Wearables in Monitoring the Health Effects of Climate Change-Induced Weather Extremes During Travel: A Data Lake Approach

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Abstract

Climate change is accelerating the frequency and severity of extreme weather events, posing unprecedented risks to the health of international travelers. Yet systematic frameworks for monitoring traveler physiological responses to these hazards remain largely absent from both research and policy. This paper proposes a conceptual framework and architectural design for a wearable-based traveler health monitoring system, underpinned by a Data Lake infrastructure. Drawing on a critical review of wearable technology capabilities and established research gaps, it is argued that integrating continuous biometric data streams with real-time climate information systems enables context-sensitive, personalized health intelligence for travelers in extreme conditions. The proposed four-layer Data Lake architecture spans data ingestion, storage, processing and analytics, and consumption layers, integrating wearable biometrics, climate data, and geospatial information. The framework is further guided by human-centered design principles including participatory governance, equity by design, accessible interfaces, and privacy by architecture. Critical research gaps are identified, including hazard bias toward heat, geographic concentration in high-income settings, and population homogeneity toward healthy adults. A research agenda is proposed to address them.

Keywords: wearable technology, climate change, travel health, data lake, extreme weather

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Introduction

Climate change is no longer a distant or abstract threat to global tourism. The global mean near-surface temperature in 2025 was about 1.43°C above the 1850–1900 average (World Meteorological Organization, 2026), and many extreme events, including heatwaves, heavy precipitation, and fire weather, have increased in frequency and/or intensity, while cold extremes remain relevant travel-health hazards despite declining global frequency (IPCC, 2021). With international tourist arrivals rising, the intersection of climate hazards and traveler health vulnerability represents a growing public health and policy challenge of substantial scale.

Despite these trends, systematic physiological monitoring of travelers during extreme weather conditions remains underdeveloped; related climate-product management and disaster-communication practices show fragmentation across contexts (Dragović et al., 2019; Kranjac-Berisavljevic et al., 2025). In travel settings, health-risk responses therefore tend to remain more reactive than anticipatory, underscoring the need for early detection and prevention. Wearable technologies and Data Lake architectures offer a technologically viable, scalable, and privacy-respecting pathway to change this (Rangarajan et al., 2018; Secara & Hordiiuk, 2024).

This paper presents a conceptual framework and system architecture for wearable-based traveler health monitoring during climate-induced weather extremes. It surveys the existing literature on wearable capabilities and identifies three foundational research gaps. It then proposes a four-layer Data Lake architecture integrating biometric, climate, and geospatial data streams, grounded in human-centered design principles. The ultimate aim is to establish the intellectual foundations for a field currently characterized by fragmentation and omission.

Literature Review

Tourism, Climate Risk and Health Vulnerability

Travelers face a distinctive combination of vulnerability factors that amplify the health risks posed by extreme weather (Ebi & Hess, 2020). Travelers shift between unfamiliar climate zones without sufficient time to acclimatize; rapid heat, humidity, or altitude exposure could trigger physiological stress responses that often go unrecognized (Leyk et al., 2019). Tourism frequently involves elevated physical activity (walking, hiking, cycling, and sightseeing at altitude), which amplifies physiological demand and makes continuous monitoring of heart rate, skin temperature, and hydration particularly critical. The disruption of baseline physiological rhythms through jet lag, irregular sleep, unusual diet, and social jetlag could weaken physiological resilience, compounding exposure risk (Kramer, 2023). Furthermore, vulnerable sub-populations including elderly travelers and those with pre-existing cardiovascular disease, diabetes, or respiratory conditions face disproportionate risk during heat or cold extremes, making personalized monitoring not a luxury but a necessity. In addition, many tourism destinations are geographically isolated from healthcare infrastructure, increasing time-to-treatment when incidents occur. Unlike occupational settings such as construction sites, where physiological monitoring frameworks are increasingly standardized, tourism lacks any equivalent monitoring infrastructure.

Wearable Technologies: Capabilities and Limitations

Wearable technologies are electronic devices worn on or near the body that continuously collect physiological, behavioral, and environmental data, transmit it wirelessly, and apply on-device or cloud-based analytics to generate actionable health insights (Dunn et al., 2018; Piwek et al., 2016). The commercially relevant categories for traveler health monitoring include consumer smartwatches and fitness bands (such as Apple Watch, Garmin, Fitbit, Huawei or Samsung Galaxy Watch), clinical-grade wearable patches and sensors (such as BioSticker, Zephyr BioHarness, and VitalPatch), smart textiles with embedded biosensors, and hearables measuring core body temperature and cardiovascular metrics.

