Monzones

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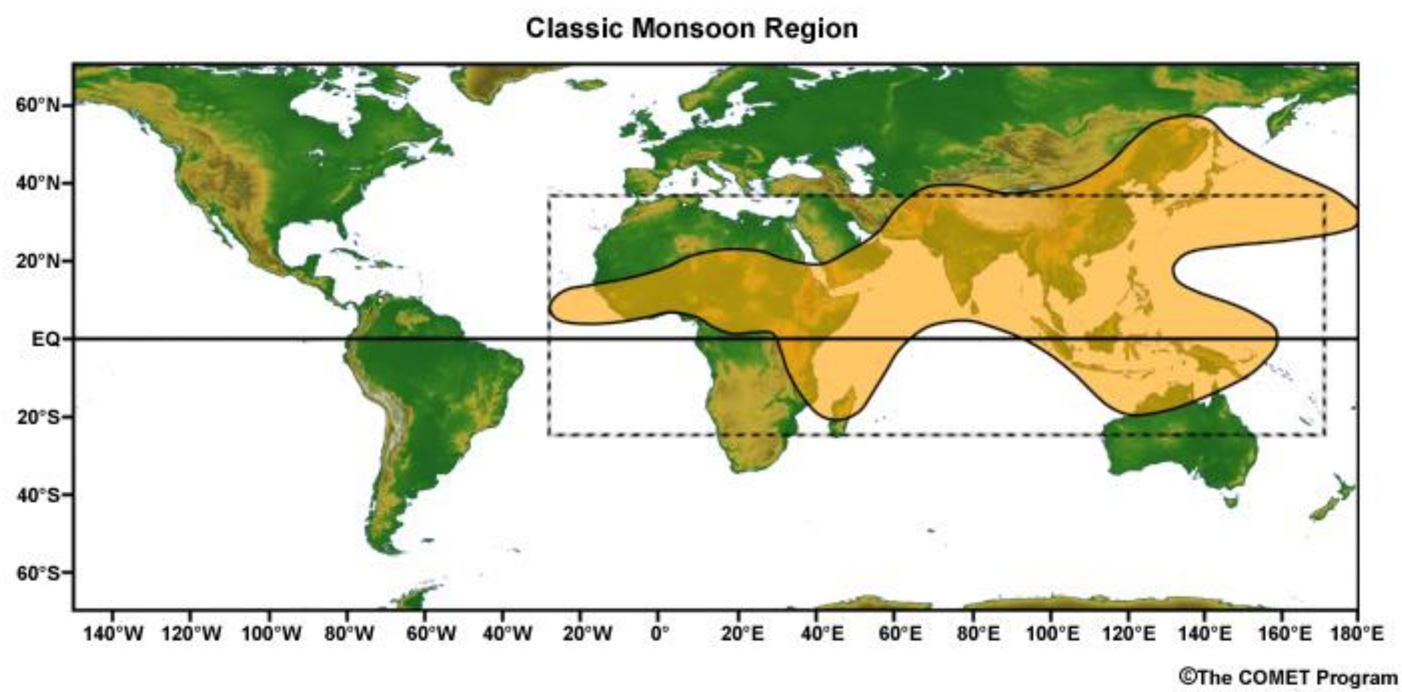
DEFINING THE MONSOON

The classical criteria for a monsoon as specified by Ramage (1971) are:

- Prevailing wind shifts 120° between January and July
- Average frequency of prevailing wind > 40%
- Speed of mean wind exceeds 3 m s-1
- Pressure patterns satisfy a steadiness criterion

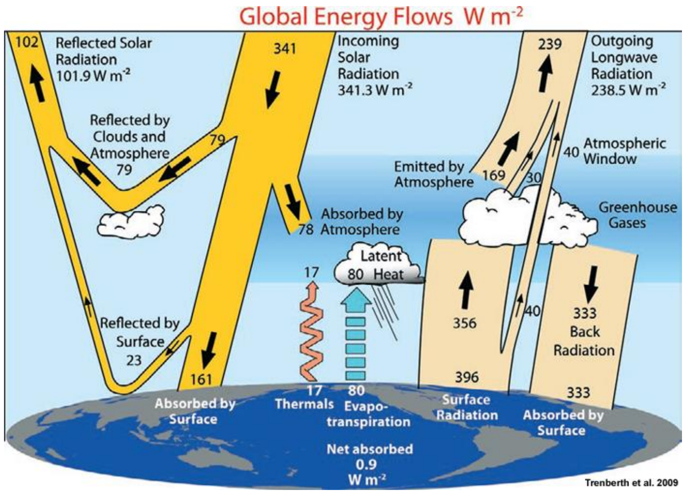
The monsoon regions for which these criteria apply are shown in the figure. The Indian monsoon matches these criteria.

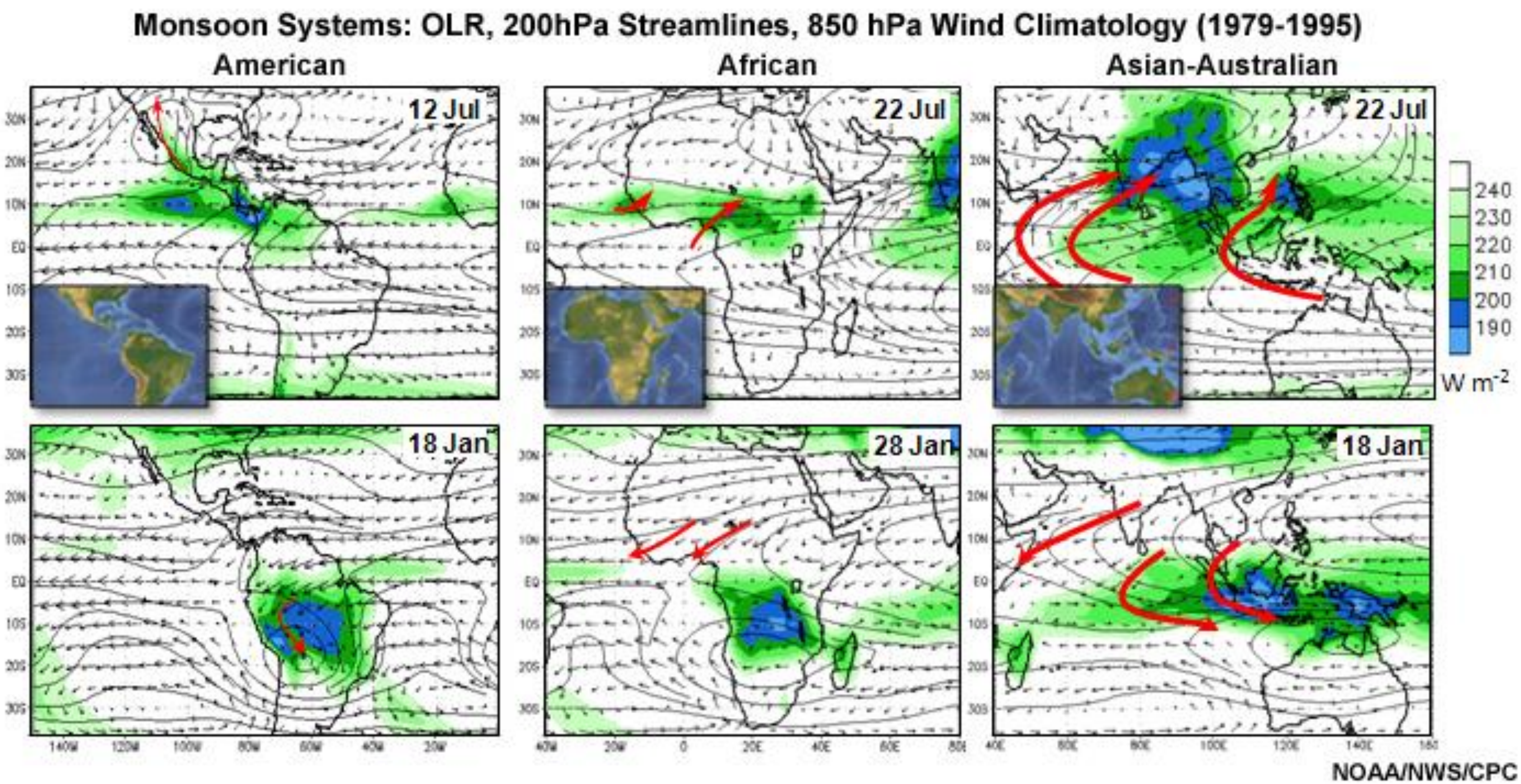


The monsoon regions as defined by Ramage (1971)

DEFINING THE MONSOON

- ✓ In the decades the monsoon regions have been expanded
- ✓ The global monsoon systems now include regions of the Americas whose summer time precipitation and wind characteristics are similar to the Indian monsoons.





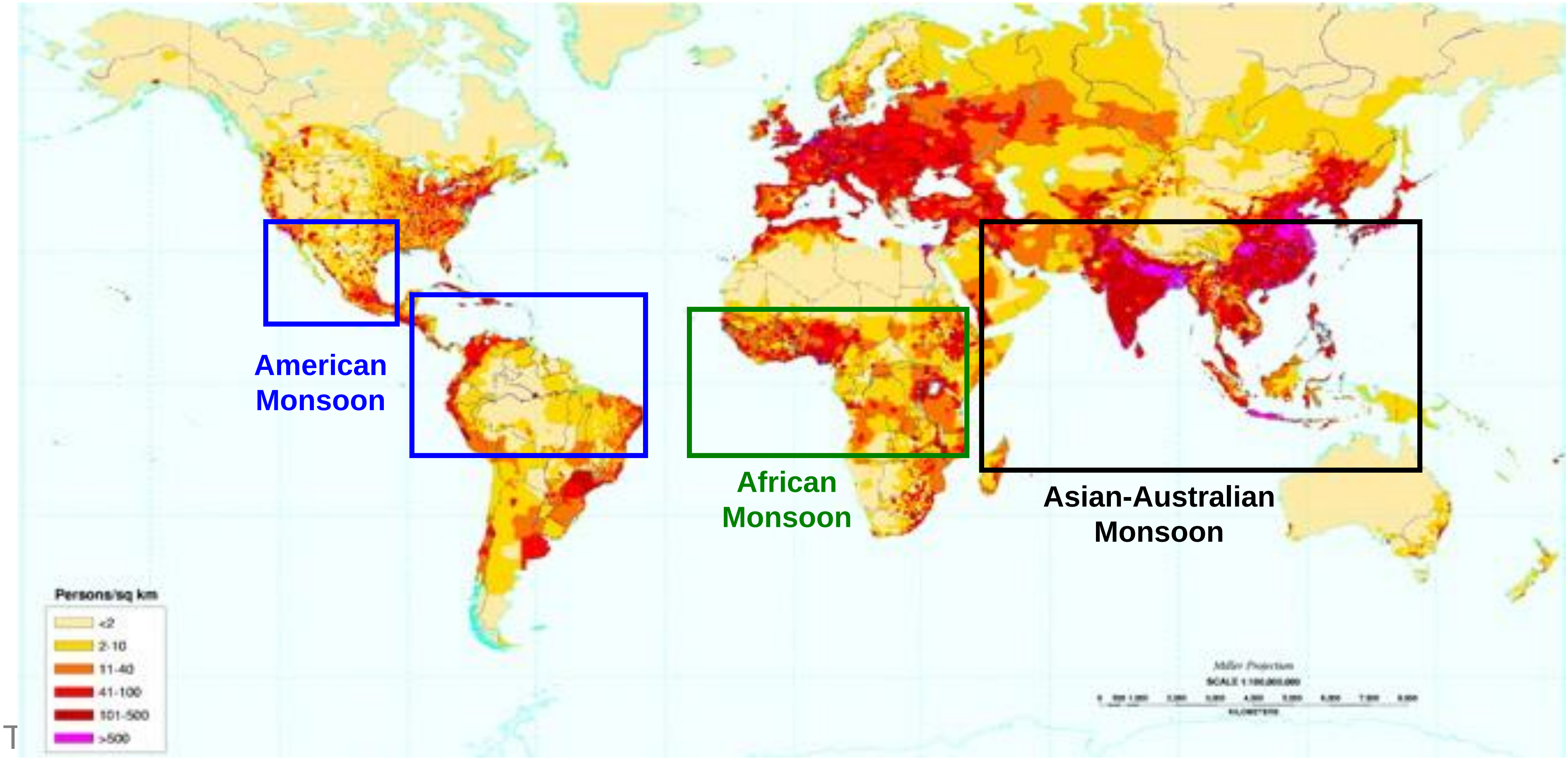
Global tropical monsoon systems near their peak periods

MONSOON IMPACTS

Large Societal Impact on Global Scale

- ✓ Monsoonal regions cover roughly ½ of the Tropics (or ¼ of the global surface area) and plays host to ~65% of the world's population

Population Density



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DEFINING THE MONSOON

- ✓ The word monsoon comes from the Arabian word 'mausim' meaning 'season' and was first used to refer to seasonal reversal of the prevailing surfaces winds over southern Asia and the Indian Ocean.

