Reanalysis activities at the NASA Global Modeling and Assimilation Office

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Steven Pawson, Ron Gelaro, Kris Wargan, Michael Bosilovich, Larry Takacs, Clara Orbe, Lauren Andrews, Rolf Reichle, Richard Cullather, Andrea Molod, Eric Hackert, Yanqiu Zhu, Larry Coy, Michael Murphy, Allison Collow.

Robert Lucchesi, Mohar Chattopadhay, Meta Sienkiewicz, Christine Bloacker, Jianjun Jin, Nathan Arnold, Gary Partyka, Austin Conaty.

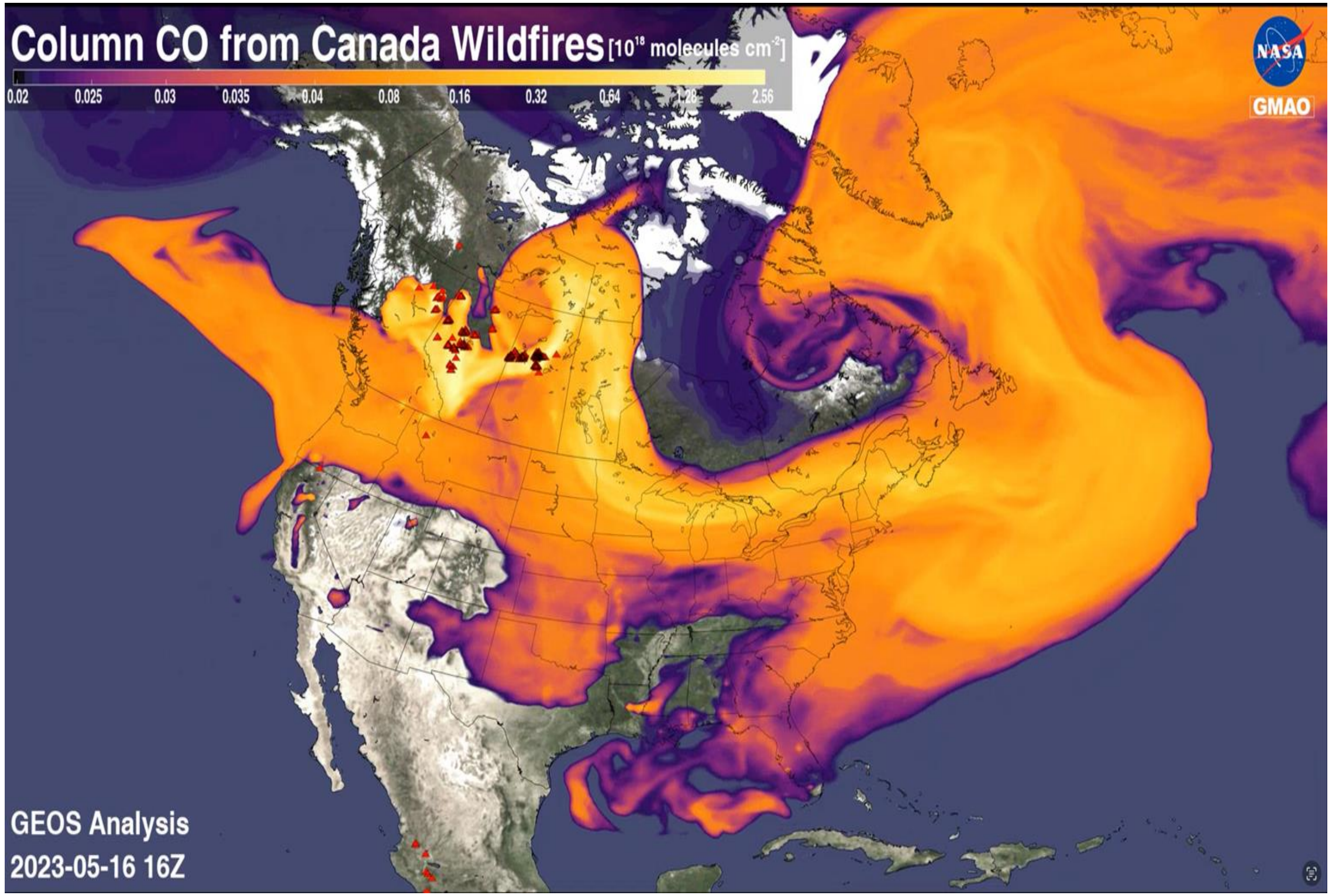
And many others

ECMWF Annual Seminar - Earth System Reanalysis. Reading, 4-8 September 2023

The Goddard Earth Observing System

A family of numerical models and data assimilation techniques to enhance NASA's suite of Earth observations

- Reanalysis development and production.
- Numerical Weather Prediction and Seasonal to Sub-seasonal (S2S) prediction systems.
- Observing system science (OSSEs), in-house GEOS Nature-Run.
- Aircraft and Satellite mission support (atmospheric conditions & product production)
- Basic & applied scientific research & development

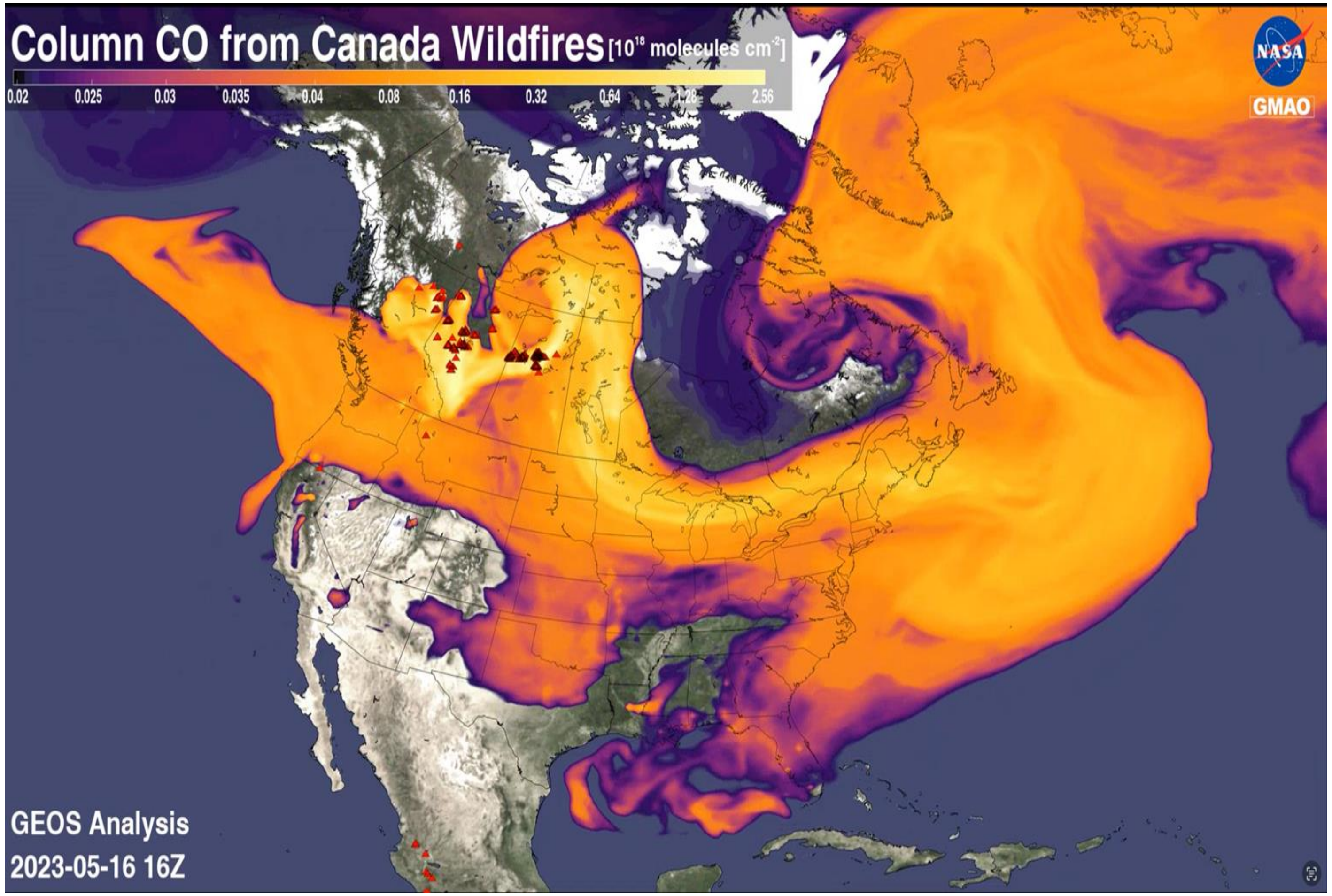


https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/.internal/Wildfires/geos-fp.cobbna%2Bqfed.nam.may-jun2023.mp4

The Goddard Earth Observing System

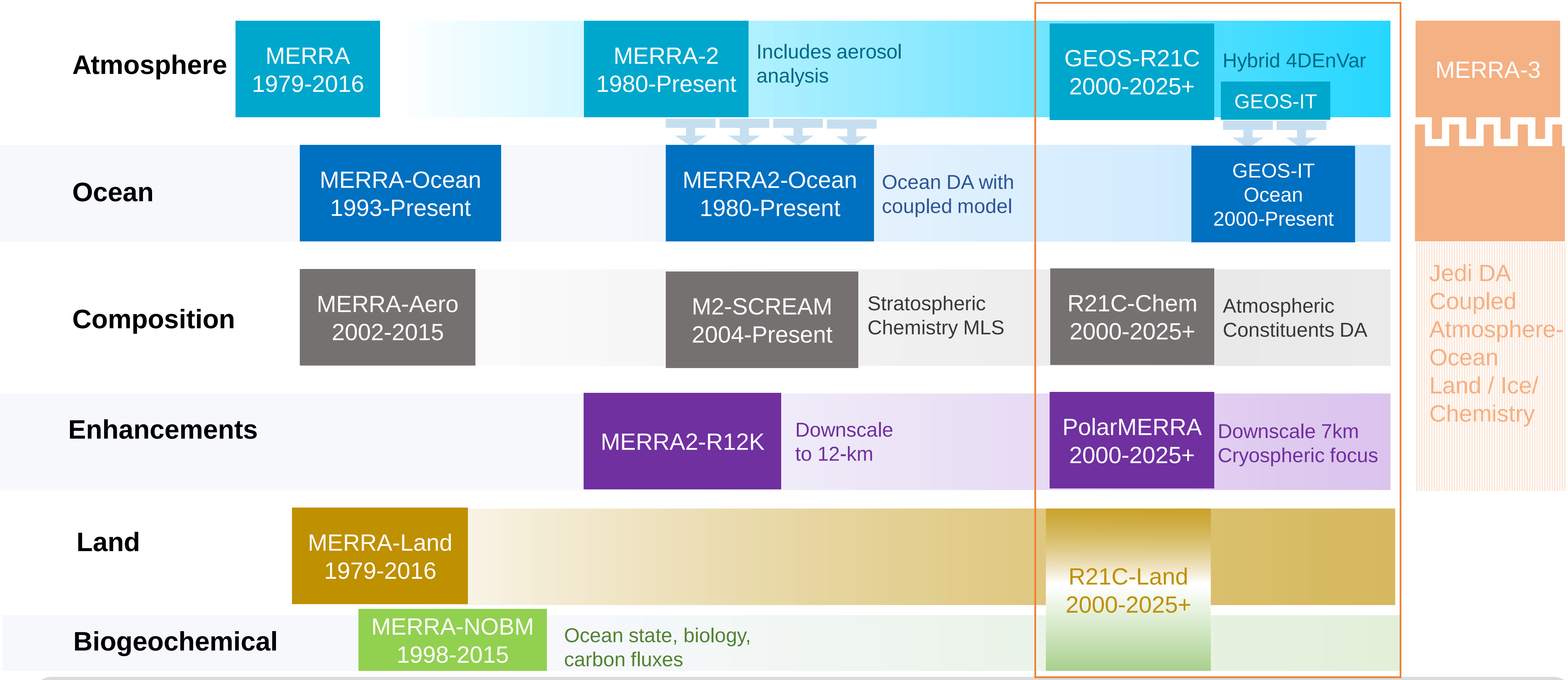
A family of numerical models and data assimilation techniques to enhance NASA’s suite of Earth observations

- Assimilation of atmospheric, land, ocean, and constituent observations. (Adas, Ldas, Odas, Codas).
- Open development & public release of products.
- Modular components include GEOS atmospheric model, MOM6/MITgcm ocean model, Catchment land model, CICE6, CTM/GEOSchem chemistry models, GOCART-2G, ISSM (soon!)
- Under development: a unified coupled DA system, based on GEOS and the Joint Effort for Data assimilation Integration (JEDI), for weather analysis and prediction, reanalysis, composition forecasting, and S2S prediction.



https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/.internal/Wildfires/geos-fp.cobbna%2Bqfed.nam.may-jun2023.mp4

GMAO reanalyses and derivative products



GEOS-R21C

An enhanced Atmospheric Reanalysis for the early 21st century

Build on the advances introduced into GEOS-FP after MERRA-2 to produce an enhanced atmospheric reanalysis for the early 21st Century.

- Targeting clouds/precipitation and surface energy balance through enhanced use of observations;
- Bridging the gap from NASA's EOS observations to the post-EOS observations;
- Opportunity to use reprocessed versions of older operational observations.

What does it take to produce a good atmospheric reanalysis that will also serve as anchor to other earth system reanalysis?

