Seasonal forecast of the carbon and water dynamics on land

Eunjee Lee

Goddard Earth Sciences Technology and Research II (GESTAR2)

University of Maryland, Baltimore County / NASA Goddard Space Flight Center

with Randal. D. Koster (NASA), Lesley E. Ott (NASA), Jana Kolassa (SSAI/NASA), Rolf Reichle (NASA), Joanna Joiner (NASA), Mauricio E. Arias (USF), Thanh Dang (USF), Fabio Farinosi (EU)

Guest presentation at the Resilient Infrastructure Technology seminar class

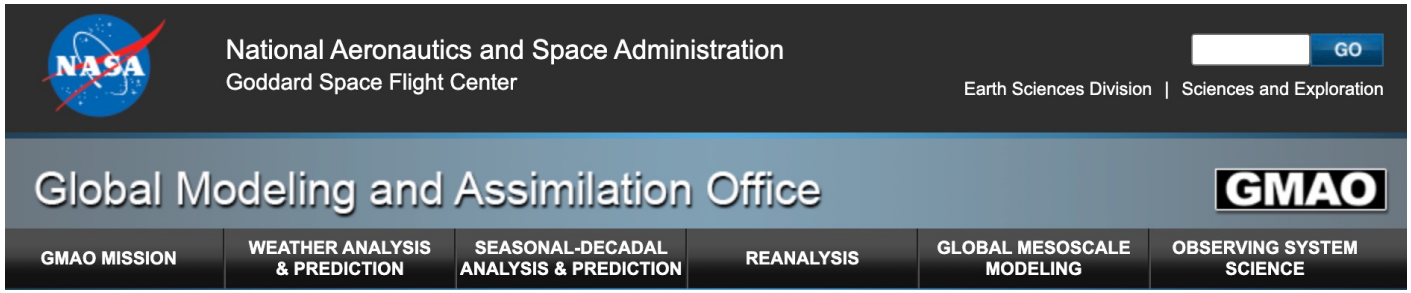
Overview

- A quick introduction to NASA Goddard Space Flight Center (NASA GSFC) and Global Modeling and Assimilation Office (GMAO)
- What is subseasonal-to-seasonal (S2S) forecast?
- Simulating land's water and carbon dynamics: Land Surface Model (LSM)
- Application of S2S water forecast to support design of resilient infrastructure
  - Develop a decision support tool that provides sub-seasonal forecasts of water availability for the Mekong River Basin (NASA SERVIR – funded project)
- Exploring seasonal forecast skill of land's carbon uptake

NASA Goddard Space Flight Center (NASA GSFC)

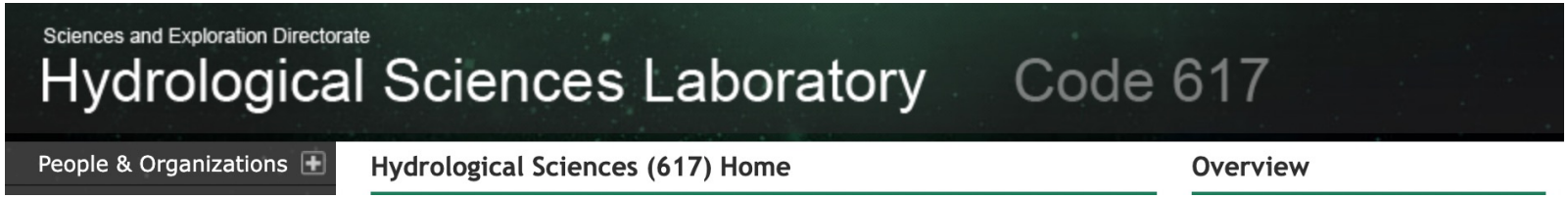
- Located outside Washington D.C. (Greenbelt, Maryland)
- Divisions: Earth Sciences, Astrophysics, Heliophysics, and Solar System
- Under the Earth Sciences Division,
  - Global Modeling and Assimilation Office
  - Goddard Institute for Space Studies
  - Labs that study atmospheric physics, dynamics and chemistry
  - Labs that study hydrosphere, biosphere, and geophysics (e.g., Hydrological sciences laboratory)

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

Hydrological Sciences Laboratory



- Located in NASA Goddard Space Flight Center
- "Examines the role of water in the Earth system to better understand, quantify, and analyze the hydrological cycle and to measure hydrological processes in order to improve prediction of the response of global hydrology to anthropogenic and/or natural climate change"
- Projects include:
  - Land Data Assimilation System (LDAS), Global Precipitation Measurement (GPM), Soil Moisture Active Passive (SMAP), Land Information System (LIS), Gravity Recovery and Climate Experiment (GRACE), and SnowEx.

What is S2S forecast?

