



The Land Surface in Earth System Reanalysis

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Introduction

- Scope and overview

Key land variables (modeling, observations, assimilation)

- Precipitation
- Soil moisture
- ...

Systems and methods

- Filtering, coupling, software

Advances, challenges, and future developments



Focus on:

- Global retrospective analysis of the atmosphere.
- Satellite era (NASA occupational hazard...).

Land assimilation in major reanalyses:

- JRA-55 [JRA-3Q], CRA-40: Snow analysis. [?]
- CFSR: Snow analysis, observed precipitation.
- MERRA-2: Observed precipitation (poor man's soil moisture/snow analysis).
- ERA5: Soil moisture, soil temperature & snow analysis.

Land assimilation:

- Much progress in land-only systems (eg, LDAS-Monde, SMAP L4 Soil Moisture, NCA-LDAS...).

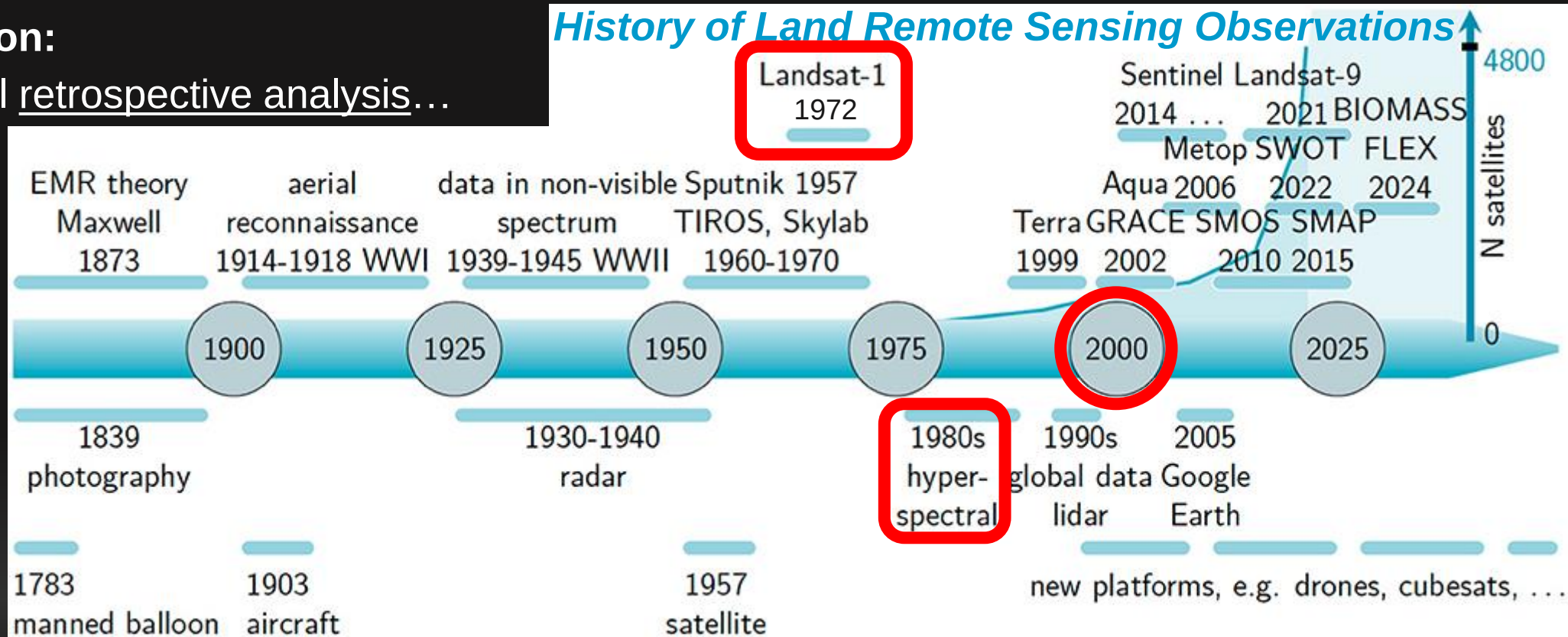
Land modeling:

- Reanalysis uses simple land models from NWP. More complexity in climate modeling (e.g., CTSM).

Scope and Overview

Focus on:

- Global retrospective analysis...



- Land assimilation: Satellite obs. of land surface water cycle mostly since ~2000.
(Exceptions: Snow cover 1967-present, SMMR 1978-87, ERS-1/2 1991-2006.)
- Land modeling: Land cover from Landsat since 1972. Vegetation indices (AVHRR) since 1980s.

Disclaimer



Not a formal review.

No claim of completeness.

Probably contains errors.

Sorry for errors and omissions – feedback is appreciated!



Introduction

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

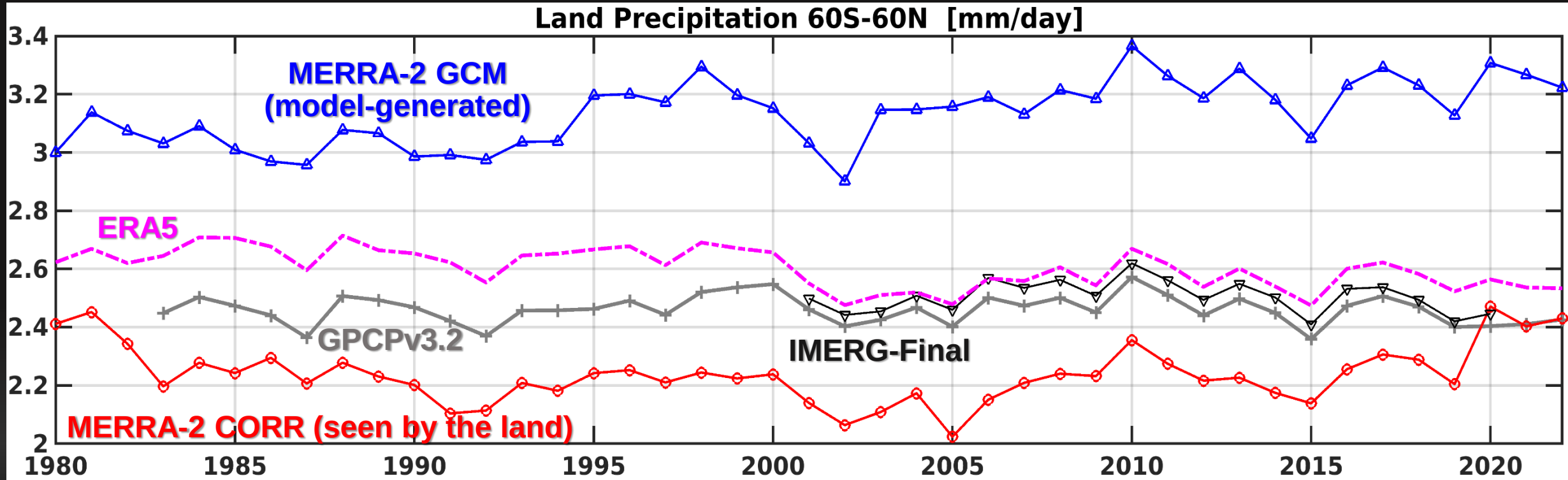
- Filtering, coupling, software

Advances, challenges, and future developments

Precipitation: Lessons from MERRA-2



Most important driver for land surface hydrology.

