Drought Monitoring and Forecasting

By
Dr. MANIRAGABA Abias
University of Lay Adventists of Kigali (UNILAK)

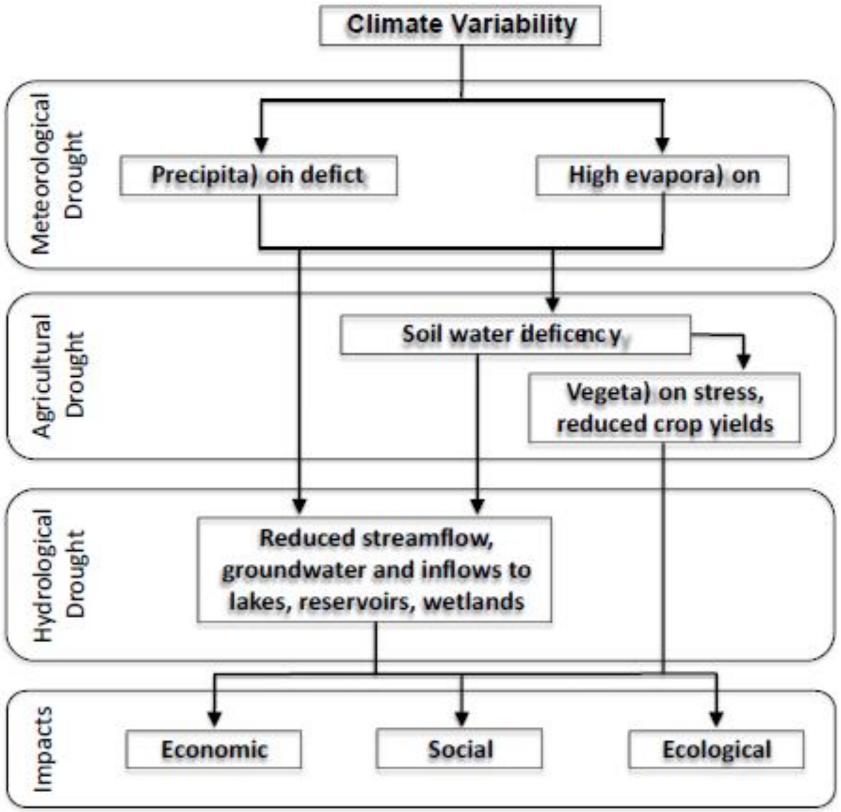
Drought

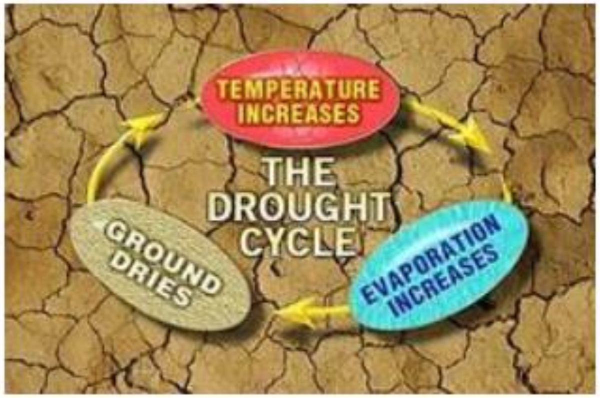
- What is Drought?

Drought is a deficiency in precipitation over an extended period, usually a month or season or more, resulting in extensive damage to crops, loss of yield, resulting in a water shortage causing adverse impacts on vegetation, animals, and/or people.

It is a normal, recurrent feature of climate that occurs in virtually all climate zones, from very wet to very dry.

Drought Types and Mechanisms



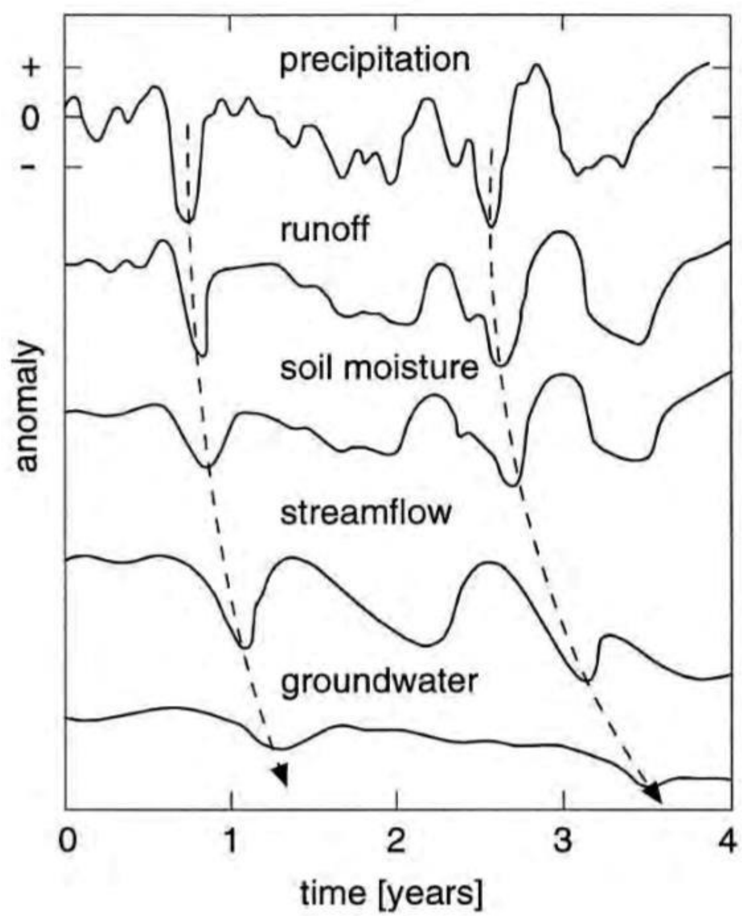


Drought Propagation

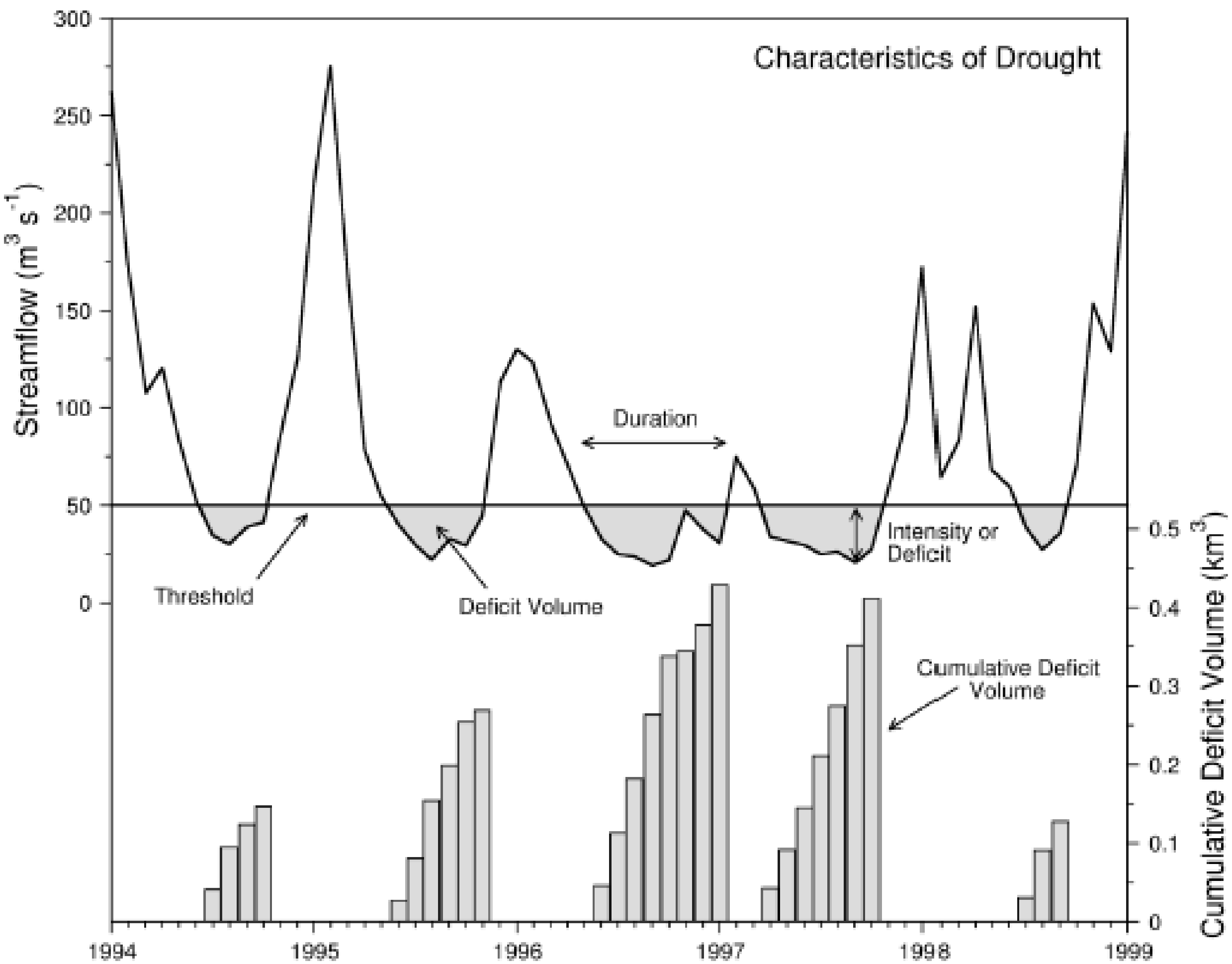
A drought event generally begins with a deficit of precipitation

- The drought signal propagates through the rest of the hydrological system
- The signal is filtered and often becomes more persistent

Conceptual figure of drought propagation through the hydrological system



Drought Characteristics



A drought is defined when the quantity drops below a threshold level.

