How Using NASA’s Observations Affects the Balance Among Spatial Resolution, Ensemble Size, and Physical Complexity in the GEOS S2S System

Steven Pawson, Andrea Molod, Eric Hackert

Global Modeling and Assimilation Office, NASA GSFC

Objective: to give an overview of how we continually develop the increasingly complex GEOS Earth System Modeling and Analysis capability to support and enhance the use of NASA’s Earth Observations in analysis and prediction

Overview of Presentation

- GMAO’s Mission: Observation-Based Modeling
- GEOS-S2S Version 2: A description in the context of development pathway
- Some impacts NASA observations that constrain the physical state
- Some impacts of NASA observations that need a more complex model
- A teaser …
- Summary and discussion points

All of the results shown are the products of a large team of researchers, including model developers, computer scientists, and experts in observing systems and data assimilation

Major Activities in GMAO: from Research to Products

Weather Analysis and Prediction	Seasonal-to-Decadal Analysis and Prediction	Reanalysis
Global Multiscale Modeling	Observing System Science	

- These (non-orthogonal) themes span GMAO's main activities
- Guiding principle: NASA's Earth Observations (use, support, planning)
- All themes include multiple elements of the Earth System

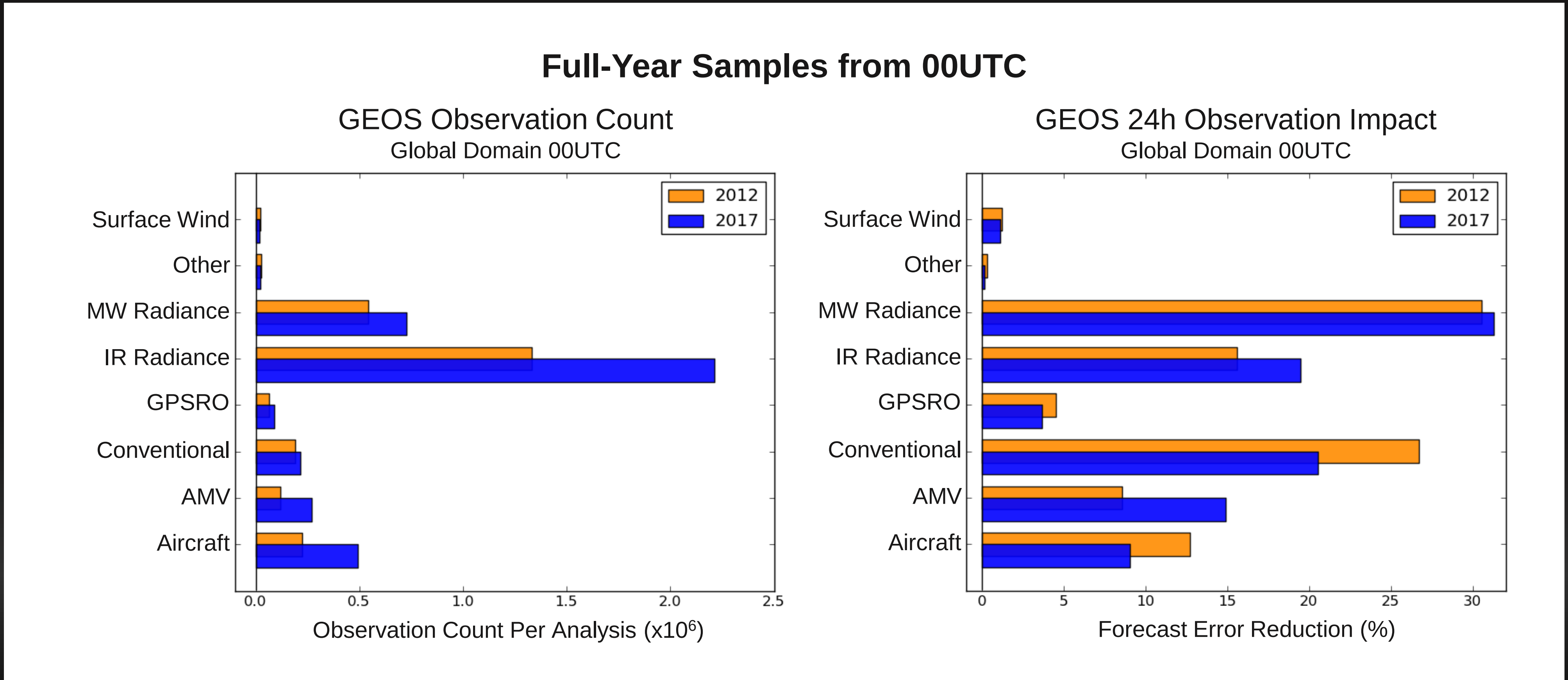
GMAO's Mission: Observation-Based Modeling