- ✓ Of all the atmospheric circulation systems, monsoons exhibit the most significant seasonal variations.

- ✓ They are a central component of the global climate system and are large enough to influence it. Monsoon anomalies may cause droughts, floods, and other extreme weather or climate events.

- ✓ Monsoon circulations are also critical to the global transport of atmospheric energy and water vapor.

- ✓ Monsoon variability has profound societal and economic influences on the regions they affect, where more than 70% of the world’s population lives. Many of these societies rely on rain-fed agriculture for their food, so the prediction of the amount, timing, and location of monsoon rains is crucial. Thus, monsoon research is essential not only for understanding global atmospheric circulation and climate change, but also for preventing and mitigating disaster and achieving sustainable development.

- ✓ **Different precipitation regimes accompanied the seasonal wind shifts; rains with onshore flow in the summer and a dry winter season with offshore flow. This simple picture has since been found to be a complex system whose onset, intensity, and break periods are among the most challenging forecast problems.**

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A CONCEPTUAL MODEL OF MONSOON EVOLUTION

What causes the monsoon? This has been a question since time immemorial. A conceptual model presented by Webster (1987) builds on the theories of Halley (1686) and Hadley (1735) and adds moisture feedback through convection.

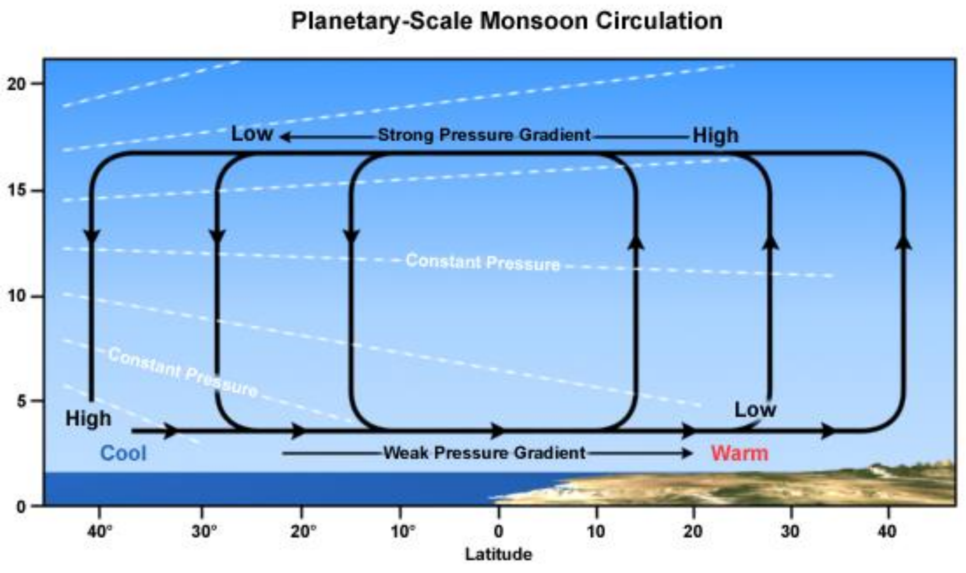
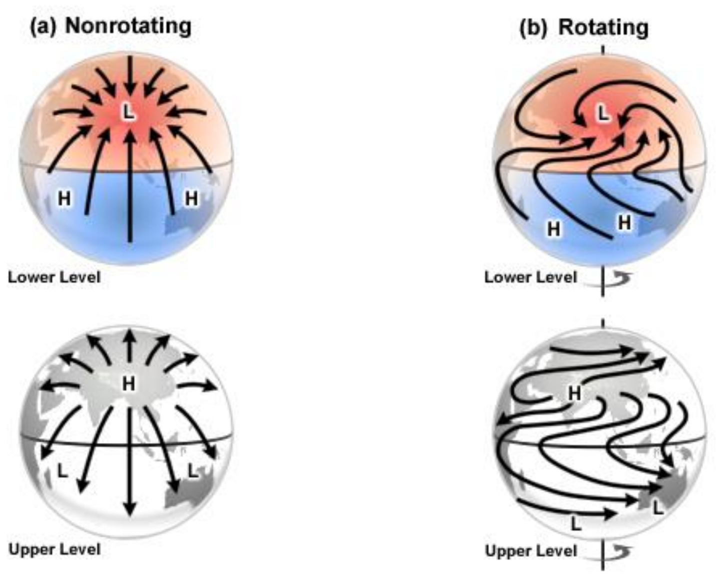


Figure illustrates the conceptual model of the planetary monsoon as a moist sea-breeze modified by the Coriolis Effect.



Cross section of circulation between warm land and cool ocean.

A CONCEPTUAL MODEL OF MONSOON EVOLUTION

- ✓ The importance of the hot land-cool ocean contrast can be questioned because the land surface temperatures actually decrease during the monsoon (but really after the monsoon onset).

- ✓ Decades of satellite imagery have shown that the south Asian monsoon is not just a local land-sea breeze. Rather it is part of the planetary-scale rain band (associated with the equatorial trough) that is present over all of the warm tropical oceans and differs only in its amplitude in the monsoon regions.

- ✓ So the planetary-scale monsoon can be considered to have these fundamental mechanisms:

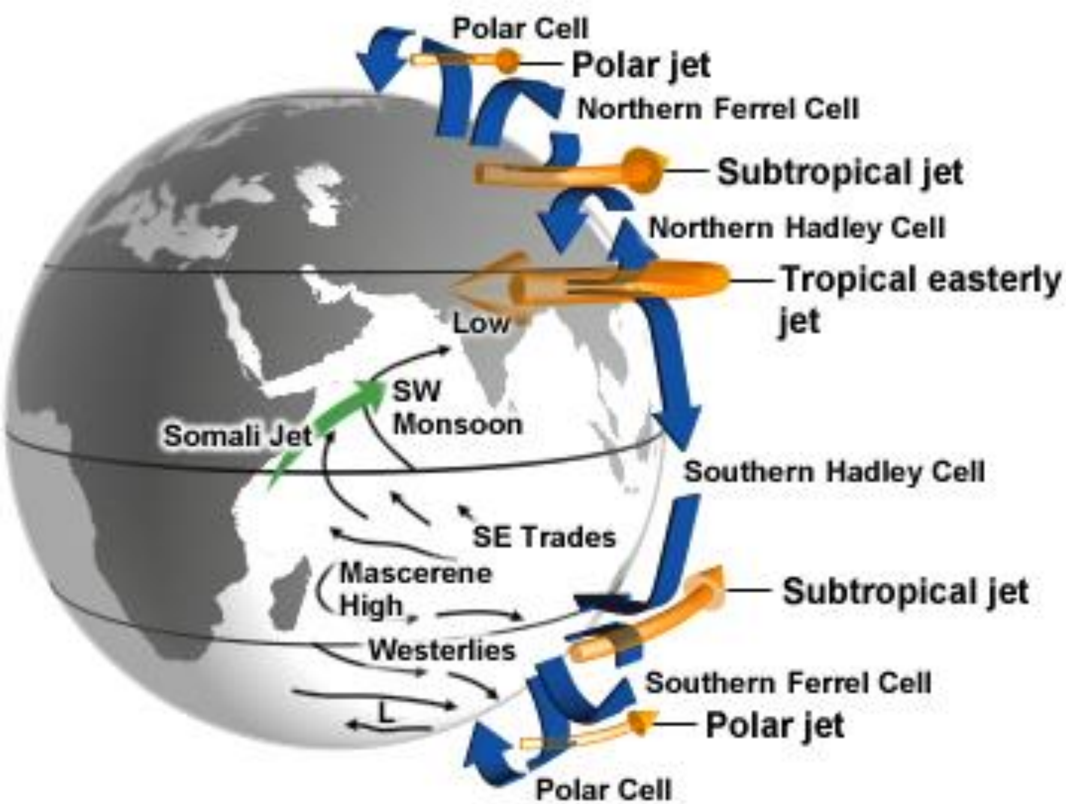
  1. **The seasonal oscillation of solar heating with net heating in the summer hemisphere, which leads to migration of the equatorial trough and the tropical convergence zones**

  2. **The differential heating between the land and ocean and the resulting pressure gradient (Halley 1686)**

  3. **The swirl introduced to the winds by the rotation of the Earth (Hadley 1735)**

  4. **Moisture processes and convection**

A CONCEPTUAL MODEL OF MONSOON EVOLUTION



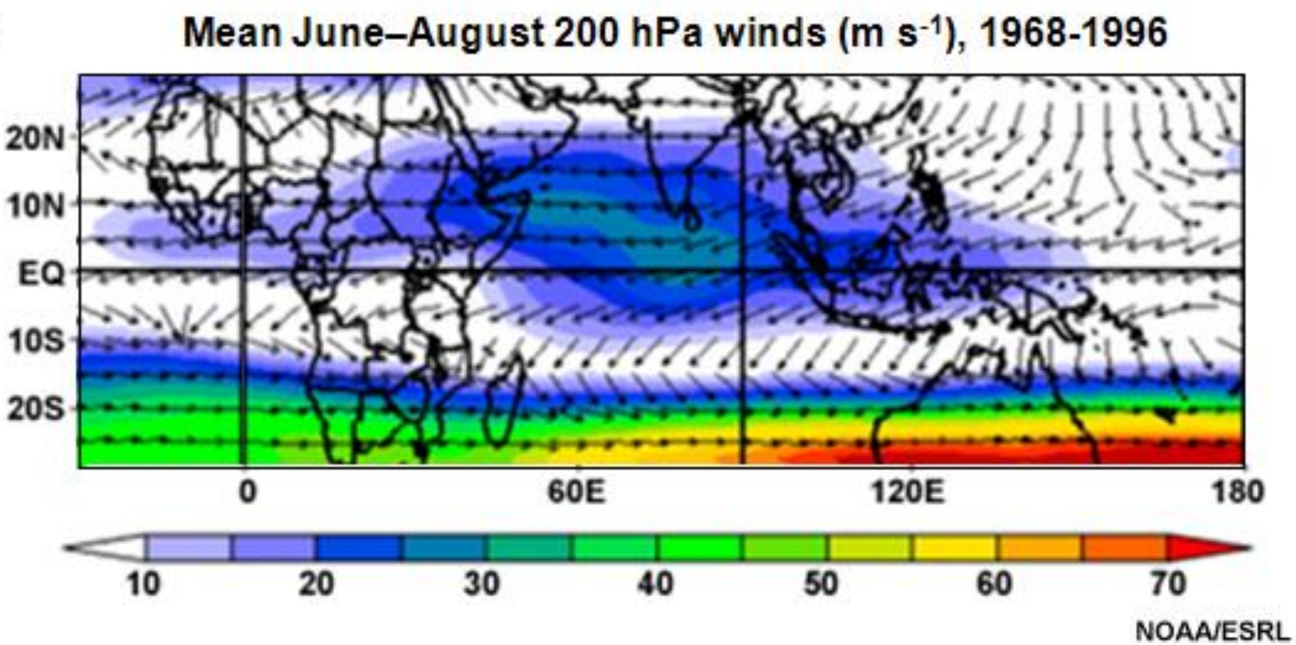
Schematic of the major circulations of the Indian Ocean, the planetary Hadley cell, the tropical easterly jet, and the Asian summer monsoon

