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ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

Level-4 Evaporative Stress Index L4(ESI_PT-JPL) Algorithm Theoretical Basis Document

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List of Acronyms

ALEXI	Atmosphere–Land Exchange Inverse
ATBD	Algorithm Theoretical Basis Document
CONUS	Contiguous United States
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ESI	Evaporative Stress Index
ET	Evapotranspiration
EVI-2	Earth Ventures Instruments, Second call
FLiES	Forest Light Environmental Simulator
HyspIRI	Hyperspectral Infrared Imager
ISS	International Space Station
L-2	Level 2
L-3	Level 3
L-4	Level 4
LE	Latent heat flux
MERRA	Modern Era Retrospective-Analysis for Research and Applications
MODIS	MODerate-resolution Imaging Spectroradiometer
PDSI	Palmer Drought Severity Index
PET	Potential evapotranspiration
PHyTIR	Prototype HyspIRI Thermal Infrared Radiometer
PT-JPL	Priestley-Taylor Jet Propulsion Laboratory
SDS	Science Data System
SPI	Standardized Precipitation Index
USDM	United States Drought Monitor
VIIRS	Visible Infrared Imaging Radiometer Suite
WSWC	Western States Water Council

Contents

1 Introduction

1.1 Purpose

Plants can use water (evapotranspiration, *ET*) at the maximum rate of atmospheric demand (i.e., the potential evapotranspiration, *PET*) [*Fisher et al.*, 2011]. Any *ET* less than the *PET* is an indicator that water supply is limited; plants may close stomata to conserve water, and productivity may therefore be less than optimal [*Fisher*, 2013]. Hence, the actual-to-potential *ET* ratio (*ET*/*PET*) is a key indicator of plant water stress. Moreover, anomalies to *ET*/*PET* against a historical baseline, known as the Evaporative Stress Index (ESI), carry valuable information regarding antecedent moisture conditions (without requiring precipitation or soil moisture information), and have been demonstrated to be powerful indicators of drought and crop stress during rapid onset (flash) drought events [*Anderson et al.*, 2007; *Anderson et al.*, 2011; *Anderson et al.*, 2013; *Otkin et al.*, 2013; *Otkin et al.*, 2014] (Figure 1).

ECOSTRESS will be producing *ET* over the entire ECOSTRESS domain as a Level-3 product, L3(ET_PT-JPL) [*Fisher and ECOSTRESS Algorithm Development Team*, 2015]. *PET* is already calculated internally as part of the PT-JPL algorithm. Thus, to generate the *ET*/*PET* indicator is straightforward, not requiring additional ancillary information or new algorithms; the L4(ESI_PT-JPL) product is a value-added science product for the ECOSTRESS mission. The L4(ESI_PT-JPL) product will be particularly valuable at the relatively high spatial and temporal resolutions of ECOSTRESS in that these characteristics will allow the data product to capture spatial heterogeneity in water stress as well as rapidly changing moisture environments that could not be detectable with coarser spatiotemporal resolutions.

We note that the ESI, as previously used and defined, required a historical baseline for anomaly detection. With ECOSTRESS, we will not have a historical baseline, nor is one producible from other instruments (e.g., Landsat, MODIS, a modeling system) at the same resolutions as ECOSTRESS; a historical archive from Landsat has not been produced and would require substantial effort beyond the scope of the mission. Hence, the ESI adaptation to ECOSTRESS will focus primarily on the stress signal derived solely from the ratio of actual to potential *ET*.

These data accompany the L4(ESI_ALEXI) product, which is produced from the L3(ET_ALEXI) algorithm targeting very localized study areas for focused investigation. The L4(ESI_PT-JPL) product allows further study by the larger science community across the entire ECOSTRESS domain.

In this Algorithm Theoretical Basis Document (ATBD), we describe the calculation of *PET*, which gets incorporated into the *ET*/*PET* indicator. The theoretical basis for the *ET* is described in the L3(ET_PT-JPL) ATBD.

1.2 Scope and Objectives

In this ATBD, we provide:

1. Justification for the choice of *ET*/*PET* algorithm;
2. Description of the general form of the algorithm;
3. Description of the *PET* parameter characteristics and requirements;
4. Required algorithm adaptations specific to the ECOSTRESS mission;
5. Required Ancillary data products with potential sources and back-up sources.

