A rigorous attribution of the demand side of drought: a case study in the Midwest US.

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The NIDIS Midwest DEWS

National Integrated Drought Information System (NIDIS)

"A drought early warning system (DEWS) utilizes new and existing networks of federal, tribal, state, local, and academic partners to make climate and drought science accessible and useful for decision makers and stakeholders."

--NIDIS

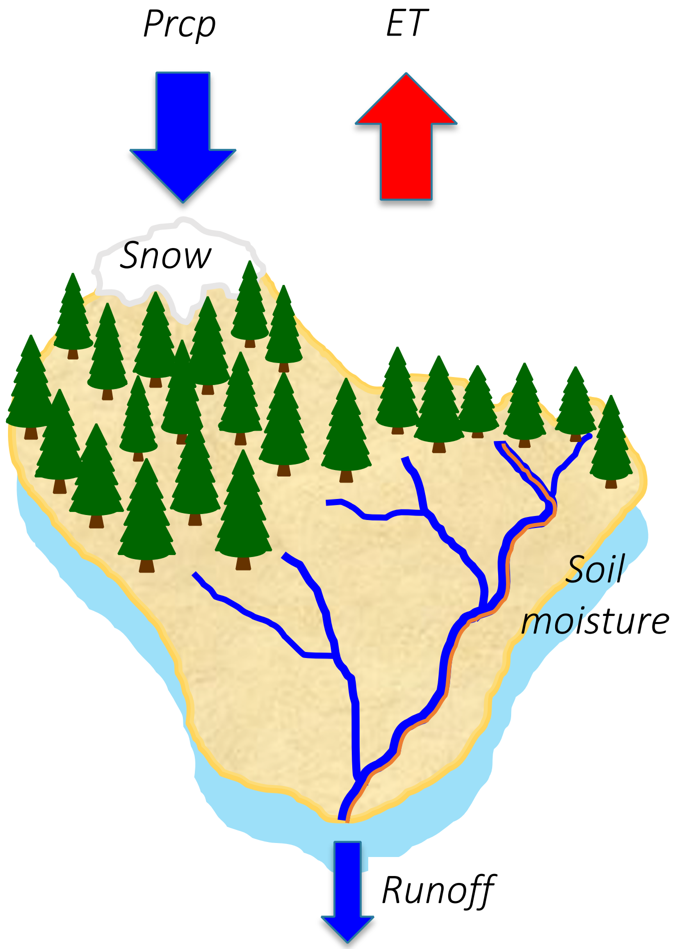
Background | *Demand side of drought*

T = *air temperature*
q = *specific humidity*
U_2 = *wind speed*
R_d = *solar radiation*

Drought = imbalance of <u>supply</u> to, and <u>demand</u> for, surface moisture

Water balance at land surface:

~ $f(Prcp, ET)$



Background | *Demand side of drought*

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q = specific humidity
U_2 *= wind speed*
R_d *= solar radiation*

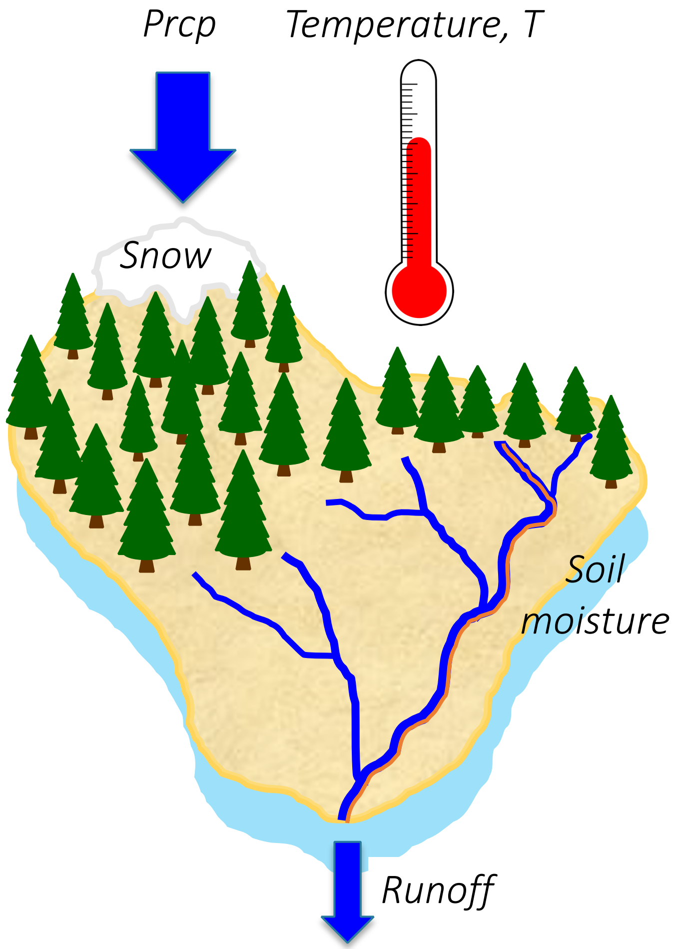
Drought = imbalance of supply to, and demand for, surface moisture

Water balance at land surface:

~ *f*(*Prcp*, *ET*)

where *ET* has long been estimated by:

