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• **Notes & Letters** •

Harnessing Crowdsourced Data and Prevalent Technologies for Atmospheric Research

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ABSTRACT

The knowledge garnered in environmental science takes a crucial part in informing decision-making in various fields, including agriculture, transportation, energy, public health and safety, and more. Understanding the basic processes in each of these fields relies greatly on progress being made in conceptual, observational and technological approaches. However, existing instruments for environmental observations are often limited as a result of technical and practical constraints. Current technologies, including remote sensing systems and ground-level measuring means, may suffer from obstacles such as low spatial representativity or a lack of precision when measuring near ground-level. These constraints often limit the ability to carry out extensive meteorological observations and, as a result, the capacity to deepen the existing understanding of atmospheric phenomena and processes. Multi-system informatics and sensing technology have become increasingly distributed as they are embedded into our environment. As they become more widely deployed, these technologies create unprecedented data streams with extraordinary levels of coverage and immediacy, providing a growing opportunity to complement traditional observation techniques using the large volumes of data created. Commercial microwave links that comprise the data transfer infrastructure of cellular communication networks are an example of these types of systems. This viewpoint letter briefly reviews various works on the subject and presents aspects concerning the added value that may be obtained as a result of the integration of these new means, which are becoming available for the first time in this era, for studying and monitoring atmospheric phenomena.

Key words: atmospheric science, IoT (Internet of Things), crowdsourced data, commercial microwave links

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Article Highlights:

- Over the past decade, multi-system informatics and IoT (Internet of Things) technologies have become increasingly distributed.
- The flow of data generated by these systems is characterized by enormous granularity, availability and coverage.
- New opportunities are being opened to utilize the newly available data for atmospheric research.

1. The opportunity: using existing data for studying and monitoring atmospheric phenomena

Over the past decade, the Internet of Things (IoT) and smart devices have become increasingly common as part of the technological infrastructure that surrounds us. The flow of data generated by these systems is characterized by enormous granularity, availability and coverage. As a result, new opportunities are being opened to utilize the newly available information for various needs and, in particular, for atmospheric research. If we consider the data generated by these means, we may notice that many produce measurements with high environmental value. To name some examples—surveillance cameras that operate in the visible light spectrum are positioned in a vast number of locations. Previous works have shown that they can be used for monitoring the temporal patterns of fine atmospheric particulate matter (Wong et al., 2007). Lab experiments have indicated a direct link between the speed of movement of car wipers and rainfall intensity, meaning advanced vehicles that store these data can, in essence, be used as moving rain gauges (Rabiei et al., 2013). Kawamura et al. (2017) revealed a novel technique for monitoring atmospheric humidity using terrestrial broadcasting waves, based on propagation delays due to water vapor. Data shared as open source from social networks have been found to be potentially effective in improving automatic weather observations. Indeed, for the most part, the initial

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weather observation is conducted automatically by dedicated sensors; however, some weather conditions are still better detected by the human eye. On the other hand, millions of "human observers" around the world use applications such as Twitter, which allows them to report publicly on subjects that are relevant to them, and in particular on weather phenomena (Cox and Plale, 2011). As was recently reviewed by Price et al. (2018), in 2020 there will be more than 20 billion smartphones carried by the public worldwide. These mobile devices are equipped with sensors that can be used for environmental monitoring on a multisource basis. Recent works indicate the ability to obtain atmospheric temperature information for the urban canopy layer (Overeem et al., 2013a), to measure atmospheric pressure (Mass and Madaus, 2014; McNicholas and Mass, 2018a), or to study atmospheric tides (Price et al., 2018). Additional studies point to the potential of using any camera-enabled smart mobile device to monitor air quality (Pan et al., 2017). Given the comprehensive coverage of these new "virtual sensors" from all land locations across the whole globe, this low-cost solution introduces a wide range of possibilities that previously could not be offered through existing technologies.

2. Data from cellular communication infrastructure as an example of an environmental monitoring tool

A key example of utilizing existing data sources for atmospheric monitoring is the use of measurements acquired by commercial microwave links (CMLs) that comprise the infrastructure for wireless data transport between cellular base stations. This technology has essentially become a valuable weather monitoring tool over the past decade (e.g., Overeem et al., 2013b; Alpert et al., 2016; Gosset et al., 2016; David and Gao, 2017; Chwala and Kunstmann, 2019). Weather phenomena and atmospheric conditions interfere with the electromagnetic waves transmitted by CMLs. Thus, these networks provide, in essence, an already-existing environmental monitoring facility. The various works done in the field indicate the ability to detect and map rainfall (e.g., Messer et al., 2006; Berne and Uijlenhoet, 2007; Chwala et al., 2012; Overeem et al., 2013b; Fencl et al., 2015), monitor fog (e.g. David et al., 2015), atmospheric moisture (David et al., 2009, 2011; Chwala et al., 2014; Alpert and Rubin, 2018) and dew (Harel et al., 2015; David et al., 2016). Recent research revealed the ability of these radio links to indirectly detect air pollution conditions (David and Gao, 2016).

