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EEFlux: A Landsat-based Evapotranspiration mapping tool on the Google Earth Engine

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Abstract. "*EEFlux*" is an acronym for '*Earth Engine Evapotranspiration Flux*.' *EEFlux* is based on the operational surface energy balance model "*METRIC*" (Mapping ET at high Resolution with Internalized Calibration), and is a Landsat-image-based process. Landsat imagery supports the production of ET maps at resolutions of 30 m, which is the scale of many human-impacted and human-interest activities including agricultural fields, forest clearcuts and vegetation systems along streams. ET over extended time periods provides valuable information regarding impacts of water consumption on Earth resources and on humans. *EEFlux* uses North American Land Data Assimilation System hourly gridded weather data collection for energy balance calibration and time integration of ET. Reference ET is calculated using the ASCE (2005) Penman-Monteith and GridMET weather data sets. The Statsgo soil data base of the USDA provides soil type information. *EEFlux* will be freely available to the public and includes a web-based operating console. This work has been supported by Google, Inc. and is possible due to the free Landsat image access afforded by the USGS.

Keywords. *Evapotranspiration, Google Earth Engine, Landsat, remote sensing, energy balance*

Introduction

The Google Earth Engine contains a full 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 patterned after the operational stand-alone model *METRIC* (mapping evapotranspiration at high resolution with internal calibration). *EEFlux* 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* implementation uses 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 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 complete Landsat scene. Applications can currently be made for the entire CONUS. Development of global applications is in progress.

Background

Evapotranspiration (ET) is often, at the same time, 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 behavior of water processes and water consumption and recycling of water on Earth, understanding health and vulnerability of vegetation systems under drought and other stresses, for understanding and managing constraints to food production, and for managing water 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* is comprised of algorithms designed for a wide range of land-uses, terrain types and ecosystems. The process 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 *EEFlux* application will be made 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 implementation of *EEFlux* onto Google EE contains 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. This requires automation of the calibration of the internal energy balance of *EEFlux* that compensates for systematic biases in Landsat fields including surface temperature and in *EEFlux* 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* produce ET at the instant of the Landsat overpass and surrounding day. 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* development is the provision of on-demand estimates of spatial distribution of water consumption by vegetation at the 30 m scale that are applicable to the 1984-present period of record for 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 tool has included:

a. Development of a strategy and coding and testing of an auto-calibration process for *EEFlux*
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 *EEFlux*-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* 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 a second tier system that permits 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* application 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 to promote universal, consistent and accurate estimation of ET and sources of algorithms and procedures.

Data Policy.

Output from *EEFlux* will be openly available to the public. We will protect *EEFlux* code to protect our intellectual investment, by creating access to *EEFlux* using the Google App Engine, but full access to running code and accessing products will be allowed.

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]**	**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, In progress
Full aerodynamic estimation of evaporation from water/snow (instead of energy balance)	✓		✓	Allen (2010a), In progress
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	Ultimately		✓	Allen and Kjaersgaard, Conference papers, in progress
Adjustment for background evaporation of image when filling in clouded regions	✓	✓	✓	Allen, Kjaersgaard, Trezza, Conference papers, internal memos
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), in progress