- temperature, *T*,
  - e.g., Thornthwaite, Hamon, Hargreaves, PDSI



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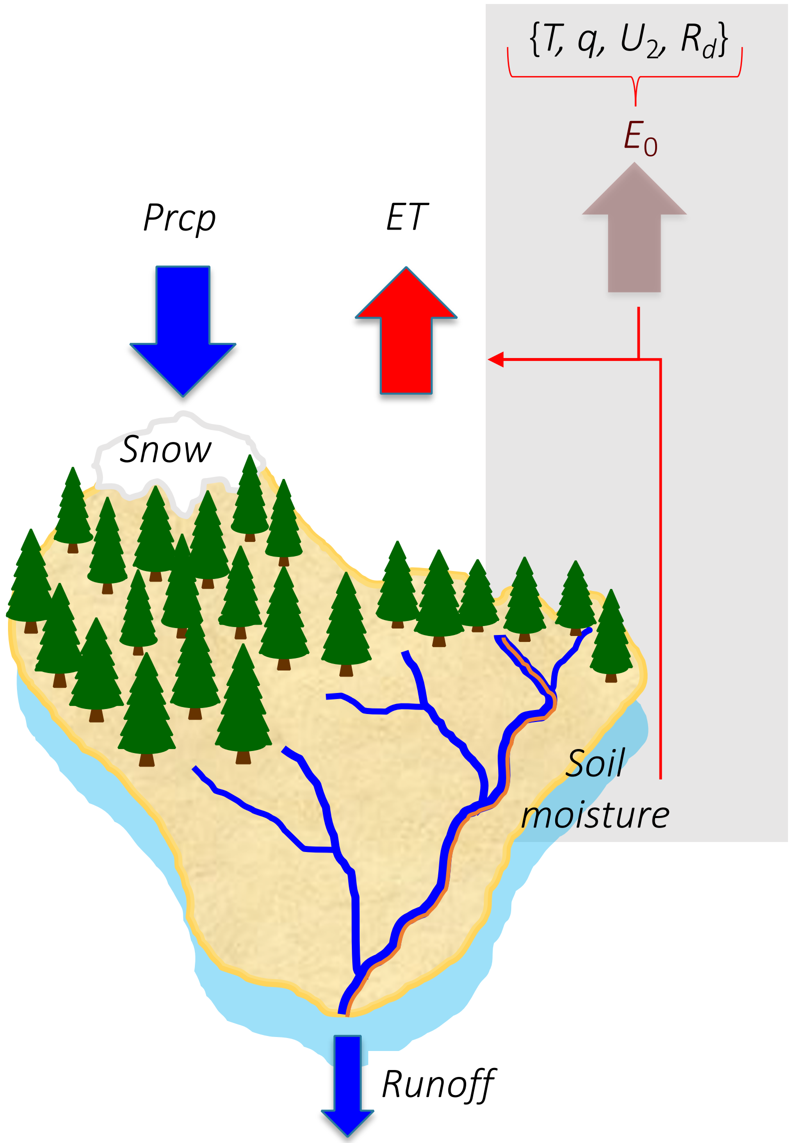
Water balance at land surface:

~ $f(Prcp, ET)$

where *ET* is more physically driven by:

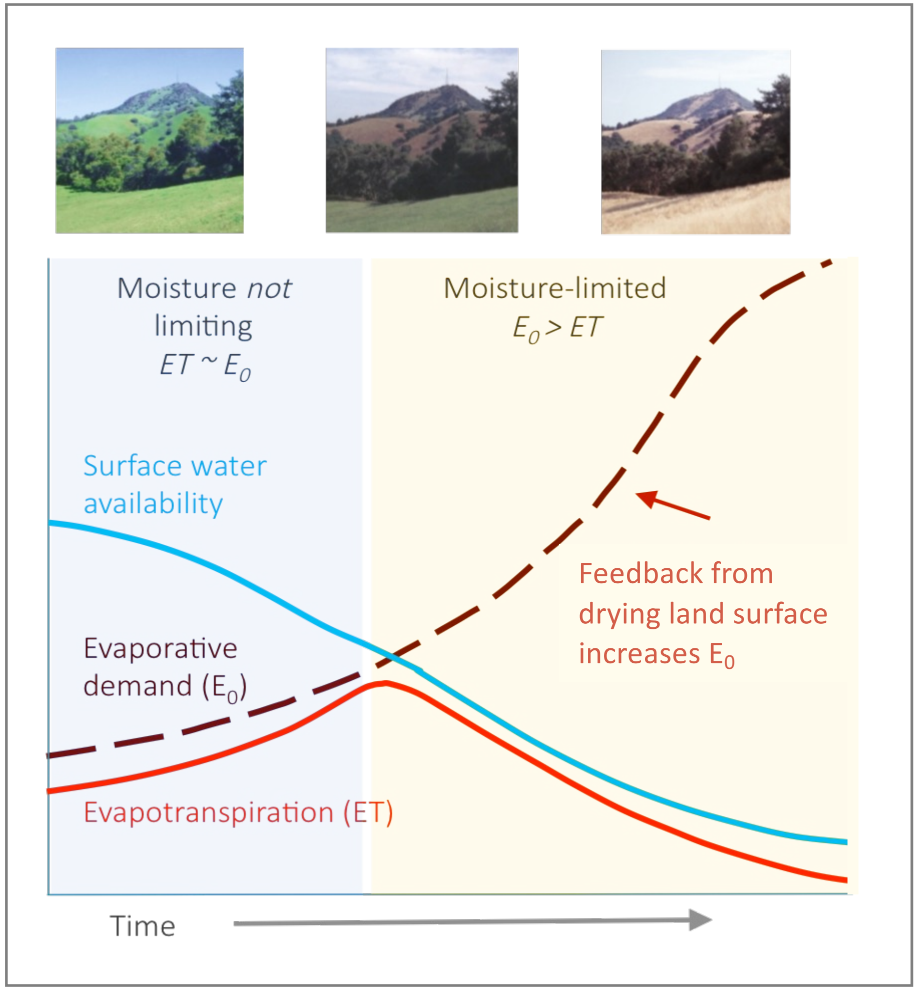
- surface moisture status,
- evaporative demand (E_0),
  - e.g., Penman-Monteith.



Background | *Land-atmosphere feedbacks in drought*

Soil moisture

Evapotranspiration (ET)



Lukas et al., Western Water Assessment (2017)

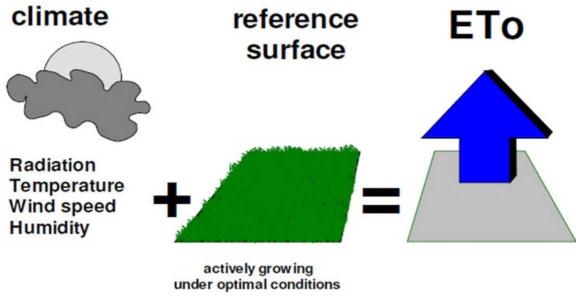
Evaporative demand (E_0)

As drought progresses:

- ET can either:
  - rise and then fall, or
  - fall immediately.
- Either case drives:
  - SM to consistently decline,
  - E_0 to consistently rise.

