Dynamic Meteorology and Climatology for Southeast Asia

Brief introduction of "Tropical Meteorology" lecture
at a Japanese university master course

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Chapter 1
Basic principles and applications to SE-Asia

1.1. Why atmospheric dynamics is necessary?

1.2. General principles governing planetary fluid

1.3. Problems in applications to SE-Asia

1.4. How to learn/educate atmospheric dynamics

1.1. Why atmospheric dynamics is necessary?

- Understanding atmospheric phenomena by a small number of physical principles
- Understanding atmospheric/hydrospheric/oceanic phenomena by common physical principles

atmosphere + hydrosphere + ocean ⇒ climate

- Numerical weather/climate prediction
- Improving operational efficiency

1.2. General principles governing planetary fluid

- Planetary (or geophysical) fluid: Gas/liquid under
  - sphericity: a＝6370 km (for the earth)
    - latitude ϕ, longitude λ, altitude z
      - eastward displacement: $dx = a \cos\phi \, d\lambda$
      - northward displacement: $dy = a \, d\phi$
  - rotaion: $\Omega = 2\pi/86164$s (for the earth)
    - Coriolis parameter: $f = 2\Omega \sin\phi$
    - Rossby parameter: $\beta = df/dy = 2\Omega \cos\phi$
  - gravitation: $g = 9.8$ m/s^2 (for the earth)
- Variables: (6 for dry atmosphere)
  - wind (or stream) velocity components: (u, v, w)
  - thermodynamical state variables: (T, p, ρ)

[- humidity (or salinity): q]

Mathematical formulation of basic principles

- Mass conservation (continuity):

$$\partial u/\partial x + \partial v/\partial y + \rho^{-1}\partial \rho w/\partial z = 0$$

- Momentum conservation (Newton's 2nd law):

$$du/dt - fv + \rho^{-1}\partial p/\partial x = F_x$$
$$dv/dt + fu + \rho^{-1}\partial p/\partial y = F_y$$
$$dw/dt + \rho^{-1}\partial p/\partial z = g$$

For atmosphere:

- Entropy conservation (1st law of thermodynamis):

$d\Theta/dt = Q/T$ [potential temperature.: $\Theta = T(p_{00}/p)^{R/Cp}$]

- Ideal gas equation (Boyle-Charles' law):

$$\rho^{-1}p = RT$$

For moist atmosphere:

- Continuity for humidity $q \Rightarrow$ Virtual temperature T_v

Everything must be expressed by a <u>superposition of solutions</u> of above 6 (7) equations!

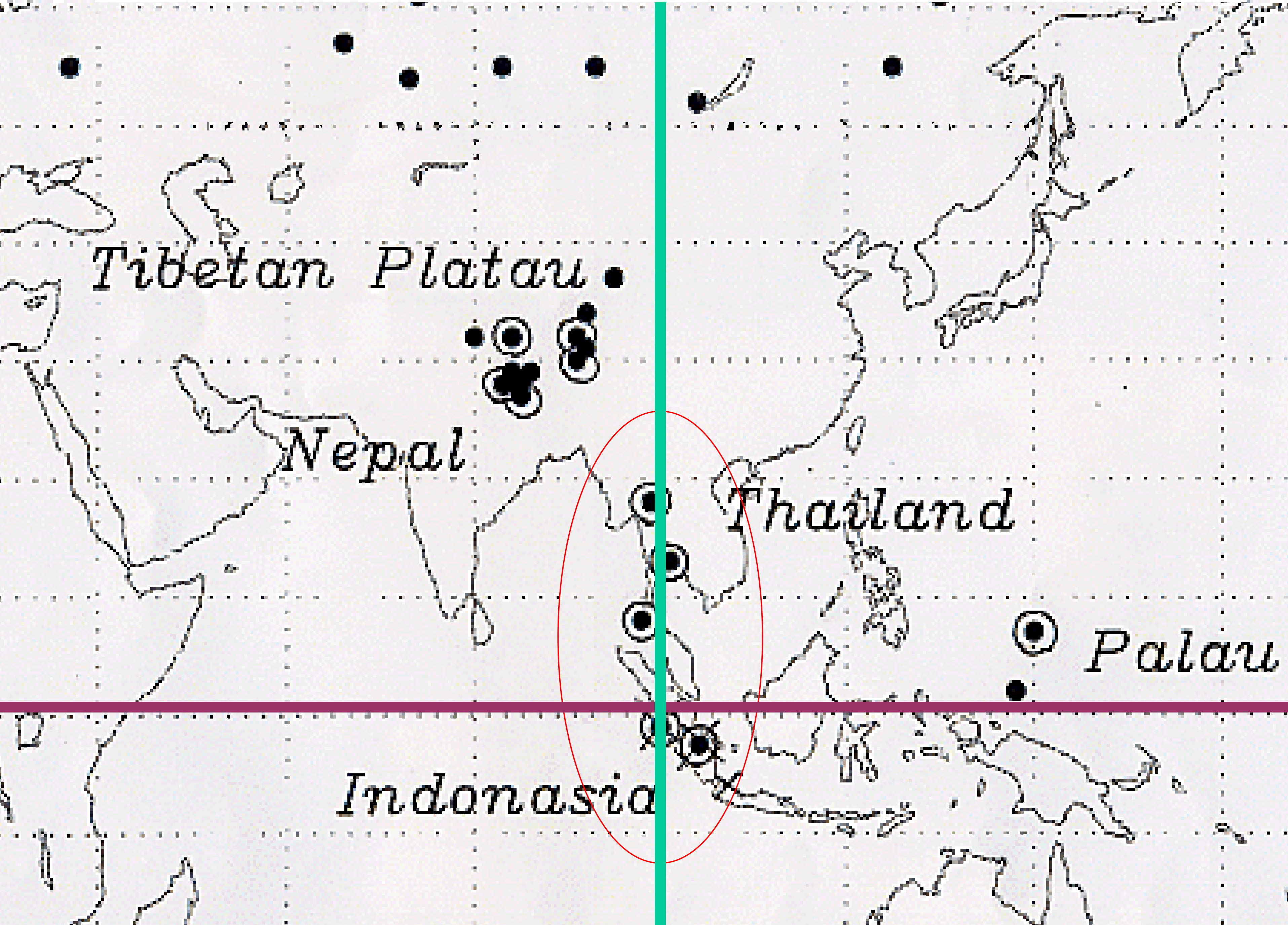
1.3 Problems in applications to SE-Asia

- Low latitude: small f (but not $\boldsymbol{\beta}$)
- High solar azimuth: Q with diurnal periodicity
  ⇒ barotropic (relatively high horizontal homogenuity)
  relatively weak seasonal variation
- High humidity: Q by latent heating
  ⇒ cloud convection, intraseasonal variations
- Complex geography: sea-land, mountain-valley, ...
  ⇒ local circulation
- Interaction with ocean
  ⇒ interannual variations

↓

Seemingly less usefulness of atmospheric dynamics

The Indochina-Sumatera Sector



1.4. How to learn/educate atmospheric dynamics

- Training of basic physics/mathematics

  (Principles are not so many! Learn them with reading papars.)

- Textbooks of mainly mid-latitude atmospheric dynamics, e.g.,

  - J.R.Holton, "An Introduction to Dynamic Meteorology", 3rd Ed., Academic Press, 1992.
  - A.E.Gill, "Atmosphere-Ocean Dynamics", McGraw-Hill?, 1982
  - R.S.Lindzen, "Dynamics in Atmospheric Physics", Cambridge University Press, 1990.
  - ･･･

- Texbooks of general meteorology with dynamical aspects:

  - D.G.Andrews, "An Introduction to Atmospheric Physics", Cambridge University Press, 2000?
  - M.L.Salby, "Fundamentals of Atmospheric Physics", Academic Press, 1996.
  - ･･･

- Textbooks of tropical meteorology/climatology without dynamics
- Environmental/geographical and geochemical knowledges

+

- Deep theoretical consideration
- Strong wishes for numerical prediction
- Spirits to establish a new meteorology

Curriculum in Dept. of Earth-Planetary Science, Kobe University

Undergraduate course: 1st/2nd years:

- Basic physics, mathematics, …
- General introduction to earth and planetary science
- Mathematical physics/computers for EPS (including exercises)

Undergraduate course: 3rd/4th years: (Students are requested to have special subjects.)

- Geophysical fluid dynamics
- Atmosphere-hydrosphere sciences
- Experiments for atmosphere-hydrosphere sciences (mainly observations)

Master course (2 years after graduation of BSc.):

- Introduction to global environmental sciences
- Mid-latitude synoptic-scale meteorology
- <u>Tropical meteorology</u>

PhD course (additional 3 years after taking MSc):

- Physical climatology of earth and other planets
- Planetary fluid physics (mainly atmosphere-ocean interaction dynamics)
- Special topics on atmosphere/hydrosphere/ocean sciences

Special lectures (4 outside scientists /year)

Seminars and colloquia

Chapter 2
Statics of moist atmosphere in tropics

2.1. Hydrostatic equilibrium

2.2. Radiative-convective equilibrium

2.3. Moisture and conditional instability

2.1. Hydrostatic equilibrium

- Horizontally homogeneous:

  $u \sim v \sim w \sim 0\,, \quad F \sim Q \sim 0$

  $-g\rho + \partial p/\partial z = 0$

  with the ideal gas equation $\rho = p/RT$

  $\Rightarrow \quad p = p_0 \exp(-z/H)\,,$

  scale hight: $H = RT/g$

- Pressure coordinate

  "omega velocity": $\omega = dp/dt = -g\rho w$

- Log-pressure coordinate:

  $\partial p/\rho = gH\partial \ln p \rightarrow -g\partial z^*\,, \quad g\partial z \rightarrow \partial\Phi$

  $\Rightarrow \quad \partial\Phi/\partial z^* = RT/H$

  p in momentum eqs. are also rewritten by Φ

  z^* may be conventionally regarded as z

2.2. Radiative-convective equilibrium

- Radiative equilibrium

  $Q = \partial/\partial z\,[S + I^{\uparrow} - I^{\downarrow}] = 0$

  (S∼0 for $z \neq 0$, ozone layer)

  $\Rightarrow \partial/\partial p\,[\sigma T^4] \sim S/p_1$

  $\Rightarrow -\partial T/\partial z$ increases downward

- Convective equilibrium (adjustment)

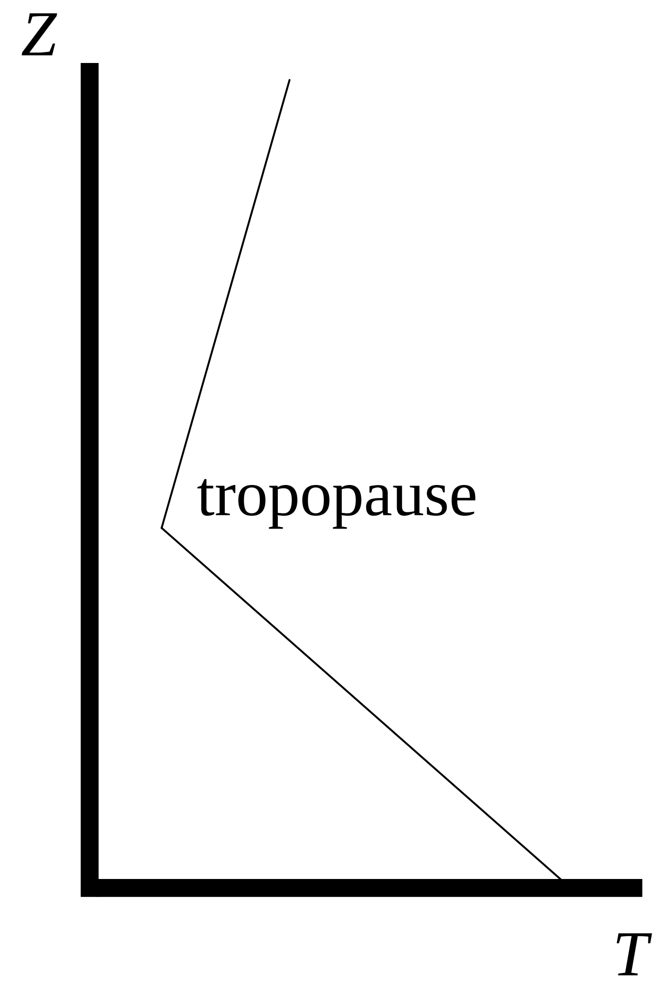
  $\partial\Theta/\partial z = 0$

  $\Rightarrow$ (dry) adiabatic lapse rate:

  $-\partial T/\partial z = g/C_p$ 10 K/km

- Separation of stratosphere (radiative)

  and troposphere (convective)



2.3. Moisture and conditional instability

Water vapor → IR absorption (warming)

Cloud → Solar rad. reflection (cooling)

