Land Surface Hydrology in Earth System Reanalysis

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Special thanks to:
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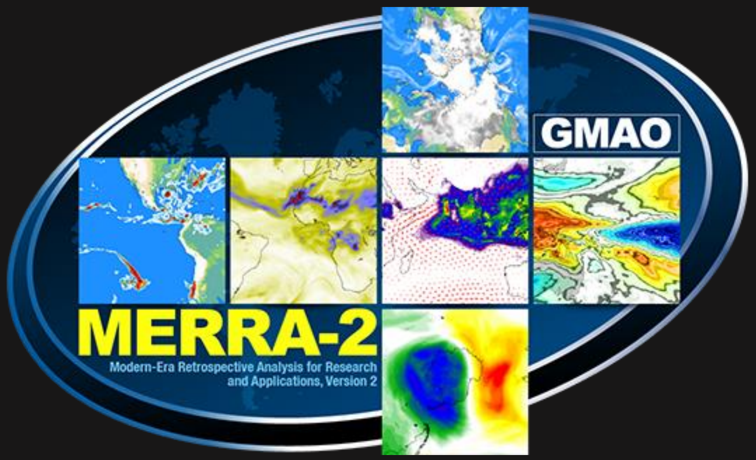
Introduction



Focus on:
- Global retrospective analysis.
- Satellite era (NASA-centric).

Major US reanalyses:
- No (or minimal) land assimilation.
- Observed precipitation (CFSR, MERRA-2) → poor man's soil moisture/snow analysis.
- ERA5: Soil moisture & snow analysis, but not using observed precipitation.

Land assimilation:
- US progress chiefly in land-only systems (e.g., SMAP Level-4 Soil Moisture, NASA LIS, …).

Grand challenge: Use land assimilation in next US Earth system reanalysis.

Overview

Key land variables (modeling, observations, assimilation)

- Precipitation
- Soil moisture
- Snow
- Terrestrial water storage
- Surface water (rivers, lakes)
- Land surface temperature
- Vegetation phenology
- Soil parameters, land cover, albedo
- Anthropogenic processes

