



Indian Ocean Dipole extremes extend seasonal predictability of North China Plain summer heat



Zhaolu Hou^{1,2}, Jianping Li^{1,2}✉, Lei Wang³, Yina Diao¹ & Shixin Zhen¹

Seasonal predictability of regional extreme heat depends on how boundary-condition signals shape intrinsic error growth. Here we examine whether May–July (MJJ) Indian Ocean Dipole (IOD) extremes modulate the predictability limit (PL) of summer extreme maximum temperature (TXx) over the North China Plain (NCP). Using ERA5-derived TXx and a nonlinear local Lyapunov exponent framework, we show that both negative and positive IOD extremes slow early TXx error growth relative to neutral IOD conditions. The NCP TXx PL increases from 2.78 months in neutral years to 4.14 months for combined IOD extremes. Composite diagnostics link this extension to organized Indo-Pacific convection, western North Pacific circulation, and local moisture–cloud–radiation constraints. TXx amplitude is not enhanced, indicating that longer predictability arises from constrained local evolution rather than stronger heat anomalies. These results identify MJJ IOD extremes as a boundary-condition context for enhanced seasonal TXx potential predictability.

Extreme summer heat is a growing climate risk over East Asia, affecting human health, agriculture, energy demand, and urban infrastructure^{1–3}. The North China Plain (NCP) is particularly vulnerable because it combines high population density, intensive agricultural production, rapid urbanization, and substantial heat-related demands on public health, energy systems, and infrastructure, together with frequent exposure to persistent summer circulation anomalies and land–atmosphere feedbacks^{4,5}. Observational and attribution studies have documented increasing hot-day frequency, rising heatwave risks, and more persistent regional heat extremes over China and the broader East Asian region^{6–11}. Recent record-breaking heat events in Asia further highlight the need for improved early warning and seasonal risk assessment^{12–15}.

Seasonal potential predictability of extreme maximum temperature (TXx) depends on both slowly varying boundary-condition signals and intrinsic atmospheric error growth. From a dynamical-systems perspective, predictability is limited by the rate at which initially similar states diverge in phase space^{16–19}. Local finite-time Lyapunov diagnostics provide a framework for quantifying state-dependent error growth and predictability limits^{20–22}. This perspective is especially relevant for regional TXx because predictability is not determined solely by the amplitude of temperature anomalies^{23,24}. A climate mode may increase the amplitude of TXx anomalies without necessarily extending predictability, whereas an organized background state may slow local trajectory divergence even when

target TXx anomalies are not amplified^{25,26}. Identifying such boundary-condition signals and circulation regimes is therefore central to understanding the sources and limits of seasonal heat predictability.

The tropical Indian Ocean provides key boundary-condition signals for the Asian–western North Pacific summer climate system^{27,28}. The Indian Ocean Dipole (IOD), characterized by a zonal sea surface temperature (SST) anomaly contrast between the western and eastern tropical Indian Ocean, can reorganize tropical convection and interact with Indo-Pacific circulation variability^{29,30}. Tropical heating anomalies can induce large-scale divergent circulation and Rossby wave responses^{31–33}. In boreal summer, Indian Ocean SST anomalies can also influence the Indo–western Pacific and East Asian climate through capacitor-like ocean–atmosphere processes and associated western North Pacific circulation anomalies^{34,35}. The western North Pacific subtropical high (WPSH), together with the Pacific–Japan/East Asia–western North Pacific teleconnection, provides additional pathways linking tropical convection to East Asian summer climate variability^{36–40}. These circulation pathways are also relevant to summer heat extremes over East Asia, including China, which have been linked to Indo-Pacific SST modes and organized atmospheric circulation anomalies^{41–44}. Together, this evidence provides a physical basis for considering Indo-Pacific SST variability as a potential source of regional summer heat predictability.

¹State Key Laboratory of Physical Oceanography/College of Oceanic and Atmospheric Sciences/Frontiers Science Center for Deep Ocean Multispheres and Earth System/Academy of the Future Ocean/Innovation Center for Ocean Carbon Neutrality, Ocean University of China, Qingdao, China. ²Laoshan Laboratory, Qingdao, China. ³Beijing Presky Technology Co. Ltd, Beijing, China. ✉e-mail: ljp@ouc.edu.cn

Despite this progress, two key issues remain unresolved. First, although most previous studies have examined seasonal mean temperature, heatwave occurrence, precipitation, or circulation responses to Indian Ocean SST variability^{35,45,46}, it remains unclear whether IOD extremes modulate the predictability limit of regional summer TXx through changes in the intrinsic error-growth environment. Second, the physical pathway linking early-summer IOD states to NCP TXx predictability remains uncertain. This pathway may involve tropical convective persistence, western North Pacific circulation anomalies, WPSH-related moisture transport, local cloud-radiation effects, or their combined effects on TXx error growth^{26,27,38,40,47}. A predictability-limit analysis therefore needs to distinguish changes in TXx anomaly amplitude from changes in the background-state organization that conditions the divergence of TXx trajectories.

Here we test whether May–July (MJJ) IOD extreme states modulate the predictability limit (PL) of NCP summer TXx and identify the associated large-scale and local physical pathways. Monthly TXx is constructed from ERA5 data (Table S1), and phase-conditioned TXx error growth is diagnosed using the nonlinear local Lyapunov exponent (NLLE) framework^{48,49}. IOD phase information is not used in the TXx analog search. Instead, it is applied only after the phase-independent analog-error trajectories have been calculated, allowing the state dependence of TXx error growth to be evaluated without embedding IOD information in analog selection. We then examine the Indo-Pacific convective background, the Indo-western Pacific–East Asian atmospheric bridge, and local moisture–cloud–radiation constraints over the NCP. We show that both negative and positive MJJ IOD extremes are associated with slower early TXx error growth and a longer PL over the NCP. This extended PL is interpreted through a mechanism in which a more organized circulation and local hydro-thermodynamic background constrain TXx evolution, rather than through amplified TXx anomalies.

Results

MJJ IOD extremes extend the predictability limit of NCP summer TXx

We first examine whether MJJ IOD states are associated with changes in the PL of summer TXx over the NCP (35°–43°N, 110°–120°E). The NCP lies within a region of high JJA TXx climatology (Fig. 1a), providing a relevant target for evaluating seasonal heat predictability. Predictability is diagnosed from error growth in the TXx anomaly phase space using the NLLE framework^{48–50}. Each reference year was subsequently assigned to the IOD phase defined by its standardized MJJ DMI (Fig. S1; Table S2). The IOD classification was applied only after the TXx analog-error trajectories had been obtained and was not used in analog selection.

The NCP-mean error-growth curves show a clear separation among IOD phases (Fig. 1b). Under neutral IOD conditions, TXx errors grow rapidly during the first several months and cross the common PL threshold at 2.78 months. In contrast, both IOD extreme branches exhibit slower early error growth and cross the threshold later, with PL values of 4.17 months for negative IOD and 4.12 months for positive IOD. The unconditioned baseline PL is 3.45 months. Thus, within this conditional sample, neutral IOD years correspond to the fastest TXx error-growth regime, whereas IOD extreme years are associated with more slowly diverging TXx trajectories.

Relative to neutral IOD years, the NCP TXx PL is longer by +1.38 and +1.33 months during negative and positive IOD phases, respectively (Fig. 1c). When the two IOD extreme branches are combined, the PL extension remains positive at +1.36 months. One-sided permutation tests yield *p*-values of 0.023, 0.029, and 0.006 for the negative-minus-neutral, positive-minus-neutral, and extreme-minus-neutral differences, respectively. Bootstrap uncertainty estimates and permutation distributions further support these phase-conditioned PL differences (Fig. S3). The positive extreme-minus-neutral PL extension remains stable across alternative NCP definitions, IOD phase thresholds, reference seasons, common and phase-dependent PL thresholds, detrended and raw anomalies, and leave-one-year-out resampling (Fig. S2; Table S3). These sensitivity tests indicate that the main PL extension is not dominated by a specific event definition,

regional averaging choice, threshold choice, anomaly treatment, or individual year.