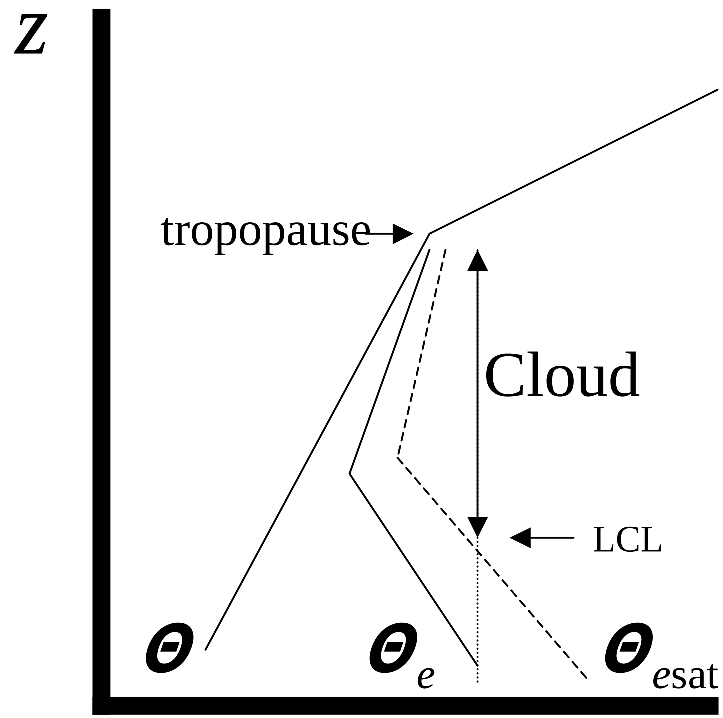
Latent heating

$$\partial \Theta / \partial z = Q_{latent}/T$$

$$\Rightarrow \partial \Theta_e / \partial z = 0$$

⇒ moist adiabatic lapse rate:

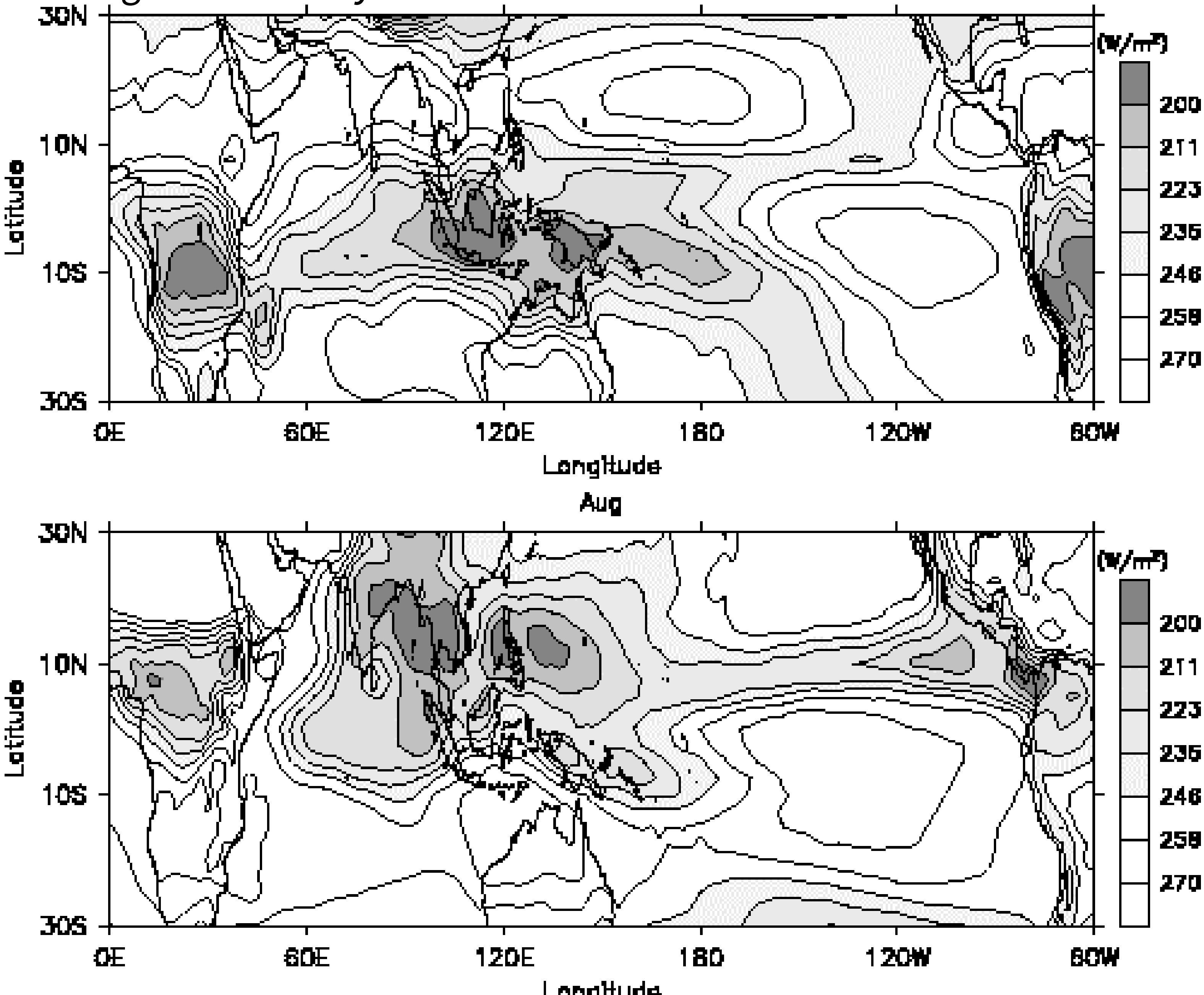
$$-\partial T/\partial z \quad 5\ \text{K/km}$$



(1979–95)

OLR longterm monthly mean

Jan



Chapter 3
Zonal-mean dynamics and meridional circulations

3.1. Equatorial easterly (trade wind)

3.2. Hadley circulation and ITCZ

3.3. Monsoon circulation

[3.4. Brewer-Dobson circulation and stratospheric ozone transport]

Axi-symmetric dynamics

- Zonally homogeneous:

$$\partial u/\partial t - f v = F$$

(angular momentum $u - fy$ conserv. → Equatorial easterly)

$$+ f u + \partial \phi/\partial y = 0$$

$$- (R/H)\, T + \partial \phi/\partial z = 0$$

$$\partial T/\partial t + (R/H)\, N^2 w = Q$$

$$\partial v/\partial y + \rho^{-1} \partial \rho w/\partial z = 0$$

⇒ "Thermal-wind" equilibrium: (without necessity of merid. circ.)

$$f\, \partial u/\partial z + (R/H)\, \partial T/\partial y = 0$$

(poleward temperature decrease → upward easterly decrease)

Near the equator ($f \to 0$):

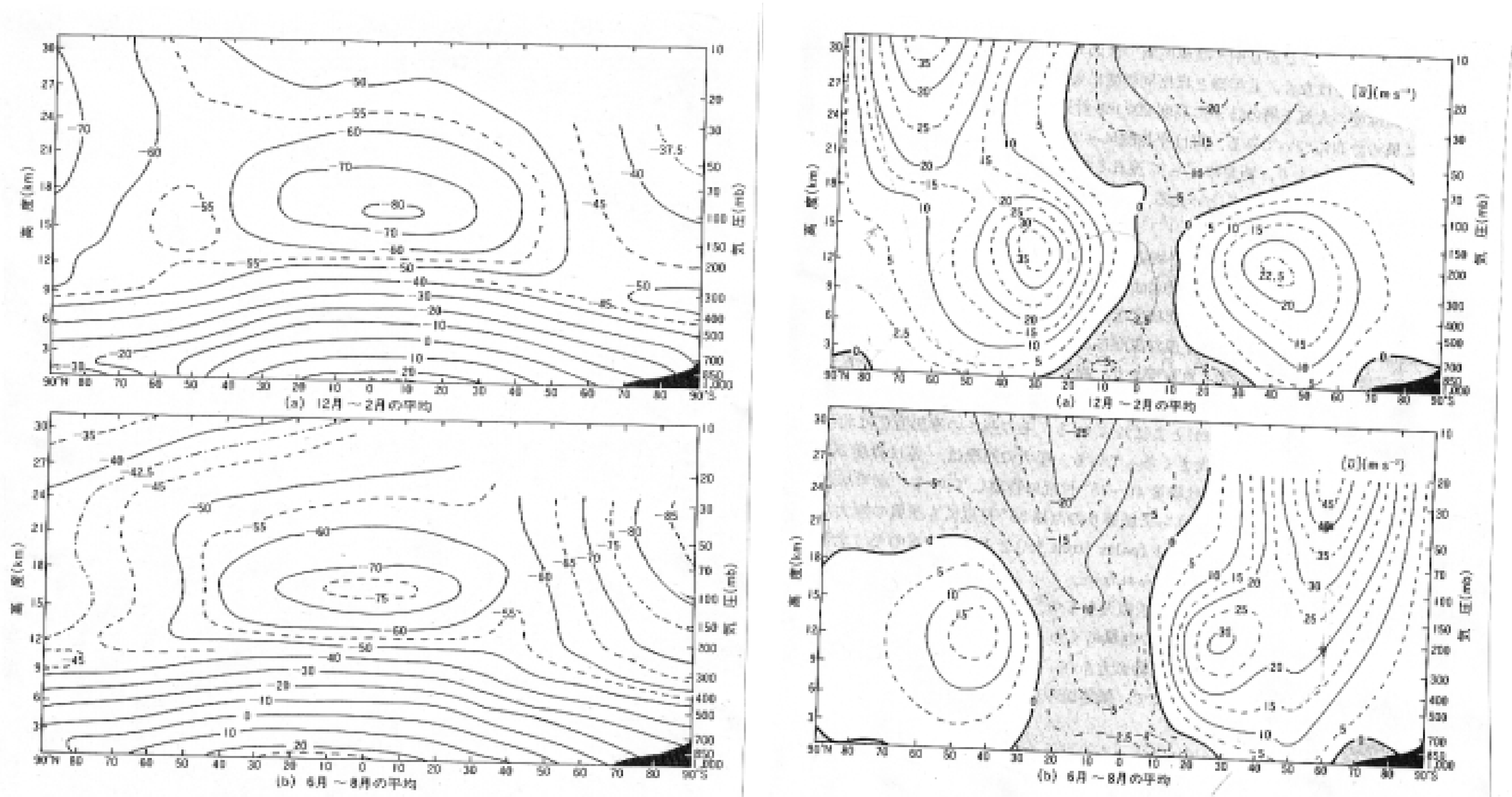
$$\beta\, \partial u/\partial z + (R/H)\, \partial^2 T/\partial y^2 = 0$$

- Slowly time-dependent: $\partial/\partial t \sim 0$

⇒ $v \sim -F/f$, $w \sim (H/R) N^{-2} Q \sim Q/\Gamma$

- Friction on easterly induces an equatorward flow.
- Heating induces an upward flow. → Meridional circulation

Zonal-mean temperature and zonal wind



Upper troposphere: Poleward temperature increase → upward easterly increase

Lower troposphere: Poleward temperature decrease →upward easterly decrease

Meridional Circulations

- Governing equation:

$$[\partial^2/\partial y^2 + (f/N)^2 \cdot \partial^2/\partial z^2] \cdot \psi = G$$

