode and El Niño events since 1958. Plotted in blue, the dipole mode index (DMI) exhibits a pattern of evolution distinctly different from that of the El Niño, which is represented by the Nino3 sea surface temperature (SST) anomalies (black line). On the other hand, equatorial zonal wind anomalies U_{eq} (plotted in red) coevolves with the DMI. All the three time series have been normalized by their respective standard deviations. We have removed variability with periods of 7 years or longer, based on harmonic analysis, from all the data sets used in this analysis. In addition, we have smoothed the time series using a 5-month running mean.

Figure 2 A composite dipole mode event. **a–d**, Evolution of composite SST and surface wind anomalies from May–June (**a**) to Nov–Dec (**d**). The statistical significance of the analysed anomalies were estimated by the two-tailed t -test. Anomalies of SSTs and winds exceeding 90% significance are indicated by shading and bold arrows, respectively.



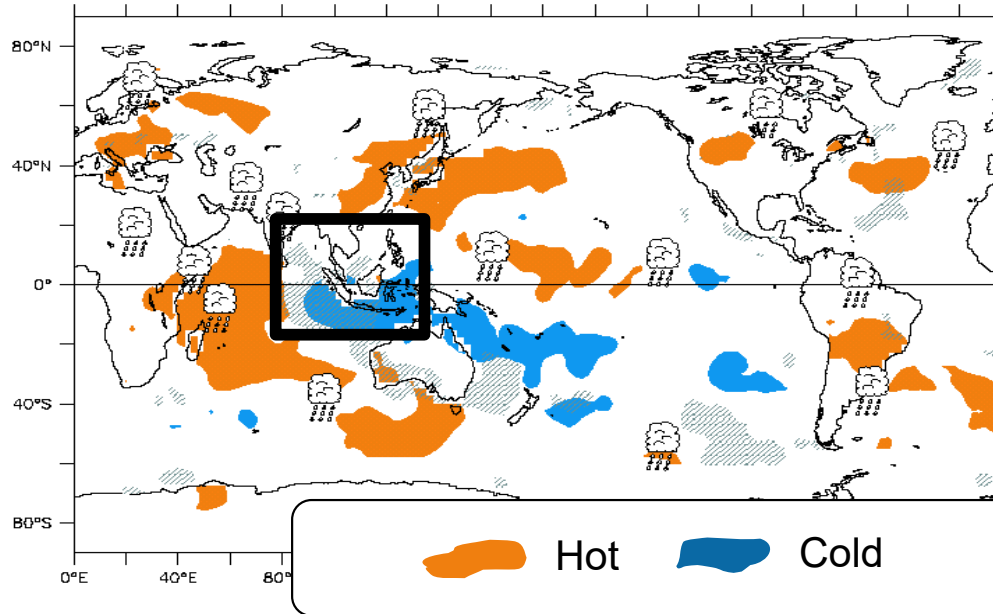
El Niño and El Niño “Modoki”



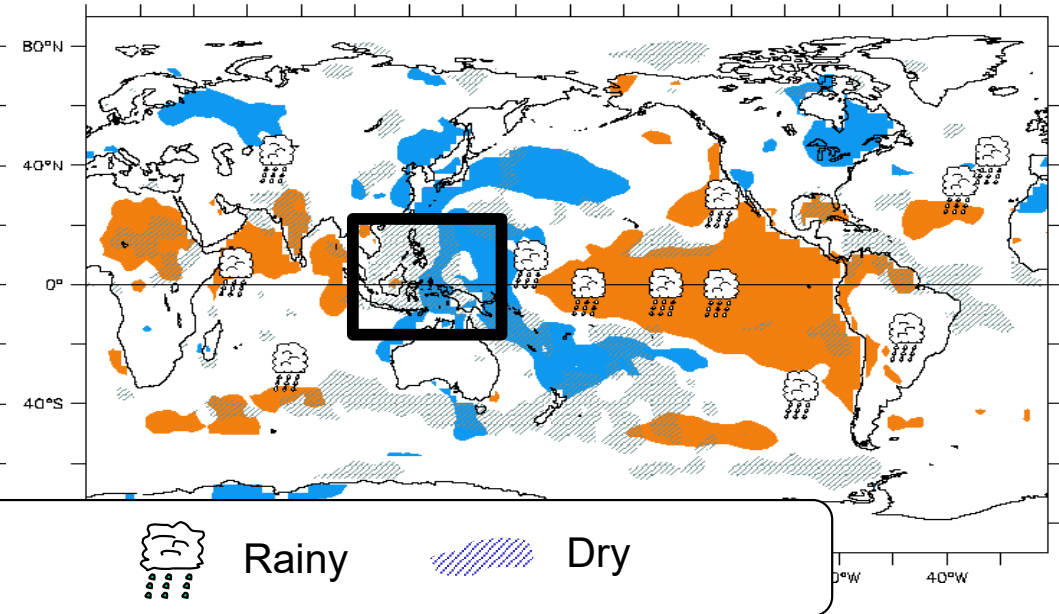


Global / local effects of IOD / ENSO

IOD effects (boreal summer/autumn)

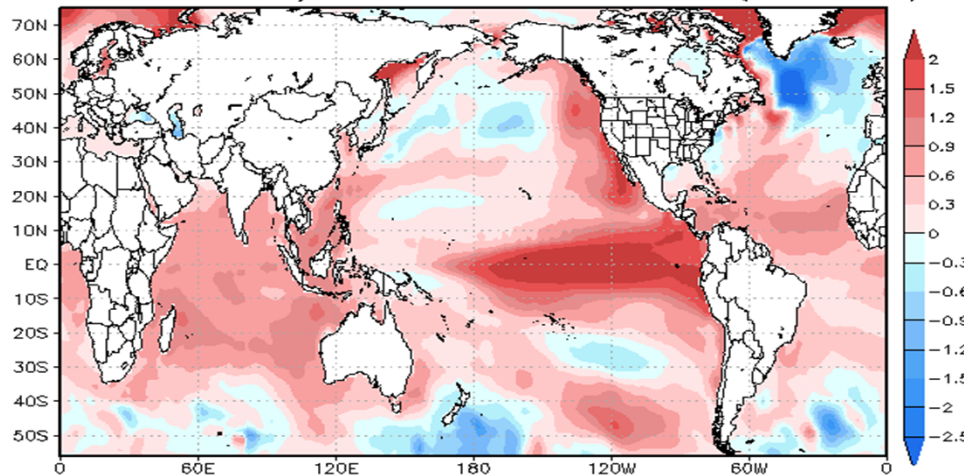


El Nino effects (boreal summer/autumn)

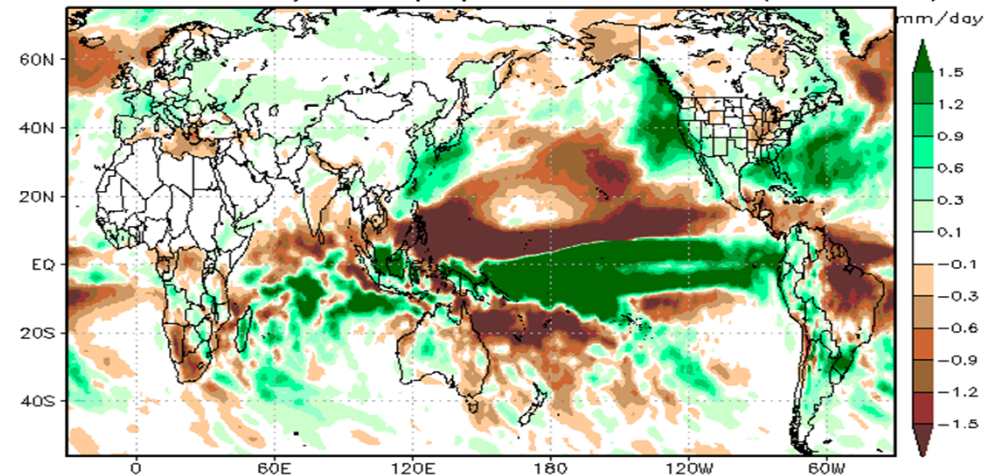


SST/rainfall for 2015-16 El Niño (SINTEX-F/JAMSTEC)

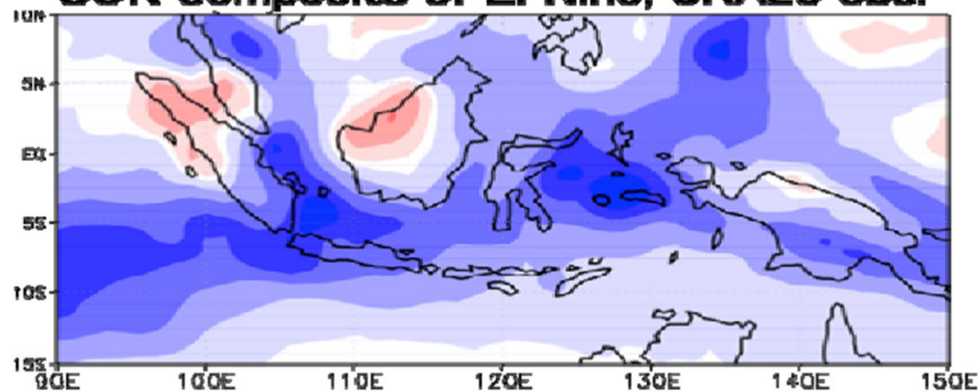
Predicted DJF2015/2016 SSTA from 1nov2015 (9-member)



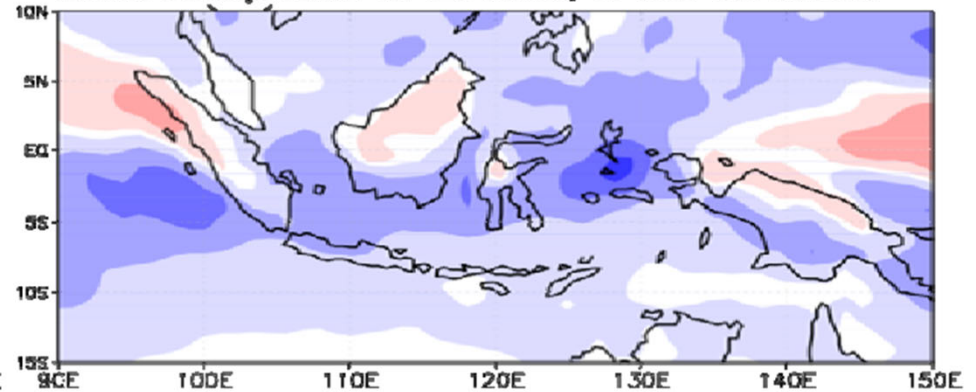
Predicted DJF2015/2016 tprepa from 1nov2015 (9-member)



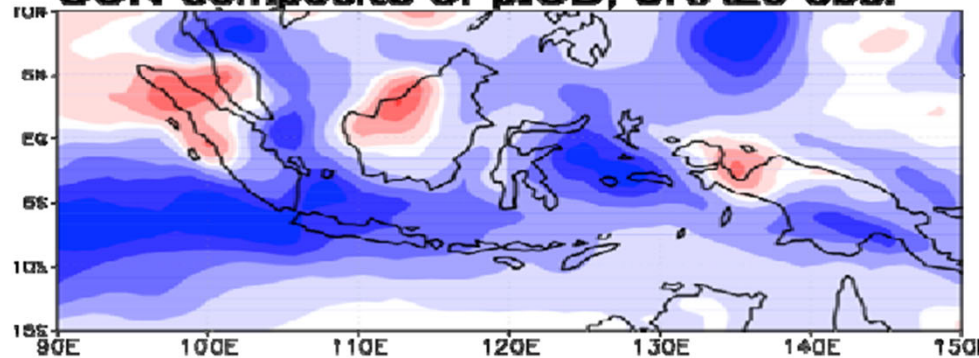
SON composite of El Nino, JRA25 obs.



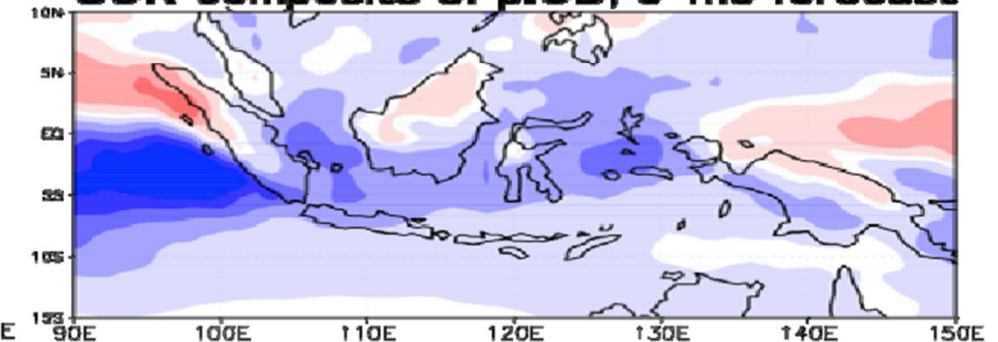
SON composite of El Nino, 3-mo forecast



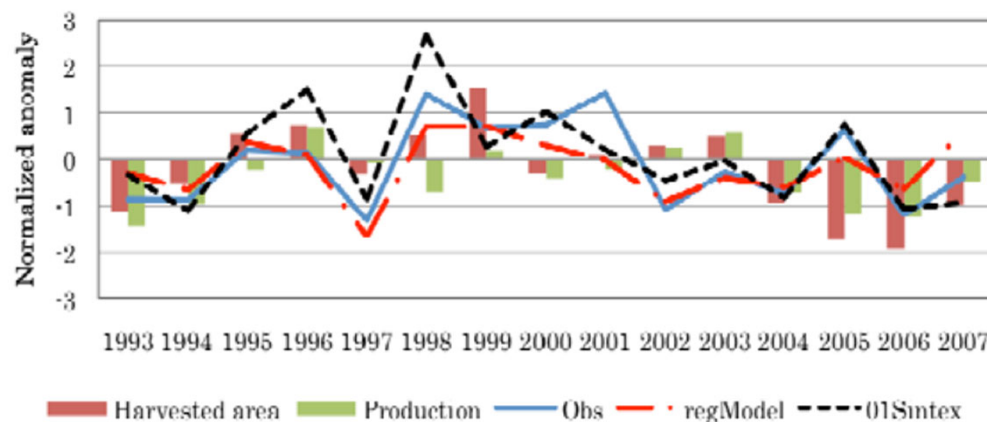
SON composite of pIOD, JRA25 obs.



