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Perspective

Drivers of East Asian summer monsoon variability: Global oceans and the Tibetan Plateau

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The East Asian summer monsoon (EASM) profoundly influences the hydroclimate, ecosystems, and water resources of a densely populated region in Asia. Anomalous EASM can lead to floods, droughts, significant economic losses, and social disruption in East Asia and Southeast Asia. Unlike the Indian and African monsoons, the EASM is shaped by both tropical and extratropical climate systems, including tropical oceanic modes, cross-equatorial airflows, the Madden-Julian Oscillation, the thermal condition of the Tibetan Plateau, the South Asia High, and the mid-latitude westerly jet. This complexity makes the EASM a challenging system to understand and predict. The variability of the EASM spans various time scales, with interannual variations contributing significantly to the total variance compared to decadal variability.

As a coupling system of land-air-sea interaction, the EASM is influenced by a complex interplay of both oceanic and terrestrial factors. Key oceanic drivers include the El Niño-Southern Oscillation (ENSO), the Indian Ocean Basin (IOB) mode, the Indian Ocean Dipole (IOD), and the Tropical North Atlantic (TNA) SST anomalies (SSTA), which can explain 40%–50% of the interannual variance of the EASM. Additionally, extratropical SSTAs, such as the North Atlantic Tripole (NAT) [1] and the Pacific Meridional Mode [2], play significant roles due to East Asia's unique geographical position. Terrestrially, the Tibetan Plateau (TP) is crucial for EASM variability [3]. It influences the EASM through its diabatic heating and snow cover, which impact key atmospheric circulation systems such as the South Asian High, the westerly jet, and the Western North Pacific Anticyclone (WNPAC). Furthermore, internal atmospheric variability in mid-high latitudes, such as the North Atlantic Oscillation (NAO) and Antarctic Oscillation (AAO), also contributes to EASM variability, though their influence is comparatively minor [4].

Current knowledge provides insights into the individual impacts of specific ocean basins and the TP on the EASM, but a substantial gap remains in understanding how cross-basin interactions and the synergistic dynamics between the Tibetan Plateau and the ocean influence the EASM. Bridging this gap, in conjunction with applying machine learning, causal analysis, and data assimilation techniques, will significantly enhance our ability to predict the EASM. Recent progress on the synergistic effects of global oceanic drivers and TP thermal forcing on the EASM is reviewed in the following text and Fig. 1.

(a) *Inter-basin air-sea interaction.* Tropical Pacific and Indian SSTA modes, including ENSO, IOB, and IOD, are recognized as important precursors of the EASM. Their combined effects also have an undeniable influence on the EASM. ENSO and the IOD are primarily linked through the Walker circulation and the Indonesian Throughflow. The combined mode—the tropical Pacific and Indian Ocean temperature anomaly mode (PIM), also known as the Indo-Pacific tripole mode—further illustrates this cross-basin connection. This mode, characterized by cold SSTAs over the Warm Pool and warm SSTAs in the eastern Pacific and western Indian Ocean, often induces increased rainfall in the middle and lower Yangtze River valley, and decreased air temperature in southern China [5]. Additionally, an intrinsic inter-basin coupled mode in the Indo-Pacific intersection area, the Indo-western Pacific Capacitor (IPOC) [6], characterized by warming in the northern Indian Ocean and cooling in the western Pacific, plays a critical role in governing monsoon variations by modulating the Walker and Hadley circulations. Generally, the IPOC's dipolar SSTA pattern influences the EASM through exciting a Gill-type response and strengthening the WNPAC, independent of ENSO forcing.

