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## Research Article

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# Asymmetric day–night warming across Pakistan, 1980–2025: diurnal temperature range compression in the irrigated Indus plains and expansion in the Karakoram

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*This work was carried out by the authors in a personal capacity. It does not represent the work, policy or position of the National Disaster Management Authority.*

## Abstract

Warming is rarely symmetric between day and night, and the sign of diurnal temperature range (DTR) change is regionally specific. We analyse 46 years (1980–2025) of ERA5 daily maximum and minimum temperature over Pakistan, for the country and its six first-order administrative regions, using Mann–Kendall tests with the Hamed–Rao serial-correlation correction, Sen's slope, and Benjamini–Hochberg control of the false discovery rate. Pakistan contains two opposing regimes. In the irrigated Indus plains, minimum temperature rose (Punjab +0.33, Sindh +0.28 °C decade<sup>-1</sup>) while maximum temperature did not change significantly (+0.04 and +0.02 °C decade<sup>-1</sup>), compressing DTR by 0.28 and 0.27 °C decade<sup>-1</sup>, some 1.2 °C over the record. In the Karakoram–Himalaya, maximum temperature rose faster than minimum temperature and DTR widened (Gilgit-Baltistan +0.11 °C decade<sup>-1</sup>). The station-based HadEX3 data set independently reproduces the plains compression but has no usable coverage in the mountains. Compression is strongest in the monsoon and post-monsoon seasons and is absent in winter and

early spring, when both extremes warm together. Warm nights (TN90p) increased nationally from 7.8% to 20.5% of nights, faster than warm days (8.1% to 15.4%). Warming increases with elevation in maximum temperature only, so the near-surface lapse rate flattened by  $0.062\text{ }^{\circ}\text{C km}^{-1}\text{ decade}^{-1}$ . Detrended correlations link plains compression to declining surface solar radiation and rising water vapour, and mountain expansion to low-cloud loss. Because minimum and maximum temperature are changing at different rates and in different directions, mean temperature alone misrepresents Pakistan's warming for agriculture and health.

**Keywords:** Diurnal temperature range; asymmetric warming; ERA5; elevation-dependent warming; Pakistan

## 1. Introduction

Global land surface warming since the mid-twentieth century has not been uniform through the day. Early syntheses of station records found that daily minimum temperature ( $T_{\min}$ ) rose roughly twice as fast as daily maximum temperature ( $T_{\max}$ ) between the 1950s and 1990s, so the diurnal temperature range ( $\text{DTR} = T_{\max} - T_{\min}$ ) narrowed over most land areas (Karl et al., 1993; Easterling et al., 1997). Later updates showed that global DTR decline largely stalled after about 1980, as  $T_{\max}$  caught up with  $T_{\min}$  (Vose et al., 2005). They also showed that the sign and magnitude of DTR trends differ strongly between regions and between data sets (Thorne et al., 2016; Sun et al., 2019). DTR is physically linked to cloud cover, soil moisture, precipitation and atmospheric water vapour (Dai et al., 1999; Zhou et al., 2009), and to aerosol-driven dimming and brightening of surface solar radiation (Wild et al., 2007). DTR trends therefore integrate several regional forcings, rather than being a simple fingerprint of greenhouse warming.

Changes in the day–night balance matter for more than climatology. Elevated night temperatures increase dark respiration and shorten grain-filling in cereals; field and yield-record studies attribute significant losses in rice and wheat to warmer nights (Peng et al., 2004; García et al., 2015). Late-season heat accelerates wheat senescence in the Indo-Gangetic plains (Lobell et al., 2012). For human health, warm nights limit physiological recovery from daytime heat and are independently associated with excess mortality (Murage et al., 2017; He et al., 2022).

Pakistan spans sea-level deserts in Sindh and Balochistan, the irrigated Indus plains of Punjab, and the Karakoram–Himalaya of Gilgit-Baltistan (GB), with elevations exceeding 8,000 m. That range makes it a natural laboratory for regionally contrasting DTR behaviour. Previous national studies report robust warming in mean temperature (del Río et al., 2013) and spatially heterogeneous trends in heat-wave indices (Khan et al., 2019). Station-based analyses of the diurnal cycle have produced a mixed picture. Iqbal et al. (2016) documented contrasting changes in maximum and minimum temperature across Pakistan's station network. Hussain et al. (2023) found that annual  $T_{\min}$ ,  $T_{\max}$  and DTR increased significantly over most homogeneous climatic sub-regions during 1961–2017, with summer decreases. They also found that  $T_{\min}$  trends switched from decreasing (1961–1989) to increasing (1990–2017). Hina et al. (2024) examined climate-change indices across Pakistan's agro-ecological zones and their large-scale drivers.

In the Upper Indus Basin, station data show winter  $T_{\max}$  warming and DTR *widening*, together with summer cooling (Fowler and Archer, 2006), and Karakoram temperature variability is strongly controlled by regional circulation (Forsythe et al., 2017). Globally, the classical pattern of nights warming faster than days reversed after about 1990:  $T_{\max}$  accelerated and land DTR switched from  $-0.08$  to  $+0.06$  °C decade<sup>-1</sup>, largely because cloud cover declined (Zhong et al., 2023). Conversely, irrigation expansion suppresses daytime maxima regionally (Kueppers et al.,

2007; Lobell et al., 2008). That could narrow DTR in Punjab and Sindh by a mechanism unrelated to nocturnal heat trapping.

Pakistan's diurnal asymmetry may therefore have either sign, and it may differ between zones and seasons. Existing studies rely on station networks that are sparse in Balochistan and Gilgit-Baltistan and end in 2017 or earlier. They also do not jointly examine cropping-season DTR, warm-night indices, elevation dependence and physical drivers under serial-correlation-robust, multiplicity-controlled statistics.

This study addresses these gaps for 1980–2025. Its aims are to:

1. quantify annual and seasonal (including Rabi and Kharif) trends in  $T_{\min}$ ,  $T_{\max}$  and DTR for Pakistan and each of its six first-order administrative regions, using serial-correlation-robust non-parametric statistics with false-discovery-rate control;
2. test whether, where and when warming is asymmetric, in either direction (DTR compression or expansion), using ERA5 reanalysis and an independent station-based data set (CRU TS 4.10);
3. assess changes in warm nights and warm days, and the elevation dependence of day and night warming; and
4. relate interannual DTR variability to cloud cover, water vapour and surface radiation, in order to interpret the trends physically.

A secondary contribution is methodological. We show that a widely used point-sampled archive product contains a 2017 discontinuity large enough to fabricate a nocturnal-warming signal in mountain regions. Homogeneity testing is therefore a prerequisite for DTR trend analysis in complex terrain.

## 88 2. Data and Methods

### 89 2.1 Study area

90 The domain comprises Punjab (205,344 km<sup>2</sup>), Sindh (140,914 km<sup>2</sup>), Khyber Pakhtunkhwa (KP;  
91 101,741 km<sup>2</sup>), Balochistan (347,190 km<sup>2</sup>), Gilgit-Baltistan (72,971 km<sup>2</sup>) and Azad Jammu &  
92 Kashmir (AJK; 13,297 km<sup>2</sup>). Together these span the four broad agro-ecological settings used in  
93 this paper:

- 94 • the irrigated Indus plains (Punjab, Sindh);
- 95 • the arid western plateau (Balochistan);
- 96 • the sub-humid to humid foothills and mountains (KP, AJK); and
- 97 • the high-mountain cryosphere (GB).

98 Islamabad Capital Territory is included in the national aggregate but is too small (~900 km<sup>2</sup>) to  
99 analyse separately. Provincial boundaries are taken from geoBoundaries ADM1 (Runfola et al.,  
100 2020) (Fig. 1).

### 101 2.2 Temperature data

102 **ERA5.** Hourly 2 m air temperature from the ERA5 reanalysis (Hersbach et al., 2020) was  
103 retrieved from the Copernicus Climate Data Store for 1980–2025 on the native 0.25° grid (23.5–  
104 37.5°N, 60.5–78.0°E). Daily  $T_{\max}$  and  $T_{\min}$  were computed as the maximum and minimum of the  
105 24 hourly values within each Pakistan Standard Time (UTC+5) calendar day, and DTR as their  
106 difference. Daily values were averaged over all grid cells whose centres fall within each region,  
107 weighted by the cosine of latitude.  $T_{\max}$  and  $T_{\min}$  thus share an identical spatial footprint, which is  
108 a necessary condition for a meaningful DTR. Annual and seasonal means were formed from  
109 complete seasons only.

**High-mountain sampling.** A GB area mean is dominated by valley and mid-slope cells, and at 0.25° resolution it is warm-biased relative to the high Karakoram. We therefore also extracted ERA5 at 20 fixed high-elevation sample points in GB (2,535–5,682 m; mean 4,317 m), using the nearest grid cell. Each point value was adjusted to the true point elevation with a constant lapse rate of 6.5 °C km<sup>-1</sup> relative to the ERA5 model orography. This adjustment corrects absolute temperatures. Because it is constant in time and identical for  $T_{\max}$  and  $T_{\min}$ , it leaves trends and DTR unchanged. To examine elevation-dependent warming (Pepin et al., 2015), all grid cells in Pakistan were additionally stratified into five elevation bands (<500, 500–1,500, 1,500–3,000, 3,000–4,500 and >4,500 m), and cos-latitude-weighted band means of  $T_{\min}$ ,  $T_{\max}$ , their average and DTR were analysed. The near-surface environmental lapse rate  $\Gamma$  was estimated for each year as the negative slope of a cos-latitude-weighted least-squares regression of annual mean temperature on model elevation across all Pakistan cells, and its trend was tested in the same way as the temperature series.