SON composite of pIOD, 3-mo forecast



Makassar South Sulawesi

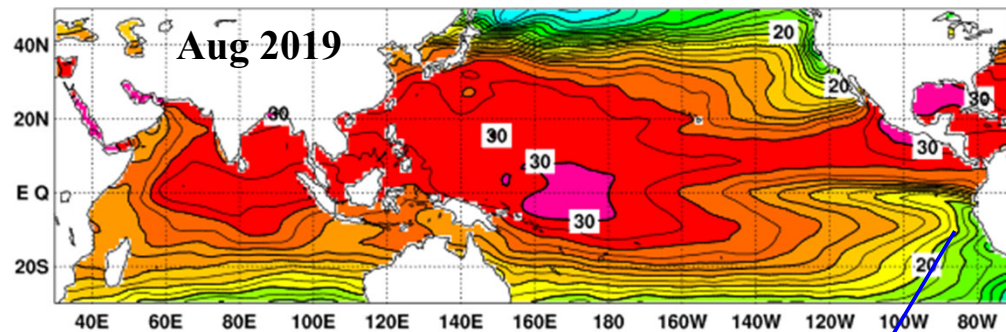


Forest fires - transboundary haze (1994, 1998, 2006, 1205)

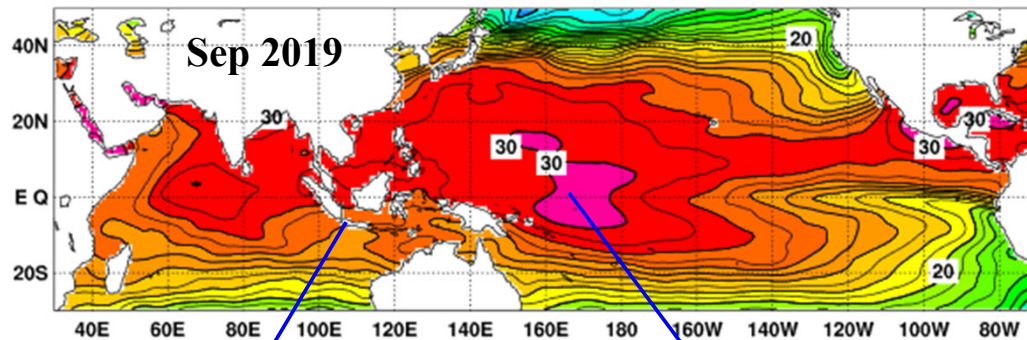


(R. Hidayat, 2013)

Sea surface temperature (JMA)

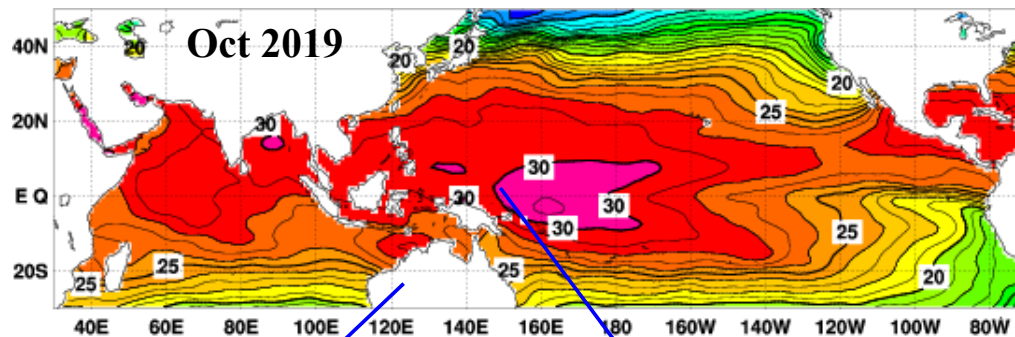


End of El Nino. Return of cold water to off Peru.



Cold eastern Indian Ocean
(Dipole mode)

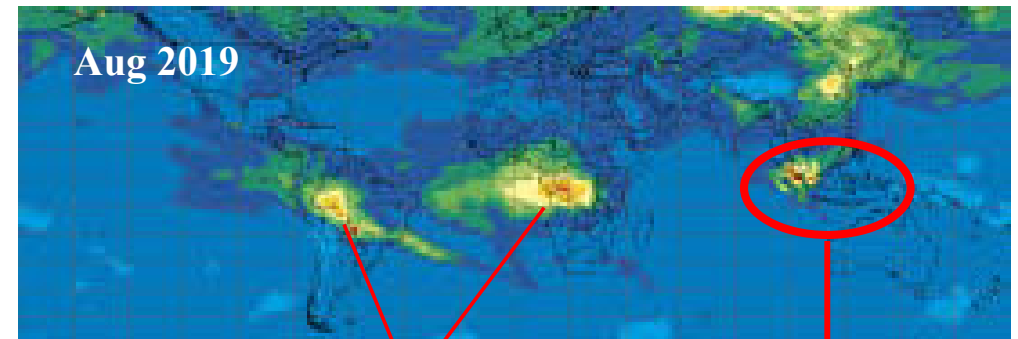
No return of warm water to IMC
(El Nino *modoki*)



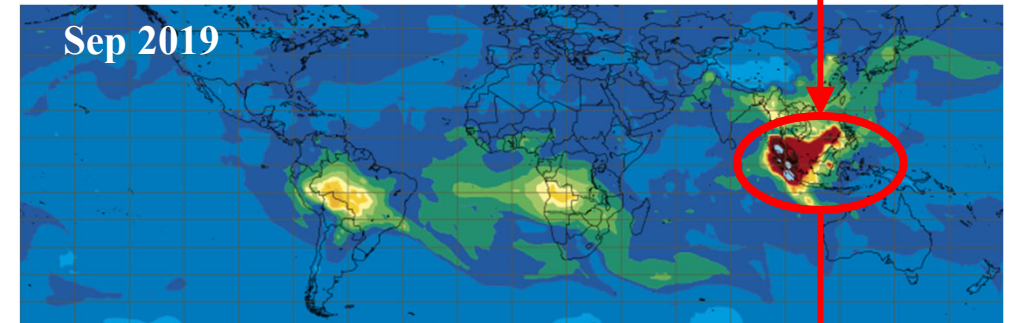
Australia going to summer

Warm water returning gradually to IMC
(Approach to normal rainy season)

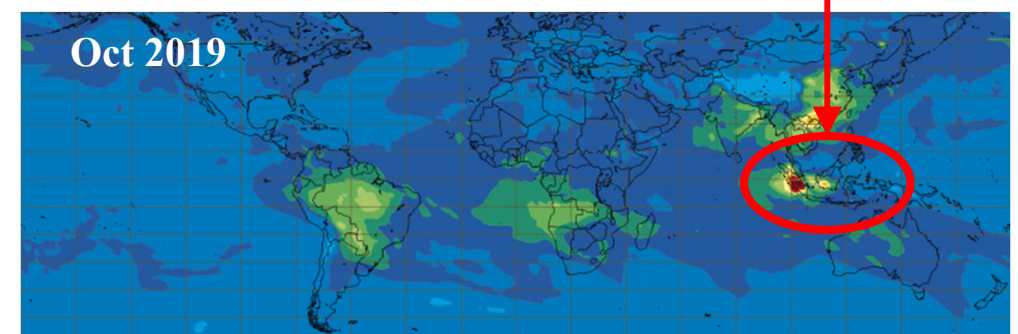
CO (correlated with PM) distribution (ECMWF)



Fires in South America and
Africa weakened



Peak of IMC fire

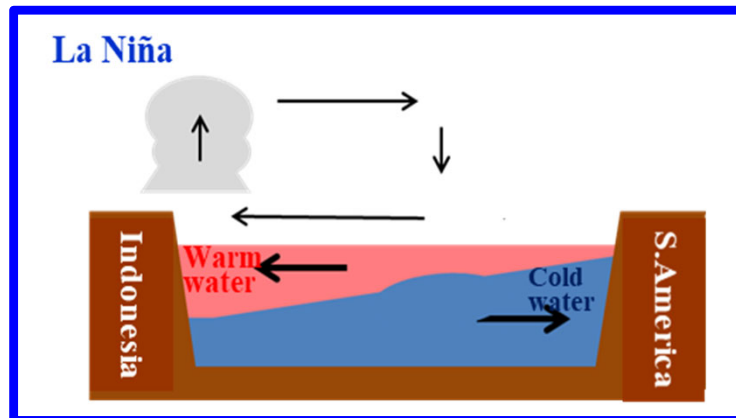
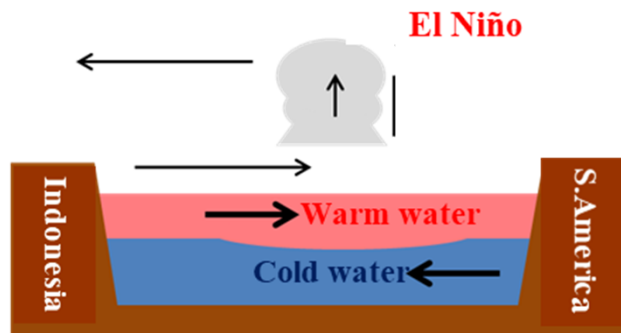
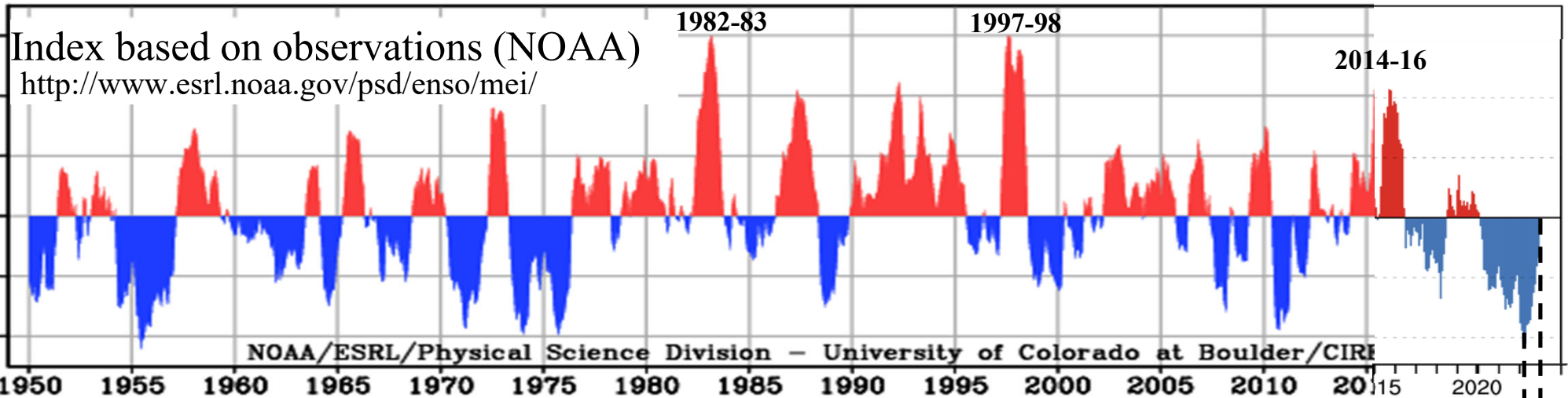


IMC fire weakened

El Niño-Southern Oscillation (ENSO)

