Recent developments in reanalysis at NASA GMAO

From MERRA-2 to GEOS-R21C and MERRA-3

Amal EL Akkraoui[a,b]

Contributors: Larry Takacs[a,b], Kris Wargan[a,b], Jianjun Jin[a,b], Richard Cullather[a,b], Christine Bloecker[a,b], Ron Gelaro[a], and Steven Pawson[a] and many others that are acknowledged throughout the slides.

[a]GMAO, Earth Sciences Division, Sciences and Exploration Directorate, NASA GSFC.

[b]Science Systems and Applications, Inc. (SSAI)

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- GMAO continues its incremental progress towards an Integrated Earth System Reanalysis through a combination of systems with increased levels of complexity and coupling.
- A new 25+ year atmospheric retrospective analysis, GEOS-R21C, is planed as a modern baseline for the atmospheric component of the future Coupled Reanalysis MERRA-3.
- With two proposed off-line derivative products for the chemistry and the cryosphere, GEOS-R21C will be an opportunity to further understand the interactions between the atmosphere and other Earth System components.

This talk will present the plans and progress towards GEOS-R21C and how it fits in relations to MERRA-2 and future MERRA-3.

GMAO reanalyses and derivative products

Atmosphere
- MERRA 1979-2016
- MERRA-2 1980-Present
- Includes aerosol analysis

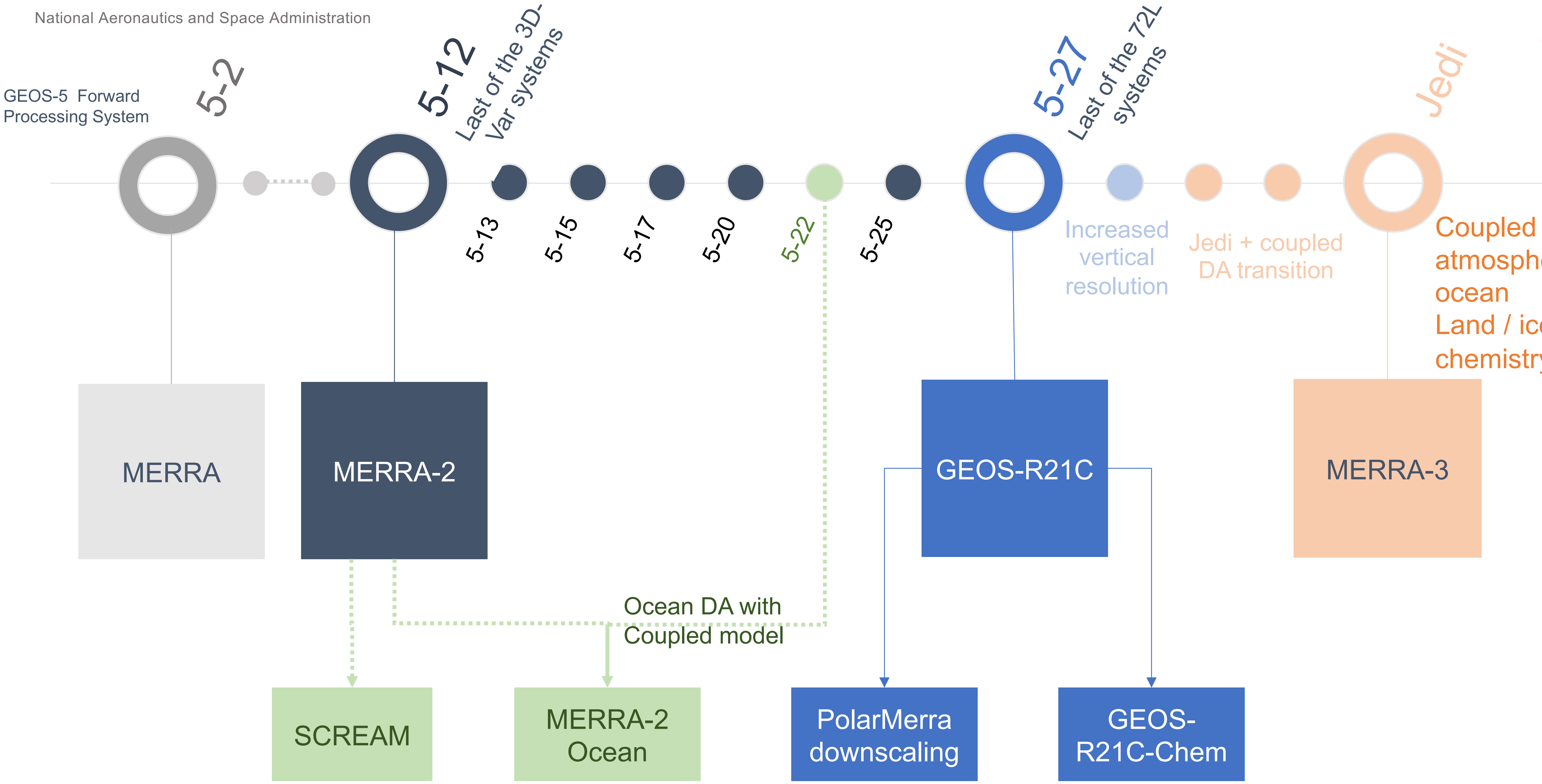
Ocean
- MERRA-Ocean 1993-Present
- MERRA2-Ocean 1980-Present
- Ocean DA with coupled model

Composition
- MERRA-Aero 2002-2015
- SCREAM 2004-Present
- Stratospheric Chemistry MLS

Enhancements
- MERRA-Land 1979-2016
- MERRA2-R12K
- Downscale to 12-km

Biogeochemical
- MERRA-NOBM 1998-2015
- Ocean state, biology, carbon fluxes

MERRA-3


GEOS-5 Forward Processing System
5-2
5-12
Last of the 3D-Var systems
5-13
5-15
5-17
5-20
5-22
5-25
5-27
Last of the 72L systems
Increased vertical resolution
Jedi + coupled DA transition
Jedi
Coupled DA atmosphere-ocean Land / ice/ chemistry
MERRA
MERRA-2
GEOS-R21C
MERRA-3
Ocean DA with Coupled model
SCREAM
MERRA-2 Ocean
PolarMerra downscaling
GEOS-R21C-Chem

GEOS-R21C: An Enhanced Atmospheric Reanalysis

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.

Targeting a 25-km resolution system that uses hybrid 4D-EnVar all-sky data assimilation and covers the period 2000-onwards.

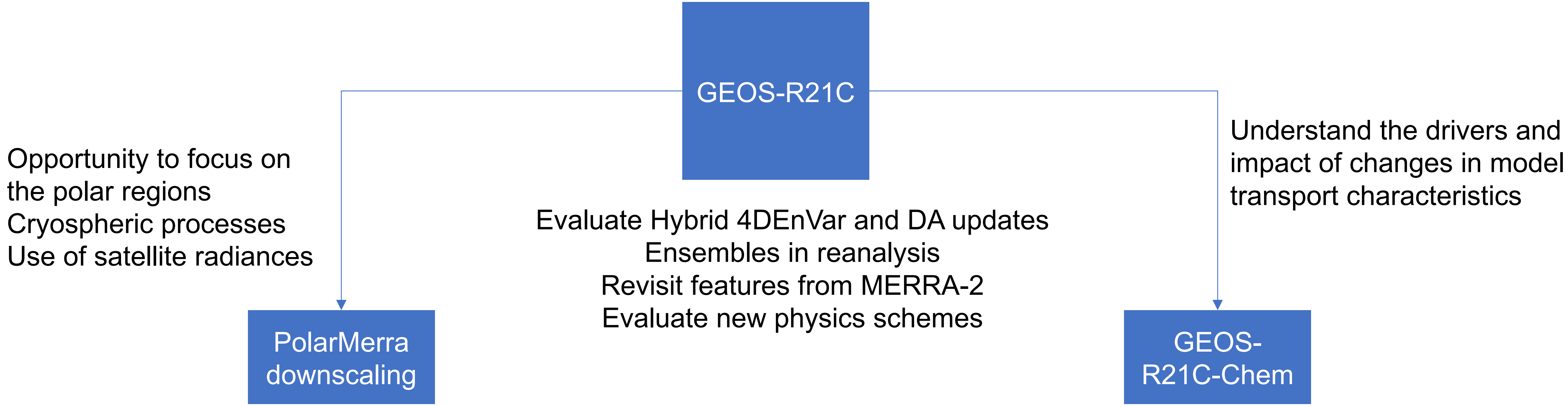
Continue focus on atmospheric composition, via a proposed offline "derivative" reanalysis for atmospheric constituents using CoDAS and GEOS-Chem.

Enhance focus on cryospheric processes, via a proposed additional activity, Polar MERRA downscaling.

A potential step towards a Level-4 product for NASA's PMM Science Team.

GEOS-R21C: An Enhanced Atmospheric Reanalysis

GEOS-R21C is not a replacement to MERRA-2, but rather a stepping-stone towards MERRA-3, providing a baseline for its atmospheric component and the opportunity to explore aspects of Earth System coupling with other offline components.



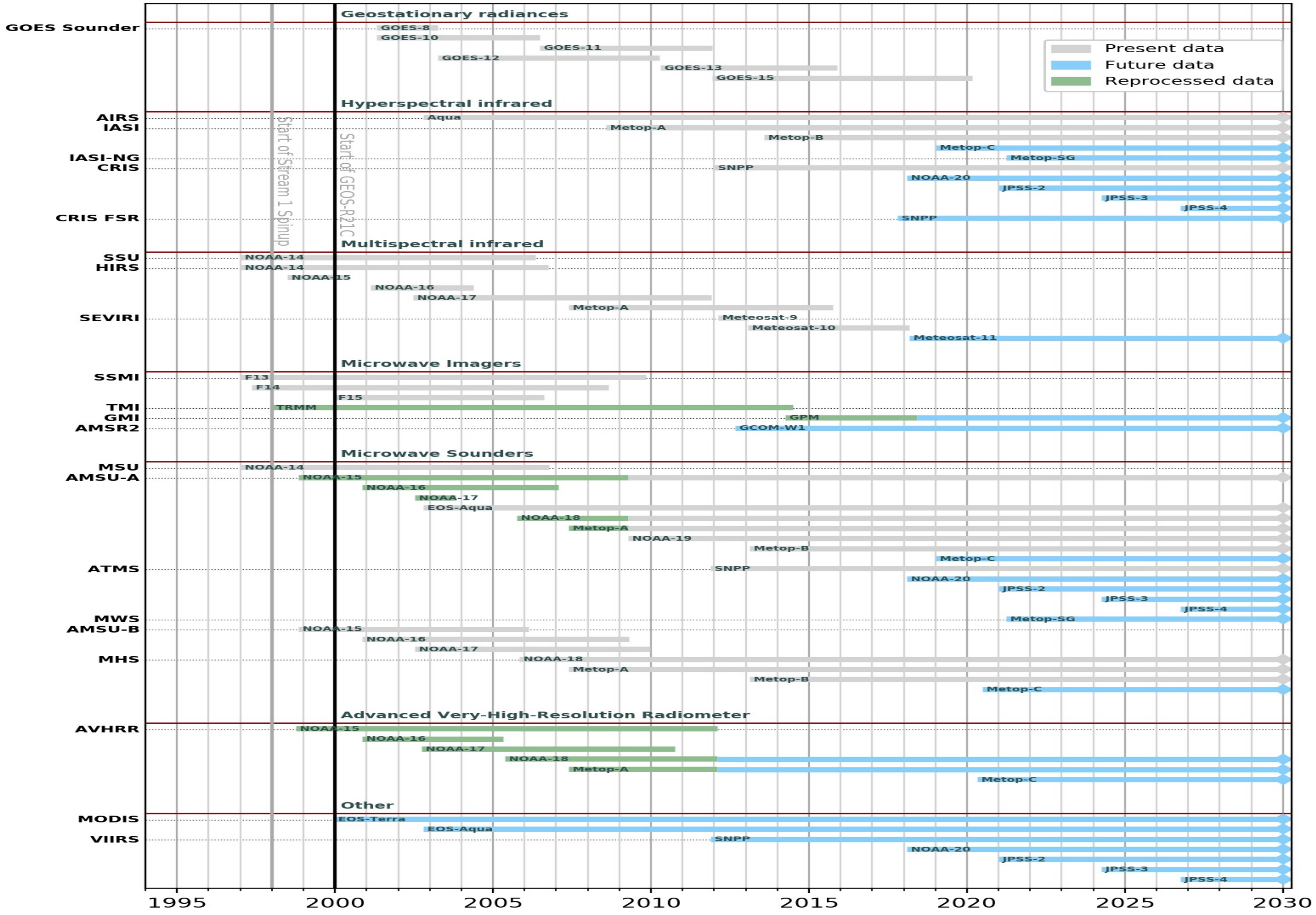
Observing system for GEOS-R21C

Mohar Chattopadyay, Meta Sienkiewicz, Kris Wargan, Jianjun Jin, Rob Lucchesi, Bryan Karpowicz, Will McCarty, Amal El Akkraoui, Christine Bloecker, Larry Coy, Karki Mahendra, Akira Sewnath

