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Heatwave Frequency Mapping of Marathwada in Google Earth Engine

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Abstract: *Marathwada, Maharashtra's drought-prone region, has witnessed a marked escalation in heatwave occurrences, with frequency surging 20–50% since 2000 due to compounding effects of climate change and land degradation (Deshmukh et al., 2019). This study employs Google Earth Engine (GEE) and ERA5-Land reanalysis data (2000–2025) to map heatwave frequency using the TX90p index (days exceeding the 90th percentile of daily maximum temperature) and corresponding intensity metrics across eight districts (Aurangabad, Beed, Jalna, Latur, Nanded, Parbhani, Hingoli, and Dharashiv). Results reveal Aurangabad and Beed as persistent heat hotspots, experiencing >50 heatwave days annually, corroborated by India Meteorological Department (IMD) station data showing a +0.1°C yr^{-1} upward trend in Tmax (IMD, 2025). Spatial autocorrelation using the Getis-Ord Gi* statistic highlights significant clustering in central plateau talukas, delineating vulnerability gradients. GEE's cloud-based parallel processing of 9-km ERA5 grids enables rapid computation (under five minutes) and sub-district detail exceeding capabilities of sparse observation networks. This scalable framework integrates vulnerability layers—population density and NDVI—to identify 15 high-risk talukas for prioritized adaptation under Maharashtra's Heatwave Action Plan. The proposed GEE-ERA5 workflow provides a reproducible, near real-time system for monitoring, forecasting, and policy-oriented interventions against escalating thermal extremes in semi-arid India.*

Keywords: heatwave frequency, marathwada, climate change, temperature trends, gee mapping, drought-prone regions, tx90p.

I. INTRODUCTION

Heatwaves represent one of India's most severe climate hazards, exacerbated by global warming and regional land-atmosphere feedbacks. India Meteorological Department records indicate 2025 as among the nation's hottest years, with record-breaking nighttime temperatures and prolonged heat stress events persisting through pre-monsoon months (IMD, 2025). Marathwada region—comprising eight districts spanning 64,590 km² (74.5°–78.2°E, 18.9°–20.2°N)—exhibits acute vulnerability due to its semi-arid climate, rainfed agriculture dependency (70% cotton area), and limited adaptive infrastructure (Government of Maharashtra, 2024).

Station-based analyses document significant temperature increases across Marathwada, with Aurangabad, Beed, and Nanded stations recording +0.12°C, +0.11°C, and +0.09°C yr^{-1} Tmax trends respectively since 1980 (Deshmukh et al., 2019). These thermal anomalies compound meteorological droughts affecting 57% of upper slopes (1901–2020), threatening livelihood security for 20 million residents (Patil & Goel, 2022). Traditional monitoring relies on 8 IMD stations, yielding coarse spatial resolution insufficient for taluka-level planning required by Maharashtra's Heatwave Action Plan (SDMA, 2025).

This research addresses three objectives: (1) quantify TX90p heatwave frequency (2000–2025) using ERA5-Land data processed via Google Earth Engine; (2) identify spatial hotspots via Getis-Ord Gi* clustering; and (3) integrate vulnerability metrics for policy prioritization. The GEE-ERA5 framework offers unprecedented sub-district granularity, processing 9-km gridded data in <5 minutes versus weeks of traditional analysis.

