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Global production and free access to Landsat-scale Evapotranspiration with EEFlux and eeMETRIC

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ABSTRACT. EEFlux (Earth Engine Evapotranspiration Flux) is a version of the METRIC (mapping evapotranspiration at high resolution with internal calibration) application that operates on the Google Earth Engine (EE). EEFlux has a web-based interface and provides free public access to transform Landsat images into 30 m spatial evapotranspiration (ET) data for terrestrial land areas around the globe. EE holds the entire Landsat archive to power EEFlux along with NLDAS/CFSV2 gridded weather data for estimating reference ET.

EEFlux is a part of the upcoming OpenET platform (https://openetdata.org/) that has leveraged nonprofit funding to provide ET information to all of the lower 48 states for free, as a means to foster water exchange between agriculture, cities and environment (Melton et al., 2020). The METRIC version in OpenET is named eeMETRIC, and includes cloud detection and time integration of ET snapshots into monthly ET estimates. EEFlux and eeMETRIC employ METRIC's "mountain" algorithms for estimating aerodynamics and solar radiation in complex terrain. Calibration is automated and ET images are computed for download in seconds using EE's large computational capacity.

Keywords. EEFLUX; eeMETRIC; Energy Balance; Evapotranspiration; Google Earth Engine; Landsat; METRIC;

Introduction

The Google Earth Engine contains a complete archive of the Landsat image collection since 1984 and provides full access to the Google cloud computing system. This resource, in conjunction with access to a suite of gridded weather system data, has facilitated the development of an application tool for mapping evapotranspiration (ET) at the field scale. The tool, named *EEFlux*, for Earth Engine Evapotranspiration Flux, is based on the operational stand-alone model *METRIC* (mapping evapotranspiration at high resolution with internal calibration). *EEFlux* and its OpenET counterpart *eeMETRIC* is a full surface energy balance model, producing estimates of net radiation (R_n), sensible heat flux to the air (H), and conductive heat flux to the ground (G). ET is estimated from these surface energy balance components as a residual ($ET = R_n - H - G$), where actual ET may be constrained by soil water availability. The *EEFlux* and *eeMETRIC* implementations use the North American Land Data Assimilation System (NLDAS) hourly gridded weather data collection on Earth Engine for both energy balance calibration and for time integration of ET between Landsat image dates. The NLDAS data are used to calculate reference ET using solar radiation, wind speed, specific humidity and air temperature via the American Society of Civil Engineers (2005) Penman-Monteith equation for the tall (alfalfa) reference. The system estimates residual evaporation at the time of the image via a daily soil water balance. The soil water balance is driven by the GridMET system of Abatzoglou (2011) that produces 4 km grids of evaporation from a bare soil condition for the continental US (CONUS). The Statsgo soil data base of the USDA provides soil type information. *EEFlux* runs rapidly on the Earth Engine, requiring only seconds to produce an ET image for a single Landsat scene. This platform is currently available for the majority of the Earth's surface.

Background

Evapotranspiration (ET) is often the single most important and most uncertain parameter in water planning and allocation models used at the federal, state and local levels. Knowledge of ET is essential for understanding the pathways of water processes and water consumption as well as understanding health and vulnerability of vegetation systems under drought and other stresses. Additionally, accurate ET estimates are critical for managing constraints to food production and water rights in the US and globally. *EEFlux* calculates ET using a surface energy balance derived from thermal and reflected imagery of Landsat and was developed from the image-based process model *METRIC* (Allen et al., 2007a,b, 2010, 2013a,b, Irmak-Kilic et al., 2011, Morton, Huntington et al., 2013). *METRIC* subroutines designed for a wide range of land-uses, terrain types and ecosystems. The METRIC model has been adopted by a number of western states (see applications map) that include CA, OR, NV, ID, NE, CO, NM, MT, WY and TX. The *EEFlux* project has been funded by Google, Inc., with foundational support by the University of Idaho, University of Nebraska-Lincoln, Desert Research Institute, and by USGS via the Landsat Science Team. Web sites describing METRIC and applications are housed by the University of Idaho and by the Idaho Department of Water Resources.

The *eeMETRIC* application is similar to *EEFlux*, but is designed to be accessed via an Application Programming Interface (API) so that it can be accessed by outside users via calls to Earth Engine. The *EEFlux* application is freely available to the public via Earth Engine and includes a web-based operating console and means to download ET images as geoTiff files. The ET maps produced by *EEFlux* have 30 m resolution and are useful for water resources management, for crop production studies, estimating depletions of ground-water and surface water by irrigation, and to estimate water consumption by native vegetation.

