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## **d2 Humid-heat extremes over land**—K. M. Willett, R.M. Horton, Y. T. E. Lo, C.

Raymond, C. D. W. Rogers, and D. Wang

Following an exceptional increase in the intensity and frequency of high humid heat in 2023, 2024 continued the upward trajectory (Fig. 2.d.2.1; Table 2.d.2.1). Maximum humid-heat intensity ( $T_wX$ ; Table 2.d.2.1; annual median of the global land median monthly maximum wet-bulb temperature) was 0.5°C higher than the 1991–2020 average and only slightly lower than 2023 (0.6°C). Remarkably, high daily-maximum humid-heat frequency ( $T_wX90p$ ; Table 2.d.2.1; annual sum of global mean days per month with daily-maximum wet-bulb temperature exceeding the local 90th percentile) far exceeded the previous record, at 35.6 days above average versus 26.1 days in 2023. These values are based on the gridded HadISDH.extremes.1.2.0.2024f (Willett, 2023a,b,c; Willett et al. 2024) dataset, where monthly indices of daily maximum and minimum wet-bulb temperature are used as a measure of humid heat. Note that for the purposes of this review we use ‘humid heat’ as an energetic term that includes the contribution of temperature and moisture over the entire globe and annual cycle, rather than focusing exclusively on regions and seasons where temperature and moisture are high.

For all specific thresholds of  $T_wX$  exceedance (Fig. 2.d.2.1d; Table 2.d.2.1), 2024 had record-high frequencies for the second consecutive year. For  $T_wX25$ ,  $T_wX27$ , and  $T_wX29$ , these anomalies (with respect to the 1991–2020 base period) were 11.0 days, 13.8 days, and 1.7 days, respectively.  $T_wX31$  anomalies were tied for record-most frequent with both 2023 and 1998, at 0.2 days. In much of the tropics, almost every day of the year exceeds the  $T_w=25$  °C threshold. Hence, the maximum possible globally averaged anomaly for  $T_wX25$  is constrained and therefore can be less than the anomalies for  $T_wX27$ .

In 2024, most global land regions experienced more intense ( $T_wX$ ) and more frequent ( $T_wX90p$ ) high daily-maximum humid-heat days than the 1991–2020 average (Plates 2.1j ,k; Fig. 2.d.2.2e, f). The frequency of high daily-maximum humid heat was particularly high over India, Southeast Asia, East Asia, Australia, the Caribbean, Central America, and Europe (Plate 2.1k; Fig 2.d.2.2f). There were several small regions of negative anomalies, which are mostly consistent between  $T_wX$  and  $T_wX90p$ ; these occurred notably east of the Caspian Sea, in Mongolia, around the Red Sea, in western portions of South America, and in the Sonoran Desert of northwestern Mexico and the southwestern United States. High daily-minimum humid-heat anomalies (positive) for  $T_wN$  and  $T_wN90p$  (Appendix Figs. A2.d.2.1, A2.d.2.2b), were marginally more ubiquitous than for  $T_wX$  and  $T_wX90p$ .

Figure 2.d.2.2 presents 2024 indices by their decile relative to the historical record. Southeast Asia, eastern China, southern Japan, India, and northern Australia stood out as regions where  $T_wX25$  and  $T_wX27$  exceedances were ‘very unusually frequent’ (top decile; Figs. 2.d.2.2a,b). This was similar to 2023, but 2024 also had more widespread ‘very unusually frequent’ exceedances for the threshold of  $T_wX29$  (Fig. 2.d.2.2c)—notably over eastern China and southern Japan, reflecting a record-setting high-humid-heat event in July and early August. Counting only gridboxes where exceedances of the respective thresholds occurred climatologically ( $\geq 15$  years within the 1991–2020 period), 24%–37% of the 2024 gridbox-level high-humid-heat frequency fell in the ‘very unusually frequent’ category and just 0%–4% in the ‘very unusually infrequent’ category (not shown).