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

Example *EEFlux* 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

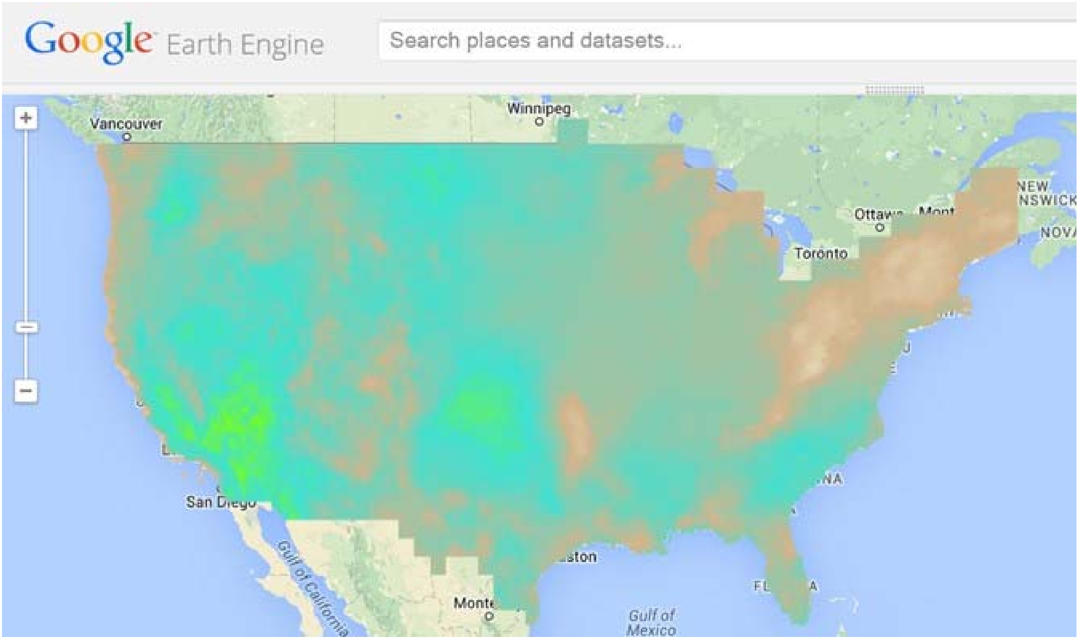

Figure 1. Example national map of hourly grass reference ET_o calculated using the ASCE standardized Penman-Monteith method applied to the 12 km gridded NLDAS weather data system. Bright greens are high ET_o and browns and light turquoise are low ET_o.

and at

https://ee-api.appspot.com/997094f81e70844bd4f50f86bf6110a9

for a national daily ET_o map based on GridMET

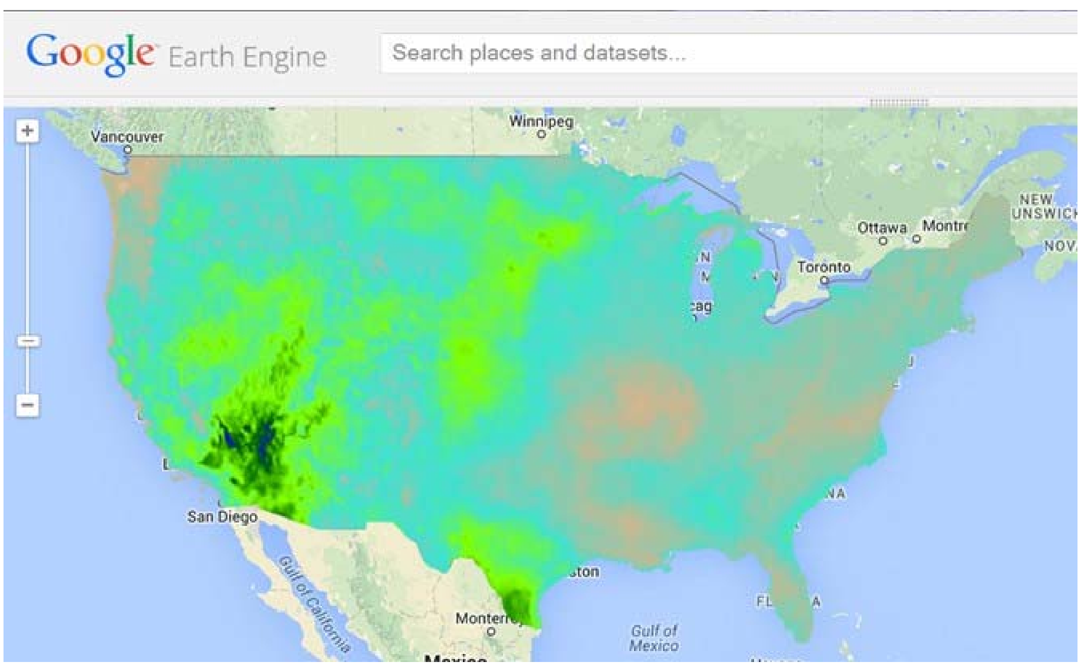

Figure 2. Example national map of daily grass reference ET_o calculated using the ASCE standardized Penman-Monteith method applied to the 4 km gridded and bias corrected GridMET weather data system of Abatzoglou (2011). Blues and dark greens are high ET_o and browns and light turquoise are low ET_o.