Background | *What is evaporative demand (E_0)?*

E_0 = evaporative demand
ET = actual evapotranspiration
ET_0 = reference ET



- E_0 is <u>**not**</u> evapotranspiration/evaporation
- E_0 is evaporation **given unlimited moisture**:
  - **Reference *ET*, ET_0**
  - Potential *ET* (*"PET"*)
  - Pan evaporation
- E_0 is used for:
  - estimating crop water requirements
  - scheduling irrigation
  - driving *ET* estimates in LSMs and R/S fusion
  - monitoring drought
- Good estimates and bad estimates:
  - **physically based**
  - radiation-based
  - temperature-based

E_0 is the *"thirst of the atmosphere"*

Background | *Estimating E_0 from reference ET*

Penman-Monteith reference *ET* (FAO-56):

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

Radiative forcing
(sunshine, *T*)

Advective forcing
(wind, humidity, *T*)

Reference crop specified:

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

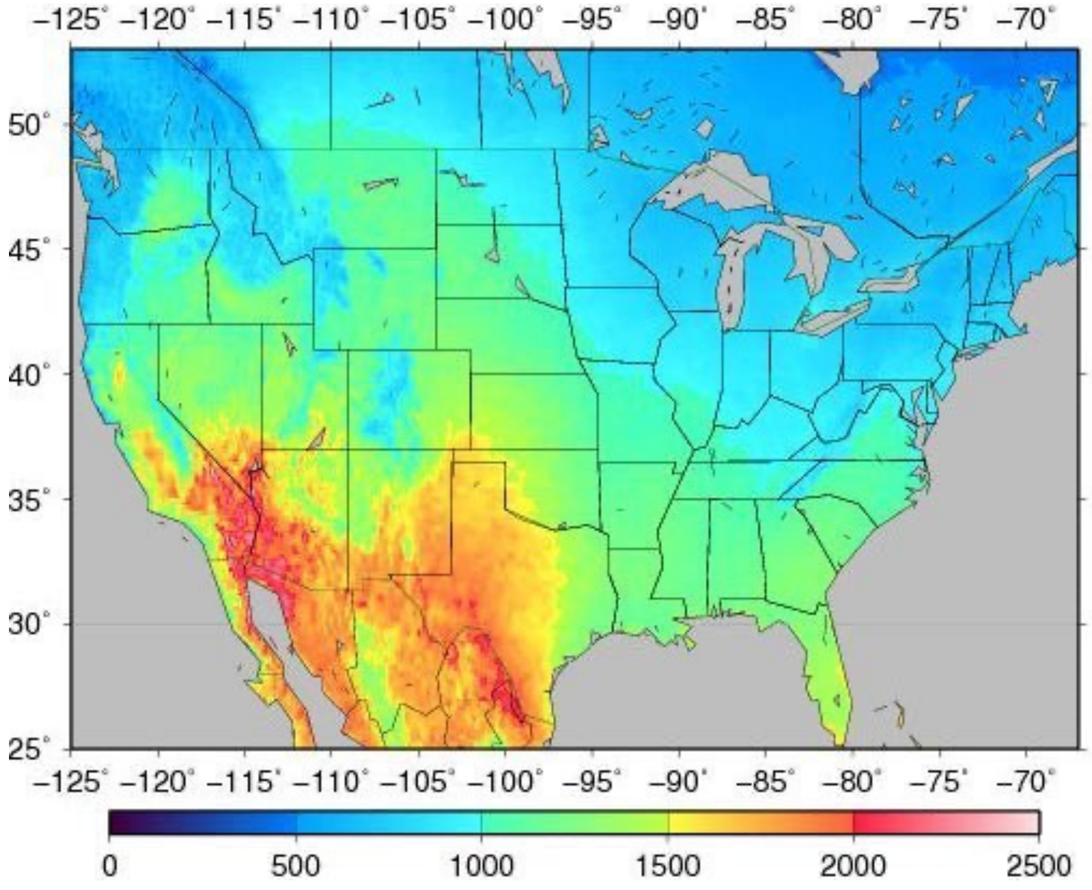
Drivers from NLDAS-2:

- temperature at 2 m
- specific humidity at surface
- downward SW at surface
- wind speed at 10 m

Reanalysis specifications:

- daily, Jan 1, 1979 – present
- latency ~ 5 days
- 0.125° lat x lon, CONUS+ (to 53°N)

Mean annual E_0 (mm), 1981-2010



Fundamental question | *Actually two questions*

How much are changes in E_0 in drought due to each driver's changes?

Decomposition

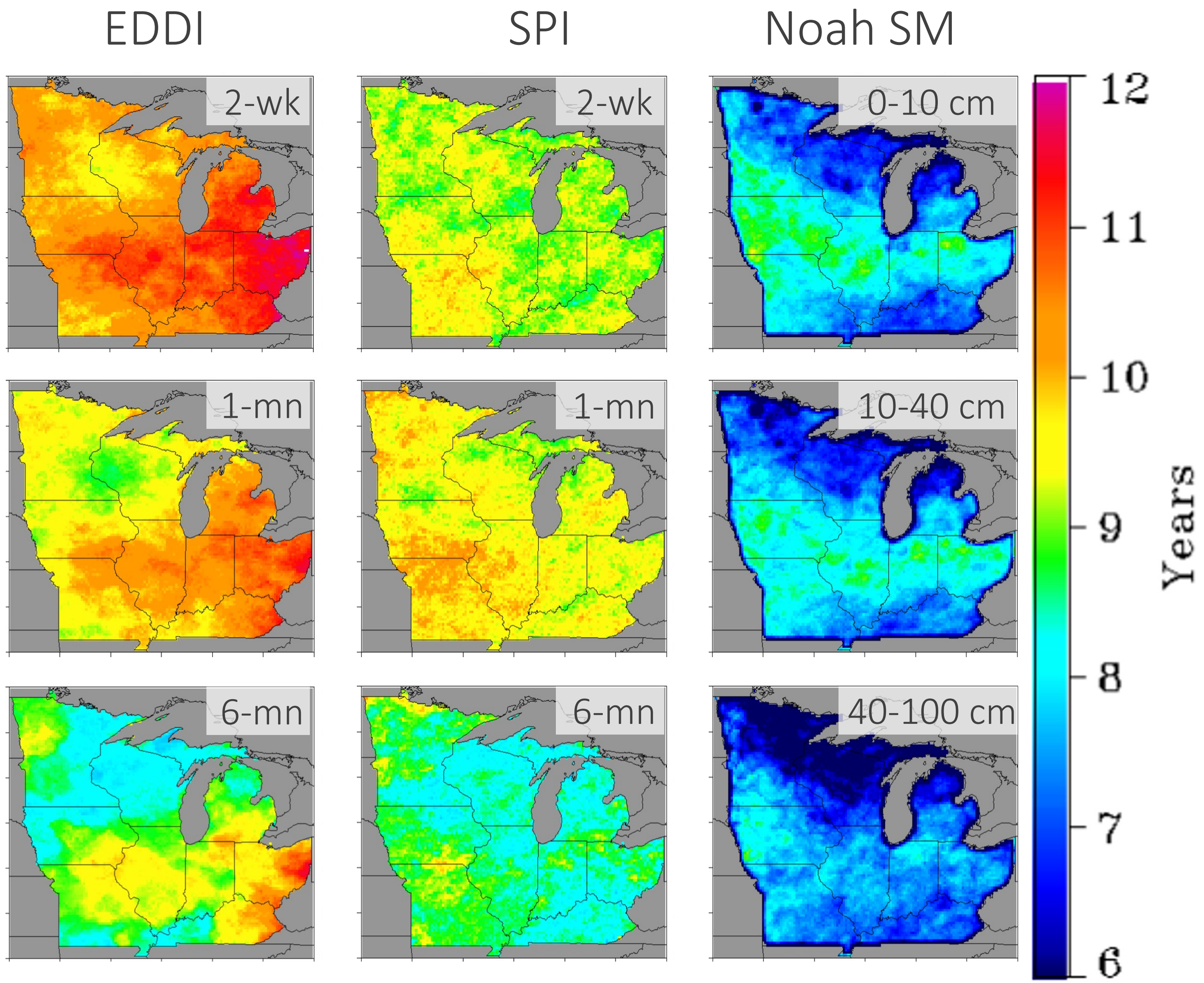
2. How do we determine **"changes in E_0 … due to each driver's changes"**?