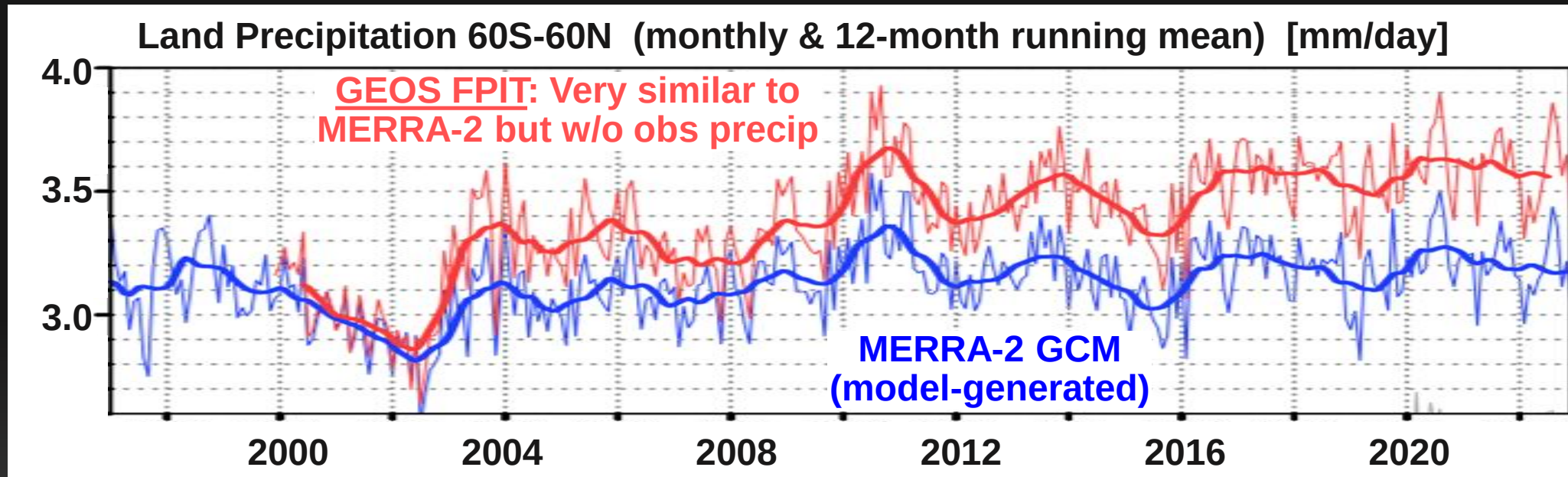


In MERRA-2, precipitation seen by the land is corrected to daily CPC gauge observations*.

Improves simulated land surface conditions (not shown).

**Except Africa & high-lats.*

Precipitation: Lessons from MERRA-2



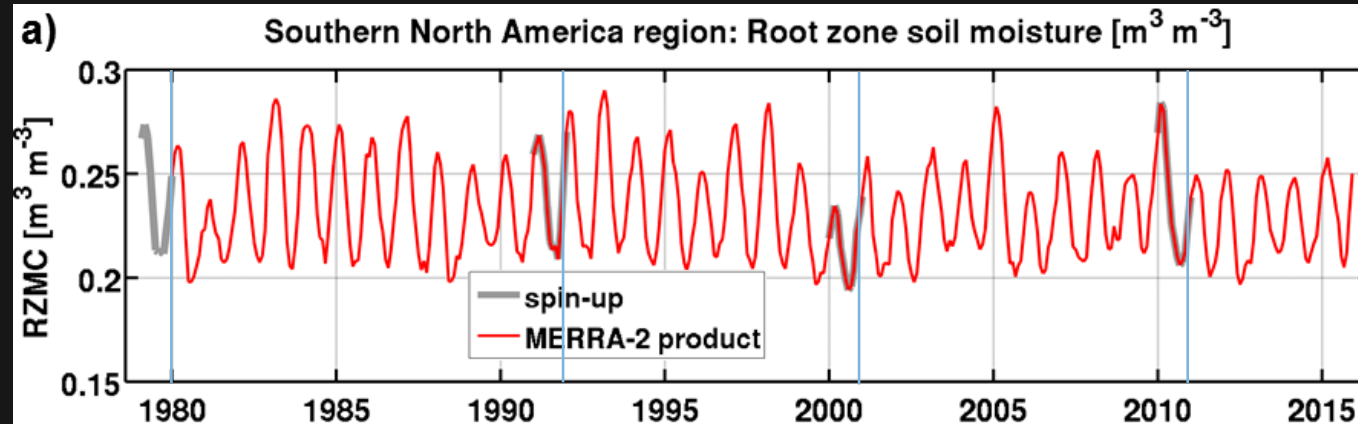
In MERRA-2, precipitation seen by the land is corrected to daily CPC gauge observations*.

Improves simulated land surface conditions (not shown).

Improves simulated precipitation output from MERRA-2.

**Except Africa & high-lats.*

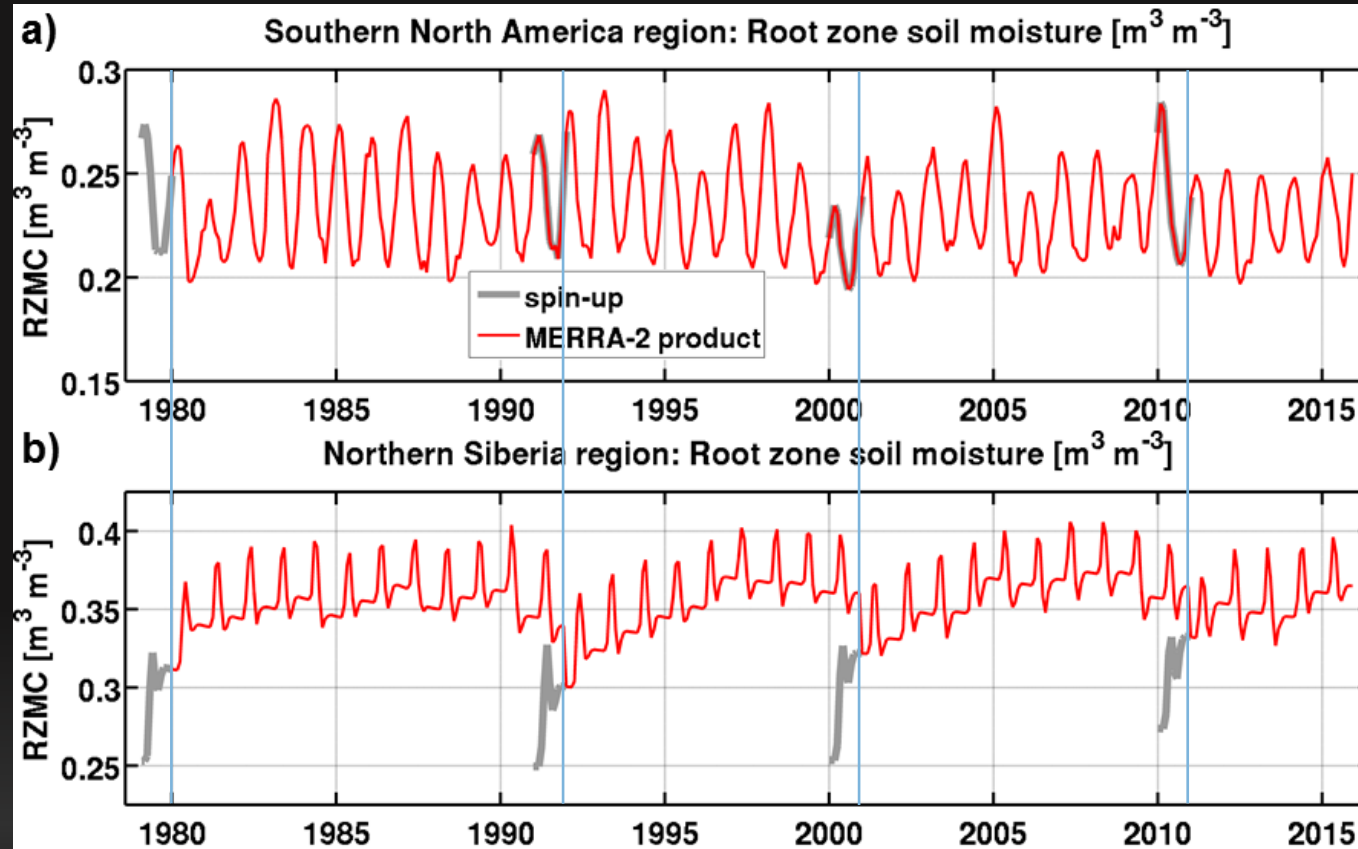
Precipitation: Lessons from MERRA-2



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

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

Precipitation: Lessons from MERRA-2



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

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.