The spatial PL difference provides additional regional support for this IOD-conditioned PL extension. The extreme-minus-neutral PL anomaly is positive over the NCP and extends across parts of northern China, with locally significant grid points at $p < 0.10$ (Fig. 1d). Although the pattern is spatially heterogeneous, the NCP box lies within a broader region of positive PL anomalies. This spatial consistency reduces the likelihood that the regional-mean PL extension reflects an isolated grid-point anomaly. Branch-specific spatial PL maps are shown in Fig. S4.

Together, these results indicate a robust conditional association between MJJ IOD extremes and slower NCP TXx error growth. We next examine whether the extended PL under IOD extremes is accompanied by organized Indo-Pacific convective anomalies, WNP/WPSH-related circulation anomalies, and local moisture–cloud–radiation constraints over the NCP.

IOD extremes are associated with organized Indo-Pacific convection and an Indo-western Pacific–East Asian circulation bridge

We next examine large-scale SST and convective anomalies over the Indo-western Pacific–East Asian sector in relation to the IOD-conditioned PL extension. The MJJ SST composites show that the phase classification captures the canonical IOD structure: negative IOD years feature cool SST anomalies over the western Indian Ocean and warm anomalies toward the eastern Indian Ocean–Maritime Continent, whereas positive IOD years exhibit the opposite zonal contrast (Fig. 2a, b). This east–west SST contrast captures the canonical definition of the IOD and the corresponding shifts in tropical Indian Ocean convection^{29,30,51}. Thus, the IOD phases used to condition the PL analysis in Fig. 1 represent physically meaningful tropical SST states rather than arbitrary subsets of years.

The associated convective anomalies indicate that these SST states project onto organized atmospheric backgrounds during JJA (Fig. 2c, d). During negative IOD years, enhanced convection extends from the eastern Indian Ocean–Maritime Continent (EIO/MC) toward the Bay of Bengal–East Asia sector; regional –OLR and precipitation anomalies over EIO/MC are +5.92 W m^{–2} and +0.98 mm day^{–1}, respectively. The NCP also shows positive JJA –OLR and precipitation anomalies (+3.73 W m^{–2} and +1.04 mm day^{–1}), whereas the western North Pacific (WNP) exhibits suppressed convection and reduced precipitation. Positive IOD years are not a mirror image of the negative branch: the convective anomaly shifts westward to the western Indian Ocean, where JJA –OLR and precipitation anomalies reach +10.25 W m^{–2} and +0.89 mm day^{–1}. The NCP remains characterized by positive JJA –OLR and precipitation anomalies (+2.49 W m^{–2} and +0.33 mm day^{–1}), and the combined IOD extreme category retains positive NCP anomalies (+3.11 W m^{–2} and +0.69 mm day^{–1}). These regional contrasts are quantified in Fig. S5 and Table S4. These results indicate that dynamically distinct IOD backgrounds can converge onto a similar NCP moisture–convection signature, which provides a regional background-state context for the IOD-conditioned PL extension.

Together, these results indicate that the longer PL under IOD extremes does not reflect a simple linear response to the sign of the dipole mode index. Rather, both IOD extreme branches correspond to organized tropical convective backgrounds, despite their different centers of action. Such convective organization is dynamically relevant because tropical heating anomalies and capacitor-like Indo-western Pacific ocean–atmosphere processes provide established pathways to WNP and East Asian circulation anomalies^{28,31,34,35,52}. Because MJJ and JJA share June–July, the Fig. 2 composites should be interpreted as evidence of persistence or seasonal projection of the early-summer Indo-Pacific convective background, rather than as an independent lead–lag causal test. With this caveat, these composites provide the upstream convective context for the PL differences in Fig. 1 and motivate examining the Indo-western Pacific–East Asian circulation bridge in Fig. 3.

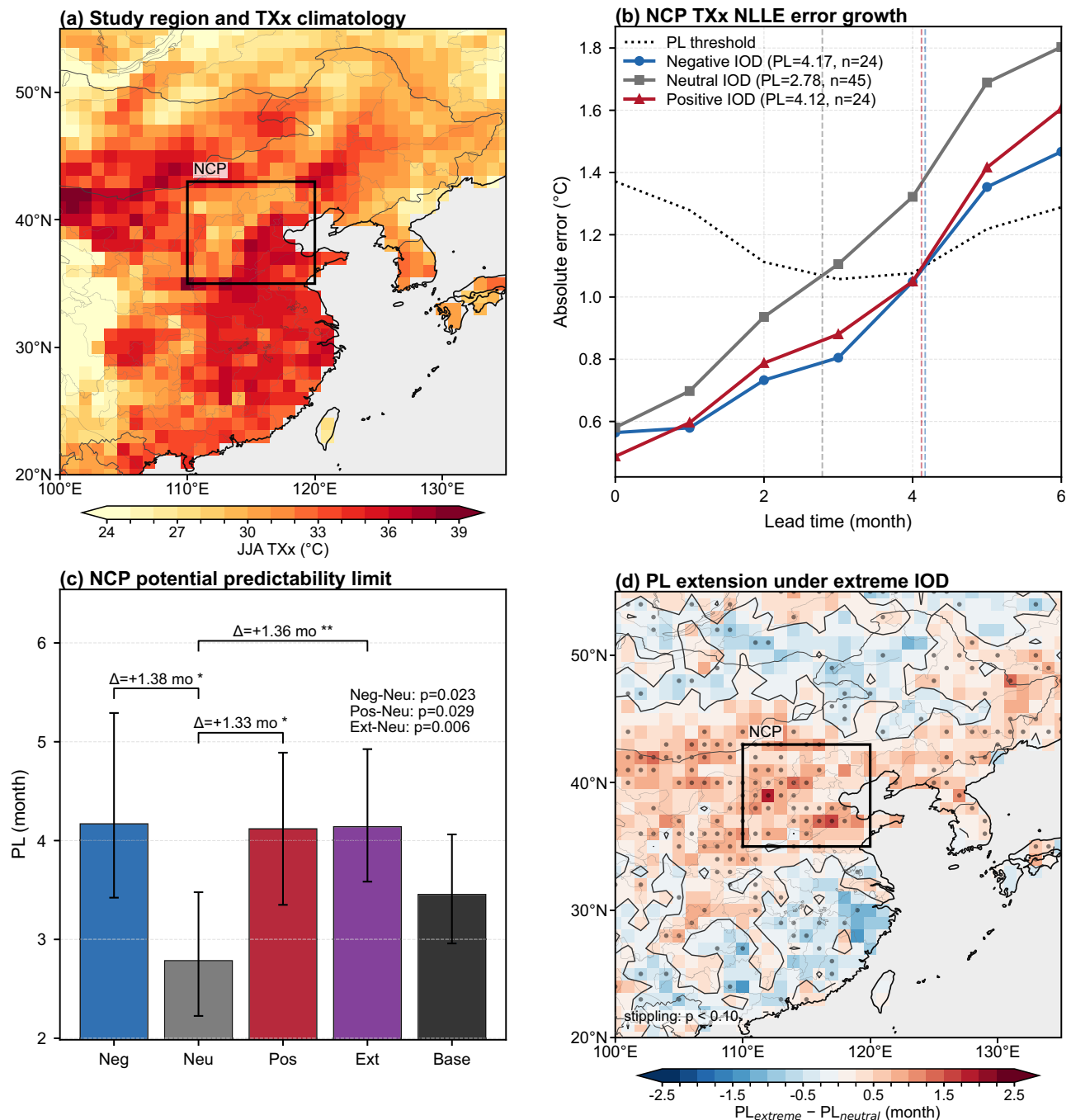


Fig. 1 | MJJ IOD extreme states extend the PL of North China Plain summer TXx. **a** Study region and ERA5 JJA TXx climatology during 1993–2023. The black rectangle denotes the North China Plain (NCP; 35°–43°N, 110°–120°E). **b** NCP-mean NLLE absolute-error growth curves of TXx for target JJA states conditioned on negative, neutral, and positive MJJ IOD phases. The dotted black curve denotes the common predictability limit (PL) threshold. Values in parentheses indicate the estimated PL and the number of effective reference states. **c** NCP TXx PLs under