High humid heat is of particular concern to human health (Xu et al. 2025), including its daily-maximum values (Matthews et al. 2025) and nighttime values (Okamoto-Mizuno et al. 1999). This year, four new indices are introduced. We present the annual median daily-minimum wet-bulb temperature ( $T_{wN}$ ) and frequency of days with unusually high minimum wet-bulb temperature ( $T_{wN90p}$ ). We also introduce low humid-heat (i.e., fresh-cool) day frequencies ( $T_{wX10p}$ ,  $T_{wN10p}$ ), defined in Table 2.d.2.1 (Figs. 2.d.2.1a–c). Daily-minimum wet-bulb temperatures are not always representative of nighttime wet-bulb temperatures, and so we avoid that distinction here. The timeseries of  $T_{wN}$  indices closely follow the  $T_{wX}$  equivalents.  $T_{wN}$  in 2024 was well above average ( $+0.7^{\circ}\text{C}$ ) and only a fraction of a degree cooler than 2023.  $T_{wN90p}$  was 34.4 days above average in 2024, breaking the record set in 2023 (23.8 days). Overall, 1973–2024 trends in daily-minimum and daily-maximum humid-heat intensity ( $T_{wX}=0.13\pm0.03\text{ decade}^{-1}$ ;  $T_{wN}=0.18\pm0.03^{\circ}\text{C decade}^{-1}$ ) and high humid-heat frequency ( $T_{wX90p}=5.36\pm1.73\text{ days year}^{-1}\text{ decade}^{-1}$ ;  $T_{wN90p}=5.39\pm1.50\text{ days year}^{-1}\text{ decade}^{-1}$ ) were all similar, robustly portraying increasing humid heat.

As for the equivalent dry-bulb temperature extremes (section 2.b.4), frequencies of low humid-heat days (Fig. 2.d.2.1c) have decreased substantially, with the rate being similar to but slightly faster than for high humid-heat days.  $T_{wX10p}$  and  $T_{wN10p}$  were 19 days and 18.4 days below the 1991–2020 average in 2024, respectively, both of which were new record lows.

**Table 2.d.2.1. Definitions of 10 humid-heat indices and their respective recent global land annual anomalies (1991–2020 base period). The global annual anomalies for the exceedance indices (not  $T_wX$  or  $T_wN$ ) are the sum of the monthly spatial means over the globe. For  $T_wX$  and  $T_wN$ , the median is used as a more robust measure in the presence of outliers, finding the median first over space for each month and then over time.**

| Index     | Description                                                                                                               | Meaning                                                                       | 2021<br>Global<br>Anomaly | 2022<br>Global<br>Anomaly | 2023<br>Global<br>Anomaly | 2024<br>Global<br>Anomaly |
|-----------|---------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| $T_wX$    | Annual median of monthly maximum wet-bulb temperature                                                                     | Intensity of daily maximum humid heat                                         | 0.2°C                     | 0.1°C                     | 0.6°C                     | 0.5°C                     |
| $T_wN$    | Annual median of monthly minimum wet-bulb temperature                                                                     | Intensity of daily minimum humid heat                                         | 0.3°C                     | 0.2°C                     | 0.7°C                     | 0.7°C                     |
| $T_wX90p$ | Days per year exceeding the 90th percentile of the climatological daily maximum wet-bulb temperature (seasonally varying) | Frequency of high daily maximum humid-heat days relative to local climatology | 8.4 days                  | 7.5 days                  | 26.1 days                 | 35.6 days                 |
| $T_wX10p$ | Days per year below the 10th percentile of the climatological daily maximum wet-bulb temperature (seasonally varying)     | Frequency of low daily maximum humid-heat days relative to local climatology  | –8.1 days                 | –6.8 days                 | –14.8 days                | –19 days                  |
| $T_wN90p$ | Days per year exceeding the 90th percentile of the climatological daily minimum wet-bulb temperature (seasonally varying) | Frequency of high daily minimum humid-heat days relative to local climatology | 6.4 days                  | 6.7 days                  | 23.8 days                 | 34.4 days                 |
| $T_wN10p$ | Days per year below the 10th percentile of the climatological daily minimum wet-bulb temperature (seasonally varying)     | Frequency of low daily minimum humid-heat days relative to local climatology  | –6.2 days                 | –5.9 days                 | –12.6 days                | –18.4 days                |
| $T_wX25$  | Days per year where the daily maximum wet-bulb temperature was $\geq 25^\circ\text{C}$                                    | Frequency of moderately extreme humid-heat days                               | 3.6 days                  | 4.1 days                  | 6.1 days                  | 11.0 days                 |
| $T_wX27$  | Days per year where the daily maximum wet-bulb temperature was $\geq 27^\circ\text{C}$                                    | Frequency of extreme humid-heat days                                          | 3.6 days                  | 3.5 days                  | 9.3 days                  | 13.8 days                 |
| $T_wX29$  | Days per year where the daily maximum wet-bulb temperature was $\geq 29^\circ\text{C}$                                    | Frequency of very extreme humid-heat days                                     | 0.4 days                  | 0.5 days                  | 1.4 days                  | 1.7 days                  |
| $T_wX31$  | Days per year where the daily maximum wet-bulb temperature was $\geq 31^\circ\text{C}$                                    | Frequency of severe humid-heat days                                           | 0.1 days                  | –0.0 days                 | 0.2 days                  | 0.2 days                  |