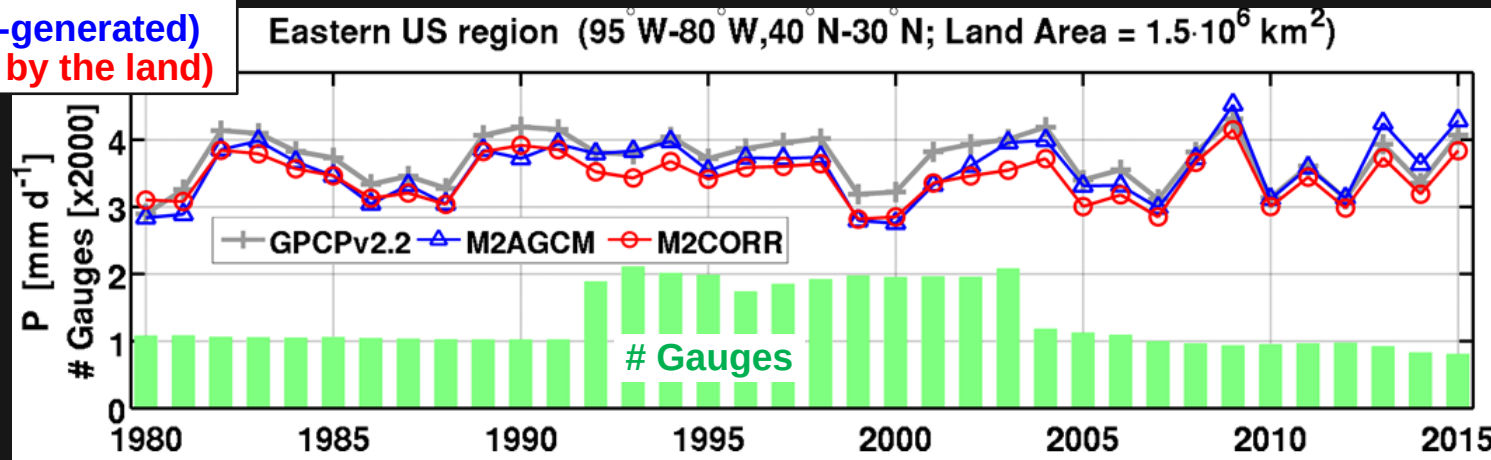
ERA5 also has discontinuities
(Sabater et al 2021, doi:10.5194/essd-13-4349-2021)

Precipitation: Lessons from MERRA-2



GPCPv2.2
MERRA-2 GCM (model-generated)
MERRA-2 CORR (seen by the land)

Eastern US
looks good
(generally well
instrumented).



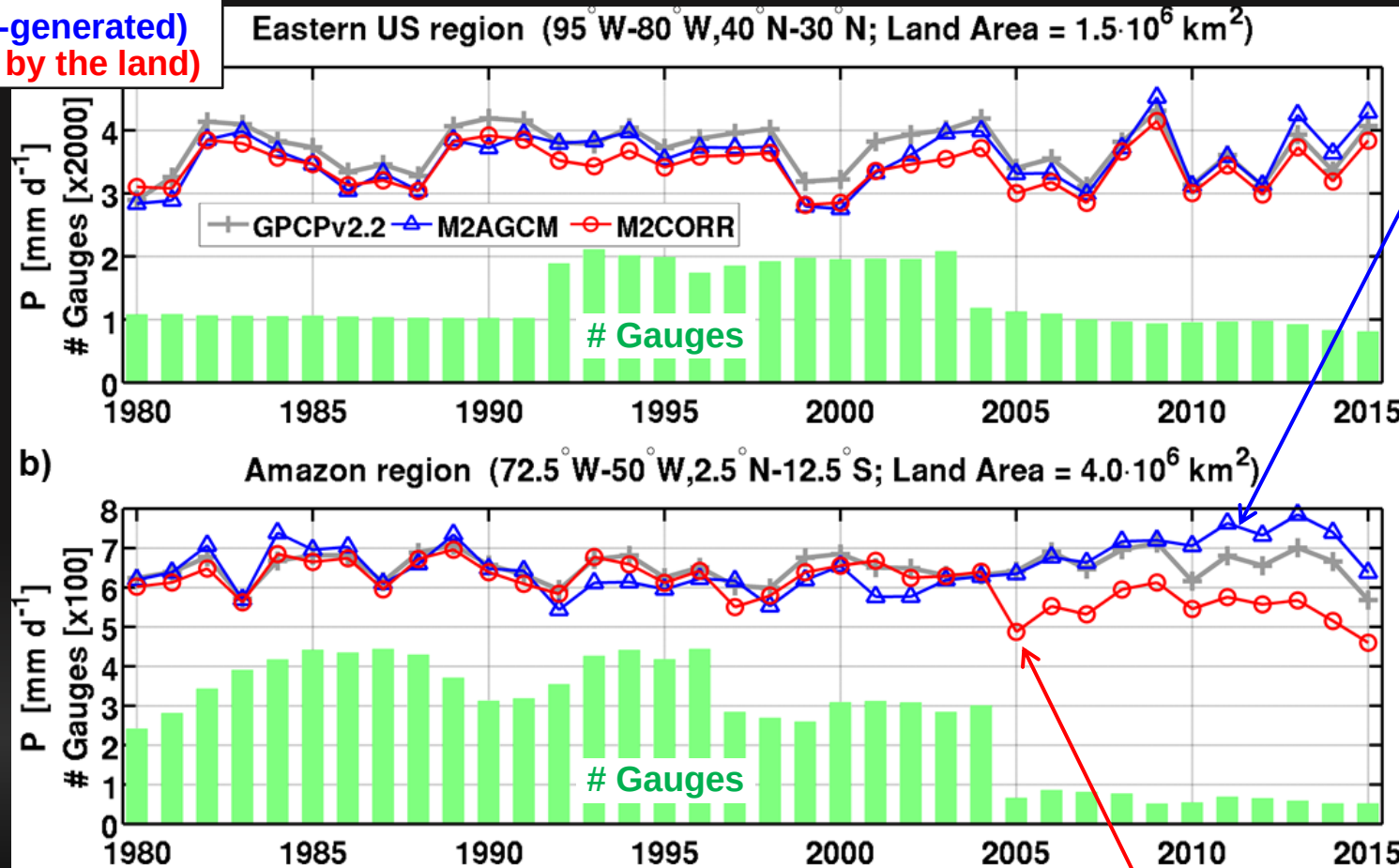
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Precipitation: Lessons from MERRA-2

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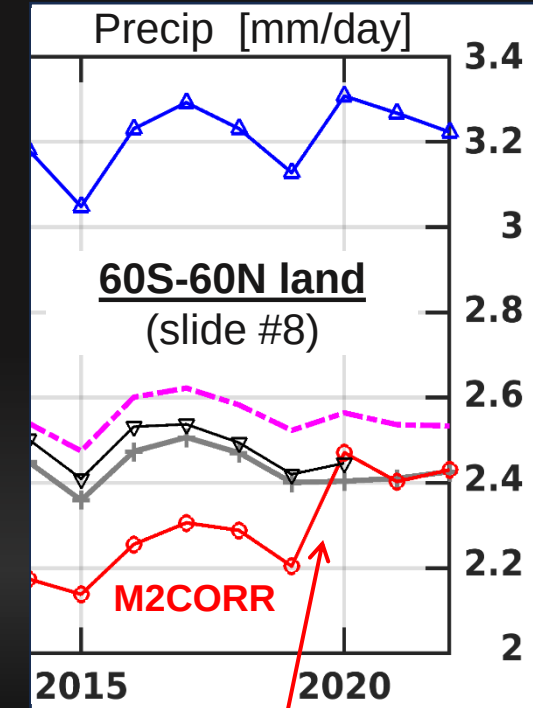
Eastern US
looks good
(generally well
instrumented).