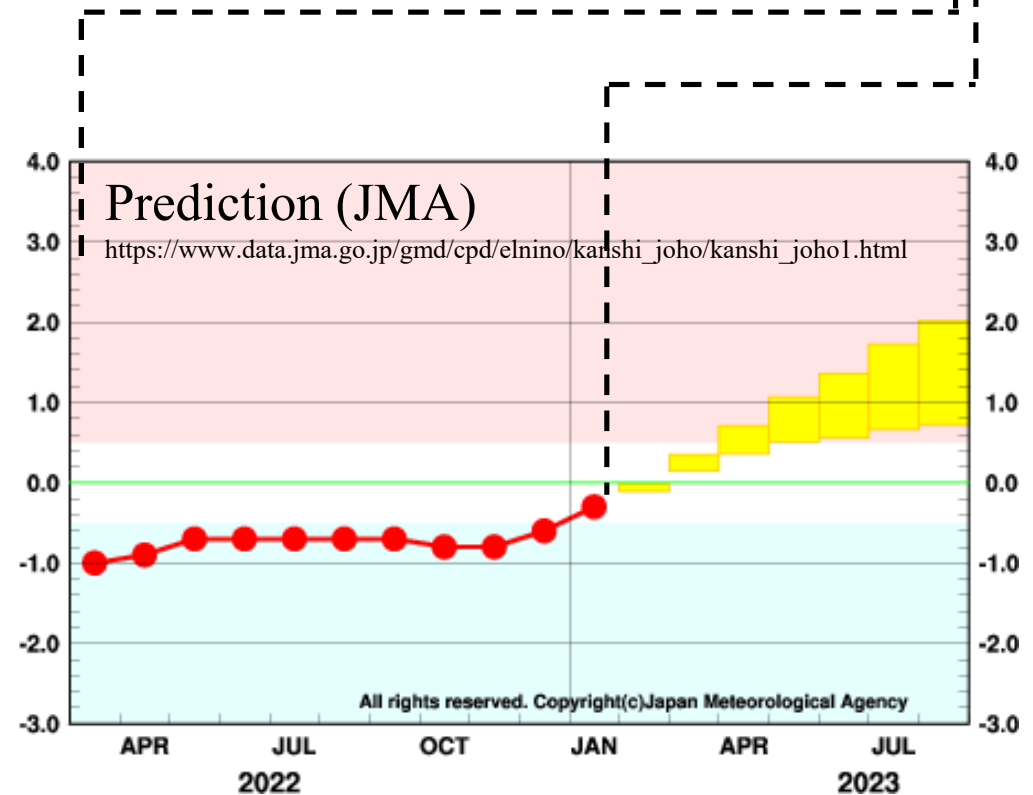
El Niño

La Niña



El Niño

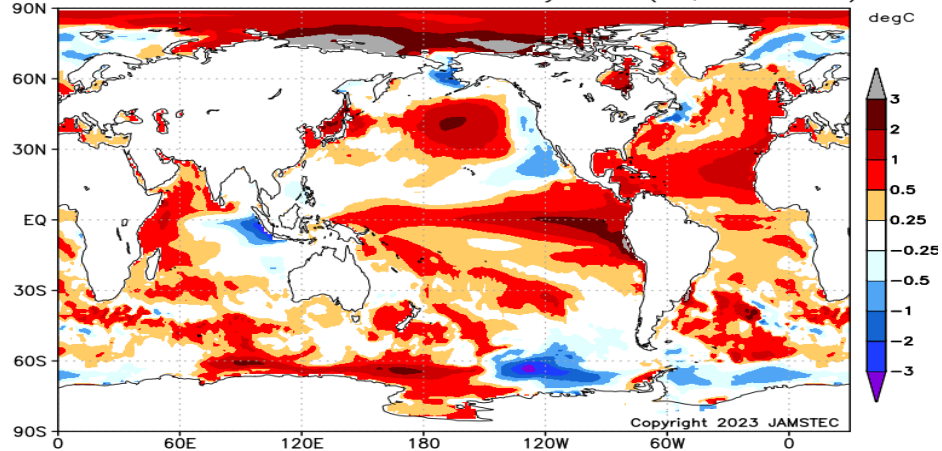
La Niña



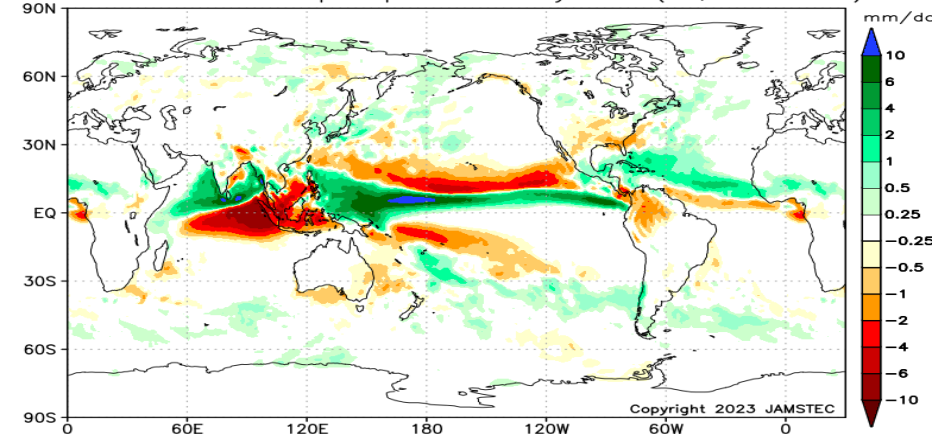
SST and precipitation anomalies predicted by SINTEX-F/JAMSTEC

<https://www.jamstec.go.jp/aplinfo/sintexf/e/seasonal/outlook.html>

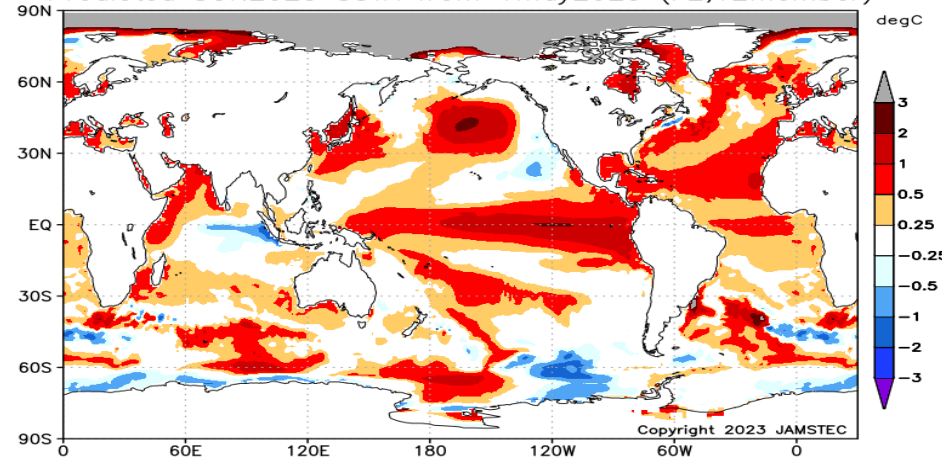
Predicted JJA2023 SSTA from 1may2023 (F2,12member)



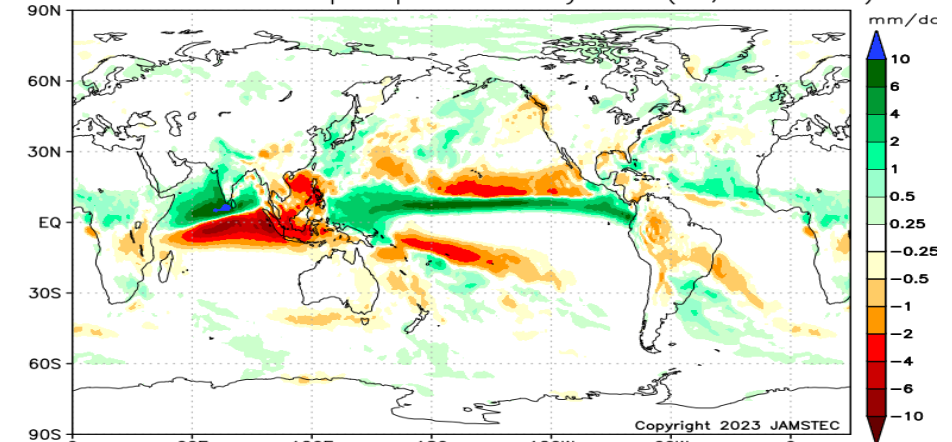
Predicted JJA2023 precip from 1may2023 (F2,12member)



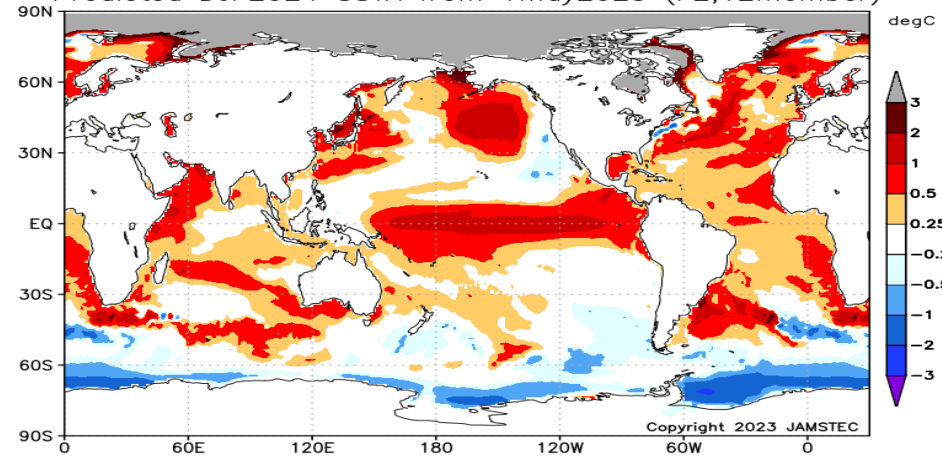
Predicted SON2023 SSTA from 1may2023 (F2,12member)



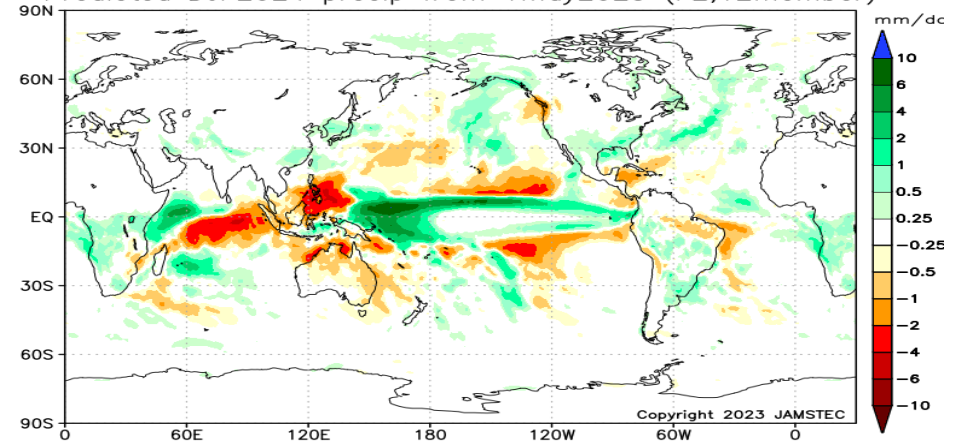
Predicted SON2023 precip from 1may2023 (F2,12member)



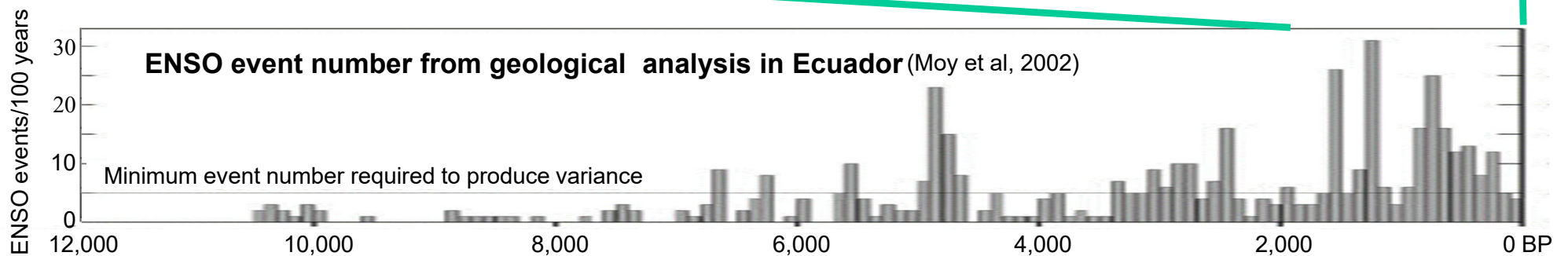
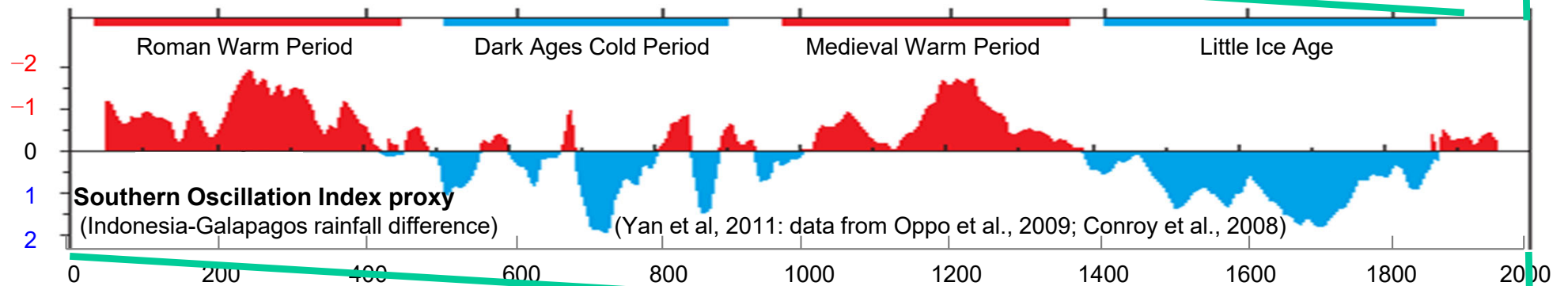
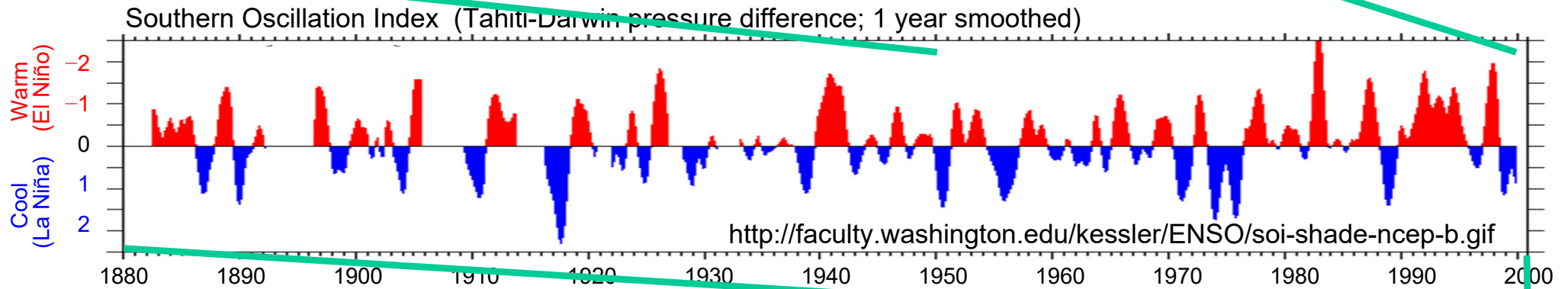
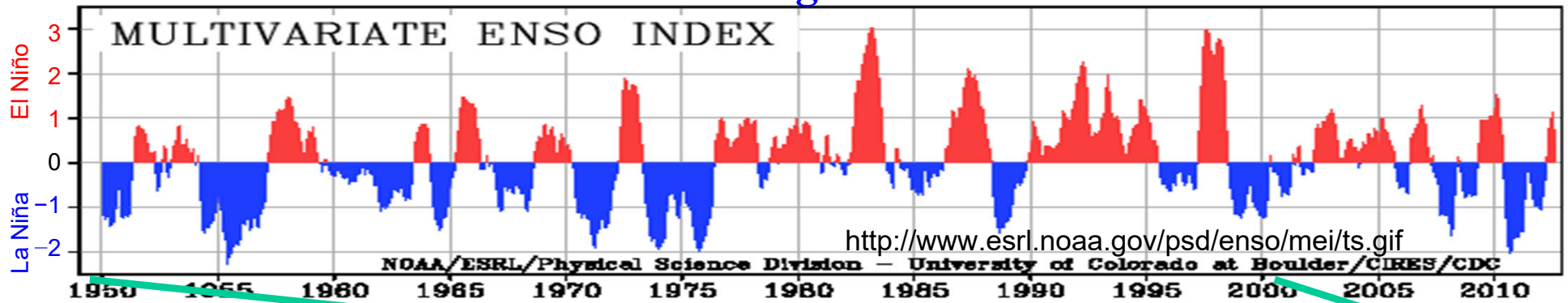
Predicted DJF2024 SSTA from 1may2023 (F2,12member)



Predicted DJF2024 precip from 1may2023 (F2,12member)



