CubeSats in hydrology: ultra-high resolution insights into vegetation dynamics and terrestrial evaporation

M. F. McCabe\textsuperscript{1}©, B. Aragon\textsuperscript{1}, R. Houborg\textsuperscript{1}© and J. Mascaro\textsuperscript{2}

\textsuperscript{1} Water Desalination and Reuse Center, Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.
\textsuperscript{2} Planet, 346 9th Street, San Francisco, CA 94103.

Corresponding author: Matthew McCabe (matthew.mccabe@kaust.edu.sa)

Key Points:

- CubeSat systems have the potential to revolutionize earth observation and advance hydrological remote sensing
- CubeSats offer improved spatiotemporal insights, providing ultra-high resolution and near daily global revisit times
- We present the highest resolution estimates of evaporation ever retrieved from space, and the first LAI from CubeSat data
Abstract

Satellite-based remote sensing has generally necessitated a trade-off between spatial resolution and temporal frequency, affecting the capacity to observe fast hydrological processes and rapidly changing land surface conditions. An avenue for overcoming these spatiotemporal restrictions is the concept of using constellations of satellites, as opposed to the mission focus exemplified by the more conventional space-agency approach to earth observation. Referred to as CubeSats, these platforms offer the potential to provide new insights into a range of earth system variables and processes. Their emergence heralds a paradigm shift from single-sensor launches to an operational approach that envisions tens to hundreds of small, lightweight and comparatively inexpensive satellites placed into a range of low earth orbits. Although current systems are largely limited to sensing in the optical portion of the electromagnetic spectrum, we demonstrate the opportunity and potential that CubeSats present the hydrological community via the retrieval of vegetation dynamics and terrestrial evaporation and foreshadow future sensing capabilities.

1 A New Paradigm in Earth Observation

Remotely sensed observations of the terrestrial surface have provided extraordinary insight into hydrologic systems [Lettenmaier et al., 2015], from characterizing regional scale water balance components [Sheffield et al., 2009], to quantifying global scale estimates of evaporative fluxes [Miralles et al., 2016], soil moisture variations [Dorigo et al., 2017] and water storage dynamics [Richey et al., 2015]. These insights have been enabled by national space agencies and their launch of an expanding number of satellite missions [Belward and Skøien, 2015], providing an unprecedented capability for earth system monitoring. Space-based platforms offer an unparalleled advantage relative to other observing systems, such as in situ networks or even unmanned autonomous vehicles (UAVs) [McCabe et al., 2017]. Still, there remains an inevitable compromise between the resolvable resolution and the frequency of observation, i.e. the higher the spatial detail, the poorer the temporal repeat-rate. Of course the converse is also true, with geostationary platforms overcoming the temporal limitation of polar-orbiting systems only at the expense of a rather coarse spatial resolution. While a range of current low earth orbiting systems can be used to retrieve land surface variables at high resolution (100 m scales), they are only able to do so intermittently, as a consequence of orbital constraints, cloud contamination and other atmospheric influences, which limit the achievable temporal frequency. For example, while the 5-day repeat cycle of the paired Sentinel 2 satellites [Deusch et al., 2012] has greatly improved the probability of obtaining clear-sky imagery, the 16-day return interval of the Landsat satellite series means that it might be several weeks before a clear-sky estimate can be obtained.