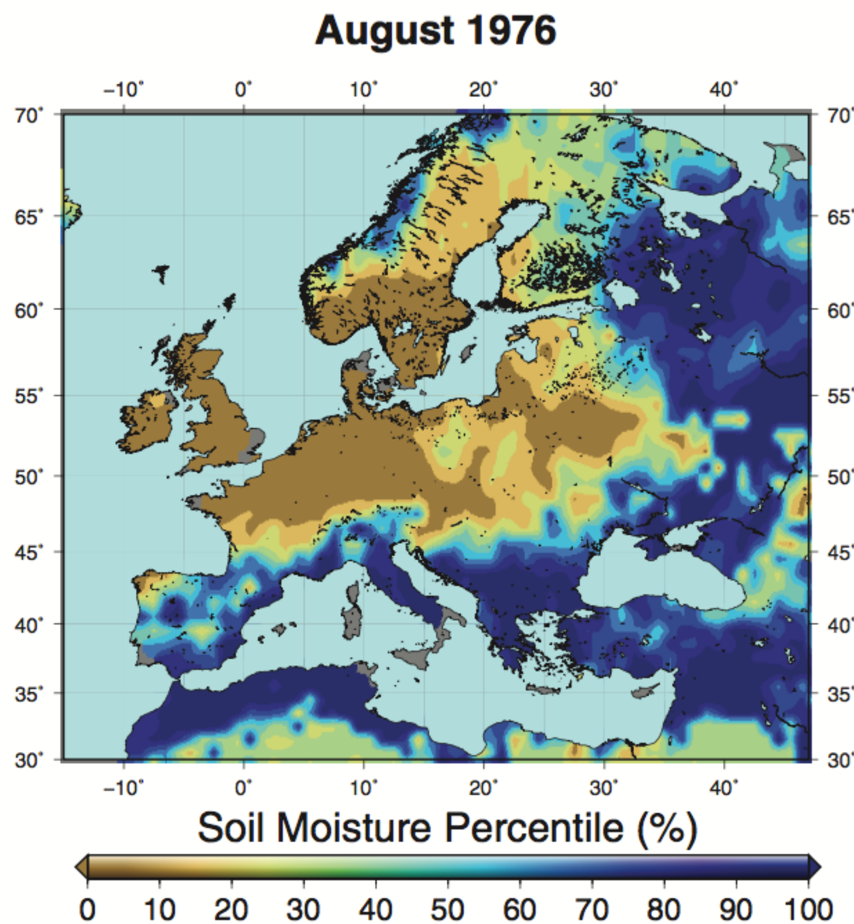
- The time that the index is below the threshold is the duration of the drought.
- The level below the threshold at any particular time is the deficit, magnitude or intensity of the drought.
- The severity describes the combined duration and intensity/magnitude of the drought, calculated as the intensity multiplied by the duration. This is also often referred to as the deficit volume for hydrological

Spatial Characteristics of Drought

. Droughts can further be characterized by their spatial extent

•For example, by identifying connected regions of low index values, such as soil moisture from models/satellite retrievals, or measured streamflow at various gauging sites.

•Indices can be defined based on the area in drought (e.g. % or fraction) or the average severity over the region.



Impacts in Africa

By 2050, potential mean production losses for sub-Saharan Africa are predicted to be high (*Schlenker and Lobell, 2010*).

Why Forecasting of Climate, Hydrology, or Water Resources? What is it?

What is it?

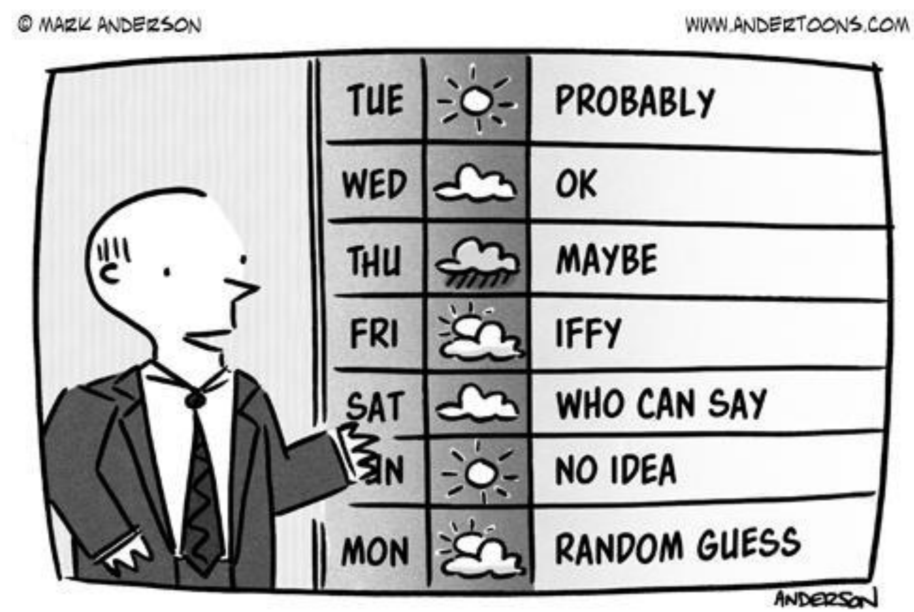
- Forecasting climate, availability of water, or extreme events (droughts, floods) over the next weeks, months or years

Why is it important?

- Decisions can be made that could saves lives, increases income, reduces losses, increases productivity, … (DRR)
- Water resources management can be improved or optimized

- Flood warnings, drought early warning

How can we possibly forecast something so far in the future?



"And now the 7-day forecast..."

▪ Forecasting relies on the inertia in the climate system (the tendency for aspects of the system to persist in a certain state) and teleconnections between these states and the variable of interest (e.g. streamflow at a certain locations).

•These sources of predictability can be the ocean temperature, soil moisture, snow pack, …, each persists at different time scales

Forecasting, Predictions and Projections

Some definitions

- Forecasting: making an estimate of what will happen in the future (exact or deterministic)
- Prediction: making an estimate of what might happen in the future (inexact or probabilistic)
- Projections: making an estimate of a plausible future (inexact)

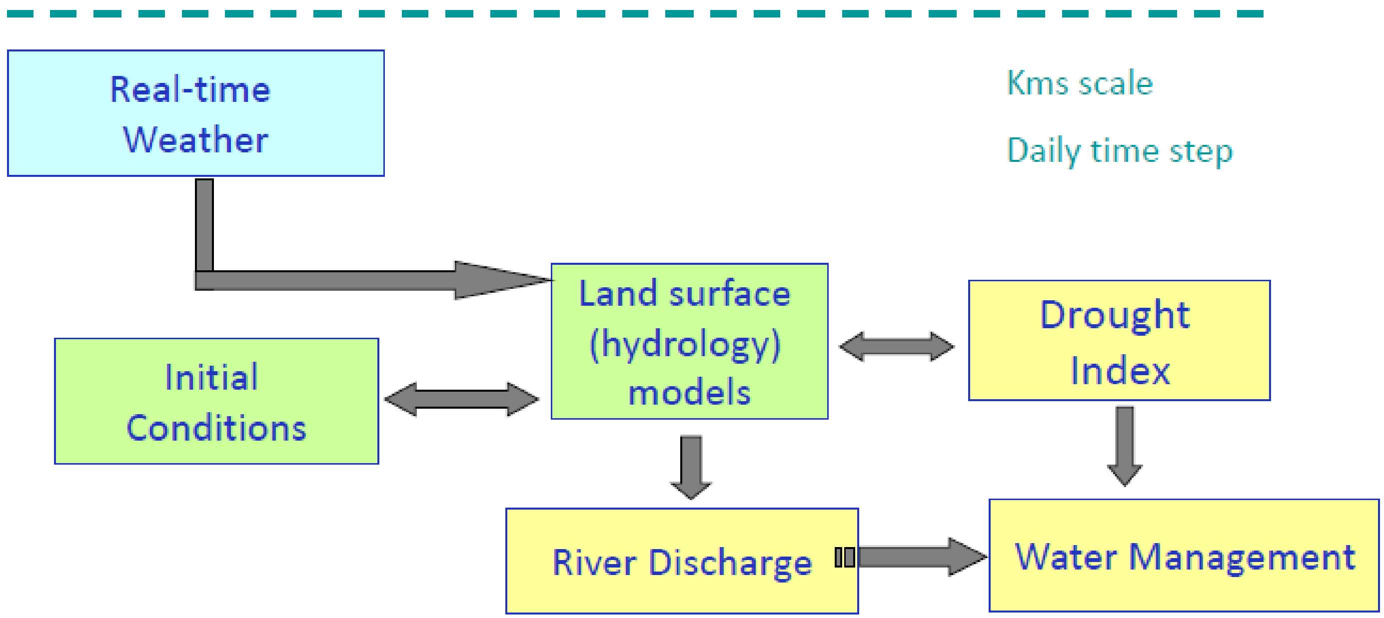
Deterministic versus probabilistic

- Deterministic process is exactly defined, e.g. it will rain next week
- Probabilistic process captures the uncertainty, e.g. 30% change of rain