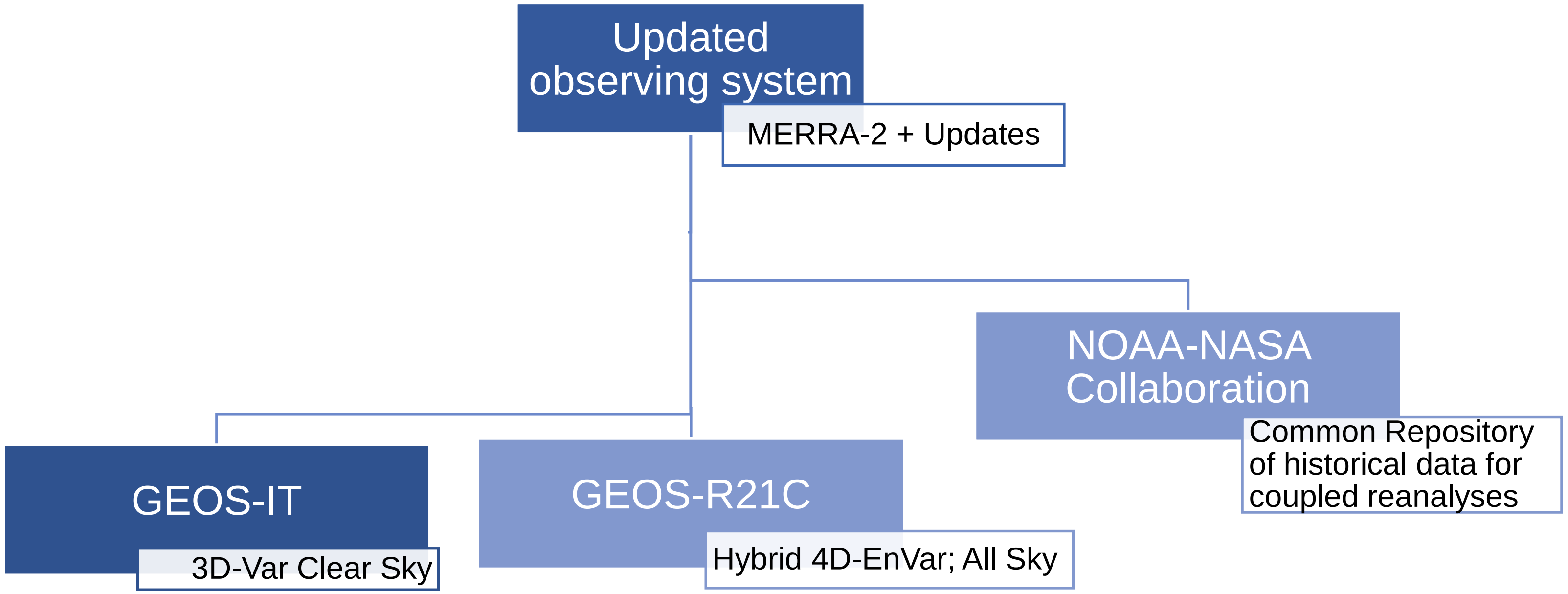
GEOS-R21C
- Hybrid 4DEnVar all-sky DA
- 2000-onwards; 25-km resolution
- Revisited features from MERRA-2
- Uncertainty estimates through ensembles

- **PolarMerra**: Off-line high-resolution downscaled reanalysis for the polar regions
- **R21C-Chem**: Off-line atmospheric composition reanalysis of atmospheric constituents using CoDAS and GEOS-Chem, R21C-Chem
- **R21C-Land**: Details TBD
- **Ocean?**

Data preparation never ends

At every step of a reanalysis project, there's cause to question the data.

GEOS-R21C uses an updated observing system that evolved from MERRA-2 observational data holding



- **Updated** versions of older operational observations (AMSU-A, AVHRR, AMV, SBUV-2, MLS, TMI, COSMIC, aeronet, MODIS).
- **New** data (OMPS-NP, OMPS-NM, COSMIC2, GMI, AMSR-2, AMSR-E, Metop-C, JPSS, commercial data, possibly VIIRS…)
- **All-sky** data assimilation (GMI, TMI, MHS, AMSR-2, AMSR-E, SSM/I).

Data preparation never ends

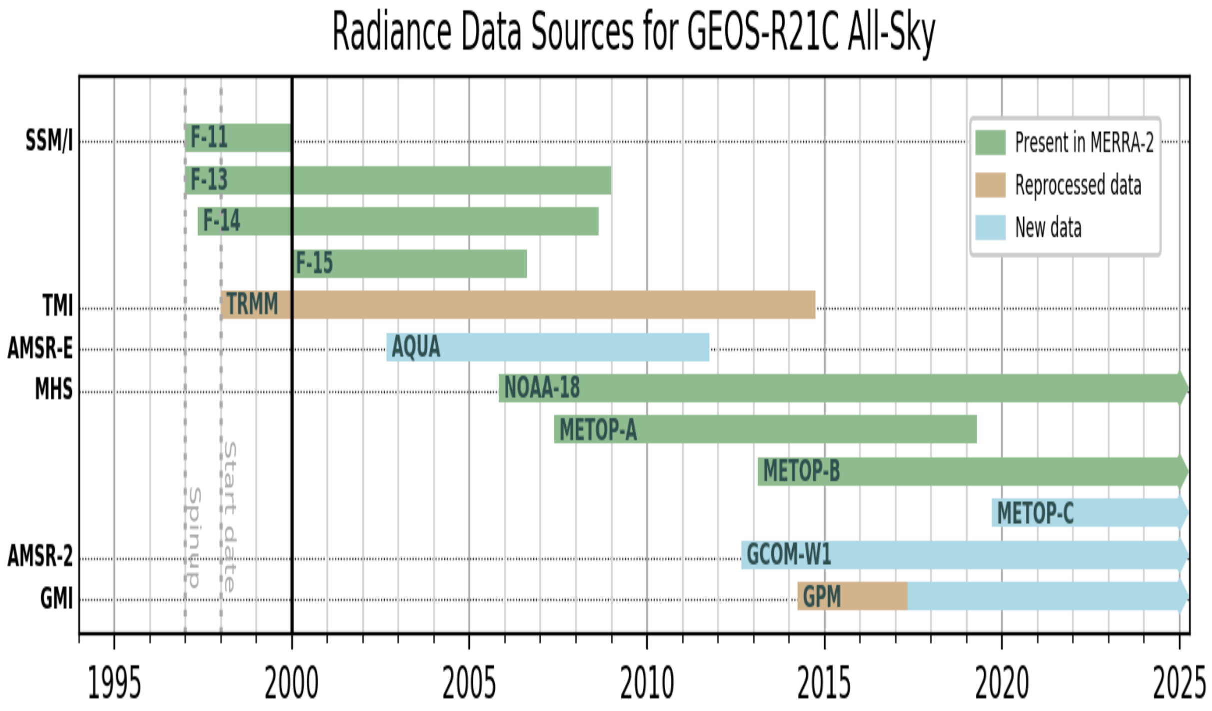
At every step of a reanalysis project, there's cause to question the data.

Each new reanalysis project offers a chance to incorporate new or revisited data.

GEOS-R21C assimilates SSM/I, TMI, AMSRE, AMSR2, GMI, MHS in all-sky conditions.

All-sky microwave radiance data assimilation framework adds:

- New control variables for hydrometeors (rain, snow, cloud liquid, cloud ice);
- Improved radiative transfer in cloudy condition;
- New background and observation error models;
- Modified quality control and bias correction.



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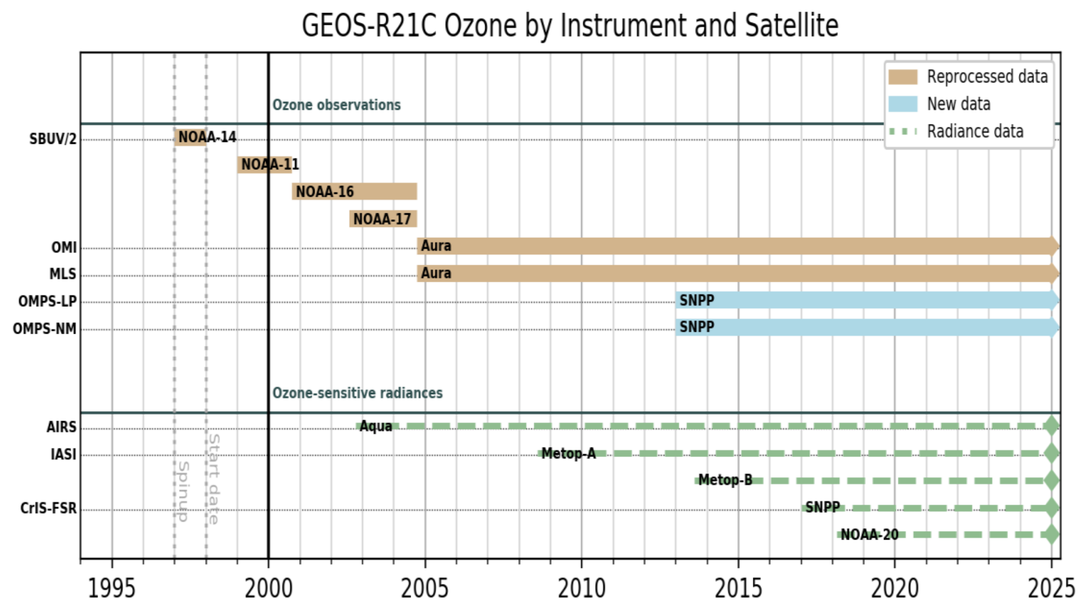
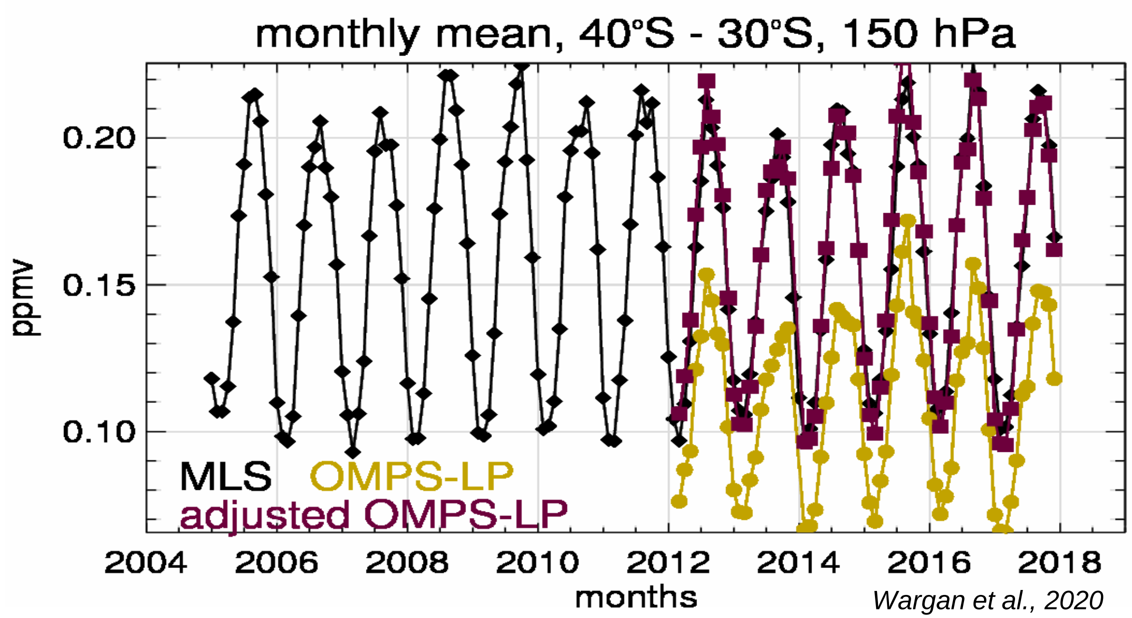




- Assimilation of ozone-sensitive radiances in 9.6μm for the first time in a GMAO reanalysis.
- Homogenization is applied to ensure continuity in Total column ozone (OMI and OMPS-NM) and ozone profiles (MLS and OMPS-LP).

Data preparation never ends

At every step of a reanalysis project, there’s cause to question the data.

Leverage known data issues from previous reanalyses.

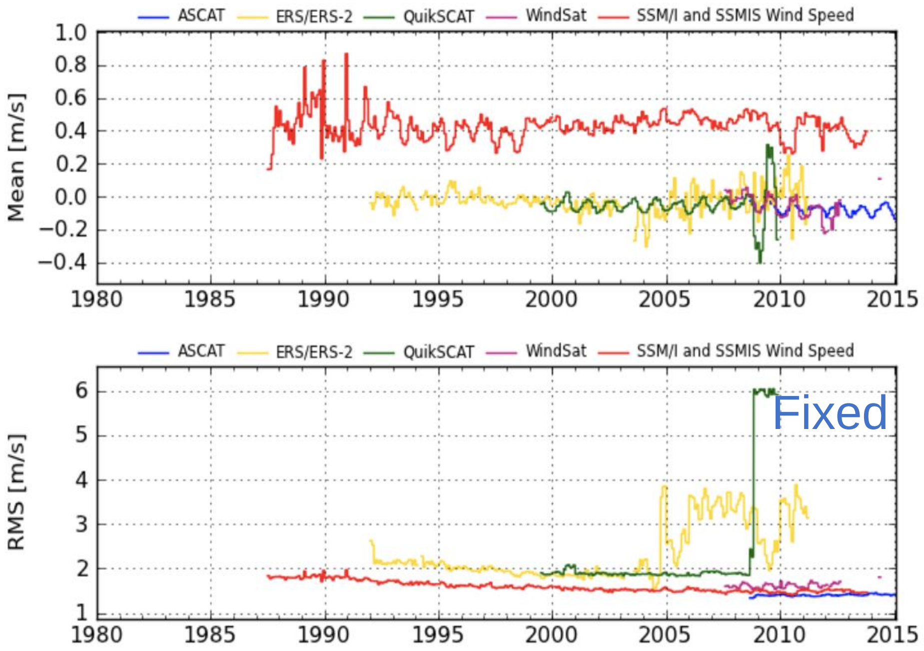


Figure 14 - The background departure monthly RMS (top) and mean (bottom) for satellite-retrieved surface vector winds from ASCAT (blue), ERS & ERS-2 (yellow), QuikSCAT (green), and WindSat (purple), as well as for SSM/I & SSMIS retrieved wind speed.

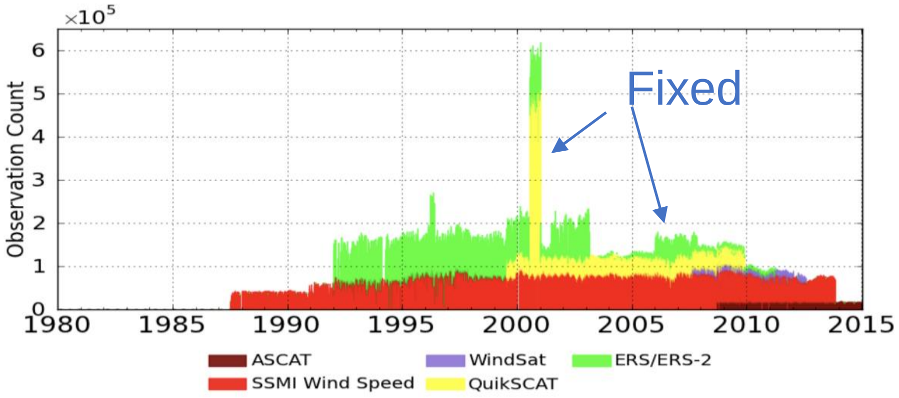


Figure 4 - Time series of input retrieved surface winds for 1 January 1980 – 31 December 2014. All observations are surface wind vectors except for the SSMI wind speed retrievals. These observations are included in the “Sfc Winds” group in Figure 1.

Clean up process of MERRA-2 data involved:

- Duplicates removed (QuickSCAT, ERS-2);
- Issues fixed (surface elevation in QuickSCAT);
- Other usage decisions (No SSMI wind speed, blackout dates during periods of sporadic behavior periods).