While orbital considerations present as a technical constraint, an ongoing challenge facing the earth observation community is how to maintain the high level of innovation and novel science that has been facilitated by agency driven remote sensing programs in the face of static, or even shrinking, budgets. With mission costs for benchmark hydrology-related satellite programs such as Landsat-8, the Gravity Recovery and Climate Experiment (GRACE) and the Soil Moisture Active Passive (SMAP) systems approaching the order of one billion dollars each, finding more cost-efficient approaches to earth observation is a needed priority. A rather obvious approach that is advocated by the CubeSat concept [Puig-Suari et al., 2001] is to make satellites smaller and lighter, and thus cheaper to launch. The single-unit (1U) CubeSat measures 10 x 10 x
11.35 cm and typically weighs less than 1.33 kg, representing the base level building block for such systems. These single units can be modularized to form larger configurations (i.e. 3U, 6U, or 12U), depending on the particular needs and operational requirements of any specific satellite system. Leveraging smartphone and automotive driven advances in power supply, sensor miniaturization and computational capacity, CubeSats have taken advantage of commercial off-the-shelf components to deliver a robust and purpose-specific sensing solution. The cost advantage of launching multiple small and lightweight satellite systems has been facilitated in large part by the emergence of reusable rocket programs, such as those developed by SpaceX and Blue Origin, or the disposable launch solution offered by Rocket Lab. These commercial operations have considerably reduced the cost of placing an object into space, putting the capability of launching a CubeSat into the hands of not just private industry [Selva and Krejci, 2012], but also the individual investigator: a game-changing proposition in earth observation.

So far, it has mostly been the commercial sector who have exploited these technologies and fast-tracked the development and deployment of CubeSat systems. One example is Planet (www.planet.com), a seven-year old aerospace and data analytics company [Planet Team, 2017] that has launched more than 280 CubeSats since 2013. Currently, nearly 150 of these small shoe-box sized systems are deployed in various low-earth sun-synchronous orbits, providing a capacity for better than daily global coverage, particularly at high latitudes. NASA has its own innovative program [Crusan and Galica, 2016], with the CubeSat Launch Initiative (http://go.nasa.gov/CubeSat_initiative) supporting the development of more than 50 1U and 3U CubeSats since 2010. CubeSat technology demonstration efforts, emerging from collaborations between industry, government and research, have also presented a range of sensors and systems capable of retrieving variables pertinent to hydrological investigations. Beyond providing enhanced multi-spectral visible and near infrared imaging, various CubeSat proposals include a tri-band microwave radiometer and GPS radio occultation sensor to profile atmospheric water vapor and cloud ice [Marinan et al., 2016], a prototype Ka band radar system for improved rainfall and weather forecasting [Peral et al., 2015], and a trio of systems designed to advance the next generation of atmospheric infrared sounders [Pagano, 2017]. Uncooled microbolometers have been proposed for field-scale thermal infrared sensing [Puschell and Masini, 2014], advancing the retrieval potential of surface temperature and radiation budget components. Selva and Krejci [2012] provide a comprehensive review of CubeSat capabilities, outlining a list of 21 potential measurement categories that include hydrology relevant parameters.

Through leveraging high resolution imagery with a high-cadence orbital configuration, CubeSats offer a valuable new information resource for earth observation that can overcome existing spatiotemporal divides. However, they are not without limitations. Both their size and capacity to provide needed power requirements inevitably restrict the types of sensors that can currently be deployed. For instance, power limitations mean that active radar for retrieving soil moisture, or lidar systems for surface topography, are unlikely to be realized (although GNSS reflectometry presents as a possible retrieval alternative for these variables [Carreno-Luengo et al., 2014]). Still, numerous hydrological advances have developed from utilizing optical imagery either alone, or in concert with other sensing platforms, and further instrument advances are likely to expand upon this potential. Here we explore some recently developed CubeSat-based retrieval examples, focusing on the estimation of vegetation dynamics and terrestrial evaporation and highlighting the spatiotemporal advantage of these emerging CubeSat systems.
2 Ultra-high Resolution Retrieval of Leaf Area Index and Crop Water Use