$$v = -\partial\psi/\partial z, \quad w = \partial\psi/\partial y$$

- Symmetric forcing: $G \sim -\sin ly \sin mz$

⇒Hadley circulation: $\psi \sim \sin ly \sin mz$

$(v \sim -\sin ly \cos mz,\ w \sim \cos ly \sin mz)$

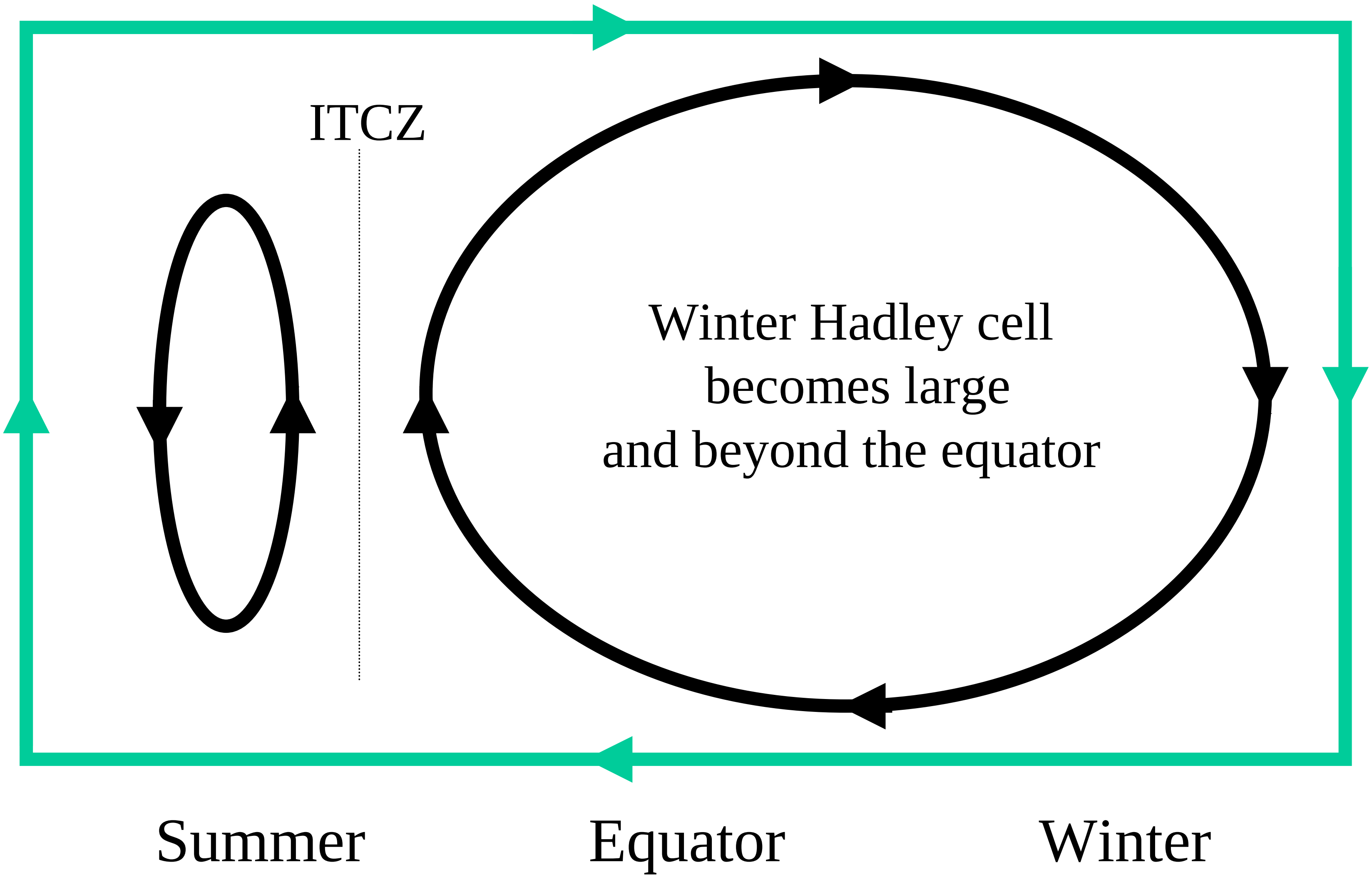
- Antisymmetric forcing: $G \sim \cos ly \sin mz$

⇒ Monsoon circulation: $\psi \sim -\cos ly \sin mz$

$(v \sim \cos ly \cos mz,\ w \sim \sin ly \sin mz)$

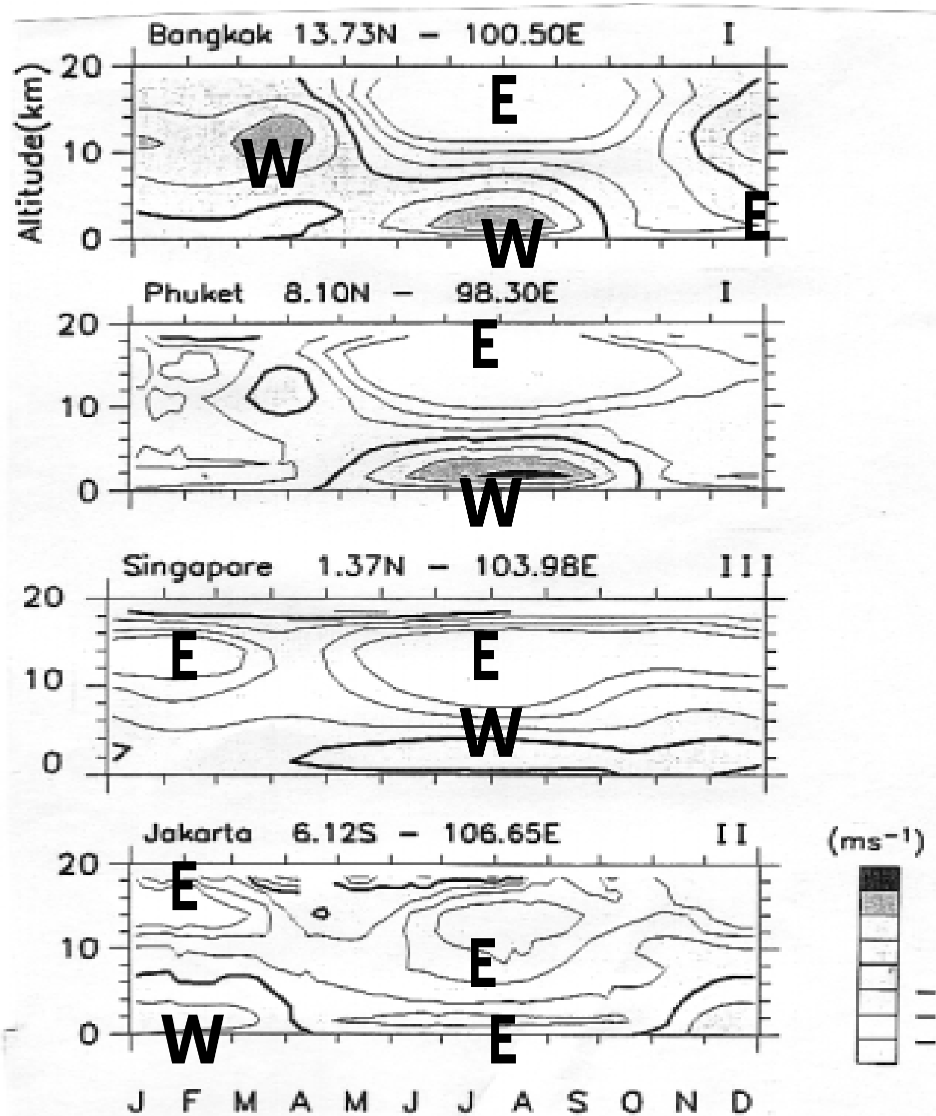
(For details, Holton, Chapter 10)

Monsoon and Hadley circulations

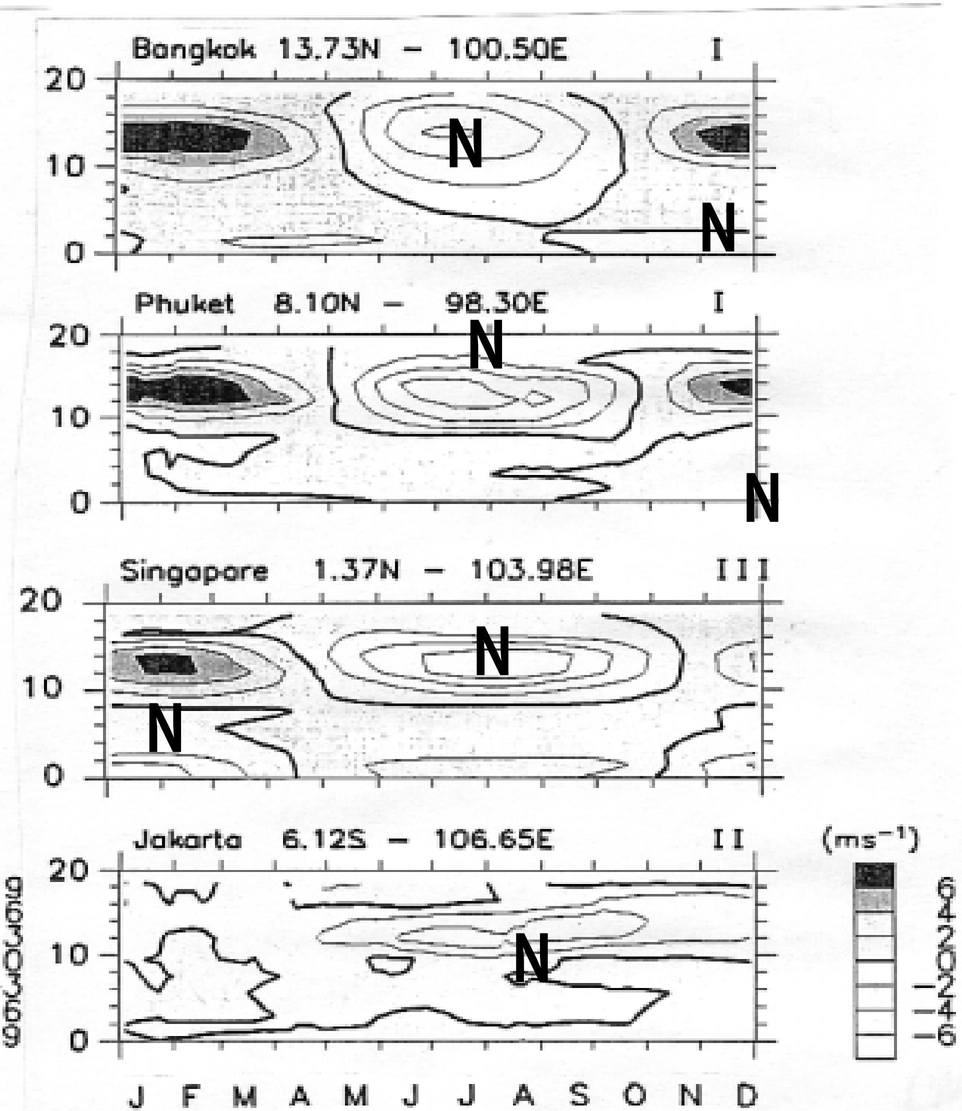


Seasonal-vertical variations

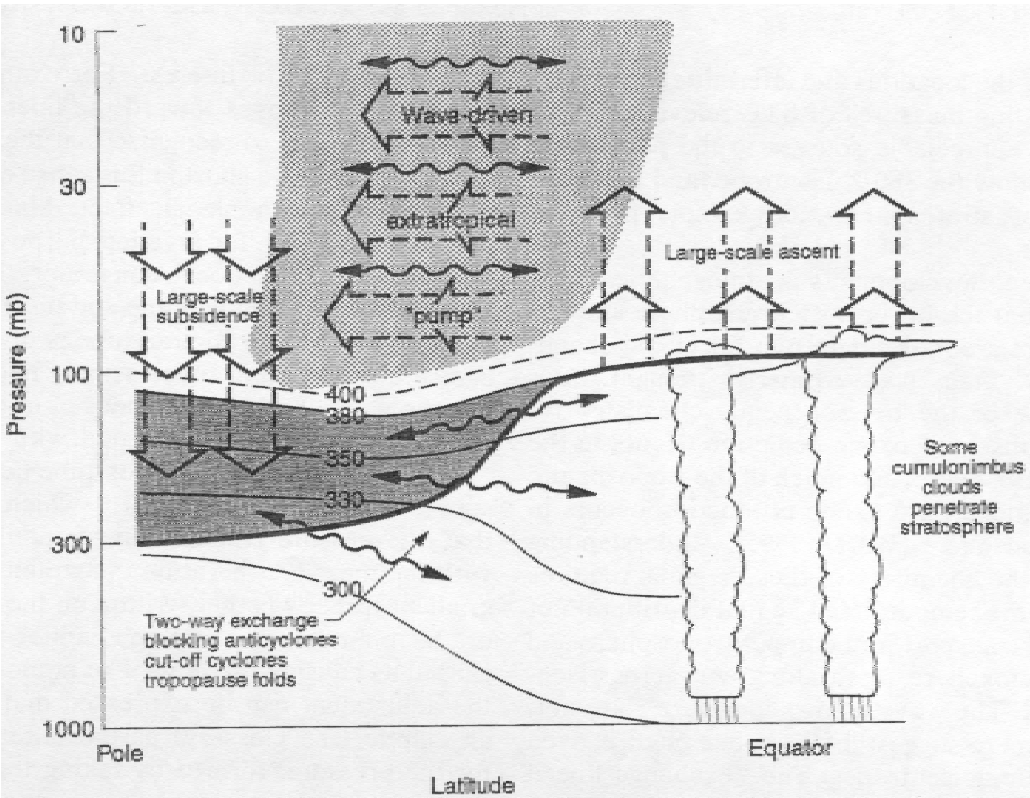
Zonal Wind
(affected by Monsoon)



Meridional Wind
(Hadley +Monsoon)



Stratospheric response to tropospheric convection



(Holton, 1995)

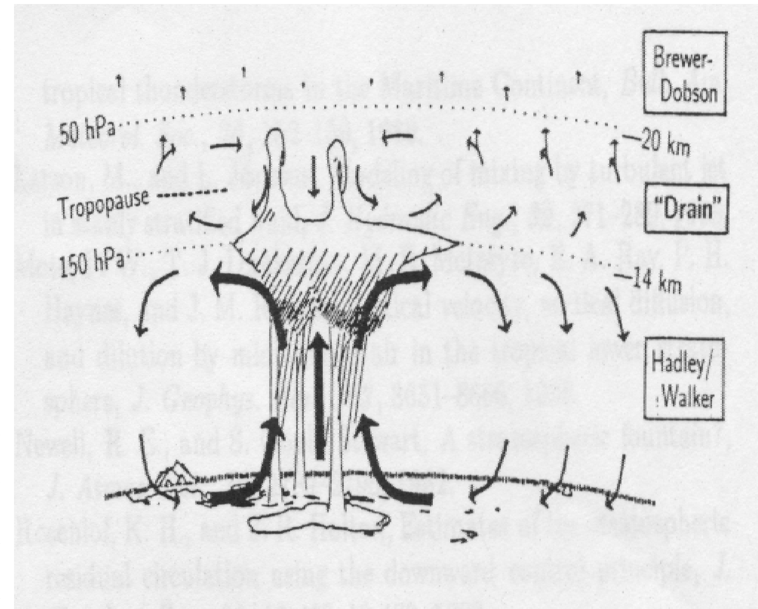


Figure 4. Illustration of the diabatic mean flow (arrows) and its relationship to the locations of deep convection and convective outflows.