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

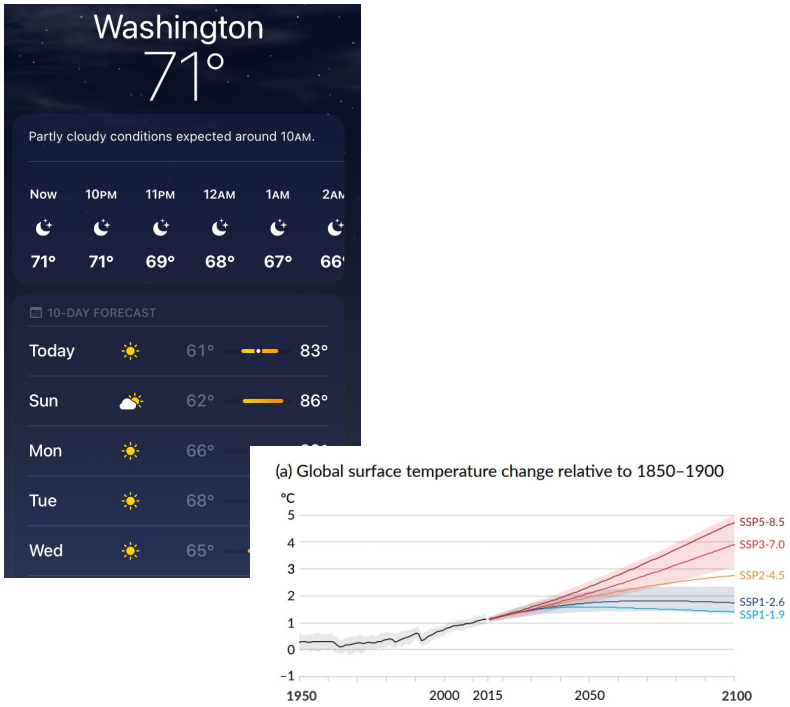


Figure SPM.8.a (IPCC report AR6 SPM)

Subseasonal-to-seasonal (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

Land Surface Model (LSM)

Simulating energy, water and carbon dynamics of the terrestrial ecosystem

Catchment model: NASA GMAO's land surface model

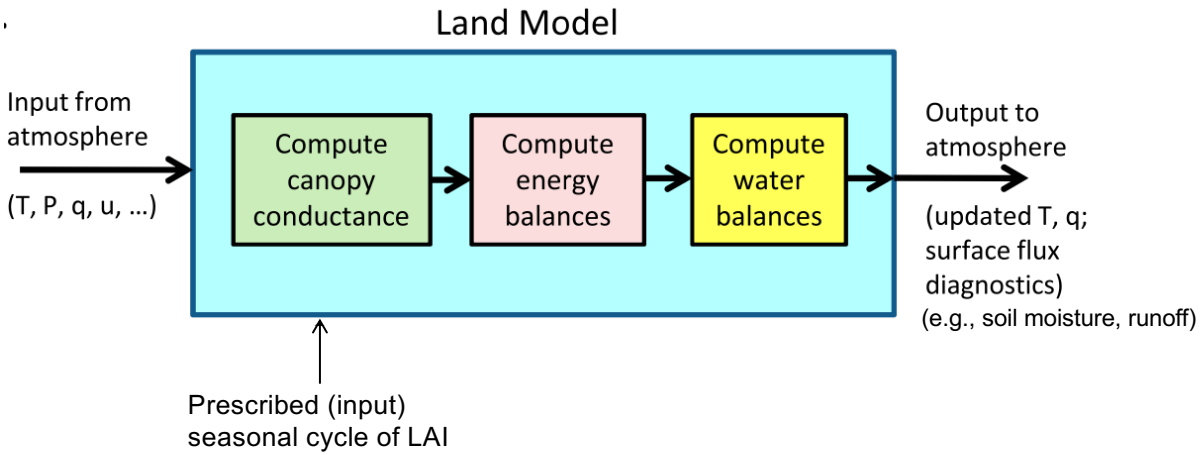


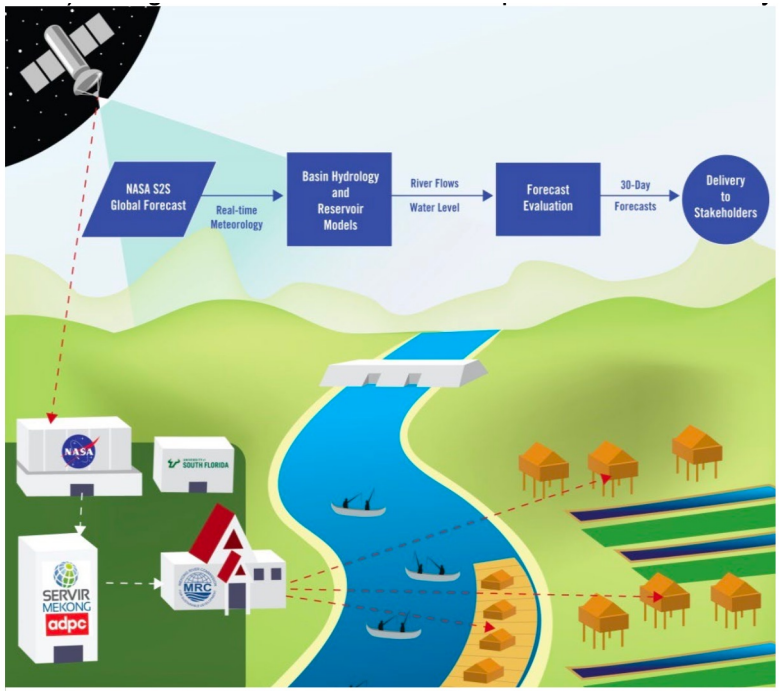
Figure modified from Koster et al. (2014)

- Simulates **energy and water dynamics** (Koster et al., 2000)
- 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 hydrological variables can be generated.