Although there are notable limitations to what may be achievable (and retrievable) from utilizing CubeSats, their suitability in exploiting optical sensor technology provides an array of retrieval opportunities pertinent to hydrology. The information content embedded in spatially distributed optical remote sensing data has provided a basis for improving the evaluation of hydrological models [Immerzeel and Droogers, 2008], mapping river process, form and function [Marcus and Fonstad, 2008], as well as providing needed multi-variate datasets for novel hydrological data assimilation [Xie and Zhang, 2010]. As a more focused example, the use of optical remote sensing data to characterize the spatial and temporal development of vegetation and terrestrial evaporation has a wide range of hydrological applications, from improving water resources management [Bastiaanssen et al., 2005; Van Dijk and Renzullo, 2011], to enhancing our understanding of land-atmosphere feedbacks [Miralles et al., 2011], or in the evaluation of next-generation hyper-resolution models [Bierkens et al., 2015]. Obtaining the necessary observations required to inform management decisions has routinely been hindered by resolution constraints, either in the spatial or temporal domain. For instance, although optically driven metrics of vegetation health and condition can be resolved at the $10^1$ m scale using traditional satellite platforms [Houborg et al., 2015], the temporal frequency is generally sub-optimal for monitoring rapid land use and land cover changes that may result from deforestation, biomass burning or agricultural production. Likewise, land surface evaporation can be determined at relatively high resolutions ($10^1$-$10^2$ m scale) using either infrequent Landsat imagery [Bastiaanssen et al., 1998] or via downscaling approaches based upon coarse resolution geostationary or polar orbiting satellites [Anderson et al., 2011; Norman et al., 2003], but such approaches lack the daily resolution desired by many segments of the hydrologic community [Fisher et al., 2017].

Here we explore the recent advances that are being enabled by CubeSat approaches by demonstrating the enhanced retrieval capacity in terms of the leaf area index (LAI) and land surface evaporation: two variables that are of interest in water, carbon, and energy balance studies [Anderson et al., 2008], precision agriculture applications [Elarab et al., 2015] and studies of the hydrological cycle in general [Donohue et al., 2007; Nemani and Running, 1989]. To demonstrate this potential, we use Planet’s Planetscope sensors, which adopt the 3U CubeSat form factor (i.e., 10 x 10 x 30 cm). The Planet CubeSat constellation provides an unprecedented observing potential, approaching daily nadir-pointing terrestrial imaging of the earth surface in four spectral bands (i.e., blue, green, red, and NIR). Flocks of these CubeSats operate in the International Space Station orbit (approx. 400 km altitude), with a variable equatorial overpass time and a ground sampling distance (GSD) of 3.1 m. However, the majority of these so-called “Doves” are now deployed into sun synchronous orbits (approx. 475 km orbit altitude), with an equatorial overpass time of between 9:30 – 11:30 am (local time) and a 3.7 m GSD. Here we compare CubeSat retrievals against Landsat-8 data, which offers a 16-day repeat cycle and an equatorial crossing time of around 10:00 am ± 15 min (local time).

One of the benefits of high spatial resolution and near real-time daily global coverage is the temporal insights that such data allow. To demonstrate this potential, we present a temporal sequence of CubeSat-derived LAI, together with a coincident Landsat-based estimate (see Figure 1). The Landsat-based LAI is determined via the implementation of a machine learning and hybrid training approach applied to a broad set of Landsat-8 vegetation index predictor variables.
A Spatio-Temporal Enhancement Method (STEM) [Houborg et al., 2016] was adapted to exploit the detail rich CubeSat data, facilitating the production of high resolution LAI. At the core of this retrieval technique is a non-parametric scheme that adopts a model tree regression approach to “learn” associations between a training dataset of input explanatory variables (i.e., the Planet multi-spectral data) and the target variable (Landsat-8 LAI). Further details of the approach can be found in Houborg and McCabe [2016].

**Figure 1.** The CubeSat advantage of combining high-spatial resolution retrievals with a frequent return interval. Here a landcover change event that is absent in a) the Landsat-LAI imagery (30 m resolution) from day-of-year (DOY) 339 (December 4th, 2016), is captured in b) a subsequent CubeSat-LAI overpass (approximately 3-m resolution) on DOY 340 (December 5th, 2016). Four smaller center-pivot systems captured by c) Landsat and d) CubeSat data, further illustrate the resolution advantage, identifying within-field and within-crop variations absent from coarser scale LAI retrievals.

