Modeling carbon and water dynamics on land and its applications

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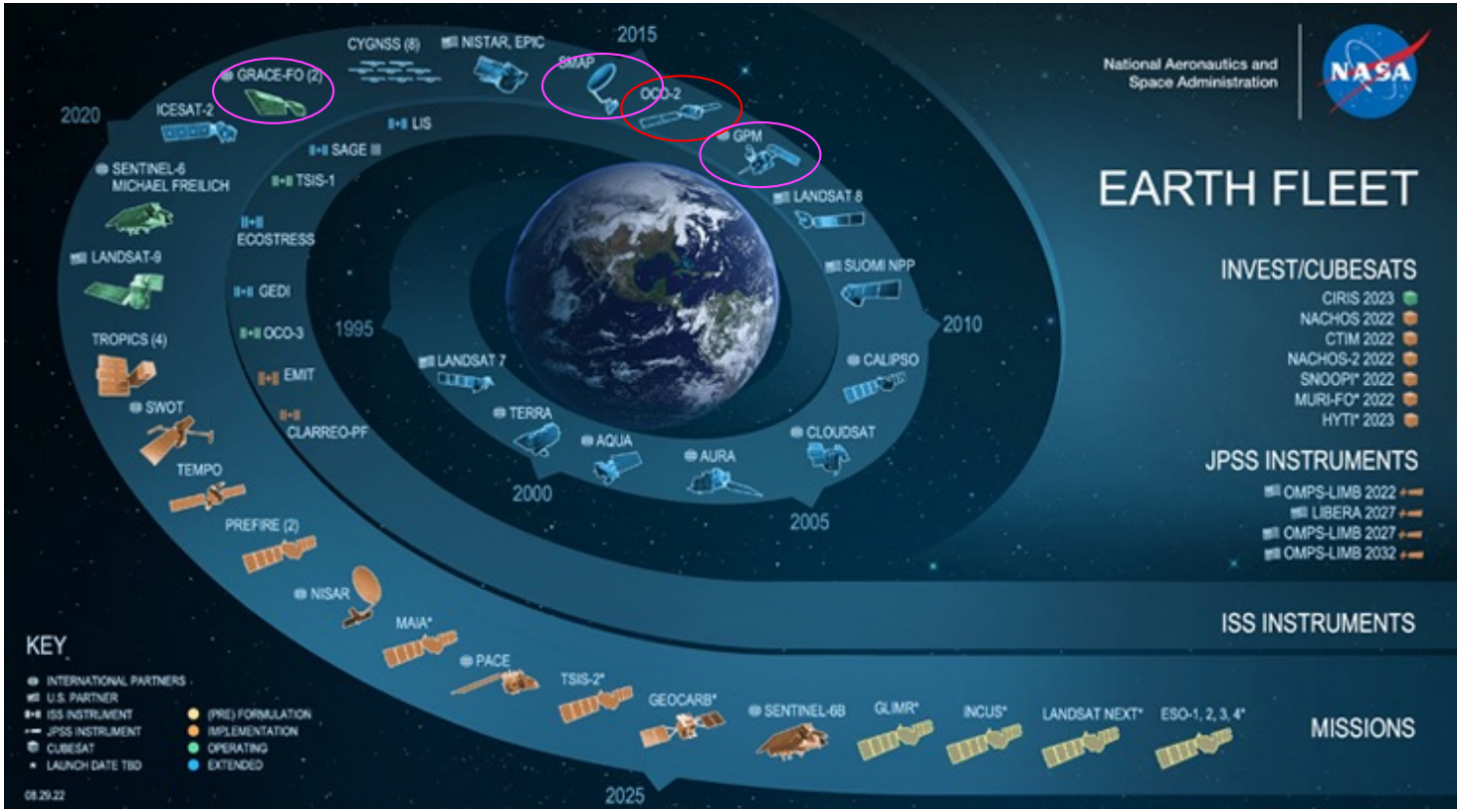
Overview

- Introduction
- Land Surface Model: Simulating land's water and carbon dynamics
- Application of modeling to support decision-making process in planning sustainable energy production and resilient infrastructure
  - Develop a decision support tool that provides sub-seasonal forecasts of water availability for the Mekong River Basin
- Exploring seasonal forecast skill of land's carbon uptake

NASA Goddard Space Flight Center

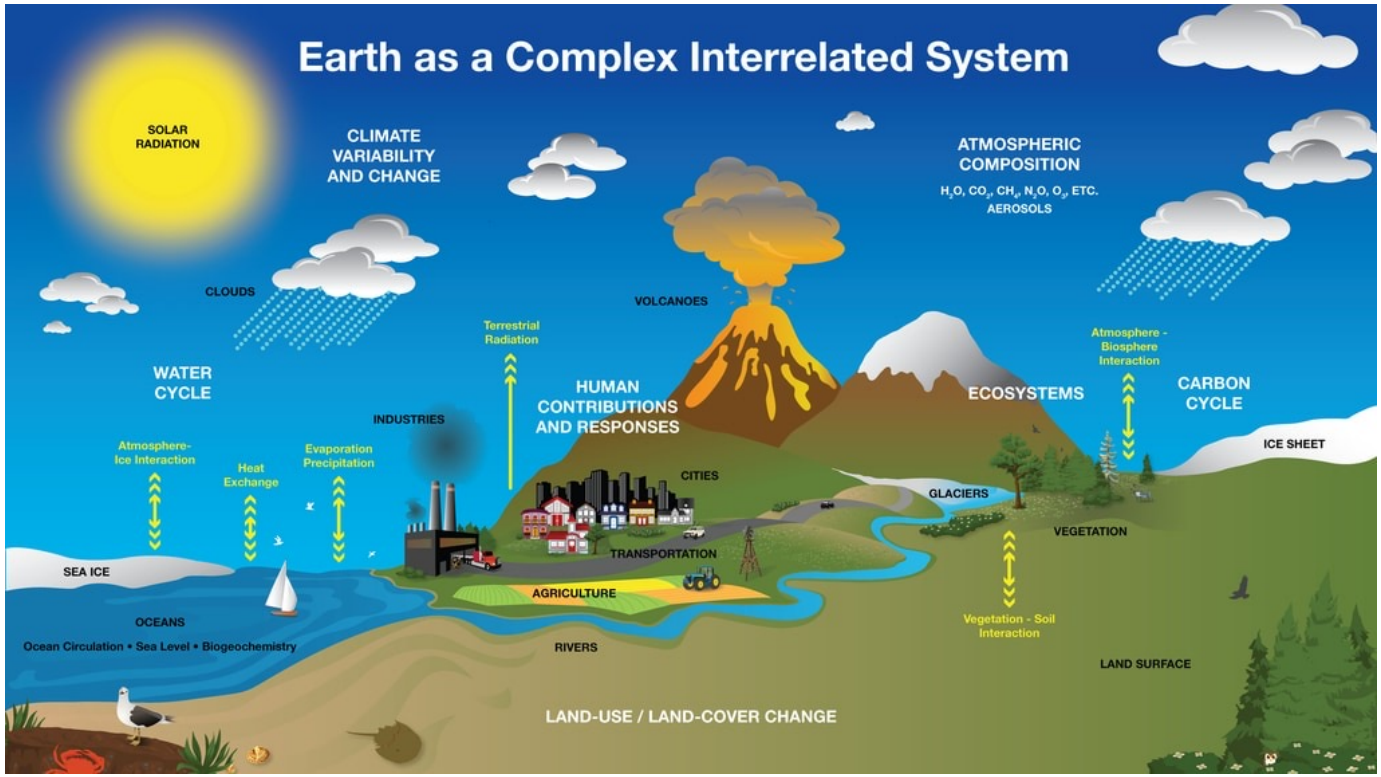
- Located outside Washington D.C. (Greenbelt, Maryland)
- Divisions: Earth Sciences, Astrophysics, Heliophysics, and Solar System
- Under the Earth Sciences Division (ESD)
  - Global Modeling and Assimilation Office
  - Goddard Institute for Space Studies
  - Laboratories that study the atmosphere, the hydrosphere, the biosphere, and geophysics.