(j) Maximum  $T_{wet}$

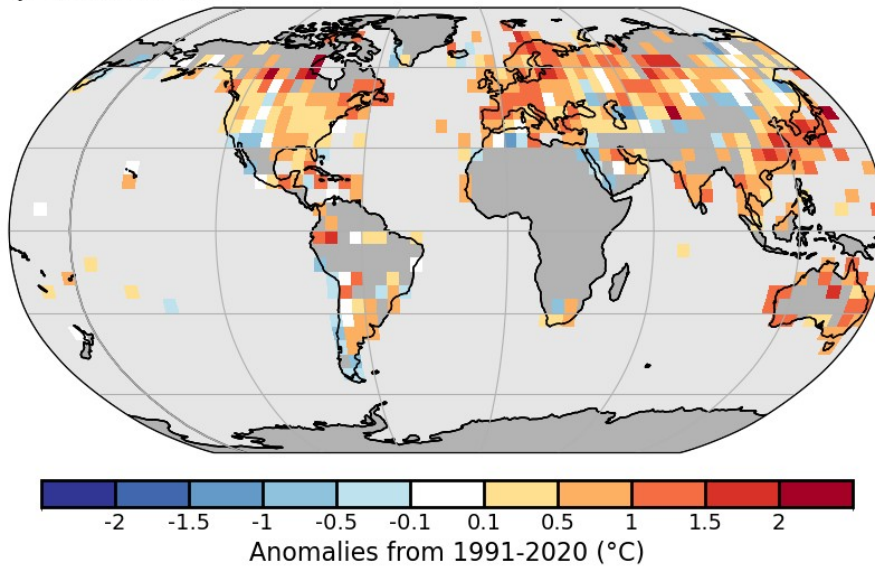


**Plate 2.1j.** 2024 daily-maximum humid-heat intensity anomalies as measured by the annual median of global median monthly daily-maximum wet-bulb temperature ( $T_wX$ ) from HadISDH.extremes. White gridboxes (over land) represent regions with insufficient data.

(k) High humid-heat days ( $TwX90p$ )

