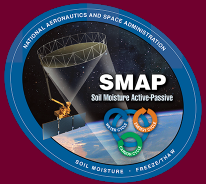
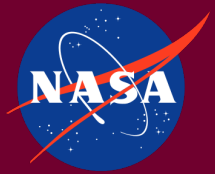




Measuring ecosystem function and water use from space: From satellites to simulations

K. Arthur Endsley
Numerical Terradynamic Simulation Group (NTSG)
W.A. Franke College of Forestry and Conservation

March 3, 2026

Studying Geophysics in Alaska, Summer 2009

Michigan Technological University

Studying Geophysics in Alaska, Summer 2009

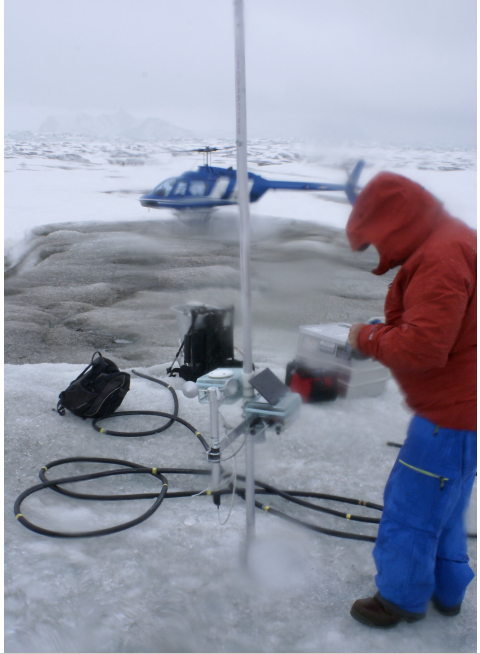
“Remote sensing” of a glacial moraine’s sub-surface water table to investigate a salt-water wedge.

Michigan Technological University

Berg Lake, Alaska,
August 2010

Installing depth and temperature gauges in pro-glacial lake.

Michigan Technological University



Field work at the Bering Glacier, June 2012

Michigan Technological University

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Returning to the Glacier, August 2012

World-wide, melting glaciers and ice sheets have contributed 1.5 inches to sea-level rise since 1992.

Michigan Technological University

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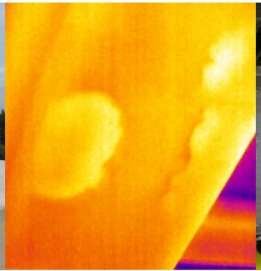
Soil moisture measurements in Alaska, July 2012

Staying dry at Bonanza Creek Long-Term Ecological Research (LTER) site

Bering Glacier research program de-funded the same year.

Remote Sensing of Bridge Condition

3D Optics	Thermal Infrared (IR)	Digital Image Correlation	Ultra-Wide Band Radar
			
Percent spalled, volume and area of spalls, IRI, crack patterns, density	Percent delaminated area, location of delaminations	Deflection, vibration	Percent delaminated area, location of delaminations

Graduate research in Detroit, Michigan, May 2016

Visiting abandoned and re-purposed parcels after the Great Recession

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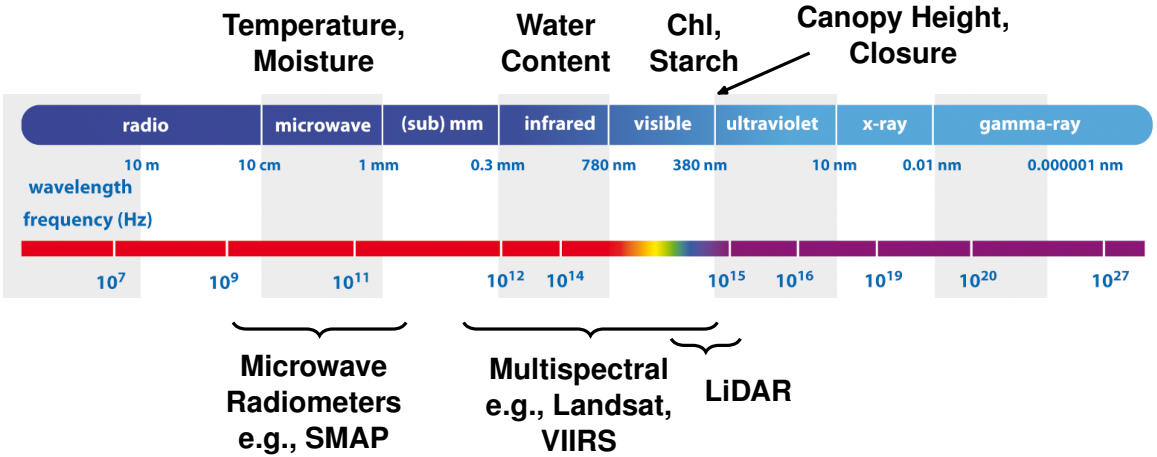
Finished PhD, started work at Univ. Montana, August 2019

(I rarely get paid to go into the field now, but I got to do NASA fieldwork in Alaska again in 2024.)

