# Heat Waves in India: Patterns, Associations, and Subseasonal Prediction Skill

## Theme-1: Observational evidence of Heatwave trends

**Author(s):** Raju Mandal[1], Susmitha Joseph[1], Shubham Waje[1], Anurag Chaudhary[1], A. Dey[1], Mahesh Kalshetti[1] and A. K. Sahai[1]

[1] Indian Institute of Tropical Meteorology (IITM), Pune-411008, India

**Raju Mandal, Ph.D.**

**Scientist-D, IITM Pune**

**Email**: raju.cat@tropmet.res.in

# Background

- Heatwaves are typically linked to anticyclonic circulations in the middle and upper troposphere, which extend into the lower troposphere and dynamically cause strong subsidence, clear skies, warm air advection, and developed hot conditions at the surface (*Black et al. 2004; Meehl and Tebaldi 2004; Perkins 2015*).
- There are other factors that modulate the HWs. For example, extreme minimum temperature and high humidity.
- The development of a persistent high-pressure system (blocking high) in the upper level of the atmosphere, responsible for long-lasting elevated temperature conditions (*Dole et al. 2011; Hudson et al. 2011; Matsueda 2011*).
- It is well known that HWs over India are connected to climate modes like the El Niño-Southern Oscillation (ENSO) (*De and Mukhopadhyay 1998, Pai et al. 2013, Rohini et al. 2016, Ratnam et al. 2016* ).
- Researchers have demonstrated that the frequency of severe HWs will increase by 30 times under the increase in global mean temperature by the end of the 21st century (*Mishra et al. 2017*).
- The present study analyses the patterns of the HWs over Indian HW-prone regions and examines the association between large-scale parameters and HWs.
- Furthermore, ERPSv2 is introduced in this study, and its subseasonal prediction skill is assessed.

# Data

- High-resolution daily gridded (0.5°×0.5°) IMD observed maximum temperature (Tmax) dataset (1951-2023) has been used (*Srivastava et al. 2009*).

- The daily gridded (2.5°×2.5°) NCEP Reanalysis dataset (*Kalnay et al. 1996*) has been used for the composite analysis. The NOAA High-Resolution Sea Surface Temperature (SST) dataset (*Reynolds et al. 2007; Huang et al. 2021*) is used for the composite analysis of SST.

- The model hindcast/forecast data (0.5°×0.5°) are derived from a Multi-Physics-Multi-Ensemble (MPME) prediction system (*Sahai et al. 2021; Kaur et al. 2022*) that has been built in-house at IITM, Pune.

- Model simulations are performed for six physics and with three ensembles (control + 2 perturbations) for each. Thus, a total of 18 members are made. The hindcast runs are made from 2003 to 2018 on the fly and the forecast is available for 2023.

# Methodology

## HW criteria (*Mandal et al. 2019*)

A HW day is considered if:

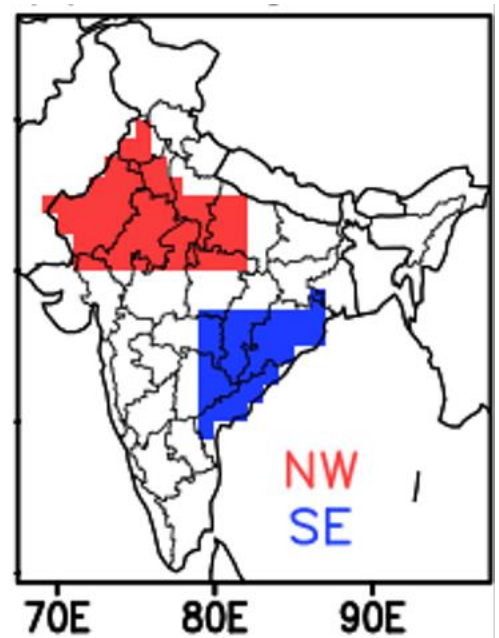
i. Its Tmax is > 36°C and ≥ the climatological 95th percentile value (derived from daily temperatures during MAMJ) and also its deviation from the mean is > 3.5°C on that day.

ii. Or, its Tmax is > 44°C.

## Identification of HW spells (*Mandal et al. 2019*)

i. Based on the area-averaged daily Tmax values exceeding a threshold of 43°C and 40°C for a minimum of 6 consecutive days for NW and SE, respectively.

ii. To gain deeper insights, these spells with at least one overlapping day are segregated as NWSE spells.



# Methodology

**The bias correction method:**

$$F_{bc}(t) = F_{raw}(t) - F_{clim}(t) + O_{clim}(t)$$

Climatologies have been calculated over the hindcast period from 2003 to 2018.