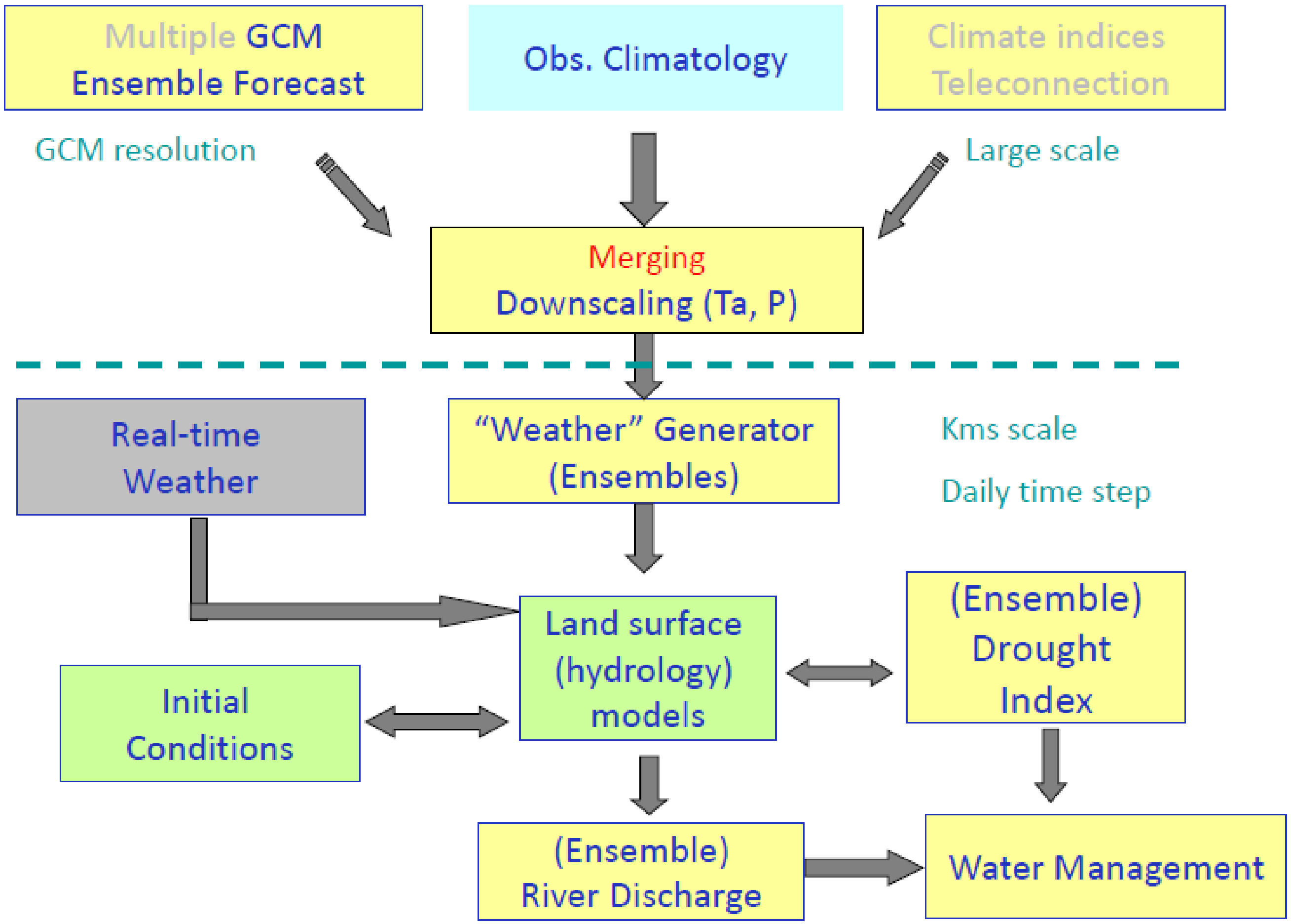
Two Main Types of Forecasting

- Statistical:
  - pros (easy to use; based on real data; simple)
  - cons (empirical so no direct physical basis; may be associative; assumes stationarity)
- Dynamical(physically-based model):
  - pros (physical basis, can be used for attribution)
  - cons (complex; skill dependent on model; challenged by chaos of climate systems)

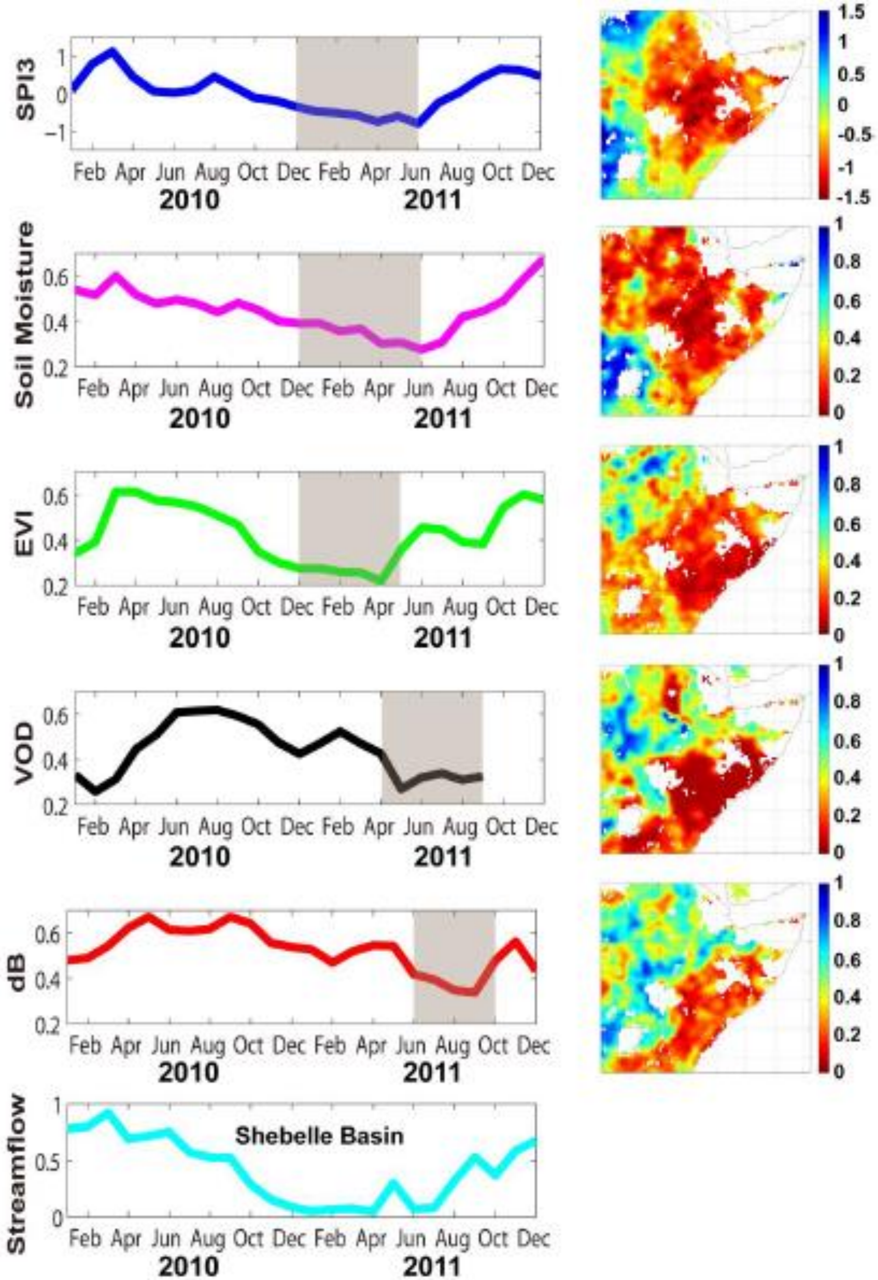
Hydrologic Monitoring and Prediction System