Overall intent: to demonstrate added value of NASA's unique observations for weather analysis and prediction, reanalysis, and subseasonal-to-seasonal prediction.

Examples:

1. All-Sky radiances from NASA/JAXA Global Precipitation Mission on weather analysis and prediction
2. Impacts of ozone from NASA's EOS-Aura mission in MERRA-2 reanalysis – ability to detect trends in the lower stratosphere
3. Use of aerosol observations from NASA's MODIS instruments (on EOS-Aqua and Terra) plus AVHRR in MERRA-2

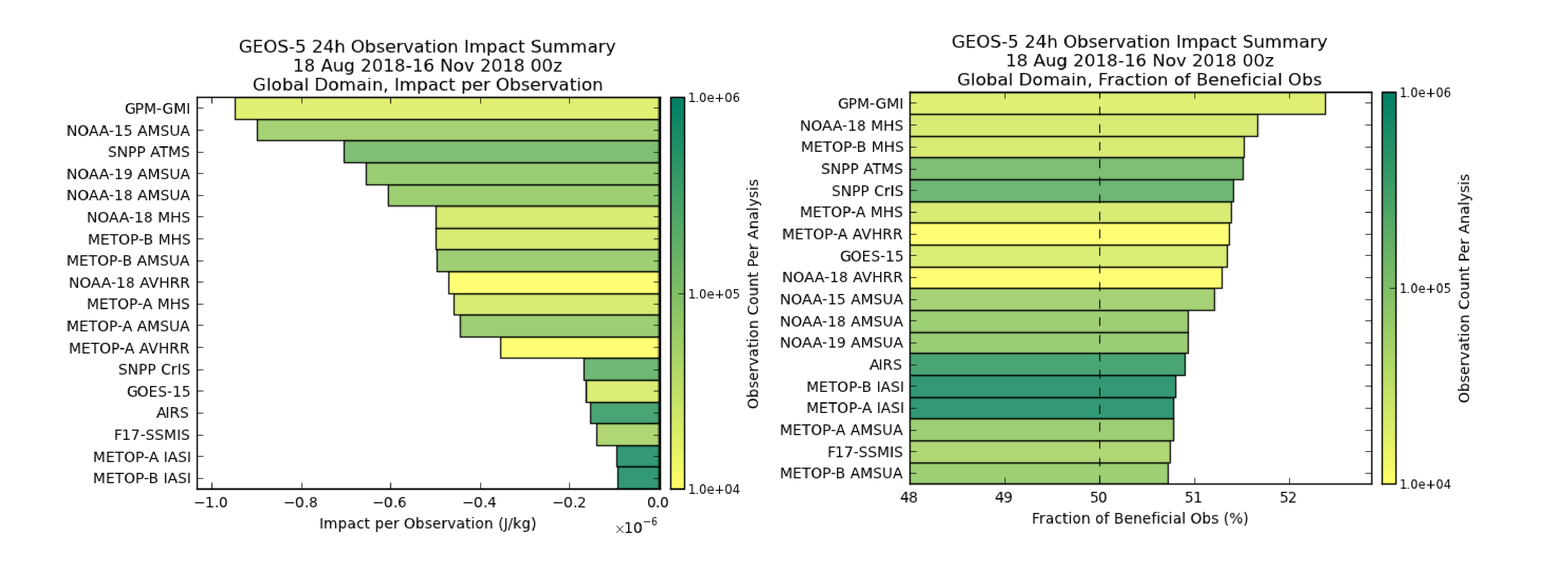
FSOI Results: Changes from 2012 to 2017



2012: GEOS "weather system" used a 3D-Var approach: c360L72 model; 0.5º analysis
2017: Transittion to hybrid 4D-EnVar was complete: c720L72 model; 0.5º analysis; c180L72 32-member ensemble
70% of the total observation impact in 2017 by this measure is from satellites

Gelaro et al.

