Environmental and Body-Mass Determinants of Distance-Running Pace

A quantitative model for race-day pace adjustment, with its derivation and limits

Brown Family Sports Editorial · Kelowna, British Columbia, Canada
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ABSTRACT

Distance-running performance degrades asymmetrically with ambient temperature, and the degradation is neither uniform across runners nor linear in the heat. We review the evidence governing that relationship — the evaporative basis of heat loss, the humidity weighting embedded in the Wet-Bulb Globe Temperature, the quadratic form of the temperature–performance curve established in a 1.79-million-finisher marathon dataset, the allometric heat-storage penalty carried by larger runners, and the cardiovascular and anticipatory mechanisms that convert accumulated heat load into a late-race collapse. We then specify in full the Total Heat Load model used in the Brown Family Sports race-day calculator: a Steadman apparent-temperature front end that folds humidity, wind, and solar load into a single effective temperature, an asymmetric quadratic penalty referenced to a 12 °C operating optimum, a bounded linear body-mass scalar, and a multiplicative acclimatization credit. Every coefficient is stated, sourced, and bounded, and the two points at which the model's calibration departs from its cited evidence base are identified explicitly rather than smoothed over. The model's central practical claim is that the heat adjustment must be applied to goal pace from the start line rather than reserved as a late-race concession, because heat load is cumulative and the physiological slow-down it imposes is involuntary. We close with the model's domain of validity and the conditions under which it should not be used.

1 Introduction

A runner arrives at a start line with a goal pace derived from training performed in other weather. On a warm, humid morning that pace is not merely ambitious; it is a different physiological task than the one it was calibrated against. The failure mode is stereotyped and widely reported by coaches: the target pace feels comfortable through the first third of the race, heart rate climbs at that same pace through the middle third, and the final third degrades into a walk or a medical-tent visit. The error is committed in the first mile and presented for payment after halfway.

The physiological literature explains this well, but it is distributed across thermoregulation, biomechanics, and epidemiological race analysis, and its practical output — how much slower, for this runner, on this day — is rarely stated in a form a runner can act on before the gun. This report has two purposes. Sections 2 and 3 assemble the evidence base. Section 4 states the Total Heat Load model in full, including every coefficient, so that the pace adjustments the Brown Family Sports calculator produces can be audited, criticised, and improved by people who did not write it.

We publish the model rather than describe it because a pace prescription that cannot be checked is not a prescription, it is an assertion.

2 Physiological background

2.1 Evaporative cooling and the vapour-pressure gradient

At the metabolic rates sustained in distance running, the great majority of heat loss must occur through the evaporation of sweat. Evaporation is driven by the water-vapour-pressure gradient between wetted skin and the surrounding air, not by air temperature as such. High ambient humidity collapses that gradient: sweat is produced and pools, but it does not evaporate, so the runner pays the full fluid and electrolyte cost of sweating while receiving little of the cooling benefit.

This is why absolute atmospheric moisture — indexed conveniently by dew point — predicts thermal strain better than relative humidity, which is a ratio and therefore varies with temperature at fixed moisture content. A 28 °C humid morning can impose a greater load on a running body than a dry 32 °C afternoon.

2.2 WBGT and the weighting of humidity

The sports-medicine standard for outdoor heat stress is the Wet-Bulb Globe Temperature [12]:

$$\mathrm{WBGT} = 0.7T_{\mathrm{wb}} + 0.2T_{\mathrm{g}} + 0.1T_{\mathrm{db}} \qquad (1)$$

where T_{wb} is natural wet-bulb temperature, T_{g} globe temperature, and T_{db} dry-bulb air temperature. The weighting is the substantive content of Equation 1: 70% of the index is the humidity and evaporation term, and only 10% is the air temperature a runner reads off a phone. This is why WBGT out-predicts both raw air temperature and shade-only heat indices.

Across the road races of the 2019 Athletics World Championships — 108 elite athletes racing at night in 29.3–32.7 °C and 46–81% relative humidity — mean performance relative to personal best correlated with race WBGT at $R^2 = 0.89$, but not with measured thermophysiological variables ($R^2 \leq 0.3$). Finishing times were 3–20% longer than personal bests [3]. Two caveats belong with that figure and are usually dropped when it is quoted: the correlation is computed across a handful of race events rather than across individuals, so the R^2 is far less powerful than its magnitude suggests, and the cohort is elite athletes in night-time conditions, not a recreational field in daylight.

