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RESEARCH ARTICLE

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Heat Force: A new operational 0–10 scale for environmental heat stress

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ABSTRACT

As national meteorological services adopt thermal indices that account for more than air temperature alone, a key challenge is making these indices understandable and useful to professional users and the general public. In June 2026, the Royal Netherlands Meteorological Institute launched *Heat Force*, a new public-facing 0–10 scale for environmental heat stress based on the Wet-Bulb Globe Temperature (WBGT). It forms part of a broader conceptual framework that distinguishes environmental heat stress (Heat Force) from individual heat susceptibility (Heat Fitness). We examine its interdisciplinary co-design between 2024 and 2026, which drew on WBGT climatology (1991–2020), existing WBGT-based guidelines, testing alternative configurations, and expert input from meteorology, climatology, public health and thermal physiology. Several configurations were considered feasible, with the final design balancing multiple sources of evidence with operational and communication considerations. The final scale consists of uniform 2°C WBGT intervals, ranging from 0 (<14°C) to 10 (≥32°C). To assess initial operational interest, we conducted a survey with professional users ($n = 46$), of whom 78% expressed interest in using Heat Force. In addition, we analysed news-media coverage following the introduction of Heat Force in 2026, identifying 366 articles mentioning Heat Force, with substantial media attention both around its launch and during exceptional heat shortly thereafter. Heat Force provides a common framework for communicating WBGT to a broad audience, with potential to support decision-making across sectors. Separating the public-facing scale from the underlying index also allows future updates to the metric while retaining a familiar communication concept.

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Introduction

Air temperature is often the primary measure used by meteorological services to monitor and warn for extreme heat [1]. However, air temperature alone does not fully characterise human heat stress, which is also influenced by humidity, wind speed and solar radiation [2]. For example, the same air temperature of 20°C can feel very different under sunny, calm conditions than under cloudy, windy conditions. As climate change increases the frequency and severity of extreme heat, sectors dealing with human heat exposure, such as event planning, occupational safety and emergency response, increasingly need thermal indices that account for these additional factors to support better decision-making [3]. National Meteorological and Hydrological Services (NMHSs) can play a central role in meeting this demand by providing authoritative, accurate and nationally consistent observations and forecasts of thermal indices. These are complementary to heatwave monitoring and warning services: where thermal indices focus on human heat stress, heatwave services focus on sustained cumulative excess heat in the environment and are relevant for all sectors [4].

A large number of thermal indices have been developed, which differ in their intended applications, data requirements, underlying assumptions and complexity [2,5]. Among these, the Wet-Bulb Globe Temperature

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(WBGT) is one of the most widely used and extensively studied, with established applications in occupational health, sport and military settings and formalisation in ISO 7243 [2,6–8]). Additionally, because the WBGT can be estimated from standard meteorological observations and, unlike some other thermal indices, does not rely on a complex physiological model, it is particularly suitable for operational implementation by national meteorological services [9].

WBGT is already becoming increasingly available through operational meteorological services. For example, Japan and Singapore use WBGT-based categories in their public heat warning systems [10,11], the U.S. National Weather Service introduced experimental WBGT forecasts in 2019 [12], and ECMWF has provided WBGT forecasts since 2024 [12]. WMO Regional Association VI (Europe) is now also exploring observational requirements for WBGT within the Global Basic Observing Network (GBON).

However, making thermal indices operationally available does not necessarily make them readily interpretable or actionable, particularly for non-expert users, as many are complex. WBGT, for example, is expressed in degrees Celsius or Fahrenheit but typically results in lower values than air temperature, which can be counter-intuitive [13]. While considerable research has focused on validating thermal indices with health outcomes [8], less attention has been given to how they can be translated into intuitive communication and decision-support products, including the design choices and trade-offs involved in doing so.

In the Netherlands, these considerations motivated the development of the Heat Force-Heat Fitness framework. Work on operational WBGT at the Royal Netherlands Meteorological Institute (KNMI) began within its multi-year programme to develop a national multi-hazard Early Warning Centre (EWC), initiated in 2020. Building on this work, the conceptual framework was developed in 2024 through the WARM project, led by the Netherlands Organisation for Applied Scientific Research (TNO) in collaboration with KNMI, the National Institute for Public Health and the Environment (RIVM), and Vrije Universiteit Amsterdam (VU).

The framework distinguished between two complementary components that follow the analogy for defining heat stress as in ISO 7243: (1) Heat Force, a scale based on WBGT that characterises environmental heat stress; and (2) Heat Fitness, a broader concept incorporating contextual information on person-, clothing- and activity-specific factors influencing heat risk (Figure 1). This distinction recognises that environmental heat stress is only one component of heat risk, whose implications also depend on activity, clothing, acclimatisation and individual susceptibility [5,7,14]. Heat Force was intended to make WBGT more intuitive to communicate and interpret, drawing on familiar environmental scales such as wind force (scale 0–12) and the UV Index (scale 0–11+). KNMI subsequently further developed the Heat Force concept into an operational product, which was officially launched on June 2 2026. To our knowledge, no national meteorological service has previously operationalised environmental heat stress as a numerical scale for public communication.

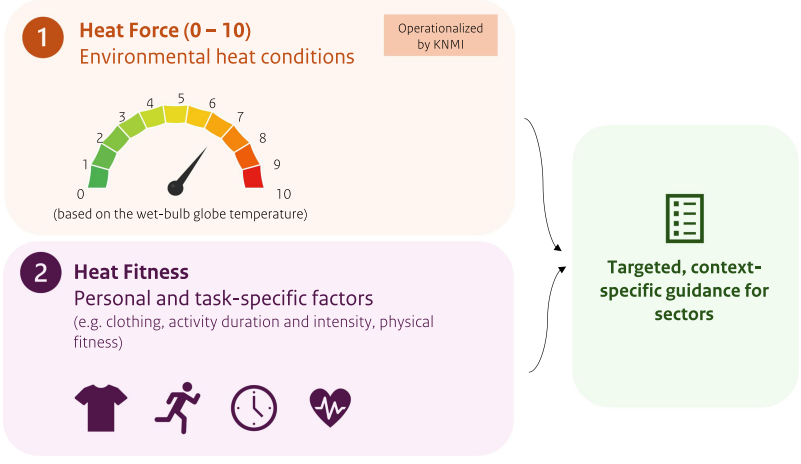


Figure 1. The Heat Force-Heat Fitness framework, co-designed by TNO, KNMI, RIVM and VU. (1) Heat Force represents environmental heat stress based on Wet-Bulb Globe Temperature (WBGT), translated into a 0–10 scale and operationalised by KNMI in 2026. (2) Heat Fitness is a broader concept that may include a range of person- and activity-specific factors. (3) Together, they support context-specific heat risk communication and decision-making.