Approach

The implementations of *EEFlux* and *eeMETRIC* onto Google EE contain robust automation and built-in expert decision-making to support open-access by large numbers of users, while at the same time, producing accurate and consistent ET maps. Implementation on EE requires automation of the calibration of the internal energy balances of *EEFlux* and *eeMETRIC.* The internal calibration compensates for systematic biases in Landsat fields including surface temperature and in *EEFlux* and *eeMETRIC* algorithms such as net radiation fluxes. The proposed auto-calibration procedure follows the statistical procedure of Allen et al., (2013a) and Morton et al., (2013), but is modified to fit requirements in EE for array-based computation and decision-making. The energy balance algorithms of *EEFlux* and *eeMETRIC* produce ET estimates at the Landsat overpass time that are extrapolated to daily values. These snapshots are transformed into total water consumption over monthly and longer periods via a robust process for time-integration of the Landsat-based ET over extended periods.

The goal of the *EEFlux* and *eeMETRIC* development is provide spatial distribution of water consumption by vegetation at the 30 m scale on demand. The applications have access to the 1984-present period of record for the thermal-equipped Landsat imagery. Produced maps will have relatively high accuracy for use in assessing depletion of surface and ground-water systems, for conducting hydrologic water balances and driving hydrologic process models, for assessing plant water stresses and reductions in biomass production, for assessing plant water use productivity, and for managing rights and access to water.

The success of the *EEFlux* development has been benefited by the teaming of three institutions – Desert Research Institute (DRI), University of Nebraska-Lincoln (UNL) and University of Idaho (UI), where each PI and supported students and staff have complementary capabilities and have conducted work components in coordination with the other universities.

The Development of the EEFlux and *eeMETRIC tools has included:*

a. Development of a strategy and coding and testing of an auto-calibration process for *EEFlux* and *eeMETRIC*
b. Upload and access to gridded weather data sets utilized to compute at-surface reflectance, calibrate *EEFlux*, operate a daily soil-water evaporation process, and that support integration of ET over time. Gridded weather data include US-wide NLDAS (12 km grid size), GridMET, and DAYMET data sets.

c. The means to time-integrate *eeMETRIC*-based ET into a continuous time series of monthly (or shorter or longer) information, for example, millimeters of ET per month per pixel, that utilizes the NLDAS, GridMET and other gridded weather data collections, automated cloud-masking and filling of images, and adjustment of image 'wetness' to improve its representation of monthly time periods.
d. Evolution of the auto-calibration process for *EEFlux* and *eeMETRIC* to be robust and stable over a wide range of land-use types, times of the year, and geographic locations and to enable automated, rapid and seamless operation by novice users unfamiliar with the ET and energy balance processes
e. Development of a web-based console system for selecting, processing and downloading results from Landsat scenes and time periods. Evolve the console to provide advanced user-driven tuning of *EEFlux* calibration of an image (primarily setting maximum and minimum values for ET) to improve accuracies.
f. Evolution of the *EEFlux* and *eeMETRIC* applications to include *METRIC* algorithms for complex terrain (Allen et al., 2013b) where radiation and aerodynamic interactions are considered. This improves accuracy for forested mountainous areas.

Development of *EEFlux* has included the translation of METRIC algorithms into equivalent algorithms for JavaScript and Python APIs of Earth Engine. Table 1 lists some of the major components and computational requirements of *EEFlux* which enable universal, consistent and accurate estimation of ET.

Data Policy

Output from *EEFlux* and *eeMETRIC* is openly available to the public. The *EEFlux* code is proprietary and protected under intellectual property rights. In the case of *eeMETRIC*, a majority of the code will be made open source in 2021, with full access to running code and accessing products.

Table 1. *EEFlux* Algorithm Implementation with cross-reference with current METRIC application attributes for Producing Instantaneous and 24-hour ET images on Landsat image dates.

Attribute or Component	*EEFlux*[1] and *eeMETRIC*	Univ. Idaho METRIC Training model	Univ. Idaho / ET+ METRIC 'Full' model	Comment / Source
Surface reflectance band-by-band with atm. correction via vapor pressure from weather station/grid	✓	✓	✓	Tasumi et al. (2008)
Albedo – surface weighting of bands	✓	✓	✓	Tasumi et al. (2008)
Tall Reference ET used at cold condition	✓	✓	✓	Allen et al. (2007a)
Soil Heat flux (G) – Ag-based function	✓	✓	✓	Tasumi (2003)
G reduction in hot, dry soils	✓	✓	✓	Allen et al. (2007a) + METRIC manual
2-stage dT function for improved performance for hot, dry surfaces	✓	✓	✓	Allen et al. (2007a) + METRIC manual
Albedo – lower limit for ag. crops to account for nadir look of Landsat	✓		✓	Allen (2010c), internal memo
Albedo – lower limit for tall trees to account for nadir look of Landsat	✓		✓	Trezza, Kjaersgaard and Allen (2009), internal memos – calibration based on MODIS
Perrier roughness function for tall trees	✓		✓	Allen and Kjaersgaard (2009), internal memos
3-source decomposition of LST for tree canopies (orchard and forest) to estimate canopy temperature for dT application			✓	Kjaersgaard and Allen (2008), internal memos
Regionalized calibration of LST retrievals from Landsat		✓	✓	Allen et al. (2007a)
Solar radiation functions for mountains	✓		✓	Allen et al. (2007a, 2008)
Long-wave radiation functions for mountains	✓		✓	Allen et al. (2008)
Cross-valley thermal loading estimation in mountains	✓		✓	Allen and Kjaersgaard (2008), int. memo
Monin-Obukhov boundary layer stability correction boost in mountains	✓		✓	Allen and Kjaersgaard (2008), internal memo
Mountain terrain roughness enhancement	✓		✓	Tasumi (2003)
Wind speed enhancement in mountains	✓		✓	Tasumi (2003)
2-stage delapsing rate on LST in steep terrain	✓	✓	✓	Allen + METRIC manual

