

Slopes rarely out-warm the floor: a 2003–2025 MODIS assessment of deep surface-based night-time inversions over the Malang basin, East Java

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Abstract

Nocturnal cold-air pools can trap heat and pollutants in basin cities, but tropical basins are seldom monitored. We assessed deep surface-based night-time inversions over the Malang basin, East Java, Indonesia, from 2003–2025 MODIS Terra and Aqua night-time land surface temperature (LST), using the difference ΔT between a slope band (900–1300 m; mean 1079 m) and the rural basin floor (≤ 600 m; mean 449 m). Of 8395 nights, 2017 had sufficient clear-sky coverage. The slope band was colder than the floor on 98 % of clear nights (median ΔT -3.1 °C, against -4.1 °C for a standard atmosphere). $\Delta T > 0$ occurred on 1.7 % of clear nights (35 nights; 95 % confidence interval 1.3–2.4 %) and on 1.3–2.2 % under a view-angle limit, removal of valley-floor pixels from the slope band and a fixed-pixel anomaly index, with median ΔT changing by less than 0.3 °C. Night-to-night variation in ΔT was not reproduced by the two overpasses about three hours apart (Spearman $\rho = 0.05$ on 351 shared nights), implying a per-overpass error of about 1 °C, as large as the night-to-night spread. A noise-only model accounts for the nights with $\Delta T > 0$ observed by Terra alone or by both sensors, but not for those observed by Aqua alone (29 observed, 3–14 expected, a lower bound because the error estimate comes from the clearest nights), which include all 14 nights with $\Delta T > 1$ °C. These nights were cloudy at $\sim 22:30$ and clear at $\sim 01:30$, wetter than average, and had an anomalously cold floor (median -4.5 °C) beneath near-normal slopes, consistent with post-rain cold pools, fog or residual cloud. After season adjustment, nights with $\Delta T > 0$ were not calmer by ERA5-Land wind and only weakly wetter. Their frequency rose after 2015 in the Aqua record only. The night-time surface urban heat island was 0.9 °C and did not affect the result. At the MODIS overpass times and 1 km scale, slopes 630 m above the floor rarely out-warm it; MODIS LST constrains the climatology of this contrast but does not identify individual inversion nights.

Plain-language summary

On calm, clear nights, cold air can pool in a valley beneath warmer air, trapping heat and pollution over the city below. We used 23 years of night-time satellite temperature measurements to check how often the hillsides around Malang, a city in a mountain-ringed basin in East Java, are warmer than the valley floor, a sign of a deep pool of cold air. This happened on fewer than 2 in 100 clear nights, and the result held when we changed how the satellite data were selected. The satellite measurements are, however, too noisy to say

which particular nights had a cold-air pool: two satellites passing three hours apart did not agree from night to night. Many of the candidate nights followed rain and may involve fog or thin cloud. The city's surfaces were almost 1 °C warmer than nearby farmland at night, but that did not change the result. Shallower cold-air pools, below the hillsides we measured, need weather stations or balloon soundings to detect.

Keywords: temperature inversion; cold-air pool; MODIS land surface temperature; retrieval uncertainty; surface urban heat island; ERA5-Land; Indonesia

1 Introduction

On clear, calm nights, radiative cooling of valley floors and drainage of cold air from surrounding slopes produce nocturnal temperature inversions and cold-air pools in basins (Whiteman, 2000). Where a city occupies the basin floor, such inversions limit vertical mixing, concentrate pollutants near the ground and shape the distribution of minimum temperatures (Lareau et al., 2013; Espín Sánchez et al., 2022). Most of what is known about basin inversions comes from mid-latitude field campaigns with dense instrumentation; tropical basin cities, where population growth is rapid and monitoring is sparse, are much less studied.

Satellite land surface temperature (LST) offers a way around the lack of stations. Night-time MODIS LST has been used to estimate near-surface lapse rates (Wang et al., 2018) and to identify cold-air pools, with station validation giving R^2 of 0.87–0.88 (Espín Sánchez et al., 2022). Two cautions apply. First, LST is a radiative skin temperature, and in complex terrain the elevational LST signal can be dominated by land-cover contrasts rather than by air temperature (Pepin et al., 2019). Second, gradients from 1 km MODIS pixels agree with coarse-scale air-temperature gradients but miss fine-scale inversions produced by cold-air drainage (Collados-Lara et al., 2021). A third caution is less often quantified: whether the night-to-night variation of an LST-based index exceeds its retrieval noise.

Malang, East Java, is a city on the floor of a basin ringed by volcanic massifs. The basin attracted public attention in February 2021, when loud booms heard across the city were attributed by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) to distant thunder trapped beneath an inversion layer (Antara, 2021). That explanation invokes a capping layer over the basin, yet no multi-year record of night-time inversions exists for Malang. Sound ducting depends mainly on elevated inversions and wind shear; the present study addresses a narrower and observable quantity, the deep surface-based inversion, in which cold air fills the basin to a height at which the slopes are warmer than the floor.

Here we build a 23-year record of the slope–floor LST contrast from MODIS night-time LST and ask four questions: (i) how often the slope band is warmer than the floor at the MODIS overpass times; (ii) whether this frequency is robust to retrieval choices, and whether individual nights can be classified reliably; (iii) whether nights with a warmer slope band are calmer, wetter, or followed by higher tropospheric NO_2 ; and (iv) how large the city's night-time surface urban heat island (SUHI) is, and whether it affects the index. The heat island measured here is the surface heat island, defined from radiative skin temperature, not the

canopy-layer heat island in air temperature; the two differ in magnitude and timing (Oke et al., 2017). All processing is done in Google Earth Engine (Gorelick et al., 2017) and released as an open notebook.

2 Study area

The analysis box spans 112.45–112.85°E and 8.20–7.80°S and contains the city of Malang and its surroundings (Figure 1). The basin floor, defined as 1 km pixels at or below 600 m, has a mean elevation of 449 m. It is bounded by the Arjuno–Welirang massif to the north-west, Kawi–Butak to the west and the Tengger–Semeru complex to the east. The slope band lies between 900 and 1300 m (mean 1079 m), 630 m above the mean floor; it includes some valley-floor pixels, for example around Batu north-west of Malang. The region has a monsoonal climate with a dry season from about May to October and a wet season from about November to April. After land-cover filtering (Section 4.1) the floor zone contains 805 pixels and the slope band 361; a further 121 floor pixels that are at least 50 % built-up form the urban floor.

