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Short communication: emerging technologies for biometeorology

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Abstract The first decade of the twenty-first century saw remarkable technological advancements for use in biometeorology. These emerging technologies have allowed for the collection of new data and have further emphasized the need for specific and/or changing systems for efficient data management, data processing, and advanced representations of new data through digital information management systems. This short communication provides an overview of new hardware and software technologies that support biometeorologists in representing and understanding the influence of atmospheric processes on living organisms.

Keywords Hardware technology · Biometeorology · Data acquisition · Sensors · Software technology · Biometeorological data processing

Introduction

The advancements in measurement technologies in the twenty-first century have vastly facilitated data acquisition across various disciplines, which has led to advancements in the interdisciplinary field of biometeorology. In 1963, Frederick Sargent II displayed foresight in stating "long-range solutions must depend upon storing and retrieving information by new technological devices" (Sargent 1963). Indeed, since the 1960s, technology has revolutionized infrastructure, healthcare, transport, and communication, as examples. Researchers and educators alike benefit from the use of a wide array of technologies to advance their impact and output, and the interdisciplinary crossover of many technologies have considerably improved our ability to tackle large projects with researchers in related sub-disciplines (Cummings and Kiesler 2005).

Biometeorologists specifically have a unique opportunity to enhance the wide ranging applicability of studies related to solving complex challenges in the twenty-first century. Further, biometeorological researchers have been pushed towards more applied studies, often involving technology, while maintaining a strong engagement with the theoretical base of biometeorology (Ebi et al. 2009). This theoretical base has also been considerably augmented over the last 60 years through the use of various novel technologies.

Citizens as scientists are more intelligent than ever before. Recent technological advancement and the increasing interests of citizens in participating in scientific activities have motivated the development of a new generation of inexpensive sensors, allowing for the measurement of a variety of environmental properties, such as atmospheric parameters. Similarly, recent improvements in the miniaturization and mobility of these sensors encourage an increasing number of citizen scientists to collect data about plants, animals, and humans (population or personal). These improvements have led to the collection of large volumes of spatial, temporal, and spectral data to study the interactions between atmospheric processes and living organisms.

Newly designed sensors and devices have provided both meteorological and biological data across increasingly vast

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Table 1 Recent hardware technologies that are used (or have potential for use) in biometeorology