The major features of the South Asian summer monsoon are:

- ✓ The monsoon low
- ✓ The low-level onshore and cross-equatorial flow
- ✓ The Mascarene High
- ✓ The updrafts in moist convection
- ✓ The upper-level high
- ✓ The TEJ, (Tropical Eastern Jet) which is the upper-level venting system for the strong southwest monsoon

A CONCEPTUAL MODEL OF MONSOON EVOLUTION

a



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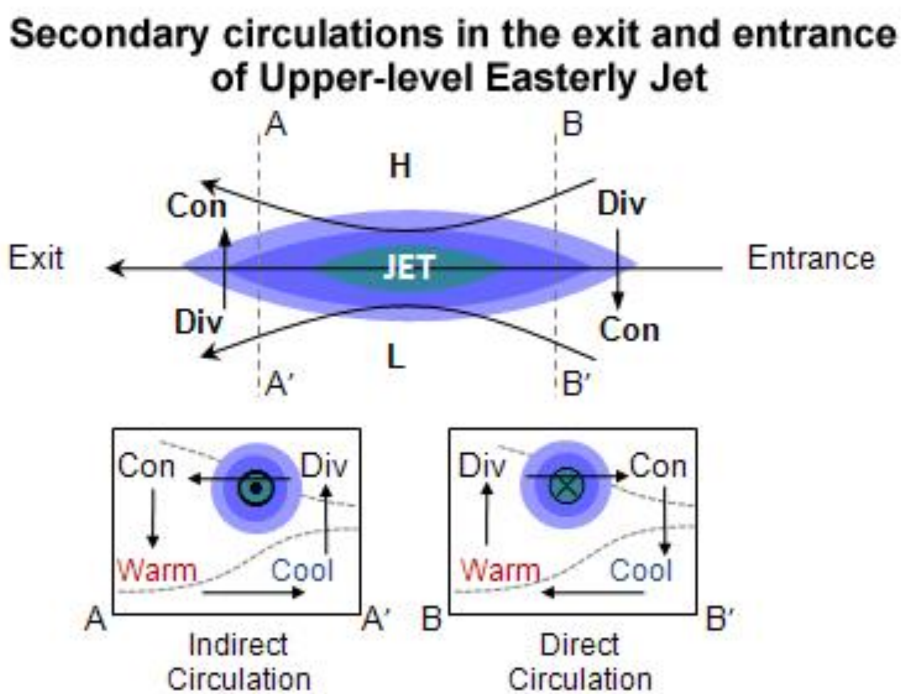
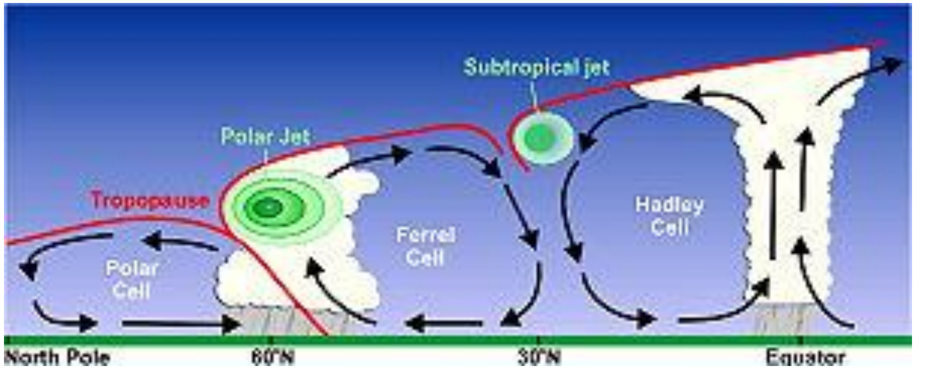
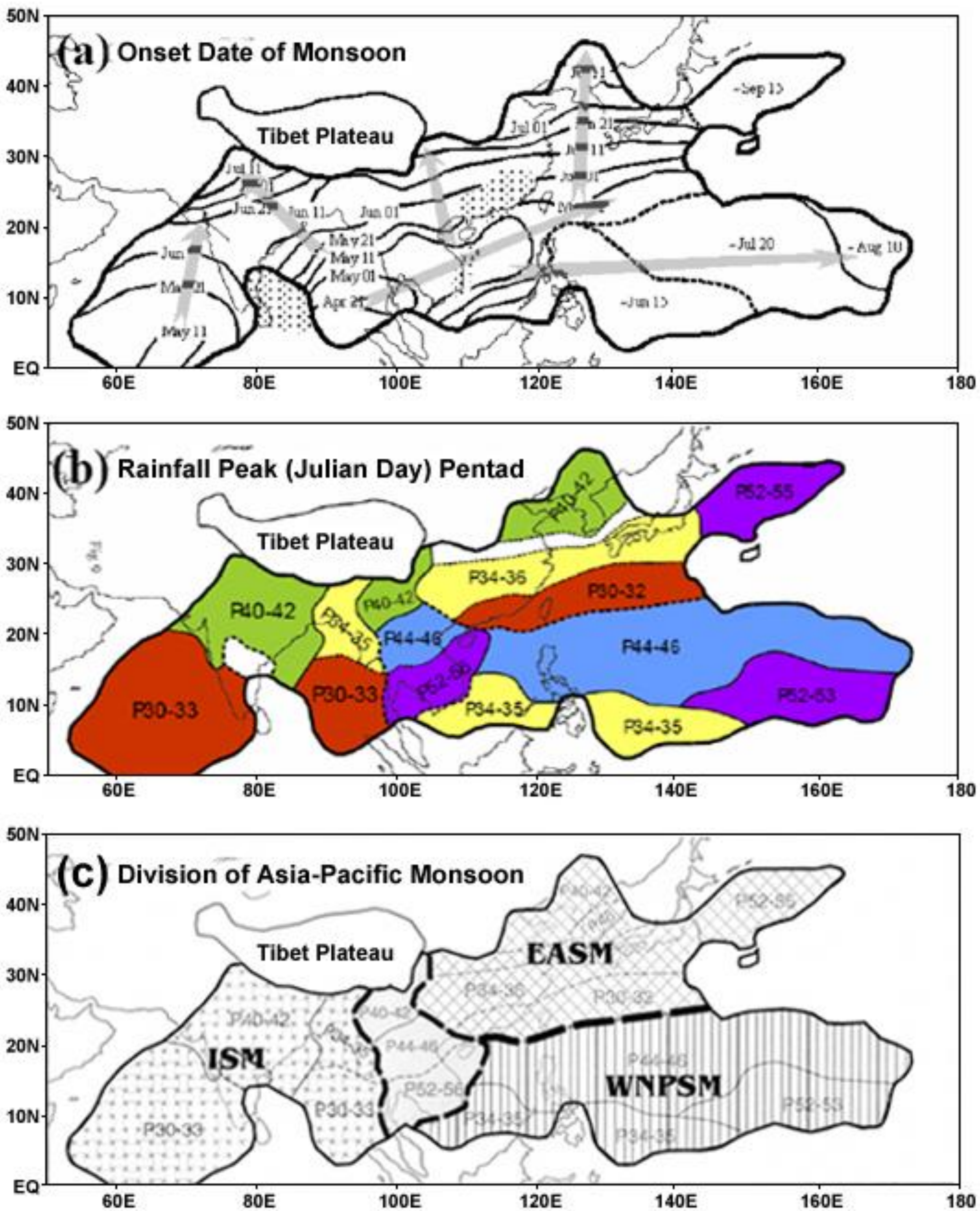


a) *Mean wind vectors at 200 hPa. Color shades mark the TEJ*

b) *A schematic of the ageostrophic motion and regions of expected upper-level divergence (rising motion) and convergence (subsidence).*



EVOLUTION OF THE ASIAN MONSOON SYSTEM



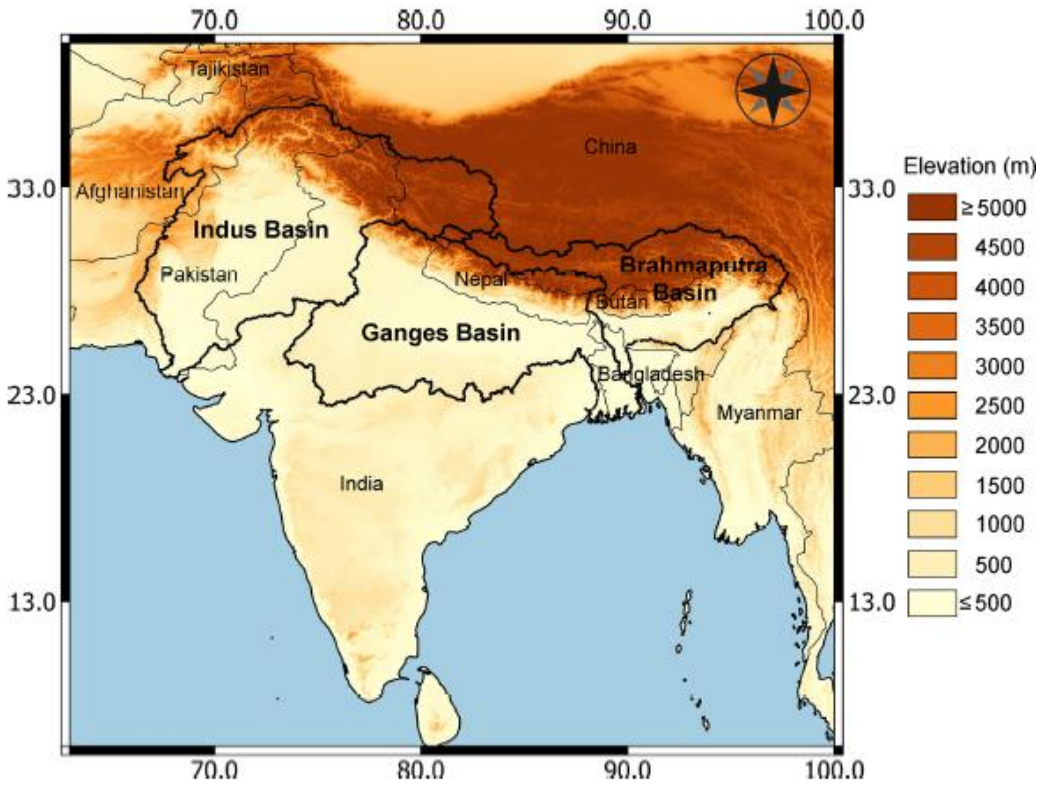
- The Asian monsoon is regionally varied.