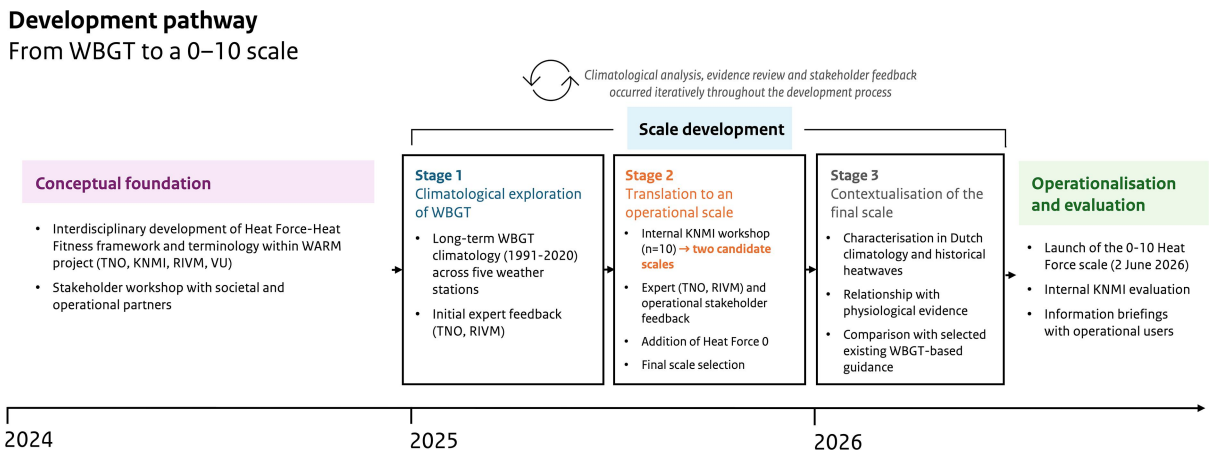


Figure 2. Development and operationalisation of the Heat Force scale, 2024–2026. Timeline of the main development activities and sources of evidence informing the Heat Force scale. Climatological analysis, evidence review and stakeholder feedback occurred iteratively throughout all stages.

This study examines the development and operationalisation of Heat Force by KNMI as a case study of translating environmental heat stress into intuitive and decision-relevant information for a broad audience. We examine its design, characteristics in the Dutch climate, and initial reception among professional users and in Dutch news media. In doing so, we aim to provide transferable lessons for other NMHSs seeking to operationalise and communicate thermal indices as part of their heat services. Specifically, we address the following research questions:

- What evidence and expertise informed the development of Heat Force, and how did these shape key design decisions?
- How does the resulting scale characterize heat stress in the Dutch climate and during historical heatwaves, and how does it relate to existing WBGT-based guidance?
- How was Heat Force initially received by professional operational users, and how visible was it in Dutch news media following its introduction?
- What broader lessons can be drawn from the development and initial operationalisation of Heat Force?

Methods

Following the initial development of the Heat Force-Heat Fitness framework in 2024, KNMI led the development of the operational Heat Force scale through an iterative process combining climatological analysis, evidence review and interdisciplinary expert input (Figure 2). Stages 1 and 2 informed the design and finalisation of the scale, while Stage 3 examined its characteristics in the Dutch climate and its relationship to physiological evidence and existing operational guidance. Input was sought throughout from thermal physiology experts at TNO and VU Amsterdam, public health experts at RIVM, and operational stakeholders.

WBGT data

Hourly WBGT was calculated using the Liljegren method [9] from observations of air temperature, relative humidity, wind speed and solar radiation at 32 automatic weather stations in the Netherlands, most with records spanning 1991–2024 (see Supplementary Materials; Table S1 for time period). Since 2026, WBGT and Heat Force have been calculated operationally at 10-minute resolution for KNMI weather stations and are publicly available through the KNMI Data Platform.[1] The operational WBGT implementation is described in [15].

Development of the Heat Force scale

The development considered several design dimensions, including the number and width of categories, category thresholds, the lower and upper boundaries of the scale, and consistency with existing WBGT guidance. Table 2 summarises these considerations and their resolution in the final scale.

Stage 1: Climatological exploration of WBGT

To inform the numerical structure of the scale, the distribution of daily maximum WBGT from April to September was analysed at De Bilt, the Dutch reference station, over the 1991–2020 climatological reference period. Percentiles from P50 to P99.9 were examined to explore potential category boundaries. Equivalent analyses were conducted for four other geographically distributed stations (Vlissingen, Twente, Maastricht and Eelde) to assess spatial variability within the Netherlands. The resulting WBGT distributions were used to explore preliminary scale configurations, which were subsequently discussed with project partners drawing on expertise in meteorology, climatology, thermal physiology and public health.

Stage 2: Translation to an operational scale

Building on this exploration, a 1.5-hour internal workshop was held at KNMI in July 2025 with operational forecasters, climatologists, climate model scientists and project management ($n = 10$). Participants reviewed the Stage 1 analyses, examples of WBGT during a Dutch heat warning episode and sport events (marathons), and existing WBGT-based guidance from sporting, occupational and military contexts (see 2.3.3). The workshop resulted in two candidate scale configurations based on rounded WBGT thresholds. Additional climatological analyses were conducted to examine their behaviour. Both configurations were subsequently presented to project partners in thermal physiology and public health, and informal feedback was sought from operational stakeholders in the police, defence, fire and public safety sectors. Together, these analyses and consultations informed the refinement and finalisation of the operational 0–10 scale.

Stage 3: Contextualisation of the final scale

Following finalisation, the Heat Force scale was contextualised in relation to (1) the Dutch climate, (2) physiological heat strain, and (3) existing WBGT-based operational guidance.

First, Heat Force levels were applied to the historical hourly WBGT dataset from 32 KNMI stations (WBGT data) to characterise the frequency, seasonal distribution and spatial variability of Heat Force levels across the Netherlands. The scale was also applied to historical heatwaves at De Bilt [16] to assess its behaviour during heatwave conditions.

Second, the Heat Force scale was compared to published experimental evidence on physiological heat tolerance from the PSU HEAT project and related studies [17–22]. The analysis considered two physiological endpoints: (1) the critical environmental limit above which a stable core temperature can no longer be maintained, and (2) the onset of sustained cardiovascular strain, indicated by heart-rate drift. Where available, thresholds were examined across age groups and activity levels, including rest (minimal metabolic heat production) and light ambulation. The PSU HEAT studies used humidity-ramp protocols, in which ambient humidity was progressively increased under controlled laboratory conditions. Reported combinations of air temperature and humidity associated with these endpoints were converted to equivalent Wet-Bulb Globe Temperature (WBGT) values and mapped onto the Heat Force scale, allowing comparison across population groups, activity levels and physiological endpoints. WBGT was calculated according to ISO 7243 as $WBGT = 0.7Twb + 0.2Tg + 0.1Tdb$, where Twb, Tg and Tdb represent wet-bulb, globe and dry-bulb (air) temperatures, respectively. As no additional radiant heat load was assumed under the laboratory conditions, $Tg \approx Tdb$, simplifying the equation to $WBGT = 0.7Twb + 0.3Tdb$. This corresponds to the ISO 7243 formulation for indoor conditions and is not strictly equivalent to the outdoor WBGT calculated operationally using the Liljegren method, which accounts for solar radiation. Where Twb was not directly reported, it was estimated from air temperature and relative humidity using the following approximation [23]: $Twb = Tdb \times \text{atan}(0.151977 \times (RH + 8.313659)\text{^}0.5) + \text{atan}(Tdb + RH) - \text{atan}(RH - 1.676331) + 0.00391838 \times RH\text{^}1.5 \times \text{atan}(0.023101 \times RH) - 4.686035$, where RH is relative humidity expressed as a percentage (0–100).