3. On added value of this novel approach

Indeed, the new data available from these various means (smartphones, social networks, etc.), and particularly from CMLs, can provide observations with considerable spatial coverage and with minimal cost. However, the accuracy of each "sensor" is lower than that of a dedicated instrument. This being the case, is it possible to produce significant information compared to that derived from specialized tools? It can be assumed that these "virtual sensors" are not a substitute for conventional monitoring means, whenever those exist in the field. The correct approach, then, is to consider these newly available sources of data as complementary measures to dedicated measurements and as a substitute during the many cases in which conventional monitoring tools are unavailable. However, the data acquired by prevalent technologies, even when taken alone, often holds enormous potential. In order to demonstrate the added value which lies in IoT data and prevalent technologies, let us focus on CMLs as an example of such a system. Atmospheric moisture is more poorly characterized than wind or even precipitation, due to the difficulty in observing the humidity field. Therefore, questions such as the magnitude of small-scale variability of moisture in the boundary layer, and its effect on convection initiation, are still unanswered (Weckwerth et al., 2004). As a result, the ability to predict convective precipitation, on the storm scale, is limited. However, for significantly improving convection initiation measurements, one will need moisture measurements at meso-γ resolution with accuracies of up to 1 g m^{-3} (Fabry, 2006). Notably, such a type of observations can be acquired using CMLs (David et al., 2019). High-resolution precipitation distribution maps can be generated using CMLs, and therefore the relationship between pollutant wash-off and rainfall provides an opportunity to potentially acquire important spatial information about air quality, as discussed in recent research (David and Gao, 2016). Moreover, liquid water content (LWC) constitutes a major parameter in fog research. Fog LWC changes in space, altitude, and over time, and is dependent on surface and atmospheric conditions (Gultepe et al., 2007). However, conventional sensors for acquiring LWC estimates are limited in the spatial range they can cover, and in their availability. It has been shown that CMLs are able to provide fog LWC estimates across large spatial regions where dedicated sensors are nonexistent. Indeed, the availability of various spectral channels from satellites provides the possibility to observe clouds, aerosols, the Earth surface, and in particular, fog (Lensky and Rosenfeld, 2008; Michael et al., 2018). However, CMLs have also been found to have potential advantages for detecting fog under challenging conditions where satellite retrievals are limited, e.g., when high-altitude clouds cover the fog as observed from the satellite vantage point (David, 2018). Alternatively, the ability to monitor rainfall in areas where radars suffer from clutter effects (Goldshtein et al., 2009) or are blocked by complex topography (David et al., 2013), has also been demonstrated.

4. Summary

The possibilities for monitoring environmental phenomena via new observational powers are many, the available information vast, and the cost minimal, since such "opportunistic sensors" are already deployed in the field. As a result, this means of monitoring the environment is becoming advantageous for atmospheric research. Notably, these newly available "virtual sensors" open the doors to the possibility of assimilating their measurements into high-resolution numerical prediction models, which could lead to improvements in the forecasting capabilities that exist today (Kawamura et al., 2017; Madaus and Mass, 2017; McNicholas and Mass, 2018b; David et al., 2019). In a practical sense, this novel approach could lay the groundwork for developing new early-warning systems against natural hazards and generating a variety of products required for a wide range of fields. Thus, the overall potential contribution to public health and safety may be invaluable.

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REFERENCES

Alpert, P., and Y. Rubin, 2018: First daily mapping of surface moisture from cellular network data and comparison with both observations/ECMWF product. *Geophys. Res. Lett.*, **45**(16), 8619–8628, https://doi.org/10.1029/2018GL078661.

Alpert, P., H. Messer, and N. David, 2016: Meteorology: Mobile networks aid weather monitoring. *Nature*, **537**(7622), 617, https://doi.org/10.1038/537617e.

Berne, A., and R. Uijlenhoet, 2007: Path-averaged rainfall estimation using microwave links: Uncertainty due to spatial rainfall variability. *Geophys. Res. Lett.*, **34**(7), L07403, https://doi.org/10.1029/2007GL029409.