Daily evaporation model with skin evaporation component for determining relative ETI at the hot pixel	✓	✓	✓	Allen (2010b), internal memo
Excess resistance for desert brush	✓		✓	Tasumi, Lorite, Allen, internal reports, manual
Land-use specific estimation of ET_{24} from ET_{inst} (equivalency of ET_rF_{24} and ET_rF_{inst} and using EF, according to land-use type)	use ETrF for ag, riparian, EF for rest, or see next entry		✓ 6 options	Allen (2010), internal memo
ET_rF_{24} transitioned to EF with decreasing soil water or perceived stress levels, especially for nonagricultural land classes	✓			
Calibration of METRIC with hourly weather data	✓	✓	✓	Allen et al., (2007a)
Calibration of METRIC in the absence of quality hourly weather data	✓		✓	Allen and Tasumi (2009), draft manuscript on sensitivity of METRIC calib.
Identification of organic mulch cover for reduction of the G estimate	✓		✓	Kra, Trezza, Allen
Full aerodynamic estimation of evaporation from water/snow (instead of energy balance)	✓		✓	Allen (2010a)
Statistical / AOI based procedure for autocalibration of METRIC energy balance	✓		✓	2008, 2009 Conference papers, Additional testing in progress
Sharpening of LST to 30 m			✓	Allen, Trezza, Robison, Kjaersgaard (2008, 2009) Conference papers, int. reports
Gapfilling SLC-off LS7 images	✓		✓	Allen, Robison, Kjaersgaard, 2008 Conference paper, internal reports
Daily gridded precipitation/ETr/evaporation model to adjust for background evaporation occurring between Landsat images	✓		✓	Kilic, Ranade, Allen and Kjaersgaard, Conference papers
Adjustment for background evaporation of image when filling in clouded regions	✓	✓	✓	Allen, Zhao, Kjaersgaard, Trezza, Conference papers, internal memos, Kjaersgaard et al., 2011
Use of gridded reference ET surface when integrating ET in time over image area	✓	✓	✓	Allen, Robison, Kjaersgaard, Conference papers
Conditioning of gridded ambient weather data to represent well-watered agricultural conditions	✓		✓	Allen (2010d), optional

[1] *EEFlux* is Earth-Engine Evaporation Flux and is a derivative of METRIC, coded specifically for Google Earth Engine.

Example *EEFlux* and *eeMETRIC* Components

The following component applications are shown here to provide examples of the structure of EE code development. These applications have been produced by the three institution *EEFlux* team and the URL addresses point to these examples of Google Earth Engine coding. It should be noted, however, that the URL addresses can only be employed by individuals who have been registered within Google Earth Engine as 'trusted users':

Reference Evapotranspiration Computation using Hourly and Daily NLDAS Data

The *EEFlux* project has scripted the American Society of Civil Engineers (ASCE) Standardized Reference Evapotranspiration (ET) algorithm to operate on two separate hourly and daily National Land Data Assimilation System gridded weather variable datasets of 12km and 4km spatial resolution. *EEFlux* has posted full scripts on the Google Earth Engine Developers Group. Playground links for computing hourly and daily reference ET, and that document examples of extracting and using NLDAS gridded weather variables are at
https://ee-api.appspot.com/73050d32f4d06d7d19acfb5382f6ad6e
for a national hourly ET_o map based on NLDAS gridded weather data and at
https://ee-api.appspot.com/997094f81e70844bd4f50f86bf6110a9
for a national daily ET_o map based on GridMET.

