Gridded weather and Reference *ET* data for US and Global *ET* mapping

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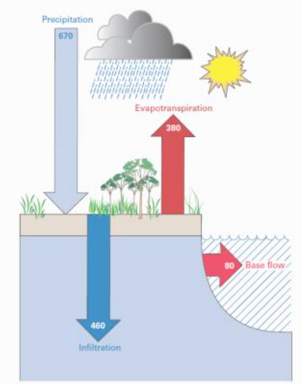
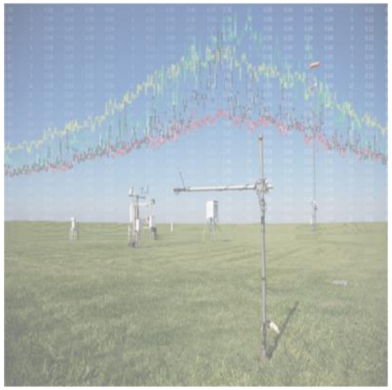
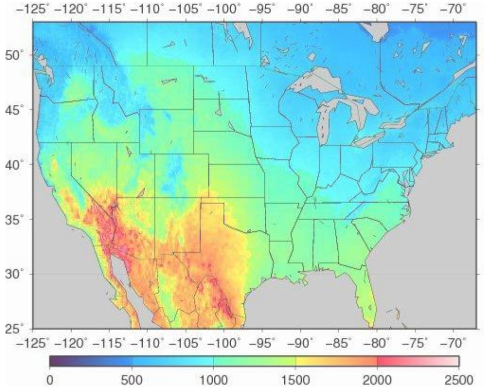
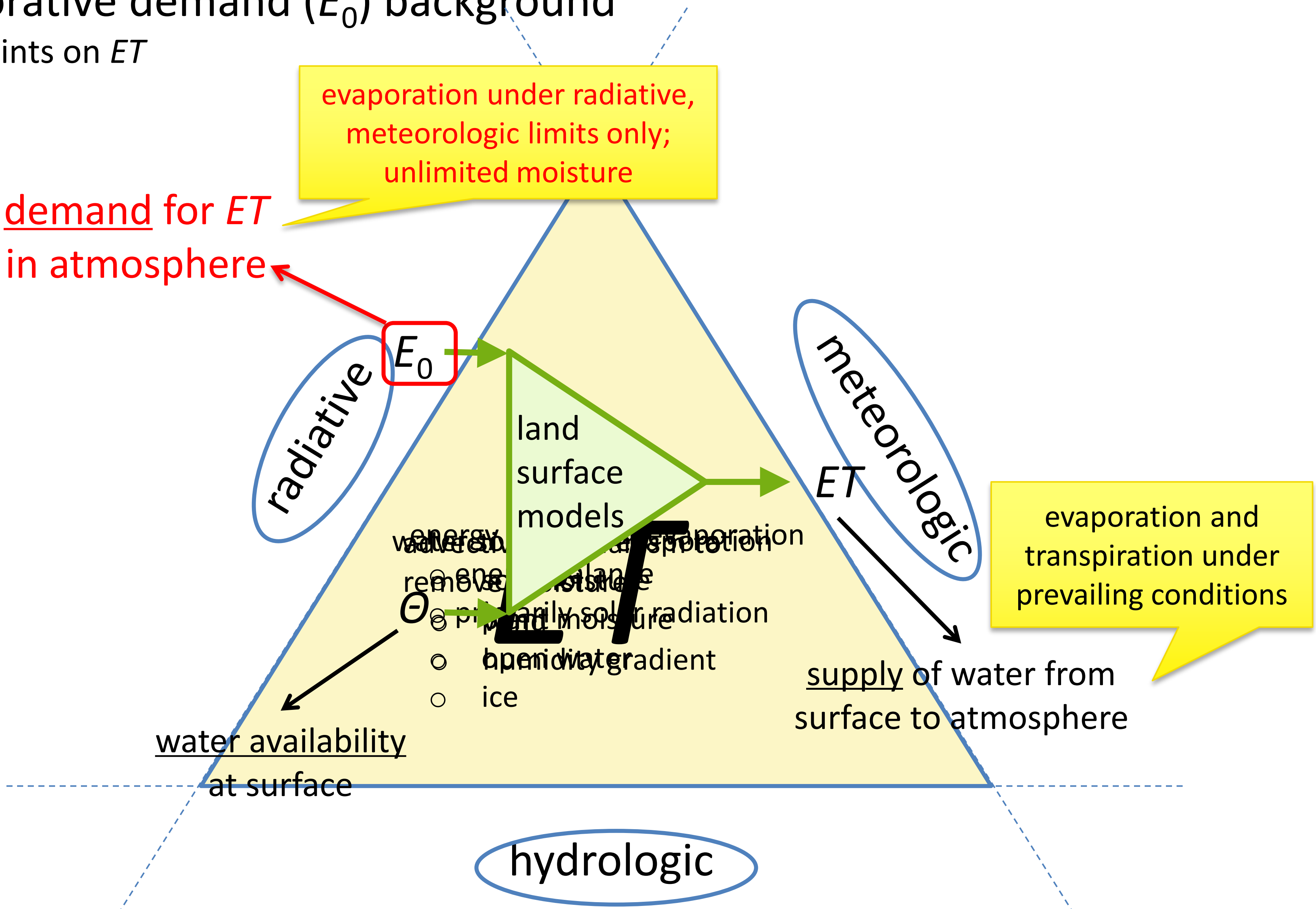






Evaporative demand (E_0) background

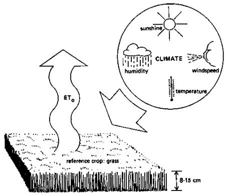
Constraints on *ET*

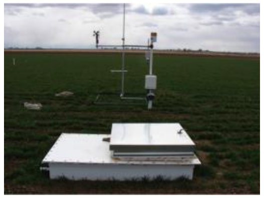


E_0 background
Variety of metrics for E_0

- potential evaporation (*PET*)

- reference crop *ET*, ET_0





- pan evaporation

ESTIMATED: from WX obs or remotely sensed data

complete physics:
- SW radiation
- LW radiation
- air temperature
- humidity
- wind speed
- atmospheric pressure

Now available as REANALYSES:
- temporally and spatially complete
- assimilation of obs in modeling framework
- spatially distributed obs that are bias-corrected against station-based and R/S data

OBSERVED: physically integrates all above drivers

Estimating reference crop ET (ET_0)

Penman-Monteith ET_0 model

λ = latent heat of vaporization
R_n = net radiation (SW + LW) at crop surface
G = ground heat flux
U_2 = 2-m wind speed
e_{sat} / e_a = saturated / actual vapor pressure
$\Delta = de_{sat}/dT$ at air temperature T
γ = psychrometric constant
type and time-step

ASCE Standardized Reference ET equation
(identical to FAO-56 on a daily basis)

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

Radiative forcing Advective forcing

CONUS work is template for global product

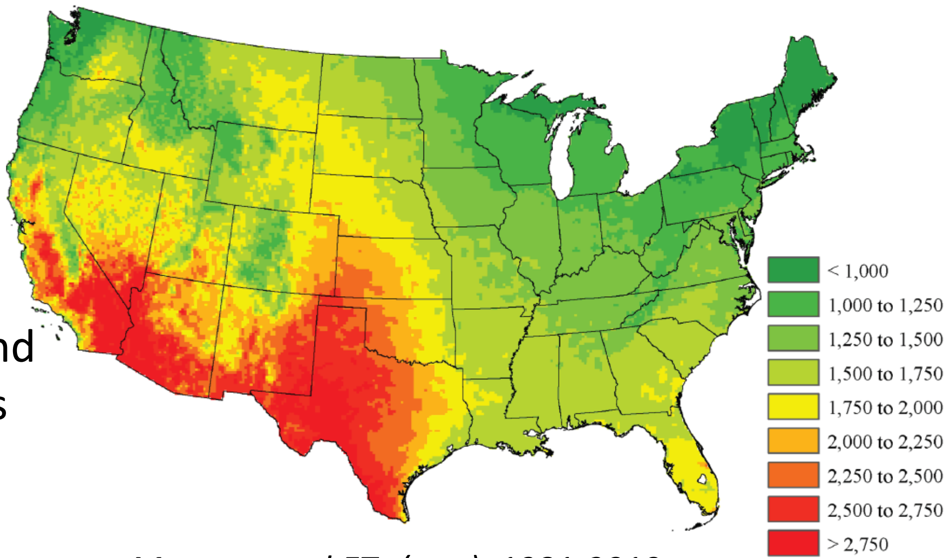
"Reference" crop is specified:

- 0.12-m grass or 0.50-m alfalfa
- well-watered , actively growing,
- completely shading the ground,
- albedo of 0.23.

Drivers from NLDAS:

- temperature at surface (2 m)
- specific humidity at surface
- downward SW at surface
- 10-m wind speed at 10 m
- daily, Jan 1, 1979 – present
- ~12-km, CONUS-wide

remotely sensed and reanalysis data



Mean annual ET_0 (mm), 1981-2010.

ET_0 reanalyses
NOAA's goals and motivations

CONUS = contiguous US
USGS = US Geological Survey
NWS = NOAA National Weather Service
NIDIS = National Integrated Drought Information System

Consistently modeled CONUS-wide ET_0 dataset:

- up-to-date, long-term, daily, dynamic, and physically based:
  - **as consistent input to *ET* estimation in USGS National Water Census to reduce uncertainty**,
  - to support NWS mission (e.g., ET_0 forecasting) and NIDIS mission (e.g., drought index).
- centrally hosted (National Water Center) and free to all.