**CRU TS 4.10.** As an observation-based check, we use the CRU TS 4.10 country-mean monthly series for Pakistan of  $T_{\min}$  (tmn),  $T_{\max}$  (tmx) and DTR (dtr) (Harris et al., 2020). CRU TS interpolates station anomalies to a 0.5° grid. Where no DTR station lies within the correlation decay distance, DTR relaxes towards climatology, which damps DTR trends in data-sparse regions. CRU cloud cover and vapour pressure are partly derived from temperature and DTR. We therefore use them only descriptively, not as independent predictors.

**HadEX3.** As an independent, purely station-based check on the DTR trends, we use HadEX3 (Dunn et al., 2020), which grids ETCCDI indices, including annual DTR, directly from quality-controlled station records on a 1.25° × 1.875° grid for 1901–2018, using angular-distance weighting. HadEX3 shares neither input data processing nor methodology with ERA5. We

compare annual DTR trends over the overlapping period 1980–2018 for every HadEX3 cell whose footprint contains Pakistani land, against the area-matched mean of the ERA5 cells inside the same footprint.

**Auxiliary ERA5 fields.** Monthly means of total and low cloud cover (tcc, lcc), total column water vapour (tcwv), and surface downward thermal (strd) and solar (ssrd) radiation, plus the model orography, were used to interpret DTR variability and to stratify trends by elevation.

**Data-quality screening of an alternative product.** An initial version of this analysis used province series assembled from the Open-Meteo historical archive, which samples ERA5-based fields at fixed points (4–32 points per region). Pettitt, SNHT and Buishand tests identified highly significant ( $p < 0.001$ ) breakpoints at 2016/17 in  $T_{\min}$  for GB (+4.7 °C), AJK (+1.7 °C) and KP (+1.5 °C). These breakpoints coincide with a documented change in the archive's default blended product, which combines ERA5, ERA5-Land and, from 2017 onwards, the 9 km ECMWF IFS HRES analysis (Open-Meteo, 2026). They do not correspond to any known climatic event. Trends computed across such a break are spurious. That product was therefore discarded in favour of the continuous ERA5 grid (see Supplementary Note S1).

## 2.3 Seasons and indices

Seasons follow both the meteorological convention (DJF, MAM, JJA, SON) and Pakistan's two cropping seasons:

- **Rabi:** November–April, assigned to the year of harvest;
- **Kharif:** May–October.

A February–March (FM) window is also reported, because a companion analysis identifies late winter and early spring as the country's fastest-warming season in  $T_{\max}$  (Junaid and Sajid, in review).

Following the ETCCDI definitions (Zhang et al., 2011), we compute:

- **TN90p / TX90p**: the percentage of days on which  $T_{\min}$  ( $T_{\max}$ ) exceeds the calendar-day 90th percentile of the 1981–2010 base period, estimated with a 5-day centred window;
- **TN10p / TX10p**: the corresponding cold-tail indices;
- **TR20 / TR25**: the annual count of nights with  $T_{\min}$  above 20 °C and 25 °C.

Percentile indices were computed on regionally averaged daily series. They therefore describe region-wide anomalous nights and days, not local extremes. Where an index is zero for most years of the record (for example TR20 in the mountain regions), a Sen slope of exactly zero can accompany a significant Mann–Kendall statistic, because the test responds to the ordering of the few non-zero years. For such indices we report the difference between the 1980–2002 and 2003–2025 period means instead of a slope.

## 2.4 Trend and homogeneity statistics

Monotonic trends were tested with the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975).

The test statistic is

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k), \quad (1)$$

with tie-corrected variance

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18}. \quad (2)$$

173 The standardized statistic is  $Z = (S - \text{sgn } S)/\sqrt{\text{Var}(S)}$ . Because annual temperature series are  
 174 often serially correlated, which inflates the MK false-positive rate,  $\text{Var}(S)$  was corrected with the  
 175 Hamed and Rao (1998) effective-sample-size factor, computed from significant lag  
 176 autocorrelations of the ranks of the detrended series. The correction factor was floored at unity,  
 177 so that the variance can only be inflated. Negative lag correlations can otherwise return a factor  
 178 below one, which would deflate the variance and overstate significance; this conservative floor is  
 179 applied throughout. All significance statements use the corrected p-value ( $p_{\text{HR}}$ ).

180 Trend magnitude was estimated with Sen's (1968) slope, the median of all pairwise slopes  
 181  $Q_{\{jk\}} = (x_j - x_k)/(j - k)$ , and is reported in  $^{\circ}\text{C decade}^{-1}$  with a 95% confidence interval  
 182 following Gilbert (1987).

183 Many tests are performed ( $7 \text{ regions} \times 8 \text{ seasons} \times 3 \text{ variables}$ , plus indices). We therefore  
 184 control the false discovery rate at 5% using the Benjamini–Hochberg procedure (Benjamini and  
 185 Hochberg, 1995; Wilks, 2016), and report the adjusted q-values. Statements of significance in  
 186 the Results refer to  $q < 0.05$  unless a raw p-value is quoted. For gridded trend maps, stippling  
 187 marks cells with local  $p < 0.05$ , and the proportion of significant cells is reported alongside.

188 **Asymmetry metric.** The ratio  $R_{\text{T}} = Q_{\text{Tmin}}/Q_{\text{Tmax}}$  becomes unbounded, and changes sign, when  
 189 the  $T_{\text{max}}$  trend is near zero, which is common in irrigated regions. We therefore quantify  
 190 asymmetry with the bounded index

$$191 \quad AI = \frac{Q_{T_{\min}} - Q_{T_{\max}}}{|Q_{T_{\min}}| + |Q_{T_{\max}}|}, \quad -1 \leq AI \leq 1, \quad (3)$$

192 where  $AI > 0$  indicates faster nocturnal warming (DTR compression) and  $AI < 0$  faster daytime  
 193 warming.  $AI = \pm 1$  when the two trends have opposite signs.  $AI$  is left undefined when  $|Q_{\text{Tmin}}| +$

$|Q_{T_{\max}}| < 0.1 \text{ }^{\circ}\text{C decade}^{-1}$ , because the index is then dominated by noise. The DTR trend itself, tested directly with MK, is the primary evidence for compression or expansion.

**Homogeneity.** Each annual series was screened with the Pettitt (1979) test and the Standard Normal Homogeneity Test (SNHT; Alexandersson, 1986), with SNHT p-values from 5,000 Monte-Carlo simulations.

**Relationships with cloud, moisture and radiation.** Relationships between DTR (and  $T_{\min}$ ,  $T_{\max}$ ) and cloud, water vapour and radiation were quantified using Pearson correlations of linearly detrended seasonal series, so that shared trends do not inflate the association.

All calculations were implemented in Python (NumPy, SciPy, pandas).

### 3. Results

#### 3.1 Annual trends and the two regimes

Every region warmed in both  $T_{\min}$  and  $T_{\max}$  over 1980–2025, but the balance between night and day differs sharply between the plains and the mountains (Table 1, Fig. 2).

Nationally,  $T_{\min}$  rose by  $0.361 \text{ }^{\circ}\text{C decade}^{-1}$  (95% CI 0.267–0.440;  $q < 0.001$ ) and  $T_{\max}$  by  $0.249 \text{ }^{\circ}\text{C decade}^{-1}$  (0.123–0.388;  $q = 0.001$ ), equivalent to 1.62 and  $1.12 \text{ }^{\circ}\text{C}$  over the 46-year record. The national annual DTR trend is negative but modest,  $-0.090 \text{ }^{\circ}\text{C decade}^{-1}$  ( $-0.180$ – $0.000$ ), and it does not survive false-discovery-rate control ( $p_{\text{HR}} = 0.049$ ,  $q = 0.066$ ). The national mean, however, averages two opposing regimes.

In the irrigated Indus plains, warming is almost entirely nocturnal. Punjab  $T_{\min}$  rose  $0.333 \text{ }^{\circ}\text{C decade}^{-1}$  ( $q < 0.001$ ) while  $T_{\max}$  did not change detectably ( $+0.040 \text{ }^{\circ}\text{C decade}^{-1}$ ,  $q = 0.542$ ); Sindh  $T_{\min}$  rose  $0.279 \text{ }^{\circ}\text{C decade}^{-1}$  ( $q < 0.001$ ) against  $T_{\max}$   $+0.015 \text{ }^{\circ}\text{C decade}^{-1}$  ( $q = 0.791$ ). DTR

215 therefore compressed strongly and significantly:  $-0.278\text{ }^{\circ}\text{C decade}^{-1}$  in Punjab and  $-0.267$  in  
 216 Sindh (both  $q < 0.001$ ), or about 1.25 and 1.20  $^{\circ}\text{C}$  over the record. The asymmetry index is 0.79  
 217 for Punjab and 0.90 for Sindh, close to its ceiling.