Reasons to update reanalysis products

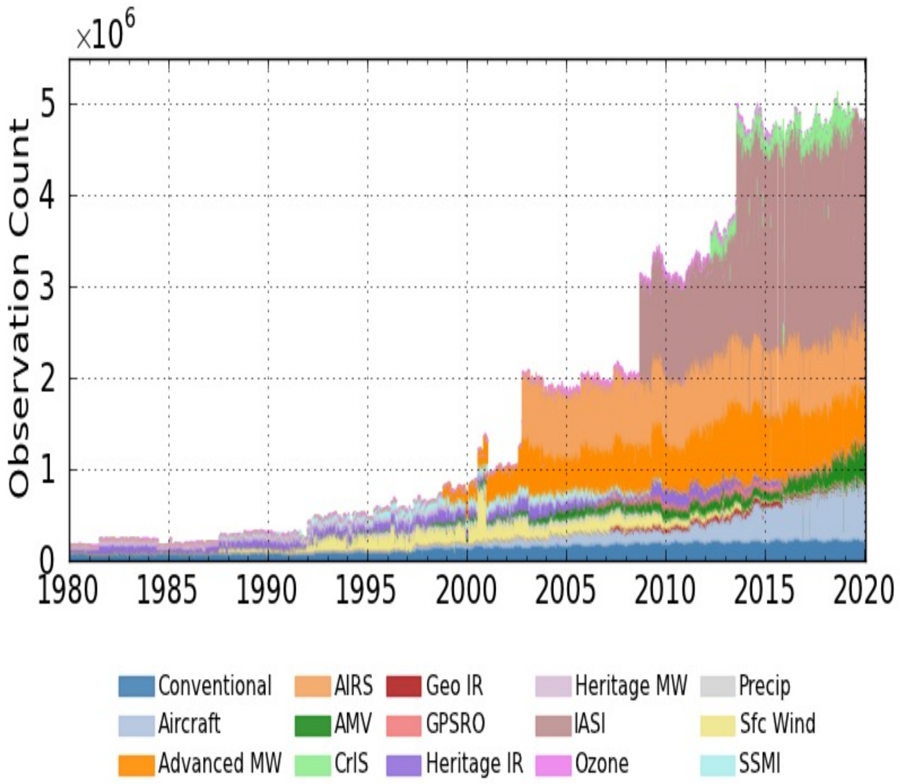
- Opportunity to use **reprocessed** versions of older operational observations. (AMSU-A, AVHRR, AMV, SBUV-2, MLS, possibly COSMIC).
- Opportunity to use **new** data (OMPS-NP, OMPS-NM, COSMIC2, Metop-C, JPSS…)
- Opportunity to **improve** the use of observations: All-sky (GMI, TMI, MHS, AMSR-2, AMSR-E, and ATMS).

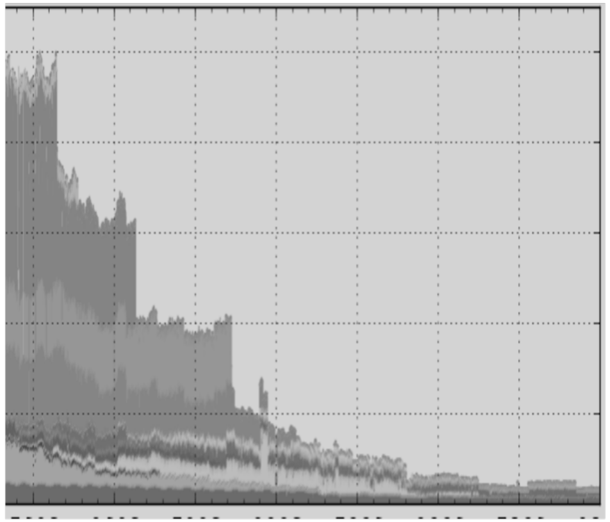
Updated Radiances since MERRA-2



Reasons to update reanalysis products

- The ability of older systems to ingest new types of observations is limited. With instrument failures, **they start running out of data.**

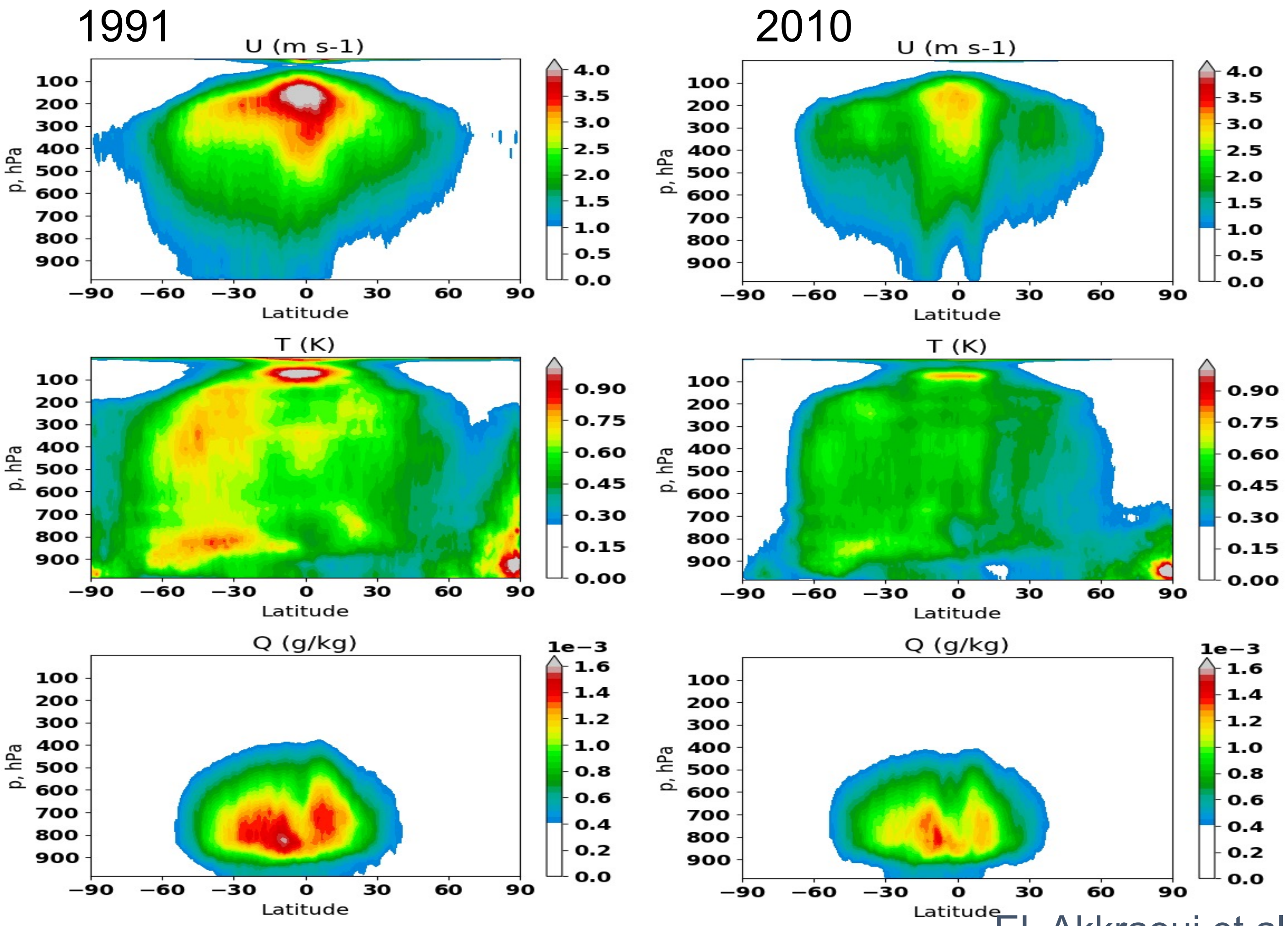




Reasons to update reanalysis products

- The ability of older systems to ingest new types of observations is limited. With instrument failures, **they start running out of data.**
- Adequate constraint from data is important.

Standard deviations of the differences between parallel streams during the overlaps of 1991 and 2010



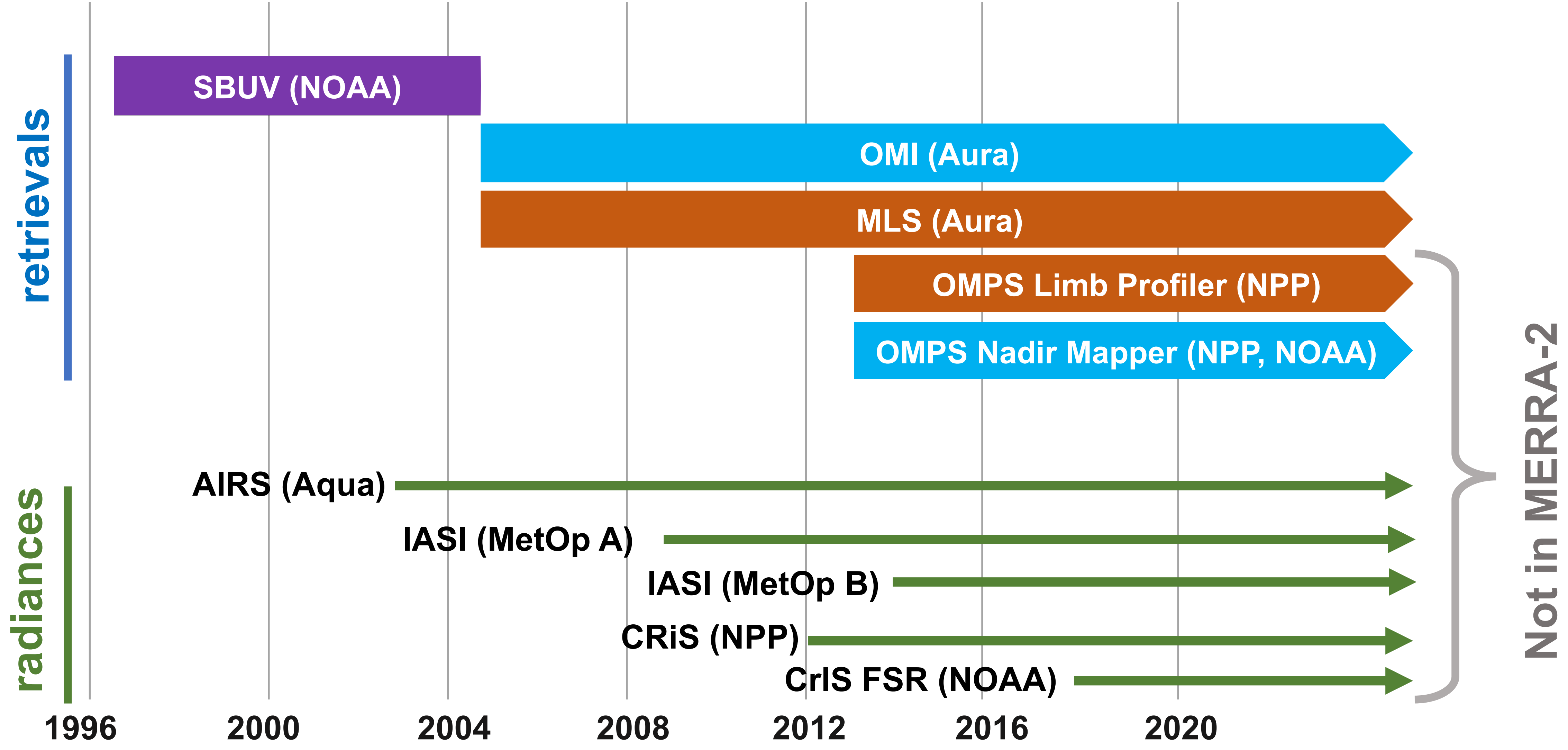
EL Akkraoui et al, 2021

Ozone Observations for GEOS-R21C

Goal: Minimize artificial discontinuities in the ozone record due to observing system changes through homogenization of input data. Quantify expected remaining discontinuities.