## Contingency tables

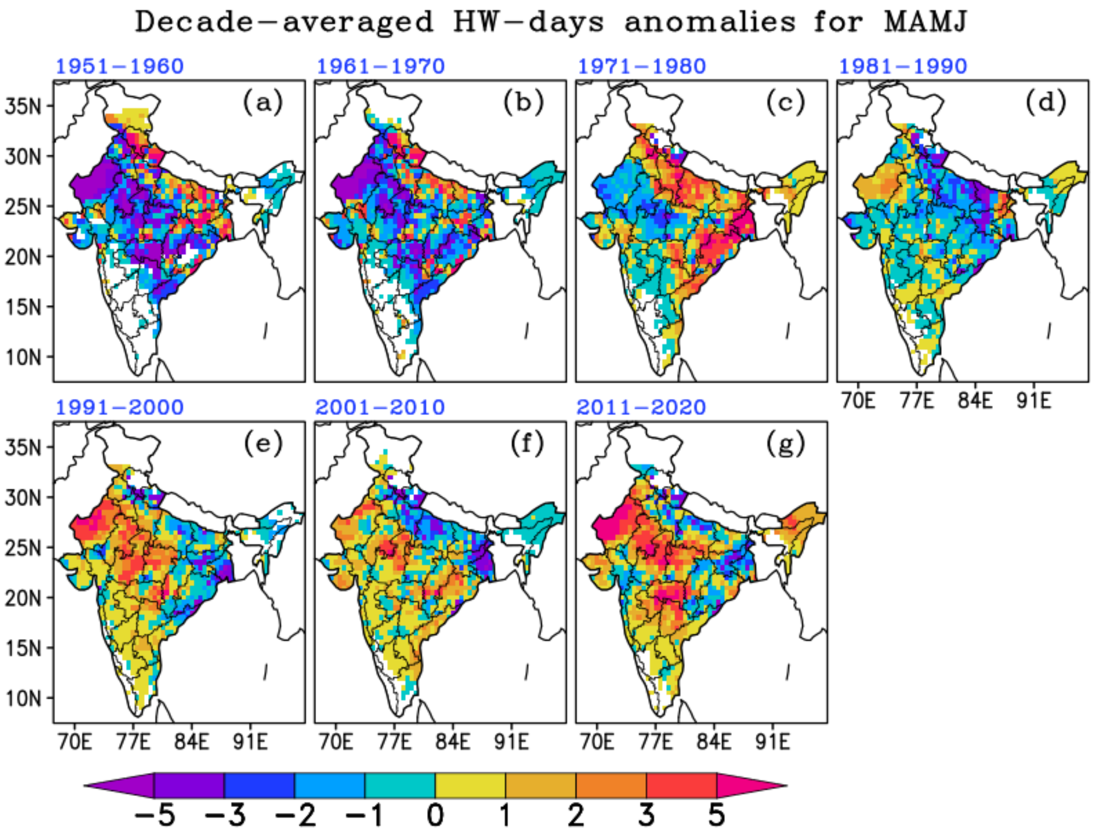
| Event forecast | Event observed | | |
|---|---|---|---|
| | **Yes** | **No** | **Marginal total** |
| **Yes** | Hit (a) | False alarm (b) | Fc Yes (a+b) |
| **No** | Miss (c) | Correct non-event (d) | Fc No (c+d) |
| **Marginal total** | Obs Yes (a+c) | Obs No (b+d) | Total a+b+c+d=n |

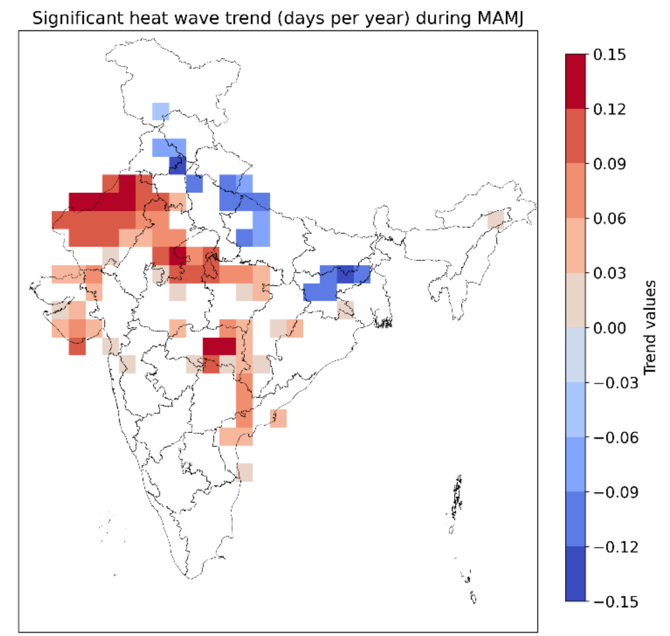
## Symmetric Extremal Dependence Index (SEDI)

$$SEDI = \frac{\log F - \log H - \log(1-F) + \log(1-H)}{\log F + \log H + \log(1-F) + \log(1-H)}$$

Hit rate $H = a/(a+c)$, false alarm rate $F = b/(b+d)$. The total number of hits (a), false-alarms (b), misses (c) and correct rejections (d) are calculated during MAMJ over the period 2003-18 as: (i) for observation: whether the proposed criteria for HW is satisfied or not for a particular day and (ii) for model: whether the proposed criterion is satisfied or not for that particular day but with a fixed probability (in percentage) of ensemble forecast. **(Haiden, T. et al. 2014, *ECMWF Newsletter No. 139*)**

# Decadal variation and spatial trend in HWs

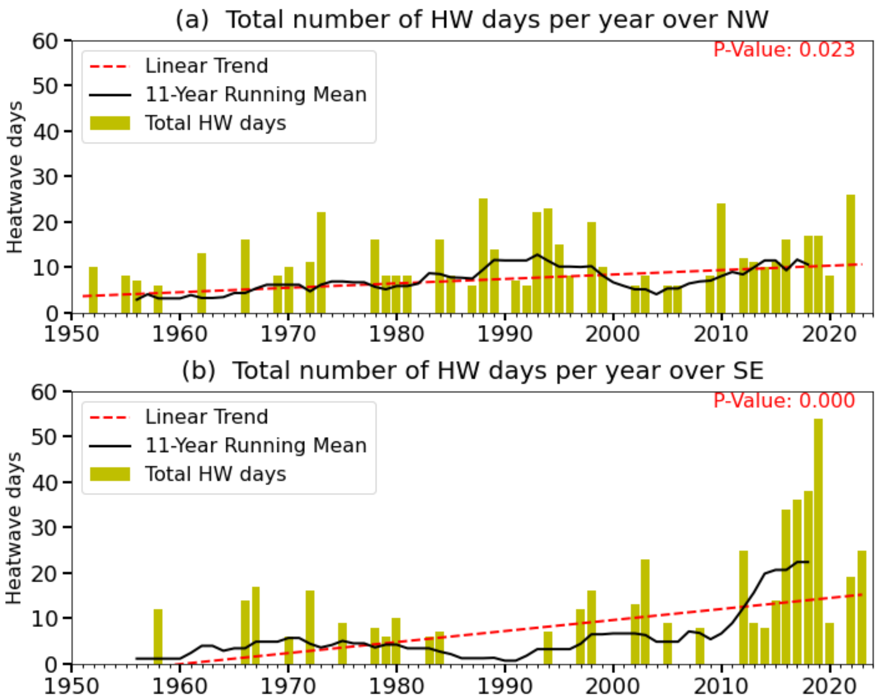



Statistically significant trends, determined at a 95% confidence level using the widely used Mann-Kendall test (Mann 1945; Kendall 1975)

