A Planetary-scale Land-sea Breeze Circulation in East Asia and the Western North Pacific
&
Maintenance Mechanisms for the Early Morning Maximum Rainfall over Southeast Asia

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Huang WR, Chan JCL, 2010. Maintenance Mechanisms for the Early Morning Maximum Rainfall over Southeast Asia. *Q. J. R. Meteorol. Soc.* (submitted).

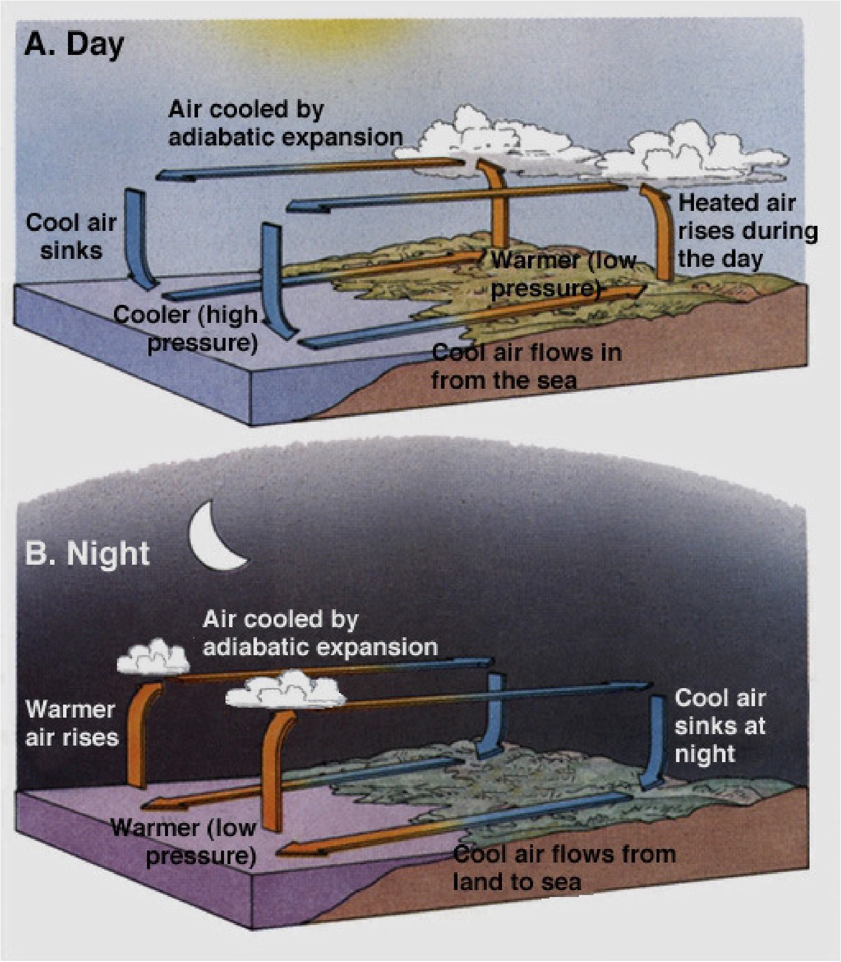
I. A Planetary-scale Land-sea Breeze Circulation in East Asia and the Western North Pacific

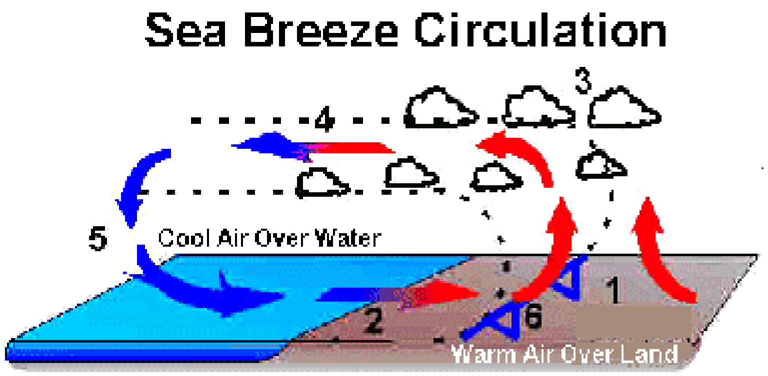
Outline

1. Introduction
2. Data
3. Results
    - Large-scale land-sea breeze (LSB) like circulation and its impact on the diurnal rainfall variation in East Asia
4. Summary

1. Introduction: land-sea breeze (LSB)

- The land-sea breeze circulation is induced by land-sea differential heating





1. Warm air over land rises
2. Sea Breeze moves inland as a mesoscale cold front
3. Cumuli develop aloft and move seaward
4. Upper level return land breeze
5. Cool air aloft sinks over water

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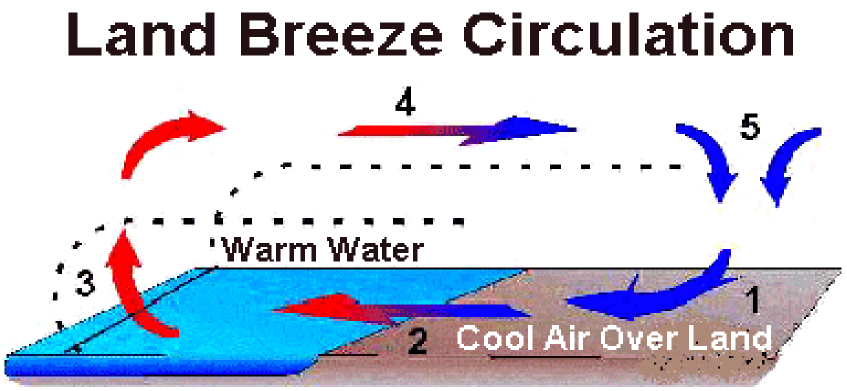
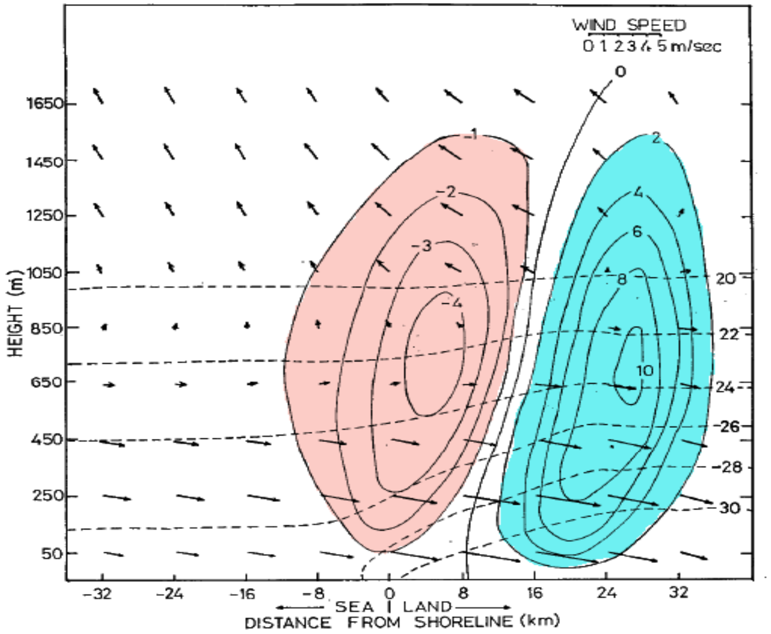
- The local land-sea breeze (LSB) along the coastline typically spans < 100 km

The Land Breeze (When searching in Google~)

As the sun sets, cooling begins along the surface of the land and sea. Like daytime heating, cooling occurs at different rates over water and land. The rapidly cooling land soon has a higher air pressure over it relative to that over the sea, and the air begins to flow down the pressure gradient seaward. This is the land breeze. It too is influenced by the roughness of the coastline, strength of the large-scale winds, and coastal configuration. Unlike the sea breeze, the land breeze is usually weaker in velocity and less common. The land breeze is often dominant for only a few hours and its direction is more variable. Nevertheless, the land breeze can penetrate the marine atmosphere for 10 kilometres (6 miles) seaward.

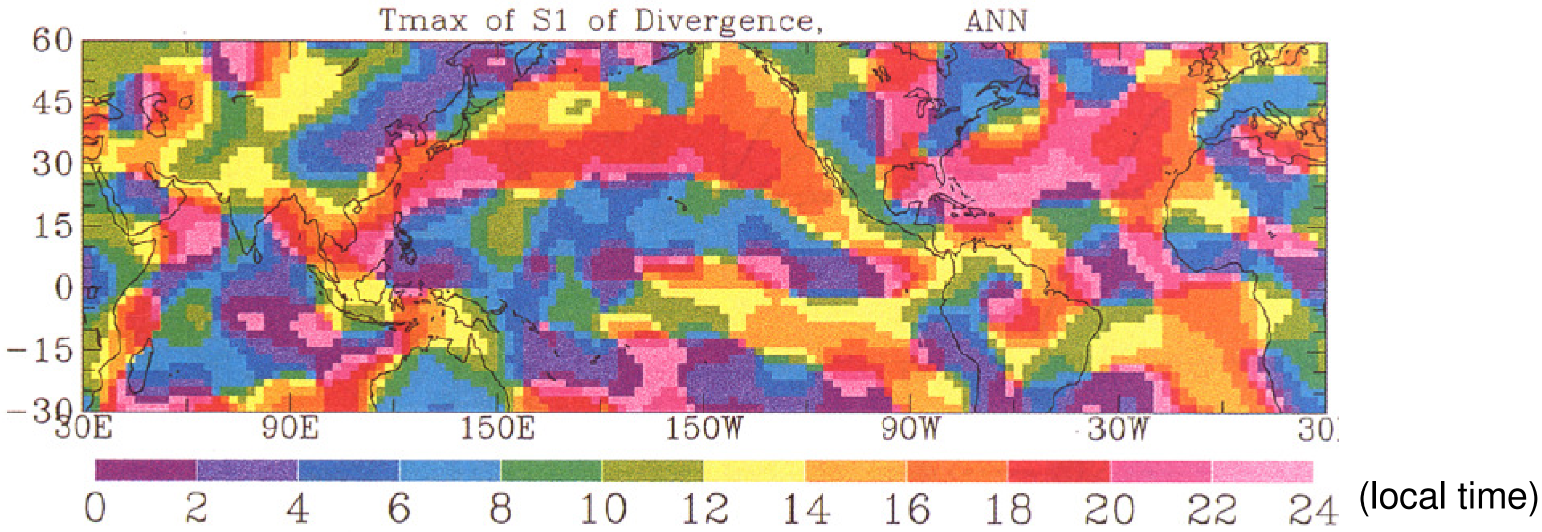


1. Cool air over land sinks
2. Land Breeze moves out over water
3. Relatively warmer water heats air which then rises
4. Upper level return sea breeze
5. Cool air over land sinks



Neumann and Mahrer 1971

In the late 90s, a concept of planetary-scale diurnal surface wind variation was proposed based on observations of the surface wind divergence (Dai and Deser 1999).



➔ This concept implies a large-scale LSB-like circulation that has not been verified. An extra force different to the land-sea differential heating must exist in order to form a circulation in such a large scale.

Motivation

As the low-level circulation is important on representing the physical processes acting above the surface and on controlling timing of the precipitation, diagnostic works of this large-scale LSB-like issue are needed before applying this concept to the adjustment of weather and climate model’s simulations.

Objective

We try to find out evidences and explanations for the existence of large-scale LSB-like circulation over the East Asia-Western Pacific region and discuss its impact on the diurnal rainfall variation.