Elsewhere,
discontinuities
because of
observing
system
changes.



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

ADAS observing
system changes.



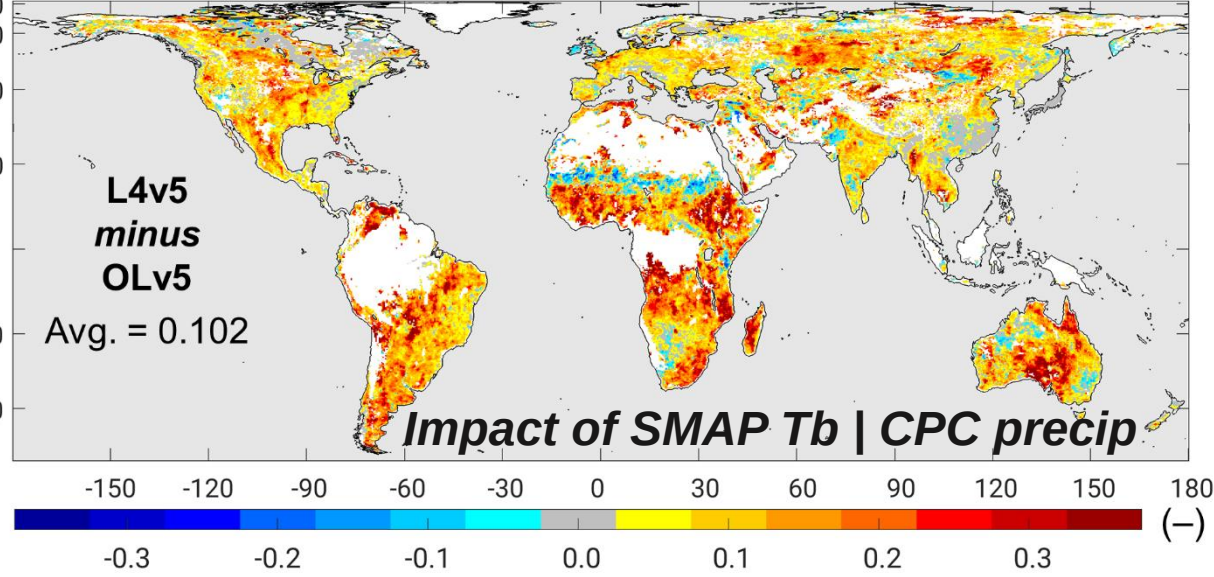
Shift in climatology.

CPC gauge product
switches from back-
processing to ops.

Precipitation: Lessons from SMAP L4 Soil Moisture

SMAP L4_SM = land-only soil moisture analysis with assimilation of SMAP Tb and observed precipitation forcing

Surface Soil Moisture Skill: L4_SM minus Open Loop (Δ anomaly R)



Reichle et al. 2023, doi:10.1175/JHM-D-23-0063.1

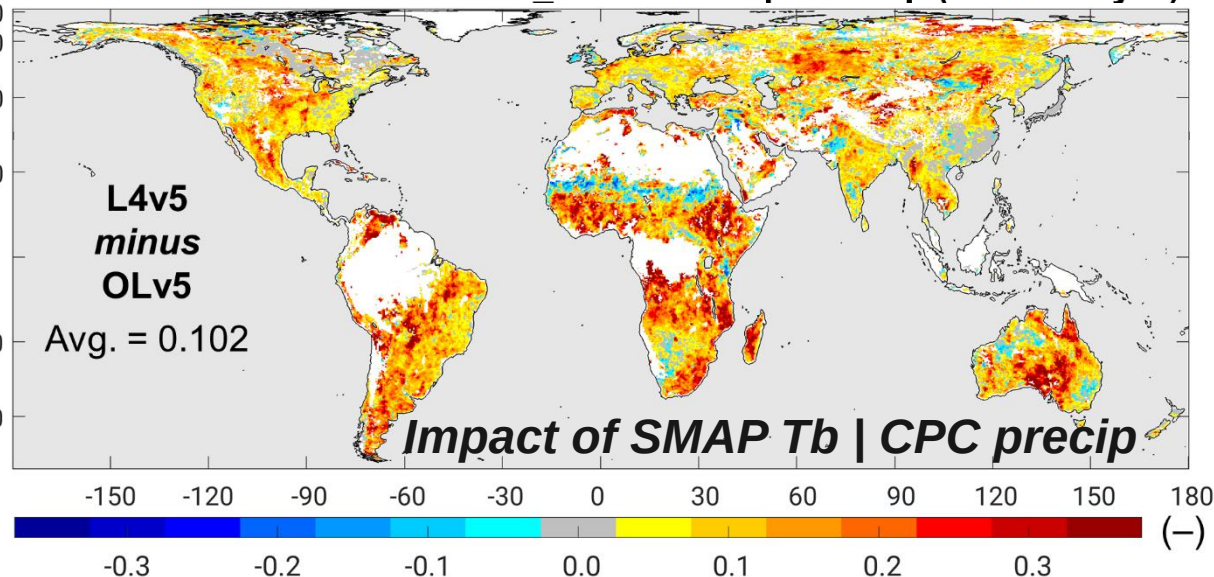
- SMAP Tb improves skill the most in S. Hemisphere
- → questionable CPC gauge precipitation.

	OLv5	L4v5
Precip.	CPCU (gauge)	
SMAP Tb	No	Yes

Precipitation: Lessons from SMAP L4 Soil Moisture

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Surface Soil Moisture Skill: L4_SM minus Open Loop (Δ anomaly R)



