# Country-wide rainfall maps from cellular communication networks

Aart Overeem[a,b,1], Hidde Leijnse[b], and Remko Uijlenhoet[a]

[a]Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen University, 6708 PB Wageningen, The Netherlands; and [b]Research and Development, Weather Service, Royal Netherlands Meteorological Institute, 3732 GK De Bilt, The Netherlands

Edited by Soroosh Sorooshian, University of California, Irvine, CA, and accepted by the Editorial Board December 8, 2012 (received for review October 16, 2012)

**Accurate and timely surface precipitation measurements are crucial for water resources management, agriculture, weather prediction, climate research, as well as ground validation of satellite-based precipitation estimates. However, the majority of the land surface of the earth lacks such data, and in many parts of the world the density of surface precipitation gauging networks is even rapidly declining. This development can potentially be counteracted by using received signal level data from the enormous number of microwave links used worldwide in commercial cellular communication networks. Along such links, radio signals propagate from a transmitting antenna at one base station to a receiving antenna at another base station. Rain-induced attenuation and, subsequently, path-averaged rainfall intensity can be retrieved from the signal's attenuation between transmitter and receiver. Here, we show how one such a network can be used to retrieve the space–time dynamics of rainfall for an entire country (The Netherlands, ∼35,500 km$^2$), based on an unprecedented number of links (∼2,400) and a rainfall retrieval algorithm that can be applied in real time. This demonstrates the potential of such networks for real-time rainfall monitoring, in particular in those parts of the world where networks of dedicated ground-based rainfall sensors are often virtually absent.**

hydrometeorology | remote sensing

The severely declining number of rain gauges in Europe, South America, and Africa [roughly a 50% decline in the period 1989–2006 for GPCC, version 5.0 (1, 2)], as well as in Asia [approximately a 50% decline in number of valid daily reports in the period 2000–2007 for APHRODITE (3)] combined with the very limited extent of the African observation network (4), calls for alternative sources of near-surface rainfall information. Microwave links from operational cellular telecommunication networks may be used for rainfall monitoring (5, 6), potentially over large parts of the land surface of the earth. Along such links, radio signals propagate from a transmitting antenna at one base station to a receiving antenna at another base station (Fig. 1 *Left*). Rain-induced attenuation and, subsequently, path-averaged rainfall intensity can be retrieved from the signal's attenuation between transmitter and receiver (5–10).

As can be seen from Fig. 2 (*Left*), large parts of the land surface of the earth are covered by cellular telecommunication networks [20% in 2007 (11)]. These networks have high densities in urban areas and are widely used in developing, newly industrialized, and developed countries. Fig. 2 (*Right*) shows that cellular telephone coverage coincides with higher population densities. Nowadays, networks cover more than 90% of the world's population (12), and ∼75% of the world's inhabitants have access to a cellular telephone (13). Because the characteristics of commercial microwave links used worldwide are similar, this indicates the great potential of rainfall monitoring using cellular telecommunication networks. In addition, link-based rainfall estimates could serve as ground validation for or complement satellite retrievals above land, and hold a promise for assimilation in numerical weather prediction and flood forecasting models as well as for comparison with climate models. For countries operating weather radars, another potential benefit of link rainfall data lies in merging with radar rainfall data, in particular to improve rainfall estimates at locations far away from the radar. In general, the number of microwave links in a country will be much larger than the number of automatic, or even daily, rain gauges, providing new opportunities to adjust radar data.