2. Data

- Seven global gridded reanalysis datasets, including NCEP-NCAR Reanalysis-1, NCEP-DOE AMIP-II, ECWMF ERA-40, ECWMF ERA-interim, JRA-25, GEOS5, and GFS

- Wind observations from several WMO surface stations and atmospheric soundings

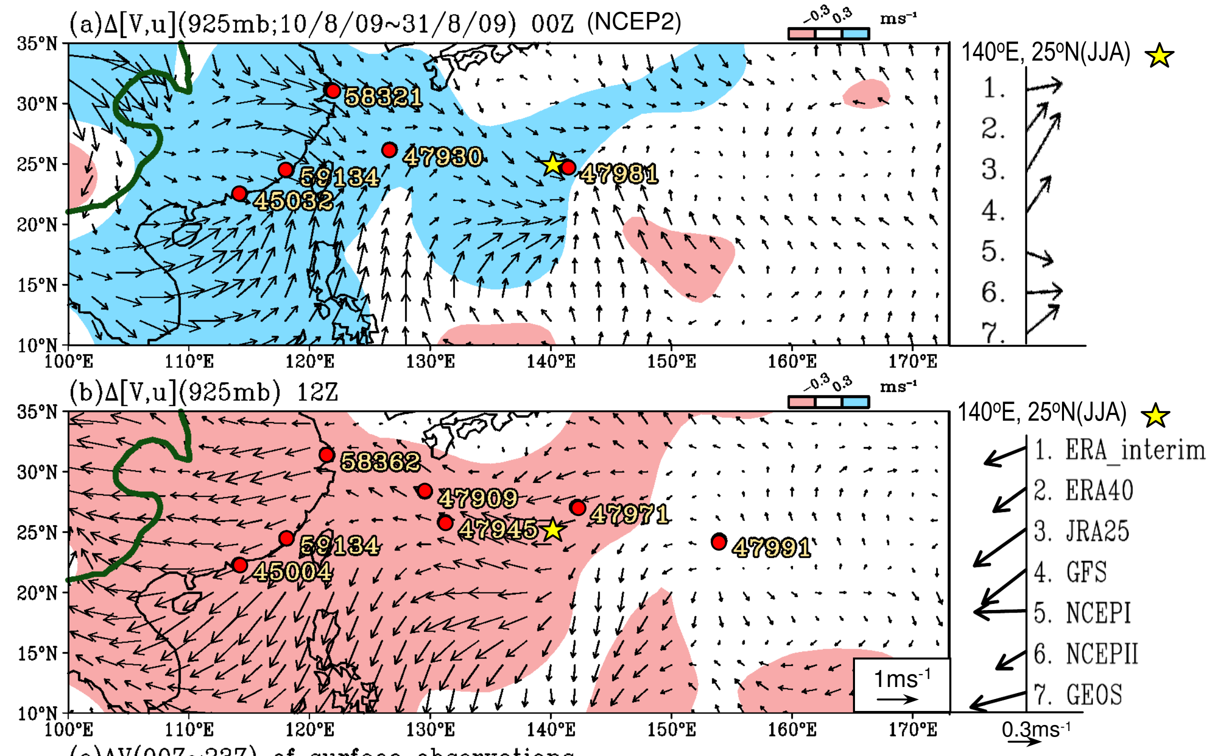
- Rainfall data
  - TRMM
  - Station

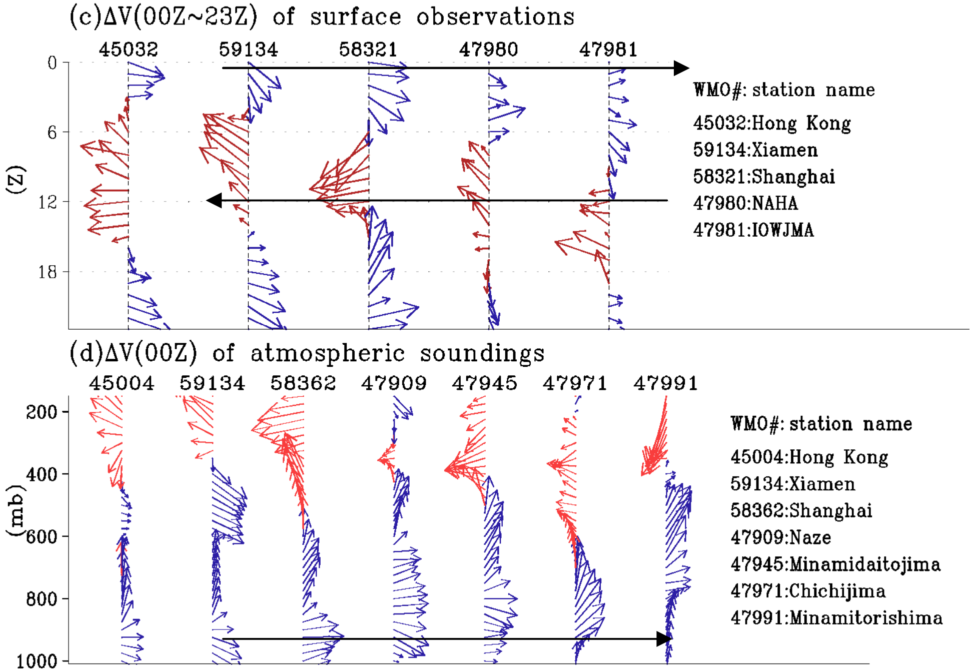
- Δ : anomalies = (specific individual time step) – daily mean of available time steps

  S1: diurnal harmonic
  S2: semi-diurnal harmonic
  From the Fourier analysis

3. Results

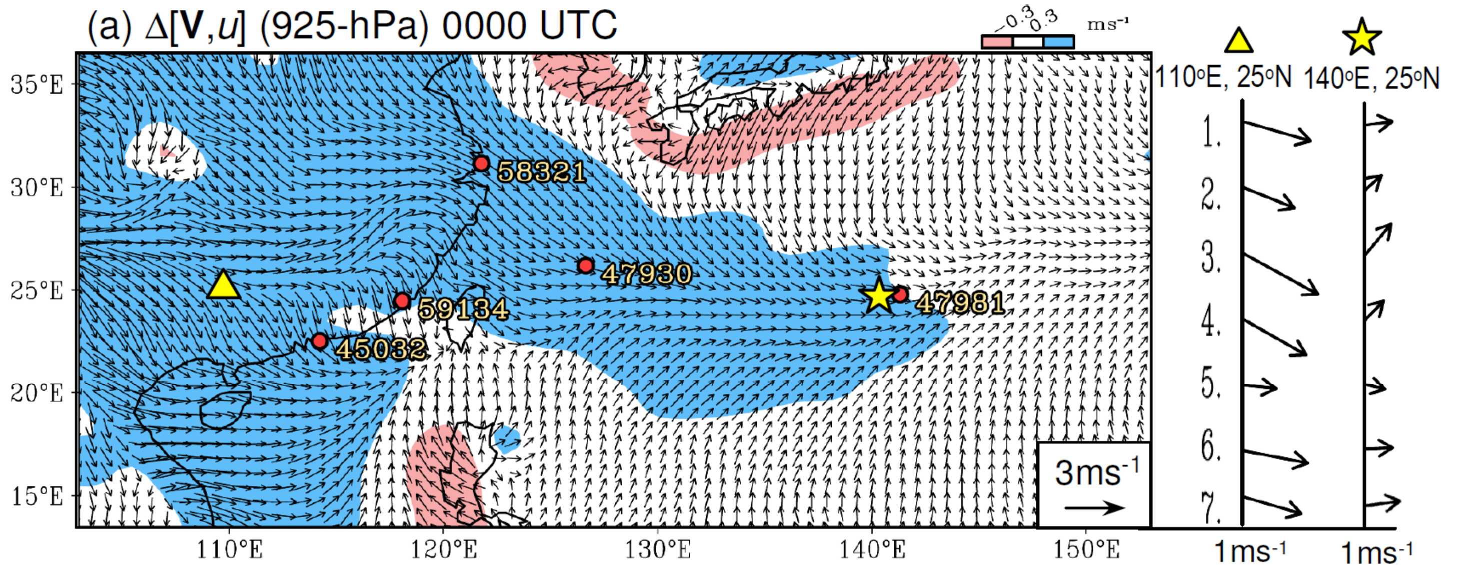
A seemingly giant land-sea breeze covers a few thousand kilometers over the Western Pacific



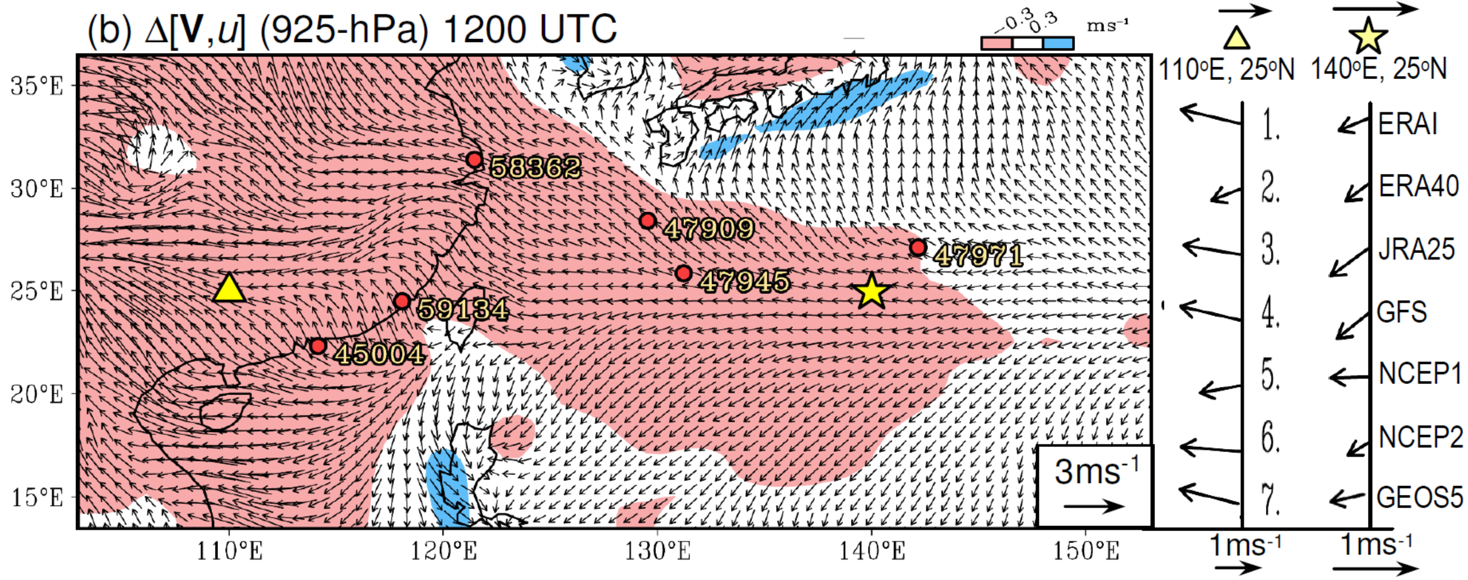


Similar feature is also observed in the higher spatial-temporal resolution of GEOS5 data

