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Harnessing ENSO Teleconnections for Six-Month Predictability of Tropical Humid Heat Stress and Its Cascading Impacts on Labour Productivity

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Abstract:
Tropical humid heat stress, measured through wet-bulb temperature (TW) and Wet Bulb Globe Temperature (WBGT), represents a compound threat combining temperature and humidity effects that routinely pushes workers toward physiological limits. Unlike episodic heatwaves, humid heat operates as a persistent background condition constraining labour capacity and economic functioning across tropical economies. This study demonstrates that El Niño–Southern Oscillation (ENSO) teleconnections exert a dominant and predictable influence on tropical humid heat stress, with strong correlation indicating predictability up to six months in advance. Physics-based statistical models explain 80% of variance in tropical mean annual maximum wet-bulb temperature (TWmax), enabling seasonal forecasts that can inform adaptation planning across agriculture, construction, public health, energy, and supply chain management. The cascading impacts are substantial: fewer than 2018 baseline conditions, labour-capacity losses reached 9–11% across tropical economies, with sectoral losses approaching 17% in agriculture and construction. Indirect exposure transmitted through supply-chain linkages often exceeds direct sectoral losses, amplifying economy-wide consequences. The six-month predictability window offers an untapped opportunity for proactive adaptation, enabling anticipatory action rather than reactive crisis response. However, realizing this potential requires building institutional capacity, translating probabilistic forecasts into actionable guidance, and addressing the adaptation deficit in rapidly growing tropical populations. Harnessing ENSO teleconnections for seasonal prediction of humid heat stress represents a tangible pathway to reduce climate vulnerability, protect worker health and productivity, and build more resilient tropical economies in a warming world.
Keywords:
ENSO teleconnections; humid heat stress; labour productivity; seasonal predictability; cascading economic impacts

I. Introduction

1.1 Background and Motivation

The tropics, defined by persistently high baseline temperatures and elevated atmospheric humidity, face disproportionately severe risks from heat-related impacts in a warming climate (Zhang et al., 2024; Goshu and Ridwan, 2026). Unlike extratropical regions where heat stress is often episodic and tied to discrete heatwave events, tropical populations are climatologically situated closer to physiological thresholds, rendering them chronically vulnerable to even modest increments in temperature and humidity. This proximity to biophysical limits means that tropical economies operate under a near-continuous heat burden that intensifies with every fraction of a degree of global warming.

Humid heat stress, quantified through metrics such as wet-bulb temperature (TW) and Wet Bulb Globe Temperature (WBGT), represents a compound threat that integrates the synergistic effects of temperature and humidity on human thermoregulation (Zhang et al.,

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2024). Wet-bulb temperature, in particular, captures the physiological limit of evaporative cooling: when TW exceeds approximately 35°C, even a healthy human at rest cannot maintain core temperature within safe bounds. WBGT, widely applied in occupational health settings, incorporates additional factors including wind speed and solar radiation, making it the standard index for assessing workplace heat exposure. Recent advances have underscored that explicit, physics-based calculations of WBGT are essential for accurate labour productivity assessments, as commonly used approximations can introduce substantial systematic biases, particularly in tropical regions where systematic underestimation may reach up to 18% (Borzino et al., 2026).

Critically, humid heat does not manifest primarily as discrete, episodic events in the tropics. Rather, it operates as a persistent background condition that routinely pushes workers toward physiological limits and reduces effective labour input throughout much of the year (Borzino et al., 2026). This chronic nature distinguishes tropical humid heat from the acute heatwaves that dominate public discourse in higher-latitude settings. As Borzino et al. (2026) observed, "Chronic humid heat is an increasingly important yet under-recognised manifestation of climate change that constrains labour capacity and economic functioning in tropical economies". The sustained, year-round exposure means that productivity losses accumulate continuously, with cascading effects that propagate through production networks and amplify economy-wide disruptions.

1.2 The Productivity Dimension

The economic consequences of tropical humid heat stress are substantial and growing. Saha et al. (2026) documented an abrupt increase in global potential productivity loss from humid heat stress since the mid 1980s, with India alone contributing over half of the total increase. This sharp acceleration coincides with Indo Pacific sea surface temperatures exceeding 28°C and rapid population growth in the most heat exposed regions, suggesting that the loss has recently crossed a critical transition into a new, more damaging state (Saha et al., 2026).

The physiological basis for these productivity losses is well established. Human labour capacity is bounded by rigid biophysical heat thresholds that remain systematically misrepresented in current climate–economic models. Empirical exposure–response functions indicate that labour capacity peaks at approximately 20.6°C wet-bulb temperature, with capacity falling below 60% when WBGT exceeds 28°C. In practical terms, work capacity "rapidly reduces as the WBGT exceeds 26–30°C, with each incremental degree of warming imposing a compounding burden on outdoor workers in agriculture, construction, and other heat exposed sectors (Borzino et al., 2026).

The magnitude of already realized losses is striking. In tropical regions, labour capacity has already fallen by up to 30% during summer months. Borzino et al. (2026) quantified that in 2018 baseline conditions, effective labour capacity losses reached 9–11% across tropical economies, with sectoral losses approaching 17% in agriculture and construction. These constraints translate into economy-wide gross output exposure of approximately USD 0.9 billion in Singapore, USD 2.6 billion in Cambodia, and USD 22.3 billion in Vietnam (2018 USD). Critically, indirect exposure transmitted through supply chain linkages often exceeds direct sectoral losses, particularly in service oriented economies, meaning that the full economic footprint of humid heat stress is substantially larger than direct sectoral impacts alone (Borzino et al., 2026; Goshu and Ridwan, 2026).

The disproportionate burden on India warrants particular attention. As the country with the largest population of outdoor workers and one of the fastest warming tropical landmasses, India accounts for more than half of the global increase in productivity losses from humid heat stress (Saha et al., 2026). Mishra et al. (2025) demonstrated that during 1980–2021, most rural to urban migration hotspots in India witnessed a significant rise in indoor wet bulb temperature, with outdoor heat stress considerably increasing and leading to a ~10% decline in labour capacity in these hotspots. Recent studies in southern India have confirmed that WBGT exposure has a significant impact on workers' perceptions of heat related illness symptoms, with informal sector workers being 17 times more likely to experience heat related productivity loss compared to formal sector employees exposed to the same temperatures (Mishra et al., 2025). Analysis of worker perception data revealed a significant association between elevated WBGT exposure and a 1.4 fold increased risk of productivity loss (95% CI 1.1–1.8), with high workload and seasonal variation emerging as strong predictors of productivity decrements (adjusted odds ratio 1.5; 95% CI 1.2–2.1) (Scientific Reports, 2026).

1.3 Research Gap and Rationale

Despite the growing recognition of humid heat stress as a critical climate risk, substantial research gaps persist. While the influence of the El Niño–Southern Oscillation (ENSO) on temperature extremes is well documented, its specific role in shaping humid heat stress and the associated productivity losses, remains underexplored. Recent work has begun to address this gap, demonstrating that ENSO exerts a dominant influence on humid heat extremes across much of the tropics at interannual timescales, acting through combined effects on both temperature and humidity (Zhang et al., 2024). Saha et al. (2026) further established that humid heat stress and productivity loss are closely linked to ENSO, allowing for predictions up to six months in advance. However, the mechanistic pathways through which ENSO teleconnections drive humid heat variability, including the relative contributions of temperature versus humidity forcing, and the modulating effects of other modes such as the Indian Ocean Dipole are not yet fully understood.

A second, more fundamental gap concerns the cascading effects from climate teleconnections through labour markets to broader economic systems. Most economy wide assessments of heat stress impacts rely on temperature based indicators or aggregate damage functions that abstract from workability thresholds and the propagation of localized labour constraints through production networks (Borzino et al., 2026). As a result, the indirect and economy wide consequences of ENSO driven humid heat events remain poorly quantified. This is a critical omission, given that indirect exposure transmitted through supply chain linkages often exceeds direct sectoral losses (Borzino et al., 2026). Without a framework that traces the full cascade from climate forcing to physiological stress to labour constraints to production network disruptions, adaptation planning remains necessarily incomplete. Global supply chains have been shown to amplify the economic costs of future extreme heat risk, with indirect losses due to economic disruptions cascading through supply chains contributing substantially to total impacts (Sun et al., 2024).