negative, neutral, positive, combined IOD extreme, and baseline conditions. The combined IOD extreme category includes negative and positive IOD years, and the baseline denotes the unconditioned estimate. Error bars indicate bootstrap 95% confidence intervals. Brackets show PL differences relative to neutral IOD conditions; asterisks denote one-sided permutation significance (* $p < 0.10$; ** $p < 0.01$). **d** Spatial distribution of the PL extension under IOD extremes, defined as $PL_{\text{extreme}} - PL_{\text{neutral}}$. Stippling denotes grid points significant at $p < 0.10$.

Figure 3 summarizes the Indo–western Pacific–East Asian circulation background during IOD extremes. At 200 hPa, both IOD branches exhibit coherent geopotential-height and divergent-circulation anomalies over the Indo–western Pacific–East Asian sector (Fig. 3a, b). During negative IOD years, positive Z200 anomalies extend from western South Asia toward northern China and the Bohai Sea region. The NCP lies near an upper-level positive height anomaly, with an NCP-mean Z200 anomaly of +11.39 gpm relative to neutral years. This pattern is consistent with an upper-

tropospheric circulation adjustment associated with enhanced convection over the EIO/MC and Bay of Bengal sectors shown in Fig. 2, as expected from tropical heating–induced circulation theory^{31,32,35,53}. Positive IOD years show a weaker but still evident NCP upper-level height anomaly (+5.63 gpm), with the upper-level pattern displaced westward in line with the western Indian Ocean convective anomaly. Additional upper-level wave activity flux and divergent-circulation diagnostics are shown in Fig. S6.

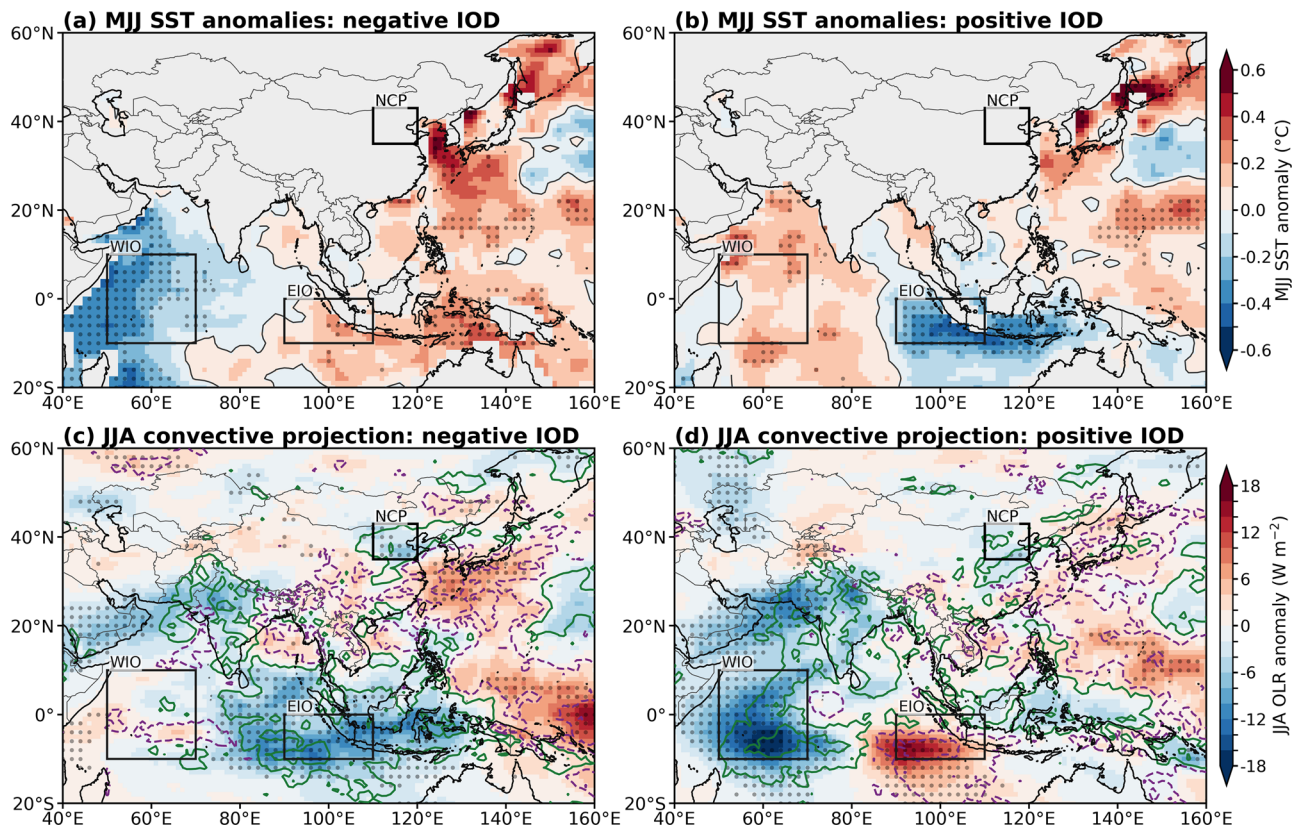


Fig. 2 | MJJ IOD extremes are associated with Indo-Pacific SST anomalies and persistent JJA convective background states. MJJ SST anomalies composited for **a** negative and **b** positive IOD phases relative to neutral IOD conditions. Black boxes denote the western Indian Ocean (WIO; 50°–70°E, 10°S–10°N), eastern Indian Ocean (EIO; 90°–110°E, 10°S–0°), and North China Plain (NCP; 35°–43°N, 110°–120°E) regions. Stippling denotes grid points significant at $p < 0.10$. JJA negative outgoing longwave radiation (–OLR) anomalies and precipitation anomalies composited for **c** negative and **d** positive IOD phases relative to neutral

IOD conditions. Shading denotes –OLR anomalies, with positive values indicating enhanced convection. Green solid and purple dashed contours denote positive and negative precipitation anomalies, respectively, at ± 0.5 and ± 2.0 mm day^{–1}. All anomalies are calculated after removing the monthly climatology and linear trend before seasonal averaging. Because MJJ and JJA overlap in June–July, these composites are interpreted as evidence of persistence or seasonal projection of the early-summer Indo-Pacific convective background rather than as an independent lead–lag causal response.