218 In Gilgit-Baltistan the pattern reverses.  $T_{\max}$  rose faster than  $T_{\min}$  (0.482 versus 0.341  $^{\circ}\text{C}$   
 219  $\text{decade}^{-1}$ , both  $q < 0.001$ ), so DTR *widened* by 0.111  $^{\circ}\text{C decade}^{-1}$  (0.040–0.173;  $q = 0.001$ ), and  
 220 AI is negative ( $-0.17$ ). The 20 high-elevation sample points give the same result (DTR  $+0.100$   
 221  $^{\circ}\text{C decade}^{-1}$ ,  $q = 0.002$ ), confirming that the expansion is not an artefact of averaging valley  
 222 cells.

223 The remaining regions are intermediate. KP and AJK warmed fastest in absolute terms ( $T_{\min}$   
 224 0.528 and 0.509  $^{\circ}\text{C decade}^{-1}$ ) with only weak DTR change ( $-0.060$ ,  $q = 0.223$ ; and  $-0.089$ ,  $q =$   
 225 0.051). Balochistan shows no significant annual DTR trend ( $+0.049$ ,  $q = 0.488$ ) but, as shown  
 226 below, strong and opposite seasonal signals.

227 **Table 1.** Annual trends in  $T_{\min}$ ,  $T_{\max}$  and DTR, 1980–2025 ( $^{\circ}\text{C decade}^{-1}$ , Sen's slope with 95%  
 228 confidence interval). Bold indicates  $q < 0.05$  after Benjamini–Hochberg correction. AI is the  
 229 asymmetry index (positive = faster night warming).

| Region   | $T_{\min}$                   | $T_{\max}$                    | DTR                                                   | AI    |
|----------|------------------------------|-------------------------------|-------------------------------------------------------|-------|
| Pakistan | <b>+0.361</b> (0.267, 0.440) | <b>+0.249</b> (0.123, 0.388)  | $-0.090$ ( $-0.180$ ,<br>0.000)                       | +0.18 |
| Punjab   | <b>+0.333</b> (0.243, 0.421) | +0.040 ( $-0.106$ ,<br>0.207) | <b><math>-0.278</math></b> ( $-0.378$ ,<br>$-0.176$ ) | +0.79 |
| Sindh    | <b>+0.279</b> (0.199, 0.341) | +0.015 ( $-0.096$ ,<br>0.125) | <b><math>-0.267</math></b> ( $-0.363$ ,<br>$-0.172$ ) | +0.90 |
| KP       | <b>+0.528</b> (0.404, 0.647) | <b>+0.445</b> (0.318, 0.614)  | $-0.060$ ( $-0.147$ ,                                 | +0.09 |

|                    |                              |                              |                              |       |
|--------------------|------------------------------|------------------------------|------------------------------|-------|
|                    |                              |                              | 0.031)                       |       |
| Balochistan        | <b>+0.328</b> (0.236, 0.424) | <b>+0.341</b> (0.201, 0.494) | +0.049 (−0.059, 0.169)       | −0.02 |
| Gilgit-Baltistan   | <b>+0.341</b> (0.232, 0.474) | <b>+0.482</b> (0.309, 0.631) | <b>+0.111</b> (0.040, 0.173) | −0.17 |
| AJK                | <b>+0.509</b> (0.395, 0.633) | <b>+0.404</b> (0.257, 0.552) | −0.089 (−0.174, −0.006)      | +0.12 |
| GB highland points | <b>+0.346</b> (0.227, 0.471) | <b>+0.459</b> (0.305, 0.625) | <b>+0.100</b> (0.040, 0.167) | −0.14 |

230

### 231 3.2 Seasonality of the asymmetry

232 DTR compression in the plains is a warm-season phenomenon (Fig. 4). Nationally, DTR fell  
233 significantly in JJA ( $-0.177$  °C decade<sup>-1</sup>,  $q = 0.003$ ), SON ( $-0.216$ ,  $q = 0.001$ ) and across the  
234 Kharif season as a whole ( $-0.194$ ,  $q = 0.002$ ), but showed no trend in DJF ( $+0.083$ ,  $q = 0.488$ ),  
235 MAM ( $+0.007$ ,  $q = 0.964$ ) or Rabi ( $+0.014$ ,  $q = 0.875$ ). Punjab and Sindh follow the national  
236 pattern with larger amplitude: SON DTR fell by  $0.426$  and  $0.450$  °C decade<sup>-1</sup> respectively (both  
237  $q < 0.001$ ), and Kharif DTR by  $0.306$  and  $0.343$  °C decade<sup>-1</sup>.

238 The absence of compression in winter and early spring is not an absence of warming. In the  
239 February–March window,  $T_{\max}$  trends are the largest of any season in every region (Pakistan  
240  $+0.595$ , Punjab  $+0.475$ , KP  $+0.745$ , Balochistan  $+0.821$  °C decade<sup>-1</sup>), and they match or exceed  
241 the  $T_{\min}$  trends, so DTR is flat or slightly widening (national  $+0.141$ ,  $q = 0.223$ ). Late-winter and  
242 early-spring warming is thus a daytime phenomenon, in contrast to the nocturnal warming of the  
243 monsoon and post-monsoon months. The consequences of that seasonal contrast for wheat are  
244 treated in the companion paper (Junaid and Sajid, in review).

Balochistan shows the clearest seasonal sign reversal within one region: DTR widened in winter (DJF  $+0.344\text{ }^{\circ}\text{C decade}^{-1}$ ,  $q = 0.005$ ; Rabi  $+0.210$ ,  $q = 0.023$ ) and narrowed in summer (JJA  $-0.149$ ,  $q = 0.018$ ). In Gilgit-Baltistan the expansion is concentrated in spring (MAM  $+0.234$ ,  $q = 0.001$ ) and the Rabi half-year ( $+0.132$ ,  $q = 0.023$ ), with no significant change in JJA or SON.

### 3.3 Spatial pattern

At the grid-cell scale the two regimes are spatially coherent (Fig. 3).  $T_{\min}$  warming is essentially universal: 100% of Pakistani cells have a positive trend and 99.6% are individually significant ( $p < 0.05$ ).  $T_{\max}$  warming is widespread but not universal: 82.2% of cells are positive, 65.0% significantly so, while 5.7% show significant cooling, concentrated in central Punjab and upper Sindh. The DTR field is split almost evenly, 38.5% of cells positive (21.4% significant) against 46.7% with significant negative trends, with the negative values forming a continuous band along the irrigated Indus corridor from lower Sindh to the Punjab plains, and the positive values covering the Karakoram, the northern mountains and western Balochistan.

### 3.4 Warm nights and warm days

Nights are warming faster than days in the indices as well as the means (Fig. 5). Nationally, TN90p increased by 5.32% of nights per decade ( $q < 0.001$ ), from a mean of 7.8% of nights in 1980–2002 to 20.5% in 2003–2025, while TX90p increased by 3.25% of days per decade, from 8.1% to 15.4%. Cold extremes declined: TN10p fell from 10.5% to 4.8% of nights ( $q < 0.001$ ), but TX10p fell only from 10.7% to 7.8% and is not significant after correction ( $q = 0.079$ ).

The regional contrast of Section 3.1 reappears. In Punjab and Sindh the warm-day indices show little change, Punjab TX90p  $+1.16\text{ }^{\circ}\text{C decade}^{-1}$  ( $q = 0.076$ ; 9.5% to 11.8%) and Sindh TX90p  $+0.46\text{ }^{\circ}\text{C decade}^{-1}$  ( $q = 0.401$ ; 9.9% to 9.5%), and the cold-day index TX10p actually rose slightly

in both (Punjab 10.2% to 11.1%; Sindh 9.9% to 11.3%; neither significant). Meanwhile warm nights roughly doubled (Punjab 8.1% to 17.7%; Sindh 8.5% to 16.9%; both  $q < 0.001$ ). In the mountains the ordering is inverted: GB warm days rose from 8.2% to 18.0% of days against warm nights from 9.0% to 15.2%, and both cold indices fell by comparable amounts.

Tropical nights increased where they already occurred: nationally TR20 rose from 119 to 135 nights per year and TR25 from 4.2 to 11.9; in Sindh TR25 rose from 151 to 166 nights. In KP, TR20 rose from 4.2 to 12.6 nights. In AJK and GB, TR20 remains at or near zero throughout (AJK 0.0 to 0.4 nights), so the significant MK statistic there reflects the appearance of a handful of non-zero years rather than a meaningful rate of change.

### 3.5 Elevation dependence and the lapse rate

Stratifying all Pakistani cells by elevation shows that elevation-dependent warming in this domain is a daytime phenomenon (Table 2).  $T_{\max}$  warming increases monotonically from  $+0.076$   $^{\circ}\text{C decade}^{-1}$  below 500 m (not significant,  $p = 0.264$ ) to  $+0.507$   $^{\circ}\text{C decade}^{-1}$  at 3,000–4,500 m, a more than sixfold increase.  $T_{\min}$  warming, in contrast, is largest in the middle bands ( $+0.405$  and  $+0.430$   $^{\circ}\text{C decade}^{-1}$  at 500–1,500 and 1,500–3,000 m) and *falls* at the highest elevations ( $+0.307$   $^{\circ}\text{C decade}^{-1}$  above 4,500 m), so it is essentially flat with height. Mean temperature therefore warms with elevation up to about 4,000 m (from  $+0.195$  to  $+0.426$   $^{\circ}\text{C decade}^{-1}$ ) and declines slightly in the highest band.