A third gap and the central motivation for the present study, concerns predictability. While seasonal forecasting of temperature and precipitation has advanced considerably, the specific predictability of humid heat stress and its productivity impacts has received limited attention. Emerging evidence indicates that on interannual timescales, strong correlation with ENSO implies that humid heat stress and productivity losses are predictable up to six months in advance (Saha et al., 2026; Zhang et al., 2024). Zhang et al. (2024) developed a multiple linear regression model that explains 80% of variance in tropical mean annual maximum wet bulb temperature (TWmax), demonstrating that these extremely humid and hot conditions on land can be predicted about five months in advance using a physics based statistical model. This six month predictability window offers an untapped opportunity for proactive adaptation planning: forecasts could inform the timing of agricultural operations, construction scheduling, public health preparedness, and supply chain risk management. However, the operationalization of such forecasts, including the development of robust statistical models, the characterisation of forecast skill across regions and seasons, and the translation of forecast signals into actionable adaptation decisions, remains in its infancy.

Collectively, these gaps define a clear research imperative: to advance the scientific understanding of ENSO driven humid heat variability, to quantify the cascading productivity and economic consequences, and to harness the six month predictability window for practical adaptation. Addressing this imperative is particularly urgent given that "accounting for humid heat stress significantly raises the estimated socioeconomic costs of climate change" and that climate impacts are creating a self reinforcing feedback loop where disruptions hinder the very development processes that contribute to emissions (Saha et al., 2026).

1.4 Research Questions and Objectives

This study is guided by three interconnected research questions that span the physical climate, labour productivity, and economic impact domains:

RQ1: How do ENSO teleconnections drive tropical humid heat stress at interannual timescales?

This question addresses the mechanistic pathways through which ENSO modulates both the temperature and humidity components of humid heat stress. Specific objectives include: (a) quantifying the relative contributions of temperature versus humidity forcing to ENSO driven humid heat variability; (b) characterizing the regional heterogeneity of ENSO teleconnections across different tropical subregions; and (c) investigating the modulating effects of other modes of variability, particularly the Indian Ocean Dipole and Atlantic modes.

RQ2: Can humid heat stress and its productivity impacts be predicted up to six months in advance?

This question focuses on the operational predictability of humid heat stress and labour capacity losses. Objectives include: (a) developing and validating physics based statistical models that explain variance in tropical annual maximum wet bulb temperatures (TWmax) using ENSO indices and warming trends; (b) assessing forecast skill across different lead times, regions, and seasons; and (c) evaluating the practical utility of such forecasts for sectoral adaptation planning.

RQ3: What are the cascading economic and social consequences of ENSO driven humid heat events?

This question extends the analysis from biophysical impacts to economy wide consequences. Objectives include: (a) quantifying the direct productivity losses in heat exposed sectors (agriculture, construction, manufacturing) under different ENSO phases; (b) tracing the propagation of labour constraints through input–output production networks to estimate indirect and economy wide exposures; and (c) identifying production network bottlenecks where protecting work capacity can yield disproportionate economy wide resilience.

By addressing these questions, this study aims to provide a comprehensive framework that bridges climate science, labour economics, and adaptation planning, demonstrating how the predictable signal of ENSO teleconnections can be harnessed to reduce vulnerability to one of the most pressing and under recognised climate risks of the twenty first century.

II. Review of Literature

2.1 Physical Mechanisms – ENSO Teleconnections and Tropical Humid Heat

a. ENSO as a Global Climate Modulator

The El Niño–Southern Oscillation (ENSO) constitutes the most prominent year-to-year climate fluctuation on Earth, alternating between anomalously warm (El Niño) and cold (La Niña) sea surface temperature (SST) conditions in the tropical Pacific (Yeh et al., 2020). El Niño events, typified by warmer central and eastern equatorial Pacific Ocean temperatures, trigger profound shifts in atmospheric circulation that modify global temperature and precipitation patterns across both tropical and extratropical regions (Yeh et al., 2020; Goshu and Ridwan, 2026a). The anomalous Pacific SSTs associated with ENSO modulate the Walker and Hadley circulations, causing profound impacts on rainfall and temperature over land and oceans (Yeh et al., 2020). Globally, El Niño events usually lead to a short-term rise in averaged temperatures, while global-mean temperatures typically decrease during La Niña events (Yeh et al., 2020).

ENSO exerts a dominant influence on humid heat extremes across much of the tropics at interannual timescales, acting through combined effects on both temperature and humidity (Birch et al., 2026; Bose et al., 2026; Goshu and Ridwan, 2026b). In equatorial Southeast Asia, El Niño is the leading driver of humid heat extremes on interannual timescales, under which humid heat extreme risk increases by three- to fivefold (Hidayat et al., 2026). This amplification reflects the capacity of ENSO to simultaneously elevate both the temperature and moisture content of the lower atmosphere, pushing tropical populations closer to physiological thresholds.

The Pacific Walker circulation, the zonal atmospheric circulation over the tropical Pacific consisting of rising air motion over Southeast Asia and descending air motion over the eastern Pacific is closely connected to ENSO and exerts strong control on the regional occurrence of weather extremes, including heatwaves, heavy precipitation and prolonged dry spells (Wang et al., 2024). The Walker circulation is modulated by ENSO and has a pronounced effect on global weather (Wang et al., 2024). Importantly, new large-scale synoptic situations that were rarely present before the 1990s have emerged in the Indo-Pacific, and these new synoptic situations are associated with an unusual proportion of heatwaves and extreme precipitation in the region (Wang et al., 2024). These changes cannot be fully explained by ENSO alone, with global warming, aerosol forcing, external forcing mechanisms and nonlinear mode interactions also contributing (Wang et al., 2024).

b. Teleconnection Pathways

The physical pathways through which ENSO modulates tropical humid heat involve a complex interplay of atmospheric convection, wave dynamics, and ocean–atmosphere coupling. Extreme wet-bulb temperatures (TW) over tropical land are coupled to the warmest sea surface temperatures by atmospheric convection and wave dynamics (Zhang et al., 2024). This coupling arises because deep convection over the warmest tropical ocean regions generates anomalous atmospheric heating, which in turn excites Rossby wave trains that propagate poleward and eastward, modifying temperature and moisture profiles over distant tropical landmasses (Zhang et al., 2024). The result is a teleconnected response wherein SST anomalies in the equatorial Pacific—particularly in the warm pool region, drive coherent variations in wet-bulb temperature across extensive areas of the tropics.

Local ENSO-driven heat flux forcing is generated by changes in SST anomalies and is ultimately linked to wind stress forcing remotely from the tropical Pacific via oceanic teleconnections (Feng et al., 2025). Decomposition of ENSO-driven net surface heat flux anomalies reveals that latent heat flux anomalies are the primary contributor to remote SST variations, with the dominant contribution arising from air–sea humidity gradient anomalies rather than wind speed anomalies (Feng et al., 2025). This indicates that the thermodynamic effect, whereby ENSO modifies the humidity gradient between the ocean surface and the overlying atmosphere, plays a more critical role than the mechanical effect of wind-induced evaporation in driving remote tropical surface temperature variability. During El Niño, negative SST anomalies generated by wind stress forcing decrease the humidity gradient and evaporation, suppressing heat loss from ocean to atmosphere, while during La Niña the opposite occurs (Feng et al., 2025).

ENSO acts through combined effects on both temperature and humidity, amplifying humid heat through multiple mechanisms (Birch et al., 2026; Bose et al., 2026). The temperature component operates through advection of warmer air masses and suppression of convective cooling, while the humidity component reflects enhanced moisture transport from warmer oceans and reduced evaporative cooling efficiency. This dual forcing distinguishes humid heat from dry-bulb temperature extremes: despite the limited overlap (approximately 19%) between wet- and dry-bulb temperature extremes, the differences in their temperature and humidity conditions and their drivers are small, underscoring the tight coupling of these variables in the tropical atmosphere (Hidayat et al., 2026).