Since the early 1980s, Atlantic SSTAs have increasingly contributed to EASM variability. TNA SSTAs interact with the Pacific and Indian Oceans, synergistically modulating the EASM. Warm TNA SSTAs trigger a La Niña-type response in the Pacific, strengthening the Walker circulation and subsequently suppressing convection in the central Pacific, which leads to a stronger WNPAC via a Rossby wave response to the west. This then causes the southerly anomalies to the west flank of WNPAC to transport more

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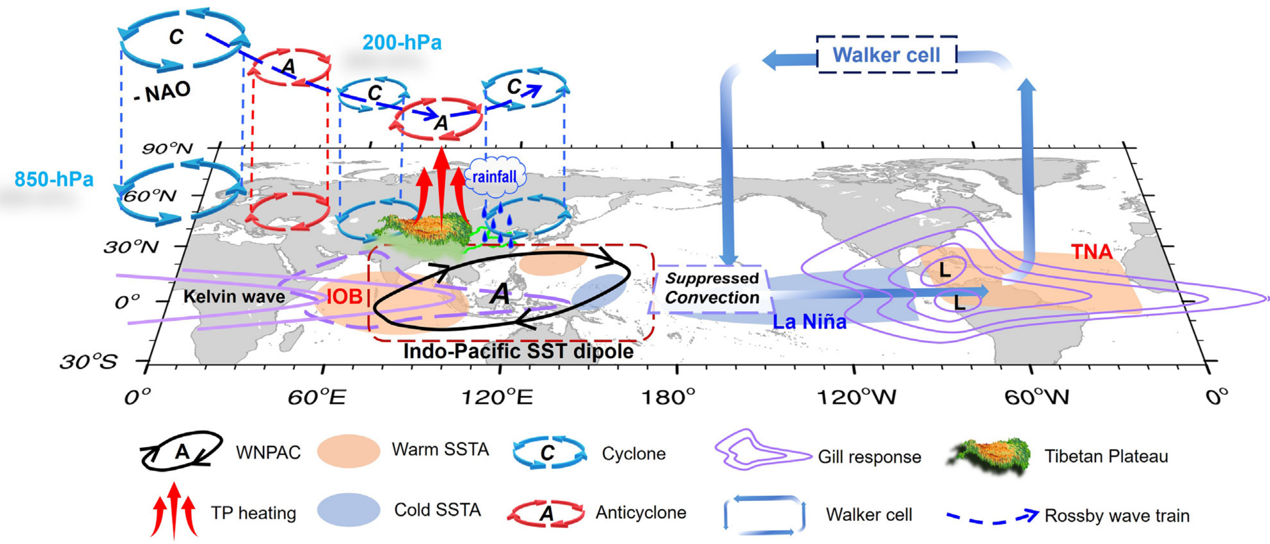

Fig. 1. Schematic diagram illustrating the physical mechanism of global air-sea processes and Tibetan Plateau (TP) thermal forcing synergistically affecting EASM variability. This figure highlights the tropical inter-basin interaction affecting the EASM, the combined effect of tropical SSTA and TP heating on the EASM, and the synergistic effect of North Atlantic Oscillation (NAO) and TP heating on the EASM. The red dashed box represents the intersection area and the intrinsic inter-basin coupled mode in this region, known as the "Indo-western Pacific Capacitor" (IPOC) or "Indo-Pacific SST dipole". Warm SSTA in the Indian Ocean (orange shading) with the Gill response (purple contours) indicate the inter-basin interaction between the Indian Ocean and tropical North Atlantic [5]. Warm SSTA in the Atlantic Ocean (orange shading), cold SSTA in the eastern Pacific (blue shading) and the Walker Cell indicate the inter-basin interaction between the tropical North Atlantic and Pacific Oceans [4]. The alternating anomalous circulation in mid-latitudes represents the Rossby wave teleconnection induced by negative NAO and its related TP heating.

moisture northwards, thus increasing EASM precipitation [7]. Furthermore, the TNA impacts the Indian Ocean, with warm TNA conditions contributing to warming in this region, which in turn can initiate the formation of the Atlantic Niño. These interconnected oceanic processes, inducing the overlapping Kelvin waves from the warm TNA and the Indian Ocean, significantly affect EASM precipitation and tropical cyclone genesis in the western North Pacific [8].