Type	Description	Current applications	Potential new applications within biometeorology	Sources and examples
Optical sensors	Ultra-compact and lightweight LiDAR 3D laser mapping and multi/hyper-spectral camera sensors provide automated, near-surface remote sensing of plant biometeorology.	• Study of the canopy phenology and biomass in precision agriculture (Matese and Di Gennaro 2015)	• Monitoring of plant water stress • Monitoring and mapping of forests degradation	• YellowScan LiDAR http://www.yellowscan.fr/ • PhenoCam https://phenocam.sr.unh.edu/webcam/ • HyTES https://hytes.jpl.nasa.gov/
Radar sensors	Small and dual polarimetric Doppler weather radars that have ultra-high-definition spatiotemporal resolution capability can grasp omni-directional parameters' intensity.	• Meteorological monitoring and analyzing system (Anagnostou et al. 2017) • Coastal upwelling detection (Raffa et al. 2017)	• Neighborhood-scale health and atmospheric hazards research • Sea level rise research	• FURUNO WR-2100 http://www.furuno.com/en/systems/meteorological-monitoring/WR-2100
Thermal sensors	Mobile, low-cost, and small thermal devices and imaging cameras (cameras designed for smartphones).	• Personal heat exposure studies (Bernhard et al. 2015; Kuras et al. 2015, 2017; Scott et al. 2017) • Intra-urban temperature variability (Scott et al. 2017) • Surface micro-urban heat island studies, location-specific	• Adaptation efforts and/or local- to global-scale climate policy • Calibration of existing spatial and thermal models • Characterize and validate generalized physiological principles and/or observations in classic heat/cold stress models for the general population across cities	• Seek Thermal http://www.thermal.com/products/ Camera • FLIR ONEhttp://www.flir.com/flirone/content/?id=81730 • iButton https://www.maximintegrated.com/en/products/digital/ibutton.html (Thermochron and Hydrochron) • Kestrel Drop https://kestrelmeters.com/products/kestrel-drop • Thermodo https://thermodo.com/
Radiation sensors	Mobile radiation sensors to measure levels of non-ionizing radiation in various human environments.	• UV exposures with time-activity patterns (Allen and McKenzie 2010; Køster et al. 2015; Pagels et al. 2016; Kuras et al. 2017; Vanos et al. 2017)	• Landscape design interventions and recreational design • Cohort studies linked to skin cancer • UV-blocking clothing effectiveness	• Geiger https://www.cooking-hacks.com/documentation/tutorials/geiger-counter-radiation-sensor-board-arduino-raspberry-pi-tutorial/Counter • Ultraviolet Dosimeters https://www.niwa.co.nz/sites/niwa.co.nz/files/personal_uv_dosimeter_badges.pdf • HOBO Pendant http://www.onsetcomp.com/products/data-loggers/ua-002-08
Physiological sensors	Wearable flexible sensors (e.g., watches or tags) that collect organisms' physiological parameters, connected to smart phone or table;t flexible skin sensors known as "Epidermal Electronics" Kim et al. (2011).	• Monitoring personal human physiology (Gerrett et al. 2013; Haj-Omar et al. 2016) • Remotely monitoring animal physiology (Neethirajan 2017) while under stress	• Real-time ambulatory monitoring of vulnerable populations (e.g., elderly, children) to environmental cold and heat • Hydration needs in humans and animals • Human thermos-physiological and thermal comfort model validations	• BioStampRC https://www.mc10inc.com/our-products/biostamprc • ŌURA Ring https://ouraring.com/the-ring/ • Embrace watch https://www.empatica.com/product-embrace
Portable, small air pollution sensors	Miniaturized and mobile sensors that measure/monitor air quality information indoors and outdoors. These sensors provide networked, GPS-enabled, fine-scale, real-time observations for more spatially congruent observations. These sensors collect data for a wide range of particles including ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO),	• Crowdsourcing and Citizen Science (Jiang et al. 2016) • Traditional monitoring occupational exposure (Sherwood and Greenhalgh 1960) • Dust storm monitoring and road conditions (Mujlid 2016) • Roadside air pollution and traffic (Jovašević-Stojanović et al. 2015; McKercher and Vanos 2017)	• Environmental justice • Agricultural and vegetation exposure to pollution • Validations of satellite air pollution information (O_3, $PM_{2.5}$)	• Smart-Citizen-Kit https://github.com/fablabbcn/Smart-Citizen-Kit • AirCasting http://www.aircasting.org/ • Aeroqual Series 500 http://www.aeroqual.com/product/series-500-portable-air-pollution-monitor Portable Monitor • Cairpol http://cairpol.com/en/home/ • SENS-IT Unitec http://www.unitec-srl.com/site/products/sens-it/ • Personal Ozone http://www.twobtech.com/pom-personal-ozone-monitor.html Monitor • TZOA

Table 1 (continued)

Type	Description	Current applications	Potential new applications within biometeorology	Sources and examples
	volatile organic compounds (VOCs), and hydrocarbons. Sensing technologies are still in development for understanding the potential of low-cost air quality sensors (McKercher et al. 2017). These sensors are often created with microcontroller kits (see below).	• Land use regression (Deville Cavellin et al. 2016) • Human health monitoring (Gozzi et al. 2016)		
Micro-controller kits	Open-source, open hardware, and small single-board computers used for building lightweight digital devices.	• Development of meteorological stations (Saini et al. 2016), air pollution sensors (Hwang and Park 2016), radiation sensors, enzymatic activity (Stadler et al. 2017), and environmental monitoring (Aursang and Dixit 2016)	• Development of autonomous, drone-based and Internet of Things (IoT) platforms for biometeorological knowledge bases	• Raspberry Pi https://www.raspberrypi.org/ • Arduino https://www.arduino.cc/ • UDOO boards http://www.udoo.org/documentation/
Unmanned aerial vehicle (UAV)	An aircraft without a human pilot aboard that provides flexible, timely, and high (spatial)-resolution (image) data for monitoring through remote sensing techniques.	• Forest monitoring (Inoue et al. 2014) • Plant health (Di Gennaro et al. 2016) • Precision agriculture (Matese and Di Gennaro 2015) • Flood monitoring (Darack 2012) (Abdelkader et al. 2013)	• Animal biometeorology • Environmental protection • Fine-scale surface urban heat island observations	• SenseFly https://www.sensefly.com/applications/agriculture.html • Dji http://www.dji.com/ • DSLRPro http://www.dslrpros.com/
Satellite	Recent Earth observation platforms developed by different space agencies (e.g., NASA and ESA) capture higher resolution images of weather patterns, vegetation, surface temperature, and other atmospheric phenomena. They perform terrestrial observations at wavelengths from optical to radio.	• Forest monitoring (Ouwehand, European Space Agency. and Living Planet Symposium (Prague) (2016) • Air pollution (Hulley et al. 2016) • Natural disaster management (Schmit et al. 2005) • Precision agriculture (Chemura et al. 2016) • Environmental protection (Kalluri et al. 2015)	• Modeling of mean radiant temperature • Landslide susceptibility mapping • Retrieval of leaf area index and fuel moisture contents • Urban studies	• GOES-16 http://www.goes-r.gov/ • Sentinel-2 http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2 • ICESat-2 http://icesat-2.gsfc.nasa.gov/ • EarthCARE http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/EarthCARE • Landsat https://landsat.usgs.gov/landsat-8-8 • SPOT-7 http://www.satimagingcorp.com/satellite-sensors/spot-7/
Citizen scientists	Networks of volunteers or not-for-profit groups that focus on training and education, as well as data collection and data analysis, related to biometeorological and associated data acquisitions.	• Air pollution monitoring (Dutta et al. 2009) • Plant phenology (Rosemartin et al. 2015; McDonough MacKenzie et al. 2016) • Weather forecasting (Gharesifard et al. 2017) • Environment protection (McKinley et al. 2016)	• Estimation of plant's and animal's ability to plastically track temperature-mediated shifts • Forecasting species responses to national forest management	• AirCasting http://aircasting.org/map • NPN https://www.usanpn.org/ • Safecast http://blog.safecast.org/ • Air Quality Egg http://airqualityegg.com/ • PEP725 http://www.pep725.eu/ • Weather Detective http://www.weatherdetective.net.au/ • Local Environmental Observer https://www.leonetwork.org/en/ • OpenAQ

