Vietnam's global warming challenge: navigating in the context of intensified extreme rainfall and worsening droughts

INTRODUCTION

Vietnam, a dynamic developing nation and a major agricultural exporter, faces growing exposure to the dual threats of droughts and extreme rainfall under global warming. Designing efficient adaptation strategies in the face of these hazards requires detailed assessments of future changes in both types of extremes across the country.

In order to inform evidence-based planning and decision-making, we provide spatially refined projections from state-of-the-art global climate models for different indicators of extreme rainfall and drought events. Despite significant uncertainties, the results suggest a general trend towards the intensification of extreme rainfall events but milder droughts at higher global warming levels. However, the general trends hide large differences among the climate models and the projections from a subset of models actually show worsening drought severity under worst-case climate scenarios.

Such evolutions will pose significant challenges across key sectors, including agriculture, water resources, and climate resilience planning. Our findings underscore the urgent need for coordinated and region-specific adaptation actions to address these growing risks.

CONTEXT & MOTIVATION

Vietnam is one of the countries most exposed to climate hazards. Over the past decades, **rising temperatures** and **shifting precipitation patterns** have disrupted agricultural productivity, water resources, and livelihoods across the country. **Droughts** are ranked as the third most costly natural hazard in Vietnam. Historical events, like the 1997–1998 and 2015–2016 droughts, inflicted massive economic losses and affected millions, with the latter causing crop failures, large saltwater intrusions in the Mekong Delta, and FAO-declared emergencies. **Heavy rains** in northern and central regions have intensified flooding, landslides, and infrastructure damage.

Despite international pledges to limit global warming, global greenhouse gas emissions are still on the rise. The 1.5°C warming threshold of the Paris Agreement is expected to be crossed in the coming years, and if current policies continue, the planet could warm by ~3°C by the end of the century. Higher global warming levels (GWLs) will increase the frequency and/or intensity of weather and climate extreme events in many world's regions. In this context, it is crucial to assess how water-related extreme events could evolve in Vietnam under different future climate scenarios.

To date, Vietnam's national climate scenarios reports, such as the Ministry of Natural Resources and Environment (MONRE)'s 2021 report, offer broad insights into future climate evolution in Vietnam, but remain constrained by the limited use of high-resolution regional climate models, hindering regional planning and comprehensive uncertainty assessment. The recent development of the CMIP6-VN dataset - a high-resolution and multi-model climate database created specifically for Vietnam - allows addressing these gaps by enabling consistent and spatially detailed evaluations of climate extreme patterns across the country.

We employed this dataset to analyze projected changes in both rainfall extremes and drought characteristics, marking the first application of a high-resolution dataset based on the latest state-of-the-art climate models for this purpose in Vietnam. By providing fine-scale insights, it helps bridge the gap between global models and local

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Geography Vietnam

needs, illustrating how regional geography — such as elevation in the Central Highlands or coastal proximity — influences exposure to extreme events.

The climate dataset

The CMIP6-VN dataset was developed using a statistical method[1] to downscale the outputs of CMIP6[2] global climate models to a spatial resolution of 10 km over Vietnam. This approach also corrects biases in CMIP6 models by aligning them with gridded observationally- based historical data, ensuring better representations of Vietnam's complex topography and climate variability. The dataset covers the historical period 1980-2014 and projections for 2015-2099 under various Shared Socio-economic Pathways (SSPs).

Study 1: extreme rainfall events

In a 1st study [1], we used the projections from 33 CMIP6 models under seven SSP scenarios.

We considered the following extreme rainfall indices:

- the annual **maximum 1-day and 5-day rainfall** (Rx1day, Rx5day);
- the annual **number of heavy rainfall days** exceeding 50 mm (R50mm) and 100 mm (R100mm);
- the annual **rainfall intensity** (RI), defined as the ratio of the total amount of rain falling during wet days to the duration of those wet days;
- the annual **number of consecutive wet days** (CWD);
- the annual **number of consecutive dry days** (CDD).