Hydrologic Monitoring and Prediction System

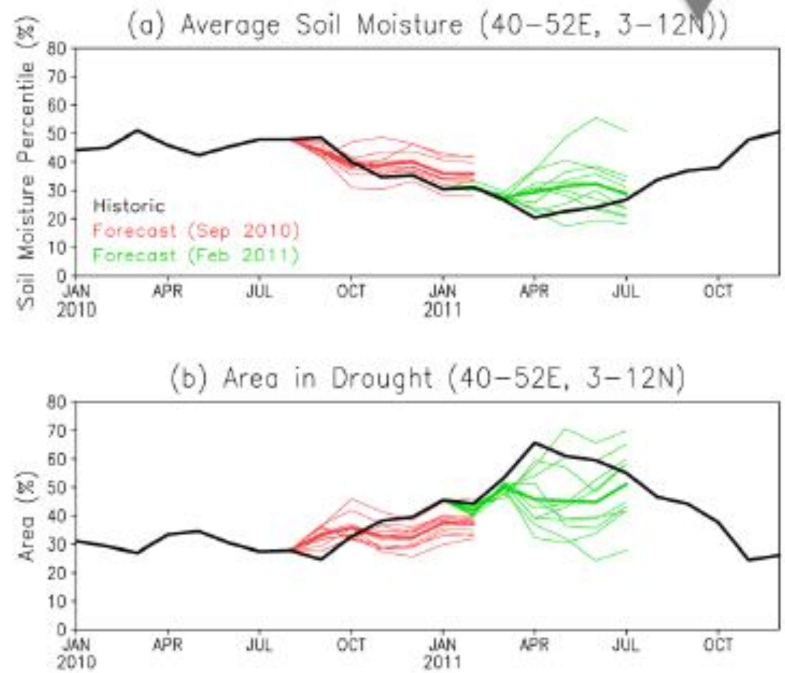


Regional Example: Horn of Africa Drought 2010-2011

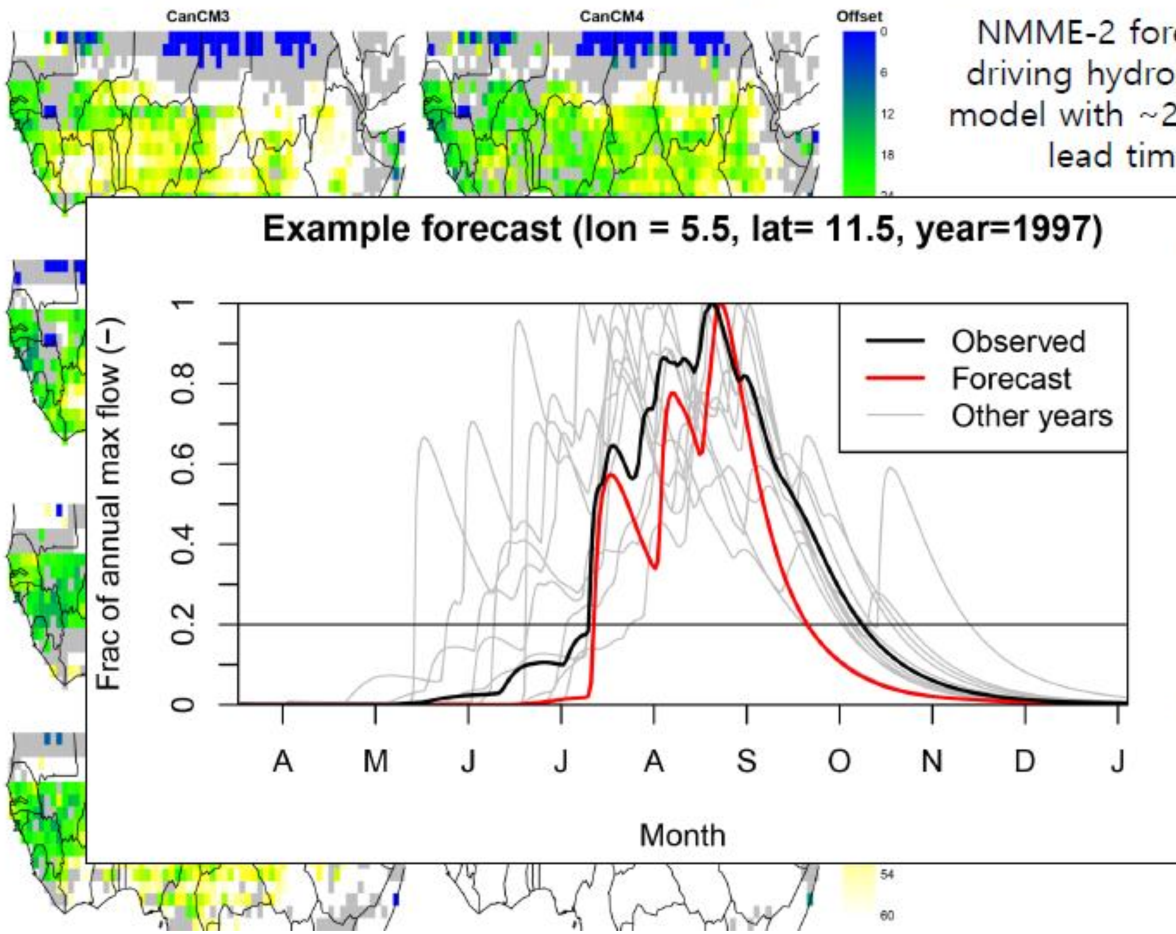


Monitoring the propagation of the drought

Seasonal forecasts (based on CFS model only)



Linking to Sub-Seasonal Hydrological Forecasts

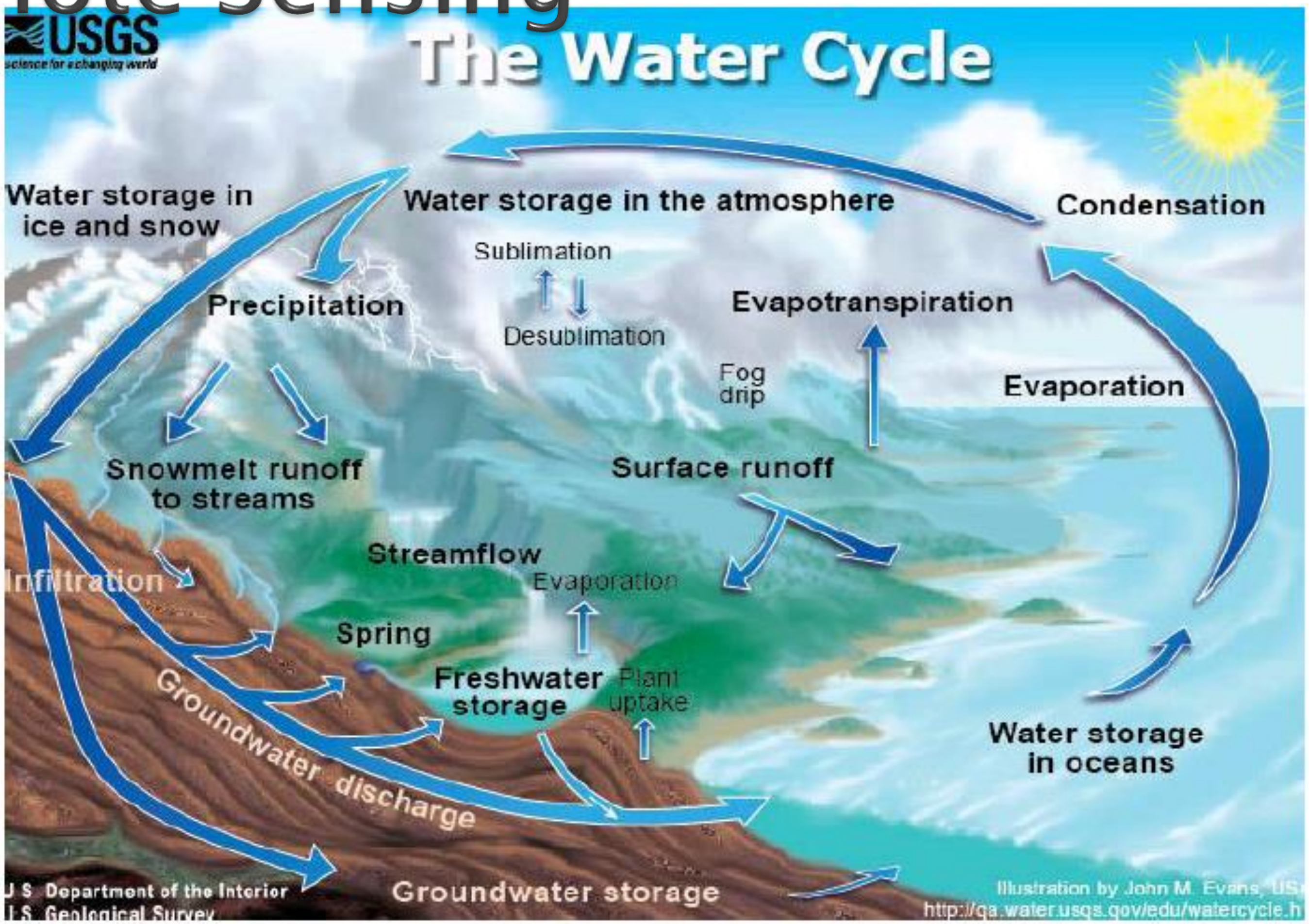


NMME-2 forecasts driving hydrological model with ~2 month lead time

season

flow

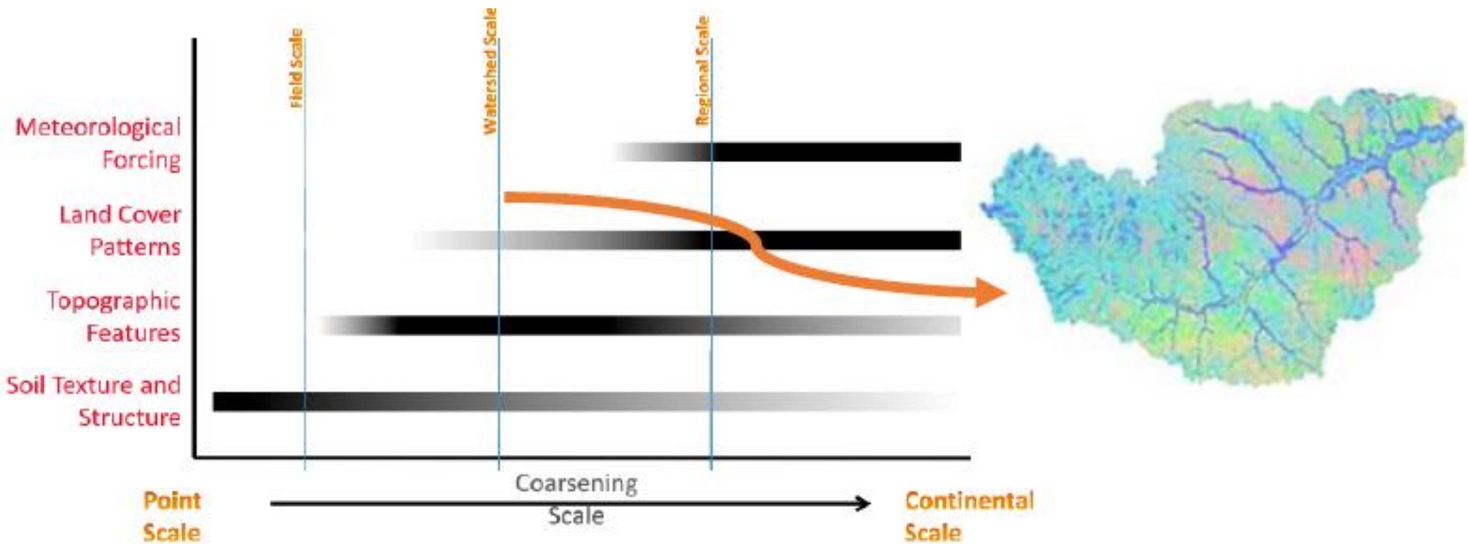
Introduction to Soil Moisture Remote Sensing