Support a Common Framework of Practice for *ET* estimation:

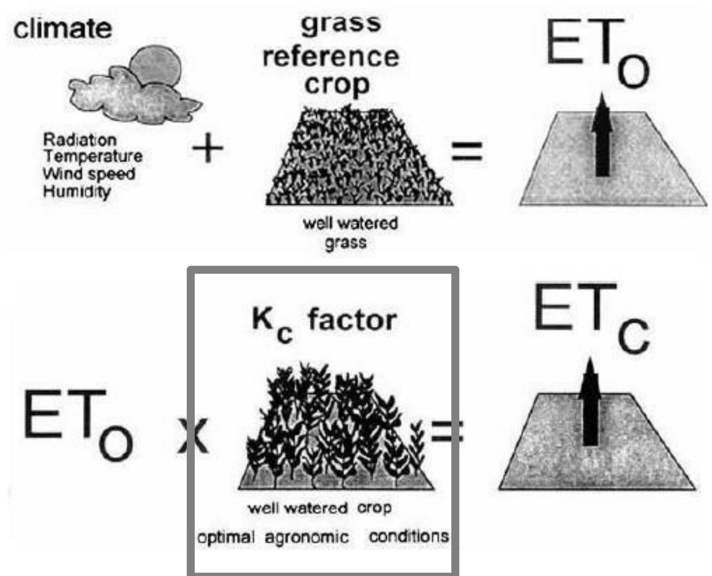
- potential duplication of effort in *ET* estimation,
  - states/agencies already invested resources in developing R/S *ET* datasets.
- guidelines and specs under development at Utah State University,
  - account for users' model preferences,
  - estimates accepted by the community.
- realize economies, meet accuracy standards.

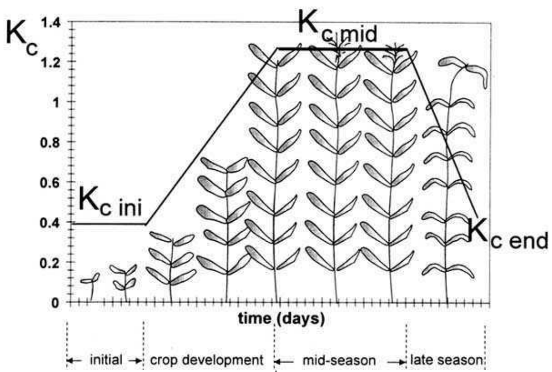
Uses of ET_0 reanalyses
Input to crop *ET* estimation

ET_0 is scaled by factors describing actual conditions to yield an actual *ET* estimate from the crop, e.g.:

k-factors for:
- crop type (*e.g., K_c*)
- crop mixture
- soil moisture
- stress
- phenology
- management
- salinity, etc.

$$ET = k_s k_c(t) ET_0 \text{ or } (k_s k_{cb} + k_e)(t) ET_0$$





Uses of ET_0 reanalyses

Input to *ET* estimation

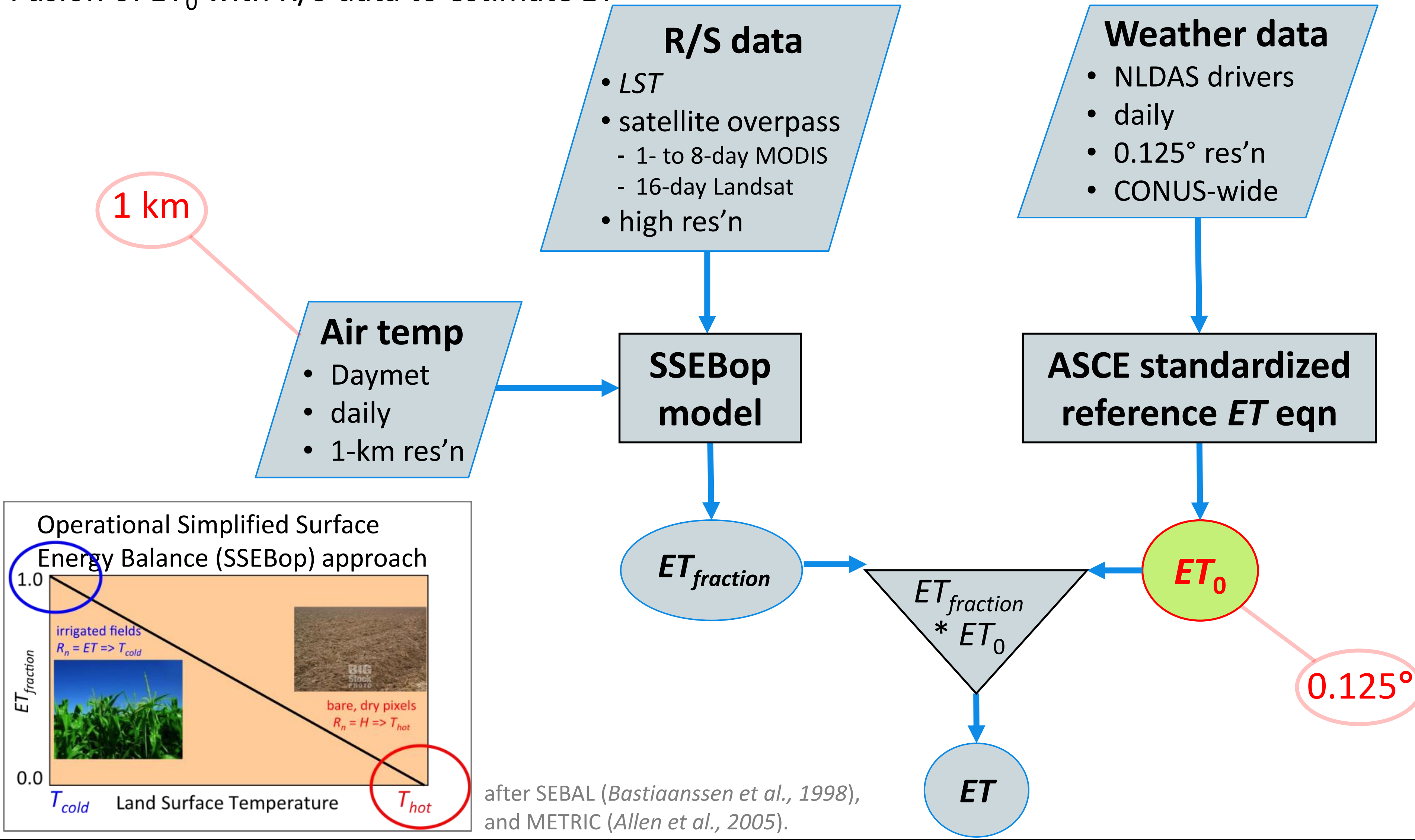
NOAA's motivation wrt National Water Census (NWC)

Provide stakeholders **technical information** and **tools** to answer two primary questions about water availability:

1. Does the Nation have enough freshwater to meet human and ecological needs?
2. Will this water be present to meet future needs?

Uses of ET_0 reanalyses

Fusion of ET_0 with R/S data to estimate ET



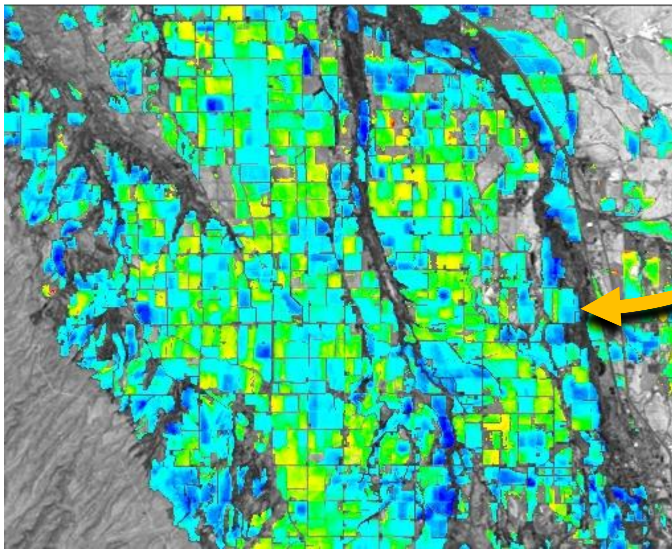
after SEBAL (*Bastiaanssen et al., 1998*), and METRIC (*Allen et al., 2005*).

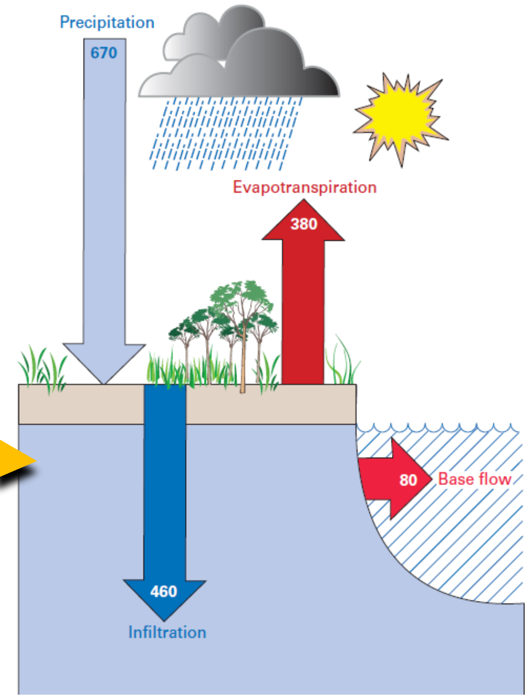
Uses of ET_0 reanalyses

Fusion of ET_0 with R/S data to estimate *ET*

Initial capability

(lumped at HUC-12 level)





Water Use Evaluations:

- LANDSAT
- Consumptive use by irrigated crops
- Crop water productivity

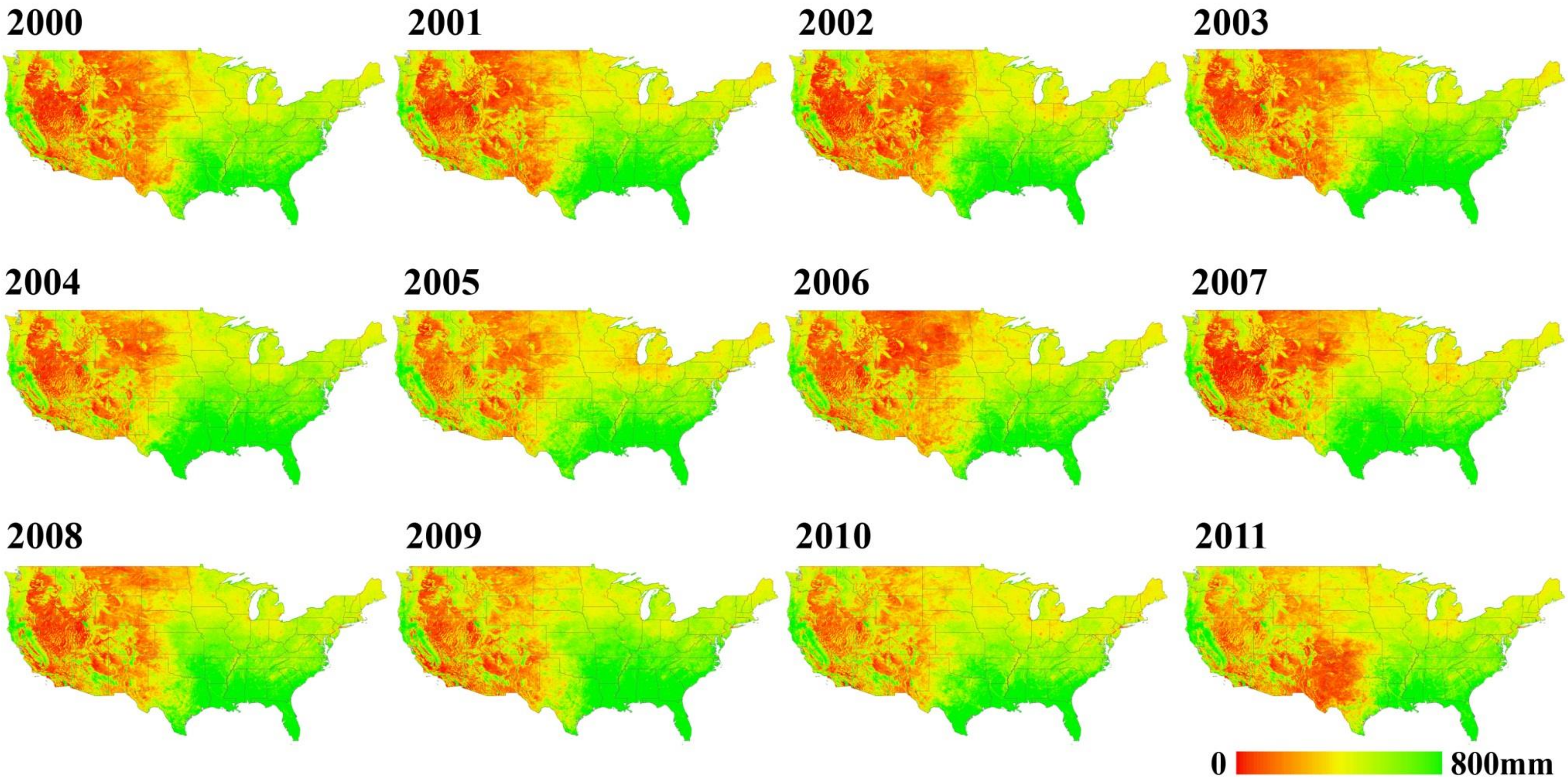
Water Availability:

- MODIS
- Landscape *ET* as a component of the overall water budget

Uses of ET_0 reanalyses

Estimating *ET* from fusion of ET_0 with R/S data

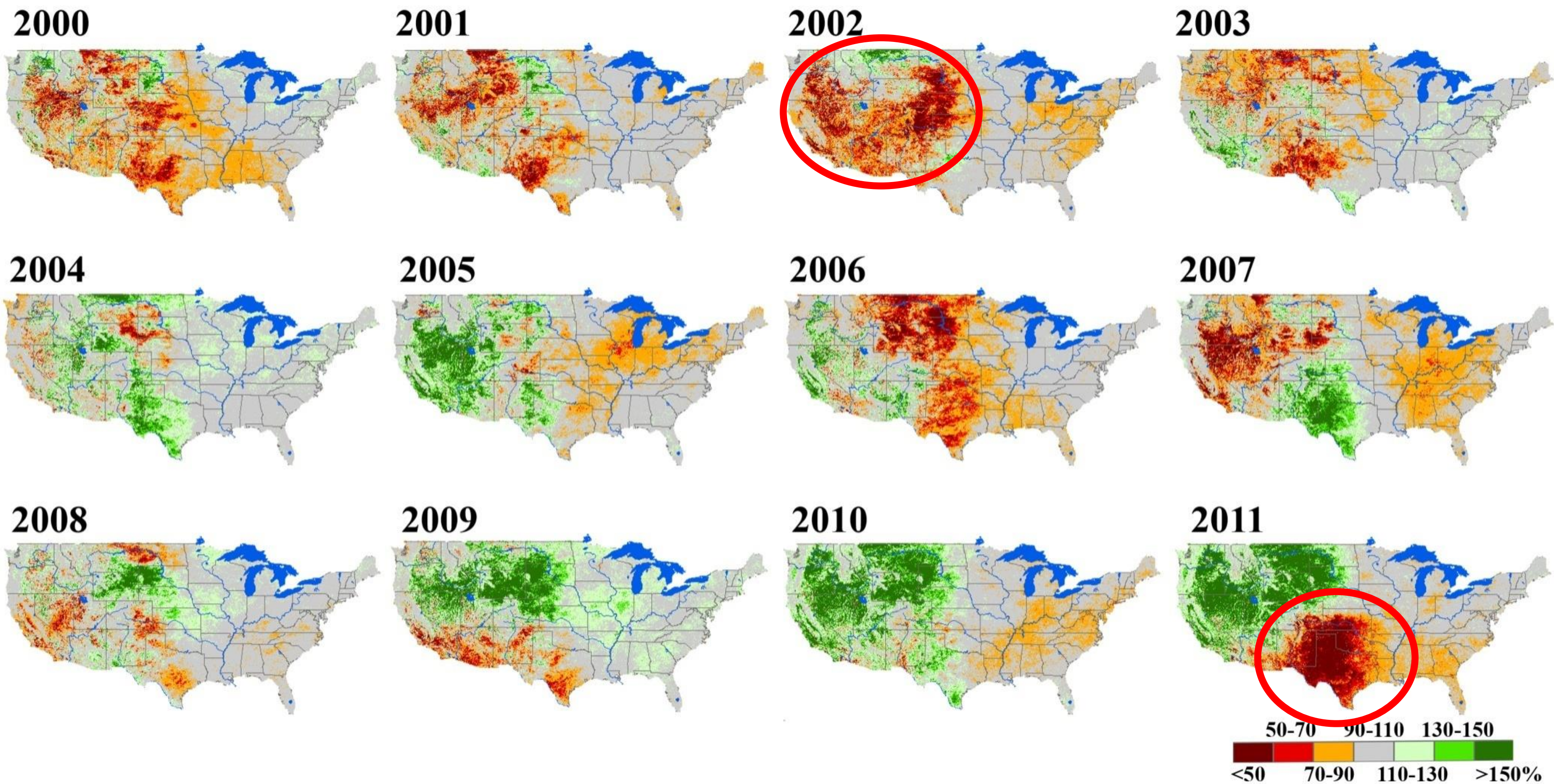
ET totals from MODIS



Uses of ET_0 reanalyses

Observing drought in *ET* from ET_0-R/S data fusion

ET anomalies from MODIS - drought signal



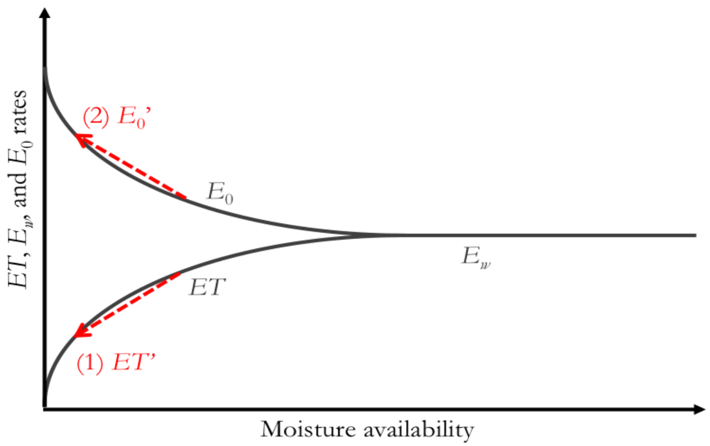
Uses of ET_0 reanalyses
Drought monitoring

ET/E_0 interactions in drought

Sustained drought - water limited

ET and E_0 vary in complementary directions:

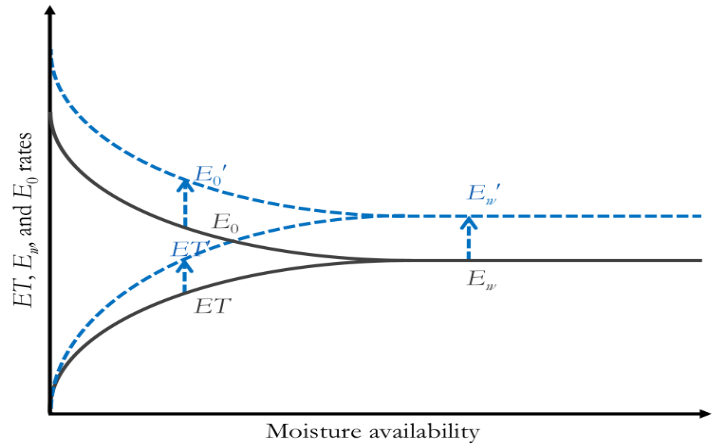
- *ET* decreases due to moisture limitations,
- E_0 increases due to energy balance favoring sensible heat over *ET*.