(a) Δ[**V**,*u*] (925-hPa) 0000 UTC

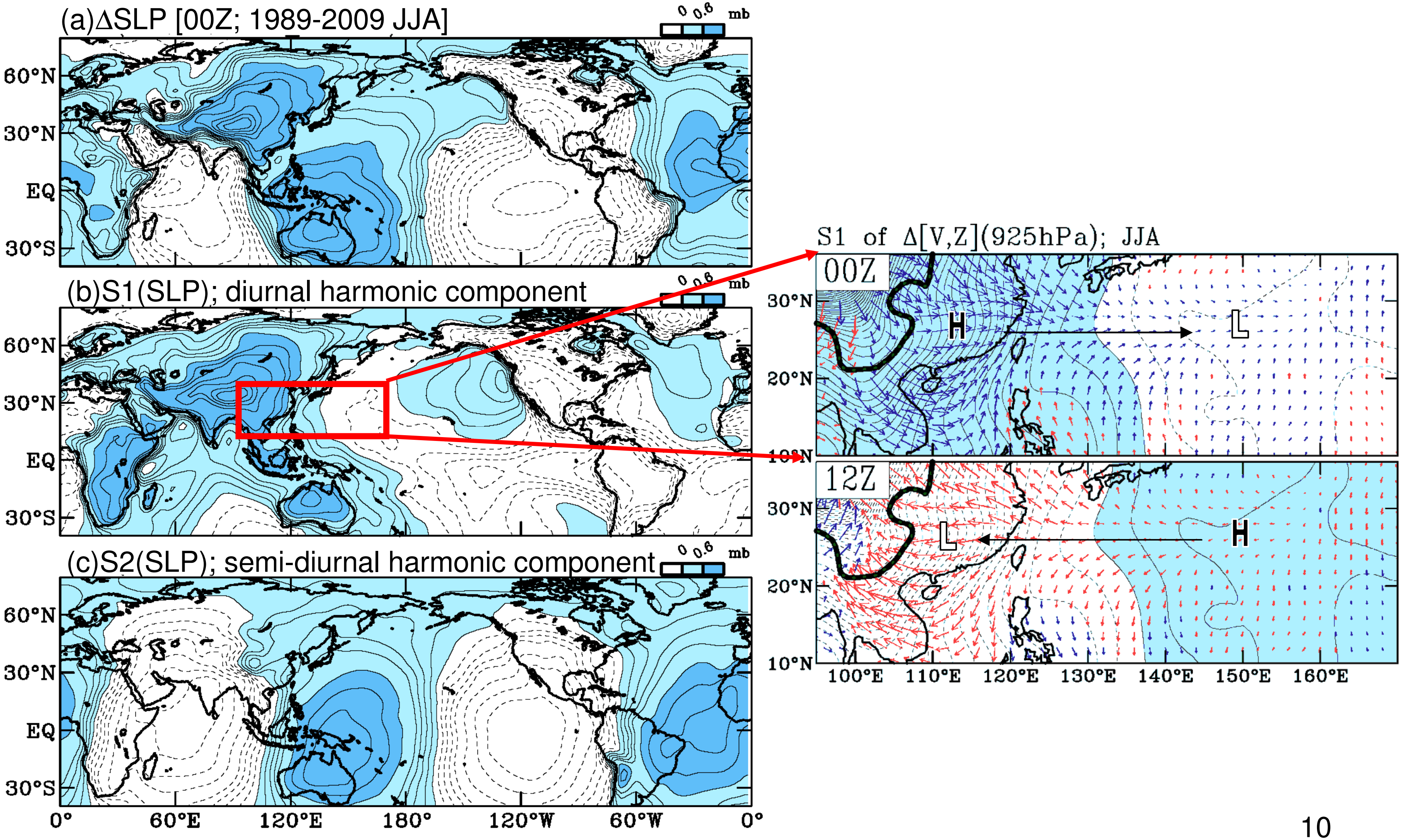


(b) Δ[**V**,*u*] (925-hPa) 1200 UTC



Possible cause of large-scale LSB-like circulation:

Pressure gradient force of global pressure tidal wave



(a)ΔSLP [00Z; 1989-2009 JJA]

(b)S1(SLP); diurnal harmonic component

(c)S2(SLP); semi-diurnal harmonic component

S1 of Δ[V,Z](925hPa); JJA

TWO questions are raised:

Q1: Does the S1(PGF) contribute most to the large-scale LSB-like circulation?

- A momentum budget equation with standard notations is examined

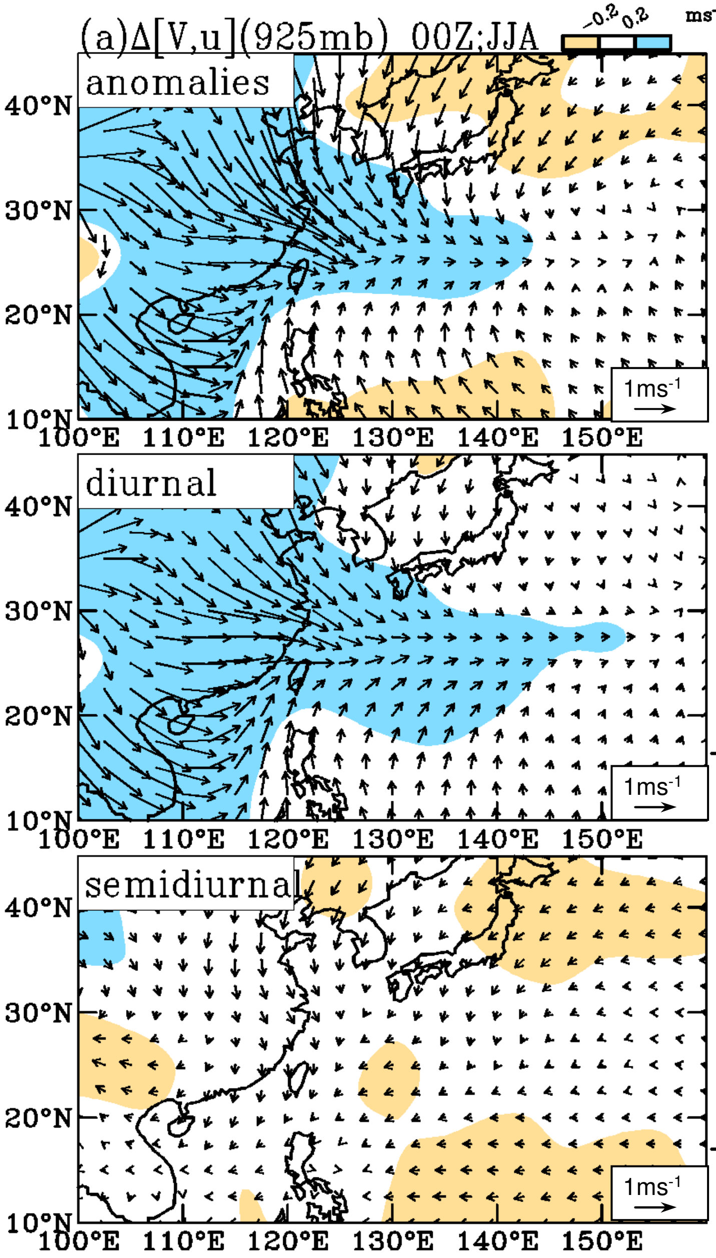
$$\frac{\partial \mathbf{V}}{\partial t} = \underbrace{-f \cdot \mathbf{k} \times \mathbf{V}}_{\text{(CF)}} \underbrace{- \frac{1}{\rho} \nabla p}_{\text{(PGF)}} + \underbrace{\frac{\partial}{\partial z}\left(K_d \frac{\partial \mathbf{V}}{\partial z}\right) + \text{residual}}_{\text{(VDIF+RES)}}$$

Q2: What is the implication of large-scale LSB-like in diurnal rainfall change?

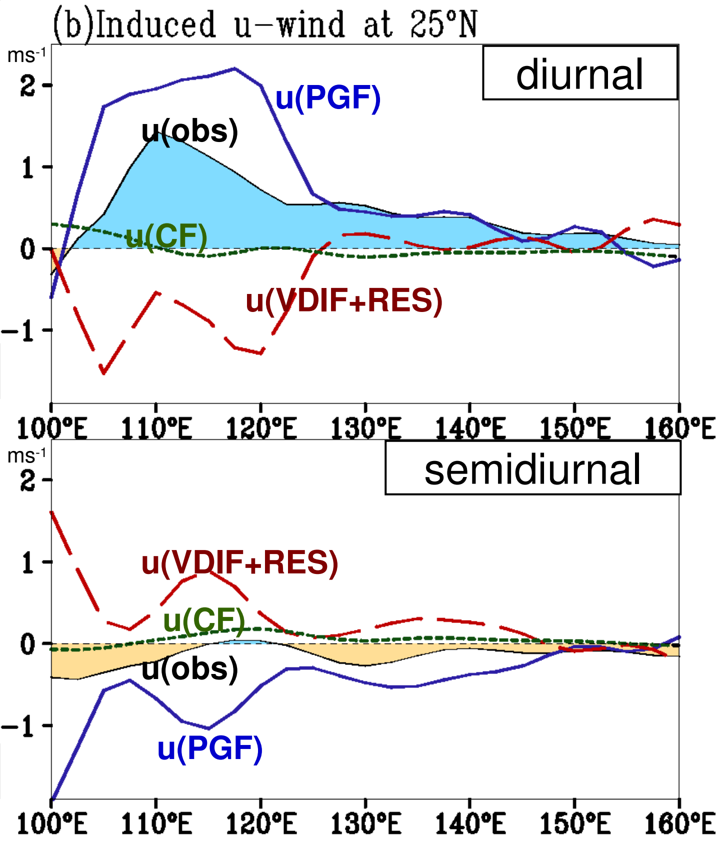
- The equivalent potential temperature is examined.

$$\theta_e = T_e \left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}} \approx \left(T + \frac{L_v}{c_p} r\right) \left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}}$$

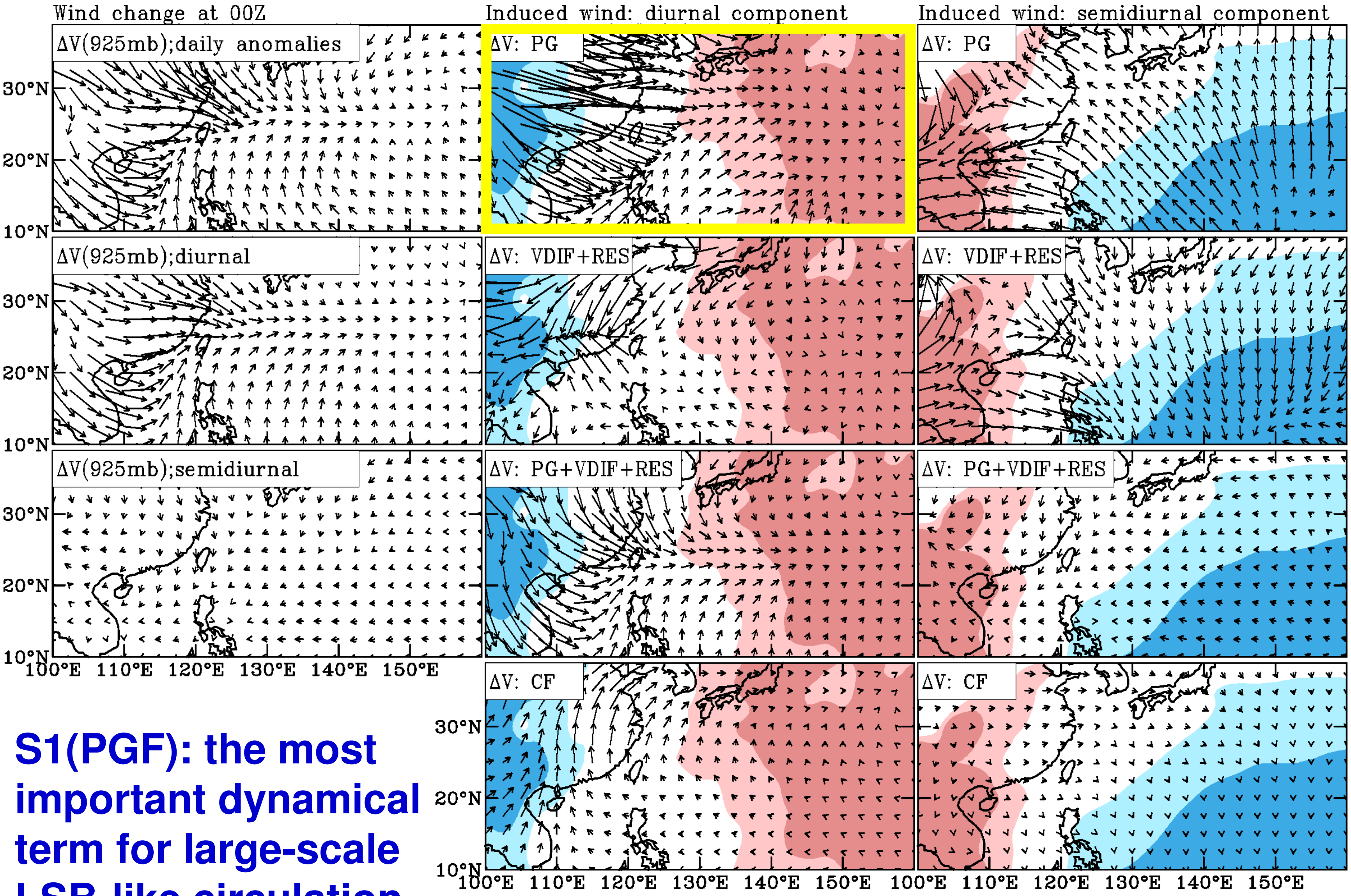
Diagnosis of momentum budget



$$\frac{\partial \mathbf{V}}{\partial t} = \underbrace{-f\cdot\mathbf{k}\times\mathbf{V}}_{\text{(CF)}} - \underbrace{\frac{1}{\rho}\nabla p}_{\text{(PGF)}} + \underbrace{\frac{\partial}{\partial z}\left(K_d\frac{\partial \mathbf{V}}{\partial z}\right) + \text{residual}}_{\text{(VDIF+RES)}}$$



Diagnosis of momentum budget



S1(PGF): the most important dynamical term for large-scale LSB-like circulation

What is the extra forcing different to land-sea differential heating for forming large-scale LSB-like circulation?