2.3 The shape of the penalty, and who pays it

Performance versus temperature is an asymmetric U. It is comparatively flat and forgiving below the optimum and steepens quadratically above it. The definitive dataset is El Helou and colleagues' analysis of 1,791,972 marathon finishers across six large city marathons, in which air temperature was the single most influential weather variable and the penalty accelerated with distance from the optimum [1]. The optimum itself is markedly cooler than most runners assume. El Helou reports optimal temperatures for maximal mean speed ranging from **3.8 °C to 9.9 °C** depending on performance level; the optima differ by level, though the pattern across levels is not simple enough to reduce to a single direction.

Critically, the penalty is not uniform across ability. Indexed to WBGT, Ely and colleagues found top men slowing approximately 1.7% → 4.5% across WBGT quartiles from 5–10 °C to 20–25 °C, and the 25th-, 50th-, 100th- and 300th-place finishers slowing progressively more than the leaders as WBGT rose [2]. Top women followed the same trend (3.2% → 5.4%), but in their case the differences between quartiles did not reach statistical significance, and the figure should be quoted as a trend rather than a result. A mass-participation heat model that applies a flat percentage across abilities is therefore mis-specified; the penalty must scale up for slower runners, and a model anchored on elite headline figures will systematically under-warn the mid-pack.

T + T_{dp} sum, °C (°F)	Feel	Pace penalty
≤ 20 (≤ 100)	Ideal	~ 0%
26–31 (110–120)	Noticeable	0.5–1.0%
37–42 (130–140)	Hard	2–3%
48–53 (150–160)	Brutal	4.5–6%
59–64 (170–180)	Dangerous	8–10%

Table 1: Practitioner temperature-plus-dew-point heuristic, expressed as the sum of air temperature and dew point. It is not itself a validated instrument, but its magnitudes are consistent with the peer-reviewed penalties in [1] and [2], and it is useful as a field check on the model of Section 4.

2.4 Body mass and the heat-storage tax

Metabolic heat production scales approximately with body mass ($\propto M$), while the surface available to dissipate it scales approximately with $M^{0.67}$. The surface-area-to-mass ratio therefore falls as $M^{-0.33}$: a larger runner generates more heat per unit of skin available to shed it, and stores heat faster.

This is measured, not merely argued. Marino and colleagues found heat storage during an 8 km time trial correlated with body mass at $r = 0.74$ at 35 °C, approximately 0.50 at 25 °C, and approximately zero at 15 °C, with running speed correlating negatively with mass in the heat [4]. Dennis and Noakes modelled the same conclusion: a larger runner reaches a limiting core temperature sooner and must slow to avoid heat illness [5]. The mass penalty is real but strictly temperature-dependent — near zero in the cool, growing with the heat. Any model that applies a fixed mass penalty irrespective of temperature is wrong in the cold.

2.5 Cardiovascular drift and anticipatory regulation

Two mechanisms convert banked early time into a late collapse.

The first is cardiovascular drift. As core temperature rises and plasma volume falls through sweating, stroke volume declines and heart rate climbs to defend cardiac output. The same pace therefore costs progressively more as the race proceeds, and the drift is steeper in heat [11].

The second is anticipatory regulation. Runners involuntarily reduce power output as core temperature approaches roughly 39–40 °C. The slow-down is imposed by physiology whether or not it was planned. Planning for it does not avoid it; it substitutes a controlled, modest, early reduction for an uncontrolled, severe, late one.

Together these establish the report's central practical claim. Because heat load accumulates and the regulatory response is involuntary, the heat adjustment belongs on the goal pace from the gun. An even or slightly negative split is the pacing pattern that survives heat; the positive split is punished more severely under heat than under any other condition [11].

2.6 Heat acclimatization

Deliberate heat exposure recovers a substantial fraction of the penalty. Ten to fourteen days of repeated exposure — on the order of 60–90 minutes per day at an elevated core temperature, for which easy running in the heat qualifies — produces improved sweating, improved skin blood flow, lowered body temperatures, reduced cardiovascular strain and improved fluid balance [10].