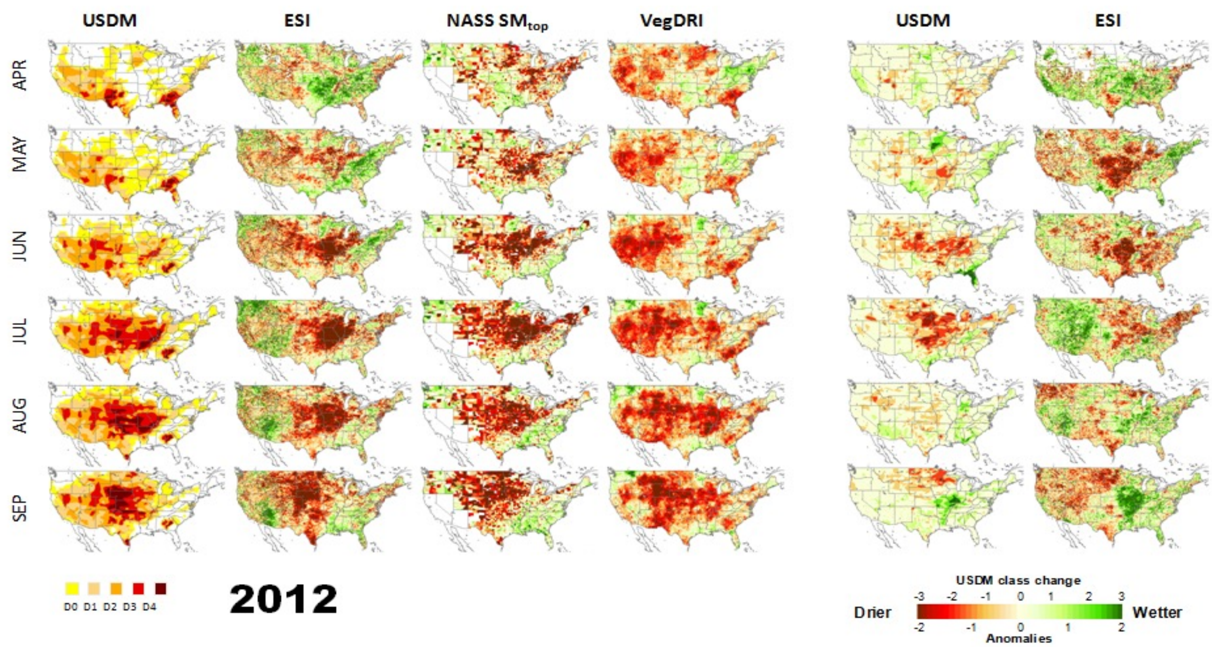

Figure 1. The Evaporative Stress Index (ESI) captured the 2012 US drought stress signal early as compared to the US Drought Monitor (USDM), National Agricultural Statistics Service (NASS) reports of topsoil moisture, and the Vegetation Drought Response Index (VegDRI) [*Otkin et al.*, 2013].

2 Parameter Description and Requirements

Attributes of the *ET*/*PET* data required by the ECOSTRESS mission include:

- Spatial resolution of 70 m x 70 m;
- Latency as required by the ECOSTRESS Science Data System (SDS) processing system;
- Includes all geographic terrestrial regions visible by the ECOSTRESS instrument (i.e., the Prototype HyspIRI Thermal Infrared Radiometer; PHyTIR) from the ISS, with priorities to the ECOSTRESS Science Objective 1 Water Use Efficiency (WUE) target regions ("hotspots"), the ECOSTRESS Science Objective 3 agricultural regions (e.g., the Contiguous United States; CONUS), and the Cal/Val sites.

3 Algorithm Selection

The *ET*/*PET* algorithm must satisfy basic criteria to be applicable for the ECOSTRESS mission:

- Physically defensible;
- Globally applicable;
- High sensitivity and dependency on remote sensing measurements;
- Relative simplicity necessary for high volume processing;
- Demonstrated sensitivity to vegetation drought conditions;

- Published record of algorithm maturity, stability, and validation.