Application of S2S water forecast to support design of resilient infrastructure

Subseasonal-to-Seasonal Forecasting for Informed Decision-Making in the Mekong River Basin (funded project)

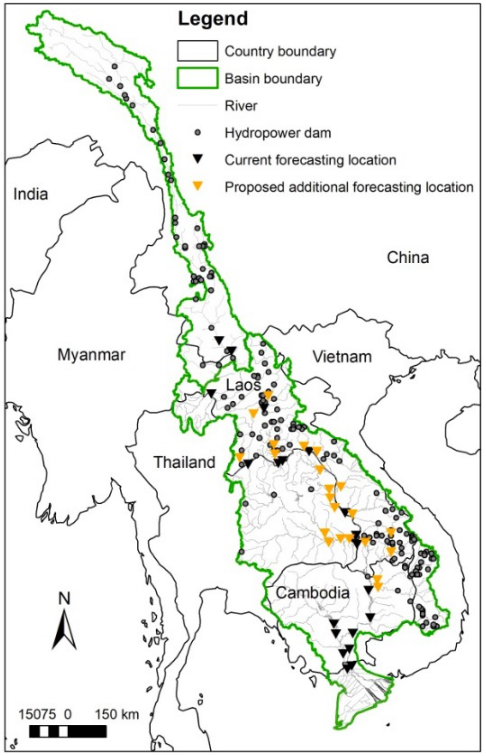
- Funded proposal (2023-2025)
- PI: Mauricio E. Arias (Univ. of South Florida)
- Co-Is: Eunjee Lee (UMBC/NASA), Randal D. Koster (NASA), Thanh Dang (USF), Miguel Laverde (Asia Disaster Preparedness Center)
- Collaborator: Fabio Farinosi (EU)
- NASA SERVIR Applied Science Team
- To develop a decision 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.

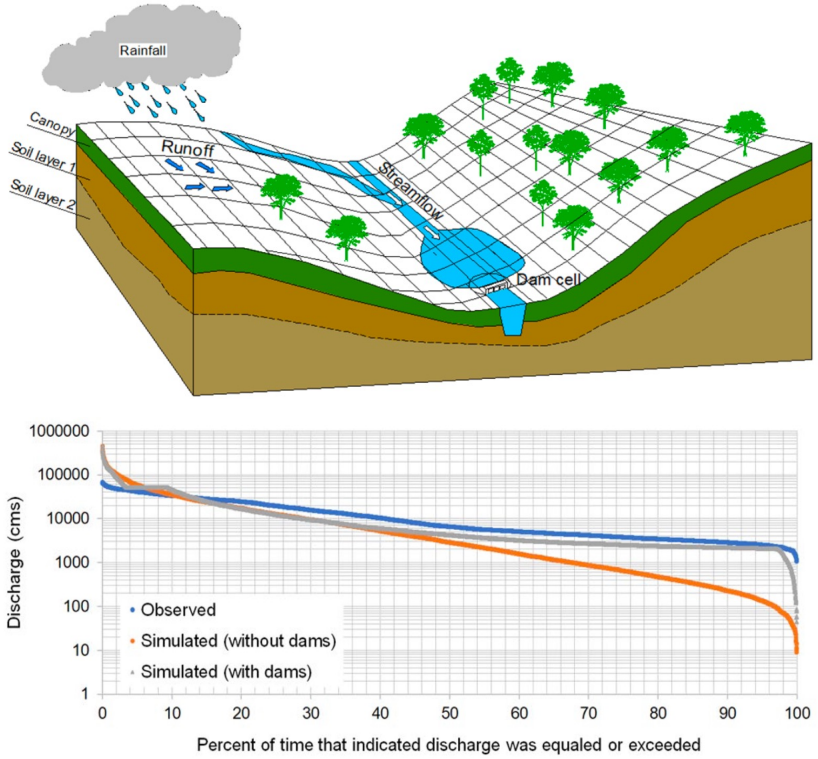
- The temporal and spatial scope of this forecast is insufficient for comprehensive basin management.



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.

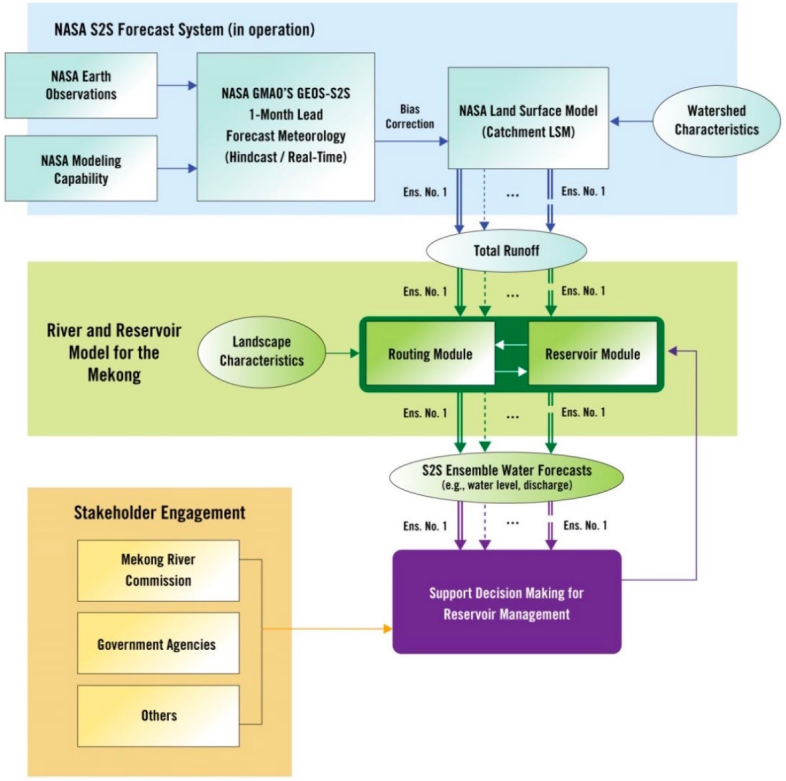
- Prediction of sub-seasonal variations in river flows on the Mekong's main stem and tributaries will be made through the joint consideration of S2S forecast runoffs and dam operations.