Table 2 Recent software technologies that are used (or can be used) in biometeorology

Type	Description	Current applications	Sources and examples
Geographic information system (GIS)	Systems that can capture, store, manipulate, analyze, manage, and present meteorological and biological spatial or geographic data. These systems can be online or open-source.	• Flood monitoring/analysis • Heat exposure analysis (Hu et al. 2017) • Meteorological analysis (Wang 2014) • Environmental data impact on animal movement (Dodge et al. 2013)	• ArcGIS online https://www.arcgis.com/home/index.html • CyberGIS http://cybergis.cigi.uiuc.edu/cyberGISwiki/doku.php • QGIS http://qgis.org/en/site/ • MeteoInfo http://www.meteothinker.com/products/meteoinfo.html • Geographical Open Data Kit http://geoodk.com/
Cloud computing systems	Platforms combine large-scale (e.g., planetary) catalog of satellite imagery and geospatial and climate datasets and analysis capabilities to detect changes, map trends.	• phenology modeling and monitoring (Cope et al., 2017) • Crop phenology mapping (Dong et al. 2016) • Land degradation (Alonso et al. 2016) • Mapping local climate zones (Bechtel et al. 2015) • Monitoring air quality (Zheng et al. 2014)	• Google Earth Engine https://earthengine.google.com/ • Climate Engine http://climateengine.org/ • Land Viewer https://lv.eosda.com/
Distributed and high-performance computing systems	Scalable systems and frameworks for interactive model evaluation and for the rapid development of climate metrics and analysis to address the pain points in the current model.	• Processing of big climate data (Guo 2016) • High-performance climate analytics (Palamuttam et al. 2015; Wilson et al. 2016) • Dust storm simulation (Xie et al. 2010)	• SciSpark https://scispark.jpl.nasa.gov/ • Hadoop http://hadoop.apache.org/
Visualization tools	(Web) software application that can find and visualize potential spatial patterns in human, animal, and plant biometeorology.	• Characterization of biodiversity and biogeographic patterns (Bik and Interactive 2014) • Recognition of patterns in seasonal wind data	• Vaex http://vaex.astro.rug.nl/ • Phinch http://phinch.org/index.html • NPN Visualization Tool http://www.usanpn.org/files/npn-viz-tool/ • Ukko http://www.project-ukko.net/
Databases	Online and free meteorological and biological data sources.	• Disease outbreak monitoring (Freifeld et al. 2008) • Real-time surveillance of emerging public health threat (Zhao et al. 2017) (Freifeld et al. 2008; Ginsberg et al. 2009; Copeland et al. 2013) • Plant phenology (Rosemartin et al. 2015)	• HealthMap http://www.healthmap.org/en/ • NASA EOSDIS https://earthdata.nasa.gov/ • AirBase http://www.eea.europa.eu/data-and-maps/data/airbase-the-european-air-quality-database-7 • WoW https://wow.metoffice.gov.uk/ • AQS Data Mart https://aqs.epa.gov/aqsweb/documents/data_mart_welcome.html • Movebank https://www.movebank.org/panel_frontpage
Crowdsourcing	Software service providers that invite volunteers to contribute to scientific projects. They support citizens, professionals, or institutions that need help to solve problems, analyze data, or complete challenging tasks that cannot be accomplished by machines alone, but require human intelligence. Crowdsourcing can be web-based, free, or open-source.	• Remote sensing image/data interpretation • Precision agriculture (Baklanov et al. 2017) • Earth observation calibration and validation (See et al. 2016)	• Crowdcrafting https://crowdcrafting.org/about • Geo-Wiki http://www.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/Geo-Wiki.en.html • Ona https://ona.io/home/ • Amazon Mechanical Turk https://www.mturk.com/mturk/welcome • GeoSurvey https://geosurvey.qed.ai/login/?next=/ • Weather Underground https://www.wunderground.com/weather/api
Programming language libraries			• SHARPpy https://github.com/sharppy/SHARPpy