Remote Sensing of Ecosystem Water and Carbon



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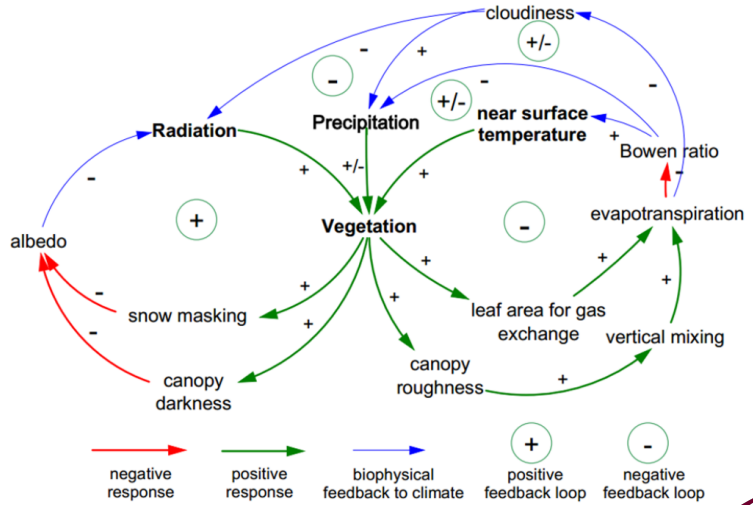
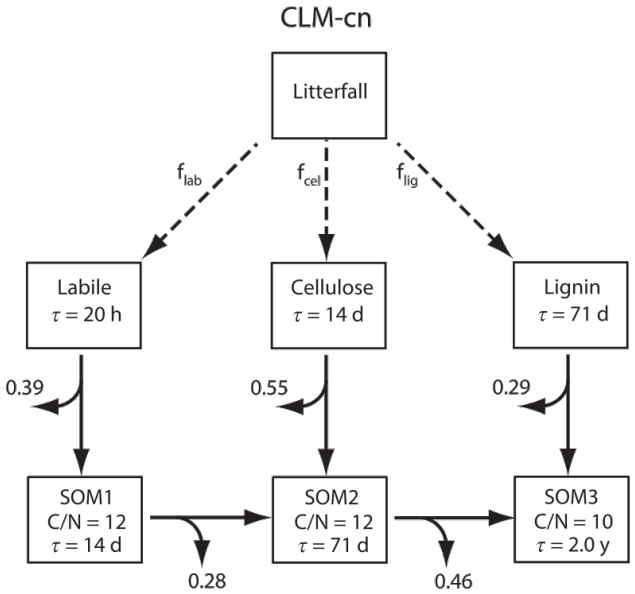
Process-based Ecosystem Models



Zhang et al. (2014, *Biogeosciences*)

Process-Based Ecosystem Models



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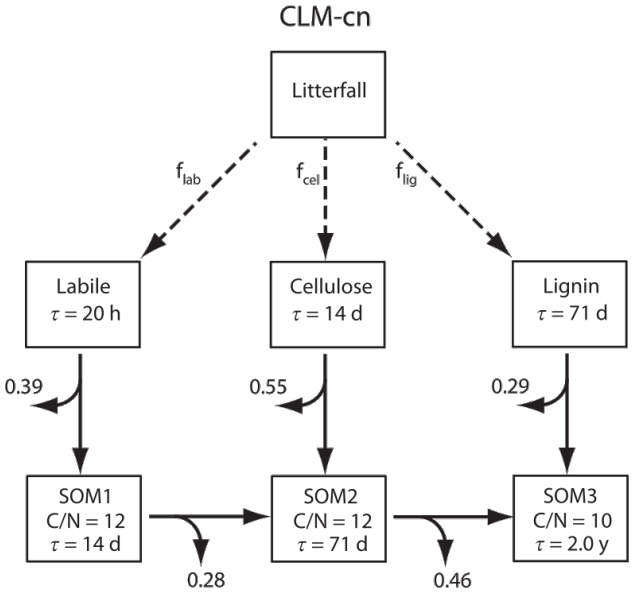
Advantages of process-based models:

- Modular
- Traceable
- Explicable
- Differentiable
- Transparent



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Implicit versus Explicit Models

You are already a modeler!

- *What time should I arrive at the airport for my flight?*
- *Will I have a good time at the party?*
- *Can I afford to eat out this weekend?*

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Implicit versus Explicit Models

You are already a modeler!

- *What time should I arrive at the airport for my flight?*
- *Will I have a good time at the party?*
- *Can I afford to eat out this weekend?*

These **implict models** are based on our prejudices, with no clear link to data.

Process-based ecosystem models are **explicit models**, where assumptions and data are clearly specified.