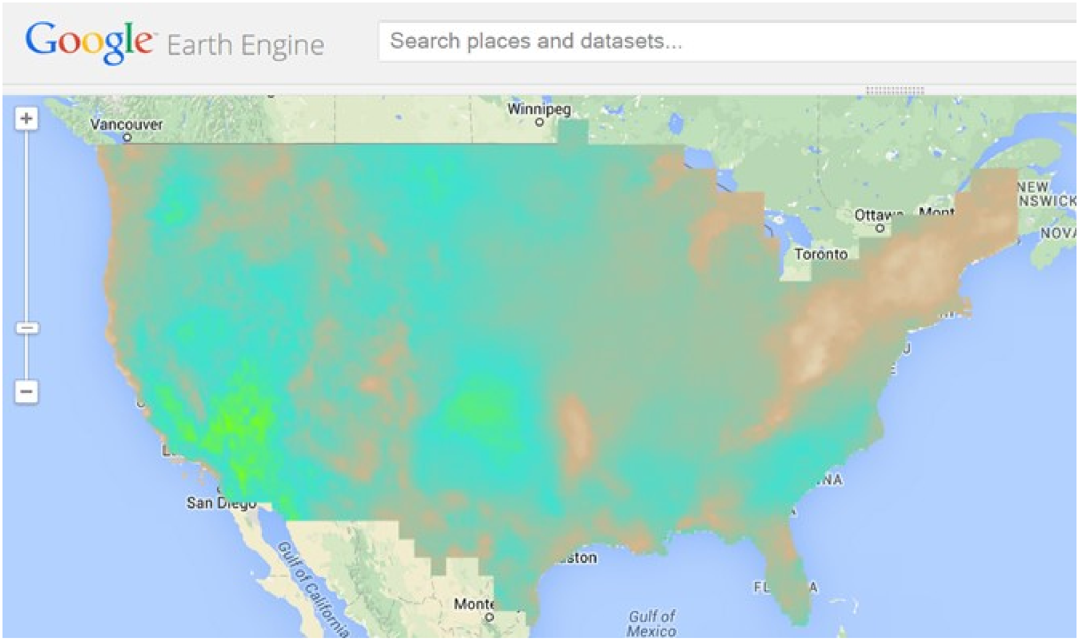

Figure 1. Example national map of hourly grass reference ET_o calculated using the ASCE standardized Penman-Monteith method applied to the 12 km gridded NLDAS weather data system. Bright greens are high ET_o and browns and light turquoise are low ET_o.

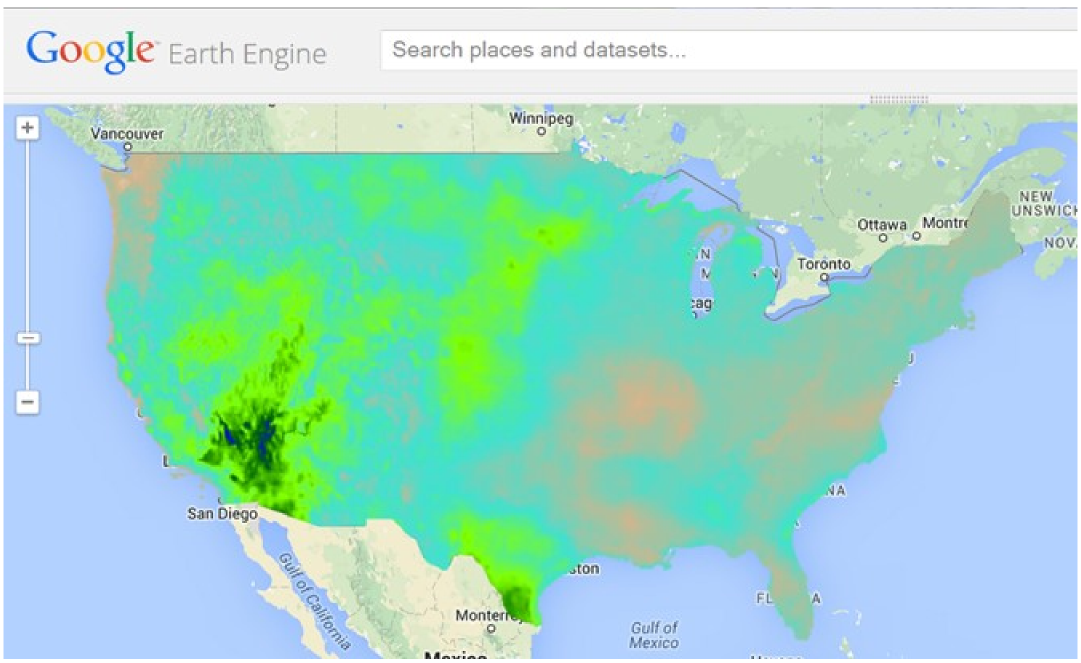

Figure 2. Example national map of daily grass reference ET_o calculated using the ASCE standardized Penman-Monteith method applied to the 4 km gridded and bias corrected GridMET weather data system of Abatzoglou (2011). Blues and dark greens are high ET_o and browns and light turquoise are low ET_o.

The reference ET represents the ET rate from an extensive surface of well-watered clipped, cool season grass and is widely used as a standardized basis for estimating 'potential' ET from any surface. The ASCE method uses the standardized Penman-Monteith method for the short (clipped grass) method. A second application has been produced that applies the 'tall' standardized ASCE reference method representing full-cover alfalfa. It is this second method that is used in the *EEFlux* and *eeMETRIC* applications for calibration, with standardized grass reference ET used in *eeMETRIC* for time integration. *"The ASCE Standardized Reference Evapotranspiration Equation*." ASCE Press, ISBN: 078440805X, Stock No: 40805. Allen, R.G., Walter, I.A., Elliot, R.L., Howell, T.A., and Itenfisu, D. (Ed.). 2005. 216 p.
https://www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/standardization

Landsat at-Surface Reflectance and Albedo

The *EEFlux* group has scripted an approach to compute at surface reflectance and albedo using Landsat data, while utilizing NLDAS gridded weather variables for atmospheric correction, and the NED digital elevation model for slope, aspect, and elevation-related corrections. The approach follows a publication by Tasumi et al., (2008). *EEFlux* has posted the full script for computing at surface reflectance and albedo on the Google Earth Engine Developers Group. The approach allows *EEFlux* computations to utilize the entire Landsat 5/7/8 archive back to year 1984. The playground link is https://ee-api.appspot.com/fba7dcd381011cd8362443a31d386383. In future applications with eeMETRIC, we will shift over to using the USGS EROS surface reflectance data collection[1], with the Tasumi functions used as backup and for near-real time processing.