Because the elevation dependence resides in  $T_{\max}$ , DTR change is itself elevation-dependent: strongly negative in the lowlands ( $-0.219$   $^{\circ}\text{C decade}^{-1}$ ,  $p < 0.001$ ), indistinguishable from zero between 500 and 3,000 m, and positive at 3,000–4,500 m ( $+0.150$ ,  $p < 0.001$ ).

Consistent with faster warming aloft, the near-surface environmental lapse rate flattened. Its mean value over the period is  $8.28\text{ }^{\circ}\text{C km}^{-1}$ , and it declined by  $0.062\text{ }^{\circ}\text{C km}^{-1}\text{ decade}^{-1}$  (95% CI  $0.031\text{--}0.094$ ;  $p_{\text{HR}} < 0.001$ ), from  $8.35\text{ }^{\circ}\text{C km}^{-1}$  averaged over 1980–2002 to  $8.21\text{ }^{\circ}\text{C km}^{-1}$  over 2003–2025.

**Table 2.** Annual trends by elevation band ( $^{\circ}\text{C decade}^{-1}$ , cos-latitude-weighted means of all Pakistan grid cells). Values in bold are significant at  $p_{\text{HR}} < 0.05$ .

| Elevation band | Cells | Mean elevation (m) | $T_{\text{mean}}$ | $T_{\text{max}}$ | $T_{\text{min}}$ | DTR           |
|----------------|-------|--------------------|-------------------|------------------|------------------|---------------|
| <500 m         | 636   | 160                | <b>+0.195</b>     | +0.076           | <b>+0.312</b>    | <b>−0.219</b> |
| 500–1,500 m    | 382   | 940                | <b>+0.379</b>     | <b>+0.387</b>    | <b>+0.405</b>    | +0.028        |
| 1,500–3,000 m  | 144   | 1,943              | <b>+0.422</b>     | <b>+0.414</b>    | <b>+0.430</b>    | +0.010        |
| 3,000–4,500 m  | 119   | 3,875              | <b>+0.426</b>     | <b>+0.507</b>    | <b>+0.342</b>    | <b>+0.150</b> |
| >4,500 m       | 34    | 4,944              | <b>+0.351</b>     | <b>+0.388</b>    | <b>+0.307</b>    | +0.055        |

### 3.6 Comparison with CRU TS 4.10 and homogeneity

The ERA5 national series agree closely with CRU TS 4.10 in the two temperature extremes (Fig. 6): annual correlations are 0.94 for  $T_{\text{min}}$  and 0.92 for  $T_{\text{max}}$ , with mean biases of +0.55 and  $-1.31\text{ }^{\circ}\text{C}$ . CRU gives national annual trends of  $+0.313\text{ }^{\circ}\text{C decade}^{-1}$  for  $T_{\text{min}}$  and  $+0.316$  for  $T_{\text{max}}$ , in the same range as ERA5 ( $+0.361$  and  $+0.249$ ).

The two products do not agree on DTR. Their annual DTR series correlate only weakly ( $r = 0.19$ ; detrended  $r = 0.22$ ), CRU DTR is  $1.85\text{ }^{\circ}\text{C}$  larger in the mean, and the CRU national DTR trend is exactly zero (Sen slope  $0.000\text{ }^{\circ}\text{C decade}^{-1}$ ,  $p_{\text{HR}} = 0.56$ ). This disagreement is expected in a country with a sparse DTR-reporting station network: where no station lies within the correlation

decay distance, CRU DTR relaxes to its climatology, which suppresses both variability and trend. We therefore treat CRU as corroboration for  $T_{\min}$  and  $T_{\max}$ , but not as an independent test of DTR. It is worth noting that the two products are not in conflict on the national annual DTR trend, which is weak and not significant in ERA5 either; the disagreement would matter most for the regional and seasonal signals, which the CRU country series cannot resolve.

Breakpoint tests flag change points in most annual series, typically between 1998 and 2006 for  $T_{\min}$  and around 1998 for  $T_{\max}$ . These are the expected response of the Pettitt and SNHT statistics to a strong monotonic trend, which both tests detect as a step near the middle of the record, and they do not coincide with any change in the ERA5 production stream. They are qualitatively different from the archive discontinuity documented in Supplementary Note S1, which is a single-year jump of up to 4.7 °C. The DTR series are the least affected: the national DTR break is not significant (Pettitt 2005,  $p = 0.076$ ), although the Punjab and Sindh DTR series do break significantly at 2005/2006 ( $p < 0.001$ ), consistent with a compression that is concentrated in the later part of the record rather than uniform across it.

### 3.7 Independent check against a station-based extremes data set

Because CRU cannot arbitrate DTR (Section 3.6), we tested the DTR trends against HadEX3, which is built from station records alone. Of the HadEX3 cells covering Pakistani land, 54 have a usable record for 1980–2018.

In the irrigated plains (east of 68°E and south of 32.5°N; 22 cells) the two products agree closely. Mean DTR trends are  $-0.247$  °C decade<sup>-1</sup> in HadEX3 and  $-0.220$  in ERA5, the sign agrees in 91% of cells, and HadEX3 returns a significant compression in all 22 of them. The central result of this paper, DTR compression in Punjab and Sindh, is therefore reproduced by an independent, station-based product that shares no data processing or methodology with the reanalysis.

Outside the plains the two disagree. Over the remaining 32 cells the mean trends are  $-0.149\text{ }^{\circ}\text{C decade}^{-1}$  in HadEX3 against  $+0.083$  in ERA5, and the sign agrees in only 25%. The HadEX3 DTR trend is negative in *every* cell over Pakistan, spanning a narrow range ( $-0.382$  to  $-0.039\text{ }^{\circ}\text{C decade}^{-1}$ ), whereas ERA5 spans  $-0.391$  to  $+0.359$ . We interpret the uniformity of the HadEX3 field as a property of its interpolation rather than evidence of a uniform trend: angular-distance weighting propagates information from the nearest stations across a decorrelation length of several hundred kilometres, and Pakistan's in-situ network is concentrated in the plains, with almost nothing in western Balochistan or the high Karakoram. Consistent with that reading, splitting cells by whether they physically contain a station does not improve agreement (56% sign agreement for cells containing a station against 48% for those without), because even station-containing cells draw on distant stations. We therefore treat HadEX3 as corroboration where the station network exists, and as uninformative where it does not.

### 3.8 Meteorological conditions accompanying the two regimes

Detrended correlations between seasonal DTR and the radiative and moisture fields are strong and consistent in sign across all regions (Table 3). Nationally, annual DTR correlates positively with surface solar radiation ( $r = +0.90$ ) and negatively with total cloud ( $-0.87$ ), low cloud ( $-0.85$ ), column water vapour ( $-0.78$ ) and downward thermal radiation ( $-0.45$ ). Interannual DTR in Pakistan is thus primarily a cloud and radiation signal.

The trends in those fields differ between the two regimes. In the plains during the Kharif season, when compression is strongest, surface solar radiation declined (national  $-1.34\text{ W m}^{-2}\text{ decade}^{-1}$ ,  $p = 0.005$ ; Sindh  $-3.05$ ,  $p < 0.001$ ) while column water vapour ( $+0.52$  and  $+1.08\text{ kg m}^{-2}$ ,  $p \leq 0.004$ ) and downward thermal radiation ( $+1.86$  and  $+2.11\text{ W m}^{-2}\text{ decade}^{-1}$ ,  $p < 0.001$ ) rose. Falling daytime insolation with rising nocturnal thermal radiation is precisely the combination

350 that suppresses  $T_{\max}$  while raising  $T_{\min}$ . In Sindh, total cloud cover also increased during Kharif  
 351 (+1.62 percentage points decade<sup>-1</sup>,  $p = 0.001$ ).

352 In the mountains the drivers run the other way. Gilgit-Baltistan lost low cloud in every season  
 353 (annual  $-0.92$  pp decade<sup>-1</sup>,  $p = 0.002$ ; MAM  $-1.23$ ,  $p = 0.009$ ) and gained surface solar radiation  
 354 in the Rabi half-year ( $+0.86$  W m<sup>-2</sup> decade<sup>-1</sup>,  $p = 0.045$ ), while its downward thermal radiation  
 355 trend is weak and not significant (annual  $+0.50$ ,  $p = 0.130$ ). Cloud loss that admits more daytime  
 356 sunshine without a compensating increase in nocturnal trapping is consistent with the observed  
 357  $T_{\max}$ -led warming and DTR expansion. AJK and KP share the cloud loss (annual low cloud  
 358  $-0.60$  and  $-0.95$  pp decade<sup>-1</sup>) but also show rising thermal radiation, which may explain why  
 359 their DTR trends are near zero.