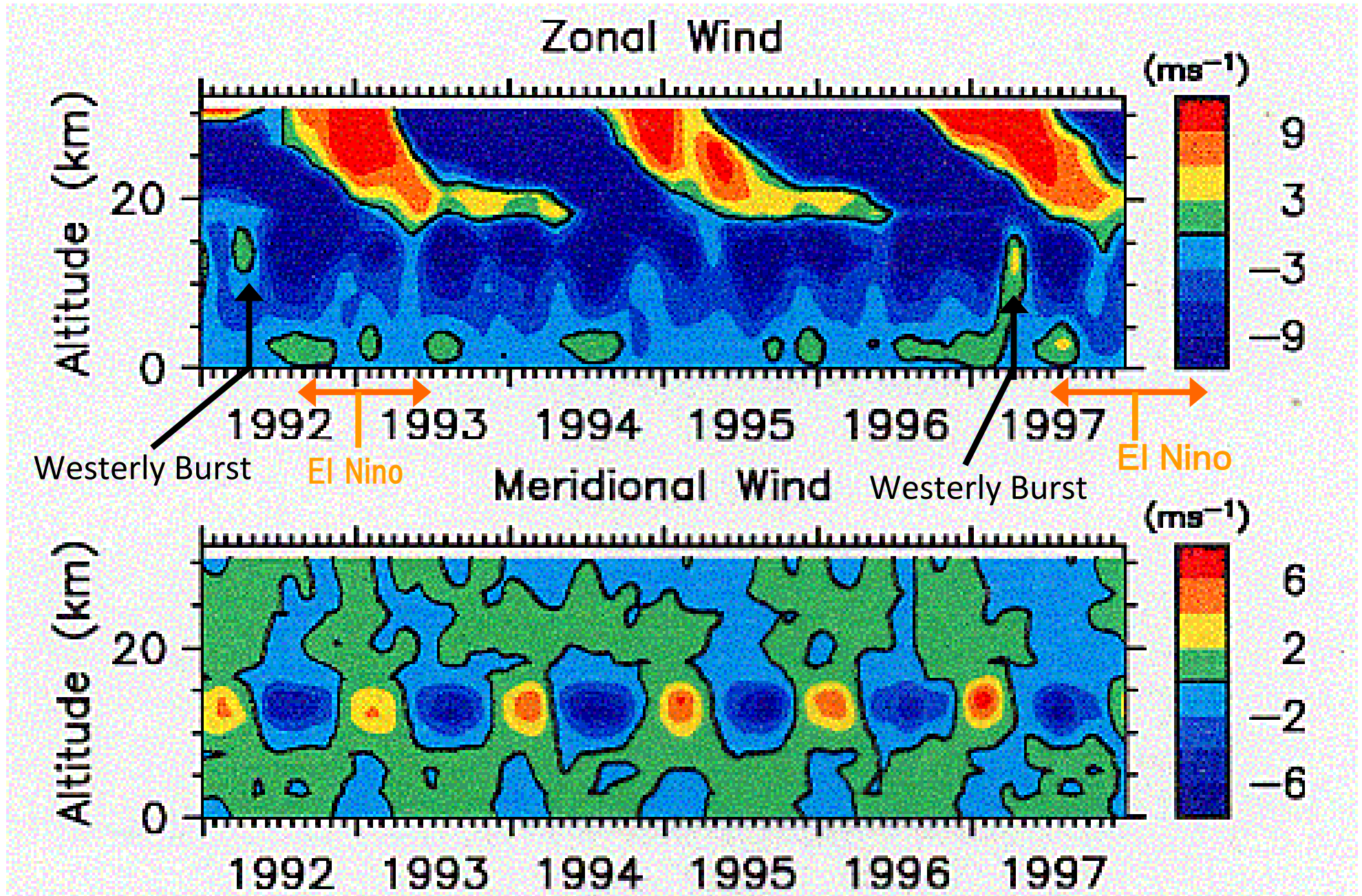
Centennial/Millennial/Holocene global climate variations and ENSO



5.4. Wave-mean flow interaction and quasi-biennial oscillation (QBO)

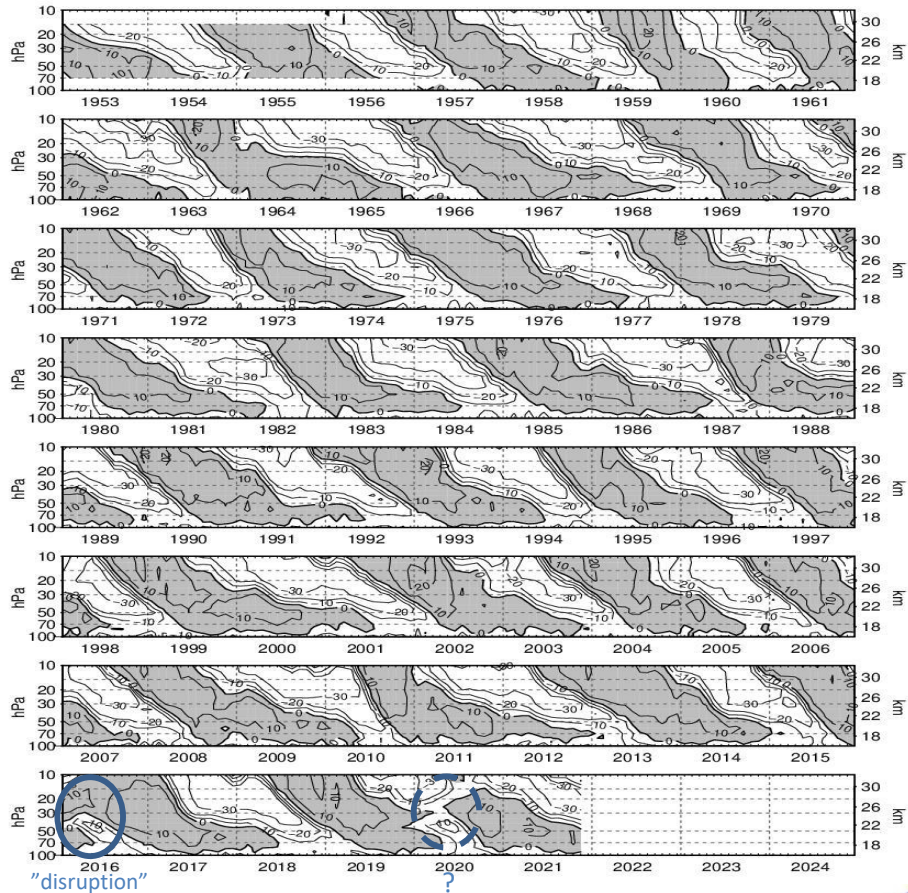
Interannual Variations of Wind over Indonesia

(Okamoto, Yamanaka et al., 2003b)

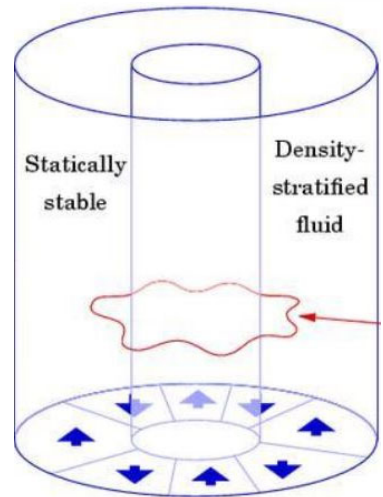
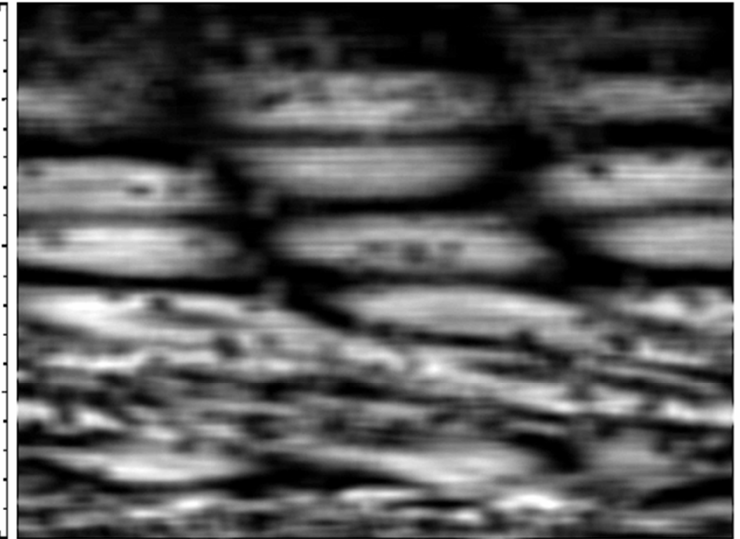
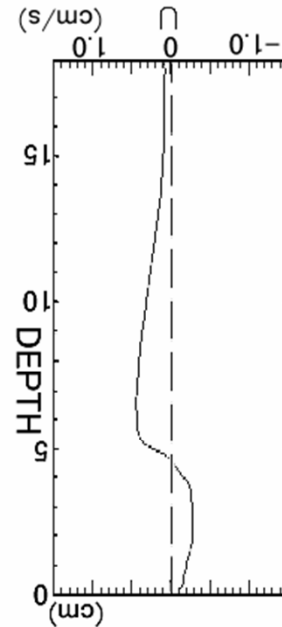
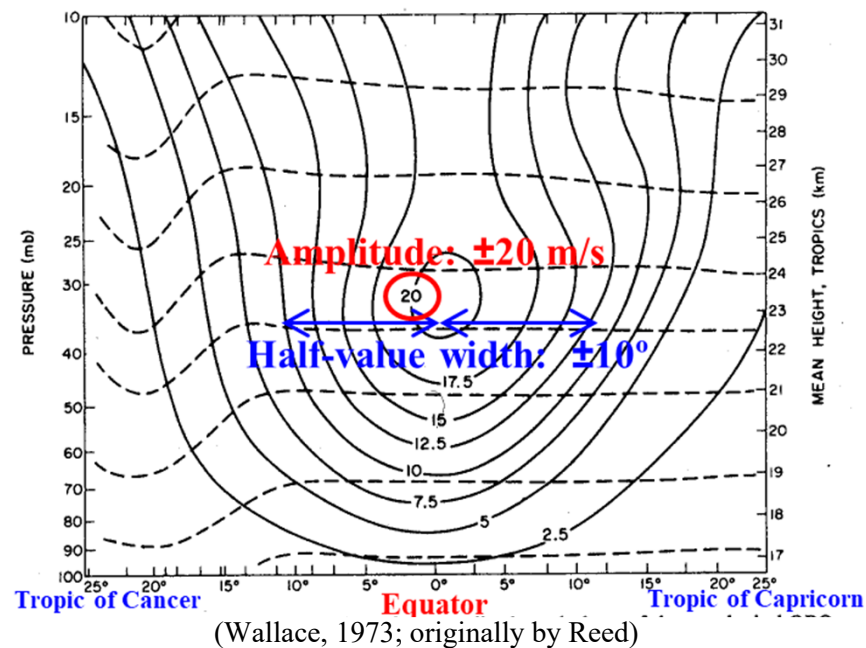


QBO needs bidirectional waves

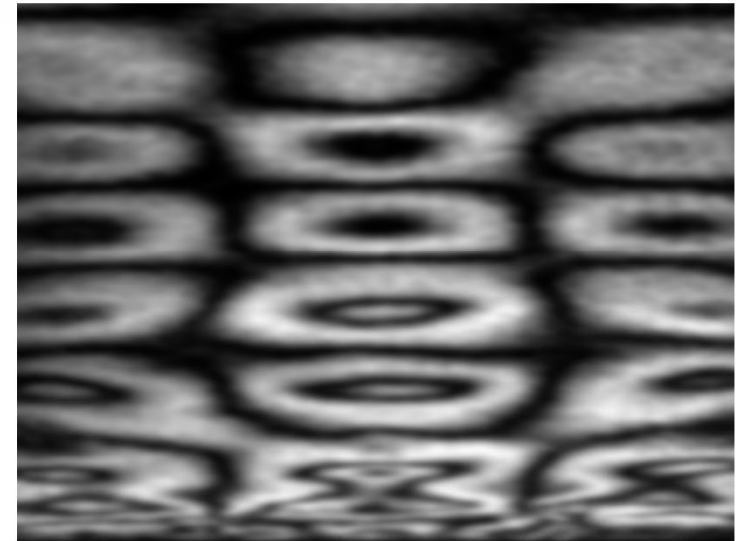
“Period”: 9 years/4 cycles $\div$ 27months $\leftarrow$ Wave momentum flux
 Zonal wind “amplitude” $\leftarrow$ Wave phase velocity (East/west **Bidirectional**)



<https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html>

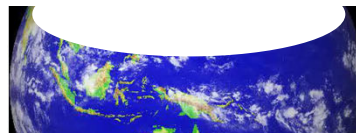


(Plumb & McEwan, 1978)



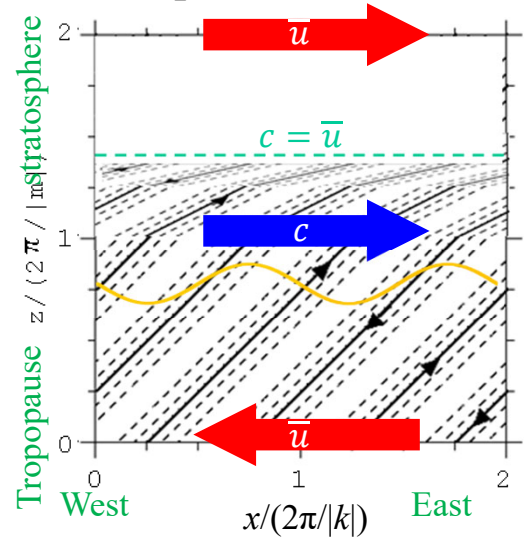
Cells appear over the whole layer without mean flow
 (Bottom-only large viscosity is impossible in labo. exp.)