Table 2 (continued)

Type	Description	Current applications	Sources and examples
	Open-source computer programs developed using programing languages such as Python and Java and statistical modeling software packages such as R.	• Native plant phenology (Filippa et al. 2016) • Crop risk zones monitoring (Filippis et al. 2016) • Meteorological time series analysis (Förster et al. 2016) • Upper-air sounding analysis and visualization (Blumberg et al. 2017) • Modeling the trajectories and fate of objects or substances drifting in the ocean, or even in the atmosphere	• opendrift https://github.com/opendrift/opendrift/wiki • Phenopix http://phenopix.r-forge.r-project.org/ • MetPy https://unidata.github.io/MetPy/ • MELODIST https://github.com/kristianfoerster/melodist/tree/v0.1.1 • Openair http://www.openair-project.org/

spatial, spectral, and temporal scales, and further across unprecedented thematic scales. Moreover, information and communication technologies have dramatically lessened the barriers to disseminating data, models, and new information across countries and disciplines faster and more reliably than ever. Large amounts of new data have concurrently highlighted the need to efficiently store, curate, analyze, and model biometeorology-related information by using more advanced hardware and software systems and combining theoretical knowledge with data-driven approaches.

This short communication provides an overview of new technologies and data infrastructures at the forefront of scientific investigations, their current or potential use in the field of biometeorology for specific research and applications, and what emerging technologies are likely to advance the field in the twenty-first century. We summarize useful new hardware (Table 1) and software (Table 2) technologies for broad use across biometeorology. The select technologies also support cross-sector collaboration and aid in creating further policy-advancing research through creating a new evidence base. As we as a community move forward into the twenty-first century, readers are encouraged to help augment the following table summaries with new technologies and methods for inclusion in later online versions of such a paper based on emerging developments in the field. To our knowledge, this is the first paper to address the technological advancements and opportunities specific to the discipline of biometeorology. The tables are not exhaustive but provide an overview of some of the most recent and more frequently used technologies related to biometeorology available at the time of publication, as well as those with which co-authors have direct experience.

Final thoughts

The tabulated state-of-the-art forms of biometeorological observations and processing capabilities will be of utmost importance as we face new, highly complex and interconnected challenges into the future. Solutions to worldwide issues that fall within the realm of biometeorology (energy use, health, poverty and food, agriculture, water, climate change adaptation, etc.) will increasingly rely upon technology. As a community of researchers, keeping abreast of the technological advances will allow biometeorology to arise as a field prepared to deal with challenges within the air, water, and land as they connect to living biological organisms. For example, progress towards finer scales of meteorological data in urban and rural areas is at the forefront of understanding the potential for impacts of heat waves on humans, plants, and animals as one of the main hazards of a changing climate. Moreover, routine collection, processing, and visualization of personal exposure data ("big data") will shift paradigms from place-based distribution of environmental hazards to a "hazardscape" that fuses time and space with humans, plants, and/or animal physiology in mathematical time-activity-exposure models.

The vast amount of new data, however, brings its own fundamental research and education challenges to the biometeorology community to take advantage of and, at the same time, contribute to the continuing advancements of big data technology. Biometeorology studies typically involve more than one of the data sources and technologies in the tables provided and sometimes require the development of new tools. Thus, to seamlessly integrate the heterogeneous data sources and tools calls for closer collaboration between the biometeorology community and related technological fields (e.g., geography, GIS, computer science).

On the education front, the escalation of data and related analytical tools highlight the needs of necessary hands-on technical and programming skills, as well as the ability to communicate the complex research effectively across disciplines and to the public. Thus, new formalized training is likely to emerge based on societal needs. Inter-technology training and education for capacity building will augment many current and future research projects that are not easily discernible in using one type of technology. Such capacity building through education may take the form of new technological opportunities which improve scientists' insight and evaluation of the impacts of past, current, and future weather conditions on living organisms.