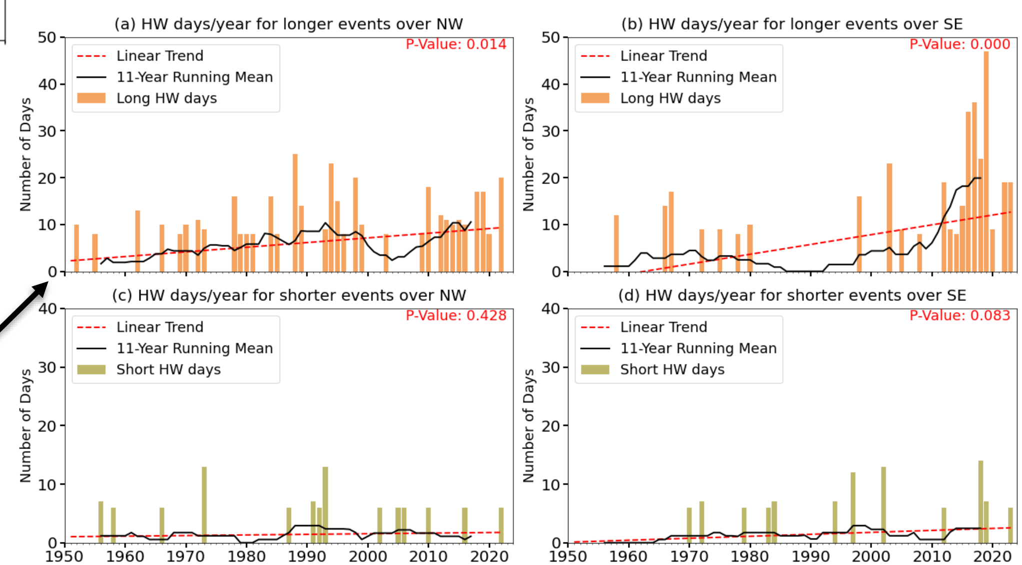
- A significant change has been observed, particularly in the recent three decades.
- This is more significant in the most recent decade. This indicates a substantial increase in the occurrence of HW days, predominantly concentrated over the NWI, CI, and SE regions.
- It is observed that the unusual HW events happen outside of the peak summer months. For example, March has exhibited a noticeable rise in HW days across several southern locations in recent times.
- A remarkable increase in total HW days/year is noticed over northwest India, central India, and southeast India.

# Results




- The total number of HW days (per year) has been observed more during the recent decades.
- Increasing trends in the total number of HW days/year are significant over both regions.
- A rising trend in the 11-year running mean may suggest a long-term change or shift in the total HW days/year over SE and could be indicative of the impact of climate change.

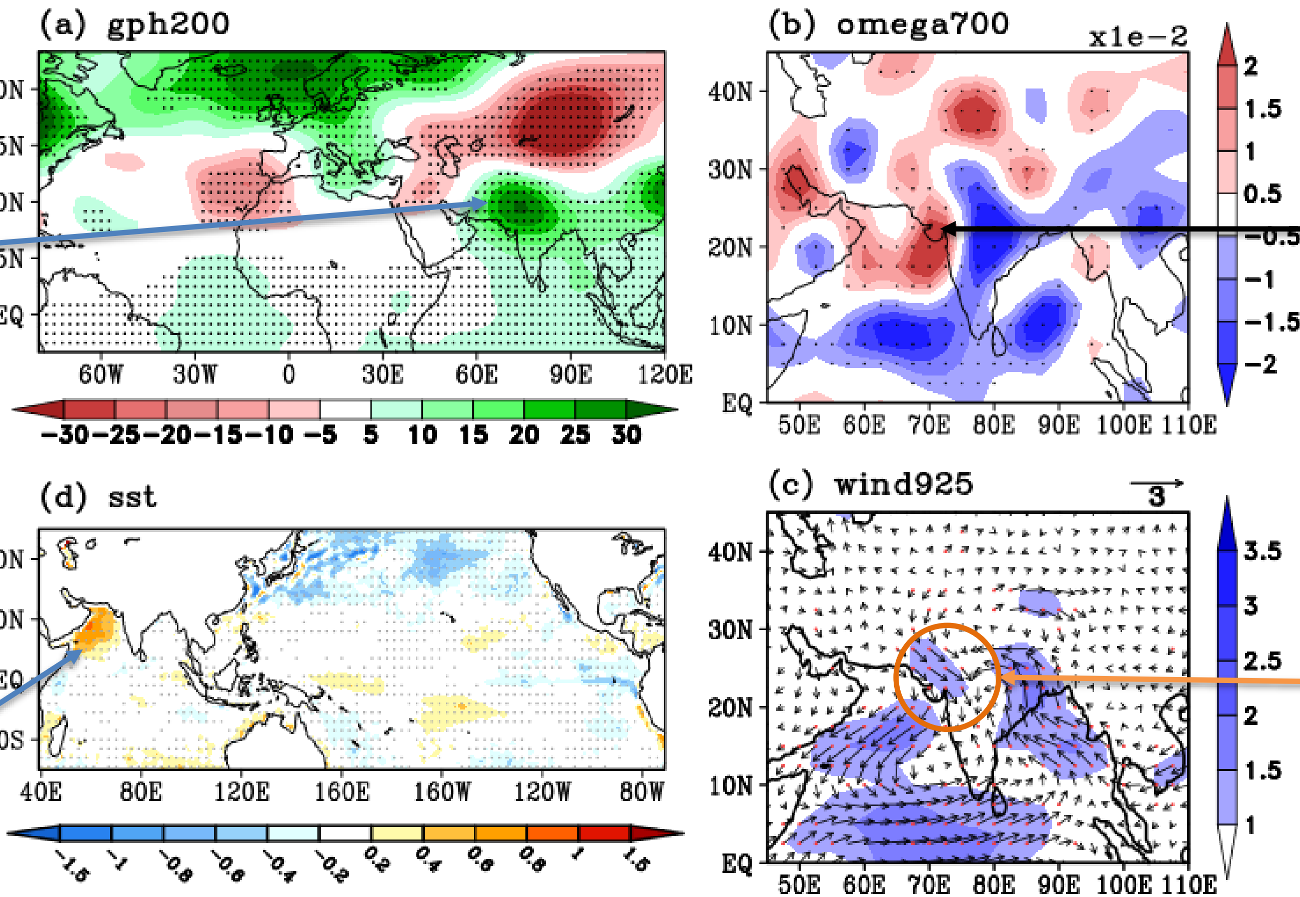
A significant trend in total HW days attributed to longer-duration events is observed for NW and SE regions. In comparison, neither region exhibits significant trends for shorter-duration events