Here, we show how one such commercial cellular communication network can be used to retrieve the space–time dynamics of rainfall for an entire country, based on ∼2,400 links and a rainfall retrieval algorithm that is applicable in real time. Received signal level data were obtained from a commercial microwave link network covering The Netherlands (35,500 km$^2$), a densely populated country in Western Europe with almost 17 million inhabitants. The available data are minimum and maximum received powers over 15-min intervals with a precision of 1 dB, based on 10-Hz sampling. A 12-d calibration and a 12-d validation dataset from June to September 2011 are used here. In general, power losses along links are measured and stored by cellular communication companies to monitor the stability of their link networks. At the used radio frequencies, these losses are, apart from free space losses, mainly the result of attenuation by rainfall. Raindrops absorb part of the incident wave and, in addition, scatter some of the energy out of the beam. The resulting attenuation becomes larger for increasing numbers and sizes of the raindrops present along the beam. Fig. 1 (*Right*) displays the locations of the used commercial microwave links, which are single-frequency links transmitting vertically polarized signals. As can be seen, the links cover a large part of the country, although they are not uniformly distributed. In urban areas, the links are shortest and the link densities are largest. Note that these links represent only part of the microwave link network of one of the three providers in The Netherlands. The total number of link paths in The Netherlands is around 5,000 for this provider and at least 8,000 for all three providers together (compared with ∼325 daily and ∼32 10-min rain gauges from the Royal Netherlands Meteorological Institute). For many link paths, microwave links measure in both directions. The links typically measure at ten to several tens of meters above the ground, use frequencies ranging from ∼13 to 40 GHz (particularly 37–40 GHz), and have an average length of 3.1 km.

Author contributions: A.O., H.L., and R.U. designed research; A.O. performed research; A.O. analyzed data; and A.O., H.L., and R.U. wrote the paper.

Conflict of interest statement: The original microwave link data cannot be provided because of a nondisclosure agreement with the supplier of the data, T-Mobile NL.

This article is a PNAS Direct Submission. S.S. is a guest editor invited by the Editorial Board.

Freely available online through the PNAS open access option.

Data deposition: The underlying radar dataset can be freely obtained at https://data.knmi.nl/portal-webapp/KNMI-Datacentrum.html. The original microwave link data cannot be provided, but derived data, i.e., link-based rainfall images in ASCII or HDF5 format, can be supplied upon request.

[1]To whom correspondence should be addressed. E-mail: aart.overeem@wur.nl.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1217961110/-/DCSupplemental.

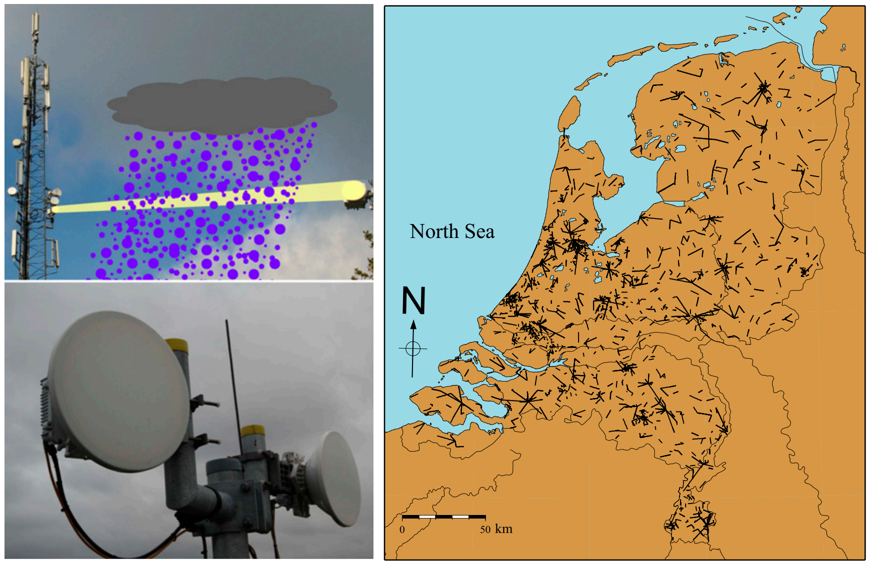


**Fig. 1.** Photos and locations of commercial microwave links. (*Upper Left*) Rainfall attenuates the electromagnetic signals transmitted from the circular antenna of one cellular communication tower to another. (*Lower Left*) A close-up of two antennas. (*Right*) Map of The Netherlands with the locations of the used 1,751 link paths from 2,902 commercial microwave links for the validation (black lines).