(Otake, Sakai, Yoden & Shiotani, 1998)
https://www2.nagare.or.jp/mm/98/otake/index_ja.htm



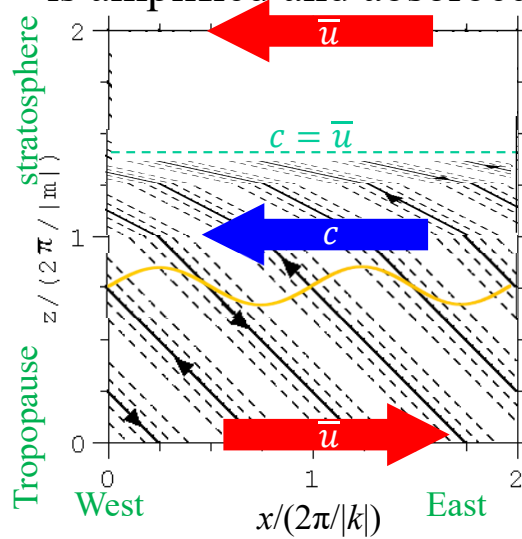
Top (radiative condition: group velocity $\partial\omega/\partial m > 0$ at $z = \infty$) $\Rightarrow$ **Upward propagating wave must be selected** (a)

In $\partial\bar{u}/\partial z > 0$, $c = \omega/k > 0$
is amplified and absorbed



$$\psi = \cos(kx - mz - \omega t)$$

In $\partial\bar{u}/\partial z < 0$, $c = -\omega/k < 0$
is amplified and absorbed



$$\psi = \cos(kx + mz + \omega t)$$

Frequency of gravity waves:

$$\omega = \hat{\omega} + k = -\frac{kN}{m} + k\bar{u}$$

Group (energy transfer) velocity:

$$\frac{\partial\omega}{\partial m} = \frac{\partial\hat{\omega}}{\partial m} = \frac{kN}{m^2} = -\frac{\hat{\omega}}{m}$$

Amplification with density decrease

or vertical wavelength $2\pi/m$ decrease

(Damping with eddy viscosity (breaking)

or viscosity/radiational cooling)

“Critical level” for waves with phase speed c equating the mean flow $\bar{u}$:

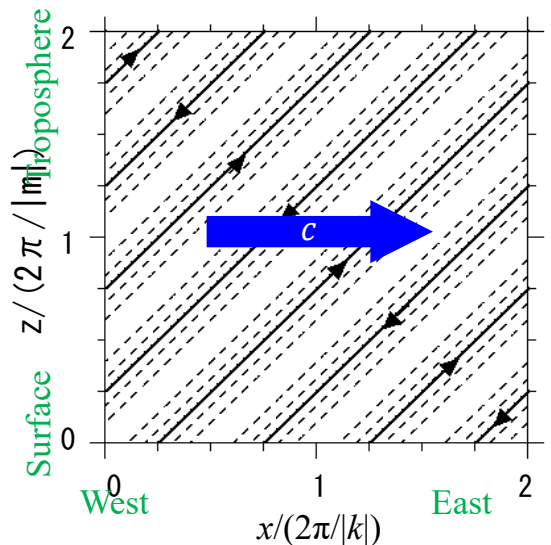
$$\hat{\omega} = \omega - k\bar{u} = k(c - \bar{u}) = 0$$

$$\rightarrow |m| = \infty, \quad \frac{\partial\omega}{\partial m} = 0$$

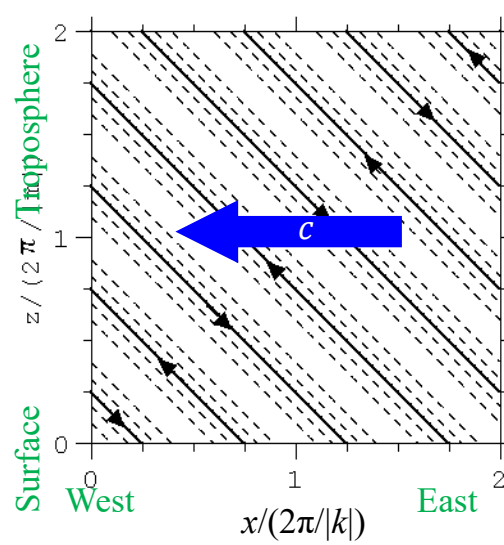
$$\frac{\partial U}{\partial t} = -\frac{1}{\rho} \frac{\partial}{\partial z} \overline{\rho u' w'} = -\frac{k}{\hat{\omega}} \overline{u' w'} \frac{\partial U}{\partial z} \equiv -W \frac{\partial U}{\partial z}$$

Wave momentum makes mean wind profile downward.

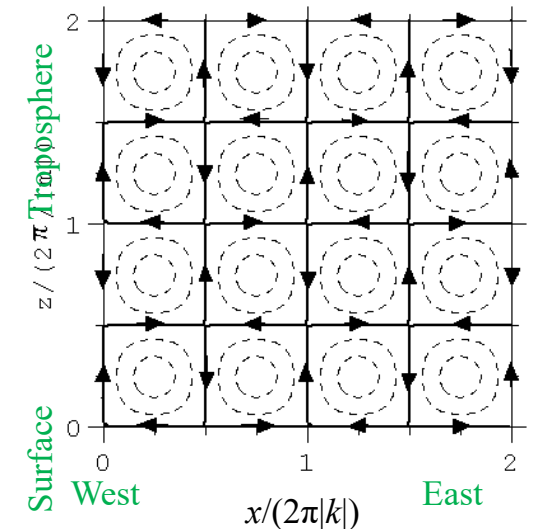
Bottom (viscid condition: $u, w = (\partial/\partial z, -\partial/\partial x)\Psi = 0$ at $z = 0$) $\Rightarrow$ **Bidirectional waves = cells in the troposphere** (b)



$$\psi = \cos(kx - mz - \omega t)$$



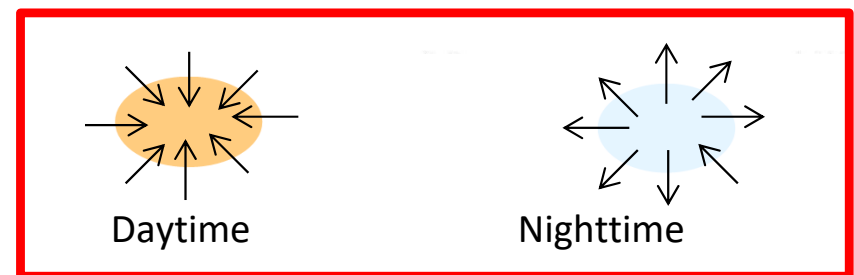
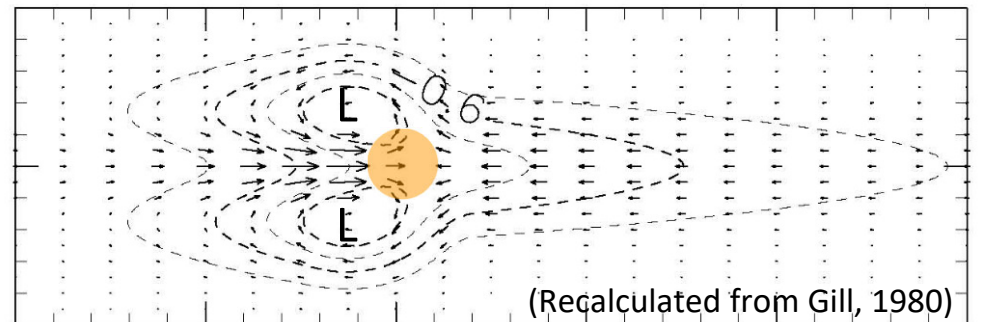
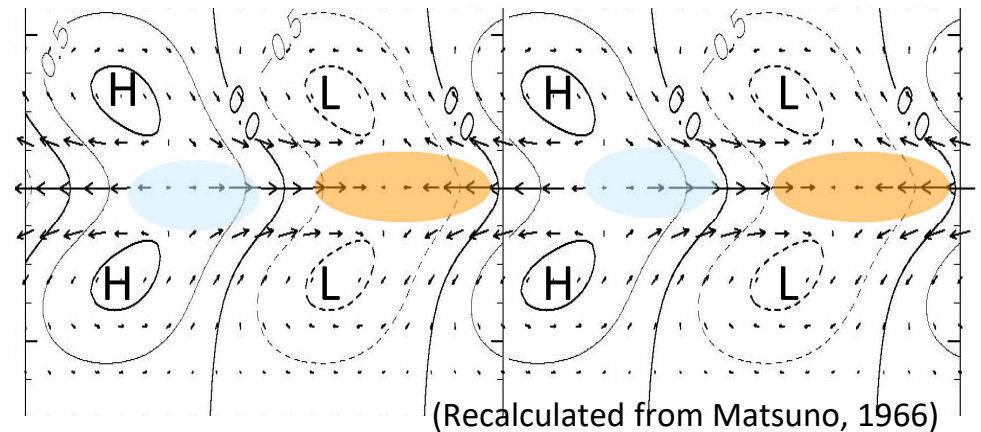
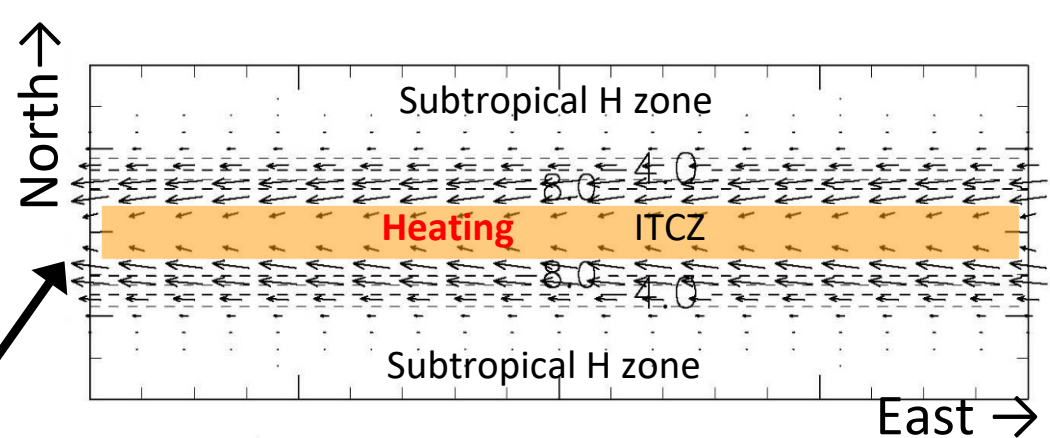
$$\psi = \cos(kx + mz + \omega t)$$



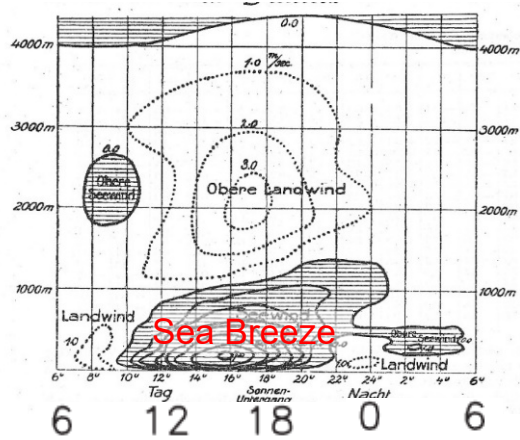
$$\Psi = \cos(kx - mz - \omega t) - \cos(kx + mz + \omega t) = 2 \sin kx \sin(mz + \omega t)$$

Equatorial Forcing and Atmospheric Response

- Stationary modes (**Kelvin+Rossby**)
 - Zonally uniform ($k=0$ or Zonal mean)
 - Symmetric $\Rightarrow$ zonal **Hadley cells (ITCZ)**
 - Anti-symmetric $\Rightarrow$ “**Monsoon**”
 - Cyclic/isolated
 - $\Rightarrow$ Zonal (Walker) circulations
 - (**Matsuno-Gill patterns**)
 - Teleconnections
 - Rossby-wave propagation
- Traveling modes (**Kelvin+Rossby**)
 - Eastward along equator (Kelvin)
 - $\Rightarrow$ **IntraSeasonal variations**
 - (Madden-Julian Oscillation, etc.)
- Regional/Local modes (**gravity waves**)
 - $\Rightarrow$ Sea-Land (Mountain-Valley) breeze circulations

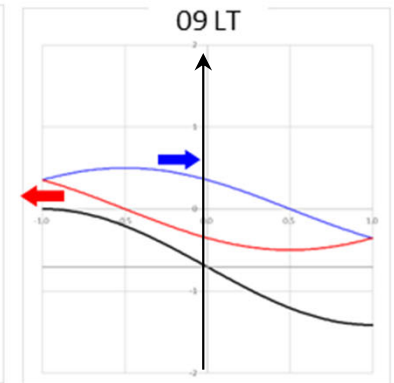
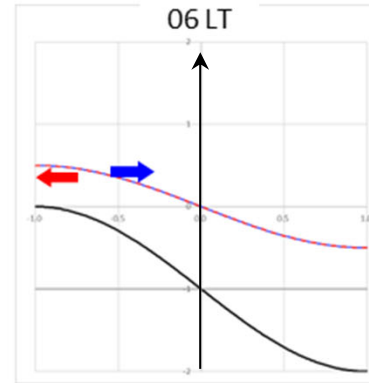
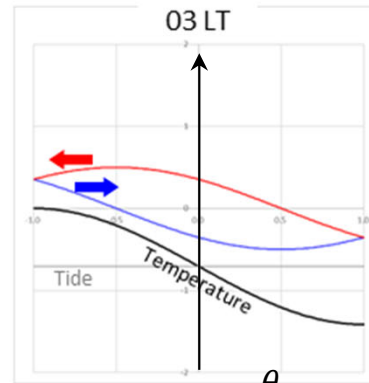
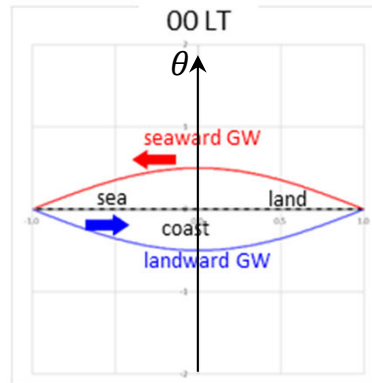
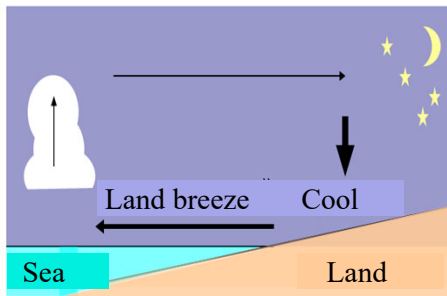
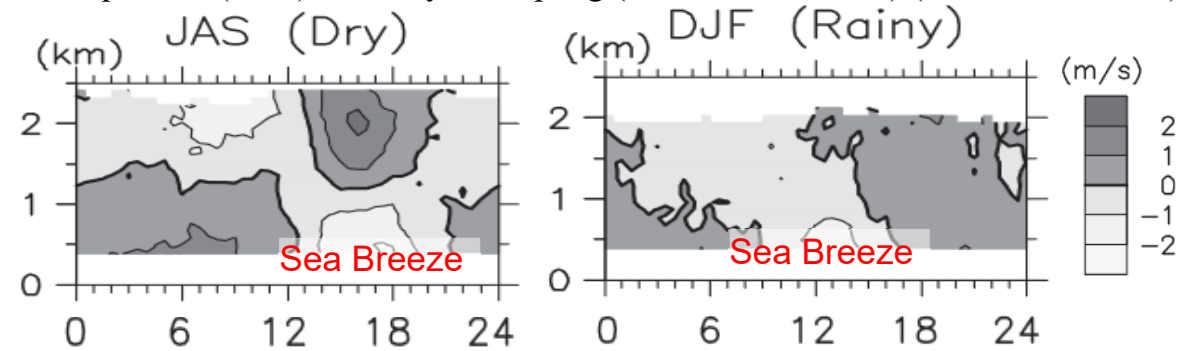