Chwala, C., and Coauthors, 2012: Precipitation observation using microwave backhaul links in the alpine and pre-alpine region of Southern Germany. *Hydrology and Earth System Sciences*, **16**(8), 2647–2661, https://doi.org/10.5194/hess-16-2647-2012.

Chwala, C., and H. Kunstmann, 2019: Commercial microwave link networks for rainfall observation: Assessment of the current status and future challenges. Wiley Interdisciplinary Reviews: *Water*, **6**(2), e1337, https://doi.org/10.1002/wat2.1337.

Chwala, C., H. Kunstmann, S. Hipp, and U. Siart, 2014: A monostatic microwave transmission experiment for line integrated precipitation and humidity remote sensing. *Atmospheric Research*, **144**, 57–72, https://doi.org/10.1016/j.atmosres.2013.05.014.

Cox, J., and B. Plale, 2011: Improving automatic weather observations with the public Twitter stream. IU School of Informatics and Computing. https://pdfs.semanticscholar.org/bbe1/0421b7238e4e6d4799a77bb79275994372e1.pdf

David, N., 2018: Utilizing microwave communication data for detecting fog where satellite retrievals are challenged. *Natural Hazards*, **94(2)**, 867–882, https://doi.org/10.1007/s11069-018-3428-3.

David, N., and H. O. Gao, 2016: Using cellular communication networks to detect air pollution. Environ. *Sci. Technol.*, **50**(17), 9442–9451, https://doi.org/10.1021/acs.est.6b00681.

Davıd, N., and H. O. Gao, 2017: Atmospheric monitoring using commercial microwave networks. *Proc. 15th International Conf. on Environmental Science and Technology*, Rhodes, Greece, Global NEST, 1–4.

David, N., P. Alpert, and H. Messer, 2009: Novel method for water vapour monitoring using wireless communication networks measurements. *Atmospheric Chemistry and Physics*, **9**(7), 2413–2418, https://doi.org/10.5194/acp-9-2413-2009.

David, N., P. Alpert, and H. Messer, 2011: Humidity measurements using commercial microwave links. Advanced Trends in Wireless Communications. M. Khatib, Ed., InTech, 520 pp.

David, N., P. Alpert, and H. Messer, 2013: The potential of cellular network infrastructures for sudden rainfall monitoring in dry climate regions. *Atmospheric Research*, **131**, 13–21, https://doi.org/10.1016/j.atmosres.2013.01.004.

David, N., O. Sendik, H. Messer, and P. Alpert, 2015: Cellular network infrastructure: The future of fog monitoring? *Bull. Amer. Meteor. Soc.*, **96**(10), 1687–1698, https://doi.org/10.1175/BAMS-D-13-00292.1.

David, N., O. Harel, P. Alpert, and H. Messer, 2016: Study of attenuation due to wet antenna in microwave radio communication. Proc. 2016 IEEE International Conf. on Acoustics, Speech and Signal Processing (ICASSP), Shanghai, China, IEEE, 4418–4422, https://doi.org/10.1109/ICASSP.2016.7472512.

David, N., O. Sendik, Y. Rubin, H. Messer, H. O. Gao, D. Rostkier-Edelstein, and P. Alpert, 2019: Analyzing the ability to reconstruct the moisture field using commercial microwave network data. *Atmospheric Research*, **219**, 213–222, https://doi.org/10.1016/j.atmosres.2018.12.025.

Fabry, F., 2006: The spatial variability of moisture in the boundary layer and its effect on convection initiation: Project-long characterization. *Mon. Wea. Rev.*, **134**(1), 79–91, https://doi.org/10.1175/MWR3055.1.

Fencl, M., J. Rieckermann, P. Sýkora, D. Stránský, and V. Bareš, 2015: Commercial microwave links instead of rain gauges: Fiction or reality? *Water Science & Technology*, **71**(1), 31–37, https://doi.org/10.2166/wst.2014.466.

Goldshtein, O., H. Messer, and A. Zinevich, 2009: Rain rate estimation using measurements from commercial telecommunications links. *IEEE Transactions on Signal Processing*, **57**(4), 1616–1625, https://doi.org/10.1109/TSP.2009.2012554.

Gosset, M., and Coauthors, 2016: Improving rainfall measurement in gauge poor regions thanks to mobile telecommunication networks. *Bull. Amer. Meteor. Soc.*, **97**(3), ES49–ES51, https://doi.org/10.1175/BAMS-D-15-00164.1.