360 **Table 3.** Trends in cloud, moisture and radiation fields, and their detrended correlation with  
 361 DTR, for the annual and Kharif seasons. Bold trends are significant at  $p_{\text{HR}} < 0.05$ .

| Region           | Season | Low cloud<br>(pp dec <sup>-1</sup> ) | TCWV (kg<br>m <sup>-2</sup> dec <sup>-1</sup> ) | SSRD (W<br>m <sup>-2</sup> dec <sup>-1</sup> ) | STRD (W<br>m <sup>-2</sup> dec <sup>-1</sup> ) | $r(\text{DTR}, \text{SSRD})$ | $r(\text{DTR}, \text{low cloud})$ |
|------------------|--------|--------------------------------------|-------------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------|-----------------------------------|
| Pakistan         | Annual | <b>-0.27</b>                         | <b>+0.25</b>                                    | -0.54                                          | <b>+1.35</b>                                   | +0.90                        | -0.85                             |
| Pakistan         | Kharif | -0.19                                | <b>+0.52</b>                                    | <b>-1.34</b>                                   | <b>+1.86</b>                                   | +0.87                        | -0.70                             |
| Punjab           | Kharif | -0.28                                | +0.23                                           | -0.71                                          | +0.90                                          | +0.78                        | -0.58                             |
| Sindh            | Kharif | +0.02                                | <b>+1.08</b>                                    | <b>-3.05</b>                                   | <b>+2.11</b>                                   | +0.87                        | -0.59                             |
| KP               | Annual | <b>-0.95</b>                         | +0.02                                           | +0.73                                          | <b>+1.00</b>                                   | +0.83                        | -0.85                             |
| Gilgit-Baltistan | Annual | <b>-0.92</b>                         | <b>+0.06</b>                                    | -0.12                                          | +0.50                                          | +0.27                        | -0.48                             |
| Gilgit-Baltistan | Rabi   | <b>-1.23</b>                         | +0.01                                           | <b>+0.86</b>                                   | -0.53                                          | +0.62                        | -0.56                             |

|     |        |              |       |       |              |       |       |
|-----|--------|--------------|-------|-------|--------------|-------|-------|
| AJK | Annual | <b>-0.60</b> | +0.12 | +0.21 | <b>+0.64</b> | +0.78 | -0.79 |
|-----|--------|--------------|-------|-------|--------------|-------|-------|

## 4. Discussion

### 4.1 One country, two asymmetries

The central result is that Pakistan does not have a single diurnal warming signature. The irrigated Indus plains show the classical twentieth-century pattern, nights warming, days not warming, DTR compressing by roughly 1.2 °C over 46 years, while the Karakoram–Himalaya show the reversed pattern that Zhong et al. (2023) report for global land after 1990, with days outpacing nights and DTR widening. A national mean conceals both: the country-average annual DTR trend ( $-0.090\text{ °C decade}^{-1}$ ) is small and does not survive multiplicity correction, yet two of its constituent regions have trends three times that size with opposite signs. Studies that report a single national DTR figure for Pakistan, in either direction, are averaging across a genuine spatial discontinuity.

This also resolves part of the disagreement in the existing literature. Hussain et al. (2023) reported increasing DTR over most homogeneous climatic regions for 1961–2017, whereas Iqbal et al. (2016) found contrasting  $T_{\max}$  and  $T_{\min}$  changes. Our results suggest both can be right for different parts of the country and different seasons: DTR is rising in the mountains and in winter, and falling in the irrigated plains during the monsoon and post-monsoon. The sign of a national figure will depend on how station networks weight those zones, and Pakistan's network is sparse in exactly the regions with the strongest signals.

## 4.2 What may be driving the plains compression

Three mechanisms plausibly contribute in the Indus plains, and the ERA5 auxiliary fields are consistent with all three acting together.

The first is irrigation. Punjab and Sindh contain one of the world's largest contiguous irrigation systems, and irrigation is known to suppress daytime maxima by partitioning surface energy into latent rather than sensible heat (Kueppers et al., 2007; Lobell et al., 2008). This mechanism acts almost exclusively on  $T_{\max}$ , which matches the near-zero  $T_{\max}$  trends we find in both provinces despite unambiguous warming at night, and it matches the localised cells of significant  $T_{\max}$  cooling in central Punjab and upper Sindh (Fig. 3b), which lie over the most intensively irrigated districts.

An important qualification applies to this interpretation, and it constrains what a reanalysis can be used to demonstrate. The ECMWF land-surface scheme underlying ERA5 has no irrigation parameterization: it applies no anthropogenic water to the soil, so the model physics cannot generate an irrigation cooling effect of its own (Balsamo et al., 2009; Hersbach et al., 2020). A suppressed daytime warming trend over the canal-command areas therefore cannot be a direct model response to irrigation. Such a signal can reach the reanalysis only indirectly, through the assimilated observations: the screen-level analysis ingests SYNOP 2 m temperature and humidity and uses them to constrain soil moisture. The ERA5 2 m temperature field nevertheless remains an analysed quantity, shaped by the model and the assimilation system as well as by the observations. The flat  $T_{\max}$  trend in Punjab and Sindh should therefore be read as an observationally constrained feature of the reanalysis rather than as a simulation of irrigation cooling, and not as a quantitative estimate of an irrigation effect.

The same argument sets the limits of the claim. Because the signal reaches the reanalysis through assimilated station data, its reliability follows station density, which is far higher in the irrigated plains than in Balochistan or the high Karakoram. Where observations are sparse, the analysis relaxes towards the model, and a model without irrigation will tend to underestimate daytime suppression. Our plains result is thus the best-constrained part of the domain, but we cannot quantify the irrigated fraction of the DTR compression from ERA5 alone, and we do not claim to have done so. Separating irrigation from aerosol dimming would require an irrigation-area reconstruction and a radiation-based attribution, neither of which is attempted here.

The second is aerosol dimming. Surface solar radiation declined significantly over Sindh ( $-1.73 \text{ W m}^{-2} \text{ decade}^{-1}$  annually,  $-3.05$  in Kharif), which is the signature of increasing atmospheric turbidity over the region, and reduced insolation directly limits daytime heating (Wild et al., 2007).

The third is the moisture and cloud response. Column water vapour rose and downward thermal radiation rose by  $1.9\text{--}2.1 \text{ W m}^{-2} \text{ decade}^{-1}$  in the Kharif season. More water vapour traps more outgoing longwave radiation at night, raising  $T_{\min}$ , while also contributing to the daytime attenuation.

The moistening is not confined to the atmospheric column. Near-surface dewpoint, computed from the same reanalysis, rose in June–August by  $+0.38 \text{ }^{\circ}\text{C decade}^{-1}$  in Punjab and  $+0.35$  in Sindh (both  $p < 0.001$ ), against June–August daily maximum temperature trends that are indistinguishable from zero in both provinces ( $-0.05$  and  $-0.06 \text{ }^{\circ}\text{C decade}^{-1}$ ). Boundary-layer moisture is therefore increasing over the irrigated plains at a rate comparable to the nocturnal warming itself, which supports the longwave pathway for the  $T_{\min}$  increase and is consistent with irrigation as a common origin for both the suppressed maxima and the added humidity. The

consequences of that moistening for human heat stress, which depends on temperature and humidity jointly, are pursued separately.

These mechanisms are not separable with the present data, and we do not attempt a formal attribution. What the detrended correlations establish is that the interannual variability of DTR in the plains is dominated by cloud and shortwave radiation ( $r \approx +0.8$  to  $+0.9$  with SSRD), so the coincidence of a declining SSRD trend with a compressing DTR trend is mechanistically coherent rather than accidental.

### 4.3 Why the mountains expand

In Gilgit-Baltistan, low cloud cover declined in every season and Rabi-season surface solar radiation increased, while downward thermal radiation showed no significant trend. Fewer clouds mean more daytime sunshine and, at the same time, more efficient nocturnal radiative cooling, a combination that raises  $T_{\max}$  more than  $T_{\min}$  and widens DTR. This is the same mechanism Zhong et al. (2023) invoke for the post-1990 global reversal, operating here in a region where the plains mechanisms (irrigation, heavy aerosol loading) are largely absent.

The elevation-band analysis sharpens this picture and, we believe, adds something to the elevation-dependent warming literature. EDW in Pakistan is carried entirely by  $T_{\max}$ : daytime warming increases more than sixfold from the lowlands to 3,000–4,500 m, whereas  $T_{\min}$  warming is essentially flat with height and is actually weakest in the highest band. The frequently invoked EDW mechanisms, snow-albedo feedback and the disproportionate longwave effect of small absolute water-vapour increases in dry cold air (Pepin et al., 2015), differ in their expected diurnal signature. Albedo feedback acts on absorbed shortwave radiation and is therefore a daytime mechanism; enhanced downward longwave is a night-time mechanism. That daytime warming dominates the elevation gradient here, while GB's downward thermal radiation

trend is insignificant, points to the shortwave pathway, albedo loss and reduced cloud, rather than the water-vapour longwave pathway, at least over this domain and period. The flattening of the environmental lapse rate by  $0.062\text{ }^{\circ}\text{C km}^{-1}\text{ decade}^{-1}$  is the vertical expression of the same asymmetry.

This mountain result rests on ERA5 alone, and we flag that explicitly. No station-based product can currently test it: HadEX3 reports a negative DTR trend over the Karakoram, but with no stations in that region the value is interpolated from far away (Section 3.7), and neither open daily archive holds a usable high-elevation Pakistani record (Section 4.5). The DTR expansion in Gilgit-Baltistan should therefore be read as a reanalysis finding awaiting in-situ confirmation. It is, in our view, the single most valuable target for future work with the Pakistan Meteorological Department's high-altitude records.