How we investigate the Earth system?
Observing the Earth from space



https://eospso.nasa.gov/content/nasas-earth-observing-system-project-science-office

How we investigate the Earth system?
Modeling the Earth system

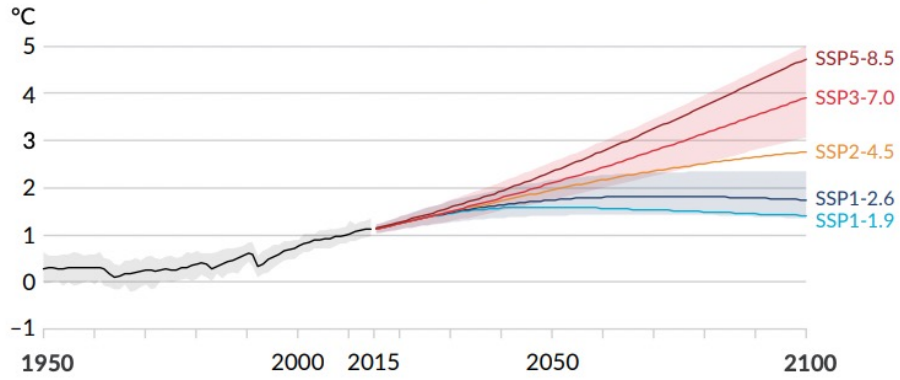


https://mynasadata.larc.nasa.gov/basic-page/earth-system-matter-and-energy-cycles

Modeling the Earth system

Modeling tools are useful for:
(1) Exploring underlying mechanisms of what we observe in the Earth system
(2) Forecasting/projecting the future states of the Earth system

Global Climate Models (GCM) or Earth System Models (ESM) are used to generate the forecasts of the future status of the Earth system (e.g., Coupled model Intercomparison Projects to support IPCC Assessment Reports).

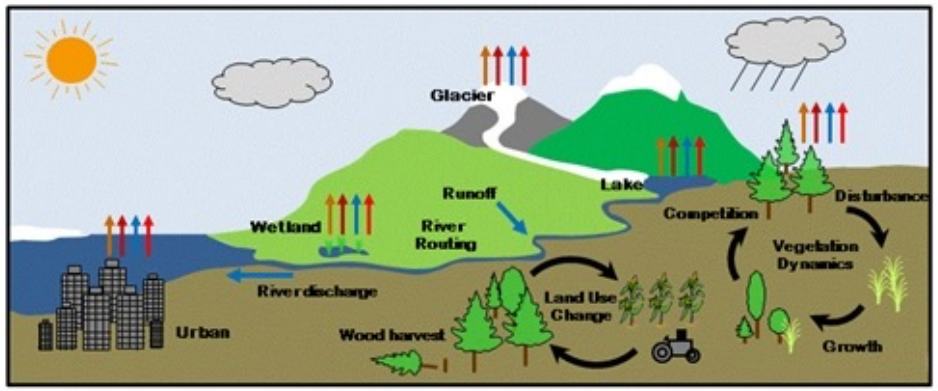


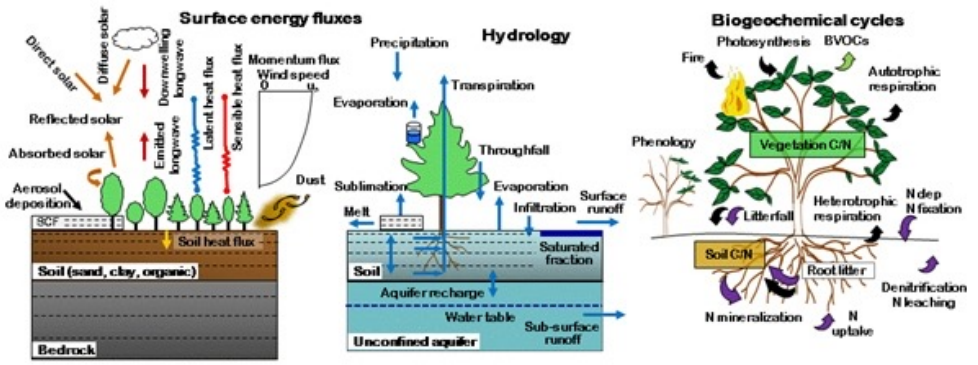
Global surface temperature change relative to 1850-1900

Figure SPM.8.a (IPCC report AR6 SPM)

Land Surface Model (LSM)

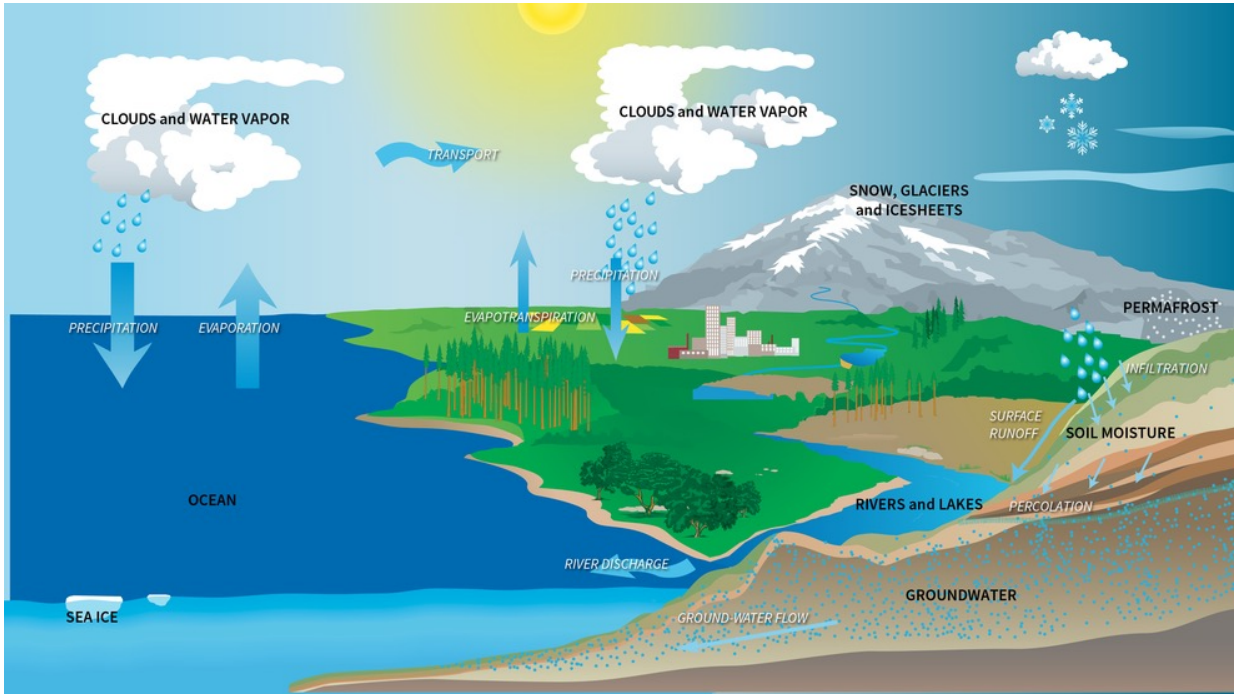
Simulating the natural processes of the terrestrial ecosystem