Flash drought - energy driven

ET and E_0 vary in a parallel direction:

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



Take home: in either drought type, E_0 increases.

Uses of ET_0 reanalyses

Drought monitoring – a new ET_0-based index

- ET_0 aggregated over a period of interest,
- Tukey plotting position formula gives probabilities:

Recommended for comparing drought indices
(*Hao and AghaKouchak*, 2014)

$$P\left(ET_{0t}\right) = \frac{i - 0.33}{n + 0.33}$$

i: rank of ET_{0t} wrt climo

n: # years in climo (35, 1980-2014)

inverse standard normal ~N(0,1)

Evaporative Demand Drought Index, *EDDI*

< 0 — *no drought* | 0 | *> 0* — *drought*

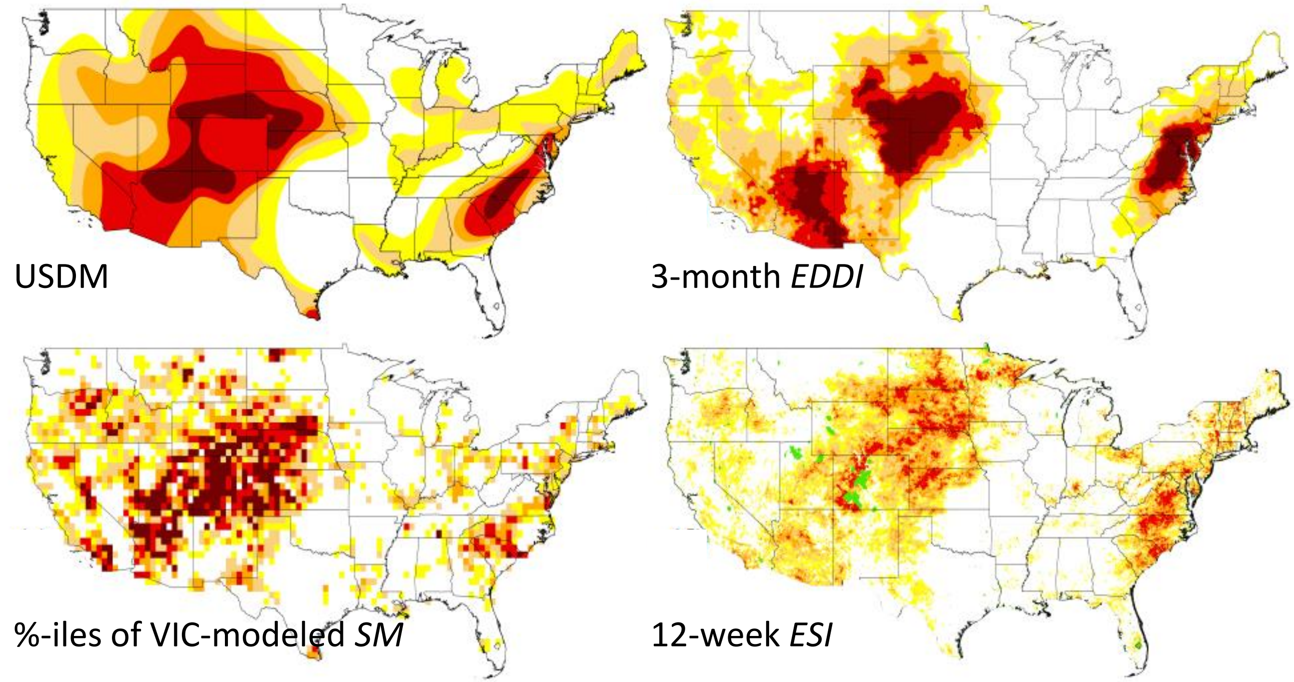
(*Hobbins et al., 2015; McEvoy et al., 2015*)

EDDI as estimator of drought

Agricultural drought

Exceptional drought in western US, 2002

Drought indices at end of July, 2002



EDDI, SM, ESI %-iles		USDM drought categories
> 70%	(yellow)	D0, Abnormally dry
> 80%	(light orange)	D1, Moderate drought
> 90%	(orange)	D2, Severe drought
> 95%	(red)	D3, Extreme drought
> 98%	(dark red)	D4, Exceptional drought

EDDI as estimator of drought

Leading indicator and flash-drought detection

Midwest flash drought, 2012

EDDI matches USDM in intensity and pattern, but leads it in drought initiation and development by up to 2 months.

EDDI %-iles		USDM drought categories
> 70%	(yellow)	D0, Abnormally dry
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> 90%	(orange)	D2, Severe drought
> 95%	(red)	D3, Extreme drought
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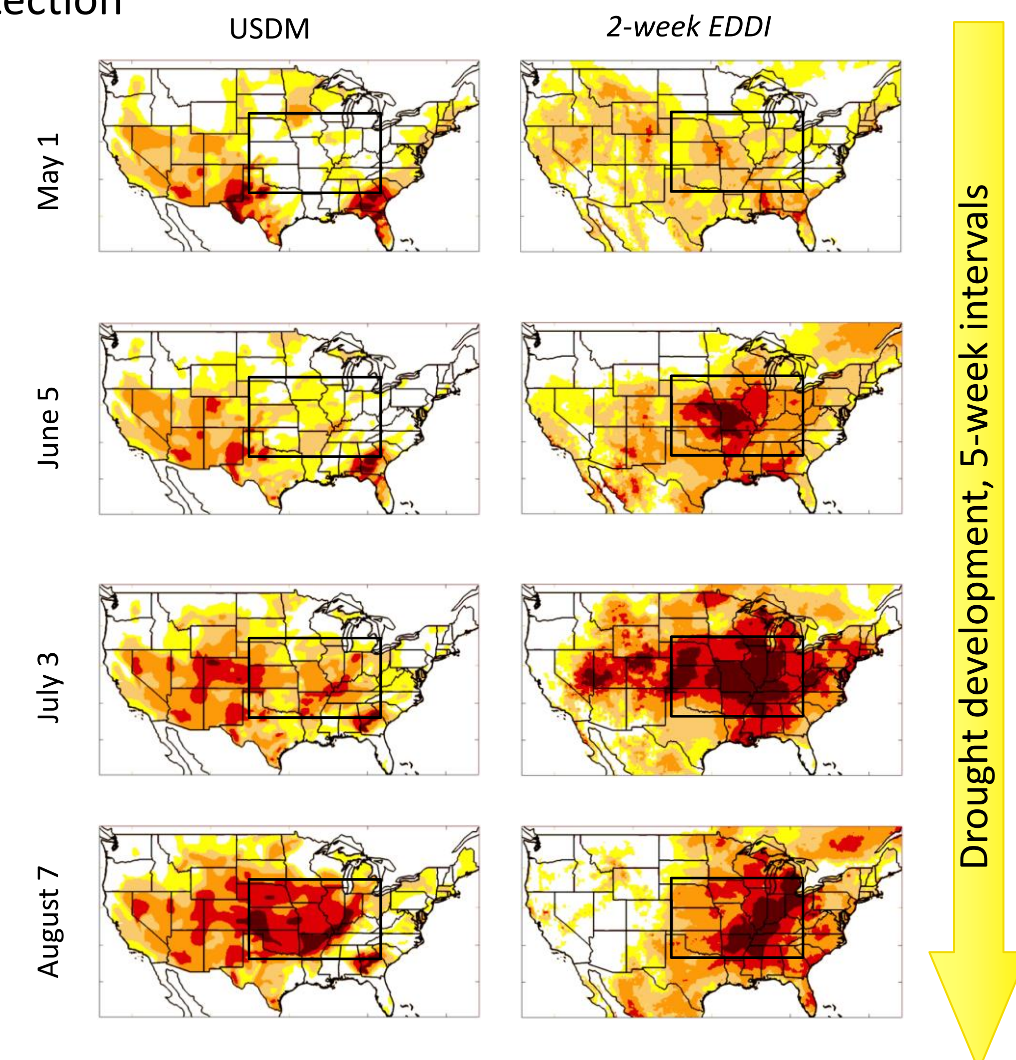