(Sherwood, 2000)

Chapter 4
Equatorial wave dynamics and ENSO

4.1. Equatorial waves

4.2. Matsuno-Gill pattern and Walker circulation

4.3. Atmosphere-ocean interaction and ENSO

[4.4. Wave-mean flow interaction and QBO]

4.1. Equatorial waves

- Perturbation equations: ($u \rightarrow u + u'$, etc.)

$$\partial u'/\partial t - \beta y\, v' + \partial \phi'/\partial x = 0$$
$$\partial v'/\partial t + \beta y\, u' + \partial \phi'/\partial y = 0$$
$$-(R/H)\, T' + \partial \phi'/\partial z = 0$$
$$\partial T'/\partial t + (R/H)\, N^2\, w' = 0$$
$$\partial v'/\partial y + \partial v'/\partial y + \rho^{-1} \partial \rho\, w'/\partial z = 0$$

- Three $\partial/\partial t$ $\Rightarrow$ 3 types of solutions:

  Eastward/westward propagating <u>inertio-gravity waves</u>

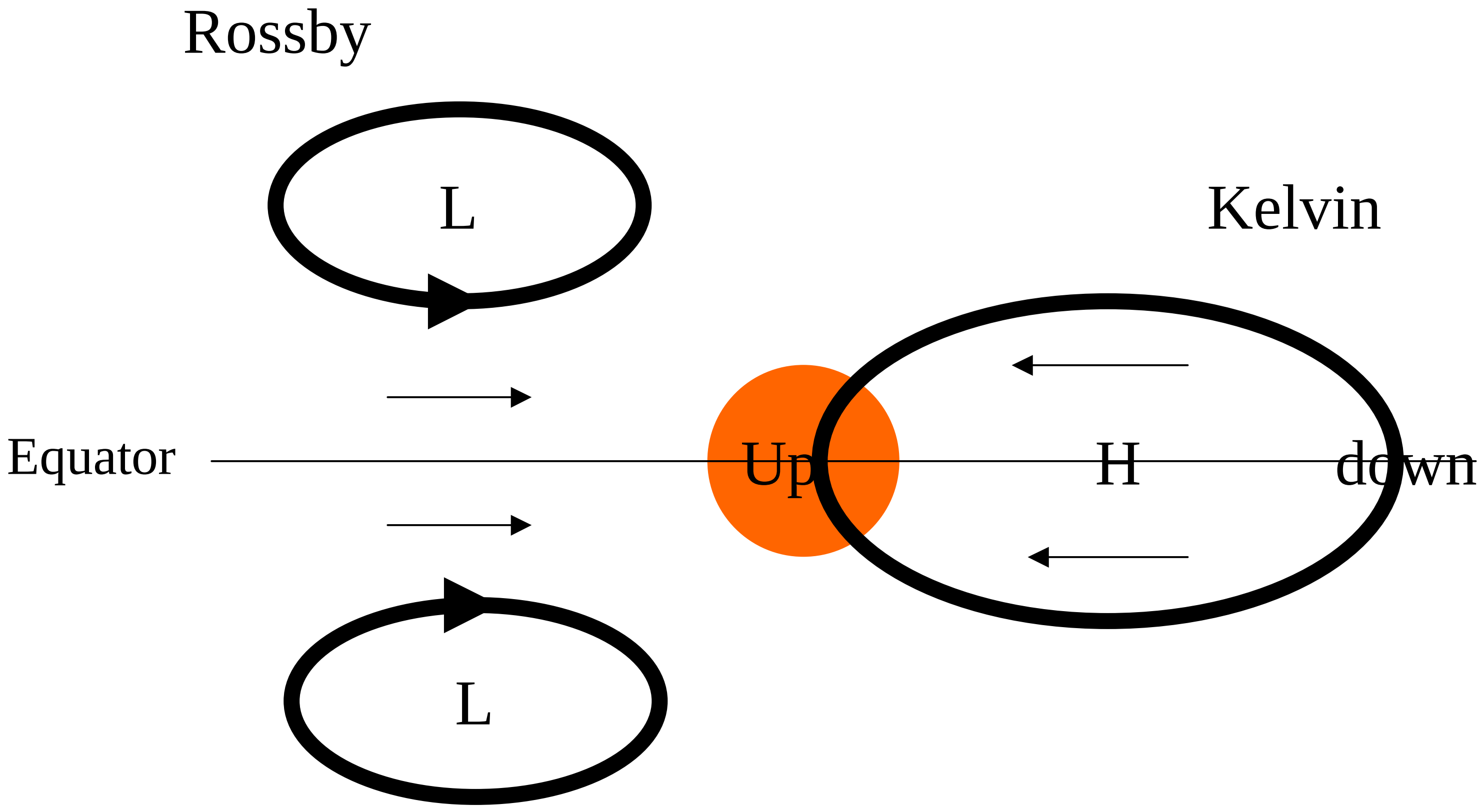
  Westward propagating <u>Rossby waves</u>

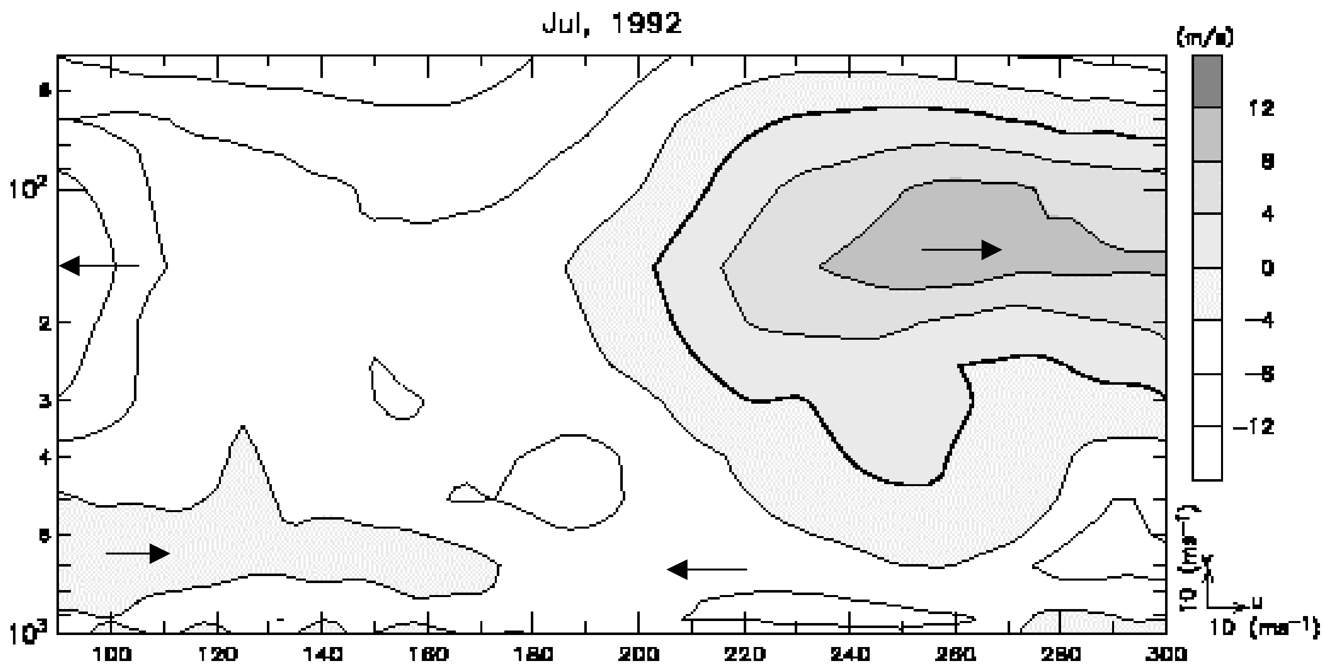
- Hermit equation and exact solutions
  including singular solutions: (Matsuno, 1966)

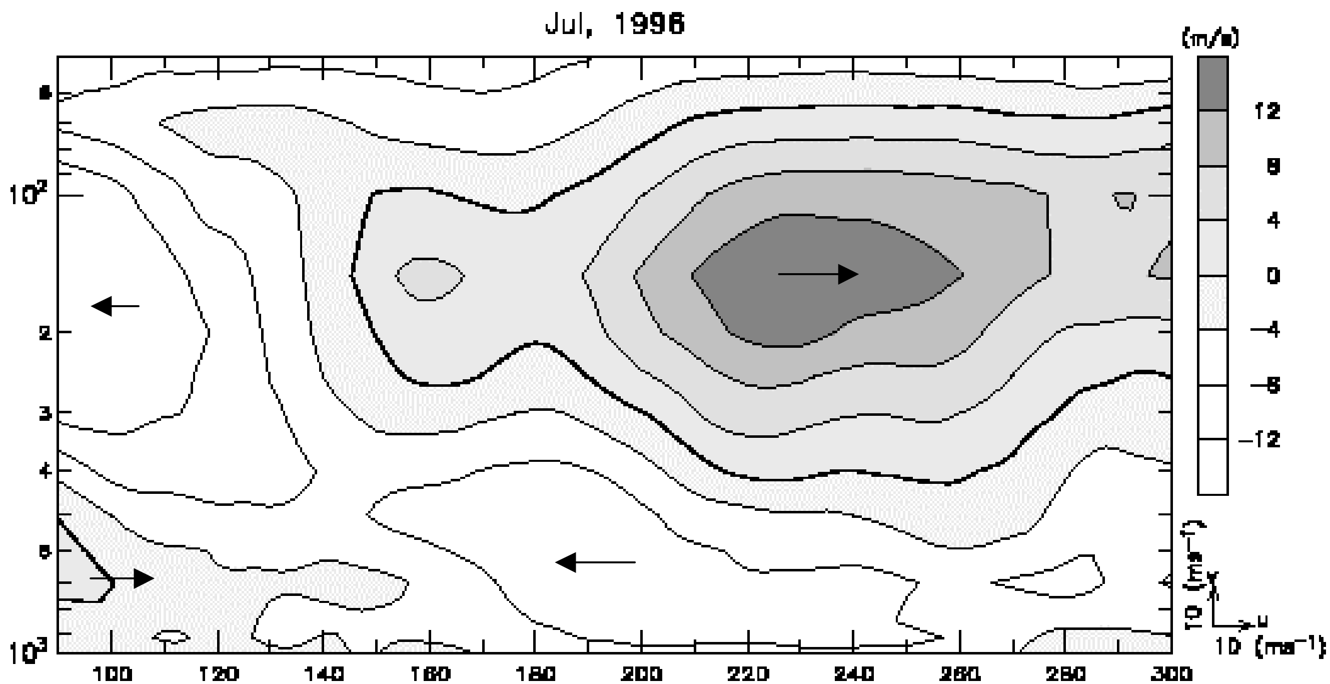
  Westward propagating <u>mixed Rossby-gravity waves</u>