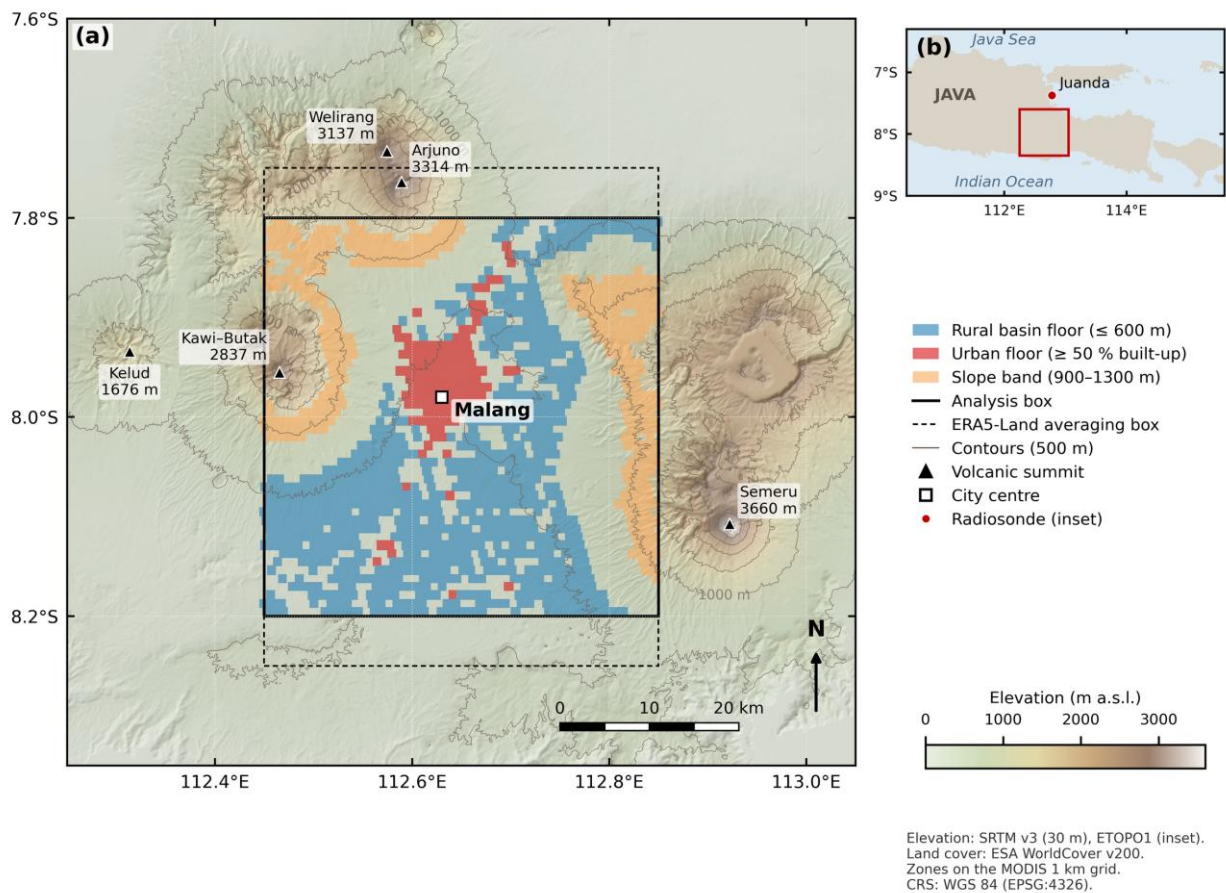


Figure 1. Study area. (a) Rural basin floor (≤ 600 m, built-up and water fractions ≤ 20 %), urban floor (≥ 50 % built-up; used for the SUHI) and slope band (900–1300 m) on the MODIS 1 km grid, with the analysis box (solid) and the ERA5-Land averaging box (dashed), over SRTM elevation with 500 m contours. (b) Location in East Java and the Juanda radiosonde station.

3 Data

All gridded datasets were accessed through Google Earth Engine in October 2026 (Table 1). Radiosonde data were downloaded from the Integrated Global Radiosonde Archive version 2 (IGRA v2; Durre et al.,

2006, 2018). Each collection was checked for images at the start and end of the study period and for the bands used.

Table 1. Datasets.

Dataset (identifier)	Variables	Resolution	Period	Use
MODIS Terra/Aqua LST v061 (MODIS/061/MOD11A1, MYD11A1; Wan, 2014)	LST_Night_1km, QC_Night, Night_view_time, Night_view_angle	~1 km, daily	2003–2025	Inversion index, SUHI, robustness
SRTM v3 (USGS/SRTMGL1_003; Farr et al., 2007)	elevation	30 m	static	Zones, TPI
ESA WorldCover v200 (ESA/WorldCover/v200; Zanaga et al., 2022)	land-cover class	10 m	2021	Land-cover filter
ERA5-Land hourly and daily (ECMWF/ERA5_LAND; Muñoz-Sabater et al., 2021)	10 m wind, surface pressure, precipitation	0.1°, hourly/daily	2003–2025	Stagnation, rainfall
Sentinel-5P TROPOMI OFFL L3 NO ₂ (COPERNICUS/S5P/OFFL/L3_NO2; Veeffkind et al., 2012)	tropospheric NO ₂ column	~1.1 km, daily	2019–2025	Next-day NO ₂
IGRA v2, Juanda (IDM00096935; Durre et al., 2018)	temperature, geopotential height	soundings, 00 UTC	2003–2025	Comparison

4 Methods

4.1 Zones and land-cover control

SRTM elevation was averaged onto the MODIS sinusoidal 1 km grid. Floor pixels are those ≤ 600 m and slope pixels those between 900 and 1300 m. To limit the land-cover confound described by Pepin et al. (2019), pixels with more than 20 % built-up or more than 20 % water cover in ESA WorldCover were excluded from both zones; floor pixels at least 50 % built-up were kept separately as the urban floor. A topographic position index (TPI), the pixel elevation minus the mean elevation within 5 km, identifies valley-floor pixels within the slope band ($TPI < -50$ m); removing them leaves 202 of the 361 slope-band pixels.

4.2 Nightly index

For each Terra (~22:30 local solar time) and Aqua (~01:30) night overpass, LST pixels were retained if the mandatory QA flag indicated good or other quality and the LST error flag was ≤ 2 K. An overpass was used only if at least 30 % of the pixels in both zones were valid. The index is

$$\Delta T = \text{mean LST(slope band)} - \text{mean LST(rural floor)}$$

and nights with $\Delta T > 0$ °C and $\Delta T > 2$ °C are reported. A standard atmosphere (6.5 °C km⁻¹) would make the slope band 4.1 °C colder than the floor. Because both terms are skin temperatures, $\Delta T > 0$ means that the slope surface about 630 m above the floor is warmer than the floor surface, the signature of a cold-air pool deep enough to reach the slope band (Whiteman, 2000). The index does not detect inversions confined below the band or elevated inversions. Overpasses after local midnight were assigned to the preceding evening using Night_view_time; when both satellites observed a night, their ΔT values were averaged. The

lapse rate of each overpass is the slope of a least-squares fit of LST on elevation over all filtered pixels below 1300 m.

4.3 Retrieval robustness

The index was recomputed with (a) view zenith angle $\leq 40^\circ$, because off-nadir footprints mix floor and slope; (b) pixels at least 2 km from any cloud-flagged pixel; and (c) the slope band without valley-floor pixels (Section 4.1). A fixed-pixel anomaly index replaces the zone means with the climatological zone difference plus the difference of zone-mean per-pixel anomalies from each sensor's calendar-month climatology, so that partial cloud cover cannot change ΔT by changing which pixels are averaged. Each variant was evaluated at 30 % and 50 % minimum coverage, and the base index at minimum coverage from 30 % to 70 % in steps of 5 %.

4.4 Overpass consistency and noise model

On nights observed by both sensors, the Aqua–Terra difference of ΔT combines retrieval error and real change between ~22:30 and ~01:30. Assuming the true ΔT changes little in three hours, the per-overpass error was estimated as the standard deviation of this difference divided by $\sqrt{2}$. A noise-only null model added errors resampled from the centred, $\sqrt{2}$ -scaled differences to the calendar-month median ΔT (for shared nights, the mean of two draws) and counted nights with $\Delta T > 0$, separately for nights observed by both sensors, by Aqua only and by Terra only (5000 draws).

4.5 Night-time surface urban heat island

The SUHI intensity is the mean LST of the urban floor minus that of the rural floor on the same overpass, kept separate from ΔT .

4.6 Stagnation and rainfall

For each night (18:00–06:00 local) we computed the mean and maximum of hourly ERA5-Land 10 m wind speed, the mean surface pressure and the daily precipitation total, averaged over the 20 whole 0.1° cells covering the box. ERA5-Land is a land-surface replay forced by ERA5 (Hersbach et al., 2020; Muñoz-Sabater et al., 2021), and its near-surface wind does not resolve drainage flows within the basin. Because nights with $\Delta T > 0$ are unevenly distributed across months, each variable was converted to a within-month percentile rank and compared with a month-stratified permutation test (labels permuted within calendar months, 5000 permutations). Runs of consecutive clear nights with $\Delta T > 0$ were counted as episodes; a cloudy night ends a run.

4.7 Interannual variation

Annual frequency of $\Delta T > 0$ (all 23 years had at least 44 clear nights) was tested with least-squares regression, the Theil–Sen estimator and the Mann–Kendall test. Because the MODIS night overpass times drift late in the record, a logistic regression of $\Delta T > 0$ on year, overpass time, wet season and zone coverage was fitted to the individual overpasses of each sensor.