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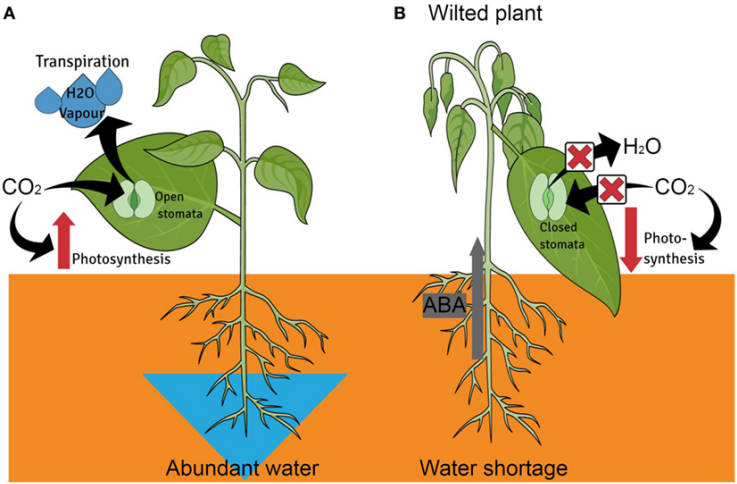
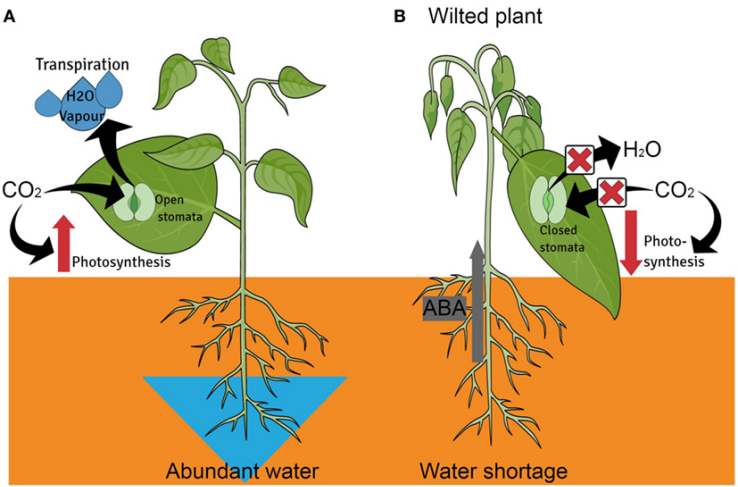
Linking Water and Carbon Cycles



van der Vyver & Peters (2017, *Front. Young Minds*)

Linking Water and Carbon Cycles



van der Vyver & Peters (2017, *Front. Young Minds*)

- Agricultural yields
- Agricultural water use requirements
- Atmospheric CO_2 that is sequestered
- Forest mortality (plants can starve without CO_2 to make food)
- Vegetation species change and change in water-use strategies

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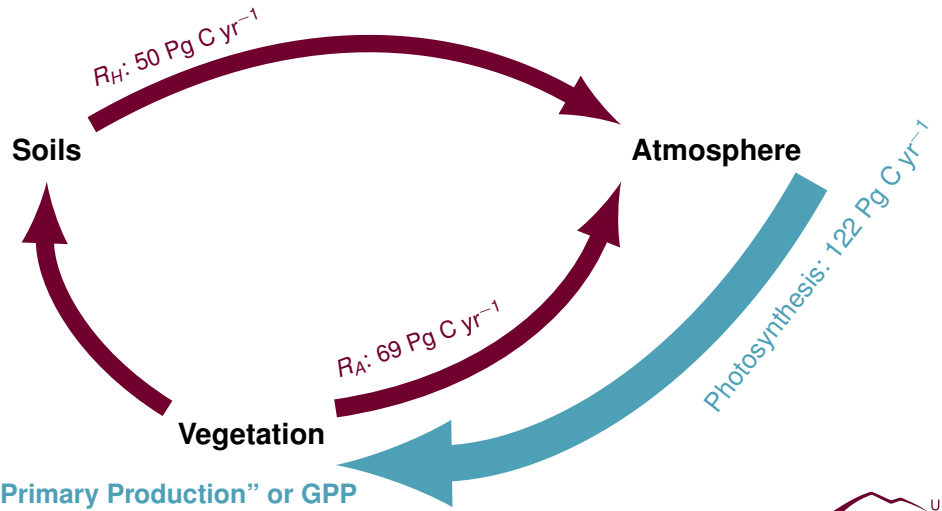
The Terrestrial Carbon Sink



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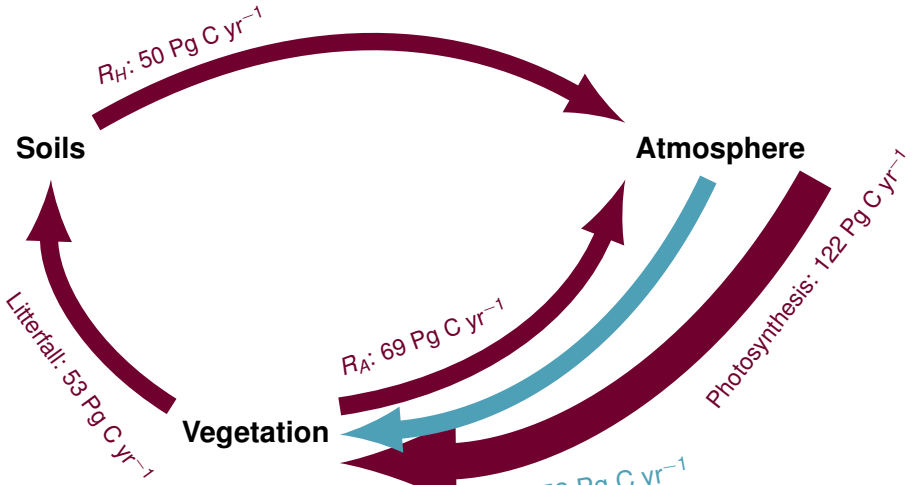
The Terrestrial Carbon Sink



