Earth observations of extreme heat events: leveraging current capabilities to enhance heat research and action

Benjamin F Zaitchik and Cascade Tuholske

1 Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, United States of America
2 Center for International Earth Science Informational Network, The Earth Institute, Columbia University, New York, NY 10964, United States of America
* Author to whom any correspondence should be addressed.
E-mail: zaitchik@jhu.edu

Keywords: Earth observation, extreme heat, climate change

1. Introduction

In the boreal summer of 2021, as heat extremes triggered mass death in ecological systems, pushed engineered systems to the breaking point, and threatened health and well-being of people across the northern hemisphere, it was impossible to ignore the intensifying nature of summertime heat. This, coming in the same months as deadly flooding and historically intense fires in multiple countries, is both alarming and profoundly unsettling. As Amitav Ghosh wrote of climate extremes: ‘they are the mysterious work of our own hands returning to haunt us in unthinkable shapes and forms’ [1]. The summer of 2021 met this vivid description. It was also a preview of greater extremes to come and an indicator that even wealthy communities are poorly prepared to reduce harm from extreme heat under climate change.

Understanding and preparing for these intensified heat extremes requires transdisciplinary collaboration across diverse communities, sectors, and fields of research. Here we highlight the powerful role that satellite-derived Earth observations (EOs) can play in these efforts. In the context of the 2021 heat extremes, we consider EO contributions in four areas: monitoring, attributing, projecting, and adapting to extreme heat events.

1.1. Heat monitoring

Reports of 2021 extreme heat events focused on temperatures recorded at synoptic weather stations. That approach is meaningful when calculating climate anomalies, but it does not address the local experience of heat. Today, the majority of the world’s population lives more than 25 km from a weather station, including billions of people in climate vulnerable regions of Asia and sub-Saharan Africa (figure 1(A)). Air temperature, meanwhile, can vary by several degrees over the scale of just a few hundred meters (figure 1(B)).

EO can fill these gaps. During the 2021 extreme heat events, EO were applied in near-real time to provide high resolution maps of heat anomalies (figure 2). But while these snapshots offer powerful images, they have yet to be operationally integrated into functional heat monitoring and response systems that reduce harm. This is not without reason. First, taken alone, satellite-derived temperature observations offer near-real time monitoring or historical records, rather than prognostic forecasts for anticipatory action. Second, our highest resolution EO offer snapshots with inconsistent temporal coverage, as they are obtained from space-borne platforms in low Earth orbit rather than geostationary orbit. This limitation is particularly problematic for thermal remote sensing: these systems are more expensive and thus less common than optical sensors, and temperature can change rapidly. As such, EO heat data does not match the heat impacts experienced on the ground. Third, the most common satellite-derived temperature observation for high resolution applications is radiometric land surface temperature (LST). While LST correlates with air temperature at large scale, it is not synonymous with local air temperature. As such, maps of LST do not translate easily into a human health discussion concerned with physiologically-relevant thresholds in air temperature or composite metrics like apparent temperature or wet bulb globe temperature (WBGT). Finally, we note that all EO data suffers from issues of cloud and atmospheric contamination, viewing geometry, and sensor degradation. Taken together, these limitations mean that EO-informed heat analyses require modeling that incorporates station observations to estimate heat impact and patterns on the ground.
Figure 1. (A) Estimated total population living within a given distance from a Global Historical Climatology Network (GHCN) or Global Summary of the Day (GSOD) station with a robust reporting record, worldwide [4]. Total populations are classified as urban, peri-urban, or rural [22]; see supplemental text for methodology (available online at stacks.iop.org/ERL/16/111002/mmedia). (B) June–September average minimum nighttime temperatures in Baltimore, Maryland, USA. Star indicates location of the official weather station, and circles are temperature at sites monitored during a heat island measurement campaign in 2016. Temperatures are highest in low income, low vegetation cover neighborhoods. Background map is remotely sensed land cover information from the Chesapeake Bay Program, with grey indicating impervious classes and green indicating grassy areas (light green) and trees (darker green).

Figure 2. ECOSTRESS LST snapshot of the Seattle, WA region at ∼1200 local time, 25 June 2021. The structure of the surface urban heat island is clearly visible. Image: NASA Earth Observatory.