The consequence for the cryosphere is that warming is concentrated in the hours when melt actually occurs. A given rise in mean temperature delivers more melt energy if it is achieved by warmer days than by warmer nights, because melt at high elevation is largely confined to the daylight hours when the surface reaches  $0\text{ }^{\circ}\text{C}$ . Assessments of Upper Indus snow and glacier response that use mean temperature alone will therefore understate the melt-relevant signal in this region, and the direction of that bias is opposite to the one they would incur in the plains.

#### 4.4 Consequences for agriculture and health

For Pakistani agriculture the relevant point is that the warming is arriving mostly at night in precisely the region that grows most of the country's food. Punjab's Rabi  $T_{\min}$  rose  $0.375\text{ }^{\circ}\text{C decade}^{-1}$ , against a Rabi  $T_{\max}$  trend that is not significant. Warm nights during grain filling shorten the grain-filling period and increase respiratory carbon loss in wheat, and have been linked to yield loss in both controlled and yield-record studies (Peng et al., 2004; García et al.,

2015). A national warming figure based on mean temperature would put the Rabi signal at about 0.33 °C decade<sup>-1</sup> and give no indication that it is almost entirely nocturnal.

For human health, the relevant index is the near-doubling of warm nights: nationally from 7.8% to 20.5% of nights between 1980–2002 and 2003–2025, and in Sindh a rise in nights above 25 °C from 151 to 166 per year. Warm nights prevent physiological recovery from daytime heat and carry mortality risk independent of daytime maxima (Murage et al., 2017; He et al., 2022). Pakistani heat-health planning, which is generally framed around daytime maximum thresholds, is therefore keyed to the one variable that is *not* changing much in Punjab and Sindh, while the variable that is changing fastest goes unmonitored.

#### 4.5 Limitations

The analysis rests on a reanalysis. ERA5 assimilates observations but is not an observation, and station density over Pakistan is low, particularly in Balochistan and the high Karakoram, so ERA5 in those regions is constrained more by the model than by data.

We attempted a direct validation against daily station records, and report the outcome because it constrains what any Pakistani DTR study can currently claim. Two archives of daily Pakistani data are openly available. In GHCN-Daily, all 35 Pakistani stations are too incomplete for annual trend analysis: the best-covered station has only 10 of 46 years with at least 300 valid days, and the median station reports 170–240 days per year. This is a gap in submission rather than in quality control, since flagged and unflagged day counts are nearly identical. The Global Summary of the Day archive has far better daily coverage, 28 Pakistani stations and 1,150 station-years over 1980–2025, but is inhomogeneous for this specific purpose. The fraction of days whose extremes are derived from hourly reports, rather than taken from explicit maximum and minimum groups, varies between 0.12 and 1.00 across the record, with abrupt shifts in

2006–2007, 2013–2014 and 2022–2023, and days with derived extremes have a DTR 2.1 °C narrower on average than days with explicit reports (median difference 2.11 °C, interquartile range 1.5–2.8 °C over the 818 station-years containing both). A time-varying mixture of two reporting conventions of that magnitude can generate an apparent DTR trend comparable to the climatic signal itself, so GSOD cannot arbitrate DTR trends without a homogenization exercise beyond the scope of this study. CRU DTR is damped by its own interpolation (Section 3.6). Our independent check therefore rests on HadEX3 (Section 3.7), which corroborates the plains result but cannot speak to the mountains. A definitive station-based validation would require the Pakistan Meteorological Department's raw daily archive, which is not publicly released.

Second, 0.25° grid cells cannot resolve the irrigation mosaic, valley-scale inversions or individual glaciers. The high-elevation point sampling mitigates but does not remove the problem, since the underlying model orography is still smoothed. Third, the mechanism analysis is correlational, and the auxiliary fields are themselves model output rather than observations. Fourth, percentile indices are computed on regional averages and describe region-wide events, not local extremes; a station-based analysis would yield larger values. Finally, 46 years is long enough to establish these trends but short relative to the multidecadal variability of the monsoon, and the Pettitt and SNHT results indicate that the plains DTR compression is concentrated after the mid-2000s rather than being uniform across the record.

## 5. Conclusions

We analysed 46 years of ERA5 daily temperature extremes over Pakistan and its six administrative regions with serial-correlation-robust, multiplicity-controlled trend statistics. The main findings are:

5. Pakistan contains two opposing diurnal warming regimes. DTR compressed significantly in the irrigated Indus plains (Punjab  $-0.278$ , Sindh  $-0.267$   $^{\circ}\text{C decade}^{-1}$ , both  $q < 0.001$ , about  $1.2$   $^{\circ}\text{C}$  over the record) and expanded in the Karakoram–Himalaya (Gilgit-Baltistan  $+0.111$   $^{\circ}\text{C decade}^{-1}$ ,  $q = 0.001$ ). The national annual mean ( $-0.090$   $^{\circ}\text{C decade}^{-1}$ ) is not significant after correction and conceals both. The plains compression is independently reproduced by the station-based HadEX3 data set (mean  $-0.247$  against  $-0.220$   $^{\circ}\text{C decade}^{-1}$ , 91% sign agreement); the mountain expansion rests on ERA5 alone, because no station-based product has usable coverage there.
6. Plains compression occurs because  $T_{\text{max}}$  is not warming there (Punjab  $+0.040$ , Sindh  $+0.015$   $^{\circ}\text{C decade}^{-1}$ , neither significant) while  $T_{\text{min}}$  rises by roughly  $0.3$   $^{\circ}\text{C decade}^{-1}$ . Significant  $T_{\text{max}}$  cooling appears in 5.7% of cells, concentrated over the most intensively irrigated districts.
7. The compression is seasonal: significant in the monsoon and post-monsoon (national JJA  $-0.177$ , SON  $-0.216$   $^{\circ}\text{C decade}^{-1}$ ) and absent in winter and early spring, when February–March  $T_{\text{max}}$  warming is the strongest of any season in every region.
8. Warm nights are increasing faster than warm days nationally (TN90p 7.8% to 20.5% of nights versus TX90p 8.1% to 15.4% of days between 1980–2002 and 2003–2025), and the ordering reverses in the mountains.
9. Elevation-dependent warming here is a daytime phenomenon:  $T_{\text{max}}$  warming rises from  $+0.076$   $^{\circ}\text{C decade}^{-1}$  below 500 m to  $+0.507$  at 3,000–4,500 m, while  $T_{\text{min}}$  warming is flat with height. The near-surface lapse rate flattened by  $0.062$   $^{\circ}\text{C km}^{-1} \text{ decade}^{-1}$ .
10. Interannual DTR is governed by cloud and surface solar radiation in every region. The plains show declining insolation with rising water vapour and thermal radiation; the mountains show low-cloud loss with rising insolation and no thermal-radiation trend.

The practical implication is that mean temperature alone is an insufficient summary of Pakistan's recent warming. It understates the melt-relevant daytime warming in the Upper Indus and it hides the nocturnal warming that is most consequential for wheat and for heat-related mortality in the plains. Impact assessments, agricultural advisories and heat-health early warning in Pakistan should be built on  $T_{\min}$  and  $T_{\max}$  separately.

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**Author contributions.** Ibrar Junaid: conceptualization, methodology, software, formal analysis, investigation, visualization, writing, original draft. Shahood Sajid: methodology, validation, writing, review and editing. Both authors read and approved the final manuscript.

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**Ethics approval.** Not applicable. This study used publicly available reanalysis and gridded climate data and involved no human or animal subjects.

## 560 Data and code availability

561 ERA5 hourly and monthly single-level data are available from the Copernicus Climate Change  
562 Service Climate Data Store (<https://doi.org/10.24381/cds.adbb2d47>;  
563 <https://doi.org/10.24381/cds.f17050d7>). CRU TS 4.10 country series are available from the  
564 Climatic Research Unit, University of East Anglia (<https://crudata.uea.ac.uk/cru/data/hrg/>).  
565 HadEX3 gridded extremes indices are available from the Met Office Hadley Centre  
566 (<https://www.metoffice.gov.uk/hadobs/hadex3/>). GHCN-Daily and the Global Summary of the  
567 Day are available from NOAA NCEI (<https://www.ncei.noaa.gov>). Provincial boundaries are  
568 from geoBoundaries (<https://www.geoboundaries.org>). The Python code used for data retrieval,  
569 homogeneity testing, trend analysis and figures, together with the derived provincial daily and  
570 annual series, is available from the corresponding author on request; a public repository link will  
571 be provided on publication.