Data preparation never ends

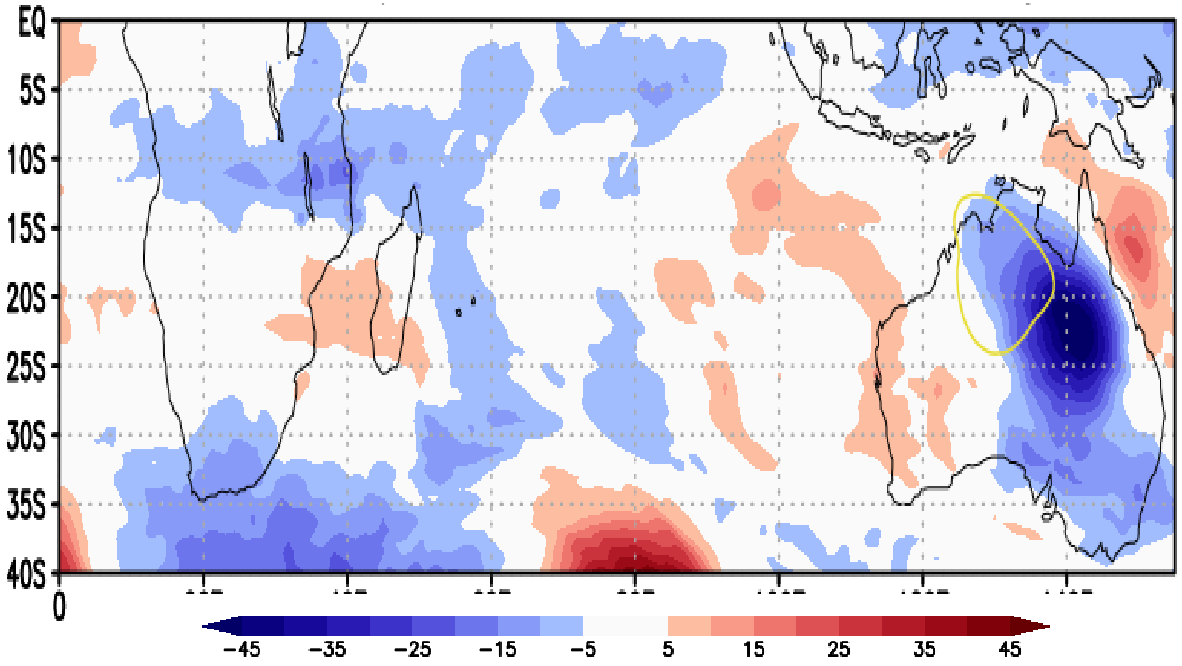
At every step of a reanalysis project, there's cause to question the data.

Open lines of communication with instrument teams. Their responsiveness is critical.

Impact of Tonga volcanic eruption on ozone data. Degradation of the UV (OMI, OMPS-LP, OMPS-NM) ozone data post-Tonga. The strong spurious ozone anomaly from OMI is evident in MERRA-2.

OMI team provided corrected data for period of concern while OMPS team is working on a solution.

MERRA-2 total column ozone departure zonal mean - Jan 17, 2022, 12Z



MERRA-2 total ozone with the zonal mean subtracted. The faint yellow contour is M2-SCREAM water vapor at 26 hPa in excess of 10 ppmv to indicate the location of the maximum H_2O. The H_2O contour is a proxy for the volcanic plume

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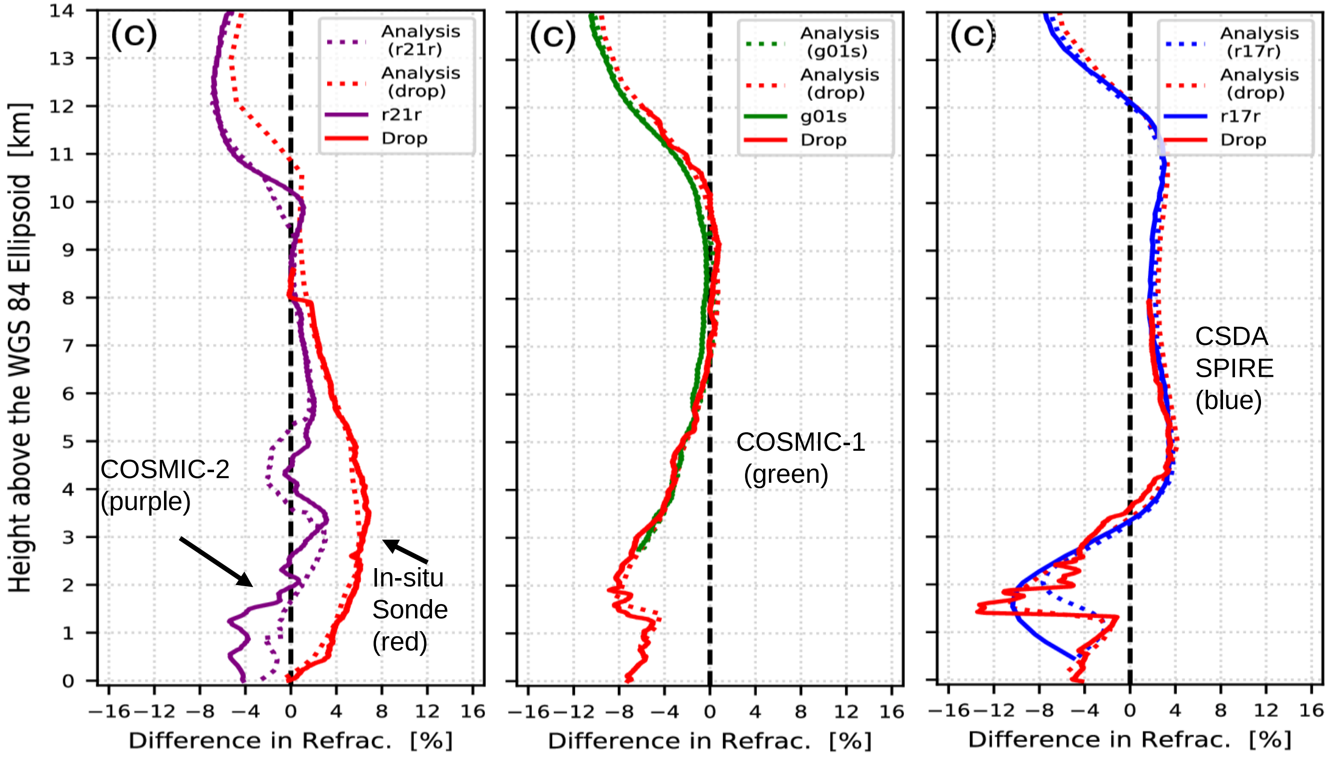
At every step of a reanalysis project, there's cause to question the data.

Data providers support is especially critical for commercial data.



from Murphy & Haase 2022 DOI: 10.3390/atmos13091495

GEOS-R21C assimilates GNSS Radio Occultation (RO) observations collected by Spire with their constellation of smallsats and purchased by NASA for its Commercial Smallsat Data Acquisition (CSDA) archive.

Left: Typical examples of refractivity profiles retrieved from Spire & COMIC as well as nearby dropsondes (red) in and near Atmospheric Rivers (ARs).

Spire refractivity profiles are extremely smooth throughout the troposphere affecting ability to resolve sharp boundaries found by dropsondes.

Spire RO data are not assimilated below 5km.

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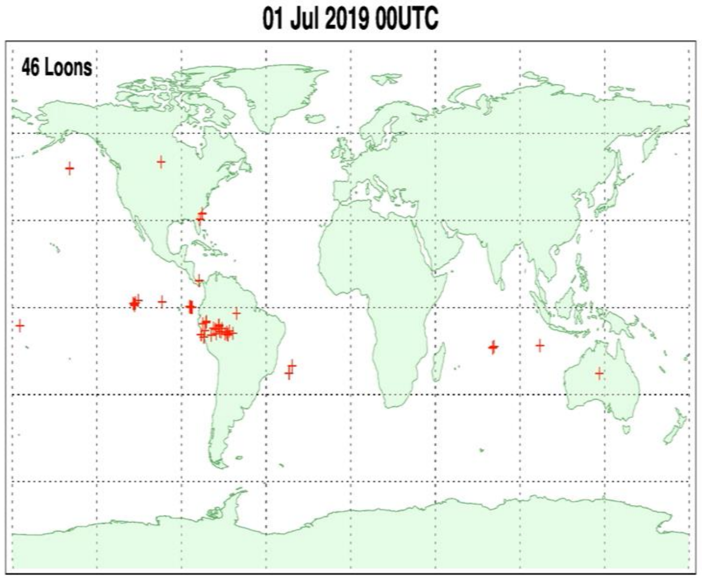

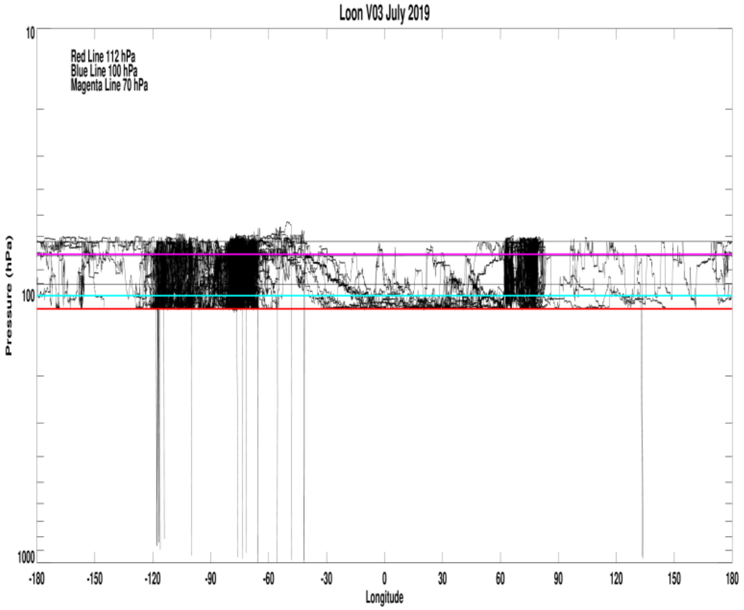

https://loon.co/

Goal: launch and maintain a fleet of balloons to provide Internet coverage to users on the ground.
Status: over 25 million km of test flights since the project began.
Flight Duration: up to 190 days in the stratosphere.
Winds: Derived from Loon Balloon GPS determined locations.

Loon balloon positions as a function of latitude vs pressure during July 2019.
The balloons typically adjust altitude between 112 hPa and 60 hPa.
Data from Bradley Rhodes, & Salvatore Candido. (2021). Loon Stratospheric Sensor Data, Version 3. Zenodo. https://doi.org/10.5281/zenodo.5119968

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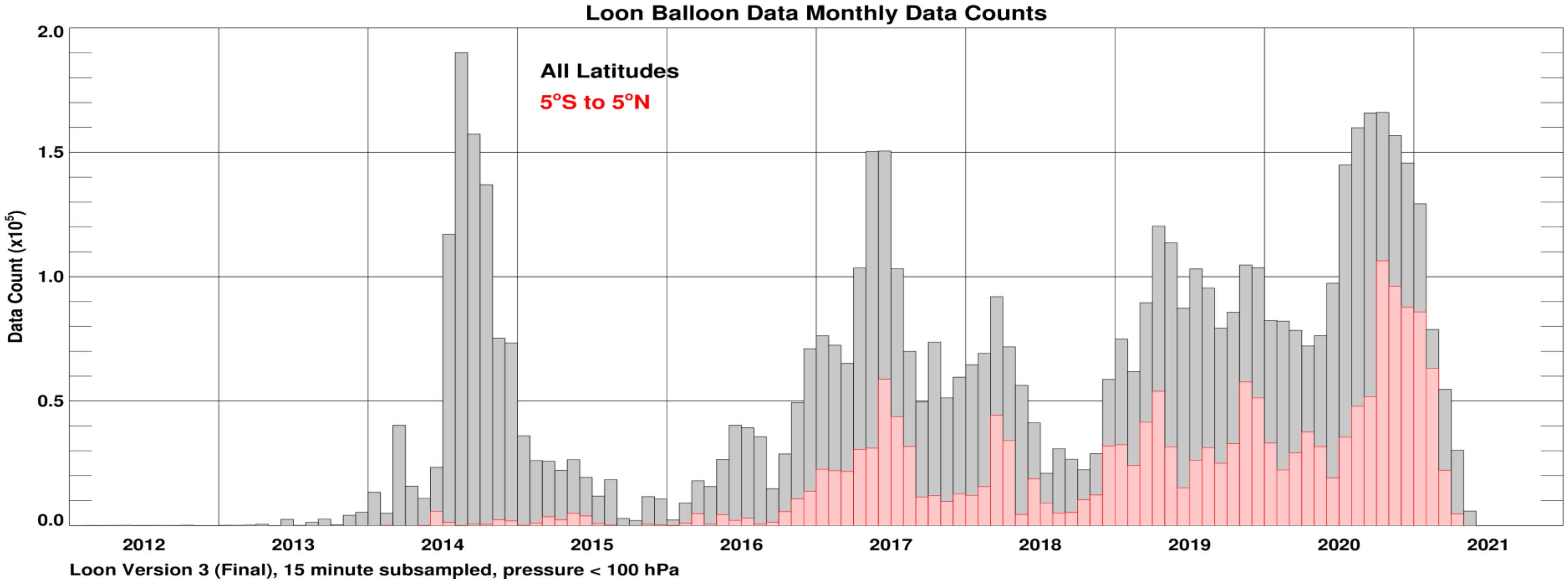


Support may not be readily available after loon balloon program ended in 2021.

Data preparation never ends

At every step of a reanalysis project, there’s cause to question the data.

Inter-Agency collaborations: NASA-NOAA project to modernize coupled reanalysis data holdings.

The NOAA-NASA project was jointly funded based on recommendations from the 2022 Future US Earth System Reanalysis in Boulder.

It establishes a framework for:

- **A curated storage for coupled reanalysis observations** including atmosphere, ocean, sea ice and composition, with cloud-based access, API, version control, and change protocols.
- **Development of shared diagnostic tools and protocols**. The Evaluation and Verification of the analysis EVA package is in development to offer automated plotting and easy comparison of Jedi-based experiments across centers.
  https://jcsda-internal.github.io/eva-docs/

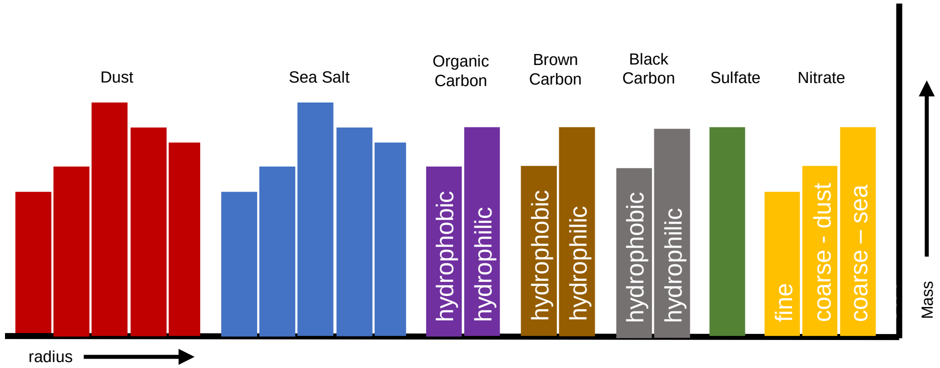
See Sergey’ talk and Jessica’s poster.