The Indian Ocean Dipole (IOD) and Atlantic modes further modulate humid heat extremes (Birch et al., 2026; Bose et al., 2026). The positive phase of the IOD, characterised by anomalously warm western Indian Ocean SSTs, can amplify humid heat over East Africa and the western Indian Ocean rim, while the Atlantic modes influence humidity transport across the equatorial Atlantic and into adjacent tropical landmasses. These inter-basin interactions create a complex mosaic of humid heat variability that cannot be understood through Pacific forcing alone. Recent work has established a unified Bayesian framework for attributing humid heat amplification to specific SST pathways, enabling separation of humidity-driven versus temperature-driven contributions to extremes (Bose et al., 2026).

c. Humidity-Driven Amplification

A defining characteristic of ENSO's influence on humid heat is the robust humidity-driven amplification that occurs under positive ENSO phases (Bose et al., 2026). This amplification arises from the fundamental thermodynamics of the atmosphere–ocean system. The ENSO-induced humidity anomaly amplifies under warming conditions, obeying

Clausius–Clapeyron scaling, which is confined to the lower troposphere (Hu et al., 2021). The Clausius–Clapeyron relationship dictates that saturation vapour pressure increases nearly exponentially with increasing temperature; consequently, the response of tropical lower tropospheric humidity to ENSO amplifies as the background climate warms, resulting in major reorganization of atmospheric temperature and circulation patterns (Hu et al., 2021).

ENSO's "heartbeat" of Pacific Trade Wind deceleration during El Niño leads to tropical sea surface warming by approximately three months, which in turn drives increases in global specific humidity (Zhang et al., 2024). As the trade winds weaken, the equatorial thermocline adjusts, allowing warmer subsurface waters to surface across the eastern and central Pacific. This warming elevates surface evaporation and, through the Clausius–Clapeyron relationship, increases the specific humidity of the overlying atmosphere. The resulting moisture anomaly is then transported by the large-scale circulation to remote tropical regions, where it combines with locally elevated temperatures to produce extreme humid heat events (Zhang et al., 2024).

The air–sea humidity difference variation is a key driver of ENSO-related remote tropical surface temperature variability (Feng et al., 2025). This mechanism operates through the latent heat flux: when ENSO modifies the humidity gradient between the ocean surface and the near-surface atmosphere, it alters the rate of evaporative cooling, which in turn modulates sea surface temperatures in remote ocean basins. This represents an addition to the wind speed and cloudiness variations that previous studies have shown to be important in ENSO teleconnections (Feng et al., 2025). The implication is that humidity not merely temperature or wind is a fundamental carrier of the ENSO signal across the tropics, and that accurate prediction of humid heat stress requires explicit representation of moisture dynamics.

The implications of this humidity-driven amplification are profound for human heat stress. Because wet-bulb temperature integrates both temperature and humidity, the Clausius–Clapeyron amplification of ENSO-driven humidity anomalies directly translates into amplified wet-bulb temperature anomalies. This means that under a warming climate, a given ENSO event will produce a larger humid heat extreme than it would have under pre-industrial conditions, a concerning prospect given that tropical regions are already approaching physiological limits.

d. Regional Variability and ENSO Flavours

The influence of ENSO on humid heat exhibits significant regional heterogeneity. Moisture anomaly conditions within humid and subhumid tropics associated with different types of El Niño and La Niña phenomena show significant heterogeneity both within and across various geographical regions (Mishra et al., 2024). This regional variability reflects the diverse ways in which ENSO-induced SST anomalies interact with local climate conditions, including background moisture availability, topography, and regional circulation patterns. Four main areas in the humid and subhumid tropics exhibit maximum effects of El Niño/La Niña events on surface moisture conditions: Southeast Asia, Australia, and other key regions where the ENSO signal is particularly strong (Mishra et al., 2024).

Different ENSO flavours, notably eastern Pacific (EP) and central Pacific (CP) El Niño events, produce distinct teleconnection patterns. EP and CP El Niño events are associated with different atmospheric teleconnection responses: EP El Niño tends to be dominant in exciting a poleward wave train pattern to the Northern Hemisphere, while CP El Niño tends to preferably produce a wave train similar to the Pacific North American pattern (Yu et al., 2024). These different wave responses produce different climate impacts: during EP El Niño, North America experiences a north-warm/south-cold response, while during CP El Niño the distribution is northeast-warm/southwest-cold (Yu et al., 2024). In the context of humid heat, EP events have been shown to produce progressively enhanced humid heat extent primarily in Mainland Southeast Asia, while CP events generate regionally varying impacts that depend on the precise location of the equatorial warming (Li et al., 2025).

The relationship between ENSO and humid heat extremes shows interdecadal variations, with strengthening correlations in recent decades. A study of southeastern China revealed a weak relationship between early winter ENSO and summer extreme humid-heat days during 1961–1993, but a significant positive correlation during 1994–2020, with El Niño events causing increased extreme humid-heat days as the main reason for the enhanced relationship (Chen et al., 2025). This strengthening correlation suggests that either the ENSO teleconnection has intensified or that the background climate has become more sensitive to ENSO forcing or both. Humid heat is most interannually concentrated in the tropics, where up to 75% of 95th-percentile wet-bulb temperature days occur in the top 25% of years, underscoring the importance of understanding interannual variability drivers such as ENSO (Reed et al., 2025).

The regional heterogeneity of ENSO's humid heat influence has important implications for prediction and adaptation. A single global ENSO index is insufficient to capture the full range of humid heat responses across the tropics; regional forecasts must account for both the flavour of the ENSO event and the specific teleconnection pathways that operate in each region. This complexity, while challenging, also offers opportunities: the distinct signatures of different ENSO flavours may enable more skillful regional predictions than a bulk ENSO index alone would permit.

III. Research Methods

3.1 Predictability – Six-Month Forecasting of Humid Heat Stress

a. The Predictability Window

The foundation for six-month predictability of tropical humid heat stress lies in the robust statistical relationship between ENSO and wet-bulb temperature extremes. On interannual timescales, strong correlation with ENSO indicates that humid heat stress and associated productivity losses are predictable up to six months in advance (Saha et al., 2026). This predictability window arises from the characteristic lagged response of the tropical climate system to ENSO forcing. Tropical wet-bulb temperatures (TW) peak approximately five months after El Niño winters, reflecting the time required for anomalous Pacific SSTs to propagate their thermodynamic influence through atmospheric teleconnections to tropical land surfaces (Zhang et al., 2024). The peak of El Niño precedes the peak in the warmest sea surface temperatures, which in turn affects the maximum TW on land, creating a forecastable signal that can be harnessed for seasonal prediction (Zhang et al., 2024).

This lagged response structure is critical for operational forecasting. Because the ENSO signal is itself predictable with skill up to 6–12 months in advance, the lagged relationship between ENSO and humid heat provides a practical basis for anticipatory action (Zhang et al., 2024). The physical mechanism underlying this lag involves the coupling of extreme wet-bulb temperatures over tropical land to the warmest sea surface temperatures through atmospheric convection and wave dynamics (Zhang et al., 2024). As El Niño develops, anomalous convection over the warmest Pacific waters excites Rossby wave trains that propagate poleward and eastward, modifying temperature and moisture profiles over tropical landmasses with a delay of several months. This intrinsic lag transforms what might otherwise be a simultaneous response into a *predictable* response, offering a window for proactive adaptation planning that is largely absent for many other climate hazards.

b. Forecasting Methodologies

Zhang et al. (2024) developed a multiple linear regression model that explains 80% of variance in tropical mean annual maximum wet-bulb temperature (TWmax) and significant regional TWmax variances (Table 1). The model considers both cumulative warming trends and preceding ENSO indices as primary predictors, with each contributing similarly to the explained variability of TWmax (Zhang et al., 2024). This physics-based statistical approach harnesses the fundamental coupling between extreme wet-bulb temperatures over tropical land and the warmest sea surface temperatures, a coupling mediated by atmospheric convection and wave dynamics (Zhang et al., 2024).