## Results and Discussion

For the used cellular network, the loss of power is inferred from the decrease in received power only, the transmit powers being nearly constant (±0.2 dB). The received signal powers have to be corrected before accurate path-averaged rainfall intensities can be obtained. Although signal losses not related to rainfall are often smaller than those during rain, they frequently occur and could result in an overestimation of rainfall intensity when not properly accounted for. Hence, a methodology is applied to remove unwanted signal fluctuations. In addition, a filter is applied to exclude a link when its received power deviates too much from that of the surrounding links over the previous 24 h (*Materials and Methods*).

Attenuation along the link path is computed from the difference between the corrected signal level and the reference level (6, 8, 14), which is assumed representative of dry weather during the previous 24 h. Mean 15-min path-averaged rainfall intensities are computed from the minimum and maximum attenuation. Part of the decrease in microwave signal power is caused by water films on the antennas, which causes an overestimation of the attenuation, and hence an overestimation of the path-averaged rainfall intensity if not properly accounted for. The rainfall retrieval algorithm includes a correction for this phenomenon. The maximum error caused by changes in specific humidity can be of the same order of magnitude as the quantization error, i.e., 1 dB, for the typical link frequencies used in cellular communication networks worldwide, i.e., 7–40 GHz (15). This error is influenced by the magnitude of the specific attenuation caused by water vapor and the rainfall retrieval relation, both of which are frequency dependent. A gauge-adjusted radar dataset is used to calibrate the microwave link rainfall retrieval algorithm and to validate link-based rainfall maps (*Materials and Methods*). Note that microwave links will in general not be suitable for measurement of nonmelting solid precipitation (16).

The 15-min link rainfall depths are used to obtain link-based country-wide rainfall maps. For ease in subsequent spatial interpolation, link rainfall depths are assumed to represent point measurements. The middle of each link is assigned the value of the path-averaged 15-min rainfall depth. The 15-min rainfall depths from observed link data are interpolated using ordinary kriging (17) to obtain rainfall maps. Fig. 3 shows a subset of link-based and radar-based country-wide maps of 15-min rainfall depths from September 10, 2011, 1845–2315 hours Coordinated

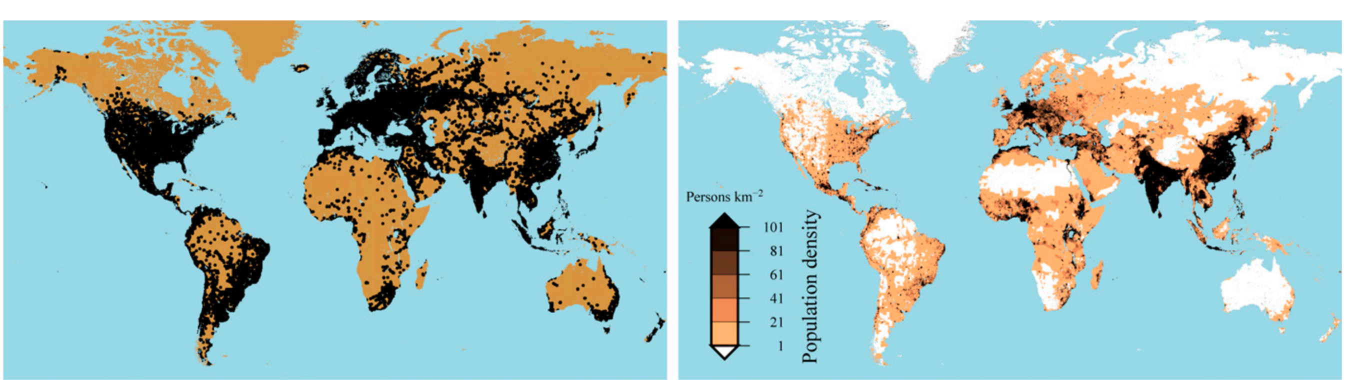


**Fig. 2.** World maps of cellular telephone coverage and population density. (*Left*) Cellular telephone coverage based on data collected by users of an Android application from September 2009 to August 2012 (data provided by opensignal.com). (*Right*) Population density in 2000 (adjusted to match United Nations totals). Data were taken from *Gridded Population of the World, Version 3* (28).