At 500 and 850 hPa, both IOD branches exhibit positive geopotential-height anomalies over the WNP and subtropical western Pacific, within the climatological subtropical-high background (Fig. 3c–f). The WPSH-mean Z500 anomalies are +2.40 and +3.00 gpm for negative and positive IOD, respectively, and the corresponding Z850 anomalies are +2.13 and +2.89 gpm. These anomalies are not centered directly over the NCP; instead, the NCP lies near the western–northwestern flank of a WNP/WPSH-related anomalous anticyclonic circulation. This pattern places the NCP on the flank of the anomalous circulation, rather than beneath a local center of subsidence and heating. The 850-hPa wind anomalies show anticyclonic flow over the South China Sea–WNP sector and southerly-to-southwesterly flow toward eastern China. Over the NCP, the 850-hPa meridional wind anomaly is positive in both branches, with a larger value under negative IOD (+0.17 m s^{–1}) than under positive IOD (+0.06 m s^{–1}). This low-level circulation pattern provides a dynamical context for the local moisture and vertical-motion anomalies examined in Fig. 4. Regional WNP/WPSH bridge indices are summarized in Fig. S7.

Together, Figs. 2 and 3 indicate that IOD extremes are associated with distinct but organized convective–circulation backgrounds over the Indo–western Pacific–East Asian sector. Although the negative and positive branches differ in their convective centers and circulation structures, the NCP lies near the flank of a WNP/WPSH-related anomalous anticyclonic circulation in both cases. This large-scale setting motivates examining whether local moisture–cloud–radiation conditions over the NCP are also organized under IOD extremes.

Local moisture–cloud–radiation constraints slow TXx error growth

Figure 4 links the large-scale circulation bridge to local TXx predictability by examining NCP moisture, vertical motion, cloud–radiation, and early TXx error growth under MJJ IOD extremes. Both IOD branches show organized low-level moisture anomalies over the Indo–western Pacific–East Asian sector (Fig. 4a, b). Over the NCP, negative IOD years show increased 850-hPa specific humidity and enhanced meridional moisture transport relative to neutral years, with differences of +0.27 g kg^{–1} and +2.19 g kg^{–1} m s^{–1}, respectively. Positive IOD years show anomalies of the same sign but of weaker magnitude, with corresponding differences of +0.08 g kg^{–1} and +1.12 g kg^{–1} m s^{–1}. These anomalies are dynamically consistent with the WNP/WPSH-related low-level circulation in Fig. 3, in which the NCP lies near the northwestern flank of the anomalous anticyclonic circulation. This pattern suggests that the local environment over the NCP under IOD extremes is not simply a dry–subsidence setting, but instead includes a more organized moisture pathway from the Indo–western Pacific sector.

The latitude–pressure sections averaged over 100°–125°E further clarify the vertical structure (Fig. 4c, d). The NCP lies within a transition zone of the anomalous meridional circulation rather than beneath a deep, vertically coherent subsidence center. In the NCP band, both IOD branches exhibit positive $-\omega$ anomalies in the middle troposphere relative to neutral years, consistent with anomalous upward motion or reduced subsidence. This feature is stronger during negative IOD years and weaker during positive IOD years. Together with enhanced low-level moisture, it supports a local environment favorable for cloud increase and reduced