Finally, the scale was compared with selected national and international WBGT-based guidance across sporting, occupational, military and emergency-response contexts, including international sports guidance

[24], two Dutch running events (Leiden Marathon, unpublished; Dam tot Damloop [25]), ISO occupational guidance [7], NATO military guidance [26], and Dutch firefighting guidance [27].

Operationalisation and initial reception

Professional user feedback

Following two information briefings on Heat Force for professional users of KNMI weather and warning information in June 2026, attendees were invited to complete a short anonymous feedback survey. The survey received 46 responses, primarily from representatives of the Dutch Safety Regions ($n = 39$; 85%), which are responsible for regional emergency preparedness and response. Other respondents represented water authorities, the national road and waterway authority (Rijkswaterstaat), and the police. The survey assessed existing use of WBGT, interest in Heat Force, intended operational applications, and preferred information delivery channels. Responses were analysed descriptively.

News media visibility analysis

To assess the initial visibility of Heat Force in Dutch news media, we searched Nexis, a database of national and regional news publications, for the exact term "hittekracht" (i.e. Heat Force in Dutch) in publications issued between January 1 and September 2 2026, yielding 499 records. We excluded automated aggregators, non-journalistic sources, duplicate records, and records in which the term appeared only in automatically generated links to related articles. Multiple versions of updated articles or liveblogs were consolidated, while identical texts published by different outlets or regional editions were retained as separate publications to reflect potential media exposure. The final dataset comprised 366 dated publications representing 205 unique exact-text groups. To compare media coverage with observed Heat Force conditions, we calculated the highest daily Heat Force across all KNMI weather stations with available data.

Results

Stage 1: Climatological exploration of WBGT

Daily maximum WBGT at De Bilt during the warm season (April–September) over the 1991–2020 reference period ranged from 2.4 to 34.2°C. The median (P50) daily maximum WBGT was 19.1°C, while the upper tail of the distribution became increasingly narrow, with P99 and P99.9 corresponding to 28.6 and 30.9°C, respectively (Figure 3). The distribution was concentrated around 16–22°C, accounting for 52.2% of all April–September days. WBGT ≥ 26°C occurred on 303 d over the 30-y period (10.1 d/y), decreasing to 97 d with WBGT ≥ 28°C (3.2 d/y), 11 d with WBGT ≥ 30°C (0.4 d/y), and only 3 d with WBGT ≥ 32°C (0.1 d/y). Percentile

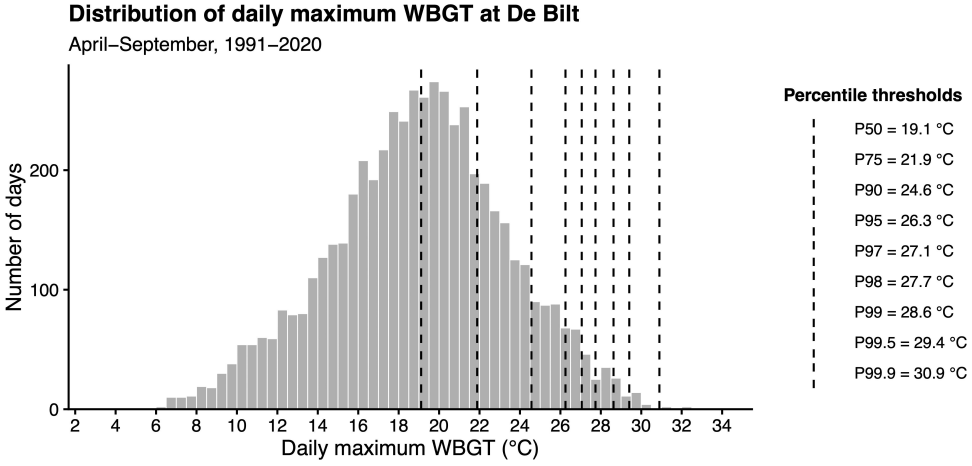


Figure 3. Distribution of daily maximum WBGT values at De Bilt during the warm season (April–September, 1991–2020). One of the percentile thresholds explored during the initial development of the Heat Force scale is shown as potential category boundaries on the right-side block.

Table 1. Heat Force scale configurations during the development process. Threshold values are given in WBGT (°C). For all intervals, the lower bound is inclusive and the upper bound is exclusive.

Heat Force scale	Percentile exploration	Candidate 1	Candidate 2	Final operational scale
0	–	<15	<15	<14
1	<19.1 (P50)	15–19	15–18	14–16
2	19.1–21.9 (P50-P75)	19–21	18–20	16–18
3	21.9–24.6 (P75-P90)	21–23	20–22	18–20
4	24.6–26.3 (P90-P95)	23–25	22–24	20–22
5	26.3–27.1 (P95-P97)	25–27	24–26	22–24
6	27.1–27.7 (P97-P98)	27–29	26–28	24–26
7	27.7–28.6 (P98-P99)	29–30	28–30	26–28
8	28.6–29.4 (P99-P99.5)	30–31	30–32	28–30
9	29.4–30.9 (P99.5-P99.9)	31–32	32–34	30–32
10	≥30.9 (P99.9)	≥32	≥34	≥32

values were broadly consistent across the five stations examined, with differences generally within 0.6°C for P50 and P99 (Figure S1).

Stage 2: Translation to an operational scale

Two candidate scale configurations resulted from the KNMI workshop (Table 1; Candidate 1 and 2). The climatological analyses in Stage 1 provided an empirical basis for the scale but did not identify a single obvious configuration. Operational forecasters noted that exact percentile-derived thresholds (e.g. P50 = 19.1°C WBGT) might imply a level of forecast precision that cannot be met, which led to the exploration of rounded whole-number thresholds. Both candidate scales extended beyond the percentile-based configuration, below P50 at the lower end and above P99.9 at the upper end. Candidate scale 1 used wider intervals at lower levels and narrower 1°C intervals at the upper end, reaching Heat Force 10 at ≥32°C WBGT. Candidate scale 2 used predominantly 2°C intervals and reached Heat Force 10 at ≥34°C WBGT.

Following the workshop, both candidate scales were applied to the historical WBGT record at De Bilt (1991–2024) to examine how their different configurations affected the frequency of Heat Force levels (Table S2). Differences were most apparent at the upper end of the scale. Heat Force 7 occurred on 27 d under candidate 1 compared with 94 d under candidate 2 over the 34-y period, while Heat Force 8 occurred on 6 and 9 d, respectively. Conversely, Heat Force 9–10 occurred slightly more frequently under candidate 1 than candidate 2. Heat Force 10 was rare under both configurations, occurring on 3 d under candidate 1 and 1 d under candidate 2.

The two candidate scales were subsequently presented to operational stakeholders via the network of KNMI, TNO and RIVM. Stakeholder preferences differed by sector: representatives from the police and defence preferred candidate scale 1, whereas representatives from the fire and public safety sectors preferred candidate scale 2, broadly reflecting alignment with their respective existing guidelines. As no clear preference emerged from the expert review, and stakeholder preferences largely reflected sector-specific applications, the final decision prioritized the intended purpose of Heat Force as a simple and consistent public-facing scale for communicating environmental heat stress.