"Net Primary Production" or NPP

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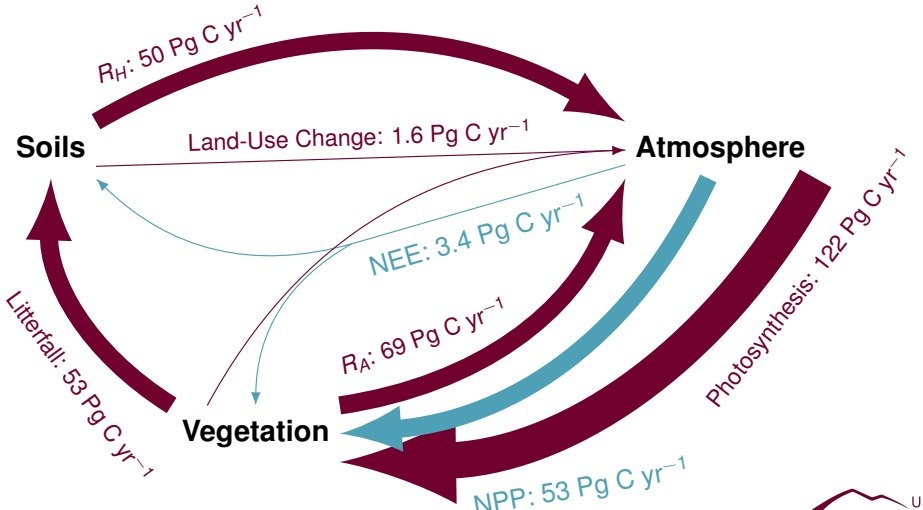
The Terrestrial Carbon Sink



Zaehle (2013); Friedlingstein et al. (2020)

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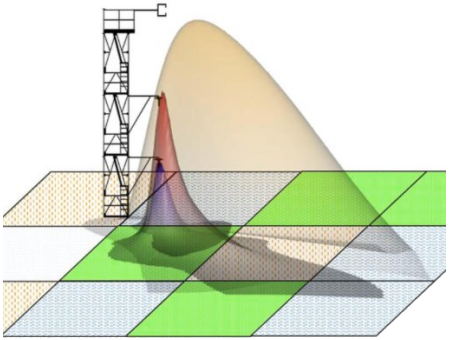
Ground-Based Measurements of NEE and GPP



Eddy covariance towers measure net (CO_2) gas exchange **("net ecosystem exchange" or NEE)** between ground and atmosphere; can also measure net flux of water vapor

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Two Satellite Missions for Ecosystem Science

Soil Moisture Active Passive (SMAP)

Terra/Aqua MODIS (and VIIRS)

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NASA Soil Moisture Active Passive (SMAP) Mission

- Launched in 2015, collecting passive L-band microwave data since March 2015
- Twice-daily observations of **surface soil temperature and moisture**
- Two **model-enhanced** data products: Level 4 Soil Moisture (L4SM)[1] and Level 4 Carbon (L4C)[2,3]

[1]Reichle et al. (2017, *J. Hydrometeorology*); [2]Jones et al. (2017); [3]Endsley et al. (*In Review*)

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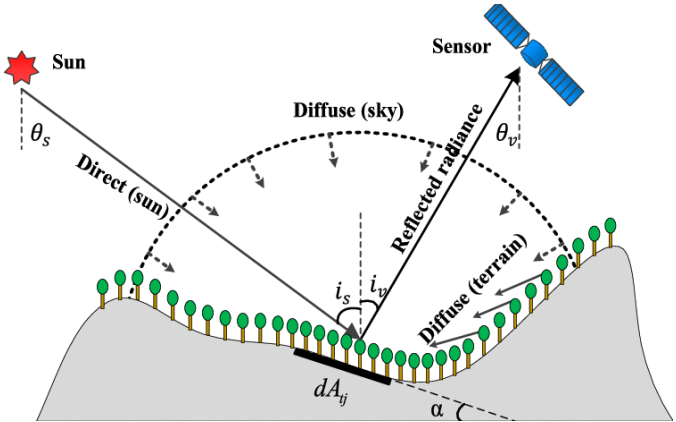
The Light-Use Efficiency Model

How much photosynthetic canopy is in a given pixel?