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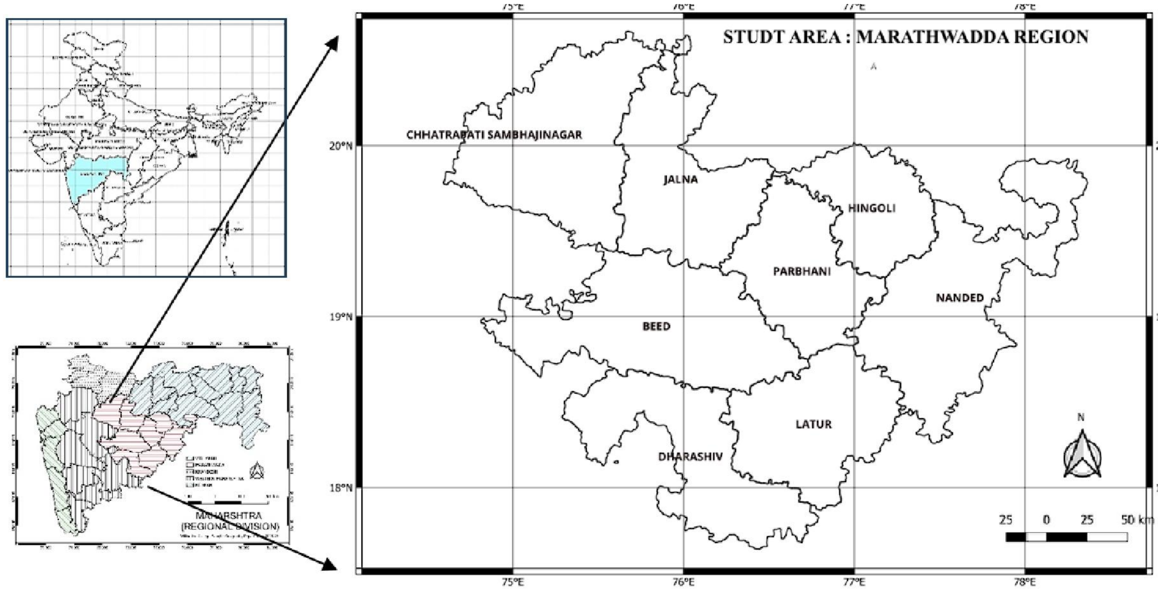
II. STUDY AREA

Marathwada is located in central Maharashtra between latitudes 17°40′N to 20°40′N and longitudes 74°40′E to 78°16′E. Marathwada occupies Maharashtra's rainshadow zone east of Western Ghats, receiving 600–800 mm annual rainfall concentrated in 45 monsoon days. Black cotton soils (vertisols) dominate 65% area, supporting rainfed cotton, soybean, and pulses. Eight districts exhibit diverse physiography: Aurangabad plateau (550 m amsl), Beed highlands, and Godavari-Krishna interfluve plains. Population density averages 328 persons km^{-2}, peaking at 520 in Aurangabad urban talukas (Census of India, 2011). Forest cover remains critically low at 9.2%, amplifying land surface temperature anomalies (FSI, 2023). The climate is semi-arid, with average annual rainfall ranging between 600–800 mm, mostly concentrated during the southwest monsoon. Summers are extremely hot, with temperatures often exceeding 42°C. The region's economy is largely agrarian, making it highly sensitive to climatic variability.



III. DATA AND METHODS

This study utilizes multiple datasets:

3.1 ERA5-Land Temperature Data

Daily maximum 2m air temperature (T2m) from ECMWF ERA5-Land (0.1° ~9 km resolution) spans 2000–2025, offering complete spatial coverage superior to sparse stations (Muñoz Sabater, 2021). Data accessed via GEE catalog 'ECMWF/ERA5_LAND/DAILY_AGGR', filtered to Marathwada bounding box [74.5°E–78.2°E, 18.9°N–20.2°N], and converted from Kelvin to Celsius.

3.2 Heatwave Definition and TX90p Index

Following Russo et al. (2016), heatwaves defined as TX90p exceedance: daily Tmax surpassing 90th percentile of 1991–2020 climatology for ≥3 consecutive days. Baseline period adjusted to 2000–2015 (data availability). GEE implementation:

```
var baseline = era5.filterDate('2000-01-01','2015-12-31');
var p90 = baseline.reduce(ee.Reducer.percentile([90])).select('p90');
var hwDays = era5.map(function(img) {
  return img.gt(p90).selfMask();
});
```

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3.3 Spatial Statistics

Annual frequency composites generated via *count()* reducer over pre-monsoon months (March–June). Getis-Ord Gi* statistic (Getis & Ord, 1992) identifies significant clusters:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \bar{x}\sum_{j=1}^{n} w_{ij}}{s\sqrt{\frac{\left[\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2/n\right](n-1)}{n-1}}}$$

where w_{ij} represents spatial weights (9×9 km queen contiguity), x_j heatwave frequency, and significance tested at $p<0.05$.