Systems and methods

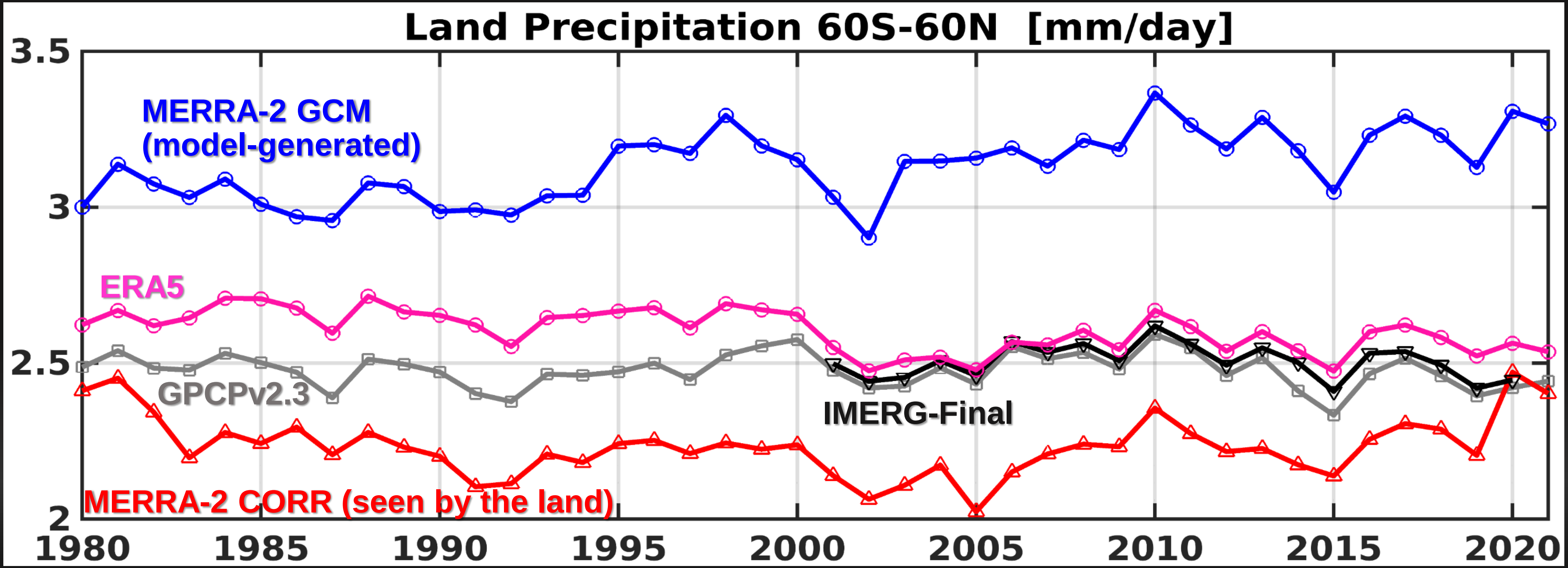
- Filtering, coupling, software

Towards workshop outcomes

- Advances, barriers, requirements

Precipitation (MERRA-2)

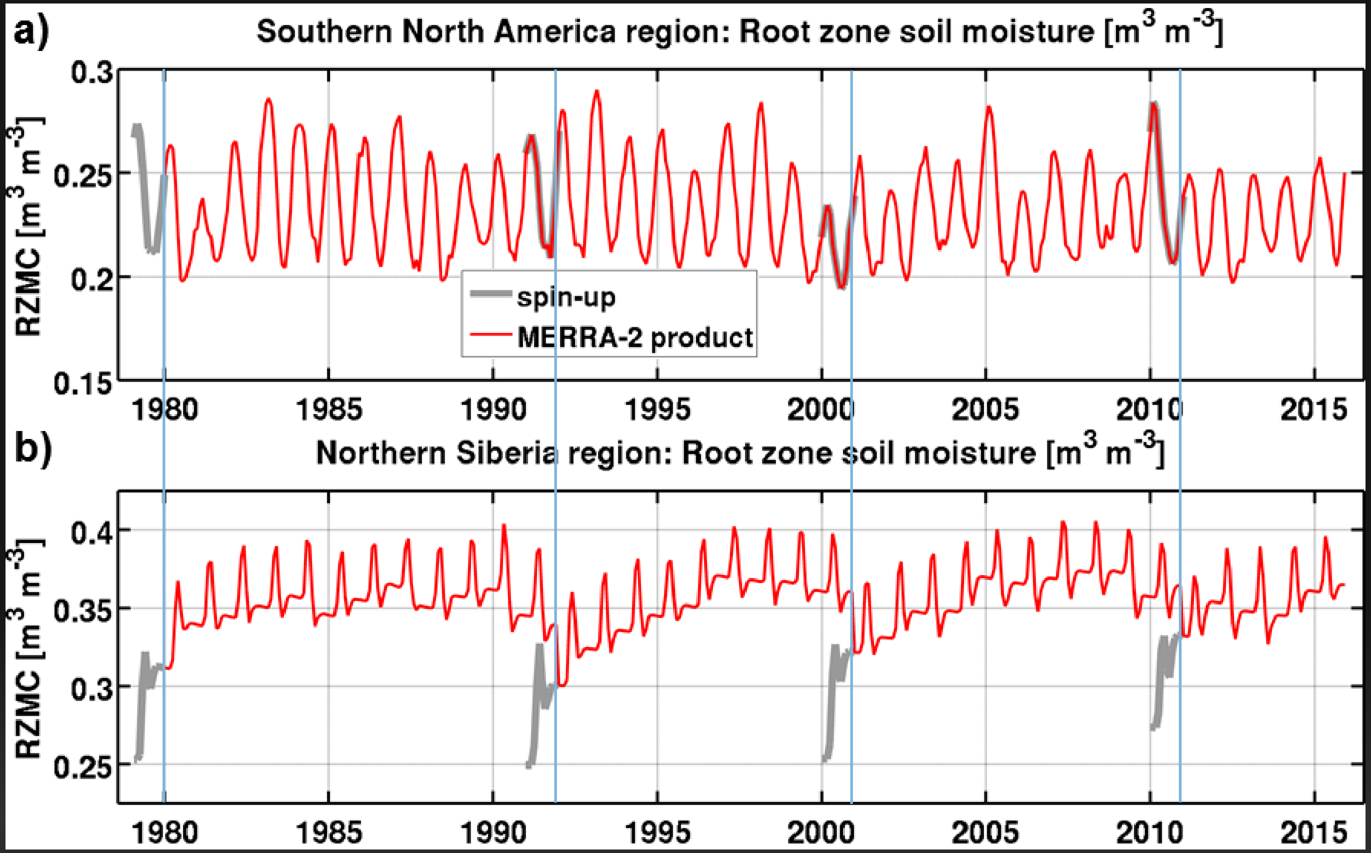
Most important driver for land surface hydrology.