4.8 Next-day NO₂, land cover and radiosonde

TROPOMI overpasses at ~13:30 local, so night D was paired with the tropospheric NO₂ column over the rural floor on day $D + 1$, as a value and as an anomaly from its calendar-month mean. The whole index was recomputed without the land-cover filter. For the radiosonde comparison, the nearest IGRA station, Juanda (IDM00096935; 2.8 m above sea level, 71 km from the box centre), gives at 00 UTC (07 WIB) the warmest temperature among reported levels above the surface and within 1.5 km of it, minus the surface temperature, paired with the MODIS index of the preceding evening.

4.9 Statistics

Proportions are given with 95 % Wilson confidence intervals and compared with Fisher's exact test; distributions with two-sided Mann–Whitney U tests; agreement between variables with Spearman rank correlation.

5 Results

5.1 Sampling

Of 16 756 overpasses, enough cloud-free pixels were available on 2017 of 8395 nights (24 %): 351 observed by both sensors, 1015 by Aqua only and 651 by Terra only. Sampling follows the monsoon: July and August each contributed 350–380 clear nights over the 23 years, whereas December, January and February each contributed fewer than 25 (Figure 2c). Results for the wet season therefore rest on few nights.

5.2 Slope–floor contrast

The slope band was colder than the floor on 98.3 % of clear nights. The median ΔT was -3.10 °C (interquartile range -3.56 to -2.56 °C), and monthly medians ranged from -3.02 °C in July to -3.76 °C in December (Figure 2b). The median lapse rate was -4.9 °C km⁻¹ (interquartile range -5.6 to -4.0), and ΔT exceeded the standard-atmosphere value of -4.1 °C on 93 % of clear nights. $\Delta T > 0$ occurred on 1.7 % of clear nights (35 nights; 95 % CI 1.3–2.4 %) and $\Delta T > 2$ °C on five: 30 July 2016, 8 August 2022, 8 December 2023, and 6 and 28 April 2025. By month, frequency was zero in January, March and May, 1.0–2.5 % from June to November, and higher in February (2 of 15 nights), April (7 of 89) and December (1 of 13) (Figure 2a). Pooled, the wet season (November–April) had 4.4 % (12 of 271) against 1.3 % in the dry season (23 of 1746; Fisher $p = 0.001$). The 35 nights formed 34 episodes; the longest, 11–12 April 2003, lasted two nights.

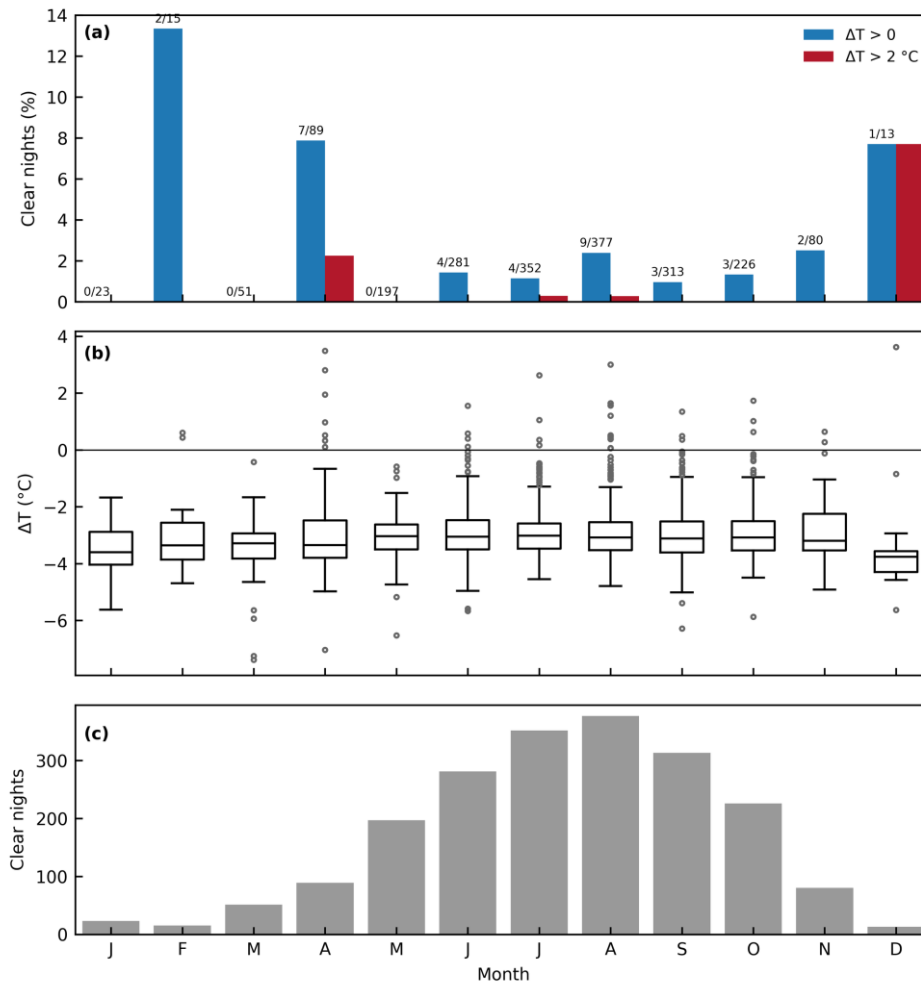


Figure 2. Seasonal cycle, 2003–2025. (a) Percentage of clear nights with $\Delta T > 0$ and $\Delta T > 2$ °C; labels give nights with $\Delta T > 0$ and clear nights. (b) Distribution of ΔT (slope band minus rural floor) by month. (c) Clear nights per calendar month, all years.

5.3 Retrieval robustness

The frequency of $\Delta T > 0$ and the median ΔT changed little across the variants (Table 2; Figure S1). Limiting the view zenith angle to 40° gave 1.3 % (12 of 896 nights), removing valley-floor pixels from the slope band gave 2.2 % (44 of 2035) with a median ΔT 0.24 °C less negative, and the fixed-pixel anomaly index gave 1.5 % (30 of 2017). Between 30 % and 60 % minimum coverage the frequency stayed between 1.4 % and 2.2 %; at 65 % and 70 % none of 62 and 26 nights had $\Delta T > 0$, which at the base rate of 1.7 % has probability 0.34 and 0.63. Median zone coverage on overpasses with $\Delta T > 0$ was the same as on other overpasses (floor 0.47 vs 0.45; slope band 0.50 vs 0.51). The 2 km cloud buffer left 77 nights, none with $\Delta T > 0$ (95 % CI 0–4.8 %).

Table 2. Retrieval robustness. Frequency of $\Delta T > 0$ per clear night, median ΔT and Spearman correlation of Aqua and Terra ΔT on nights observed by both sensors. VZA: view zenith angle; TPI: topographic position index.

Index and pixel selection	Min. coverage	Nights	$\Delta T > 0$	% (95 % CI)	Median ΔT (°C)	Aqua–Terra ρ (n)
Zone mean, base	30 %	2017	35	1.7 (1.3–2.4)	–3.10	0.05 (351)
Zone mean, base	50 %	500	9	1.8 (0.9–3.4)	–3.11	– (10)
Zone mean, VZA $\leq 40^\circ$	30 %	896	12	1.3 (0.8–2.3)	–3.22	– (7)
Zone mean, 2 km cloud buffer	30 %	77	0	0.0 (0.0–4.8)	–3.06	– (0)
Zone mean, valley floors removed (TPI ≥ -50 m)	30 %	2035	44	2.2 (1.6–2.9)	–2.86	0.04 (356)
Zone mean, valley floors removed (TPI ≥ -50 m)	50 %	518	12	2.3 (1.3–4.0)	–2.83	–0.18 (11)
Fixed-pixel anomaly, base	30 %	2017	30	1.5 (1.0–2.1)	–3.10	0.06 (351)

Variants with fewer than ten nights at 50 % coverage (VZA $\leq 40^\circ$: 1 of 128; cloud buffer: 0 of 2) are listed in Table S1.