FSOI including GPM/GMI All-Sky Radiances



- All-sky radiances from the Global Precipitation Mission Microwave Imager (GMI) demonstrate the value of novel information in the GEOS system
- GMI data have the highest impact per observation of all the radiance observation types despite their relatively low number of observations

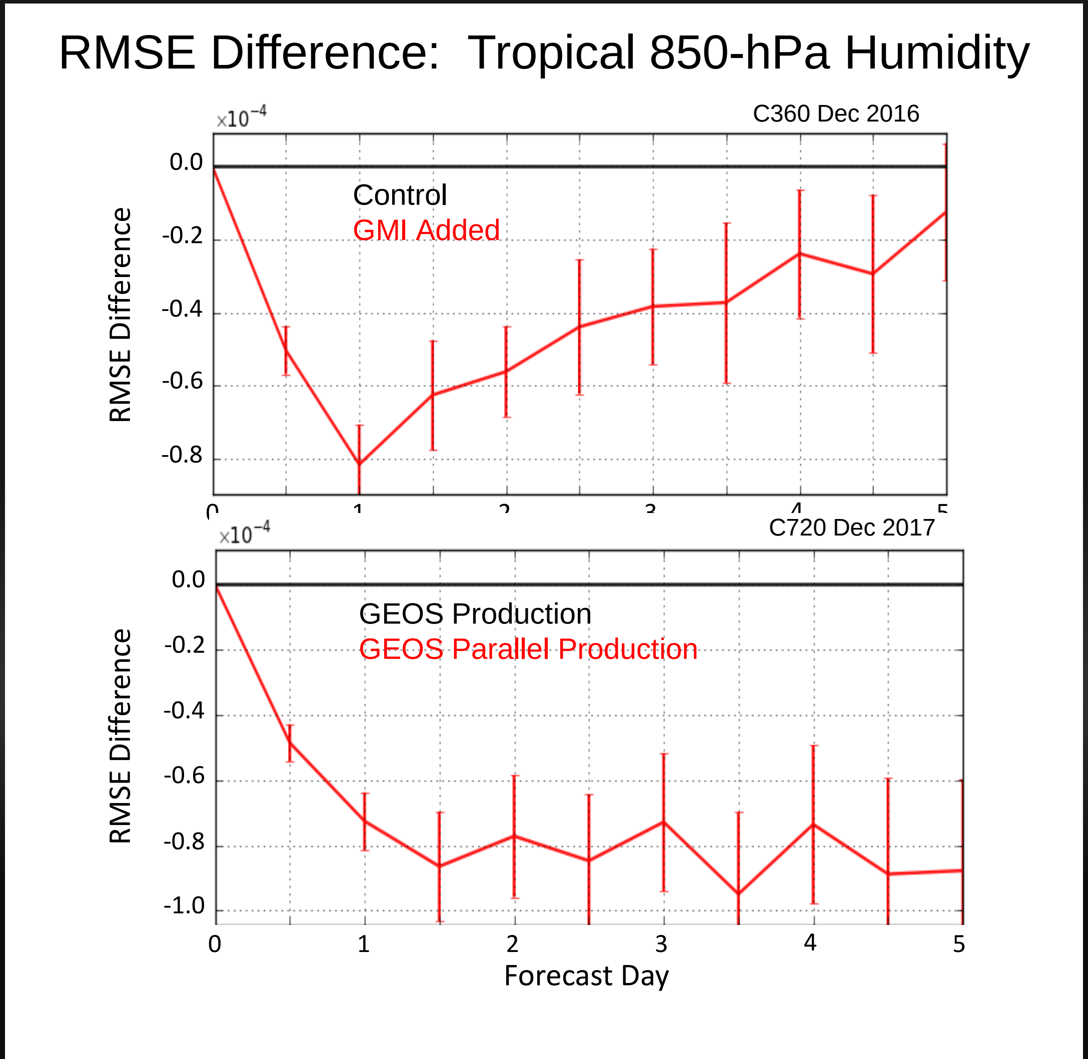
Impact of GMI All-Sky Radiances on Forecast Skill

Data impacts (top panel):

- Adding GMI all-sky radiances improves the initial state and leads to reduced forecast error, especially in the Tropics.
- Largest impact is at day-one, with diminishing impact thereafter.