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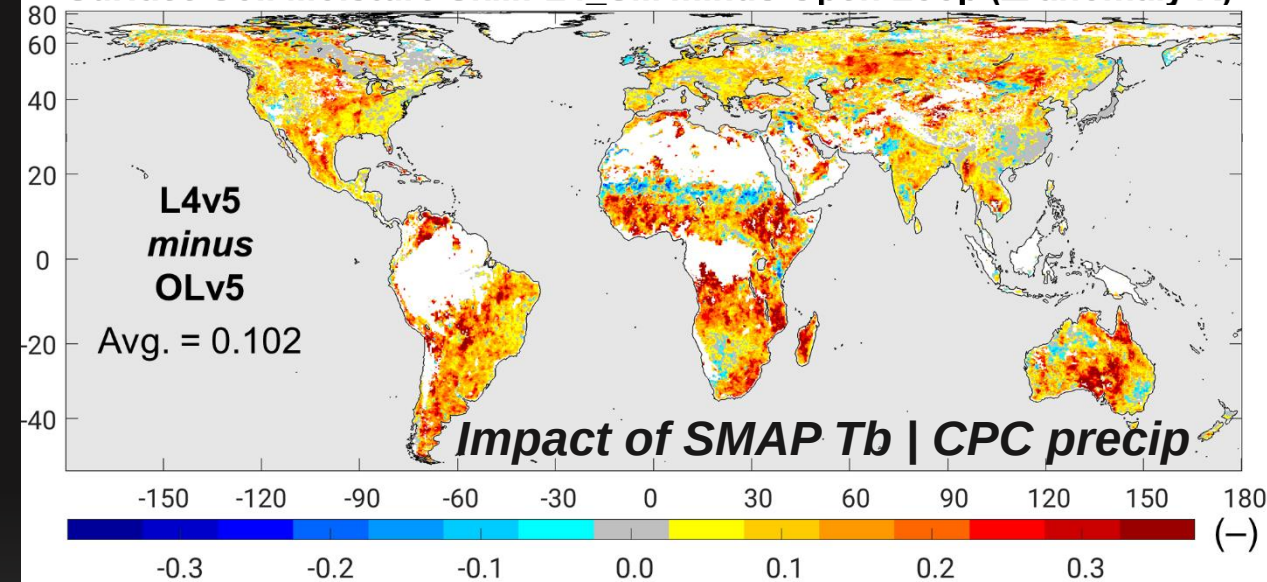
- SMAP Tb improves skill the most in S. Hemisphere
- → questionable CPC gauge precipitation.

	OLv5	L4v5	OLv6	L4v6
Precip.	CPCU (gauge)		IMERG (sat/gauge)	
SMAP Tb	No	Yes	No	Yes

Precipitation: Lessons from SMAP L4 Soil Moisture

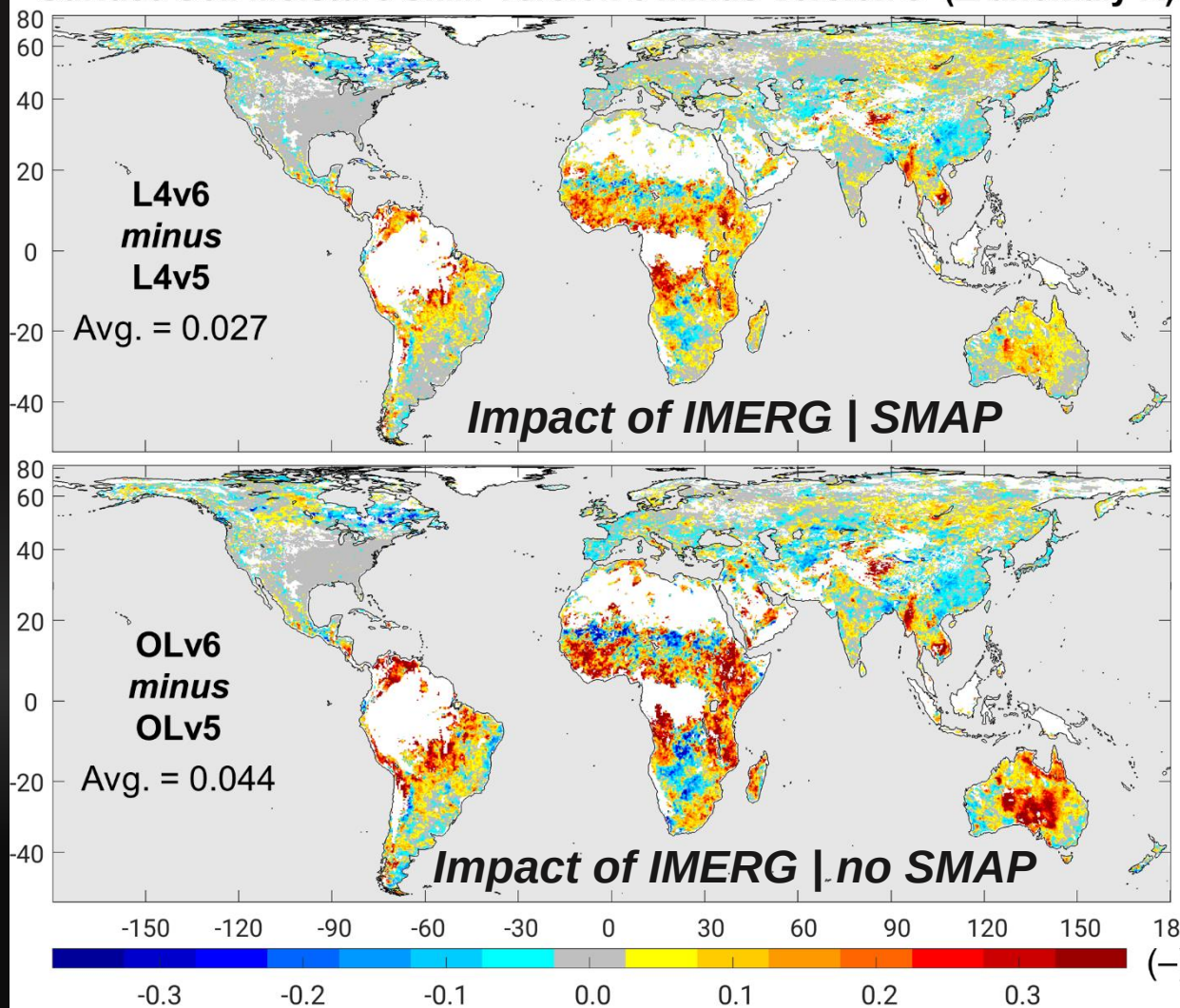
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Surface Soil Moisture Skill: L4_SM minus Open Loop (Δ anomaly R)



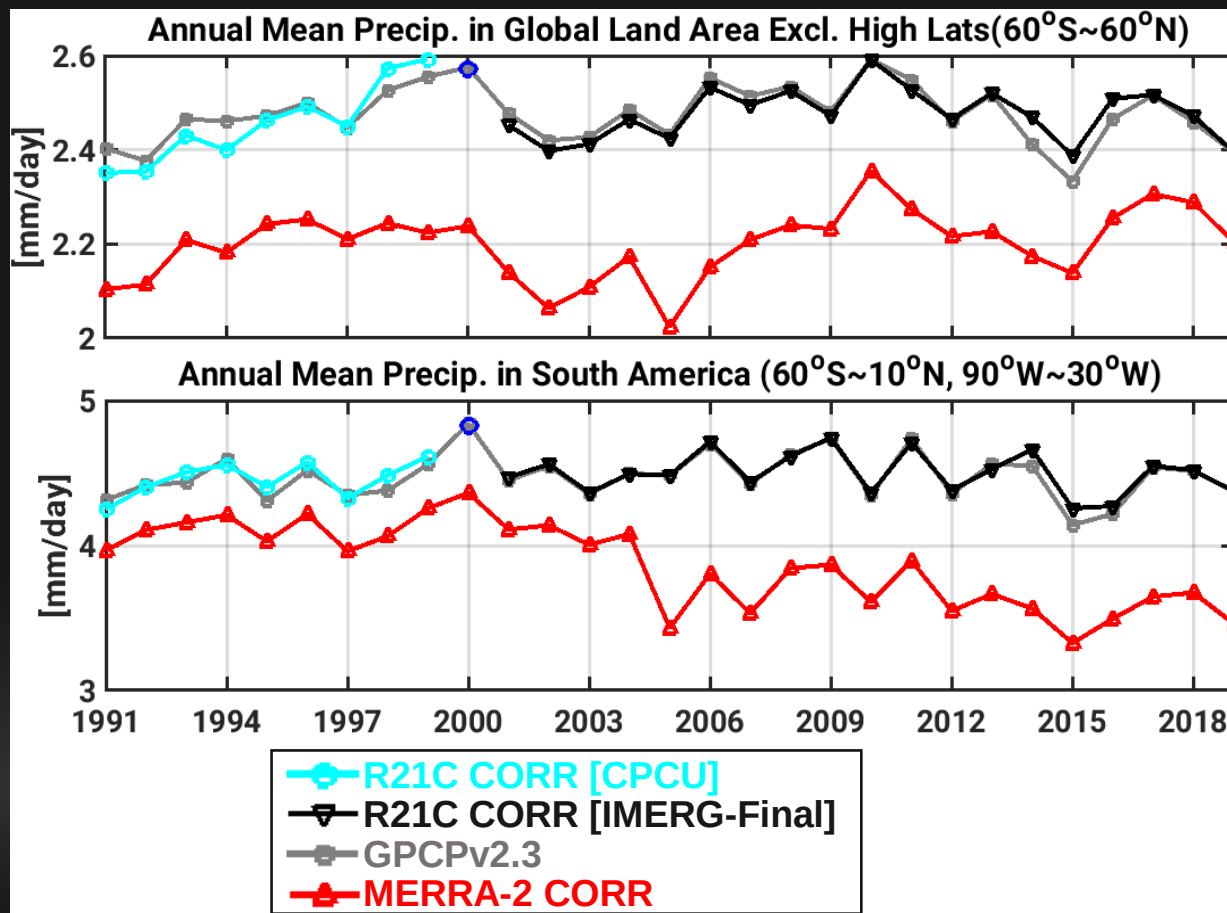
- SMAP Tb improves skill the most in S. Hemisphere
- → questionable CPC gauge precipitation.
- IMERG satellite-gauge precip better in S. Hemisphere.
- SMAP Tb partly corrects for questionable precipitation.