GOCART2G

Aerosol Module and Goddard Aerosol Assimilation System (GAAS)

A refactoring of the source code to allow for future development, reduce inefficiencies.

Complemented by science updates: Introduction of brown carbon and secondary organic aerosol.



- GOCART treats the sources, sinks, and chemistry of the aerosol tracers, with transport based on GEOS meteorology.
- Dust and sea salt emissions parameterized based on wind
- Carbon, sulfate, and nitrate have anthropogenic and natural sources
- Loss processes = sedimentation, dry deposition, large scale wet removal, convective scavenging

Aerosol emissions

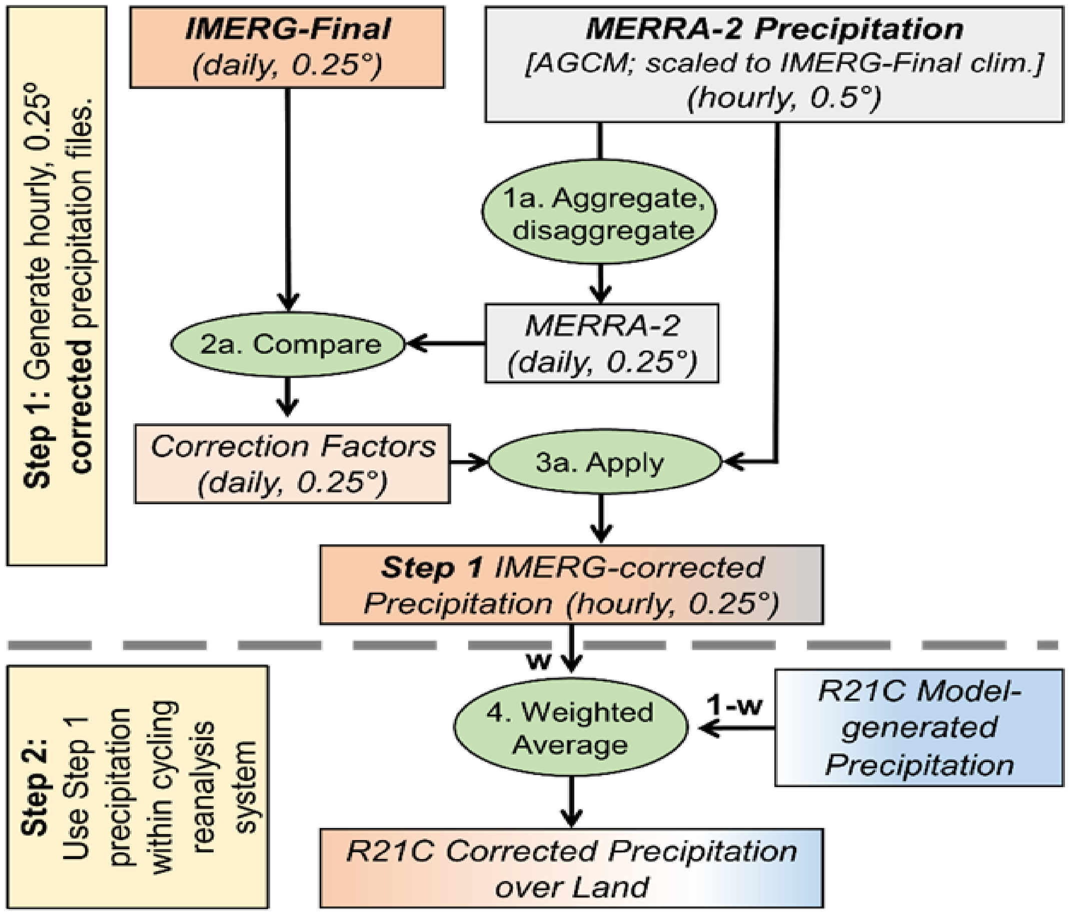
Emission Type	Species	Source	Temporal Resolution	Spatial Resolution
Anthropogenic (+ ship and aircraft)	OC, BC, SO2, SO4, NH3	CEDS (Hoesly et al., 2018)	monthly (Onset-2019) 2020->NRT is a repetition of 2019	0.5, downscaled to 0.15625
Biomass Burning	OC/BrC, BC, SO2, NH3	HFED (Randles et al., 2016)	Monthly	0.25 x 0.3125
		QFED v2.5r1 (Darmenov and da Silva, 2015)	Daily	0.1
Volcanic	SO2	Carn et al. 2017	Daily Eruptive (Onset-2021) Daily Outgassing	Point-sources
Dust	DU	Wind driven (Ginoux et al., 2001)	Model	0.5 x 0.625
Sea Salt	SS	Wind driven	Model	0.5 x 0.625
Precursor Gases	H2O2, OH, NO3	MERRA-2 GMI	monthly	0.5 x 0.625

PM2.5 part of the official GEOS-R21C product. Uncertainty on the total aerosol quantities is being considered.

Precipitation correction – Land

- In MERRA-2, precipitation seen by the land is corrected to daily/pentad gauge observations *except over the high latitudes*.
- Current version of the GEOS model shows better agreement with the data than MERRA-2, but still needs correction for the land surface conditions.
- IMERG satellite/gauge to be used in GEOS-R21C.

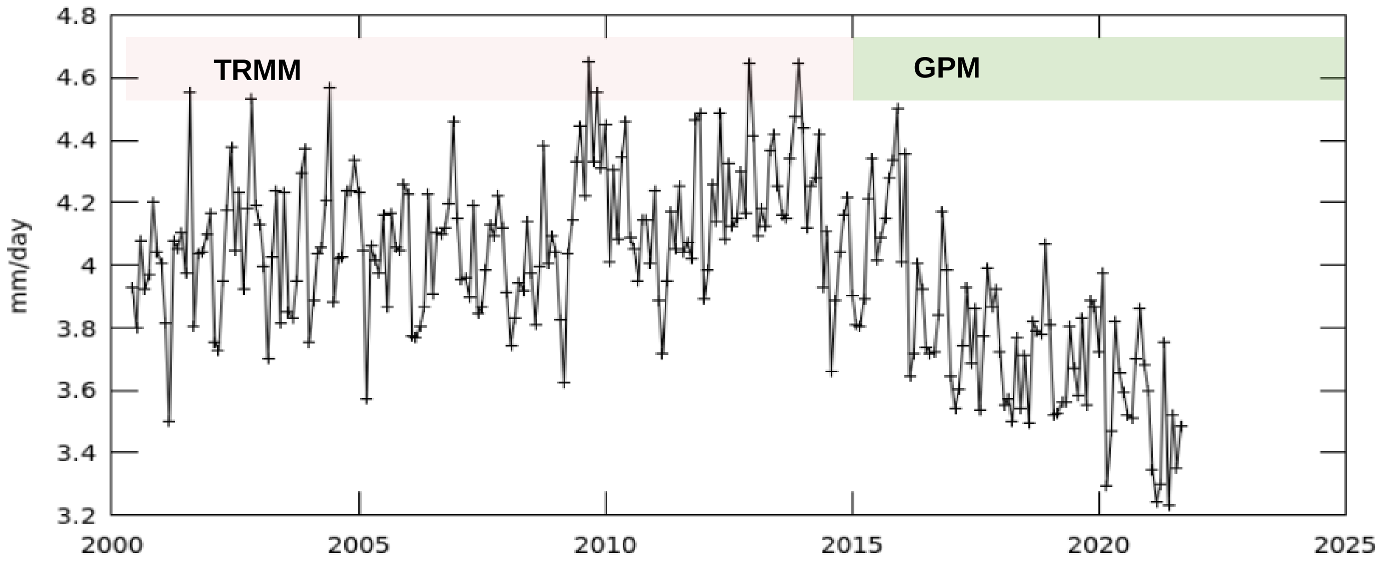
Approach for main retrospective processing period

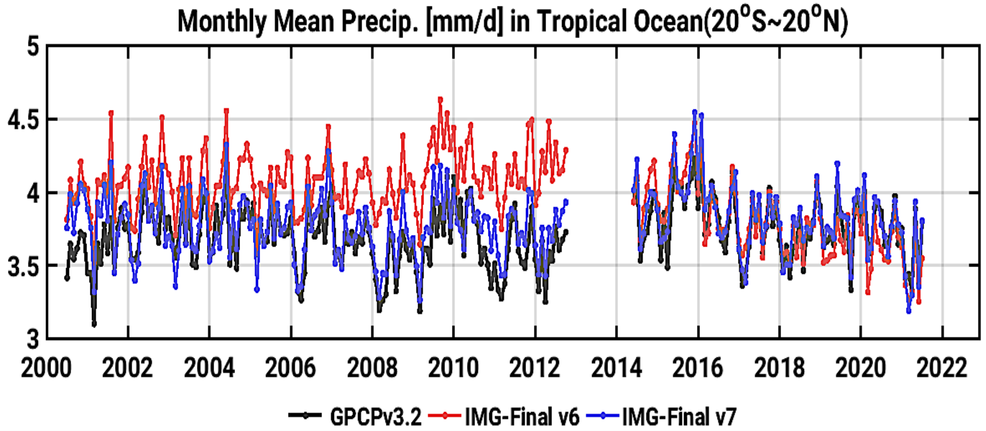


Precipitation correction – Ocean

- Corrected-precipitation is also used over oceans for the aerosol wet removal process.
- IMERG v6 was found to a large bias over the tropical oceans during the TRMM period. The bias is reduced when GPS starts.
- New IMERG version (v7) is currently in production with a first look better agreement with GPCPv3.2 both over land and over ocean.
- Fall-back strategy for R21C: IMERG-Final over land and GPCPv3.2 over oceans.

Timeseries, area-averaged of merged satellite-gauge precipitation estimates over ocean-only, 20S-20N. (IMERG-Final v06)