In MERRA-2, precipitation seen by the land is corrected to daily CPC gauge observations.

Improves simulation of land surface conditions (not shown).

Precipitation (MERRA-2)



Reichle et al. 2017, doi:10.1175/JCLI-D-16-0570.1

See reference below for relevant graphics.

Sabater et al. 2021, doi:10.5194/essd-13-4349-2021

Observed precipitation:
→ Seamless stream boundaries using (offline) land spin-up.

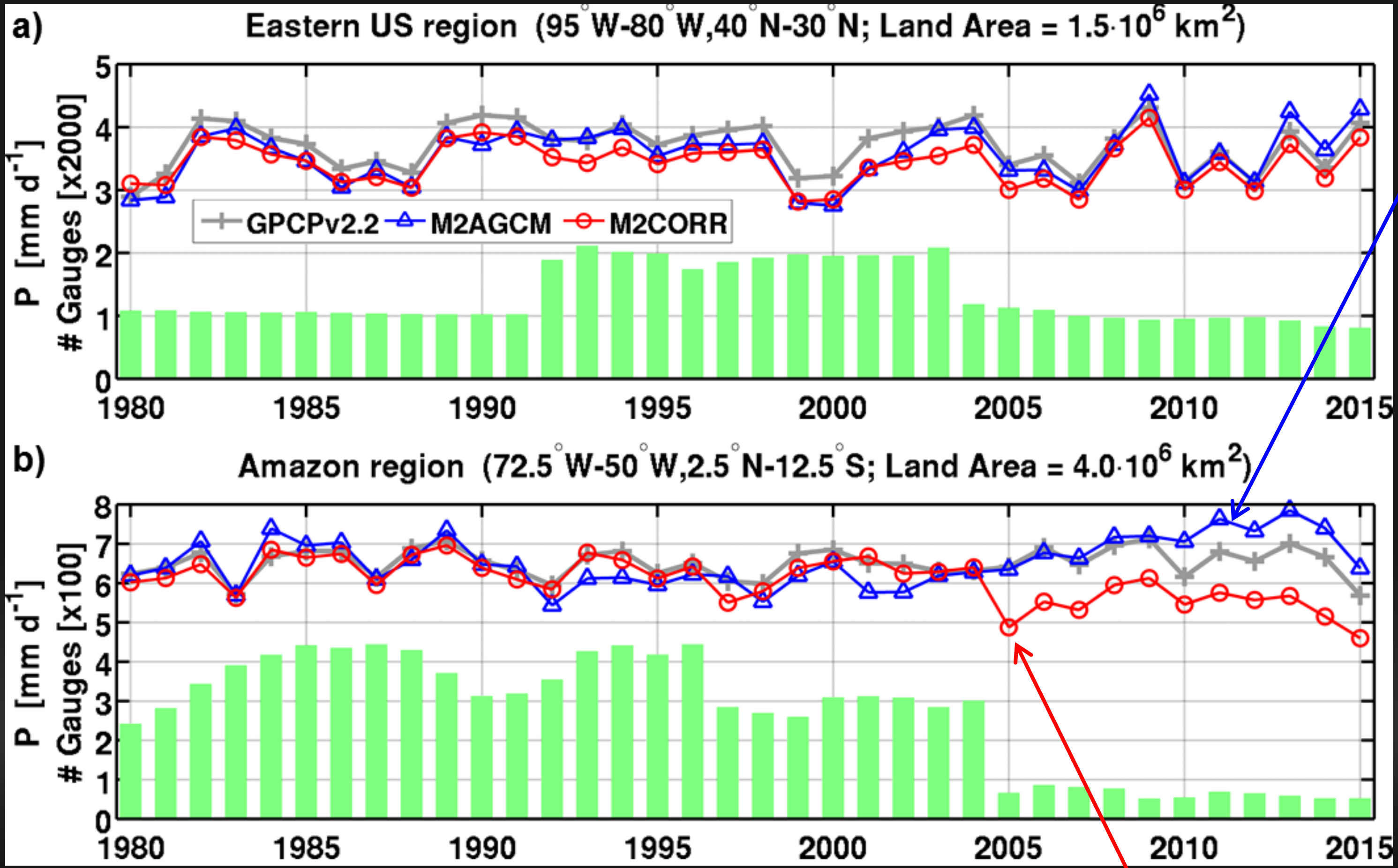
Not using observed precip. (high lats.):
→ Spin-up problems for ~1-2 years across stream boundaries.

