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ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

Level-4 Evaporative Stress Index (ESI_ALEXI) Algorithm Theoretical Basis Document

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List of Acronyms

ALEXI	Atmosphere–Land Exchange Inverse
ARS	Agricultural Research Service
ATBD	Algorithm Theoretical Basis Document
Cal/Val	Calibration and Validation
CDL	Cropland Data Layer
CFSR	Climate Forecast System Reanalysis
CONUS	Contiguous United States
DisALEXI	Disaggregated ALEXI algorithm
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ET	Evapotranspiration
EVI-2	Earth Ventures Instruments, Second call
GET-D	GOES Evapotranspiration and Drought System
HRSL	Hydrology and Remote Sensing Laboratory
ISS	International Space Station
L-2	Level 2
L-3	Level 3
LST	Land-Surface Temperature
LTAR	Long-Term Agroecosystem Research
MODIS	MODerate-resolution Imaging Spectroradiometer
NASS	National Agricultural Statistics Service
NLCD	National Land Cover Dataset
NOAA	National Oceanographic and Atmospheric Administration
PM	Penman-Monteith
RMSD	Root Mean Squared Difference
SEB	Surface Energy Balance
TIR	Thermal Infrared
TSEB	Two-Source Energy Balance
USDA	United States Department of Agriculture

Contents

1 Introduction

1.1 Purpose

Operational applications in agriculture and water resource management are increasingly requiring *timely* information about water use at *fine spatial resolution* over *large regions*. Maps of daily or weekly evapotranspiration (ET) are needed at field scale for managing irrigation, monitoring water use, and planning for future water demand. Furthermore, the drought and agricultural communities want information about soil moisture deficiencies and crop stress at similar spatiotemporal scales to inform drought response and mitigation decision making, and to update yield projections throughout the growing season. In support of these informational needs, the ECOSTRESS mission will develop datastreams describing both ET and vegetation stress at 30-m spatial resolution with frequent updates governed by the ECOSTRESS overpass schedule.

This stress information will be conveyed in terms of the impacts on evapotranspiration. ET describes both crop water use through transpiration (T) and water lost through direct soil evaporation (E), making it a good indicator of soil moisture availability and vegetation health. The value of ET as a vegetation stress signal has been long appreciated by agronomists. Jensen (1968) related ET to crop yield through the ratio of actual to reference ET, referred to here as f_{RET} but also known in agronomy as the "crop coefficient". This ratio reflects the seasonally changing balance between crop available soil water, vegetation amount, and the atmospheric demand for water vapor. The milestone publication of Doorenbos and Kassam (1979) established relationships between relative yield losses and reduction in evapotranspiration from potential levels.

While crop models typically determine f_{RET} using a simple soil water balance approach, it has been demonstrated that energy balance methods based on thermal remote sensing can provide a diagnostic assessment of this stress functional without requiring information about precipitation or soil texture (Moran 2003; Anderson et al. 2007a; Hain et al. 2009). This is a benefit for large area mapping of ET and crop stress, particularly in data-sparse regions or areas where the local rainfall-driven water balance may be modified by shallow water tables, irrigation or drainage (Hain et al. 2015). In this approach, a surface energy balance model is used to transform thermal retrievals of land-surface temperature (LST) into estimates of evaporative cooling required to maintain LST given a specified radiation load (Kalma et al. 2008; Kustas and Anderson 2009).

The Evaporative Stress Index (ESI), representing standardized anomalies in f_{RET} derived via energy balance, was developed as a remote sensing indicator of agricultural drought and vegetation stress (Anderson et al. 2007b). Regional ESI products (3-10 km resolution) generated with LST retrievals from geostationary (GEO) satellites have demonstrated good correspondence with standard drought indicators (Anderson et al. 2011; 2013), but with advantages in timely detection of drought impacts on agroecosystems as they develop on the ground (Anderson et al. 2015; 2016b; 2016a). The coarse resolution afforded by GEO platforms, however, results in mixed pixels, combining stress signals from multiple land-cover types and land/water-management strategies.