Extratropical SSTAs in the North Atlantic and North Pacific also play an important role in influencing the EASM. The North Atlantic tripole mode – characterized by warming in the northwestern Atlantic and cooling in the subpolar and tropical Atlantic in positive phases – facilitates a Rossby wave train across the Atlantic-Eurasia region, strengthening the East Asian subtropical front via high-pressure anomalies over the Ural Mountains, thereby increasing rainfall in the Yangtze River valley [9]. Meanwhile, the Victoria Mode and the Pacific Meridional Mode, key SST modes in the North Pacific, also profoundly affect the EASM. The positive phase of the Pacific Meridional Mode, with El Niño-like SSTA over the Pacific, triggers a Gill-type response with a prominent anomalous cyclone over the western North Pacific. The anomalous westerlies to its south result in enhanced moisture and decreased zonal vertical wind shear, favoring the occurrence of tropical cyclones over the western North Pacific and extreme EASM rainfall [2]. These mid-latitude air-sea processes underscore the complex and significant role of extratropical SSTAs in regulating the EASM.

(b) *The Tibetan Plateau as a climate bridge.* The TP influences the EASM both directly as an intense and elevated heat source and indirectly as a climate bridge, modulating the relationship between SSTAs and the EASM. Directly, TP diabatic heating (i.e., surface sensible heating, condensation latent heating, or their combination) generates a cyclonic anomaly in the lower atmosphere and an anticyclonic anomaly in the upper troposphere. This circulation anomaly propagates eastward, favoring torrential rain along the Yangtze River in summer through strong upward motion and abundant water vapor transport [3]. In contrast, the influence of the TP thermal forcing on the Southeast Asian summer monsoon is different. The upward motion over the TP due to diabatic heating is compensated by sinking motion over Southeast Asia, leading to a weaker monsoon there [10]. In addition, TP snow is a non-negligible indicator of TP thermal conditions, which can exert profound impacts on the EASM through diabatic cooling, snow-hydrology effects, and albedo effects.

As a bridge, the TP also modulates the relationship between tropical SSTAs and the EASM. Warm IOB SSTA excites an atmospheric Kelvin wave response and enhances anomalous anticyclone over the Bay and Bengal, leading to southwesterlies that transport abundant water vapor to the southeastern TP and increase TP thermal heating. The westerly anomaly over TP also adjusts meridional temperature gradient, leading to anomalous ascent and increased precipitation over the Yangtze River Basin [11]. Additionally, the TP heating effect varies between the developing and decaying phases of ENSO. In ENSO developing years, weakened TP diabatic heating reduces EASM precipitation accompanied by an anomalous cyclone over the northwestern Pacific and an anticyclone in North China. In contrast, during the decaying phase, TP heating induces an anomalous anticyclone in South China and enhances EASM precipitation [12]. Moreover, warm TNA SSTAs, alongside the warm IOB, can amplify TP rainfall and heating, thereby jointly influencing the EASM and leading to deficient precipitation in South China and the Indochina Peninsula [10].

TP thermal forcing also regulates SSTAs through air-sea interaction. Adjacent to the Indian Ocean, the elevated TP thermal forcing induces a low-level southwesterly response over the northern Indian Ocean, strengthening climatological circulation and inducing a cooling response in the Indian Ocean by enhancing surface evaporation. The TP affects the North Pacific Ocean's SSTAs and mixed-layer temperature, with enhanced TP heating generating a downstream Rossby wave train and influencing North Pacific SSTAs, which act as a capacitor of TP heating [13]. Furthermore, TP heating anomalies serve as a repeater, amplifying the climate effects of mid-latitude North Atlantic air-sea processes on the EASM. Winter-spring North Atlantic tripole SST anomalies, coupled with the winter NAO, trigger enhanced TP heating, which influences EASM precipitation and temperature patterns across East China [1]. Summer NAO also directly affects TP climate anomalies, with negative summer NAO phases enhancing rainfall and heating over the southeastern TP, subsequently boosting EASM rainfall [4].