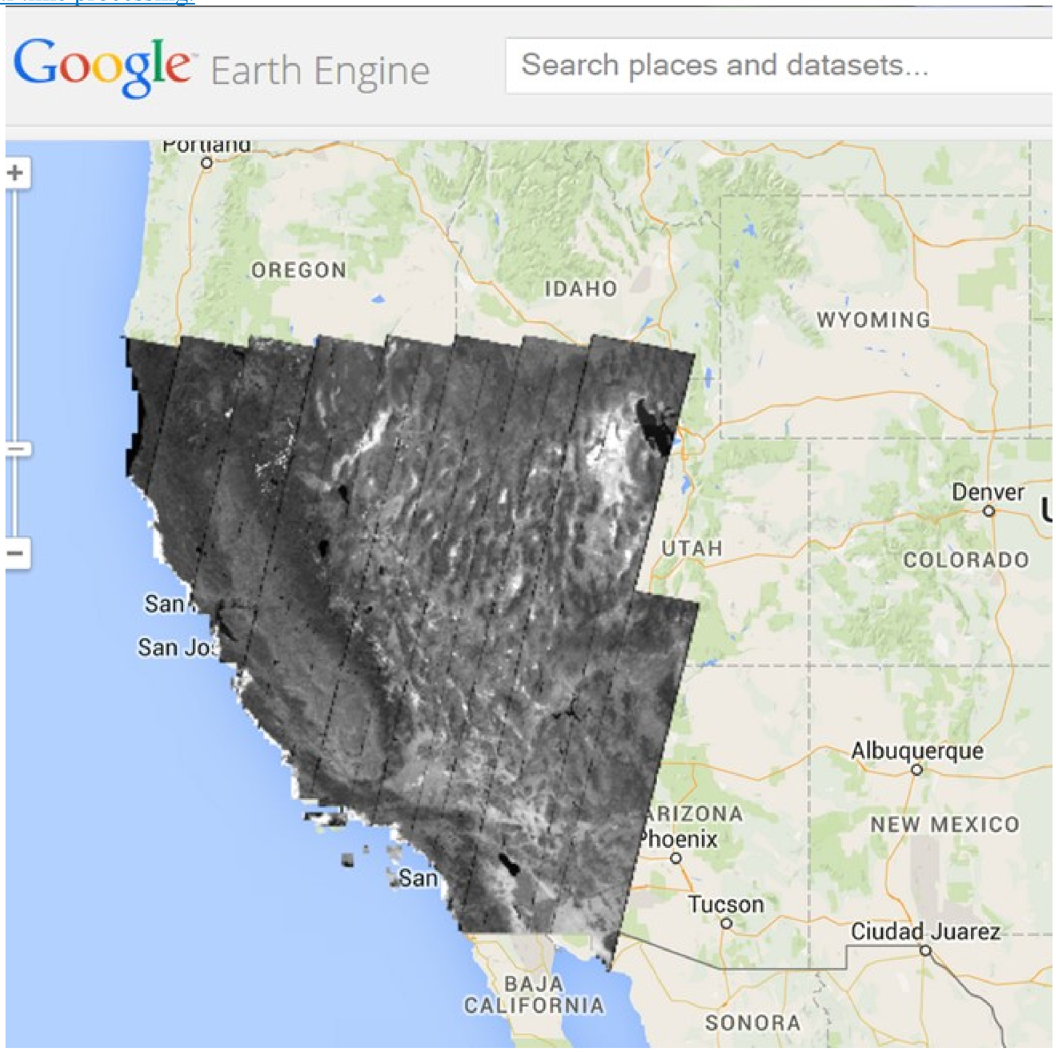

Figure 3. Surface albedo for nine Landsat paths covering California and Nevada during July 1993 based on *EEFlux* algorithms for surface reflectance that utilize Tasumi et al., (2008) procedures.

Figures 4 and 5 show an example application of the full *EEFlux* code to produce ET_rF for a Landsat 8 image taken in July 2014 for WRS path 45, row 30 covering the Upper Klamath Basin of California and Oregon. ET_rF is ET expressed as a fraction of reference ET, where, in this case, the basis is the tall alfalfa reference, so that ET_rF tends to range from 0 to 1. ET_rF is similar to the commonly used crop coefficient, K_c.