Determining drought

1. What does **"in drought"** mean?

Determining drought | *Drought frequency (1980-2020)*

- Drought defined as periods of ≥ D1 drought, extending ≥ 2 weeks, covering ≥ 50% of Midwest DEWS
- **EDDI**: # years drought > 80 %ile conditions
- **SPI**: # years drought < 20 %ile conditions
- pentad data converted to daily grids
- **Noah SM**: # years drought < 20 %ile conditions
- edge effect due to boxcar spatial smoothing applied to original drought index



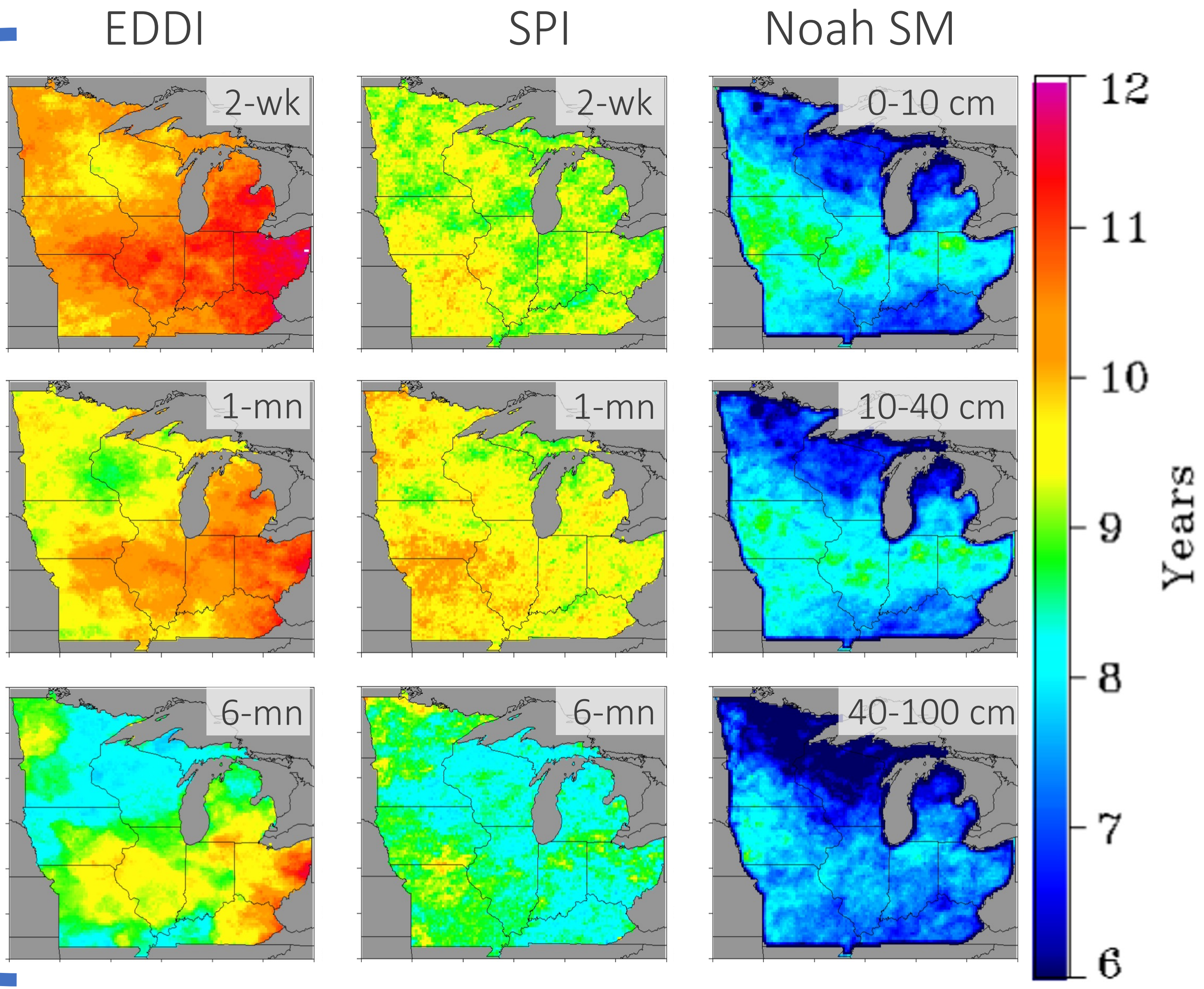
Determining drought | *Drought frequency (1980-2020)*

Nine daily timeseries:

- Evaporative demand (3)
- Precipitation (3)
- Soil moisture (3)
- Different depths and timescales

Single “consensus” drought timeseries

consensus ≥ 3 is drought



Attribution | *Diagnosing drought's demand side*

What drives changes in E_0?

$$E_0 \sim ET_0 = \frac{0.408\Delta R_n + \gamma \frac{C_n}{T+273} U(e_{sat} - e_a)}{\Delta + \gamma(1 + C_d U)}$$

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E_0 = f(T_{max}, T_{min}, R_d, q, U_2), so

T_{max}	maximum temperature
T_{min}	minimum temperature
q	specific humidity
R_d	downwelling SW radiation
U_2	2-m wind speed
ε	closing error, due to non-linearity

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$$E_0 \sim ET_0 = \frac{0.408\Delta R_n + \gamma \frac{C_n}{T+273} U(e_{sat} - e_a)}{\Delta + \gamma(1 + C_d U)}$$