ECOSTRESS has the spatial and temporal resolution to facilitate mapping of the f_{RET} stress index *at the scales that land and water is being actively managed* over agricultural landscapes. Because ECOSTRESS will have a relatively short mission lifetime, it cannot provide the long baseline required to compute true ESI anomaly products. Still, ECOSTRESS provides the means to better understand the physiological responses that drive these anomalies. ECOSTRESS f_{RET} time-series will provide diagnostic information about drought resilience at patch scale due to variability in, e.g., plant rooting depth, vegetation type/crop varietal, groundwater access, or crop/water management strategy. The high temporal revisit of ECOSTRESS will enable quantification of drought impact early warning capacity conveyed by TIR imaging, particularly during flash drought events that are not well-captured in standard precipitation-based indices. Unambiguous detection of stress during critical phenological phases in crop development is key to improving crop yield monitoring, both within the U.S. and globally.

In this Algorithm Theoretical Basis Document (ATBD), we describe the approach used to generate L4(ESI_ALEXI) maps of actual-to-reference ET ratio using ET products described in the L3(ET_ALEXI) ATBD.

1.2 Scope and Objectives

In this ATBD, we provide:

1. Description of the f_{RET} dataset characteristics and requirements;
2. Justification for the choice of algorithm;
3. Description of the general form of the algorithm;
4. Required algorithm adaptations specific to the ECOSTRESS mission;
5. Required ancillary data products with potential sources and back-up sources;

2 Dataset Description and Requirements

Attributes of the L4(ESI_ALEXI) f_{RET} data produced for the ECOSTRESS mission include:

- Spatial resolution of 30 x 30 m, on grid consistent with Landsat Worldwide Reference System (WRS-2);
- Developed on ECOSTRESS overpass dates for pixels that are clear at the overpass time of the International Space Station (ISS);
- Latency as required by the ECOSTRESS Science Data System (SDS) processing system;
- Includes target agricultural sites within the continental United States (CONUS).

3 Algorithm Selection

The reference ET ratio formulation described here was devised to be optimally conforming to the operational GET-D ESI dataset generated by NOAA. This dataset was selected for downscaling analyses using ECOSTRESS ET products due to the following attributes:

- Physically defensible;
- Good performance within targeted agricultural regions;

- High sensitivity and dependency on remote sensing measurements;
- Published record of algorithm maturity, stability, and validation.

The Evaporative Stress Index (ESI) is computed from clear-sky estimates of the relative ET fraction, f_{RET} = ET/ETo, where ET is actual ET retrieved using the Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model and ETo is the Penman-Monteith (FAO-56 PM) reference ET for grass as described by Allen et al. (1998). Normalizing by reference ET serves to reduce impact of drivers of the evaporative flux that are less directly related to soil moisture limitations (e.g., insolation load and atmospheric demand). To identify areas where f_{RET} is higher or lower than normal for a given time interval within the growing season, ESI is expressed as a seasonally varying standardized anomaly in f_{RET} with respect to long-term baseline conditions.