Surface Soil Moisture Skill: Version 6 minus Version 5 (Δ anomaly R)



Reichle et al. 2023, doi:10.1175/JHM-D-23-0063.1

Precipitation: NASA R21C



Reichle et al. 2023, in preparation

R21C = 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



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).

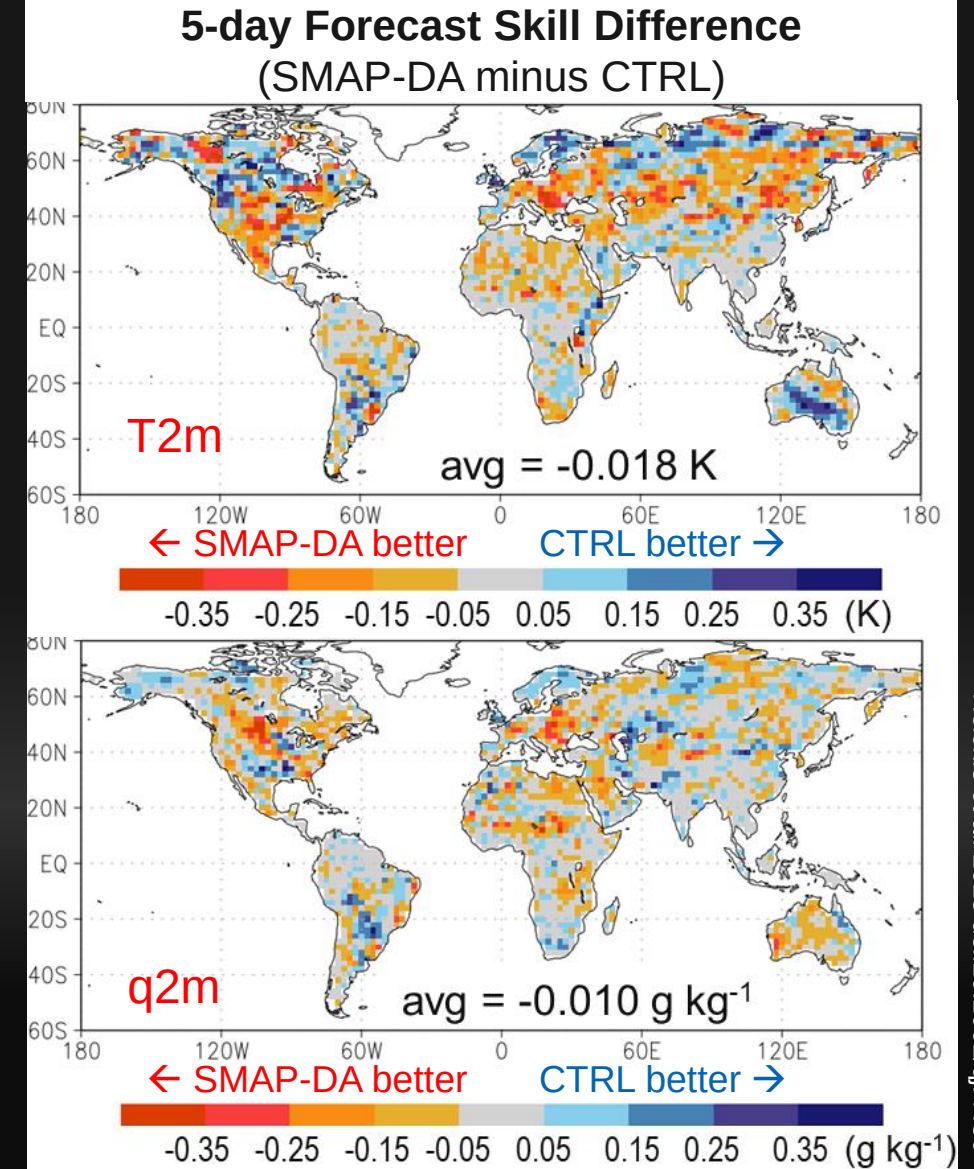
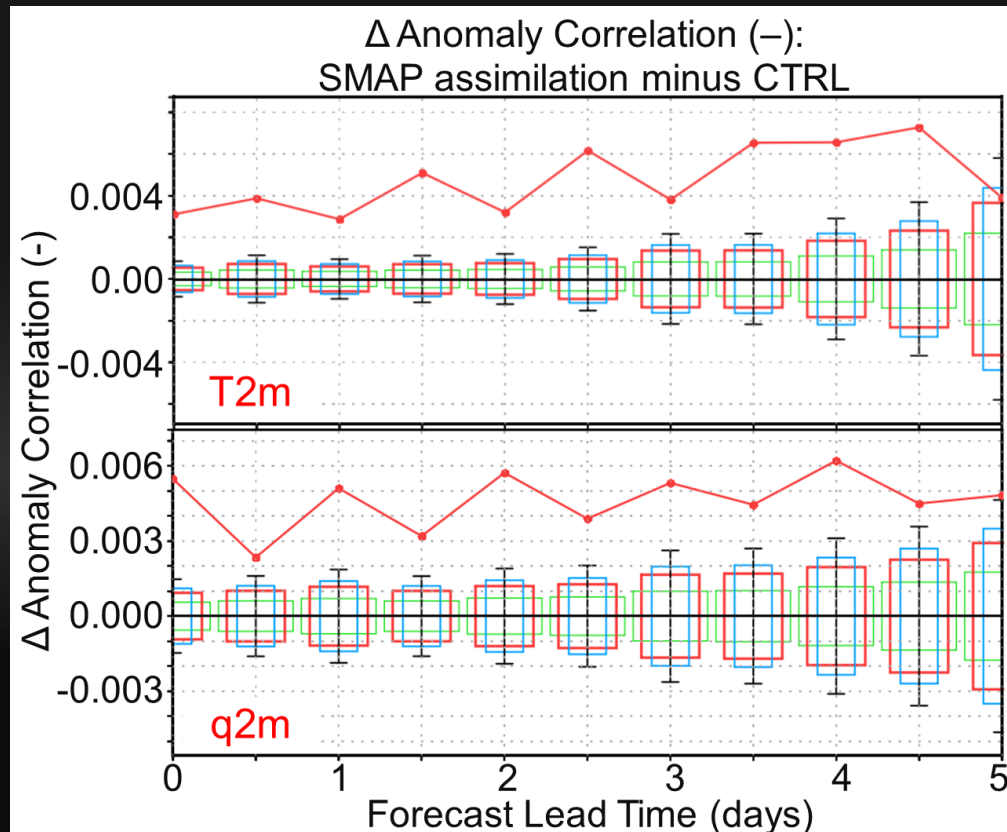
See reference for relevant graphic.