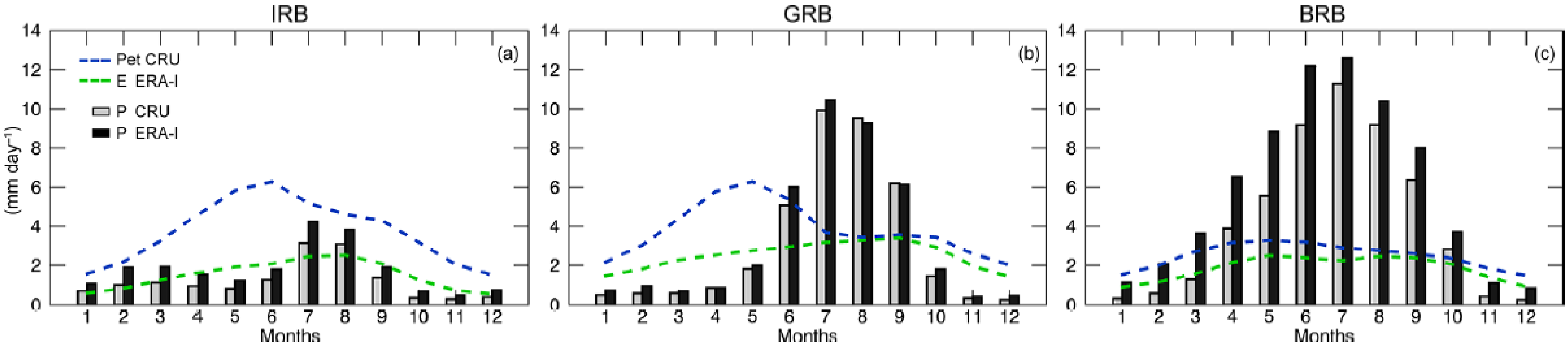
- The earliest onset is over the southern Bay of Bengal in late April, over the Indo-Chinese peninsula and south India in early May, and then it progresses north and northestward into the continent reaching Japan by late June to July.(Figure a). By the end of the peak season over Japan, the monsoon is already retreating over India (Figure b).

- Given the regional evolution**, the Asian monsoon can be divided into two separate but interactive monsoon sub-systems**: the Indian Summer Monsoon or South Asian monsoon and the East Asian monsoon (Figure c). The latter can be sub-divided into the East Asian and Western North Pacific monsoon.

a) Mean onset date and (b) peak pentad of the Asian summer monsoon rainy season; (c) division of the Asian monsoon.

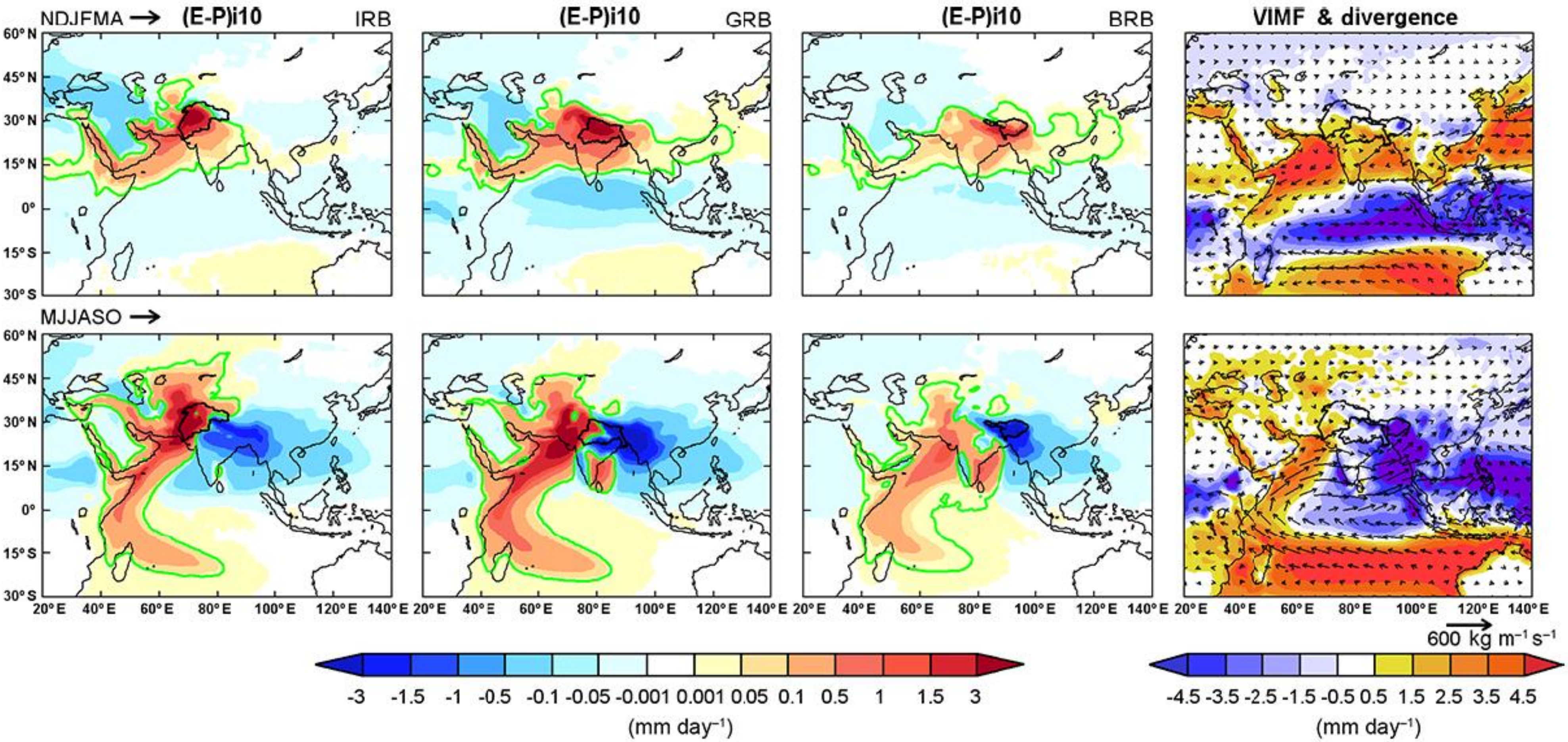
EVOLUTION OF THE ASIAN MONSOON SYSTEM





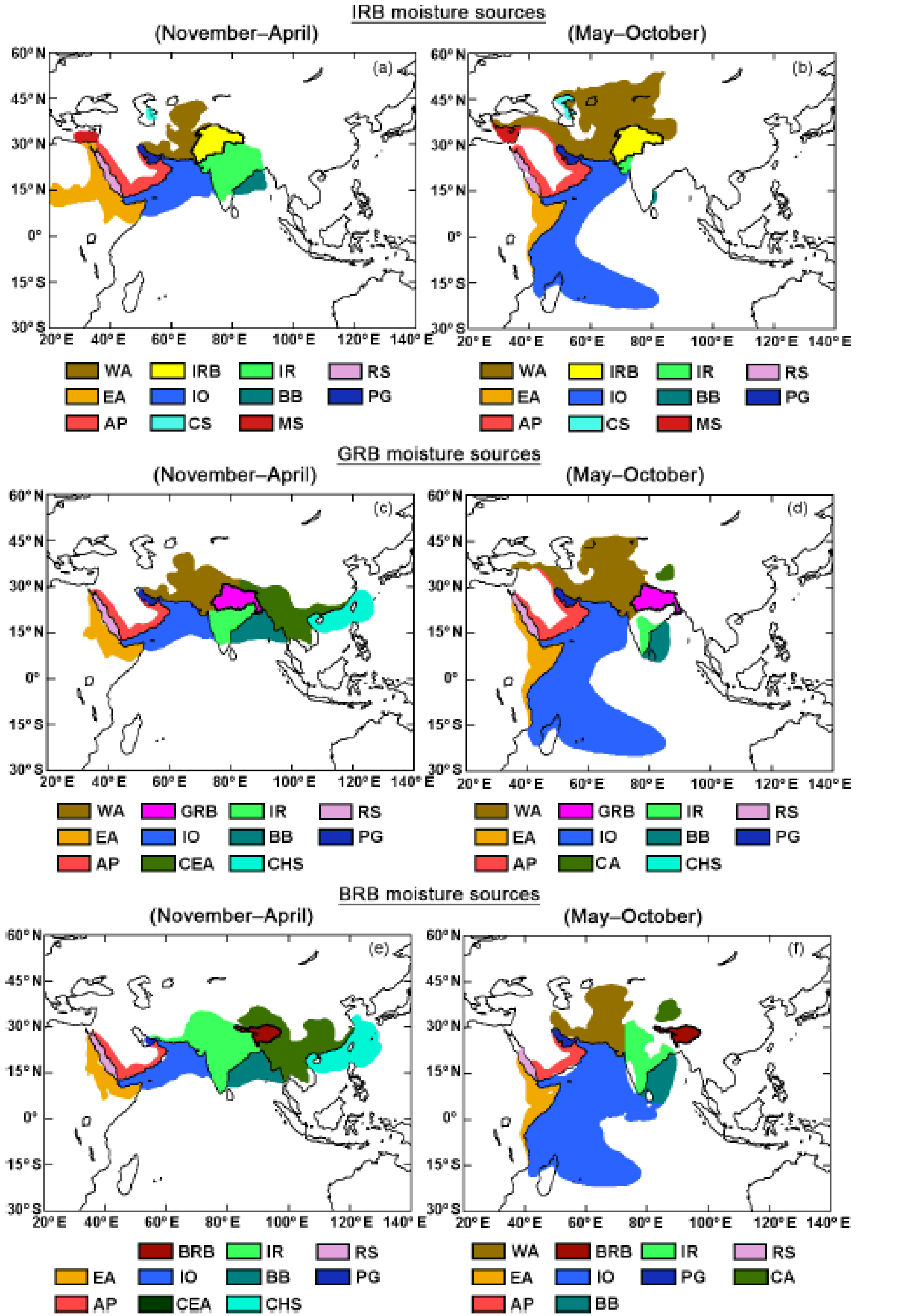
EVOLUTION OF THE ASIAN MONSOON SYSTEM

Fuentes y Sumideros de Humedad (Backward analysis) VIMF



EVOLUTION OF THE ASIAN MONSOON SYSTEM

Figura Esquemática de las fuentes de humedad más importantes para la precipitación en cada cuenca



Daily cumulative precipitation anomalies ***(C'm)***

D(m, n) is the daily basin rainfall for day ***n*** of year ***m***, and ***C*** is the climatology of the annual mean of the precipitation at each basin over ***N*** *(= 365 or 366)* days for ***M*** years.

$$C'm\,(i) = \sum_{n=1}^{i} [Dm\,(n) - C],$$

$$C = \frac{1}{MN} \sum_{m=1}^{M} \sum_{n=1}^{N} D\,(m, n)\,,$$

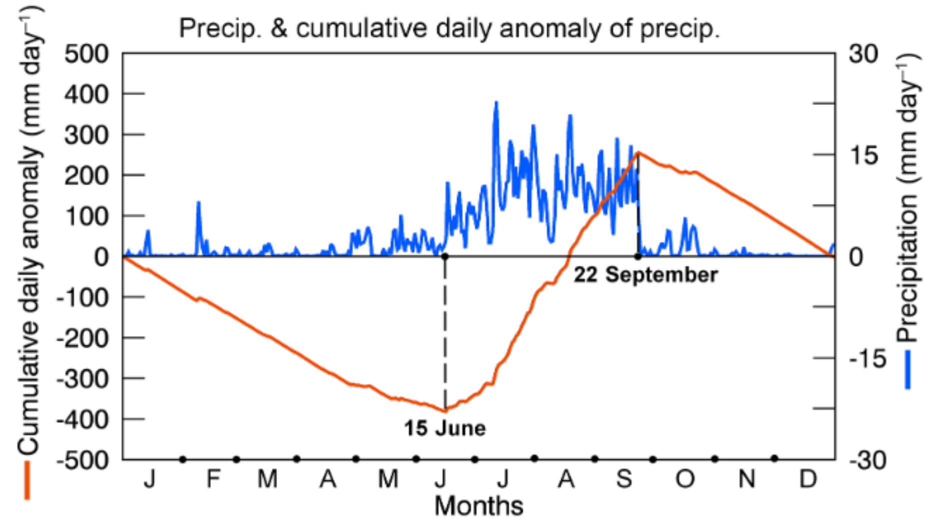


Figure 9. Daily precipitation (blue line) and the cumulative daily anomaly of the precipitation (orange line) (from CHIRPS) over the GRB during 2010. 15 June (22 September) represents the minimum (maximum) cumulative daily anomaly of the precipitation.