Kris Wargan, Bryan Karpowicz, Steven Pawson, Amal El Akkraoui & Christine Bloecker

Ozone data for GEOS-R21C



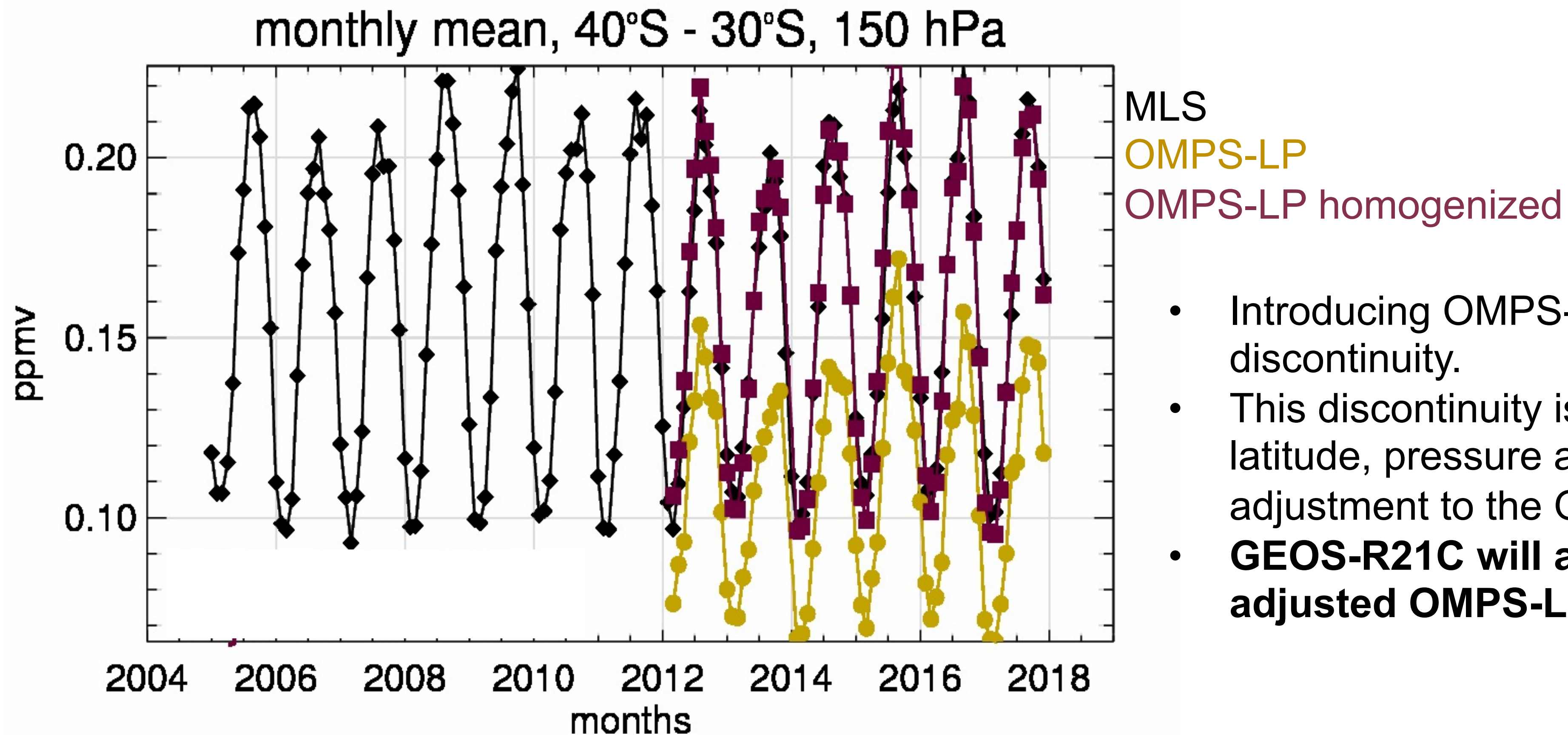
Ozone data for GEOS-R21C

Relative biases among data sources in a changing observing system can lead to discontinuities and pose a problem for trend studies.

- Ozone observing system changes in MERRA-2: 2004 (SBUV→Aura transition) and 2015-2016 (a change of MLS data versions).
- Many new data types compared to MERRA-2; new versions of old data.
- Assimilation of ozone-sensitive radiances for the first time in a GMAO reanalysis.

For GEOS-R21C, homogenization is applied to ensure continuity in Total column ozone (OMI and OMPS-NM) and ozone profiles (MLS and OMPS-LP).

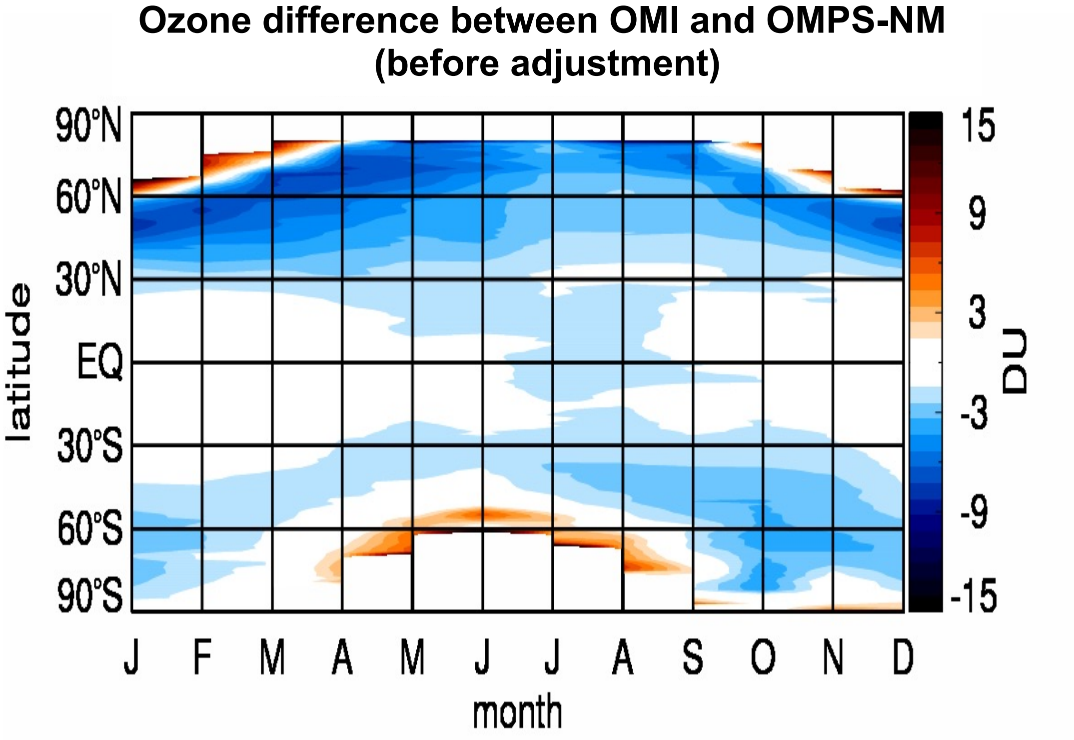
Homogenization to ensure continuity in ozone profiles (MLS and OMPS-LP)

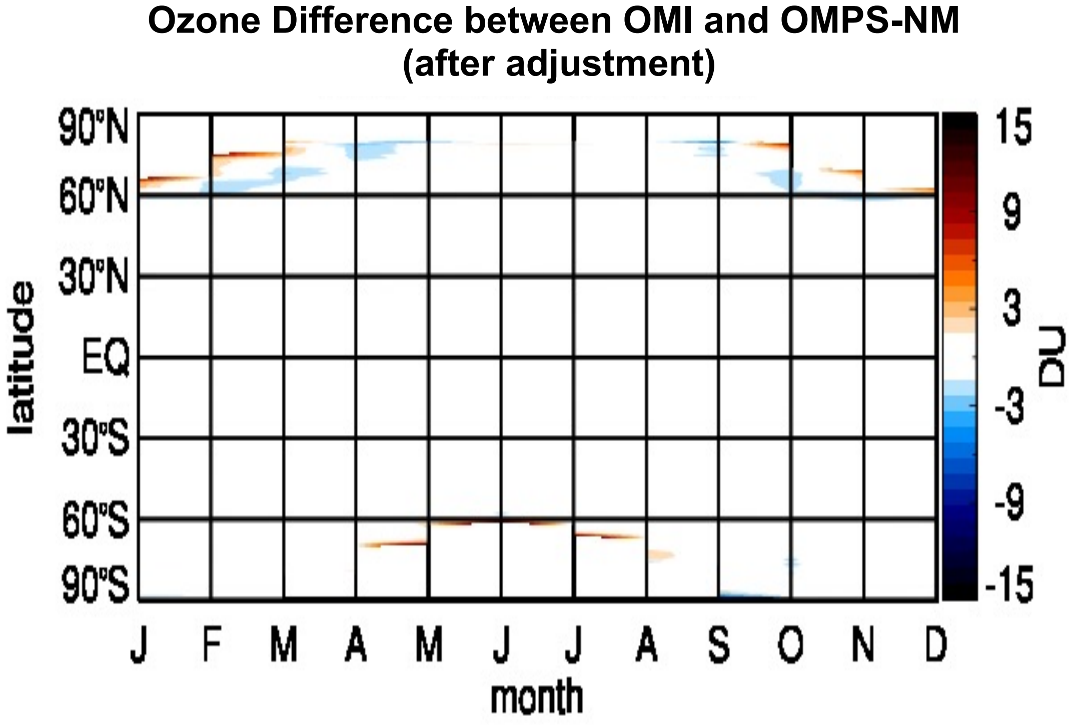


- Introducing OMPS-LP would lead to a discontinuity.
- This discontinuity is eliminated by a latitude, pressure and month dependent adjustment to the OMPS-LP data.
- **GEOS-R21C will assimilate the adjusted OMPS-LP data.**

Wargan et al., 2020

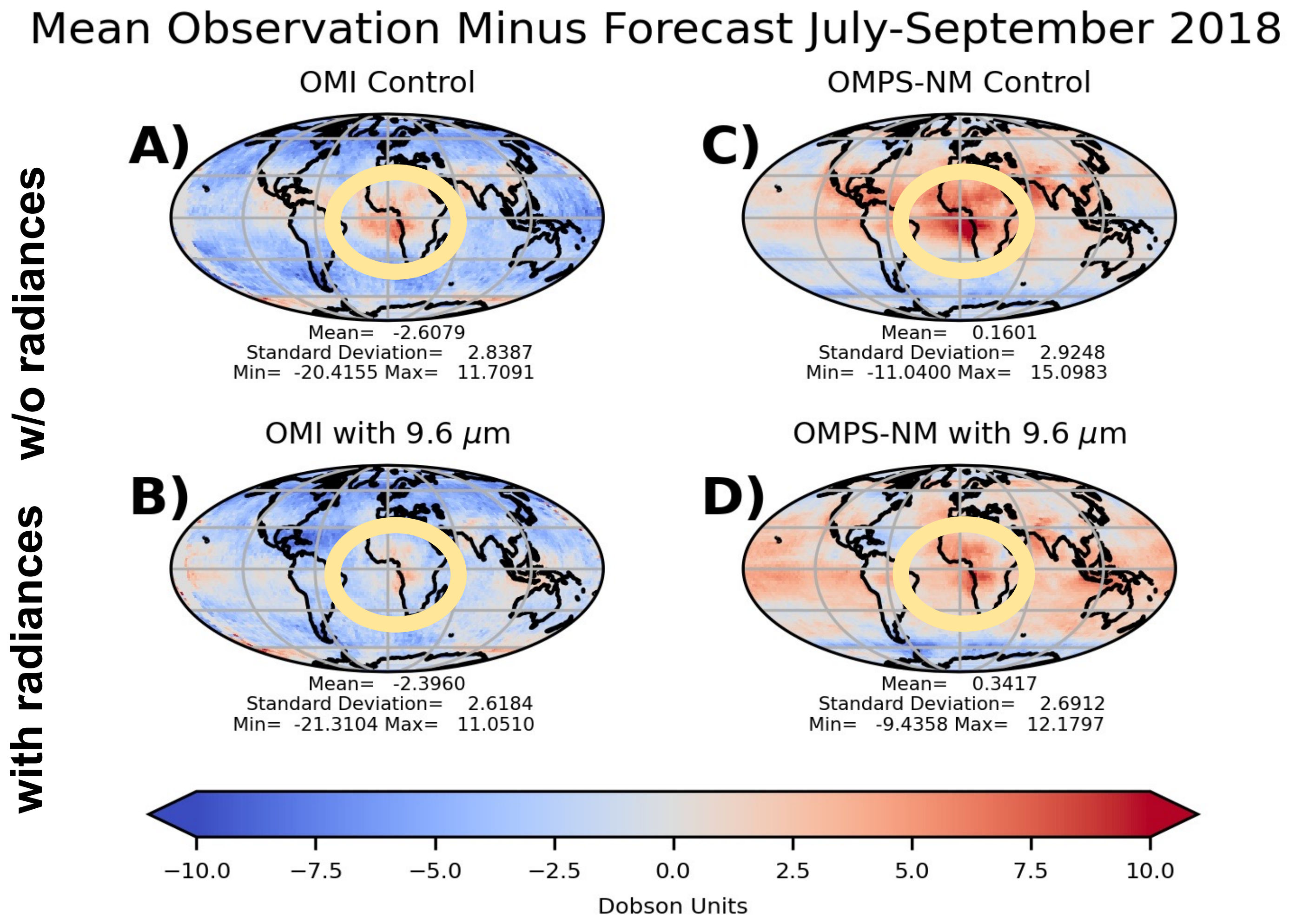
Homogenization to ensure continuity in total ozone (OMI and OMPS-NM)





Relative bias was subtracted from OMI data. Adjustment based on 2013-2019 monthly climatology
GEOS-R21C will assimilate adjusted OMI data

Ozone-sensitive radiances (9.6µm)



Assimilation of ozone-sensitive channels at 9.6µm from AIRS, AISI and CriS resulted in a significant reduction of total ozone departures from observations in the tropical Atlantic.