The physiological parameters that can be estimated or measured by current wearable devices include heart rate (HR), heart rate variability (HRV), blood oxygen saturation (SpO2), peripheral skin temperature, and sleep architecture. Regarding HR, elevated readings in response to heat or cold stress may signal cardiovascular strain; however, consumer-device accuracy varies by device, movement conditions, and user characteristics, and therefore requires validation against medical-grade monitors (Bent et al., 2020). HRV reflects autonomic nervous system function and physiological resilience, with reduced HRV during travel indicating cumulative stress, poor sleep, or dehydration often before subjective symptoms appear. SpO2 is critical for detecting high-altitude illness and respiratory compromise in high-altitude settings (Luks et al., 2024). Wearable actigraphy reliably estimates total sleep time, efficiency, and REM proportion, which are key predictors of physiological resilience during extreme exposure (Peake et al., 2018). Despite rapid market growth, the application of wearables to traveler health monitoring in extreme climate conditions remains underdeveloped as both a research and policy domain.

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Research Gaps

Three foundational gaps characterize the current state of research. The first is a hazard bias toward heat: a substantial share of wearable health monitoring and environmental exposure studies relevant to travel, outdoor recreation, and outdoor work focuses on thermal stress, specifically heat (Friedrich et al., 2025; Helbig et al., 2021). Yet travel health monitoring must address the full spectrum of climate-induced hazards, including cold stress, high-altitude illness, flooding, wildfire smoke exposure, and vector-borne disease risk.

The second gap is geographic concentration: most studies are conducted in North America and Europe, systematically underrepresenting lower- and middle-income regions and other settings exposed to high climate-related health risks (Helbig et al., 2021).

The third gap is population homogeneity: most studies involve healthy, physically active adults, while elderly travelers and those with cardiovascular disease, diabetes, or respiratory conditions remain underrepresented despite being among the populations at highest risk (Chen et al., 2025; Friedrich et al., 2025).

Proposed Framework

The Data Lake as Enabling Infrastructure

A data lake is a centralized repository that stores large volumes of heterogeneous data, including structured, semi-structured, and unstructured data, in their native format and provides a common access interface for analysis (Derakhshannia et al., 2020; Hai et al., 2023). Unlike traditional data warehouses, data lakes, with their schema-on-read paradigm, have been proposed as more flexible systems in which raw data are directly stored in their original format associated with metadata, to be accessed and transformed only when users need to process or analyze them (Guyot et al., 2022). This characteristic is particularly valuable for traveler health monitoring, where the combination of data types (biometric streams, geospatial records, climate observations, and population health databases) is heterogeneous, high-velocity, and not fully defined in advance. For this reason, a data lake is better suited than a conventional warehouse when sensor, environmental, and spatial variables may be added incrementally and analyzed for purposes not specified at ingestion. Core architectural principles include schema-on-read to preserve original data fidelity, multi-modal data support, cloud-native scalability, and a governance layer encompassing metadata management, access control, data lineage, and GDPR compliance (Fang, 2015).

The proposed architecture integrates heterogeneous data streams from wearables, climate information systems, and geospatial platforms into a unified analytical environment across four functional layers (Table 1).

Table 1
Four-Layer Data Lake Architecture for Wearable-Based Traveler Health Monitoring

Layer 1 Ingestion layer	**Layer 2** Storage layer	**Layer 3** Processing and analytics layer	**Layer 4** Consumption and application layer
Provides raw data ingest from multiple simultaneous sources: wearable biometric streams (HR, HRV, SpO2, skin temperature, sleep, and galvanic skin response) transmitted via Bluetooth or ANT+; climate information	Operates a two-zone model. The raw zone preserves a native-format, immutable data archive of all original biometric and environmental records. The curated zone contains cleaned, harmonized, and	Hosts multimodal analytical engines including stream processing for real-time biometric alert generation, machine learning models for personalized risk scoring based on individual physiological baselines, and	Includes human-centered interfaces and outputs: a traveler personal health dashboard with real-time alerts and personalized guidance; a tourism operator dashboard for group monitoring during

systems including the World Meteorological Organization (WMO), the Copernicus Climate Data Store, and NOAA providing real-time weather data and forecasts; geospatial APIs including OpenStreetMap, Google Maps, and Esri ArcGIS for location context; and tourism and public health databases from UN Tourism, WHO, and national health agencies.	quality-controlled datasets ready for analysis. A metadata catalog supports data lineage and discoverability, while GDPR-compliant encryption and role-based access control govern all data access.	Explainable AI (XAI) to provide transparent and human-interpretable health recommendations.	guided tours and excursions; public health and emergency management APIs for local authority alerting; and open data exports for research and policy communities.

