

Online Resource 1 — Supplementary Information

Supplementary Information for Theoretical and Applied Climatology

A Spatially and Phenologically Aligned Agroclimatic Exposure Framework for Rice Yield Assessment across Countries

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S1. Flowering-window HD30 sensitivity

Strict exceedance days with daily $T_{max} > 30\text{ }^{\circ}\text{C}$ were reconstructed from the archived daily ERA5-Land arrays for 425 climate–phenology strata represented by 424 unique extraction points. Flowering was defined at $f = 0.70$ of the circular planting-to-harvest interval. Event counts were calculated for 11-, 15-, and 21-day flowering-centred windows and converted to a common 15-day-equivalent scale. Annual values used dynamic extensive-rice-area weights. Linear trends used Newey–West covariance with four Bartlett lags and t-based inference. This analysis concerns the global stratified exposure system, not ADM1 yield-response panels.

In the full 1961–2021 reconstruction, nine positive-weight records in the 21-day series had incomplete cross-year boundary coverage. The 11- and 15-day series were complete. To ensure comparability, the window-length sensitivity was repeated over 1962–2020, for which all three windows had complete common temporal support. The substantive conclusion was unchanged.

Table S1. Global flowering-stage HD30 trends across window lengths

Period	Window (days)	Trend (days decade ⁻¹)	HAC(4) SE	95% CI	p	Support
1961–2021	11	+0.199	0.041	0.116 to 0.281	<0.001	Complete

Period	Window (days)	Trend (days decade ⁻¹)	HAC(4) SE	95% CI	p	Support
1961–2021	15	+0.204	0.041	0.121 to 0.286	<0.001	Complete
1961–2021	21	+0.200	0.041	0.117 to 0.283	<0.001	9 incomplete records excluded
1962–2020	11	+0.187	0.044	0.099 to 0.274	<0.001	Common support
1962–2020	15	+0.192	0.044	0.105 to 0.280	<0.001	Common support
1962–2020	21	+0.188	0.043	0.101 to 0.275	<0.001	Common support

Note. Trends are expressed as 15-day-equivalent strict exceedance days ($T_{\max} > 30^{\circ}\text{C}$) per decade. Confidence intervals and p-values use HAC(4) covariance with t-based inference.

S2. Archived alternative-panel inferential diagnostic

Restricted-residual wild-cluster bootstrap-t inference used Rademacher weights, 999 replications, and seed 20260816. The four Asian country panels are exact archived stage-offset alternatives but are not exact reproductions of every frozen primary Table 3 coefficient. Brazil uses a representative-point construction. These results are therefore inferential diagnostics and do not replace the primary model.

Table S2. Wild-cluster bootstrap results from archived alternative panels

Country	N	ADM1 clusters	Association (% °C ⁻¹)	CRV1 SE (log scale)	Wild-bootstrap p	Classification
China	1,482	26	+1.236	0.0046	0.017	Archived alternative panel
Japan	2,854	47	+0.143	0.0018	0.401	Archived alternative panel
India	1,666	34	−1.231	0.0082	0.160	Archived alternative panel
Philippines	2,685	79	+0.770	0.0056	0.165	Archived alternative panel

Country	N	ADM1 clusters	Association (% °C ⁻¹)	CRV1 SE (log scale)	Wild-bootstrap p	Classification
Brazil	1,240	27	-2.643	0.0125	0.042	Representative-point diagnostic

Note. Associations are exact percentage transformations of the DTR coefficients. CRV1 SE is reported on the log-yield coefficient scale.

S3. Interpretation boundary

The supplementary HD30 reconstruction tests threshold and window sensitivity of global flowering-stage exposure. It does not estimate ADM1 HD30–yield associations. The archived bootstrap panels assess whether inference remains conservative under alternative archived representations; because they do not exactly reproduce all frozen primary coefficients, they should not be interpreted as exact robustness tests of the main Table 3 estimates.