KNMI operational forecasters favoured consistent 2°C intervals and even-numbered thresholds, which were considered easier to communicate, interpret and apply operationally. Based on these considerations, KNMI selected a final operational scale with uniform 2°C intervals from 14 to 32°C WBGT, Heat Force 0 below 14°C, and Heat Force 10 for WBGT ≥ 32°C (Table 1). The final configuration therefore combined the regular interval structure of candidate scale 2 with the lower Heat Force 10 threshold of candidate scale 1. Table 2 summarises the main design considerations and how they were resolved in the final scale.

Stage 3: Contextualisation of the final scale

The final Heat Force scale ranges from 0 to 10, with uniform 2°C WBGT intervals between 14 and 32°C, Heat Force 0 below 14°C, and Heat Force 10 at WBGT ≥ 32°C. The resulting scale can be expressed as:

Table 2. Key design considerations for translating WBGT into an operational heat scale and their application to Heat Force.

Design consideration	Question for operationalisation	Application to Heat Force
Scale architecture	How many levels should the scale contain?	A 0–10 scale was selected for simplicity, providing sufficient granularity and easy to communicate. Heat Force 0 was added to distinguish conditions with no environmental heat stress.
Climatological representation	How should the scale reflect the observed distribution of WBGT?	Dutch WBGT climatology (1991–2020) was used to establish the range and frequency of conditions and to evaluate candidate configurations, but not to identify category boundaries directly from percentiles.
Lower boundary	Where should the scale begin?	Heat Force 0 was defined as <14°C WBGT, informed by physiological expert input and the observation that the reviewed WBGT guidance generally did not identify heat-related restrictions below this level.
Upper boundary and future relevance under climate change	How should the upper end of the scale represent rare conditions while remaining relevant as extreme WBGT values become more frequent under climate change?	Heat Force 10 was set at ≥32°C WBGT, a level reached on only 3 d (four hours) at De Bilt between 1991–2024. A higher threshold of 34°C was considered to account for increasing extremes under climate change, but would represent conditions that are extremely rare in the current Dutch climate, reducing differentiation across the range of conditions more commonly experienced. Moreover, after the scale was established, WBGT around 32°C was found to correspond to reported physiological limits and to highly restrictive or cessation thresholds in several existing guidelines, providing additional support for the predefined boundary.
Interval size	How finely should categories be spaced, and how should thresholds support operational use?	Uniform 2°C intervals were selected over narrower 1°C or variable intervals to support operational simplicity and reduce sensitivity to forecast uncertainty. Operational forecasters also preferred rounded, even-numbered thresholds because they were easier to interpret and apply.
Seasonal availability	Should the scale be communicated year-round or only during the warm season?	Seasonal availability (March–October) was initially considered, but year-round availability was eventually selected to maintain continuity for users within the KNMI mobile app.
Physiological evidence	To what extent can physiological evidence inform category boundaries?	Available international physiological evidence identified relevant reference points, but did not support a distinct physiological threshold for each Heat Force category; the scale categories were therefore not defined as physiological thresholds.
Existing WBGT guidance	How should existing sector-specific WBGT thresholds inform category boundaries?	Existing guidance was used to contextualise rather than directly define category boundaries because thresholds varied substantially by population, activity and application.
Action perspective	At what WBGT values should different advice or actions be communicated to the public?	At this stage, no recommendations were assigned to specific Heat Force levels. Appropriate evidence-based guidelines could inform future recommendations tailored to different Heat Force levels, populations and activities, including vulnerable groups.
Expert review	What is the preference of relevant experts between scale configurations?	The candidate scales were presented to thermophysiological and public health experts. A clear preference would have guided selection of the final configuration; as no clear overall preference emerged, KNMI selected the final configuration primarily on the basis of operational considerations.

$$HeatForce = \min\left(10, \max\left(0, \frac{WBGT - 12}{2}\right)\right)$$

The following sections contextualise the final scale in relation to Dutch climatology, physiological heat strain and existing WBGT-based guidance.

Climatological characteristics

As expected, Heat Force shows a strong seasonal cycle as air temperature is a main component of the underlying WBGT calculation (Figure 4(b)). From November to March at station De Bilt during 1991–2024, the median daily maximum Heat Force was 0, although occasional days reached Heat Force 3–4 as early as March and as late as November. Heat Force increased through spring and was highest in summer, with median daily