ERA5 also has discontinuities.

Precipitation (MERRA-2)

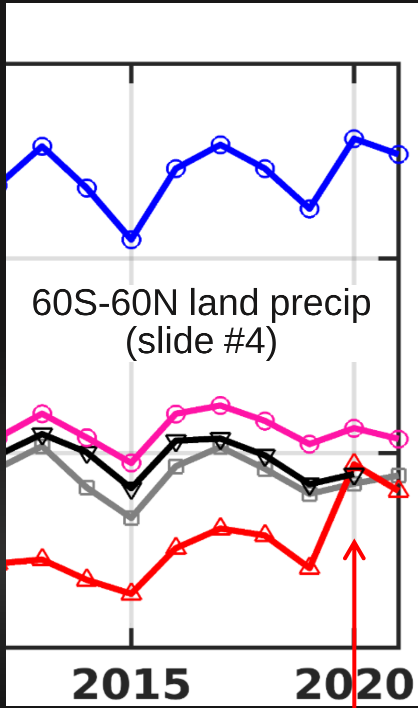
Eastern US looks good (generally well instrumented).

Elsewhere, discontinuities because of observing system changes.



Reichle et al. 2017, doi:10.1175/JCLI-D-16-0570.1

ADAS observing system changes.

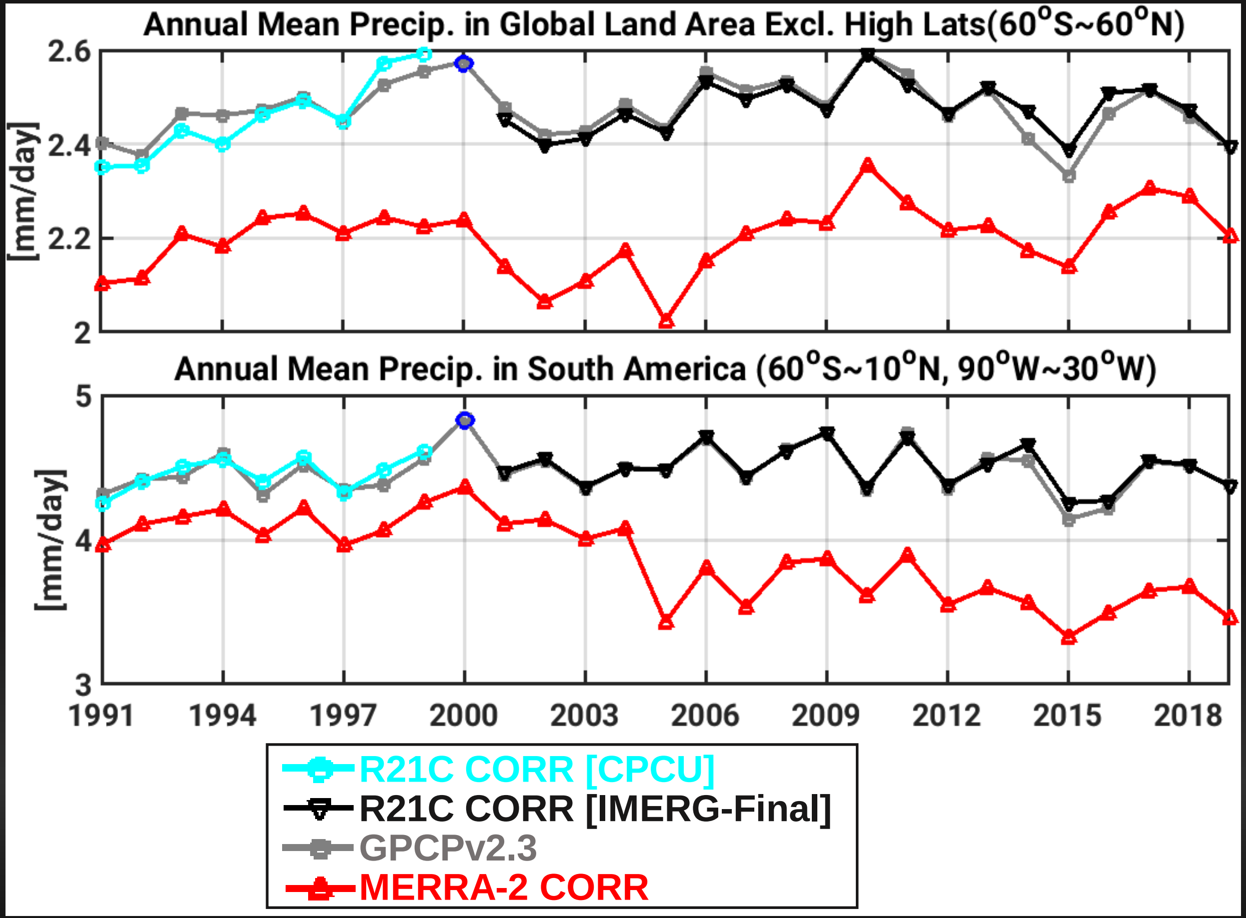


CPC gauge product switches from back-processing to ops.

CPC staff retired, pandemic restrictions.

Precipitation (R21C)

National Aeronautics and Space Administration



Reichle et al. 2022, in preparation

R21C = GEOS Reanalysis of the 21st century (production starting soon)

Using IMERG-Final (multi-satellite + gauges).

Eliminates low bias and discontinuities seen in CPC-corrected MERRA-2 precipitation.