Table 1: Overview of the Zhang et al. (2024) TWmax Forecasting Model

Model Feature	Specification
Target Variable	Tropical annual maximum of daily maximum wet-bulb temperature (TWmax)
Model Type	Multiple linear regression (physics-based statistical model)
Predictors	Cumulative warming trends + El Niño–Southern Oscillation (ENSO) indices
Explained Variance (Tropical Mean)	80%
Explained Variance (Regional)	Significant regional TWmax variances explained
Forecast Lead Time	~5 months
Physical Basis	Coupling of TW over land to warmest SSTs via atmospheric convection and wave dynamics

The methodological innovation lies in its simplicity and physical interpretability. Unlike purely empirical statistical models that may capture spurious correlations, the Zhang et al. (2024) framework is grounded in known physical mechanisms: the response of tropical lower tropospheric humidity to ENSO amplifies under warming conditions, and this amplification follows Clausius–Clapeyron scaling (Hu et al., 2021). The predictive model considers both cumulative warming trends and preceding ENSO indices, with each contributing similarly to the explained variability of TWmax (Zhang et al., 2024). Retrospective six-month lead hindcasts demonstrate operational feasibility, confirming that the model skillfully captures both the magnitude and timing of TWmax variations across the tropics (Zhang et al., 2024).
Regional TWmax can be predicted with significant skill in specific areas, though the forecast skill varies considerably across different tropical subregions (Zhang et al., 2024). The model's regional predictions are particularly valuable because the socioeconomic impacts of humid heat stress are inherently local: agricultural planning, public health preparedness, and labour scheduling all require region-specific information. The ability to forecast regional TWmax—rather than a single tropical mean, substantially enhances the practical utility of the forecasting system.

c. Case Study: The 2023–2024 El Niño

The predictive capability of ENSO-based humid heat forecasting was dramatically demonstrated by the strong-to-very-strong El Niño event that developed in 2023. With an Oceanic Niño Index of approximately 2.0 at the end of 2023, the Zhang et al. (2024) model suggested a 2024 tropical land mean TWmax of 26.2°C (25.9–26.4°C) , with a 68% chance (24%–94%) of breaking existing records (Zhang et al., 2024). This forecast, issued approximately five months in advance, provided a concrete, probabilistic warning that the tropics could experience unprecedented humid heat conditions in the following year.

This case study demonstrates the practical utility of ENSO-based humid heat forecasting in several ways. First, it shows that the forecasting system can produce *actionable* probabilistic statements with quantified uncertainty, a critical requirement for decision-making under risk. Second, it illustrates the integration of two primary forcing factors: the strong El Niño signal and the cumulative warming trend. The combination of a strong El Niño event with the current level of accumulated warming raised the probability of TWmax records in the following year to about 68% (Zhang et al., 2024). Third, it confirms that the forecast lead time (approximately five months) is sufficient for meaningful adaptation planning across multiple sectors.

Figure 1 shows the forecasted 2024 Tropical Land Mean TWmax under Strong El Niño Conditions

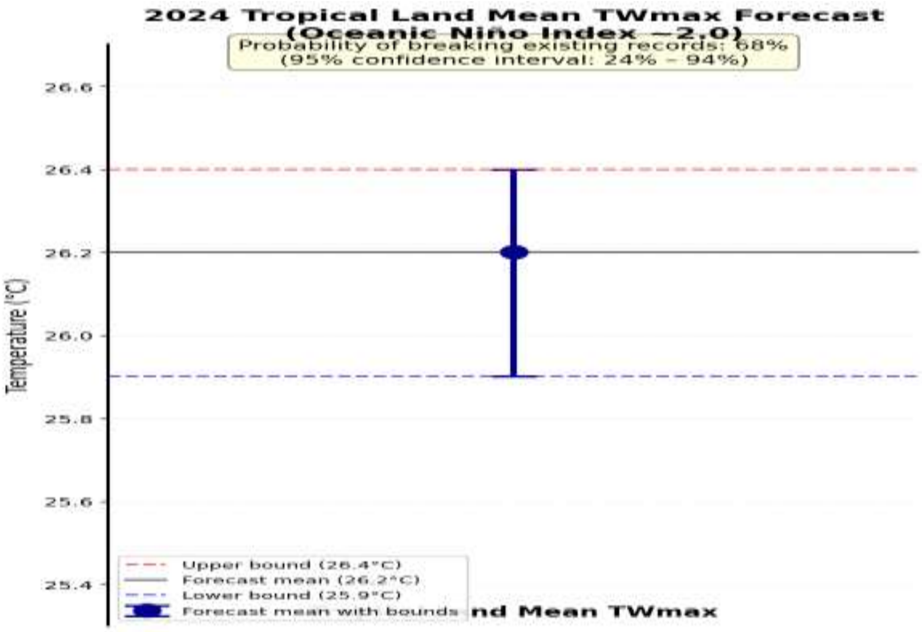

Figure 1. Projected 2024 tropical mean TWmax (26.2°C; 95% CI: 25.9–26.4°C) under strong El Niño, indicating 68% probability of exceeding historical records.

The 2023–2024 case also underscores the accelerating nature of humid heat risk. The forecasted TWmax of 26.2°C represents not merely an extreme year but a threshold that, under pre-industrial conditions, would have been virtually impossible to reach (Figure 1). That such a value can now be forecasted with 68% probability reflects the combined influence of anthropogenic warming and natural ENSO variability, a combination that is progressively pushing tropical humid heat into uncharted territory.

d. Limitations and Challenges

Despite the demonstrated skill of ENSO-based humid heat forecasting, several important limitations and challenges must be acknowledged. The spring predictability barrier, a well-documented phenomenon in which ENSO forecast skill declines markedly during the boreal spring (March–May), remains a critical constraint (Climate.gov, 2023). The spring predictability barrier has been theorized to result from air–sea interaction, upper-ocean advection, and thermocline-mixed layer processes that make the coupled ocean–atmosphere system particularly sensitive to initial condition errors during this season (Climate.gov, 2023; npj Climate and Atmospheric Science, 2025). The spring predictability barrier substantially limits our ability to predict ENSO events with confidence during this period, which in turn degrades the skill of derived humid heat forecasts (Climate.gov, 2023) (Table 2).

Forecast skill deteriorates rapidly beyond 6–9 months. While ENSO itself can be predicted with some skill up to 12 months in advance, the skill for humid heat forecasts declines more steeply because the lagged relationship between ENSO and TWmax amplifies any errors in the underlying ENSO prediction (Zhang et al., 2024). This limits the operational utility of very-long-lead forecasts and suggests that the optimal window for decision-making is approximately three to six months in advance, sufficient for many adaptation actions but not for long-term infrastructure planning.

Regional forecast skill varies considerably across different tropical regions. The Zhang et al. (2024) model explains significant regional TWmax variances, but the explained variance is not uniform: some regions exhibit much stronger ENSO teleconnections than others, and the forecast skill reflects this heterogeneity. Regions with weaker ENSO influences or regions where other modes of variability dominate will have lower forecast skill and greater uncertainty. This regional variability poses challenges for operational implementation, as a single forecasting system must accommodate diverse regional responses.

Interactions with other modes of variability may modulate predictability in ways that are not fully captured by simple ENSO-based models. The Indian Ocean Dipole (IOD) and Atlantic modes further modulate humid heat extremes, with the IOD exhibiting particularly important effects on East Africa and the western Indian Ocean rim (Birch et al., 2026; Bose et al., 2026). The combined effects of ENSO and IOD can amplify or dampen humid heat risk depending on their respective phases, and these interactions are not yet fully understood (Bose et al., 2026). Assessing whether ENSO–IOD combinations amplify or dampen humid heat risk remains an active area of research (Bose et al., 2026). Similarly, the Atlantic modes influence humidity transport across the equatorial Atlantic, adding another layer of complexity to the predictability problem.

Table 2: Key Limitations and Challenges in ENSO-Based Humid Heat Forecasting

Limitation	Description	Implication for Forecasting
Spring Predictability Barrier	Reduced ENSO forecast accuracy during boreal spring (March–May) due to air–sea interaction and thermocline processes	Degraded forecast skill for humid heat during the spring season
Lead Time Decay	Forecast skill deteriorates rapidly beyond 6–9 months	Limits operational utility for long-lead planning (>6 months)
Regional Heterogeneity	ENSO teleconnection strength varies considerably across tropical subregions	Uneven forecast skill; region-specific models required
Other Modes of Variability	IOD and Atlantic modes modulate humid heat extremes independently	ENSO-only models may miss important variability; interactions not fully understood

Climate Change Non-Stationarity	Warming trends alter the baseline relationship between ENSO and humid heat	Model coefficients may need updating as climate warms
Data Availability	Sparse observational networks in some tropical regions	Limits model calibration and validation in data-poor areas

Finally, the non-stationarity of the climate system under global warming poses a fundamental challenge. The relationship between ENSO and humid heat is not static: as the background climate warms, the response of tropical lower tropospheric humidity to ENSO amplifies (Hu et al., 2021). This means that model coefficients derived from historical data may not remain valid under future climate conditions, requiring ongoing recalibration and validation. The intensification of ENSO-induced atmospheric anomalies under greenhouse warming, including the amplification of ENSO-driven variability in tropical humidity, implies that the forecasting system must be adaptive and regularly updated to maintain skill (Hu et al., 2021).

