ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

Level-4 Water Use Efficiency L4(WUE) Algorithm Theoretical Basis Document

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May 2018
ECOSTRESS Science Document no. D-94649
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATBD</td>
<td>Algorithm Theoretical Basis Document</td>
</tr>
<tr>
<td>CONUS</td>
<td>Contiguous United States</td>
</tr>
<tr>
<td>ECOSTRESS</td>
<td>ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>GPP</td>
<td>Gross Primary Production</td>
</tr>
<tr>
<td>HyspIRI</td>
<td>Hyperspectral Infrared Imager</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>L-3</td>
<td>Level 3</td>
</tr>
<tr>
<td>L-4</td>
<td>Level 4</td>
</tr>
<tr>
<td>MODIS</td>
<td>MODerate-resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>OCO</td>
<td>Orbiting Carbon Observatory</td>
</tr>
<tr>
<td>PHyTIR</td>
<td>Prototype HyspIRI Thermal Infrared Radiometer</td>
</tr>
<tr>
<td>PT-JPL</td>
<td>Priestley-Taylor Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>SDS</td>
<td>Science Data System</td>
</tr>
<tr>
<td>SIF</td>
<td>Solar induced chlorophyll fluorescence</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive</td>
</tr>
<tr>
<td>VIIRS</td>
<td>Visible Infrared Imaging Radiometer Suite</td>
</tr>
<tr>
<td>WUE</td>
<td>Water Use Efficiency</td>
</tr>
</tbody>
</table>
# Contents

1 Introduction .......................................................................................................................... 1  
  1.1 Purpose ............................................................................................................................. 1  
  1.2 Scope and Objectives ....................................................................................................... 1  

2 Parameter Description and Requirements .............................................................................. 1  

3 Algorithm Selection .............................................................................................................. 2  

4 Water Use Efficiency Retrieval .......................................................................................... 3  
  4.1 Water Use Efficiency (WUE) .......................................................................................... 3  
  4.2 Gross Primary Production (GPP) .................................................................................... 3  
    4.2.1 Diurnal cycling .......................................................................................................... 5  
    4.2.2 Spatial resolution improvements .............................................................................. 6  

5 Mask/Flag Derivation .......................................................................................................... 7  

6 Metadata ............................................................................................................................ 8  

7 Acknowledgements .............................................................................................................. 8  

8 References ........................................................................................................................... 9  

1 Introduction

1.1 Purpose

Plants and ecosystems have highly disparate water consumption (i.e., evapotranspiration, ET) needs based on their evolutionary histories, local plasticity and adaptations. Some plants are more efficient with their water use than others, subsequently fixing relatively greater amounts of carbon (C) through photosynthesis (gross primary production, GPP) per unit of water lost through ET. This C gain relative to water lost is termed the Water Use Efficiency (WUE) [Stanhill, 1986; Stewart and Steiner, 1990; Steduto, 1996]. During times of water shortage or drought, less water use efficient plants may be more vulnerable to stress or mortality than are plants with higher WUE [Keenan et al., 2013]. Knowing what and where the WUE is of different plants and ecosystems will advance the understanding of how the terrestrial biosphere is responding to changes in climate. A relatively high spatial resolution is necessary to capture WUE differences in ecosystems with diverse species assemblages.

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]. To generate WUE the L4(WUE) product must ingest an ancillary GPP product to combine with the L3 ET product concurrently measured/produced during the L3 ET ECOSTRESS production.

In this Algorithm Theoretical Basis Document (ATBD), we describe the calculation of WUE and the ingestion of the GPP product. The theoretical basis for the ECOSTRESS ET is described in the ECOSTRESS L3(ET_PT-JPL) ATBD. The ECOSTRESS L4(WUE) product is a value-added product to ECOSTRESS.