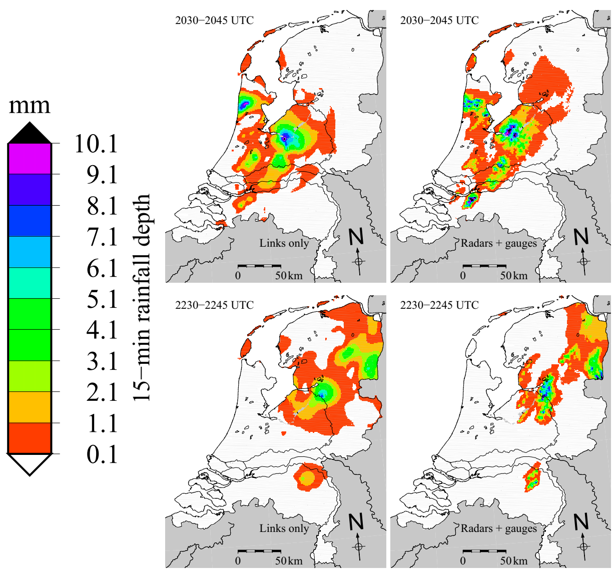


**Fig. 3.** Space–time dynamics of 15-min rainfall depths (two panels per time step) from links (*Left*) and radars plus gauges (*Right*) for September 10, 2011, 2030–2045 and 2230–2245 hours UTC (validation). The movie is provided as Movie S1 for September 10, 2011, 1845–2315 hours UTC. Based on 6% less link paths than the average number of link paths for the 12-d validation data set.

Universal Time (UTC), an independent validation (the movie is provided as Movie S1). These 15-min rainfall maps are solely based on data from 2,272 links on average (1,420 link paths on average, many of them two-way). Rain storms travel from the southwestern to the northeastern part of the country. The global evolution of rainfall fields can be accurately retrieved from the microwave link data. Individual storms can often be recognized by the cellular telecommunication network. Although local differences between link and radar rainfall depths do occur, the general resemblance is good, especially if one takes into account the fact that these links have not been designed to be used as path-average rain gauges. This example shows the potential of microwave links for monitoring rainfall on short timescales, which is highly relevant for areas lacking weather radar and/or rain gauge data.

The 15-min link rainfall maps from the 12-d validation data set are accumulated to daily rainfall maps and compared with the radar-based accumulations in Fig. S1. Note that radar provides complete coverage with one observation per 1 $km^2$ every 5 min, whereas the link network provides observations of on average 1,514 link paths on a 15-min basis with an average length of 3.1 km. Although radar reveals more spatial detail in the daily rainfall depths, the rainfall patterns of the different observational systems correspond closely for most days. The quality of the 12 daily link-based rainfall maps is confirmed by Fig. 4 (*Left*): The bias is almost zero, the coefficient of variation (CV) (i.e., the ratio of the SD of the differences to the mean radar rainfall depth) is 0.53, and the coefficient of determination ($\rho^2$) (i.e., the fraction of explained variance) is 0.73. Fig. 4 (*Right*) also provides a scatter density plot for the 15-min rainfall maps of the 12-d validation data set. The 15-min rainfall depths have been averaged in space. An area size of 81 $km^2$ (i.e., 9 km × 9 km, the size of a small city) has been chosen to limit representativeness errors in space and time. The bias is almost zero, CV is 1.13, and $\rho^2$ is 0.49.