IV. Result and Discussion

4.1 Cascading Impacts – From Heat Stress to Labour Productivity Loss

a. Physiological and Occupational Thresholds

Human labour capacity is fundamentally bounded by rigid biophysical heat thresholds rooted in the thermodynamics of human thermoregulation. The efficiency of heat dissipation from the human body depends critically on the Wet Bulb Globe Temperature (WBGT), an environmental index that aggregates dry-air temperature, humidity, wind speed, and solar radiation. When WBGT exceeds critical thresholds, the body's ability to maintain core temperature within the narrow band near 37°C becomes progressively compromised, necessitating reductions in work rate or the introduction of rest periods.

The exposure–response relationship between WBGT and labour productivity is well established in the occupational health literature. In regions where WBGT exceeds 25°C, productivity declines significantly. The threshold for heavy labour is not deterministic, ranging from 25°C to 26°C depending on workers' heat tolerance; workers with relatively low tolerance experience productivity losses beginning at 25°C, while those with high tolerance may maintain full capacity until 26°C. The International Organization for Standardization (ISO 7243) provides the standard framework for estimating heat load on working populations, with WBGT values above 24–26°C triggering progressive reductions in work rate. At light work intensity (200 Watts), the need for rest periods begins at a WBGT of 31°C, while at heavy work intensity (500 W), this threshold occurs at approximately 25.5°C.

Empirical studies have quantified the productivity decline with remarkable consistency. Sahu et al. (2013) estimated that approximately 5% of work output is lost for each °C of WBGT increase above 26°C. Field observations confirm that the hourly number of tasks completed is significantly reduced at WBGT > 26°C, with losses of approximately 5% per °C of increased WBGT. The European Commission's Joint Research Centre formalizes this relationship, noting that if WBGT is less than 25°C there is no loss in labour productivity, with decline calculable for all WBGT values greater than or equal to 25°C.

The prevalence of these impacts is substantial. Approximately 40% of workers report productivity loss on the hottest days. Importantly, these are not merely acute effects during extreme events; in the tropics, chronic humid heat operates as a persistent background condition that routinely pushes workers toward physiological limits. The sustained nature of this exposure means that productivity losses accumulate continuously, with cascading effects that propagate through production networks and amplify economy-wide disruptions.

b. Quantifying Productivity Losses

The magnitude of already-realized productivity losses is substantial and growing. Under 2018 baseline conditions, effective labour-capacity losses reached 9–11% across tropical economies, with sectoral losses approaching 17% in agriculture and construction. These losses reflect the combined influence of observed climate conditions and the structural characteristics of tropical economies, where large fractions of the workforce are employed in heat-exposed sectors.

The disproportionate burden on India—the country with the largest population of outdoor workers and one of the fastest-warming tropical landmasses is particularly striking. During 1980–2021, most rural-to-urban migration hotspots in north, east, and southern India witnessed a significant rise in wet-bulb temperature, indicating elevated indoor heat stress. Over that interval, outdoor heat stress considerably increased and led to a ~10% decline in labour capacity in these migration hotspots. All 50 urban migration hotspots examined witnessed a significant reduction in mean daily labour capacity in the March–October period during the current (1980–2021) climate compared to the baseline (1950–1976). Two urban areas experienced about 10% reduction in labour capacity during 1980–2021, while 25 urban areas witnessed 5% or more reduction. The frequency of days with mean daily labour capacity less than 50% during March–October increased significantly from 25 to 230 days between 1980 and 2021. Productivity losses of up to 35% have been noted in outdoor workers engaging in physically demanding tasks.

Figure 2 illustrates the trajectory of labour capacity decline in Indian migration hotspots from 1980 to 2021, showing the progressive erosion of work capacity across the major urban centres that attract rural-to-urban migrants.

Figure 2 illustrates the progressive erosion of labour capacity in Indian migration hotspots during March–October from 1980 to 2021. Compared to the 1950–1976 baseline (95%), current capacity has declined by a mean of 5% (range: 0–10%), falling to 85–95% across most urban areas. This loss reflects the combined influence of rising wet-bulb temperatures and ENSO-driven humid heat amplification. Critically, the frequency of days with labour capacity dropping below 50% has increased dramatically—from 25 days in 1980 to 230 days in 2021 (Mishra et al., 2025). This 820% increase underscores the chronic nature of humid heat stress in tropical economies, where persistent exposure—rather than episodic extremes—erodes productive capacity. The findings demonstrate that ENSO-driven humid heat events are already imposing measurable constraints on labour availability, with cascading implications for economic output and worker livelihoods across India's rapidly urbanizing regions.

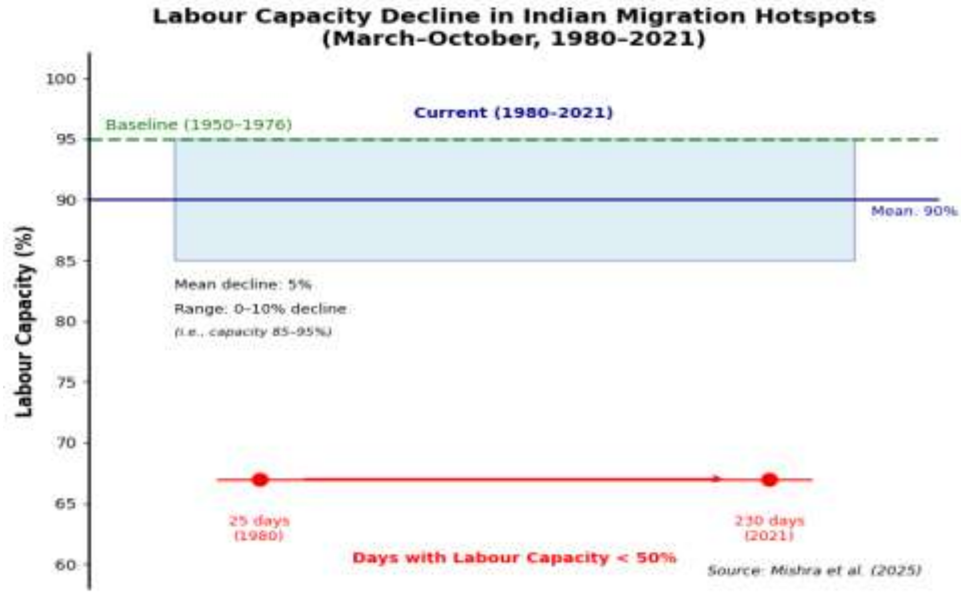

Figure 2: Labour capacity decline in Indian migration hotspots (1980–2021), showing 5% mean reduction and 25→230 days below 50% capacity.

2000 and 2016, the labour capacity of rural populations during summer months fell by 5.3% due to rising heat; in tropical regions, capacity fell by up to 30%. These losses reflect not only the direct physiological constraints imposed by rising temperatures but also the compounding effect of increasing humidity, which amplifies heat stress through reduced evaporative cooling efficiency.

Looking forward, the trajectory is deeply concerning. Global mean labour productivity in crop production is projected to decrease by 5% (lower bound) to 18% (higher bound) by the end of the century due to heat stress under RCP 6.0, with especially pronounced effects in Africa, South Asia, and Southeast Asia. The median labour capacity in Indian migration hotspots is projected to decrease to 71% and 62% under 3°C and 4°C global warming scenarios, compared to 86% during the baseline period. Nearly 90% of urban areas exceeded mean annual labour capacity of 80% during the baseline period; under global warming of 1.5°C, 2°C, 3°C, and 4°C, only 35, 25, 13, and 8 urban areas are projected to maintain a labour capacity of at least 80%.

c. Economic Consequences

The economic consequences of humid heat-induced productivity losses are substantial and propagate through multiple channels. Economy-wide gross output exposure in 2018 reached approximately USD 0.9 billion in Singapore, USD 2.6 billion in Cambodia, and USD 22.3 billion in Vietnam (2018 USD). These figures reflect the direct value-added losses in heat-exposed sectors, but they substantially underestimate the full economic footprint because they do not capture the propagation of labour constraints through production networks.