These radiances are assimilated over ocean only for now.

Karpowicz et al., 2021, submitted

All-sky Assimilation in GEOS-R21C

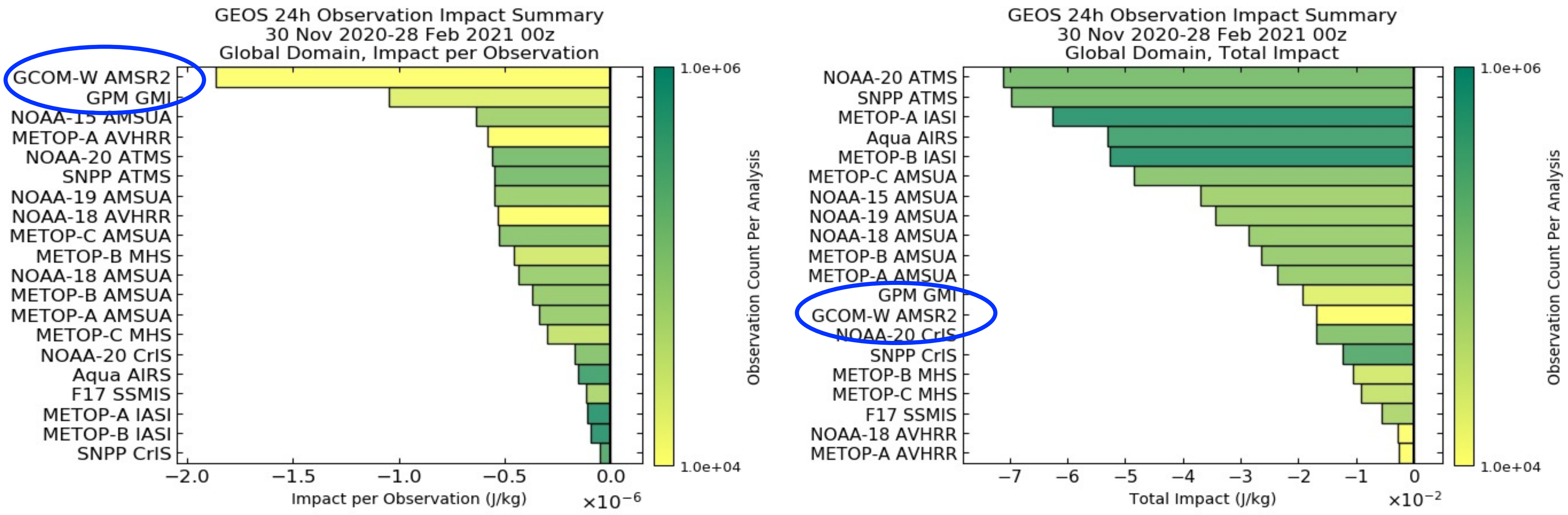
Goal: Assimilate SSM/I, TMI, AMSRE, AMSR2, GMI, MHS and ATMS in all-sky conditions. All-sky microwave radiance data assimilation framework has been implemented in GEOS (Kim et al, MWR, 2020). GMI, AMSR-2, MHS and soon ATMS are being assimilated in GEOS FP and have positive impact.

All-sky DA framework

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.

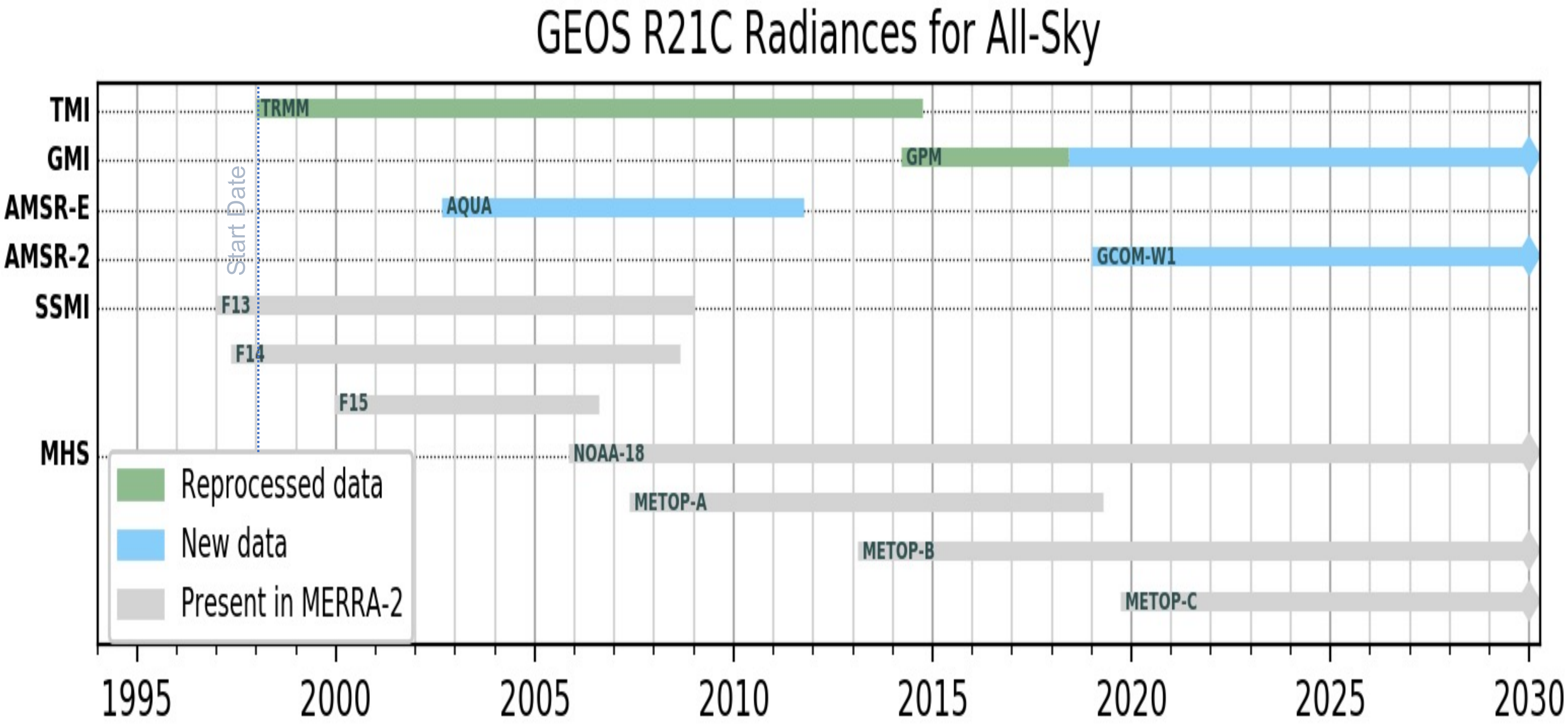
Jianjun Jin, Min-Jeong Kim, Will McCarty, and Amal El Akkraoui

Impacts of assimilating GMI and AMSR2 All-sky radiances in GEOS-5



AMSR2 and GMI have largest impact per observations among satellite radiance data but have less observations.

All-sky radiances in GEOS-R21C

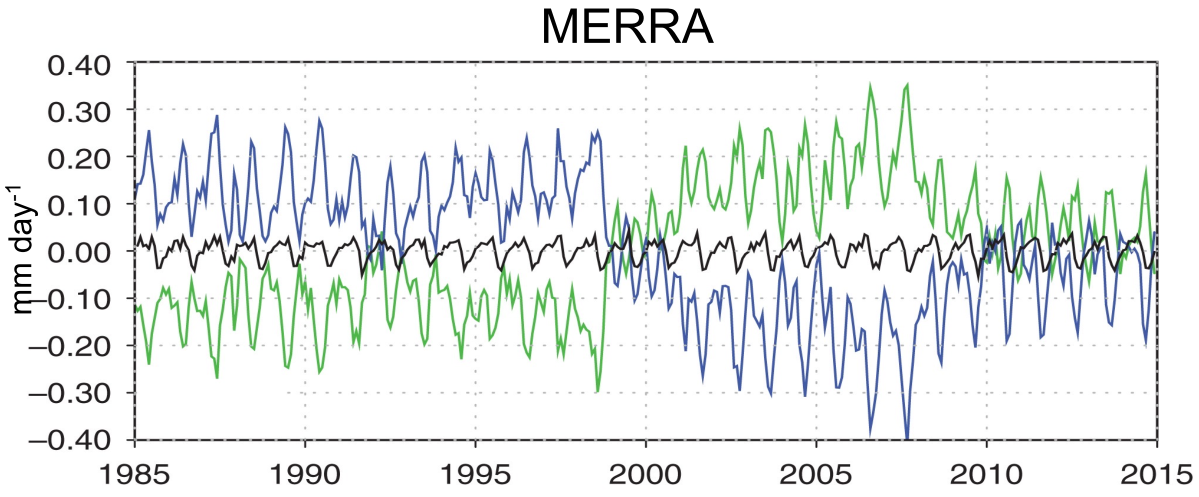


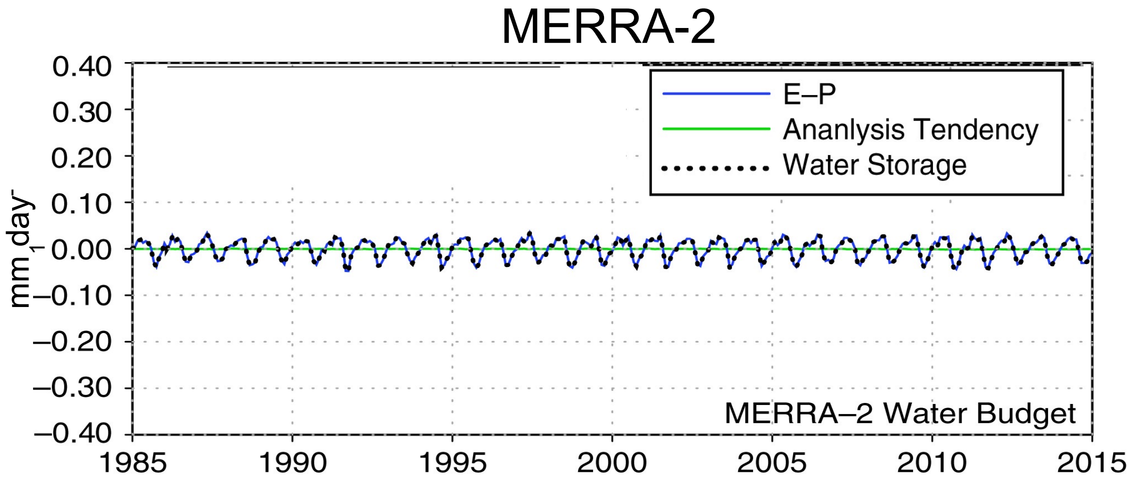
(+ All-Sky ATMS)