  Eastward propagating <u>Kelvin waves</u>

4.2. Matsuno-Gill pattern and Walker circulation





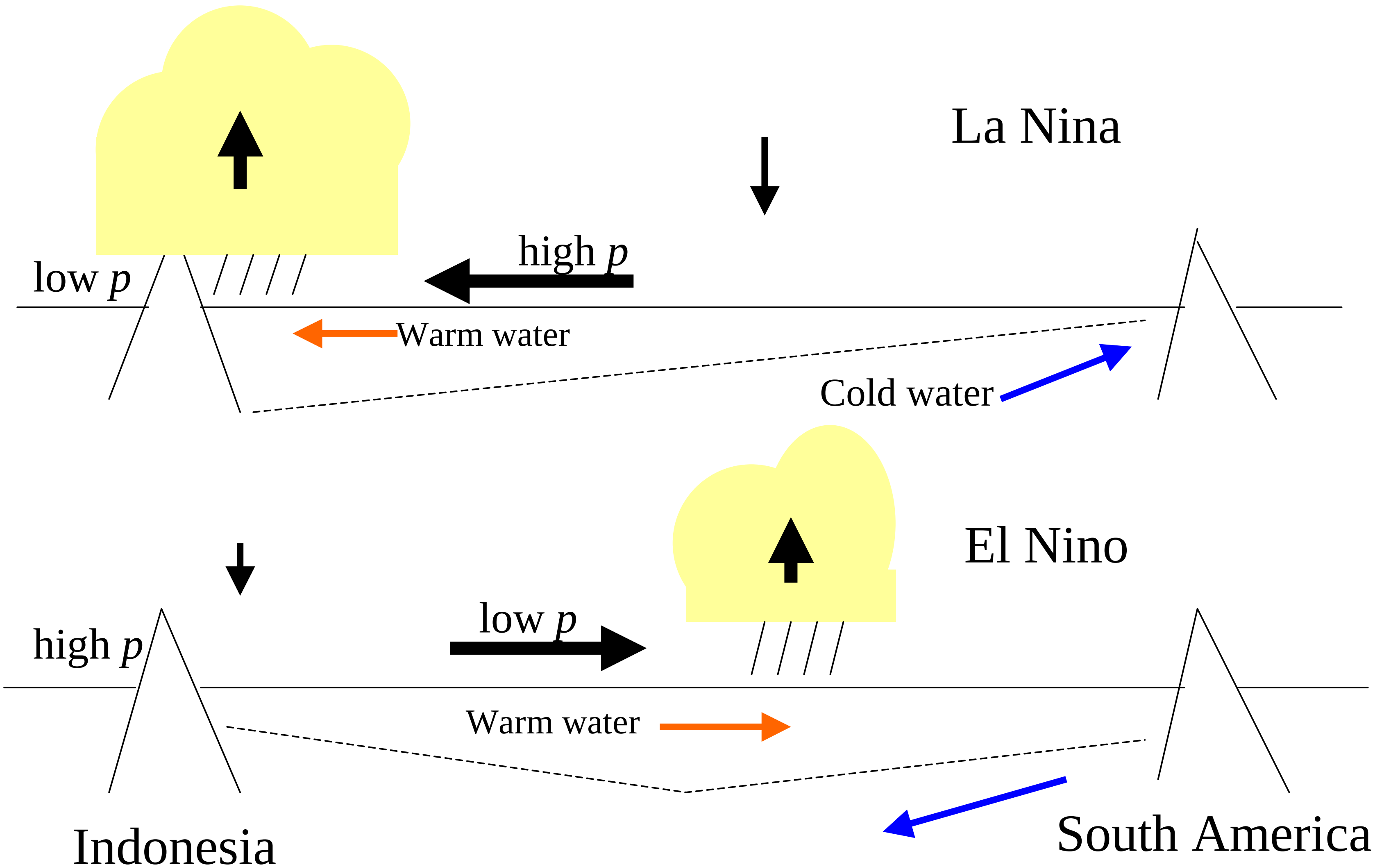


Zonal Section of Zonal Wind

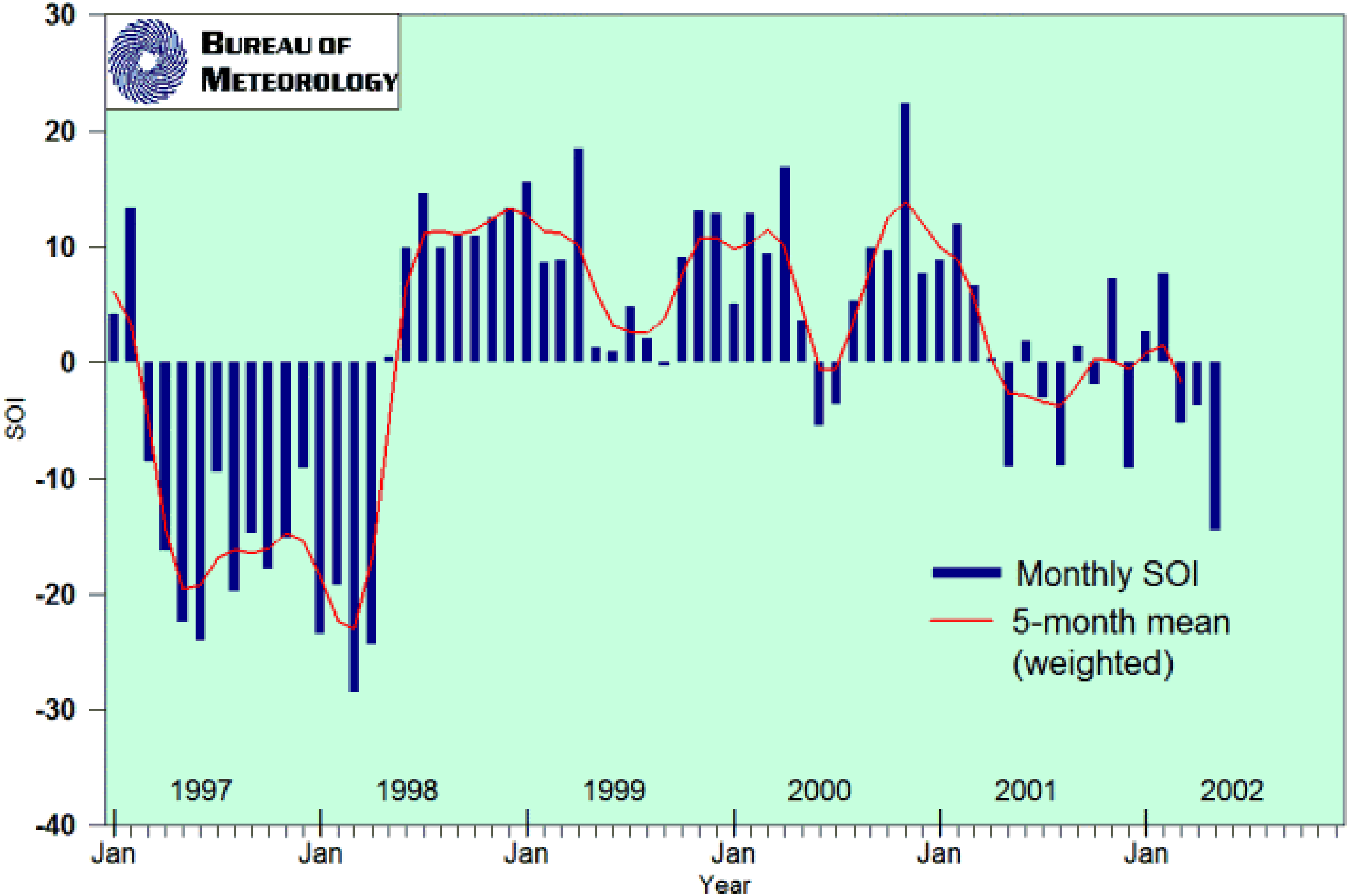
↓

Walker Circulation

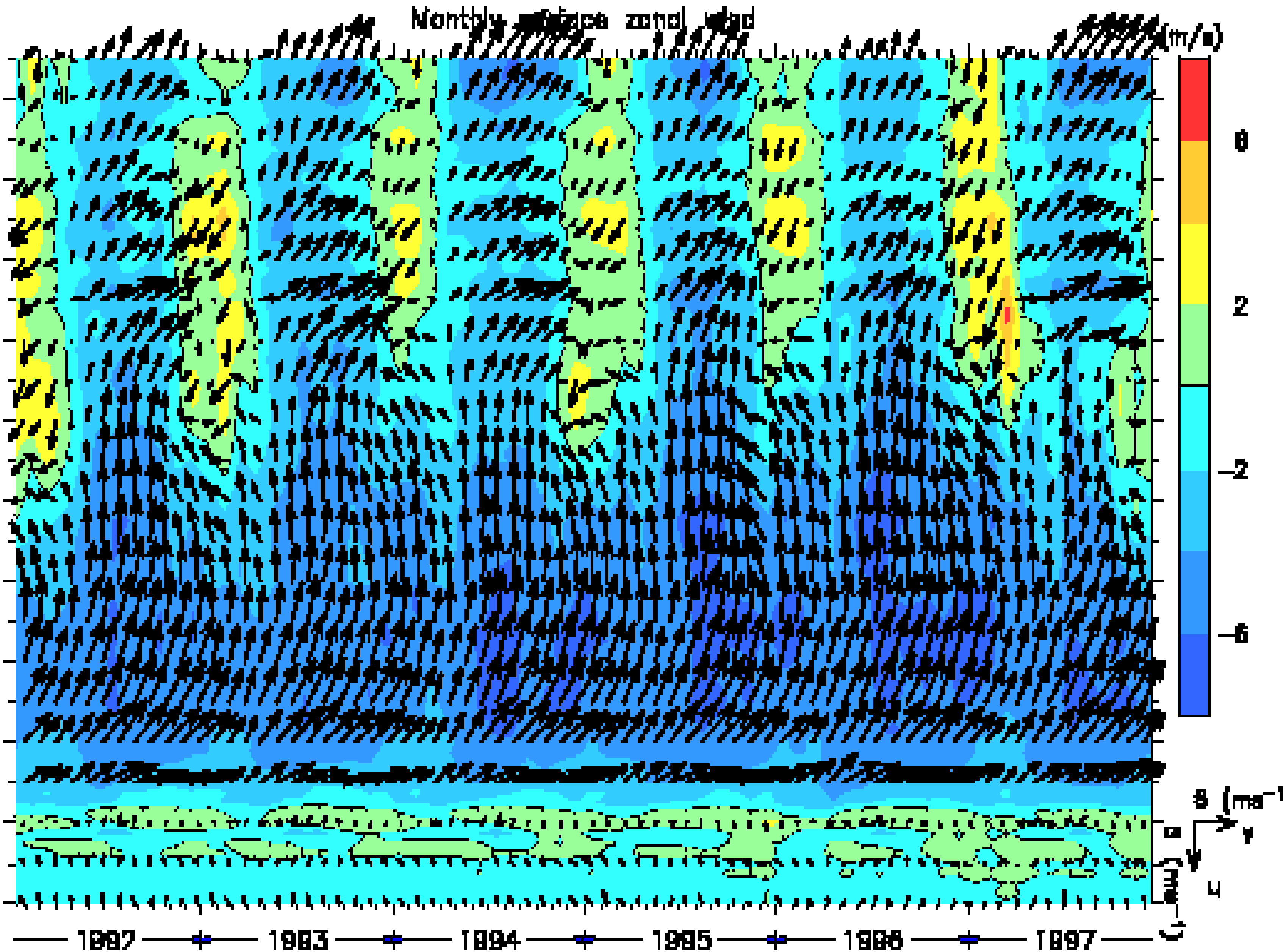
4.3. Atmosphere-ocean interaction and ENSO



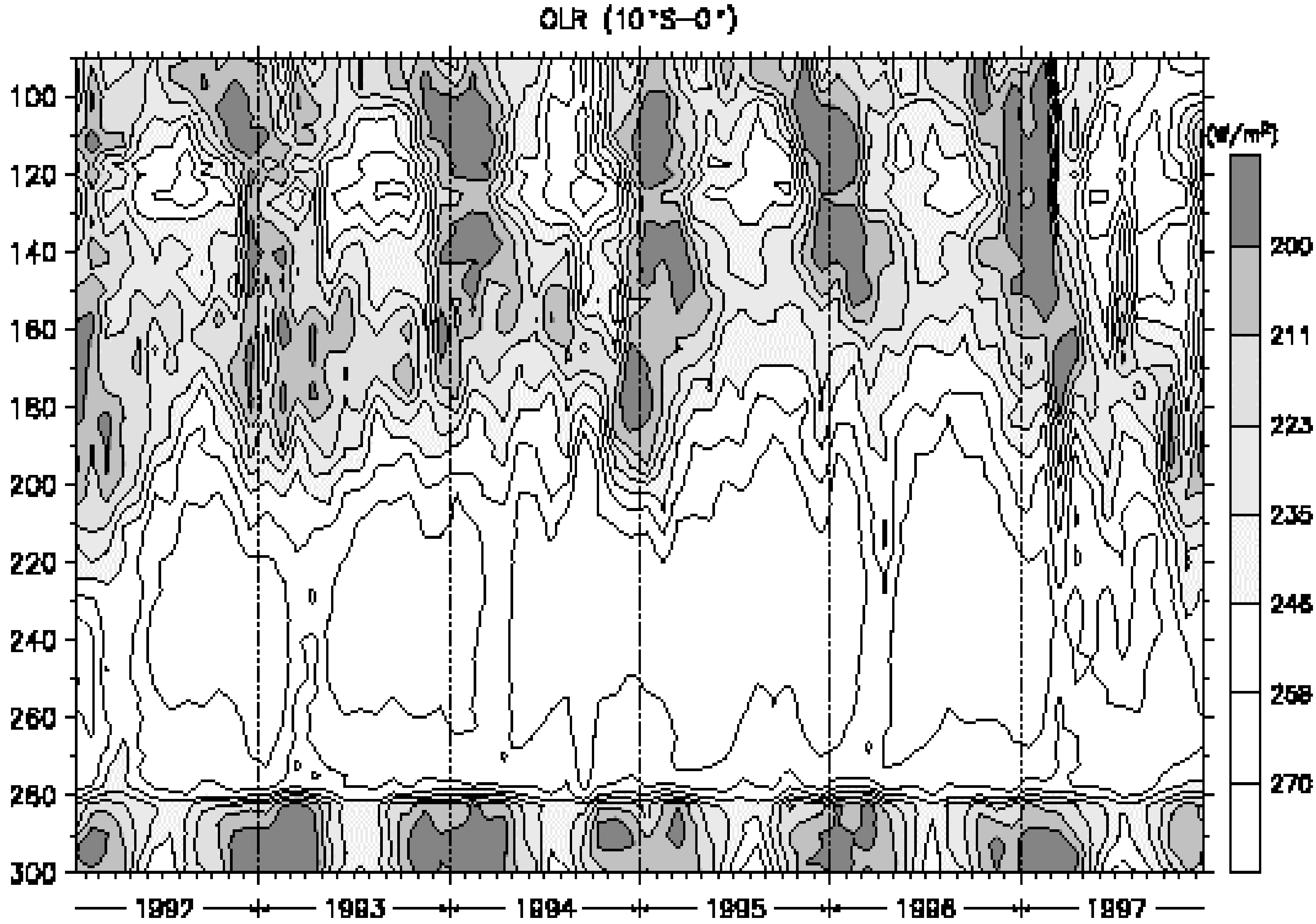
Southern Oscillation Index (SOI)
1997-2002