IMERG-Final latency >3 months!

→ Close to real-time, use satellite-only IMERG-Late (as in current SMAP L4 ops).

→ Only small degradation in soil moisture.

IMERG version change underway…

Soil Moisture

Couples land surface water, energy & carbon cycles.

Satellite observations:

- SMOS (2010-), SMAP (2015-), CIMR (2025-)
- ASCAT (2007-), Sentinel-1 (2016-), NISAR (2024-)
- ESA-CCI multi-sensor products (~1978-)

In situ observations:

Screen-level T2m, q2m (used in soil moisture analysis in European & Canadian systems; under development at NOAA).

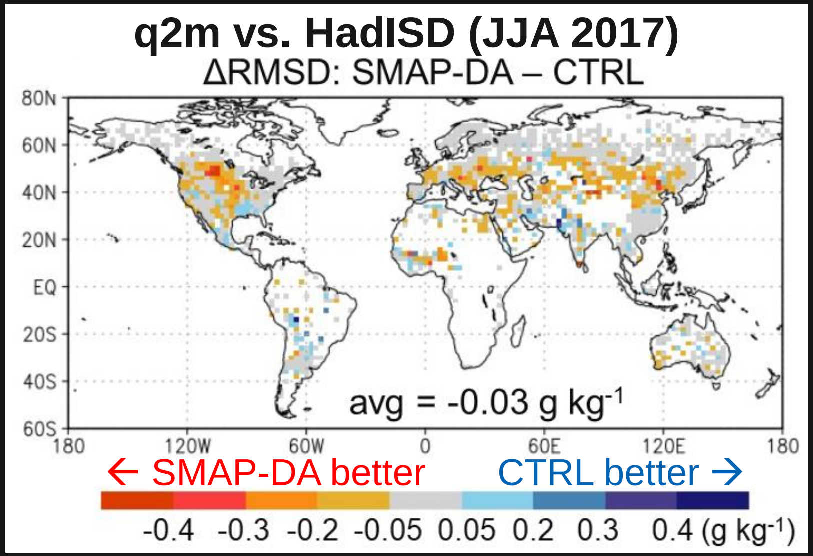
See reference below for relevant graphics.

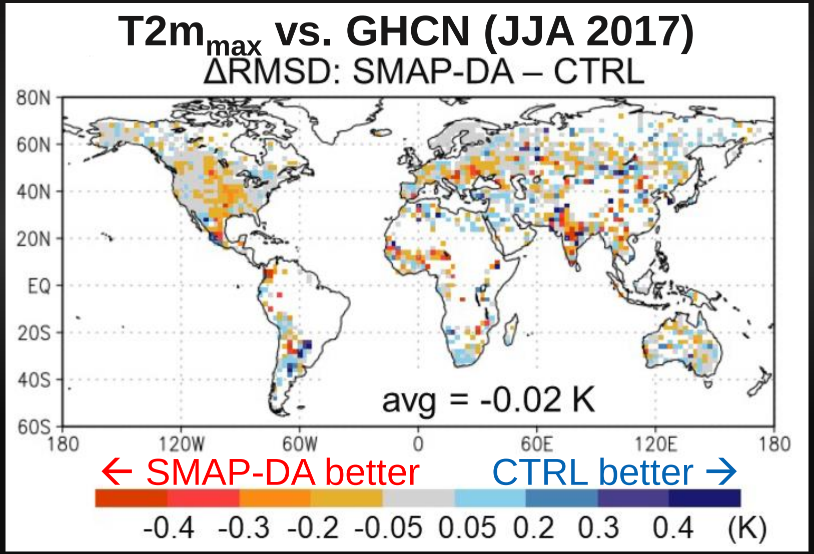
Van der Schalie et al. 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Soil Moisture