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. A second application has been produced that applies the 'tall' ASCE reference method representing full-cover alfalfa (Allen et al., 2005). It is this second method that is used in the *EEFlux* application for calibration and time integration, since the tall reference provides a good approximation of maximum or near maximum ET.

http://www.kimberly.uidaho.edu/water/asceewri/

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

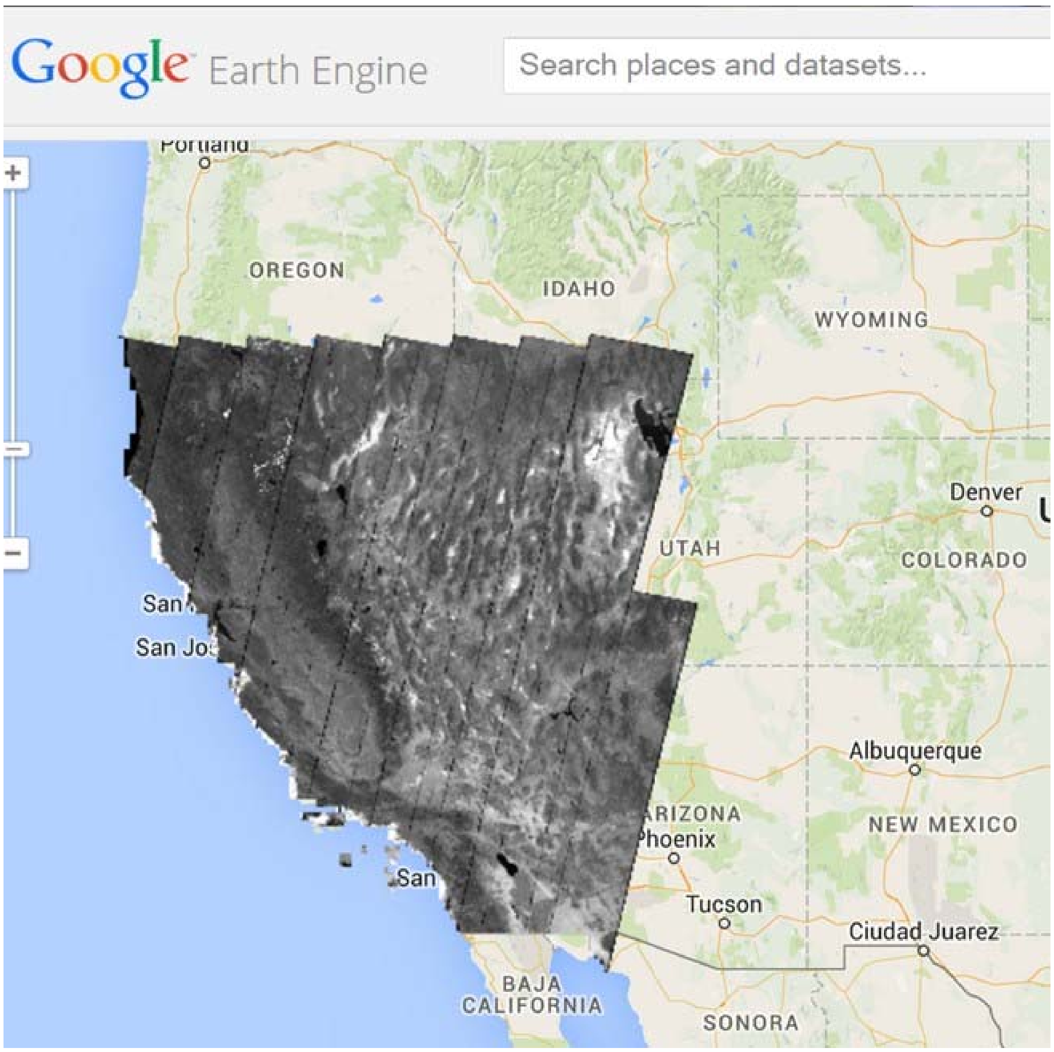

Figure 3. Surface albedo for nine Landsat paths covering California and Nevada during July 1993 based on *EEFlux* algorithms for surface reflectance that utilize Tasumi et al., (2008) procedures.

Figures 4 and 5 show an example application of the full *EEFlux* code to produce ETrF 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.

