Drought in Africa: Understanding and Exploiting the Demand Perspective Using a New Evaporative Demand Reanalysis

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Abstract

In operational analyses of the surface moisture imbalance that defines drought, the supply aspect has generally been well characterized by precipitation; however, the same count be said of the demand side—a function of evaporative demand (E0) and surface moisture availability. In drought monitoring, E0 is often poorly parameterized by a climatological mean, by non-physically based estimates, or is neglected entirely. One problem has been a paucity of driver data—on temperature, humidity, solar radiation, and wind speed—required to fully characterize E0. This deficient E0 modeling is particularly troublesome over data-sparse regions that are also home to drought-vulnerable populations, such as across much of Africa. There is thus urgent need for global E0 estimates for physically accurate drought analyses and food security assessments; further we need an improved understanding of how E0 and drought interact and to exploit these interactions in drought monitoring. In this presentation we explore ways to meet these needs. From MERRA-2—an accurate, fine-resolution land-surface/atmosphere reanalysis—we have developed a >38-year, daily, global Penman-Monteith reference ET dataset as a fully physical metric of E0. This dataset is valuable for examining hydroclimatic changes and extremes. A novel drought index based on this dataset—the Evaporative Demand Drought Index (EDDI)—represents drought's demand perspective, and permits early warning and ongoing monitoring of agricultural flash drought and hydrologic drought. We highlight the findings of our examination of E0-drought interactions and using EDDI in Africa. Using reference ET as an E0 metric has permitted explicit attribution of the variability of E0 across Africa, and of E0 anomalies associated with canonical droughts in the Sahel region. This analysis determines where, when, and to what relative degree each of the individual drivers of E0 affects the demand side of drought. Using independent estimates of drought across space and time—CHIRPS precipitation and the Normalized Difference Vegetation Index for 1982-2015—we examine the differences between drought and non-drought periods, and between precipitation-forced droughts and droughts forced by a combination of precipitation and E0.

Drought in Africa: Understanding and exploiting the demand perspective using a new evaporative demand reanalysis.

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Abstract:

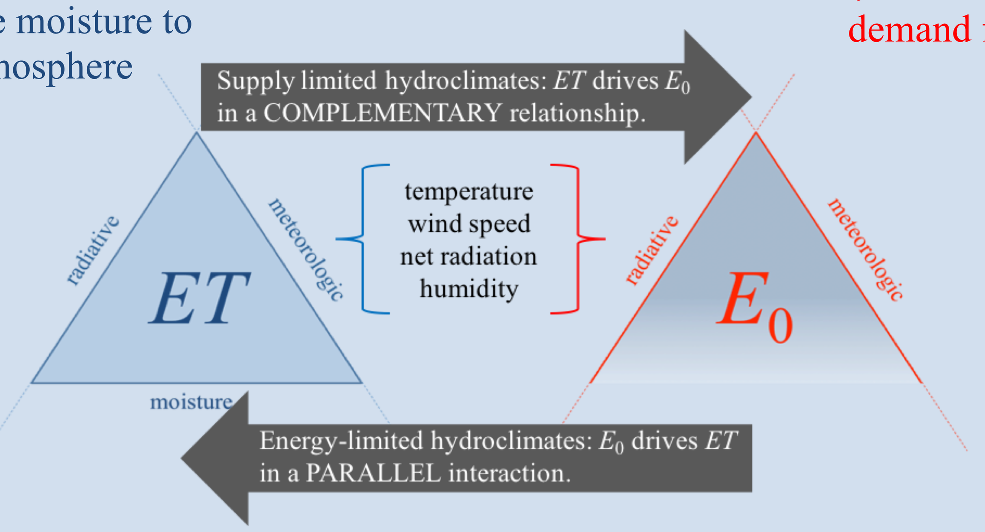
In operational analyses of the surface moisture imbalance that defines drought, the supply aspect (i.e., precipitation) has generally long been well characterized; however, the same cannot be said for the demand side—evapotranspiration (*ET*), driven by evaporative demand (E_0) and surface moisture availability. E_0 is often poorly parameterized or neglected entirely. One problem has been a paucity of driver data—temperature, humidity, solar radiation, and wind speed data—required for a full characterization. This deficient E_0 modeling is particularly troublesome over data-sparse regions that are also home to drought-vulnerable populations, such as across much of Africa.