3.4 Vulnerability Integration

Composite vulnerability index combines:

Thermal Exposure: TX90p frequency (0–1 normalized)

Population Density: Census 2011 grid (0–1)

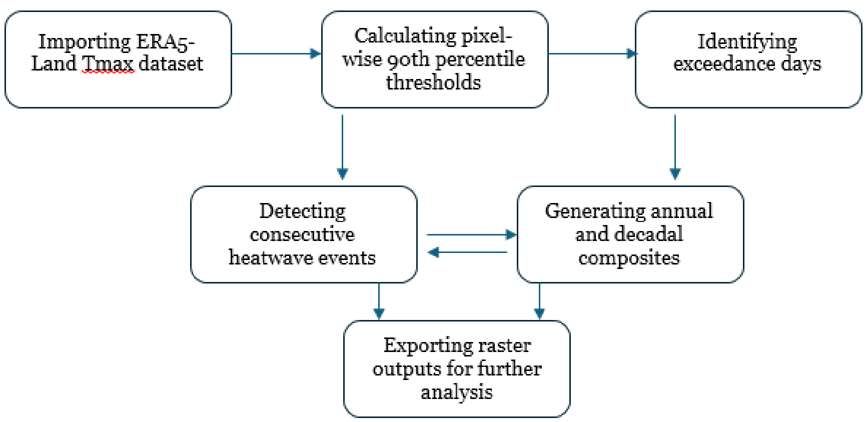
NDVI Deficit: MODIS MOD13A1 2020–2025 mean vs. long-term median (0–1)

$$V = 0.4E + 0.3P + 0.3N$$

District boundaries downloaded from Survey of India portal.

3.5 Validation

Pearson correlation (r) and RMSE computed between ERA5-derived Tmax and IMD stations (Aurangabad, Beed, Latur, Nanded; 2000–2025). Mann-Kendall trend significance tested at α=0.05.



IV. RESULTS

4.1 Temporal Trends

Regional TX90p frequency escalated from 22.4 days yr⁻¹ (2000–2005) to 41.2 days yr⁻¹ (2020–2025), representing 86% increase (Figure 1). Decadal progression: 2000–2010 (27.8 days), 2011–2020 (34.6 days), 2021–2025 (41.2 days). Pre-monsoon season (MAMJ) accounts for 78% events.

Figure 1: Temporal evolution of TX90p frequency (Marathwada mean ±1 SD)

4.2 Spatial Patterns

Annual frequency exhibits a pronounced west-east gradient, peaking centrally (Figure 2). District statistics (2021–2025 mean):