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 of land's carbon uptake

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.**

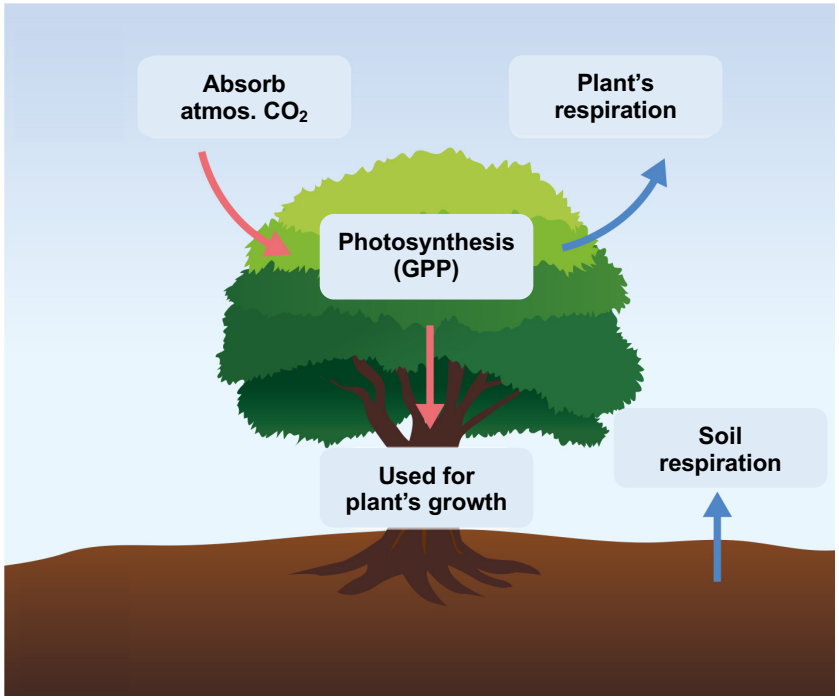
- Why do we care about the seasonal carbon forecast?
  - To improve future S2S forecast system, which will ultimately include the full biogeochemical cycle, we need the information about how the system will behave with the carbon cycle.
  - Carbon forecasts can eventually support a wider range of end 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.

Recap land's carbon and water dynamics



Net carbon uptake by land ecosystem = GPP – Respirations

Catchment-CN: NASA GMAO's carbon-enhanced LSM

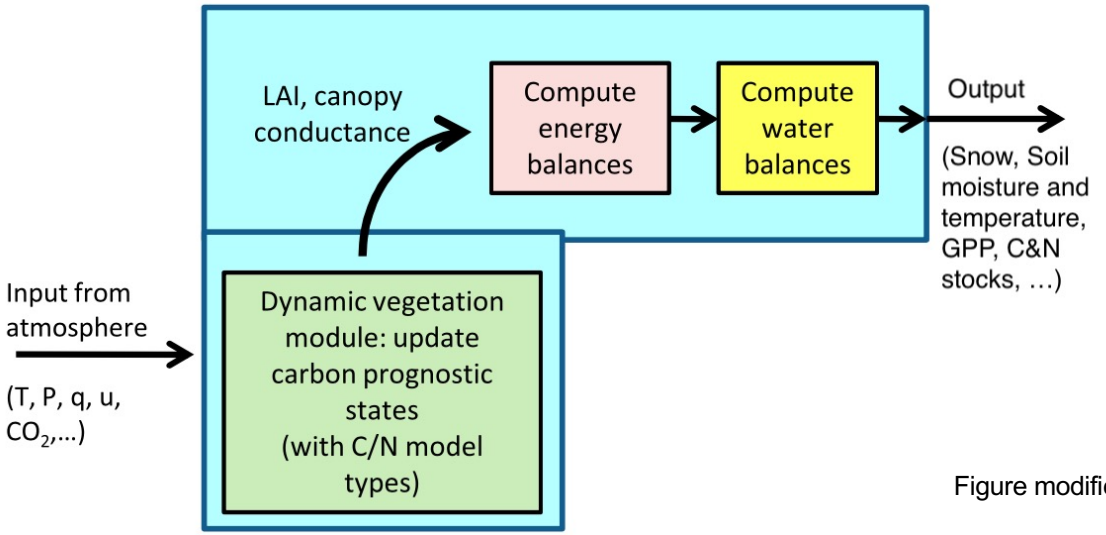
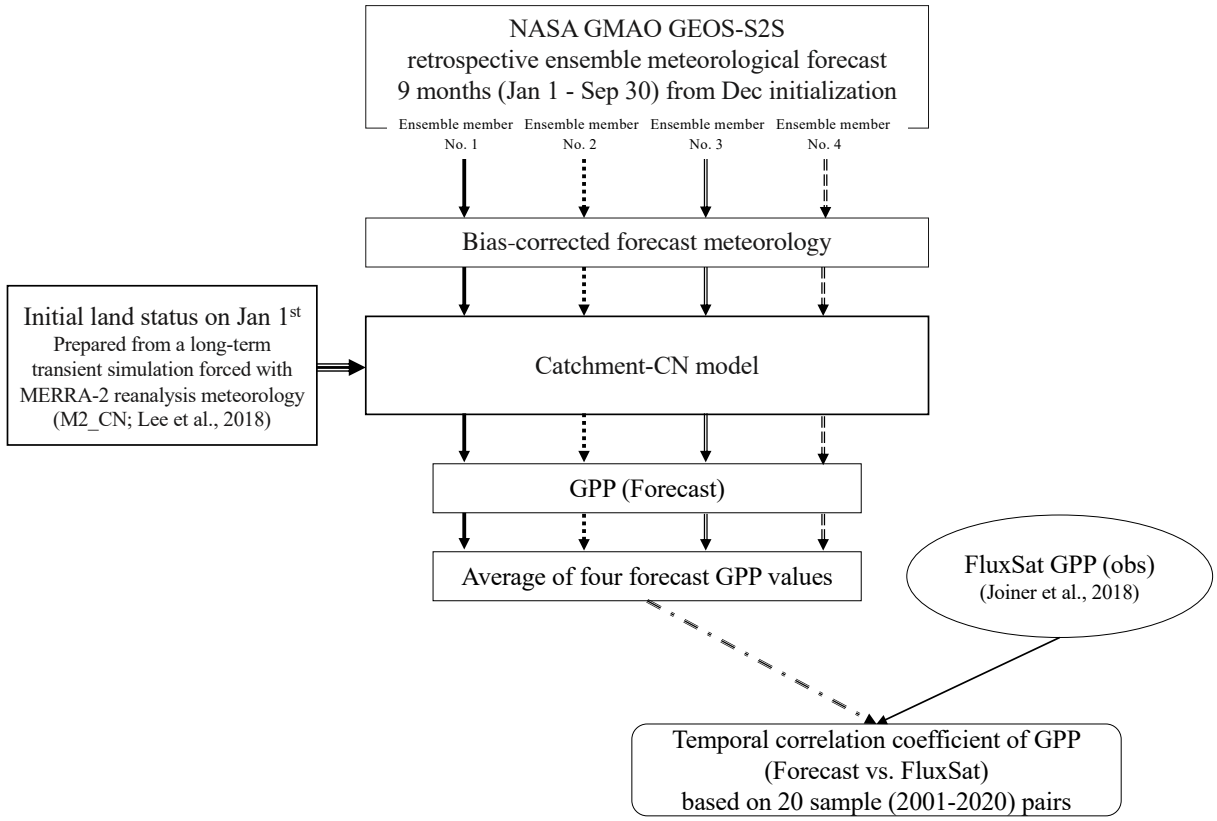