The magnitudes require care, because the figures in wide circulation are larger than the current quantitative synthesis supports. A 2025 Bayesian meta-regression of heat-acclimation kinetics reports [14]:

- Plasma volume expansion of **5.6% (90% CrI 3.8–7.0)**, against the 10–12% frequently quoted in practitioner writing.
- Time-trial performance improvement of **3.1% (1.8–4.5)** — the metric most relevant to racing.
- Much larger apparent gains on open-ended metrics — time to exhaustion 49% (35–61), incremental exercise time 14% (7–24) — which reflect the known sensitivity of those protocols rather than a comparable performance effect.

The discrepancy matters. A runner told to expect a 5–15% improvement and delivered roughly 3% on race-relevant terms has been mis-sold, and citing the time-to-exhaustion figure as though it were a race outcome is the single most common error in popular heat-acclimation writing. This report uses the time-trial estimate.

The adaptations decay at different rates. Plasma-volume gains arrive fastest and fade fastest, giving way over days 8–14 to more durable skin-blood-flow and central-volume changes. The practical consequence is scheduling: the final heat exposure should fall a few days before the race, and a long cool taper immediately before a hot race forfeits the fastest-decaying component of the adaptation.

2.7 Body mass and the metabolic cost of running

Separately from heat, mass carries a mechanical cost. The energetic cost of running is dominated by the cost of supporting body weight — up to approximately 74% of net metabolic cost. Teunissen, Grabowski and Kram separated weight from inertial mass and showed the penalty tracks weight and rises approximately in proportion to added load [6] Arellano and Kram's task-by-task partitioning is consistent [7].

Cureton and Sparling's added-weight experiments quantified the performance consequence directly, loading participants with vests at 5%, 10% and 15% of body weight [8,9]. The performance cost falls near 1–1.4% per 1% of excess body mass. The resulting **pace** penalty is somewhat smaller, in the region of 0.7–1.0% per 1%, because the oxygen-cost-to-velocity relationship is mildly supralinear. This is the empirical content of the coaching heuristic of roughly two seconds per mile per pound.

The fractional pace penalty is approximately constant across race distance, since running economy is nearly speed-independent. A larger per-mile physiological penalty at 5 km is therefore not well supported. What is defensible is a power-to-weight leverage argument: a 5 km is contested near velocity at $\dot{V}O_2$max (roughly 95–100%), so mass constrains ceiling speed directly, whereas a marathon (roughly 75–85%) or an ultra (roughly 50–70%) is limited more by fatigue, fuelling and durability, where a pound has less leverage over a pace already well below the power ceiling.

3 The Total Heat Load model

This section specifies the model in full. Temperatures are °C, wind speed v_w is $\mathrm{m \cdot s^{-1}}$ (user input in $\mathrm{km \cdot h^{-1}}$ or mph is converted before use), mass is kg, and outputs are percentage adjustments to goal pace, positive meaning slower.

Brown Family Sports publishes two heat calculators. This section documents the **Total** model, which is the one the companion article directs runners to. A separate simplified calculator uses a different humidity approximation and adds an explicit net wind-drag term; it is not described here, and the two should not be conflated.

3.1 Effective temperature

Humidity, wind and solar load are folded into a single effective temperature before any penalty is computed. Water-vapour pressure is obtained from a Magnus-form saturation expression,

$$e = \left(\frac{\mathrm{RH}}{100}\right) \cdot 6.105 \exp\left(\frac{17.27 T_a}{237.7 + T_a}\right) \qquad (2)$$

in hPa, and combined into the Steadman apparent temperature [13],

$$T_{\mathrm{app}} = T_a + 0.33e - 0.70 v_w - 4.00 \qquad (3)$$

with a fixed additive term for direct solar exposure, which shade-based indices by construction omit:

$$T_{\mathrm{eff}} = T_{\mathrm{app}} + \begin{cases} 3.5 & \text{full sun} \\ 0.0 & \text{overcast or shade} \end{cases} \qquad (4)$$

Dew point, used for the field heuristic of Table 1, follows the same Magnus constants:

$$\gamma = \ln\left(\frac{\mathrm{RH}}{100}\right) + \frac{17.27 T_a}{237.7 + T_a}, \quad T_{\mathrm{dp}} = \frac{237.7\gamma}{17.27 - \gamma} \qquad (5)$$

The choice to anchor on dry-bulb air temperature and reconstruct the humidity weighting through Equation 3, rather than to require WBGT directly, is deliberate. The largest evidence base — El Helou's 1.79 million finishers [1] — is indexed to air temperature, and no recreational runner possesses a wet-bulb globe thermometer. Equation 3 is the pragmatic reconciliation of an air-temperature evidence base with a WBGT reality.