There is thus urgent need for global E_0 estimates for physically accurate drought analyses and food security assessments; further we need an improved understanding of how E_0 and drought interact and to exploit these interactions in drought monitoring. This project explores ways to meet these needs.

From an accurate, fine-resolution land-surface/atmosphere reanalysis (i.e., the Modern-Era Retrospective analysis for Research and Applications, Version 2, MERRA-2), we have developed a >38-year, daily, global Penman-Monteith reference *ET* dataset as a fully physical metric of E_0. This dataset is valuable for examining hydroclimatic changes and extremes. A novel drought index based on this dataset—the Evaporative Demand Drought Index (EDDI)—represents drought's demand perspective, permitting early warning and ongoing monitoring of agricultural and hydrological drought.

Background:

Actual evapotranspiration (*ET*) / evaporative demand (E_0) relations

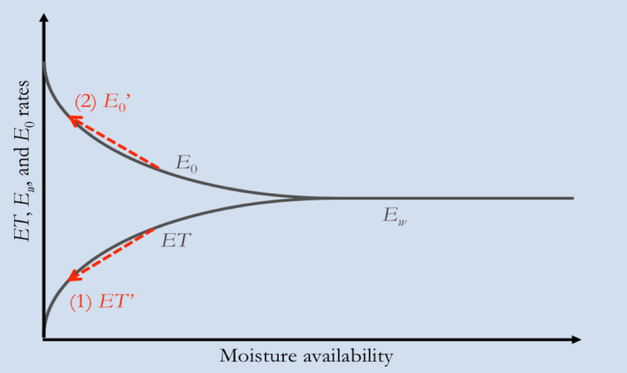


- E_0 is *ET* unconstrained by moisture availability.
- Traditionally, $ET = f(E_0, \text{moisture})$
- E_0 easier to estimate than *ET*

Sustained drought - water limited

Water limitations drive *ET* and E_0 in complementary directions:

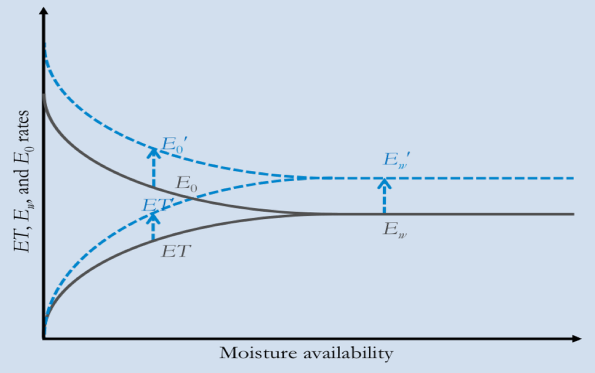
- *ET* decreases due to moisture limitations,
- E_0 increases due to energy balance favoring sensible heat over λET.



Flash drought - energy driven

Energy limitations drive *ET* and E_0 in parallel directions:

- *ET* and E_0 increase due to increases in advection or energy availability,
- moisture may not be limiting.



E_0 increases in both sustained and flash droughts

Developing the E_0 reanalysis:

For E_0 we use reference evapotranspiration *ET* (ET_0), from the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 1995)

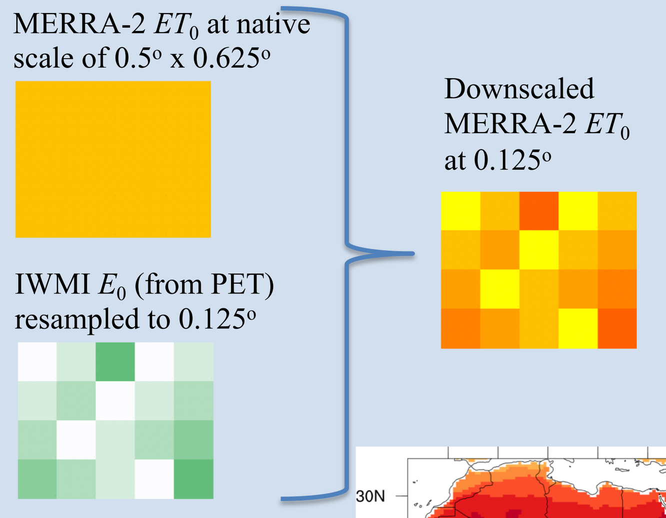
$$ET_0 = \underbrace{\frac{0.408\Delta}{\Delta+\gamma(1+C_d U_2)}(R_n + L_n - G)\frac{86400}{10^6}}_{\text{Radiative forcing}} + \underbrace{\frac{\gamma \frac{C_n}{T}}{\Delta+\gamma(1+C_d U_2)} U_2 \frac{(e_{sat}-e_a)}{10^3}}_{\text{Advective forcing}}$$