https://www.cesm.ucar.edu/models/clm

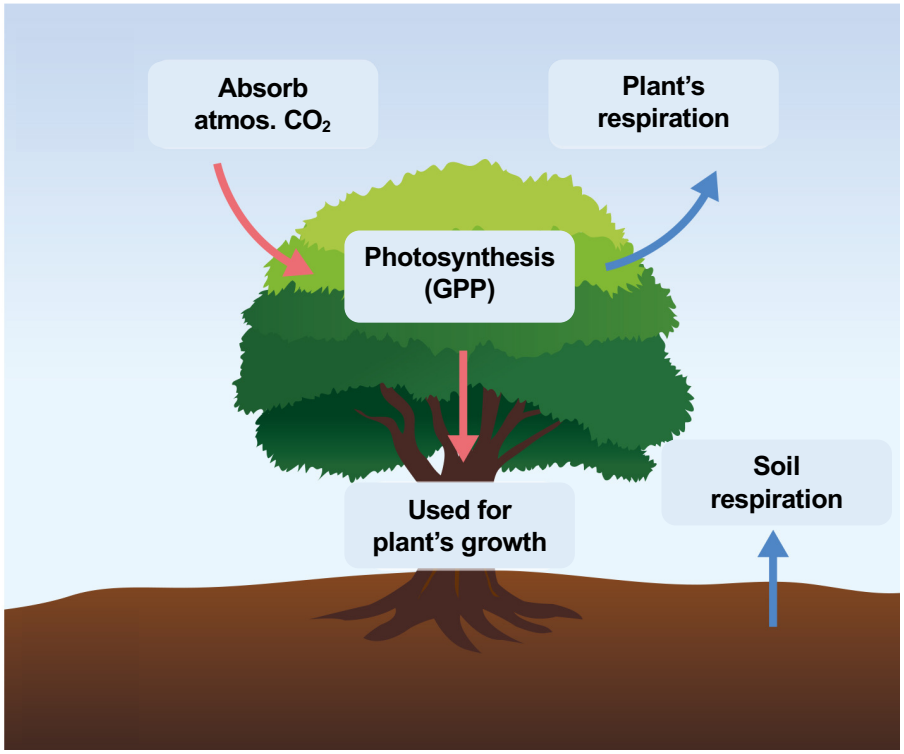
Water cycle



Water evaporates from Earth's surface -> Rises into the atmosphere -> Cools and condenses to form clouds -> Falls again to the land surface -> Some water returns to atmosphere interacting with vegetation -> Remaining water goes into the soil and/or flows to merge into rivers and oceans

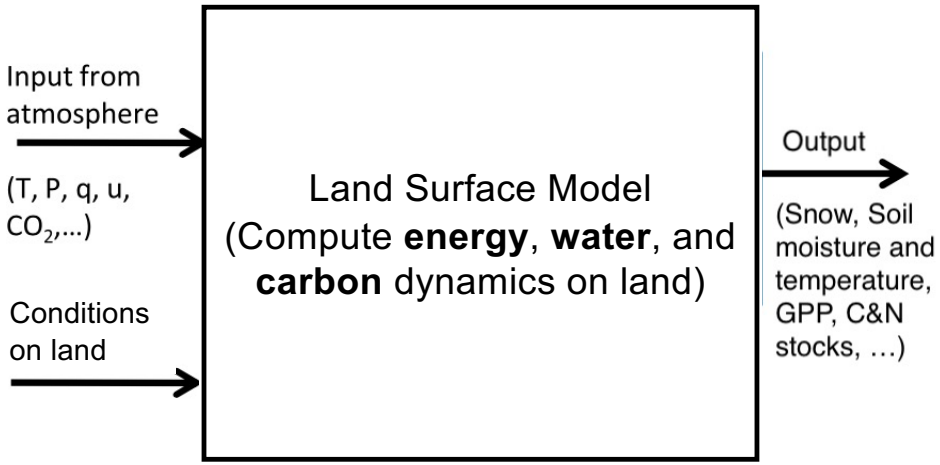
https://www.nasa.gov/feature/goddard/nasa-balances-water-budget-with-new-estimates-of-liquid-assets

Carbon dynamics on land



Net carbon uptake by land ecosystem = Gross Primary Production – Respirations

Land Surface Model (LSM)



- Inputs to the land model
  - Meteorological variables (e.g., air temperature, rainfall, incoming radiation)
  - Initial condition of land (e.g., vegetation and soil status, land-use scenario)
- Outputs from the land model
  - Water variables (e.g., soil moisture, runoff) and carbon variables (e.g., GPP, NEP)
- Used as **the stand-alone version (offline)** or the coupled version to the atmosphere, serving as a land component in a GCM or ESM

Application of land modeling to support decision-making process to support sustainable energy planning and resilient infrastructure

Develop a decision support tool that provides sub-seasonal forecasts of water availability for the Mekong River Basin (funded project, starting in Jan 2023)

Weather prediction? Climate projection? Seasonal forecast?

- All simulate changes in meteorology.
  - Temperature, precipitation, wind, radiation etc.