Soil Moisture

- 75% of land precipitation globally enters the soil
- Soil moisture provides
  - all the water for natural and cultivated agriculture
  - and almost all the water that enters groundwater reservoirs (recharge)
- Soil moisture is highly variable spatially – controlled by different drivers depending on the scale = important especially for agriculture

Dominant physical controls on soil moisture spatial variability as a function of scale



(Crow et al., 2012)

Importance of Soil Moisture

- "*In the structure and functioning of landscapes, soils are the matrix through which energy, water, biomass, and nutrients flow…the interface in the cycling of water between the atmosphere and land…the location of large transformations of energy.*" *Bonan, 2002*

Definitions: Soil Moisture

Volumetric water content (theta) also called water content or soil moisture content

$\Theta = V_w/V_s$

Where Vw is the volume of water Vs of the volume of the soil column

Θ ranges from > 0 to porosity

The total amount of water stored in any layer of soil (soil water storage) is usually expressed as depth (mm) of water which is:

SM (mm) $= \Theta$ x depth of soil layer

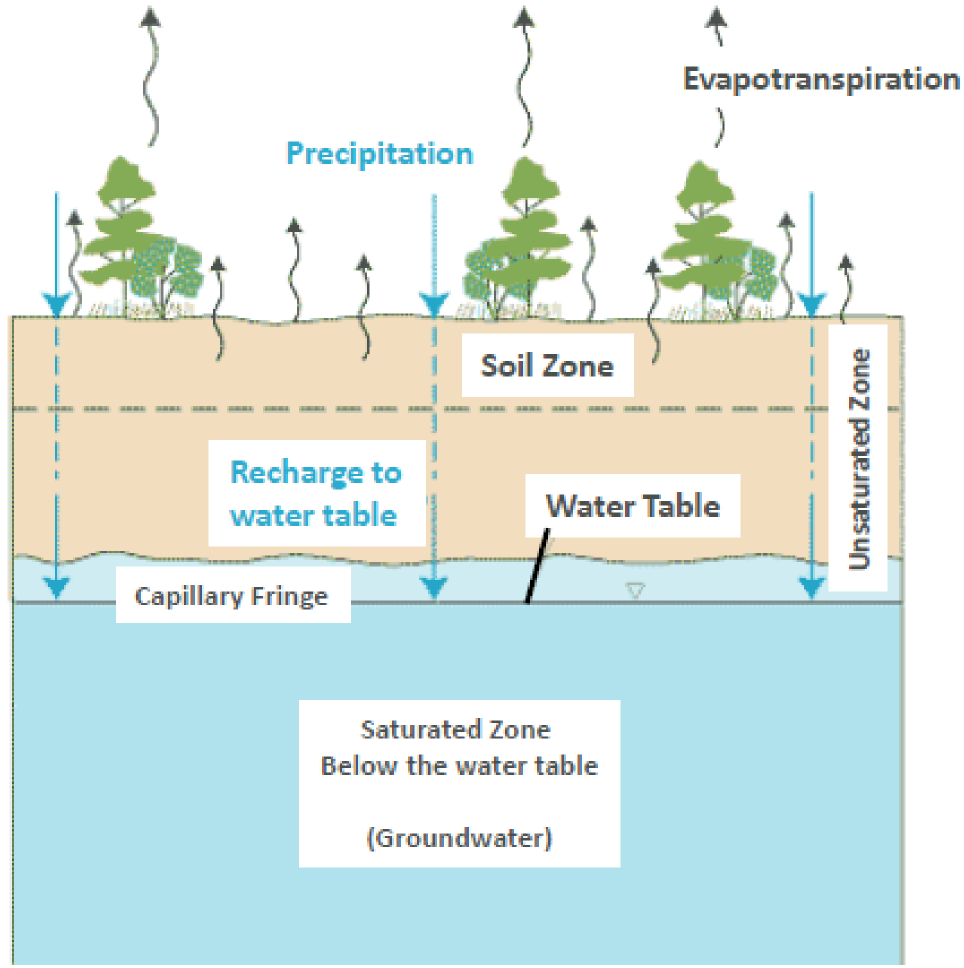
Saturation or wetness is the proportion of the soil pores that contains water (0-1)

Definitions: Soil Structure

- Soils Composed of:
  - Organic Matter (>80% organic soil, <10% mineral soil)
  - Minerals (From parent geology, ~55% in mineral soil)
  - Air
  - Water
- Type, abundance, arrangement of particles govern heat flow, water flow, nutrient availability

Water Movement in the Unsaturated Zone

- Unsaturated (Vadose) Zone
  - Zone between the land surface and water table
  - Soil pores contain water and air (pressure < atmos)
- Infiltration
  - Occurs if soil pores near the surface are not completely filled
- Drainage
  - Water can move through the UZ to the saturated zone (GW) as recharge, via gravity and pressure gradients
- Water table
  - Divide between UZ and SZ
  - Pressure is at atmospheric
  - Capillary fringe just above the water table due to capillary forces
  - SZ is under positive pressure



Why Remote Sensing of Soil Moisture?

Ground-based measurements of soil moisture have the advantage of frequent updates, but are generally sparse and unavailable in many parts of the world, and often short-term.

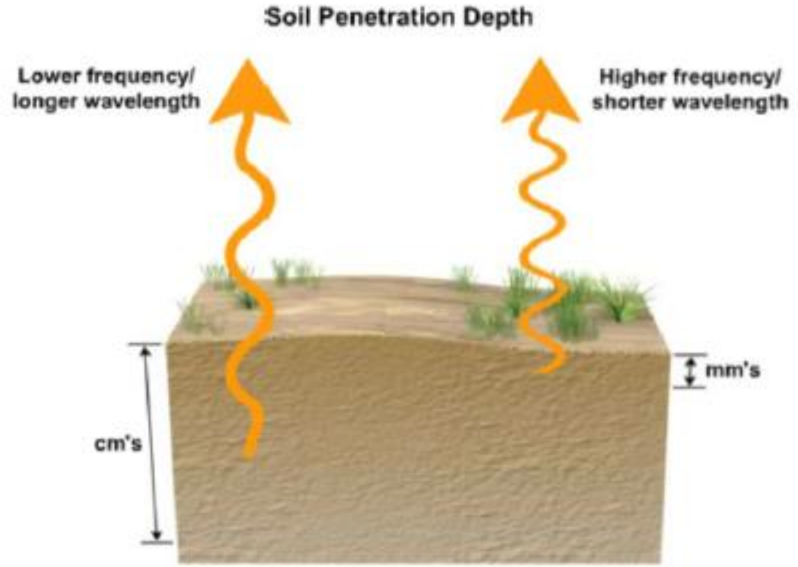
- RS provides **global coverage at reasonably high resolution**
- Many polar-orbiting satellites employ an **all-weather microwave remote sensing capability that provides global coverage.**
- Microwave radiation, particularly at lower frequencies, is very sensitive to changes in surface moisture and penetrates all but the densest and precipitating cloud cover.

What the Satellite Sensor "Sees"

Another important consideration when observing soil with microwave wavelengths is the penetration depth.

•The penetration depth is deeper for lower microwave frequencies (1-10 GHz for example) because the longer wavelengths are less absorbed and scattered by the soil.

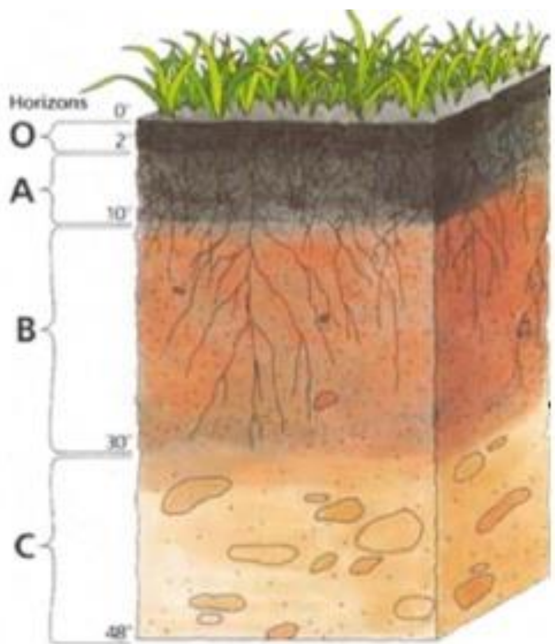
•In contrast, the penetration is significantly less at higher frequencies (e.g. 85-89 GHz), only convey information about the top few millimeters of soil.