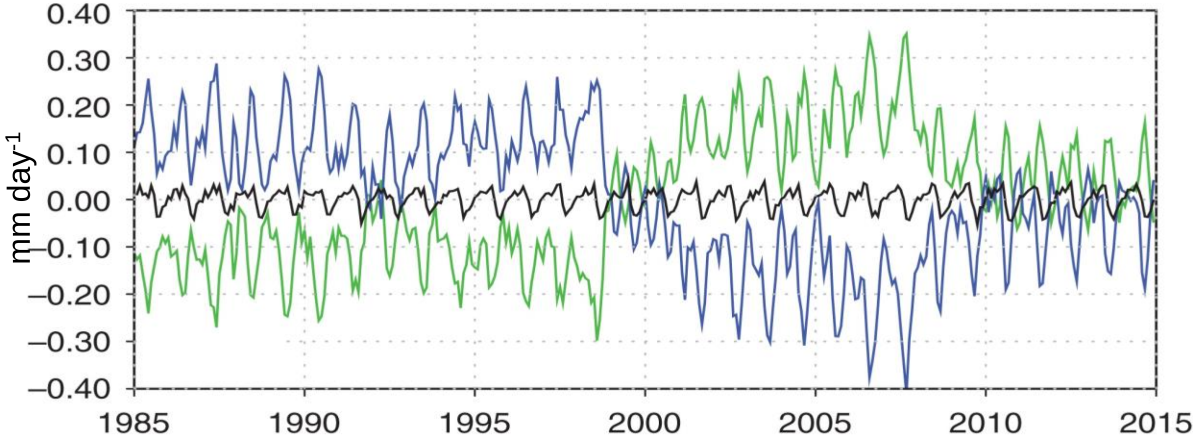




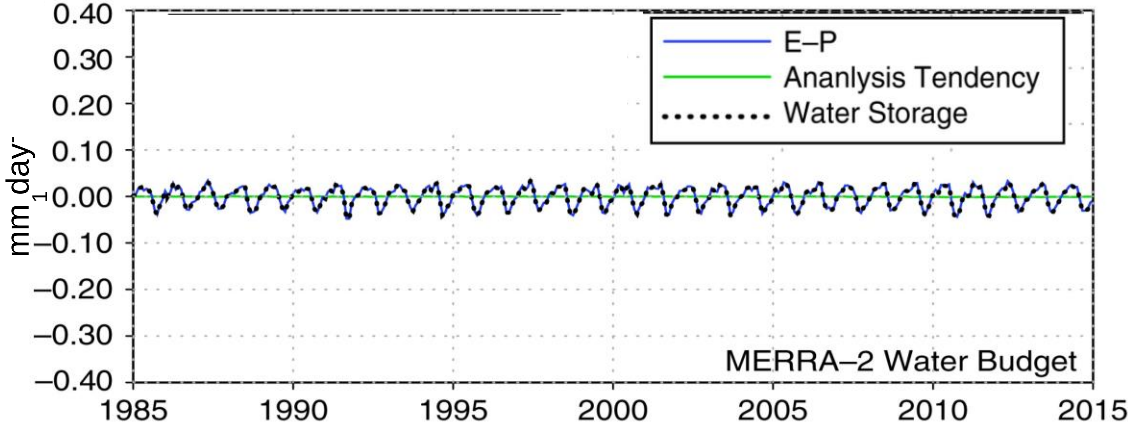
Global Constraints

Dry Mass Conservation in MERRA-2

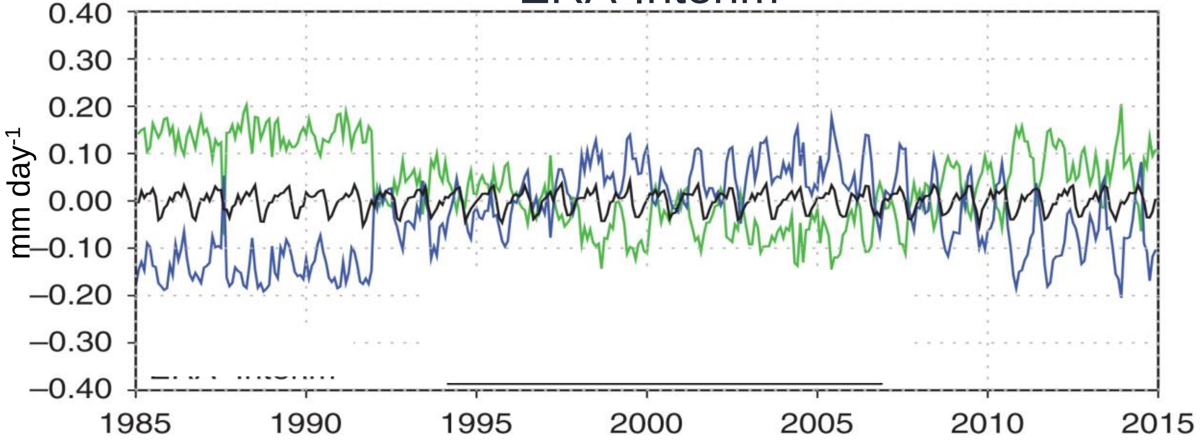
MERRA



MERRA-2



ERA-Interim

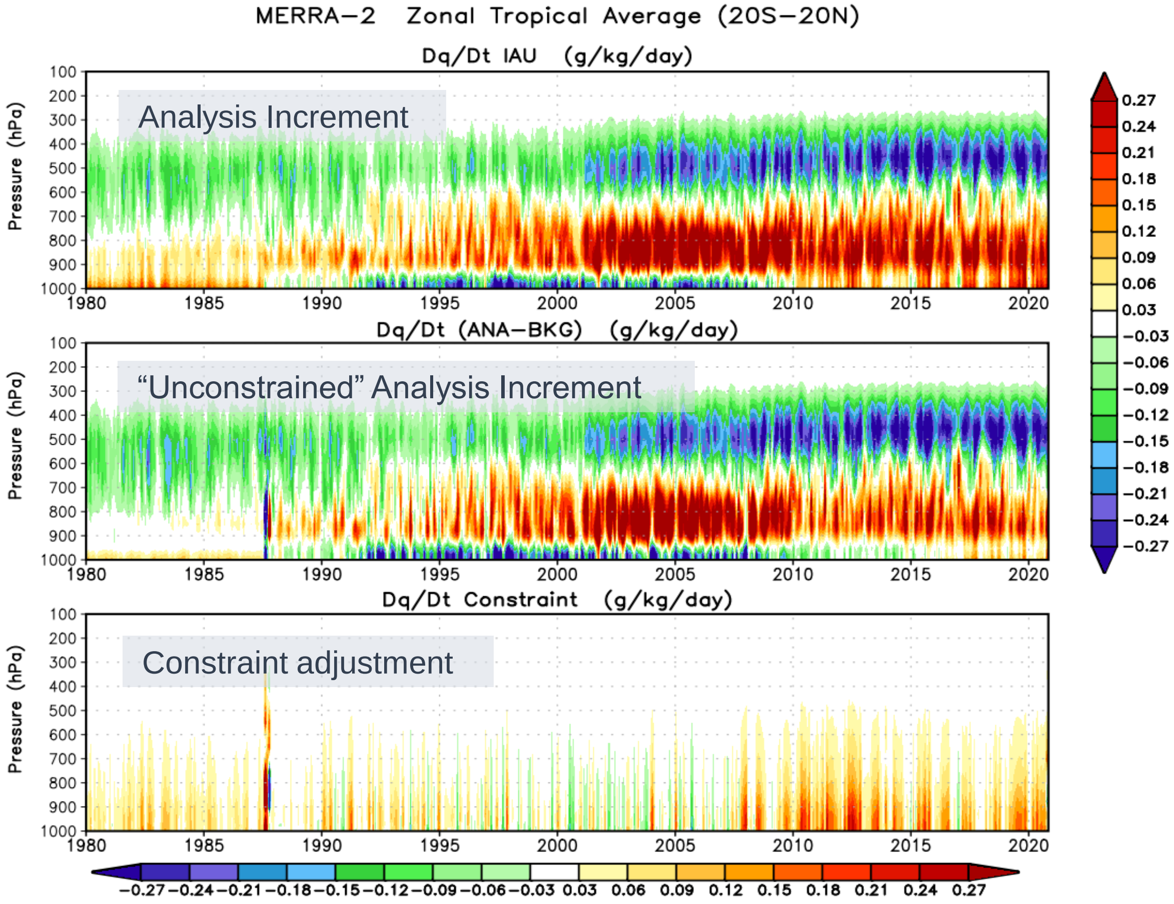


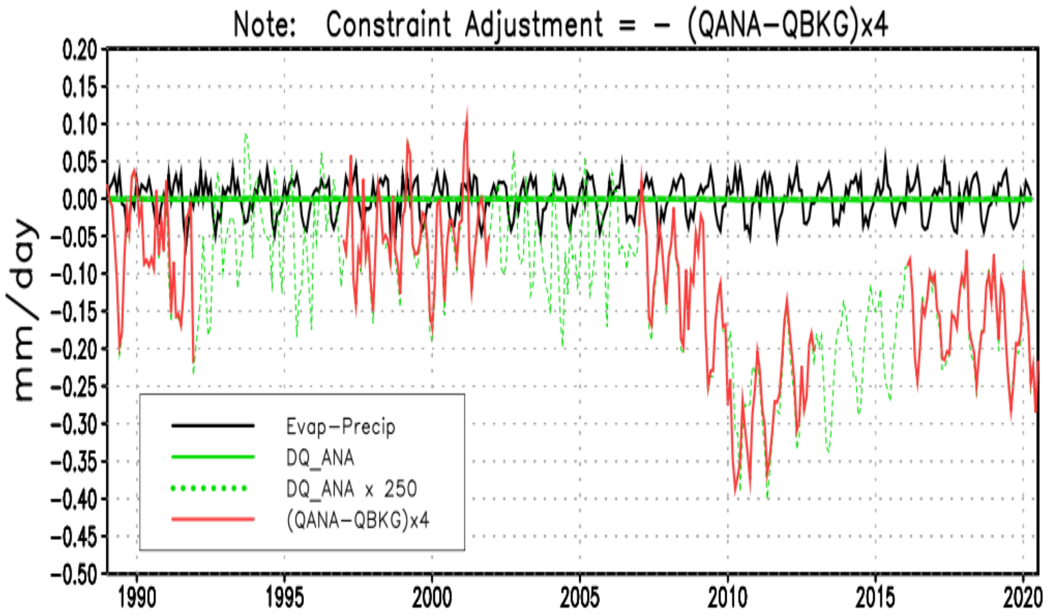
- Constraint applied in MERRA-2 conserves dry-mass and provides E-P balance;
- Reduces spurious jumps in precipitation due to observing system changes.

Global Constraints

Dry Mass Conservation in MERRA-2

Globally Integrated Constraint adjustment

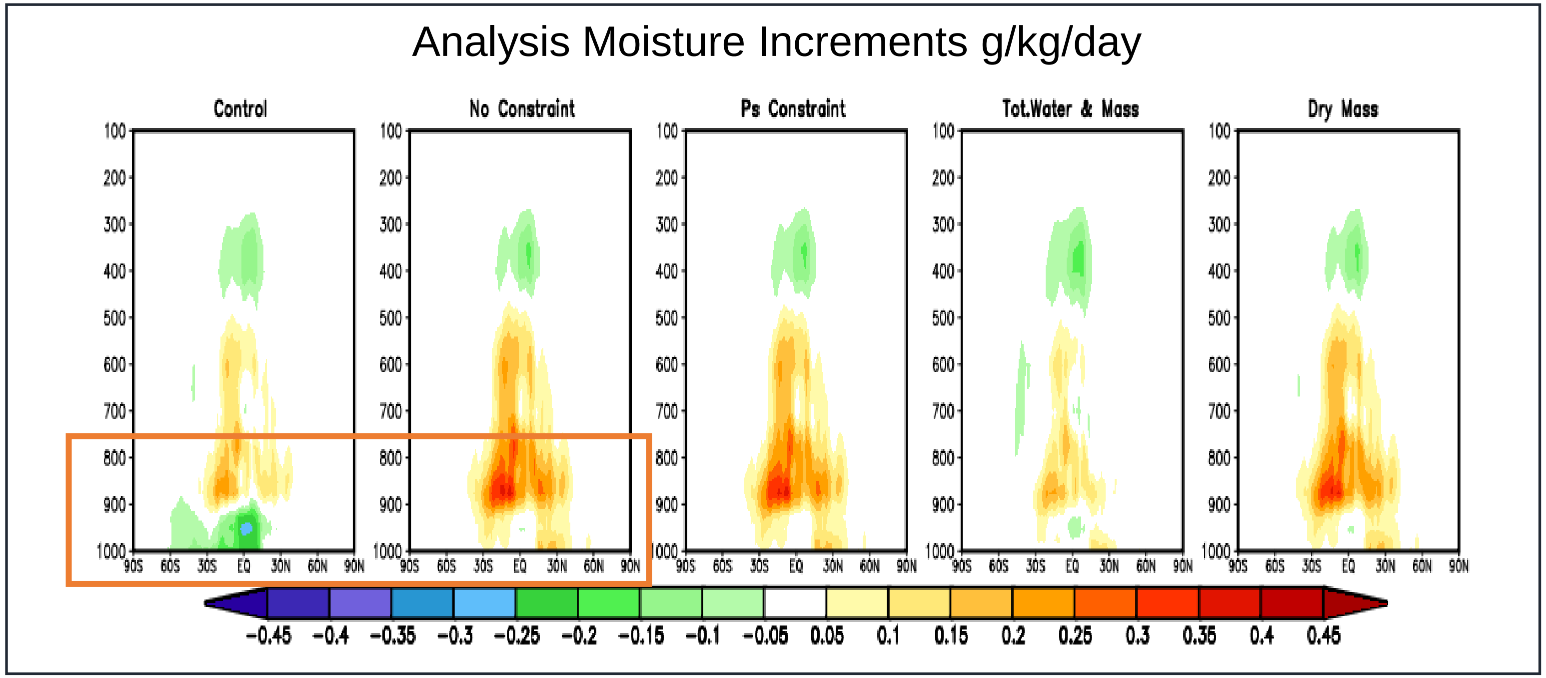




Impact on the dry mass constraint on the adjusted moisture analysis tendencies becomes more significant with observing system changes.

Global Constraints

Dry Mass Conservation in MERRA-2



MERRA-2 dry-mass constraint formulation uses a variational procedure to individually conserve the globally integrated total mass and the globally integrated water mass.

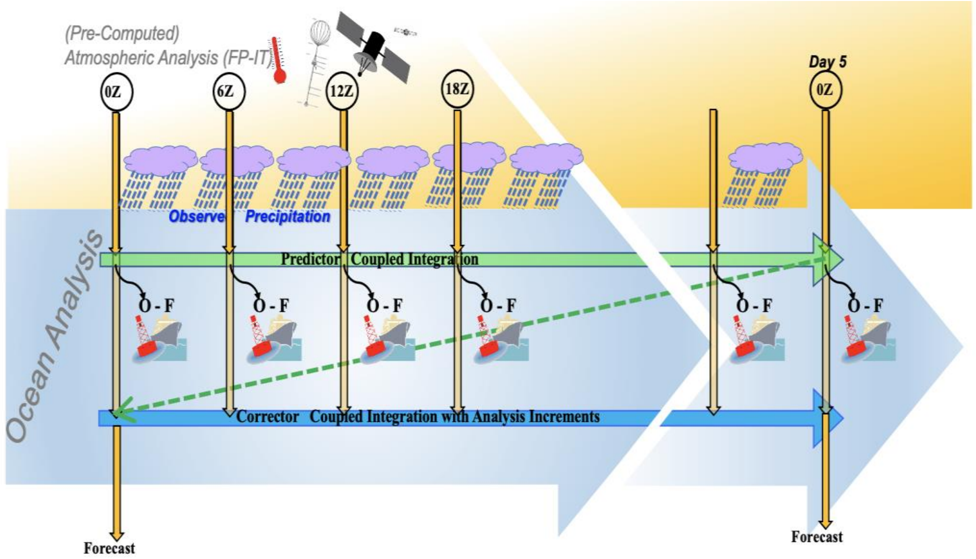
Candidate reformulations of the constraint were tested for GEOS-R21C along with no-constraint. However, it was found that a coordinated re-tuning of the model physics is required to maintain model skills.

MERRA-2/GEOS-IT Ocean

One-way Coupled Ocean reanalysis and GMAO Seasonal to sub-seasonal system S2S-v3

Model

- AGCM: Recent GEOS version + two-moment cloud microphysics;
- OGCM: MOM5, ~0.25 deg, 50 levels; Ice Sheet runoff to proper location;
- New "atmosphere-ocean interface layer" - diurnal warming and cool layer;
- Sea Ice: CICE-4;
- Forecasts and Hindcasts: initialized from "MERRA-2/GEOS-IT Ocean" analysis, new perturbation/ ensemble strategy;



One-way Coupled Ocean Data Assimilation reanalysis "MERRA-2 Ocean / GEOS-IT Ocean"

- atmosphere is "replayed" (regular replay) to MERRA-2 or GEOS_IT; Aerosol is "replayed" to analyzed aerosol optical depth.
- precipitation correction; data assimilation with LETKF.

Observations

- nudging of SST and sea ice fraction from MERRA-2/GEOS-IT, new technique for sea ice;
- assimilation of *in situ* Tz and Sz including Argo, XBT, CTD, tropical moorings;
- assimilation of satellite along-track ADT (Jason, Saral, ERS, GEOSAT, HY-2A, CryoSat-2);
- assimilation of SMAP, Aquarius sea surface salinity.

MERRA-2/GEOS-IT Ocean

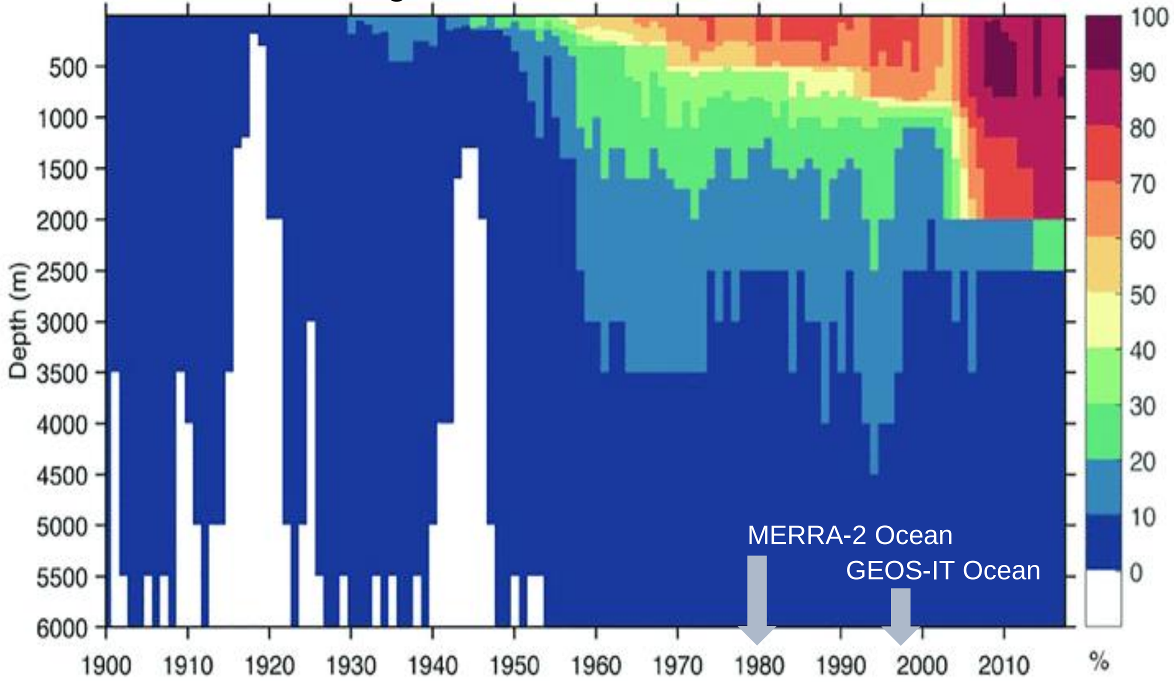
One-way Coupled Ocean reanalysis and GMAO Seasonal to sub-seasonal system S2S-v3

R21C also introduces a new atmosphere-ocean interface layer; diurnal warming and cool layer.