As can be seen from Figure 1, there are distinct spatial advantages afforded by the CubeSat data. Ignoring the capacity to resolve actual wheel tracks from the center-pivot (at distinct intervals of approximately 50 m), the high resolution provides valuable insights into the
within-field scale variability. Fig. 1b shows a field with an approximate diameter of 800 m, capturing the commencement of a harvesting event that is clearly visible along the perimeter. The event is entirely missed by the Landsat image of the day before (Fig. 1a) and would not be captured until a subsequent overpass at least 16 days later. Fig 1c and 1d further highlight the enhanced detail from a collection of smaller center pivots (each of diameter of approx. 250 m) undergoing field trials of different crops under production. The discrimination of within crop and within field variability is largely absent in the Landsat retrievals, whereas the CubeSat data provide considerable detail and insight.

Crop water use estimates were simulated at both the Landsat (30 m) and CubeSat (3 m) scale using satellite specific LAI retrievals and ground-based meteorological measurements, together with the Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) evaporation model [Fisher et al., 2008]. PT-JPL is a parsimonious evaporation scheme that has been evaluated across a wide range of landscapes, biome types and scales [Ershadi et al., 2014; Miralles et al., 2016]. Despite its minimal data requirements (air temperature, humidity, net radiation and vegetation indices) and relative simplicity, PT-JPL routinely outperforms more sophisticated modeling schemes [McCabe et al., 2016]. To take advantage of the high resolution LAI retrievals derived from the CubeSat data, the original model was modified to better partition net radiation into soil and canopy components and to provide an improved estimate of the green fractional cover [Campbell and Norman, 1998]. Soil heat flux (G) was adapted following Santanello and Friedl [2003], yielding a spatially varying G dependent on the net radiation.

Instantaneous flux estimates derived from PT-JPL were extrapolated to daily totals following Colaizzi et al. [2006], yielding crop water use values of between 0-6 mm across the fields. Preliminary comparison against an eddy covariance tower positioned adjacent to an alfalfa pivot showed good agreement with satellite derived fluxes. Detailed assessment of model simulations over a longer period and under varying stages of vegetation growth and condition are currently being performed to further evaluate the robustness of this particular modeling approach. However, just the qualitative information that is gained from these ultra-high resolution images is considerable. The spatial insight provided by the CubeSat-based estimates illustrates an unprecedented level of detail at both the within- and between-field scales, with information on cropping stage, distributed farm-scale water use patterns, and the identification of areas impacted by either nutrient or water stress all apparent. The temporal development of water use patterns within fields, as presented in Fig 2c-e, provides a degree of information that is unattainable from agency-based platforms. The water-stressed or under-vegetated portions of the field (i.e. the brown regions in the lower center-pivot) are seen to recover through time, presumably reflecting a rapid greening-up of this alfalfa crop during the 7-day observation period. While elements of these behaviors are observed in the Landsat retrievals (Fig 2b,f), they are either masked or overstated relative to the fine-resolution CubeSat estimates. Certainly, the 16-day repeat cycle typical of Landsat overpasses will miss a range of crop development stages, patterns, and variability. It is worth noting that (to the authors knowledge), Figure 2 details the highest resolution estimate of evaporation ever retrieved from a space-based platform.
Figure 2. a) PT-JPL based crop water use (mm/day) derived from ultra-high resolution CubeSat-LAI and ground based meteorological data for DOY 275 (October 1st, 2016). (b,f) Two separate Landsat images on DOY 275 and 291 bound a temporal sequence of CubeSat imagery (c-e) for DOY 275, 277 and 282, respectively. Brown areas within the center-pivots denote no to low vegetation cover, while the desert background is depicted as a false colour composite.