While significant progress has been made in investigating the drivers of the EASM variability from the perspective of atmosphere-land-sea interaction, there are still challenges in understanding mechanisms of EASM variability and accurately predicting the EASM: (1) Understanding the role of the TP in regulating the EASM is limited by sparse observations over the TP. Despite an increase in meteorological stations and field campaigns in recent decades, there remains a noticeable gap in direct observations of critical factors such as diabatic heating, cloud formations, surface snow, and precipitation. (2) While considerable research has focused on the interannual variability of the EASM, the subseasonal to seasonal fluctuations are equally critical. These time scales see a complex interplay of numerous influencing factors, necessitating a swift and robust methodology to identify those with causal impacts. (3) Integrating our knowledge of the land-air-sea mechanisms driving the EASM into its prediction models remains a formidable challenge. Currently, there appears to be a disconnect between the theoretical understanding of these mechanisms and their practical application in forecasting the EASM. Overcoming this divide is paramount for enhancing the accuracy and reliability of EASM predictions. To address these challenges, we propose new research perspectives, incorporating new data, and employing novel methods.

(a) *New perspectives*. Most existing studies on the oceanic influence on the EASM focus on SST, but subsurface sea temperature and ocean heat content may also influence EASM variability. Additionally, the role of the Atlantic Meridional Overturning Circulation (AMOC) in regulating the EASM is not clear. The AMOC may influence the East Asian climate not only at centennial-millennial time scales, but also at decadal-interannual time scales. Furthermore, research on the subseasonal-seasonal variability of the EASM, crucial for climate prediction, is inadequate. Overcoming this limitation may involve studying the impact of cross-seasonal signals on the TP, such as surface sensible heating, snow cover, and soil moisture, on the predictability of the EASM and rainfall intensity. Moreover, investigating the future change of the annual cycle of the East Asian monsoon is a crucial research topic. Understanding the changes in the onset and duration of the monsoon season and how these changes are governed by tropical oceans and TP thermal forcing is essential for projecting the hydroclimate of East Asia in the future.

(b) *New data*. To address limited observations over the TP, China initiated a national research program called "Changes in the Land-Air Coupled System over the Tibetan Plateau and its Impacts on Global Climate (LASTPIC)" in 2014. This program has established an *in situ* observational network with improved spatial coverage and developed a novel data assimilation product, the China Meteorological Administration Land Data Assimilation System V2.0 (CLDAS-V2.0), which provides variables such as precipitation, soil moisture, and other surface fluxes over the TP at a high horizontal resolution of 0.0625°×0.0625° [3]. These new datasets will enable us to uncover more detailed land–atmosphere processes over the TP. Additionally, novel satellite retrievals of cloud properties have revealed previously unknown vertical structures and frequencies of clouds and precipitation over the TP. The continuous use of these satellite retrievals and *in-situ* observations of clouds and precipitation will further elucidate cloud-radiation-climate feedbacks over the TP, enhancing our understanding of precipitation and thermal conditions over the TP and facilitating the prediction and projection of the EASM.

(c) *Novel methods*. In recent years, powerful analytical methods, including machine learning and causal inference, have emerged in climate science. Machine learning, with its unparalleled capacity to process and analyze vast datasets, offers a swift and efficient means of sifting through numerous potential factors to pinpoint those with significant impacts on the EASM. This rapid identification process not only saves valuable time but also directs research efforts more effectively. Following this, causal inference steps in as a powerful tool to rigorously test these identified relationships, determining their causality and robustness [14]. Applying these methods to the study of EASM variability can improve our ability to predict the EASM by identifying the key factors at play.