- Time scale of interest varies.
  - Weather forecast: up to 5~10 days
  - Climate projection: several decades (e.g., year 2050) or a century (e.g., year 2100)
  - Subseasonal-to-Seasonal (S2S) forecast: longer than a week, up to several months

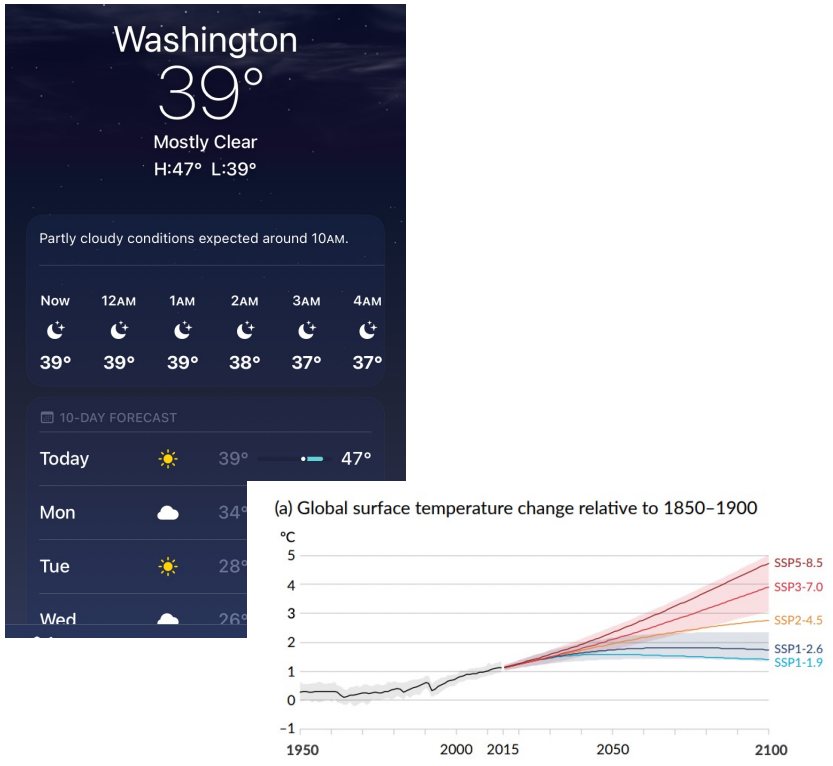
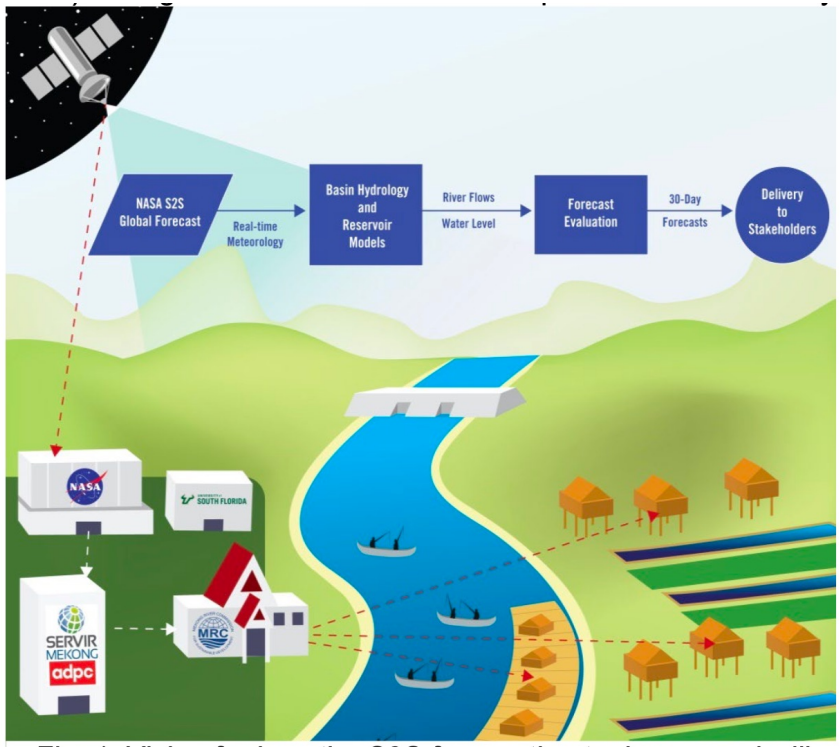


Figure SPM.8.a (IPCC report AR6 SPM)

Subseasonal-to-Seasonal Forecasting for Informed Decision-Making in the Mekong River Basin

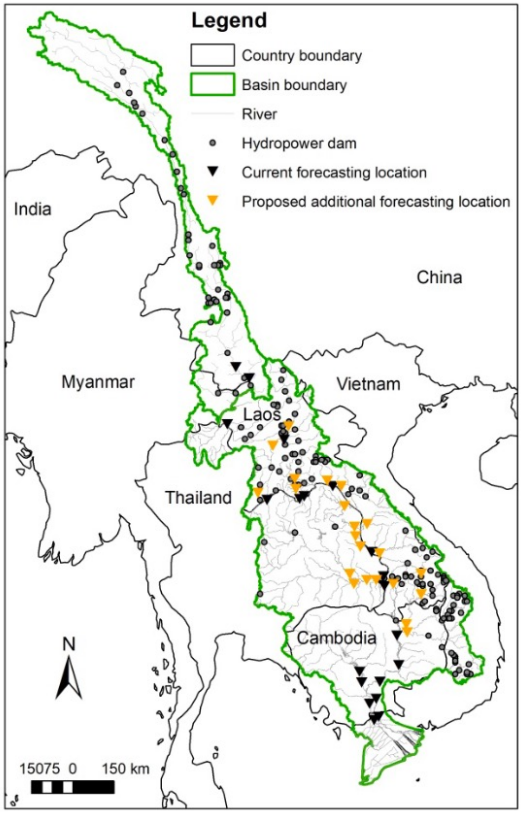
- Funded proposal (2023-2025)
- PI: Mauricio E. Arias (Univ. of South Florida)
- Co-Is: Eunjee Lee (UMBC/NASA), Randal D. Koster (NASA), Thanh Dang (USF), Miguel Laverde (Asia Disaster Preparedness Center)
- Collaborator: Fabio Farinosi (EU)
- NASA SERVIR Applied Science Team
- To develop a decision support tool that provides sub-seasonal forecasts of water availability for the Mekong River Basin using NASA's S2S forecast system.



Subseasonal-to-Seasonal Forecasting for Informed Decision-Making in the Mekong River Basin

- Currently, the Mekong River Commission forecast system provides river level forecasts for 1~5 days (derived from weather forecast) along the Mekong's main stem.