It is important to recognize that the spatial variability inherent in PT-JPL retrievals is driven in large part by the underlying variability in LAI, especially since homogeneous tower-based meteorology was assumed across the image extent. Although the model has been tested at sub-daily resolutions with pleasing results [McCabe et al., 2016; Michel et al., 2016], the daily integrated values are likely more representative of actual water use conditions than instantaneous retrievals. Furthermore, the characterization of surface fluxes in arid environments is particularly challenging, with advection of hot and dry winds from the surrounding desert moving across the irrigated fields and influence energy budget considerations. Here, we have employed PT-JPL only to illustrate the insights that can be gained through using CubeSat derived LAI (in combination with ground-based meteorological forcing) to derive fine-scale estimates of crop water use. Future contributions will explore adaptations and comparisons of several modeling approaches that exploit high resolution satellite data, exploring the insights that can be gained from using thermal based evaporation approaches versus vegetation driven techniques.
3 Risks and Limitations of the CubeSat Approach

The opportunities afforded by the expanding availability of CubeSat configurations represent a potential game-changer in earth observation [McCabe et al., 2017]. The convergence of spatial and temporal resolution offers a satellite-based framework for informing hydrological and land management decisions in near-real time, with a frequency that enables rapid response to dynamic events. The ability to extract actionable intelligence from such platforms has implications across a range of application targets, including precision agriculture, water resources planning, surface water (and storage) changes, flood inundation mapping, coastal erosion, and the monitoring of rapid land cover and land use changes, to name a few. However, it is the complementary nature of these platforms that is likely to see the biggest impact on hydrological investigations. Although sensing just the optical portions of the electromagnetic spectrum, there is considerable history in using such data for augmenting and improving related hydrological observations. For example, applications related to downscaling land surface temperature [Agam et al., 2007] and soil moisture [Piles et al., 2011], characterizing the smaller scale heterogeneity within coarse resolution soil moisture fields [Kim and Hogue, 2012], or providing improved estimates of discharge through monitoring changes in the effective width of rivers [Bjerklie et al., 2005], are all examples where optically based sensing systems can be leveraged.

Yet, while diverse application of these data can be envisioned, CubeSats are not without their limitations. The achievable spectral resolution is comparatively low and each CubeSat is associated with a unique spectral response, which can result in cross-sensor inconsistencies. Indeed, the radiometric quality of CubeSat data is not equivalent to rigorously calibrated satellites such as Landsat and Sentinel. To address this specific issue, Planet satellites undergo on-orbit cross-calibration, using a mix of tandem observations (not only from Planet Doves, but also from RapidEye, Landsat and Sentinel) at pseudo-invariant calibration sites, as well as lunar observations [Chander et al., 2013]. Preliminary assessments against a limited dataset of homogeneous test sites indicates a 1-sigma radiometric uncertainty of around 5-6% after on-orbit cross-calibration. As an alternative, machine learning based approaches using sensor-to-sensor reflectance calibrations have been proposed [Houborg and McCabe, 2016].

A further consideration in the use of commercial systems is that access and availability is unlikely to follow the same model as government supported space agencies, since the driver behind commercial systems is economic, rather than public good. In general, most commercial offerings are prohibitively expensive for routine research use, limiting the uptake and application of ultra-high resolution data, especially when more than a single overpass is required. While Planet is a for-profit, mission-driven company, they currently provide limited freemium offerings to both general and academic users. Undoubtedly, the potential for CubeSat and other microsatellite platforms to advance our earth observing capabilities will be more rapidly realized if commercial operators incorporate and maintain a “research-friendly” access model. But data access and availability remain key considerations that emerge from this new earth observing paradigm. More generally, how commercial enterprises might manage data continuity, quality, and even the archiving of historical data (which may have a lower economic value) are factors that will impact the use of these data sources. In terms of the archiving and access challenge, cloud storage and application programming interfaces (APIs) now feature as common elements in many commercial distribution efforts, mirroring the increasing presence of space agency...
products on commercial storage platforms (i.e. Google Earth Engine; Amazon Web Services)\cite{Gorelick2017}. So, while challenges remain, storing, accessing and interpreting the vast amounts of earth observation data being collected are no longer the constraints they once were.