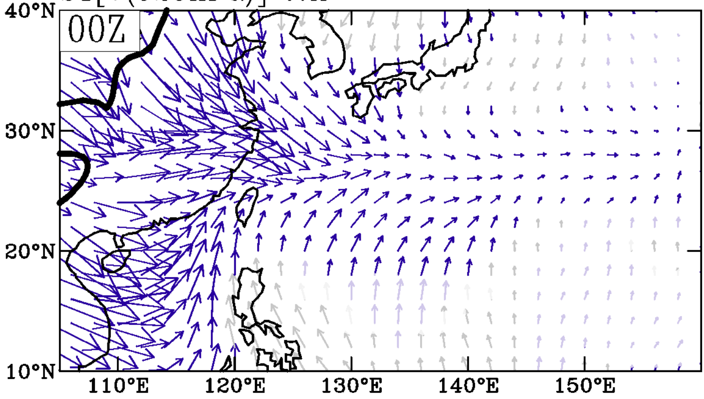
S1(SLP)

- Migrating component:
  forced by water vapor and ozone heatings
  (Lindzen 1967; Groves and Wilson 1982)
- Non-migrating component:
  forced by latent heat released and sensible heat due to land–sea differences and topography
  (Forbes and Groves 1987; Tsuda and Kato 1989)

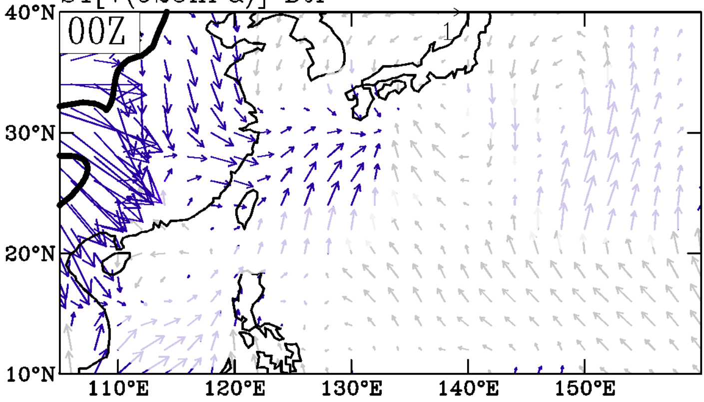
⇨ Likely, the forces that generate the global migrating tidal component of S1(SLP) are the extra forces for explaining the large-scale LSB-like circulation

Seasonal variation of LSB-like circulation

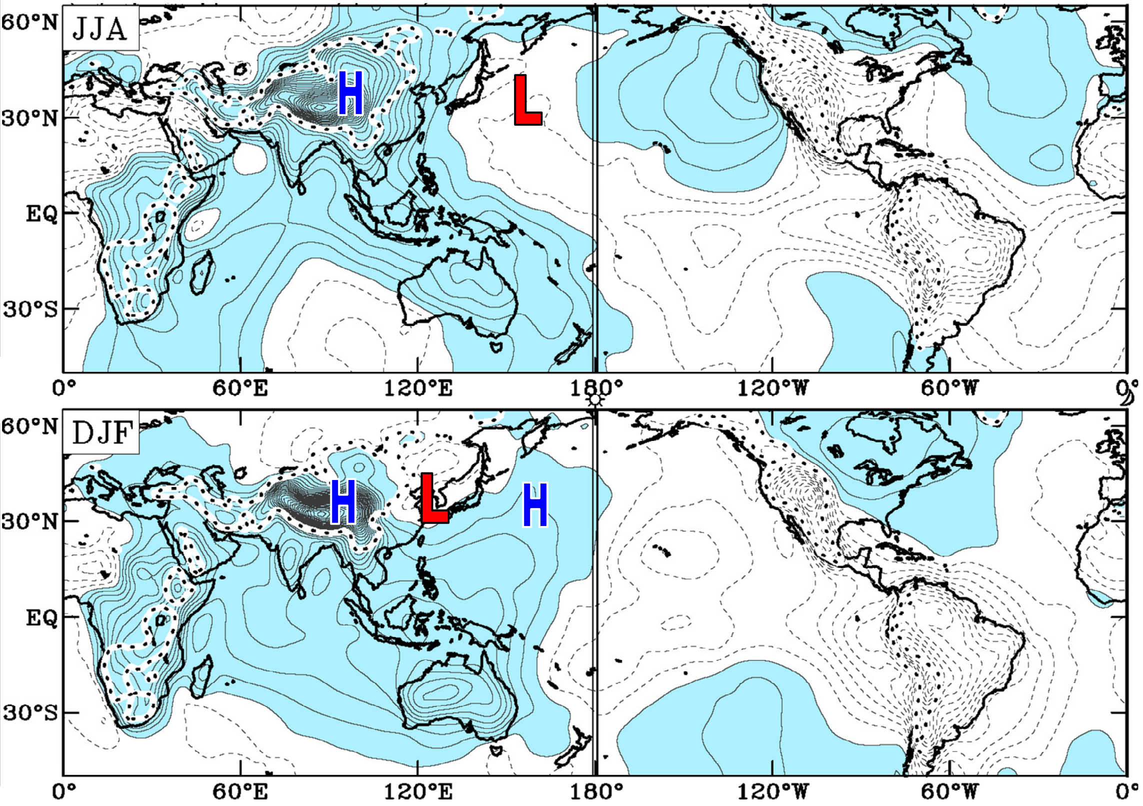
S1[V(925hPa)] JJA



S1[V(925hPa)] DJF

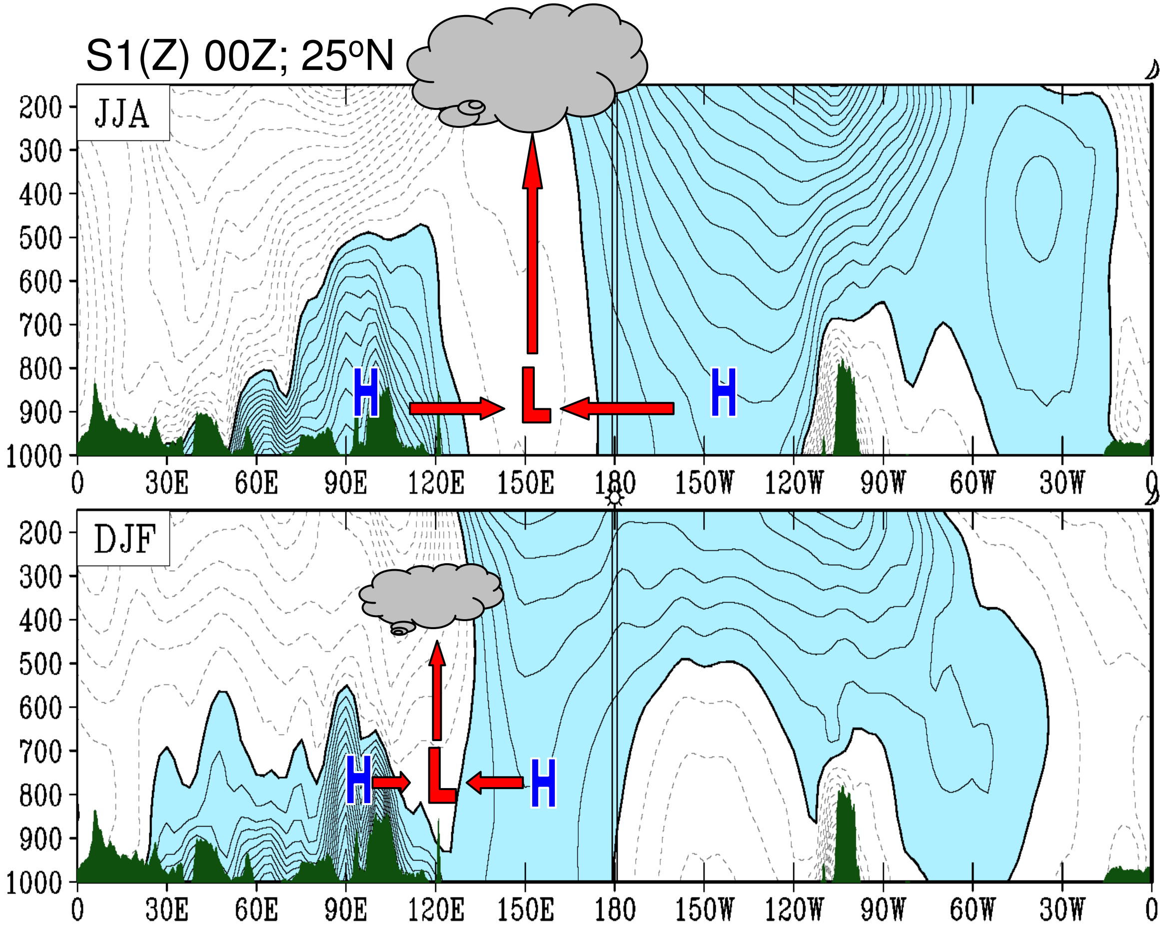


(a) S1[Z(925hpa)] 00Z



Seasonal variation of S1(Z) at 25°N

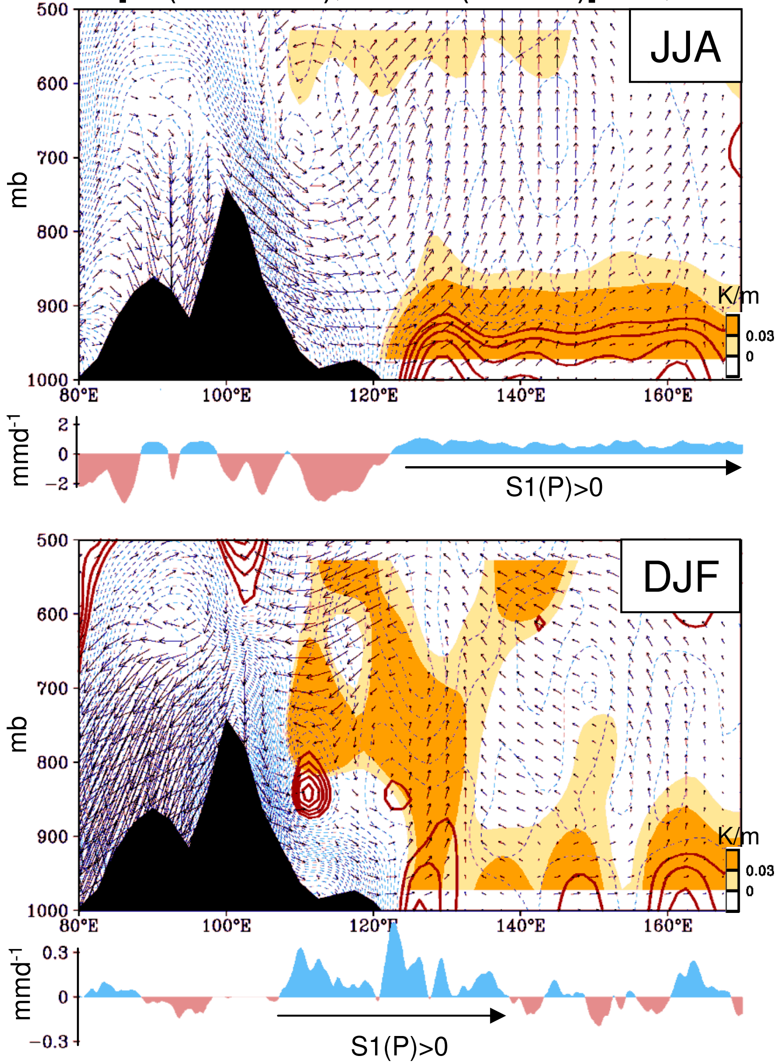
- Because the thermally driven global migrating tide follows the movement of the sun, seasonal variation in this migrating tidal wave occur as the tilt of Earth changes.