Diurnal-cycle sea-land breeze circulation: observation and mechanism

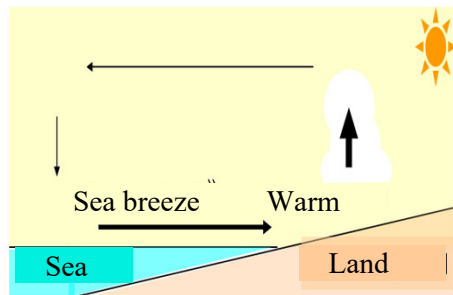
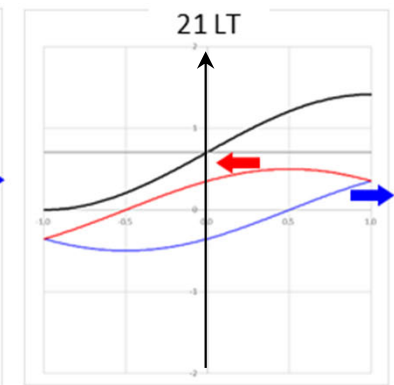
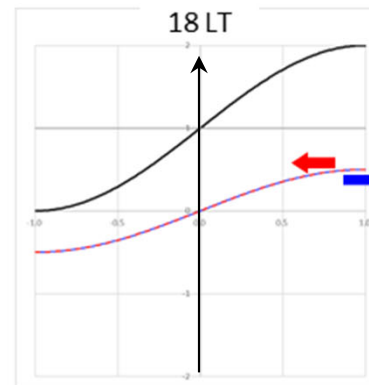
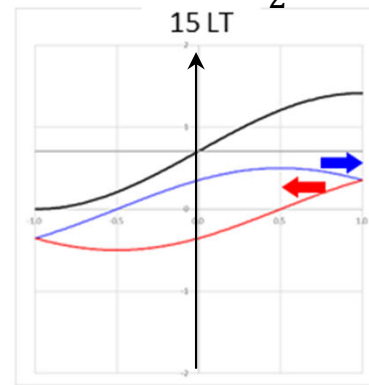
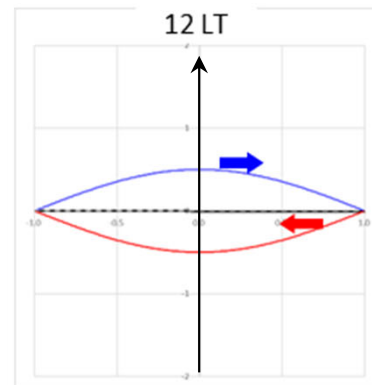


Pilot balloons launched hourly at Batavia (1905–15) (van Bemmelen, 1922)

Wind profiler (BLR) minutely at Serpong (1993–99, 2001–02) (Araki et al., 2006)



$$\theta = \theta_0 - \theta_1 (\sin kx + 1) \sin \omega t = \theta_0 - \frac{\theta_1}{2} [\cos(kx - \omega t) - \cos(kx + \omega t) + 2 \sin \omega t] \quad \text{at } z = 0,$$

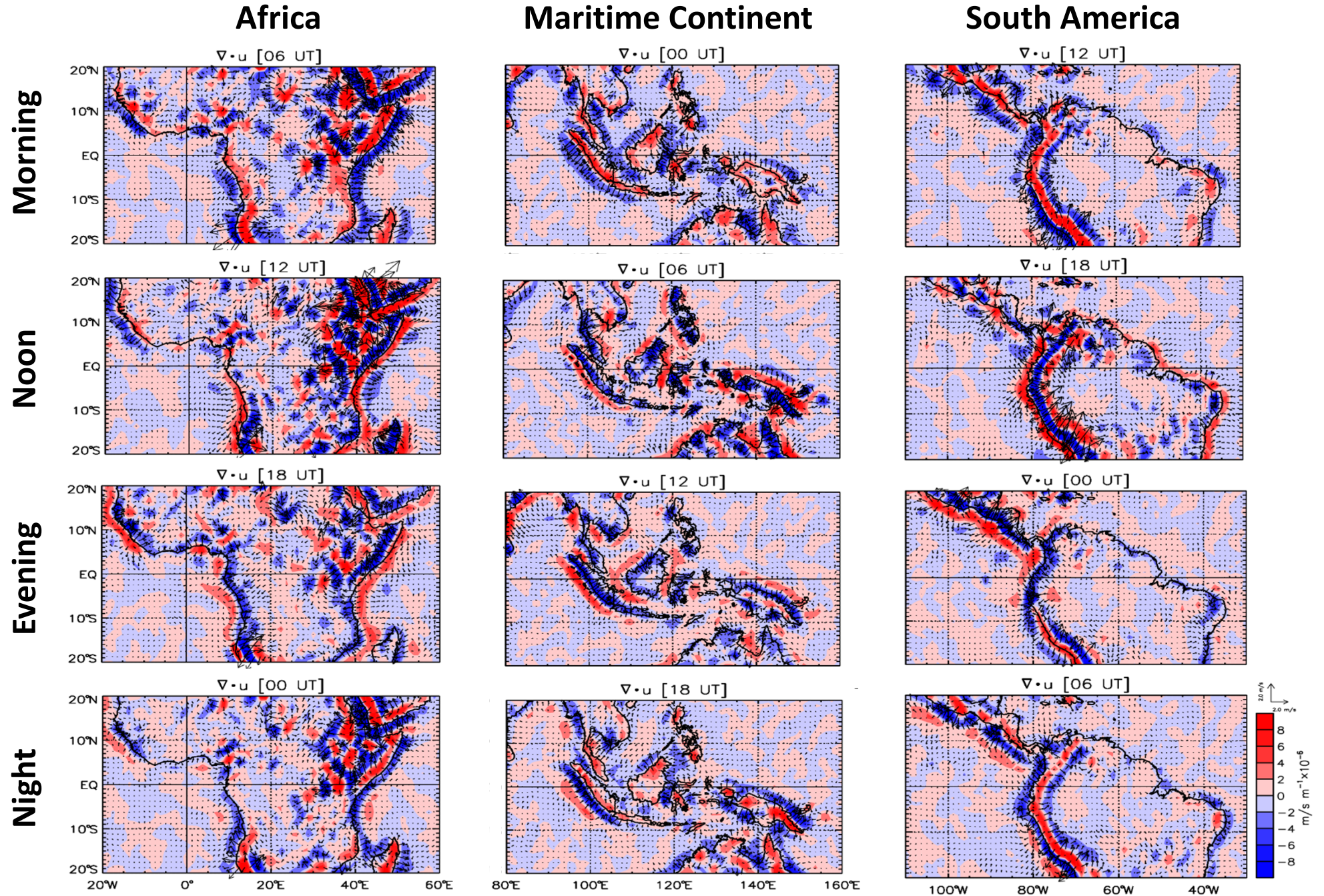


Temperature contrast: Stronger on land / weaker on sea with interannual variations (ENSO/IOD)



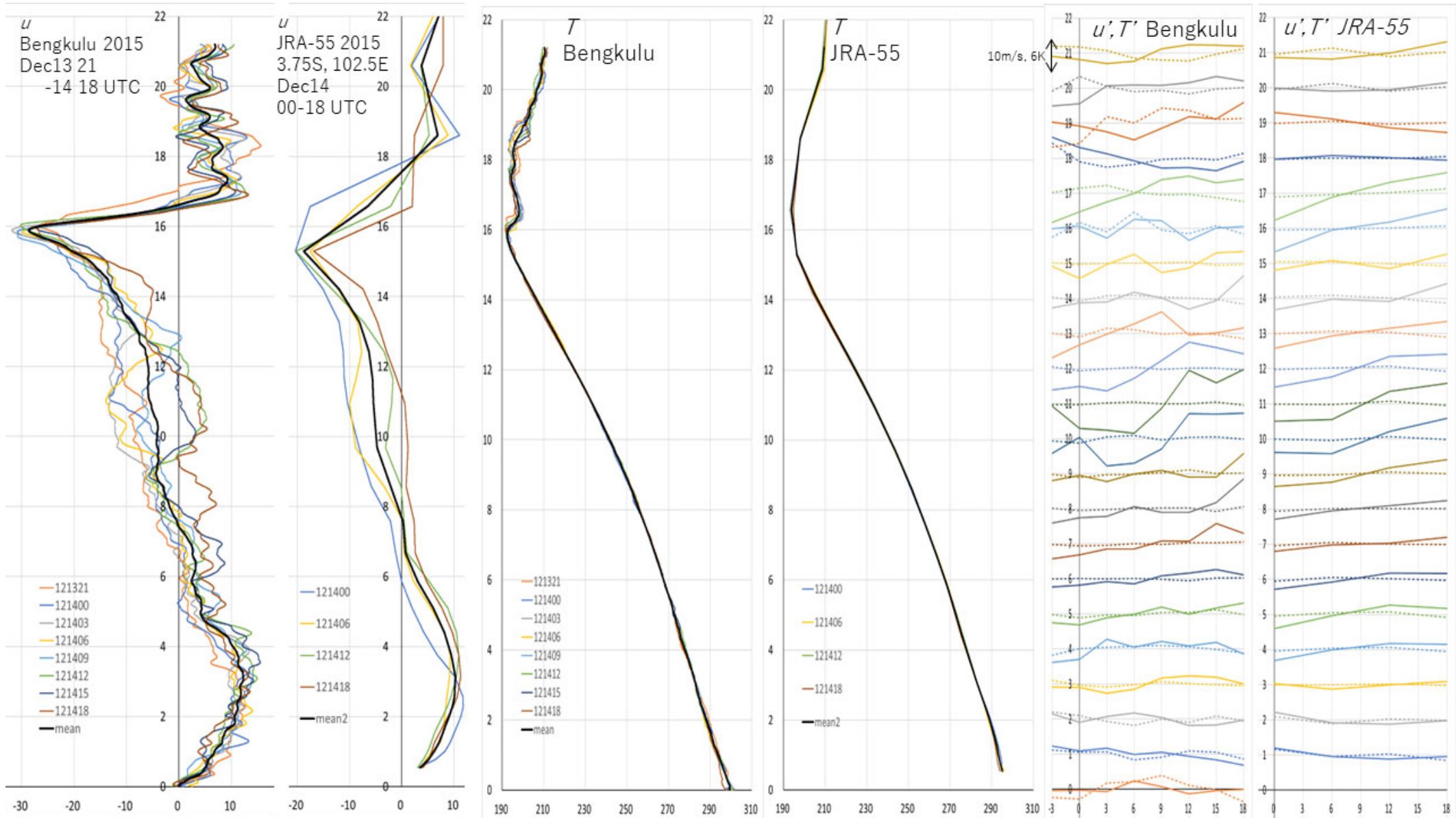
Sea-land breeze circulation = **Bidirectional (land-/sea-ward) gravity waves** + global diurnal tide

40-year (1981–2020) mean longitudinally 30° high-passed anomalies of daily-mean surface wind and horizontal divergence (cold color: ascending)



(Yamanaka and Ogino, 2023, in preparation)

Comparison between 'unreported' radiosondes at Bengkulu and JRA-55



Zonal wind

- Troposphere: well-reproduced
- Stratosphere: vertically coarse

Temperature

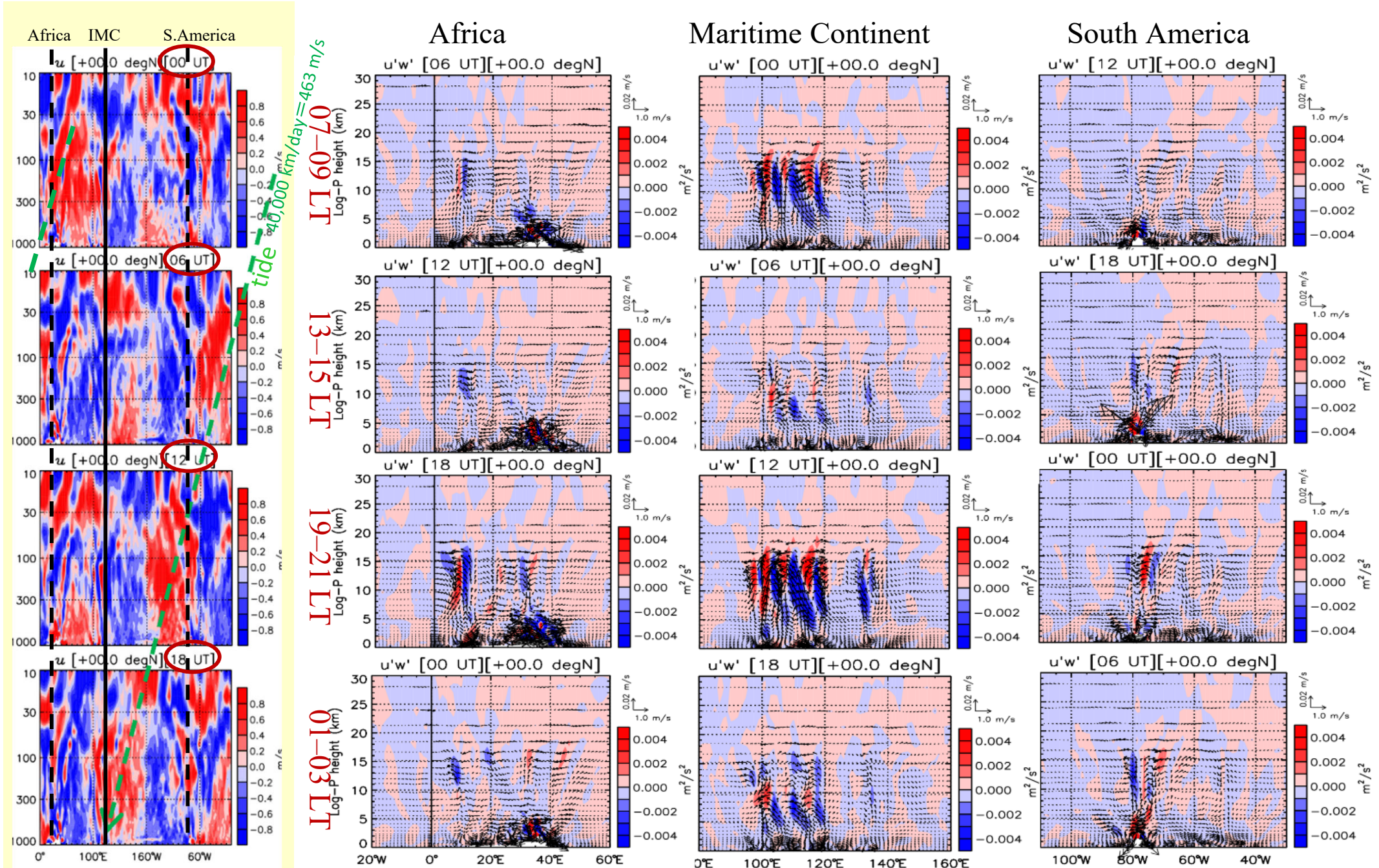
- Troposphere: very accurate
- Surface topography: coarse

Anomaly from daily-mean

- Temperature: much weaker
- Wind: 60%

Diurnal gravity waves underestimated → Large-scale waves overestimated?