References

Abdelkader M, Shaqura M, Claudel CG, Gueaieb W (2013) A UAV based system for real time flash flood monitoring in desert environments using Lagrangian microsensors. In: 2013 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, pp 25–34. doi: 10.1109/ICUAS.2013.6564670

Allen MW, McKenzie RL (2010) Electronic UV dosimeters for research and education. In: NIWA UV Workshop, Queenstown, pp 7–9

Alonso A, Muñoz-Carpena R, Kennedy RE, Murcia C (2016) Wetland landscape spatio-temporal degradation dynamics using the new Google Earth Engine cloud-based platform: opportunities for non-specialists in remote sensing. ASABE, St. Joseph. doi:10.13031/trans.59.11608

Anagnostou MN, Kalogiros J, Nikolopoulos E, Derin Y, Anagnostou EN, Borga M (2017) Satellite rainfall error analysis with the use of high-resolution X-band dual-polarization radar observations over the Italian Alps. Springer, Cham, pp 279–286. doi:10.1007/978-3-319-35095-0_39

Aursang SV, Dixit SK (2016) Automated environmental data acquisition system using Raspberry Pi. Int J Sci Eng Comput Technol Indian Association of Health, Research and Welfare, 6(7):282

Baklanov A, Fritz S, Khachay M, Nurmukhametov O, Salk C, See L, Shchepashchenko D (2017) Vote aggregation techniques in the Geo-Wiki crowdsourcing game: a case study. Springer, Cham, pp 41–50. doi:10.1007/978-3-319-52920-2_4

Bechtel B, Alexander PJ, Böhner J, Ching J, Conrad O, Feddema J, Mills G, See L, Stewart I (2015) Mapping local climate zones for a worldwide database of the form and function of cities. ISPRS International Journal of Geo-Information 4(1):199–219. doi:10.3390/ijgi4010199

Bernhard MC, Kent ST, Sloan ME, Evans MB, McClure LA, Gohlke JM (2015) Measuring personal heat exposure in an urban and rural environment. Environ Res 137:410–418. doi:10.1016/j.envres.2014.11.002

Bik HM, Interactive P (2014) Phinch: an interactive, exploratory data visualization framework for–Omic datasets. bioRxiv, 009944. http://www.biorxiv.org/content/early/2014/10/03/009944

Blumberg WG, Halbert KT, Supinie TA, Marsh PT, Thompson RL, Hart JA (2017) SHARPpy: an open source sounding analysis toolkit for the atmospheric sciences. Bull Am Meteorol Soc. doi: 10.1175/BAMS-D-15-00309.1

Chemura, A., Mutanga, O. and Dube, T. (2016) Separability of coffee leaf rust infection levels with machine learning methods at Sentinel-2 MSI spectral resolutions, Precision Agriculture. Springer US, pp. 1–23. doi: 10.1007/s11119-016-9495-0.

Cope M, Mikhailova E, Post C, Schlautman M, McMillan P (2017) Developing an integrated cloud-based spatial-temporal system for monitoring phenology. Eco Inform 39:123–129

Copeland P, Romano R, Zhang T, Hecht G, Zigmond D, Stefansen C (2013) Google disease trends: an update. Nature 457:1012–1014

Cummings JN, Kiesler S (2005) Collaborative research across disciplinary and organizational boundaries. Soc Stud Sci Sage PublicationsSage CA, Thousand Oaks, 35(5):703–722. doi: 10.1177/0306312705055535.

Darack E (2012) UAVs: the new frontier for weather research and prediction. Weatherwise Taylor & Francis Group, 65(2):20–27. doi: 10.1080/00431672.2012.653935

Deville Cavellin L, Weichenthal S, Tack R, Ragettli MS, Smargiassi A, Hatzopoulou M (2016) Investigating the use of portable air pollution sensors to capture the spatial variability of traffic-related air pollution. Environ Sci Technol American Chemical Society, 50(1):313–320. doi: 10.1021/acs.est.5b04235

Di Gennaro SF, Di Gennaro SF, Battiston E, Marco SD, Facini O, Matese A, Nocentini M, Palliotti A, Mugnai L (2016) Unmanned Aerial Vehicle (UAV)-based remote sensing to monitor grapevine leaf stripe disease within a vineyard affected by esca complex. Phytopathol Mediterr 55(2):262–275. doi:10.14601/Phytopathol_Mediterr-18312

Dodge S, Bohrer G, Weinzierl R, Davidson SC, Kays R, Douglas D, Cruz S, Han J, Brandes D, Wikelski M (2013) The environmental-data automated track annotation (Env-DATA) system: linking animal tracks with environmental data. Movement Ecology 1(1):3. doi:10.1186/2051-3933-1-3

Dong J, Xiao X, Menarguez MA, Zhang G, Qin Y, Thau D, Biradar C, III BM (2016) Mapping paddy rice planting area in northeastern Asia with Landsat 8 images, phenology-based algorithm and Google Earth Engine. Remote Sens Environ 185:142–154. doi:10.1016/j.rse.2016.02.016