# Composites for NW spells

Presence of positive height anomalies over northern India

Significant positive SST anomalies; high SSTs over the IO positively correlated with the Tmax over HW zones of India (Naveena et al. 2021)

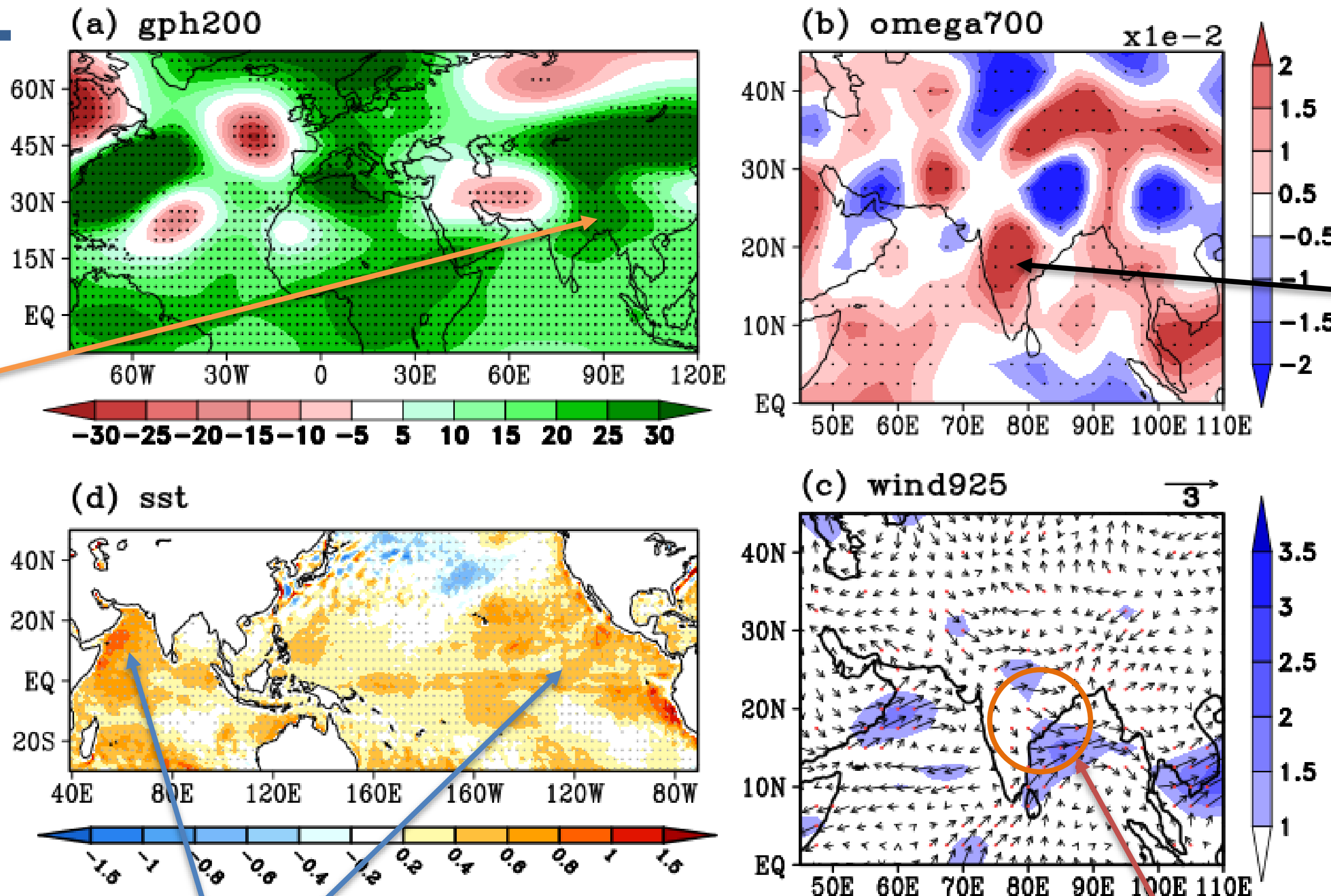



Strong sinking motion over the NW regions

Strong north-westerly winds are observed at the lower (925 hPa) level

Composites of (a) geopotential height (in $m$) at 200 hPa level, (b) Omega (in $Pa/s$) at 700 hPa level [positive/negative values represent sinking/rising motion], (c) wind vectors at 925 hPa level with magnitude (in $m/s$) in colour shade, and (d) sea surface temperature (in °C) for NW-spells.