3.2 The core penalty function

The penalty is referenced to an operating optimum of $T_{\mathrm{opt}} = 12°C$. With $\Delta T = T_{\mathrm{eff}} - T_{\mathrm{opt}}$,

$$g(\Delta T) = \begin{cases} 0.09\Delta T + 0.0095\Delta T^2 & \Delta T \geq 0 \\ \max(-0.7, 0.05\Delta T) & \Delta T < 0 \end{cases} \qquad (6)$$

The quadratic form above the optimum is the functional shape reported in [1]. Below the optimum the response is linear, shallow, and floored at −0.7%: cooling confers a small benefit that saturates quickly, and the asymmetry of Equation 6 encodes the central asymmetry of the U-curve — a little cold is nearly free, a lot of heat is not.

Two disclosures are owed here.

First, **$T_{\mathrm{opt}} = 12$ °C sits above the 3.8–9.9 °C range El Helou reports** (Section 2.3). It is an operating choice, not a value taken from [1], and it is deliberately conservative: setting the reference warmer than the measured optimum means the model returns a smaller penalty on mild days than a strictly El Helou-calibrated reference would. Readers recalibrating this model should treat 12 °C as the parameter most in need of revision, and we flag it rather than present it as sourced.

Second, **in the Total model the penalty is floored at zero**, $P = \max(0, g(\Delta T) \cdot S(m))$, so the negative branch of Equation 6 never contributes. The model therefore never predicts that cold weather makes a runner faster than the reference. The branch is retained in Equation 6 because it is present in the implementation and because a future revision may expose it.

3.3 Body-mass scaling

The allometric argument of Section 2.4 enters as a bounded linear scalar on the penalty, referenced to a 75 kg runner:

$$S(m) = \text{clip}(1 + 0.006(m - 75), 0.85, 1.40) \quad (7)$$

$$P_{\text{heat}} = g(\Delta T) \cdot S(m) \quad (8)$$

Two properties of Equation 8 are worth stating explicitly. First, because S multiplies g rather than adding to it, the mass penalty vanishes as $\Delta T \to 0$ — reproducing Marino's finding that the body-mass correlation with heat storage falls to approximately zero at 15 °C [4]. A mass term that entered additively would wrongly penalise a large runner on a cold day. Second, the clip bounds keep the scalar within $[0.85, 1.40]$, so the model does not extrapolate to physiologically implausible masses.

3.4 Wind

In the Total model wind enters **only once**, as a cooling credit, through the $-0.70v_w$ term inside Equation 3. There is no separate aerodynamic drag term in this model.

This is a simplification with a known sign. Over a race run in approximately equal parts head- and tailwind, headwind drag grows with the square of relative velocity and therefore costs more than the tailwind returns, leaving a small net aerodynamic cost — the same asymmetry that governs net uphill and downhill running. By omitting it, the Total model is mildly optimistic in windy conditions: it credits the cooling and not the drag. The simplified calculator referred to in Section 3 applies an explicit quadratic net-drag term for this reason; folding an equivalent term into the Total model is the most defensible immediate improvement to it.

3.5 Acclimatization

A completed 10–14 day acclimatization protocol enters as a multiplicative credit on the heat penalty:

$$P_{\text{heat}}^{\text{accl}} = 0.72 \cdot P_{\text{heat}} \quad (9)$$

The 0.72 factor removes 28% of the heat penalty. Sanity-checked against [14] rather than against the inflated figures: on a day carrying a 5% heat penalty, Equation 9 returns about 1.4 percentage points, which sits inside the 3.1% (1.8–4.5) time-trial improvement the meta-regression reports and is therefore not over-generous. It remains a calibration choice rather than a fitted value, and self-directed acclimatization in the field should be expected to fall short of the controlled protocols that meta-regression pools.