Hao et al. (2018, *IEEE TGARS*)

The **fraction of photosynthetically active radiation (fPAR)** is similar to NDVI, but is computed through complex **radiative transfer modeling.**

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Modeling GPP with SMAP Measurements

fPAR is used to determine **how much solar energy is absorbed during photosynthesis (APAR):**

$$\text{APAR} = \text{fPAR} \times [\text{Incoming solar energy}]$$

Daily rate of atmospheric carbon (C) absorbed:

$$\text{GPP} = \underbrace{\varepsilon_{max} \times \text{APAR}}_{\substack{\text{Solar energy} \\ \text{conversion rate}}} \times \underbrace{f(T_{min}) \times f(\text{VPD})}_{\text{Climate constraints}} \times \underbrace{f(\text{Frozen?}) \times f(\text{Soil Moisture})}_{\text{SMAP Observations}}$$

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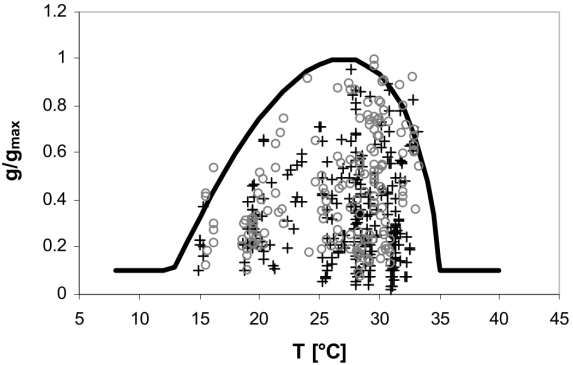
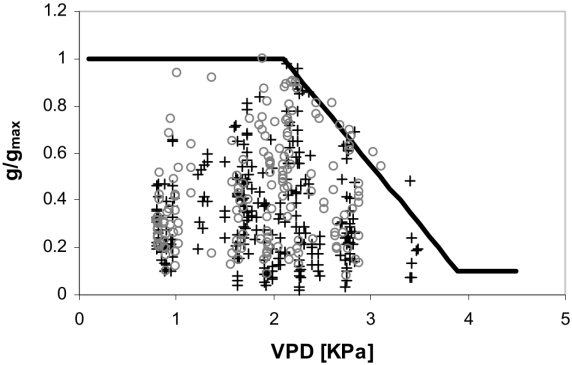
Modeling GPP with SMAP Measurements (2)

The impact of minimum temperature or soil moisture on GPP is modeled using **"boundary line analysis;"** i.e., empirical functions $f(\cdot)$, modeled independently:





Gerosa et al. (2012)

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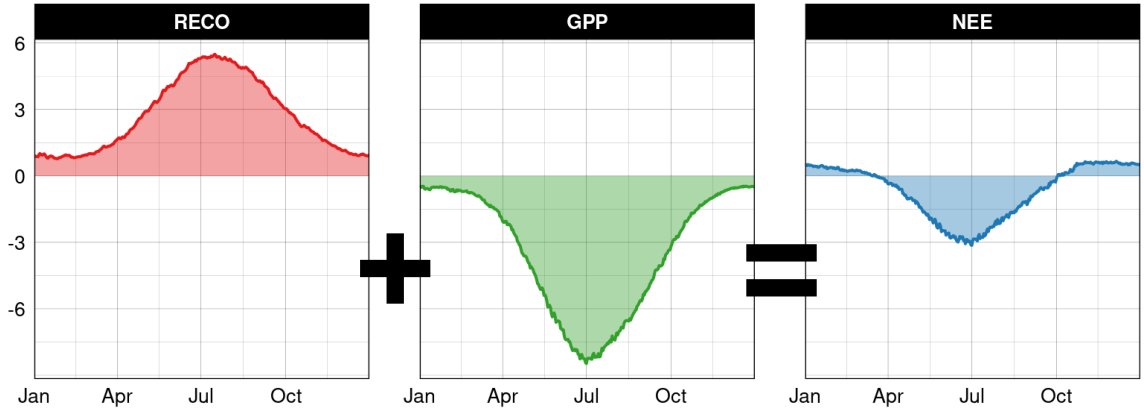
SMAP L4C Daily Carbon Budget



$$\text{NEE} = R_H + (R_A - \text{GPP})$$

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SMAP Level 4 Carbon Data Visualization

Link to NASA Worldwind

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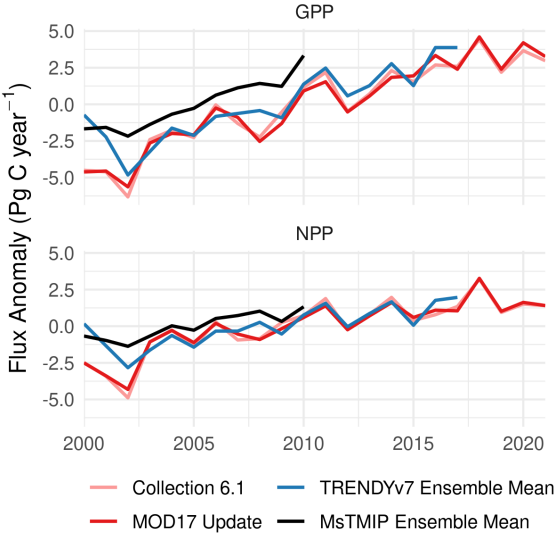
Increasing Terrestrial C Uptake



Gradually increasing land C uptake (GPP) and assimilation (NPP) are consistent with CO_2 fertilization and global expansion in leaf area, but rates have slowed in recent years.[1]