$E_0 = \mathrm{f}(T_{max}, T_{min}, R_d, q, U_2)$, so

$$\Delta E_0 = \frac{\partial E_0}{\partial T_{max}} \Delta T_{max} + \frac{\partial E_0}{\partial T_{min}} \Delta T_{min} + \frac{\partial E_0}{\partial R_d} \Delta R_d + \frac{\partial E_0}{\partial U_2} \Delta U_2 + \frac{\partial E_0}{\partial q} \Delta q + \varepsilon$$

derived analytically

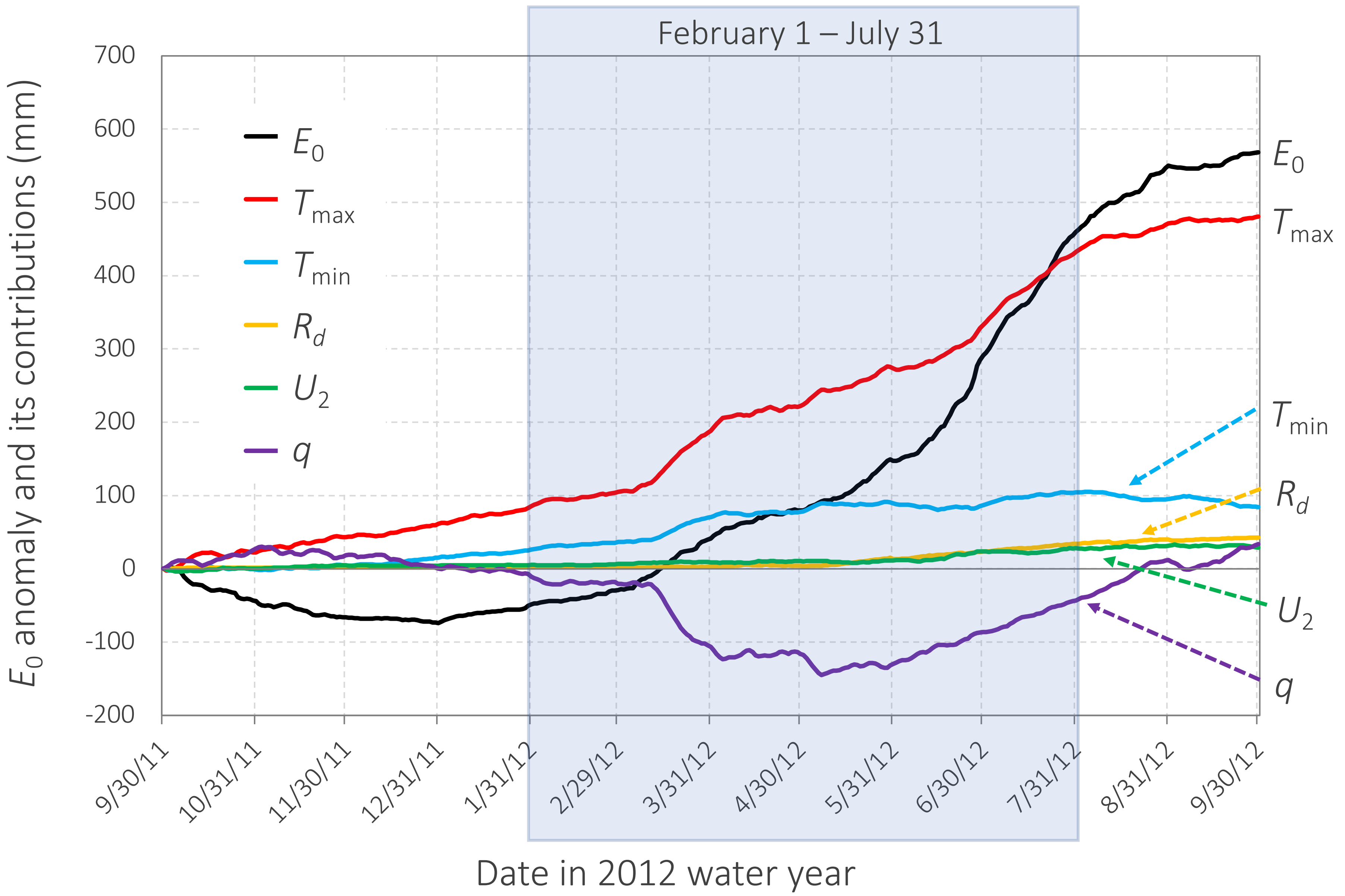
anomalies observed in reanalyses

closure error due to non-linearities in E_0 expression

$$\frac{\partial ET_r}{\partial T} = \frac{\left\{ 0.408\overline{\Delta}\left[\overline{R}_n \frac{4169.871 - 2\overline{T}}{(\overline{T} - 35.85)^2} - 4\sigma f_{cd}\left(0.34 - 0.14\sqrt{\overline{e}_a}\right)\overline{T}^3 \right] + \gamma C_n \frac{\overline{U}}{\overline{T}}\left[\overline{e}_{sat} \frac{4098.171}{(\overline{T} - 35.85)^2} - \frac{1}{\overline{T}}(\overline{e}_{sat} - \overline{e}_a) \right] \right\}}{\overline{\Delta} + \gamma(1 + C_d \overline{U})} + \frac{\frac{4169.871 - 2\overline{T}}{(\overline{T} - 35.85)^2}\overline{\Delta}\left[0.408\overline{\Delta}\,\overline{R}_n + \gamma \frac{C_n}{\overline{T}}\overline{U}(\overline{e}_{sat} - \overline{e}_a) \right]}{\left[\overline{\Delta} + \gamma(1 + C_d \overline{U})\right]^2}$$