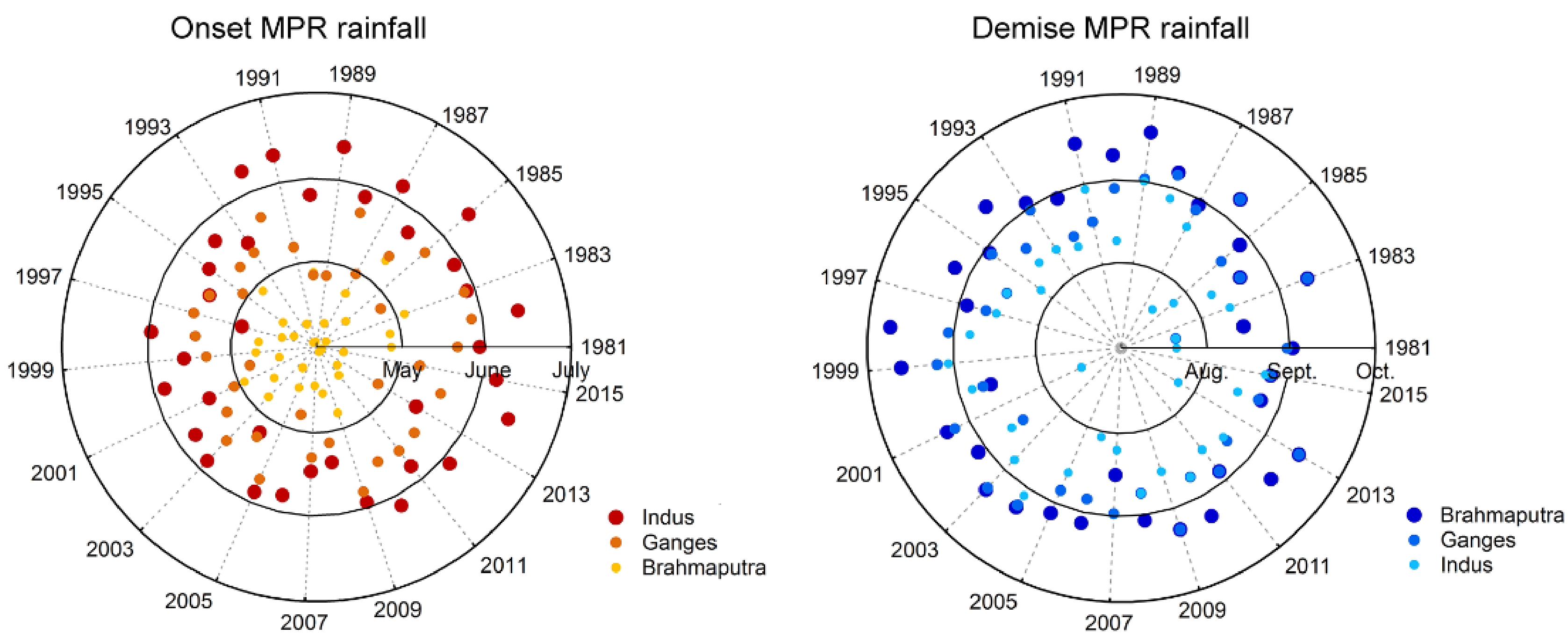
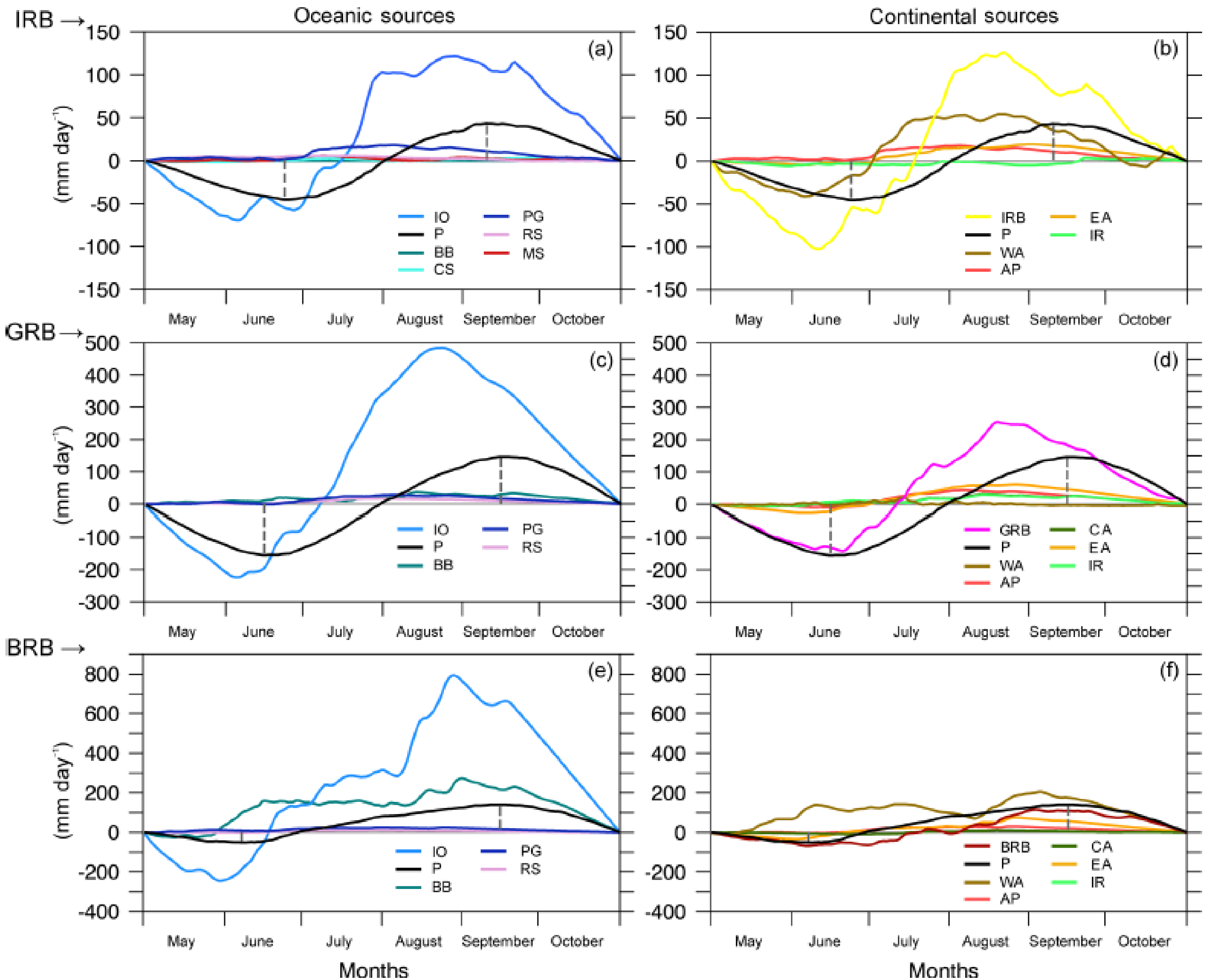
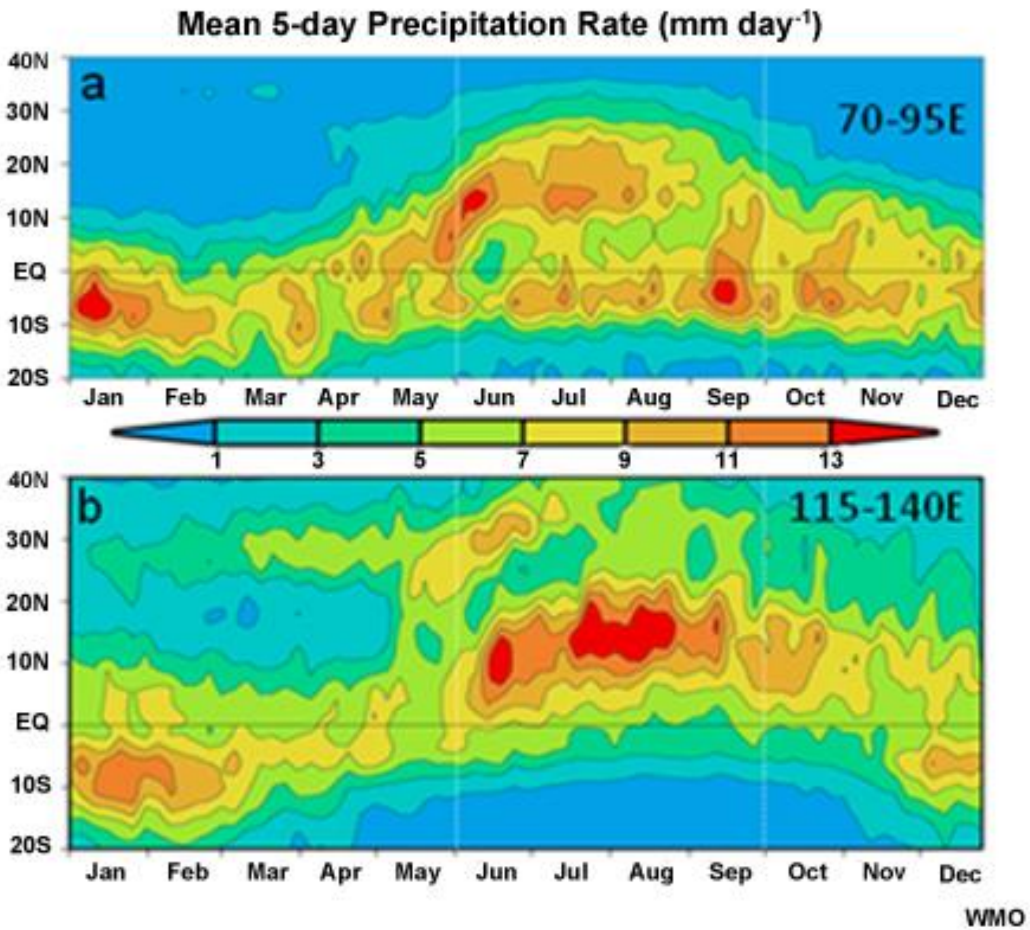


Figure 10. Onset and demise of the monsoonal rainfall for the Indus, Ganges, and Brahmaputra river basins.