3.6 Racing-weight dividend

Mass reduction is credited at approximately 0.9% pace per 1% of body mass lost, the mid-point of the 0.7–1.0% range implied by [6], [8] and [9], with a small additional uplift at short race distances reflecting the power-to-weight leverage argument of Section 2.7, tapering to zero by the half marathon.

This term is subject to a hard guardrail. It is valid only within approximately ±10% of body mass, and only for fat loss. Below a healthy body-composition floor, further loss reduces power output and invites relative energy deficiency in sport. The model must never imply monotonic gain from mass reduction, and the calculator surfaces an explicit warning beyond the 10% bound.

3.7 Composition and domain of validity

The terms compose additively into a net pace adjustment,

$$P_{\text{total}} = \max(0, g(\Delta T) \cdot S(m)) \cdot a + P_{\text{altitude}} - P_{\text{weight}} \quad (10)$$

where $a = 0.72$ if acclimatized and 1.0 otherwise, and the altitude term applies above approximately 300 m and is capped at 12%. Wind and solar load do not appear in Equation 10 because they have already been absorbed into T_{eff} by Equation 3 and Equation 4.

The model is a starting point, not a prescription. Its principal limitations are stated plainly:

- **Individual variation is large.** Sweat rate, sweat sodium concentration, body composition and acclimatization state vary substantially between runners, and the model has no access to any of them beyond mass.
- **The coefficients are calibrated, not fitted per-runner.** They derive from population-level datasets [1,2] and are appropriate to a population, not to an individual on a specific day.
- **The short-race uplift is a practitioner heuristic**, deliberately modest, and is the weakest-supported term in the model.
- **The 12 °C reference is an operating choice**, warmer than the 3.8–9.9 °C optima reported in [1], and is the parameter most in need of recalibration.
- **Net aerodynamic drag is omitted**, making the model mildly optimistic in strong wind.
- **Radiant load is coarse.** A single +3.5 °C solar term cannot represent the difference between a shaded river path and open asphalt.
- **The model does not know the course.** Surface, crowding, aid-station density and access to external cooling all matter and are absent.

4 Practical application

The model's output is a single adjusted pace, and its use is governed by one rule that follows from Section 2.5: apply the adjustment from the first step, not from halfway.

The operational sequence is:

1. **Two weeks out.** Begin deliberate heat exposure on most days, scheduling the final session a few days before the race rather than tapering into cool conditions.

2. **Race week.** Obtain forecast air temperature, relative humidity, wind and cloud cover.
3. **Race morning.** Compute T_{eff} via Equation 4 and the adjustment via Equation 10. Accept the resulting pace as the target.
4. **First third.** Hold the adjusted pace deliberately. It should feel too easy. This is the model working, not a failure of effort.
5. **Throughout.** Drink to thirst; replace sodium rather than water alone; cool the skin externally; use shade where the course offers it.
6. **Final third.** If the day has gone well, this is where the reserve is spent.

The counterintuitive element is the third step. A pace that feels too easy at 5 km on a hot day is generally the correct pace, because the thermal load that will make it hard has not yet accumulated.

5 Conclusion

The temperature–performance relationship in distance running is well-characterised, quadratic above a cool optimum, and steeper for slower and larger runners than the elite headline figures suggest. The practical difficulty has never been the physiology; it has been converting it into a number a runner can act on before the start rather than diagnose afterwards.

The Total Heat Load model is one such conversion. It is deliberately simple, every coefficient in it is stated above, and several of those coefficients are more confidently sourced than others. We publish it in this form so that its errors are findable.

Safety. Heat and dehydration are dangerous. Chills, goosebumps, cessation of sweating, disorientation or confusion during exercise in heat require immediate cessation of exercise and medical attention. Racing-weight guidance applies to fat loss within a healthy range only. Nothing in this report is medical advice.

6 References

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Companion article: *Heat, Humidity & Weight: The Case for Actually Running Slower*, brownfamilysports.com/articles/running-in-heat-humidity-weight/. Calculator: brownfamilysports.com/running-pace-calculators/#heat.