1.2 Scope and Objectives

In this ATBD, we provide:

1. Description of the general form of the WUE equation;
2. Description of the GPP ancillary data ingestion.

2 Parameter Description and Requirements

Attributes of the WUE 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 (Figure 1).
Algorithm Selection

The WUE 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.
4 Water Use Efficiency Retrieval

4.1 Water Use Efficiency (WUE)

WUE is defined as the ratio of the amount of C fixed in units of GPP (g C m\(^{-2}\) d\(^{-1}\)) per amount of water lost in units of ET (kg H\(_2\)O m\(^{-2}\) d\(^{-1}\)), which reduces to a daily ratio (g C kg\(^{-1}\) H\(_2\)O):

\[
WUE = \frac{GPP}{ET}
\]  (1)

High values indicate efficient plants, and low values indicate inefficient plants. 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].

4.2 Gross Primary Production (GPP)

The GPP ancillary product may be ingested from any number of sources: MODIS [Zhao et al., 2005], SMAP [Kimball et al., 2014], OCO-2 [Frankenberg et al., 2011; Frankenberg et al., 2014], VIIRS, and OCO-3 [Eldering et al., 2015]. The MODIS product is ideal for ECOSTRESS because it aligns with the other MODIS ancillary products already being ingested into the L3(ET_PT-JPL) algorithm/product, it is given at relatively high spatial and temporal resolutions (1 km, 8-day), and has been vetted in the scientific literature [Heinsch et al., 2006; Turner et al., 2006; Zhang et al., 2012] (Figure 2). VIIRS is expected to mirror many of the major MODIS products, including the GPP product [Dungan et al., 2014]. SMAP now provides a high quality GPP product as part of the SMAP L4 carbon product with good temporal resolution and moderate spatial resolution, largely based on MODIS measurements [Kimball et al., 2014] (Figure 3). OCO-2 provides a key
The **L4(WUE)** algorithm is adapted to handle both the MODIS GPP and OCO-2 SIF-based GPP inputs, with MODIS being the top priority due to its spatial resolution. The GPP product will be ingested operationally into the JPL L3/L4 team’s data production stream, divided by the L3(ET_PT-JPL) product, and supplied as **WUE** back to the SDS for delivery to the DAAC according to the ECOSTRESS data delivery schedule. An example of the ECOSTRESS **WUE** simulated from VIIRS LST with MODIS GPP for a single day is given in Figure 5. The accuracy of the **WUE** is dependent on the accuracies of the L3(ET_PT-JPL) and **GPP** products. Higher accuracies and precisions enable small detection differences between ecosystems.

**Figure 3.** Gross Primary Production (GPP) from the SMAP L4_C product. [Kimball et al., 2014]

**Figure 4.** Solar induced chlorophyll fluorescence (SIF) from OCO-2 is linearly proportional to Gross Primary Production (GPP) [Frankenberg et al., 2011; Frankenberg et al., 2014].
4.2.1 Diurnal cycling

Except for OCO-3, all the GPP options derive from polar orbiters with consistent overpass times, unlike the precessing orbit of ECOSTRESS on the ISS. Thus, the GPP product must be statistically shifted to the overpass time of ECOSTRESS for the given day. What is traditionally done, generally, is to construct a date and latitudinal-varying sinusoidal curve mimicking the sunrise-to-sunset radiation intensity [Bisht et al., 2005]. The relative ratios of the instantaneously observed variables (e.g., the GPP-to-\( R_n \) ratio) are assumed to be held constant throughout that curve/day. Additional refinement may be invoked to include the probabilistic or observed fraction of cloud cover throughout the day and seasonally, land cover or vegetation type-specific parameterizations, and/or dynamically changing relative ratios of the variables of interest.

Because \( R_n \) is a major driver of GPP, we initialize the diurnal cycle calculation with \( R_n \). Lagouarde and Brunet [1993] first developed the framework to obtain the diurnal cycle of \( T_s \) from a sinusoidal function with the day length and amplitude equal to the difference between maximum \( T_s \) and minimum \( T_a \). Bisht et al. [2005] later adapted that to clear sky \( R_n \) diurnal cycling:

\[
R_n(t) = R_{n,max} \sin \left( \pi \left( \frac{t - t_{rise}}{t_{set} - t_{rise}} \right) \right) \tag{9}
\]

where \( R_{n,max} \) is the maximum value of \( R_n \) observed during the given day, and \( t_{rise} \) and \( t_{set} \) are the local times at which \( R_n \) becomes positive and negative, respectively.