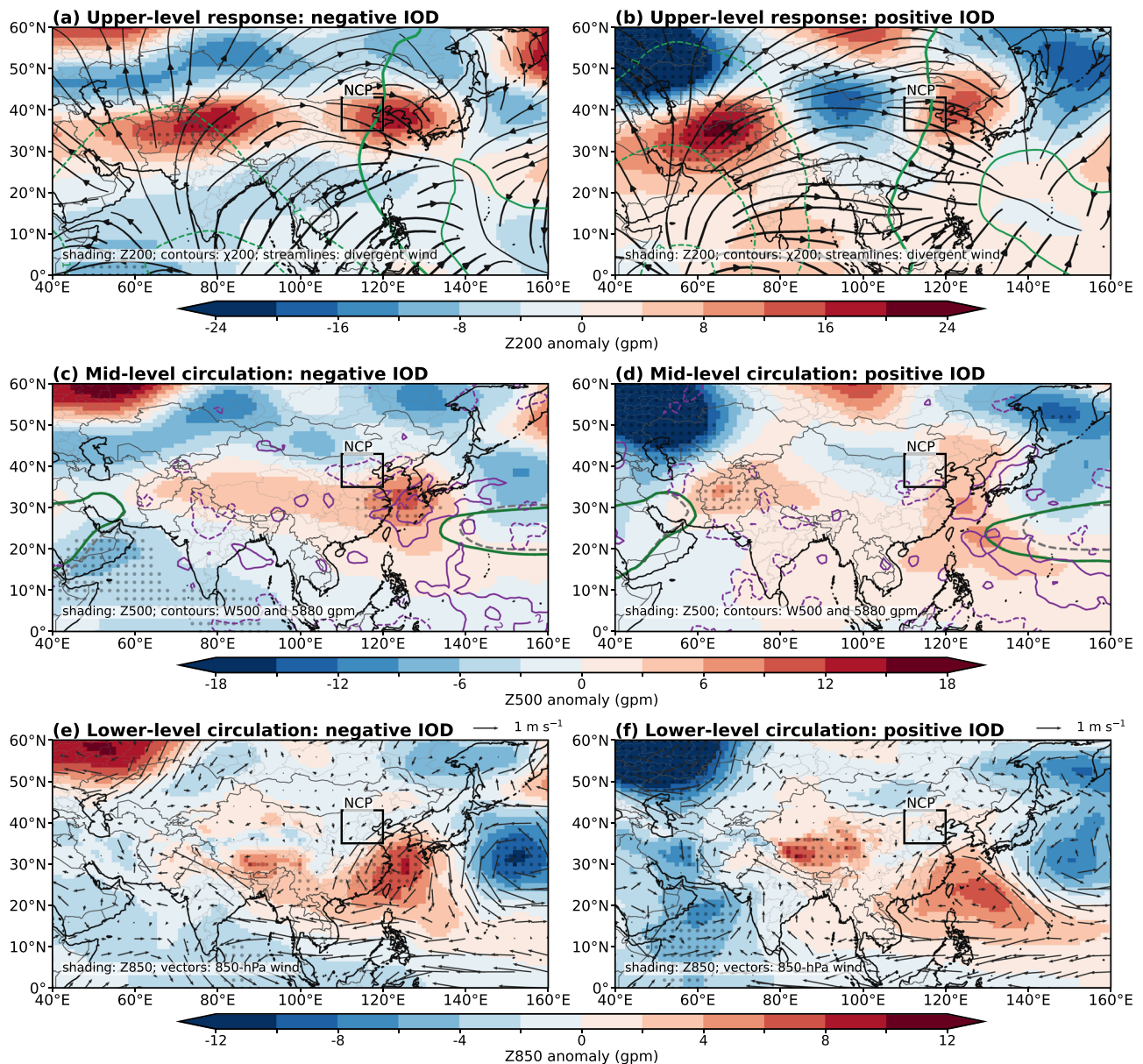


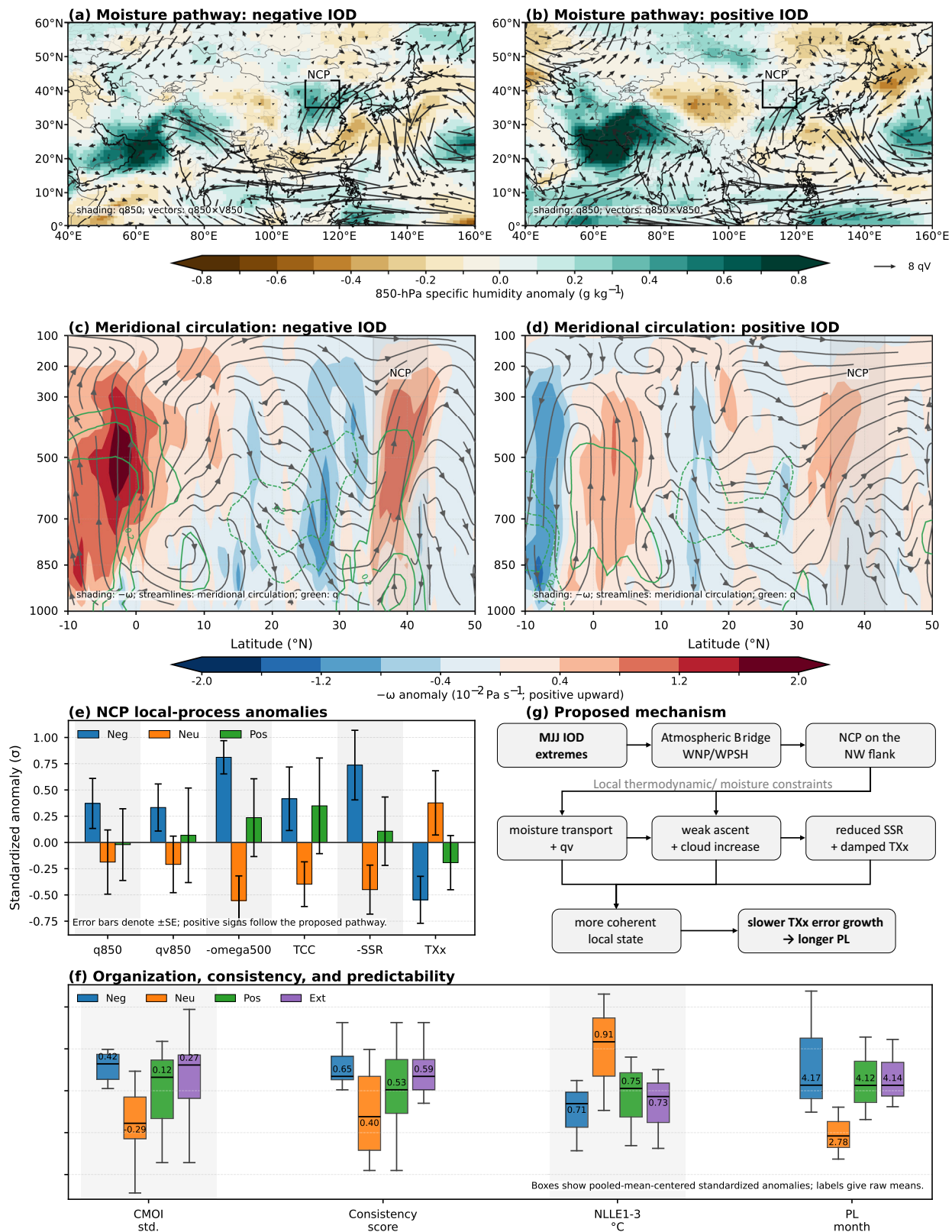
Fig. 3 | Dynamical bridge linking MJJ IOD extremes to East Asian circulation anomalies. JJA atmospheric circulation anomalies are composited for negative and positive MJJ IOD phases relative to neutral IOD years. The left and right columns show negative-minus-neutral and positive-minus-neutral composites, respectively. **a, b** 200-hPa geopotential-height anomalies (shading; gpm), 200-hPa velocity-potential anomalies (green contours; $10^6 \text{ m}^2 \text{ s}^{-1}$; solid, positive; dashed, negative), and 200-hPa divergent-wind anomaly streamlines derived from global Helmholtz decomposition. **c, d** 500-hPa geopotential-height anomalies (shading; gpm), 500-

hPa vertical-velocity anomalies (purple contours; $10^{-2} \text{ Pa s}^{-1}$; solid, positive/downward motion; dashed, negative/upward motion), and 5880-gpm contours of 500-hPa geopotential height. Gray dashed contours denote neutral IOD years, and green solid contours denote the corresponding IOD phase. **e, f** 850-hPa geopotential-height anomalies (shading; gpm) and 850-hPa wind anomaly vectors. Stippling denotes grid points where geopotential-height anomalies are significant at $p < 0.10$ based on two-sided Welch's t -tests. All anomalies are calculated after removing the monthly climatology and linear trend before JJA averaging.

surface shortwave heating. Such a moisture–cloud–radiation pathway is physically consistent with established land–atmosphere and surface-energy-budget controls on temperature variability, in which moisture availability, cloudiness, and shortwave radiation regulate daytime maximum temperature^{47,54,55}. The NCP local-process composites provide quantitative support for this interpretation (Fig. 4e). Relative to neutral IOD years, negative IOD years show enhanced $-\omega 500$ ($+1.16 \times 10^{-2} \text{ Pa s}^{-1}$), increased total cloud cover (TCC; $+2.50\%$), and reduced surface solar radiation, expressed as $+7.24 \text{ W m}^{-2}$ in $-\text{SSR}$. Positive IOD years also exhibit enhanced $-\omega 500$ ($+0.67 \times 10^{-2} \text{ Pa s}^{-1}$), increased cloud cover ($+2.30\%$), and reduced surface solar radiation ($+3.40 \text{ W m}^{-2}$ in $-\text{SSR}$). Importantly, TXx itself does not increase under these organized local-process backgrounds. Instead, NCP TXx is lower than in neutral years by

-0.76°C for negative IOD and -0.47°C for positive IOD. This distinction is central to the predictability interpretation: the longer PL under IOD extremes is not a consequence of stronger TXx amplitude, but instead supports the interpretation of a constrained local hydro-thermodynamic state that reduces the divergence of TXx trajectories.

The CMOI and process-chain consistency score provide two complementary descriptive summaries of local background-state organization. The CMOI averages six standardized circulation, moisture, cloud, and radiation components, whereas the consistency score measures the fraction of five local-process variables that exhibit the pathway-consistent sign. Neither metric includes TXx, which is retained only as a response variable. The CMOI is positive during both IOD extreme branches but negative during neutral IOD years, with values of 0.42 ± 0.17 for negative IOD,



-0.29 ± 0.15 for neutral IOD, and 0.12 ± 0.20 for positive IOD. The combined IOD extreme category has a CMOI of 0.27 ± 0.13 , and the extreme-minus-neutral contrast is significant at $p = 0.010$. The process-chain consistency score shows a consistent phase dependence, increasing from 0.40 ± 0.05 in neutral IOD years to 0.65 ± 0.04 in negative IOD years and

0.53 ± 0.08 in positive IOD years, with a combined extreme value of 0.59 ± 0.05 .

These organized local conditions are accompanied by slower early TXx error growth. The mean NLE error over leads 1–3 months decreases from 0.91°C in neutral IOD years to 0.71°C during negative IOD years, 0.75°C during positive IOD years, and 0.73°C for the combined extreme category

Fig. 4 | Local moisture–cloud–radiation constraints link MJJ IOD extremes to an extended NCP TXx predictability limit. JJA 850-hPa specific-humidity anomalies (shading; g kg^{-1}) and moisture-flux anomalies (vectors; $q_{850} \mathbf{V}_{850}$, where q_{850} is 850-hPa specific humidity and $\mathbf{V}_{850}$ is the 850-hPa horizontal wind vector) for a negative and b positive MJJ IOD phases relative to neutral years. The black rectangle denotes the NCP. Latitude–pressure sections averaged over 100° – 125°E for c negative and d positive IOD composites relative to neutral years. Shading denotes $-\omega$ anomalies, where ω is pressure vertical velocity; positive values indicate anomalous upward motion or reduced subsidence; gray streamlines show anomalous meridional circulation, and green contours denote specific-humidity anomalies. e Standardized NCP local-process anomalies associated with the proposed moisture–cloud–radiation pathway, including q_{850} , meridional moisture transport

$q_{850} \mathbf{V}_{850}$, $-\omega_{500}$, total cloud cover, negative surface solar radiation ($-\text{SSR}$), and TXx. Positive signs follow the proposed pathway for the first five variables, whereas TXx is shown only as a response variable. Error bars denote ± 1 standard error. f Phase dependence of the circulation–moisture organization index (CMOI), process-chain consistency score, early NLE error growth averaged over leads 1–3 months, and NCP TXx PL. Boxes are displayed as pooled-mean-centered standardized anomalies to allow comparison among variables with different units; labels give the original phase-mean values. g Schematic summary of the proposed pathway by which MJJ IOD extremes are associated with an organized Indo–western Pacific atmospheric bridge and NCP local hydro-thermodynamic background, which constrain TXx evolution, slow early TXx error growth, and extend PL.