Gultepe, I., and Coauthors, 2007: Fog research: A review of past achievements and future perspectives. *Pure Appl. Geophys.*, **164**, 1121–1159, https://doi.org/10.1007/s00024-007-0211-x.

Harel, O., N. David, P. Alpert, and H. Messer, 2015: The potential of microwave communication networks to detect dew—Experimental study. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **8**(9), 4396–4404, https://doi.org/10.1109/JSTARS.2015.2465909.

Kawamura, S., and Coauthors, 2017: Water vapor estimation using digital terrestrial broadcasting waves. *Radio Sci.*, **52**(3), 367–377, https://doi.org/10.1002/2016RS006191.

Lensky, I. M., and D. Rosenfeld, 2008: Clouds-aerosols-precipitation satellite analysis tool (CAPSAT). *Atmospheric Chemistry and Physics*, **8**(22), 6739–6753, https://doi.org/10.5194/acp-8-6739-2008.

Madaus, L. E., and C. F. Mass, 2017: Evaluating smartphone pressure observations for mesoscale analyses and forecasts. *Wea. Forecasting*, **32**(2), 511–531, https://doi.org/10.1175/WAF-D-16-0135.1.

Mass, C. F., and L. E. Madaus, 2014: Surface pressure observations from smartphones: A potential revolution for high-resolution weather prediction? *Bull. Amer. Meteor. Soc.*, **95**(9), 1343–

1349, https://doi.org/10.1175/BAMS-D-13-00188.1.

McNicholas, C., and C. F. Mass, 2018a. Smartphone pressure collection and bias correction using machine learning. *J. Atmos. Oceanic Technol.*, **35**(3), 523–540, https://doi.org/10.1175/JTECH-D-17-0096.1.

McNicholas, C., and C. F. Mass, 2018b: Impacts of assimilating smartphone pressure observations on forecast skill during two case studies in the pacific northwest. *Wea. Forecasting*, **33**(5), 1375–1396, https://doi.org/10.1175/WAF-D-18-0085.1.

Messer, H., A. Zinevich, and P. Alpert, 2006: Environmental monitoring by wireless communication networks. *Science*, **312**(5774), 713, https://doi.org/10.1126/science.1120034.

Michael, Y., I. M. Lensky, S. Brenner, A. Tchetchik, N. Tessler, and D. Helman, 2018: Economic assessment of fire damage to urban forest in the wildland–urban interface using planet satellites constellation images. *Remote Sens.*, **10**(9), 1479, https://doi.org/10.3390/rs10091479.

Overeem, A., J. C. R. Robinson, H. Leijnse, G. J. Steeneveld, B. K. P. Horn, and R. Uijlenhoet, 2013a: Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophys. Res. Lett.*, **40**(15), 4081–4085, https://doi.org/10.1002/grl.50786.

Overeem, A., H. Leijnse, and R. Uijlenhoet, 2013b: Country-wide rainfall maps from cellular communication networks. *Proc. Natl. Acad. Sci.*, **110**(8), 2741–2745, https://doi.org/10.1073/pnas.1217961110.

Pan, Z. X., H. Yu, C. Y. Miao, and C. Leung, 2017: Crowdsensing air quality with camera-enabled mobile devices. Proceedings of the. Twenty-Ninth AAAI Conference. on Innovative Applications, San Francisco, CA, AAAI, 4728–4733.

Price, C., R. Maor, and H. Shachaf, 2018: Using smartphones for monitoring atmospheric tides. *Journal of Atmospheric and Solar-Terrestrial Physics*, **174**, 1–4, https://doi.org/10.1016/j.jastp.2018.04.015.

Rabiei, E., U. Haberlandt, M. Sester, and D. Fitzner, 2013: Rainfall estimation using moving cars as rain gauges-laboratory experiments. *Hydrology and Earth System Sciences*, **17**(11), 4701–4712, https://doi.org/10.5194/hess-17-4701-2013.

Weckwerth, T. M., and Coauthors, 2004: An overview of the international H2O project (IHOP_2002) and some preliminary highlights. *Bull. Amer. Meteor. Soc.*, **85**, 253–278, https://doi.org/10.1175/BAMS-85-2-253.

Wong, C. J., M. Z. MatJafri, K. Abdullah, H. S. Lim, and K. L. Low, 2007: Temporal air quality monitoring using surveillance camera. *Proc. 2007 IEEE International Geoscience and Remote Sensing Symposium*, Barcelona, Spain, IEEE, 2864–2868, https://doi.org/10.1109/IGARSS.2007.4423441.