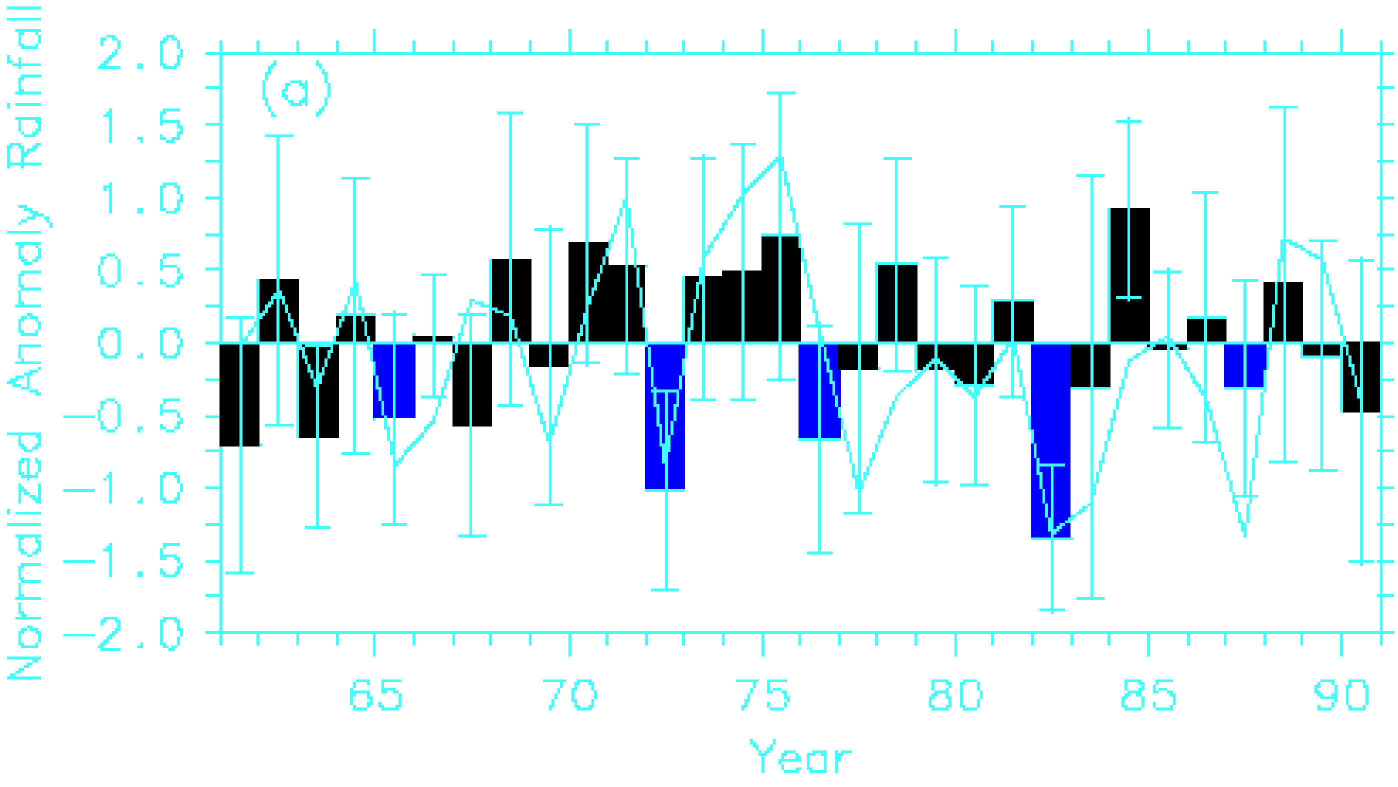
Interannual variation of surface wind over Equatorial Pacific

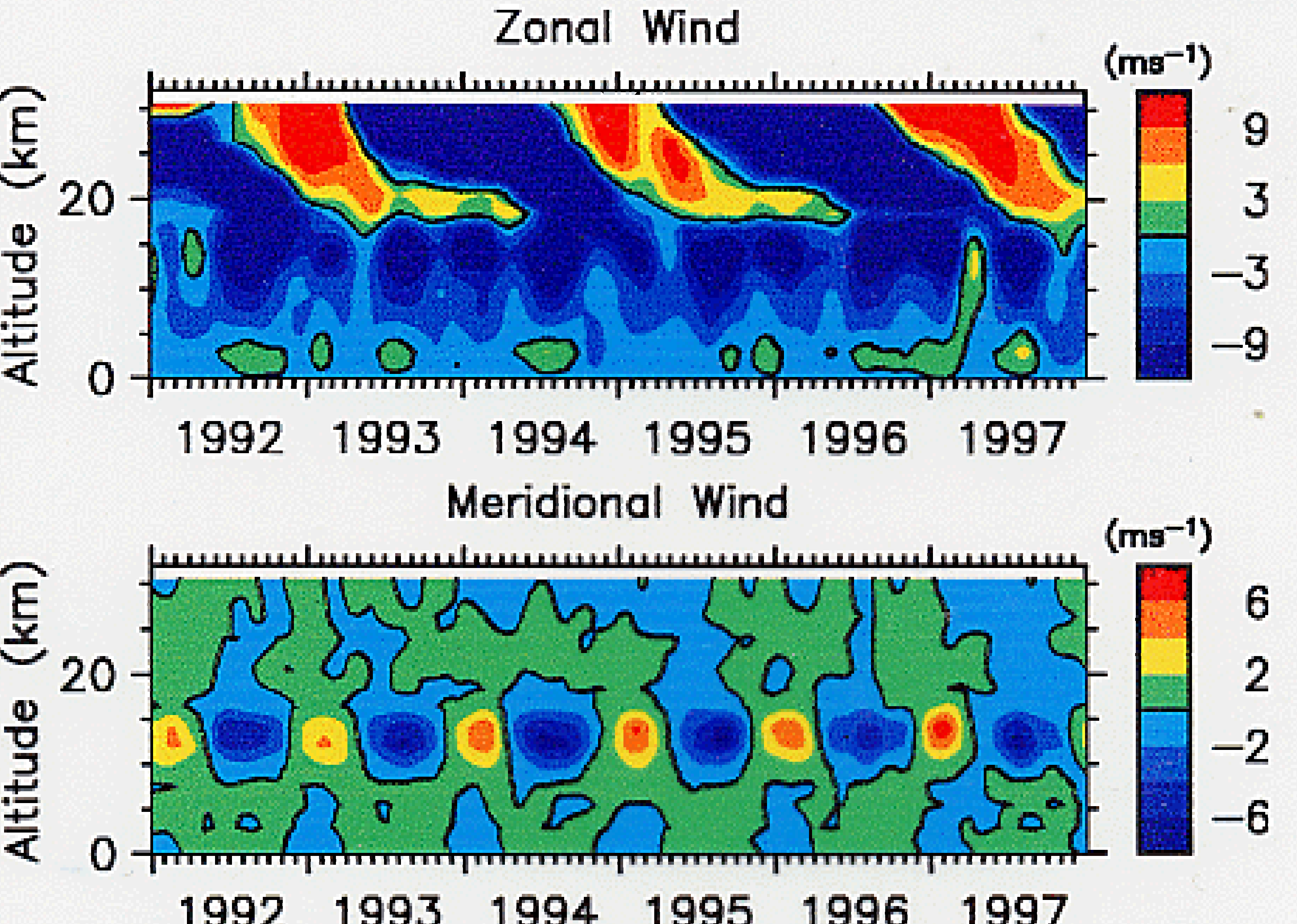


Interannual variations of OLR over equatorial Pacific



Indonesian Rainfall and SOI





Zonal Wind
(ms^{-1})
9
3
−3
−9
Altitude (km)
20
0
1992 1993 1994 1995 1996 1997
Meridional Wind
(ms^{-1})
6
2
−2
−6
Altitude (km)
20
0
1992 1993 1994 1995 1996 1997

Interannual Variations

- Daily rainfall (Hamada et al., 2002; JMSJ)
- Rawinsondes (Okamoto et al., 2002; submitted)
- Rainwater isotope (Ichiyanagi et al., 2002;GRL)

- ENSO, QBO
- Decadal-scale variations

Chapter 5
Cloud convection dynamics and tropical cyclone

5.1. Horizontal convection and local circulation

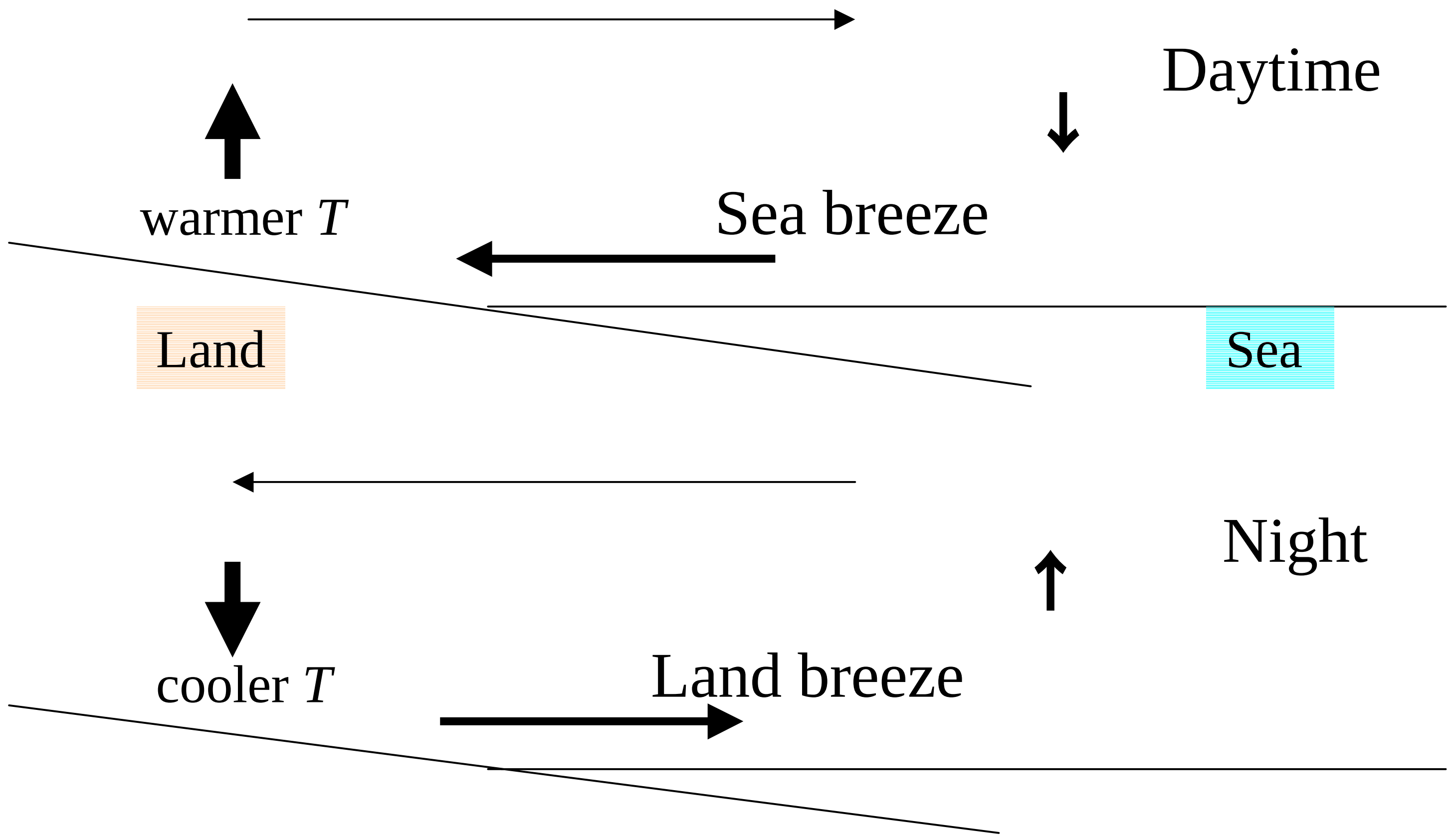
5.2. Vertical convection and cloud dynamics