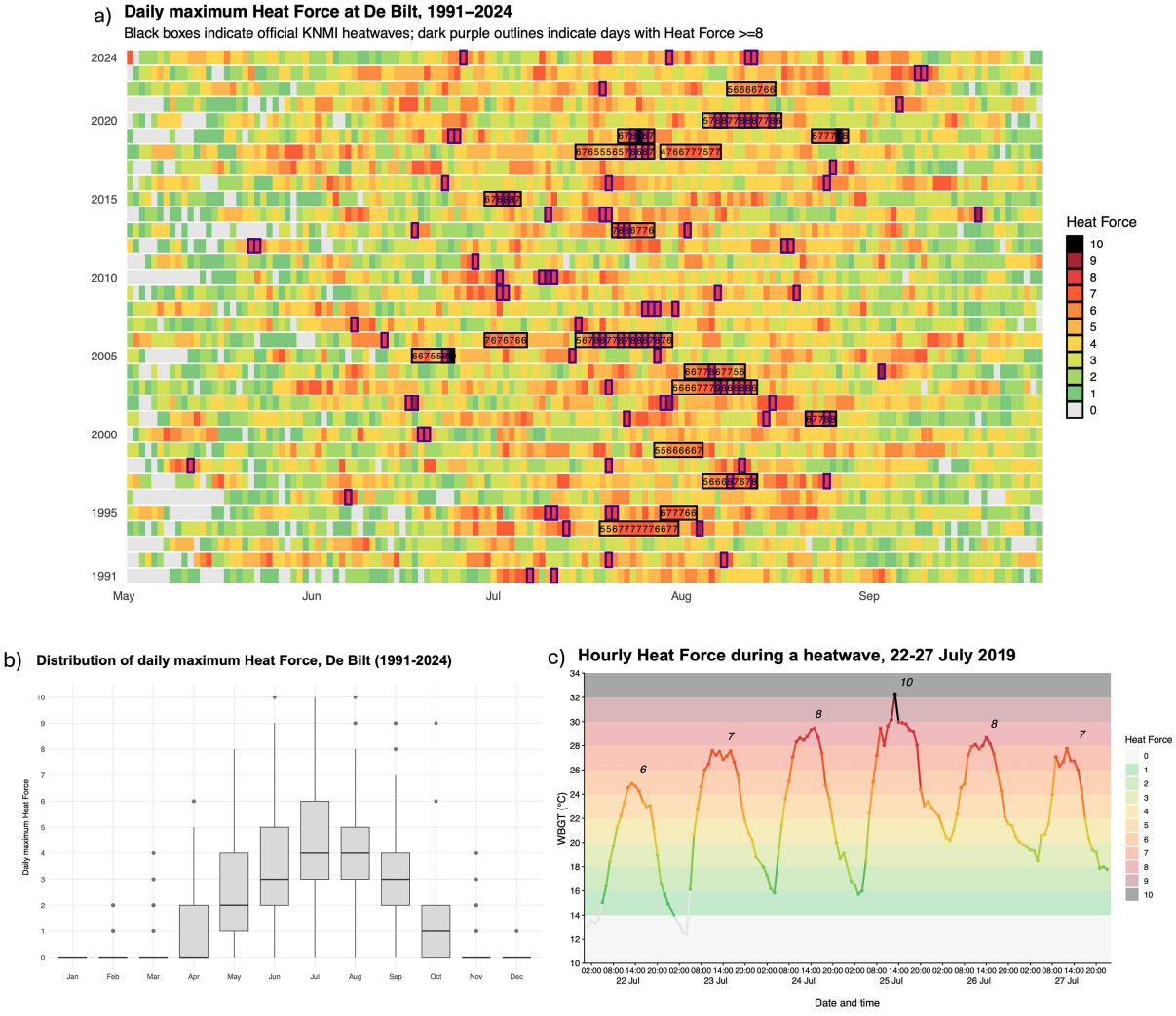


Figure 4. Climatological and temporal characteristics of Heat Force at De Bilt. (a) Daily maximum Heat Force from May to October, 1991–2024. Black boxes indicate heatwaves, with numbers within showing the maximum Heat Force reached during each heatwave; purple outlines indicate days reaching Heat Force ≥ 8. (b) Monthly distribution of daily maximum Heat Force, 1991–2024. (c) Hourly WBGT and corresponding Heat Force during the July 22–27 2019 heatwave, including July 25, when the record maximum air temperature of 37.5°C was observed at De Bilt.

Table 3. Final Heat Force scale and historical frequency at De Bilt, 1991–2024. The lower bound is inclusive and the upper bound is exclusive. Days represent the number of days on which each Heat Force level was the daily maximum; Hours represent the total number of hours during which each level occurred.

Heat Force	WBGT range (°C)	Days	Hours
0	<14	6,139	213,811
1	14–16	1,087	27,048
2	16–18	1,215	21,927
3	18–20	1,277	15,804
4	20–22	1,150	9,731
5	22–24	752	5,499
6	24–26	458	2,830
7	26–28	235	1,128
8	28–30	94	260
9	30–32	9	13
10	≥32	3	4

maxima of 3 in June and September and 4 in July and August. High Heat Force conditions (≥8) occurred from May to October, while Heat Force 10 was confined to June, July, and August. For De Bilt, the highest levels were rare: Heat Force 8 was reached on 94 d, Heat Force 9 on 9 d, and Heat Force 10 on 3 d, corresponding to only 4 hours in total (Table 3). Heat Force 10 also varied spatially across the Netherlands, with several stations recording no occurrences during the study period and higher frequencies at some inland stations. The highest number of hours was recorded at Arcen (29 hours), followed by Ell and Heino (9 hours each).

High Heat Force was not restricted to heatwaves (Figure 4(a)). Across heatwave days, daily maximum Heat Force ranged from 4 to 10, with two-thirds (66.5%) reaching a maximum of Heat Force 6 or 7. Of the 106 d reaching Heat Force 8 or higher, 37 (35%) occurred during heatwaves and 69 (65%) on other days. All official heatwaves at De Bilt occurred between June and August, compared with the broader May–October occurrence of Heat Force ≥ 8. Of the 9 d reaching Heat Force 9, two occurred during heatwaves, whereas all three Heat Force 10 d occurred during heatwaves.

High Heat Force conditions were generally short-lived. Episodes reaching Heat Force 8 or higher at De Bilt averaged 1.4 consecutive days; 90% lasted no more than 2 d and none exceeded 3 d. Within individual days, the median duration of Heat Force 8 or higher was 2 hours. The longest duration was 11 hours on July 25 2019, when a record maximum air temperature of 37.5°C was observed at De Bilt (Figure 4(c)).

Comparison with physiological heat tolerance limits

Published physiological heat tolerance limits, expressed as equivalent WBGT values, generally corresponded to the upper Heat Force levels. The critical WBGT for maintaining heat balance in healthy young adults averaged 32.9 ± 0.5°C [28], while [22] reported a higher critical WBGT of 35.2°C in very fit adults. Published experimental data also revealed differences by age, activity level and physiological endpoint (Figure 5). The onset of sustained cardiovascular strain occurred at approximately 28–31°C WBGT (Heat Force 8–9) in older adults, compared with 30–33°C WBGT (Heat Force 9–10) in younger adults, a difference of approximately one Heat Force level. Critical limits for maintaining a stable core temperature showed a similar age-related pattern, occurring at approximately Heat Force 8–10 in older adults and Heat Force 9–10 in younger adults [18–21]. Physical activity further lowered physiological thresholds. In young adults, critical limits decreased from approximately 34–35°C WBGT (Heat Force 10) at rest to 30–32°C WBGT (Heat Force 9–10) during light

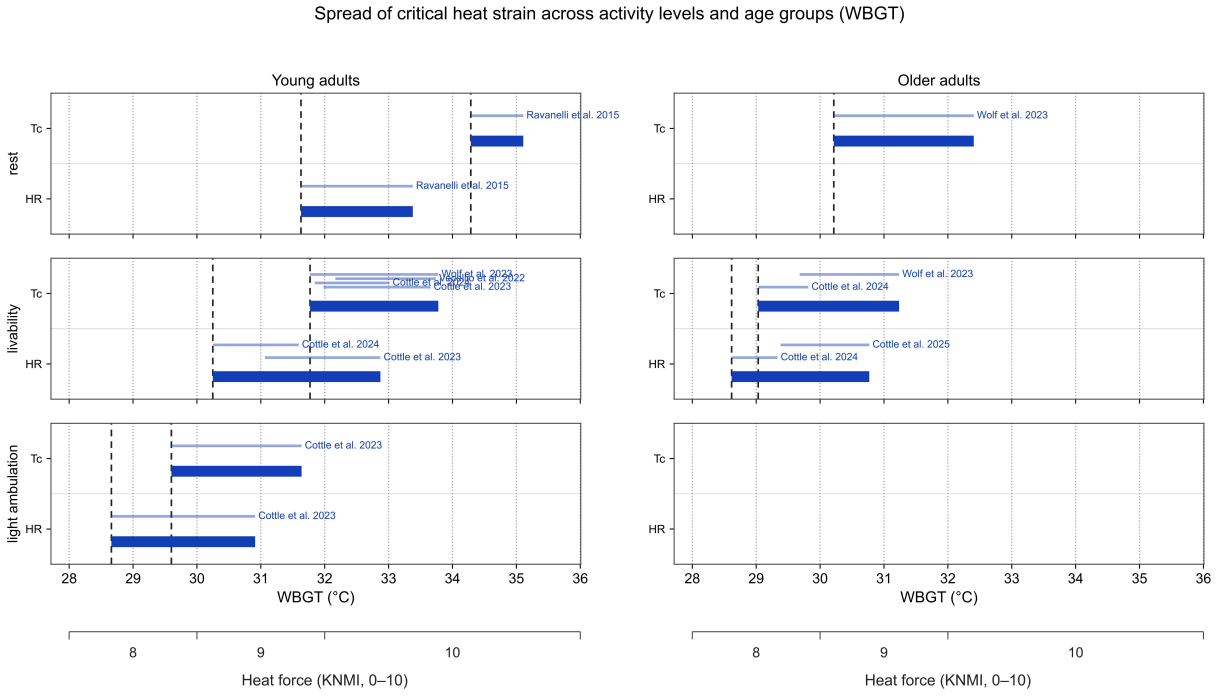


Figure 5. Physiological heat-tolerance thresholds expressed as WBGT equivalents and mapped onto the Heat Force scale. Thresholds vary by age and activity level and should be interpreted as conservative reference points (Tc: the critical environmental limit above which a stable core temperature can no longer be maintained; HR: the critical cardiovascular limit above which heart rate increases (cardiac drift)).

ambulation. Similarly, the onset of sustained cardiovascular strain shifted from Heat Force 10 at rest to Heat Force 8–9 during light ambulation. Variation was observed both between studies and within population groups. Importantly, these limits should not be interpreted as the levels at which heat becomes a concern. Significant physiological strain may occur at lower Heat Force levels, particularly among older and clinically vulnerable individuals.