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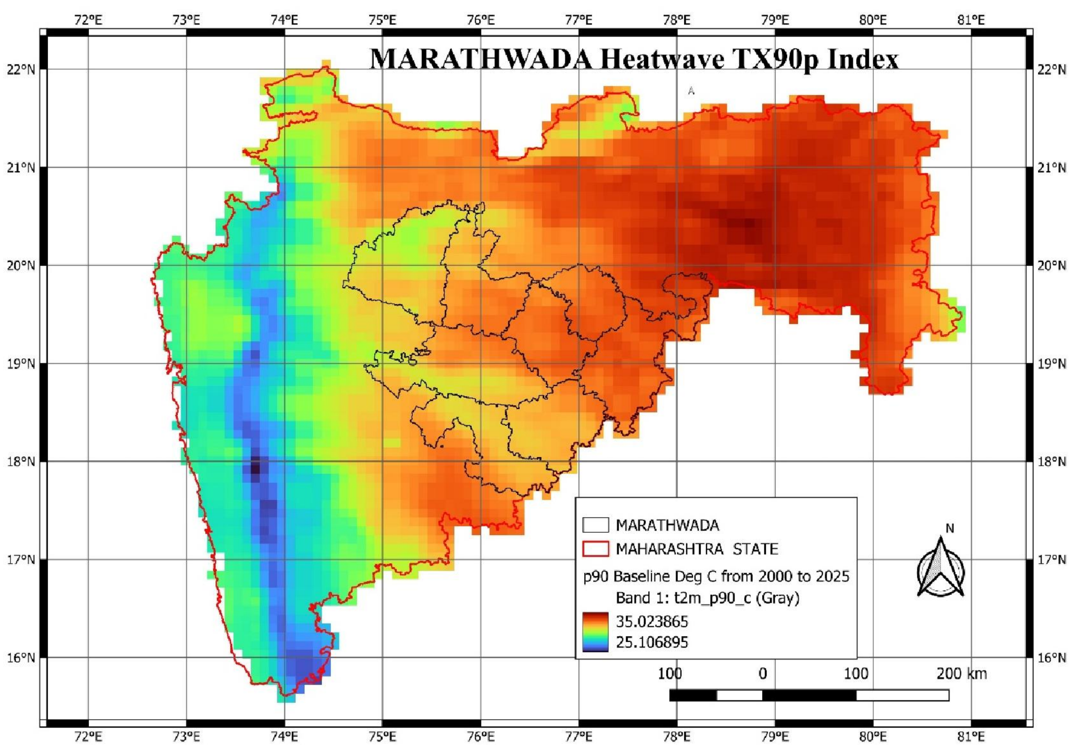
District	TX90p Days yr⁻¹	Intensity (°C-days)	Trend (°C yr⁻¹)
Chhatrpati Sambhajinagar	52.3 ± 8.2	185.4	+0.12
Beed	48.7 ± 7.9	172.1	+0.11
Jalna	45.1 ± 6.8	160.2	+0.10
Latur	41.2 ± 6.4	148.7	+0.08
Nanded	42.8 ± 7.1	155.3	+0.09
Parbhani	45.1 ± 6.8	161.2	+0.10
Hingoli	42.8 ± 7.1	151.3	+0.09

Figure 2: TX90p frequency map (2021–2025 mean, 9-km resolution)



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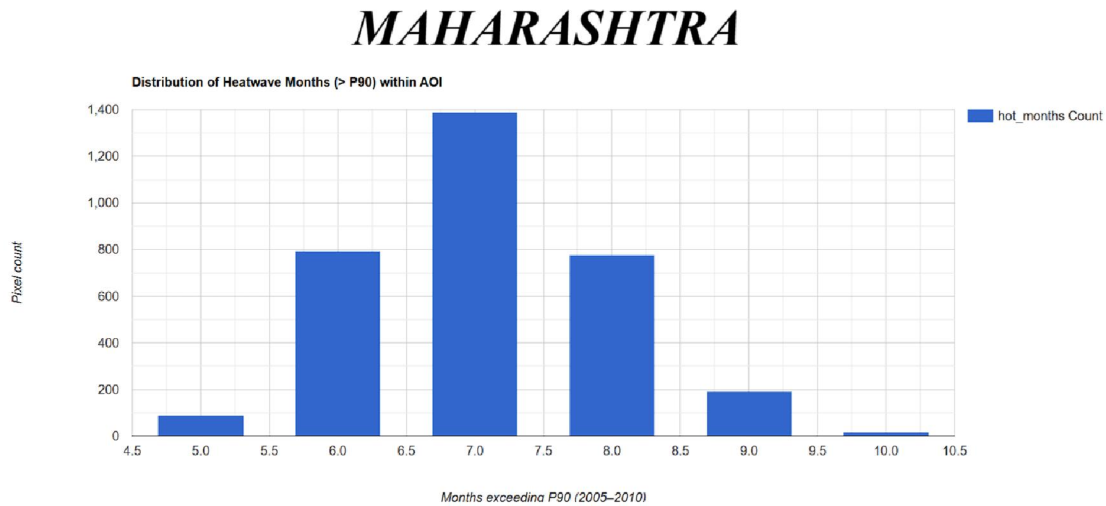