5.4 Sensor consistency and night types

On the 351 nights observed by both sensors, Aqua and Terra ΔT were uncorrelated (Spearman $\rho = 0.05$, $p = 0.38$; Figure 3a). Their variances were 1.06 and 0.88 °C² and their covariance 0.03 °C², so almost none of the night-to-night variance is common to the two overpasses. The implied per-overpass error is 0.97 °C, against a standard deviation of 1.03 °C for the nightly index. Aqua flagged $\Delta T > 0$ on 4 and Terra on 5 of the shared nights, on no night in common; with flags this rare, 0.06 joint detections would be expected even if they were independent. After averaging, none of the shared nights had $\Delta T > 0$ (95 % CI 0–1.1 %).

Over all clear nights, Aqua recorded $\Delta T > 0$ on 2.4 % of its nights (33 of 1366) and Terra on 1.1 % (11 of 1002; Fisher $p = 0.020$). The difference lies in the nights observed by one sensor only: 29 of 1015 Aqua-only nights (2.9 %; 95 % CI 2.0–4.1 %) against 6 of 651 Terra-only nights (0.9 %; 0.4–2.0 %). The noise-only model reproduces the shared nights (0 observed, 0.1 expected) and the Terra-only nights (6 observed, 5.1 expected, 95 % range 1–10), but not the Aqua-only nights (29 observed, 7.6 expected, 3–14; none of 5000 draws reached 29) (Figure S2). All 14 nights with $\Delta T > 1$ °C, including the five above 2 °C, are Aqua-only nights; the largest ΔT on a Terra-only night was 0.52 °C (Table S3). Aqua-only nights, on which the scene was cloudy at ~22:30 and clear at ~01:30, were wetter than other clear nights (median within-month precipitation percentile 57 against 45) and more often in the wet season (17 % against 12 % and 6 %).

On all 35 nights with $\Delta T > 0$ the rural-floor LST was at least 2.2 °C below its calendar-month mean (median –4.5 °C), whereas the slope band was 0.5 °C below its mean (Figure S3). Because ΔT on other nights is about –3 °C, a large negative floor anomaly is required for $\Delta T > 0$; the informative result is that the slope band was near normal, not warmer than normal.

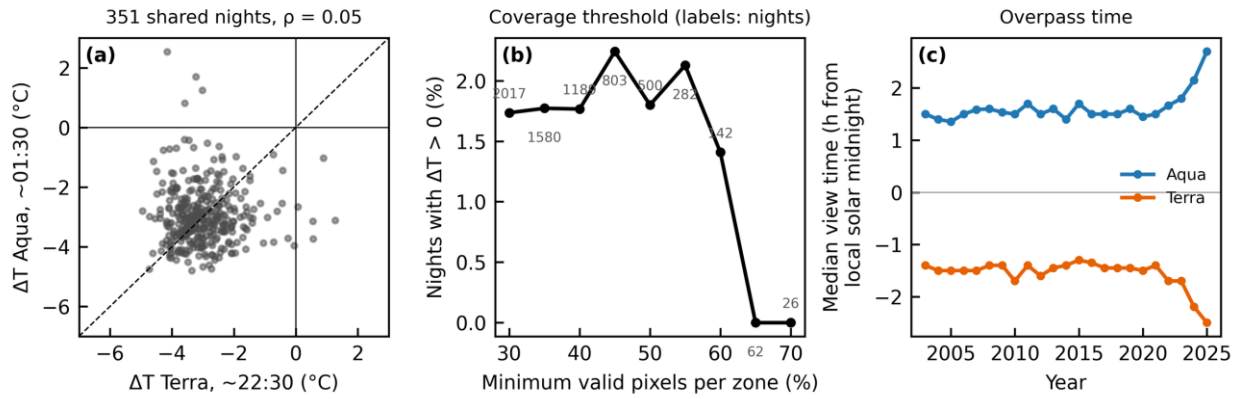


Figure 3. Diagnostics. (a) Terra (~22:30) against Aqua (~01:30) ΔT on the 351 nights observed by both sensors; dashed line 1:1. (b) Percentage of clear nights with $\Delta T > 0$ against the minimum fraction of valid pixels required in each zone; labels give the number of clear nights. (c) Median overpass time by year and sensor, in hours from local solar midnight.

5.5 Stagnation and rainfall

Without season adjustment, nights with $\Delta T > 0$ had similar night-mean wind (median 1.08 vs 1.16 m s^{-1} , $p = 0.20$) and higher daily precipitation (1.34 vs 0.58 mm, $p = 0.0015$). After conversion to within-month percentiles, they sat at the 50th percentile of night-mean wind (permutation $p = 0.91$), the 56th of maximum wind ($p = 0.85$), the 49th of surface pressure ($p = 0.30$) and the 66th of precipitation ($p = 0.035$) (Figure 5). Most of the raw precipitation contrast therefore reflects the seasonal distribution of these nights.

5.6 Interannual variation and overpass time

Annual frequency of $\Delta T > 0$ increased by 1.4 percentage points per decade by least squares ($p = 0.043$), by 0.9 by Theil–Sen, and the Mann–Kendall test was not significant ($\tau = 0.28$, $p = 0.07$). The record resembles a step: 0.8 % of clear nights in 2003–2014 (9 of 1109) against 2.9 % in 2015–2025 (26 of 908), with no nights with $\Delta T > 0$ in 2006, 2008, 2010 or 2012–2015. The change is confined to Aqua-only nights (7 of 545 before 2015, 22 of 470 after), and to the Aqua record (Figure 4). In the logistic model the Aqua year coefficient was +0.96 per decade (odds ratio 2.6; $p = 0.002$) after adjustment for overpass time ($p = 0.19$), season and coverage, and the Terra coefficient +0.33 ($p = 0.49$). Median overpass times were stable at about 01:30 (Aqua) and 22:30 (Terra) until 2021 and drifted to 02:42 and 21:30 by 2025 (Figure 3c).

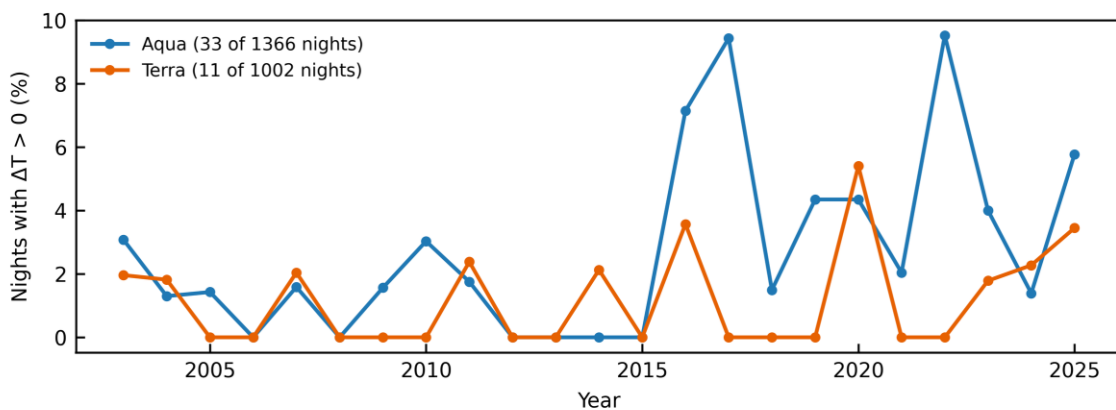


Figure 4. Annual percentage of clear nights with $\Delta T > 0$, by sensor.

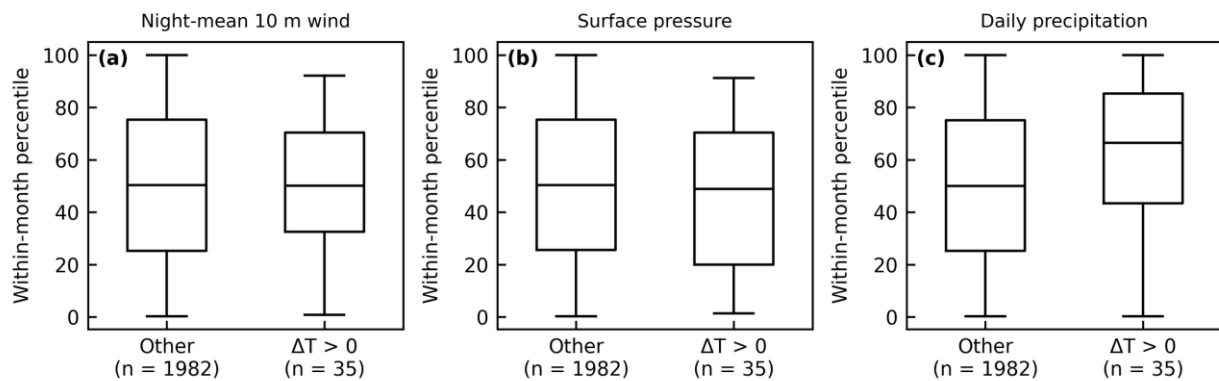


Figure 5. Season-adjusted meteorology on nights with $\Delta T > 0$ and other clear nights: within-month percentile ranks of (a) ERA5-Land night-mean 10 m wind speed, (b) night-mean surface pressure and (c) daily precipitation.