Consistent with reports of saturation of Amazon forest C sink in 2000s,[2] of African forests in 2010s.[3]

Endsley et al. (2023); [1]Wang et al. (2020); [2]Peñuelas et al. (2017); [3]Hubau et al. (2020)

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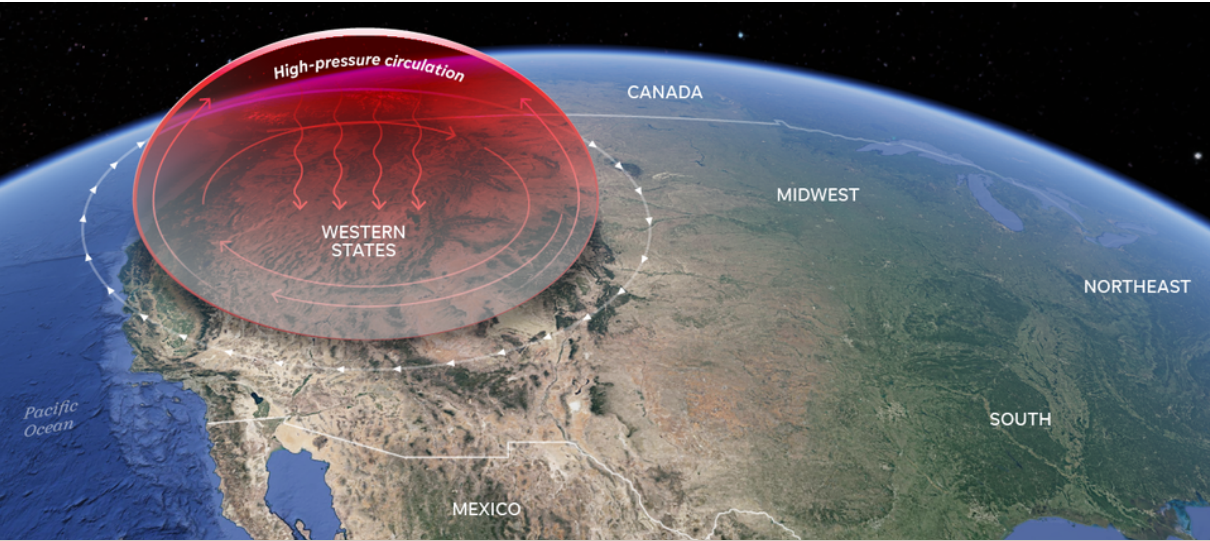
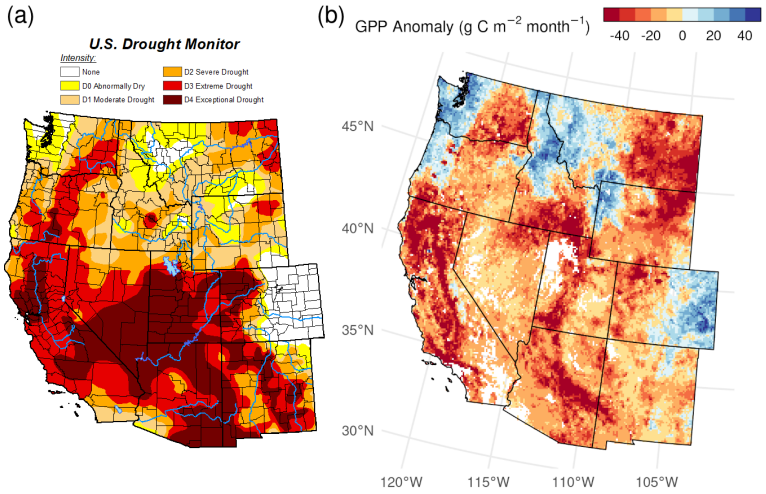
Remember Summer 2021? (And 2024)



SMAP: Predicting Drought Impacts



Pacific Northwest Heat Dome (2021) brought highest recorded air temperatures, in some locations exceeding 40-45℃. Within days, **widespread leaf damage** was observed.[1]

SMAP helps to identify the spatial pattern, magnitude of impacts on GPP.

Endsley et al. (*In Review*); [1]Klein et al. (2022)

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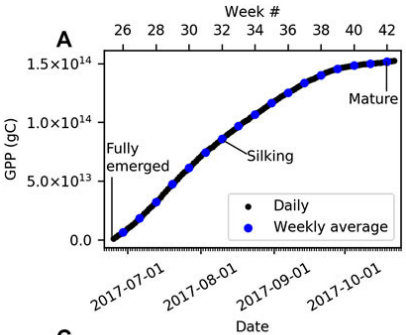
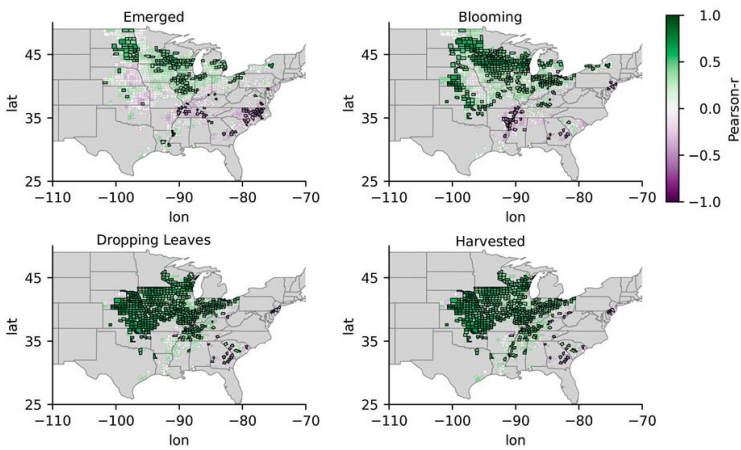
SMAP: Predicting Crop Conditions and Yields