S4. Exact harmonized ADM1 window-length sensitivity

The archived harmonized ADM1 panels for China, Japan, and India contained directly comparable 11-, 15-, and 21-day flowering-centred DTR models using ADM1-specific phenology, the same fixed-effects structure, and ADM1-clustered standard errors. Brazil and the Philippines were not included in this exact window comparison because the archived sensitivity workbook did not contain equivalent harmonized window panels for those countries. The country panels retain their original analysis periods; this section is therefore neither a balanced common-calendar-period analysis nor a five-country robustness test.

Table S3. ADM1 DTR–yield associations across flowering-window lengths

Country	Window (days)	Association (% °C ⁻¹)	95% CI	p
China	11	+0.675	-0.052 to +1.406	0.069
China	15	+1.185	+0.272 to +2.107	0.011
China	21	+1.345	+0.383 to +2.317	0.006
Japan	11	+0.144	-0.114 to +0.404	0.274
Japan	15	+0.169	-0.172 to +0.511	0.332

Country	Window (days)	Association (% °C ⁻¹)	95% CI	p
Japan	21	+0.008	-0.501 to +0.520	0.975
India	11	-0.971	-2.410 to +0.490	0.192
India	15	-1.200	-2.762 to +0.386	0.137
India	21	-1.412	-3.133 to +0.340	0.114

Note. All estimates use ADM1-specific phenology and the harmonized ADM1-clustered model. The 15-day specification is primary.

S5. Leave-one-ADM1-out influence analysis

Leave-one-ADM1-out analyses were available for the exact harmonized China, Japan, and India panels. The summaries below report the range of re-estimated DTR associations, directional retention relative to the corresponding full-sample coefficient, the share of omission models with $p < 0.05$, and the omitted unit producing the largest absolute change from the full-sample estimate.

Table S4. Leave-one-ADM1-out robustness summaries

Country	Omissions	Association range (% °C ⁻¹)	Direction retained	p < 0.05	Largest-change omission
China	26	+0.902 to +1.347	100%	100%	Ningxia
Japan	47	+0.093 to +0.248	100%	0%	Aomori
India	34	-1.583 to -0.804	100%	3%	Rajasthan

Note. Direction retained refers to the sign of the corresponding full-sample 15-day DTR coefficient. Statistical significance is reported descriptively and is not used as an inclusion criterion.

S6. Leave-one-decade-out temporal influence analysis

Leave-one-decade-out analyses evaluated whether the harmonized 15-day association was dependent on a single calendar decade. These diagnostics were available for China, Japan, and India.

Table S5. Leave-one-decade-out robustness summaries

Country	Omissions	Association range (% °C ⁻¹)	Direction retained	p < 0.05	Largest-change decade
China	6	+0.687 to +1.351	100%	83%	1960
Japan	7	-0.142 to +0.266	86%	0%	1970
India	7	-1.509 to -0.551	100%	0%	2000

Note. Omitted decades are labelled by their starting year. The omission models retain the primary exposure construction and fixed-effects structure.

S7. Fixed versus dynamic production-weight climate trends

Country-level climate trends were calculated primarily with fixed production shares from the first five sample years and compared with annual dynamic production weights. Fixed weights retain a time-invariant production-referenced spatial support, whereas dynamic weights allow the climate series to change with the geography of production and contemporaneous outcomes. Both remain crop-referenced rather than unweighted national land-area averages.

Table S6. Country-level thermal trends under fixed primary and dynamic sensitivity weights

Country	Metric	Dynamic trend	Dynamic p	Fixed trend	Fixed p
China	Tmean	-0.011	0.787	+0.126	0.007
China	DTR	+0.059	0.100	+0.030	0.401
Japan	Tmean	+0.112	0.066	+0.112	0.066
Japan	DTR	+0.019	0.435	+0.019	0.435

Country	Metric	Dynamic trend	Dynamic p	Fixed trend	Fixed p
India	Tmean	+0.074	0.019	+0.075	0.016
India	DTR	-0.136	<0.001	-0.148	<0.001
Brazil	Tmean	+0.104	0.033	+0.105	0.031
Brazil	DTR	+0.047	0.131	+0.047	0.135
Philippines	Tmean	+0.081	0.069	+0.081	0.069
Philippines	DTR	-0.091	0.022	-0.091	0.022

Note. Trends are °C decade⁻¹ and use HAC(3) inference. Fixed weights use mean ADM1 production shares from the first five years of each country-specific sample and constitute the primary climatological series; dynamic annual weights are the aggregation sensitivity.