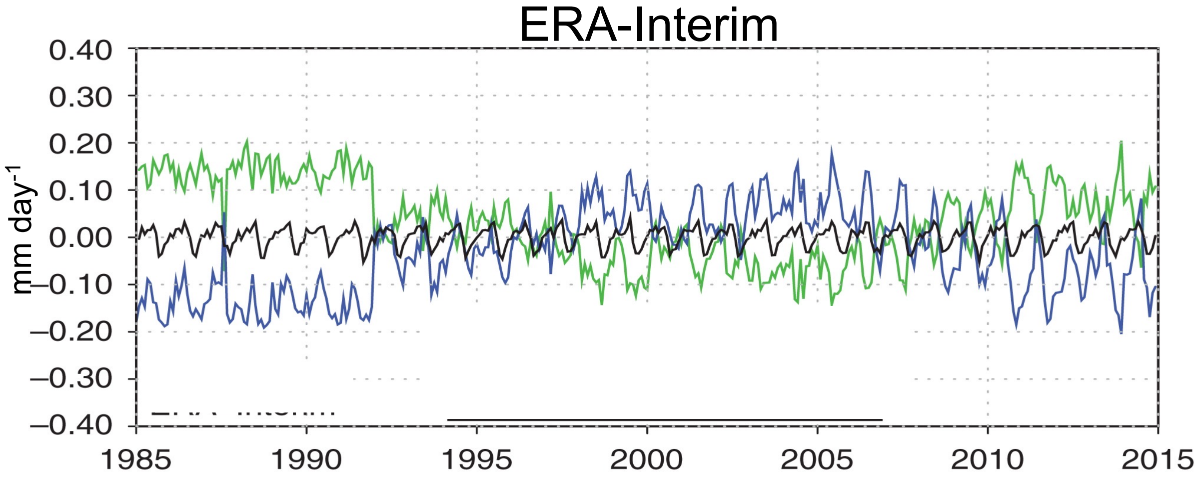
A Re-Examination of Global Constraints in MERRA-2

Larry Takacs, Amal El Akkraoui and Ron Gelaro

Dry Mass Conservation







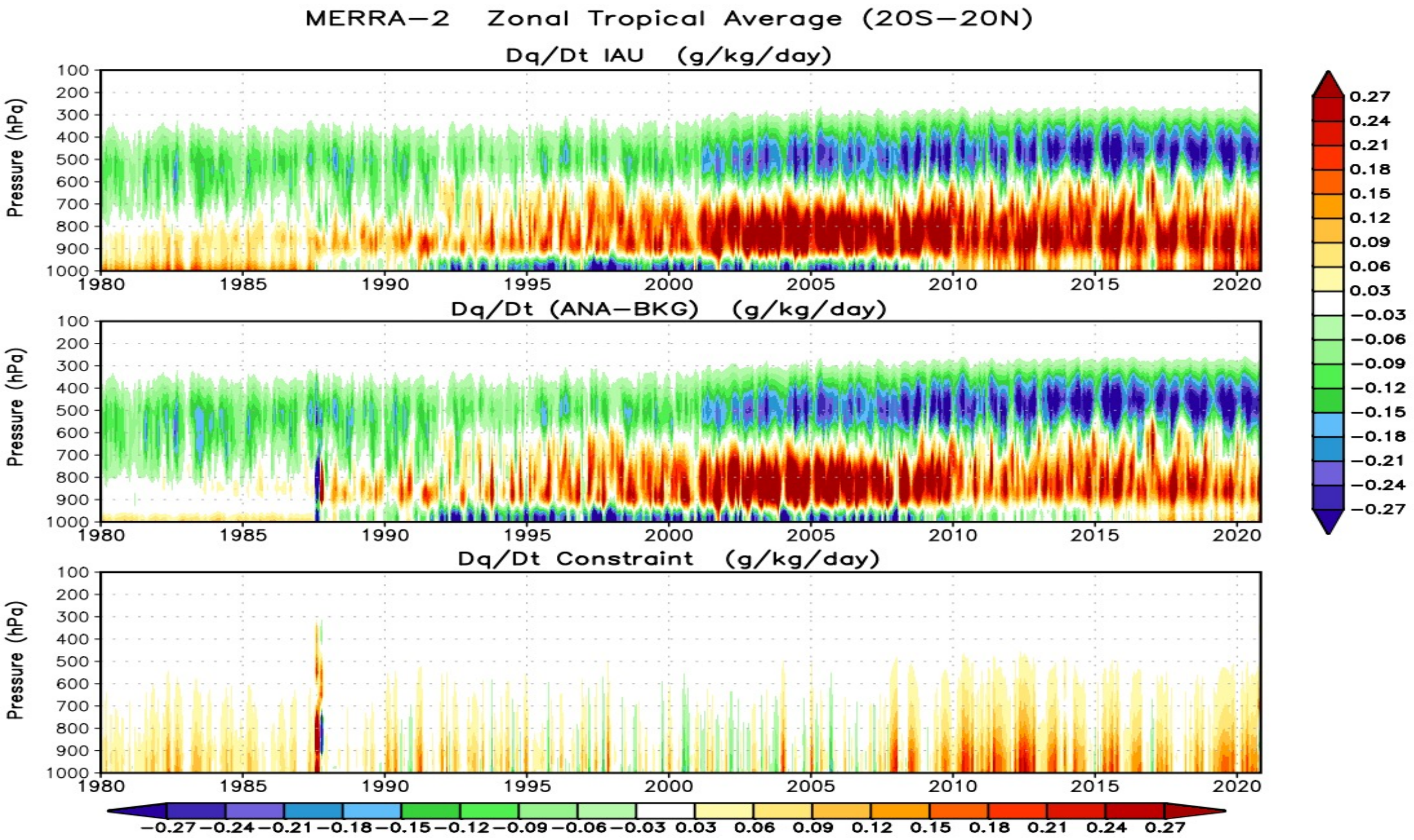
- Constraint applied in MERRA-2 conserves dry-mass and provides E-P balance;
- Reduces spurious jumps in precipitation due to observing system changes.

Globally Integrated Constraint adjustment

Analysis Increment

"Unconstrained" Analysis Increment

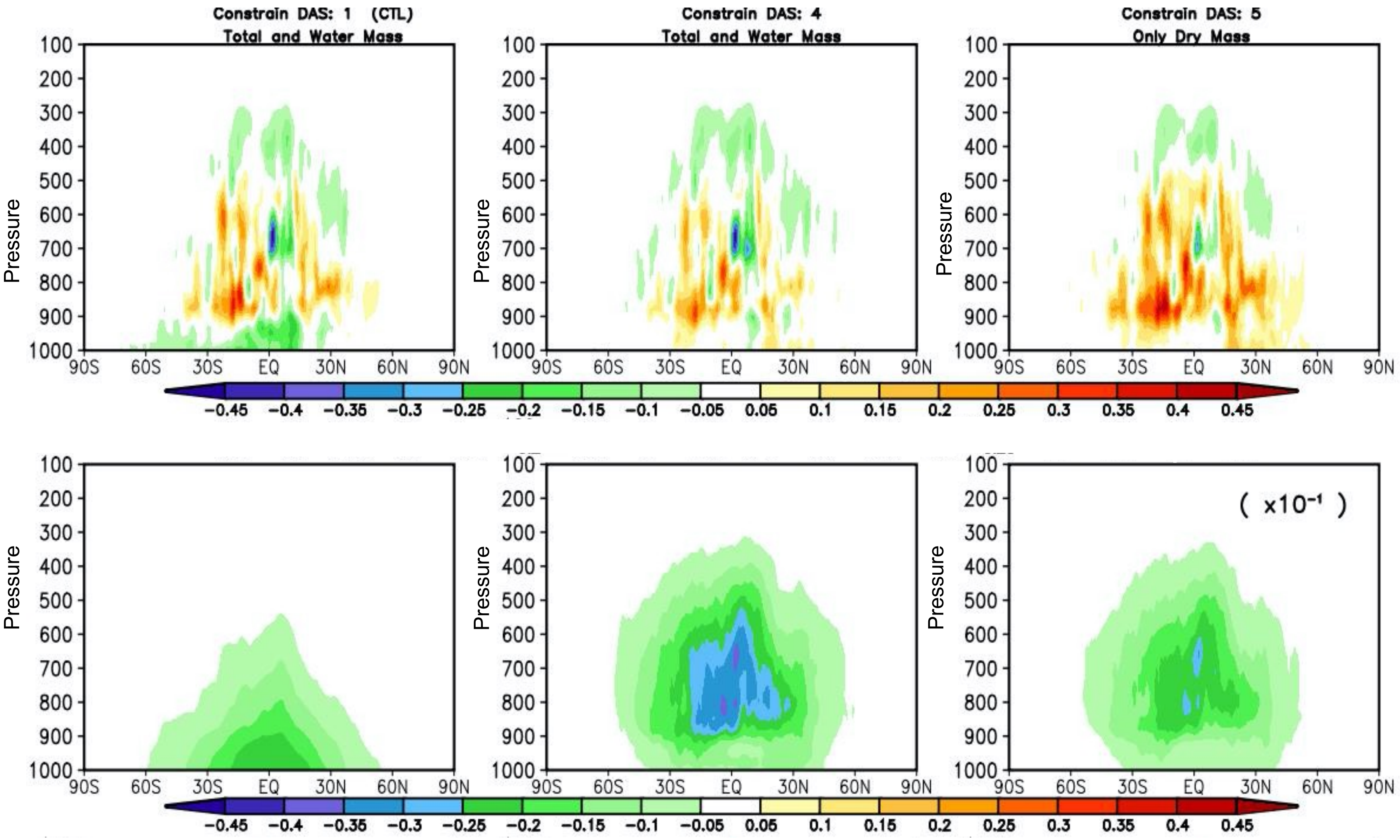
Constraint adjustment



Dry Mass Constraint Reformulation Attempts

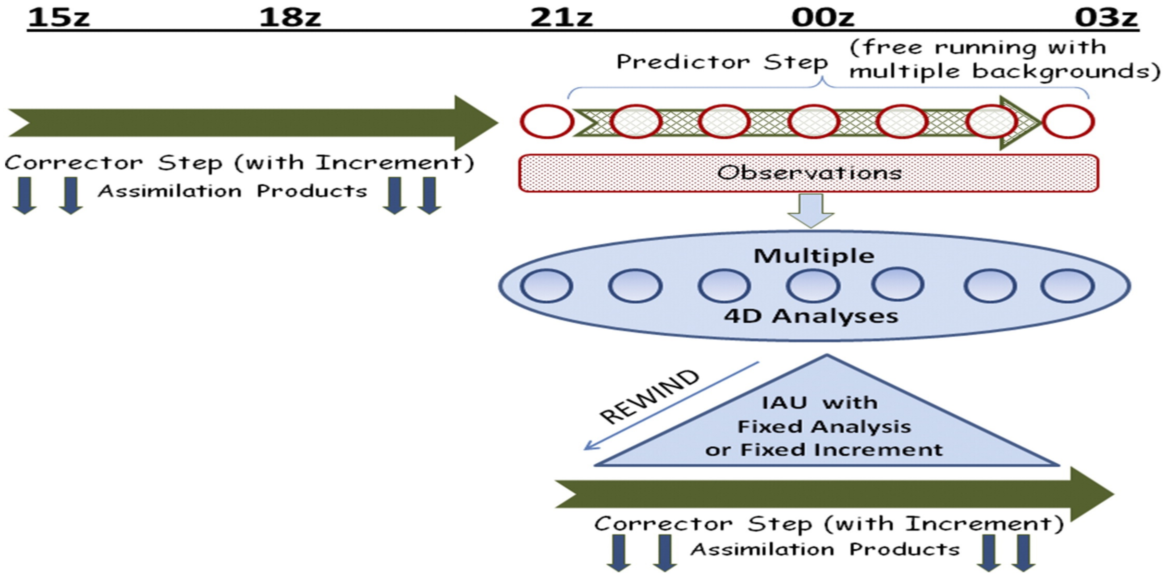
Final increment Specific humidity (g/kg/day)