Nonetheless, recent advances highlight the advantages of EO-derived heat observation and the potential for globally-comprehensive operational EO heat monitoring. Snapshot satellite LST images have been used to train deep learning algorithms to downscale weather model output to the resolution of time-evolving urban heat islands [2], setting the stage for neighborhood-resolution heat forecasts. Continuous in time, hyperlocal daily air temperature estimates have been achieved by merging satellite-derived estimates of LST, topography, and other landscape factors with crowd-sourced air temperature measurements [3]. At slightly coarser scales, LST observations from geostationary satellites have been merged with in-situ station data to provide estimates of daily air temperature at 0.05° resolution, with nearly global coverage, and with a >30 year baseline [4]. Such longitudinal, satellite-informed estimates can be used to pinpoint how changes in extreme heat dynamics, including multivariate metrics like WBGT, intersect with demographic change to identify areas of concern worldwide [5].

Moving forward, these methods and observing capabilities can be applied to high resolution operational heat monitoring and forecasting. Doing so, however, requires that government EO agencies and
the private sector prioritize high resolution thermal infrared sensors, which has historically been challenging due to cost. There is also a need to expand in situ monitoring networks and campaigns, especially given the global decline in weather stations [4], in order to train and evaluate algorithms that derive air temperature and heat metrics from satellite measurements. Finally, efficient workflows need to be established that integrate satellite imagery to heat forecasts and warning systems in real time. Working with large satellite data is not easy, and in many cases satellite information needs to be integrated with numerical models to provide complete and timely monitoring and forecasts. Effective collaboration is required to realize the potential of these powerful but technically demanding heat warning systems.

It must be emphasized that capturing localized heat extremes has real-world implications, particularly when applied to climate adaptation. Identifying spatial and temporal trends of changing extreme heat exposure, versus temperature alone, can inform anticipatory action and early warning priorities worldwide. This information can be leveraged to identify targeted adaptations under limited financial resources [6]. Heat records that fail to capture localized hotspots like urban heat islands, meanwhile, systematically undervalue benefits of climate action and adaptation, harming those who have fewest resources to adapt and come from structurally-marginalized communities [7].

1.2. Attribution

The capabilities that make satellite-derived EO powerful for heat monitoring and forecast can also be applied to enhance the value of extreme heat attribution studies. Event attribution questions have become a standard part of the conversation whenever a real or perceived extreme climate event strikes, and researchers are now able to provide rapid, quantitative estimates of the extent to which global warming has increased the probability or intensity of a heat extreme. Indeed, a rapid attribution study of one major 2021 heat extreme appeared within weeks of the event [8].

Attribution studies like this are important tools for understanding climate change risks. They also play an emerging role in financial [9] and legal analysis [10]: quantitative attribution analyses provide estimates of the influence that climate trends have on asset vulnerability, and they can be applied to assign responsibility for damages incurred by greenhouse gas induced climate change. As the use of attribution analysis for these purposes becomes more common, there will be a call for finer-scale, impacts-oriented mapping of heat extremes and their attributable damages. Attribution at this level requires integration of satellite-derived EO for high resolution vulnerability and impacts analysis and monitoring of spatially-distributed heat conditions [11].

This integration can take several forms. For example, high resolution heat maps can be combined with relevant vulnerability data and health records to translate a climate attribution statement (the temperature anomaly was ‘X times more likely’) to a damages analysis (the event ‘was X times more deadly’) that is geographically and demographically specific, including distributional effects relevant to climate justice. EO can also be applied to quantify the respective roles of large-scale warming and local landscape factors. The potential to exceed a specified health-relevant heat threshold, for example, can be enhanced by both climate change and an urban heat island. Satellites are already used to quantify LST differences associated with economic status, historical housing policy, or settlement type [7, 12]. To apply these capabilities to rapid and replicable attribution studies, satellite-based heat downscaling techniques must be integrated into the climate attribution workflow. This is not a trivial effort, in particular because satellite records are short and, for thermal infrared measurements, sensitive to cloud cover. Multiscale, multisensor integration is required to overcome these limitations for robust application to attribution analysis.Attributing health impacts, meanwhile, requires continued work to connect satellite-derived heat metrics to health outcomes—an effort that is already well underway [13], but that is difficult due to the challenge of obtaining health impacts data at high spatio-temporal resolution [14].