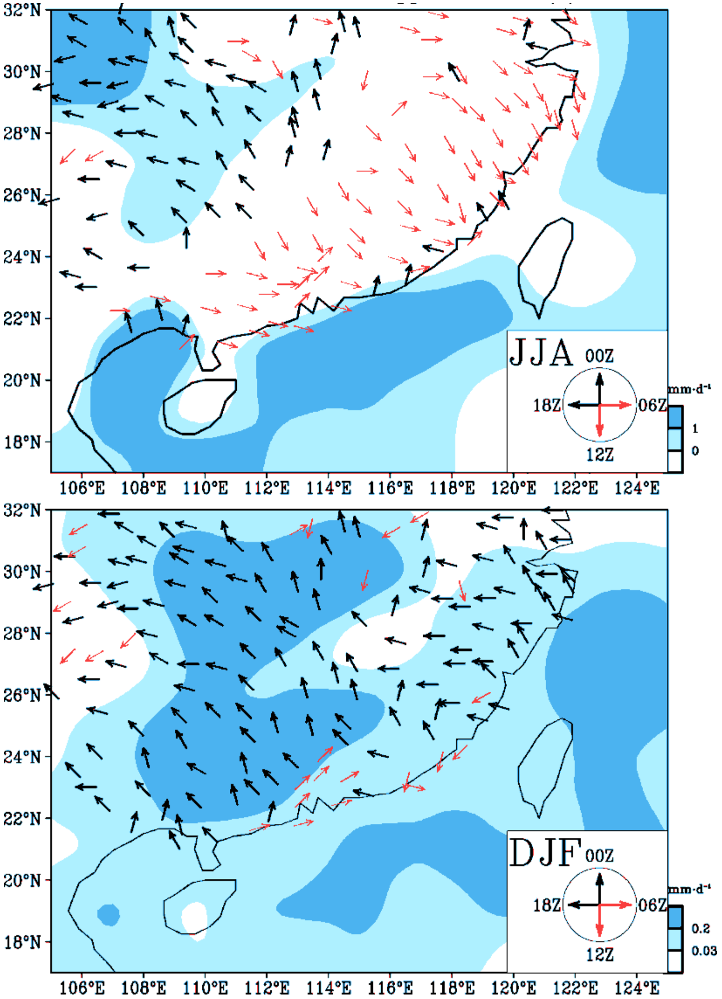
The seasonally varying downward propagating global migrating tidal wave combining with the non-migrating tidal wave results in the dimension change of giant land-sea breeze.

Q: What is the implication of seasonal LSB change in diurnal precipitation change?

Seasonal variation of θ_e vs. ΔP



S1[θe(contoured),-∂θe/∂z(shaded)] 00Z; 25°N



Timing of maximum ΔP stippled with S1(P) at 00Z

Li, J., R. Yu, and T. Zhou, 2008: **Seasonal Variation of the Diurnal Cycle of Rainfall in Southern Contiguous China.** *J. Climate*, **21**, 6036‐6043.

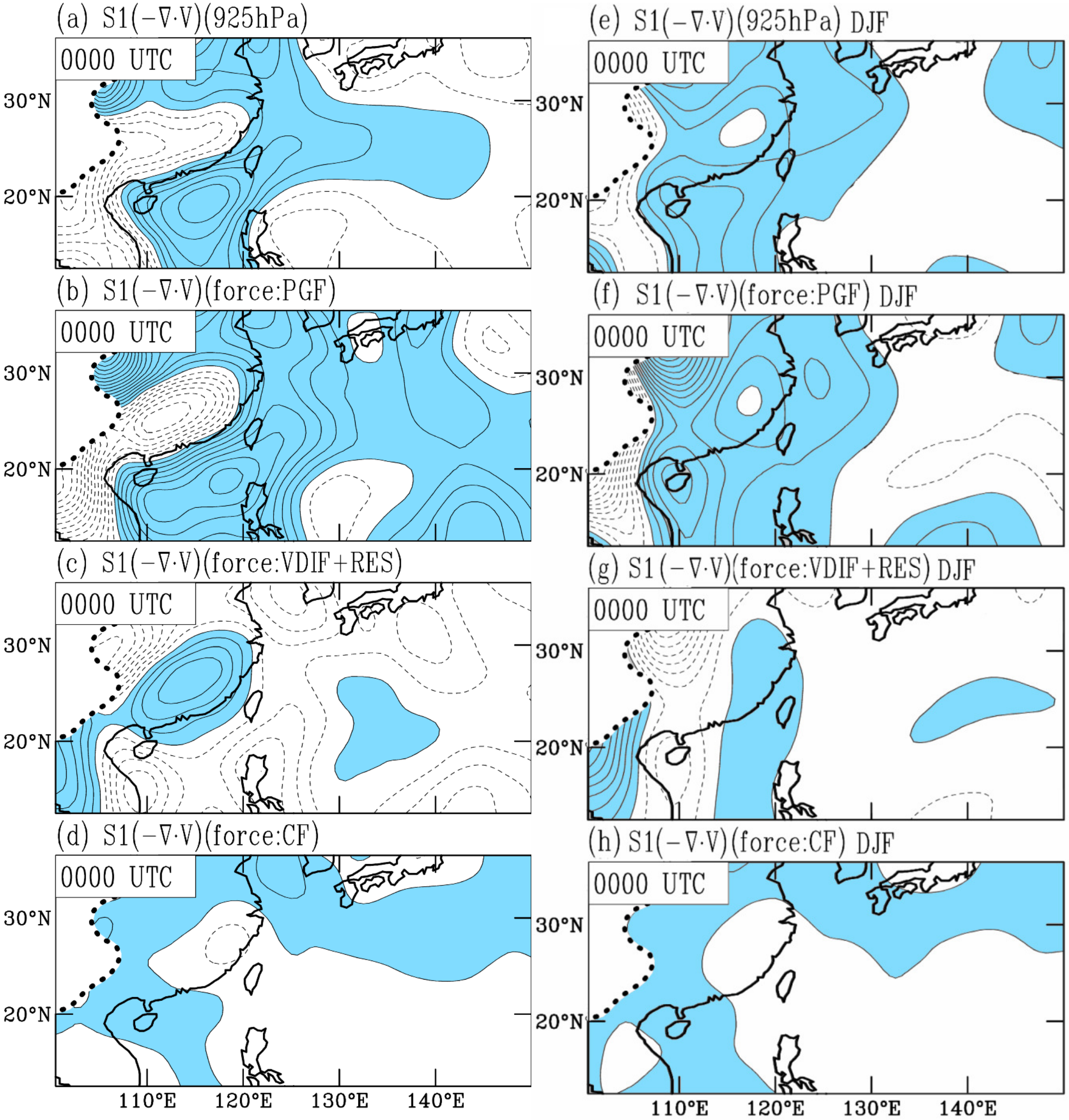
Seasonal variation of diurnally-varying wind convergence/divergence

JJA **DJF**

Force: PGF

Force: VDIF+RES

Force: CF



$S1(-\nabla \cdot \mathbf{V})$

⇓

S1(P)

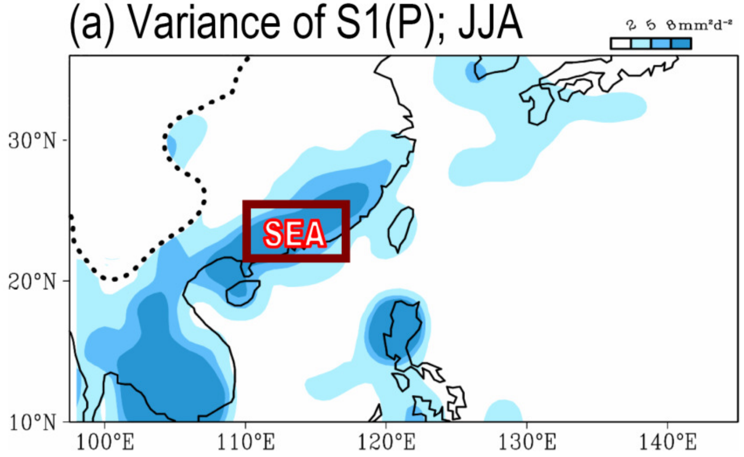
Water Vapor Budget Analyses

$$P = E + (-\nabla \cdot \mathbf{Q}) + (-\frac{\partial W}{\partial t})$$

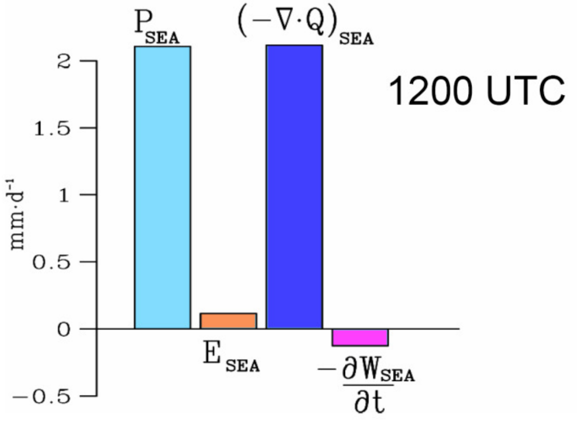
W: total precipitable water
∇•*Q*: convergence or divergence of vertical-integrated water vapor flux
P : precipitation
E : evaporation.