# Composites for SE spells




Positive gph200 anomalies are also seen across central, southeast, and northeast India

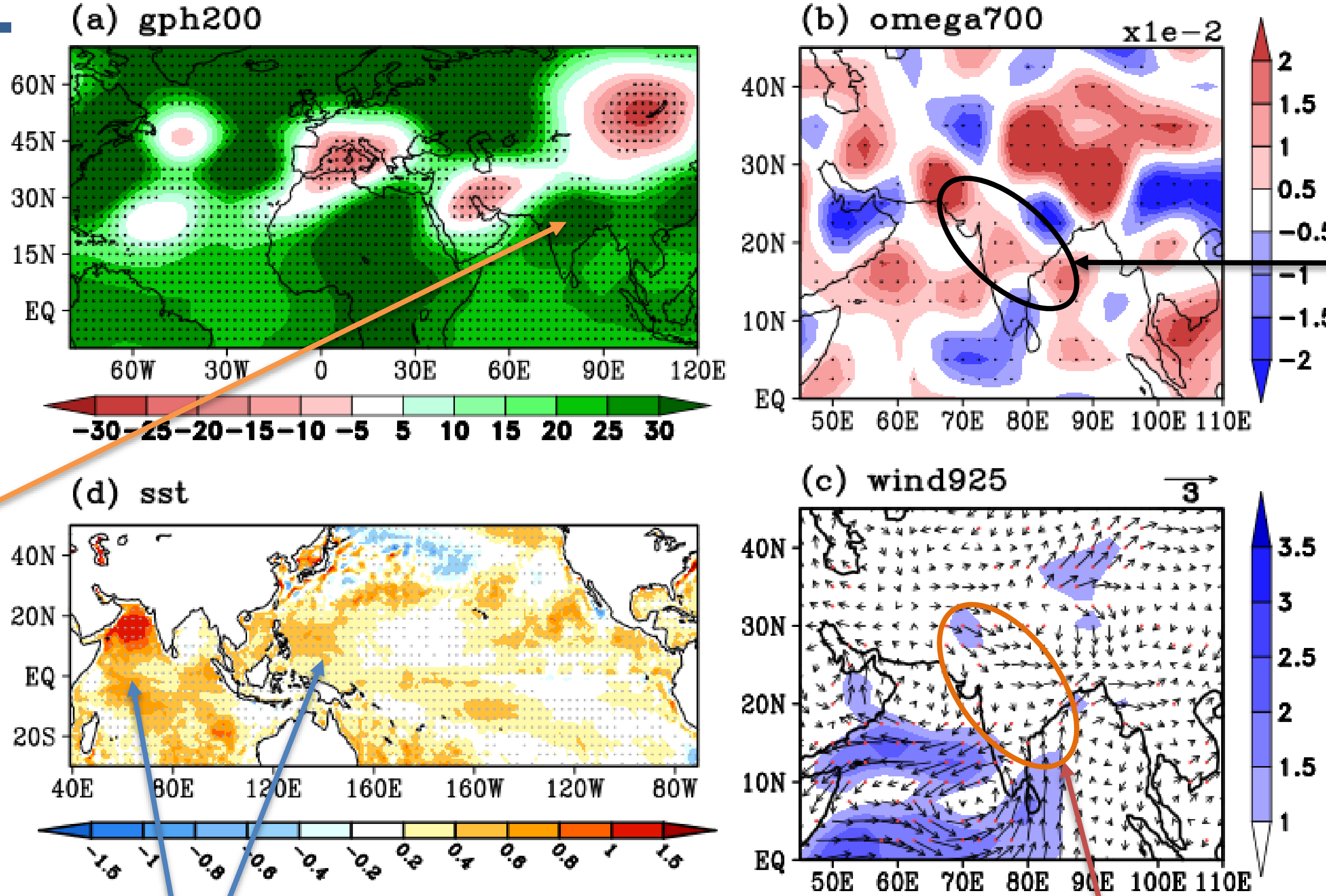
Substantial downdraft (positive omega700 anomalies) over the central part of the country

El Niño episodes have an impact on the HWs over the SE region by influencing the southwesterly wind (Murari et al. 2016); high SST values over the IO and the Pacific Niño region, indicating their association with the occurrence of HWs over SE.

anomalous divergent winds at lower levels (wind925) are seen moving out of the southeast parts of India, resulting in an absence of strong sea breeze and accelerating HW-like conditions (Singh and Kumar 2018).

# Composites for NWSE spells

A quasi-stationary Rossby wave pattern over northern mid-latitude, resulting in persistent weather patterns over certain regions; An anomalous high is seen across the whole of India, enhance the likelihood of heatwave conditions by promoting subsidence