Accumulated anomalies |(E-P)i10<0| & precipitaion



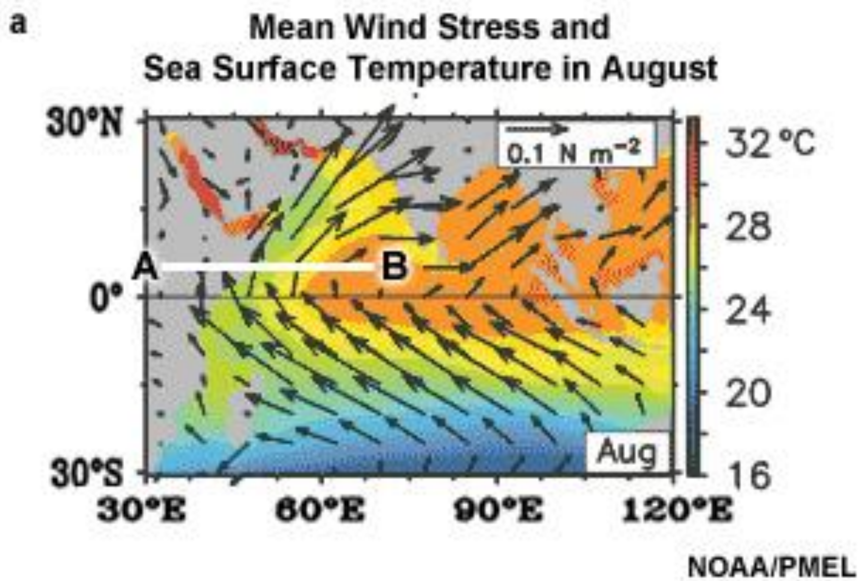
EVOLUTION OF THE ASIAN MONSOON SYSTEM

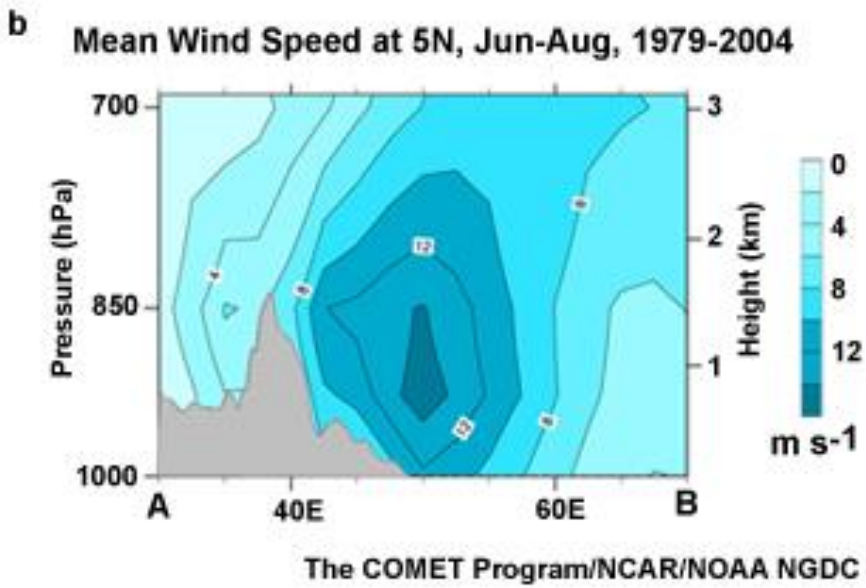


Climatological pentad (5-day) mean precipitation rate (mm day-1) averaged over (a) the Indian sector (70°E-95°E) and (b) the western Pacific sector (115°E-140°E).

- ✓ The South Asian monsoon is the northern branch of the seasonal migration of the east-west oriented precipitation belt (the ITCZ)
- ✓ The precipitation belt migrates from the southern to the Northern Hemisphere in the boreal summer and vice versa in the boreal winter (austral summer).
- ✓ The northern most extent of the tropical rain belt in the South Asian monsoon is about 20°N and it retreats to about 5°S during the winter.
- ✓ Two locations are favorable for the rain band: over the heated subcontinent (in keeping with the early theories) and the warm eastern equatorial Indian Ocean.
- ✓ This oceanic cloud band can aid or suppress the main monsoon rains. If the oceanic precipitation is intense, it leads to subsidence over land.

EVOLUTION OF THE ASIAN MONSOON SYSTEM





- ✓ Strong surface temperature gradients (Figure a) lead to large-scale pressure gradients and cross-equatorial winds between the south and north Indian Ocean.
- ✓ Over India, the mean surface pressure at 20°N ranges from 1016 hPa in the winter to 1002 hPa at the peak of the summer monsoon.
- ✓ The Somali Jet is the result of the strong temperature and pressure gradients and channeling of the cross-equatorial flow by the East African Mountains (Figure b).

(a) Mean wind stress at the ocean surface showing the low-level Somali Jet which results from the strong cross equatorial pressure gradient and the high terrain of East Africa. (b) Cross section along 5°N showing the magnitude and areal extent of the jet core

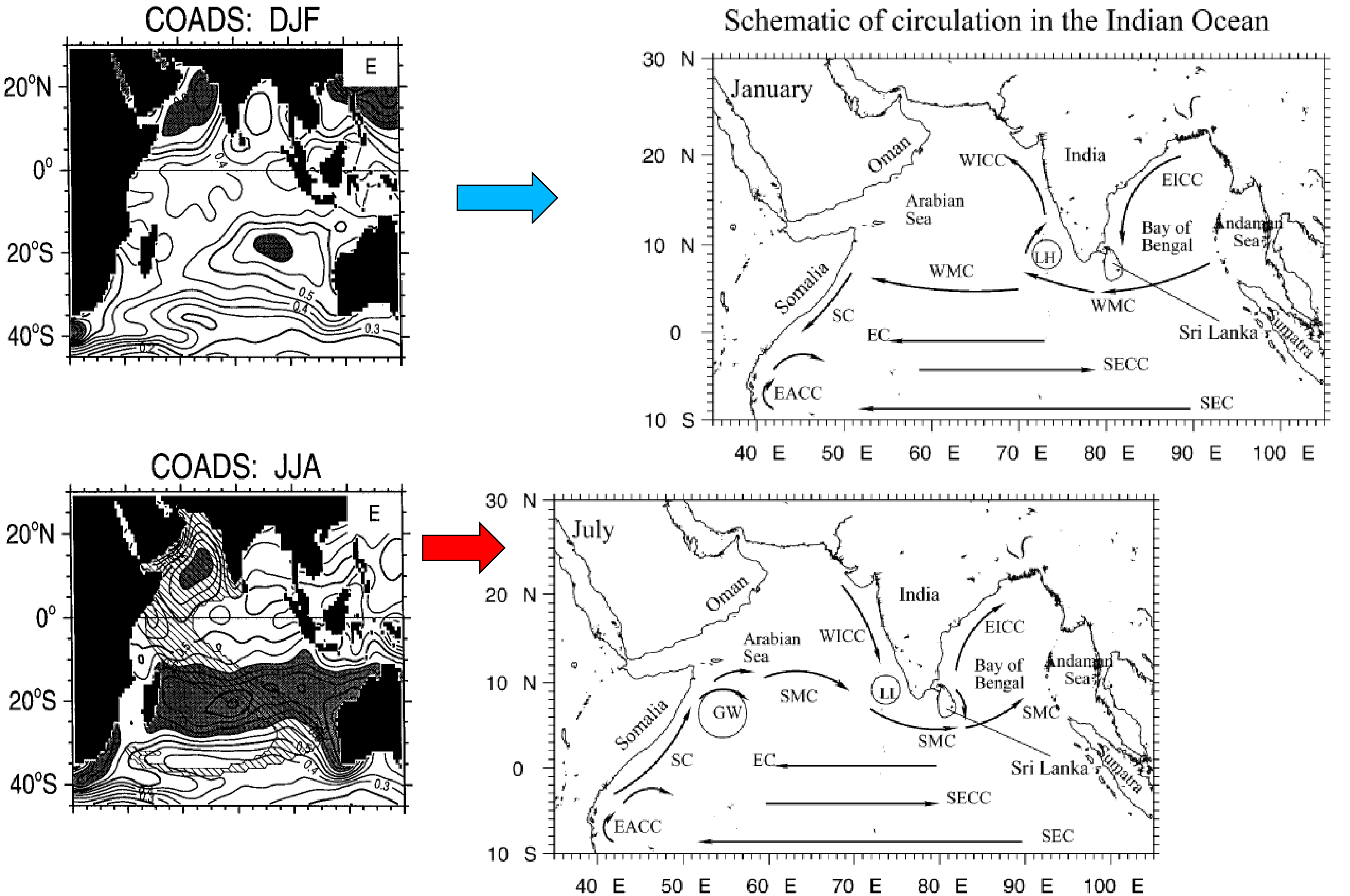
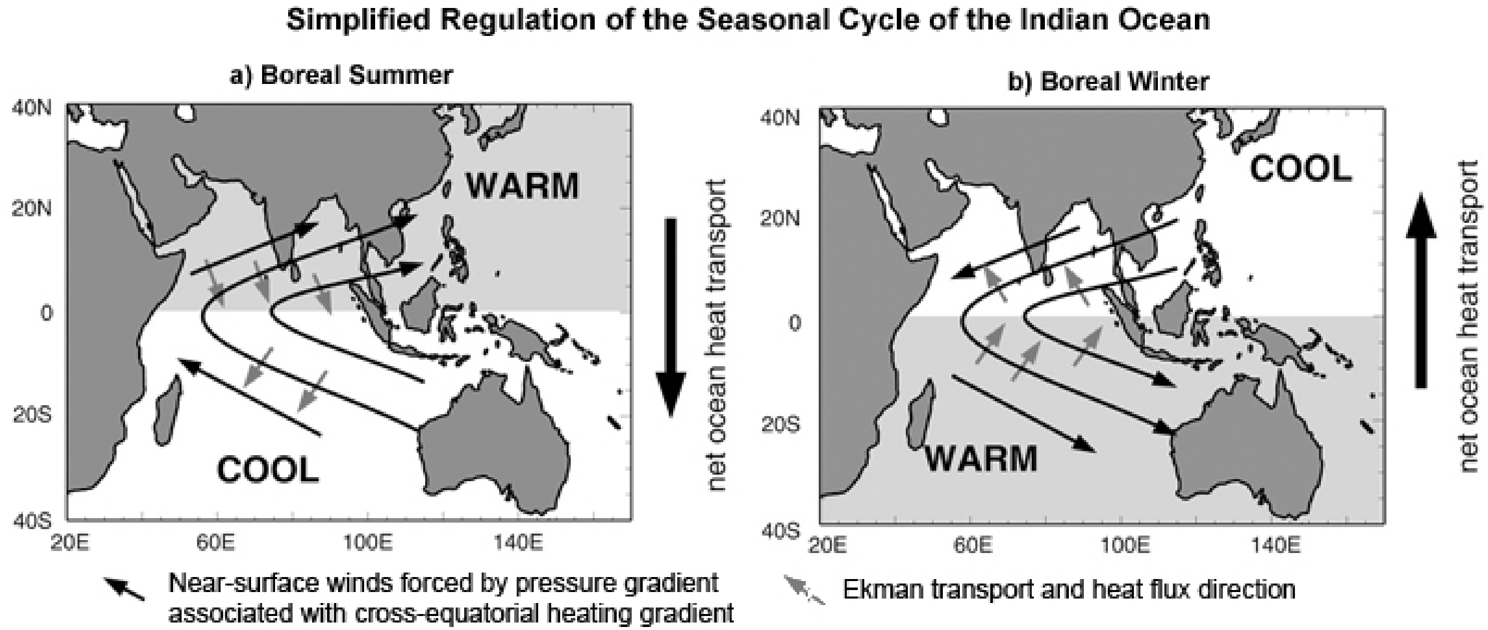


Fig. 2. Schematic representation of the circulation, as described in the literature, in the Indian Ocean during January (winter monsoon) and July (summer monsoon). The abbreviations are as follows: SC, Somali Current; EC, Equatorial Current; SMC, Summer Monsoon Current; WMC, Winter Monsoon Current; EICC, East India Coastal Current; WICC, West India Coastal Curent; SECC, South Equatorial Counter Current, EACC, East African Coastal Current; SEC, South Equatorial Current; LH, Lakshadweep high; LL, Lakshadweep low; and GW, Great Whirl.