(Fig. 4f). The corresponding PL increases from 2.78 months in neutral IOD years to 4.17 months during negative IOD years, 4.12 months during positive IOD years, and 4.14 months for the combined extreme category. This covariation among CMOI, process-chain consistency, early NLE error, and PL supports the interpretation that IOD extremes are associated with a more organized local background state for NCP TXx evolution. The monthly evolution of the local-process anomalies and the component-level robustness of the CMOI are shown in Figs. S9 and S10.

Figure 4g summarizes the proposed pathway. Under MJJ IOD extremes, an Indo–western Pacific–East Asian atmospheric bridge is characterized by a WNP/WPSH-related anomalous anticyclonic circulation, with the NCP located near its northwestern flank. The associated moisture transport, weak ascent or reduced subsidence, increased cloud cover, and reduced surface solar radiation represent local constraints on TXx evolution. This process chain does not imply that all IOD extreme years produce identical local weather anomalies. Rather, together with Figs. 2 and 3, this process chain provides a physically consistent explanation for the slower TXx error growth and longer PL documented in Fig. 1. These results support the interpretation that extended NCP summer TXx predictability under IOD extremes arises from organized background-state constraints on local TXx evolution rather than from amplified heat extremes.

Discussion

This study identifies MJJ IOD extreme states as a boundary-condition context for extended PL of summer TXx over the NCP. In the NLE framework^{21,48,50,56}, TXx errors grow more slowly under both negative and positive IOD extremes than under neutral IOD conditions, and the PL increases from 2.78 months in neutral years to about 4.1 months under IOD extremes. This extension is supported by phase-conditioned error-growth curves, bootstrap and permutation tests, sensitivity analyses, and positive spatial PL anomalies over northern China. The close agreement between ERA5 and CPC in detrended TXx variability, together with the independent CPC reproduction of the phase-conditioned PL extension, indicates that the central result is not an artifact of ERA5-specific near-surface temperature characteristics (Figs. S11, S12). Because IOD phase information is not used in the analog search, the phase dependence reflects a conditional difference in TXx error-growth behavior rather than an artifact introduced by analog selection.

The physical diagnostics indicate that this predictability signal is linked to background-state organization over the Indo–western Pacific–East Asian sector. The MJJ SST composites capture canonical IOD structures^{29,30}, while the associated JJA convective composites indicate persistence or seasonal projection of the early-summer Indo-Pacific convective background. This background is accompanied by upper-level divergent circulation anomalies, Rossby wave-type adjustment, and a WNP/WPSH-related circulation environment in which the NCP lies near the flank of an anomalous anticyclonic system^{27,28,31,32,35,36,40}. This atmospheric bridge provides a physically plausible pathway linking tropical Indian Ocean variability to the regional environment in which NCP TXx trajectories evolve. Because MJJ and JJA overlap in June–July, this diagnostic pathway should be interpreted as

evidence of seasonal continuity in the Indo-Pacific atmospheric background rather than as a fully independent lead–lag causal response.

A central implication is that a longer PL does not require amplified TXx anomalies. NCP TXx is lower, rather than higher, under both IOD extreme branches relative to neutral IOD years. Instead, the longer PL occurs under a more organized local hydro-thermodynamic background, characterized by enhanced low-level moisture, weak ascent or reduced subsidence, increased cloud cover, and reduced surface solar radiation. The CMOI, process-chain consistency score, early NLE error, and PL show a coherent phase dependence, consistent with slower divergence of TXx trajectories under IOD extremes. This interpretation connects established land–atmosphere and surface-energy-budget controls on warm-season temperature variability^{26,47,54,57,58} with a predictability-limit perspective: local moisture–cloud–radiation organization can constrain uncertainty growth even when TXx amplitude itself is not amplified.

The negative and positive IOD branches share this common predictability outcome despite dynamically distinct backgrounds. Negative IOD years feature enhanced convection over the eastern Indian Ocean–Maritime Continent and Bay of Bengal sectors and a stronger upper-level height anomaly near the NCP. Positive IOD years are linked to a westward-shifted western Indian Ocean convective anomaly and upper-level circulation pattern. Despite these differences, in both branches the NCP lies near the northwestern flank of a WNP/WPSH-related anomalous anticyclonic circulation and is accompanied by organized local moisture–cloud–radiation conditions. The common feature is therefore not a linear response to the sign of the dipole mode index, but the association between organized IOD extreme backgrounds and reduced TXx error growth. This distinction highlights that the influence of a climate mode on regional predictability need not scale directly with the amplitude or uniqueness of its mean climate response. A background state that produces a modest or non-unique hydroclimatic anomaly may still impose coherent constraints on error evolution, and such constraints can be detected through the NLE framework.

Previous studies have shown that Atlantic multidecadal variability can affect Eurasian warm-season circulation through stationary-wave pathways, while Pacific and Atlantic oceanic modes can modulate East Asian summer climate; the lower-tropospheric anomalies identified here also resemble a PJ/EAP-like configuration^{36, 59–61}. After jointly removing the linear contributions of concurrent JJA Niño3.4, PDO, and AMV-related SST variability, the original-to-residual pattern correlations remain 0.92–0.95 for the negative-IOD Z200–Z850 anomalies and exceed 0.99 for the positive-IOD branch. Thus, the broad circulation structures are not fully attributable to these concurrent SST modes, although ENSO partly modulates the amplitude of the negative-IOD response. The similarity between the two IOD branches increases from 0.35 at 200 hPa to 0.77 at 850 hPa, indicating that their commonality is concentrated in the lower-tropospheric WNP–East Asian pathway rather than in the upper-level Eurasian wave pattern. We therefore interpret the low-level anomalies as a PJ/EAP-like pathway onto which IOD-related convection may project, rather than as an IOD-specific teleconnection.

Complementing these circulation-field controls, the ENSO and basin-wide Indian Ocean sensitivity analyses further suggest that the IOD-conditioned PL extension is not fully attributable to other large-scale SST modes (Fig. S8). After linearly removing Niño3.4, IOBM, or both from the DMI, the extreme-minus-neutral PL extension remains positive, with values of +1.00, +0.92, and +0.98 months, respectively. Excluding strong ENSO years, the PL extension also remains positive (+0.97 months). These tests do not imply that IOD, ENSO, and IOBM variability are dynamically independent. Rather, they suggest that the IOD-conditioned predictability signal is not fully explained by concurrent ENSO or IOBM variability.

Several limitations should be noted. The phase-conditioned sample is limited, and the NLLE calculation requires complete forward TXx trajectories for each reference state. The composite diagnostics support the physical consistency of the proposed pathway but cannot by themselves establish causality. Because the MJJ DMI overlaps with the JJA TXx season in June and July, these composites should be interpreted as indicating persistence and seasonal projection of Indo-Pacific background states rather than as independent lead-lag causal tests. The CMOI and process-chain consistency score are diagnostic summaries of background-state organization rather than predictive models. The analysis is also based on reanalysis-derived TXx and circulation fields. The PL estimated here should therefore be interpreted as a reanalysis-based estimate of potential predictability, rather than as evidence for a guaranteed improvement in initialized or operational forecast skill. Initialized seasonal prediction systems, large-ensemble simulations, and targeted pacemaker or sensitivity experiments are needed to quantify the causal contribution of Indian Ocean forcing and to further separate this contribution from ENSO-related and internally generated atmospheric variability.