graphics - courtesy of Dan McEvoy, DRI

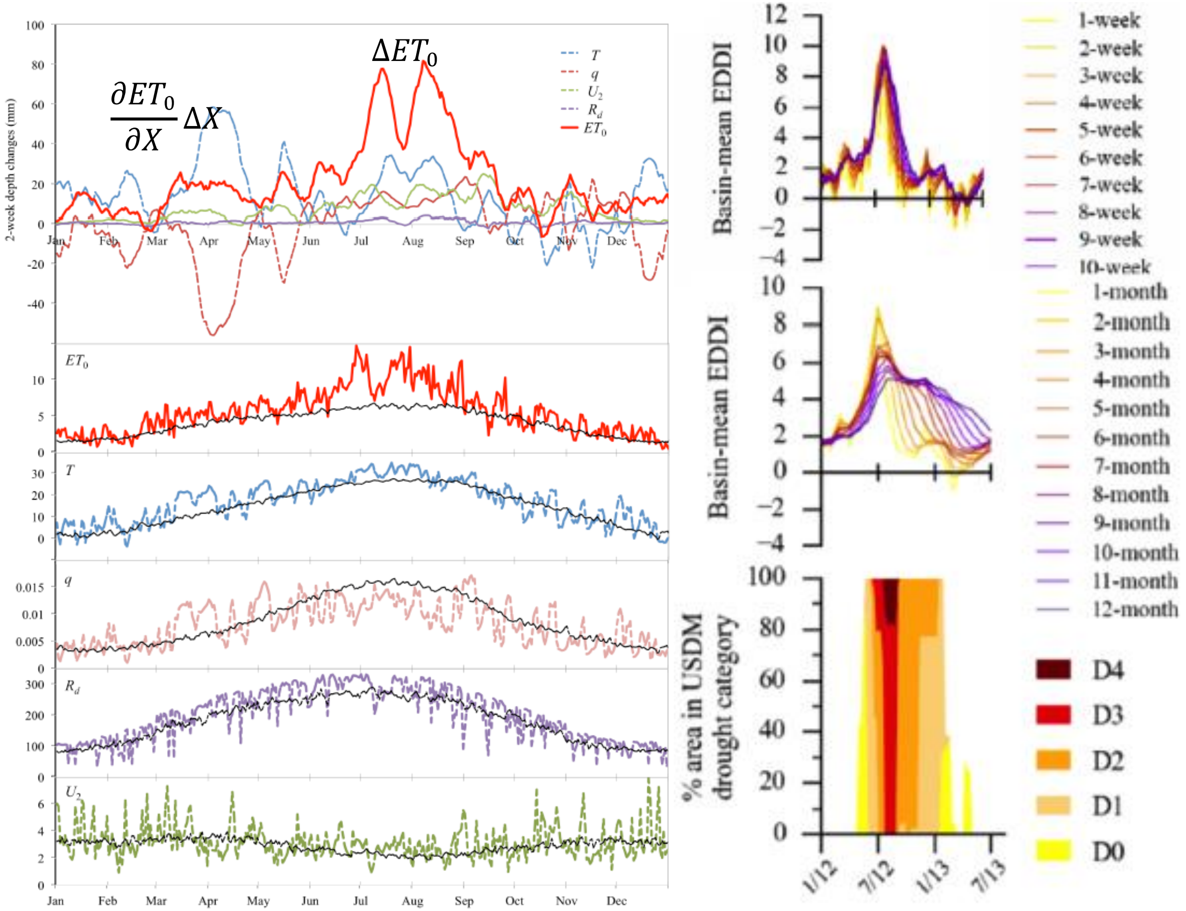
EDDI as estimator of drought

Attribution of drought

$$EDDI = f(\Delta ET_0)$$

$$\Delta ET_0 = \frac{\partial ET_0}{\partial T}\Delta T + \frac{\partial ET_0}{\partial R_d}\Delta R_d + \frac{\partial ET_0}{\partial q}\Delta q + \frac{\partial ET_0}{\partial U_{10}}\Delta U_{10}$$

2-week *EDDI*, Current River, MO, 2012-2013



Global ET_0

Development for FEWS NET

FEWS NET = Famine Early Warning Systems Networks
IWMI = International Water Management Institute
GDAS = Global Data Assimilation System
ERA = ECMWF Reanalysis
ECMWF = European Center for Medium range Weather Forecasting

Currently, to estimate *ET*, FEWS NET uses:

- IWMI surfaces of ET_0 climatology,
- GDAS (NOAA NCEP) drivers used for dynamic ET_0:
  - *Air temperature*
  - *Station pressure*
  - *Wind speed*
  - *Relative humidity*
  - SW_{up}, SW_{down}, LW_{up}, LW_{down}

GDAS data originally 0.3° res, released at 1°, 6-hourly

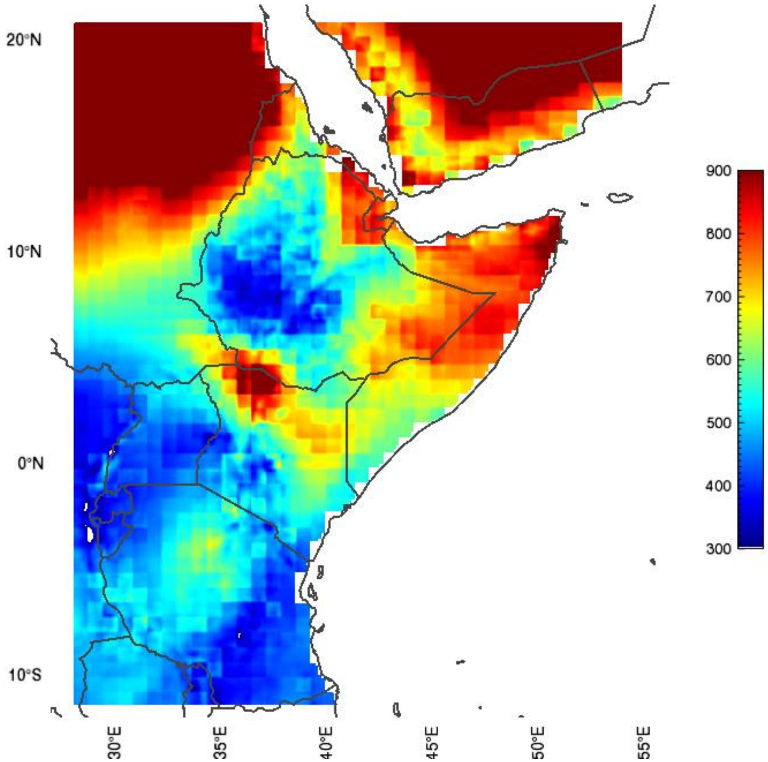
ne tropics"

ways for
s options

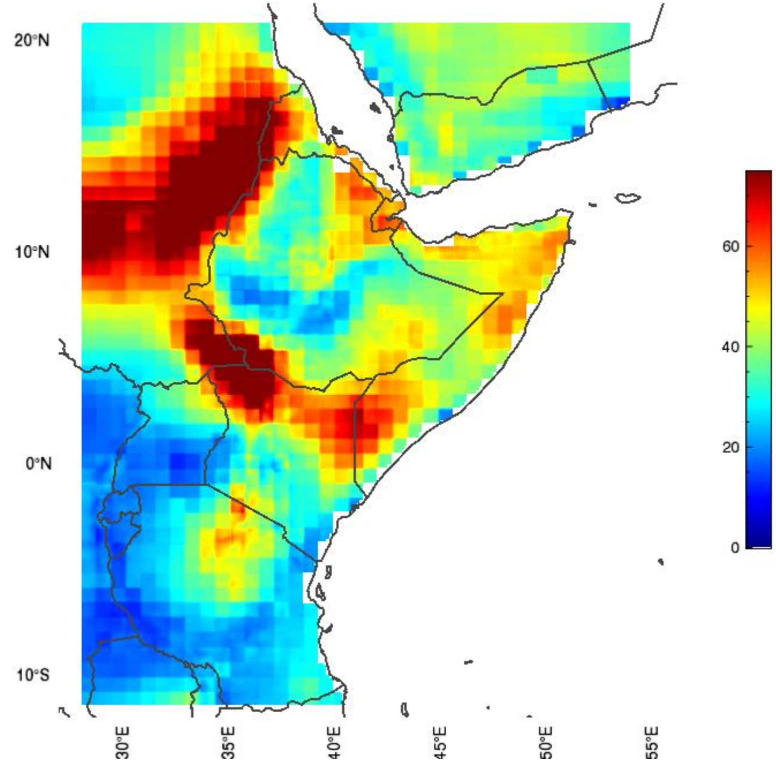
Global ET_0

ERA-Interim ET_0, 1981-2010

Mean MAMJ ET_0 (mm)



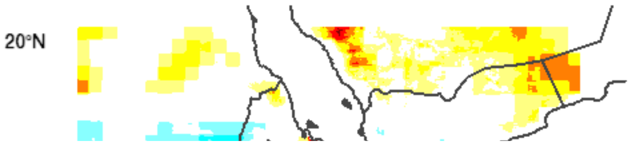
Stdev MAMJ ET_0 (mm)

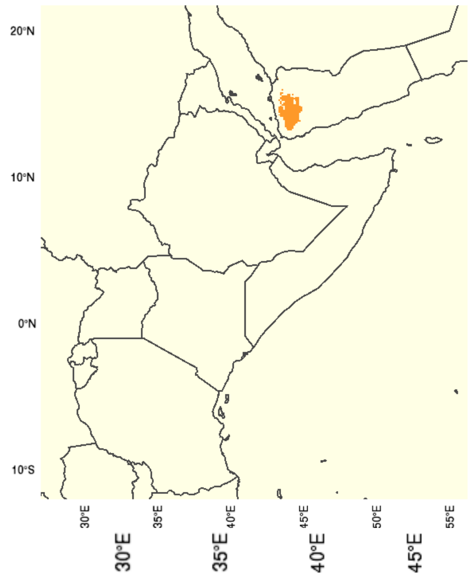


Global ET_0

Drought monitoring – Standardized Precipitation Evapotranspiration Index (SPEI)