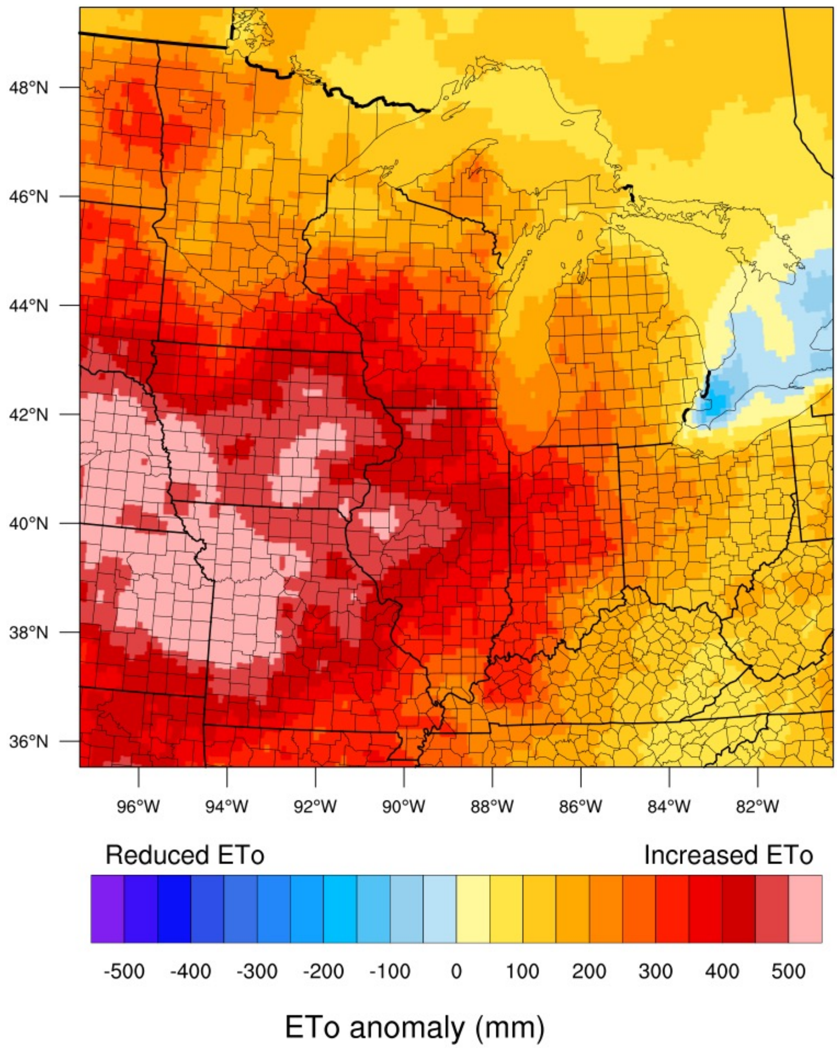
(Hobbins, *TransASABE* 2016)