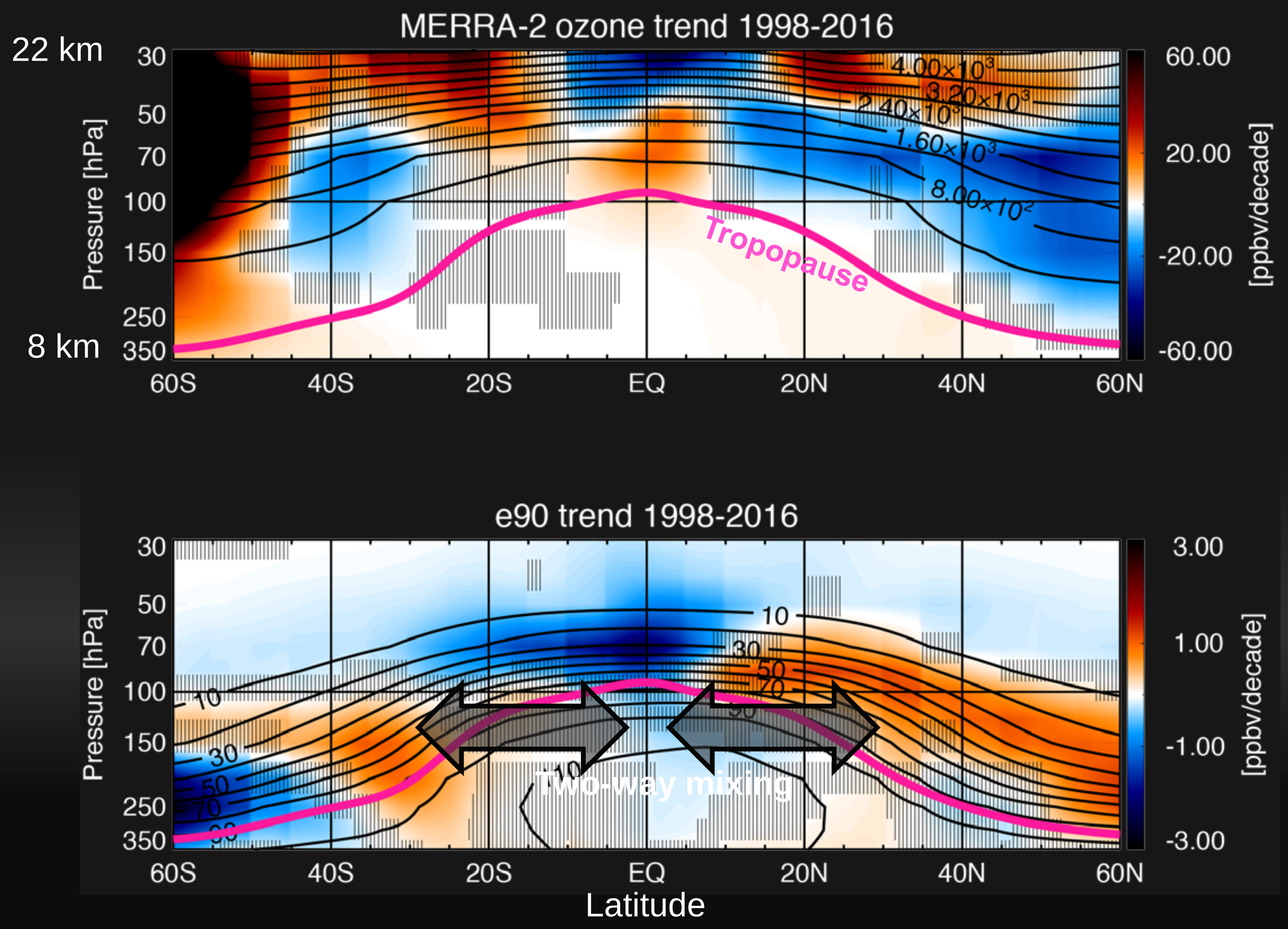
Data and model impacts (bottom panel):

- Combining GMI assimilation with improved model physics extends the beneficial impacts throughout the five-day forecast period.
- This was implemented in GEOS FP system in late 2017.