Our analysis focused on four GWLs: 1.5ºC, 2ºC, 3ºC, and 4ºC above pre-industrial levels. These GWLs were defined using a 20-year moving window centered on the year each level was exceeded. The timing when a GWL might be crossed depends on the climate model and on the global greenhouse gas (GHG) emission

scenario. High GWLs are representative of high-emissions futures.

The different indices are calculated for each GWL as averages across all climate models and SSP scenarios that reach this GWL, and compared to the 1995-2014 baseline.

Projection uncertainty was evaluated using the signal-to-noise ratio (SNR)[3]. SNR>1 indicates higher model agreement and greater confidence in the projections, whereas SNR<1 corresponds to low model agreement and high uncertainty.

Study 2: a focus on drought events

In a 2nd study [2] we selected a subset of 22 models under 3 SSP scenarios - SSP1-2.6 for low GHG emissions, SSP2-4.5 for medium, and SSP5-8.5 for high emissions. Drought occurrence was characterized using the **SPEI-12** index (see Box 1), which integrates the effects of both precipitation and temperature. We calculated the key characteristics of drought events through the following indices:

- **frequency**: total number of events during the study period;
- **duration**: number of months per event;
- **severity**: the sum of the monthly SPEI-12 absolute values over the duration of the event;
- **intensity**: calculated as severity divided by duration;

- **inter-arrival time**: number of months between 2 events.

Projected changes - compared to the reference period 1985-2014 - were calculated for the whole country and for its seven climatic subregions for the near future (2025-2054) and far future (2070-2099) under the 3 SSPs, as well as for GWLs from 1.5ºC to 4ºC (similar to study 1).

In addition, for an accurate assessment of drought risks, we studied[4] the joint probability distributions of drought duration and severity, enabling the estimation of return periods for extreme events. This probabilistic approach accounts for dependencies between drought metrics, providing insights into rare but high-impact events.

We also conducted sensitivity analyses to assess the relative impact of precipitation and temperature changes on future drought risk.

RESULTS

Intensification of extreme rainfalls.

The findings of study 1 [1] reveal a marked intensification of rainfall extremes across Vietnam under all considered GWLs, from 1.5ºC to 4ºC above pre-industrial conditions. Analysis of precipitation-related extreme indices demonstrates a systematic increase in both the

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Box 1. Characterization of drought events: the SPEI-12 index

Drought is a natural hazard caused by a prolonged deficiency in precipitation relative to normal expectations. However, high temperatures can significantly intensify drought severity, duration, and spatial extent, through increased evaporation rates. Thus, drought characterization based on precipitation-only metrics may underestimate future risks by not accounting for the crucial role of temperature, especially in the context of increasing hot extremes driven by climate change. Therefore, in our study [3] we chose the **Standardized Precipitation Evapotranspiration Index** (SPEI), which includes the effect of both precipitation and air temperature. Specifically, we used the SPEI-12 index, which is calculated on a monthly basis and standardized to allow comparative analysis across various regions and timescales. Basically, for a given month, the index value integrates the evolution of the water balance over the previous 12 months.

When the monthly SPEI-12 value is positive or between 0 and -0.5, there is no drought situation. Whereas when the value falls below -0.5, a drought event is identified. The lower the value, the more severe the drought event.

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magnitude and frequency of extreme rainfall events. Among these, as an illustration, the annual maximum daily precipitation (Fig. 1) exhibits a clear positive relation with higher GWLs, with country-wide averages increasing by about 6.7% relative to 1995–2014 at 1.5°C GWL, 8.9% at 2°C, 12% at 3°C, and reaching 13.8% at 4°C.

Spatially, the central regions — particularly North Central (e.g., provinces like Quang Tri) and South Central (e.g., Khanh Hoa) — record the highest Rx1day values, ranging from ~192 mm at 1.5°C GWL to 205 mm at 4°C GWL. In contrast, the northern regions — including the Northeast (e.g., Quang Ninh), Northwest (e.g., Dien Bien), Red River Delta (e.g., Hanoi), and North Central — show the most pronounced percentage increases, up to 15–20% in some areas at higher GWLs. However, due to substantial differences in precipitation projections across models, the signal-to-noise ratio remains low in all regions, highlighting the high level of uncertainty.