## Conclusions

These results confirm the usefulness of microwave links for real-time rainfall monitoring over large areas. Note that the limitations of the link data provided to us regarding precision (1 dB), temporal sampling protocol (i.e., minimum and maximum power over 15 min), and used spatial interpolation scheme (based on points rather than lines), are by no means optimal. Although some cellular telecommunication networks have a coarser precision or store only one instantaneous value per 15-min period, other networks have a higher precision [e.g., 0.1 dB (8)] and apply more frequent sampling (e.g., every minute). Note that in the tropics links often operate at lower frequencies, typically 7–13 GHz, which can increase errors in rainfall estimates due to the increased nonlinearity of the relationship between rainfall intensity and specific attenuation at lower frequencies (8, 18, 19). Microwave links can also be used to estimate rainfall intensities in regions with high topographic variability, in which case averaged rainfall intensities are obtained over slant paths (20). Preferably, the parameters of the rainfall retrieval algorithm should be recalibrated for rainfall with different characteristics,

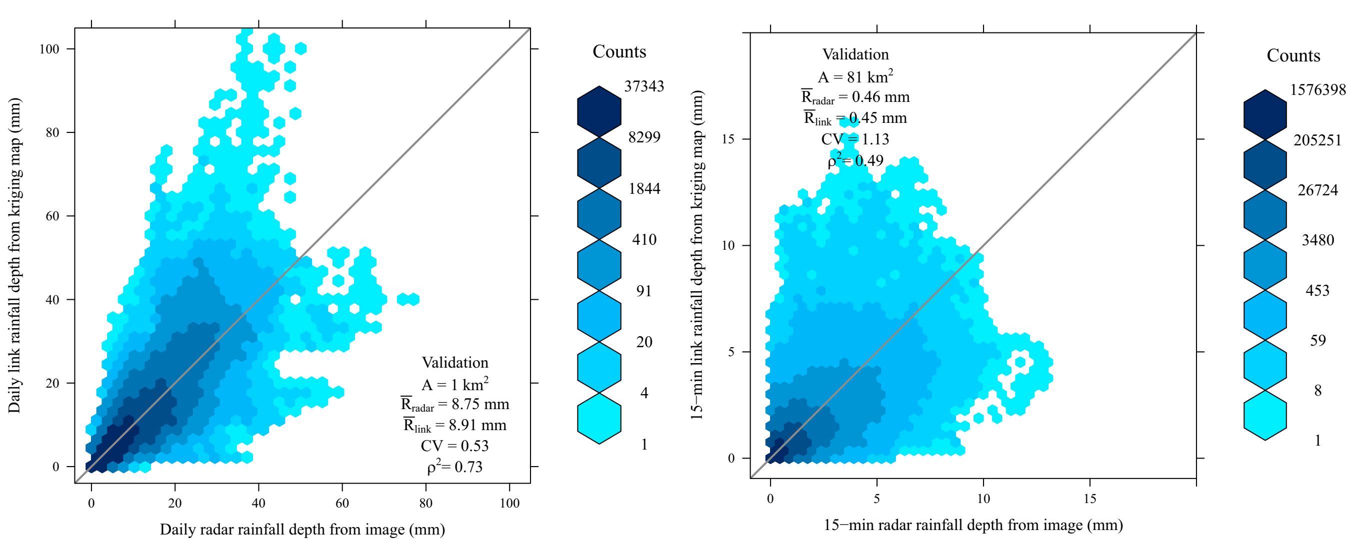


**Fig. 4.** Validation of link rainfall maps against radar rainfall maps. (*Left*) Daily rainfall depths for each radar pixel of 1 $km^2$. (*Right*) Fifteen-minute rainfall depths for an area size $A$ of 81 $km^2$. The gray line is the $y = x$ line, $\overline{R}$ denotes average rainfall depth at the radar pixel, CV is the coefficient of variation, and $\rho^2$ is the coefficient of determination. Only those rainfall depths have been used where link and/or radar have measured >0.1 mm.

i.e., for other regions, climates, and seasons. The International Telecommunication Union recommends values of the coefficients $a$ and $b$ for a range of frequencies, to be applied globally (21). These coefficients depend relatively little on temperature and drop size distribution (22).