Comparison with existing WBGT guidance

The WBGT thresholds and categories varied considerably across the sporting, occupational, military and emergency-response guidance examined (Figure 6). Most systems used fewer categories than the Heat Force scale, often with broader intervals at lower WBGT values and more closely spaced thresholds at higher values. Initial precautionary thresholds ranged from approximately 15–18°C WBGT (Heat Force 1–3) in some guidance to higher values in others. At higher WBGT values, thresholds were more closely clustered across applications. Increasingly restrictive categories commonly occurred around 26–28°C WBGT (Heat Force 7–8), while 30–32°C WBGT (Heat Force 9–10) broadly corresponded to the most restrictive categories in the guidance examined. WBGT reference values also varied with workload, acclimatisation and protective equipment. ISO 7243 specifies reference values that are 1–5°C lower for unacclimatised individuals, depending on workload [7]. NATO guidance specifies reductions of 2.8°C for body armour and 5.6–11.2°C for CBRNE protective clothing, depending on workload [26].

Operationalisation and initial reception

Heat Force was operationally launched by KNMI on June 2 2026 and made publicly available through the widely used KNMI mobile application, providing hourly and daily forecasts for the following 2 d for a user-selected location, accompanied by a colour scale ranging from green to red. The app links to the KNMI website, where more information about Heat Force can be found. WBGT observations and forecasts were also made available through KNMI's public and professional data platforms. Heat Force did not replace

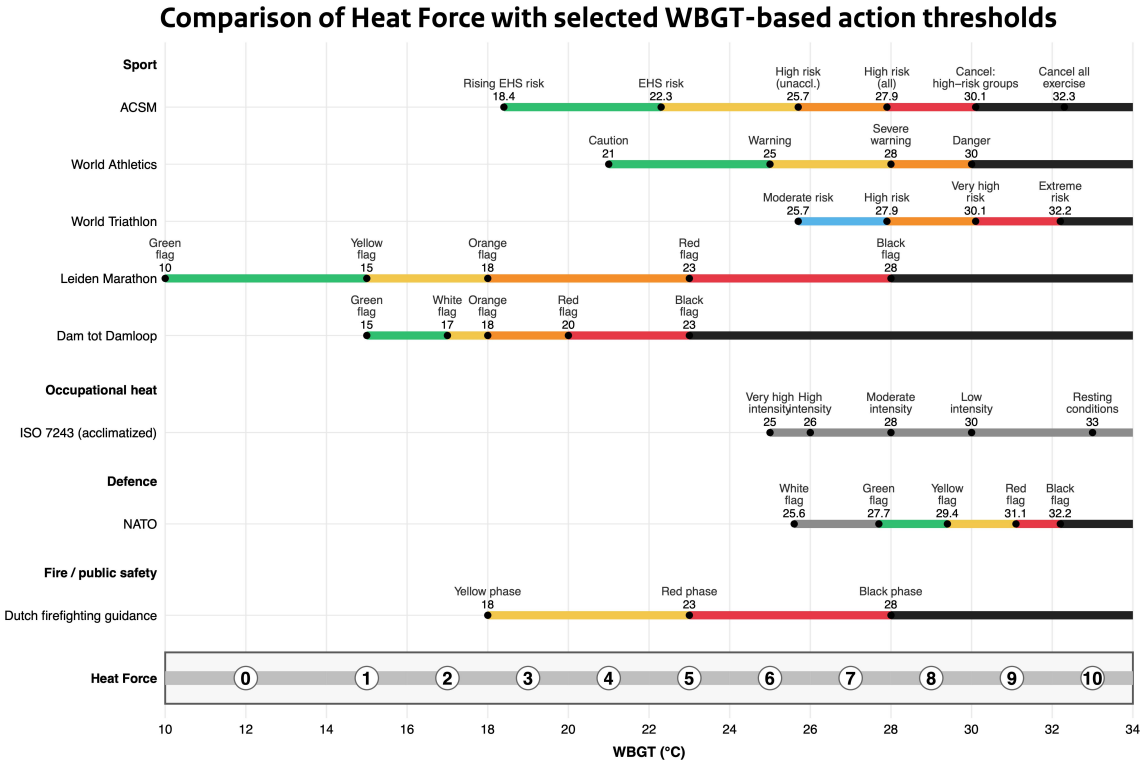


Figure 6. Comparison of the Heat Force scale with selected international and Dutch WBGT-based guidance across sport, occupational heat, defence, and fire and public safety contexts. Figure design adapted from [24].

existing temperature-based warning criteria, but was incorporated as additional information that forecasters could consider within KNMI's impact-oriented heat-warning process, without predefined Heat Force thresholds.

Professional user feedback

More than half of the survey respondents (56%) reported already using WBGT in their work, while 78% expressed interest in using Heat Force (15% were unsure, 4% indicated no interest and 2% did not respond). Among respondents who described potential applications, the most frequently mentioned use was event planning and advisory, including advice to municipalities and event organisers, crowd management, and assessment of conditions for endurance events. Other recurring applications included the safety and deployment of fire and emergency response personnel, operational planning and business continuity, and risk analysis and crisis preparedness. Respondents also indicated preferences for how Heat Force information should be delivered. The most frequently selected channel was the mijnKNMI dashboard, a dedicated web portal for professional users of KNMI data (38%), followed by API access and email; several respondents selected multiple channels.

News media visibility

We identified 366 news-media publications mentioning *hittekracht* ("Heat Force") in 2026, representing 205 unique exact-text groups and including 91 publications (24.9%) with the term in the headline (Figure 7). Sustained coverage began following the press briefing on May 20, with June accounting for 284 publications (77.6%). A first peak in news media coverage occurred around the operational launch on June 2 2026, with 42 publications on June 1. Coverage increased again when Heat Force 9 was forecast in mid-June and rose sharply during the extreme heat later that month, when Heat Force 10 was reached in Eindhoven on June 24. Coverage remained high during the Netherlands' first Code Red warning for extreme heat on June 26–27, although fewer publications mentioned Heat Force in their headlines. Overall, 123 publications (33.6%) appeared between June 24 and June 27. Later in the summer, high Heat Force conditions did not consistently coincide with increased media attention, with comparatively less coverage during Heat Force 9 and 10 conditions in late July.