Soil Moisture

CTRL = $\frac{1}{2}^\circ$ version of GEOS atm. assimilation (NWP) system.

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

→ Improved forecasts of T2m, q2m



Reichle et al. 2023 doi:10.1002/qj.4486

Critical freshwater resource for billions of people.

Observations

- Snow cover (satellite, 1967-)
- Snow depth (in situ):

Satellite retrievals not good enough.

Issues with in situ: GTS, “zero” reports
→ P. de Rosnay, ECMWF.

See reference for relevant graphic.

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



ERA5: Relatively mature snow analysis, incl. snow cover, snow depth and snow temperature.

New multi-layer snow model for ECMWF IFS.

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).

See reference for relevant graphic.

Ochi et al. 2023, 10th EARSeL Workshop on Land Ice and Snow 6-8 Feb 2023, Bern, Switzerland;
<http://www.earsel.org/SIG/Snow-Ice/>

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” (short latency under development).

See reference for relevant graphic.



Runoff → streamflow → discharge into ocean:

- Important in coupled atm.-ocean reanalysis.
- GloFAS-ERA5 (offline product).
- NASA: Simple runoff routing under development.

See reference for relevant graphic.



Surface energy balance (ERA5: FLake)

- Lake surface temperature analysis?
Not for small lakes in GEOS...

Lake water levels not simulated.

- Retrospective satellite altimetry too
coarse for inland water level analysis.

Dynamic water area fraction

- Wetlands, inundation
- Satellite obs. (optical, microwave)

See reference for relevant graphic.

Land Surface (Skin) Temperature (LST)



Not to be confused with soil temperature.

Massive amounts of LST satellite obs:

- 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 (e.g., Bosilovich et al. 2007, doi:10.2151/jmsj.85A.205)

See reference for relevant graphic.

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-)
- Solar-Induced Fluorescence (2007-)
- Microwave (veg. optical depth)

Dynamic vegetation phenology modeling:

- CTESSEL, Noah-MP, CatchmentCN
- Not yet operational; computationally demanding; 1,000s of simulation years needed for C spin-up.

See reference for relevant graphic.

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 for relevant graphic.

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

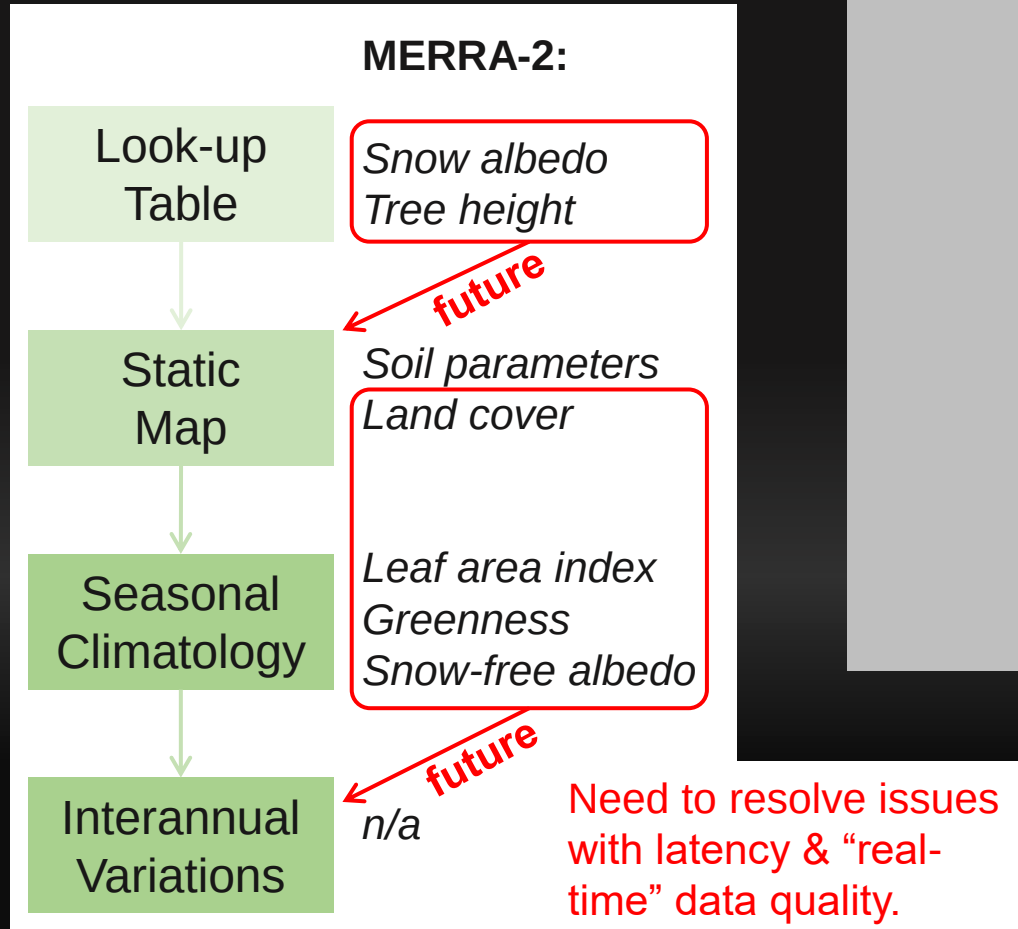
Assimilation of SMAP soil moisture does
not improve evapotranspiration (ET) or
gross primary productivity (GPP), ...

but assimilation of SMAP veg. optical depth does.

Land Model Parameters



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



See reference for relevant graphic.

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
- Urbanization

Implementation in Earth system models:

- Limited by data availability & process understanding.
- Model development:
 - Climate models: CTSM (formerly CLM).
 - NWP: Carbon/[Nitrogen]/[Fire potential] → CTESSEL, Noah-MP, GEOS CatchmentCN.
Irrigation → Noah-MP, GEOS CatchmentCN

See reference for relevant graphic.