R21C substitutes Reynolds with OSTIA-RAN SST and sea ice boundary conditions to provide foundation SST and enable skin temperature analysis using AVHRR radiances.

Curated output collection to drive ocean or coupled models.

Percentage (%) of In Situ Ocean data coverage for 3×3 boxes over the global ocean area from 5 to 6000 m.

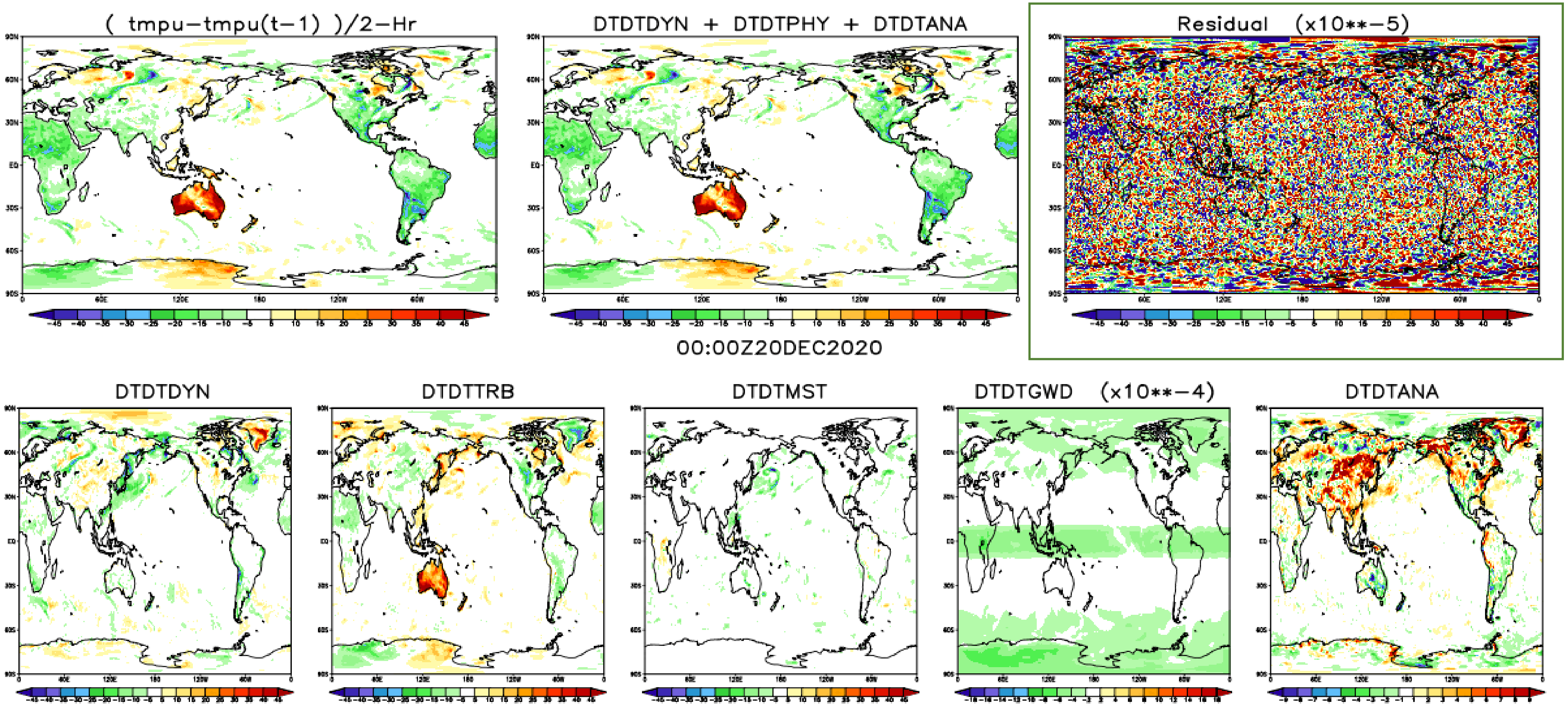


Meyssignac, B., et al. (2019)

Interface layers

Budget terms at the lowest model level

All tendency terms add up to the temperature field update.

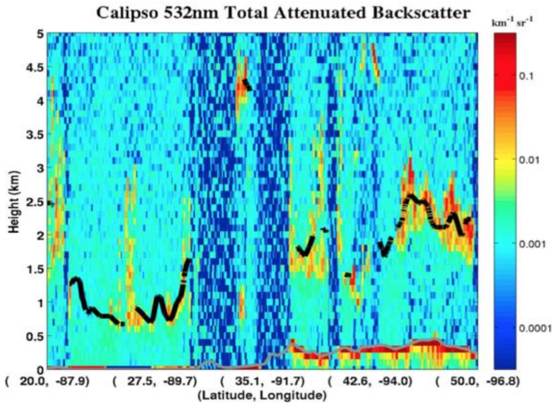


Planetary Boundary layer

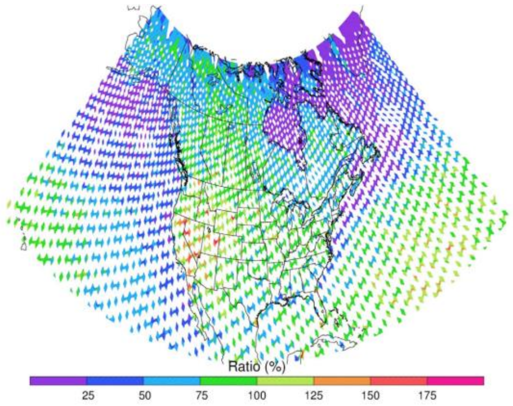
Better understand the flux balances across the earth system components

Development of PBLH assimilation in GEOS targets enhancing PBL thermodynamics and height.
Assimilation of surface-sensitive radiances over land remains a challenge due to large uncertainties in the land physical surface emissivity model used in the CRTM and uncertainties in land surface state properties.

CALIPSO

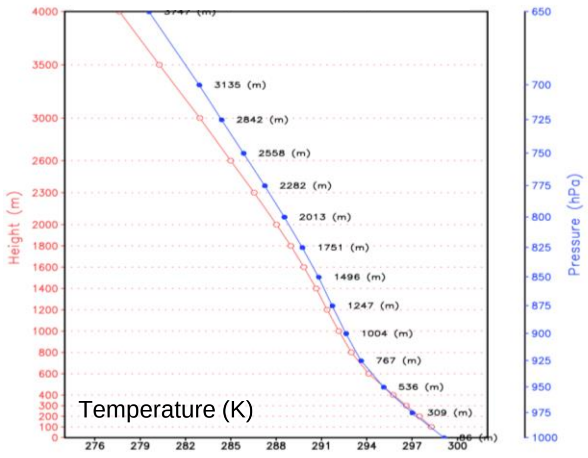


MERRA / CALIPSO PBLH ratio



McGrath-Spangler and Denning (2012)

Constant height levels



Builds on previous comparison studies of MERRA PBLH to observations: CALIPSO, MPLNET, Wind Profiler Backscatter, Multi-Angle Compact Thermal Imager…etc.

McGrath-Spangler and Denning (2012); Lewis et al. (2013); Molod et al. (2015); Dong Wu et al. (2021).

Curated GEOS-R21C collections of PBL-relevant quantities with various formulations of PBLH on constant-height diagnostic levels.

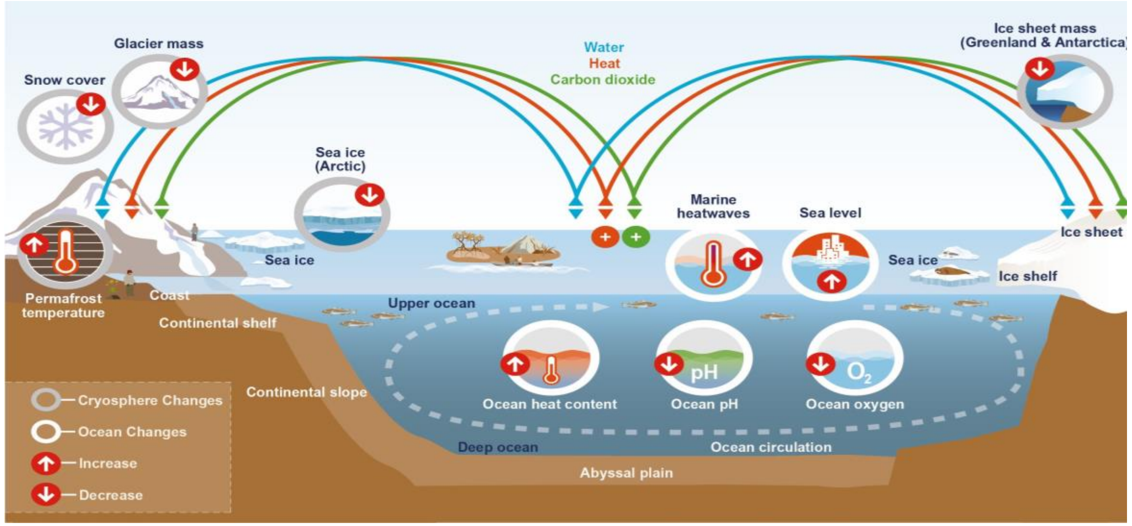
PolarMERRA

Why focus on the cryosphere?

The cryosphere is undergoing unprecedented changes, directly impacting the entire Earth System

The appropriate representation of cryospheric processes in reanalyses is directly relevant to large scale atmospheric circulation and ocean characteristics:

- Sea ice thermodynamics directly impacts the representation of Arctic Amplification;
- Glacier and ice sheet calving and runoff impact ocean circulation and sea ice formation;
- Snow cover and evolution impacts land surface energy balance;
- Permafrost evolution changes methane production and release.

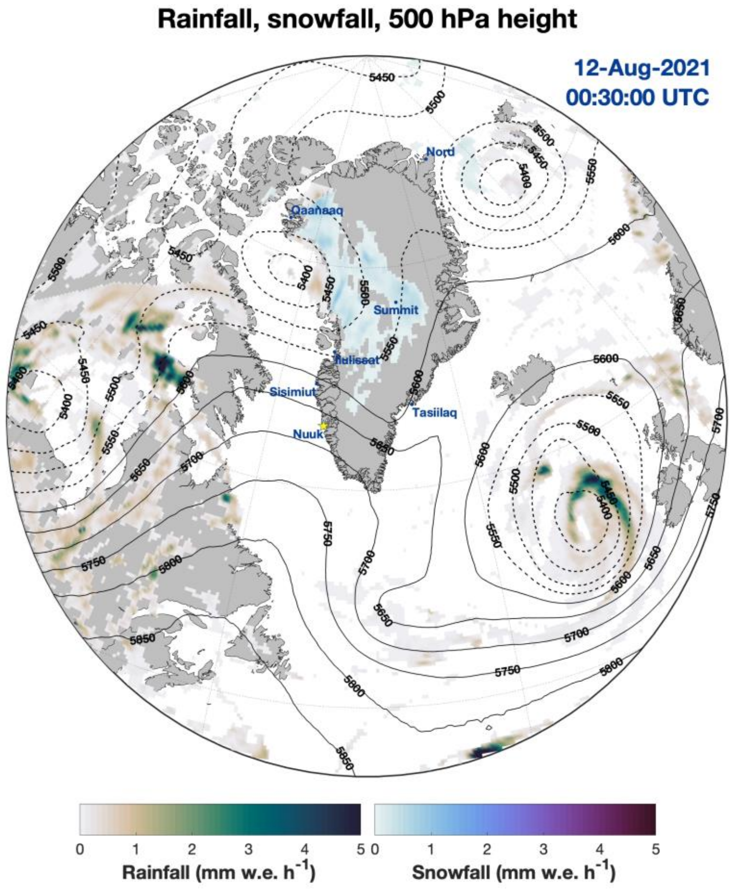


IPCC: The Ocean & Cryosphere in a Changing Climate

Improving the representation of the cryosphere in reanalyses and forecast systems has social, economic, and defense applications.

PolarMERRA

Challenges and opportunities



Current reanalysis outputs are insufficient for community needs

- Many collections lack sufficient variables for process studies and basic scientific research
- Resolution is insufficient to represent critical zones (e.g., sea ice evolution, ice sheet and glacier ablation zones)
- Heritage or overly general parameterizations impact local representation of cryospheric processes and regional climate

Large biases in temperature and precipitation exist

Polar observations are sparse

- Satellite retrievals can be difficult over ice surfaces
- In situ observations are sparse and can be short or suffer from long outages (continuously improving).

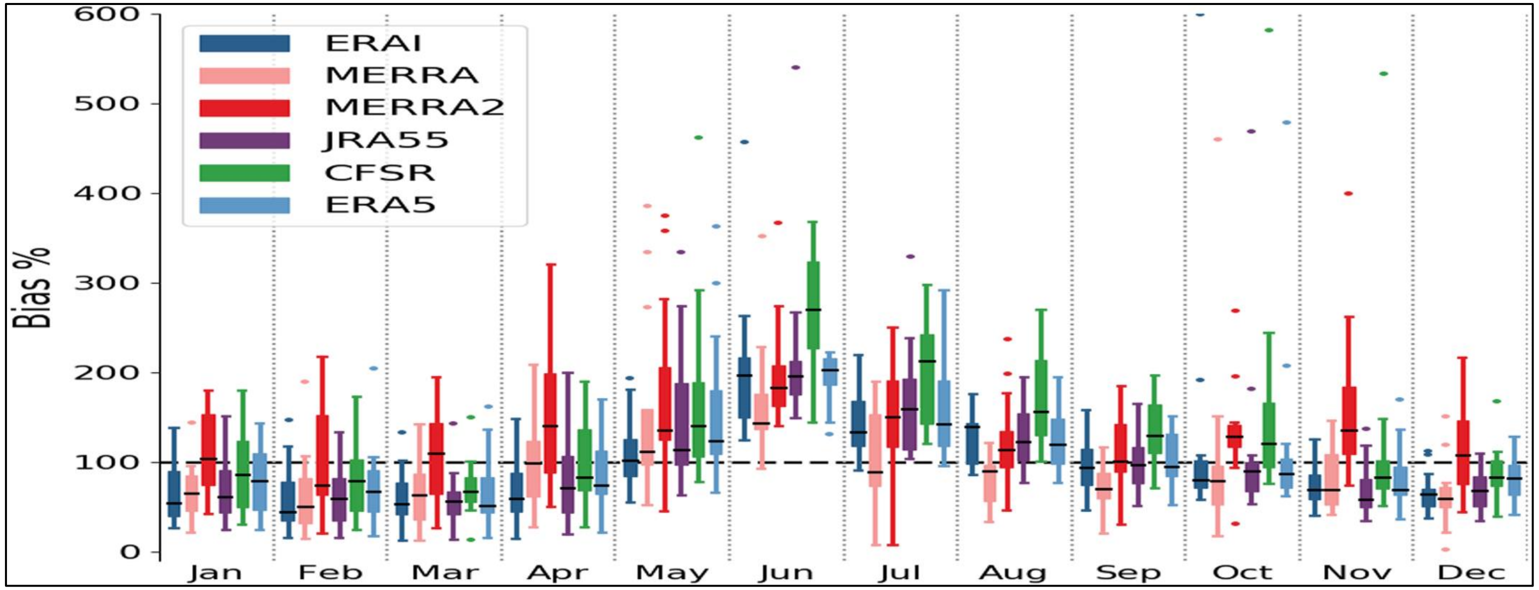
PolarMERRA

A collaboration between GMAO and the Cryospheric Sciences Lab to enhance polar process representation in reanalysis.