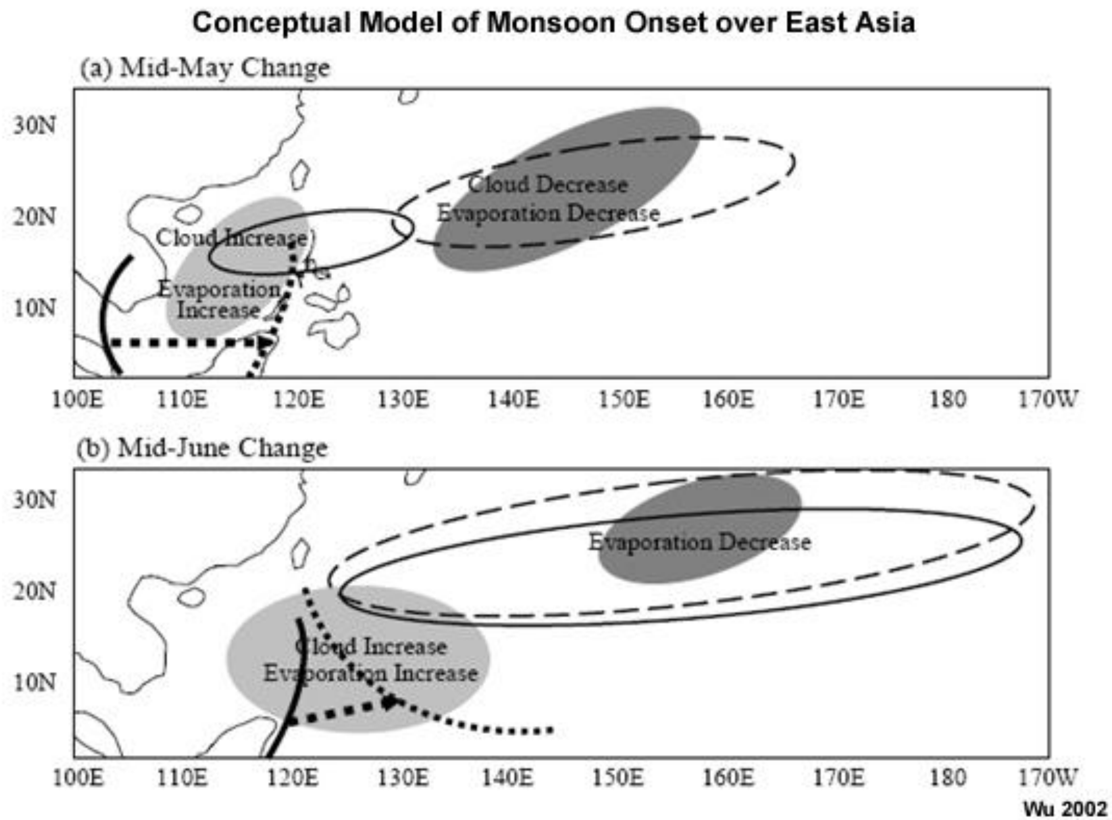
EVOLUTION OF THE ASIAN MONSOON SYSTEM



Schematic of regulation of the seasonal cycle of the Indian Ocean for (a) the boreal summer (June-September) and (b) the boreal winter (December-February). Curved solid lines indicate near-surface winds forced by the large-scale pressure gradient associated with the cross-equatorial heating gradient denoted by "WARM" and "COOL". Grey arrows denote Ekman transport and the direction of the associated heat flux.

- ✓ The annual monsoon cycle is regulated by heat transported across the equator by the atmosphere and the ocean. Oceanic heat is transported southward during the summer monsoon and northward during the winter monsoon over the Indian Ocean.
- ✓ The southward movement of heat tends to cool the South Indian Ocean while the northward transport warms the North Indian Ocean southward heat flux in the summer tends to cool the North Indian Ocean.
- ✓ **The coupled ocean-atmosphere interaction reduces the SST gradients and imposes a strong negative feedback on the system thereby regulating the seasonal extremes of the monsoon. While the north-south gradient dominates, an east-west SST gradient is also present (previous figure)**

EVOLUTION OF THE ASIAN MONSOON SYSTEM



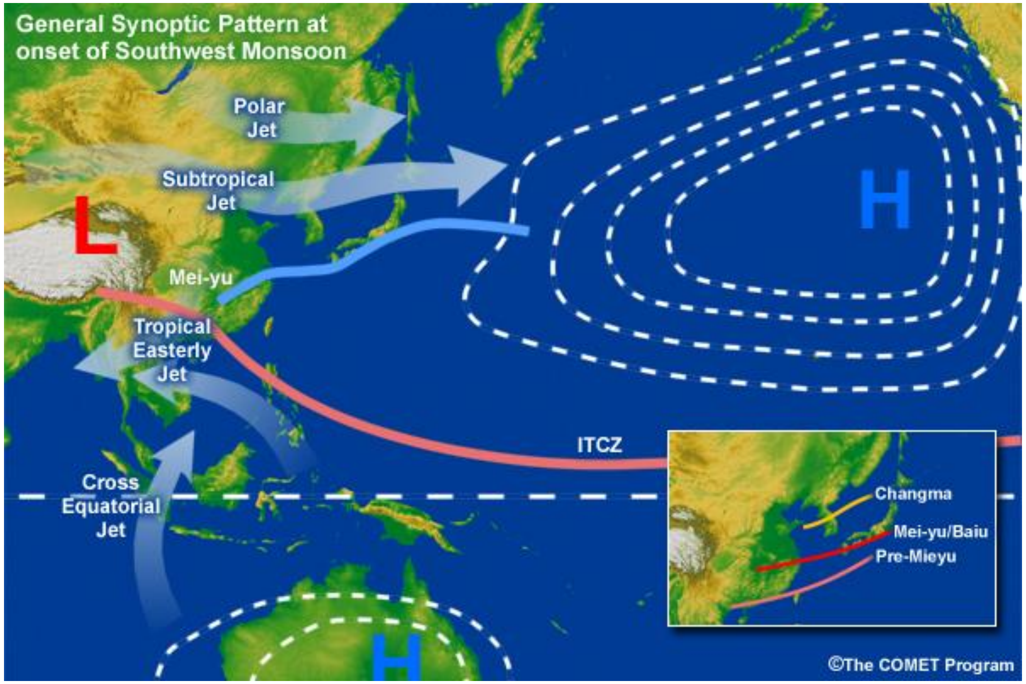
Conceptual model of the (a) mid-May and (b) mid-June monsoon onset over East Asia. Closed solid (dashed) curves mark the subtropical high before (after) onset. Light (dark) shades signify an increase (decrease) in clouds and/or evaporation. Dashed arrows show the direction of the extension of low-level westerlies.

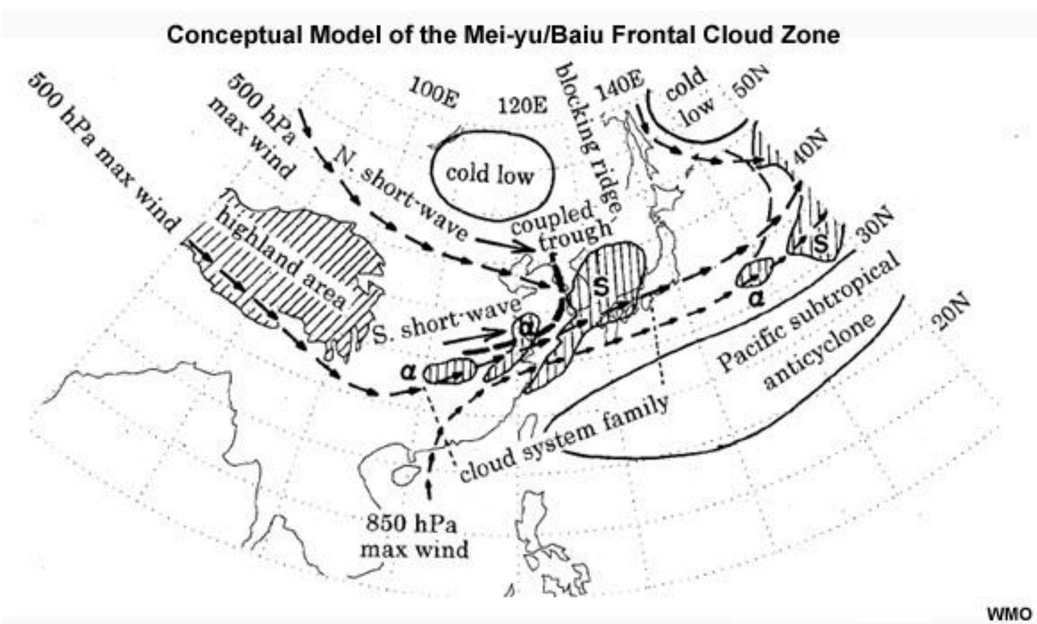
- ✓ The annual cycles of the monsoons over India and East Asia are different primarily because the atmospheric response to heating is affected by land-ocean distribution and topography.
- ✓ The strong north-south gradient between the warm land and the cool ocean, enhanced by the heating of the elevated Tibetan Plateau, creates a strong monsoon over India.
- ✓ Over East Asia, the situation is more complex. The forcing comes from both the north-south gradients between cool Australia and warm western north Pacific and east-west gradient between the heated Asian landmass and the cooler Pacific. The result is a weaker monsoon circulation and bands of precipitation along the tropical monsoon circulation and subtropical frontal zones,
- ✓ For the East Asian monsoon, the area of clouds and evaporation increases during mid-June relative to the mid-May pattern and the longitudinal extent of the southwesterly winds shifts east into the Pacific (Figure a).

- ✓ The Pacific High shifts east and north after the mid-May onset, expands, and strengthens (Figure a). A large, thermal trough replaces the subtropical ridge over the continent. Air flows into the equatorial trough, which leads to cloudiness in the ITCZ.
- ✓ The Monsoon Trough extends northwestward from the equatorial trough into the continent.
- ✓ Other features are similar to the South Asian monsoon, the TEJ in the upper troposphere and the cross-equatorial flow at low-levels. To the north at the upper levels is a weakened Subtropical High

EVOLUTION OF THE ASIAN MONSOON SYSTEM

The Mei-Yu/Baiu front





- ✓ A prominent, signature feature of the East Asian spring and early summer is the Mei-Yu/Baiu front, a semi-permanent, quasi-stationary, weak frontal zone that extends from eastern China east-northeastward into the Pacific
- ✓ To the north, in Japan, the frontal zone is called the Baiu front, and, in Korea, the Changma front (their relative locations are shown in the inset map on Figure a).
- ✓ The Mei-yu and Baiu fronts begin in mid May and continue through early to mid summer while shifting northward.