Maximum 5-day precipitation and rainfall intensity follow a similar trend, but changes also have a low statistical significance. By contrast, projected changes in the annual number of heavy (R50mm) or very heavy (R100mm) precipitation days, as well as changes in the maximum number of consecutive wet days, are minimal and not statistically significant either.

Milder drought events?

In all regions, changes in the number of consecutive dry days [1] are limited to a few additional days, though statistically significant and indicating a trend for slightly longer dry periods, which would contribute to water stress during dry seasons.

The more in-depth drought analysis, based on SPEI-12 [2], indicates that precipitation remains the main driver of future drought conditions in Vietnam, although the impact of rising temperatures should not be neglected. Hence, precipitation accounts for about 91% and 88% of SPEI-12 changes in the near and far future, respectively, under SSP2–4.5, and still for ~74% in the far future under the warmer SSP5–8.5 scenario.

Figure 1. Annual maximum daily precipitation for the baseline period (right) and projected changes at different GWLs compared to the baseline (left).
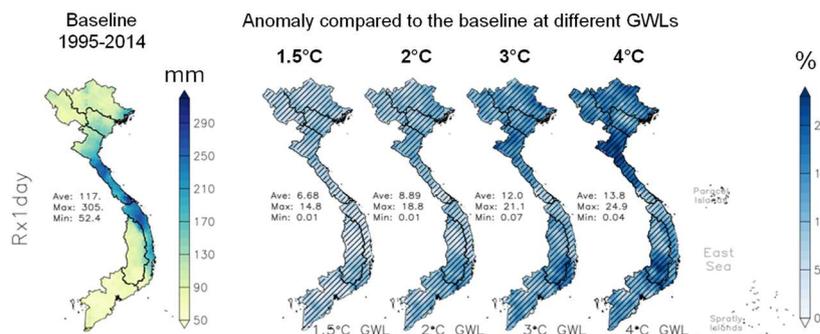
Displayed values correspond to the multi-scenario, multi-model ensemble means. Hatched areas highlight regions where SNR<1, i.e. with low model agreement and high uncertainty in the projections. Source: Modified from [1]

Figure 2. Changes in drought characteristics at 2°C (top) and 3°C (bottom) GWL compared to the baseline period (1985–2014).
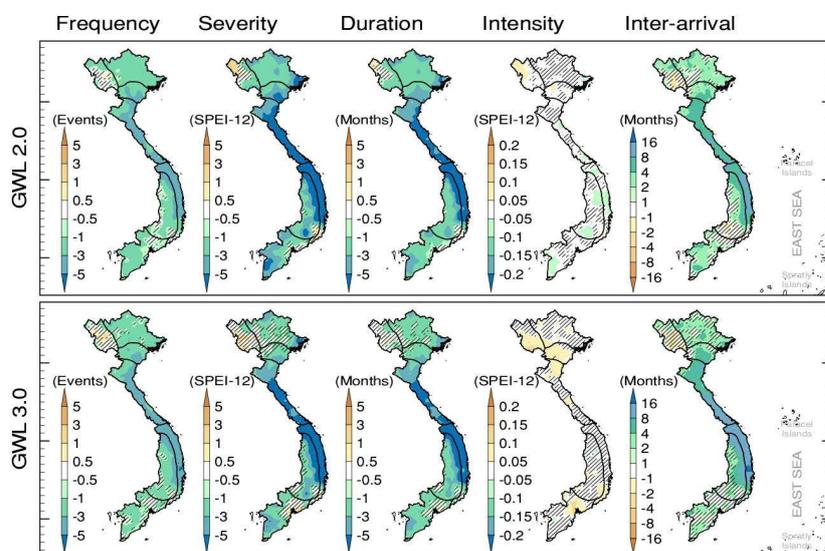
Frequency is the total number of droughts over the 21-year period while other variables are climatological means. Hatched areas indicate regions where changes are statistically insignificant (the p-value reported from a t-test is greater than 0.05). Source: Modified from [2]

Consequently, ensemble projections suggest that drought characteristics — except for intensity — are projected to become milder in the future, with the central coastal area exhibiting the most pronounced and statistically significant changes (Fig. 2). The milder tendency is driven by projected increases in rainfall that offset enhanced temperature-driven evapotranspiration.