Dutta P, Aoki PM, Kumar N, Mainwaring A, Myers C, Willett W, Woodruff A (2009) Common sense. In: Proceedings of the 7th ACM conference on embedded networked sensor systems - sensys '09, ACM Press, New York, p 349. doi: 10.1145/1644038.1644095

Ebi KL, McGregor G, Burton I (2009) The status and prospects for biometeorology. In: Biometeorology for adaptation to climate variability and change, Springer Netherlands, Dordrecht, pp 269–278. doi: 10.1007/978-1-4020-8921-3_12

Filippa G, Cremonese E, Migliavacca M, Galvagno M, Forkel M, Wingate L, Tomelleri E, Morra di Cella U, Richardson AD (2016) Phenopix: a R package for image-based vegetation phenology. Agric For Meteorol 220:141–150. doi:10.1016/j.agrformet.2016.01.006

Filippis TD, Rocchi L, Vignaroli P, Bacci M, Tarchiani V, Rapisardi E (2016) Open source geoprocessing tools and meteorological satellite data for crop risk zones monitoring in Sub-Saharan Africa. PeerJ Inc. doi:10.7287/PEERJ.PREPRINTS.2265V2

Förster K, Hanzer F, Winter B, Marke T, Strasser U (2016) An open-source MEteoroLOgical observation time series DISaggregation Tool (MELODIST v0. 1.1). Geosci Model Dev Copernicus GmbH, 9(7):2315–2333

Freifeld CC, Mandl KD, Reis BY, Brownstein JS (2008) HealthMap: global infectious disease monitoring through automated classification and visualization of internet media reports. J Am Med Inform Assoc Oxford University Press, 15(2):150–157. doi: 10.1197/jamia.M2544

Gerrett N, Redortier B, Voelcker T, Havenith G (2013) A comparison of galvanic skin conductance and skin wettedness as indicators of thermal discomfort during moderate and high metabolic rates. J Therm Biol 38(8):530–538. doi:10.1016/j.jtherbio.2013.09.003

Gharesifard M, Wehn U, van der Zaag P (2017) Towards benchmarking citizen observatories: features and functioning of online amateur weather networks. J Environ Manag. doi:10.1016/j.jenvman.2017.02.003

Ginsberg J, Mohebbi MH, Patel RS, Brammer L, Smolinski MS, Brilliant L (2009) Detecting influenza epidemics using search engine query data. Nature Nature Publishing Group, 457(7232):1012–1014. doi: 10.1038/nature07634

Gozzi F, Della Ventura G, Marcelli A (2016) Mobile monitoring of particulate matter: state of art and perspectives. Atmospheric Pollution Research 7(2):228–234. doi:10.1016/j.apr.2015.09.007

Guo X (2016) Application of meteorological big data. In: 2016 16th International Symposium on Communications and Information Technologies (ISCIT). IEEE, pp 273–279. doi: 10.1109/ISCIT.2016.7751635

Haj-Omar A, Thompson WL, Kim Y-S, Glick P, Tolley M, Coleman TP (2016) Stretchable and flexible adhesive-integrated antenna for biomedical applications. In: 2016 I.E. International Symposium on Antennas and Propagation (APSURSI), IEEE, pp 459–460. doi: 10.1109/APS.2016.7695938

Hu K, Yang X, Zhong J, Fei F, Qi J (2017) Spatially explicit mapping of heat health risk utilizing environmental and socioeconomic data. Environ Sci Technol American Chemical Society, 51(3):1498–1507. doi: 10.1021/acs.est.6b04355

Hulley GC, Duren RM, Hopkins FM, Hook SJ, Vance N, Guillevic P, Johnson WR, Eng BT, Mihaly JM, Jovanovic VM, Chazanoff SL, Staniszewski ZK, Kuai L, Worden J, Frankenberg C, Rivera G, Aubrey AD, Miller CE, Malakar NK, Sánchez Tomás JM, Holmes KT (2016) High spatial resolution imaging of methane and other trace gases with the airborne Hyperspectral Thermal Emission Spectrometer (HyTES). Atmos Meas Tech 9:2393–2408. doi:10.5194/amt-9-2393-2016

Hwang K, Park S-K (2016) Experimental study of real-time comprehensive indoor air quality. Springer, Singapore, pp 151–155. doi:10.1007/978-981-10-1536-6_20

Inoue T, Nagai S, Yamashita S, Fadaei H, Ishii R, Okabe K, Taki H, Honda Y, Kajiwara K, Suzuki R (2014) Unmanned aerial survey of fallen trees in a deciduous broadleaved forest in eastern Japan. PLoS one 9(10):e109881