Effect of the constraint



Incremental-Analysis Update

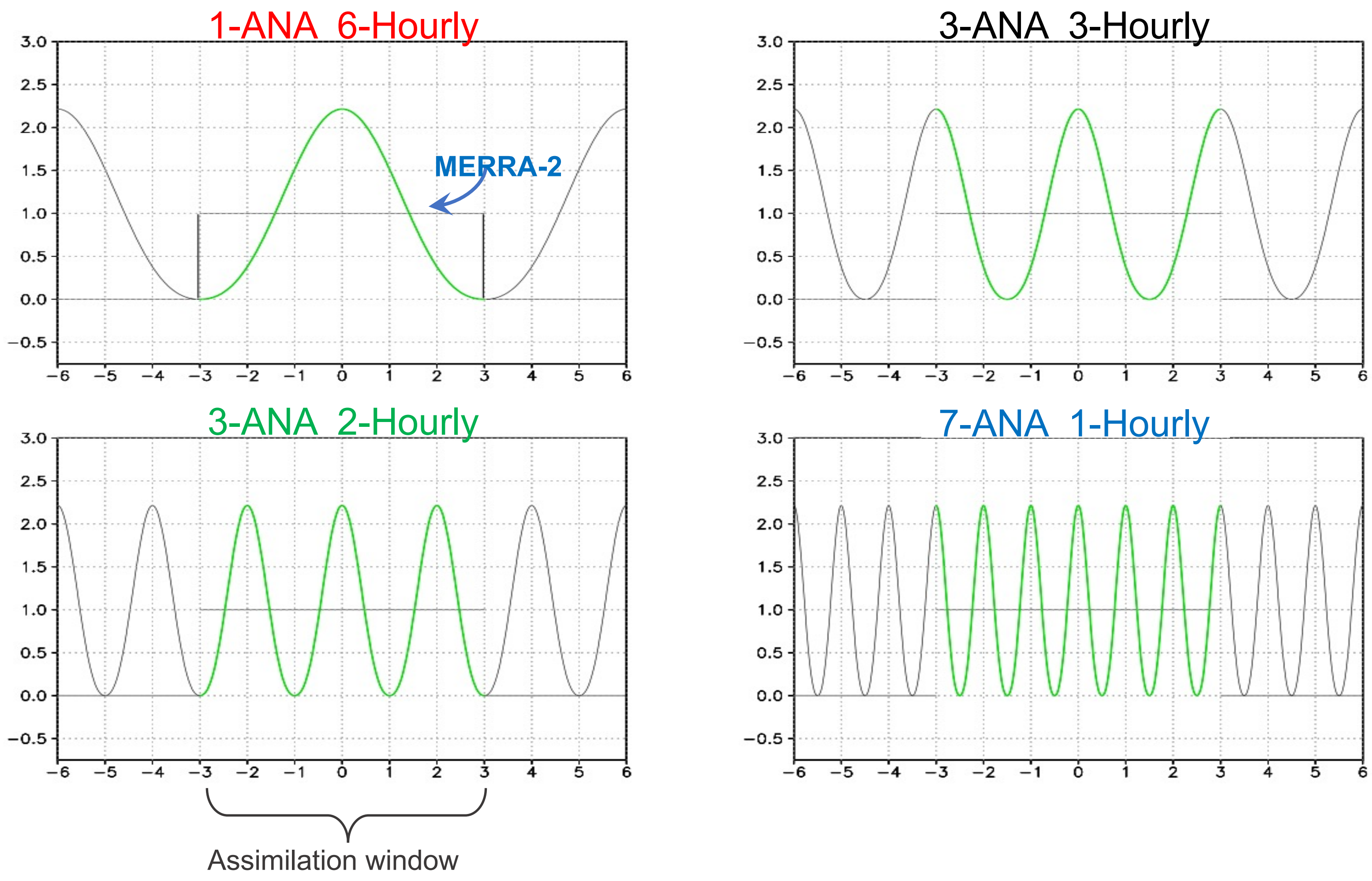
Assimilation Cycle with 4D Incremental Analysis Update



Larry Takacs, Ricardo Todling and Amal El Akkraoui

Methods for Incorporating 4D Analysis Increments

- Various methods may be used to incorporate the Multiple Analyses produced by the 4D-IAU procedure.

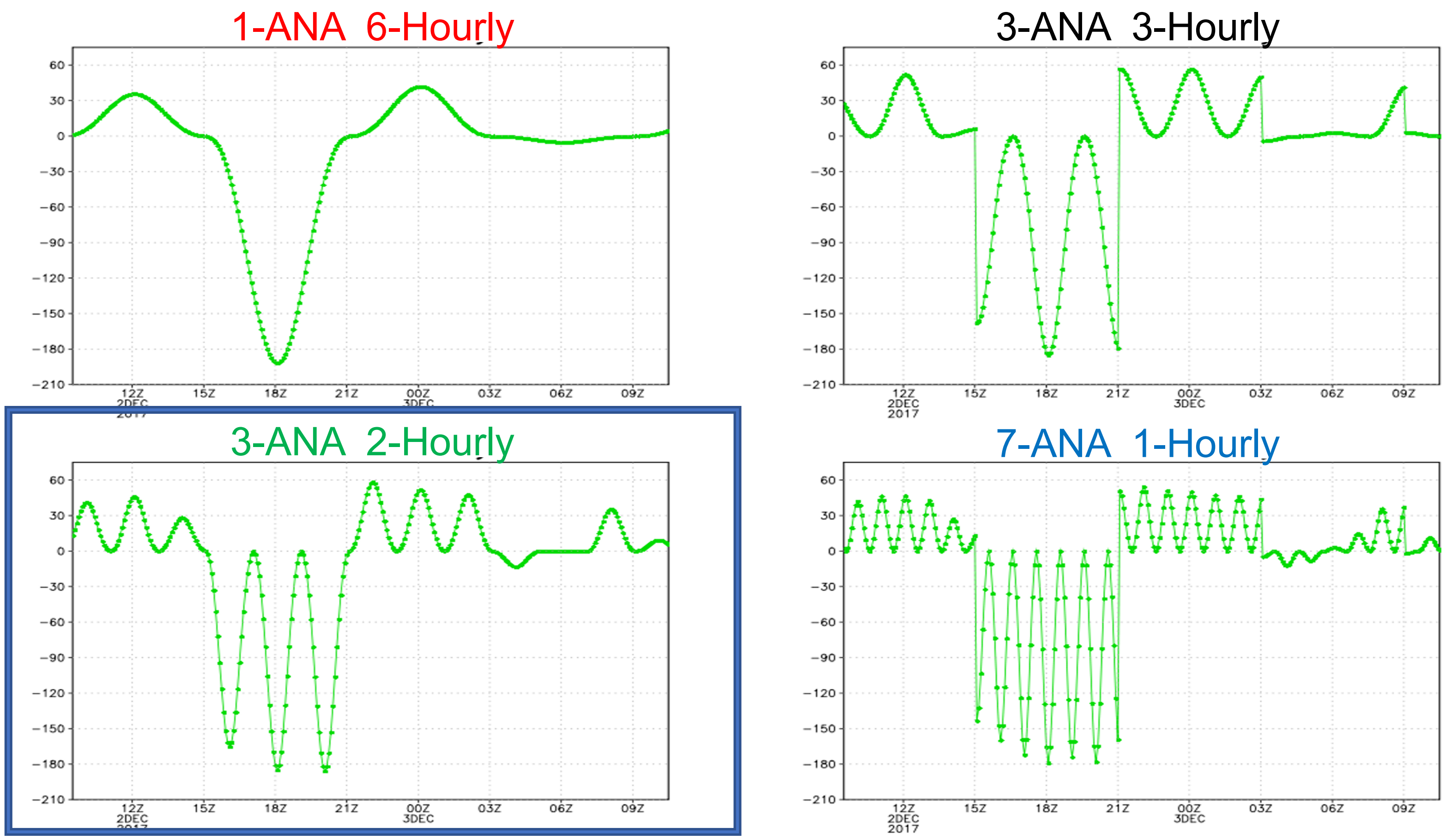


Methods for Incorporating 4D Analysis Increments

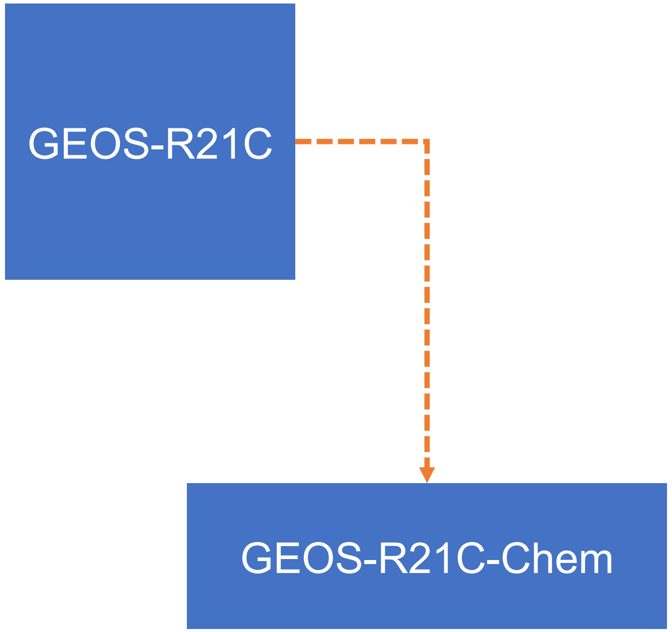
- Care must be taken to avoid the inherent instability in the IAU process and possible discontinuities between the assimilation windows.

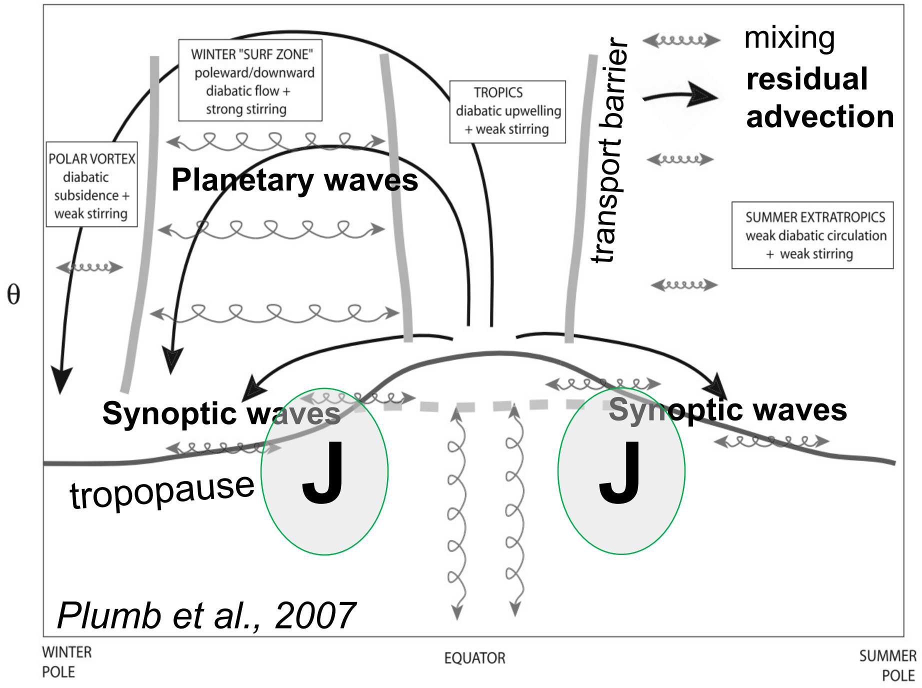
- GEOS-R21C, like current GEOS-FP, will use the three analysis increments option at 2-hourly intervals in the 4D-IAU.

Surface Pressure Tendency from Analysis (hPa/day) (Lat: 47.5N, Lon: 177W)



Model Transport





Clara Orbe, Larry Takacs, Kris Wargan, Andrea Molod and Amal El Akkraoui

Objective: Evaluation of the dynamical/convective/diffusive transport characteristics of the candidate systems for GEOS-R21C. The transport evaluation is relevant directly for constituents, but also for confidence in the process level robustness of the representation of meteorological state fields.

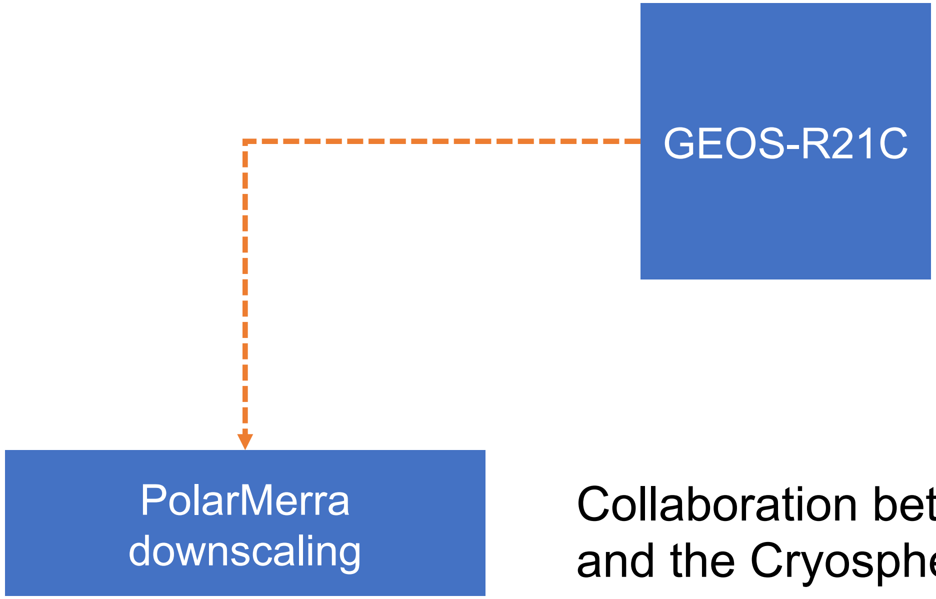
- **Short range, tropospheric transport of constituents**. For example, how long does it take for a surface-emitted constituent (sea salt, dust, moisture, heat) to be transported by advection, convection, diffusion to the top of the boundary layer, or out of the boundary layer to the free troposphere?
- **Long range, long time scale transport, involving the stratospheric circulation.** For example, what is the time scale of cross-hemispheric transport, what is the stratospheric "mean age"?
- **Links between the two timescales**, such as upper tropospheric upwelling.