CTRL =
½ deg version of GEOS atmospheric data assimilation (NWP) system.

SMAP-DA =
CTRL + weakly-coupled SMAP radiance assimilation.





Reichle et al. 2022, in preparation

Considerable q2m and T2m improvements regionally.

Not shown:
- Improvements in q extend up to ~700 mb.
- Improvements in q and T at 925 mb persist into 5-day forecasts.

Snow

Critical freshwater resource for billions of people.

See reference below for relevant graphics.

Robinson 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Observations:

- Snow cover (satellite, 1967-)
- Snow depth (in situ)
  [satellite retrievals not good enough]

Snow depth (in situ) reporting issues:

- GTS, “zero” reports → Patricia de Rosnay, ECMWF

NOAA developing OI-based snow analysis (~ECMWF) to replace existing simple scheme in GFS; tuning snow depletion curve in new multi-layer snow model (Noah-MP).

NASA implementing ensemble-based snow cover analysis (Toure et al. 2018).

Terrestrial Water Storage

Need deeper storage for drought monitoring.

Observations: GRACE & GRACE-FO (2002-)

- TWS incl. shallow & deep groundwater, rivers, lakes. → Model requirements.
- Monthly avg. → Requires non-standard analysis.
- Latency >1-month. → Cannot continue reanalysis in real-time (shorter latency under development?).

See reference below for relevant graphics.

Rodell & Wiese 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Rivers & Lakes

Runoff → streamflow → discharge into ocean:

- Important in coupled atm.-ocean reanalysis (MERRA-3).
- Simple runoff routing under development in GEOS.

Rivers & lakes:

- No lake surface temperature analysis in GEOS;
  may be sensible, but low priority.
- Water levels not yet simulated in GEOS & Noah-MP.
- Retrospective satellite altimetry anyway too coarse for inland water level analysis.

See reference below for relevant graphics.

Kim and Tokuda 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Land Surface Temperature

Massive amounts of satellite observations:

- Polar orbiting (high-resolution)
- Geostationary (diurnal cycle)
- Optical (clear-sky only)
- Microwave (clear & cloudy)
- ESA-CCI LST (Ghent et al.)

Key obstacles to LST assimilation:

- Mismatch between observed & simulated variables.
- Minimal memory.

See reference below for relevant graphics.

Ghent et al. 2022, LST CCI: Approaches to long-term data for climate, 4th International Earth Surface Working Group (IESWG) Workshop, Online.

Vegetation (Phenology)

Important for consistency of water and carbon estimates.

Abundant satellite observations:

- Optical (NDVI, FPAR, LAI; 1980s-)
- Microwave (VOD)

Dynamic vegetation phenology modeling:

- Noah-MP, CatchmentCN
- Not yet operational; computationally demanding; 1000s of simulation years needed for carbon spin-up.

See reference below for relevant graphics.

Gobron 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Vegetation (Phenology)

Assimilation in land-only systems (Albergel et al. 2017; Kumar et al. 2019, 2020).

See reference below for relevant graphics.