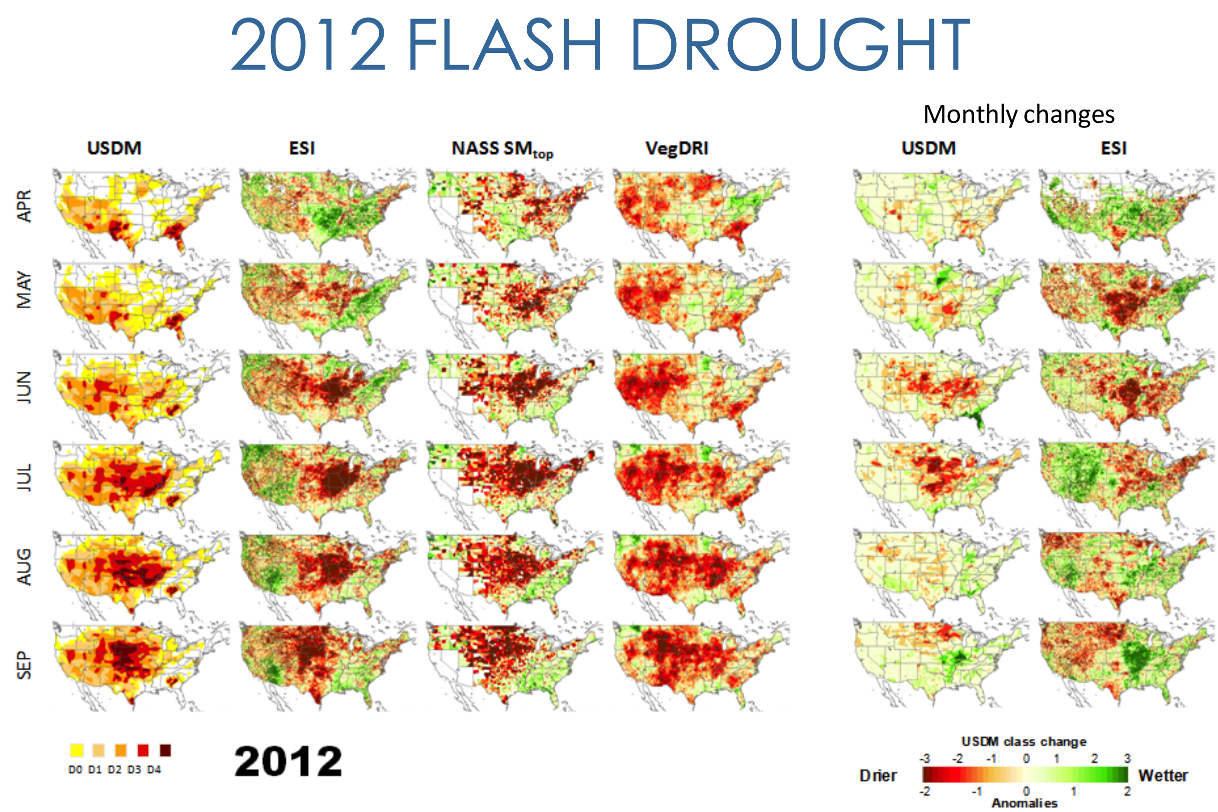

Figure 1: Monthly maps of drought depictions during the 2012 flash drought event from the US Drought Monitor (USDM), ESI, anomalies in NASS reports of county scale topsoil moisture conditions, and the Vegetation Drought Response Index (VegDRI) which is driven primarily by anomalies in the Normalized Difference Vegetation Index (NDVI). ESI captures the developing stress signal early, starting in May. This is particularly evident in the change anomalies shown in the right column, highlighting regions of rapid ESI change.

Studies (Anderson et al. 2013; Otkin et al. 2013; 2014; 2016) have demonstrated that the thermal infrared land-surface temperature (LST) inputs to the ESI algorithm provide early warning of developing crop stress during rapid onset (flash) drought events. The emergence of stress in ESI during the 2012 flash drought in the central United States preceded signals in vegetation index-based indicators and is in good accord with ground-based characterizations of topsoil moisture condition distributed by the National Agricultural Statistics Service (NASS), collected at the county level by trained observers (Fig. 1).

ESI products are operationally generated daily over North America at 8-km resolution (http://www.ospo.noaa.gov/Products/land/getd/) by NOAA's Office of Satellite and Product Operations (OSPO) as part of the Geostationary Operational Environmental Satellites (GOES) ET and Drought (GET-D) system. These continental-scale drought products are used by NOAA in monthly State of the Climate reports (https://www.ncdc.noaa.gov/sotc/) reports, and are distributed publically through the National Integrated Drought Information System (NIDIS: drought.gov) for use in U.S. and North American Drought Monitors and other monitoring applications. A 4-km version of the same modeling system for the contiguous U.S. (CONUS) is maintained at NASA Marshall Space Flight Center. Expansion to global coverage at 5-km resolution is in progress, using day-night temperature differences from the Moderate resolution Imaging Spectroradiometer (MODIS) (Hain and Anderson 2017).

The ECOSTRESS L4(ALEXI_ESI) actual-to-reference ET ratio (f_{RET}) product is designed to be compatible with the operational NOAA GET-D ESI product. Actual ET inputs are produced by spatially disaggregating the GET-D 4-km ET datasets using ECOSTRESS L2 LST data, and the same FAO-56 PM reference ET formulation is used in both systems.