[1] https://www.usgs.gov/core-science-systems/nli/landsat/landsat-surface-reflectance?qt-science_support_page_related_con=0#qt-science_support_page_related_con

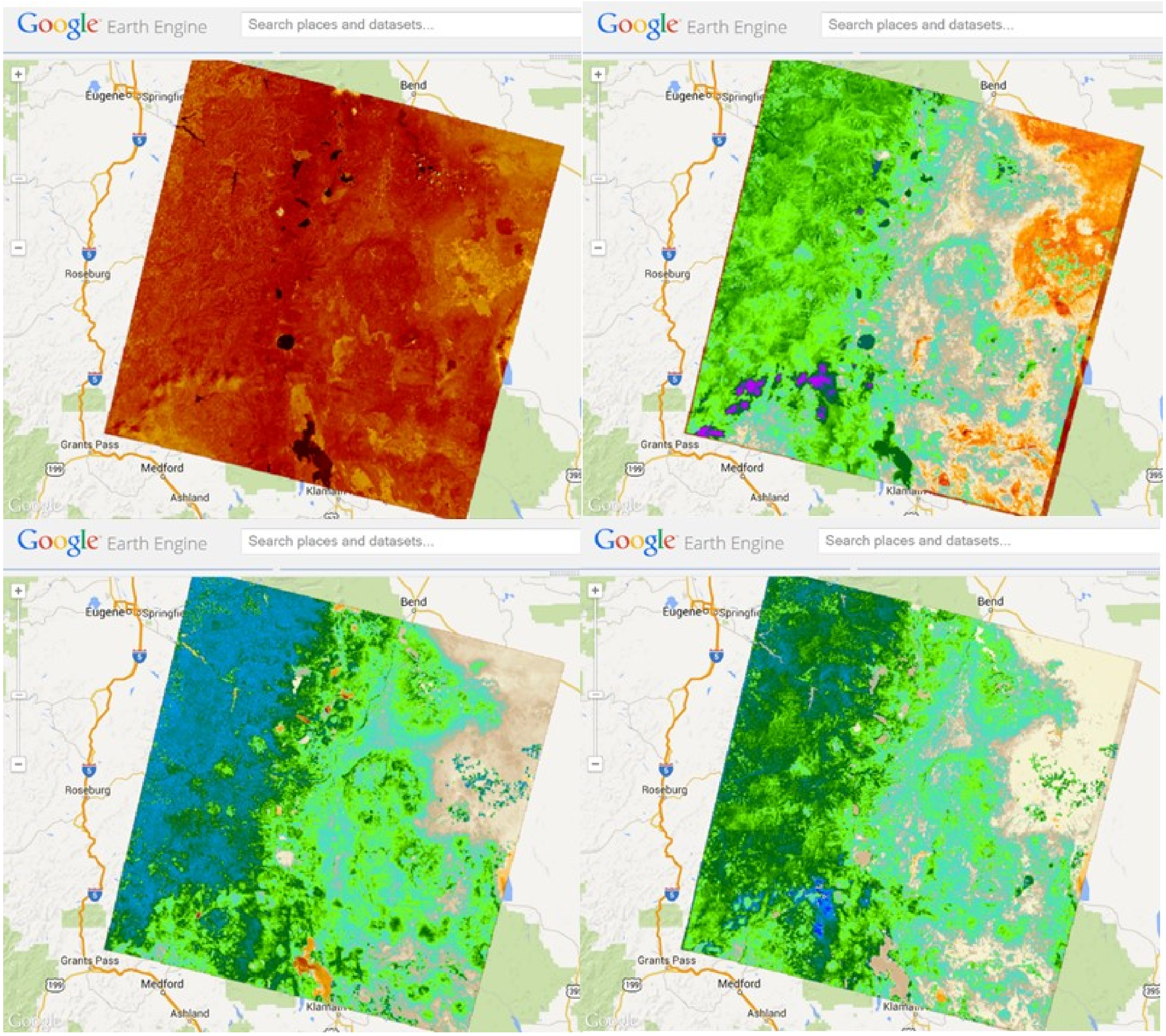

Figure 4. Landsat path 45 row 30 processed by *EEFlux* for July 15, 2014 showing a) albedo (upper left, where light orange is high albedo and dark red is low albedo. Very low albedo for water bodies is shown as blue/black); b) surface temperature (upper right, where magenta and blue are low temperature associated with clouds, greens are medium temperatures associated with high ET, and beiges and reds are high temperature associated with rangeland); c) normalized difference vegetation index (lower left where blue and dark green is high NDVI associated with forest and irrigation, light greens are medium NDVI and beige is low NDVI of rangeland); and d) ET_rF where dark green is high ET_rF (near 1.0) associated with forest and irrigated agriculture and light green and beige are low ET_rF (from 0.7 down to 0.0) associated with rangeland.