Propagation of coastal bidirectional gravity waves in JRA-55



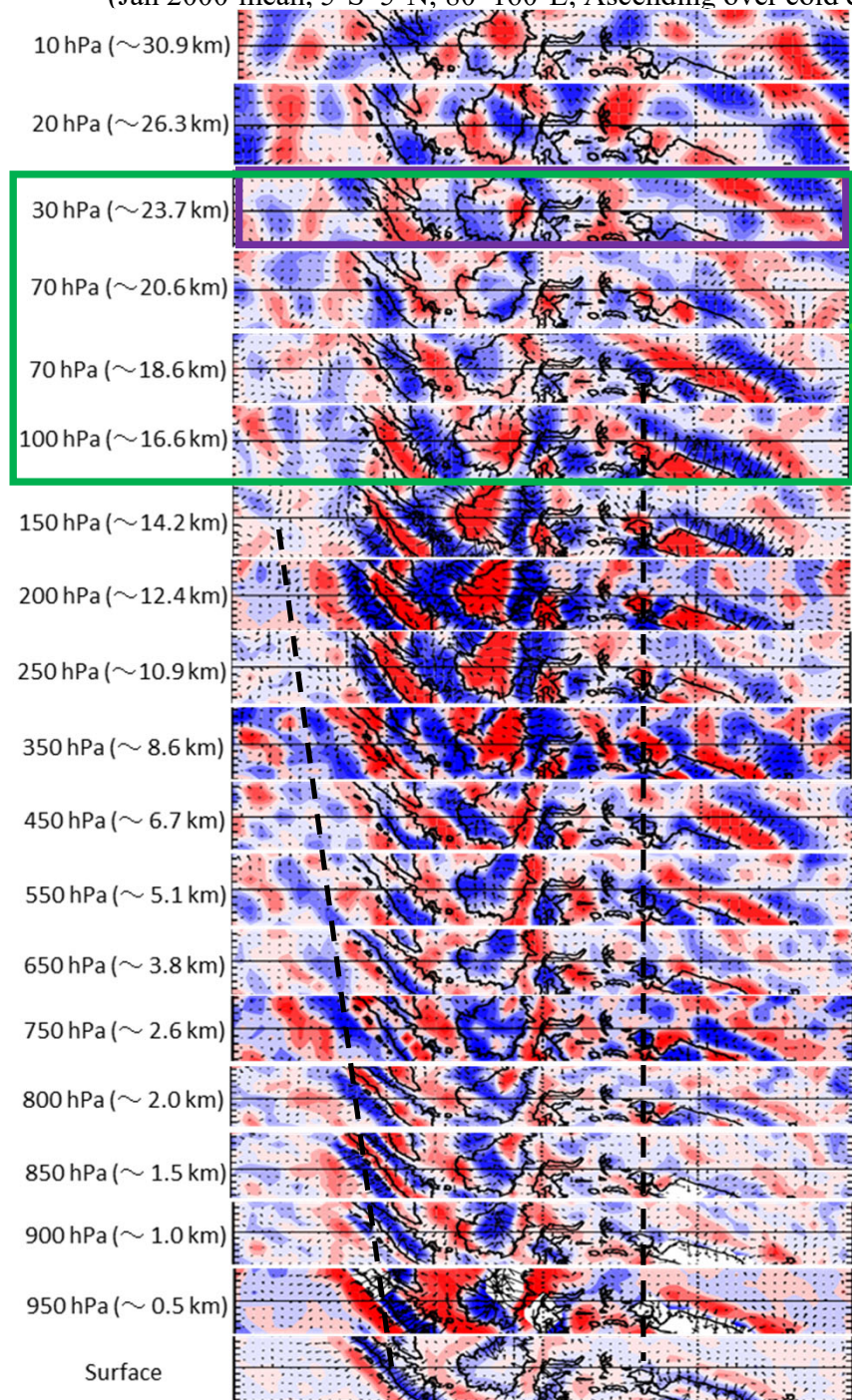
Zonal wind LT anomaly along Equator in Jan 2000 from JRA-55

30°-longitudinal-highpassed mean LT anomaly of zonal-vertical wind (vectors) and their product (contours) along Equator in JRA-55

(Yamanaka and Ogino, 2023, in preparation)

Diurnal gravity waves in JRA-55

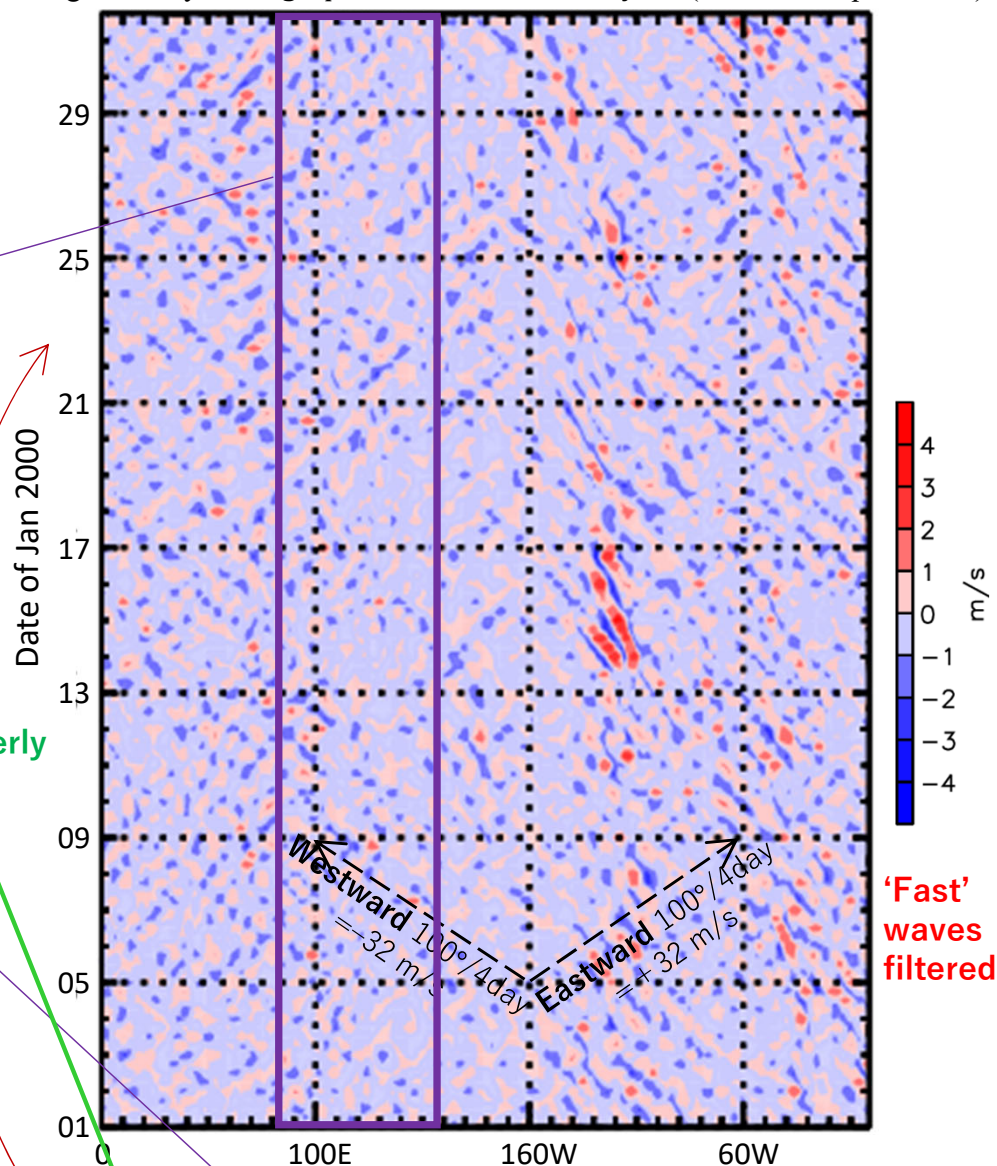
Longitudinally 30° high-passed diurnal anomaly wind & hor.conv. at 12 UT
(Jan 2000-mean, 5°S–5°N, 80–160°E; Ascending over cold color) ^{~19LT}



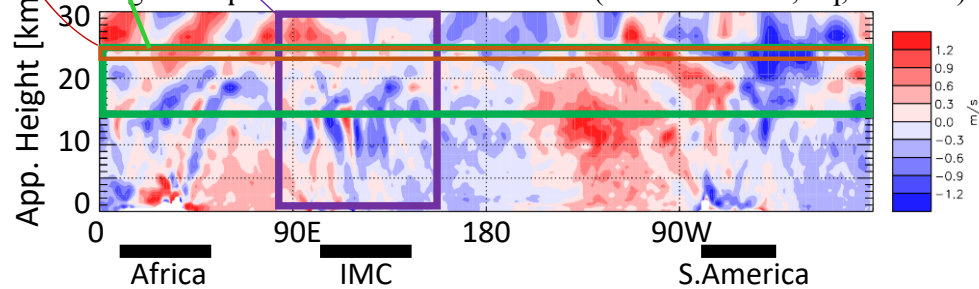
Mean westerly

$$\bar{u} > 0$$

Longitudinally 30° high-passed diurnal anomaly u' (Jan 2000, Eq, 23.7 km)



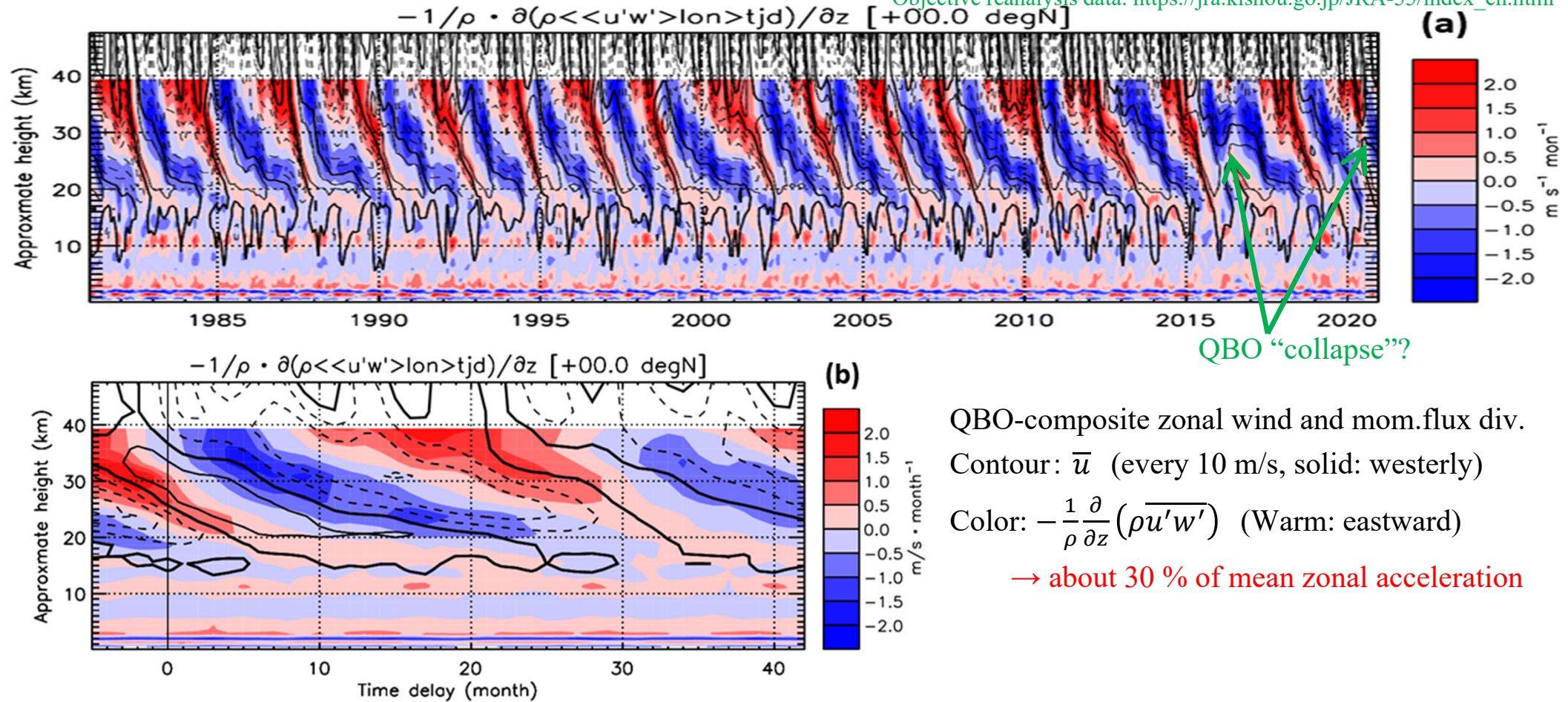
Long.30° h-p diurnal anom. u' at 12 UT (Jan 2000-mean, Eq, 23.7 km)