Kim et al.

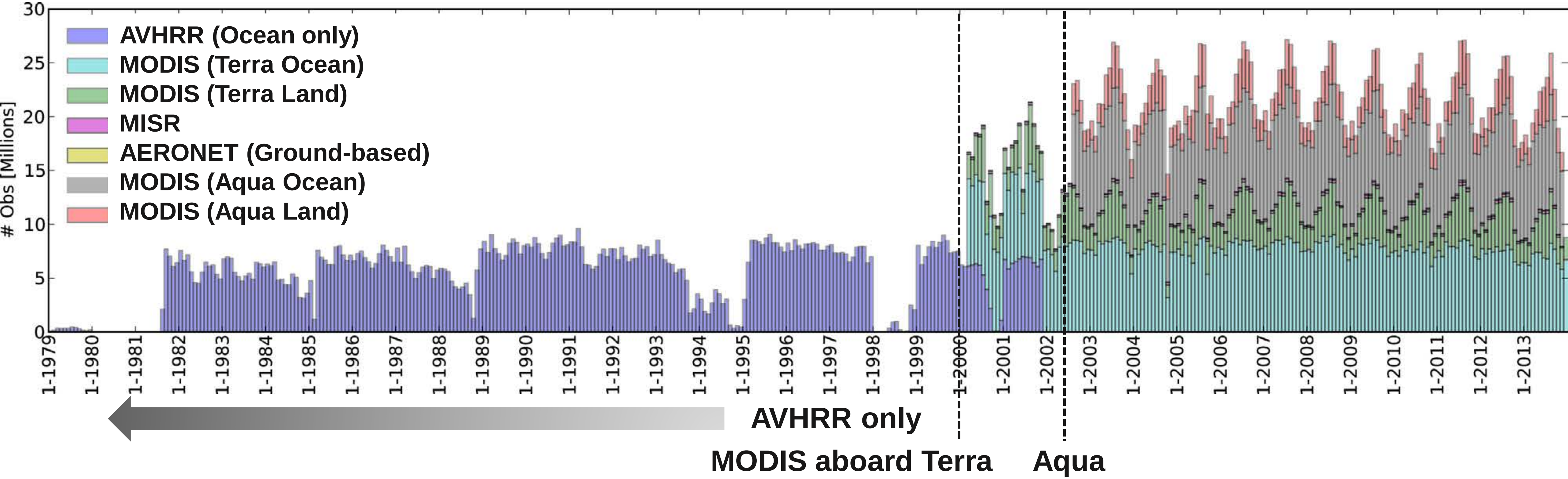
Pioneering science with MERRA-2: ozone trends



- Atmospheric ozone concentrations are increasing after 1998 because of the Montreal Protocol.
- MERRA-2 ozone just above the tropopause has continued to decline (blue shading in top panel).
- Idealized tracer experiment reveals enhanced tropical-extratropical mixing between 1998 and 2016 (bottom panel).
- Implies that transport changes between 1998 and 2016 caused ozone in the extratropical lower stratosphere to decline. Either long-term variations or a systematic change in mixing are to blame.