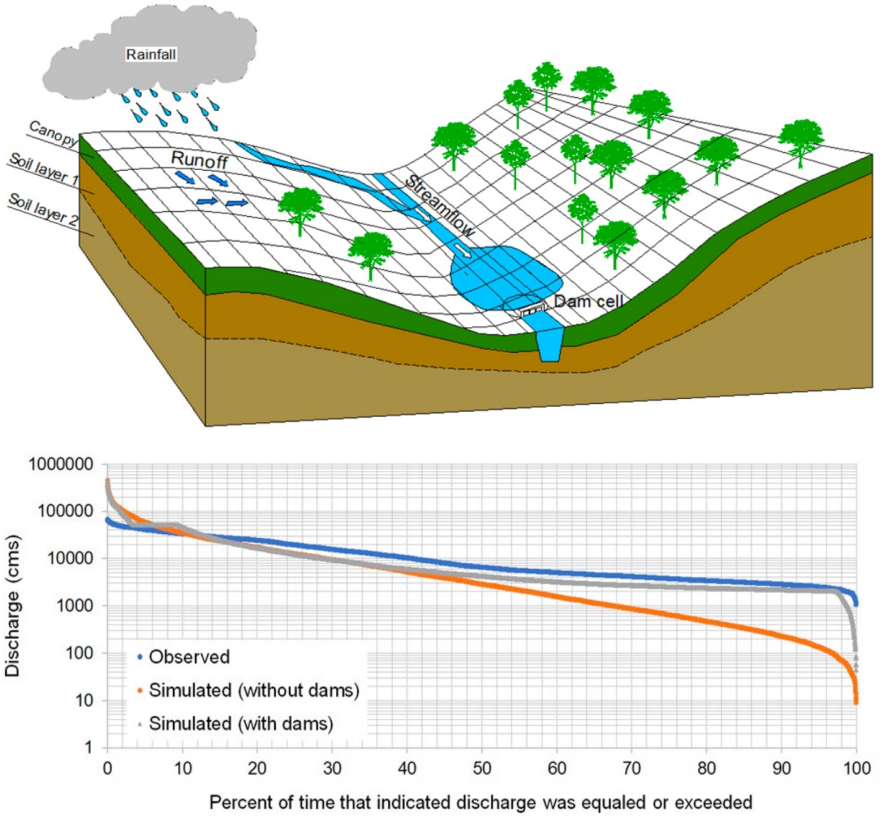
- The temporal and spatial scope of this forecast is insufficient for comprehensive basin management.



Subseasonal-to-Seasonal Forecasting for Informed Decision-Making in the Mekong River Basin

- The current water availability forecast for the basin also excludes river tributaries and hydrological alterations caused by reservoirs.

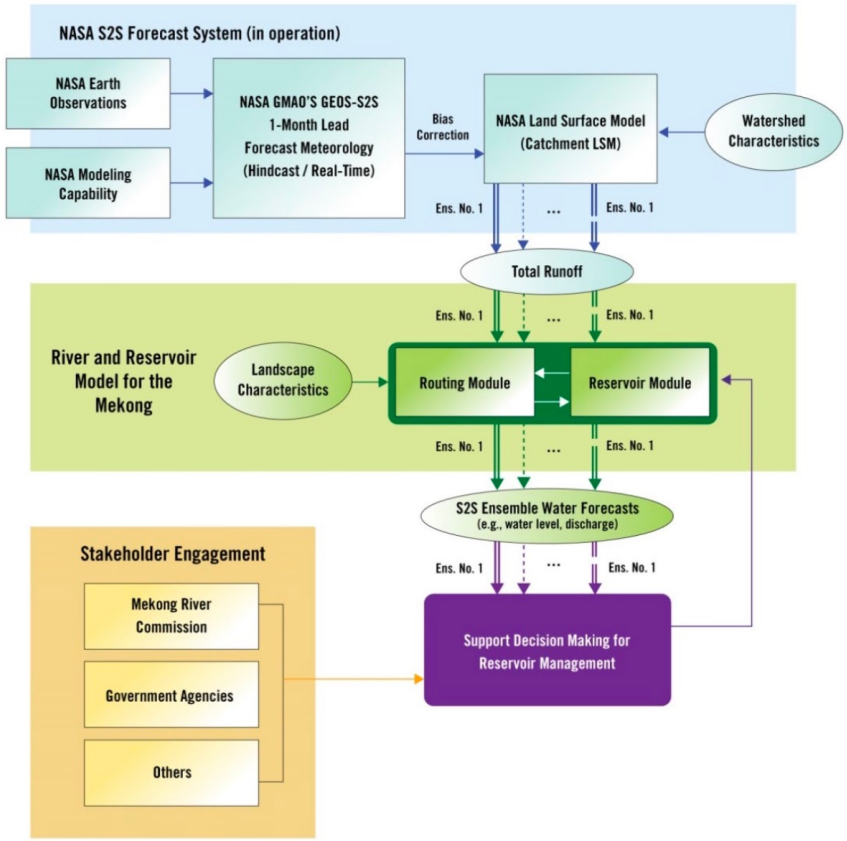
- Prediction of sub-seasonal variations in river flows on the Mekong's main stem and tributaries will be made through the joint consideration of S2S forecast runoffs and dam operations.



Subseasonal-to-Seasonal Forecasting for Informed Decision-Making in the Mekong River Basin

By integrating NASA's S2S forecasting platform with well-tested water models for the entire Mekong River Basin, this project aims to:

1) Increase temporal coverage from 5 to 30 days;
2) expand spatial coverage to include Mekong tributaries;
3) accounting for reservoirs and their operations;
4) improve overall sub-seasonal water forecast skill.



Seasonal forecast skill of land's carbon uptake

Global Modeling and Assimilation Office (GMAO)

- Located in NASA Goddard Space Flight Center
- Research activities
  - Development of NASA's Earth System Model (Global Earth Observing System)
  - Weather analysis and prediction, Seasonal-decadal analysis and prediction, Reanalysis, Global mesoscale modeling, Observing system science
- Major products
  - MERRA-2 reanalysis meteorology (1980-present)
  - GEOS subseasonal-to-seasonal (S2S) hindcast and forecast meteorology

Subseasonal-to-seasonal (S2S) forecast

- In seasonal forecasts, a coupled modeling system is initialized with realistic prognostic states (for example, by data assimilation) and run forward in ensemble mode (i.e., **multiple ensemble members** are produced).
- The forecast skill stems from the system's ability to translate the initial states into future states through the proper representation of system memory and/or the evolution of coupled climate modes.
- **More than one possible projection** due to atmospheric chaos

- NASA GMAO regularly produces S2S meteorological forecasts (GEOS S2S forecast)
  - Current version (v2): Up to 9 months, being initialized about every 5 days
  - Upcoming version (v3): as large as 40 forecast simulations per month

Seasonal forecast of ”carbon”

- In recent years, the maturity of S2S forecasts has increased substantially (Doblas-Reyes et al., 2013), allowing relevant applications such as hydrological forecasting and food security in vulnerable regions (Arsenault et al., 2020; Shukla et al., 2020).

- Forecasting of carbon variations has been addressed in only a few studies
  - Forecasts of ocean carbon anomalies (Rousseaux and Gregg, 2017; Park et al., 2019)
  - Potential predictability of land carbon (Séférian et al., 2018; Lovenduski et al., 2019)

- The carbon forecast at seasonal time scale is still an unexplored problem.

- Why do we care about the seasonal carbon forecast?
  - To improve future S2S forecast system, we need the information about how the system will behave with the carbon cycle.
  - Carbon forecasts can eventually support a wider range of end users in fire management, forestry, and agriculture.

Research objectives

- **Evaluate carbon forecast skill** by utilizing a state-of-the-art S2S forecast system and a terrestrial biosphere model, against a fully independent, remotely-sensed GPP dataset

- **Explore straightforward physical mechanisms** by which an S2S meteorological forecast can lead to skill in the forecast of terrestrial carbon fluxes.