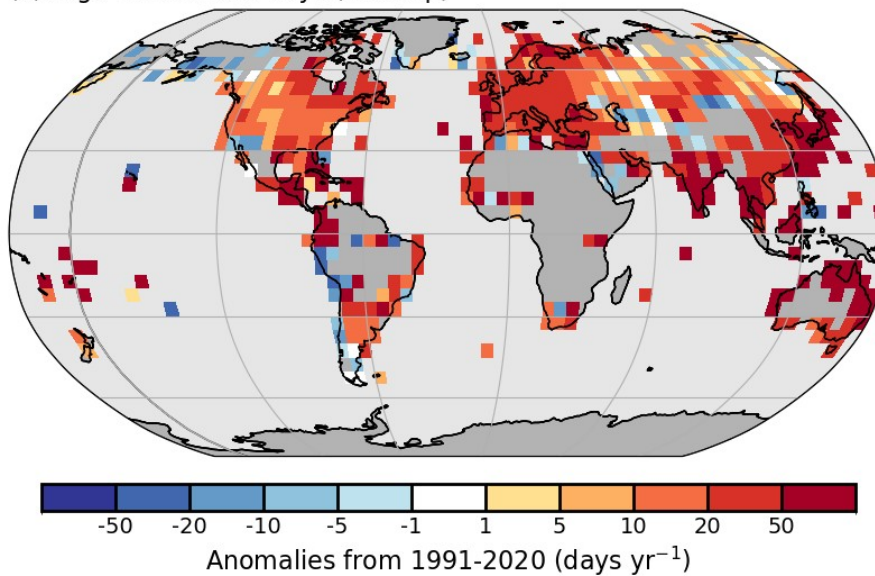
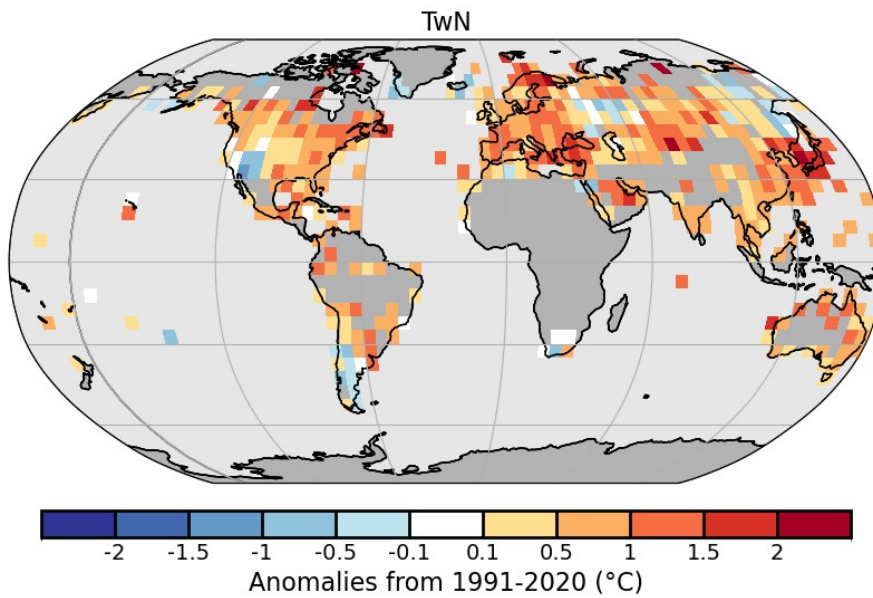
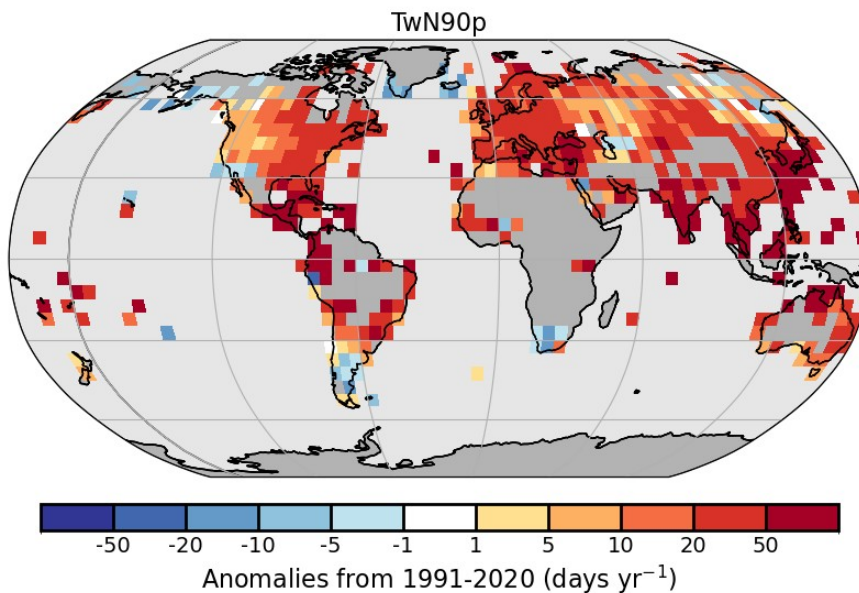


**Plate 2.1k.** 2024 high daily-maximum humid-heat frequency anomalies as measured by the number of days where the maximum wet-bulb temperature exceeds the local daily 90th percentile ( $T_wX90p$ , calculated over the 1991–2020 period) from HadISDH.extremes. White gridboxes (over land) represent regions with insufficient data.



**Appendix Fig. A2.d.2.1.** 2024 daily-minimum humid-heat intensity as measured by the annual median of the global median monthly daily-minimum wet-bulb temperature ( $T_{wN}$ ) from HadISDH.extremes. White gridboxes (over land) represent regions with insufficient data.



**Appendix Fig. A2.d.2.2.** 2024 high daily-minimum humid-heat frequency anomalies as measured by the number of days where the daily minimum wet-bulb temperature exceeds the

local daily 90th percentile (calculated over the 1991–2020 period) from

HadISDH.extremes. White gridboxes (over land) represent regions with insufficient data.