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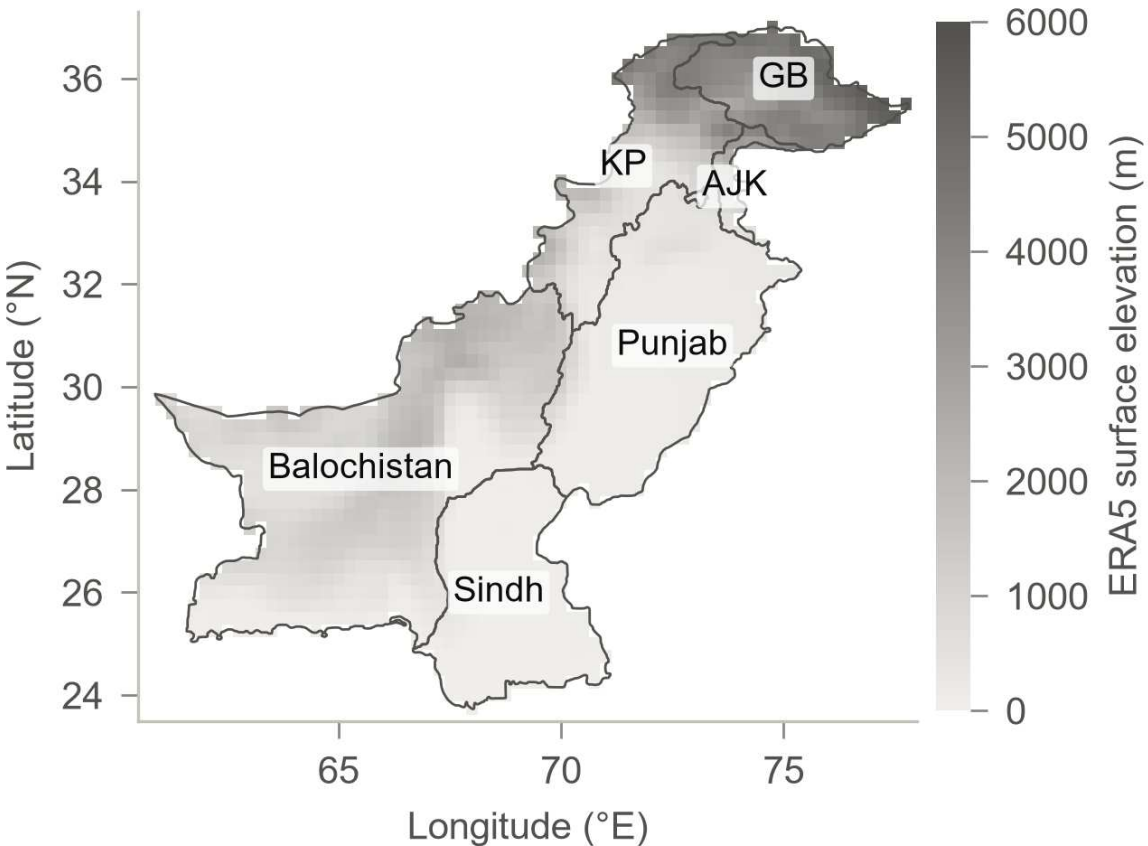
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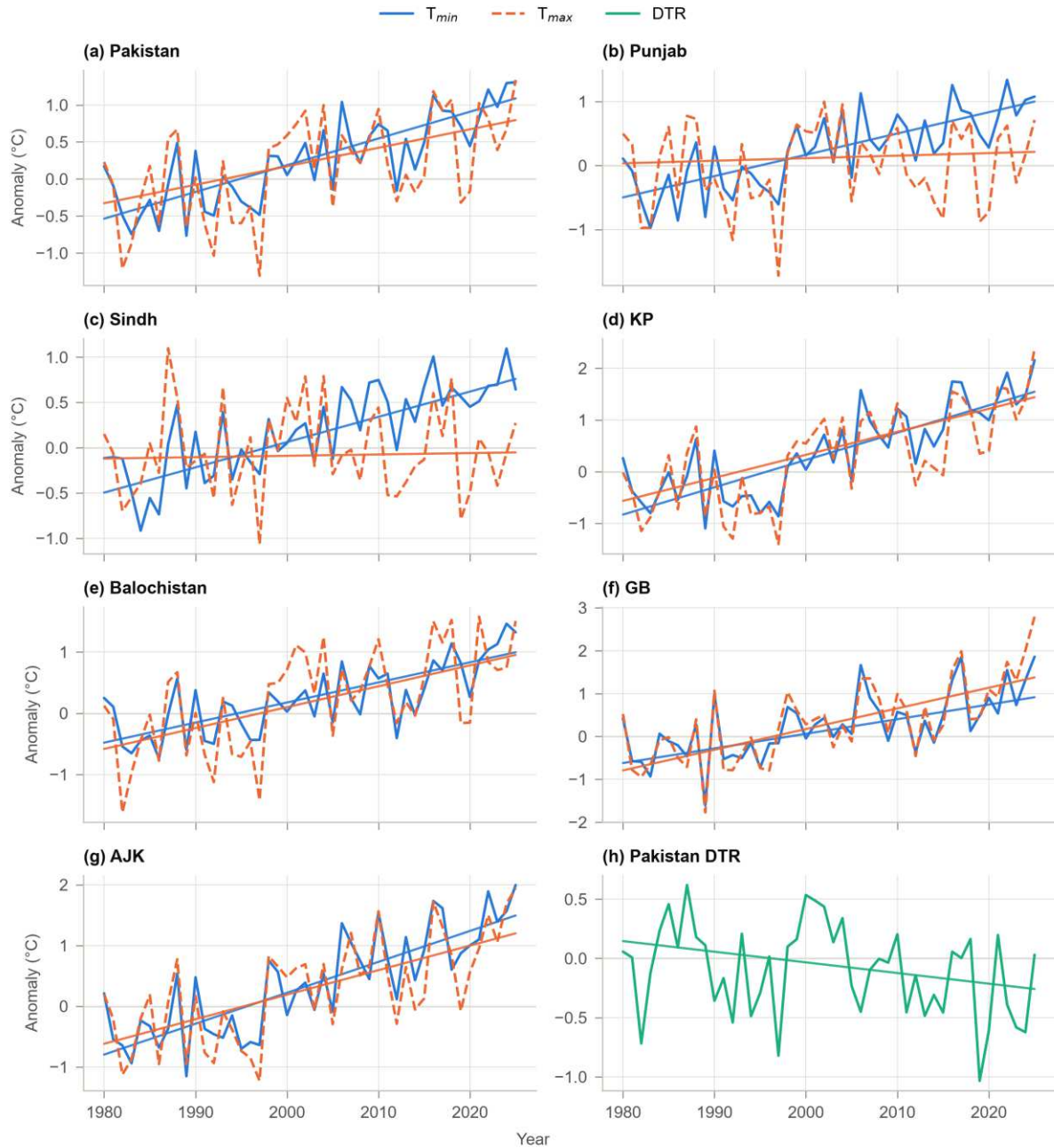
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693

694    **Figure 1.** Study area. ERA5 surface elevation over Pakistan (0.25° grid) with first-order

695    administrative boundaries from geoBoundaries. Labels mark the six regions analysed separately.



696

697 **Figure 2.** Annual mean  $T_{min}$  (solid) and  $T_{max}$  (dashed) anomalies relative to 1981–2010 for  
 698 Pakistan and each region (a–g), with Sen's slope lines, and the Pakistan DTR anomaly (h). The  
 699 divergence of the two curves in Punjab and Sindh, and their convergence in Gilgit-Baltistan, are  
 700 the two regimes described in Section 3.1.

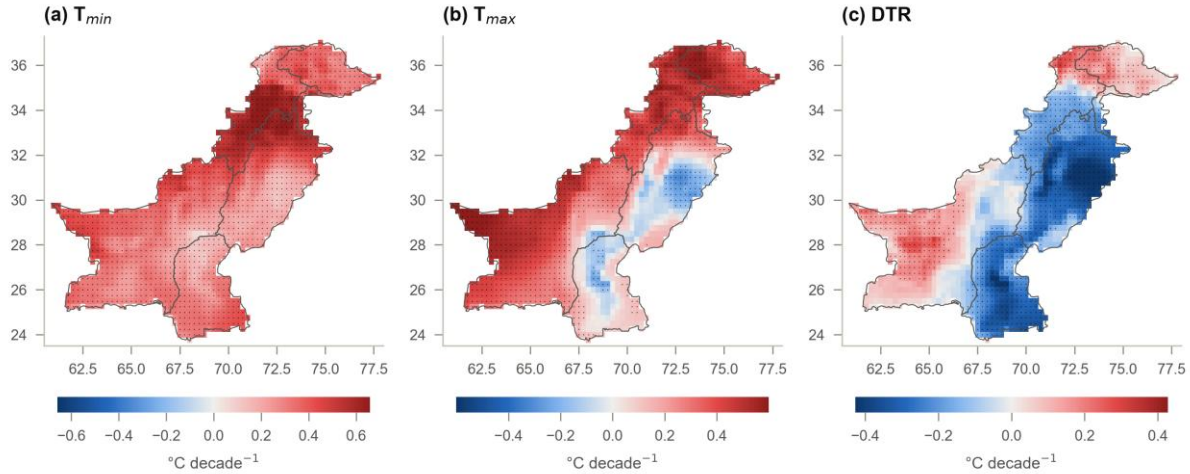


**Figure 3.** Grid-cell trends in annual (a)  $T_{min}$ , (b)  $T_{max}$  and (c) DTR, 1980–2025 ( $^{\circ}\text{C decade}^{-1}$ , Sen's slope). Stippling marks cells significant at  $p < 0.05$  (Mann–Kendall with the Hamed–Rao correction). Note the band of DTR compression along the irrigated Indus corridor and the expansion over the northern mountains.