The use of cellular communication networks for rainfall measurement fits into a broader development where sensors are used for monitoring environmental variables for which they have not specifically been designed. For instance, GPS-based measurements from ground-based receivers and satellites in low-earth orbits (e.g., refs. 23 and 24) can be used to retrieve atmospheric water vapor, and Mode-S observations from tracking and ranging air traffic control radars contain information on wind and temperature (25).

Monitoring rainfall using cellular telecommunication networks could provide a great opportunity to reduce fatalities and economic loss, e.g., by improving flood early warning systems (26). This is particularly important for densely populated delta regions where rainfall information is crucial for operational water management (27). We therefore hope that this research report will contribute to persuade cellular communication companies worldwide to provide received signal level (RSL) data from their radio link networks free of charge for both research purposes and other applications of societal relevance. Perhaps (inter)national legislation could also help to achieve this goal.

## Materials and Methods

Data from a cellular communication network have been shown to be suitable for quantitative precipitation estimation in an urban area in The Netherlands (8). Several modifications have been made to the reported algorithms, particularly to improve their applicability in real time over large areas. In addition, a filter has been developed to remove outliers.

A modified methodology is applied to distinguish between wet and dry spells and to convert minimum and maximum received signal levels to maximum and minimum attenuation, respectively (8). A 15-min interval is labeled wet if the mutual decrease in minimum received powers of nearby links in the same interval exceeds two thresholds based on the fact that rain is spatially correlated (29, 30). A filter is used to remove outliers in attenuation due to malfunctioning of link antennas. The principle of this filter is that a link is discarded if the cumulative difference between its specific attenuation and that of the surrounding links over the previous 24 h becomes smaller than $-130$ dB·km$^{-1}$. This criterion is applied to specific attenuation derived from minimum received power. The wet/dry classification algorithm and filter combined lead to a 9% reduction in the number of selected microwave links.

A gauge-adjusted radar dataset is used to calibrate the microwave link rainfall retrieval algorithm and to validate link-based rainfall maps. The quality of a similar radar dataset for another period was found to be high, enabling to derive extreme areal rainfall statistics (31–33). For the calibration, a radar dataset of path-averaged rainfall intensities over each link was constructed (8). Because of the high spatial resolution of radar data (1 km$^2$), they can be used to obtain more representative rainfall measurements along the link path than typical rain gauge network data, which will often not be available in the vicinity of a link due to the relatively low gauge network density, in particular for subdaily durations.

The core of the rainfall retrieval algorithm can be summarized as follows (8). This is the retrieval algorithm used to calculate the path-averaged mean 15-min rainfall intensity:

$$\langle R_{\min}\rangle = a\left(\frac{A_{\min}-A_a}{L}\right)^b H(A_{\min}-A_a), \qquad [1]$$

$$\langle R_{\max}\rangle = a\left(\frac{A_{\max}-A_a}{L}\right)^b H(A_{\max}-A_a), \qquad [2]$$

$$\langle R\rangle = \alpha\langle R_{\max}\rangle + (1-\alpha)\langle R_{\min}\rangle, \qquad [3]$$

where $\langle R_{\max}\rangle$ and $\langle R_{\min}\rangle$ are the maximum and minimum path-averaged rainfall intensities (in millimeters per hour), $H$ is the Heaviside function (if the argument of $H$ is smaller than zero, $H$ = 0; else, $H$ = 1), $A_a$ is the attenuation due to wet antennas (in decibels), and $\alpha$ is a coefficient that determines the contribution of the minimum and maximum rainfall intensity during a 15-min period. The effect of wet antenna attenuation is hence assumed to be constant. Values of coefficients $a$ and $b$ used in this study are those derived from measured drop size distributions (34). Daily link-based rainfall depths are compared with gauge-adjusted radar retrievals to calibrate the rainfall retrieval algorithm. A 12-d calibration data set from June and July 2011 was used to obtain optimal values: 0.33 for $\alpha$ and 2.3 dB for $A_a$. Using these optimal values, mean 15-min rainfall intensities are calculated for each link and time step for the 12-d validation data set from June, August, and September 2011.