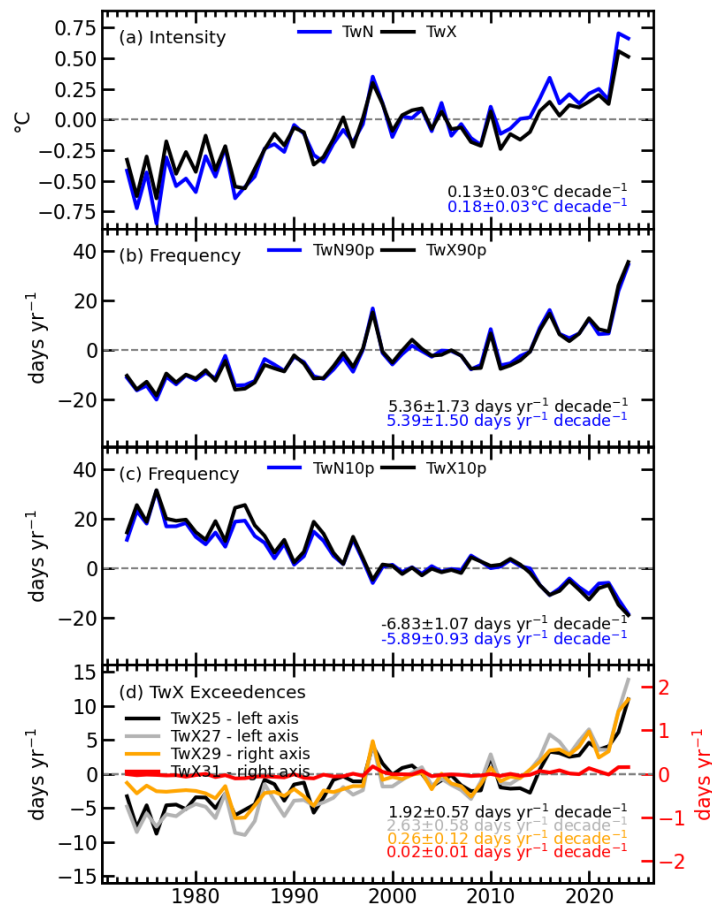


**Fig. 2.d.2.1.** Global land annual anomaly timeseries of various daily maximum and minimum wet-bulb temperature indices from HadISDH.extremes, relative to a 1991–2020 base period. Decadal trends (significant at  $p < 0.01$ ) are also shown. Trends were fitted using an ordinary least-squares linear regression with an autoregressive (1) correction following Santer et al. (2008). (a) Anomaly of the annual median of the global median monthly daily-maximum (black) and daily-minimum (blue) wet-bulb temperature ( $^\circ\text{C}$ ). (b) Anomaly of the annual sum of days where maximum (black) and minimum (blue) wet-bulb temperature exceeds the locally defined daily 90th percentile. (c) Anomaly of the annual sum of days where maximum (black) and minimum (blue) wet-bulb temperature is lower than the locally defined daily 10th percentile. (d) Anomalies of the annual sums of days where the maximum wet-bulb temperature  $\geq 25^\circ\text{C}$ ,  $27^\circ\text{C}$ ,  $29^\circ\text{C}$ , and  $31^\circ\text{C}$  thresholds. Note that coverage is skewed towards the northern extratropical latitudes with large data gaps over Africa and considerable gaps

over South America, Australia, and parts of Central Asia (see Plates 2.1j,k for spatial coverage).