Integration With Climate Information Systems

The transformative potential of Data Lake architecture lies in its integration of individual-level physiological data with environmental-level climate data, enabling context-sensitive health intelligence. On the biometric side, continuous streams include HR, HRV, SpO2, skin and core temperature, sleep stage quality, physical activity and GPS tracking, galvanic skin response as a stress proxy, and hydration proxies. These streams are fused in the Data Lake with climate information including real-time air temperature and humidity, UV index and solar radiation, wind chill and apparent temperature, air quality indicators, flood and storm alerts, and wildfire smoke plume data from satellite observation. Contextual and geospatial data, including tourist itinerary, altitude and terrain profiles, distance to healthcare facilities, local disease vector risk maps, and historical climate anomaly records, complete the integrated data environment.

The output of this integration is a compound risk score, personalized health alert, and early warning notification transmitted to the relevant stakeholder interface.

Human-Centered Design Principles

A technically sophisticated Data Lake architecture is insufficient if it does not serve the diverse needs, capabilities, and rights of its users. Therefore, foundational human-centered design principles must guide this framework (Stankov & Gretzel, 2020). Participatory data governance should treat travelers as active participants by providing granular consent mechanisms, enabling them to review and delete their data, and involving them in citizen-science and co-design processes. Equity by design should prevent the system from defaulting to healthy, affluent, technology-savvy users and should prioritize vulnerable travelers, low-connectivity contexts, and entry-level smartphones. Accessible interfaces should provide plain-language, multilingual, and multimodal alerts aligned with WCAG 2.2 AA guidance (World Wide Web

Consortium, 2024). Furthermore, a privacy-by-design architecture could employ on-device processing, differential privacy, and privacy-preserving data-sharing mechanisms to ensure that sensitive biometric data are protected by design and by default (Dwork & Roth, 2014).

The Stakeholder Ecosystem

Effective deployment requires understanding the distinct but interconnected needs and incentives of stakeholder groups connected by the Data Lake infrastructure. Individual travelers benefit from real-time personalized health alerts during extreme conditions, post-travel health summaries, and meaningful agency over their own health data. Tourism operators and guides gain access to group-level health dashboards during tours and excursions, early warning of at-risk individuals before acute events occur, and documented liability risk reduction. Local and national health authorities gain access to anonymized real-time population-level health surveillance and improved emergency resource allocation. Climate information services gain a new use case and user community for climate data outputs, and the opportunity to co-design traveler-specific climate health indices such as the Universal Thermal Climate Index (UTCI) and Wet Bulb Globe Temperature (WBGT). The research community gains unprecedented real-world datasets linking physiology, behavior, and climate, and evidence for health policy in climate adaptation planning.

Conclusion

This paper has presented a conceptual framework and architectural design for wearable-based traveler health monitoring during climate change-induced weather extremes, grounded in a Data Lake infrastructure. The framework addresses a critical and growing policy gap: the absence of systematic, real-time physiological monitoring for international travelers exposed to extreme weather conditions. The framework integrates continuous biometric monitoring with climate information systems and geospatial data to generate personalized compound risk scores and early warning alerts across four architectural layers.

The three research gaps identified above provide a targeted agenda for the research community: hazard bias toward heat, geographic concentration in high-income settings, and population homogeneity toward healthy adults.

The human-centered design principles and the stakeholder ecosystem frame the social, ethical, and institutional dimensions of deployment that technical architectures alone cannot address.

Important limitations must be acknowledged. The framework remains at a conceptual stage; pilot studies are required to validate it. Wearable accuracy varies by manufacturer, firmware, skin tone, body mass index, and motion, necessitating medical-grade validation. Cloud processing assumes connectivity that may be unavailable in mountain, coastal, and rural destinations where edge computing and offline modes will be necessary. International tourism creates complex multi-jurisdictional data governance challenges that require bespoke legal architecture. User adoption and continuous wear cannot be assumed, requiring significant investment in user experience design.

Future research should prioritize randomized controlled pilots across climate zones and high-risk cohorts including elderly travelers and those with chronic illness; benchmarking of consumer wearables against medical-grade devices under extreme conditions; AI model fairness audits to ensure equitable risk scoring across age, ethnicity, and health status; and longitudinal use of the Data Lake infrastructure to study cumulative health impacts of repeated climate-extreme exposure.

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The authors declare that Claude (Anthropic), an AI-assisted language tool, was used solely for English language editing and proofreading.

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