Attribution | *Diagnosing drought's demand side*

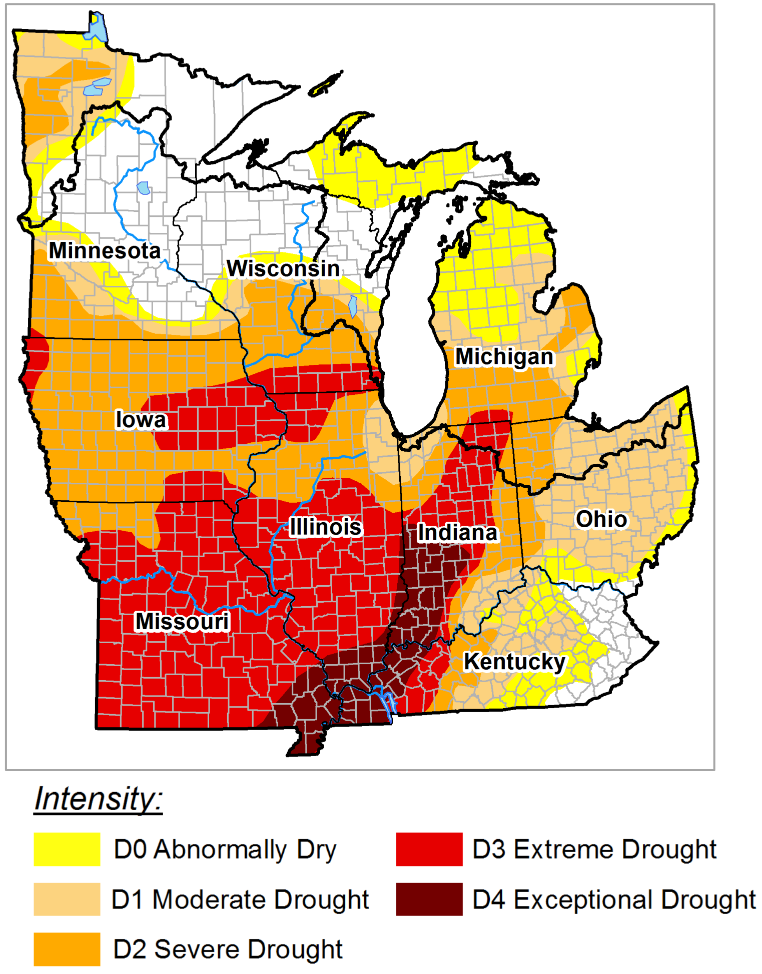


Attribution | *Midwest drought, 2012*

ET_0 anomaly – February 1 - July 31, 2012



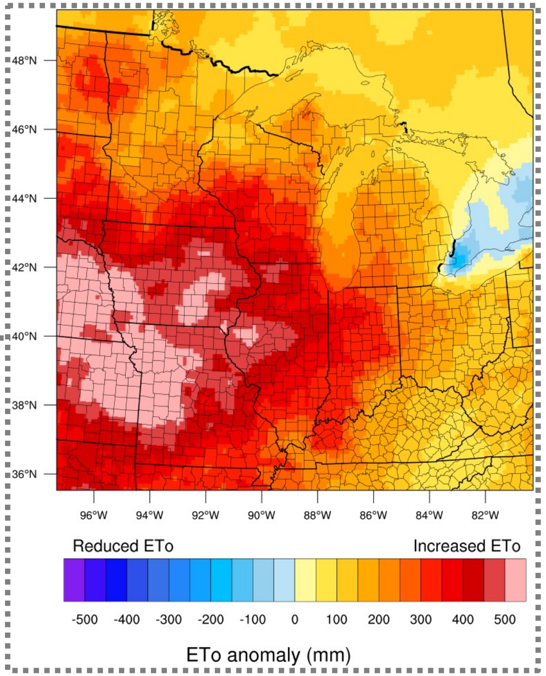
US Drought Monitor – July 31, 2012

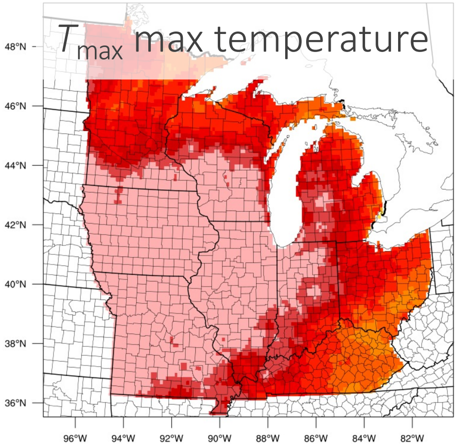


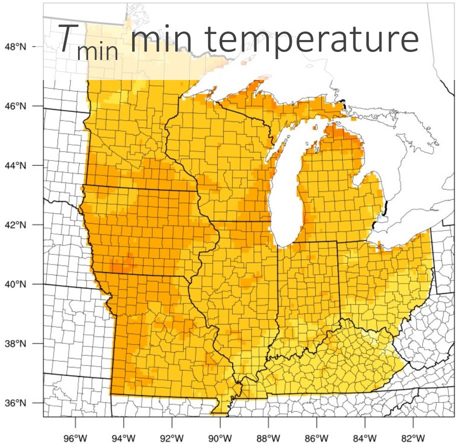
Attribution | *Midwest drought, 2012*

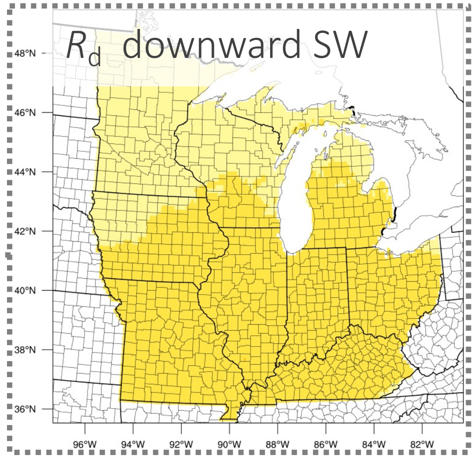
Decomposition of 6-month E_0 anomaly,
February 1 – July 31, 2012

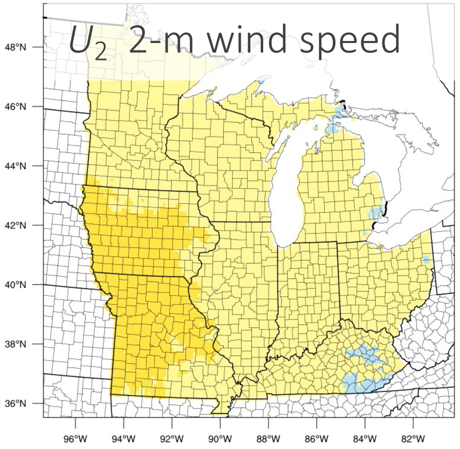
$$\Delta E_0 = \frac{\partial E_0}{\partial T_{max}} \Delta T_{max} + \frac{\partial E_0}{\partial T_{min}} \Delta T_{min} + \frac{\partial E_0}{\partial R_d} \Delta R_d + \frac{\partial E_0}{\partial U_2} \Delta U_2 + \frac{\partial E_0}{\partial q} \Delta q + \varepsilon$$