What we know so far:

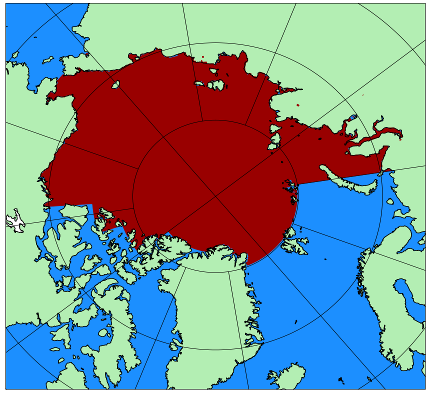
- The Brewer-Dobson Circulation (BDC) has been getting stronger in more recent model versions (e.g., stratospheric age-of-air (AOA), chemical constituents (CH4, N2O)).
- A faster BDC appears to be related to changes in wave convergence in the lower stratosphere associated with changes in (zonal wind) critical lines.
- Replay can do a good job of reproducing DAS lower stratospheric transport characteristics. But the fidelity of transport in replay simulations ultimately rests on the fidelity of the DAS.

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)

Cryospheric processes



Collaboration between GMAO and the Cryospheric lab.



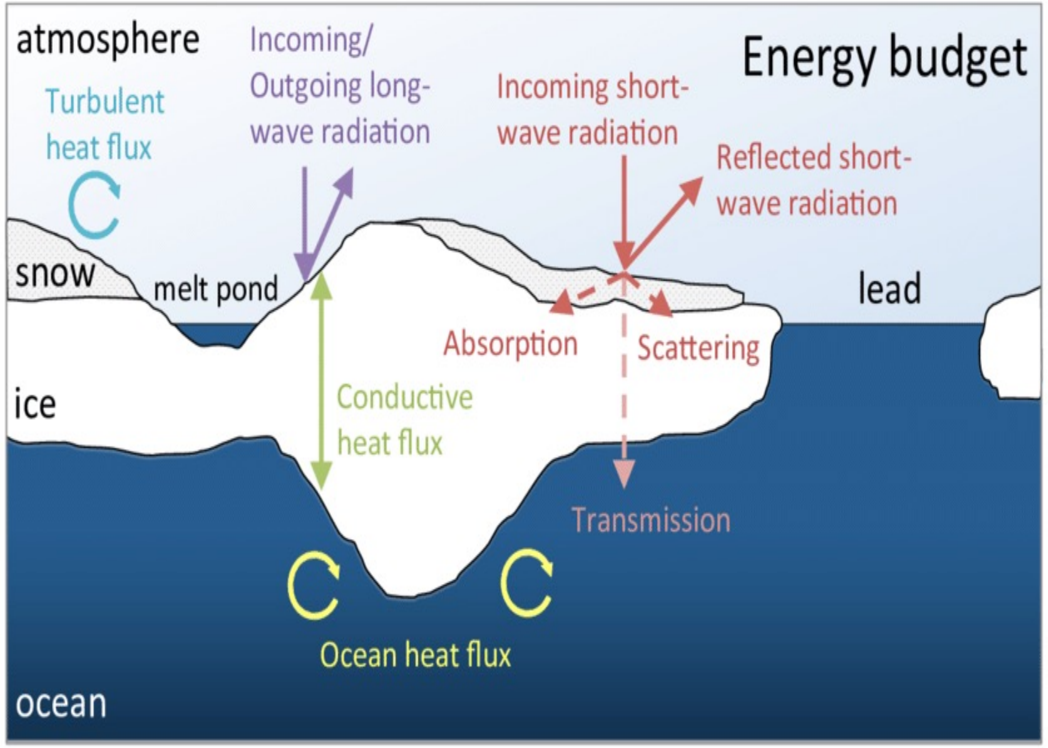
Richard Cullather, Bin Zhao, Amal El Akkraoui, Chelsea Parker, Lauren Andrews, Steven Pawson, and the Cryospheric lab team

Skin Temperature over sea ice

- Over sea ice, the model skin temperature is a product of the surface energy budget.

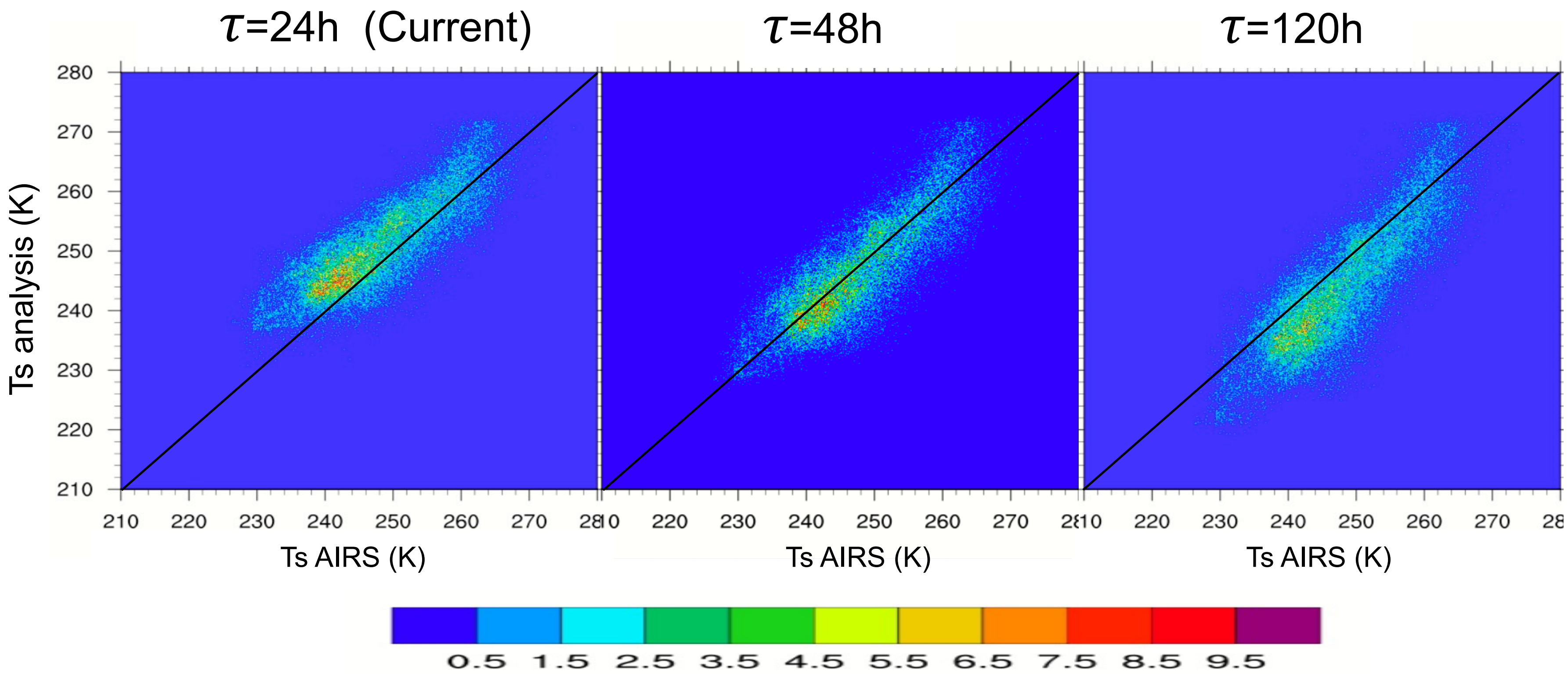
- Surface energy budget composed of LW, SW radiation, turbulent sfc/atm fluxes, *and the ocean heat flux conducted through the sea ice*.

The ocean heat flux is represented by a parameterization of the Newtonian relaxation of skin temperature to 0°C on a **tunable timescale.**



Retuning of the Newtonian relaxation timescale

Skin Temperature difference between analysis and AIRS for NH locations where the fraction of sea ice exceeds 0.5.



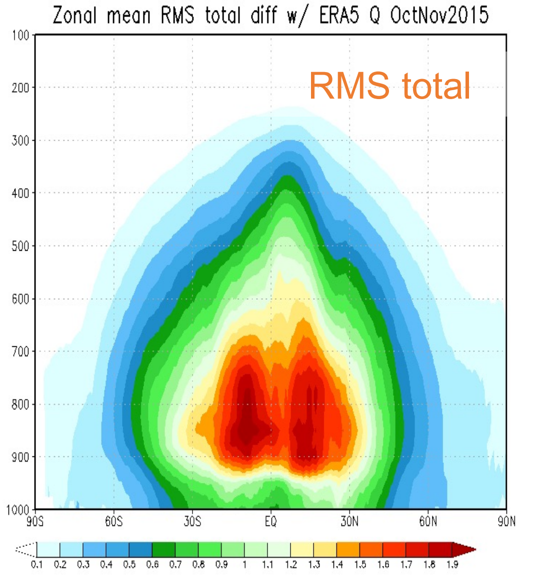
Prototype-R21C

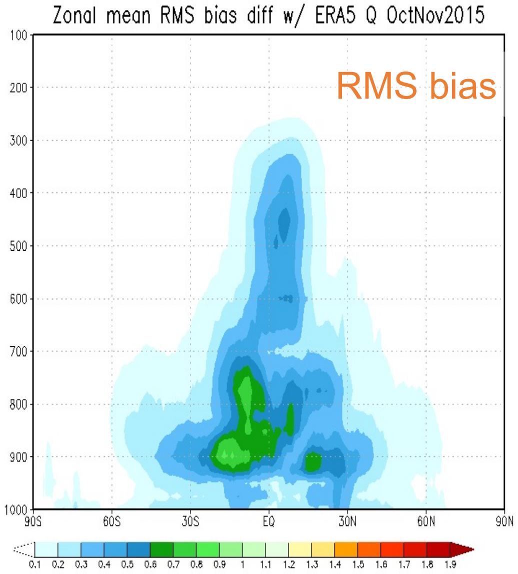
($V_{5.25}$)

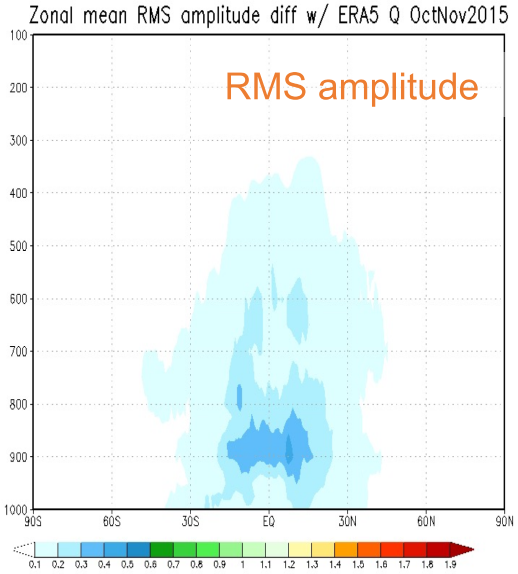
Reanalysis Team

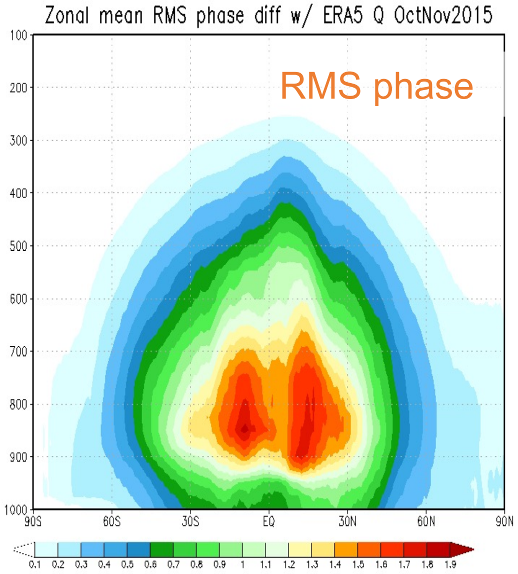
RMS Difference with ERA5 – Specific Humidity