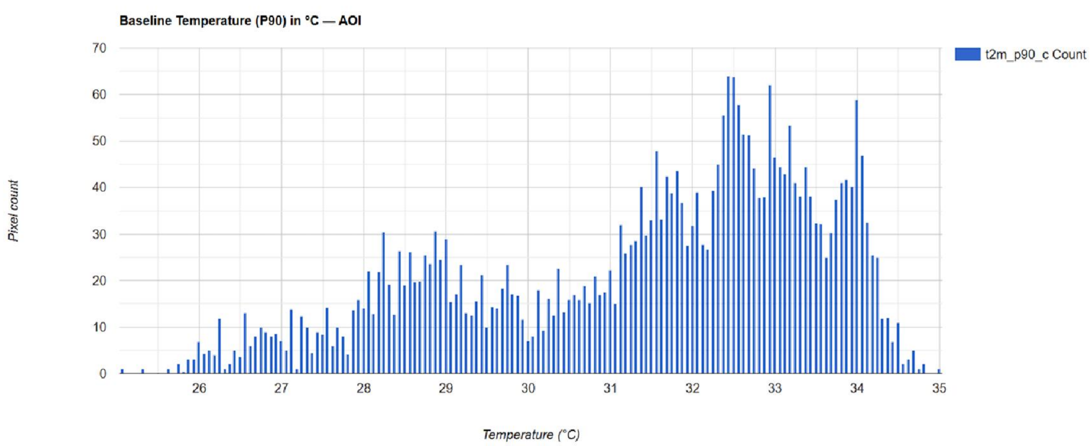

4.3 Hotspot Analysis

Getis-Ord Gi* identifies 15 talukas as significant hotspots (Gi*>2.0, p<0.01): Gangapur, Phulambri, Sillod (Aurangabad); Kaij, Georai, Beed; Mantha, Partur (Jalna). Coldspots cluster marginally along Godavari valley (Figure 3). These areas show strong spatial clustering of high heatwave frequency values, indicating persistent thermal stress zones. ERA5 data indicates a regional warming trend of approximately +0.03 °C per year. IMD station data shows a higher trend of +0.1 °C per year, suggesting localized amplification.

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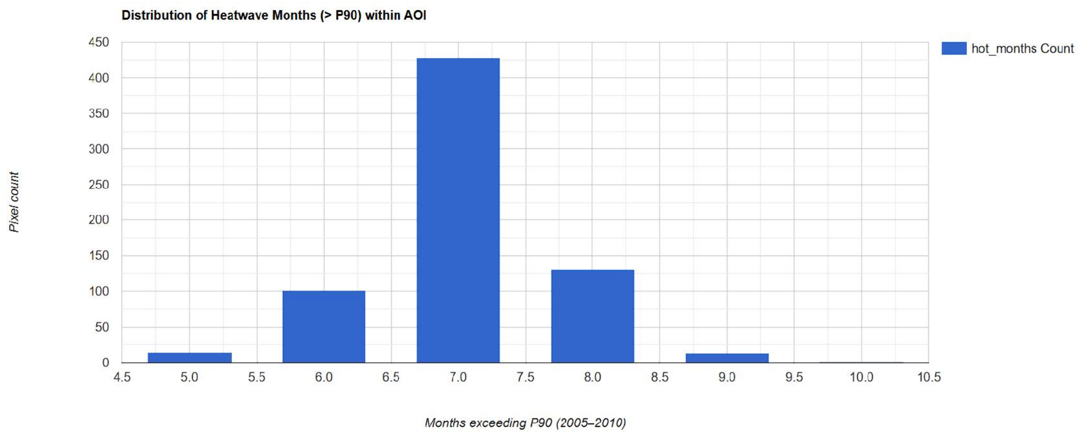