S8. China result-specification crosswalk

Several archived Chinese estimates answer related but non-identical questions. They are listed together to prevent numerical differences among the primary model, alternative-panel bootstrap diagnostic, and earlier exact-area construction analysis from being interpreted as failed numerical reproduction. Only the first row is the primary estimate reported in Table 3.

Table S7. Crosswalk of archived Chinese DTR–yield estimates

Result	Association (% °C ⁻¹)	Period	Window	Construction	Role
Main Table 3	+1.185	1961–2017	15-day centred	ADM1-specific phenology and fractional rice support	Primary
Wild-bootstrap diagnostic	+1.236	1961–2017	Archived alternative	Alternative stage-offset panel	Inferential diagnostic
Exact-area construction	+1.571	1961–2017	Days 7–21	Exact-area cluster support	Construction sensitivity

Note. The estimates are not numerically interchangeable because the temporal window, phenological linkage, spatial construction, or inferential dataset differs. The crosswalk is an audit

aid, not a meta-analysis. Crosswalk agreement in coefficient direction should not be interpreted as exact replication across specifications.

Table S8. Qualified five-country common-calendar-period DTR–yield coefficient sensitivity (1987–2017)

Country	Exposure construction	ADM1	N	Effect (% per 1 °C)	95% CI	p
China	Exact rice-area weighted	26	806	+0.157	-0.854 to 1.179	0.761
Japan	Exact rice-area weighted	47	1457	+0.066	-0.307 to 0.441	0.728
India	Exact rice-area weighted	34	963	-1.348	-2.958 to 0.288	0.106
Brazil	Representative-point diagnostic	27	829	-0.697	-2.290 to 0.923	0.397
Philippines	Exact rice-area weighted	79	2369	+0.443	-0.829 to 1.731	0.496

Note. Each country was re-estimated over the common calendar interval 1987–2017 using log yield as the outcome, flowering-centred DTR and Tmean, ADM1 fixed effects, year fixed effects, ADM1-specific linear trends, and ADM1-clustered CRV1 standard errors. Calendar coverage was aligned, but complete-case filtering yielded 806/806 possible ADM1-year observations in China, 1,457/1,457 in Japan, 963/1,054 in India, 829/837 in Brazil, and 2,369/2,449 in the Philippines. The qualified five-country equality test was Wald $\chi^2(4) = 4.00$, $p = 0.406$. Brazil uses the archived representative-point phenology diagnostic and is not directly equivalent to the exact-weight Brazilian primary coefficient.

Table S9. Exact-weight common-calendar-period coefficient-equality sensitivity

Countries	Period	χ^2	df	p	Inference
China, Japan, India, Philippines	1987–2017	3.22	3	0.358	Do not reject equality

Note. This stricter test excludes Brazil so that every included exposure panel uses the exact rice-area-weighted ADM1 construction. The covariance matrix is block diagonal because ADM1 observations do not overlap across countries.

S9. Data provenance and processing specification

Table S10 records the upstream sources used for the primary five-country analysis and the harmonized processing applied before model estimation. The Zenodo archives contain derived panels, crosswalks, and QA/QC products but do not replace the licensing and citation requirements of upstream providers.

Table S10. Upstream data sources and harmonized processing for the primary analysis

Layer/domain	Provider/product	Period/use	Processing and access
Meteorology	Copernicus CDS ERA5-Land hourly 2-m temperature	1961–2021; all countries	0.1° grid; K → °C; local- solar daily Tmax/Tmin; DOI 10.24381/cds.e2161bac
Rice distribution	GloRice v1.0	1961–2021 rice support	Annual gridded paddy- rice area; DOI 10.1038/s41597-025- 04483-1
Crop calendar	RiceAtlas	Planting and harvest timing	Flowering proxy at 0.70 of crop-cycle duration; DOI 10.1038/sdata.2017.74
ADM1 boundaries	GADM 4.1	Frozen administrative geometry	Name crosswalk and exact equal-area cell- polygon intersection; https://gadm.org/data.html
China outcomes	Mendeley provincial rice panel	1961–2017; 26 provinces	Production/harvested area or reported yield; DOI 10.17632/bms88fv7zz. 1