MERRA-2









$$\mathrm{MSE_{TOT}} = \mathrm{MSE_{BIAS}} + \mathrm{MSEAMPL} + \mathrm{MSEPHAZ}$$

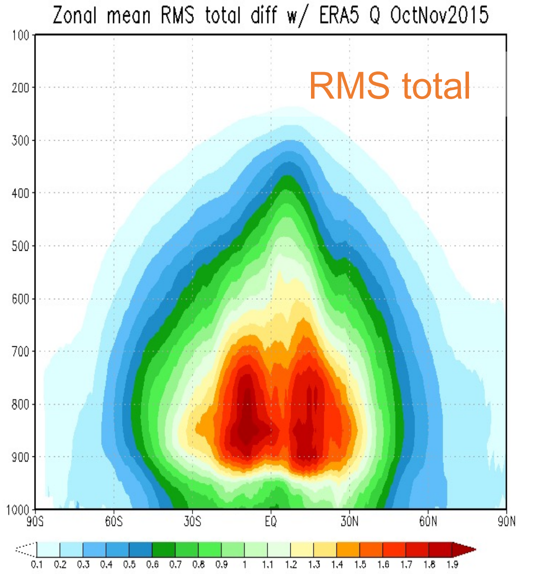
$$\mathrm{MSE_{BIAS}} = (\bar{X} - \bar{Y})^2$$

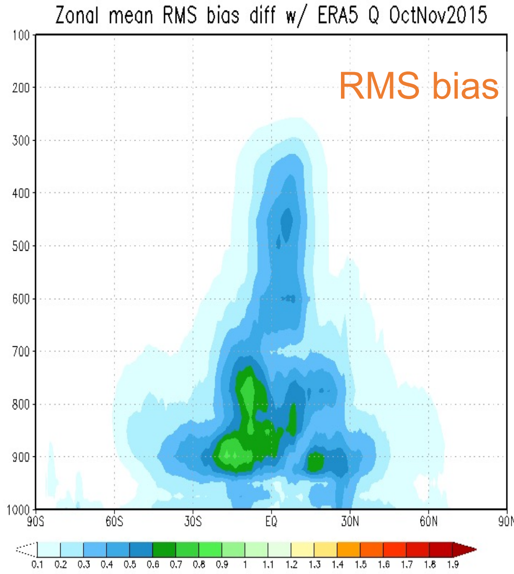
$$\mathrm{MSE_{AMPL}} = \left(\sigma(X) - \sigma(Y)\right)^2$$

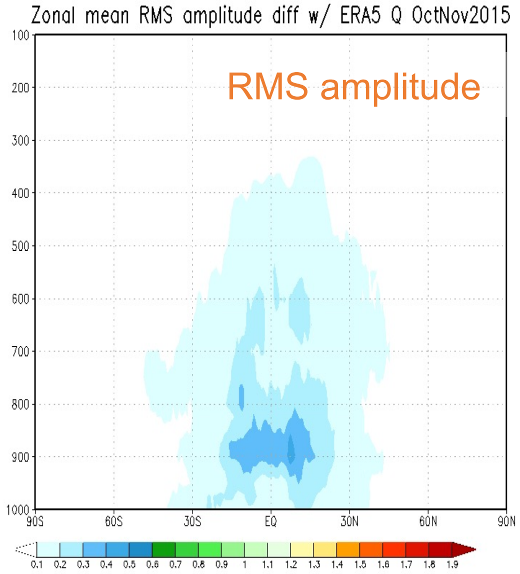
$$\mathrm{MSE_{PHAZ}} = 2\,(1 - \rho)\,\sigma(X)\sigma(Y)$$

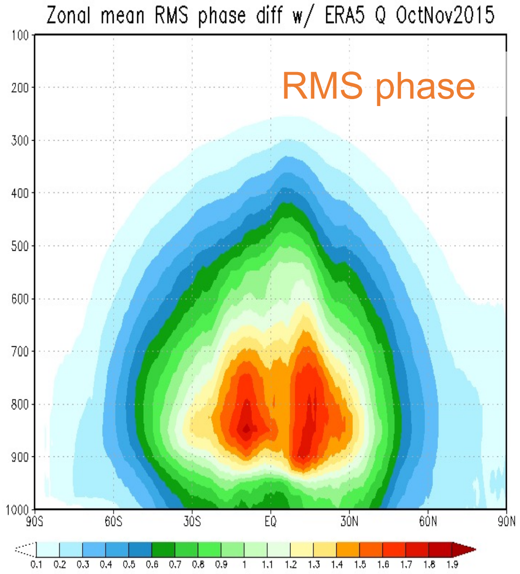
RMS Difference with ERA5 – Specific Humidity

MERRA-2

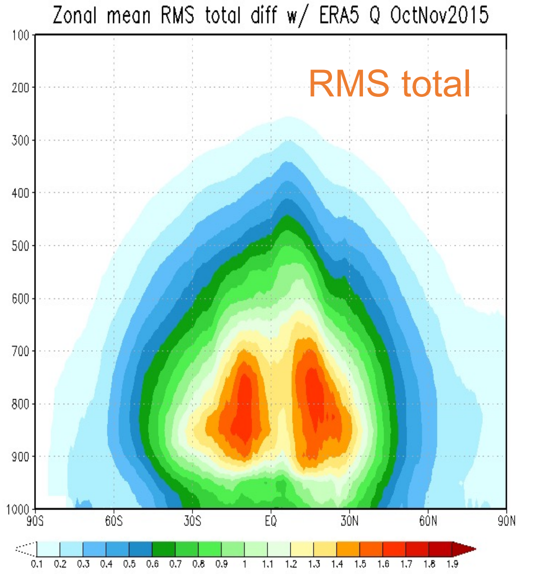


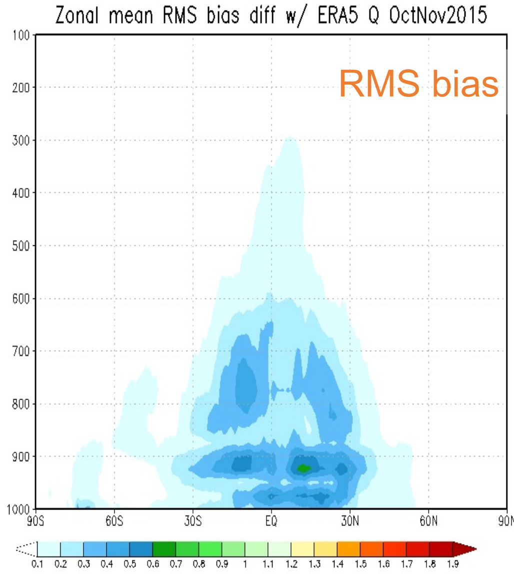


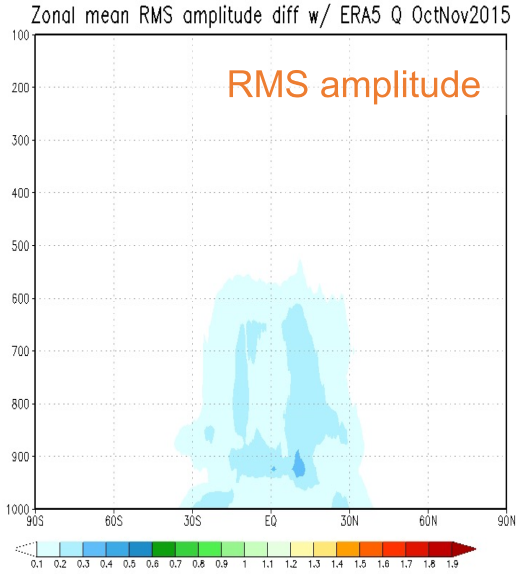


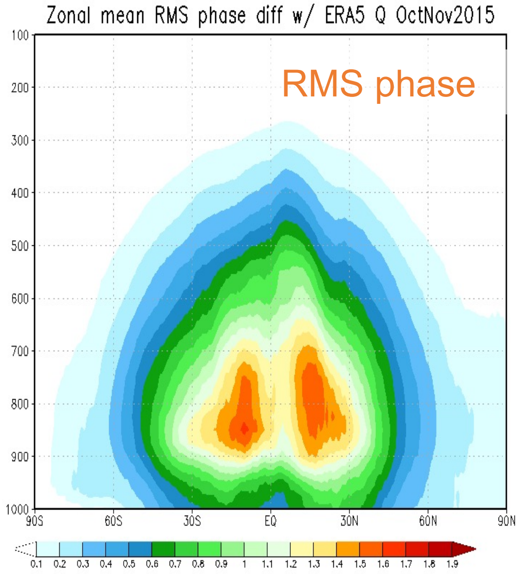


Prototype-R21C

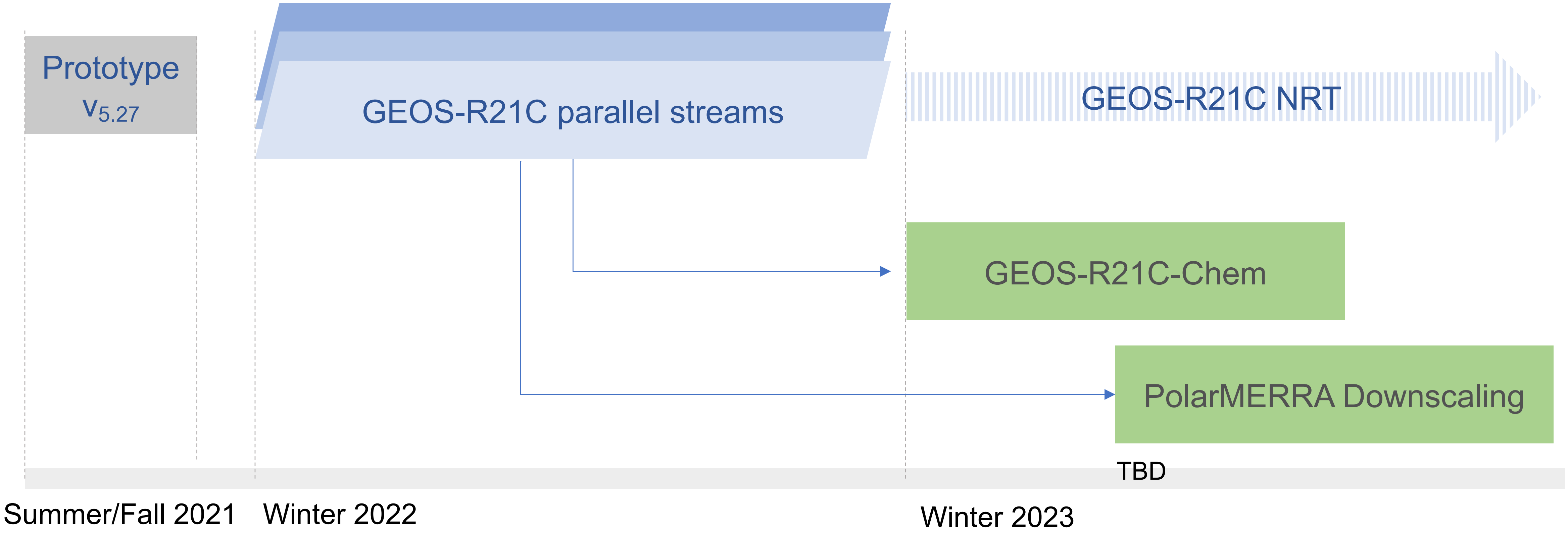








Tentative Production Plan



Summary

- The GMAO is preparing to produce a new 25+ year atmospheric reanalysis for the early 21st Century. GEOS-R21C will bridge the gap from NASA's EOS observations to the post-EOS observations and build on the advances in modeling and data assimilation introduced into GEOS-FP since MERRA-2.
- GEOS-R21C is planned as a stepping-stone towards the decadal goal of producing MERRA-3, an integrated Earth System reanalysis, coupling atmosphere, ocean, land and ice.
- Preliminary test results with a prototype-R21C are encouraging.
- On-going work: reformulation of dry-mass constraint, further assessment of model transport mechanisms, retuning of parametrization for skin temperature over sea ice, use of IMERG product for the observation-corrected model precipitations, production stream strategy.