Wurster et al. (2021, *Frontiers in Big Data*)

MODIS MOD16 Evapotranspiration (ET)

- MODIS provided the first global, weekly terrestrial productivity estimates, **for which UM Professor Steve Running won a Nobel Prize!**
- On-going, 25-year record of earth surface measurements, every 8 days at 250-m and 500-m resolution
- **Terra MODIS has reached end of useful life: Can VIIRS serve as a replacement?**

Running et al. (2004); Xiao et al. (2019, *Rem. Sens. of Environ.*)

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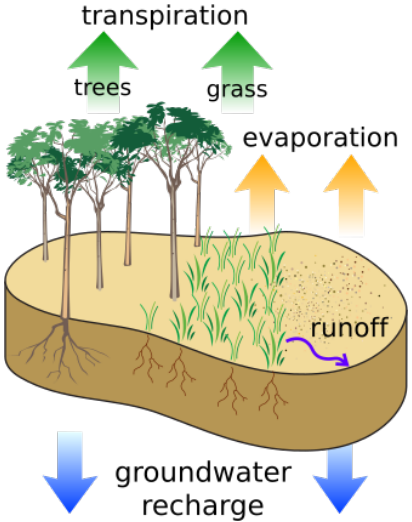
Modeling Evapotranspiration (ET)



Evapotranspiration = Transpiration + Evaporation

ET is a key flow of water in ecosystems:

$$\Delta[\text{Groundwater}] = [\text{Precip.}] - \text{ET} - [\text{Runoff}]$$

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Modeling Evapotranspiration (ET)

From Monteith (1965):

> *The evaporation of water is like a commercial transaction in which **a wet surface sells water vapour to its environment in exchange for heat…** The environment can supply heat by solar radiation, by turbulent transfer from the atmosphere, or by conduction from the soil.*

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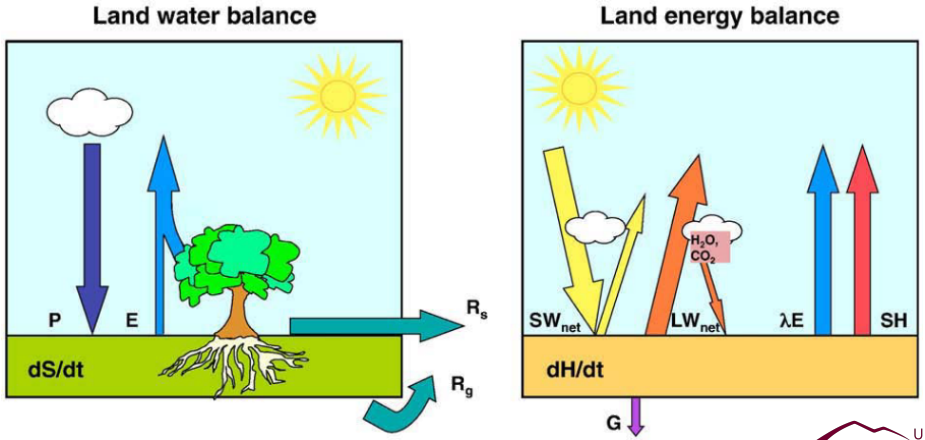
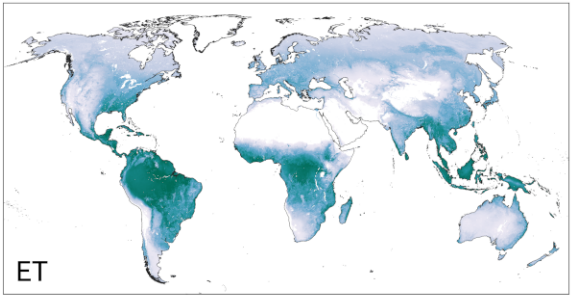
Modeling Evapotranspiration (ET)

Latent heat flux, λE: Water exchanged (vaporized) for input energy



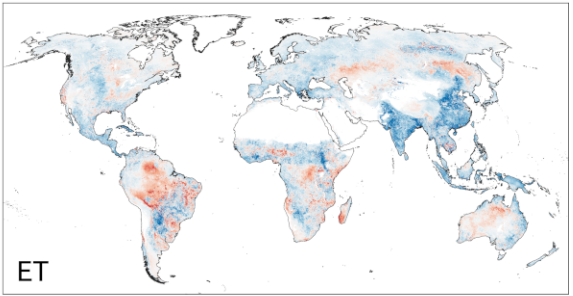
Seneviratne et al. (2010)