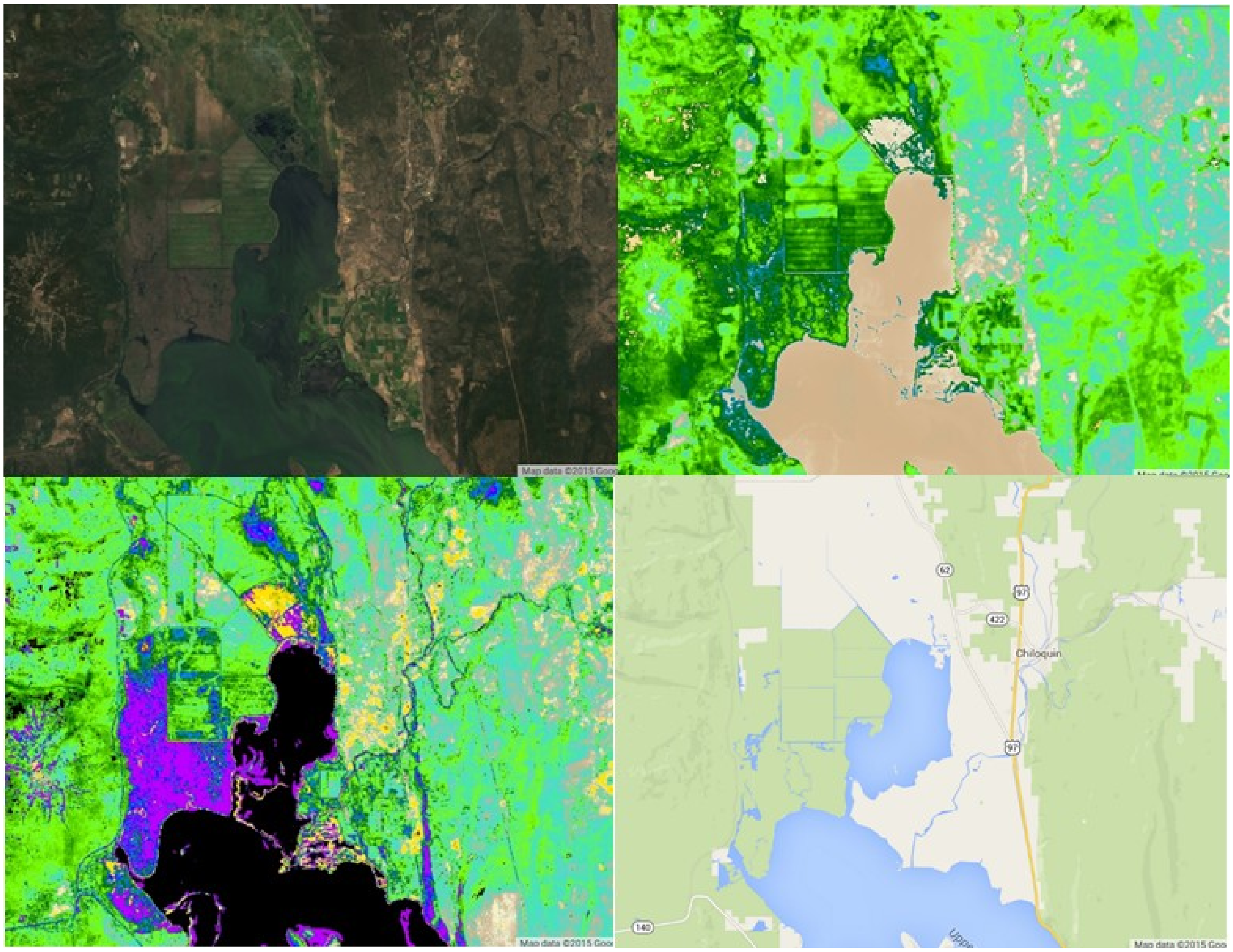

Figure 5. Area in Landsat path 45 row 30 north of Upper Klamath Lake where some irrigated lands have been retired during 2014. Image processed by *EEFlux* for July 15, 2014 showing a) 'true-color' blue-green-red composite (upper left, where light yellowish areas are fallowed areas in 2014); b) ET_rF (upper right, where dark green is high ET_rF (near 1.0) associated with forest and irrigated agriculture and light green and beige are low ET_rF (from 0.7 down to 0.0) associated with rangeland and open water); and c) the ratio of ET_rF/NDVI indicating areas of water stress (lower left, where beiges and yellow colors show areas where vegetation has low ET caused by lack of water and green colors show low levels of stress, and purple/blue areas show high ET_rF/NDVI ratios associated with wetlands). The lower right is a standard NLCD land use map.

OpenET and *eeMETRIC*

OpenET (OpenET.org) is a web- and -geodatabase-application that provides reliable and widely available spatial ET data at the field scale (30 m) from six different spatial ET methods. OpenET data are provided freely to the public and are intended for use to:

- Support water trading and transfer programs that protect the financial viability of farms during droughts while ensuring that water is also available for other beneficial uses.
- Develop more accurate water budgets and innovative management programs that ensure adequate supplies of water for agriculture, people and ecosystems over the coming decades.
- Expand ET-based irrigation practices that maximize "crop per drop" and reduce costs for fertilizer and water.