1.3. Projection

The success of climate attribution studies for the 2021 heat events was shadowed by recognition of a possible limitation in Earth system models (ESMs): had projections of climate change failed to anticipate the potential for such extremes at current greenhouse gas levels [15]?

This is a critical question. Misrepresentation of nonlinear processes that feed extremes could mean that projections underestimate the urgency of the problem, and thus overstate the anticipated efficacy of moderate emissions reductions. In the case of extreme heat, it has been argued that global climate models do not account for the implications of a slower, more meandering jet stream [16]. Researchers have also pointed to increased strength of land-atmosphere coupling in intensified heatwaves [17] and to feedbacks in urban environments [18]. These dynamics are not fully captured by climate models.

The evolving roles of surface interactions under global change are particularly relevant for EO, as satellites have long been used to study surface influences on heatwaves [19]. In the case of 2021 heat events, coupled dynamics tie directly to the problem of understanding and projecting compound climate extremes. For North America, early summer heatwaves emerged on the background of an historic drought. The extent to which drought might
intensify heat extremes under climate change is a matter of ongoing research, as are dynamics of drought-heat-fire and teleconnections to downstream regions. Satellite-derived estimates of vegetation, near-surface soil moisture, evapotranspiration, and LST, as well as satellite-informed soundings of atmospheric temperature, humidity, and cloud structure are central to these investigations. Given the importance of these processes to projected risk of heat extremes, the application of EO to improve their representation in ESMs is a high priority.

1.4. Communicating risk and informing adaptation

Notwithstanding the contributions that EO have made to characterizing heat extremes, it must be acknowledged that EO-oriented research communities have historically operated separately from public health and demography scholars, muchless anthropologists, sociologists, and critical theorists. This can lead to top-town research that is not sufficiently robust to alleviate harm [20]. Recent increases in co-development and collaboration across communities [5] is a welcome step in identifying who is most at risk and translating and communicating heat risks to stakeholders. These efforts can be enhanced by programs focused on transdisciplinary collaboration and development of accessible EO processing and interpretation tools. There are several examples of success for extreme heat in this regard, both at the national level and, through programs like the Belmont Forum, the Global Heat Health Information Network, World Meteorological Organization climate services guides, and the GEO Health Community of Practice, in international collaborations. The ambition of these programs should scale to meet the rapidly growing challenges of a warming climate.

It is also important to distinguish the roles that EO play in reactive adaptation versus anticipatory adaptation to extreme heat. An effective forecast and early warning system, for example, is a tool for reactive adaptation. Early warning systems enable individuals to make behavioral changes to reduce heat exposure, and they allow institutions to offer basic heat relief services like cooling centers and hydration stations. EO capabilities exist to provide early warning—indeed, 5 billion people live in regions of the world that have reasonably predictable meteorology—but many of these regions do not have adequate warning systems [21]. Enhanced efforts to operationalize accessible warning systems, combined with integration of high-resolution EO to localize heat forecasts, can offer significant climate services in the short-term and contribute to reactive adaptation under climate change.

Anticipatory adaptation, which requires that decisions and investments be made in advance of future risk, can present a greater communication challenge. One strategy is to integrate attribution and projections to monitoring and early warning systems. Doing so can help to bridge the conceptual divide between current impact and future risk. Satellite-derived heat analysis and projection can bring this link to local level, offering maps and storylines that emphasize how local conditions mediate the experience of an extreme heat event, and how this experience would change with and without anticipatory adaptations such as urban heat island mitigation and investment in sustainable cooling infrastructure.

2. Conclusion

In summary, the contribution of EO to understand and manage extreme heat events like those seen in 2021 would benefit from coordination and communication at multiple levels:

- Greater integration within the research and observations communities, including work to align environmental observations with data on health and social vulnerability and collaborations that apply high-resolution EO to risk monitoring and forecast, climate attribution studies, and climate model development.
- A resourced commitment to transdisciplinary collaboration beyond traditional research communities, to bring stakeholder priorities to bear on the development of EO systems and products and leverages EO to address heat resilience goals.
- Communication tools that apply EO to bridge the gap between real-time heat response and future heat risks, such that investments in present day climate services can be leveraged to enhance anticipatory adaptation to increases in extreme heat.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://ghsl.jrc.ec.europa.eu/datasets.php.

Acknowledgments

The authors co-chair the GEO Health Community of Practice Small Work Group on Heat. We are indebted to the Community of Practice and the Work Group for discussions that motivated this manuscript.