5.7 SUHI, land cover, NO_2 and radiosonde

The SUHI was positive on 91 % of the 879 nights with enough valid urban pixels, with a median of 0.92 °C (interquartile range 0.51–1.38 °C). Without the land-cover filter, $\Delta T > 0$ occurred on 1.5 % of 2146 clear nights; on the 1930 nights valid in both versions, 30 of the 36 nights flagged by either version were flagged by both, ΔT shifted by a median of 0.12 °C, and by more than 1 °C on 18 nights (Figure S4). Of 516 clear nights followed by a valid TROPOMI day, 12 had $\Delta T > 0$; next-day NO_2 did not differ (anomaly +2.1 vs −1.1 $\mu\text{mol m}^{-2}$, $p = 0.44$; Figure S5). Juanda radiosonde inversion strength was uncorrelated with ΔT ($\rho = 0.03$, $p = 0.18$, $n = 1667$; Figure S6); the soundings showed a low-level inversion on 38 nights and MODIS $\Delta T > 0$ on 29, with none in common.

Table 3. Summary of results (land-cover filter on unless stated).

Quantity	Value
Floor / slope band / urban floor pixels (slope band without valley floors)	805 / 361 / 121 (202)
Mean elevation, floor / slope band	449 m / 1079 m
Clear nights (of 8395): both sensors / Aqua only / Terra only	2017 (24 %): 351 / 1015 / 651
Median ΔT (interquartile range); median lapse rate	−3.10 °C (−3.56 to −2.56); −4.9 °C km ^{−1}
Nights with $\Delta T > 0$; $\Delta T > 2$ °C	35 (1.7 %; 95 % CI 1.3–2.4 %); 5
$\Delta T > 0$ across robustness variants	1.3–2.2 %; median ΔT −3.22 to −2.83 °C
Aqua–Terra ΔT on shared nights	$\rho = 0.05$; covariance 0.03 °C ² ; per-overpass error 0.97 °C
$\Delta T > 0$, observed vs noise-only expected (95 % range)	Aqua only 29 vs 7.6 (3–14); Terra only 6 vs 5.1 (1–10); shared 0 vs 0.1
$\Delta T > 0$, wet / dry season	4.4 % / 1.3 % ($p = 0.001$)
Floor / slope LST anomaly on $\Delta T > 0$ nights (median)	−4.5 °C / −0.5 °C
Within-month percentile on $\Delta T > 0$ nights: wind, pressure, precipitation	50 ($p = 0.91$), 49 ($p = 0.30$), 66 ($p = 0.035$)
$\Delta T > 0$, 2003–2014 / 2015–2025	0.8 % / 2.9 %
Logistic year coefficient, Aqua / Terra	+0.96 per decade ($p = 0.002$) / +0.33 ($p = 0.49$)
Median overpass time, 2003–2021 → 2025	Aqua 01:30 → 02:42; Terra 22:30 → 21:30
Night-time SUHI (median, IQR)	+0.92 °C (0.51–1.38), positive on 91 % of 879 nights
Land-cover filter: nights flagged by both / either version	30 / 36

Quantity	Value
Next-day NO ₂ anomaly, $\Delta T > 0$ vs other (n = 12 / 504)	+2.1 vs -1.1 $\mu\text{mol m}^{-2}$ ($p = 0.44$)
Radiosonde comparison (Juanda, n = 1667)	$\rho = 0.03$ ($p = 0.18$)

6 Discussion

6.1 Slopes rarely out-warm the floor

At the MODIS overpass times and at 1 km scale, the slope band 630 m above the floor is warmer than the floor on 1.3–2.3 % of clear nights in every variant evaluated on 500 or more nights, and the median contrast of about -3°C changes by less than 0.3°C between variants. The typical gradient is weaker than a standard atmosphere, which points to a stable nocturnal layer, but a cold-air pool deep enough to leave the 900–1300 m slopes warmer than the floor is rare. This frequency is not a lower bound on inversions in general. An inversion confined to the lowest 100–300 m and topped by a normal lapse rate would leave the slope band colder than the floor; 1 km pixels average out drainage channels where fine-scale inversions are strongest (Collados-Lara et al., 2021); and the overpasses sample the evening and early night, before the coldest hours near dawn.

6.2 Individual nights are not resolved

Two overpasses three hours apart share almost none of their night-to-night variation in ΔT , and the implied retrieval error (about 1°C per overpass) is as large as the night-to-night spread of the index. Real changes in the nocturnal boundary layer between $\sim 22:30$ and $\sim 01:30$ contribute to the Aqua–Terra difference, so 0.97°C is an upper bound on the error; but if a substantial part of the night-to-night variation were real and persistent over three hours, the two sensors would be correlated. The index therefore constrains the climatological contrast, which averages over many nights, but cannot classify individual nights. The catalogue of nights with $\Delta T > 0$ (Table S3), the episode counts and the pairing of nights with next-day NO₂ inherit this limitation.

6.3 The Aqua-only excess: cold pools after rain, fog or cloud

The noise-only model explains the nights with $\Delta T > 0$ seen by Terra alone or by both sensors, but not the excess on Aqua-only nights, which also contain every night with $\Delta T > 1^\circ\text{C}$. The model draws its errors from the 351 shared nights, the clearest in the record. Aqua-only nights are partly cloudy, and their ΔT is more variable (standard deviation 1.19°C , against 1.03°C for Aqua on shared nights), so the model probably underestimates the noise on these nights. The expected count of 7.6 is therefore a lower bound, and the true excess may be smaller than it appears. These nights were cloudy at $\sim 22:30$ and clear at $\sim 01:30$, followed wetter days, and had a floor 2–8 $^\circ\text{C}$ colder than normal beneath near-normal slopes. Three explanations fit. A rain-wetted floor under clearing skies can cool rapidly by evaporation and radiation while the slopes are ventilated, producing a genuine cold pool. Valley fog or low stratus over the floor, itself a product of a moist cold pool, would make MODIS measure the colder fog top rather than the ground. Residual cloud that escapes the QA screening would lower floor LST without any inversion. The view-angle, valley-floor and fixed-pixel variants do not remove the excess, and zone coverage on these nights is

normal, so partial-coverage sampling is not the cause. The present data cannot separate these cases (Section 7).

6.4 Interannual variation

The rise after 2015 is confined to Aqua-only nights and to the Aqua record, survives adjustment for overpass time in the logistic model, and is absent from Terra. Both night overpass times drifted after 2021, by about an hour by 2025, which shifts Aqua towards dawn and Terra towards the evening; this drift postdates the step. We did not test links to interannual rainfall such as the wet dry seasons reported for 2016 and 2022. Because the increase is sensor-specific and concentrated in the category of nights that the noise model does not explain, we do not interpret it as a climatic change.

6.5 NO₂, SUHI and validation

The absence of a next-day NO₂ signal is uninformative: only 12 nights with $\Delta T > 0$ had TROPOMI data, the midday overpass follows several hours of daytime mixing, and individual nights are not reliably classified (Section 6.2). The night-time SUHI of about 0.9 °C is comparable in sign and order of magnitude to surface heat islands reported for other cities (Oke et al., 2017); it should not be read as an air-temperature difference. Because the slope band is almost entirely non-urban and the rural floor excludes built-up pixels, the land-cover filter changed the frequency little. The radiosonde comparison is not a validation in either direction: Juanda lies 71 km away on the coastal plain, its 07 WIB launch follows sunrise, and IGRA provides only standard and significant levels.