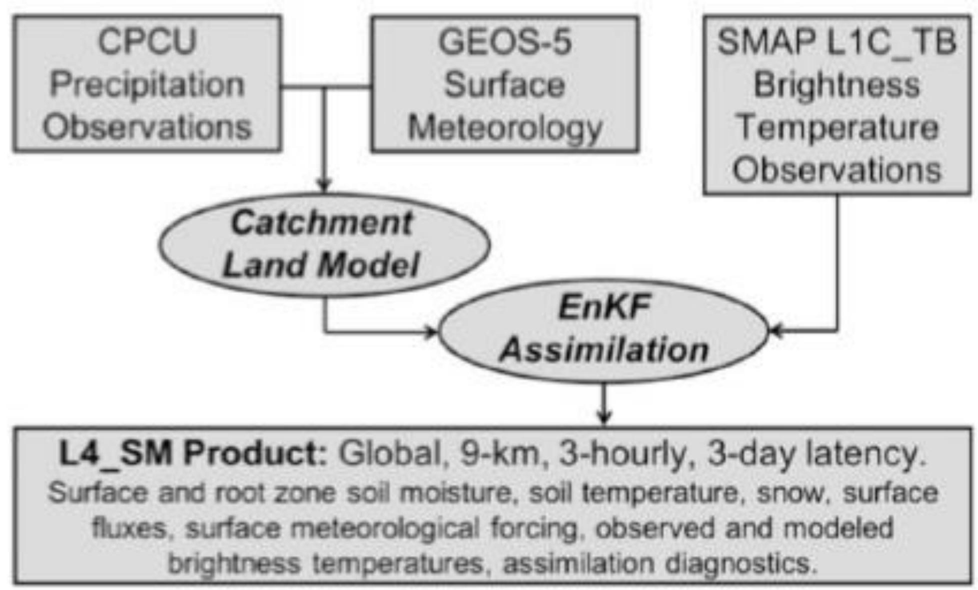


Retrieving Root Zone Soil Moisture

Sensors only measure the top mm to few cms of the soil, but the root zone is the most important for applications

- RZSM can be retrieved by assimilating satellite soil moisture measurements (retrieved soil moisture or brightness temperature) into a land surface or hydrological model





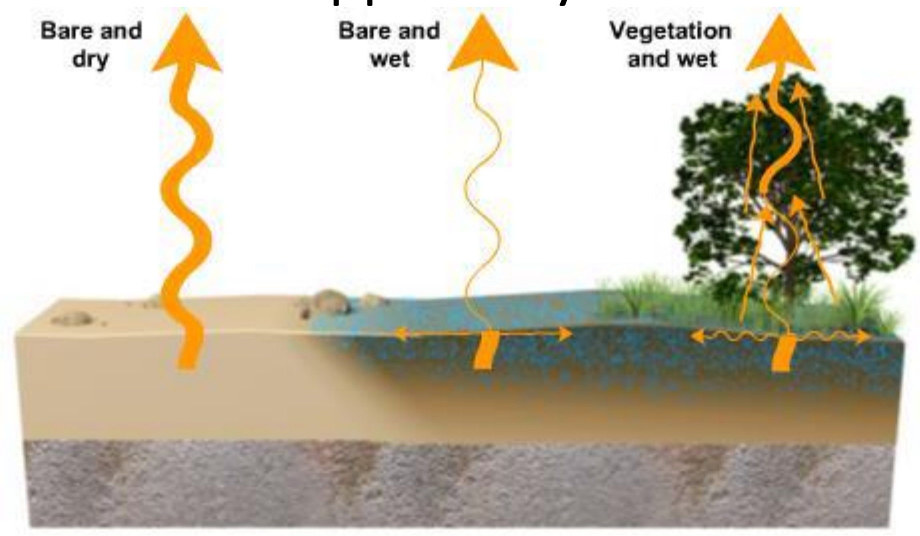
Complicating Factors

Vegetation and surface roughness interfere with the signal being emitted from the Earth's surface.

•Vegetation emits its own microwave radiation, which can be confused with the desired soil emission.

•As the figure shows, vegetation acts to increase the emissivity for an otherwise wet surface below.

•This increases the observed microwave brightness temperature and makes the surface appear dryer than it really is.



Trade-Offs in Microwave Sensing of SM

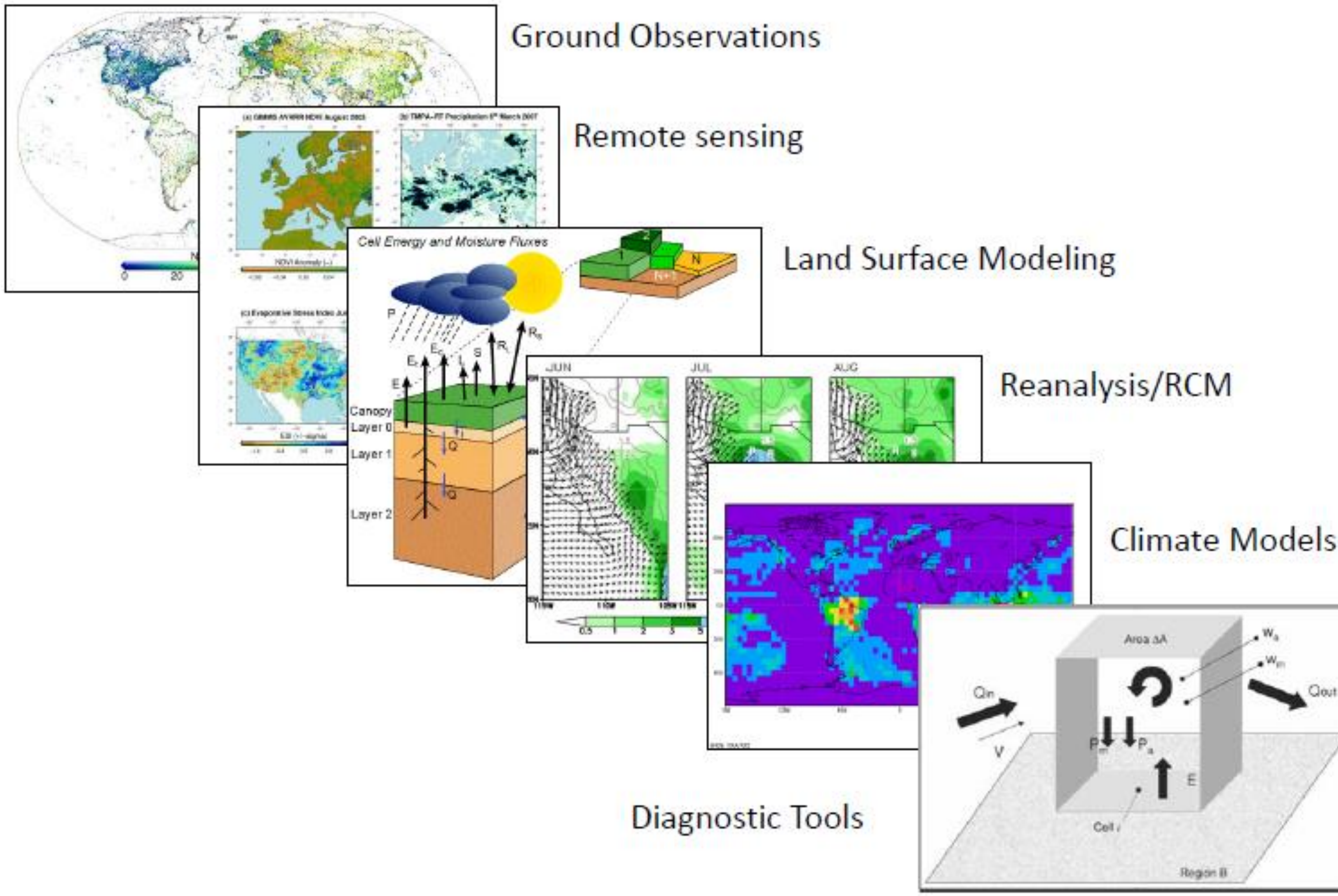
Active measurements are somewhat more sensitive to surface roughness and vegetation structure than passive measurements but:

- Are not affected by surface temperature (above 0^{o}C)
- Have a much higher spatial resolution

Disadvantages of microwave soil moisture Sensors:

- only see the top cm of soil
- use models to get RZSM
- cannot penetrate dense vegetation
- restrict to less vegetated areas or estimate vegetation water content
- low resolution for passive (10s km) because of low energy in MW region
- Combine with active or downscale with models
- radio frequency interference
- remove or restrict to outside of RFI

Research Tools that We Use



Ground Observations

Remote sensing

Land Surface Modeling

Reanalysis/RCM

Climate Models

Diagnostic Tools

The Terrestrial Water Balance or Budget

A water budget is an accounting of the rates of water movement and the change in water storage in all or parts of the atmosphere, land surface, and subsurface.

•Although simple in concept, water budgets may be difficult to accurately determine.

Why is it important?

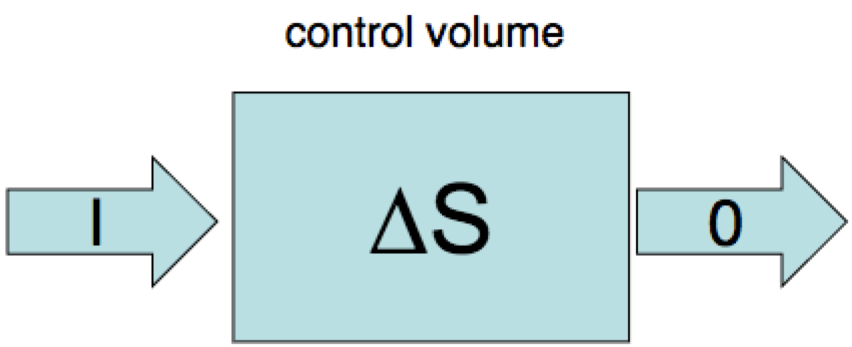
- Conducting water balance estimation provides you with a comprehensive understanding of the water flow system and water resources in your area

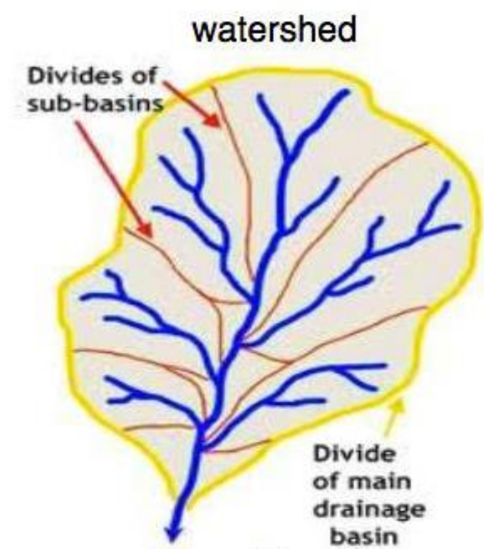
- Water balance estimation is an important tool to assess the current status and trends in water resource availability in an area over a specific period of time

- Water balance estimates strengthen water management decision-making, by assessing and improving the validity of visions, scenarios and strategies.