Figure modified from Koster et al. (2014)

- 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 (overview)

- We generated ensemble carbon forecasts by using NASA's Catchment-CN model offline, forced with bias-corrected forecast meteorology.
- Four ensemble hindcast meteorology are used for each forecast year.
- The GPP forecast skill was evaluated with the observation-based GPP (FluxSat GPP)



How was each carbon forecast generated?

- In each offline Catchment-CN simulation, computations were performed on **9km equal-area grid** (Brodzik et al., 2012).
- The bias-corrected meteorological forcing in the forecast (0.5° lat × 0.625° lon) was applied to the grid using nearest neighbor interpolation.
- Different 9-km land elements below a 0.5° × 0.625° grid cell (that shares a same meteorological forcing) behave differently due to differences in sub-grid heterogeneity (e.g., topographical character, vegetation type, soil type).
- The average value of the atmospheric CO_2 concentration at the land surface over 2001–2020 (391 ppm) was applied globally in all simulations.
- **All carbon forecasts started on Jan 1st** of the corresponding forecast year and ended on Sep 30th.

Preparation of land initial condition for January 1st

- The **January 1st land initial states** (snow cover, soil moisture, soil temperature, and C&N reservoir) for a given forecast year were **extracted from a long-term offline Catchment-CN simulation**, driven with MERRA-2 reanalysis meteorological forcing.
- The long-term simulation used the same nearest neighbor interpolation on the same 9-km grid and representation of the land surface's character.
- To mimic realistic land states (carbon, water and energy), **we first spun-up the model** to mimic the condition of the pre-industrial period, applying multiple cycles of 1981–2015 MERRA-2 forcing (at least 2,000 simulation years) **with 280 ppm of CO_2**.
- **We then drove the model** with additional cycles of the MERRA-2 forcing to represent **1850 to present with the steadily increasing CO_2 concentration** along the way to the present value (to mimic the transient character and carbon sink in Nature).
- The simulation produced the carbon, water, and energy states we need for the offline forecast initializations (Lee et al., 2018).

Experimental design (CTRL)

- We chose the ensemble members that were **initialized on four different days** in December of the year preceding the forecast year.
- While the ensemble size is small, it introduces at least some degree of **internal meteorological variability into our carbon forecasts.**
- In CTRL, the simulations used the land initial conditions that are appropriate for the retrospective forecast years.

Total 80 simulations (4 ensemble members x 20 years) of 9-month (Jan-Sep) retrospective carbon forecasts.