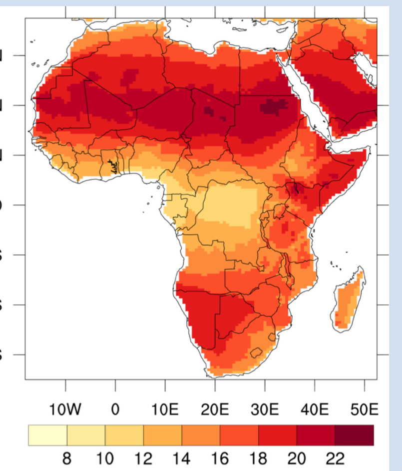
Drivers are from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) :

- *T*, 2-m temperature
- *q*, 2-m specific humidity
- R_d, downward SW radiation
- U_2, 2-m wind speed
- *Pa*, surface pressure

- daily,
- Jan 1, 1980 – present,
- 0.5° lat x 0.625° long,
- 0.125° lat, long,
- global coverage

To develop a finer-resolution product, we downscale the native-resolution E_0, with sub-grid variability to match the spatial variability of fine-scale surfaces of mean monthly potential *ET* from the International Water Management Institute (IWMI).





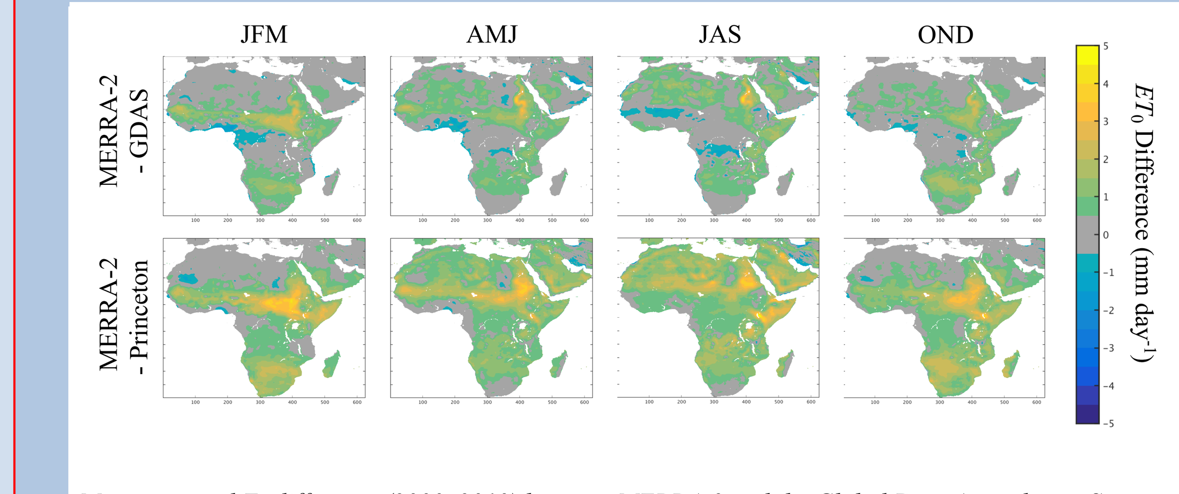
Mean annual ET_0 for a short reference crop (i.e., 0.12-m grass), 1980-2010.

ET_0 is higher where it is warmer, drier, sunnier, and/or windier.