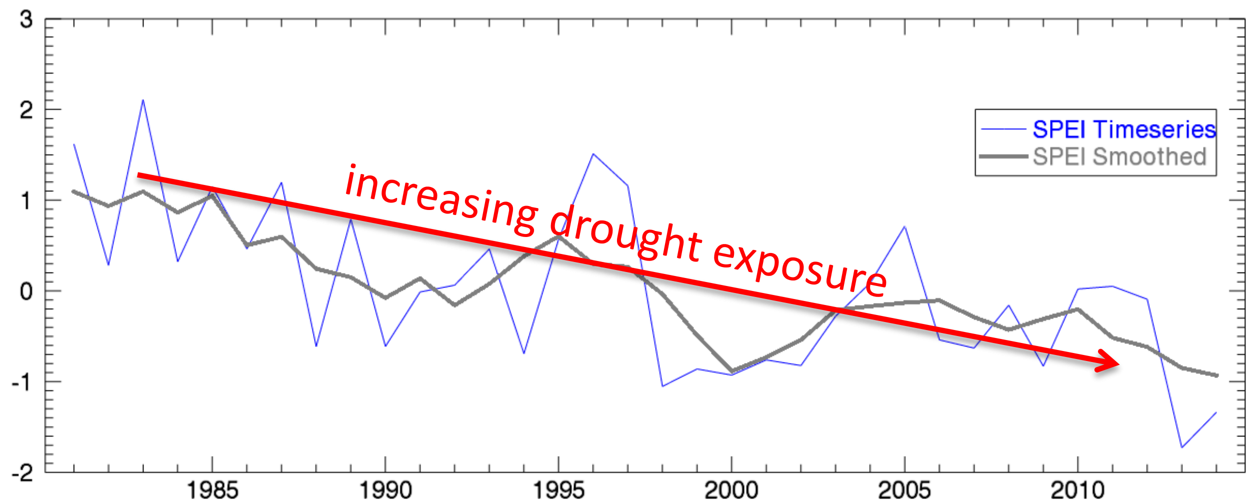
SPEI, using CHIRPS *Prcp* and ERA-Interim ET_0
MAMJ, 1984





$$SPEI = f\left(Prcp - ET_0\right)$$

SPEI, W. Yemen, MAMJ, 1980-2014



SPEI - Vicente-Serrano et al. (2010)
graphics - courtesy of Greg Husak, FEWS NET, UCSB

Summary

<u>Reanalyses</u> can provide seamless ET_0 coverage in space and time:

- derived from assimilation of R/S data, station observations,
- many (most?) will provide all variables needed for ET_0.

Various applications of <u>ET_0 reanalyses</u>:

- crop ET estimation and irrigation scheduling,
- landscape-scale ET estimation,
- drought monitoring:
  - in established drought indices (SPEI),
  - in a new stand-alone, leading indicator of drought (EDDI),
  - provide physically based data-stream in other drought indices.
- fire-risk forecasting.

ET_0 can be <u>forecast</u> seasonally (and short term) at higher skills than Prcp.

<u>Warning</u>: *T*-based ET_0 (or E_0) parameterizations are convenient and easy… but dangerous. Not recommended:

- for any seasons at all points,
- for all seasons at any points,
- ever for trend analyses.

Future and Ongoing Work

FEWS NET global ET_0 reanalyses

- Select optimal data streams to drive global ET_0 reanalysis:
  - currently ERA-Interim data used.
- Establish how uncertainty varies spatially between and within continents.
- Determine optimal ET_0 input streams to FEWS NET *ET*:
  - real-time observation and modeling vs. climatology.
- Verification against available data, e.g.:
  - FAO station ET_0 data or climatologies (station or 16-km gridded, 1960-1990), or from International Water Management Institute.
  - NCDC Global Summary of the Day (GSOD) station-based obs used to generate point ET_0 estimates. Includes ET_0-necessary drivers except R_d.
- Assimilation of ET_0 observations (e.g., *Chaney et al.*, J. Climate, 2014).

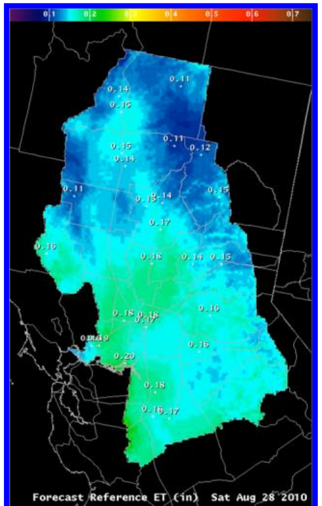
Future and Ongoing Work

NOAA's CONUS-wide ET_0 reanalyses

- Multi-generational ET_0 reanalyses:
  - Gen-1: increase resolution, bias-correct wrt PRISM (Univ. of Idaho)
  - Gen-2: incorporate data assimilation of ET_0 observations (Colorado State Univ.)
- Ambient conditioning of ET_0 reanalyses:
  - reflect actual surface conditions.
- Forecasting:
  - daily to weekly forecasts (FRET; NWS),
  - seasonal predictions (DRI),
  - climate-scale projections (USGS).

FRET – original delivery

Forecast surface, generated at WFO



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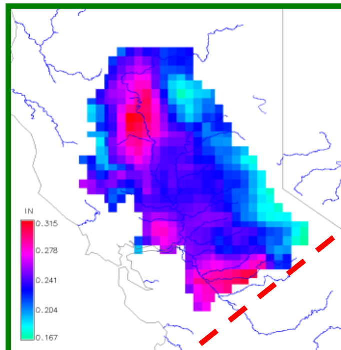
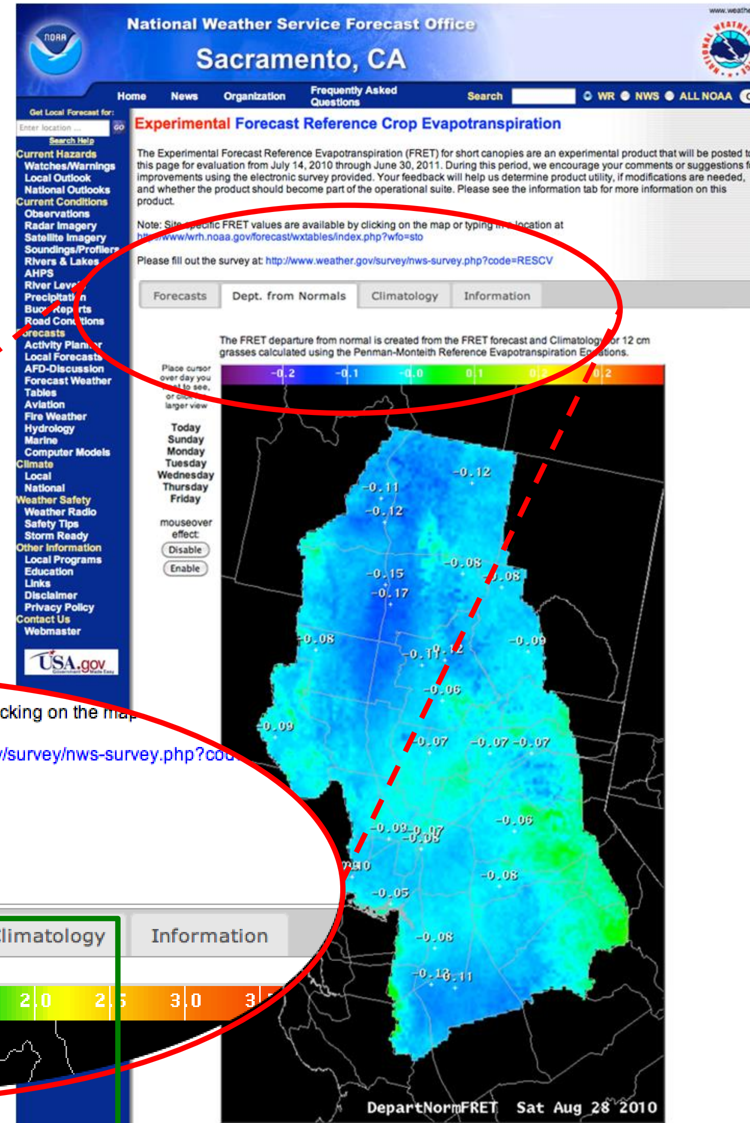
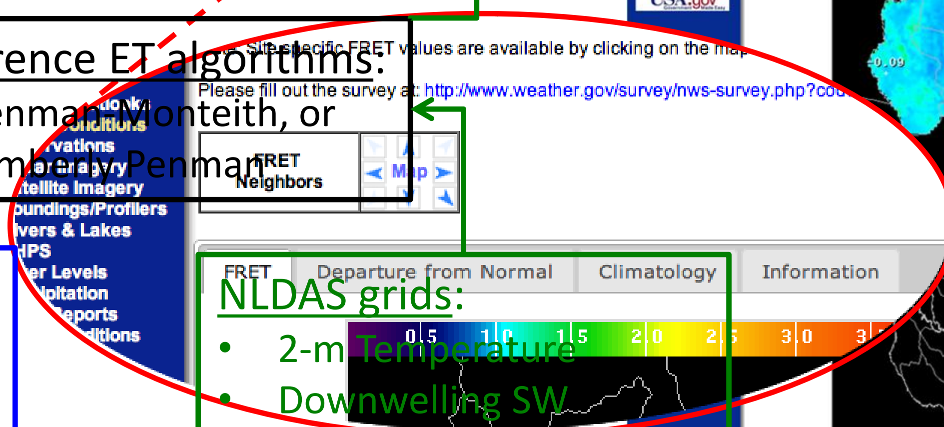
NLDAS climatology surface, specific to 2-wk period, WFO







Reference ET algorithms:

- Penman-Monteith, or
- Kimberly Penman

Forecast grids:

- Temperature
- Sky cover
- Wind speed
- Relative humidity

NLDAS grids:

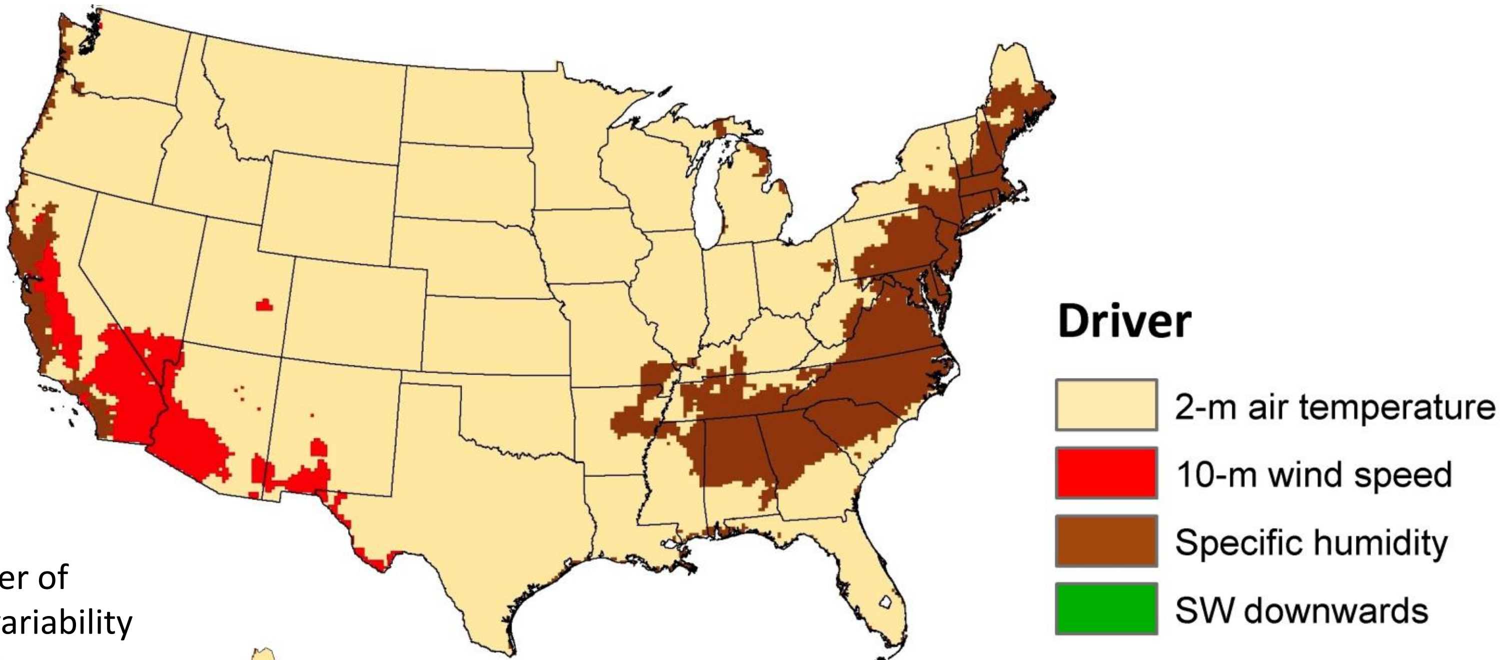
- 2-m Temperature
- Downwelling SW
- 10-m wind vectors
- Atmospheric pressure
- Specific humidity

FRET website for Sacramento, CA:
http://www.wrh.noaa.gov/forecast/evap/FRET/FRET.php?wfo=sto

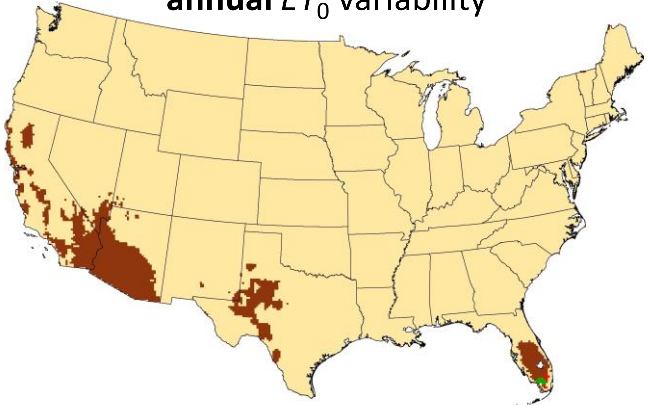
Short-term variability of E_0:
Top driver of daily variability, by month

Top driver of **daily** ET_0 variability, by month

December



Top driver of
annual ET_0 variability



Variability of ET_0 and dominant drivers temporally dynamic:

- non-*T* drivers dominate over much of CONUS during the growing season;
- dominant driver varies significantly with time-step.

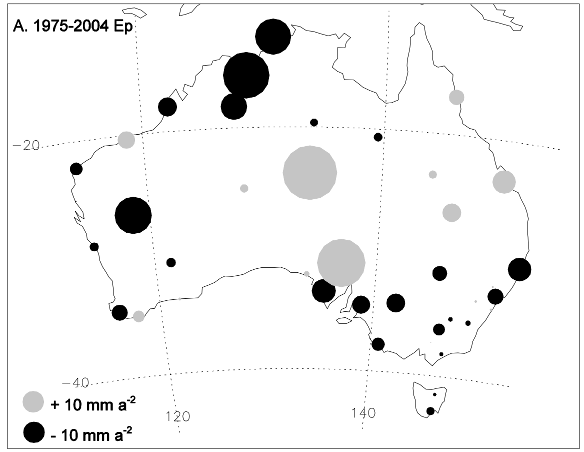
Underscore importance of fully physical ET_0 estimators:

- i.e., not relying on *T*-based parameterizations.

Decadal-scale E_0 trend attribution:

Decomposing observed E_{pan}-trend forcings

dE_0/dt = -2.0 mm/yr²

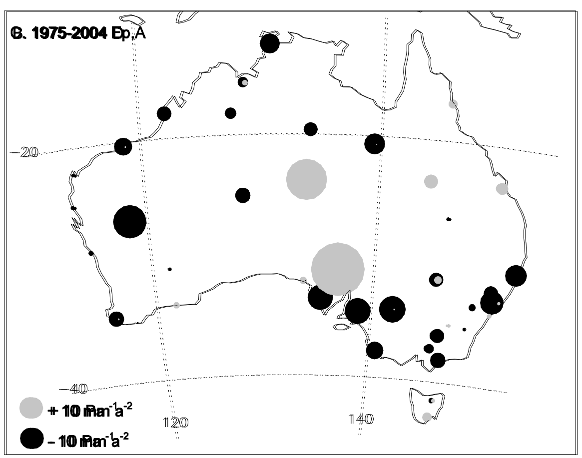


$$E_{pan} \sim E_0 = E_{0,Advective} + E_{0,Radiative}$$

$dVPD/dt$ = -0.2 Pa/yr

$dE_{0,VPD}/dt$ = 0.0 mm/yr²

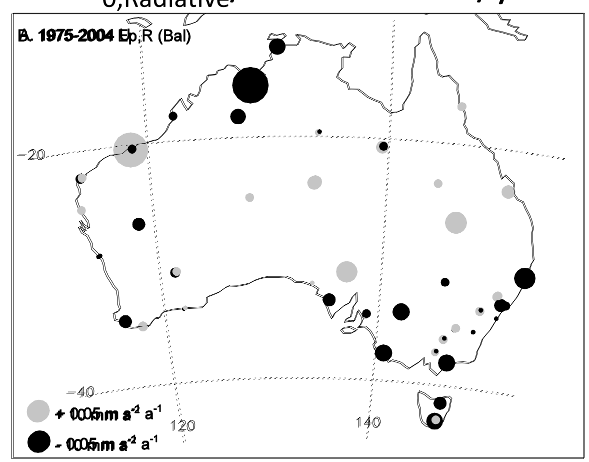
$dE_{0,Advective}/dt$ = -2.6 mm/yr²



dU_2/dt = -0.01 m/sec/yr

$dE_{0,U2}/dt$ = -2.7 mm/yr²

$dE_{0,Radiative}/dt$ = +0.6 mm/yr²

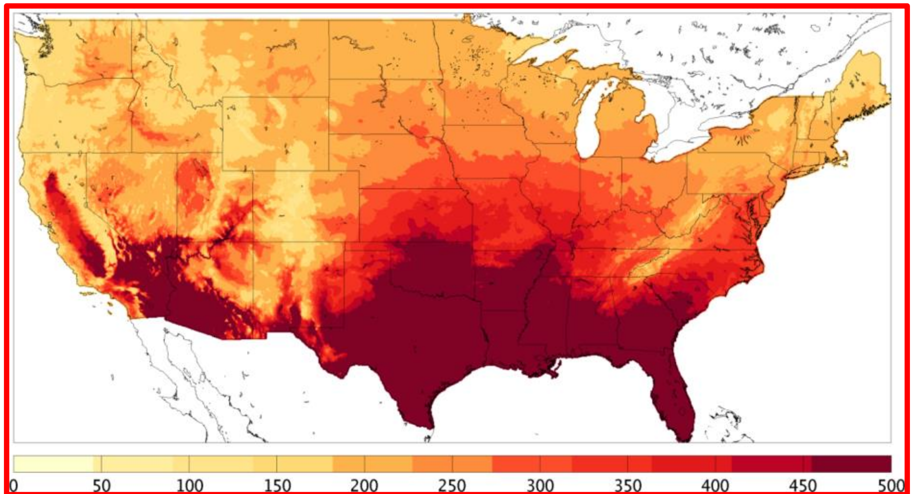


Climate-scale E_0 projections:

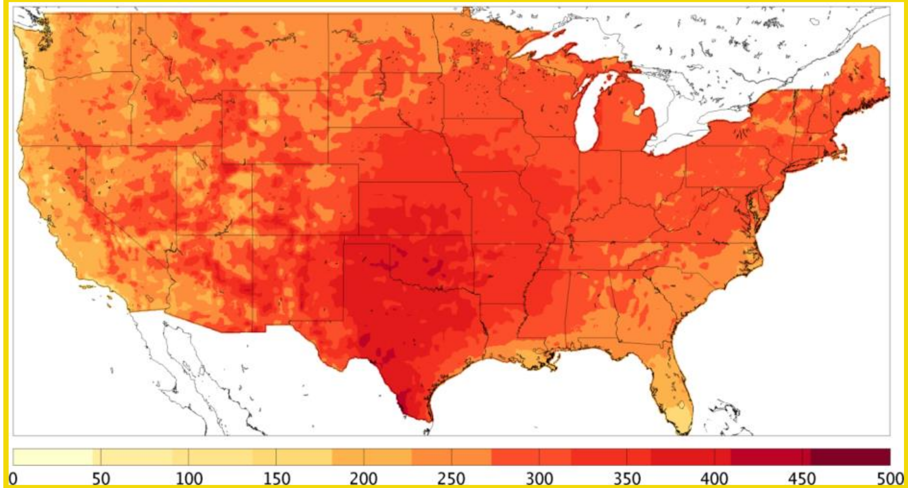
Physically based vs. T-based E_0 climate projections