MODIS MOD16 Evapotranspiration Model



Mean Annual ET (2000-2023)
(mm H_2O $year^{-1}$)

0 ≥1300



Trend in Mean Annual ET (2000-2023)
(mm H_2O $year^{-2}$)

-10 10

- Modified Penman-Monteith approach
- Global, 8-day ET and PET with 500-m resolution
- 2000-Present, now continuous with VIIRS sensors

Endsley et al. (2025, *J. Hydrometeorology*); Mu et al. (2011)

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MODIS MOD16 Evapotranspiration Model (2)

The Penman-Monteith model (used in MOD16) is based on two big ideas:

1. Determine **how much energy is available to vaporize water** (conservation of energy)
2. Determine **when to stop vaporizing water,** i.e., when the air is saturated

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MODIS MOD16 Evapotranspiration Model (2)

The Penman-Monteith model (used in MOD16) is based on two big ideas:

1. Determine **how much energy is available to vaporize water** (conservation of energy)
2. Determine **when to stop vaporizing water,** i.e., when the air is saturated

Three components in MOD16:

- **Transpiration** of water from plants
- **Evaporation from soil**
- **Evaporation from wet canopy** (i.e., water on leaves)

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Polar-orbiting meteorological satellite
Polar-orbiting earth resources satellite
Geostationary meteorological satellite
High-altitude aircraft
International aircraft
Meteorological research aircraft
Radiosonde
Baseline air pollution station
Meteorological satellite ground station
Automated river-height and rain gauges
Pilotless aircraft
Automatic weather station
Wind profiler
Voluntary observing ship
Domestic aircraft
Meteorological observing station
Over-the-horizon radar
Drifting buoy

What Remote Sensing Data Predict ET?

Canopy transpiration depends on fPAR, Leaf Area Index

- From MODIS or VIIRS multispectral observations

Evaporation also depends on fPAR, i.e., how much bare ground versus vegetation cover?

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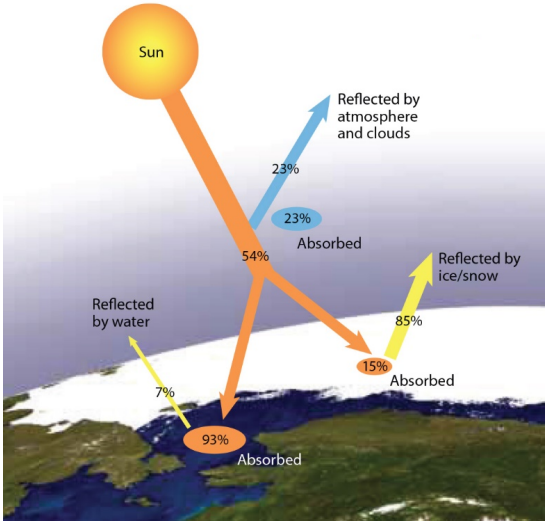
What Remote Sensing Data Predict ET?



Surface albedo, α, is an important, remotely sensed quantity that determines how much radiation (R_{net}) is available to vaporize water:

$$R_{net} = [\text{Solar energy}] \times (1 - \alpha) + [\text{Earth's thermal energy}]$$

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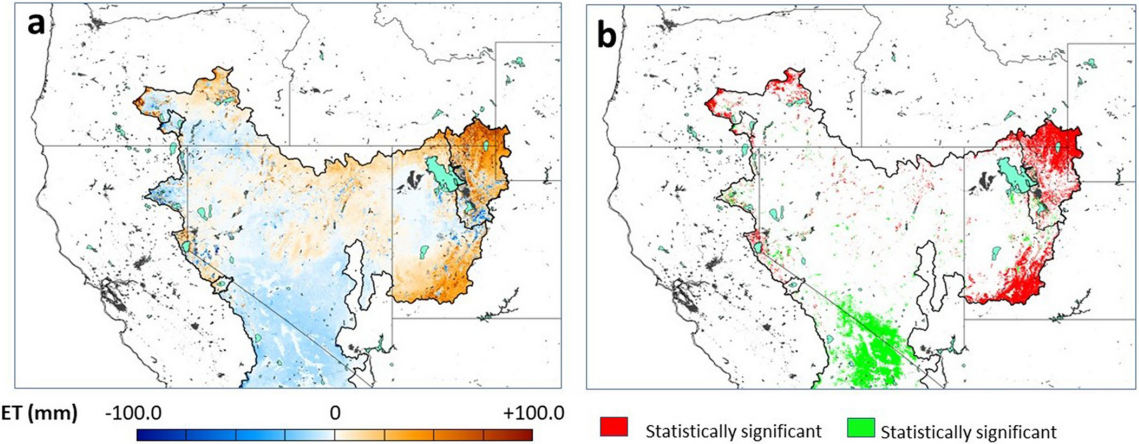
MOD16: Improved Understanding of Lake Dessication



Hall et al. (2023)

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Thanks! Questions?

Photo by A. Endsley

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