$$S1(P) \sim S1(-\nabla \cdot \mathbf{Q})$$

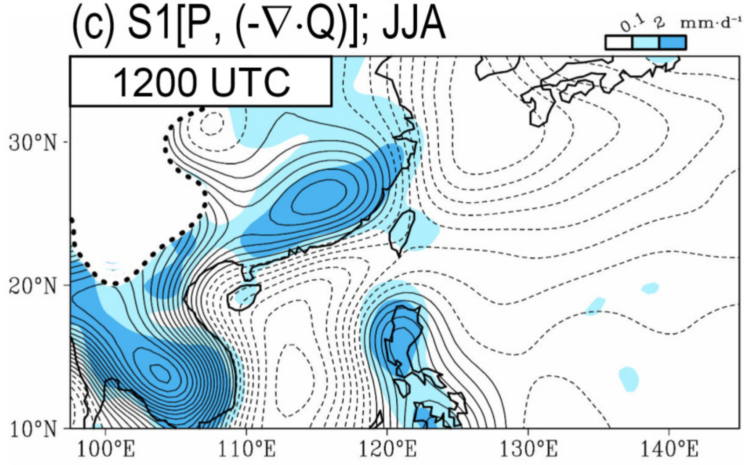
(a) Variance of S1(P); JJA



(b) S1 of water vapor budget; JJA



(c) S1[P, (-∇·Q)]; JJA



Summary

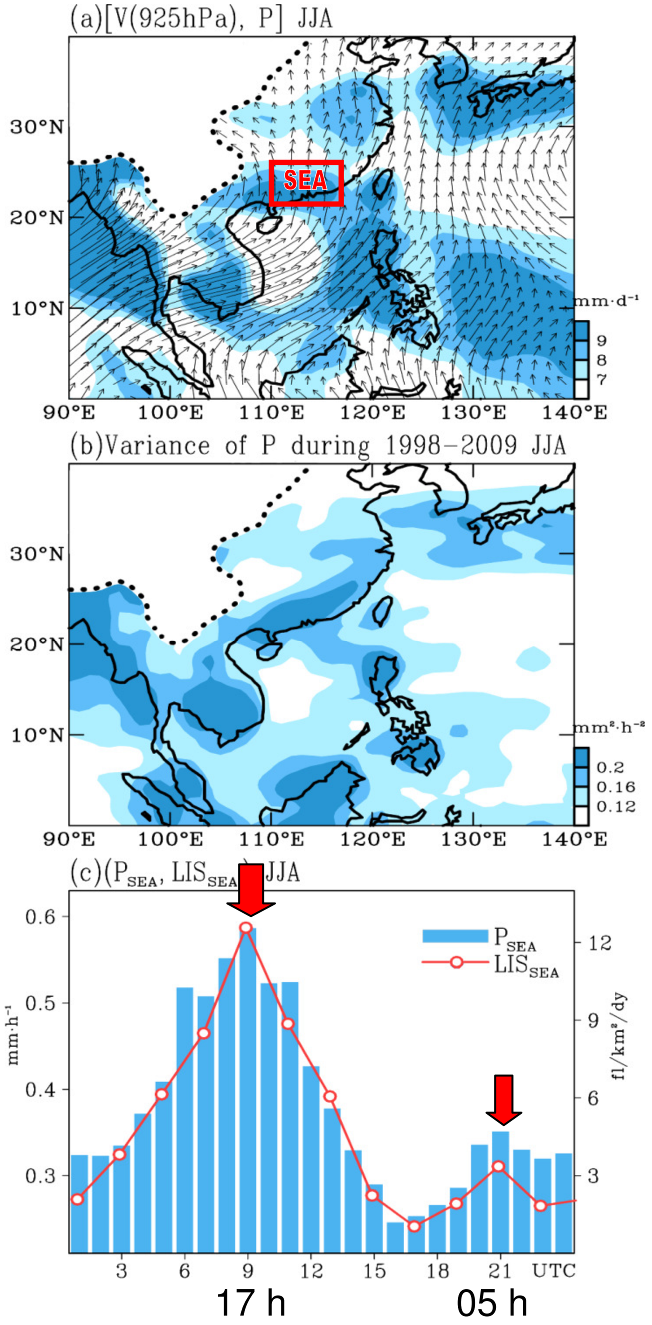
- The local land-sea breeze along the coastline typically spans less than a hundred kilometers into the ocean. Here we found that the land-sea breeze circulation is coupled with the global-scale diurnal tide. The coupling forms a seemingly giant land-sea breeze that covers a thousand kilometers over the Western Pacific.

- Examination of the momentum budget indicates that the atmospheric diurnal tidal wave contributes the most to this circulation feature.

- The seasonal variations of the diurnal tidal wave and the continental heat content combined result in the dimension change of this giant land-sea breeze. Such seasonal contrast leads to the timing difference of diurnal rainfall in East Asia between summer and winter.

II. Maintenance Mechanisms for the Early Morning Maximum Rainfall over Southeast Asia

1. Introduction

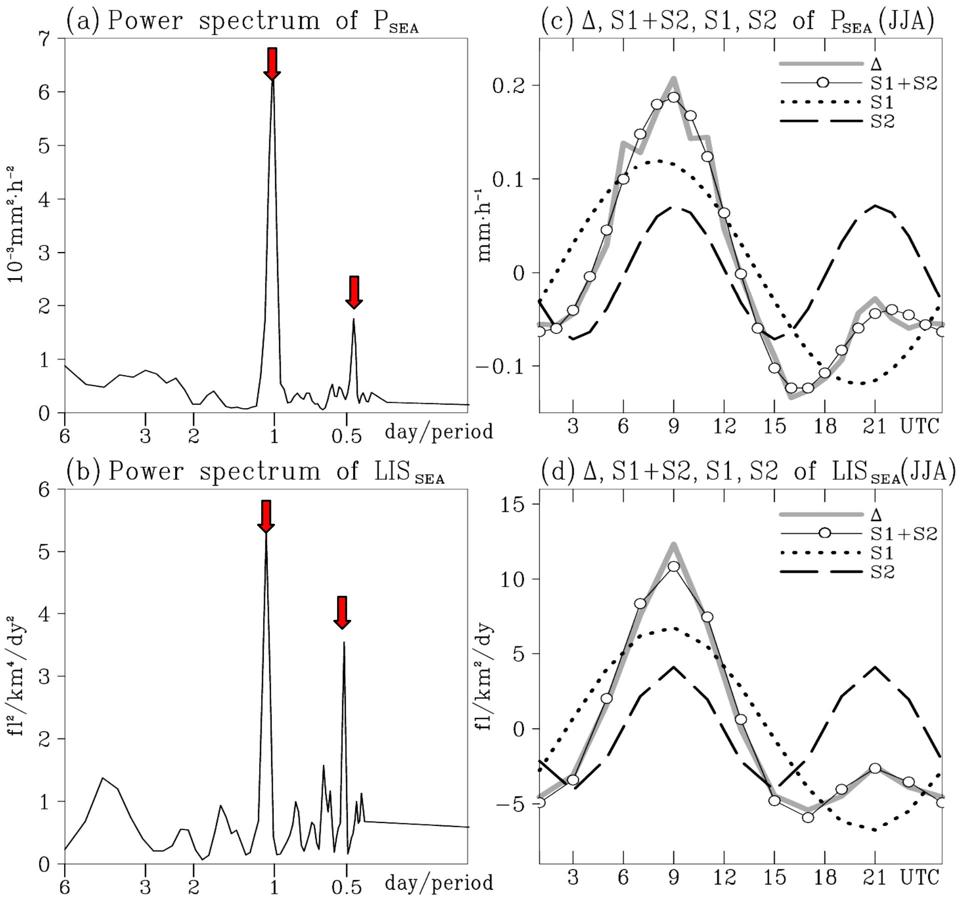


Climate features of rainfall over Southeast Asia (SEA) in summer

- Large amount of rainfall over SEA is modulated by the monsoonal flow
- Large hour to hour rainfall variability
- The hourly rainfall (P) and lightning activities (LIS) consists of two peaks within a day
- The afternoon rainfall maximum is generally recognized to be mainly modulated by the diurnally-varying wind introduced by the land-sea and mountain-valley differential heating (e.g., Dai, 2001)

Question:
What causes the early morning rainfall maximum?

The importance of diurnal (S1) and semidiurnal (S2) variations



- About 97% and 98% of ΔP and ΔLIS is explained by their S1+S2 harmonic modes
- The variance of S2(*P*) and S2(LIS) contributes to ~ 30% and 35 % of the variance of Δ*P* and ΔLIS over SEA respectively.
- The S2 oscillation is found to be more important than the diurnal oscillation for determining the timing of early morning rainfall peak.

Literature Review

Previous studies investigating the possible causes of nocturnal rainfall over the Yangtze River region, Hong Kong, and Taiwan found that the nocturnal instability over these areas can be initiated by

1. the diurnally-varying low-level atmospheric thermal advection (e.g., Ramage 1952; Chen et al. 2010)
2. the radiative cooling at the top of the cloud (e.g., Gray and Jacobson 1977; Chen et al. 2010), and
3. the convergence of surface wind and water vapor flux (e.g., Wai et al. 1996; Chen et al. 1999).

Hypotheses

- We propose that all these mechanisms have impacts on the formation of the early morning maximum P_{SEA} as well.
- We further hypothesize that the physical mechanisms involved for the formation of semi-diurnal oscillation of rainfall are important and non-negligible for the occurrence of an early morning maximum P_{SEA}.

Objective

The objective of this study is to find out the possible causes of early morning rainfall maximum over SEA, which are important because a proper conceptual model for the formation of early morning P_{SEA} and $S2(P)_{SEA}$ that contributes ~ 30% of the total variability of P_{SEA} within a day can have significant implication on the improvement of weather and climate simulations over SEA.

2. Data and Methodology

- 3hourly GEOS5 reanalyses data. TRMM rainfall and lightning activities. Could top pressure from ISCCP.

- Δ : anomalies = (specific individual time step) – daily mean of available time steps

  S1: diurnal harmonic

  S2: semi-diurnal harmonic

  From the Fourier analysis

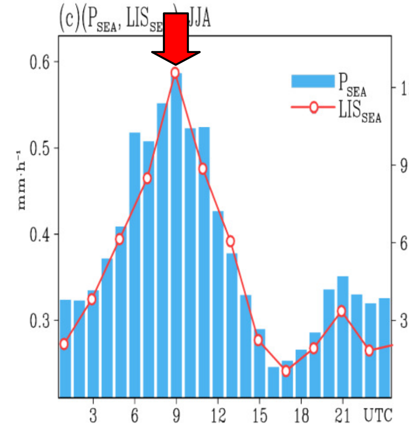
- The atmospheric heat budget and the water vapor budget are examined for exploring the role of

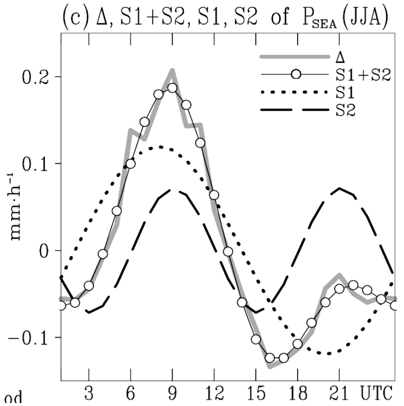
  a. diurnally-varying low-level atmospheric thermal advection
  b. Hyrdrological cycle-radiation interaction

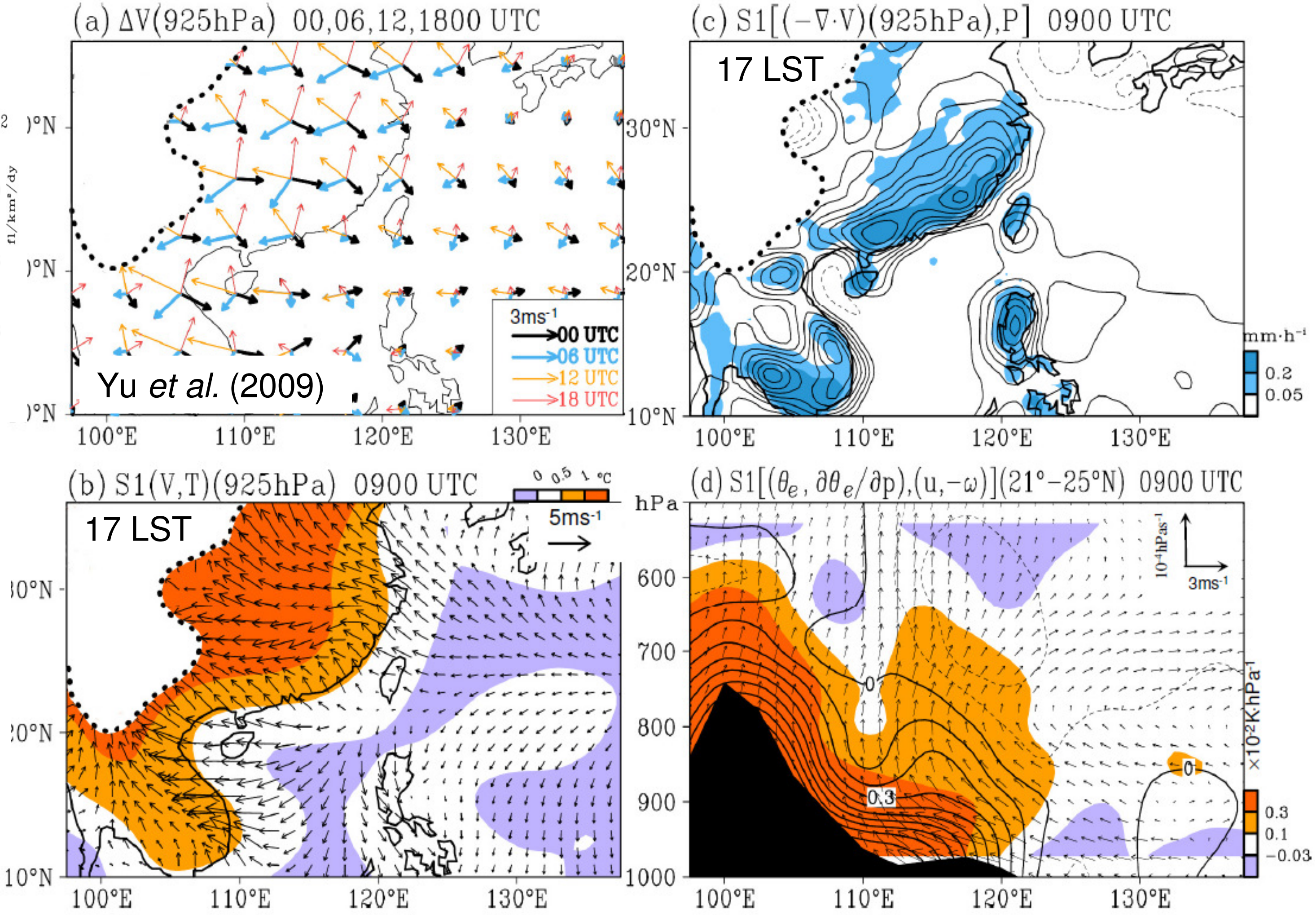
  on affecting the early morning instability and rainfall over SEA