(a) General synoptic pattern at the onset of the East Asian monsoon. Inset map shows the relative locations of the Mei-yu/Baiu, and Changma fronts. (b) Conceptual model of the Mei-yu/Baiu frontal cloud zone. Note the hatched areas representing a family of cloud systems along the front, the 850 hPa low-level jet, and the mid-tropospheric maximum wind tracks (short-waves develop along this track and enhance instability and ascent).

The Mei-Yu/Baiu front

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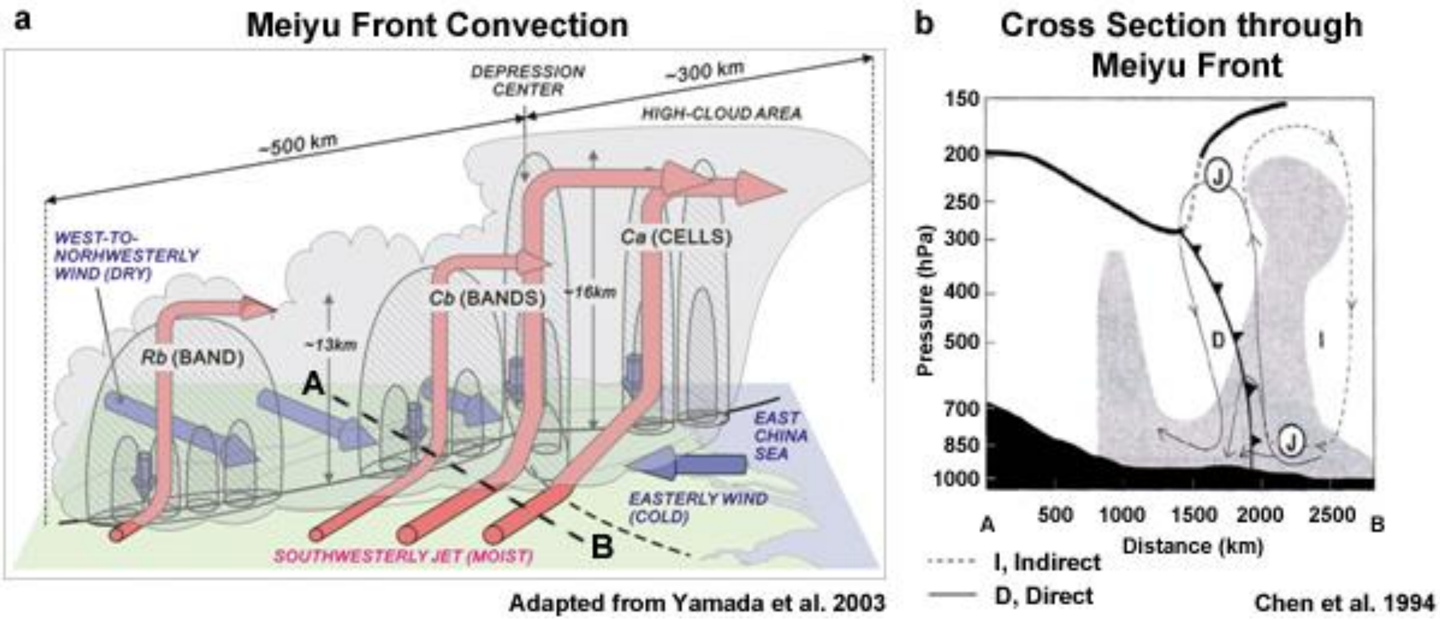


(a)Schematic of 3-D structure of large MCS along Mei-Yu/Baiu front.

(b) Schematic diagram showing the flow structure of an observed Mei-yu front. The thin solid line depicts the direct (D) circulation while the thin dashed line depicts the indirect (I) circulation. The heavy solid line shows the frontal position. The character J denotes the jet positions. The thick heavy line represents the tropopause boundary. Regions with relative humidity greater than 70% are shaded.

- ✓ The Mei-yu front is the focal point for persistent heavy precipitation produced by mesoscale convective systems (MCSs) that form and track eastward along the front.

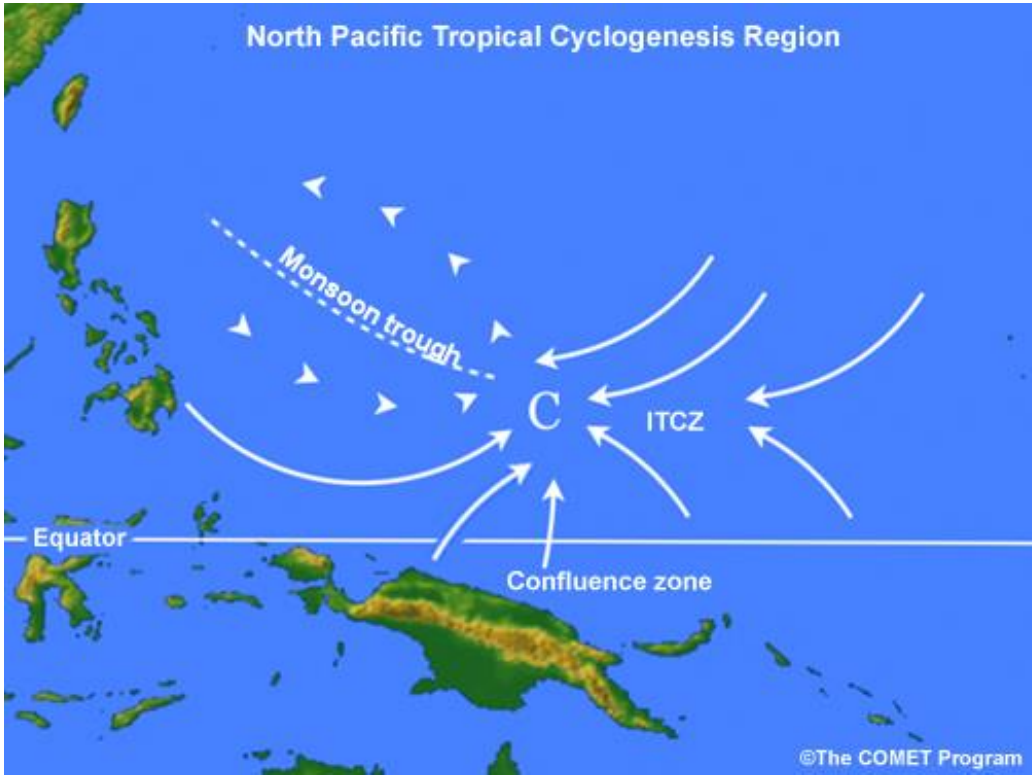
- ✓ Instability, strong rising motion, and persistent deep convection are associated with a low-level jet that brings warm moist air from the South China and Bay of Bengal, low-level warm-air advection, and upper-level divergence, strongest in the right forward quadrant of the Subtropical Jet (Figure).

- ✓ Most of the heavy rain is south and east of the front, an area of high relative humidity.

- ✓ The Baiu front is more typically midlatitude in structure. Weak cyclonic disturbances move along the Baiu front at 3-day intervals. They bring stratus, fog, and light rain to northern edge of the front and thunderstorms and heavy rain along and immediately south of the front.

EVOLUTION OF THE ASIAN MONSOON SYSTEM

West Pacific monsoon trough



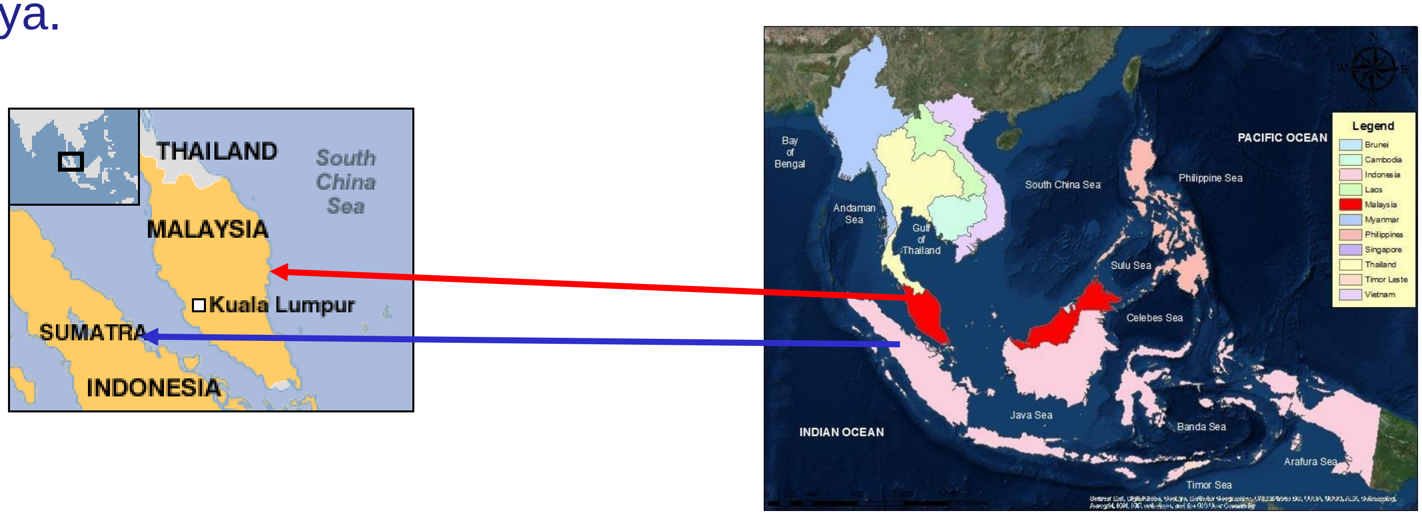
Schematic of the western North Pacific tropical cyclogenesis region partitioned into a monsoon trough zone and the near-equatorial ITCZ, meeting at a confluence zone.

- ✓ The Western North Pacific monsoon region has the highest frequency of tropical cyclones on Earth, mainly because the tropical western Pacific is the warmest part of the tropical ocean.
- ✓ Tropical cyclogenesis is most common in the monsoon trough (Figure) and the location of the monsoon trough has major influence on the distribution of tropical cyclone activity in this region**.**
- ✓ Large-scale cyclonic vorticity in the monsoon trough is derived from the low-level equatorial westerly or southwesterly winds induced by the Australian High, and the subtropical easterly trade winds (Figure).

EVOLUTION OF THE ASIAN MONSOON SYSTEM

East Indian Ocean summer monsoon systems

- ✓ The Eastern Indian Ocean has its characteristic summer monsoon thunderstorm system, such as the **Sumatras.**
- ✓ The **Sumatras** are eastward moving, short-lived squall lines that form over the Straits of Malacca in the low-level convergence between land breezes from Sumatra and Malaya.



- ✓ They form at night, during predawn hours, and attain lengths of 200-300 km while moving east to Malaysia and Singapore.
- ✓ Sumatras are critical to the regional rainfall; they produce heavy rain and occur about 3-4 times per month.

MONSOON IMPACTS

Large Societal Impact on Global Scale

- ✓ Most agriculture and the economies of these regions are intimately tied to the monsoons
- ✓ Interannual (and climatic) variability of monsoon "onset" and intensity can be catastrophic