Ordinary kriging is used here to obtain 15-min rainfall maps because it is ideally suited for dealing with heterogeneously distributed data locations. This method requires a variogram model. Errors can occur when the estimation of variogram model coefficients would be carried out for each 15-min time step separately. Therefore, a more robust procedure is followed. The sill and range of a spherical variogram model have been expressed as a function of duration (1–24 h) and day of year using rain gauge data from The Netherlands (30). These relationships are extrapolated to 15 min. The nugget is set equal to 0.1 times the sill.

**ACKNOWLEDGMENTS.** We gratefully acknowledge Ronald Kloeg and Ralph Koppelaar from T-Mobile NL for providing the cellular telecommunication link data. We thank Marc Bierkens (Utrecht University) for his advice concerning kriging and Manuel Rios Gaona for programming part of the kriging script. We also thank James Robinson from OpenSignal for providing the worldwide cellular phone coverage data and Adriaan J. Teuling (Wageningen University) for his comments on our manuscript. This work was financially supported by The Netherlands Technology Foundation STW (project 11944).

1. Walsh D (July 2, 2012) The tricky business of counting rain. *NY Times*, Available at http://green.blogs.nytimes.com/2012/07/02/do-not-publish-the-tricky-business-of-counting-rain. Accessed January 5, 2013.
2. Lorenz C, Kunstmann H (2012) The hydrological cycle in three state-of-the-art reanalyses: Intercomparison and performance analysis. *J Hydrometeorol* 13(5):1397–1420.
3. Yatagai A, et al. (2012) APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bull Am Meteorol Soc* 93(9):1401–1415.
4. Trans-African Hydro-Meteorological Observatory. Available at www.tahmo.org/. Accessed January 5, 2013.
5. Messer H, Zinevich A, Alpert P (2006) Environmental monitoring by wireless communication networks. *Science* 312(5774):713.
6. Leijnse H, Uijlenhoet R, Stricker JNM (2007) Rainfall measurement using radio links from cellular communication networks. *Water Resour Res* 43(3):W03201.
7. Zinevich A. Messer H, Alpert P (2009) Frontal rainfall observation by a commercial microwave communication network. *J Appl Meteorol Climatol* 48(7):1317–1334.
8. Overeem A, Leijnse H, Uijlenhoet R (2011) Measuring urban rainfall using microwave links from commercial cellular communication networks. *Water Resour Res* 47(12): W12505.
9. Overeem A, Leijnse H, Uijlenhoet R (2012) Quantitative precipitation estimation using commercial microwave links. *Weather Radar and Hydrology, Proceedings of a symposium Held in Exeter, UK, April 2011*, eds Moore RJ, Cole SJ, Illingworth AJ (International Association of Hydrological Sciences, Wallingford, UK), pp 129–134.
10. Rayitsfeld A, Samuels R, Zinevich A, Hadar U, Alpert P (2012) Comparison of two methodologies for long term rainfall monitoring using a commercial microwave communication system. *Atmos Res* 104–105:119–127.
11. Association GSM *Universal Access. How Mobile Can Bring Communications to All*. Available at www.gsma.com/publicpolicy/wp-content/uploads/2012/03/universalaccessfullreport.pdf. Accessed January 5, 2013.
12. Association GSM Available at www.gsma.com/aboutus/gsm-technology/gsm/. Accessed January 5, 2013.
13. World Bank (2012) Mobile phone access reaches three quarters of planet's population. Available at www.worldbank.org/en/news/2012/07/17/mobile-phone-access-reaches-three-quarters-planets-population. Accessed January 5, 2013.
14. Fenicia F, et al. (2012) Microwave links for rainfall estimation in an urban environment: Insights from an experimental setup in Luxembourg-City. *J Hydrol (Amst)* 464–465:69–78.
15. Ulaby FT, Moore RK, Fung AK (1981) Microwave remote sensing fundamentals and radiometry. *Microwave Remote Sensing: Active and Passive* (Addison-Wesley, Reading, MA), Vol I, Chap 5, pp 256–343.
16. Vivekanandan J, Martner BE, Politovich MK, Zhang G (1999) Retrieval of atmospheric liquid and ice characteristics using dual-wavelength radar observations. *IEEE Trans Geosci Rem Sens* 37(5):2325–2334.
17. Matheron G (1963) Principles of geostatistics. *Econ Geol* 58(8):1246–1266.
18. Berne A, Uijlenhoet R (2007) Path-averaged rainfall estimation using microwave links: Uncertainty due to spatial rainfall variability. *Geophys Res Lett* 34(7):L07403.