3. Results

General characteristics of diurnal variations over SEA- The formation of afternoon rainfall maximum



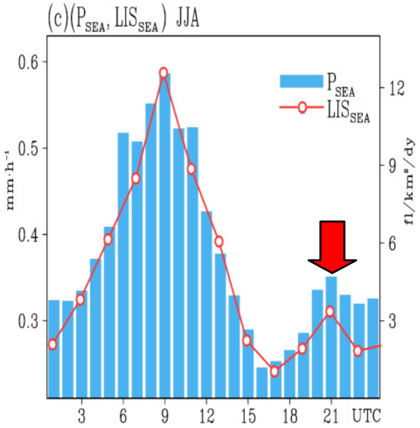




The atmospheric heat budget equation

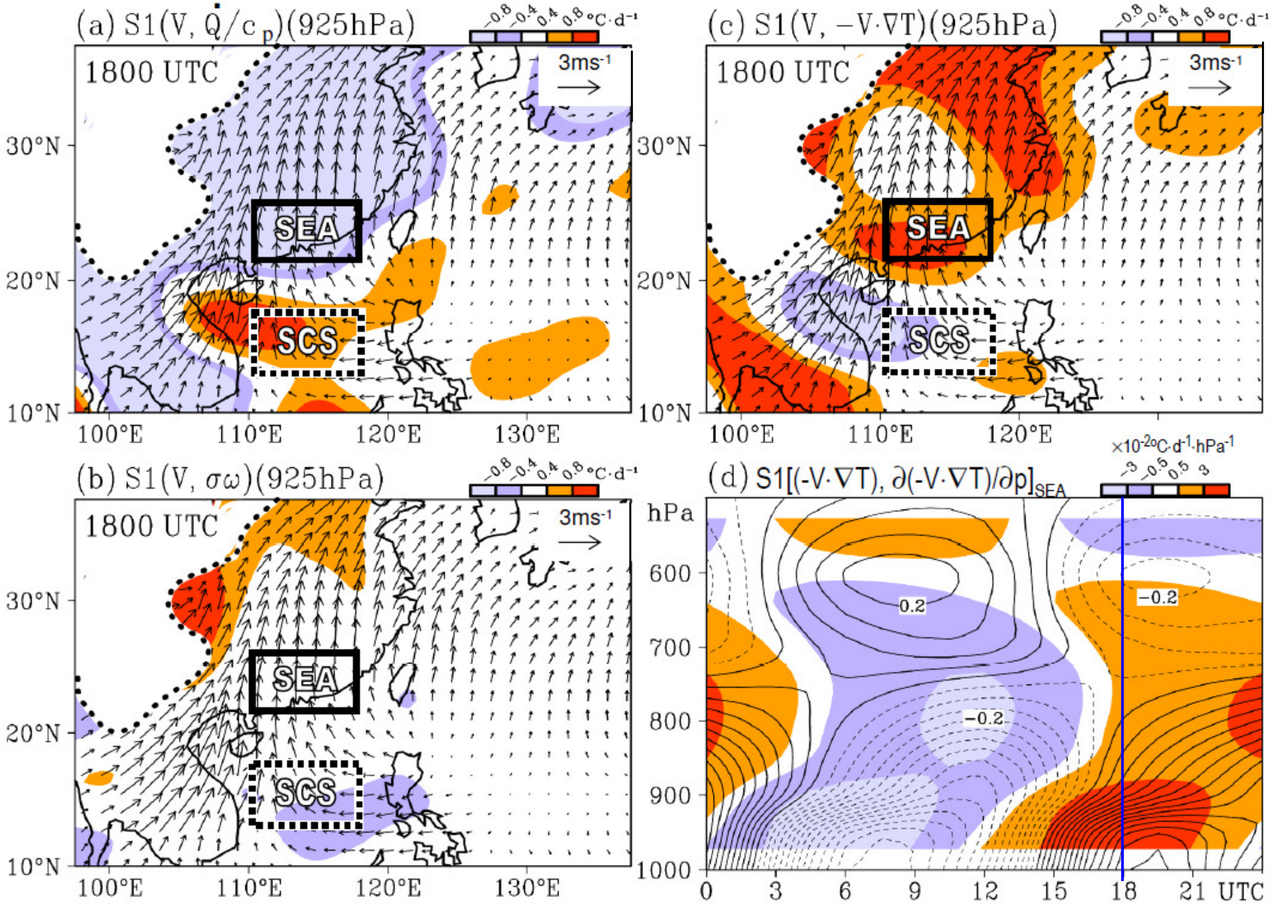
$$\underbrace{\frac{\partial T}{\partial \mathrm{t}}}_{\mathrm{DT}} = \underbrace{\frac{\dot{Q}}{c_p}}_{\mathrm{DIA}} + \underbrace{\sigma\omega}_{\mathrm{VA}} + \underbrace{(-\mathbf{V} \bullet \nabla T)}_{\mathrm{HA}},$$

$$\mathrm{T} = \int_{\mathrm{t}-3\mathrm{h}}^{\mathrm{t}} [\mathrm{DIA} + \mathrm{VA} + \mathrm{HA}]\,\mathrm{dt}$$



- To know the atmospheric thermal condition over SEA in the early morning at 2100 UTC (0500 h), we examine the variations of three heating terms at 1800 UTC (0200 h).

The diagnosis of atmospheric heat budget at 1800 UTC



DIA

HA

VA

- S1(HA) seems to be the one which is able to reduce the early morning atmospheric stability caused by S1(DIA).
- The occurrence of maximum low-level warm air advection is in conjunction with the occurrence of an upper-level cold air advection at 1800 UTC ➔ reduce the stability at 2100 UTC

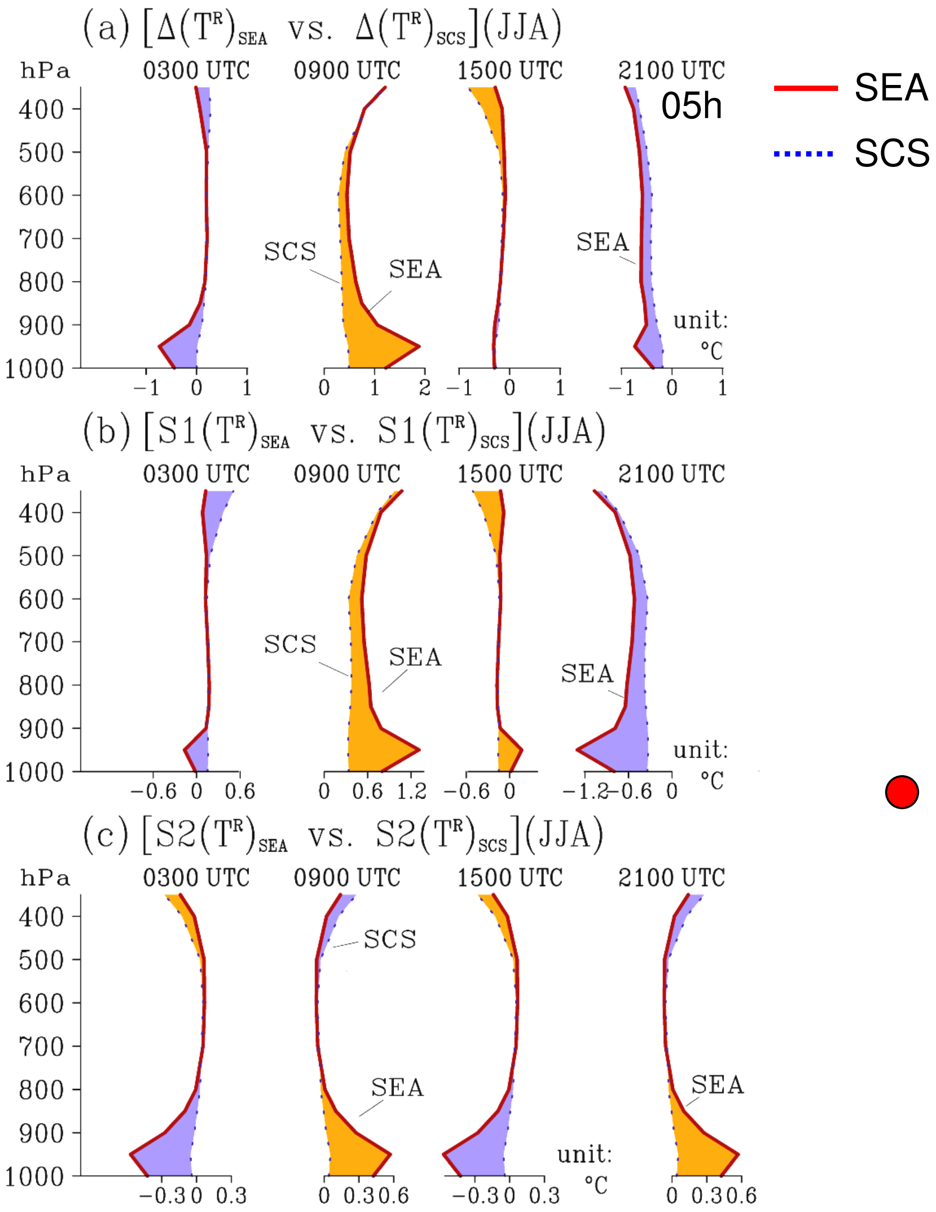
The temperature change in the early morning after scale analysis

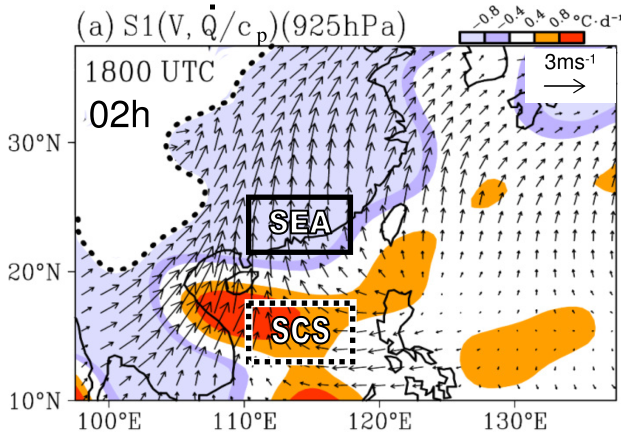
$$
\begin{aligned}
\Delta T &= \mathrm{S1}(T)+\mathrm{S2}(T) \\
&= \mathrm{S1}(T^{\mathrm{DIA}})+\mathrm{S1}(T^{\mathrm{HA}})+\mathrm{S1}\cancel{(T^{\mathrm{VA}}})+\mathrm{S2}(T^{\mathrm{DIA}})+\mathrm{S2}\cancel{(T^{\mathrm{HA}})}+\mathrm{S2}\cancel{(T^{\mathrm{VA}})} \\
&\approx \mathrm{S1}(T^{\mathrm{DIA}})+\mathrm{S1}(T^{\mathrm{HA}})+\mathrm{S2}(T^{\mathrm{DIA}}).
\end{aligned}
$$

- It is known that the radiative heating/cooling is one of the major diabatic processes included in the DIA term (Holton 1992).
- Gray and Jacobson (1977) suggested that the tropospheric radiative cooling between the deep convective system and its surrounding cloud-free region is the main reason for explaining the morning rainfall maximum associated with cumulus convection.
- Here, we examine the difference of temperature changes induced by the net radiation (denoted by T^R) between SEA and SCS.