Layer/domain	Provider/product	Period/use	Processing and access
Japan outcomes	Statistics of Japan e-Stat / MAFF crop statistics	1961–2021; 47 prefectures	Production and harvested area; survey 00500215; https://www.e-stat.go.jp/en/statistics/00500215
India outcomes	Unified Portal for Agricultural Statistics (UPAg)	1966–2021; 34 states	Statewise area, production and yield; https://upag.gov.in/
Brazil outcomes	IBGE PAM / SIDRA Table 5457	1974–2021; 27 states	Harvested area and quantity produced; yield = production/area; https://sidra.ibge.gov.br/tabela/5457
Philippines outcomes	Philippine Statistics Authority OpenSTAT	1987–2021; 79 provinces	Annual palay production and harvested area by province; https://openstat.psa.gov.ph/PXWeb/pxweb/en/DB/DB_2E_CS/

Note. All outcome panels were harmonized to ADM1-year observations, checked for duplicate administrative records and production–area–yield identity errors, and merged to frozen GADM 4.1 crosswalks. Complete-case model samples required finite yield, flowering-centred DTR, and flowering-centred Tmean. Access links were verified in August 2026.

S10. Three-ADM1 same-grid spatial-support benchmark

A paired whole-area versus rice-area-weighted benchmark was completed for Anhui, Guangdong, and Heilongjiang in 1961, 1989, and 2017. Both supports used the same ERA5-Land 0.1° cells, grid-cell local-solar-day offset floor($\text{longitude}/15 + 0.5$), RiceAtlas-derived phenological components, and 15-day flowering-centred windows. Whole-area weights were exact ERA5 cell-by-GADM 4.1 ADM1 intersection areas in EPSG:6933. Rice weights were derived from the exact 5-arcmin member-cell support mapped to the nearest identical ERA5 cell. The analysis required complete Tmax and Tmin coverage for every local-solar zone.

All 30 NetCDF files passed checks of variable, 153-day period, spatial extent, dimensions, plausible temperature range, daily completeness, and partial-cell loss. The benchmark therefore yielded nine complete ADM1-year pairs. Table S11 reports rice-weighted minus whole-area

differences; absolute values, file-level validation, phenology components, finite-weight checks, and formulas are provided in Online Resource 2.

ERA5-Land cells without finite land-temperature values were excluded before aggregation, and the remaining weights were renormalized within each support. The minimum finite-weight shares occurred in Guangdong (0.9755 for whole-area support and 0.9973 for rice support); Anhui and Heilongjiang retained 1.0000. These stable land-mask exclusions were identical for Tmax and Tmin and across the three years and therefore do not represent missing local days or within-file partial-cell loss.

Table S11. Same-grid rice-weighted minus whole-area flowering-stage thermal exposure differences

Province	Year	$\Delta T_{\max}$ (°C)	$\Delta T_{\min}$ (°C)	ΔT_{mean} (°C)	ΔDTR (°C)
Anhui	1961	+0.446	+0.571	+0.509	−0.125
Anhui	1989	+0.109	+0.475	+0.292	−0.366
Anhui	2017	+0.224	+0.410	+0.317	−0.186
Guangdong	1961	+0.305	+0.352	+0.328	−0.047
Guangdong	1989	+0.350	+0.448	+0.399	−0.099
Guangdong	2017	+0.402	+0.440	+0.421	−0.038
Heilongjiang	1961	+1.040	+1.064	+1.052	−0.023
Heilongjiang	1989	+1.486	+1.520	+1.503	−0.034
Heilongjiang	2017	+1.083	+0.846	+0.965	+0.237

Note. Positive values indicate higher rice-area-weighted exposure. Tmean was higher over rice support in all nine comparisons (mean +0.643 °C; range +0.292 to +1.503 °C). DTR was lower in eight comparisons and higher only in Heilongjiang in 2017 (overall mean −0.076 °C; range −0.366 to +0.237 °C). These are exposure-construction comparisons and not yield-model estimates.