6.6 Implications for the 2021 Malang booms

The explanation offered for the February 2021 booms requires a layer that channels sound, which in practice means an elevated inversion or strong wind shear; the slope–floor index cannot detect either. The record shows that deep surface-based inversions reaching the slopes are uncommon at night, especially in the dry season, but it cannot test the night in question: February contributed 15 clear nights in 23 years, and individual nights are not resolved.

7 Future research

Four data sources would resolve the questions this record leaves open. First, air temperature from station pairs at different heights within the basin, such as the BMKG climatology station at Karangploso on the floor and sites on the surrounding slopes, would test the index directly and measure inversions shallower than the slope band, which MODIS cannot see. Second, night-time visibility, present weather and cloud reports from Abdul Rachman Saleh airport on the basin floor would show whether the Aqua-only nights with $\Delta T > 0$ are clear-sky cold pools or fog. Third, hourly geostationary thermal imagery from Himawari-8/9, available since July 2015 (Bessho et al., 2016), would follow the slope–floor contrast through the whole night, including the hours before dawn, and show cloud evolution between the Terra and Aqua overpasses. Fourth, a retrieval with an independent cloud mask and the MOD21/MYD21 temperature–emissivity separation product would test whether residual cloud contributes to the Aqua-only excess. Atmospheric

profiles over the basin, from dedicated soundings or remote sensing, are needed to test the acoustic-ducting explanation of the 2021 booms.

8 Conclusions

A 23-year MODIS night-time LST record shows that slopes 630 m above the Malang basin floor are warmer than the floor on 1.3–2.2 % of clear nights at the overpass times, a result insensitive to view angle, valley-floor pixels, coverage threshold, land cover and the averaging method. The record constrains this climatology but not individual nights: the two overpasses do not reproduce each other's night-to-night variation, and the per-overpass error is about 1 °C. Nights with $\Delta T > 0$ beyond the noise expectation occur only when the scene clears between the Terra and Aqua overpasses, follow wetter days and show a strongly cooled floor; whether they are cold pools, fog or residual cloud cannot be decided with the available ground data. The rise in their frequency after 2015 is specific to Aqua and is not interpreted as climatic. The city adds a night-time SUHI of about 0.9 °C but does not change the result. The open Earth Engine workflow, including the overpass-consistency check, can be applied to other tropical basin cities.

Data and code availability

The notebook (basin_inversion_malang.ipynb, version 1.1.0, MIT licence), all output tables and figures, the radiosonde source file as downloaded, and the Supplementary Material are archived at Zenodo, doi: 10.5281/zenodo.23115887. Input datasets are openly available through Google Earth Engine under the identifiers in Table 1 and from NOAA NCEI (IGRA v2).

Author contributions

RAW: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – original draft.

Competing interests

The authors declare no competing interests.

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Supplementary Material

Slopes rarely out-warm the floor: a 2003–2025 MODIS assessment of deep surface-based night-time inversions over the Malang basin, East Java

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Contents: Tables S1–S7, Figures S1–S6. All tables and figures are produced by sections A7–A9 of basin_inversion_malang.ipynb (v1.1.0) from the archived output tables; the source file is given in each caption. ΔT is the mean LST of the slope band (900–1300 m) minus that of the rural basin floor (≤ 600 m). Clear night: at least 30 % valid pixels in both zones unless stated. Shared night: observed by both Terra (~22:30) and Aqua (~01:30). Confidence intervals are 95 % Wilson intervals.

Tables

Table S1. Retrieval robustness variants. Base: mandatory QA good or other, LST error ≤ 2 K. VZA: view zenith angle. Valley floors removed: slope-band pixels with TPI < -50 m excluded (202 of 361 pixels remain). Fixed-pixel anomaly: climatological zone difference plus difference of zone-mean per-pixel anomalies from the calendar-month climatology. Joint: shared nights with $\Delta T > 0$ from both sensors. ρ : Spearman correlation of Aqua and Terra ΔT on shared nights (not computed for ≤ 10 nights). Source: robustness_summary.csv.

Index, pixel selection	Min. cov.	Nights	$\Delta T > 0$	%	95 % CI	Median ΔT (°C)	Shared nights	Joint	ρ
Zone mean, base	30 %	2017	35	1.74	1.3–2.4	–3.10	351	0	0.05
Zone mean, base	50 %	500	9	1.80	0.9–3.4	–3.11	10	0	–
Zone mean, VZA $\leq 40^\circ$	30 %	896	12	1.34	0.8–2.3	–3.22	7	0	–
Zone mean, VZA $\leq 40^\circ$	50 %	128	1	0.78	0.1–4.3	–3.21	0	–	–
Zone mean, 2 km cloud buffer	30 %	77	0	0.00	0.0–4.8	–3.06	0	–	–
Zone mean, 2 km cloud buffer	50 %	2	0	0.00	0.0–65.8	–3.09	0	–	–
Zone mean, valley floors removed	30 %	2035	44	2.16	1.6–2.9	–2.86	356	0	0.04
Zone mean, valley floors removed	50 %	518	12	2.32	1.3–4.0	–2.83	11	0	–0.18
Fixed-pixel anomaly, base	30 %	2017	30	1.49	1.0–2.1	–3.10	351	0	0.06
Fixed-pixel anomaly, base	50 %	500	9	1.80	0.9–3.4	–3.10	10	0	–

Table S2. Pixel availability by selection, over 16 756 overpasses. Coverage: valid fraction of zone pixels, median over overpasses with at least one valid pixel. Source: robustness_availability.csv.

Selection	Median floor coverage	Median slope-band coverage	Overpasses, any valid	Overpasses, ≥ 30 %	Overpasses, ≥ 50 %
base	0.25	0.32	6923	2368	510
VZA $\leq 40^\circ$	0.23	0.25	3452	903	128
2 km cloud buffer	0.05	0.07	5858	77	2
valley floors removed	0.25	0.33	6845	2391	529

Table S3. Clear nights with $\Delta T > 0$, 2003–2025 ($n = 35$). Sensor: overpass that met the coverage threshold. Anomalies: LST minus calendar-month mean over clear nights. Coverage: valid fraction of zone pixels. Wind:

ERA5-Land night-mean 10 m speed (18:00–06:00 local). p' : surface-pressure anomaly from calendar-month mean. Precip.: ERA5-Land daily total; pct: within-month percentile. Source: supp_inversion_nights.csv.