4 Retrieval of actual-to-reference ET ratio (f_{RET})

4.1 Actual ET

Procedures for generating ECOSTRESS L3(ET_ALEXI) actual ET products at 30-m resolution on ECOSTRESS overpass dates using the ALEXI disaggregation (DisALEXI) algorithm are described in the L3(ET_ALEXI) ATBD.

4.2 Reference ET

Reference ET used in the ALEXI L4 ECOSTRESS f_{RET} products will be consistent with the data layers used in the construction of the operational NOAA-based ESI datasets to facilitate direct comparisons and relative downscaling.

The NOAA ESI uses the FAO-56 Penman-Monteith (PM) formulation for reference ET (*ETo*) over a grass reference surface, as described by Allen et al., (1998). The PM combination equation for ET, including both energy balance and advective effects, is formulated as

$$\lambda ETo = \frac{\Delta(RN-G)+\rho_a c_p \frac{(e_s-e_a)}{r_a}}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)} \quad \text{(Eq. 1)}$$

where *RN* is the net radiation, *G* is the soil heat flux, (e_s - e_a) is the vapor pressure deficit in the air layer just above the surface, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the bulk surface and aerodynamic resistances.

Assuming a hypothetical well-watered reference surface with uniform characteristics, many of the inputs to Eq. 1 can be simplified, removing dependencies on specific surface conditions. Allen et al. (1998) give the following simplified equation for hourly *ETo* (mm hr-1) for a grass reference surface "with an assumed crop height of 0.12m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23":

$$ETo = \frac{0.408\Delta(RN-G)+\gamma\frac{37}{T_a+273}u(e^o(T_a)-e_a)}{\Delta+\gamma(1+0.24u)} \quad \text{(Eq. 2)}$$

Here, *u* is the average hourly wind speed (m s-1), $e^o(T_a)$ is the saturation vapor pressure at air temperature T_a (C), e_a is the average hourly vapor pressure (kPa), and the wind coefficient 0.24 is consistent with daytime recommended values for a short reference crop (Allen et al. 2005). Net radiation (*RN*) and soil heat (G) (both in MJ m-2 h-1) for the reference surface are computed from measurements of solar radiation (R_g) as described in the FAO-56 report (Chapter 2), with *G* assumed to be approximately 0.1*RN* at the hourly timestep.

4.3 Gridded f_{RET} datasets

For each ECOSTRESS overpass day, *ETo* is computed at an hourly timestep using gridded (0.25^o resolution) meteorological inputs from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010). Data fields used include solar radiation (R_g, at 1-hr native temporal resolution) and surface wind speed (u), vapor pressure (e_a), and air temperature (T_a) (all at 3-hr timesteps). These CFSR fields are resampled onto the L3(ALEXI_ET) 30-m grids using nearest neighbor pixel assignment, then spatially smoothed with a Gaussian function to reduce edge effects at the 0.25^o scale. The 3-hr u, e_a and T_a fields are linearly interpolated in time to hourly timesteps, while R_g is provided at hourly by CFSR. These hourly data are used to compute *ETo* at hourly timesteps with Eq. 2, then the hourly reference are time-integrated to a daily value (*ETod*) for the overpass day.

For clear pixels within the ET grid, we compute

$$f_{RET} = \frac{ETd}{ETod} \qquad \text{(Eq. 3)}$$

where *ETd* is the actual daily ET retrieved for the ECOSTRESS overpass date as part of the ECOSTRESS L3(ALEXI_ET) processing system. Gridded f_{RET} datasets are generated over the agricultural landscape targets identified in the L3(ALEXI_ET) ATBD.

5 Data Processing

The f_{RET} processing stream is controlled by a Perl script calling subcomponents coded in C and ENVI/IDL and runs on a Linux RedHat operating system. This stream is schematized in Fig. 2, and is integrated with the USDA ET L-3 processing stream (see ATBD).