20-model mean results for RCP85, E_p, 2070-2099 minus 1950-2005

Δ Thornthwaite (mm/year)



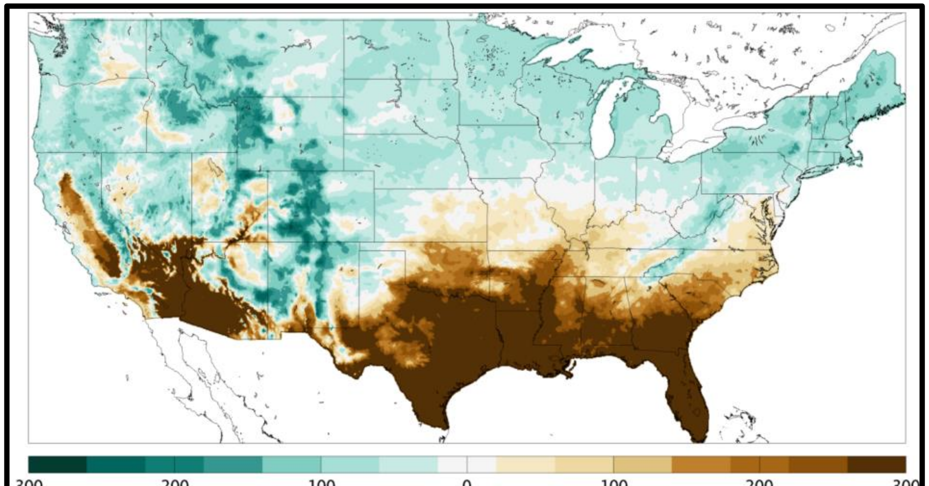
Δ Penman-Monteith (mm/year)



$$\Delta E_p(T) = f\left(\left.\frac{\partial E_p}{\partial T}\right|_{\bar{T}}, \Delta T\right)$$

$$\Delta E_p(T,SW,SH,U) = f\left(\left.\frac{\partial E_p}{\partial T}\right|_{\bar{T}}, \Delta T, \left.\frac{\partial E_p}{\partial SW}\right|_{\overline{SW}}, \Delta SW, \left.\frac{\partial E_p}{\partial SH}\right|_{\overline{SH}}, \Delta SH, \left.\frac{\partial E_p}{\partial U}\right|_{\bar{U}}, \Delta U\right)$$

Δ Thornthwaite – Δ Penman-Monteith



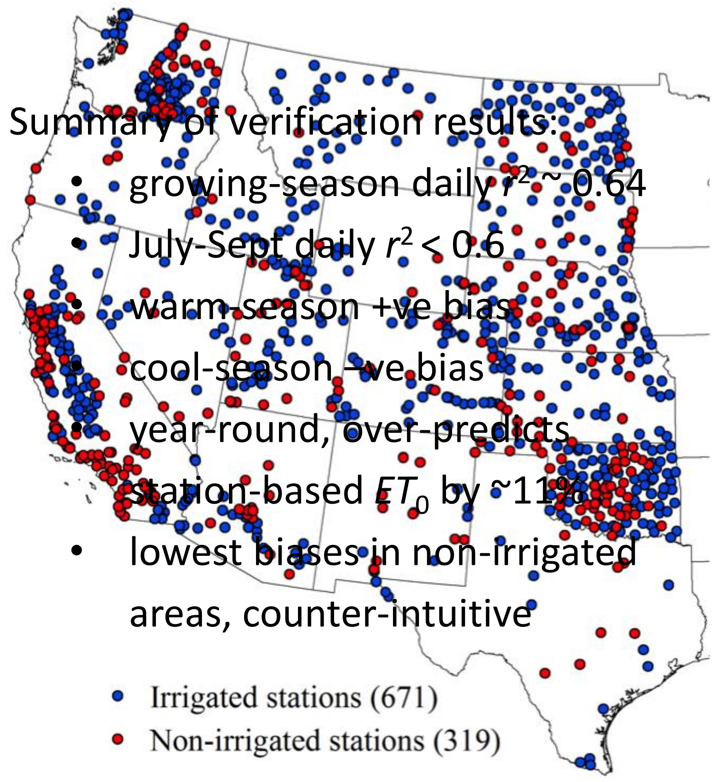
T-based ΔE_p:

- overestimated in hotter regions;
- underestimated in colder regions.

ET_0 reanalysis – Gen-0:
Verification

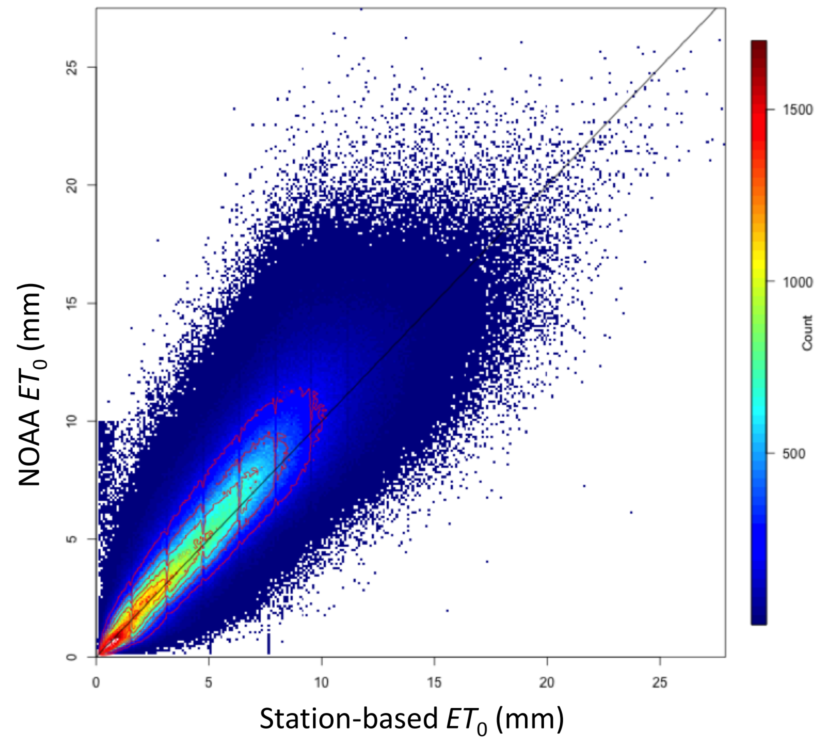
Verification of Gen-0 ET_0 against station-based estimates:

- ➢ ET_0 point data from in-situ weather station networks
- ➢ western US verification only, so far
- ➢ Desert Research Institute; Utah State University; USDA-ARS (Bushland, TX)`



Summary of verification results:

- growing-season daily r^2 ~ 0.64
- July-Sept daily r^2 < 0.6
- warm-season +ve bias
- cool-season –ve bias
- year-round, over-predicts station-based ET_0 by ~11%
- lowest biases in non-irrigated areas, counter-intuitive

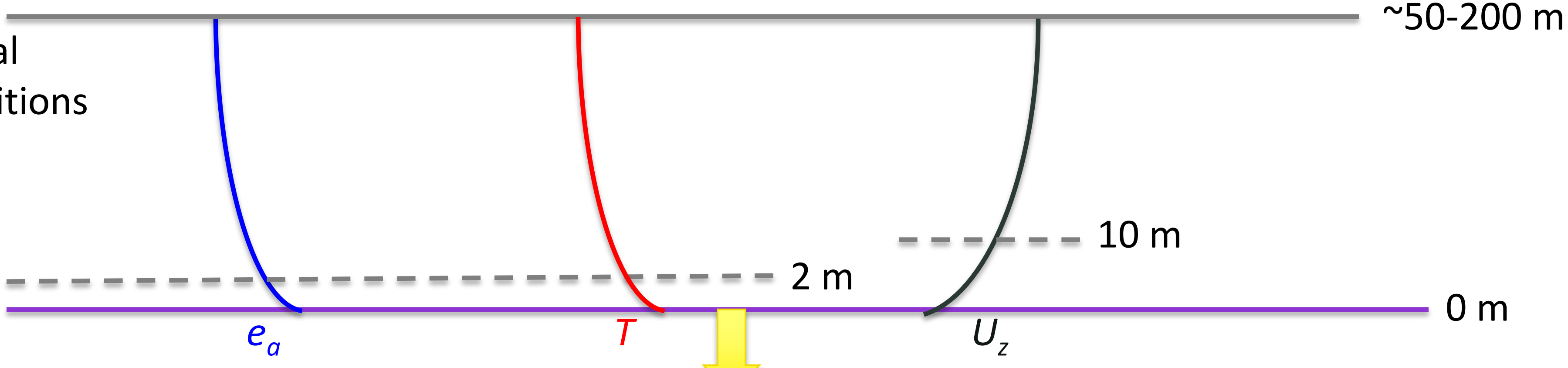


All stations, all year, daily ET_0

ET_0 reanalysis – steps to Gen-2:

Ambient conditioning of NLDAS drivers

Actual conditions
- arid



- extrapolate drivers to a blending-height in the boundary layer

Reference conditions
- well-watered