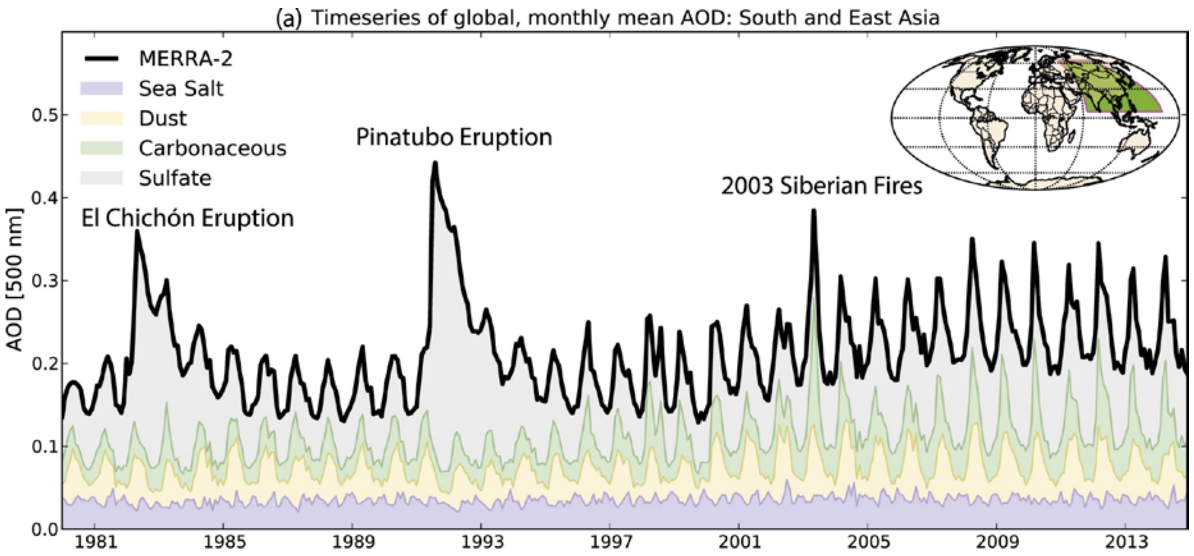
Wargan et al., 2018, *GRL*

Aerosol Assimilation in MERRA-2



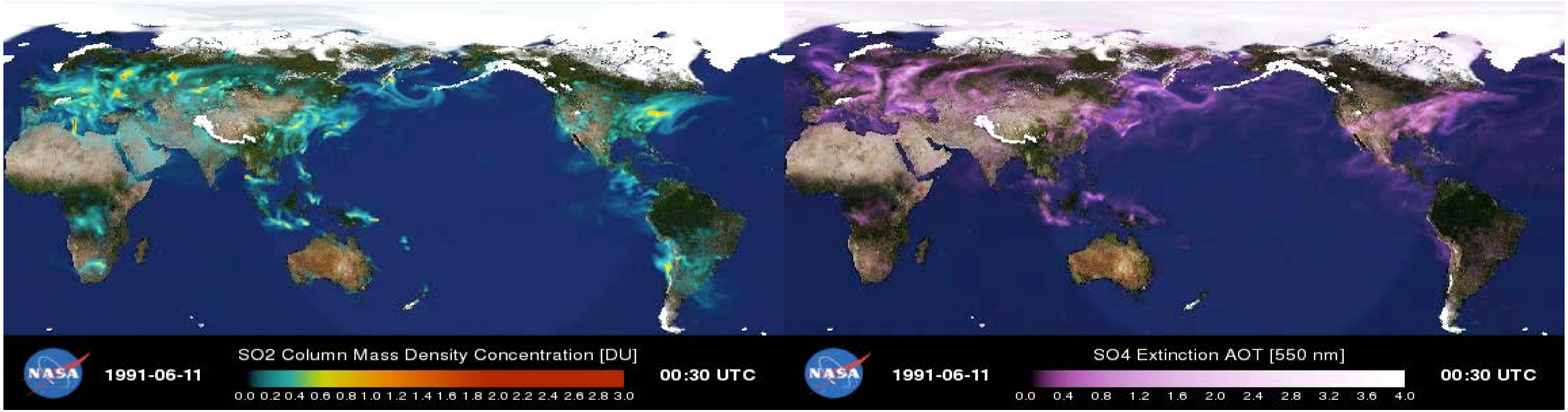
MERRA-2 is the first multi-decadal global reanalysis to include aerosols alongside meteorology

Randles et al., 2017, *J. Clim.*



Volcanic aerosols in MERRA-2

- First aerosol assimilation to include major historic volcanic events
- Movie shows the co-evolution of gaseous SO_2 emissions from Pinatubo (left) and formation of the the sulfate aerosol plume (right) as SO_2 is converted into particles.