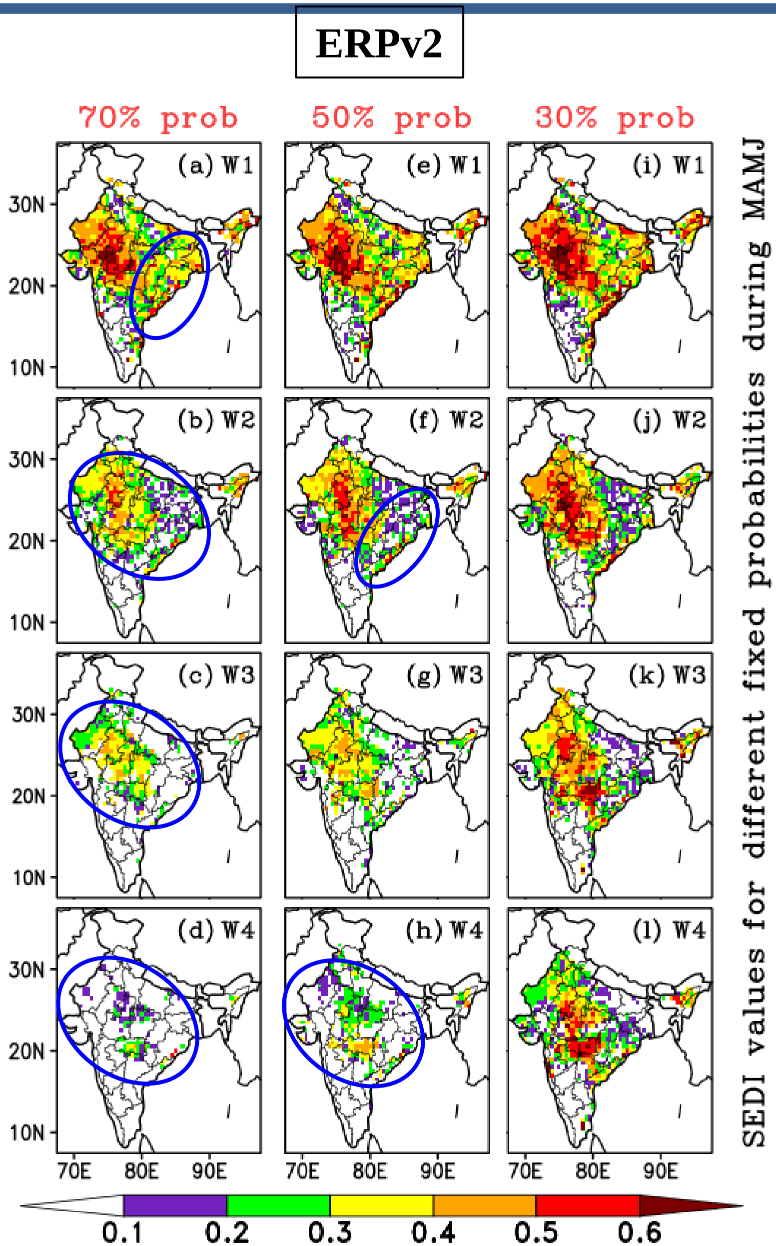


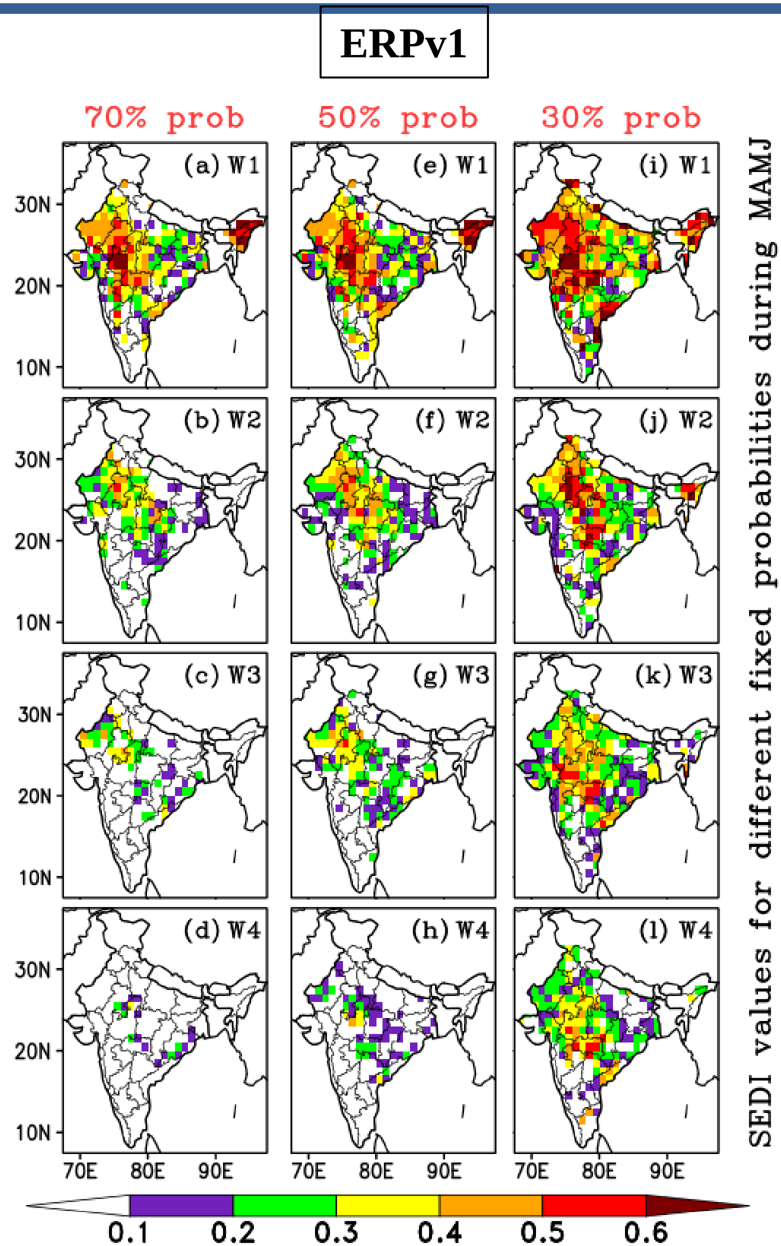

Sinking motions seen over the NW, central and SE regions

significant positive anomalies prevail over the West Pacific and Equatorial Indian Ocean, with very high positive values over the Arabian Sea; Warming in the Western Pacific can also influence large-scale atmospheric circulation patterns, such as the jet stream and atmospheric blocking events.