Exploiting evaporative demand in drought monitoring in Africa:

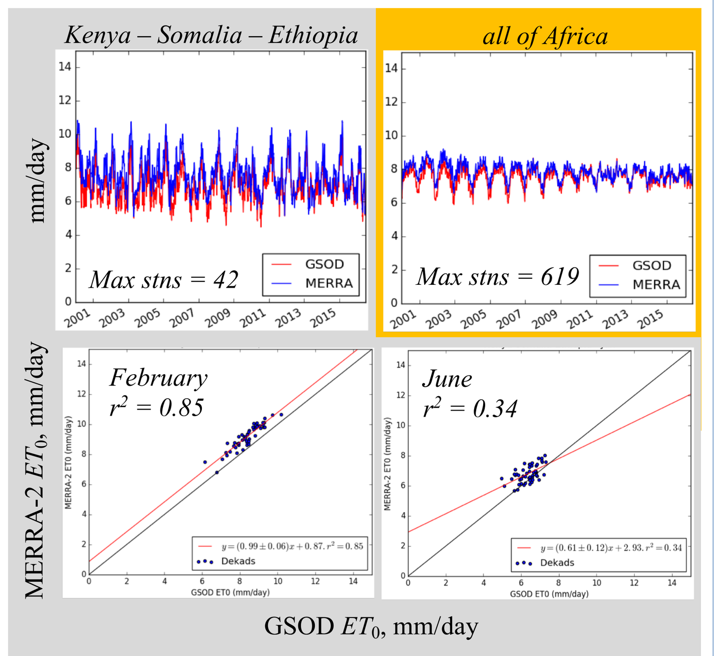
Verification of the E_0 reanalysis:

vs. other reanalyses / gridded datasets:



Mean seasonal E_0 difference (2000–2010) between MERRA-2 and the Global Data Assimilation System (GDAS) and the Princeton Global Forcing dataset version 3.

vs. station-based observations:



MERRA-2 ET_0 verified against ET_0 derived from T, q, and U_2 from Global Summary of the Day (GSOD) station observations combined with R_d from Global Land Data Assimilation System GLDAS) v2.1.

Decomposing the variability of the demand side of drought:

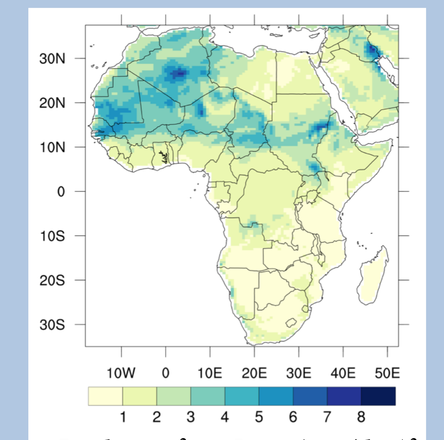
The demand side of drought is driven by variations in evaporative demand (E_0). Here we decompose, across space and time, how much each of the drivers is responsible for the variability of E_0.

$ET_0 = f\{T, q, U_2, R_d\}$, so the contribution to the variability in E_0 (i.e., to $\sigma_{ET_0}{}^2$) by each variable *X* is:

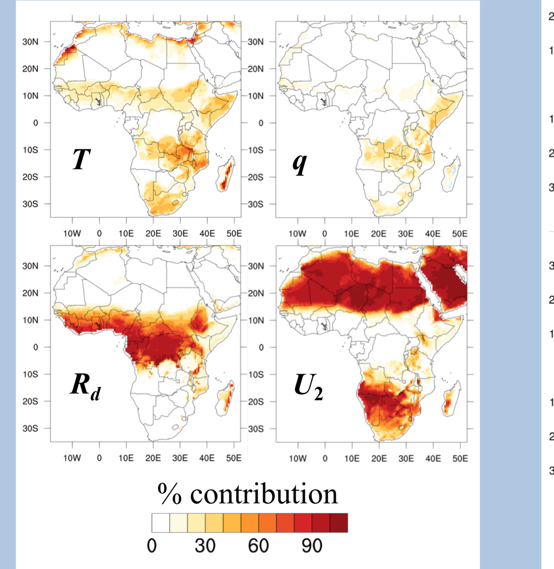
$$F_X = \left(\frac{\partial ET_0}{\partial X}\right)^2 \sigma_X^2 + \sum_{i=1}^{3} \frac{\partial ET_0}{\partial X}\frac{\partial ET_0}{\partial Y_i}\sigma_{X,Y_i}$$

where:

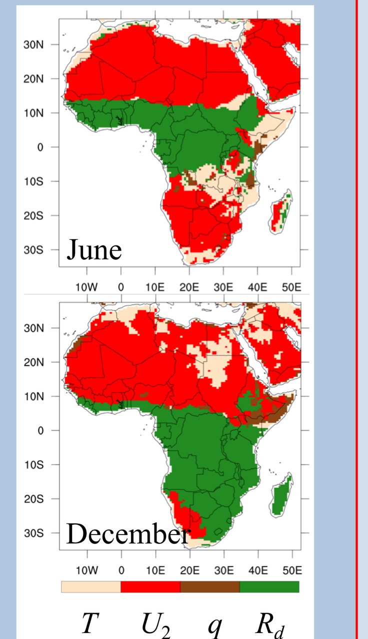
- $\{X, Y\} = \{T, q, U_2, R_d\}$,
- sensitivities ($\partial ET_0/\partial X$, $\partial ET_0/\partial Y_i$) are derived analytically (*Hobbins*, 2016), and
- variances ($\sigma_X{}^2$) and covariances (σ_{X,Y_i}) are observed in the MERRA-2 reanalyses.



Daily $\sigma_{ET_0}{}^2$ in June (mm/day)^2



Each driver's contribution (F_X) to daily E_0 variability (June example).



Dominant driver of daily E_0 variability in June (top) and December (bottom).

Attributing the demand side of drought:

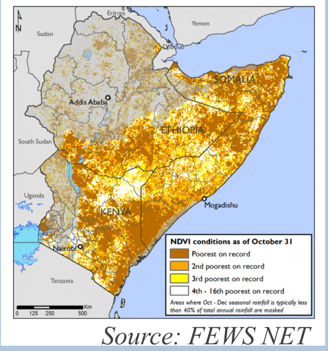
Here, the E_0 signal is decomposed for a severe drought over the Horn of Africa in 2016.

Changes in ET_0 (ΔET_0) under drought arise from all of its drivers:

$ET_0 = f(T, R_d, q, U_2)$, so

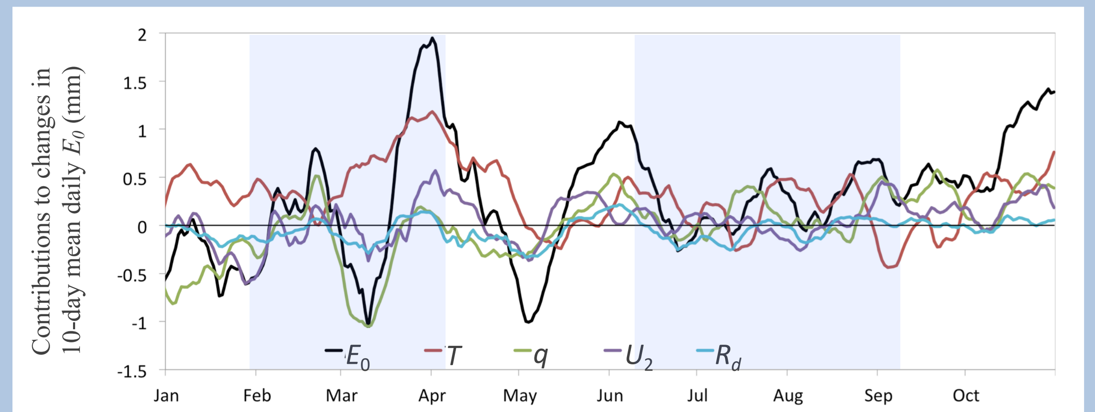
$$\Delta ET_0 = \frac{\partial ET_0}{\partial T}\Delta T + \frac{\partial ET_0}{\partial R_d}\Delta R_d + \frac{\partial ET_0}{\partial q}\Delta q + \frac{\partial ET_0}{\partial U_2}\Delta U_2$$

where sensitivities (e.g., $\partial ET_0/\partial T$) are derived analytically (*Hobbins*, 2016), and anomalies (e.g., ΔT) are observed in the MERRA-2 reanalyses.



Source: FEWS NET

From below, we see that changing E_0 is dynamically forced by elevated *T*. Peaks in E_0 anomaly coincide with elevated U_2 and/or *q* minima, troughs with *q* maxima. R_d plays little role in the drought development.