Overall, these results suggest that late-spring to early-summer Indian Ocean states are linked to the seasonal error-growth environment of NCP summer TXx. During IOD extreme states, the Indo-western Pacific-East Asian atmospheric bridge and the local moisture-cloud-radiation background correspond to slower early TXx error growth and a longer PL. This finding is relevant for seasonal heat-risk assessment given projected increases in severe heat extremes and heatwave duration under continued warming^{10,14,62,63}. More broadly, the results highlight that potential predictability should be assessed not only in terms of climate-anomaly amplitude, but also in terms of background-state organization that shapes the rate of local uncertainty growth.

Methods

Data

This study examines the seasonal PL of summer TXx over the NCP during 1993–2023. TXx was derived from the ERA5 single-level variable “maximum 2-m temperature since previous post-processing” at hourly resolution⁶⁴. Daily TXx was calculated as the maximum hourly value within each day, and monthly TXx was then defined as the maximum daily TXx within each calendar month. TXx data for 2024–2025 were used only to complete 24-month forward trajectories for late-sample reference states and were not used to define IOD phases, climatologies, thresholds, or composite samples.

ERA5 monthly fields were used for circulation and local-process diagnostics, including geopotential height, horizontal winds, vertical velocity, specific humidity, total cloud cover, surface solar radiation, top net thermal radiation, and precipitation. The sign-reversed outgoing longwave radiation diagnostic, $-OLR$, was used so that positive anomalies indicate enhanced convection. Monthly SST from NOAA ERSSTv6 was used to define the IOD index⁶⁵. All variables were converted to monthly anomalies by removing the 1993–2023 monthly climatology, and a linear trend was removed before seasonal averaging unless otherwise stated. Sensitivity tests using raw anomalies are provided in the Supplementary Information.

IOD phases and study regions

The NCP is defined as 35°–43°N, 110°–120°E. The IOD is represented by the MJJ dipole mode index (DMI), defined as the area-mean SST anomaly

difference between the western Indian Ocean (50°–70°E, 10°S–10°N) and the eastern Indian Ocean (90°–110°E, 10°S–0°)^{29,30}. The MJJ DMI was standardized over 1993–2023 before phase classification. MJJ was selected to characterize the late-spring to early-summer zonal SST-gradient state over the tropical Indian Ocean rather than the mature autumn IOD. This season is temporally relevant to the onset and evolution of JJA TXx, whereas a conventional SON DMI occurs after the target summer. Because MJJ partly overlaps JJA, the DMI classification is used as a retrospective conditioning variable for state-dependent predictability rather than as an operational predictor available at all MAM reference times.

Negative, neutral, and positive IOD phases were defined using the lower and upper quartiles of the standardized MJJ DMI during 1993–2023. Years below the lower quartile were classified as negative IOD years, years above the upper quartile as positive IOD years, and the remaining years as neutral IOD years. The combined IOD extreme category was formed by pooling both negative and positive IOD years. This definition yielded 8 negative, 15 neutral, and 8 positive IOD years, corresponding to 16 IOD extreme years. The same phase classification was used for the PL analysis and for all composite diagnostics. The MJJ IOD phase classification, phase years, and quartile thresholds are documented in Table S2 and Fig. S1.

NLLE-based predictability limit

The PL of NCP summer TXx was quantified using an NLLE framework^{48,50,66}. For a nonlinear dynamical system, let $\mathbf{x}(t)$ denote the system state and $\delta(t)$ denote the error vector between two initially close states, and t_0 denote the initial time. The finite-time local error-growth rate is defined as

$$\lambda[\mathbf{x}(t_0), \delta(t_0), \tau] = \frac{1}{\tau} \ln \frac{\|\delta(t_0 + \tau)\|}{\|\delta(t_0)\|}, \quad (1)$$

where λ is the local finite-time error-growth rate, τ is the evolution time, and $\|\cdot\|$ denotes the Euclidean norm. Because the governing equations for monthly TXx are not explicitly known, error growth was estimated from reanalysis-derived TXx trajectories using a local dynamical analog approach^{66–68}. This reanalysis-based PL diagnoses the intrinsic divergence of TXx analog-error trajectories and should be distinguished from realized forecast skill in initialized seasonal prediction systems.

The June–August (JJA) TXx anomaly states were used as target states. Each calendar year was assigned to the IOD phase defined by its standardized MJJ DMI. Thus, the effective numbers of reference states were 24 for negative IOD years, 45 for neutral IOD years, 24 for positive IOD years, and 93 for all years combined. For each reference state, a 24-month forward TXx anomaly trajectory was constructed. TXx data for 2024–2025 were used only to complete these forward trajectories for the final reference years. Candidate analog states were drawn from all JJA TXx anomaly target states during 1993–2023 with complete 24-month forward trajectories, irrespective of IOD phase, after excluding the reference state itself from its own candidate pool. IOD phase labels were assigned only after all reference–analog error trajectories had been obtained. Thus, the phase-conditioned error-growth curves were constructed by post-stratifying the TXx analog-error trajectories. Details of the local dynamical analog criterion and the global-attraction-radius-based PL threshold are provided in Text S2.

Let $X_i(t)$ be the TXx anomaly trajectory initialized from reference state $X_i(t_0)$, and let $X_j(t)$ be an analog trajectory indexed by j and selected from historical TXx states. For a lead time k in months, the analog error is $e_{ij}(k) = |X_i(t_0 + k) - X_j(t_0 + k)|$.

For each reference state i , the state-level absolute error growth was calculated by averaging over its analog set A_i :

$$E_i(k) = \frac{1}{|A_i|} \sum_{j \in A_i} e_{ij}(k), \quad (2)$$

where A_i is the analog set for reference state i , and $|A_i|$ is the number of analogs. For each IOD phase p , the phase-conditioned error-growth curve

was obtained by averaging $E_i(k)$ over all reference states R_p belonging to that phase:

$$E_p(k) = \frac{1}{|R_p|} \sum_{i \in R_p} E_i(k), \quad (3)$$

where p denotes negative, neutral, positive, or combined IOD extreme conditions, R_p is the set of reference states in phase p , and $|R_p|$ is the number of reference states in that phase. The PL T_p is defined as the first lead time at which the phase-conditioned error-growth curve reaches a common error threshold E_{th} :

$$T_p = \min \left\{ k : E_p(k) \geq E_{th} \right\}. \quad (4)$$

The common threshold was defined as $E_{th} = \alpha R$, where R is the monthly TXx global attractor radius⁴⁸ and α was fixed across all IOD phases. In the main analysis, $\alpha = 0.90$. The same threshold E_{th} was used for all IOD phases, so differences in T_p mainly reflect differences in TXx error growth rather than phase-dependent threshold choices. If the threshold crossing occurred between two adjacent monthly leads, T_p was estimated by linear interpolation:

$$T_p = k_1 + \frac{E_{th} - E_p(k_1)}{E_p(k_2) - E_p(k_1)} (k_2 - k_1), \quad (5)$$

where k_1 and k_2 are the two adjacent leads satisfying $E_p(k_1) < E_{th} \leq E_p(k_2)$. Sensitivity to threshold choices was assessed in Fig. S2.

Uncertainty ranges of phase-conditioned PL values were estimated using bootstrap resampling by year. Significance of PL differences relative to neutral IOD conditions was assessed using permutation tests in which IOD phase labels were randomly reassigned to reference years. Spatial PL maps were calculated grid point by grid point using the same conditional framework, with significance assessed using Welch's t tests. Additional sensitivity tests, including alternative NCP boxes, tercile versus quartile IOD classification, common versus phase-dependent thresholds, detrended versus raw anomalies, and leave-one-year-out sampling, are documented in Text S2 and Figs. S2–S4.