NASA's Land Surface Model (Catchment-CN model)

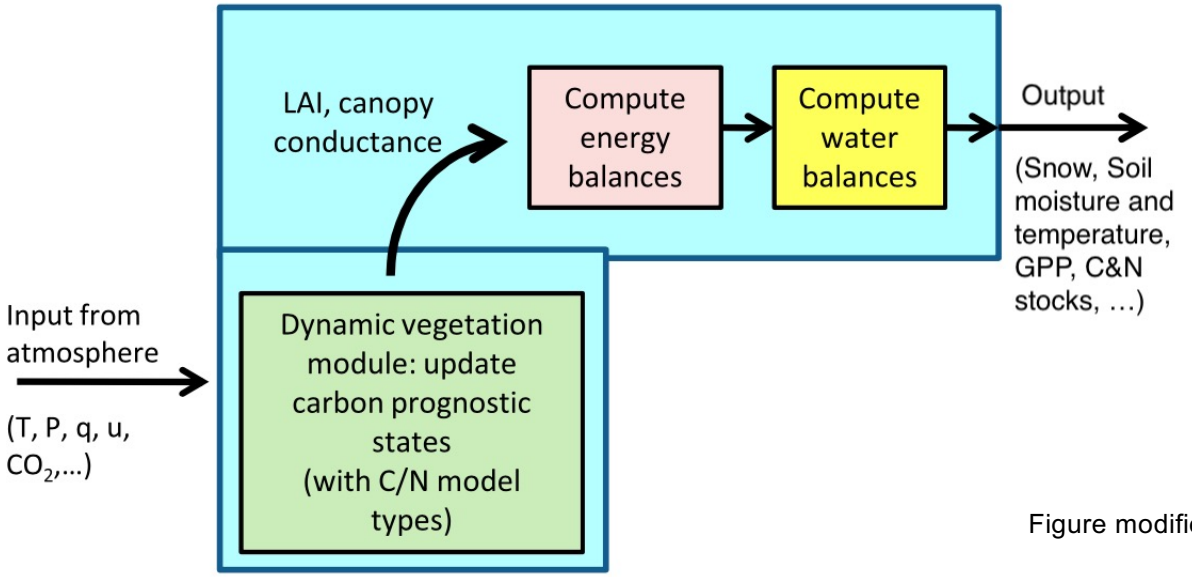
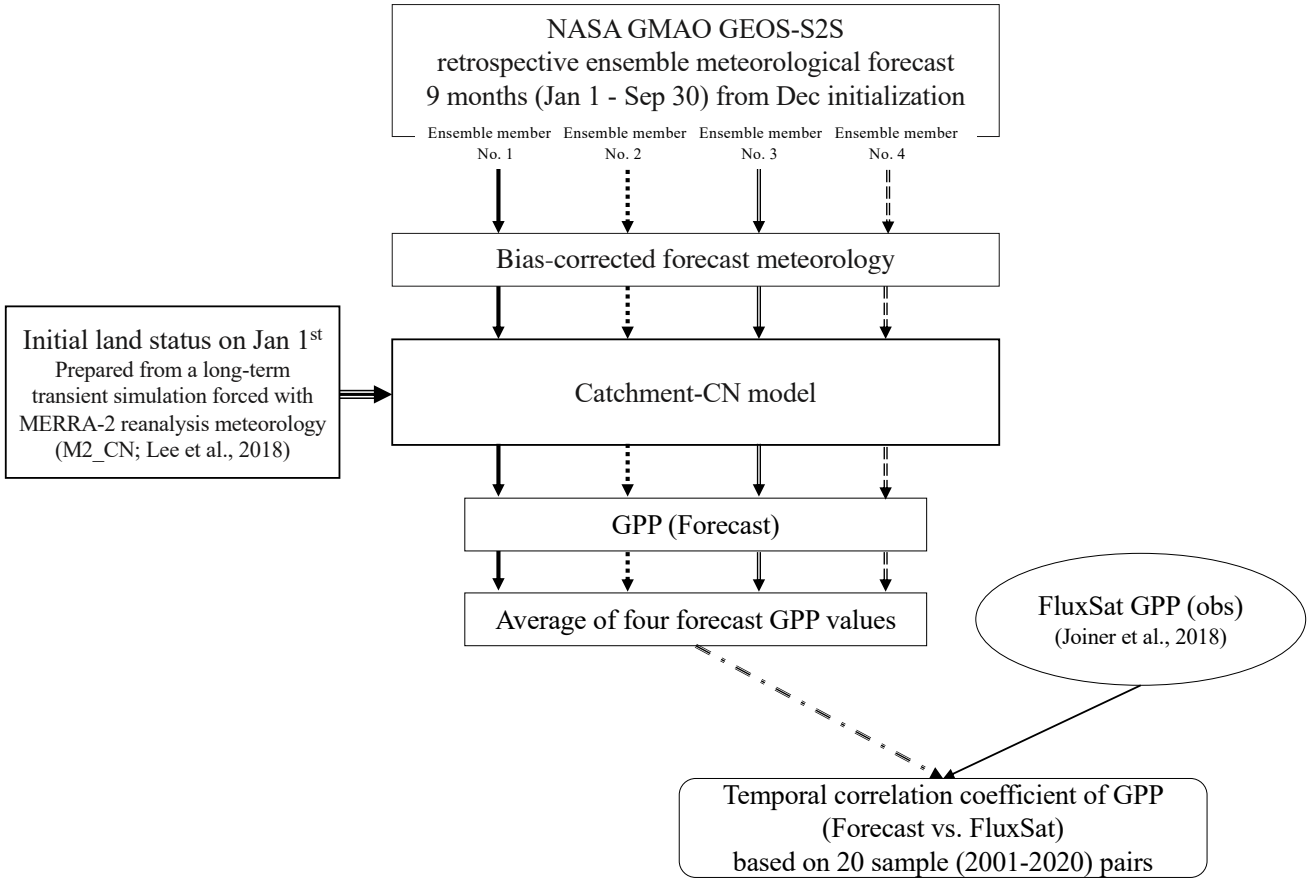


Figure modified from Koster et al. (2014)

- Use **energy and water dynamics** from Catchment LSM (Koster et al., 2000)
- Merged **carbon and nitrogen dynamics** from NCAR-CLM (v4 and now integrating v5)
- Serves as a land component in NASA's GEOS Earth System Model
- Using the stand-alone version (offline), forced by S2S meteorological forecast, seasonal forecasts of water and carbon cycle dynamics can be generated.