The Water Balance and the Principle of Conservation

- Principle of Conservation:
- inputs –outputs = change in storage
- $I - O = \Delta S$





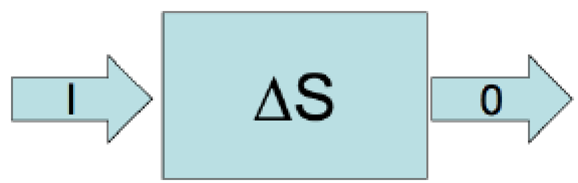
The water balance strictly refers to a control volume, but often applied to a geographic region, most commonly a large basin or a catchment/watershed

The Water Budget Equation

- Conservation of mass requires that, within a specific area over a specific period of time, water inflows are equal to water outflows, plus or minus any change of storage within the area of interest.
- The water entering an area has to leave the area or be stored within the area.
- The simplest from of water balance equation is as follows:

$$I - O = \Delta S$$

$$P - ET - R = \Delta S$$



Components of the water budget:

P	= Precipitation (flux)
ET	= Evapotranspiration (flux)
R	= Runoff (flux)
	= or Q when referring to river discharge
ΔS	= Change in storage (change in state)

More complex forms

•An expanded form of the water budget appropriate for many hydrologic studies can be written as (Scanlon et al., 2002):

$$P + Qswin + Qgwin = ETsw + ETgw + ETuz + \Delta Ssw + \Delta Ssnow + \Delta Suz + \Delta Sgw + Qgwout + RO + Qbf$$

where the superscripts refer to surface water (*sw), ground water (gw), unsaturated zone (uz); RO is surface runoff; Qgwoutrefers to both ground-water flow out of the site and any withdrawal by pumping; and Qbfis base flow (ground-water discharge to streams).*

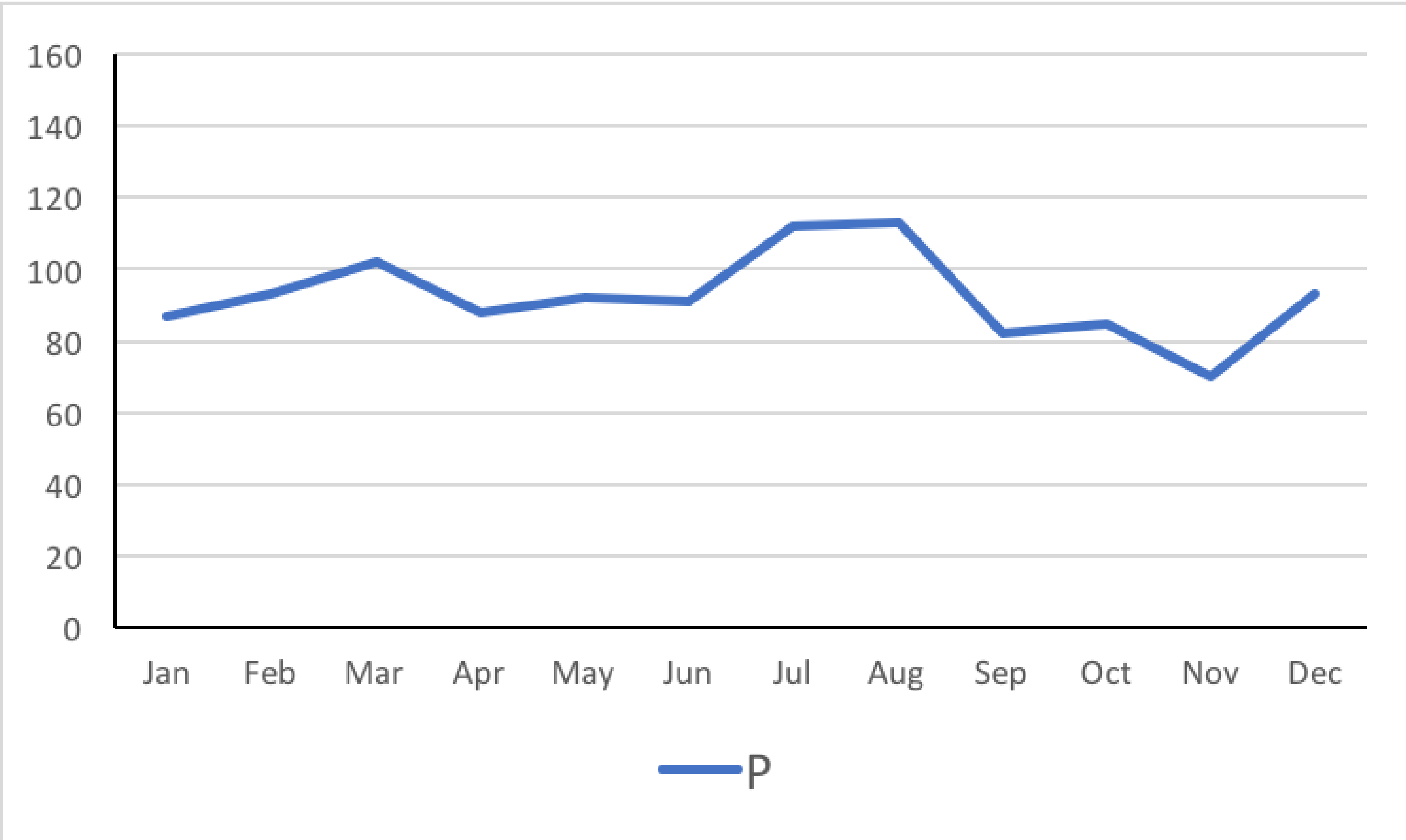
•It is unlikely that all elements in the above equation will be of importance at any one site; some will be of negligible magnitude and can be ignored.

How does the water budget change over time?

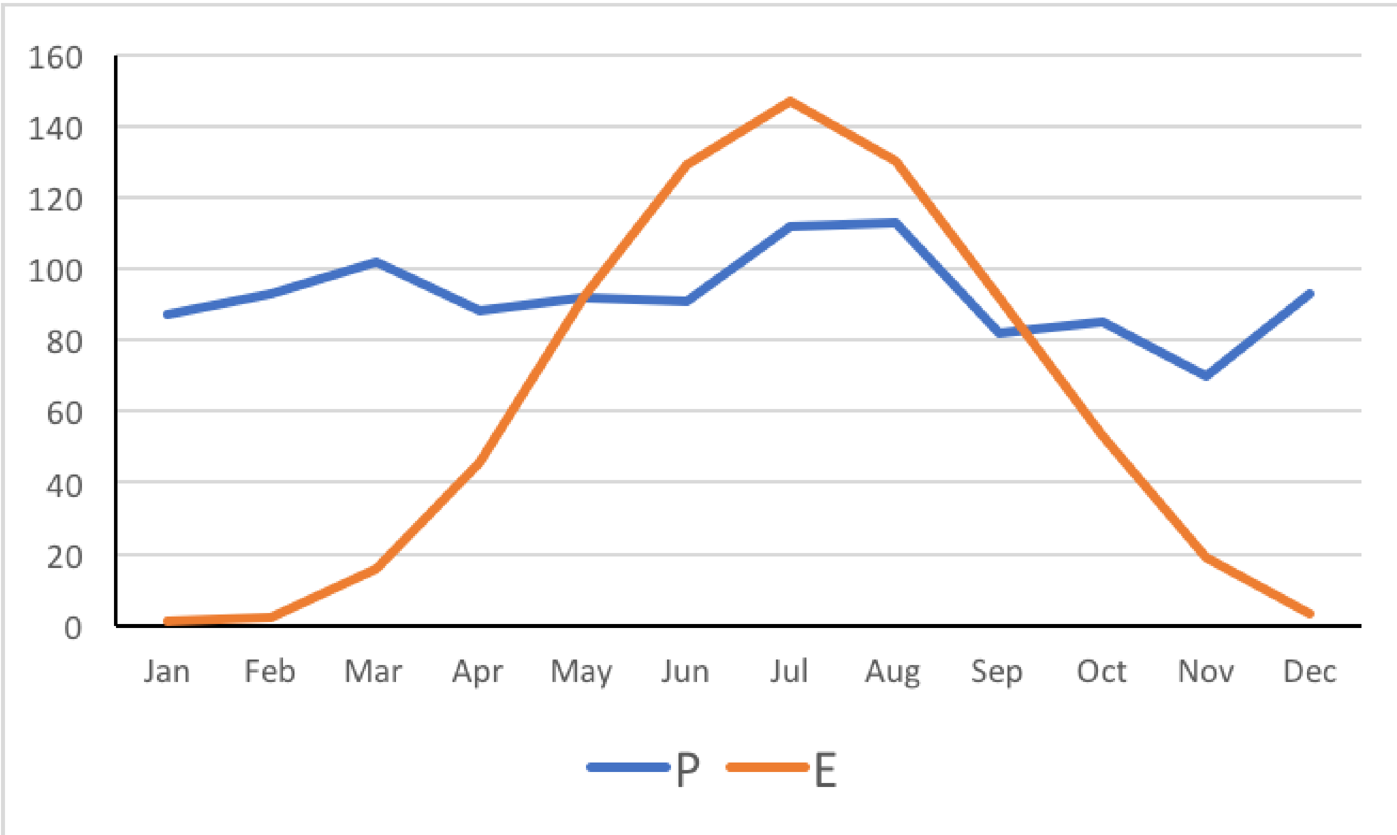
Typically, water budgets are tabulated in spreadsheets or tables such as that shown in table below, which contains monthly and yearly data for Seabrook, New Jersey, USA