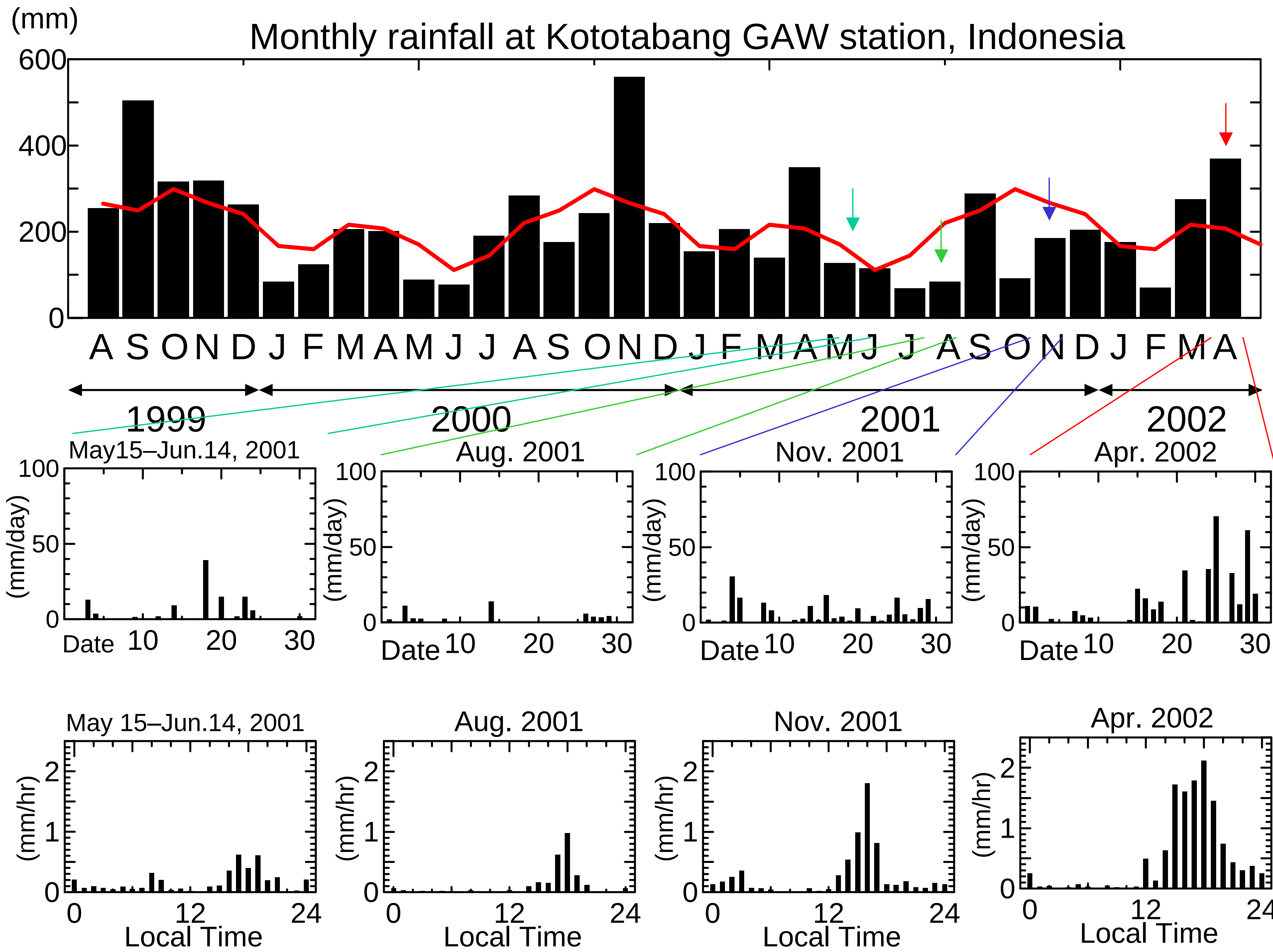
5.3. CISK and tropical cyclone

5.4. Cloud organization and intraseasonal variation

5.1. Horizontal convection and local circulation

Forced motion under stable stratification with differential heating:
Sea-land/mountain-valley breeze; City (“Heat island”) circulation





(mm)
Monthly rainfall at Kototabang GAW station, Indonesia
600
400
200
0
A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A
1999
2000
2001
2002
May15–Jun.14, 2001
Aug. 2001
Nov. 2001
Apr. 2002
100
50
0
(mm/day)
Date 10 20 30
May 15–Jun.14, 2001
Aug. 2001
Nov. 2001
Apr. 2002
2
1
0
(mm/hr)
0 12 24
Local Time

5.2. Vertical convection and cloud dynamics

- Vertical heat transport:
  - Radiation: electromagnetic (without any media)
  - Conduction: molecule motions
  - Convection: hydrodynamic motions
- Classical hydrodynamics of convection
  - Rayleigh-Taylor, Benard-Rayleigh, …
  - viscosity, gravity
- (Conditionally) Unstable stratification
  - Latent heating ⇒ “Pseudo”-adiabatic process
  - Equivalent potential temperature
- Coupling with cloud microphysics
  - Condensation/evaporation, freezing/melting, sublimation
  - Heterogeneous growing, aerosol nuclei, chemistry, electricity
  - Warm rain: stochastic coalescence, droplet/drizzle/raindrop
  - Cold rain: ice crystal/snow/graupel /hail

5.3. CISK and tropical cyclone

- Cumulus parameterization schemes:
  - Manabe: "Convective adjustment"
  - Kuo: $Q \sim -\alpha (T - T_c)$
  - Ooyama: $Q \sim \eta$ (entrainment) $\cdot\, \Gamma \cdot w|_{\text{PBL top}}$
  - Arakawa-Schubert: Statistics of subgrid clouds
- CISK = Convective instability of the second kind

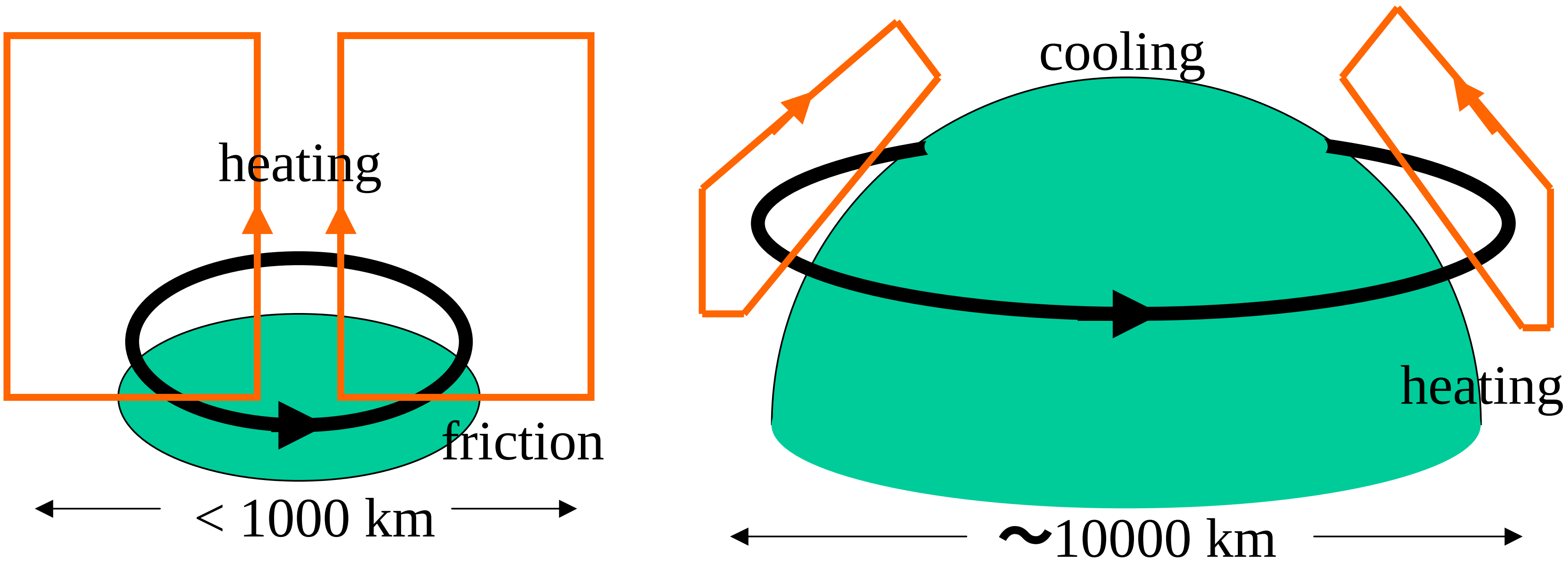
  Vortex generation due to Ekman pumping at PBL top
- Tropical cyclone (Typhoon)
  - Tangential (gradient) wind: Coriolis + centrifugal = pres.grad.

    Coriolis force ⇒ Cyclone only in sub-tropics ($\phi > 10$ deg)
  - Radial (Ekman) wind: Coriolis + centrifugal = friction

    Centrifugal force ⇒ no intrusion of outside air into "Eye"
  - Warm-core, "eye-wall" cloud, spiral rainband
  - Typhoon activity and its interannual variation (ENSO)

Typhoon as a "mini-earth"

with different heating distribution



Tangential wind ⇔ Pressure gradient

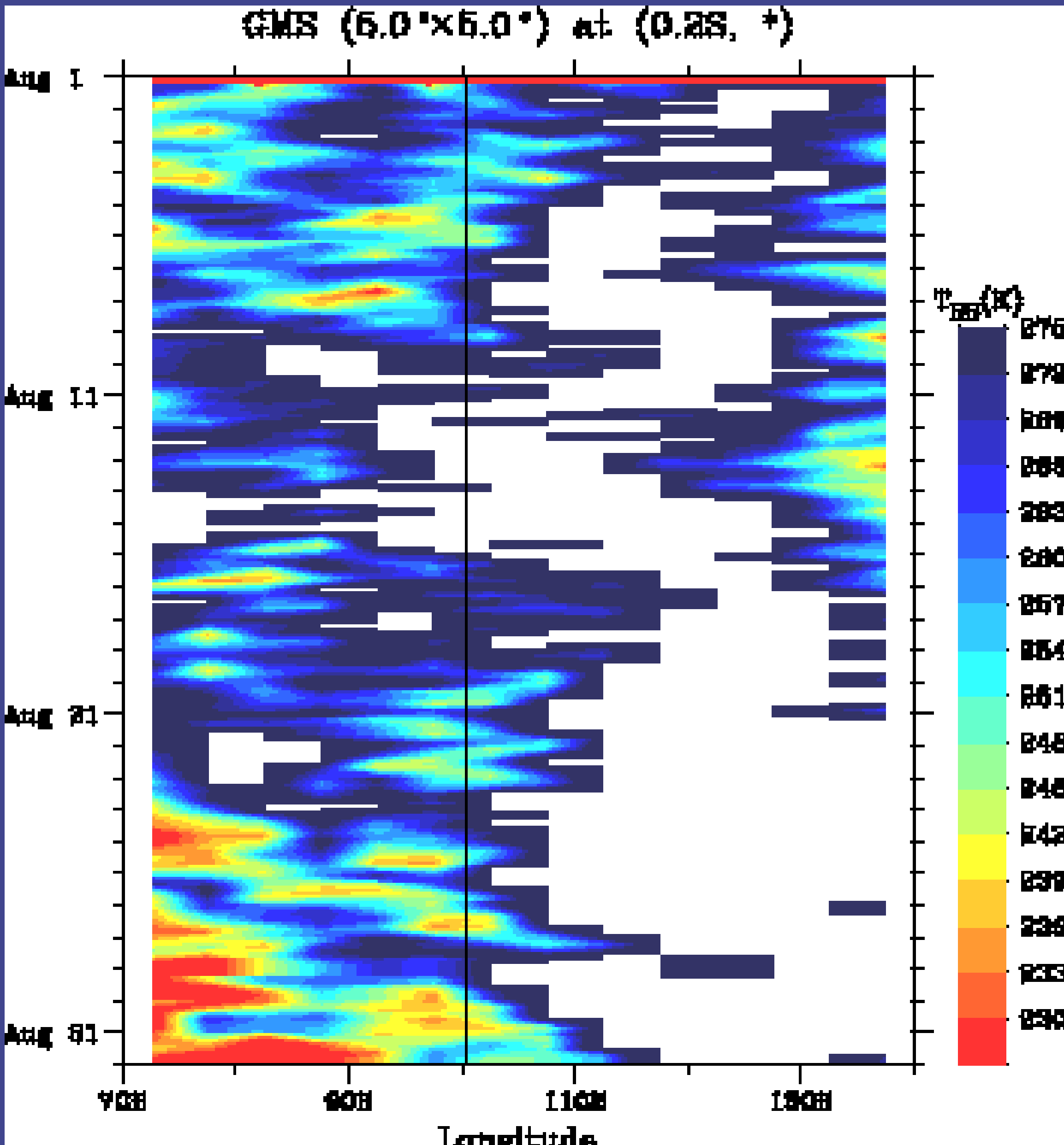
Radial wind ⇔ Surface friction, turbulence /drag