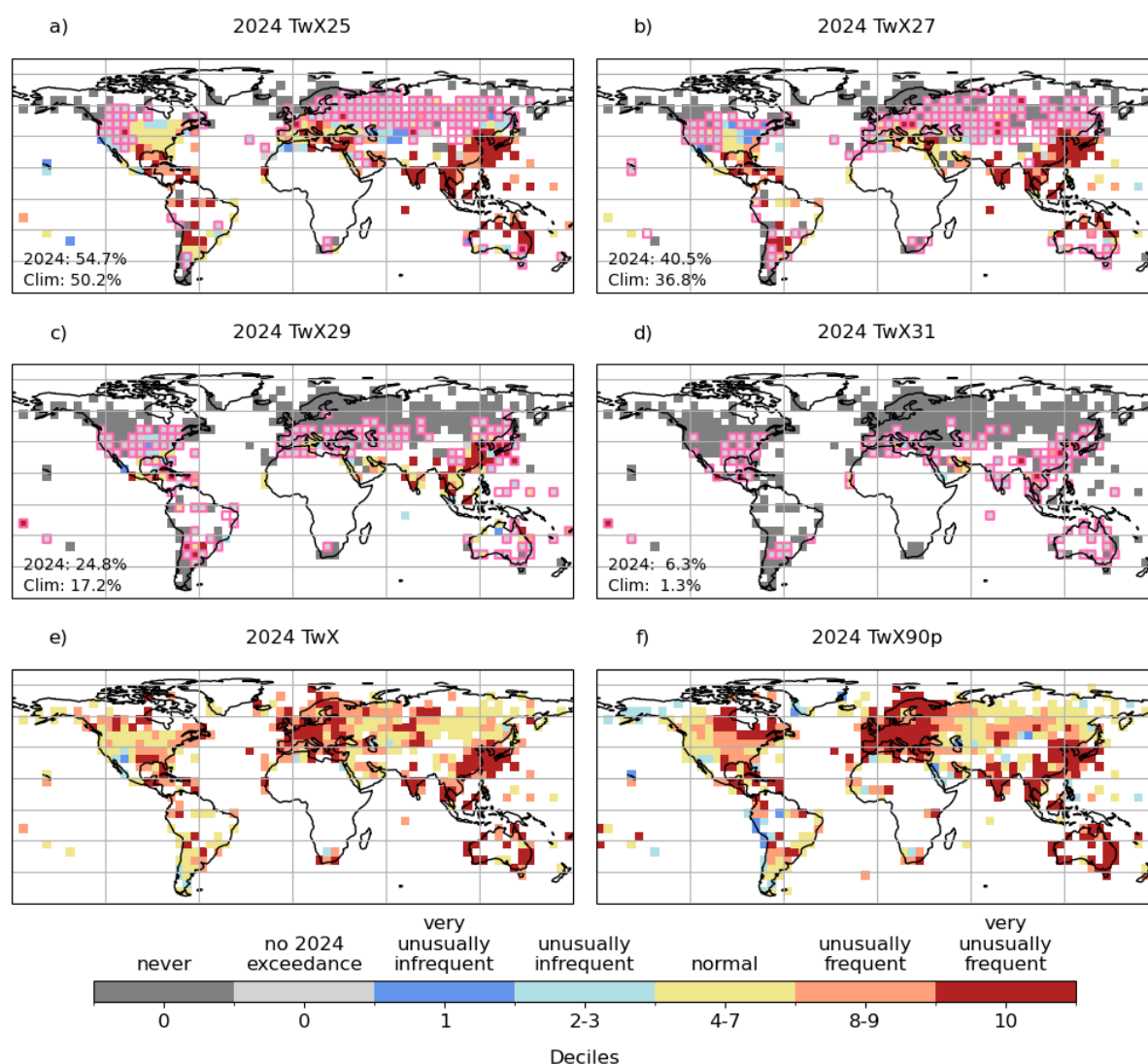


**Fig. 2.d.2.2.** High humid-heat extremes of 2024 as deciles over the period 1973–2024, ranking the number of days with maximum  $T_w \geq$  (a)  $25^\circ\text{C}$  ( $T_wX25$ ), (b)  $27^\circ\text{C}$  ( $T_wX27$ ), (c)  $29^\circ\text{C}$  ( $T_wX29$ ), and (d)  $31^\circ\text{C}$  ( $T_wX31$ ), (e) the annual median of monthly maximum  $T_w$  ( $T_wX$ ) as anomalies and (f) annual sum of days with maximum  $T_w >$  local daily 90th percentile ( $T_wX90p$ ) as anomalies. For (a)–(d) only, the gray “never” and “no 2024 exceedance” categories are used, and gridboxes bounded in pink indicate  $<15$  years within the 1991–2020 period when exceedances occur. These panels are annotated with the percentage of observed gridbox area where an exceedance occurred in 2024 and climatologically (including only gridboxes with  $\geq 15$  years of at least one exceedance between 1991–2020). Data have been screened to remove gridboxes where temporal completeness is less than 70% ( $<36$  years in 52), with whole years removed if one or more months are missing.