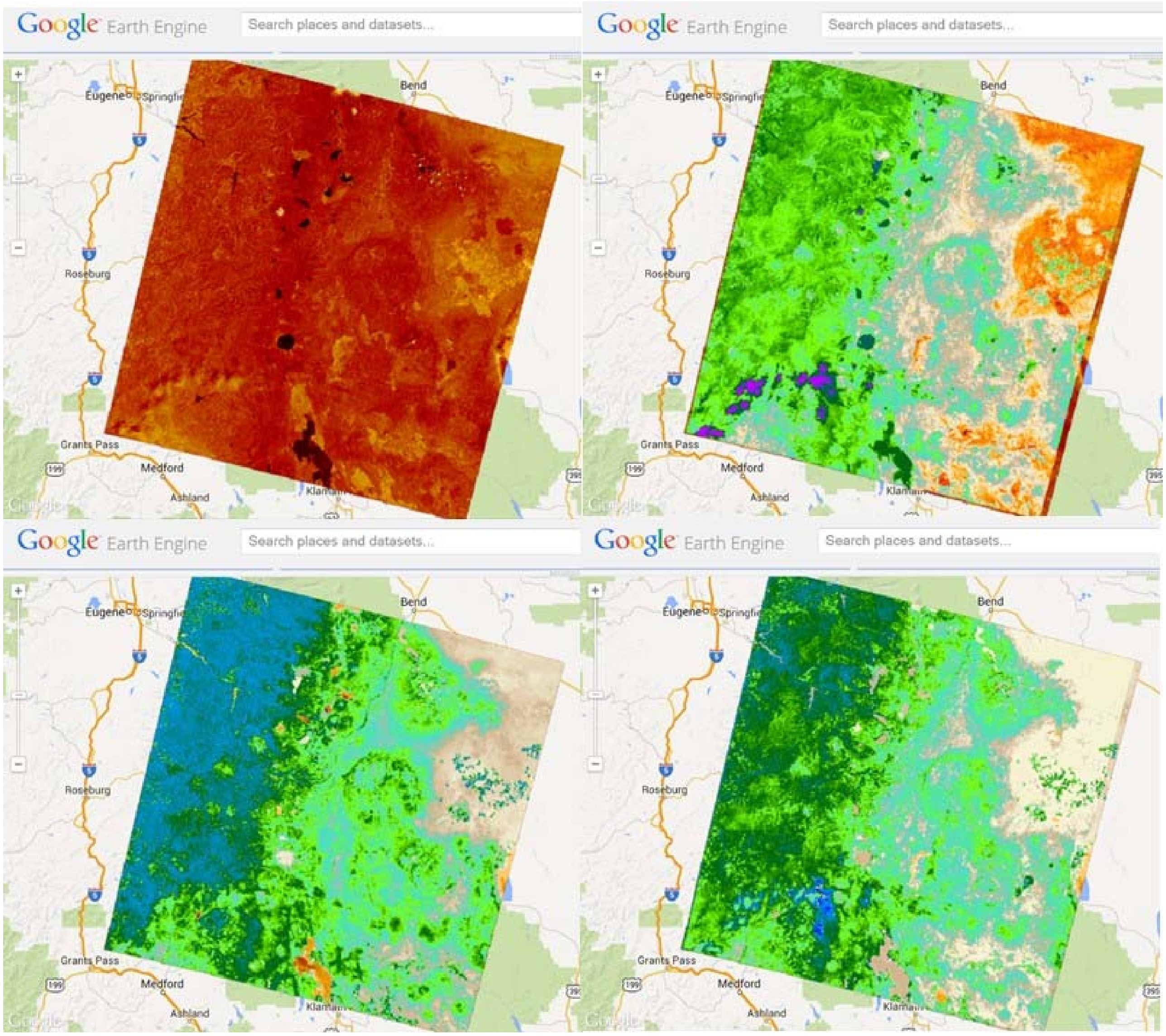

Figure 4. Landsat path 45 row 30 processed by *EEFlux* for July 15, 2014 showing a) albedo (upper left, where light orange is high albedo and dark red is low albedo. Very low albedo for water bodies is shown as blue/black); b) surface temperature (upper right, where magenta and blue are low temperature 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.