The use of machine learning approaches and attribution analysis can extract global climate signals to further enhance our understanding of the EASM [15]. As demonstrated in Fig. 2, visual attribution analysis based on machine learning reveals that the spring surface sensible heat flux and surface temperature in certain regions exhibit exceptional predictive ability. The primary sources of these high predictive abilities stem from tropical signals, specifically from the tropical central and western Pacific and the tropical Atlantic (Fig. 2a). Although the tropical Pacific and Atlantic contribute significantly to the EASM, the signal from the TP has also been found to be prominent (Fig. 2b), suggesting that the interactions between tropical oceans and the TP, as well as their individual effects, play a critical role in predicting the EASM. Therefore, future research on the prediction of the EASM should consider

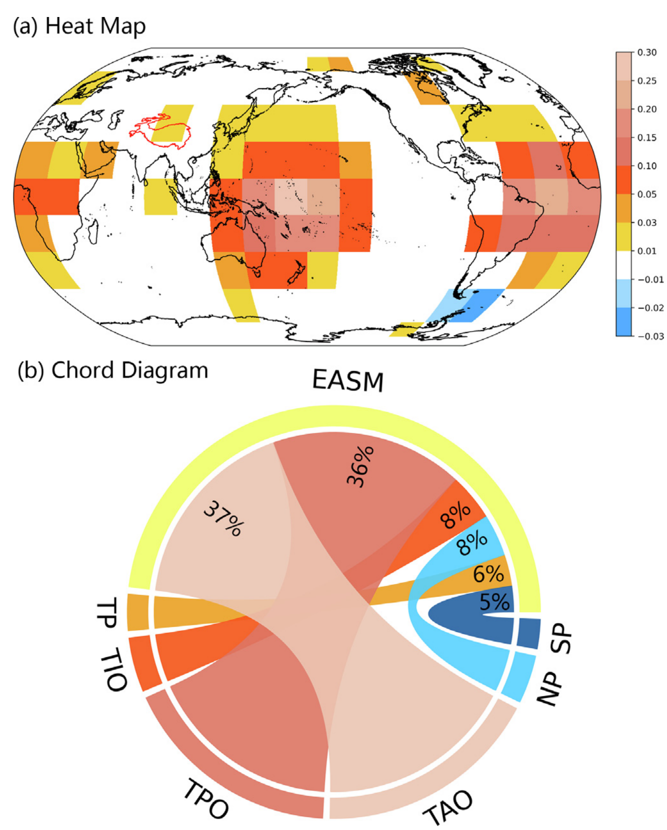

Fig. 2. (a) The heat map of EASM reproduced from Tang and Duan [15], which represents the influence of key regions in boreal spring on the interannual variability of EASM. (b) The chord diagram derived from the heat map, driving factors include the Tropical Indian Ocean (TIO), Tropical Pacific Ocean (TPO), Tropical Atlantic Ocean (TAO), TP, North Pole (NP) and South Pole (SP). The width of the edge indicates the effect strength. The numbers in (b) roughly represent the percentage of explain variance by each driving factor.

the combined effects of different signals, an area where machine learning excels.

Machine learning can also be directly applied to the prediction of the EASM. By building machine learning models that incorporate key predictors of the EASM, we can surpass the limitations of conventional statistical approaches, to handle complex, nonlinear relationships. Furthermore, machine learning can be employed to downscale model forecasts, significantly improving the spatial resolution of prediction outputs. Beyond these applications, the integration of machine learning into data assimilation through optimizing data assimilation processes and covariance estimations can enhance the accuracy of forecast systems.

While the machine learning offers significant advantages in predicting and understanding the EASM, it is crucial to acknowledge that current mainstream machine learning methods are lack of physical constraints. This means that while machine learning can efficiently identify potential causative relationships among vast datasets, there is a risk of deriving conclusions that may not be physically plausible. Fortunately, the development of physically constrained or explainable machine learning models represents a promising frontier. These models aim to integrate our existing physical understanding of the EASM into the machine learning framework. This approach enhances the reliability of the predictions by ensuring they are grounded in physical reality and bridges the gap between theoretical understanding and practical prediction capabilities.

Furthermore, advances in climate modeling, such as variable-resolution climate models, have made it possible to investigate the impact of the complex terrain of the TP on the EASM. In addition, large ensemble model simulations, such as single model initial-condition large ensembles, can help disentangle anthropogenic and internal climate variability in the EASM, potentially providing greater insight into future projections of the EASM.

Conflict of interest

The authors declare that they have no conflict of interest.

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