Indirect exposure transmitted through supply-chain linkages often exceeds direct sectoral losses, particularly in service-oriented economies. In Cambodia and Vietnam, for example, the indirect effects of labour-capacity constraints in agriculture and construction propagate through input–output linkages to affect manufacturing, logistics, and services sectors that are not directly heat-exposed. This amplification means that the full economic burden of humid heat stress is substantially larger than direct impacts alone would suggest.

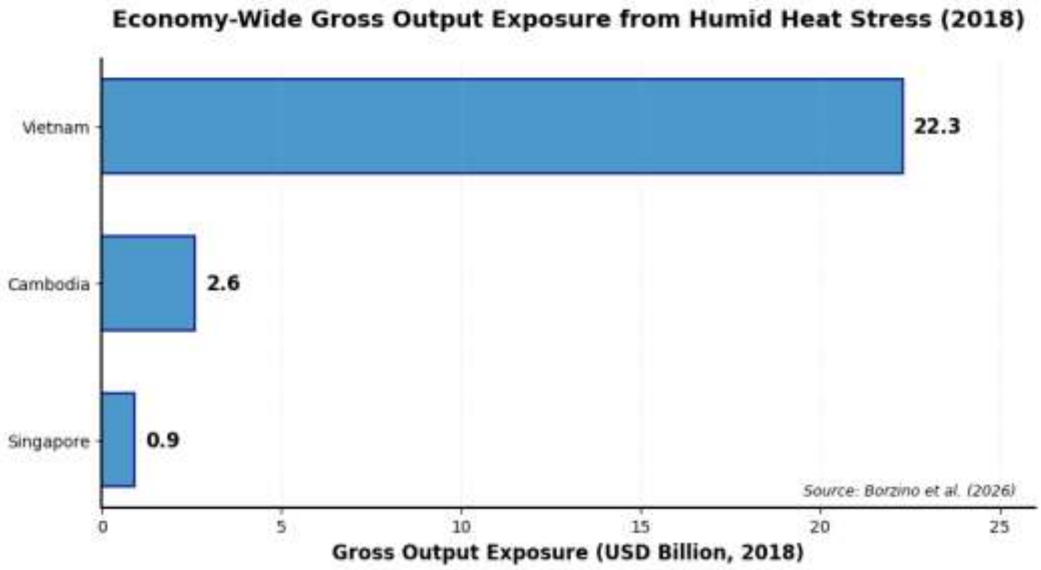

Figure 3: Economy-Wide Gross Output Exposure from Humid Heat Stress (2018)

Figure 3 presents economy-wide gross output exposure from humid heat stress across three Southeast Asian economies in 2018. Vietnam exhibits the highest exposure at USD 22.3 billion, substantially exceeding Cambodia (USD 2.6 billion) and Singapore (USD 0.9 billion). This disparity reflects Vietnam's larger agricultural and manufacturing workforce operating under chronic humid heat conditions (Borzino et al., 2026). Critically, these direct sectoral losses underestimate total economic impacts, as indirect exposure transmitted through supply-chain linkages often exceeds direct losses, particularly in service-oriented economies like Singapore (Borzino et al., 2026). The cascading propagation of labour constraints through input-output networks amplifies economy-wide vulnerability. These findings underscore that humid heat stress imposes a substantial and inequitable burden on tropical economies, with the largest exposures concentrated in countries where adaptation capacity may be most limited, highlighting the urgent need for targeted policy interventions.

At the firm level, the impacts are equally significant. One additional day above 32°C in any given year lowers annual payroll by 0.04% (Somanathan et al., 2021). In India, a one-degree increase in mean temperature reduced net earnings by 16%, while a one-degree increase in wet-bulb temperature cut earnings by 19%; workers averaging Rs. 268 per day lost over Rs. 40 per day per degree of wet-bulb temperature increase.

The macroeconomic scale of these losses is staggering. Between 2001 and 2020, India lost an estimated 259 billion labour hours annually due to heat stress, a productivity loss exceeding $600 billion each year. At the global scale, these losses are thought to total 490 billion potential labour hours in 2022. Global supply chains amplify these economic costs: the global annual incremental gross domestic product loss from extreme heat risk increases exponentially, with labour productivity losses (18–37%) and indirect losses through supply chains contributing substantially to total impacts.

d. Cascading Effects through Production Networks

Chronic humid heat operates as a routine operating constraint, creating production-network bottlenecks that propagate through increasingly interconnected global supply chains. Unlike episodic heatwaves that may be managed through short-term adaptations, chronic humid heat imposes a persistent drag on productive capacity that cannot be fully offset through temporary measures. This persistence fundamentally alters the economics of production in tropical regions, creating structural vulnerabilities that are baked into the operating models of firms and industries.

Recent research has demonstrated that regional production disruptions propagate through global supply chains, inducing spillover effects and macroeconomic losses. Since the beginning of the 21st century, the structural evolution of the global supply network has been such as to foster an increase of climate-related production losses. Economic connectivity has augmented in ways that facilitate the cascading of production loss from heat-stressed regions to downstream sectors and geographically distant economies. When firms in the economic system suffer a negative shock, such as a shortage of labour supply during extreme heat stress; their production is constrained, and these constraints propagate through supply chains as downstream firms face shortages of intermediate inputs.

The cascading effects are evident across multiple sectors. In garment manufacturing, a sector that combines large numbers of workers in close proximity, high volumes of heat-generating equipment, and often poorly ventilated buildings, rising temperatures and humidity are reducing productivity, affecting product quality, and threatening delivery schedules in some of the world's key garment-producing regions. Managers across factories in India have reported productivity reductions of approximately 3% to 10% and absenteeism increases of approximately 2% to 5% during peak summer months. Similar patterns are observed in Bangladesh, Vietnam, and Pakistan, where workers in the world's biggest garment manufacturing hubs are increasingly exposed to extreme heat.

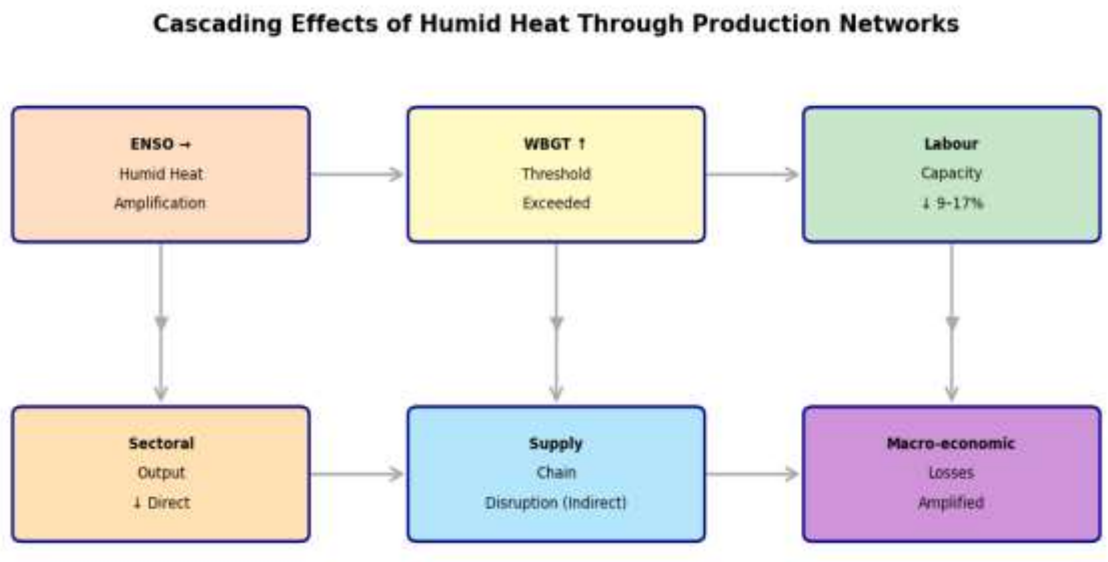

Figure 4: Cascading Effects of Humid Heat through Production Networks

Figure 4 illustrates the mechanistic cascade from ENSO-driven humid heat amplification through to macroeconomic losses. The flowchart depicts three sequential stages: first, ENSO forces humid heat amplification and WBGT threshold exceedance, reducing labour capacity by 9–17% (Borzino et al., 2026). Second, these labour constraints propagate through production networks, generating direct sectoral output losses and indirect supply chain disruptions (Borzino et al., 2026). Finally, cascading effects amplify into economy-wide macroeconomic losses, consistent with global supply chain modelling (Sun et al., 2024). Critically, indirect exposure often exceeds direct losses, particularly in service-oriented economies (Borzino et al., 2026). The figure emphasises that chronic humid heat operates as a routine operating constraint, where protecting work capacity at critical network nodes yields disproportionate economy-wide resilience. This cascading framework highlights the need for integrated adaptation strategies addressing both direct workplace interventions and supply chain resilience.