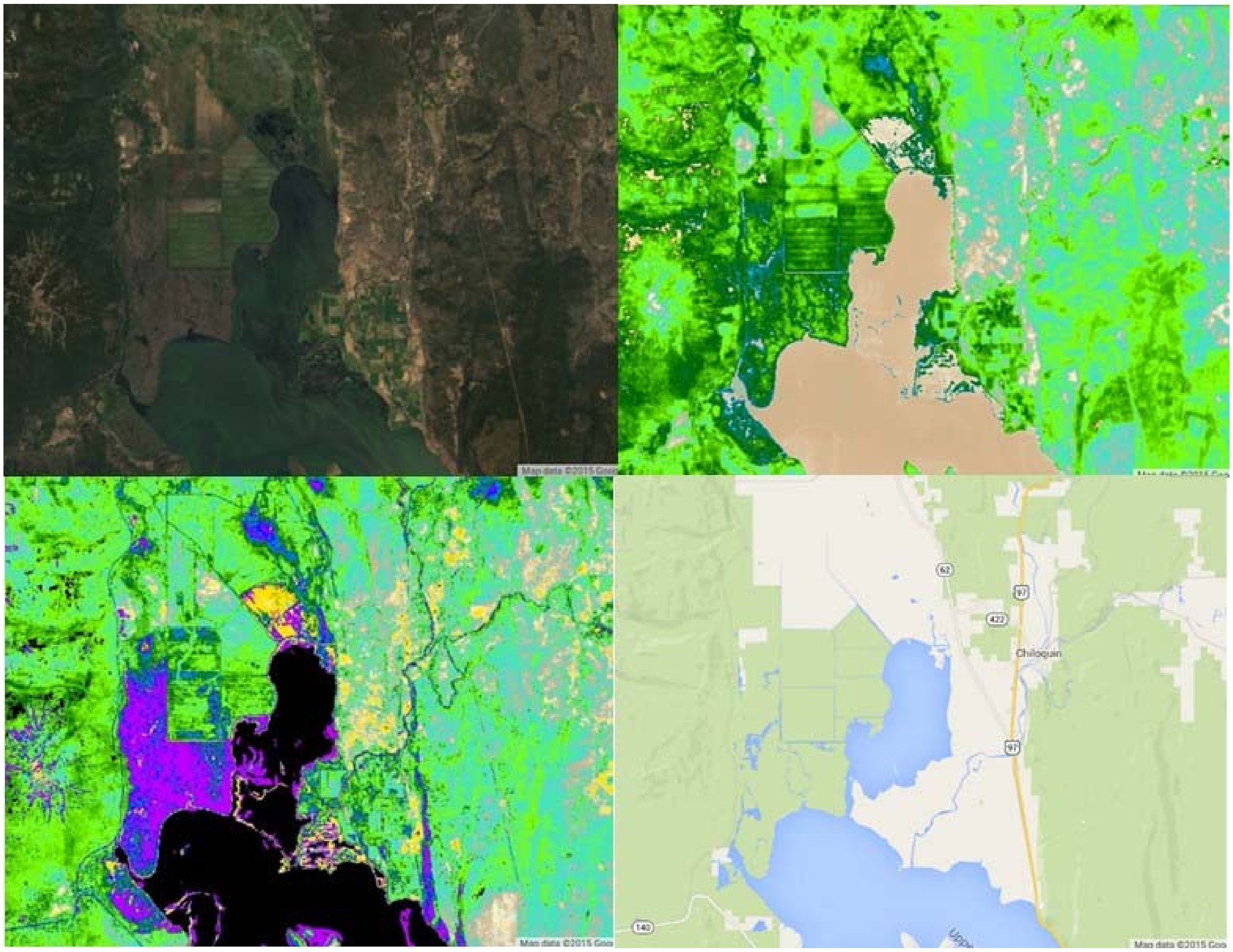

Figure 5. Area in Landsat path 45 row 30 north of Upper Klamath Lake where some irrigated lands have been retired during 2014. Image processed by *EEFlux* for July 15, 2014 showing a) ‘true-color’ blue-green-red composite (upper left, where light yellowish areas are fallowed areas in 2014); b) ET_rF (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 final *EEFlux* product will utilize a web-based ‘console’ that is accessible by users via a web-site, with planned free access and download of products for the level 1 version in the form of geo-tiff files. Second and third level versions that will allow for user intervention, iterative review and tuning of ET images will be provided via a subscription service, if desired.

Summary

The *EEFlux* tool has been developed to take advantage of the cloud computing power of Google Earth Engine that is specifically tailored to geographic information processing. *EEFlux* also takes strong advantage of the nearly full Landsat archive housed on Earth Engine, provided by the United States Geological Survey. The goal of *EEFlux* 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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