The corresponding \( R_{n,max} \) for the time of overpass (\( t_{overpass} \)) is given as:

![ECOSTRESS Water Use Efficiency Simulation](image-url)
ECOSTRESS LEVEL-4 WATER USE EFFICIENCY L4(WUE) ATBD

$$R_{n,max} = \frac{R_{n,overpass}}{\sin\left(\pi \frac{t_{overpass} - t_{rise}}{t_{set} - t_{rise}}\right)}$$

(10)

The daily average $R_n$ is given as:

$$R_{n,daily} = \frac{\int_{t_{rise}}^{t_{set}} R_n(t) \, dt}{\int_{t_{rise}}^{t_{set}} \, dt} = \frac{2R_{n,max}}{\pi} = \frac{2R_{n,overpass}}{\pi \sin\left(\pi \frac{t_{overpass} - t_{rise}}{t_{set} - t_{rise}}\right)}$$

(11)

The daily-to-instantaneous $R_n$ ratio is therefore:

$$\frac{R_{n,daily}}{R_{n,overpass}} = \frac{2}{\pi \sin\left(\pi \frac{T - 2a}{2T}\right)}$$

(12)

where $T$ is day length (i.e., $t_{set}$ minus $t_{rise}$), and $a$ is the difference in time between when $R_n$ is maximum and when the satellite overpasses.

For ECOSTRESS, the general form of this equation is applied every day to each of the diurnally-varying $R_n$ drivers (excluding solar zenith angle and $T$, and $r_s$, the latter two of which are measured at diurnally-varying times of day directly from ECOSTRESS), but the modified instantaneous values are extracted from the equation rather than the daily average. Issues of extrapolation into cloud cover are circumvented because ECOSTRESS will produce ET only under clear-sky conditions; similarly, ECOSTRESS will not produce WUE if GPP is unavailable due to cloud cover.

### 4.2.2 Spatial resolution improvements

The L3(ET_PT-JPL) ECOSTRESS product will be given at 70 m x 70 m spatial resolution (though with caveats—see, L3(ET_PT-JPL) ATBD). The GPP product will be provided at a spatial resolution coarser than ECOSTRESS, e.g., 1 km x 1 km from MODIS. The GPP product will be sub-sampled to match the 70 m x 70 m ECOSTRESS spatial resolution both for consistency as well as use of the high resolution of the ET product; however, we caution analyses of WUE at <1 km as the “true” resolution will be somewhere between 70 m and 1 km, depending on the relative sensitivity of WUE to ET for any given place and time, as well as the relative sub-pixel homogeneity/heterogeneity of the GPP pixel.
5 Mask/Flag Derivation
The L3(ET_PT-JPL) quality flags are carried over identically to L4(WUE). No additional quality flags are incorporated from those provided by the ancillary GPP product (Table 1):

Table 1. ECOSTRESS L4(WUE) MODIS ancillary data flags and responses to poor quality.

<table>
<thead>
<tr>
<th>Input product</th>
<th>Quality Flag</th>
<th>Response to poor quality</th>
</tr>
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<tbody>
<tr>
<td>MODIS GPP</td>
<td>N/A</td>
<td>N/A</td>
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</table>
6 Metadata
- unit of measurement: units of $GPP$ per units of $ET$ (g C kg$^{-1}$ H$_2$O)
- range of measurement: 0 to 10
- 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)

7 Acknowledgements
We thank Gregory Halverson, Laura Jewell, and Gregory Moore for contributions to the algorithm development described in this ATBD.
8 References


Eldering, A., R. Basilio, and M. Bennett (2015), The OCO-3 Mission: Overview of Science Objectives and Status, in American Geophysical Union Fall Meeting, edited, San Francisco.