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



Introduction

Key land variables (modeling, observations, assimilation)

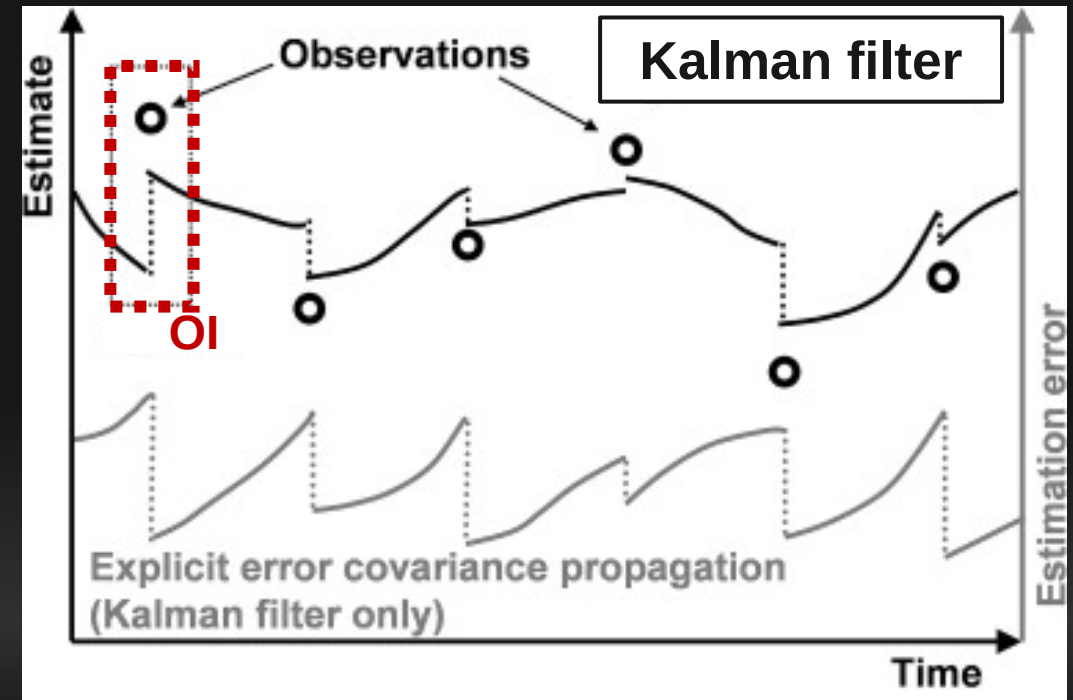
- Precipitation
- Soil moisture
- ...

Systems and methods

- Filtering, coupling, software

Advances, challenges, and future developments

- Land assimilation systems mostly use filtering, incl. 1D or 2D Optimal Interpolation (OI; no error propagation) and Kalman filter variants (Simplified EKF, EnKF, LETKF).
- Land model adjoint difficult to obtain and maintain.



Reichle 2008, doi:10.1016/j.advwatres.2008.01.001



ECMWF land
analysis in
separate modules.

Soil moisture and
soil/snow
temperature
analysis is “1D”.

Ensemble
information used
for linearized obs
operator in SEKF.

See reference for relevant graphic.

E. Pinnington et al. 2023; https://aimesproject.org/lda_workshop_2023

ERA6/7: Unify into a single, multi-variate, ensemble-based and spatially distributed (“3D”) approach.

NASA GEOS land analysis is already ensemble-based and “3D” but (still) univariate (soil moisture).

Systems and Methods



Coupling of land and atmospheric
analysis components:

- ERA5, NASA/GEOS [research]:
Weakly-coupled.
- NOAA/GFS: Developing strongly-
coupled analysis (see C. Draper this Fri).

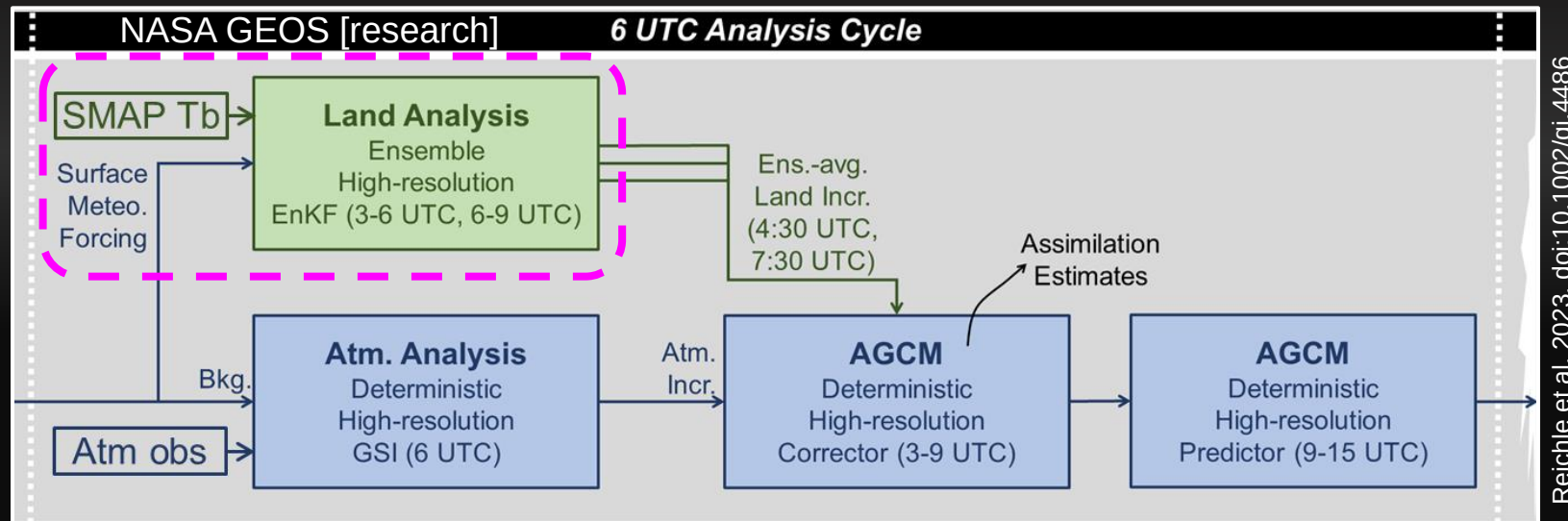
*See reference for
relevant graphic.*

Hersbach et al. 2018, ERA Report Series 27

ERA6/7:
Move
LDAS
into outer
loop.

*See reference for
relevant graphic.*

Quasi-strong coupling





Software		Partners
JEDI	Joint Effort for Data Assimilation Integration	NOAA, NASA, UK Met Office, ...
OOPS	Object Oriented Prediction System	ECMWF
ESMF	Earth System Modeling Framework	NASA, NOAA, DoD, NSF
DART	Data Assimilation Research Testbed	NCAR, NSF
LIS	Land Information System	NASA, NOAA, DoD
GEOSIdas	Goddard Earth Observing System LDAS	NASA
SURFEX	SURFace EXternalisee	Meteo-France
CaLDAS	Canadian LDAS	ECCE

Variety software systems and frameworks in use. Impediment to collaboration.

JEDI: Model-agnostic, modern s/w principles, broad partnership.

NASA: Land assimilation not yet routinely used in NWP operations or (atm.) reanalysis.

→ No reference product exists for JEDI land assimilation development.



Methods:

- Assimilation of satellite observations for land hydrology (precipitation, soil moisture, snow) is maturing.
 - Offline and (weakly) coupled with atmospheric analysis.
- Emerging dynamic vegetation phenology (carbon) modeling and assimilation.

“Minimum” Set of Land Surface Observations for Next-Generation Global Reanalysis (Satellite Era):

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

Summary – Challenges



Science:

- Few remote sensing observations of the land prior to ~2000.
- Land models are very different across centers and land assimilation is highly model-specific.
- Assimilation of terrestrial water storage observations requires non-standard method.

Organizational:

- Land assimilation development at each center starting from very different foundations.
- Coordination between LDAS & ADAS teams can be difficult.
- Lack of qualified staff.
- Legacy software maintenance and cleanup.
- Collaborations face many obstacles (technical, interagency, international).



Improve land models:

- Evolution of land cover, dynamic veg. phenology.
- Irrigation and groundwater pumping.
- Lakes, river routing.
- ...

Improve land assimilation:

- Multi-sensor, multi-variate land analysis.
- Observation operators for satellite radiances/backscatter → reduce reliance on retrieval products.
- Spatio-temporal characterization of observation and model errors.
- Uncertainty estimates (ensemble-based assimilation).
- Bias correction and assimilation “efficiency”.
- Non-linearity in land models and non-Gaussian errors.
- Strongly coupled land-atmosphere analysis.