Stage 1: Develop an assessment framework for the GEOS system and enhance polar parameterizations. This includes evaluating present cryospheric biases and refining sea ice and glacier conditions.

Reanalyses globally overestimate precipitation, especially in the Arctic. In MERRA-2, this bias mainly comes from drizzle, significantly affecting near-surface conditions.

Arctic precipitation biases



(Barrett et al., 2020)

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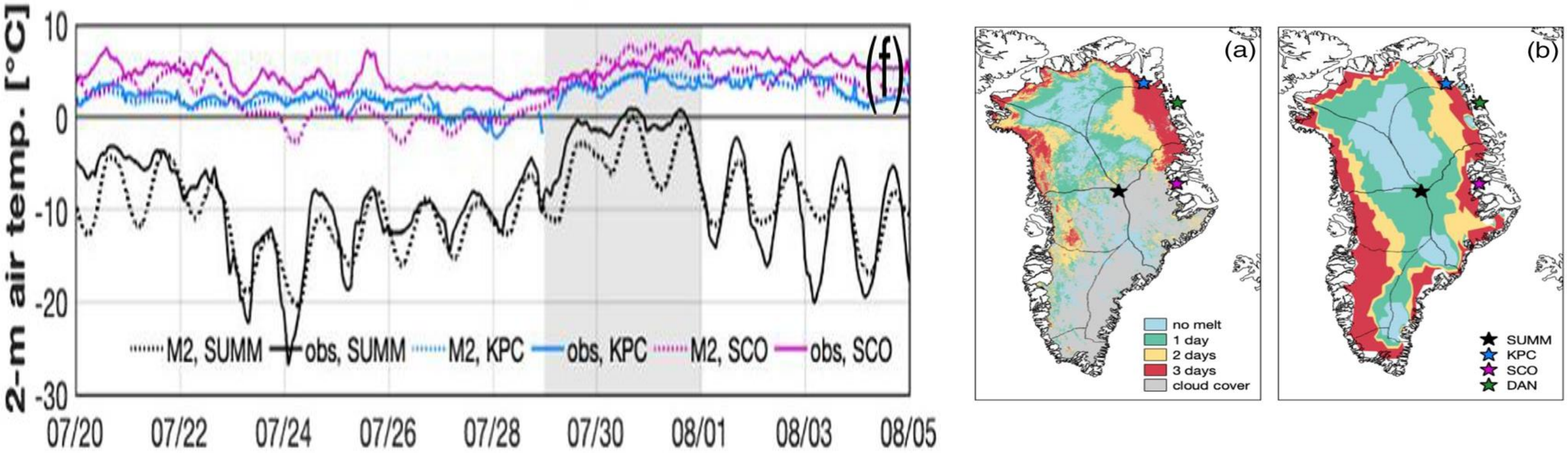
Surface air temperatures and melt across ice sheets



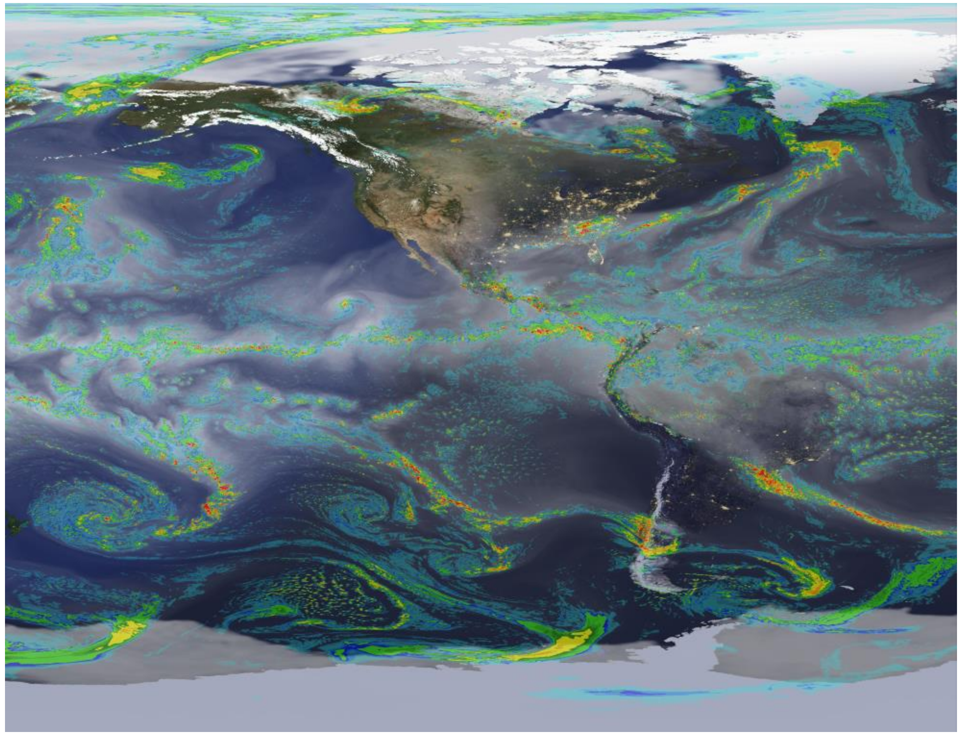
Cullather et al., 2020

MERRA-2 performs well for glacier and ice sheet surface temperatures. Despite resolution challenges, its melt extent and runoff are comparable to regional climate models/reanalyses.

PolarMERRA

A collaboration between GMAO and the Cryospheric Sciences Lab to enhance polar process representation in reanalysis.

Stage 2: Downscaled replay of GEOS-21C with a global ~7km horizontal resolution to enhance storm representation, snow accumulation, and melt gradients in complex terrains.



Precipitation
GEOS-5 Nature Run, Ganymed Release, 7km; 16 June 2006

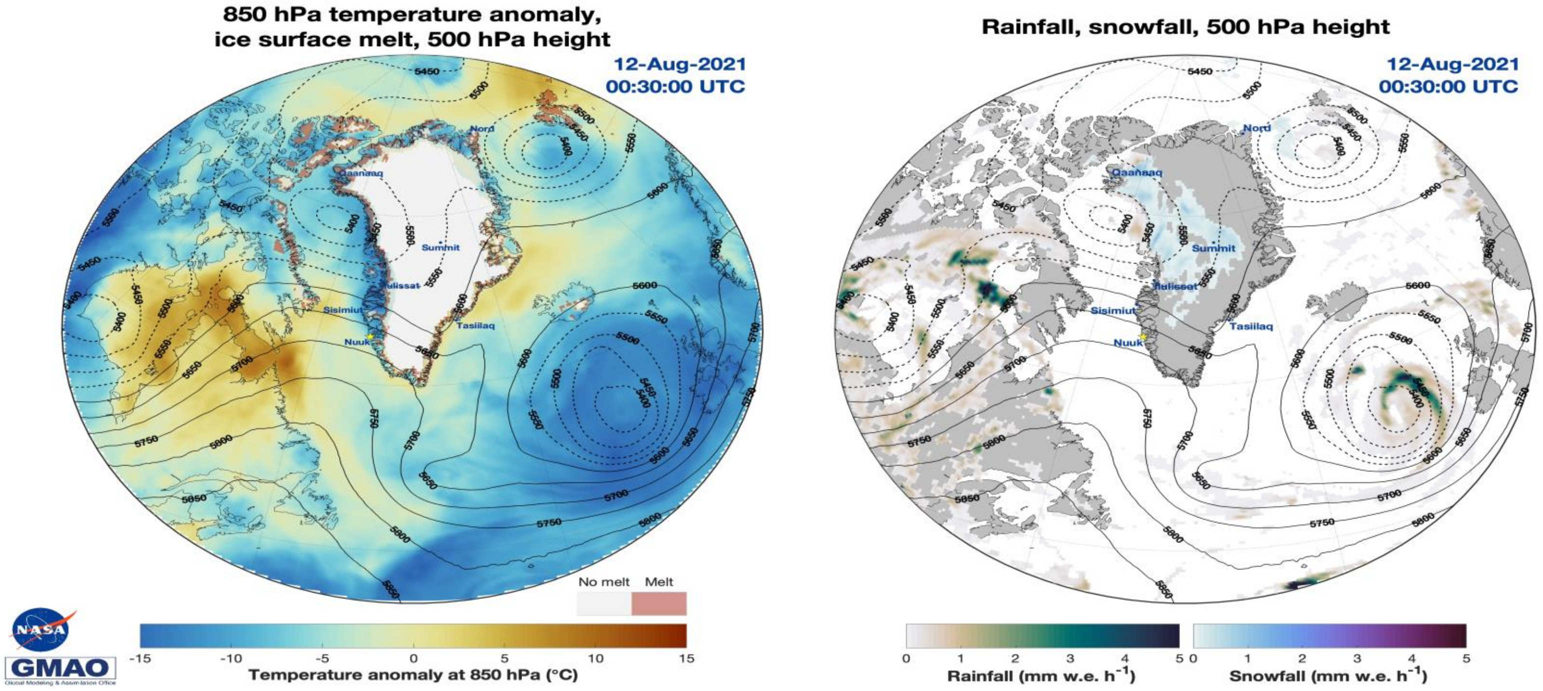
- Downscaled replay with updated model version and truncated GEOS-R21C analysis increments to include further improvements to land ice and sea ice representation.
- A 7km horizontal resolution balances complex physics and computational resource needs.
- 1998 – 2025, same length as GEOS-R21C.

GEOS-R21C features detailed polar-specific collections of relevance to the cryosphere.

PolarMERRA

A collaboration between GMAO and the Cryospheric Sciences Lab to enhance polar process representation in reanalysis.

Stage 3: Collaborations to enhance polar understanding and knowledge transfer for future coupled reanalyses (GEOS-ISM coupling, cryospheric data assimilation, and other improvements.



R21C-Chem

The first “all”-atmosphere chemical reanalysis produced at GMAO

Composition (or “chemical”) reanalyses are relatively new

Tropospheric / air quality focus

- MACC, CAMS Interim, CAMS (Copernicus)
- TCR-1, TCR-2 (JPL)
- RAQMS (U of Wisconsin)

Stratosphere

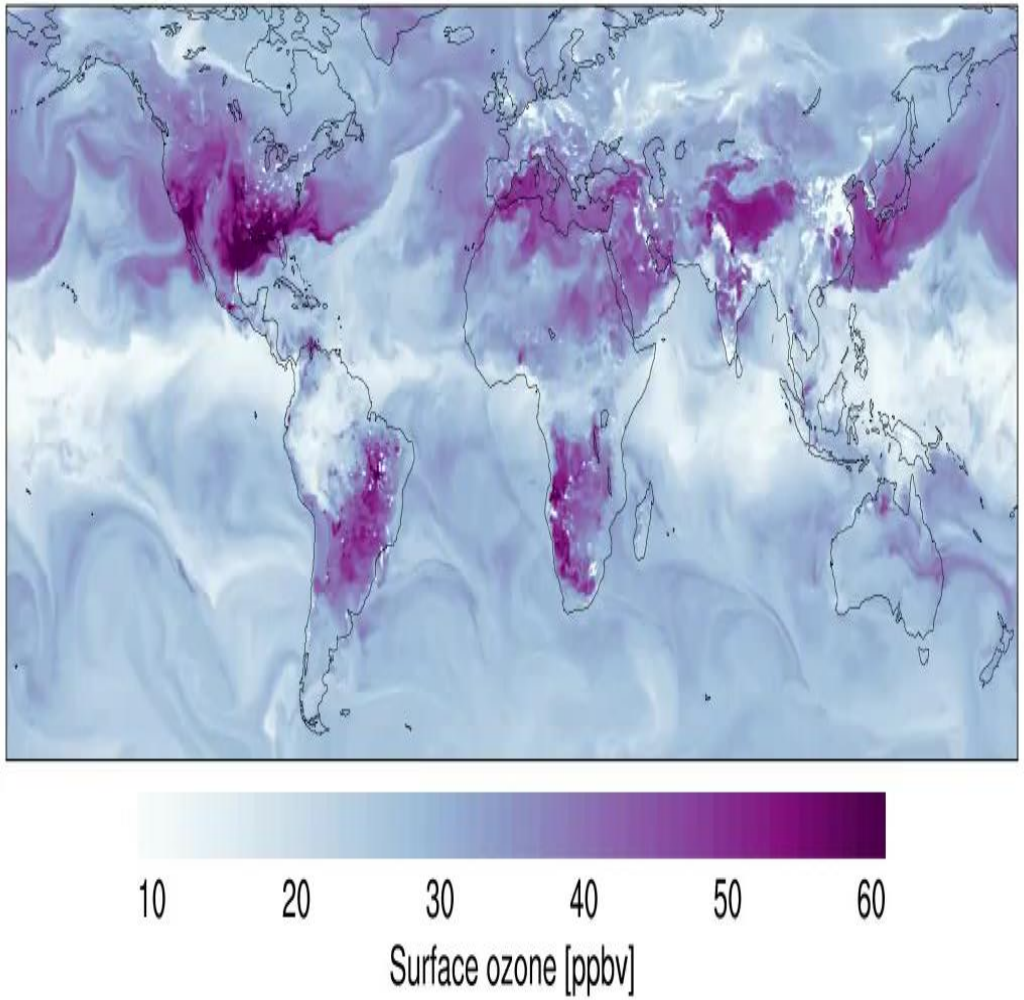
- BRAM, BRAM2 (BIRA-IASB)
- M2-SCREAM (GMAO)

R21C-Chem includes both tropospheric and stratospheric trace gases. Constrained by temperature, winds, surface pressure, tropospheric water vapor from the atmospheric reanalysis.

R21C-Chem development expands/builds on existing capabilities:

- GEOS Chemistry model (GEOS-Chem);
- MERRA-2 Stratospheric Composition Reanalysis of Aura MLS (M2-SCREAM);
- Carbon data assimilation;
- Tropospheric constituents and air quality modelling and assimilation.

GEOS-Chem is successfully used in GEOS Composition Forecast (GEOS-CF)



R21C-Chem

The first “all”-atmosphere chemical reanalysis produced at GMAO

R21C-Chem assimilates selected gases important for stratospheric and tropospheric chemistry, with the Constituent Data Assimilation System (**CoDAS**).