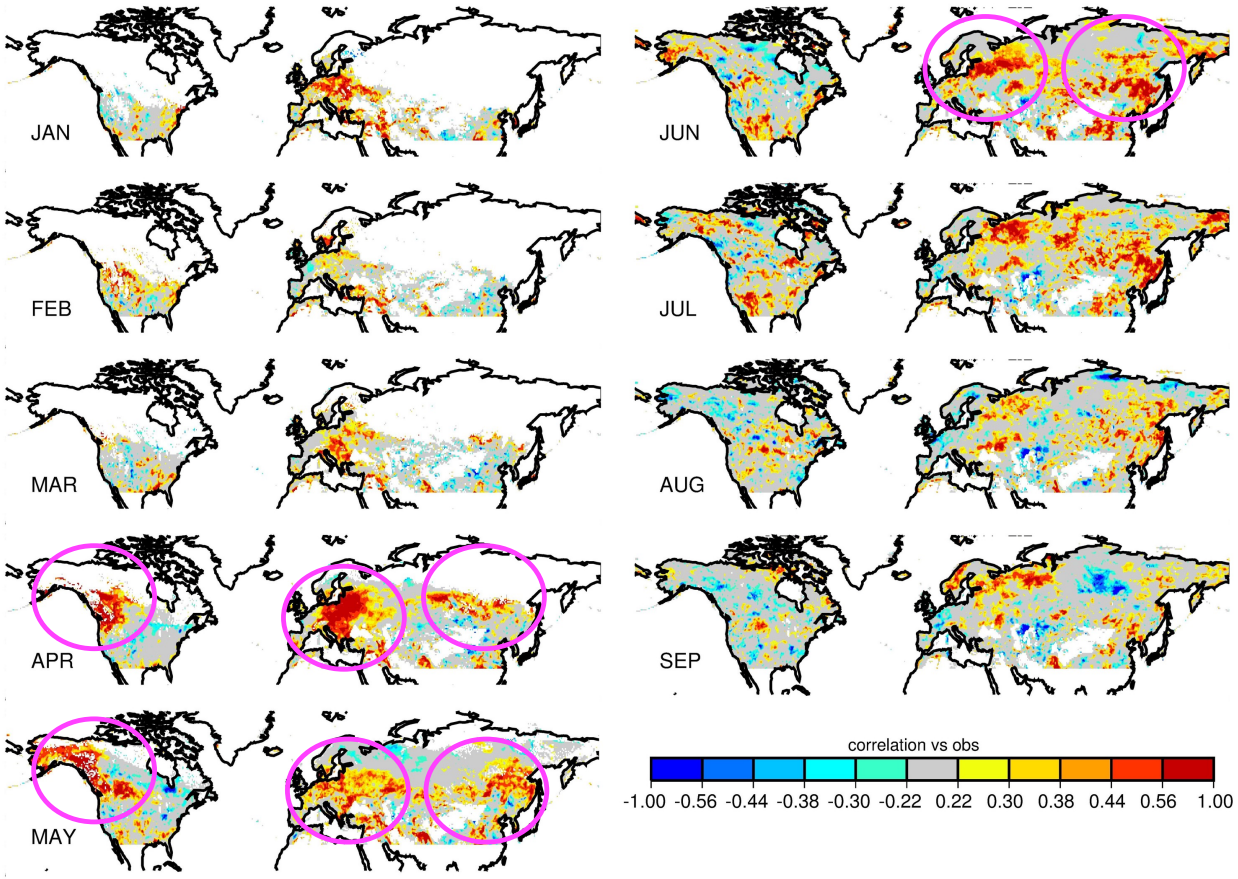
Experimental design

- We generated **ensemble carbon forecasts** by using offline Catchment-CN model, forced with bias-corrected forecast meteorology.
- The GPP forecast skill was evaluated with the observation-based GPP (FluxSat GPP).
- Correlation coefficients (Pearson's r), based on 20 sample pairs (2001-2020).



Forecast skill of monthly GPP (Forecast GPP in CTRL vs. observed GPP)

- Skillful GPP forecast in northwestern N America, eastern Europe, and Eurasia
- High skill in April and May (4th & 5th forecast lead months). However, meteorological forecast skill does not explain the high carbon forecast skill at such long lead months.
- **Some other factors (must) contribute** to the seasonal carbon forecast in mid- and high-latitudes during spring



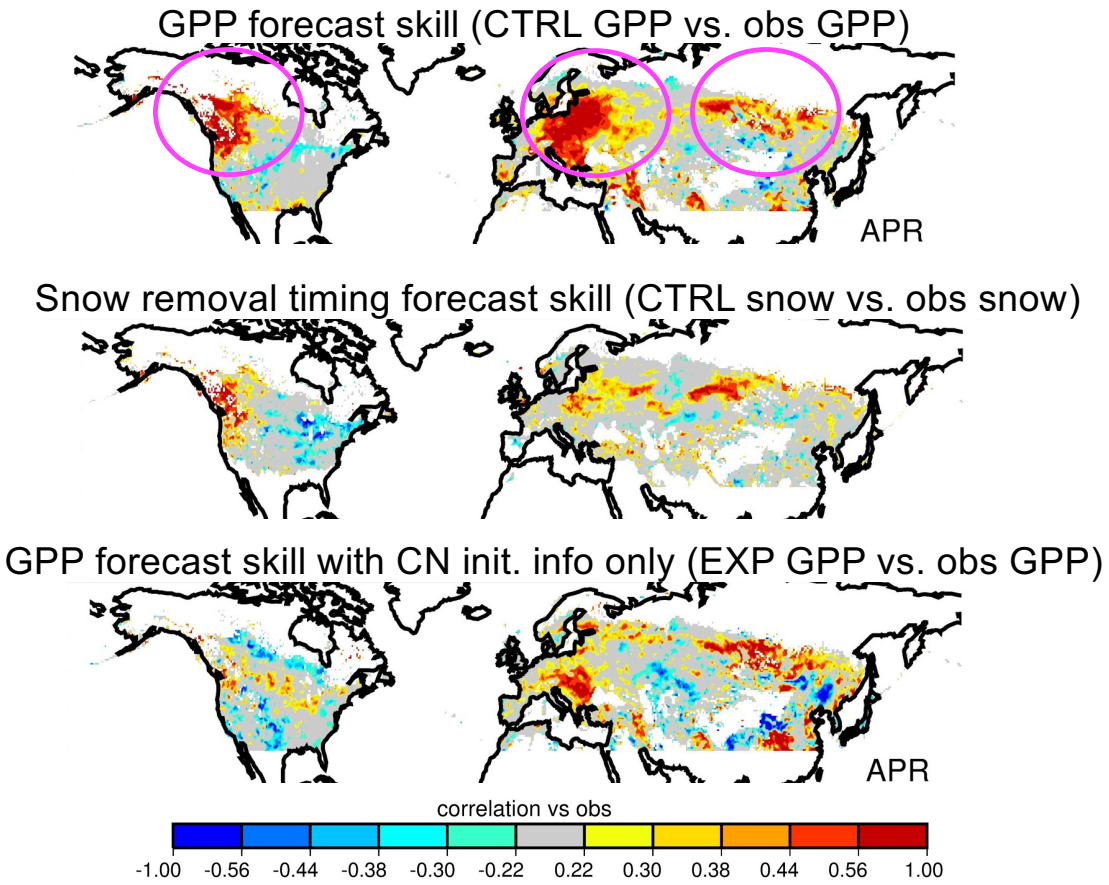
Snowcover removal timing and a supplemental experiment (EXP) design

- Snow cover removal day was defined as:
  - When daily snow mass becomes lower than 1 kg/m^2 (or 1 mm of snow water equivalent (SWE)) and,
  - The snow mass remains below the threshold for the following 7 consecutive days

- EXP suite
  - Same as CTRL, except for retaining the inter-annual variation of the CN initialization on Jan 1st and fixing other conditions as those in year 2013.
  - No inter-annual variability in forecast meteorology and snow and soil moisture initialization is allowed.