Critically, the cascading effects are not uniform across the production network. Protecting work capacity at critical nodes can yield disproportionate economy-wide resilience. Network bottlenecks, sectors or regions where labour constraints propagate most extensively through the production network, represent high-leverage adaptation points where targeted interventions can yield benefits far exceeding their direct costs. This insight has profound implications for adaptation prioritization: rather than attempting to protect all workers equally, strategic investments in heat-resilient infrastructure, work-rest schedules, and cooling technologies at network-critical nodes can substantially reduce economy-wide vulnerability.

The implications for global economic governance are equally significant. As Sun et al. (2024) demonstrate, global supply chains amplify economic costs of future extreme heat risk. The structural evolution of the global supply network has been such as to foster an increase of climate-related production losses, meaning that the economic consequences of humid heat stress are not confined to tropical regions but propagate globally through trade and investment linkages. Addressing this challenge requires not only local adaptation but also international cooperation to build resilience into the architecture of global production networks.

4.2 Adaptive Planning and Decision-Support Applications

a. The Six-Month Warning Window

The demonstrated six-month predictability of tropical humid heat stress and its associated productivity losses offers a practical and actionable window for adaptive planning and mitigation (Saha et al., 2026; Zhang et al., 2024). Unlike weather forecasts that provide only days of notice, this seasonal lead time enables a fundamental shift from reactive crisis management to proactive, anticipatory action across multiple sectors. On interannual timescales, strong correlation with ENSO indicates that such losses are predictable up to six months in advance, offering a window for adaptive planning (Saha et al., 2026; Goshu, 2026). The predictability window rooted in the lagged response of tropical wet-bulb temperatures to ENSO forcing, whereby tropical wet-bulb temperatures peak approximately five months after El Niño winters, provides sufficient time to mobilise resources, adjust operational schedules, and implement protective measures before the onset of extreme heat conditions (Zhang et al., 2024). Critically, this window aligns with key decision-making horizons in agriculture, public health, and infrastructure planning. Early warning enables societies to prepare for extreme heat rather than simply respond to it, reducing both the human and economic costs of humid heat stress (Zhang et al., 2024).

The value of this lead time is increasingly recognised by international organisations and national governments. Climate information only becomes valuable when it informs decisions, shapes public policy, and reaches end-users preparing for critical seasonal activities. The six-month forecast window transforms climate information from an academic exercise into an operational tool for decision-making.

b. Sectoral Applications

The six-month predictability window has diverse applications across economic sectors, each with specific decision-making horizons and adaptation pathways.

Agriculture represents perhaps the most immediate and consequential application. ENSO variability influences nearly two-thirds of global croplands and has historically driven drought, flood, heat stress, wildfire risk, and yield losses. With six-month lead times, farmers and agricultural planners can make informed decisions regarding crop selection, planting and harvesting schedules, and labour allocation. In some locations, crop yield shocks can be predicted more than six months ahead of time, in certain cases, before a crop is even planted (Anderson et al., 2024). The Famine Early Warning Systems Network (FEWS NET) has demonstrated the value of this approach, warning of potential ENSO impacts more than a year ahead of harvest and beginning to warn of likely impacts as early as nine months before harvest (Anderson et al., 2024). Seasonal labour demand, livestock health, and irrigation scheduling can all be optimised using ENSO-based forecasts.

Construction faces unique vulnerabilities to humid heat stress, as outdoor work cannot easily be relocated or rescheduled at short notice. With six-month forecasts, construction firms can plan work-rest cycles tailored to expected heat conditions. Research has demonstrated that adaptive work-rest schedules designed to accommodate physiological variations in workers' responses to heat, can ensure worker safety while enhancing operational efficiency. Allocating more rest time in hotter conditions can paradoxically increase productive time by preventing heat-related illness and exhaustion. Infrastructure project scheduling can also be adjusted to avoid peak heat periods, reducing delays and cost overruns.

Public Health systems can leverage six-month forecasts to strengthen heat-health warning systems (HHWS) and allocate resources proactively. Heat-health warning systems have been shown to be cost-effective adaptation options that can reduce heat-related mortality and morbidity, particularly among vulnerable groups such as the elderly (Rao-Skirbekk et al., 2025). With advanced warning, health authorities can: (i) issue public awareness campaigns before extreme heat arrives; (ii) preposition supplies and staff in high-risk areas; (iii) activate overflow helplines and outreach activities; and (iv) coordinates with emergency services for anticipated surges in heat-related illness. Among adaptation measures, early warning systems show the greatest return on investment, with benefit-to-cost ratios of approximately 50:1 (npj Urban Sustainability, 2025). Investments in early warning systems deliver substantial returns: urban heat wave warning systems in Indian cities show average returns of approximately $50 for every $1 invested (npj Urban Sustainability, 2025).

Energy systems face significant pressure during humid heat events due to surging cooling demand. Six-month forecasts enable energy planners to anticipate demand peaks, secure additional generation capacity, and manage grid stability. Reservoir release rules and hydropower dispatch can be optimised based on expected temperature and precipitation patterns. This is particularly critical in regions where cooling demand already strains electricity infrastructure during extreme heat events.

Supply Chain Management can benefit from identifying vulnerable nodes in production networks before heat stress events occur. With six-month warning, firms can: (i) diversify sourcing to reduce exposure to heat-constrained regions; (ii) build inventory buffers in anticipation of production disruptions; (iii) adjust logistics routes to avoid heat-impacted areas; and (iv) implement contingency plans for critical suppliers. Given that indirect exposure through supply-chain linkages often exceeds direct sectoral losses, this anticipatory approach can yield substantial resilience benefits (Borzino et al., 2026).

c. Policy and Institutional Frameworks

Realizing the benefits of six-month predictability requires robust policy and institutional frameworks that translate forecast signals into action. The first priority is the integration of ENSO-based humid heat forecasts into existing seasonal forecasting systems. Global climate forecasting centres have strengthened climate observation systems, seasonal forecasting capacities, climate services, and early warning mechanisms. However, humid heat-specific products—forecasts of wet-bulb temperature and WBGT, rather than dry-bulb temperature alone—remain underdeveloped. National meteorological services must be resourced to produce and disseminate these specialized forecasts. The development of a multiple linear regression model that explains 80% of variance in tropical mean TWmax and significant regional TWmax variances demonstrates the feasibility of operationalizing such forecasts (Zhang et al., 2024).

Development of sector-specific heat stress action plans with six-month lead times represents the second priority. These plans should specify: (i) trigger points for different levels of action; (ii) responsible agencies and their roles; (iii) pre-positioning of resources; (iv) communication protocols; and (v) monitoring and evaluation frameworks. The 2026 El Niño preparedness efforts in Africa provide a model: technical workshops consolidated sub-regional forecasts into a harmonized continental outlook, supporting timely decision-making for agriculture, energy, health, infrastructure, tourism, and water resources.

Mainstreaming predictability into climate adaptation prioritization is the third priority. Climate adaptation planning often focuses on long-term trends and gradual changes, neglecting interannual variability driven by ENSO. By incorporating seasonal predictability into national adaptation plans and sectoral strategies, governments can address both chronic and acute climate risks. This requires: (i) updating policy frameworks to reflect the six-month predictability window; (ii) aligning climate-funded projects with heat-ready multi-hazard early warning systems; and (iii) pooling regional investments to lower unit costs and expand coverage.