19. Leijnse H, Uijlenhoet R, Berne A (2010) Errors and uncertainties in microwave link rainfall estimation explored using drop size measurements and high-resolution radar data. *J Hydrometeorol* 11(6):1330–1344.
20. Chwala C, et al. (2012) Precipitation observation using microwave backhaul links in the alpine and pre-alpine region of Southern Germany. *Hydrol Earth Syst Sci* 16(1): 2647–2661.
21. International Telecommunication Union (2012) Recommendation ITU-R P.838-3: Specific attenuation model for rain for use in prediction methods. Available at www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.838-3-200503-I!!PDF-E.pdf. Accessed January 5, 2013.
22. Leijnse H, Uijlenhoet R, Stricker JNM (2007) Hydrometeorological application of a microwave link: 2. Precipitation. *Water Resour Res* 43(4):W04417.
23. Bengtsson L, et al. (2003) The use of GPS measurements for water vapor determination. *Bull Am Meteorol Soc* 84(9):1249–1258.
24. de Haan S, Holleman I, Holtslag AAM (2009) Real-time water vapor maps from a GPS surface network: Construction, validation, and applications. *J Appl Meteorol Climatol* 48(7):1302–1316.
25. de Haan S, Stoffelen A (2012) Assimilation of high-resolution Mode-S wind and temperature observations in a regional NWP model for nowcasting applications. *Weather Forecast* 27(4):918–937.
26. di Baldassarre G, et al. (2010) Flood fatalities in Africa: From diagnosis to mitigation. *Geophys Res Lett* 37(22):L22402.
27. Syvitski JPM, et al. (2009) Sinking deltas due to human activities. *Nat Geosci* 2: 681–686.
28. Center for International Earth Science Information Network, Columbia University; Centro Internacional de Agricultura Tropical (2005) *Gridded Population of the World Version 3 (GPWv3): Population Density Grids* (Palisades, NY: Socioeconomic Data and Applications Center, Columbia University). Available at http://sedac.ciesin.columbia.edu/gpw. Accessed January 5, 2013.
29. Berne A, Delrieu G, Creutin J, Obled C (2004) Temporal and spatial resolution of rainfall measurements required for urban hydrology. *J Hydrol (Amst)* 299(3-4): 166–179.
30. van de Beek CZ, Leijnse H, Torfs PJJF, Uijlenhoet R (2012) Seasonal semi-variance of Dutch rainfall at hourly to daily scales. *Adv Water Resour* 45:76–85.
31. Overeem A, Buishand TA, Holleman I (2009) Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar. *Water Resour Res* 45(10): W10424.
32. Overeem A, Holleman I, Buishand TA (2009) Derivation of a 10-year radar-based climatology of rainfall. *J Appl Meteorol Climatol* 48(7):1448–1463.
33. Overeem A, Buishand TA, Holleman I, Uijlenhoet R (2010) Extreme value modeling of areal rainfall from weather radar. *Water Resour Res* 46(9):W09514.
34. Leijnse H, Uijlenhoet R, Stricker JNM (2008) Microwave link rainfall estimation: Effects of link length and frequency, temporal sampling, power resolution, and wet antenna attenuation. *Adv Water Resour* 31(11):1481–1493.