ORCID iD

Benjamin F Zaitchik  https://orcid.org/0000-0002-0698-0658

References

[1] Ghosh A 2016 The Great Derangement: Climate Change and the Unthinkable (Chicago, IL: The University of Chicago)
[2] Oh J W, Ngarambe J, Duhirewe P N, Yun G Y and Santamouris M 2020 Using deep-learning to forecast the
magnitudes and characteristics of urban heat island in Seoul
Korea Sci. Rep. 10 3559
[3] Venter Z S, Krog N H and Barton D N 2020 Linking green
infrastructure to urban heat and human health risk
mitigation in Oslo, Norway Sci. Total Environ. 709 136193
[4] Verdin A, Funk C, Peterson P, Landsfeld M, Tuholske C and
Grace K 2020 Development and validation of the
CHIRTS-daily quasi-global high-resolution daily
temperature data set Sci. Data 7 1–14
[5] Tuholske C et al Global urban population exposure to
extreme heat Proc. Natl Acad. Sci. 118 e2024792118
[6] Estrada F, Botzen W W and Tol R S 2017 A global economic
assessment of city policies to reduce climate change impacts
Nat. Clim. Change 7 403–6
[7] Hoffman J S, Shandas V and Pendleton N 2020 The effects of
historical housing policies on resident exposure to
intra-urban heat: a study of 108 US urban areas Climate
8 12
[8] Philip S Y et al 2021 Rapid attribution analysis of the
extraordinary heatwave on the Pacific Coast of the US and
Canada June 2021 World Weather Attribution (available at:
www.worldweatherattribution.org/wp-content/uploads/
NW-US-extreme-heat-2021-scientific-report-WWA.pdf)
(Accessed 26 August 2021)
[9] Bressler R D 2021 The mortality cost of carbon Nat.
Commun. 12 1–12
[10] Lloyd E A and Shepherd T G 2021 Climate change
attribution and legal contexts: evidence and the role of
storylines Clim. Change 167 1–13
[11] Huilley G, Shivers S, Wetherley E and Cudd R 2019 New
ECOSTRESS and MODIS land surface temperature data
reveal fine-scale heat vulnerability in cities: a case study for
Los Angeles County, California Remote Sens. 11 2136
[12] Hsu A, Sheriff G, Chakraborty T and Manya D 2021
Disproportionate exposure to urban heat island intensity
across major US cities Nat. Commun. 12 2721
[13] Laaidi K, Zeghnoun A, Dousset B, Breitn P, Varendorren S,
Giraudet E and Beadeau P 2012 The impact of heat islands
on mortality in Paris during the August 2003 heat wave
Environ. Health Perspect. 120 254–9
[14] Mora C et al 2017 Global risk of deadly heat Nat. Clim.
Change 7 501–6
[15] Harrabin R 2021 Climate change: science failed to predict
flood and heat intensity BBC News (available at:
www.bbc.com/news/science-environment-57863205)
(Accessed 26 August 2021)
[16] Francis J A and Vavrus S J 2015 Evidence for a wavier jet
stream in response to rapid Arctic warming Environ. Res.
Lett. 10 014005
[17] Sato T and Nakamura T 2019 Intensification of hot Eurasian
summers by climate change and land–atmosphere
interactions Sci. Rep. 9 1–8
[18] Masson V, Lemonsu A, Hidalgo J and Voogt J 2020 Urban
climates and climate change Annu. Rev. Environ. Resour.
45 411–44
[19] Zaitchik B F, Macalady A K, Bonneau I. R and Smith R B
2006 Europe’s 2003 heat wave: a satellite view of impacts and
land–atmosphere feedbacks Int. J. Climatol. 26 743–69
[20] Vanos J K, Baldwin J W, Jay O and Ebi K I 2020 Simplicity
lacks robustness when projecting heat-health outcomes in a
changing climate Nat. Commun. 11 1–5
[21] de Perez E C, van Aalst M, Bischiniotis K, Mason S,
Nissan H, Pappenberger F, Stephens E, Zsoter E and van den
Hurk B 2018 Global predictability of temperature extremes
Environ. Res. Lett. 13 054017
[22] Florczyk A J et al 2019 GHSL Data Package 2019, EUR 29788
EN (Luxembourg: EUR) (https://doi.org/10.2760/290498)