Jiang Q, Kresin F, Bregt AK, Kooistra L, Pareschi E, van Putten E, Volten H, Wesseling J (2016) Citizen sensing for improved urban environmental monitoring. J Sens Hindawi Publishing Corporation, 2016: 1–9. doi: 10.1155/2016/5656245

Jovašević-Stojanović M, Bartonova A, Topalović D, Lazović I, Pokrić B, Ristovski Z (2015) On the use of small and cheaper sensors and devices for indicative citizen-based monitoring of respirable particulate matter. Environ Pollut 206:696–704. doi:10.1016/j.envpol.2015.08.035

Kalluri S, Gundy J, Haman B, Paullin A, Van Rompay P, Vititoe D, Weiner A (2015) A high performance remote sensing product generation system based on a service oriented architecture for the next generation of geostationary operational environmental satellites. Remote Sens Multidisciplinary Digital Publishing Institute, 7(8): 10385–10399. doi: 10.3390/rs70810385

Kim DH, Lu N, Ma R, Kim YS, Kim RH, Wang S, Wu J, Won SM, Tao H, Islam A, Yu KJ, Kim TI, Chowdhury R, Ying M, Xu L, Li M, Chung HJ, Keum H, McCormick M, Liu P, Zhang YW, Omenetto FG, Huang Y, Coleman T, Rogers JA (2011) Epidermal electronics. Science, 333(6044):838–843

Køster B, Søndergaard J, Nielsen JB, Allen M, Bjerregaard M, Olsen A, Bentzen J (2015) Feasibility of smartphone diaries and personal dosimeters to quantitatively study exposure to ultraviolet radiation in a small national sample. Photodermatology, Photoimmunology & Photomedicine 31(5):252–260. doi:10.1111/phpp.12179

Kuras ER, Hondula DM, Brown-Saracino J (2015) Heterogeneity in individually experienced temperatures (IETs) within an urban neighborhood: insights from a new approach to measuring heat exposure. Int J Biometeorol Springer Berlin Heidelberg, 59(10):1363–1372. doi: 10.1007/s00484-014-0946-x

Kuras E, Bernhard M, Calkins M, Ebi K, Hess J, Kintziger K, Jagger M, Middel A, Scott AA, Spector J, Uejio C, Vanos J, Zaitchik B, Gohlke J, Hondula D (2017) Opportunities and challenges for personal heat exposure research. Environ Health Perspect. doi:10.1289/EHP556

Matese A, Di Gennaro SF (2015) Technology in precision viticulture: a state of the art review. Int J Wine Res Dove Press, 7:69. doi: 10.2147/IJWR.S69405

McDonough MacKenzie C, Murray G, Primack R, Weihrauch D (2016) Lessons from citizen science: assessing volunteer-collected plant phenology data with Mountain Watch. Biol Conserv. doi:10.1016/j.biocon.2016.07.027

McKercher GR, Vanos JK (2017) Low-cost mobile air pollution monitoring in urban environments: a pilot study in Lubbock, Texas. Environ Technol 1–10. doi: 10.1080/09593330.2017.1332106

McKercher GR, Salmond JA, Vanos JK (2017) Characteristics and applications of small, portable gaseous air pollution monitors. Environ Pollut 223:102–110. doi:10.1016/j.envpol.2016.12.045

McKinley DC, Miller-Rushing AJ, Ballard HL, Bonney R, Brown H, Cook-Patton SC, Evans DM, French RA, Parrish JK, Phillips TB, Ryan SF, Shanley LA, Shirk JL, Stepenuck KF, Weltzin JF, Wiggins A, Boyle OD, Briggs RD, Chapin SF, Hewitt DA, Preuss PW, Soukup MA (2016) Citizen science can improve conservation science, natural resource management, and environmental protection. Biol Conserv. doi:10.1016/j.biocon.2016.05.015

Mujlid HM (2016) Real-time monitoring of sand and dust storm winds using wireless sensor technology. Available at https://repository.lib.fit.edu/handle/11141/1073. Accessed 13 Mar 2017

Neethirajan S (2017) Recent advances in wearable sensors for animal health management. Sensing and Bio-Sensing Research 12:15–29. doi:10.1016/j.sbsr.2016.11.004

Ouwehand L, European Space Agency, Living Planet Symposium (Prague) (2016) Living planet symposium 2016: proceedings. ESA Communications. Available at http://adsabs.harvard.edu/abs/2016ESASP.740E.200L. Accessed 9 Mar 2017

Pagels P, Wester U, Söderström M, Lindelöf B, Boldemann C (2016) Suberythemal sun exposures at Swedish schools depend on sky views of the outdoor environments—possible implications for pupils health. Photochem Photobiol 92(1):201–207. doi:10.1111/php.12540