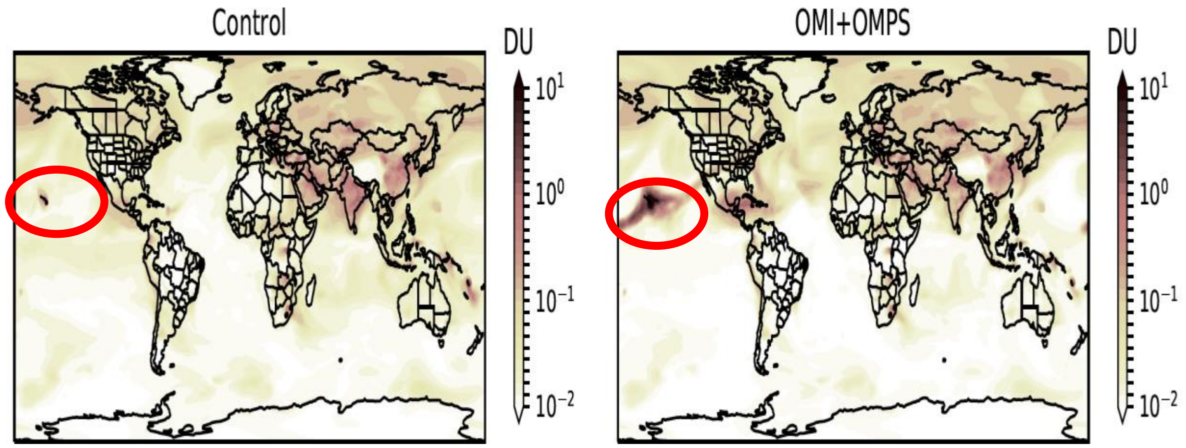
Assimilated species and sensors

	Sensor	Molecules	Observation type
Retrievals	OMI, OMPS, TROPOMI	NO_2, SO_2, O_3	Column
	SCIAMACHY, GOSAT, TROPOMI	CH_4	Column
	SCIAMACHY, GOSAT, OCO	CO_2	Column
	MOPITT TIR & NIR	CO	Column
	MLS	O_3, HCl,HNO_3,N_2O, H_2O, CH_3Cl, CO	Stratospheric limb profiles
	OMPS-LP	O_3	Stratospheric limb profiles

	Sensor	Wavelength	Comment
Radiances	AIRS, IASI (MetOp-A,B), CrIS FSR (potentially)	9.6 μm	Ozone-sensitive channels

* NEW

Simulated SO2 total column [DU] for Dec 6, 2022



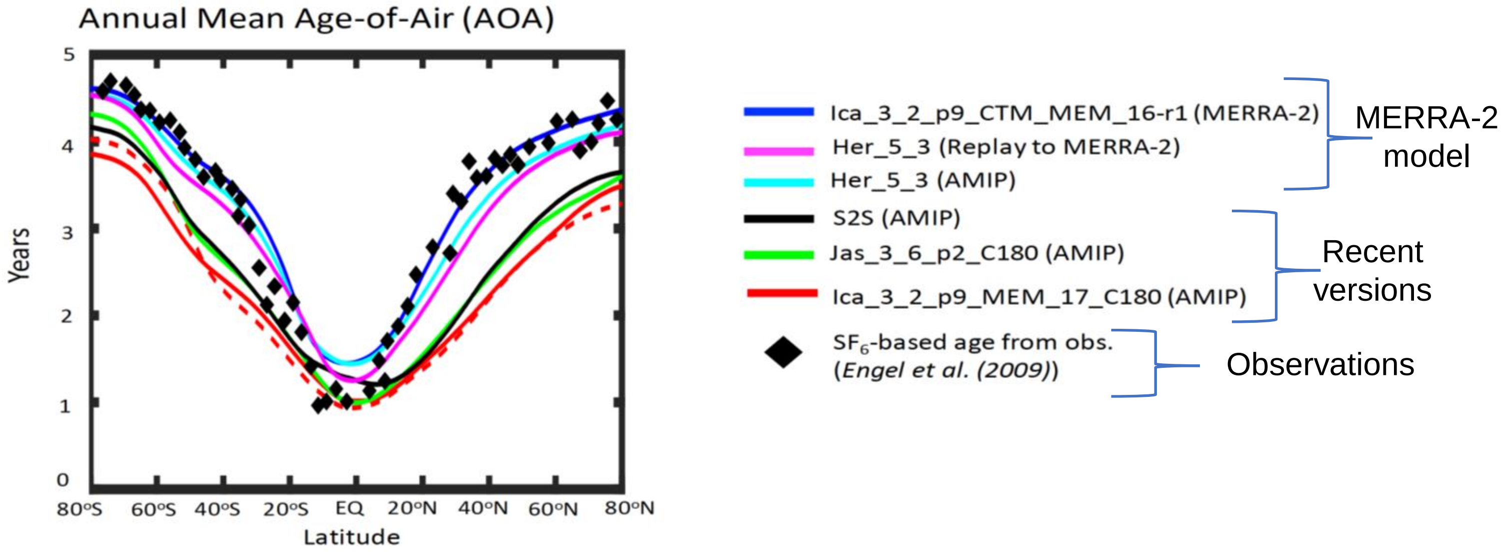
Mauna Loa eruption only captured in runs with assimilation

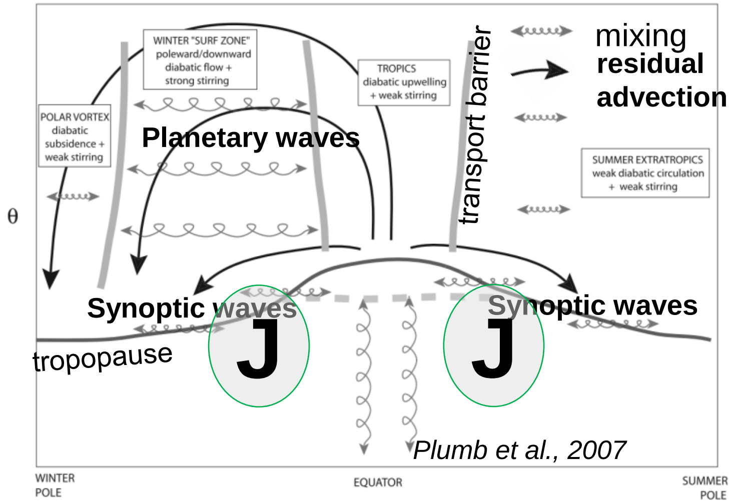
CoDAS: Originally developed in GSI for carbon DA, the modules is designed to be tracer agnostic and can assimilate any type of retrieved constituent observations with an averaging kernel or at a point.

Stratospheric transport in GEOS

The curious case of Age Of Air (AOA)

The Brewer-Dobson Circulation (BDC) has been getting stronger in more recent GEOS model versions which translates in younger mean ages and shows up in real chemical constituents (CH4, N2O).





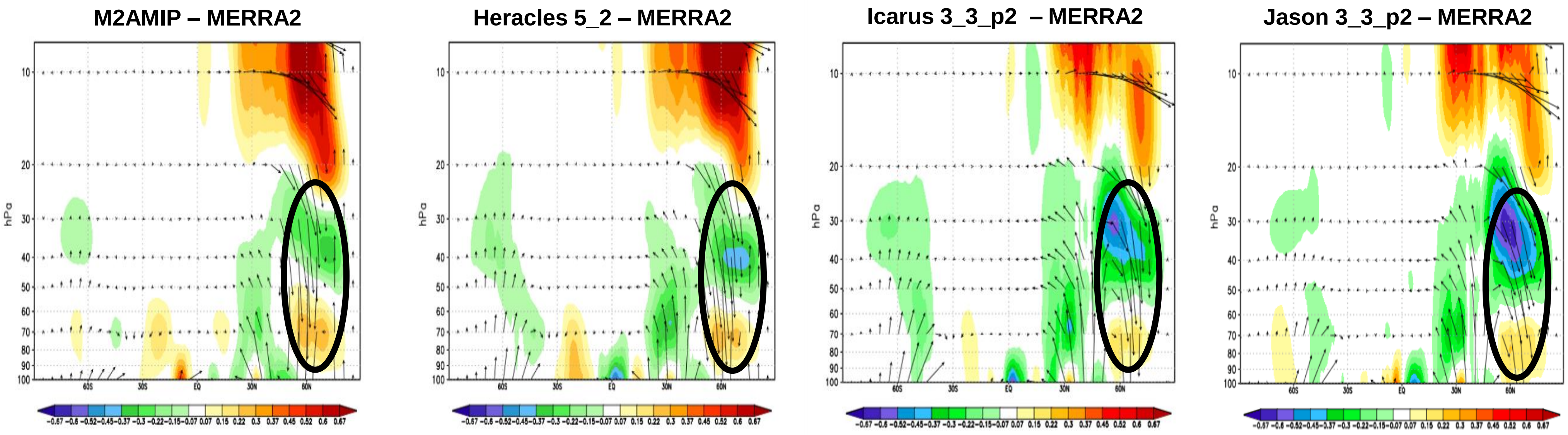
Brewer-Dobson circulation:
Global mass circulation of tropospheric air through the stratosphere. Characterized by tropospheric air rising into the stratosphere in the Tropics, moving poleward before descending in the middle and high latitudes. Butchart, N. (2014)

Stratospheric transport in GEOS

The curious case of Age Of Air (AOA)

The stratospheric mean age-of-air is, to first order, determined by the strength of lower stratospheric ascent between the turnaround latitudes (Hall and Plumb, (1994), Butchart et al. (2001))

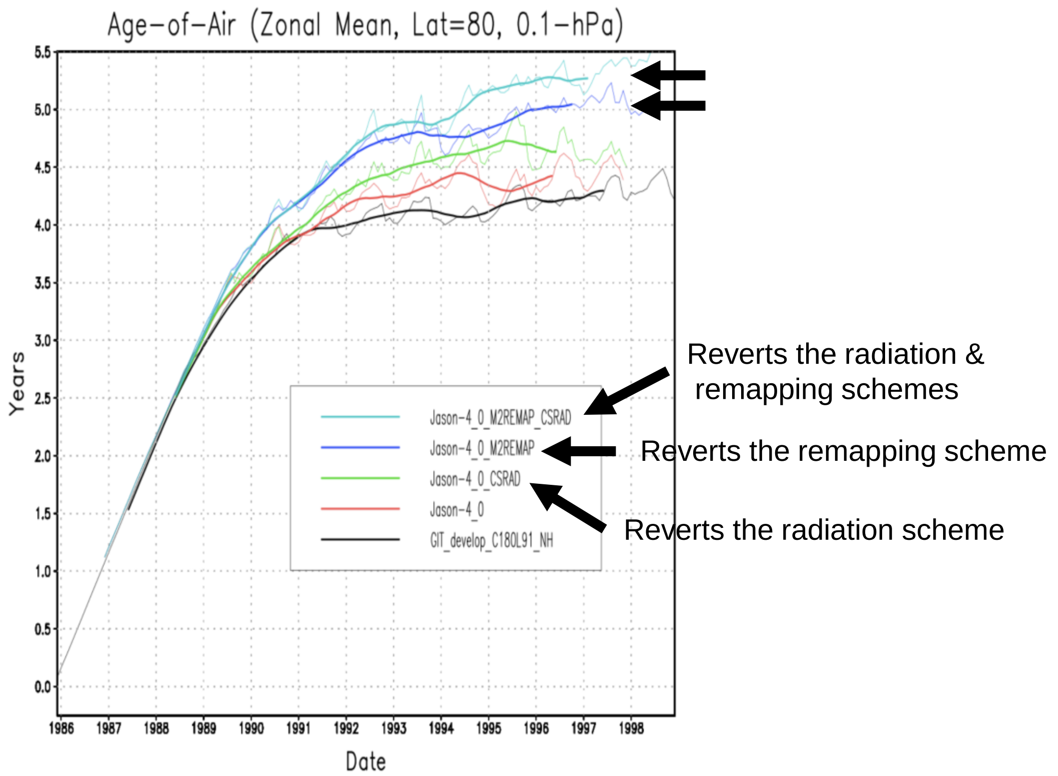
A faster BDC appears to be related to changes in wave convergence in the lower stratosphere associated with changes in (zonal wind) critical lines.



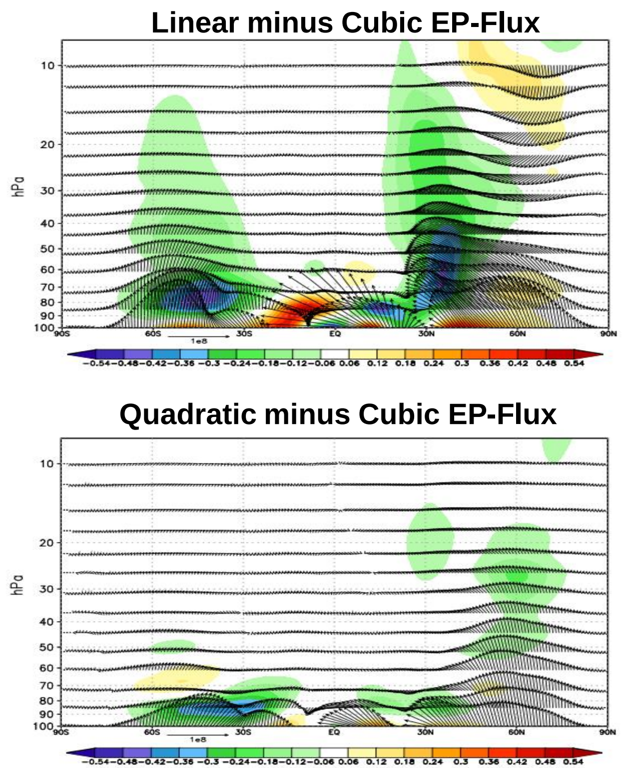
Stratospheric transport in GEOS

The curious case of Age Of Air (AOA)

Sensitivity of AOA to radiation and remapping schemes



Sensitivity of w* to the order of the remapping scheme



This effort demonstrated the transport character change in recent versions of the GEOS model and identified robust drivers of stratospheric transport in GEOS. But addressing the issue may require a retuning of model physics and/or the parametrizations in the remapping scheme.

Takeaways

- GMAO continues its incremental progress towards an Integrated Earth System Reanalysis through a combination of systems with increased levels of complexity and coupling.
- The GMAO is preparing to produce a new 25+ year atmospheric reanalysis for the early 21st Century (GEOS-R21C) along with derivative reanalyses for the cryosphere (PolarMERRA downscaling), atmospheric chemistry (R21C-Chem), and the land (R21C-Land). Production starts in Q4 2023.
- Most reanalysis systems rely on a frozen version of an NWP system to that have gone through consecutive upgrades aimed at improving NWP skill. However, NWP evaluation metrics are not designed to be climate-proof.

  The onus is on the reanalysis teams to make the case for new metrics that are critical to the health of future reanalyses.
- As reanalysis systems grow increasingly more complex (coupling) and more expensive (time and computing resources), we need to leverage the NWP test/validation procedures to include key metrics even when these only pertain to reanalysis.

  When possible, to breakdown slow-varying processes into key drivers that may be examined in a reasonably controlled test framework. (Easier said than done!)