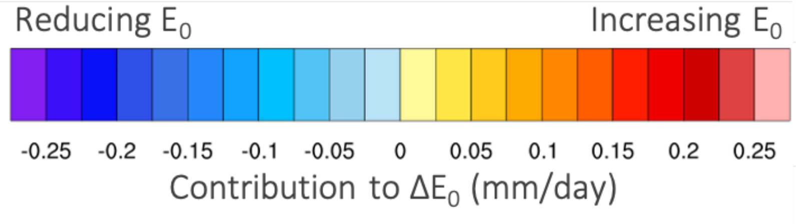


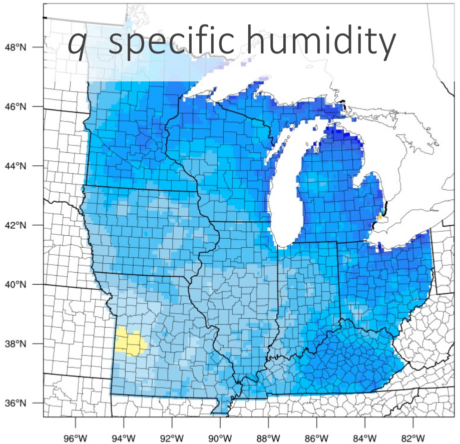








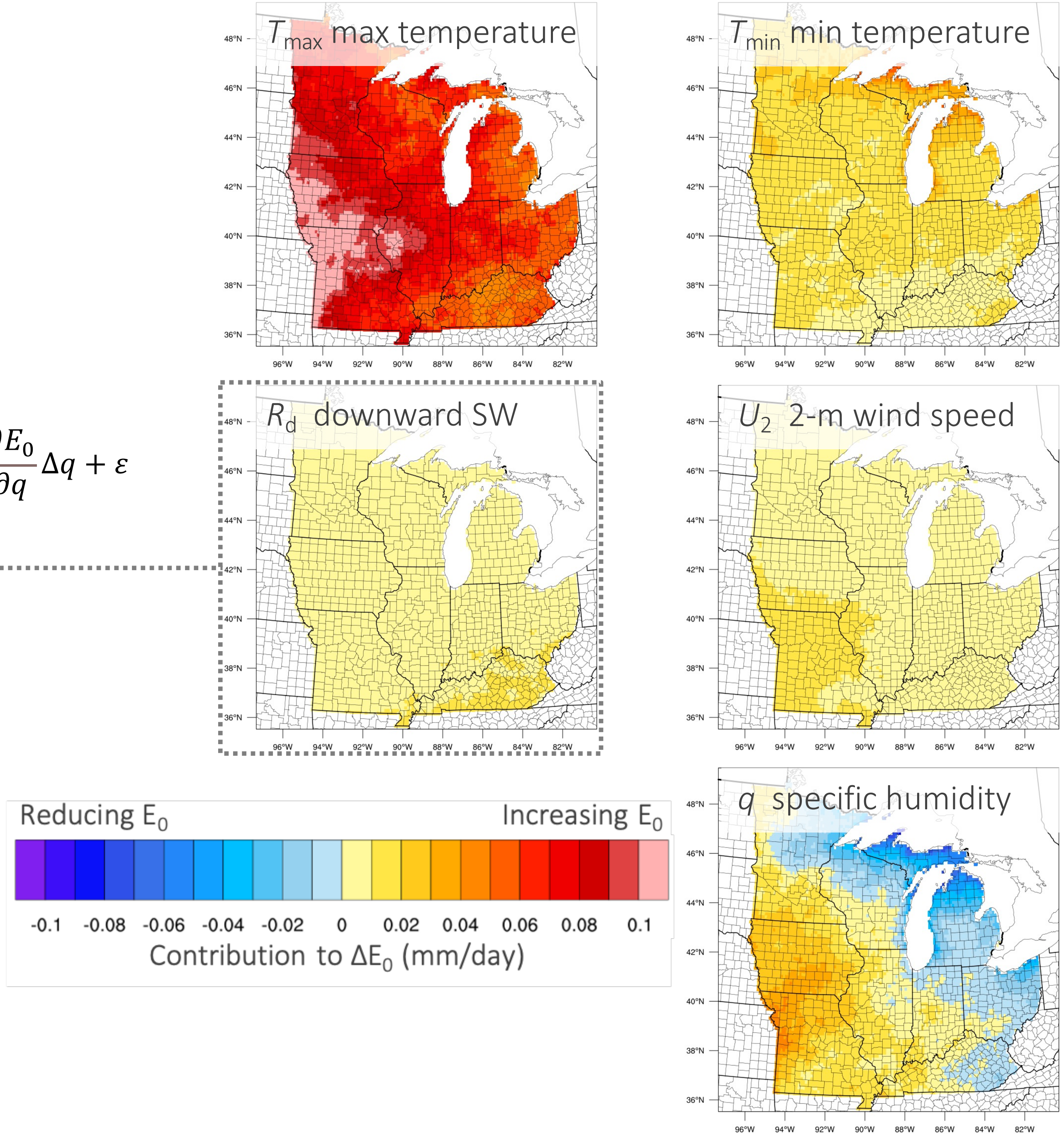




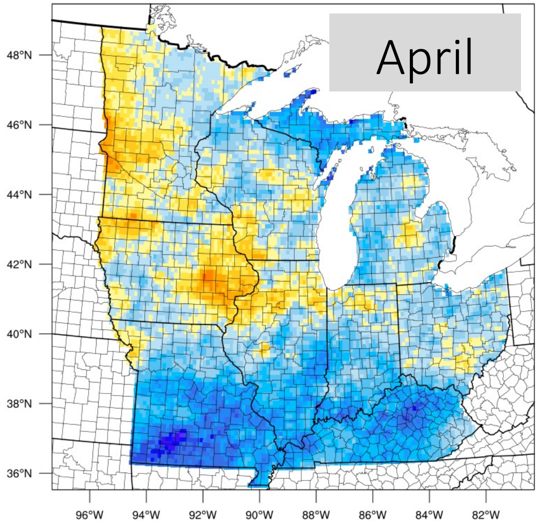
Attribution | *All droughts, 1981-2020*

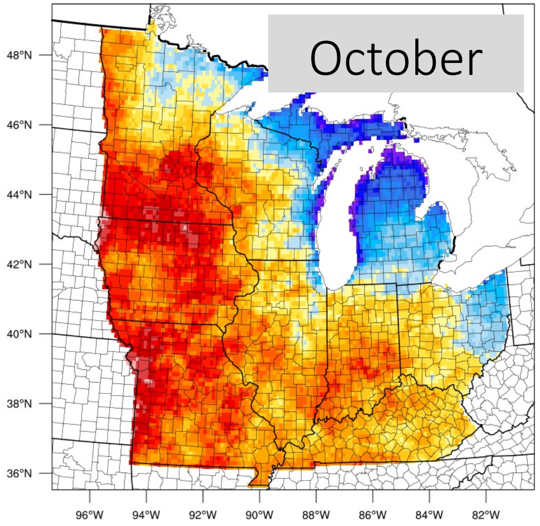
Decomposition of all-droughts E_0 anomaly, 1981 – 2020

$$\Delta E_0 = \frac{\partial E_0}{\partial T_{max}} \Delta T_{max} + \frac{\partial E_0}{\partial T_{min}} \Delta T_{min} + \frac{\partial E_0}{\partial R_d} \Delta R_d + \frac{\partial E_0}{\partial U_2} \Delta U_2 + \frac{\partial E_0}{\partial q} \Delta q + \varepsilon$$



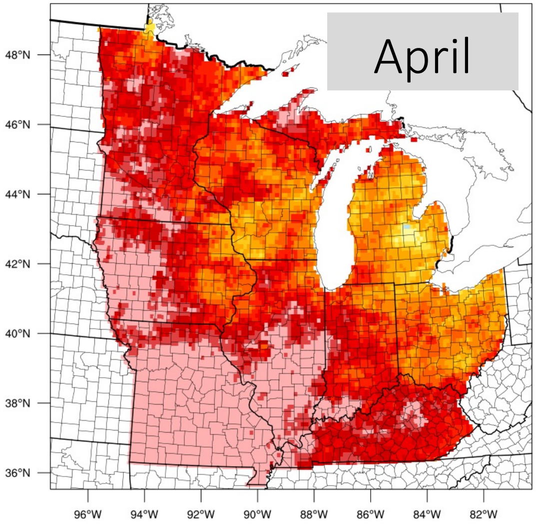
Attribution | *Seasonal and regional differences in driver strengths*

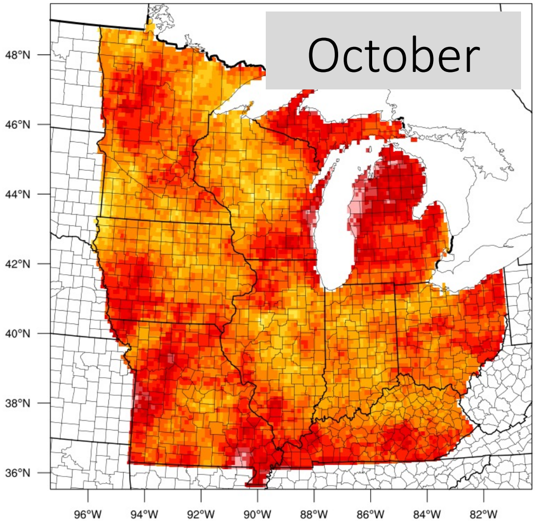


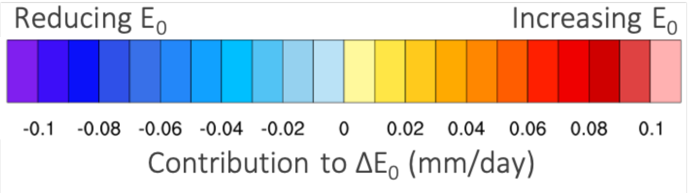


q, specific humidity

T$_{max}$, maximum temperature







Take-home messages | *From 30,000 feet to ground level*

- Demand side of drought can now be better parameterized and diagnosed.
- Temperature-based demand drivers should be avoided.
- There is valuable information in analytical decomposition of demand side of drought.
- Work to do:
  - Research application and operational applications:
    - T_{max}, T_{min} vs. T ?
    - How to present live attribution to end-users?
    - Engagement of wildfire community.
  - Treatment of closure error.
  - Many moving parts, lots of results and applications.
- Impacts of individual drivers on drought's demand side vary regionally and seasonally. In Midwest:
  - T_{max} has the most significant impact.
  - R_d and U_2 have very little impact.