Night	Sensor	ΔT (°C)	Floor anom. (°C)	Slope anom. (°C)	Floor cov.	Slope cov.	Wind (m s ⁻¹)	p' (hPa)	Precip. (mm)	Precip. pct
2003-04-11	Aqua	0.51	−2.57	0.86	0.67	0.59	1.00	1.81	2.78	54
2003-04-12	Terra	0.33	−3.56	−0.31	0.31	0.40	0.84	1.40	0.22	2
2003-08-30	Aqua	1.20	−4.78	−0.67	0.41	0.73	1.10	1.35	0.13	29
2004-04-21	Terra	0.11	−4.73	−1.71	0.35	0.57	0.68	0.34	1.93	43
2004-09-27	Aqua	0.37	−2.74	0.59	0.61	0.34	0.98	−0.87	0.64	60
2005-08-25	Aqua	0.46	−3.12	0.25	0.41	0.34	1.32	0.69	2.41	92
2007-08-02	Aqua	0.06	−5.45	−2.49	0.53	0.60	1.39	0.97	0.00	0
2009-10-04	Aqua	0.63	−4.80	−1.29	0.38	0.56	1.32	2.16	0.78	51
2011-06-18	Aqua	0.40	−5.70	−2.39	0.55	0.47	1.28	0.42	1.20	67
2016-07-26	Aqua	0.17	−3.48	−0.40	0.31	0.59	1.26	0.55	1.12	77
2016-07-30	Aqua	2.63	−4.99	0.54	0.63	0.79	1.06	0.47	0.53	59
2016-08-01	Terra	0.52	−2.81	0.62	0.73	0.50	1.19	−0.36	2.16	91
2017-07-07	Aqua	0.35	−3.83	−0.57	0.46	0.52	1.33	2.01	1.34	81
2017-08-08	Aqua	0.07	−3.27	−0.30	0.34	0.57	0.99	1.65	0.71	71
2017-08-11	Aqua	1.57	−5.60	−1.13	0.51	0.37	1.23	0.56	0.28	44
2017-09-29	Aqua	1.34	−3.81	0.50	0.48	0.50	1.29	1.07	0.91	70
2017-10-08	Aqua	1.02	−3.22	0.67	0.62	0.57	1.03	−0.98	3.80	90
2018-11-30	Aqua	0.27	−5.82	−2.65	0.50	0.38	1.00	1.97	16.61	96
2019-02-25	Aqua	0.60	−3.51	−0.01	0.54	0.70	0.74	2.21	3.63	20
2019-06-13	Aqua	0.58	−2.45	1.04	0.53	0.47	1.42	1.66	1.73	75
2019-11-02	Aqua	0.64	−4.46	−0.92	0.50	0.39	1.15	2.19	25.92	100
2020-04-20	Aqua	1.95	−6.17	−1.31	0.44	0.50	0.93	0.06	3.95	63
2020-06-05	Terra	0.11	−4.51	−1.49	0.49	0.51	1.24	0.26	0.93	62
2021-04-25	Aqua	0.98	−4.01	−0.12	0.37	0.75	0.76	0.82	4.69	71
2022-08-08	Aqua	3.01	−6.44	−0.53	0.47	0.37	1.37	−1.68	0.37	53
2022-08-15	Aqua	0.38	−5.29	−2.00	0.66	0.36	0.63	−0.54	5.14	98
2022-08-28	Aqua	1.64	−5.10	−0.55	0.59	0.71	1.41	−2.03	2.46	92
2022-10-13	Aqua	1.73	−5.66	−1.05	0.35	0.33	1.01	−4.42	11.43	98
2023-06-26	Aqua	1.56	−5.30	−0.83	0.57	0.75	0.98	−3.47	1.69	74
2023-09-19	Terra	0.49	−3.30	0.14	0.44	0.47	1.35	−3.13	0.19	34
2023-12-08	Aqua	3.62	−7.64	−0.80	0.38	0.73	0.68	−2.13	17.96	92
2024-02-14	Terra	0.43	−2.24	1.08	0.40	0.39	0.45	−1.76	5.14	33
2024-07-28	Aqua	1.06	−3.57	0.40	0.57	0.47	1.51	−3.52	0.67	66
2025-04-06	Aqua	3.49	−6.45	−0.05	0.48	0.68	0.57	−2.31	0.40	9
2025-04-28	Aqua	2.81	−7.14	−1.42	0.60	0.64	1.08	−3.86	0.46	10

Table S4. Noise-only null model. Per-overpass error drawn from the centred Aqua–Terra ΔT differences on the 351 shared nights divided by $\sqrt{2}$, added to the calendar-month median ΔT ; shared nights use the mean of two draws;

5000 draws, seed 0. p: fraction of draws with at least the observed count. Per-overpass error SD 0.97 °C; Aqua–Terra covariance 0.03 °C²; Spearman ρ 0.05. Source: supp_noise_model.csv.

Night type	Nights	Observed $\Delta T > 0$	Null mean	Null 95 % range	p
Both sensors	351	0	0.1	0–1	1.000
Aqua only	1015	29	7.6	3–14	< 0.0002
Terra only	651	6	5.1	1–10	0.402
All	2017	35	12.9	6–20	< 0.0002

Table S5. Statistics by night type. Wet season: November–April. Source: supp_night_types.csv.

Quantity	Both sensors	Aqua only	Terra only
Nights	351	1015	651
$\Delta T > 0$	0	29	6
$\Delta T > 0$ (% , 95 % CI)	0.00 (0.0–1.1)	2.86 (2.0–4.1)	0.92 (0.4–2.0)
Median ΔT (°C)	–3.07	–3.07	–3.16
SD of ΔT (°C)	0.71	1.19	0.88
Wet-season share	0.06	0.17	0.12
Median within-month precipitation percentile	45.0	56.9	44.7
$\Delta T > 0$, 2003–2014	0 of 204	7 of 545	2 of 360
$\Delta T > 0$, 2015–2025	0 of 147	22 of 470	4 of 291

Table S6. Sensitivity to the minimum valid-pixel fraction required in each zone (base selection). p(0): probability of no $\Delta T > 0$ nights at the base rate of 1.74 %. Source: supp_coverage_threshold.csv.

Min. coverage	Nights	$\Delta T > 0$	%	95 % CI	p(0)
30 %	2017	35	1.74	1.3–2.4	–
35 %	1580	28	1.77	1.2–2.5	–
40 %	1189	21	1.77	1.2–2.7	–
45 %	803	18	2.24	1.4–3.5	–
50 %	500	9	1.80	0.9–3.4	–
55 %	282	6	2.13	1.0–4.6	–
60 %	142	2	1.41	0.4–5.0	–
65 %	62	0	0.00	0.0–5.8	0.337
70 %	26	0	0.00	0.0–12.9	0.634

Table S7. Median night overpass time over the basin floor by year (local solar time, from Night_view_time), clear overpasses. Source: supp_overpass_time.csv (hours from local solar midnight).

Year	Terra	Aqua	Year	Terra	Aqua
2003	22:36	01:30	2015	22:42	01:42
2004	22:30	01:24	2016	22:39	01:30
2005	22:30	01:21	2017	22:33	01:30
2006	22:30	01:30	2018	22:33	01:30
2007	22:30	01:35	2019	22:33	01:36
2008	22:36	01:36	2020	22:30	01:27
2009	22:36	01:32	2021	22:36	01:30
2010	22:18	01:30	2022	22:18	01:40

Year	Terra	Aqua	Year	Terra	Aqua
2011	22:36	01:42	2023	22:18	01:48
2012	22:24	01:30	2024	21:48	02:09
2013	22:33	01:36	2025	21:30	02:42
2014	22:36	01:24			

Figures

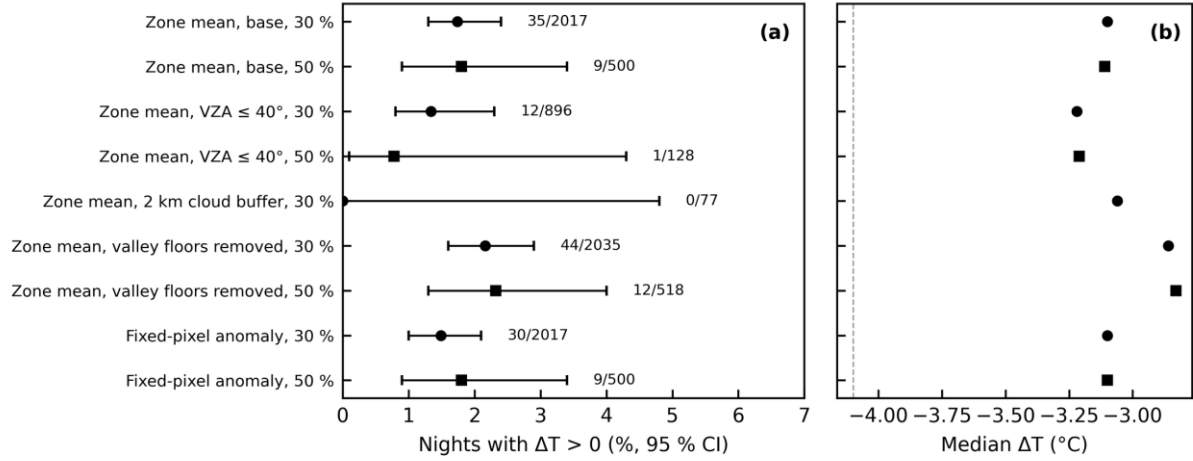


Figure S1. Retrieval robustness. (a) Percentage of clear nights with $\Delta T > 0$ with 95 % CI; labels: nights with $\Delta T > 0$ / clear nights; circles 30 %, squares 50 % minimum coverage. (b) Median ΔT ; dashed line: standard-atmosphere value (-4.1°C). Variants with fewer than 10 nights omitted (Table S1).