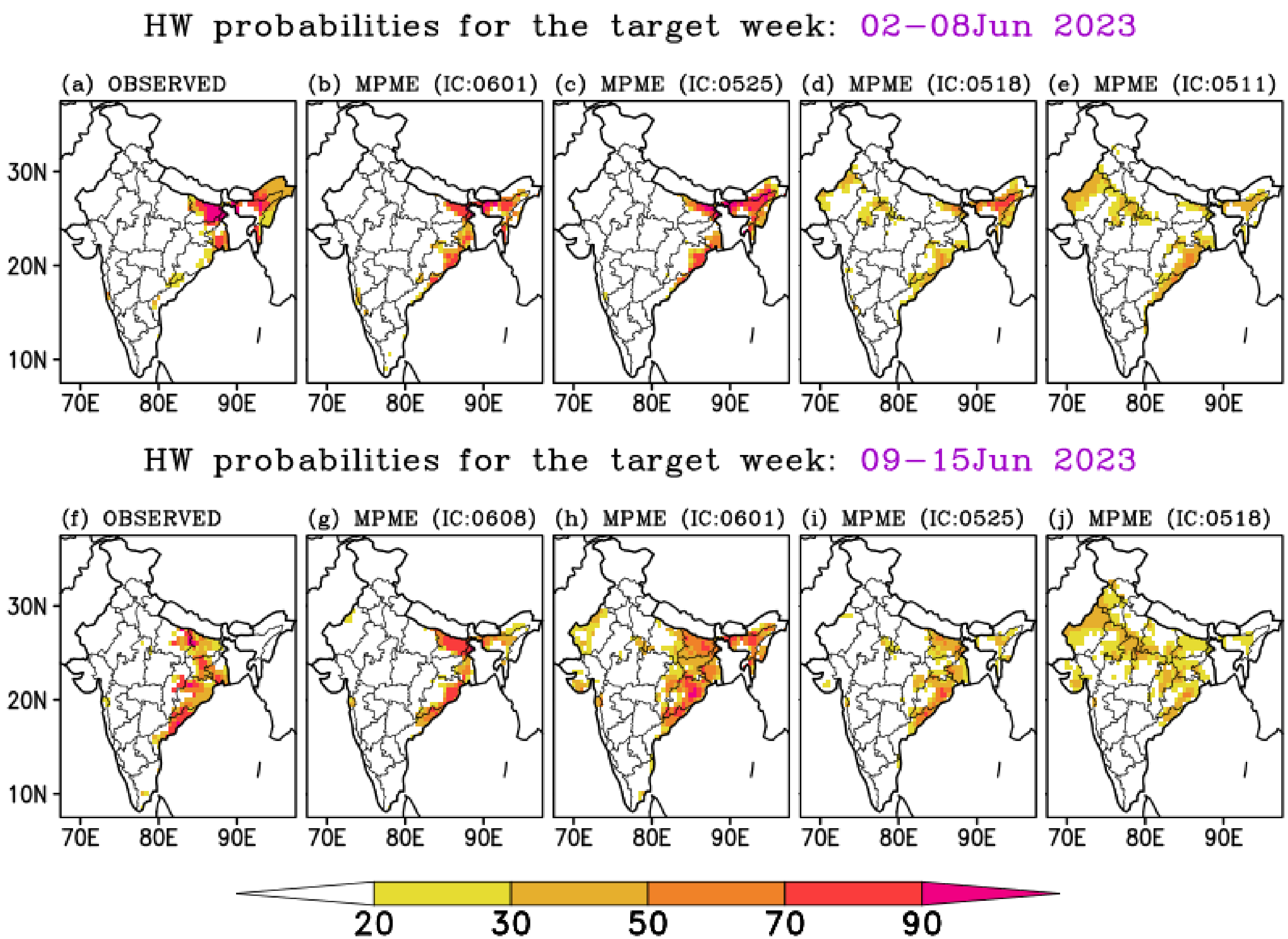
Northwesterly winds prevail over NW parts and move towards the SE regions; it can be speculated that typically HW originates over NW India and moves slowly south-eastward.

# SEDI scores during MAMJ for the hindcast period 2003-2018



# Verification of the ERP for HW event: 02-15 June 2023




The model shows its usefulness in forecasting HWs with a four-week lead time by effectively capturing the temporal and spatial characteristics of the observed occurrence.

# Summary

- The findings show a considerable rise in the occurrence of HWs over the central, southeast, and northwest regions during post-2000, indicating a temporal and spatial intensification of extreme summer conditions.
- An analysis of spatial HW trends reveals a significant increase in total HW days/year over northwest, central, and southeast India.
- The study investigates large-scale characteristics linked to different kinds of HW spells, emphasising the significance of the oceans and atmospheric variables on heatwave patterns.
- The study offers insightful information about ERPSv2's ability to forecast, which has implications for understanding and predicting HW events in areas that are vulnerable to HW.
- The effectiveness of ERPSv2 in forecasting real-time HW events is validated by a case study on a disastrous HW event that occurred in June 2023.
- The findings delivered here have implications for public health measures and planning for climate resilience, given the region's increasing occurrences of HWs.

# Acknowledgements


- Organizing committee of the Annual Monsoon Workshop and National Symposium on "Understanding the science of heatwaves under the warming scenario and challenges ahead," 2024
- Director, IITM
- Project Director and Deputy Project Director of ERPAS, IITM
- NCEP, IMD, NCMRWF, INCOIS, Aditya/Pratyush HPC Support team
- All ERPAS group members