Composite diagnostics of upstream convective background and atmospheric bridge

Composite diagnostics were used to characterize the SST, convective, and circulation backgrounds associated with IOD-conditioned TXx error growth. Unless otherwise stated, composites were calculated as phase-minus-neutral differences. MJJ SST composites were used to verify the IOD phase structure. JJA –OLR and precipitation composites were used to assess whether the MJJ IOD states project onto, or persist into, the summer Indo-Pacific convective background. Because MJJ and JJA share June and July, these composites are interpreted as persistence or seasonal-projection diagnostics rather than as independent lead-lag causal tests. Regional convective anomalies are summarized in Fig. S5 and Table S4.

The atmospheric bridge was diagnosed using JJA composites of 200-, 500-, and 850-hPa circulation fields. At 200 hPa, the global horizontal wind field was decomposed into rotational and divergent components using Helmholtz decomposition⁶⁹. The velocity potential and divergent-wind anomalies were analyzed together with 200-hPa geopotential height anomalies to characterize upper-level divergent circulation and wave-type adjustments^{31,32,69}. At 500 hPa, geopotential height anomalies, vertical velocity anomalies, and the 5880-gpm contour were used to characterize the WNP/WPSH-related circulation background^{27,35}. At 850 hPa, geopotential height and wind anomalies were used to diagnose the low-level anticyclonic circulation and moisture-transport pathway.

For composite maps and regional diagnostics, statistical significance was assessed using two-sided Welch's t tests between each IOD phase and

neutral IOD years. Map stippling denotes $p < 0.10$. Additional upper-level wave-activity flux diagnostics⁷⁰ and regional WNP/WPSH bridge indices are provided in Figs. S6 and S7.

Local process diagnostics and organization metrics

Local process diagnostics were used to examine whether the large-scale circulation background is associated with coherent hydro-thermodynamic anomalies over the NCP. The examined variables included 850-hPa specific humidity, 850-hPa moisture flux, moisture-flux convergence, 500-hPa vertical velocity, total cloud cover, surface solar radiation, and TXx. The 850-hPa moisture flux is defined as $\mathbf{F}_{q,850} = q_{850} \mathbf{V}_{850}$, where q_{850} is 850-hPa specific humidity and $\mathbf{V}_{850} = (u_{850}, v_{850})$ is the 850-hPa horizontal wind vector, with u_{850} and v_{850} denoting zonal and meridional wind components. The 850-hPa moisture-flux convergence is defined as

$$\text{MFC}_{850} = -\nabla \cdot \mathbf{F}_{q,850} = -\nabla \cdot (q_{850} \mathbf{V}_{850}). \quad (6)$$

The meridional moisture transport is represented by $q_{850} v_{850}$, where v_{850} is the 850-hPa meridional wind. Latitude–pressure sections were averaged over 100°–125°E and displayed over 10°S–50°N and 1000–200 hPa to show the meridional circulation and vertical-motion structure from the tropical Indo-western Pacific sector to East Asia and the NCP. In spatial maps and latitude–pressure sections, vertical motion is shown as $-\omega$, where ω is pressure vertical velocity, positive $-\omega$ values indicate anomalous ascent or reduced subsidence. The local-process index $-\omega_{500}$ denotes the NCP-mean 500-hPa value of this sign-reversed vertical velocity used in the regional diagnostics.

To summarize the degree of pathway-consistent local background organization, we defined a circulation–moisture organization index (CMOI) as a descriptive diagnostic. The CMOI included six standardized components: NCP-mean 200-hPa geopotential height, WPSH-region 500-hPa geopotential height, NCP-mean 850-hPa specific humidity, NCP-mean 850-hPa moisture-flux convergence, NCP-mean total cloud cover, and negative NCP-mean surface solar radiation. The WPSH region is defined as 15°–30°N, 110°–150°E. Let $P_{l,y}$ denote component l in year y , and let $Z_{l,y}$ be its standardized anomaly over 1993–2023: $Z_{l,y} = \frac{P_{l,y} - \bar{P}_l}{\sigma(P_l)}$. Here $\bar{P}_l$ and $\sigma(P_l)$ denote the 1993–2023 mean and standard deviation of component l , respectively. The CMOI is then defined as

$$\text{CMOI}_y = \frac{1}{6} \left[Z_{Z200\text{NCP},y}, |Z_{Z500\text{WPSH},y}|, Z_{q850\text{NCP},y}, |Z_{\text{MFC}850\text{NCP},y}|, |Z_{\text{TCCNCP},y}|, |Z_{-\text{SSRNCP},y}| \right]. \quad (7)$$

All six CMOI components were calculated from detrended JJA anomalies and standardized over the common 1993–2023 reference period before averaging. Component signs were oriented so that positive values indicate pathway-consistent circulation–moisture–cloud–radiation conditions, including positive NCP Z200, WPSH Z500, NCP q_{850} , NCP MFC850, NCP TCC, and reduced NCP SSR.

A process-chain consistency score was also calculated to quantify how often the local process variables follow the expected sign of the moisture–cloud–radiation pathway. The five variables included in the score were NCP-mean q_{850} , meridional moisture transport $q_{850} v_{850}$, $-\omega_{500}$, total cloud cover, and –SSR. Let $I_{l,y}$ be a binary indicator of whether variable l in year y follows the pathway-consistent sign. The consistency score was then defined as

$$C_y = \frac{1}{5} \sum_{l=1}^5 I_{l,y}, \quad (8)$$

Because all five variables were defined so that positive anomalies are pathway-consistent, $I_{l,y} = 1$ when the corresponding detrended JJA anomaly is positive and $I_l(y) = 0$ otherwise. Thus, C_y ranges from 0 to 1, with larger values indicating that a greater fraction of local process variables

follow the proposed moisture–cloud–radiation pathway in that year. All variables entering the CMOI and the process-chain consistency score were standardized over the same 1993–2023 reference period after removing the monthly climatology and linear trend. TXx was excluded from both metrics and was treated only as a response variable, avoiding circular interpretation between the organization metrics and TXx predictability.

The CMOI and process-chain consistency score were compared with early NLE error growth averaged over leads 1–3 months and with the phase-conditioned PL. These diagnostics were used to assess whether local background organization is associated with slower TXx error growth under IOD extreme conditions. Definitions and robustness tests are provided in Table S5 and Figs. S9–S10.

Data availability

All datasets used in this study are publicly available. ERA5 hourly maximum 2-m temperature since previous post-processing was obtained from the ERA5 product <https://doi.org/10.24381/cds.adbb2d47>. ERA5 monthly averaged single-level fields were obtained from the ERA5 monthly single-level product <https://doi.org/10.24381/cds.f17050d7>. ERA5 monthly pressure-level fields were obtained from the ERA5 product <https://doi.org/10.24381/cds.6860a573>. NOAA ERSTv6 sea surface temperature was obtained from the NOAA Physical Sciences Laboratory (<https://psl.noaa.gov/data/gridded/data.noaa.ersst.v6.html>). The processed data and figure data generated in this study are available from the corresponding author upon reasonable request. No proprietary data were used.

Code availability

All analyses were performed using Python. The custom analysis and plotting codes used in this study are available from the corresponding author upon reasonable request.

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Author contributions

Z.H. designed the research, performed the analyses, prepared the figures, and wrote the initial draft. J.L. supervised the project and provided funding support. L.W., Y.D., and S.Z. contributed to the interpretation of the results and revision of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Jianping Li.

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