Year	Catchment-CN simulation start date	Catchment-CN simulation end date	S2S meteorological forecast forcing
2001	Jan 1, 2001	Sep 30, 2001	Ensemble member 1 (initialized in Dec 27, 2000)
			Ensemble member 2 (initialized in Dec 22, 2000)
			Ensemble member 3 (initialized in Dec 17, 2000)
			Ensemble member 4 (initialized in Dec 12, 2000)
2002	Jan 1, 2002	Sep 30, 2002	Ensemble member 1 (initialized in Dec 27, 2001)
			Ensemble member 2 (initialized in Dec 22, 2001)
			Ensemble member 3 (initialized in Dec 17, 2001)
			Ensemble member 4 (initialized in Dec 12, 2001)
…	…	…	…
2020	Jan 1, 2020	Sep 30, 2020	Ensemble member 1 (initialized in Dec 27, 2019)
			Ensemble member 2 (initialized in Dec 22, 2019)
			Ensemble member 3 (initialized in Dec 17, 2019)
			Ensemble member 4 (initialized in Dec 12, 2019)

Supplemental experiment (EXP) and analysis metric

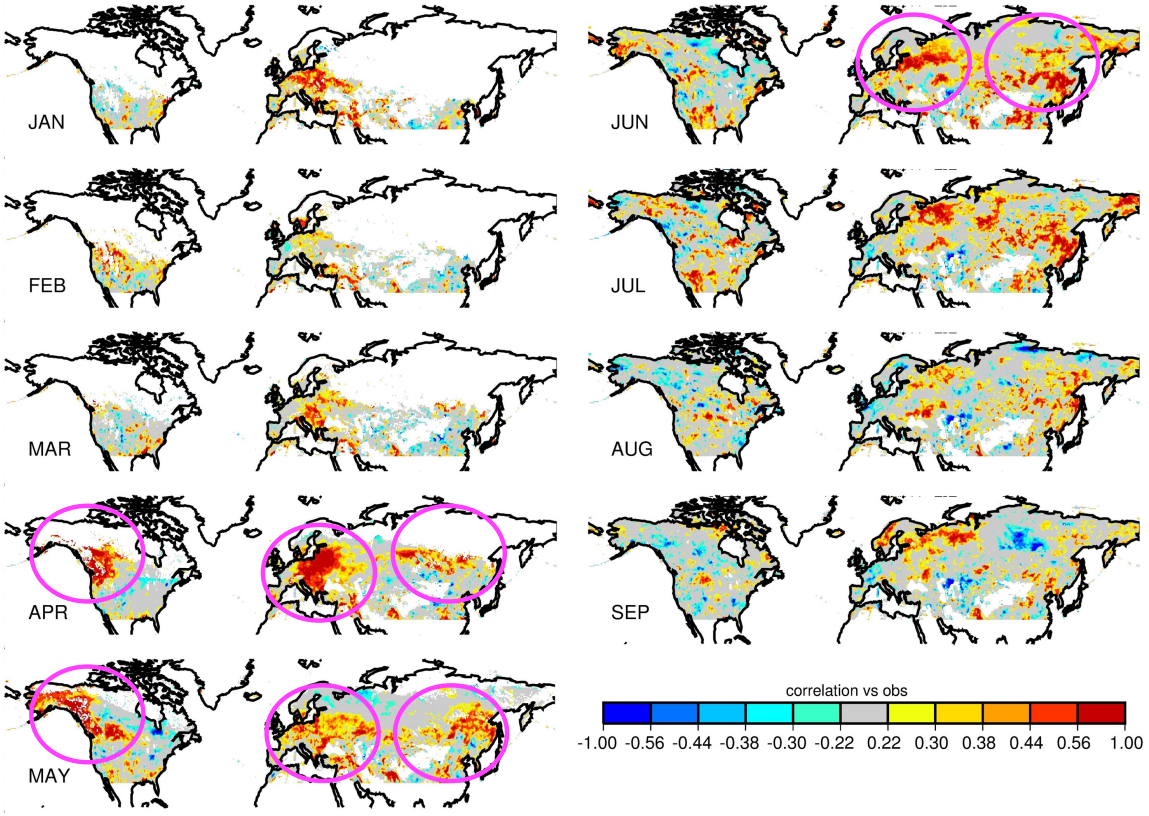
- EXP suite
  - Same as CTRL, except for retaining the inter-annual variation of the carbon and nitrogen initialization on Jan 1st and fixing other conditions as those in year 2013.
  - No inter-annual variability in forecast meteorology and snow and soil moisture initialization is allowed.

- 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 seven consecutive days

- Evaluation metric of forecast skill
  - Correlation coefficients (Pearson's r) between the forecast and the observation, based on 20 sample pairs (i.e., one pair for each forecast year in 2001-2020)