**Thanks for your attention!**

# Verification of the ERP for different events

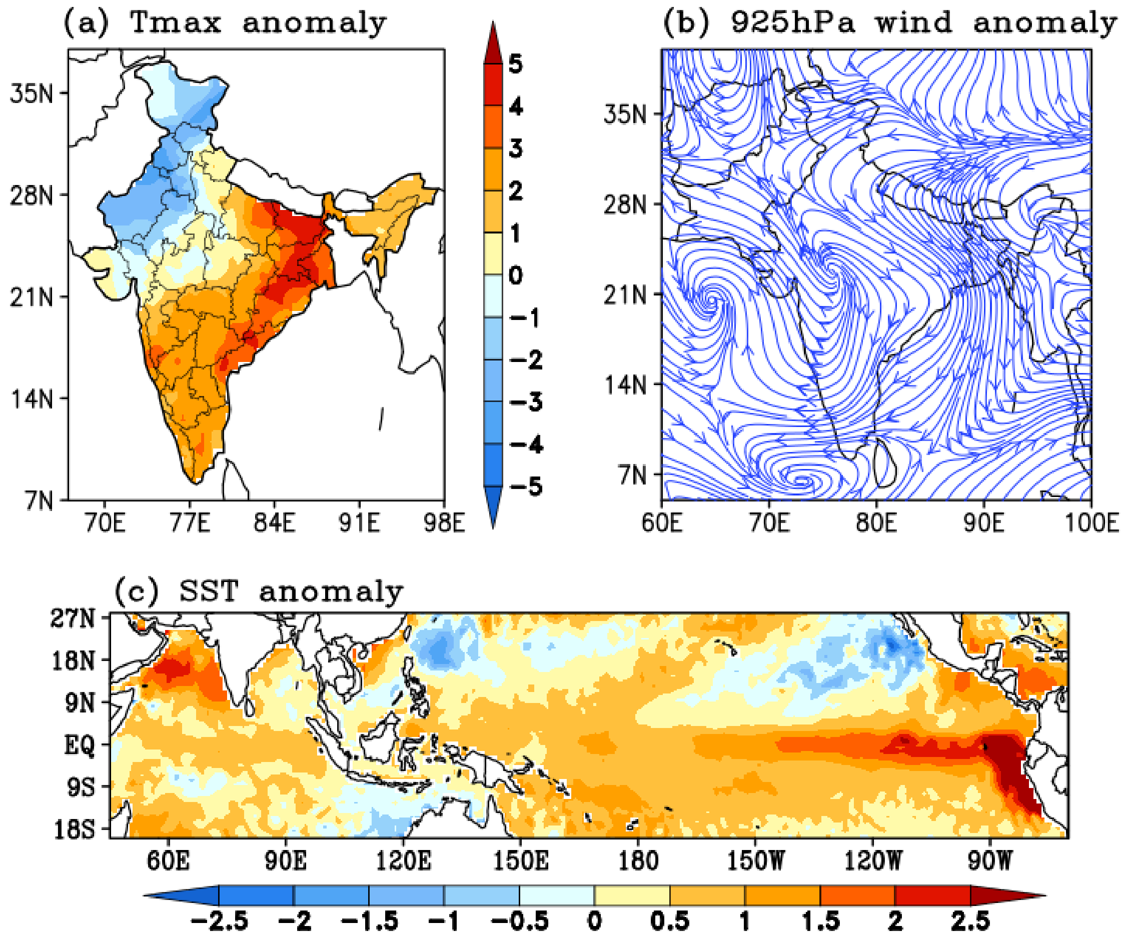



Fig.S1

# Decade averaged HW days anomaly for March

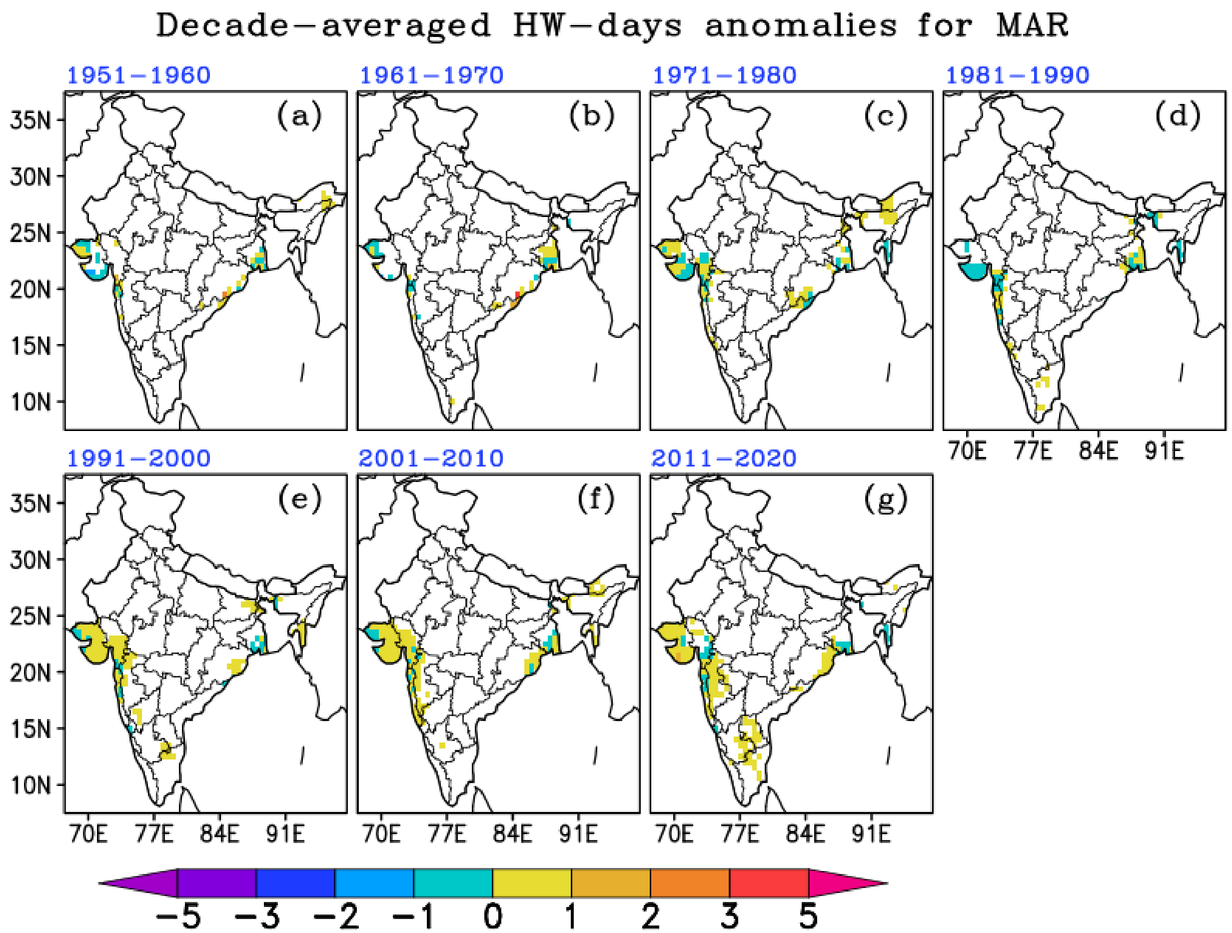



Fig.S2