But a subset of models projects worsening droughts.

However, not all climate models in the database project wetter conditions. To prepare for the most severe climate change scenarios in terms of droughts in Vietnam, we analyzed the projections of six climate models exhibiting the most pronounced drying trends. With this subset of models, droughts actually

appear to occur more frequently, exhibiting higher severity and longer duration, particularly in Northern, Southern and the Central Highlands of Vietnam. The intensity and inter-arrival time also exhibit a tendency toward worsening.

These worst-case projections further shows that rare and severe drought events tend to be even more prolonged and severe under warmer future scenarios. The largest changes are projected for the most severe events, with a 50-year return period — i.e., events with an annual probability of occurrence of 1/50 — especially in the Northwest, the Red River Delta, and the Central Highlands. Such extremes, rare but high-impact events, indicate a potential rise in

systemic risk for water-dependent sectors.

IMPLICATIONS

Our findings indicate growing challenges in water availability and water management as global warming intensifies. In some areas, particularly along the central coast and northern uplands, increased rainfall intensity concentrated over short durations may exceed the capacity of existing drainage infrastructure, thereby exacerbating flood risks and leading to economic losses estimated in billions of VND annually. In contrast, other regions — especially the Southern region and the Central Highlands — could face longer dry periods in worst-case scenarios, leading to insufficient water for irrigation, reduced crop yields, and growing pressure on groundwater resources, which are already overexploited in many areas.

However, the wide spread of precipitation projections across climate models means that the magnitude of future changes remains highly uncertain. Such uncertainty is a challenging issue to tailor efficient adaptation plans to future extreme precipitation and drought changes. Our results highlight that it is not possible to use the output of a single climate model or even a small subset of models as inputs for long-term adaptation strategies. Assessing uncertainties and low-probability events requires the use of a large climate model ensemble or a subset representative of the full range of projections.

Nevertheless, the ensemble-mean projections consistently indicate the direction of change toward increasingly intense rainfall extremes, while worsening drought conditions are possible under some worst-case scenarios. This suggests that while specific outcomes may vary, the overall risk trajectory is clear and demands proactive measures. Changes are expected to occur even under relatively moderate warming scenarios, with early signs already observable at the 1.5°C GWL, signaling that adaptation should begin immediately to avoid locked-in vulnerabilities.

RECOMMENDATIONS

To cope with intensified extreme rainfall and potentially worsening drought risks in Vietnam's warmer future, immediate and coordinated actions are required. These actions should be **adaptive and flexible**, recognizing the uncertainties in climate projections and regional variations. "**No-regret strategies**" will also be valuable, i.e. strategies yielding benefits even if real future climate changes differ from current projections. The following key measures are recommended (but not limited to):

- Strengthen climate-resilient water management.
  - Enhance integrated water resources management;
  - Upgrade water storage and distribution systems;
  - Promote water-saving practices; protect and recharge groundwater;
  - Adopt climate-smart agriculture: use drought- and flood-tolerant crop varieties, adjust planting calendars, and diversify income sources.
- Enhance hydro-meteorological **early warning systems** and expand community-based disaster **preparedness**.
- **Strengthen data accessibility.** Expand access to hydro-meteorological data portals, promoting the sharing of observation data and high-resolution model outputs to advance climate science in Vietnam and support the continued development of additional climate datasets for multi-sectoral applications.
- Strengthen governance and capacity
  - Mainstream adaptation into policies and budgets: ensure consistency between the National Adaptation Plan (NAP), Nationally Determined Contributions (NDC), and provincial development plans to create a coherent, climate-resilient policy framework.
  - Strengthen institutional and technical capacities through localized planning, enhanced cross-sectoral coordination, and targeted training programs.
  - Foster multi-stakeholder partnerships involving government, private sector, academia, and communities to co-design and implement adaptation strategies.

REFERENCES

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