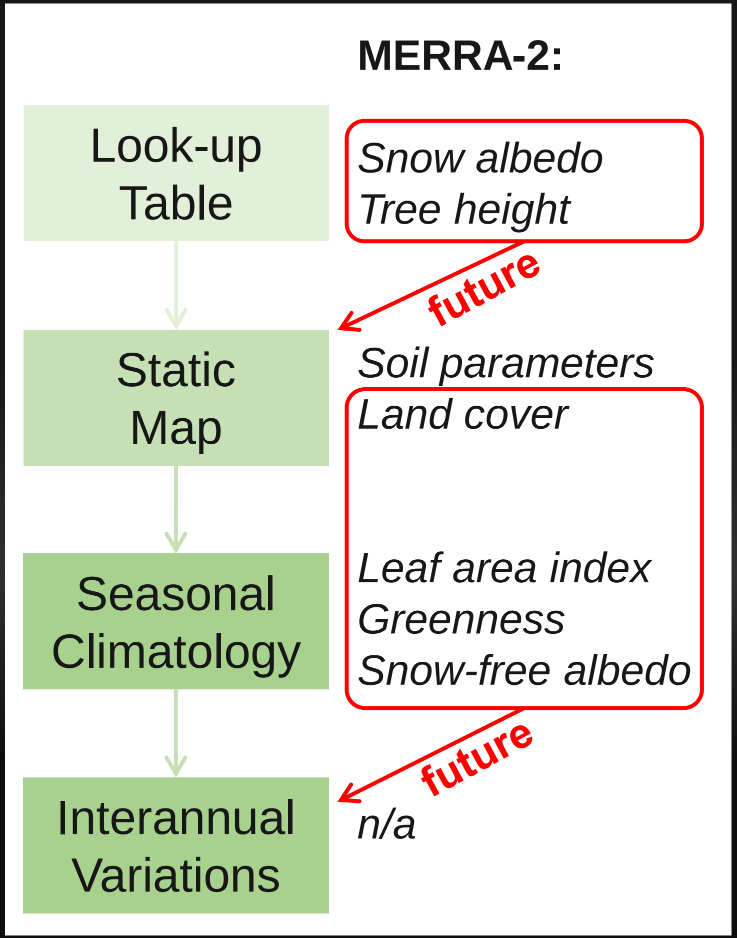
Kumar et al. 2020, doi:10.5194/hess-24-3431-2020

Assimilation of SMAP soil moisture does <u>not</u> improve evapotranspiration (ET) or gross primary productivity (GPP), …

but assimilation of SMAP vegetation optical depth (VOD) does.

Land Model Parameters

Abundant satellite observations of land surface properties (Landsat, MODIS, VIIRS, Sentinel-2, Icesat-2, …)



See reference below for relevant graphics.

Duveiller and Gobron 2021, ed. Dunn et al., doi:10.1175/BAMS-D-21-0098.1

Anthropogenic Processes

Human impact on land water, energy and carbon cycles:

- Irrigation (groundwater and surface water)
- Artificial wetland drainage
- Forest harvest & tree species selection (incl. deforestation)
- Crop harvest & rotation
- Grazing and mowing
- Tillage
- Fertilization
- Fire for land management

See reference below for relevant graphics.

Pongratz et al. 2018, doi:10.1111/gcb.13988

Implementation in Earth system models:

- Limited by data availability & process understanding.
- Model development:
  - Noah-MP (incl. carbon).
  - CatchmentCN (carbon/nitrogen).
  - GEOS irrigation module.

Systems and Methods

Land assimilation mostly uses Kalman filter variants (EKF, EnKF, LETKF), because land model adjoint difficult to obtain & maintain.

Coupling of land and atmospheric analysis components:

- GEOS: Weakly-coupled (~ECMWF); taking advantage of mature off-line assimilation system.
- GFS: Focus on strongly-coupled analysis.

Software infrastructure:

- DART, GEOSldas, [JEDI], LIS, …
- Land assimilation not yet routinely used in ADAS operations.

→ No reference system exists for JEDI land assimilation development.

Towards Workshop Outcomes (5-10 Year Horizon)

1. Most significant advances:

- Assimilation of satellite observations for land hydrology (precipitation, soil moisture, snow).
- Emerging dynamic vegetation phenology modeling and assimilation.

2. Most significant barriers:

- Land assimilation is highly model-specific (Catchment[CN] & Noah[-MP] are very different).
- NOAA and NASA land assimilation development from different foundations.
- Difficult coordination between LDAS & ADAS teams.
- Lack of qualified staff.
- Legacy software maintenance and cleanup.

3.Collaborations:

- See item 2.

To be discussed, corrected, and amended!

4. Critical requirements:

- Land assimilation for hydrology, incl. satellite-based land model parameters.
- Improved lake & river modeling.
- Model components for human-driven land processes.

5. Observations:

- Precipitation (daily, quasi-global, stable, short latency).
- Soil moisture, T2m, q2m.
- Snow cover, snow depth.
- Interannually-varying land cover, albedo, and vegetation parameters.

6. Scientifically mature model components:

- Land water & energy exchange.

7. Uncertainty:

- Ensemble-based assimilation.

Thanks for listening!