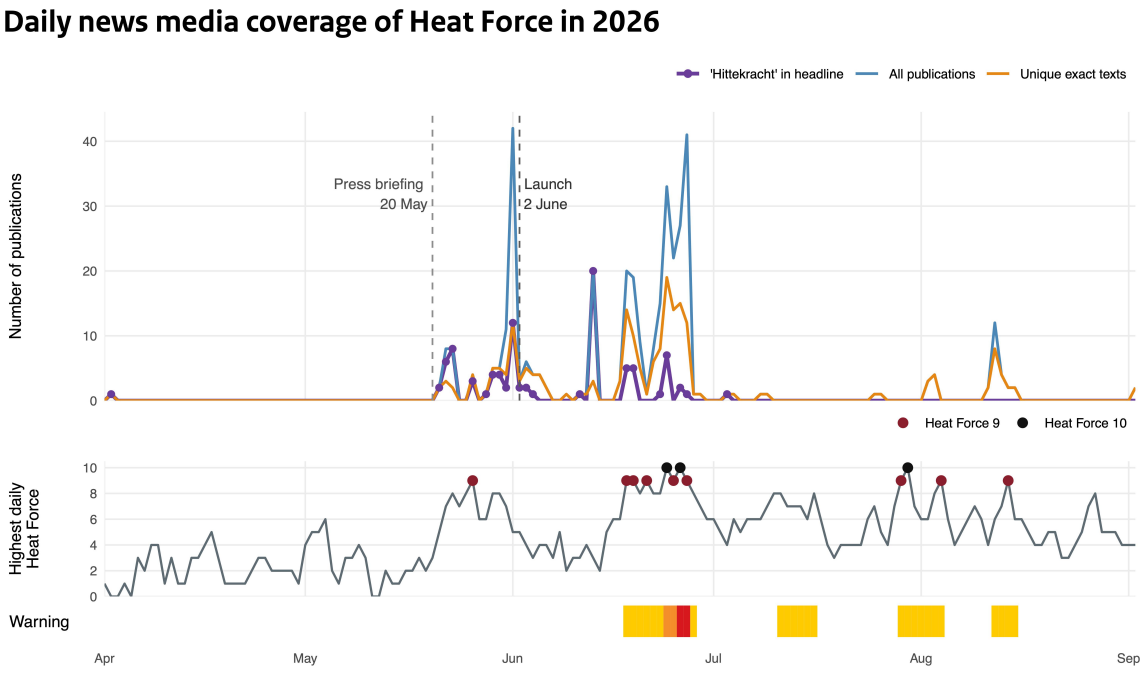


Figure 7. Daily news-media coverage of Heat Force in 2026 in relation to observed Heat Force and heat warnings.

Discussion

Heat Force as a new scale for environmental heat stress

As climate change increases heat-related risks, national meteorological services can support decision-making across sectors by providing nationally consistent information on thermal indices that capture environmental factors influencing human heat stress beyond air temperature alone [29]. Such information can complement heat warnings, as certain activities may pose heat-related risks even when conditions do not warrant population-wide warnings. In the Netherlands, demand for such information has grown in recent years, as endurance sport events have experienced heat-related illness, including fatalities, and substantial pressure on medical services at relatively moderate air temperatures [30,31].

As thermal indices can be complex and difficult to interpret, translating them into accessible information is important for effective decision-making. Familiar scales, such as those for wind force, UV radiation, and air pollution, inspired the development of a similar scale for environmental heat stress through Heat Force. Heat Force builds on this approach by communicating environmental heat stress through a simple numerical scale for a broader public, while retaining access to the underlying WBGT values for professional users. Separating the scale from the underlying index also allows thresholds to be revised, or potentially a different thermal index to be adopted as scientific evidence evolves, while keeping a familiar communication framework over the years. The concept could also be applied in other countries, although the thresholds may need to be adapted to local climates. Comparison to the Beaufort wind force scale provides an interesting example: wind-speed thresholds initially differed between countries before becoming internationally standardised [32]. The scale was also extended in some regions to represent stronger winds. A similar approach could be explored for Heat Force, with experience from different climates helping to determine whether common international thresholds would be feasible and desirable.

As extreme WBGT conditions become more frequent under climate change, a future question is whether Heat Force thresholds should remain fixed or be adjusted over time. Fixed thresholds would preserve a consistent relationship with environmental heat stress, while adjustments could maintain differentiation between increasingly common and exceptional conditions.

From scientific evidence to operational design

The development of Heat Force took place over approximately 2 y, bringing together expertise in meteorology, climatology, thermal physiology and public health from national institutions. The available evidence did not point to a single optimal scale configuration. Dutch climatology established the range and frequency of WBGT conditions but did not determine where to place thresholds, while percentile-derived thresholds were considered unnecessarily precise for forecasting and communication. Different operational users also preferred different scale configurations, partly because these aligned better with their existing guidance. KNMI's operational and communication needs therefore played a decisive role in selecting the final scale. Uniform 2°C intervals and rounded, even-numbered thresholds were selected to provide a consistent progression that was easy to communicate and use in practice. Other configurations, including narrower intervals at high WBGT values, would also have been defensible.

Comparison with physiological evidence showed that the upper Heat Force levels broadly overlapped with reported heat-tolerance limits (Figure 5) and increasingly restrictive WBGT guidance (Figure 6). However, physiological heat tolerance also depends on age, acclimatisation, clothing, physical fitness, health status, activity level and exposure duration [8,33]. For example, acclimatised individuals generally tolerate higher heat loads, while protective clothing and higher activity levels can increase physiological heat strain [7,34]. The same Heat Force level may therefore be tolerable during sedentary exposure but require additional precautions during endurance exercise or physically demanding work [35]. Heat Force levels should consequently be interpreted as environmental reference points rather than universal physiological or action thresholds.

This is also why the broader Heat Force-Heat Fitness framework is needed, which follows the approach adopted in ISO 7243 [7]. Heat Force describes environmental heat stress, while Heat Fitness accounts for the person- and activity-specific factors that influence its consequences. This distinction allows a common environmental scale to be used across sectors while recognising that different populations and activities

may require different protective actions. Although simple recommendations for individual Heat Force levels were considered during development, these were not included at this stage due to the difficulty of formulating sufficiently distinct and scientifically supported recommendations, as well as the limited space available in the KNMI app. However, the absence of specific action perspective at different Heat Force levels may limit the actionability of Heat Force. Further research could support the development of Heat Fitness and associated recommendations for different populations and activities, although establishing evidence-based guidance remains challenging due to individual and contextual differences in heat tolerance (e.g [36]).

Heat Force as a complement to existing heat(wave) warnings

Although Heat Force was developed primarily for the general public, the survey suggests potential value for professional users as well. More than half of our survey respondents already used WBGT, while 78% expressed interest in Heat Force for applications including event planning, emergency response and operational preparedness. The simplified scale may support rapid interpretation and communication, and underlying WBGT values remain available where greater precision is needed. Sectors could also use Heat Force as a common environmental reference when developing guidance tailored to their populations, activities and operational needs.