Development of the OpenET platform is supported by the S.D. Bechtel, Jr. Foundation, the Gordon and Betty Moore Foundation, the Walton Family Foundation, the Windward Fund, and the NASA Applied Science Program. In-kind support is provided by partners in the agricultural and water management communities, Google Earth Engine, and the Water Funder Initiative. OpenET operates on the Google Earth Engine. Applications are programmed in Java-script language.

EEFlux has been evolved to function in the OpenET environment as one of six difference spatial ET models and has been renamed *eeMETRIC*. Ultimately, access to *eeMETRIC* and the other spatial models will be open source, with application programming interfaces (API's) made available to be called by outside users. Currently, an ET data archive is being constructed for the continental US, with an ultimate goal of producing ET information for the globe. In *eeMETRIC*, Landsat imagery are utilized for 30 m spatial resolution, supplemented during periods of extended cloudiness by a combination of VIIRS thermal data and Sentinel 2 short-wave data.

OpenET contains a geodatabase that holds irrigation/field parcels for most western US states. Users can produce reports of ET aggregated over the parcels on a monthly time scale.

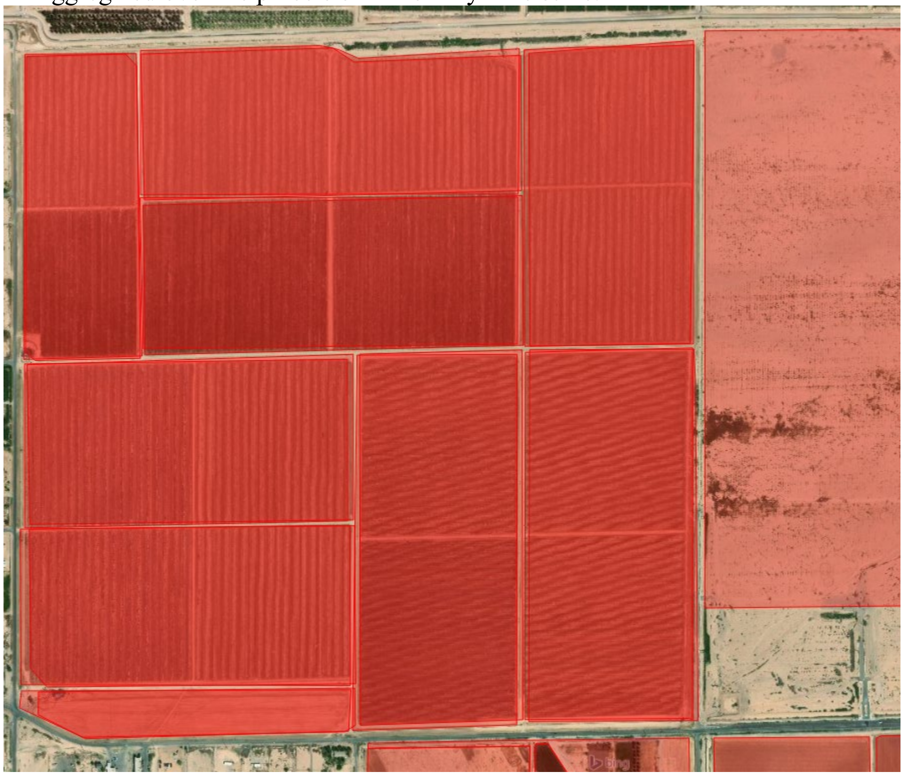

Figure 6. Close up of field parcels contained in OpenET outlined in light yellow and red lines.

Comparisons with Ground-Data

Spatial ET estimates by the EEFlux tool have been compared against ET estimates produced by manually applied METRIC models in Nebraska, Idaho and California (Foolad et al., 2018). The comparison results show that EEFlux was able to calculate ET_rF and ET values in agricultural areas that are comparable to those produced by trained METRIC users and that are generally within accepted accuracy ranges. Ratios of EEFlux estimates to METRIC estimates averaged 0.99 with standard deviation of 0.15 over nine location-date combinations. Root mean square error (RMSE) averaged 1.1 mm per day with standard deviation of 0.4 mm.

Spatial ET estimates by eeMETRIC are being compared against eddy covariance measurement data from more than 100 Ameriflux and USDA research sites in the USA. Preliminary results indicate that ratios of integrated monthly ET against measurements average 1.03 for agricultural land uses, 1.2 for shrublands, 1.15 for grasslands, 0.76 for evergreen forests, and 0.98 for mixed forests. RMSE for these classes were 18, 28, 12, 16 and 1 mm per month. Details of the comparisons against the six OpenET models are in preparation as a journal paper.

Summary

The *EEFlux* and *eeMETRIC* tools have been developed to take advantage of the cloud computing power of Google Earth Engine that is specifically tailored to geographic information processing. *EEFlux* and *eeMETRIC* also take strong advantage of the nearly full Landsat archive housed on Earth Engine, provided by the United States Geological Survey. The goal of *EEFlux* and *eeMETRIC* is to provide relatively high accuracy maps of evapotranspiration over large areas at 30 m resolution and for users who may not have high levels of background in ET physics and computation.

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