A fourth and critical priority is addressing the self-reinforcing feedback loop where climate impacts undermine development pathways (Saha et al., 2026). As humid heat stress erodes labour productivity, economic growth slows, reducing the fiscal capacity for adaptation investments. This creates a vicious cycle: heat reduces income, which limits adaptation, which increases vulnerability to future heat (Saha et al., 2026). Breaking this cycle requires: (i) dedicated financing mechanisms for heat adaptation; (ii) integration of heat resilience into development planning; and (iii) international support for vulnerable tropical economies.

d. Challenges to Implementation

Despite the clear potential of ENSO-based humid heat forecasting, significant challenges impede its operationalization.

Translating forecast signals into anticipatory action across food, land, and water systems remains the foremost challenge. Historical experience demonstrates that even when skilled forecasts are available, mobilising resources and acting ahead of impacts is difficult. The gap between forecast issuance and action reflects multiple barriers: (i) unclear lines of responsibility for acting on forecasts; (ii) insufficient funding for anticipatory action; (iii) lack of pre-agreed trigger mechanisms; and (iv) competing priorities that crowd out proactive measures.

Building institutional capacity in vulnerable tropical economies is essential but challenging. Many countries in the tropics have poorly developed systems for communicating forecasts to users, under-resourced local institutions, and limited forecasting infrastructure. Evaluations have repeatedly highlighted structural weaknesses in how early warning systems are designed and implemented. Low awareness of ENSO, a lack of institutional pathways for providing forecasts and understanding their implications and limitations, and a possible lack of political incentives have prevented potentially available forecasts from being used. Greater efforts must be made to assure closer articulation with end-users and to co-produce climate services that meet their needs.

Communicating probabilistic forecasts effectively to end-users presents a third challenge. Many users simply do not understand how to interpret probabilistic forecast information. There is often a sharp divide between forecasters and forecast users, with no users invited to consensus forecast groups. Efforts to communicate probability forecasts through workshops have produced inconsistent results and persistent confusion. Challenges such as difficulties in making climate data relevant, comprehensible, and accessible to different end-users, and cultural differences between climate and health professionals, need to be accounted for while implementing these services (Rao-Skirbekk et al., 2025). Effective communication requires: (i) translation of probabilistic information into actionable guidance; (ii) visualisation tools that convey uncertainty clearly; (iii) training for intermediaries who bridge forecasters and end-users; and (iv) direct feedback mechanisms from users to improve forecast products.

Overcoming the "adaptation deficit" in rapidly growing tropical populations is perhaps the most profound challenge. The adaptation deficit, the gap between current adaptation levels and what is needed to manage climate risks is largest in precisely the regions most exposed to humid heat stress (Saha et al., 2026). Rapid population growth in tropical cities and peri-urban areas means that the number of people exposed to humid heat is increasing faster than adaptation investments can keep pace. Addressing this deficit requires: (i) accelerated investment in heat-resilient infrastructure; (ii) expansion of social protection programmes that reach heat-exposed workers; (iii) integration of heat adaptation into urban planning; and (iv) international climate finance that prioritizes the most vulnerable regions.

Finally, the success of seasonal forecasts depends on consensus among participating institutions. Fragmented climate governance, limited data sharing and collaboration, and inadequate coordination between meteorological services and sectoral agencies undermine forecast effectiveness. Building the institutional architecture for sustained, coordinated action, including clear mandates, dedicated funding, and accountability mechanisms is essential for translating forecast skill into realized benefits.

V. Conclusions

Synthesis of Key Findings

This study has demonstrated that ENSO teleconnections exert a dominant and predictable influence on tropical humid heat stress, with profound implications for labour productivity and economic functioning across the tropics. The physical mechanisms underpinning this relationship involve the coupling of extreme wet-bulb temperatures over tropical land to the warmest sea surface temperatures through atmospheric convection and wave dynamics. ENSO acts through combined effects on both temperature and humidity, with humidity-driven amplification representing a critical pathway through which El Niño events intensify heat stress beyond what temperature alone would predict.

A central contribution of this work is the demonstration that six-month lead predictability of humid heat stress is achievable through physics-based statistical models that explain 80% of variance in tropical mean annual maximum wet-bulb temperature. This predictability window is not merely an academic curiosity but a practical tool that can inform adaptation planning across agriculture, construction, public health, energy, and supply chain management. The case study of the 2023–2024 El Niño validated this approach, showing that a strong El Niño event with an Oceanic Niño Index of approximately 2.0 implied a 68% chance of breaking existing TWmax records in 2024.

The cascading productivity and economic consequences of humid heat stress are substantial. In 2018 baseline conditions, effective labour-capacity losses reached 9–11% across tropical economies, with sectoral losses approaching 17% in agriculture and construction. In India alone, outdoor heat stress has led to a ~10% decline in labour capacity in migration hotspots, with the frequency of days with labour capacity below 50% increasing from 25 to 230 days between 1980 and 2021. Economy-wide gross output exposure reached USD 22.3 billion in Vietnam, USD 2.6 billion in Cambodia, and USD 0.9 billion in Singapore in 2018. Critically, indirect exposure transmitted through supply-chain linkages often exceeds direct sectoral losses, meaning that the full economic footprint is substantially larger than direct impacts alone would suggest. The predictability window enables proactive adaptation and resilience-building, offering a tangible opportunity to reduce climate vulnerability in the tropics.

Broader Implications

These findings carry profound implications for our understanding of climate change impacts and adaptation priorities. Accounting for humid heat stress significantly raises the estimated socioeconomic costs of climate change. Traditional impact assessments that rely on dry-bulb temperature or aggregate damage functions systematically underestimate the true burden of warming on tropical economies. When humidity is explicitly considered, the productivity losses are substantially larger, and the economic consequences propagate through global supply chains to affect distant economies.

Climate change impacts may be much more costly than previously estimated when extreme humid heat is considered. The combination of rising baseline temperatures, increasing absolute humidity, and ENSO-driven interannual variability creates conditions under which tropical populations are pushed closer to physiological thresholds more frequently and with greater intensity. The finding that global agricultural labour productivity could decrease by 18% by the end of the century under RCP 6.0, with pronounced effects in Africa, South Asia, and Southeast Asia, underscores the urgency of this challenge.

The findings highlight a feedback loop where climate disruptions hinder development processes. As humid heat stress erodes labour productivity, economic growth slows, reducing the fiscal capacity for adaptation investments. This creates a self-reinforcing cycle: heat reduces income, which limits adaptation, which increases vulnerability to future heat. Breaking this cycle requires dedicated financing mechanisms, integration of heat resilience into development planning, and international support for vulnerable tropical economies.

Research Gaps and Future Priorities

Despite the progress demonstrated in this study, substantial research gaps remain. Improving regional-scale forecast skill for humid heat extremes is a critical priority. While the Zhang et al. (2024) model explains significant variance in tropical mean TWmax, regional forecast skill varies considerably, and many regions remain underserved by current forecasting capabilities.

Understanding interactions between ENSO and other modes of variability, particularly the Indian Ocean Dipole (IOD) and Atlantic modes, requires further investigation. These modes can amplify or dampen ENSO-driven humid heat extremes, and their interactions are not yet fully understood. Assessing whether ENSO-IOD combinations amplify or dampen humid heat risk remains an active area of research.

the full economic ripple effects through global production networks represents a third priority. While this study has demonstrated the importance of supply-chain propagation, comprehensive assessments that trace the full cascade from ENSO forcing through labour constraints to global economic impacts are needed. This requires integration of climate, labour, and economic models in a unified framework.

Developing integrated assessment models that incorporate ENSO-driven humid heat predictability is essential for informing adaptation investment decisions. Current integrated assessment models (IAMs) typically do not account for interannual variability or the specific physiological constraints imposed by humid heat. Incorporating these factors would substantially improve the robustness of climate-economic projections.

Finally, assessing adaptation effectiveness and cost-benefit ratios of early warning systems is critical for guiding investment decisions. While early warning systems have been shown to be cost-effective, with benefit-to-cost ratios of approximately 50:1 in some contexts, systematic evaluations across different tropical regions and sectors are needed to identify where investments yield the greatest returns.

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