Month	P	E	R	ds/dt
Jan	87	1	61	25
Feb	93	2	76	15
Mar	102	16	81	5
Apr	88	46	61	-19
May	92	92	31	-31
Jun	91	129	15	-53
Jul	112	147	8	-43
Aug	113	130	4	-21
Sep	82	92	2	-12
Oct	85	53	1	31
Nov	70	19	1	50
Dec	93	3	37	53
Total	1108	730	378	0

Seasonal Cycle of Precipitation

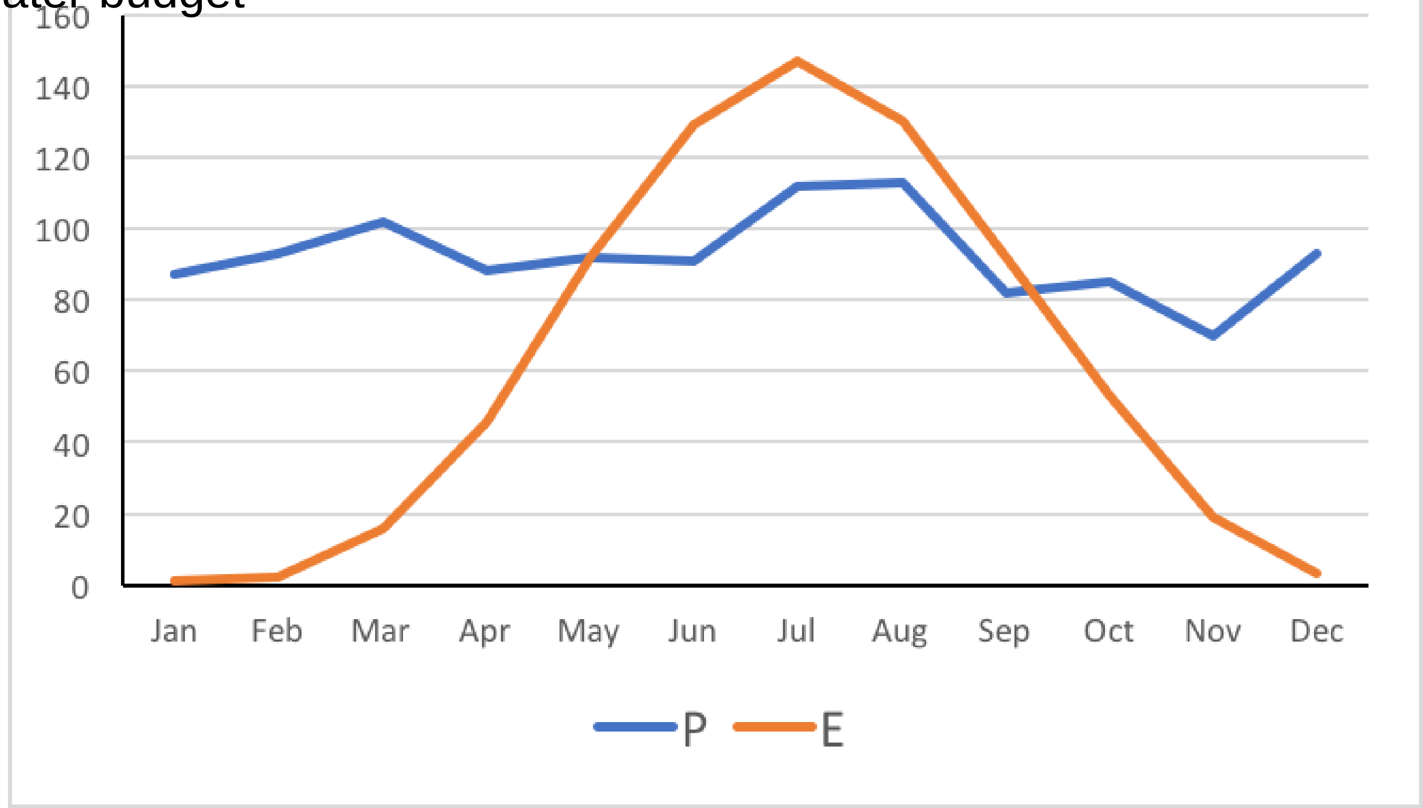


Seasonal Cycle of Evapotranspiration



Surplus and Deficit

- When P > E there is a water surplus
- When E > P there is a water deficit -a loss of soil moisture and a deficit in the water budget



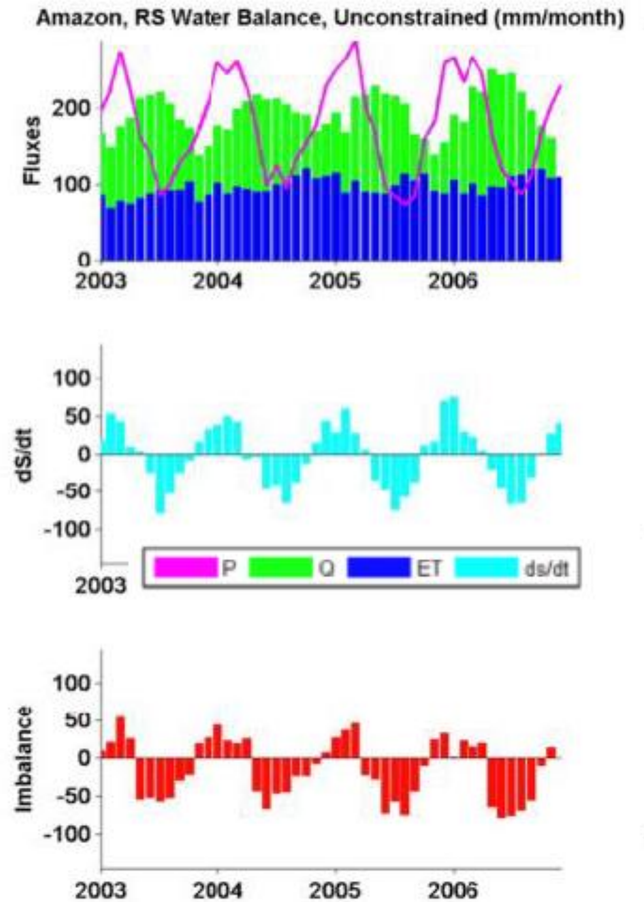
A Challenge: Closing the water budget from different data sources

$$\Delta S = P - ET - Q$$

$$P - ET - Q - \Delta S = 0$$

From independent sources:

$$P - ET - Q - \Delta S = \varepsilon$$



Independent estimates of the water budget do not provide closure

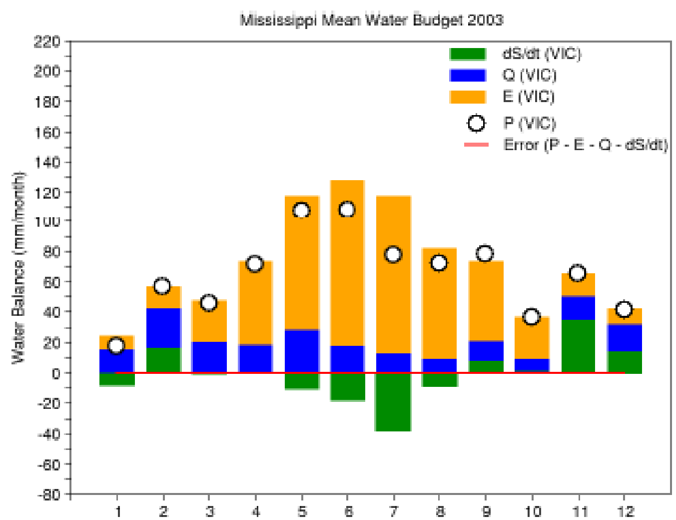
How can the uncertainties be reduced (ε = 0) to close the water budget?

Quantifying the Water Budget from Satellites

The land water budget:

$$\frac{dS}{dt} = P - ET - Q$$

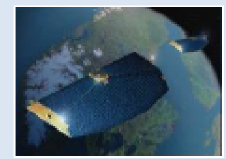
What the budget should look like?
(from modeling, forced closure)



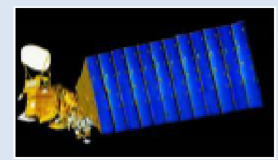
Sheffield and Wood, 2011

What if we calculated the water budget from satellite data?

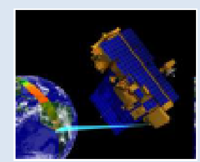
dS/dt from GRACE



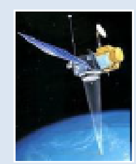
ET from CERES / MODIS / AIRS



P from GPM



Q from TOPEX/POSEIDON/JASON



Practices

- Tutorials are available for those who wish to go in deep of presentation of the workshop:
  - Chadfdm_tutorial
  - Practical_drought_analysis
  - Practical_sm_remote_sensing
  - Practical_ water_budgets

Thank You!
Merci!
Murakoze!