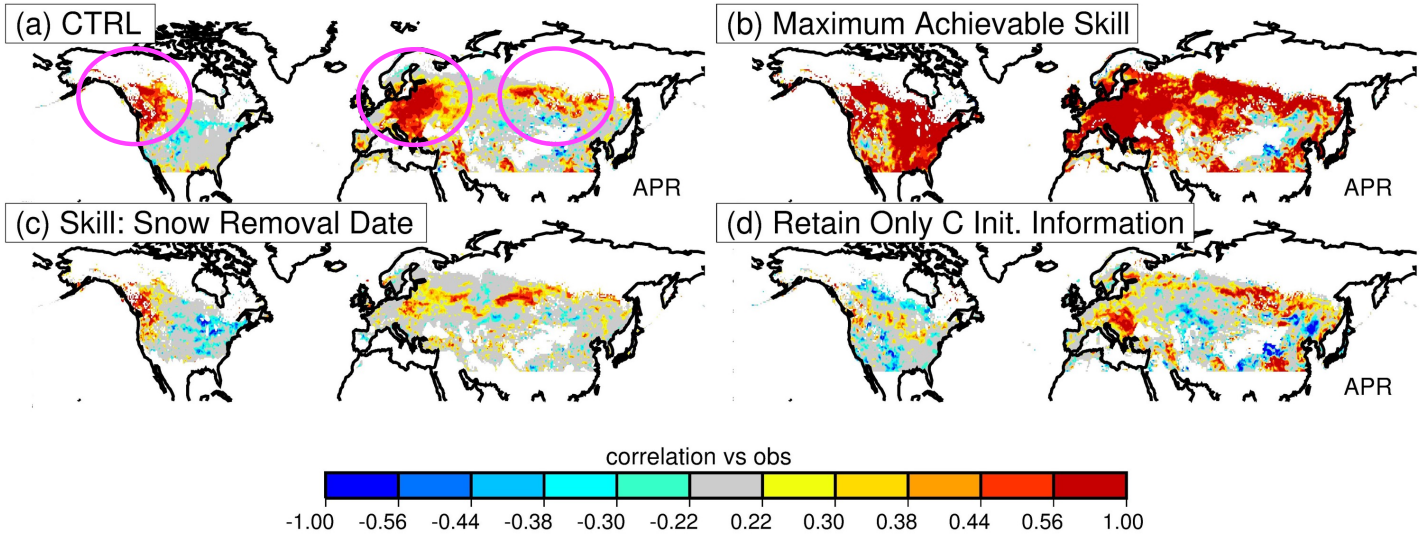
Forecast skill of monthly GPP (Forecast CTRL vs. observed GPP)

- Skillful GPP forecast in northwestern North America, eastern Europe, and Eurasia
- High skill in April and May (4th & 5th forecast lead months)
- 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



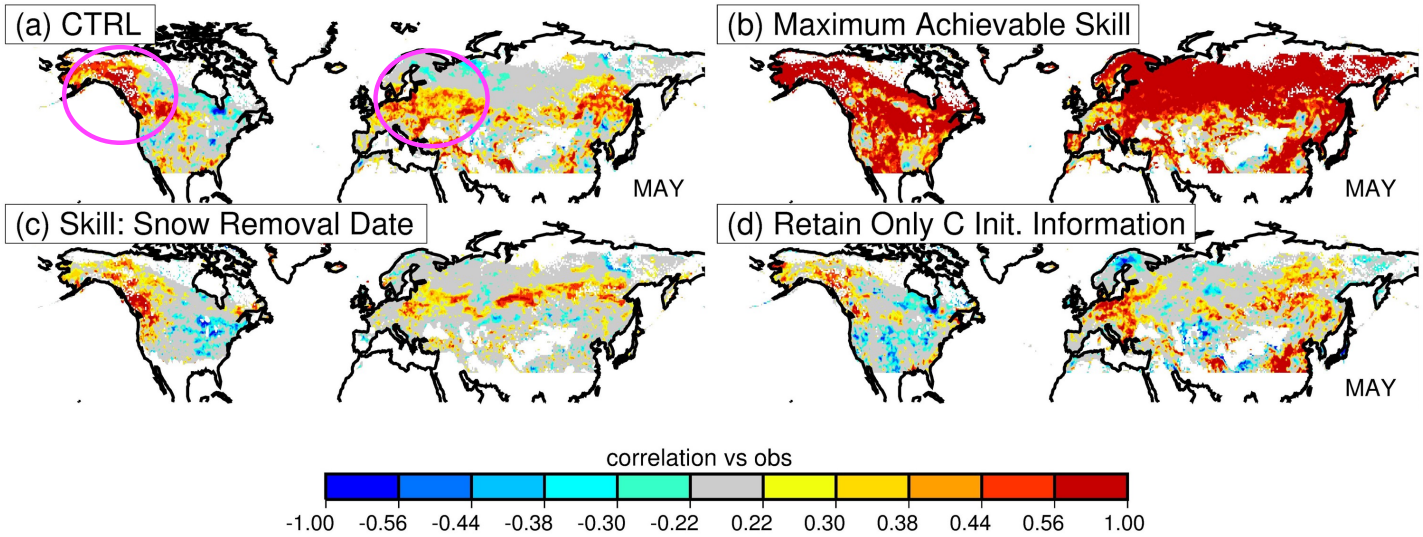
Lee et al. 2022, GRL

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 C initialization appears in southeastern Europe and in eastern Asia