There are numerous drought indicators available, yet most suffer from a lack of a direct connection to vegetation response and stress. For instance, most drought indicators missed the intensity and magnitude of the 2012 US Midwest drought [*Freedman*, 2012]. It was hypothesized that the inability of our current drought indicators to fully describe large droughts, such as the 2012 US Midwest drought, was due to a lack of land–atmosphere coupling in most indicators [*Roundy et al.*, 2013]. Drought indicators, such as the Standardized Precipitation Index (SPI), typically ignore water demand, instead focusing on water supply [*Guttman*, 1999]. But, a reduction in precipitation (supply) would not necessarily result in a drought if there was also a reduction in *ET* (demand) [*Fisher and Andreadis*, 2014]. Conversely, no reduction in precipitation could still result in a drought if there was an increase in *ET*. Indices such as the Palmer Drought Severity Index (PDSI) attempt to address demand through inclusion of temperature [*Alley*, 1984], which is one of many controls on *ET* [*Fisher et al.*, 2011]. But, an increase in temperature does not necessarily result in an increase in *ET* if, for example, humidity remained high and incoming radiation decreased; similarly, *ET* could increase with constant temperature if the air became particularly dry and net radiation levels increased [*Fisher et al.*, 2011]. Soil moisture indices come close to connecting supply and demand, but struggle to capture root-zone heterogeneity, i.e., what the plants are actually responding to, and are also highly uncertain due to lack of observational constraint [*Heim Jr*, 2002; *Narasimhan and Srinivasan*, 2005].

One of the only drought indicators to capture the onset, duration, magnitude, and intensity of these mega-droughts is the ESI, which detects plant stress to water based on the anomalous reduction in *ET* relative to potential *ET* as determined by the atmosphere [*Anderson et al.*, 2013; *Otkin et al.*, 2013]. Anomalies to ESI, or to *ET* more generally, provide a climate indicator that integrates both supply and demand, as well as the direct connection to what plants are receiving in water (which can vary based on root length and soil water properties—both of which are not observable at large scales) [*Phillips et al.*, 2009; *Phillips et al.*, 2010]. In both drought and non-drought settings, *ET* is the primary variable used by agriculture to manage irrigation—water is applied in quantities so that the actual *ET* matches the potential *ET* as determined by the atmosphere, or, the land–atmosphere coupling [*Allen et al.*, 1998]. Agriculture is the primary societal consumer of water across the world, and the sector most devastated by droughts [*Morton*, 2007]; rangelands and natural ecosystems are also highly sensitive water consumers, which can have societal impacts when drought-affected (e.g., fires) [*Dale et al.*, 2001]. *ET* is the hydrological variable that best describes plant behavior and response to changing water conditions, and can potentially be the most beneficial and directly useable observable by the water resource management and decision-making communities. In a recent meeting of the Western States Water Council (WSWC) at NASA JPL, most states expressed a primary need for *ET* estimates to help management decisions. Moreover, remotely sensed *ET* estimates can be provided at spatial scales (30 m – 1 km) that managers can operate on, unlike coarser indicators such as the USDM [*Allen et al.*, 2011]. A water manager equipped with water use/demand information that identifies differences in highly heterogeneous landscapes can manage water allocations much more precisely; coarse-scale information makes no differentiation at these scales. Moreover, most water managers have found that the US Drought Monitor is not useful for their applications [*Steinemann*, 2014].

4 Evapotranspiration Stress Retrieval

4.1 *ET* stress signal based on the Evaporative Stress Index

The *ET* stress signal, as defined as *ET* relative to *PET*, ranges from 0-1 (unitless; 0 being full water stress, 1 being no water stress), and is simply calculated as:

$$ET\ Stress\ Signal = \frac{ET}{PET} \tag{1}$$

The theoretical basis and algorithmic procedures for producing *ET* are described in the ECOSTRESS L3(ET_PT-JPL) ATBD [*Fisher and ECOSTRESS Algorithm Development Team*, 2015].

PET for L4(ESI_PT-JPL) is derived from the Priestley-Taylor [1972] equation, which is a reduced version of the Penman-Monteith [1965] equation, eliminating the need to parameterize stomatal and aerodynamic resistances, leaving only equilibrium evaporation multiplied by a constant (1.26) called the α coefficient:

$$PET = \alpha \frac{\Delta}{\Delta + \gamma} R_n \tag{2}$$

where Δ is the slope of the saturation-to-vapour pressure curve (dependent on near surface air temperature, T_a, and water vapour pressure, e_a), γ is the psychrometric constant, and R_n is net radiation (W m^{-2}). The Priestley-Taylor equation gives the amount of *ET* that will occur if water is not limiting. *PET* is given in units[1] of R_n, or W m^{-2}, and is therefore considered as an energy variable, i.e., *LE*.

An example of the ECOSTRESS ESI (*ET*/*PET*) simulated from VIIRS LST for a single day is given in Figure 2. The accuracy of the L4(ESI_PT-JPL) product is dependent on the accuracy of the L3(ET_PT-JPL) product. Higher accuracies and precisions enable small detection differences between ecosystems.