APRIL (4th lead month)
Contribution of initialization to GPP forecast skill

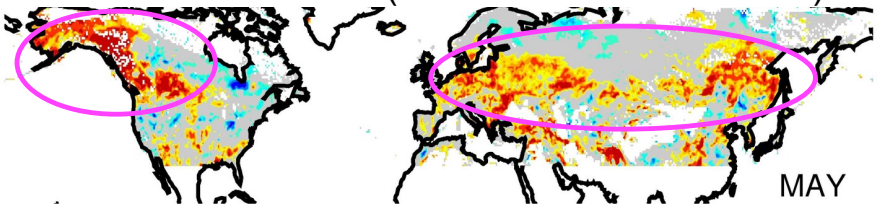
- Contribution of snow initialization appears in northwestern North America and parts of Eurasia.
- Contribution of carbon and nitrogen (CN) initialization appears in southeastern Europe and in eastern Asia.



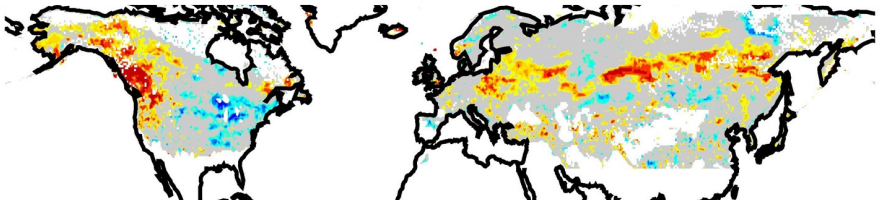
MAY (5th lead month)
Contribution of initialization to GPP forecast skill

- Contribution of snow initialization still appears in northwestern North America and parts of Eurasia.
- The importance of carbon and vegetation (CN) initialization appears in part of Europe and Asia.

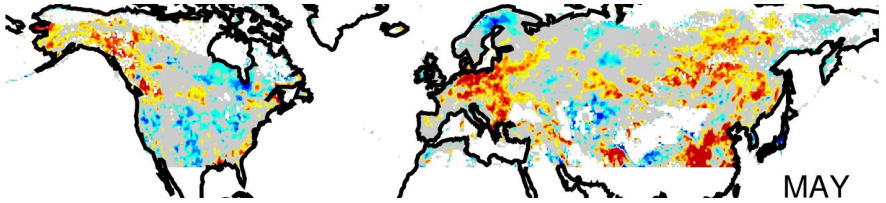
GPP forecast skill (CTRL GPP vs. obs GPP)

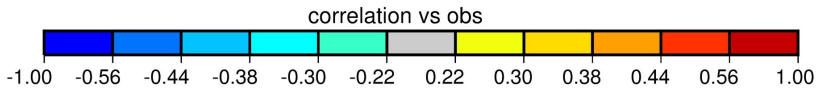


Snow removal timing forecast skill (CTRL snow vs. obs snow)



GPP forecast skill with CN init. info only (EXP GPP vs. obs GPP)

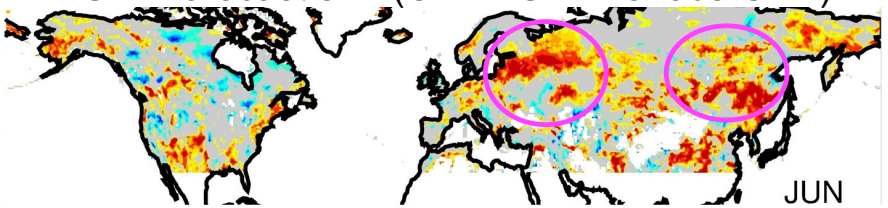




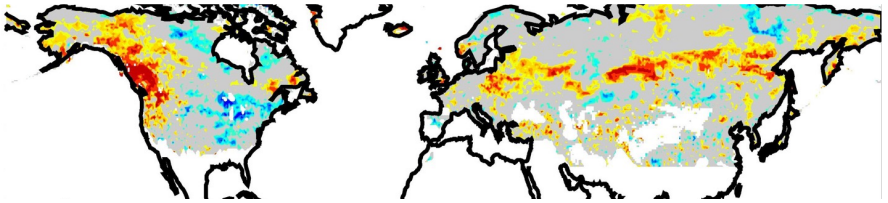
JUNE (6th lead month)
Contribution of initialization to GPP forecast skill

- The importance of carbon and vegetation initialization appears to be higher in later/longer forecast lead months.

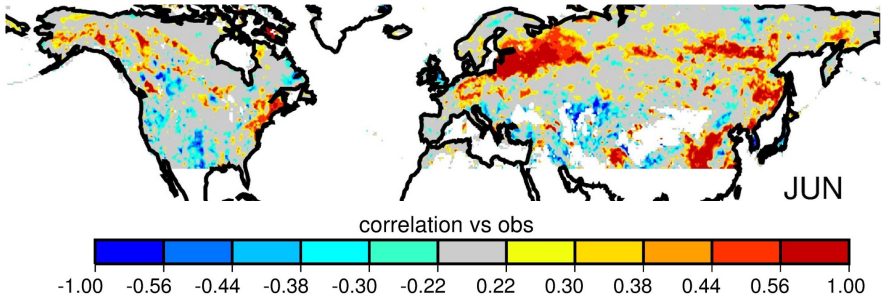
GPP forecast skill (CTRL GPP vs. obs GPP)



Snow removal timing forecast skill (CTRL snow vs. obs snow)



GPP forecast skill with CN init. info only (EXP GPP vs. obs GPP)



Effects of snow initialization and CN initialization on seasonal carbon forecast skill

Snow initialization

- Snowpack initialized in January sit undisturbed on the surface until the spring snow-melt season.
- The information contained in the initial snowpack provides a latent predictability to the climate system (Guo et al., 2012), helping determine when the snow will finally melt away and spring vegetation growth (carbon uptake) can begin.

Carbon & Nitrogen initialization

- Another potential source of GPP forecast skill.
- The storage of carbon and nitrogen represents another relatively “slow” component of the coupled Earth system.
- Vegetation places carbon and nitrogen in different reservoirs partly for use in later production. Thus, the vegetation's established storage distribution helps set the stage for plant health and productivity during the subsequent year.

Summary of seasonal carbon forecast study

1. This study demonstrate an ability to accurately forecast spring-summer carbon uptake at multi-month leads and highlights the significance of land initialization in S2S carbon forecasts.
2. The delay associated with the snow initialization is a notable lead (three to five months) for forecast skill realization. Much of the snowpack sits undisturbed on the surface until the spring snowmelt season, providing a latent predictability to the forecast system.
3. In addition to the snow initialization, the carbon reservoirs initialization is important in certain key regions and at later forecast lead months.
4. In central-eastern Eurasia, soil moisture and snow initialization may both contribute to GPP forecast skill in part by controlling growing season moisture variability.
5. Snowpack initialization and carbon reservoir initialization provide contributions to GPP forecast skill in largely complementary areas.

Thank you for your attention!