From the start of its development, an important question was how Heat Force should relate to the existing heat warning system. Heat Force did not replace the established temperature-based warning criteria [37] but was incorporated into operational guidance as additional information for forecasters, in line with KNMI's impact-oriented warning approach. It was considered during the issuance of warnings for the exceptional heat in June 2026 and was also communicated through the National Heat-Health Action Plan (HHAP), when high air temperatures coincided with unusually high humidity and Heat Force 10 was reached. As NMHSs expand their heat services to include thermal indices which are relevant for human health, these should be viewed as complementary to existing heat(wave) monitoring and warning systems which monitor sustained heat in the environment and are relevant for multiple sectors [4].

Concerns were raised within KNMI that introducing Heat Force alongside existing heat(wave) warnings could lead to information overload for the public. As the two products capture different aspects of heat, they may also provide contradicting information, for example when high Heat Force levels and high air temperatures do not coincide in time or space [15,38]. Our analysis showed that almost two-thirds of days reaching Heat Force ≥ 8 occurred outside heatwaves and can happen from May to October. Although the two products provide complementary information, clearly distinguishing their respective roles is important to avoid confusion among both forecasters and the public.

Forecastability is another consideration. While air temperature can generally be forecast reliably at longer lead times, WBGT also depends on humidity, wind speed and solar radiation, introducing additional sources of uncertainty. This may limit the reliability of Heat Force forecasts at longer lead times, when organisations need information to prepare. Temperature-based criteria therefore remain important for activating the national HHAP and early actions, while Heat Force could provide complementary information closer to an event. Further research should quantify WBGT forecast uncertainty across lead times and weather conditions, including how uncertainty propagates from the underlying variables, to determine how reliably it can support operational decisions.

Lessons from operationalisation and future development

The development of Heat Force shows the importance of multidisciplinary collaboration in translating scientific research into an operational service. Over approximately 2 y (2024–2026), expertise in meteorology, climatology, thermal physiology and public health was combined, as well as coordination across KNMI teams responsible for observations, climate science, forecasting and operational services. Existing institutional partnerships and professional networks also helped bring relevant expertise into the development process. Development was iterative, with scale configurations repeatedly tested against historical data, discussed with experts and refined. The initial conceptual framework was developed with partner organisations, after which Heat Force entered a research-to-operations phase that began within KNMI's Early Warning Centre (EWC) programme and continued beyond it, leading to operational implementation.

Early engagement with societal partners was also important. Preliminary versions of the Heat Force-Heat Fitness framework were discussed with stakeholders from national government, public health, emergency management and occupational health, including at the 2024 symposium of the Dutch Occupational Hygiene Society. This provided opportunities to consider different applications and may have increased familiarity with the concept before its launch.

The launch in June 2026 provided an opportunity to observe the initial reception of Heat Force. The scale received substantial news-media attention, which increased during the exceptional heat shortly afterwards, when Heat Force 10 was reached only less than a month after operationalisation. Coverage shifted from explaining the new concept towards reporting observed and forecast Heat Force levels, suggesting rapid initial uptake of the terminology in news reporting.

Several limitations should be considered. The co-design process and professional-user survey involved relatively small and specific groups of stakeholders, limiting the range and generalisability of perspectives captured. Continued operational use will however provide opportunities to engage a broader range of users and inform future refinements. The physiological evidence used to contextualise Heat Force was derived from controlled laboratory studies involving selected population groups in the United States and may not be generalisable to the wider population. Furthermore, the humidity-ramp protocols used in the PSU HEAT studies involved relatively short exposures. Although these thresholds have been compared with those observed during longer exposures [22], recent evidence suggests that humidity-ramp protocols may yield conservative estimates of physiological heat tolerance relative to prolonged exposure under constant environmental conditions [39]. Finally, although Heat Force was designed as a public-facing scale, the general public was not consulted during its development, and public understanding and use were not formally evaluated. News-media uptake provides an initial indication of exposure to the terminology but not of its comprehension or use.

Furthermore, Heat Force represents outdoor environmental heat stress based on meteorological observations and forecasts and does not necessarily reflect local exposure conditions. In particular, heat stress in urban environments, near built surfaces or indoors may differ substantially from conditions represented by reference weather stations [36,40]. KNMI plans to improve spatial representation by integrating observations from the WOW-NL citizen science network, comprising over 1,000 stations [41], to develop higher-resolution (1×1 km) WBGT maps, although these may still not fully capture local exposure conditions.

Additionally, future research should focus on evaluating how the general public perceives, understands and uses Heat Force, how professional users apply it and whether the simplified scale provides useful information alongside WBGT values. An important next step is to develop the concept Heat Fitness further, translating Heat Force into evidence-based guidance for specific populations and activities, such as older adults at rest with standard apparel or marathon runners, as well as the general population. This will require continued collaboration between researchers and operational users.

Conclusion

As meteorological services increasingly provide thermal indices alongside air temperature, a key challenge is translating this information into a form that is accessible to the general public and useful for decision-making across professional sectors. This study documented the development of Heat Force, a WBGT-based 0–10 scale operationalised by KNMI in June 2026. The development process showed that there is no single scientifically optimal way to make this translation. Long-term climatology, existing WBGT guidance and interdisciplinary expert input helped define reasonable options, while operational and communication needs shaped the final design. Subsequent comparison with physiological evidence provided important context for interpreting the resulting scale, while reinforcing why individual Heat Force levels should not be understood as physiological thresholds.

Heat Force provides regularly updated information on environmental heat stress throughout the year, complementing established temperature-based heat warnings. This information can help identify heat stress conditions relevant to particular activities and settings, including conditions that may not warrant population-wide heat warnings. Initial findings also suggest that, although developed primarily as a public-facing scale, Heat Force may be useful to professional users across different sectors. A key

next step is to further develop Heat Fitness by linking Heat Force to personal factors that influence heat risk, such as clothing, activity and physical health, to develop evidence-based guidance for different populations and settings.

More broadly, the case demonstrates the importance of interdisciplinary expertise, coordination across research and operational teams and early engagement with users when translating a scientific index into operational practice. Initial interest among professional users and uptake in the news media were substantial, although longer-term evaluation is needed to understand how Heat Force is interpreted and used in practice. The Heat Force approach may provide a useful model for other meteorological services seeking to translate thermal indices into accessible information for the public and professional users.

Note

1. Available at: https://dataplatform [16]. l/dataset/wet-bulb-globe-temperature-3-0.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Abbreviations

API	Application Programming Interface
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosive
ECMWF	European Centre for Medium-Range Weather Forecasts
EWC	Early Warning Centre
GBON	Global Basic Observing Network
GHHIN	Global Heat Health Information Network
HHAP	Heat-Health Action Plan
ISO	International Organization for Standardization
KNMI	Royal Netherlands Meteorological Institute
NATO	North Atlantic Treaty Organization
NEA	National Environment Agency
NMHS	National Meteorological and Hydrological Service
PSU HEAT	Pennsylvania State University Human Environmental Age Thresholds project
RH	Relative Humidity
RIVM	National Institute for Public Health and the Environment
TNO	Netherlands Organisation for Applied Scientific Research
UNDRR	United Nations Office for Disaster Risk Reduction
VU	Vrije Universiteit Amsterdam
WBGT	Wet-Bulb Globe Temperature
WMO	World Meteorological Organization
WOW-NL	Weather Observations Website Netherlands

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