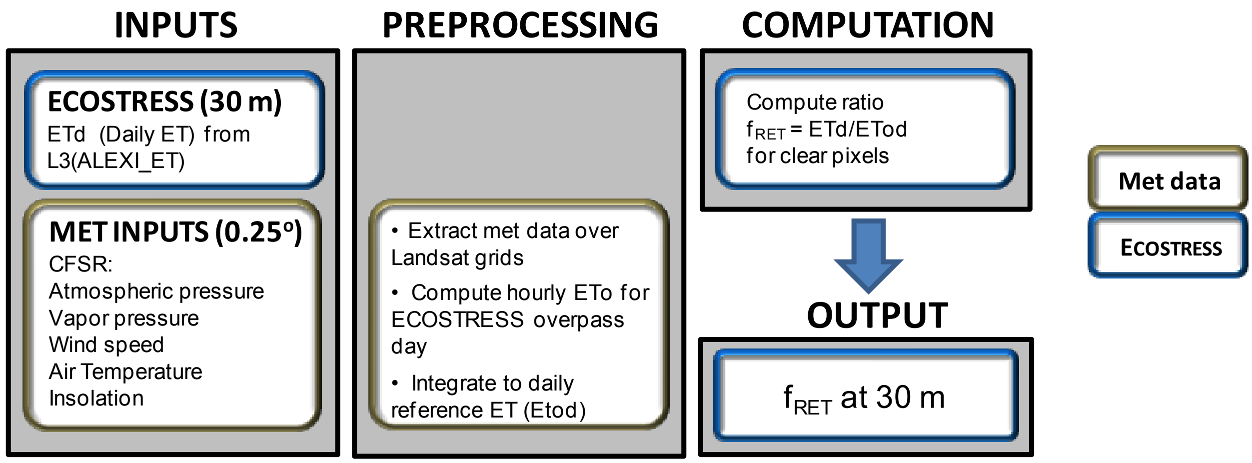

Figure 2: Conceptual diagram describing computation of L-4(ALEXI_ESI) reference ET ratio.

The input ingestion component of the system is executed as part of the L3(ALEXI_ET) processing system. This component ingests CSFR datasets from NOAA-NESDIS via FTP. and computes hourly reference ET for use in upscaling actual ET retrieved at the ECOSTRESS overpass time to a daily (24-hr) total (*ETod*).

As a final step in support of the L4 ESI production, the ALEXI system computes hourly and daily reference ET on ECOSTRESS overpass dates. Then, using *ETod* and *ETd* from L3(ALEXI_ET), the ratio of actual-to-reference ET (f_{RET}) is computed for clear pixels in the ECOSTRESS LST product (Eq. 3).

The f_{RET} data generated using Eq. 3 will be archived at HRSL over the defined target areas, and then automatically transferred to the ECOSTRESS SDS for storage and further organization for analysis and dissemination.

6 Mask/Flag Derivation

UPDATE FOR DISALEXI:

For T_s and e_a, the ECOSTRESS L2 flags are used to provide quality information for the L3 ET

Table 1. ECOSTRESS L3 ET MODIS ancillary data flags and responses to poor quality.

Input product	Quality Flag	Response to poor quality
MODIS Aerosol	Quality assurance	Remove
MODIS Albedo	Quality assurance	Replace outliers with spatiotemporal average of adjacent values
MODIS Cloud	Quality assurance	Remove
MODIS Atmospheric Profile	Quality assurance	Remove
MODIS fPAR, LAI	N/A	Replace outliers with spatiotemporal average of adjacent values
MODIS Land Cover	N/A	N/A
MODIS NDVI	N/A	Replace outliers with spatiotemporal average of adjacent values

product. Additional quality flags are incorporated from those provided by the ancillary MODIS products (Table 2):

7 Metadata

- unit of measurement: unitless (mm d-1 per mm d-1)
- range of measurement: approximately 0 to 1
- projection: UTM
- spatial resolution: 30 m x 30 m
- temporal resolution: dynamically varying with precessing ISS overpass; represents daily value on day of overpass, local time
- spatial extent: target agricultural sites
- 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: X
- no data value: -9999
- bad data values: -9999
- flags: quality level 1-4 (best to worst)

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