$$
T^{\mathrm{R}} = \int_{\mathrm{t-3h}}^{\mathrm{t}} \left[\frac{\partial T}{\partial \mathrm{t}}^{\mathrm{SW}} + \frac{\partial T}{\partial \mathrm{t}}^{\mathrm{LW}}\right] \mathrm{dt}
$$

The land-sea differential radiative heating

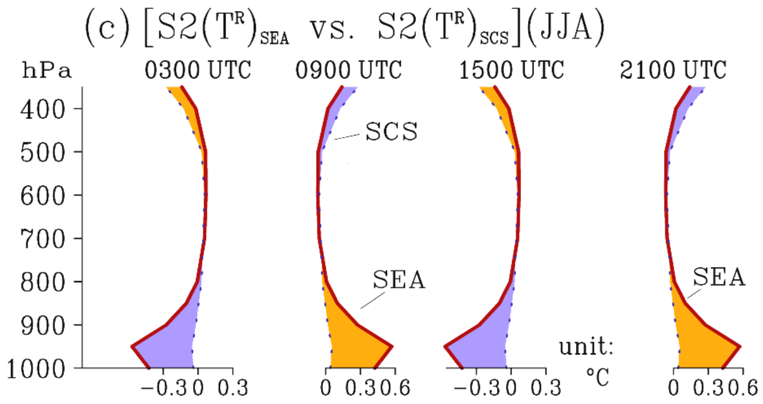




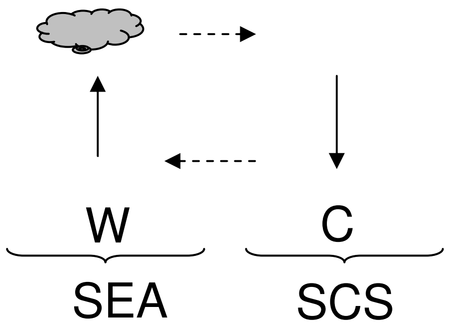
$$T^{R} = \int_{t-3h}^{t} \left[\frac{\partial T^{SW}}{\partial t} + \frac{\partial T^{LW}}{\partial t} \right] dt$$

- In contrast to the temporal evolution of S1(T^{R}), the low-level S2(T^{R})$_{SEA}$ is warmer than S2(T^{R})$_{SCS}$ at both 0900 and 2100 UTC.

The semi-diurnal harmonic of hydrological cycle-radiation interaction



2100 UTC (0500 h)

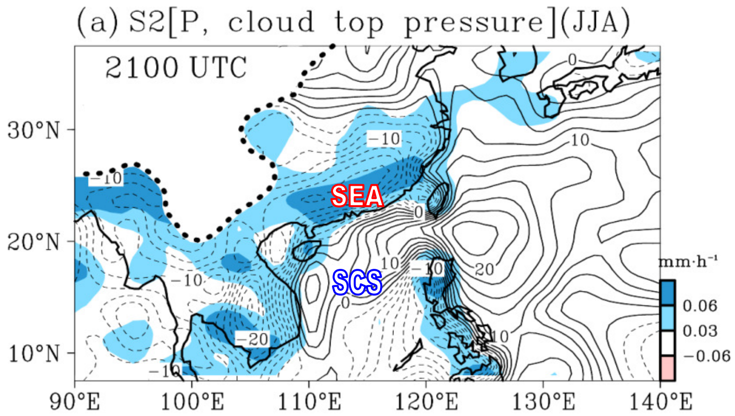


W

C

SEA

SCS



- The vertical distribution of S2(T^R) at 2100 UTC likely leads to a secondary circulation with upward motion over SEA and downward motion over SCS and, in turn, forms a S2(*P*) peak over SEA.

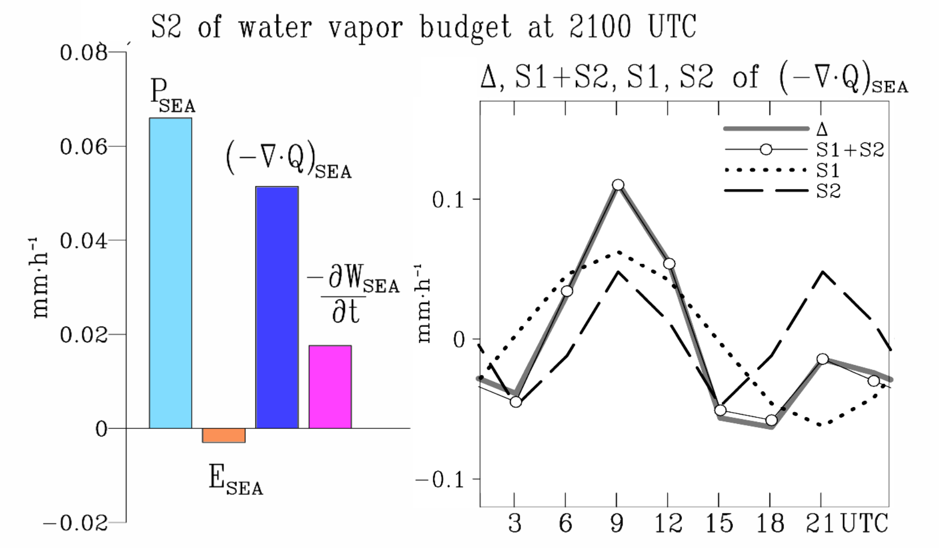
⇩

Evidence:
lower cloud top pressure with higher cloud top appears over SEA rather than SCS

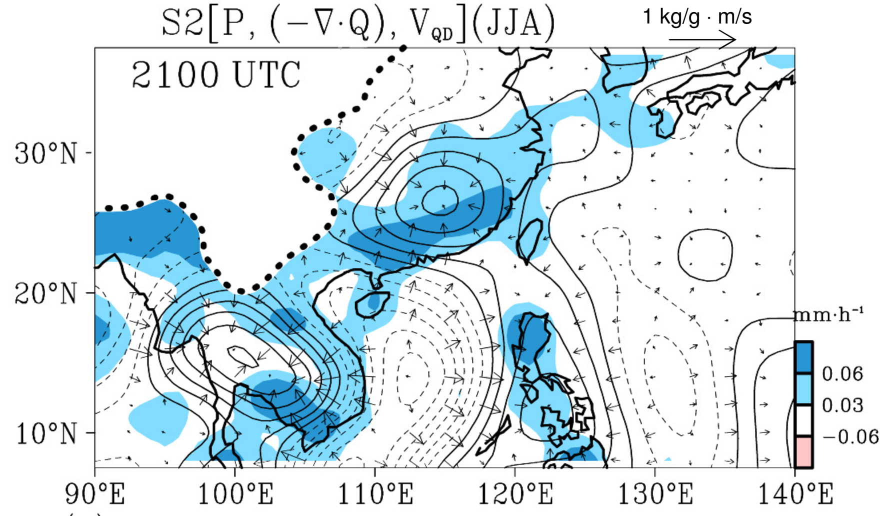
The water vapor budget analysis

$$P = E + (-\nabla\cdot\mathbf{Q}) + \left(-\frac{\partial W}{\partial t}\right)$$

$$S2(P)_{SEA} \sim S2(-\nabla\bullet\mathbf{Q})_{SEA}$$

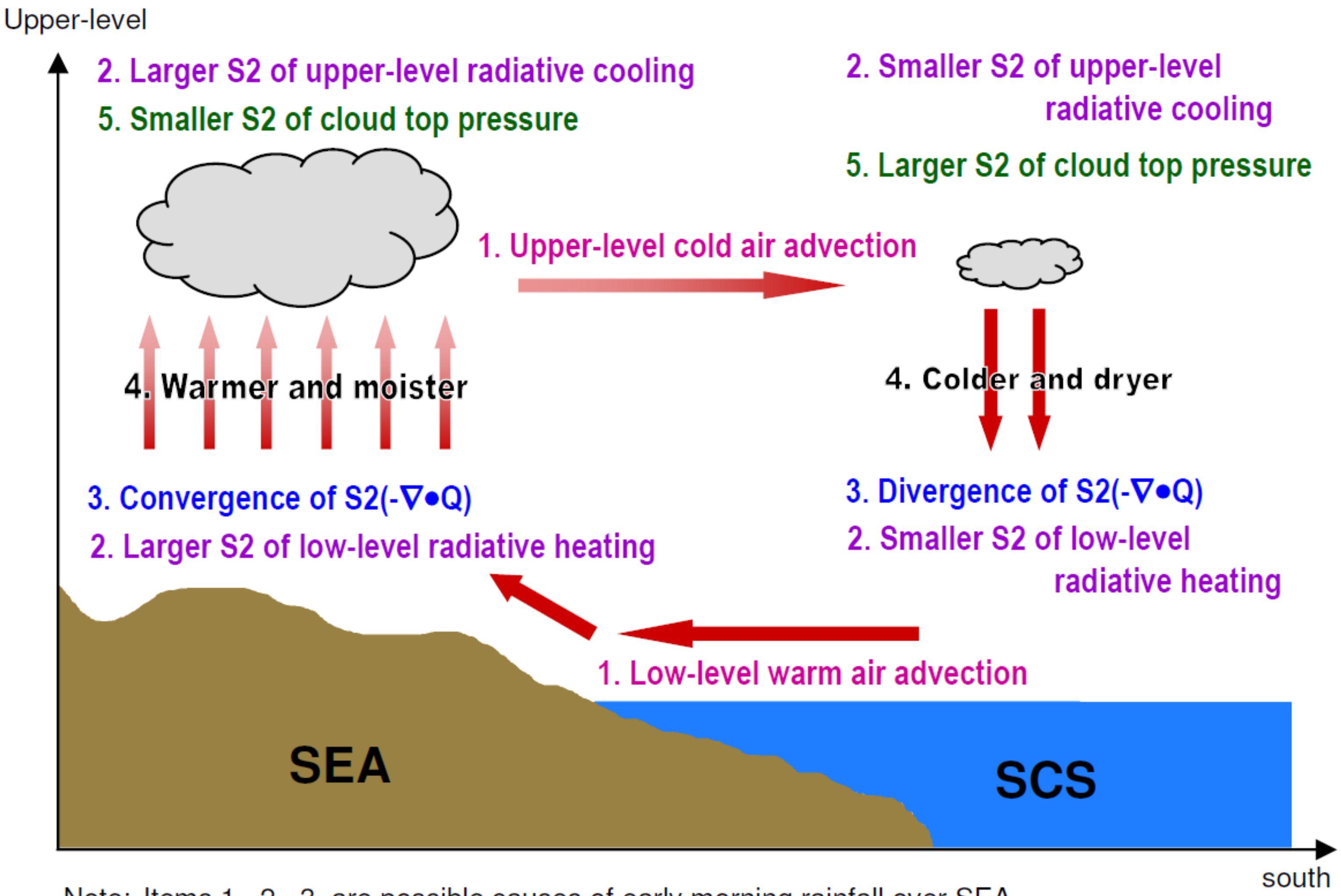


- In response to the S2 harmonic of land-sea differential radiative heating/cooling between SEA and SCS, the S2 harmonic of hydrological circulation shows the water vapor transporting from SCS to SEA to maintain the early morning rainfall maximum over SEA



Summary

The formation of early morning maximum rainfall at 2100 UTC/0500 h over SEA



Upper-level

2. Larger S2 of upper-level radiative cooling

5. Smaller S2 of cloud top pressure

2. Smaller S2 of upper-level radiative cooling

5. Larger S2 of cloud top pressure

1. Upper-level cold air advection

4. Warmer and moister

4. Colder and dryer

3. Convergence of S2(-∇•Q)

2. Larger S2 of low-level radiative heating

3. Divergence of S2(-∇•Q)

2. Smaller S2 of low-level radiative heating

1. Low-level warm air advection

SEA

SCS

south

Note: Items 1., 2., 3. are possible causes of early morning rainfall over SEA
Items 4. and 5. are features related to items 1-3

Thank You !