A “fast and nimble” agile-aerospace approach to earth observation goes some way to explaining the recent growth in CubeSat remote sensing. One advantage of this concept is that it provides an ideal platform for technology demonstration and testing, such that advances in sensor and instrument design can be more rapidly prototyped and deployed. A consequence of this is that data continuity, at least in the tradition of the Landsat Data Continuity Mission \cite{Irons2012}, is less likely to be prioritized, especially when system upgrades and innovations can be readily and rapidly implemented. Instrument continuity is also a function of the reduced lifespan of CubeSats, which can be anywhere from weeks to a few years, meaning that instruments will routinely be replaced by successive upgrades. Instrument evolution will also be a function of business driven motivations to adapt to new technologies and sensor advances as the market (rather than the research community) dictates. From an academic standpoint, this can be viewed as either a positive or a negative, depending upon ones perspective, but it is hard to forecast given that researchers are unlikely to be involved in the decision making process (as opposed to, for instance, informing mission priorities through avenues such as the National Academies Decadal Surveys \cite{NationalResearchCouncil2007}).

\section{4 Realizing the Opportunity}

It is becoming increasingly clear that the emergence of new players in the CubeSat and small-satellite arena are changing the nature of how earth observation data are collected, stored, distributed and analyzed. The costs of satellite manufacturing have decreased considerably as technological improvements allow for more compact satellites, driven in large part by the use of off-the-shelf sensing components, power supplies, CPUs and solid-state drives. Launch costs have also decreased dramatically. SpaceX now flies a base Falcon 9 rocket for approximately $60M (USD), which compares to the higher (often unpublished) costs of comparable competing rockets. Likewise, the standardization of CubeSats using the “U” form-factor has allowed them to fly on many more rockets, often as secondary payload. As evidence, the year 2017 saw the largest number of satellites placed on a single rocket (104 on the Polar Satellite Launch Vehicle, which launched from India on February 14). By most estimates, 2017 also witnessed the greatest number of earth observation satellites ever deployed, repeating a trend that has been evident in recent years \cite{Belward2015} and that is projected to continue.

The increasing presence of commercially driven CubeSat platforms might be considered as a “disruption” to the traditional space agency approach to earth observation \cite{McCabe2017}. As with any disruptive event, both opportunities and challenges will result. The spatial and temporal advances that have been enabled by the delivery of constellations of CubeSat systems have provided a new information resource for the hydrological sciences. To date, the sensors onboard these platforms operate predominantly in the visible to near infrared portion of the electromagnetic spectrum, supplementing rather than supplanting the full-array of sensing possibilities upon which the hydrological community rely. However, advances in sensing capabilities, instrumentation, and on-board power management, have the potential to expand future observation capacity. A CubeSat constellation with the capacity to monitor the dynamic
land surface condition would facilitate not only the detection of vegetation health and condition, as explored here, but also allow monitoring of natural disasters such as floods, landslides and earthquakes [Kääb et al., 2017], the delineation of surface water changes and changes in lake and river extent [Pekel et al., 2016], or any other application where timely and repeatable information is needed to procure actionable intelligence.

Naturally, there are inevitable challenges and concerns as to how these (to date) largely commercially driven activities will benefit research efforts, particularly as relates to data access, distribution, storage and quality. How the community might navigate, and ideally help in steering some of these developments, remains to be seen. Increased community uptake and engagement in the use of these data streams is certainly one means of guiding the evolution of this technology. What has become apparent is that CubeSats provide an unprecedented capacity to exploit a new and novel platform for hydrological investigation, enhancing not only the retrieval of a range of earth system variables, but offering new insights into hydrological process and behavior across spatial and temporal scales. We are in the midst of a golden-age in earth observation in terms of data availability and technological capacity, providing a unique opportunity to reshape our earth observing potential. A new paradigm is upon us, and our community has every potential to benefit from it.

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