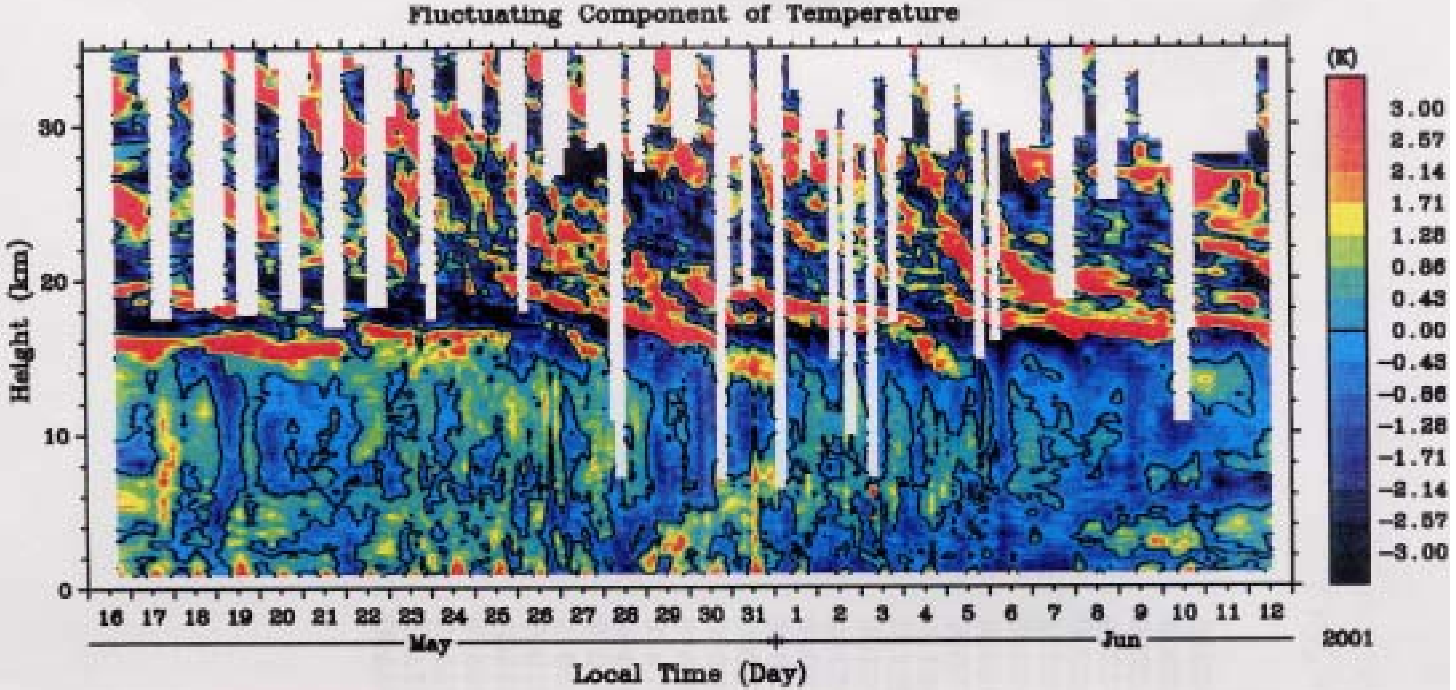
Vertical velocity ⇔ Latent heat by cloud/precipitation

5.4. Cloud organization and intraseasonal variation

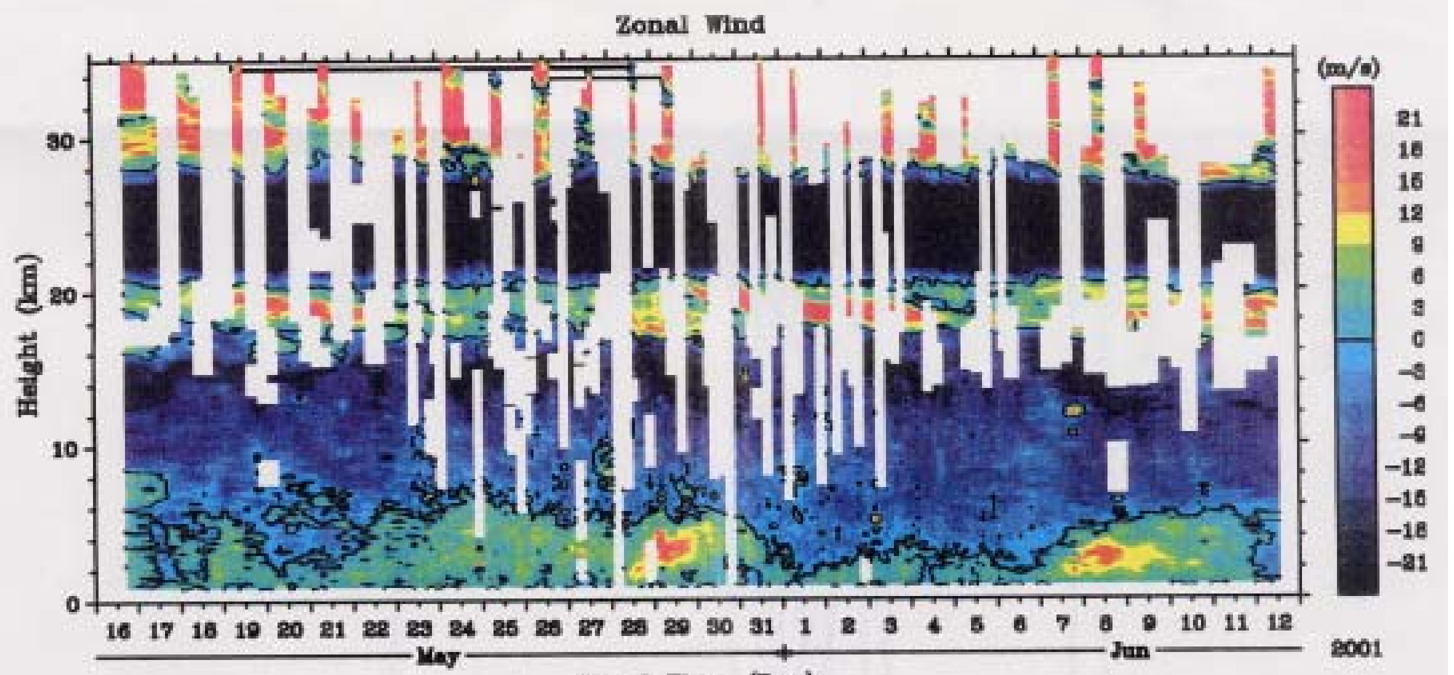
- Wave-CISK and cloud organization mechanisms
  - Kelvin-wavelike, eastward-propagating ISV (Hayashi-Sumi)
- Cloud hierarchical structure observed by GMS
  - Eastward-propagating super-cluster and 30-60 day ISV
    (Madden-Julian, Yasunari, …, Nitta et al.)
  - Westward-propagating clusters inside ISV
    (Nakazawa, Takayabu, …)
- Modulation of ISV observed by rawinsondes, profilers, GPS, etc.
  Jawa (Hashiguchi et al. 1995; Tsuda et al., 1995; …)
  Sumatera (Wu et al, 2002; Mori et al., 2002)
  - 3D structure of ISV by composite analysis of rawinsonde data
  - Quasi-4-day period (Widiyatmi et al., 2000, 2001)
    longer than – 2-day period over Pacific (Takayabu, ….)
  - Interaction with local diurnal circulations
    North Jawa (Hashiguchi et al., 1995; Araki et al., 2002)
    Sumatera (Murata et al., 2002; Sakurai et al., 2002)

T_{BB} by GMS


GMS (5.0°×5.0°) at (0.2S, *)
Aug 1
Aug 11
Aug 21
Aug 31
70E
90E
110E
130E
Longitude
T_{BB} (K)
275
272
269
266
263
260
257
254
251
248
245
242
239
236
233
230

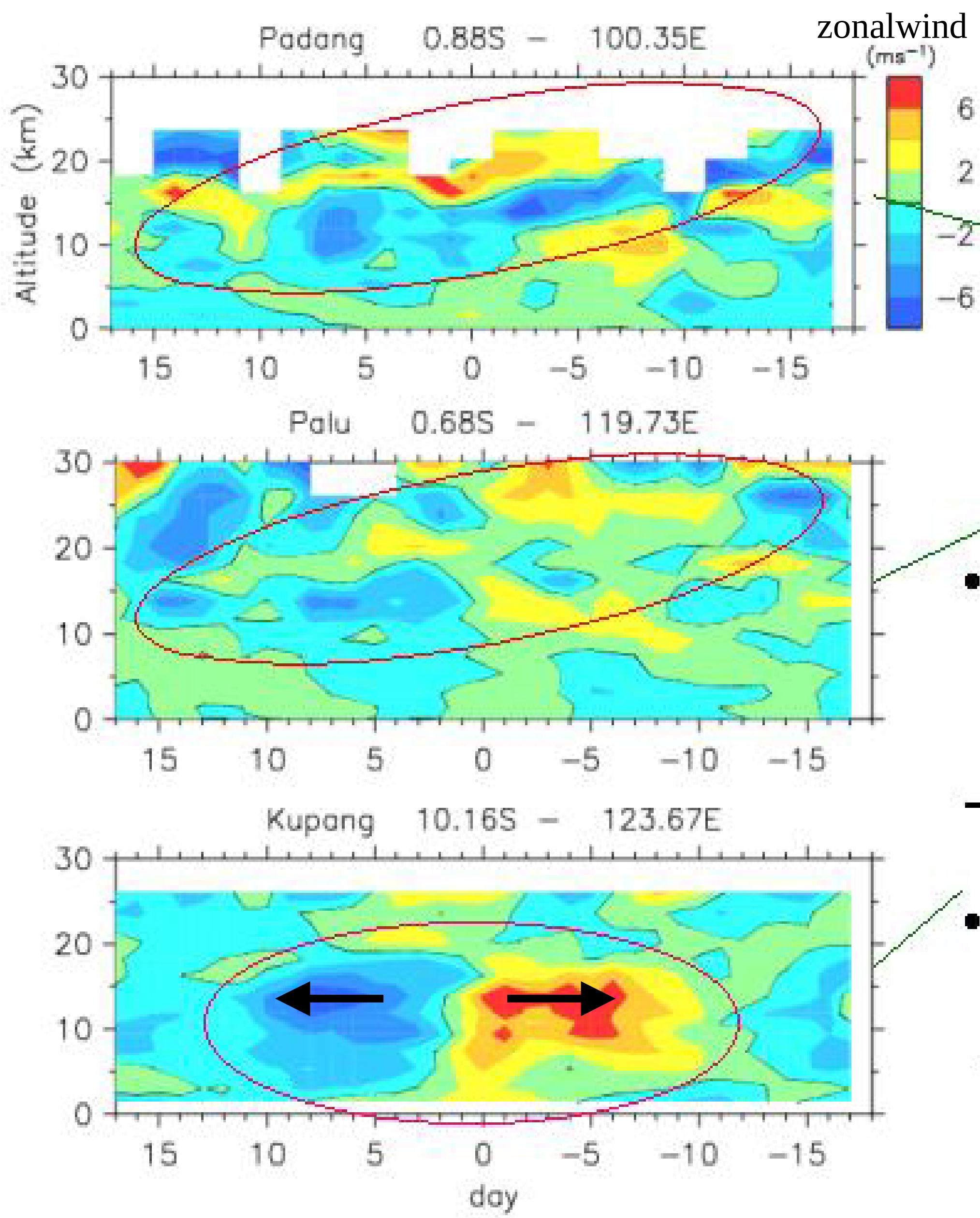


Fluctuating Component of Temperature
Height (km)
0
10
20
30
(K)
3.00
2.57
2.14
1.71
1.28
0.86
0.43
0.00
-0.43
-0.86
-1.28
-1.71
-2.14
-2.57
-3.00
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12
May
Jun
2001
Local Time (Day)

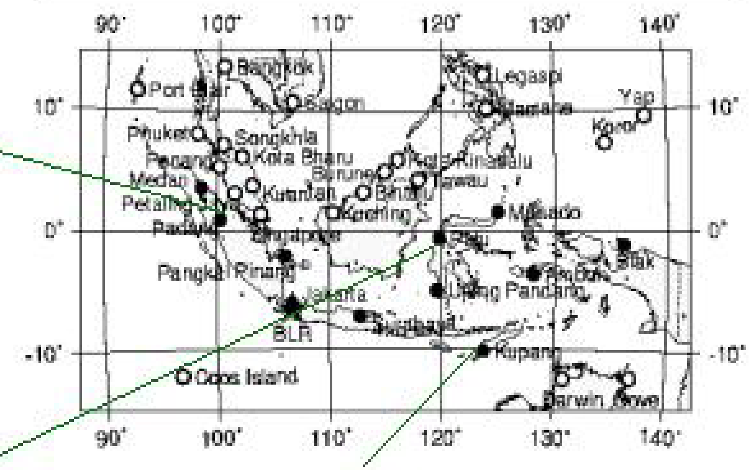


Zonal Wind
Height (km)
0
10
20
30
(m/s)
21
18
15
12
9
6
3
0
-3
-6
-9
-12
-15
-18
-21
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12
May
Jun
2001

Composite analysis of rawinsonde data around humidity maximum



+ : westerly (→), − : easterly (←)



- Waves with downward progression (vicinity of the Eq.) (Seen also temp.)

→**Kelvin waves!?**

- **Divergence** around 15km and **Convergence** near the ground (dominates in the S.H.)

Remarks

Local diurnal variations

↑↓ Cloud generation/modification

Intraseasonal variations

↑↓ Sseasonal march modification

Seasonal and nterannual variations

Conclusion

- Meteorological/climatological phenomena in SE-Asia are understood as a sum of solutions of the basic equations of atmospheric dynamics such as
  - Trade wind, Hadley and monsoon circulations,
  - Matsuno-Gill patterns and intraseasonal variations,
  - Local circulations and clouds.

- Education courses somewhat different from standard (mid-lat.) one of atmospheric dynamics must be established.

- Observations also must be continued and extended in order to obtain evidence of each component much more, as well as new theoretical concept from accumulated observational evidence.