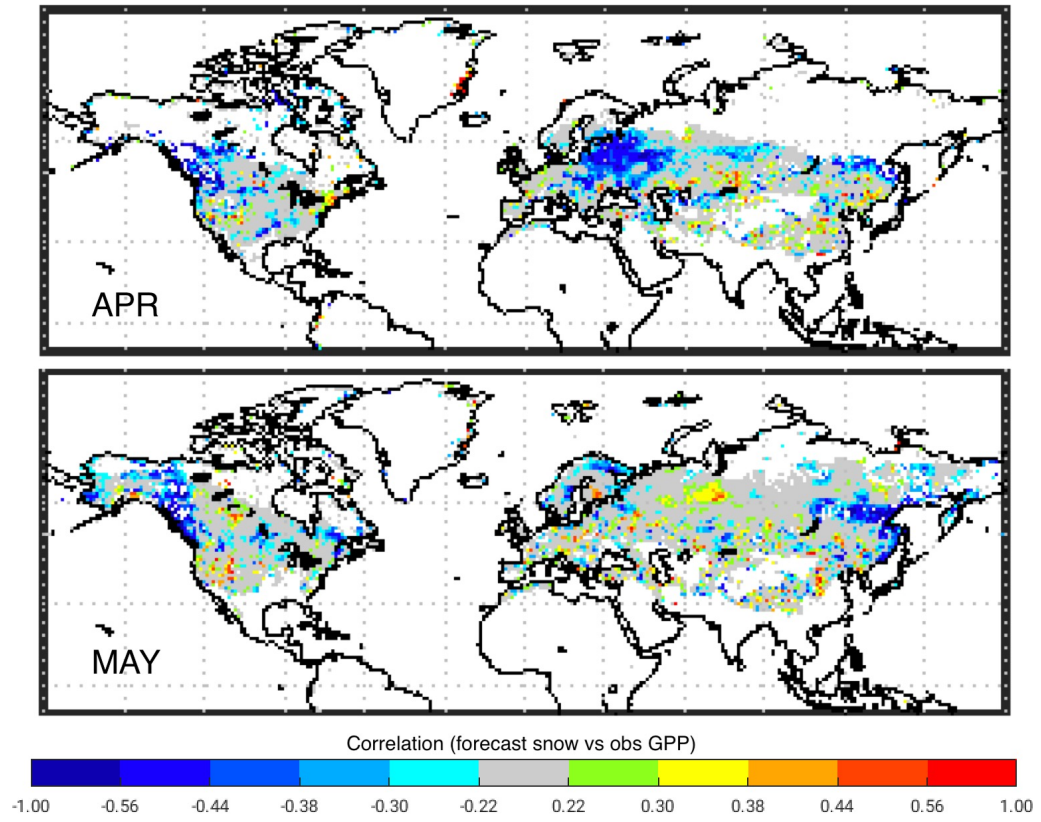
MAY (5th lead month)
Contribution of initialization to GPP forecast skill



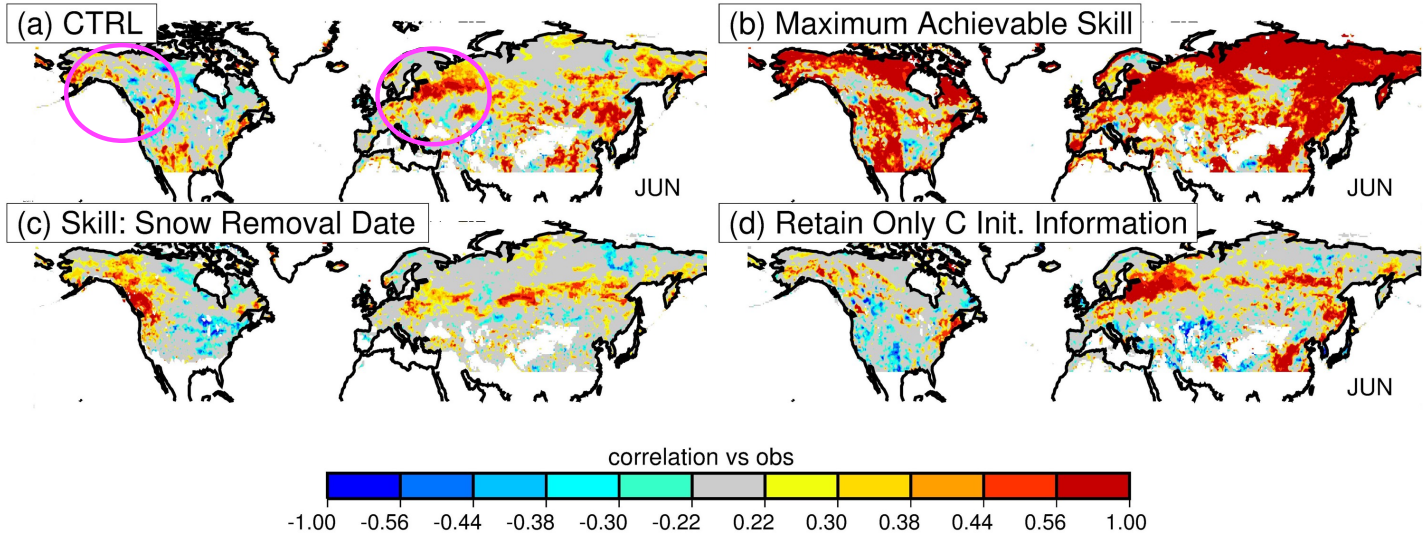
- Contribution of snow initialization appears in northwestern North America and parts of Eurasia.
- The importance of carbon and vegetation initialization appears to be higher in later forecast lead months.

Snow initialization: Forecast snow (CTRL) vs. obs GPP (FluxSat)

- Connection between the forecast accuracies of snowpack removal and GPP
- 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.



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



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

Carbon and 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
- Impact on GPP forecast skill in certain key regions (e.g., southeastern Europe).
- Vegetation places carbon and nitrogen in different reservoirs partly for use in later production. Thus, the vegetation's established storage distribution going into autumn helps set the stage for plant health and productivity during the subsequent year.
- Snowpack initialization and carbon reservoir initialization provide contributions to GPP forecast skill in largely complementary areas

Summary of seasonal forecast of carbon 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. Given that S2S meteorological forecast skill is generally elusive, our finding is significant especially over mid- and high latitude continents.
3. 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.
4. In addition to the snow initialization, the carbon reservoirs initialization is important in certain key regions (e.g., southeastern Europe) and at later forecast lead months.
5. In central-eastern Eurasia, soil moisture and snow initialization may both contribute to GPP forecast skill in part by controlling growing season moisture variability.