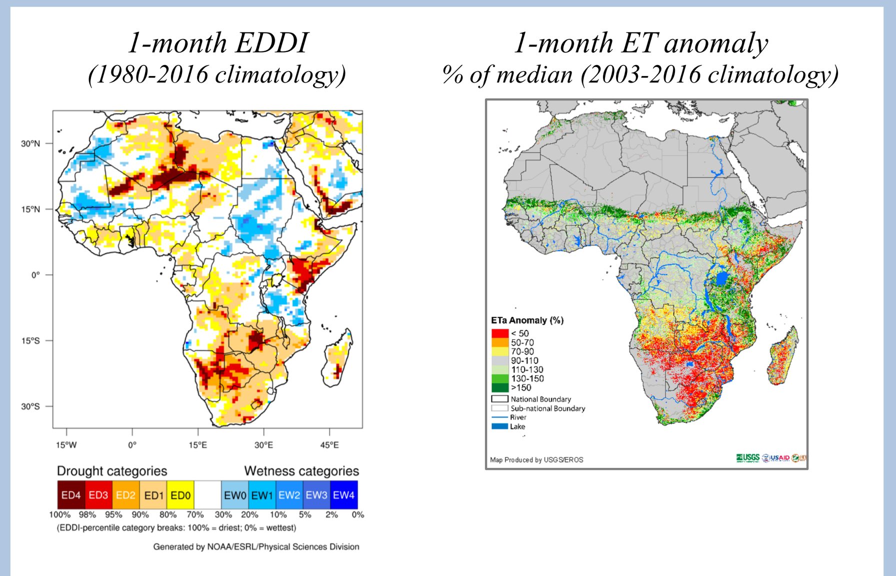


Evaporative Demand Drought Index (EDDI):

EDDI tracks how atmospheric evaporative demand changes in response to drying (and wetting) of the land surface, due to the interactions of surface moisture conditions and the overlying air (see Background), and plots the percentiles of accumulated ET_0 relative relative to its climatology (Hobbins et al., 2016).

EDDI is calculated at various timescales (from dekadal to 12-monthly), so as to reflect the different physical dynamics that drive drying of the surface.

EDDI has been shown to perform well as a leading indicator of drought across the continental US (Hobbins et al., 2016).



EDDI (left) and 1-month ET anomaly (right) for October 31, 2016.

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Conclusions:

Main findings:

- E_0 represents the demand side of drought, which has heretofore been characterized poorly (e.g., by temperature-based parameterizations).
- Physically based E_0 relates directly to *ET* and to drought dynamics, increasing in both flash and sustained drought.
- Exploiting E_0 (in EDDI) can yield early warning of agricultural and hydrologic drought.
- Using ASCE ET_0 to drive *EDDI* permits decomposition of evaporative drivers of drought.
- *EDDI* permits near real-time drought monitoring and early warning.
- Drivers of E_0 variability (i.e., of drought) vary with season and region.

Various applications of the ET_0 reanalysis:

- As a stand-alone, leading drought indicator in FEWS NET's agro-climatological input suite – Evaporative Demand Drought Index (EDDI).
- To drive E_0 in crop monitoring tools (e.g., the Water Requirement Satisfaction Index, WRSI), and in drought monitoring tools (e.g., the Palmer Drought Severity Index, PDSI, and the Standardized Precipitation Evapotranspiration Index, SPEI).
- As an input to R/S fusion algorithms to estimate *ET*.
- As a reference against which to assess skill of ET_0 forecasts.

ET_0 and EDDI data access:

- ET_0 reanalysis:
  - long crop (0.5-m alfalfa) and short crop (0.12-m grass)
  - coarse scale:
    - 0. 5° lat x 0. 625° long
    - 1.8 MB / day
    - ftp .cdc.noaa.gov/Projects/RefET/global/Gen-0/coarse_resolution/data_v2/
  - fine scale:
    - 0.125° lat, long
    - 31.6 MB / day
    - ftp .cdc.noaa.gov/Projects/RefET/global/Gen-0/fine_resolution/data_v2/
- EDDI data:
  - 15 timescales / month
  - 31.6 MB / timescale
  - ftp://ftp.cdc.noaa.gov/Projects/EDDI/global_archive/
- Data latency:
  - > 1 month for QA/QC'ed drivers
  - ~12 days for pre-QA/QC'ed drivers