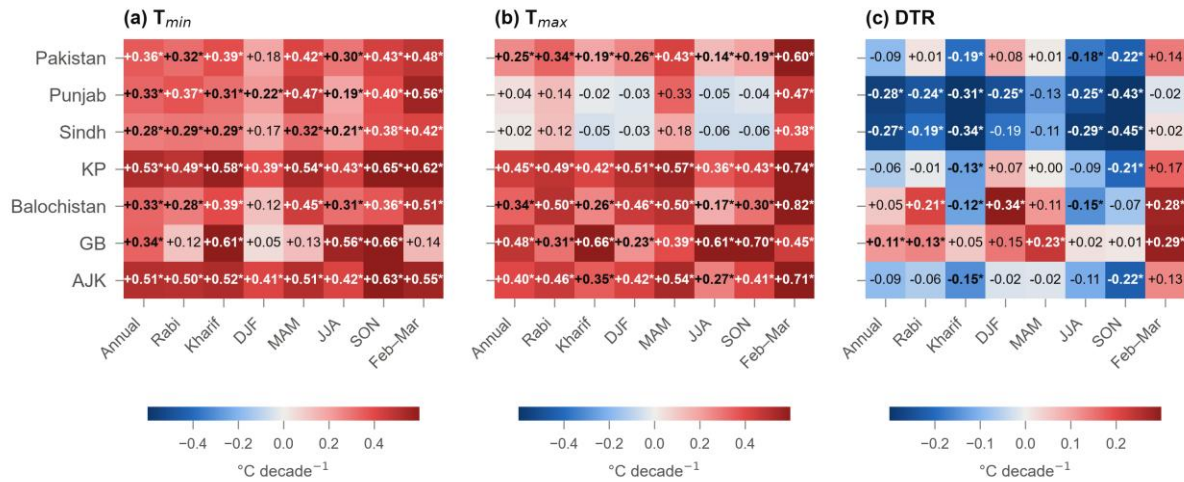


**Figure 4.** Seasonal and annual trends in (a)  $T_{min}$ , (b)  $T_{max}$  and (c) DTR by region ( $^{\circ}\text{C decade}^{-1}$ ). Asterisks and bold type mark trends significant at  $q < 0.05$  after Benjamini–Hochberg correction.

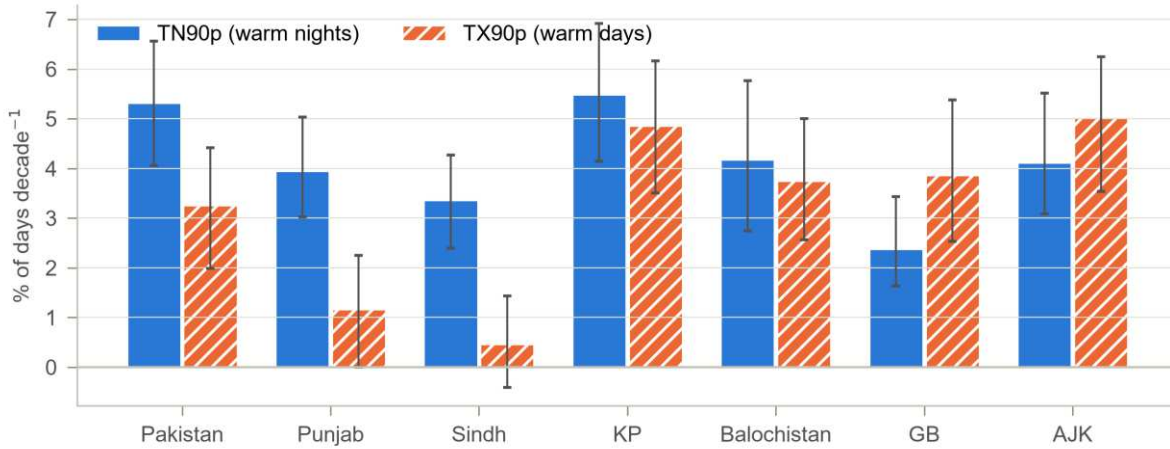


**Figure 5.** Trends in warm nights (TN90p) and warm days (TX90p) by region, in percentage of days per decade, with 95% confidence intervals on Sen's slope.

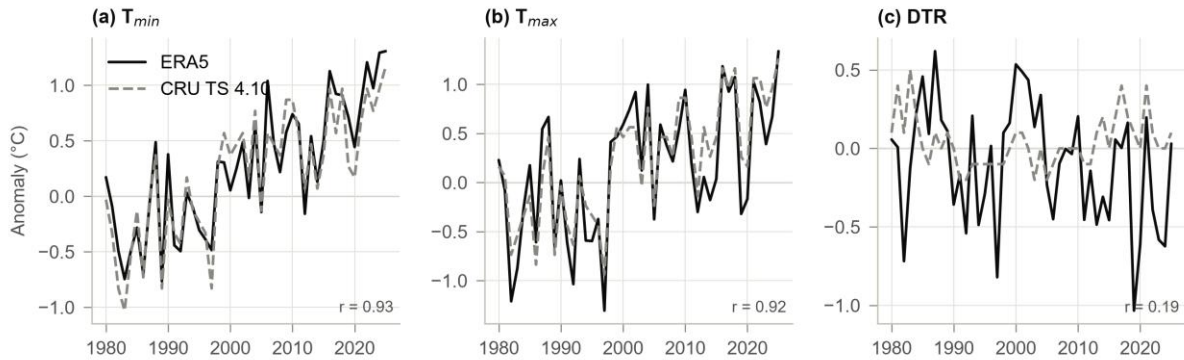


**Figure 6.** ERA5 and CRU TS 4.10 national annual anomalies (relative to 1981–2010) for (a)  $T_{min}$ , (b)  $T_{max}$  and (c) DTR, with the correlation between them. The products agree closely for the two temperature extremes and disagree for DTR (Section 3.6).

## Supplementary Note S1. Discontinuities in point-sampled archive series

An initial version of this study used province-mean daily  $T_{max}$  and  $T_{min}$  assembled from the Open-Meteo historical archive. The archive's default product was sampled at fixed points: 19 in

Punjab, 13 in Sindh, 9 in KP, 32 in Balochistan, 20 in GB and 4 in AJK. Two defects make these series unsuitable for trend analysis.

First, the 1980  $T_{\max}$  values came from a different retrieval: a full  $0.25^\circ$  grid (e.g. 306 cells in Punjab and 162 in KP) rather than the fixed points used for every other year and for  $T_{\min}$ . In 1980,  $T_{\max}$  and  $T_{\min}$  therefore describe different areas, so the 1980 DTR is meaningless. The KP 1980  $T_{\max}$  ( $17.7^\circ\text{C}$ ) is also  $4\text{--}8^\circ\text{C}$  below every other year ( $22.0\text{--}26.1^\circ\text{C}$ ).

Second, all six regional  $T_{\min}$  series contain breakpoints that are significant under the Pettitt and SNHT tests (Table S1). The largest occur at 2016/17 in the mountain regions. That is the year from which the archive's default blend incorporates the 9 km ECMWF IFS HRES analysis in place of ERA5/ERA5-Land. Its differently resolved orography changes the temperature of high-elevation sample points abruptly.

**Table S1.** Homogeneity of annual-mean  $T_{\min}$  in the point-sampled archive series, 1981–2025 (SNHT p-values from 5,000 Monte-Carlo simulations).

| Region                | Mean 1981–2016<br>( $^\circ\text{C}$ ) | Mean 2017–2025<br>( $^\circ\text{C}$ ) | Difference ( $^\circ\text{C}$ ) | Pettitt break (p) | SNHT break (p) |
|-----------------------|----------------------------------------|----------------------------------------|---------------------------------|-------------------|----------------|
| Punjab                | 18.43                                  | 18.92                                  | +0.49                           | 1998 (0.003)      | 1998 (0.001)   |
| Sindh                 | 21.06                                  | 21.49                                  | +0.43                           | 2006 (0.001)      | 2015 (<0.001)  |
| Khyber<br>Pakhtunkhwa | 12.40                                  | 13.94                                  | +1.55                           | 1999 (<0.001)     | 2016 (<0.001)  |
| Balochistan           | 16.02                                  | 17.06                                  | +1.04                           | 2006 (<0.001)     | 2016 (<0.001)  |
| Gilgit-Baltistan      | −14.86                                 | −10.16                                 | +4.70                           | 2016 (0.001)      | 2017 (<0.001)  |
| Azad Kashmir          | 4.93                                   | 6.67                                   | +1.73                           | 2006 (0.001)      | 2016 (<0.001)  |

733 The lowland differences are compatible with ordinary warming. The GB step of +4.7 °C,  
734 occurring essentially in a single year, is roughly an order of magnitude larger than any plausible  
735 decadal warming rate. Across this discontinuity, Sen's slope yields a GB  $T_{\min}$  trend of +0.50 °C  
736 decade<sup>-1</sup>, compared with +0.34 °C decade<sup>-1</sup> (95% CI 0.23–0.47) from the continuous ERA5 grid  
737 over the same region and period, an inflation of nearly 50% produced entirely by the product  
738 change. Trends computed from blended archive products should therefore be screened for  
739 homogeneity. Where a single, temporally consistent model configuration is available, it should  
740 be preferred, as done here with ERA5.