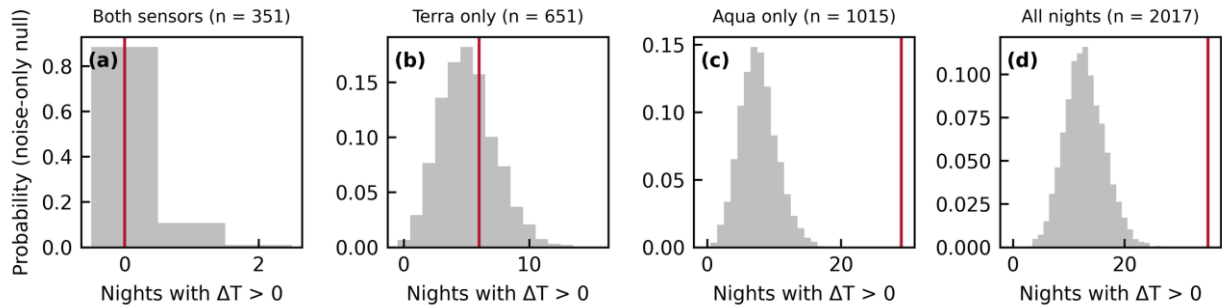


Figure S2. Noise-only null distributions of the number of nights with $\Delta T > 0$ (grey) and observed counts (red line), for nights observed by (a) both sensors, (b) Terra only, (c) Aqua only and (d) all nights (Table S4).

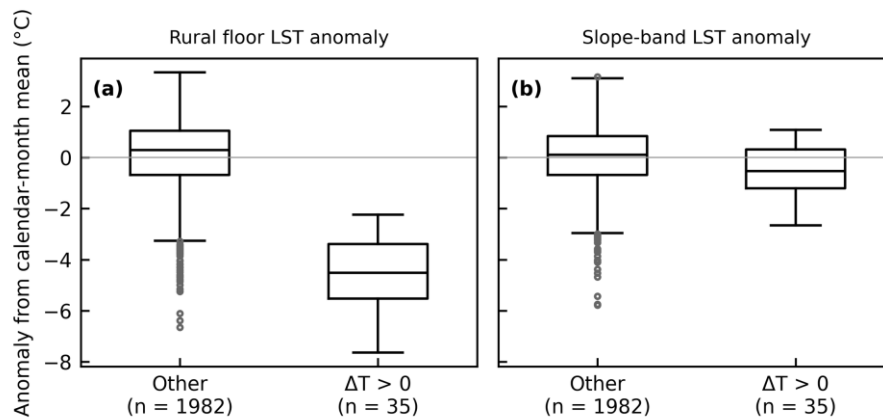


Figure S3. LST anomalies from the calendar-month mean on nights with $\Delta T > 0$ and other clear nights: (a) rural floor, (b) slope band.

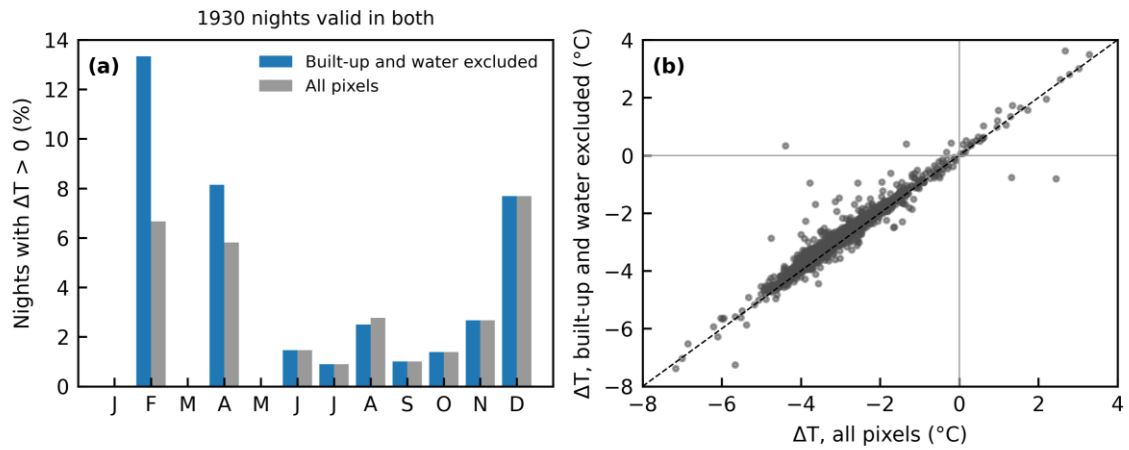


Figure S4. Land-cover sensitivity on the 1930 nights valid with and without the land-cover filter. (a) Monthly percentage of nights with $\Delta T > 0$. (b) ΔT with built-up and water pixels excluded against ΔT with all pixels; dashed line 1:1. Source: landcover_sensitivity.csv.

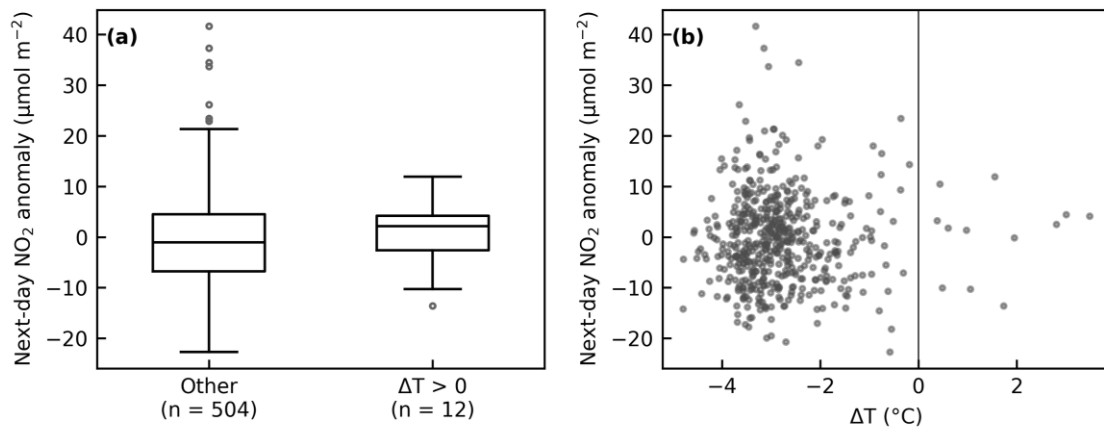


Figure S5. Sentinel-5P TROPOMI tropospheric NO_2 anomaly over the rural floor on the day after each clear night (calendar-month mean removed), 2019–2025. (a) Nights with $\Delta T > 0$ and other nights. (b) Against ΔT . Source: s5p_no2_daily_v3.csv, nightly_inversion_index.csv.

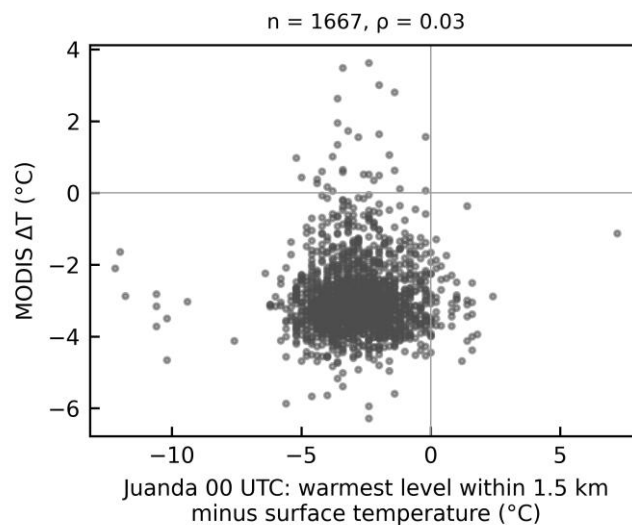


Figure S6. MODIS ΔT against Juanda (IDM00096935) 00 UTC radiosonde inversion strength: warmest reported level within 1.5 km above the surface minus surface temperature, paired with the preceding evening ($n = 1667$). Source: validation_igra.csv.