[1] Water fluxes such as precipitation and *ET* can be given in units of depth per time (i.e., mm·day^{-1}); the units are consistent when they are in volume per area per time (i.e., $m^3 \cdot ha^{-1} \cdot day^{-1}$). 1 m^3 is equal to 1000 litres. Water can also be expressed in units of mass—1 kg of water is equal to 1 mm of water spread over 1 m^2. *ET*, like R_n, can be expressed in units of energy too. Because it requires 2.45 MJ to vaporize 1 kg of water (at 20°C), 1 kg of water is therefore equivalent to 2.45 MJ; 1 mm of water is thus equal to 2.45 MJ·m^{-2}.

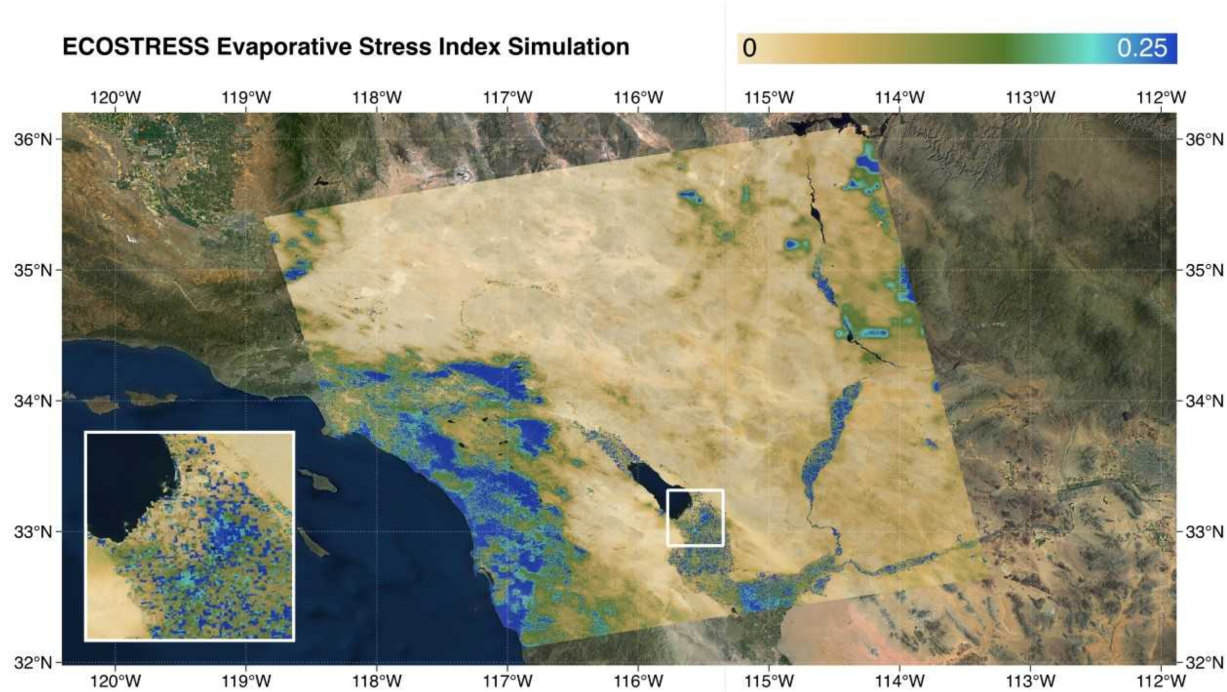

Figure 2. ECOSTRESS ESI (ET/PET) simulated from VIIRS LST for a single day shows regions of high water stress (beige) and low water stress (blues).

5 Mask/Flag Derivation

The L3(ET_PT-JPL) quality flags are carried over identically to L4(ESI_PT-JPL). Additional quality flags are incorporated from those provided by the ancillary MODIS products.

6 Metadata

- unit of measurement: unitless (W m^{-2} per W m^{-2})
- range of measurement: 0 to 1
- projection: ECOSTRESS swath
- spatial resolution: 70 m x 70 m
- temporal resolution: dynamically varying with precessing ISS overpass; instantaneous throughout the day, local time
- spatial extent: all land globally, excluding poleward ±60°
- start date time: near real-time
- end data time: near real-time
- number of bands: not applicable
- data type: float
- min value: 0
- max value: 3000
- no data value: 9999
- bad data values: 9999
- flags: quality level 1-4 (best to worst)

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