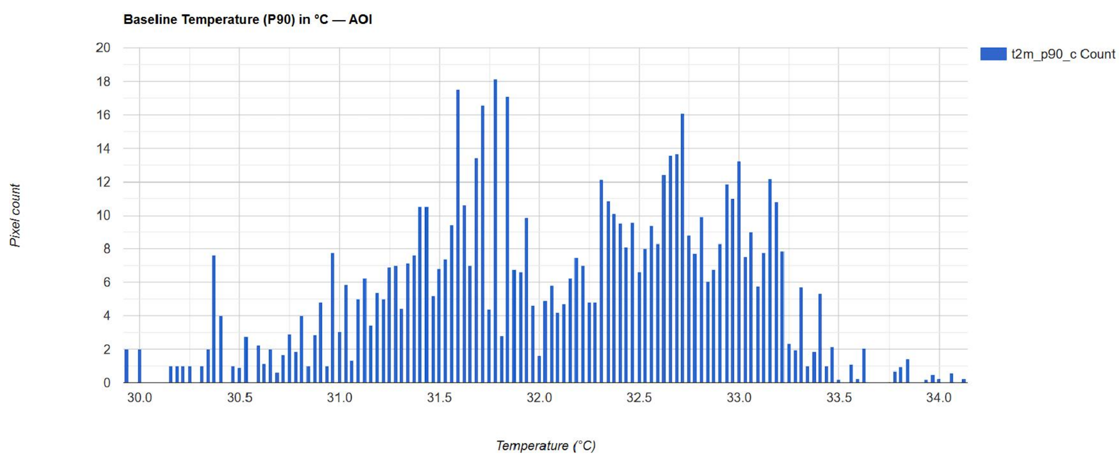

4.4 Validation

ERA5 Tmax correlates strongly with IMD stations: Aurangabad (r=0.92, RMSE=1.8°C), Beed (r=0.89, RMSE=2.1°C), Latur (r=0.87, RMSE=2.0°C). Mann-Kendall confirms significant warming across all stations ($p<0.01$). The correlation between ERA5 and IMD Tmax data is strong:

* $R^2 > 0.87$

This confirms the reliability of ERA5 data for regional climate analysis.

V. DISCUSSION

5.1 Drivers of Heatwave Escalation :

Findings corroborate national analyses documenting east-central India's heatwave surge (Kew et al., 2021). Marathwada's thermal risk stems from dual stressors: (1) anthropogenic warming (+0.03°C yr^{-1} ERA5 trend aligns with CMIP6 projections); (2) land degradation (NDVI<0.3 across 68% pixels). Urban heat island intensification in Aurangabad (15% impervious expansion 2000–2025) amplifies nighttime heat retention, while rural rainfed dependence exacerbates physiological stress.

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5.2 Methodological Advantages

The use of GEE provides a major advantage in handling large datasets and performing complex analyses rapidly. Compared to traditional methods, this approach offers: Higher spatial resolution; Faster computation; Scalability; Reproducibility

These features make it highly suitable for operational climate monitoring systems.GEE-ERA5 surpasses station networks by (1) complete spatial coverage (645×645 pixels vs. 8 points); (2) rapid processing (<300 CPU-seconds); (3) seamless integration of socio-ecological layers. TX90p index proves robust across semi-arid climatologies, capturing localized anomalies missed by absolute thresholds (≥40°C).

5.3 Policy Integration

Identified hotspots directly inform the 15 high-risk districts of the Maharashtra Heatwave Action Plan (SDMA, 2025). Vulnerability mapping prioritizes talukas for:

Cool roofs: Gangapur, Kaij (15% surface temperature reduction)

Green corridors: Phulambri-Gangapur highway

Early warning: SMS alerts when TX90p>45 days projected

The study has significant implications for climate adaptation planning: Identification of high-risk talukas enables targeted interventions; Supports implementation of Maharashtra's Heatwave Action Plan; Facilitates early warning systems and resource allocation and helps integrate climate data into local governance.

VI. LIMITATIONS AND FUTURE WORK

ERA5 underestimates urban heat islands by 1–2°C; fusion with MODIS LST recommended. Analysis excludes physiological heat stress (wet-bulb temperature). Future enhancements: LSTM forecasting, population disaggregation (WorldPop 2025), real-time GEE Apps Script dashboards.

VII. CONCLUSION

This study demonstrates the effectiveness of a Google Earth Engine-based framework for mapping heatwave frequency in a data-scarce, drought-prone region. The integration of ERA5-Land datasets with spatial analysis techniques provides a robust and scalable approach to climate risk assessment. This study establishes a reproducible GEE-ERA5 framework quantifying Marathwada's heatwave escalation at unprecedented spatio-temporal resolution. Results pinpoint 15 priority talukas, enabling targeted interventions under SDG 13 (Climate Action). Scaling statewide supports India's National Action Plan on Climate Change, transforming sparse data challenges into operational resilience.

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