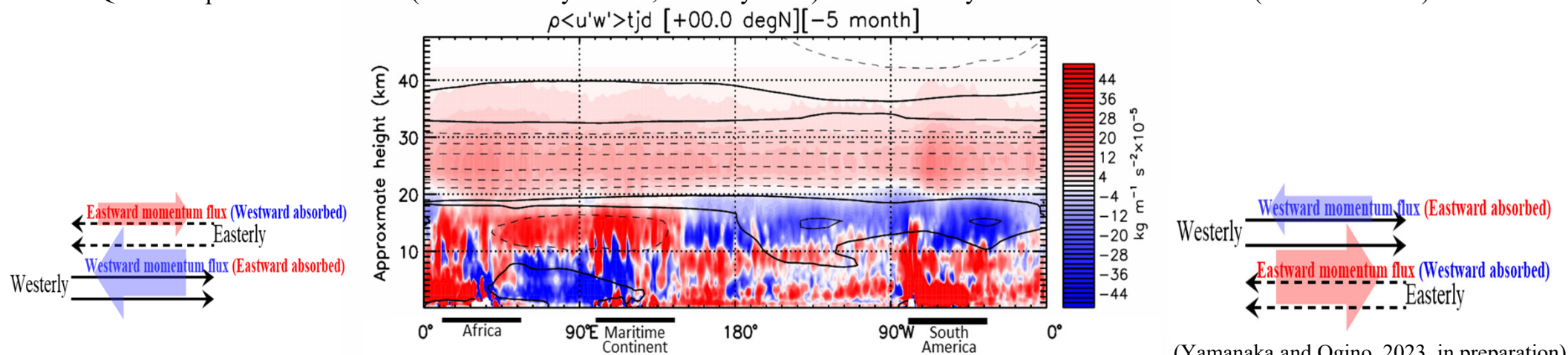
(Yamanaka and Ogino, 2023, in preparation)

Zonal-mean equatorial zonal wind and “diurnal wave” mom.flux div. (JRA-55)

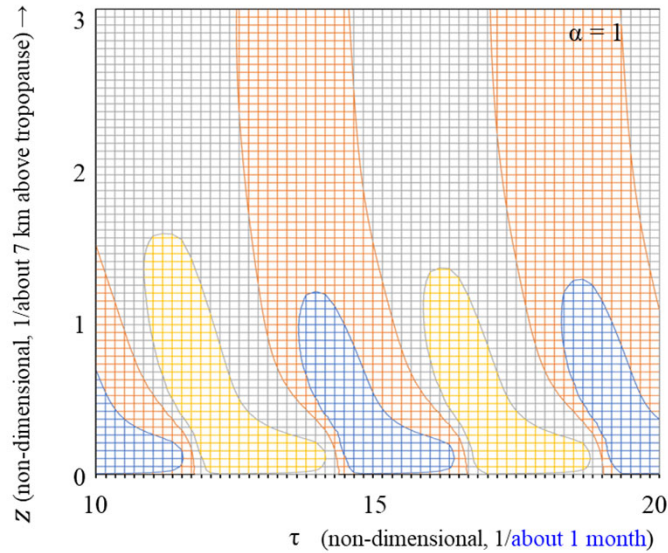
Objective reanalysis data: https://jra.kishou.go.jp/JRA-55/index_en.html



QBO-composited zonal wind (contours every 10 m/s, westerly solid) and diurnal-cycle wave momentum flux (warm eastward)



Application of Plumb's (1977) model



**CDC land-sea temperature
contrast remarkableness**

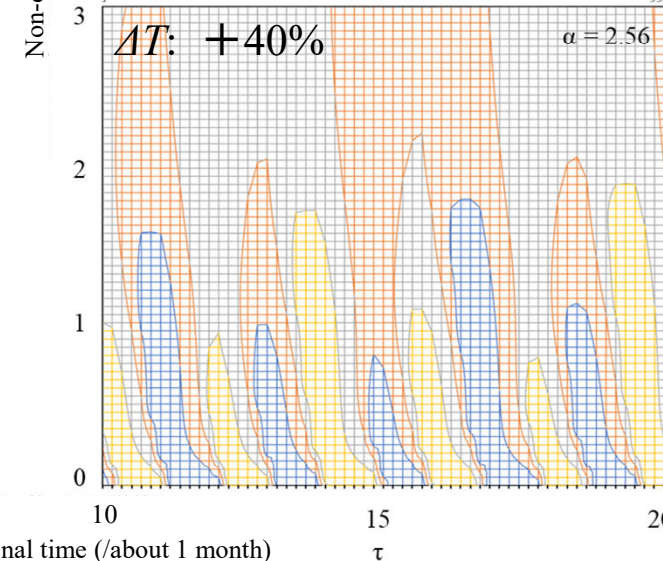
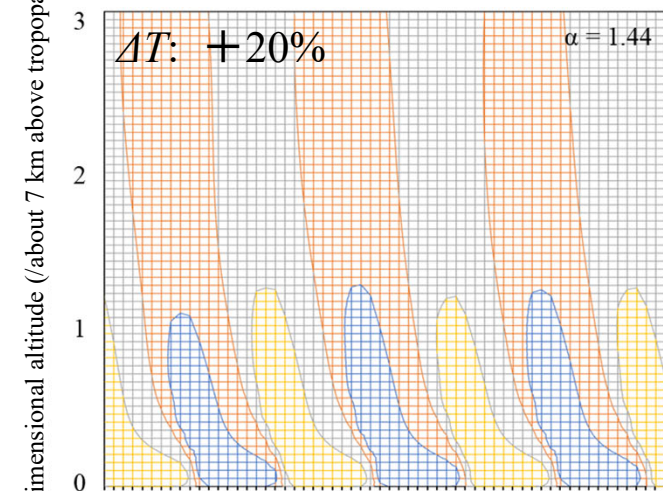
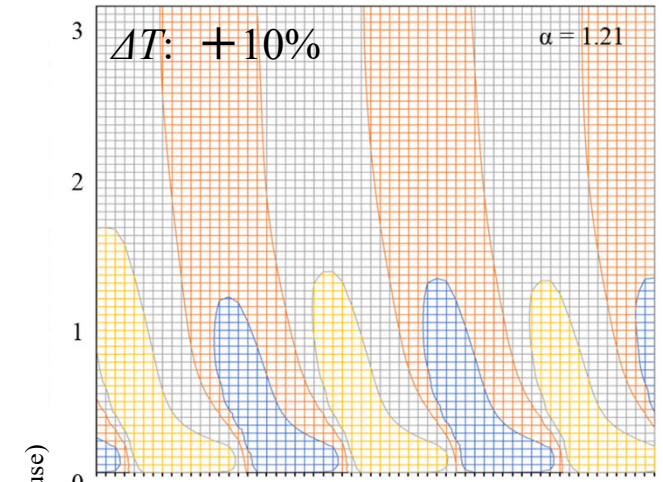
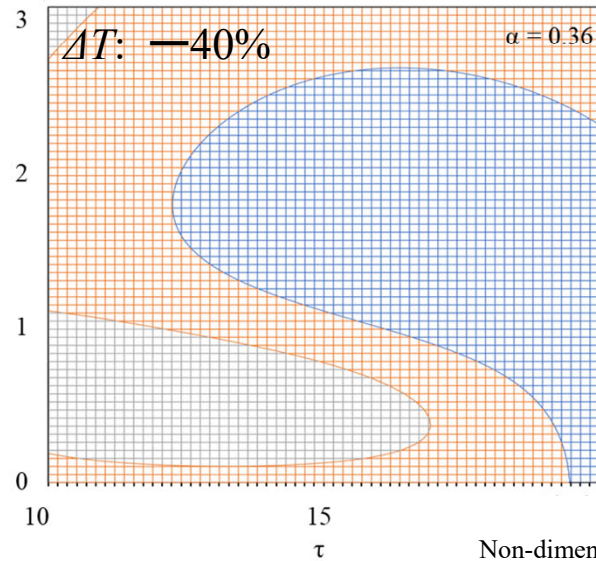
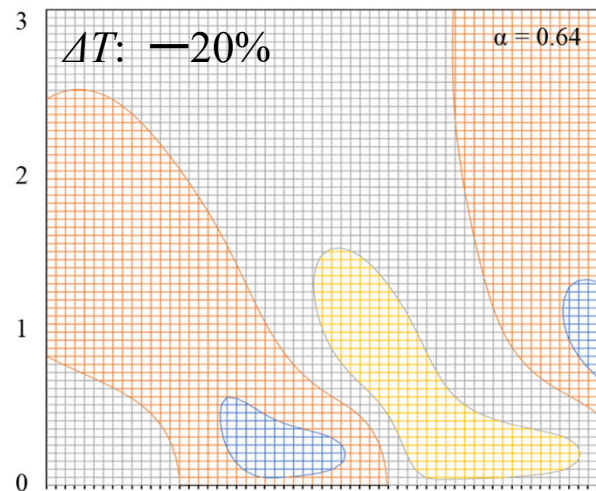
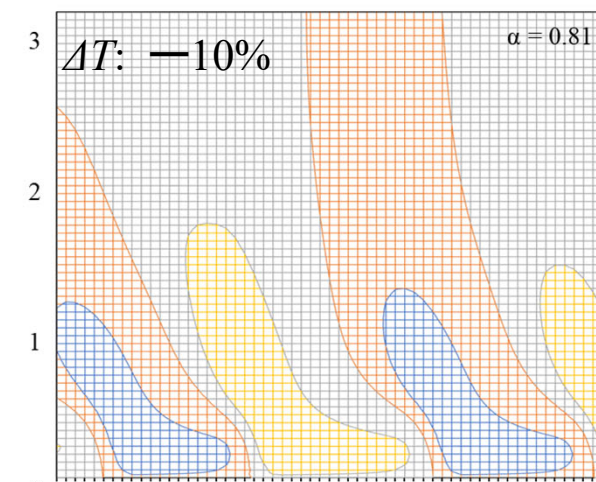


GW momentum flux intensity



QBO period shortening

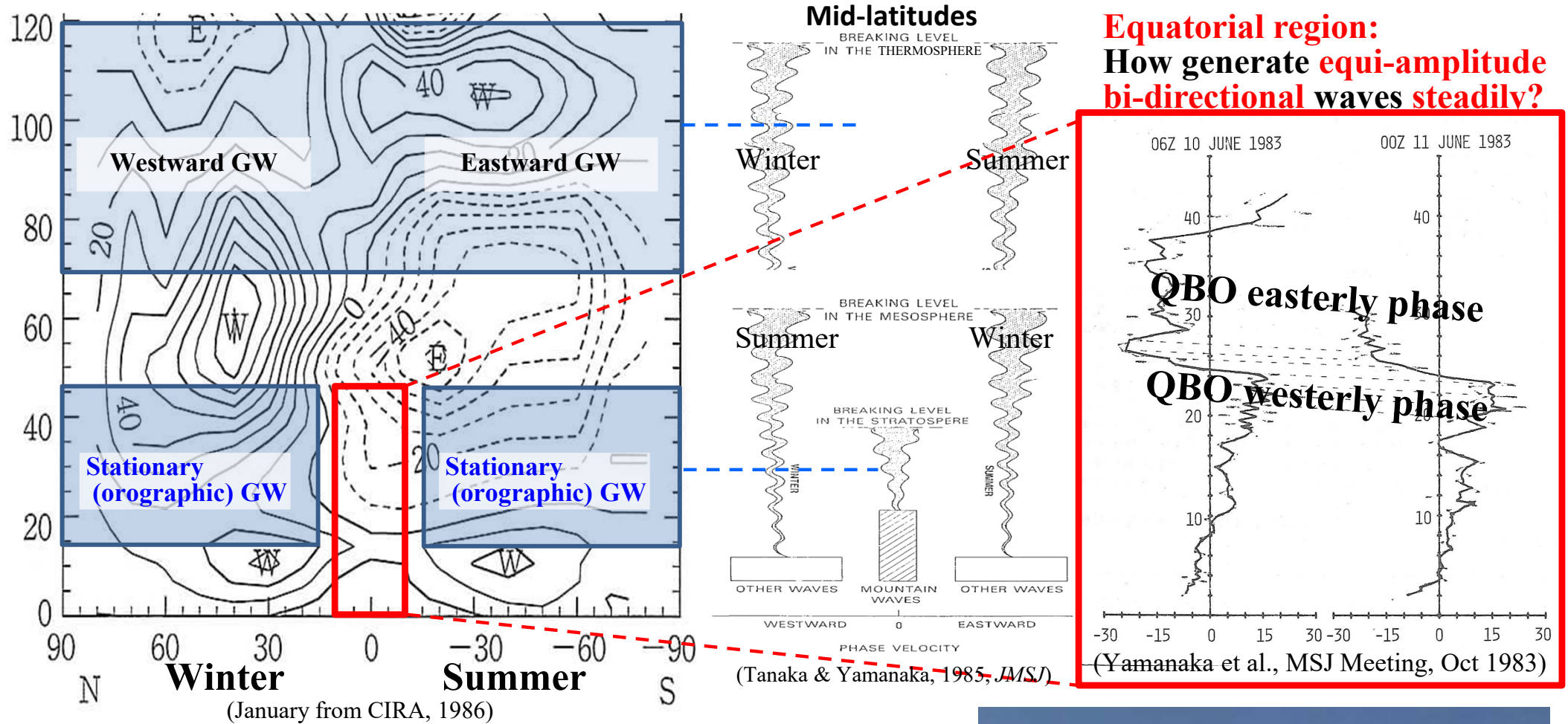
- Land-sea temperature contrast ΔT varying with land conditions and oceanic interannual/intraseasonal variations (ENSO, IOD, MJO).
- No QBO if $\Delta T < -40\%$.
- Double periodicity if $\Delta T > +40\%$.



Non-dimensional time (/about 1 month)

Non-dimensional altitude (/about 7 km above tropopause)

Gravity waves and middle atmosphere dynamics in 1980s



- *Stationary* waves generate *weak* wind layer
- *Traveling* waves generate *inverse* wind layer

Balloons for Solar Eclipse, 11 Jun 1983 at Watukosek, Jawa Timur (NAO, ISAS (now JAXA), LAPAN (now BRIN); started in 1981)