Palamuttam R, Mogrovejo RM, Mattmann C, Wilson B, Whitehall K, Verma R, McGibbney L, Ramirez P (2015) SciSpark: applying in-memory distributed computing to weather event detection and tracking. In: 2015 I.E. International Conference on Big Data (Big Data), IEEE, pp 2020–2026. doi: 10.1109/BigData.2015.7363983

Raffa F, Ludeno G, Patti B, Soldovieri F, Mazzola S, Serafino F, Raffa F, Ludeno G, Patti B, Soldovieri F, Mazzola S, Serafino F (2017) X-band wave radar for coastal upwelling detection off the southern coast of Sicily. J Atmos Ocean Technol 34(1):21–31. doi:10.1175/JTECH-D-16-0049.1

Rosemartin AH, Denny EG, Weltzin JF, Lee Marsh R, Wilson BE, Mehdipoor H, Zurita-Milla R, Schwartz MD (2015) Lilac and honeysuckle phenology data 1956–2014. Sci Data Nature Publishing Group, 2:150038. doi: 10.1038/sdata.2015.38

Saini H, Thakur A, Ahuja S, Sabharwal N, Kumar N (2016) Arduino based automatic wireless weather station with remote graphical application and alerts. In: 2016 3rd International Conference on Signal Processing and Integrated Networks (SPIN), IEEE, pp 605–609. doi: 10.1109/SPIN.2016.7566768

Sargent F (1963) The nature and nurture of biometeorology. AIBS Bull 13(3):20. doi:10.2307/1293081

Schmit TJ, Gunshor MM, Menzel WP, Gurka JJ, Li J, Bachmeier AS, Schmit TJ, Gunshor MM, Menzel WP, Gurka JJ, Li J, Bachmeier AS (2005) Introducing the next-generation Advanced Baseline Imager of GOES-R. Bull Am Meteorol Soc 86(8):1079–1096. doi: 10.1175/BAMS-86-8-1079

Scott AA, Zaitchik B, Waugh DW, O'Meara K, Scott AA, Zaitchik B, Waugh DW, O'Meara K (2017) Intraurban temperature variability in Baltimore. J Appl Meteorol Climatol 56(1):159–171. doi:10.1175/JAMC-D-16-0232.1

See L, Fritz S, Dias E, Hendriks E, Mijling B, Snik F, Stammes P, Vescovi FD, Zeug G, Mathieu P-P, et al (2016) Supporting earth-observation calibration and validation: a new generation of tools for crowdsourcing and citizen science. IEEE Geosci Remote Sens Mag IEEE, 4(3):38–50

Sherwood RJ, Greenhalgh DMS (1960) A personal air sampler. Ann Occup Hyg Lond 2(2):127–132

Stadler P, Farnleitner AH, Zessner M (2017) Development and evaluation of a self-cleaning custom-built auto sampler controlled by a low-cost RaspberryPi microcomputer for online enzymatic activity measurements. Talanta 162:390–397. doi:10.1016/j.talanta.2016.10.031

Vanos JK, McKercher GR, Naughton K, Lochbaum M (2017) Schoolyard shade and sun exposure: assessment of personal monitoring during children's physical activity. Photochem Photobiol. doi: 10.1111/php.12721

Wang YQ (2014) MeteoInfo: GIS software for meteorological data visualization and analysis. Meteorol. Appl John Wiley & Sons, Ltd, 21(2):360–368. doi: 10.1002/met.1345

Wilson B, Palamuttam R, Whitehall K, Mattmann C, Goodman A, Boustani M, Shah S, Zimdars P, Ramirez P (2016) SciSpark: highly interactive in-memory science data analytics. In: 2016 I.E. International Conference on Big Data (Big Data), IEEE, pp 2964–2973. doi: 10.1109/BigData.2016.7840948

Xie J, Yang C, Zhou B, Huang Q (2010) High-performance computing for the simulation of dust storms. Comput Environ Urban Syst 34(4):278–290. doi:10.1016/j.compenvurbsys.2009.08.002

Zhao N, Cao G, Vanos JK, Vecellio DJ (2017) The effects of synoptic weather on influenza infection incidences: a retrospective study utilizing digital disease surveillance. Int J Biometeorol Springer Berlin Heidelberg, pp 1–16. doi: 10.1007/s00484-017-1306-4

Zheng Y, Chen X, Jin Q, Chen Y, Qu X, Liu X, Chang E, Ma W-Y, Rui Y, Sun W (2014) A cloud-based knowledge discovery system for monitoring fine-grained air quality. MSR-TR-2014–40, Tech Rep