Randles et al., 2017, *J. Clim.*

Reanalyses with GEOS Systems

MERRA (2009)	MERRA-2 (2015)	"GEOS Reanalysis of the 2000s" (~2020)	MERRA-3? (~2022)
MERRA Meteorology 0.5º L72, 3DVar MERRA-Land MERRA-Ocean MERRA-Aero	MERRA-2 Meteorology-Land-Ice-Aerosol-Ozone c180 L72, 3DVar (M2-Ocean)	"GEOS Reanalysis of the 2000s" Meteorology-Land-Ice-Ocean Skin-Aerosol-Composition c360 L72, 4DEnVar (target)	MERRA-3? Coupled analysis: Meteorology-Land Ice-Ocean (Comp., Biology) C360/0.1º ocean (target)
Modern Era Retrospective analysis for Research and Applications "Climate reanalysis" 1980-2016	MERRA-2 Step towards Earth System with aerosols, ice, ozone, … "Climate reanalysis" 1980-202x	G2000s 4D system focused on NASA observations with sensitivity studies "Process reanalysis" 2000-2020	MERRA-3 Coupled Earth System Reanalysis "Climate reanalysis" 1980-202x

Reanalyses with GEOS Systems in Relation to S2S Systems

MERRA (2009)
Meteorology

0.5º L72, 3DVar

MERRA-Land
MERRA-Ocean
MERRA-Aero

MERRA-2 (2015)
Meteorology-Land-Ice-Aerosol-Ozone

c180 L72, 3DVar

(M2-Ocean)

"GEOS Reanalysis of the 2000s" (~2020)
Meteorology-Land-Ice-Ocean Skin-Aerosol-Composition

c360 L72, 4DEnVar (target)

MERRA-3? (~2022)
Coupled analysis: Meteorology-Land Ice-Ocean (Comp., Biology)

C360/0.1º ocean (target)

S2S Version 1 (2009)
1º atmosphere;
0.5º ocean (MOM4)
Ocean Initialization: MERRA-Ocean(OI)

S2S Version 2 (2017)
c180 atmosphere
0.5º ocean (MOM5)
Ocean Initialization: EnKF-capable

S2S Version 3 (~2020)
c180 atmosphere
0.5º ocean (MOM5)
Ocean Initialization: M2-Ocean

S2S Version 4 (~2023)
C360/0.1º ocean?
GEOS-7; MOM6; CICE5
Coupled IC from MERRA-3
Other feedbacks?

GEOS-S2S Version 2

- A step towards Version 3, which will include advanced ocean-sea ice analysis and along-track satellite observations (MERRA-2 Ocean)
- Improves upon several known deficiencies of Version 1, largely due to an aging system
- Allows for the use of more NASA observations across the Earth System, to test sensitivities and impacts
- Ensemble size is small – four per month for reforecasts; nine per month in real time (since late 2016)
- Some results are shown in this presentation – first some descriptions and evaluation

GEOS-S2S Version 1: retired in April 2018

Model

- AGCM: Post-MERRA generation, Lat/Lon grid at 1º, 72 hybrid sigma-pressure levels; meteorology only
- OGCM: MOM4, ~0.5º, 40 levels;
- Sea Ice: CICE-4.0

Coupled Ocean Data Assimilation System

- atmosphere is "replayed" to MERRA, precipitation correction over land;
- EnOI ocean and sea ice analysis – run from 1980 to present ("MERRA-ocean");
- Forecasts: initialized from ODAS, perturbations from analysis differences and Bred Vectors;
- Hindcasts: initialized from MERRA-ocean, perturbations from analysis differences and Bred Vectors;

Observations

- assimilation of SST from CMIP5 prior to 1982 and Reynolds from 1982 to present;
- assimilation of *in situ* Tz and Sz including Argo, XBT, CTD, tropical moorings;
- sea ice concentration from the National Snow and Ice Data Center (NSIDC).

GEOS-S2S Version 2: in production since November 2017

Model

- AGCM: Post MERRA-2 generation, cubed sphere grid at ~0.5º, 72 hybrid sigma/pressure levels; GOCART interactive aerosol model, cloud indirect effect (2-moment cloud microphysics); MERRA-2 generation cryosphere;
- OGCM: MOM5, ~0.5º, 40 levels;
- Sea Ice: CICE-4.0.

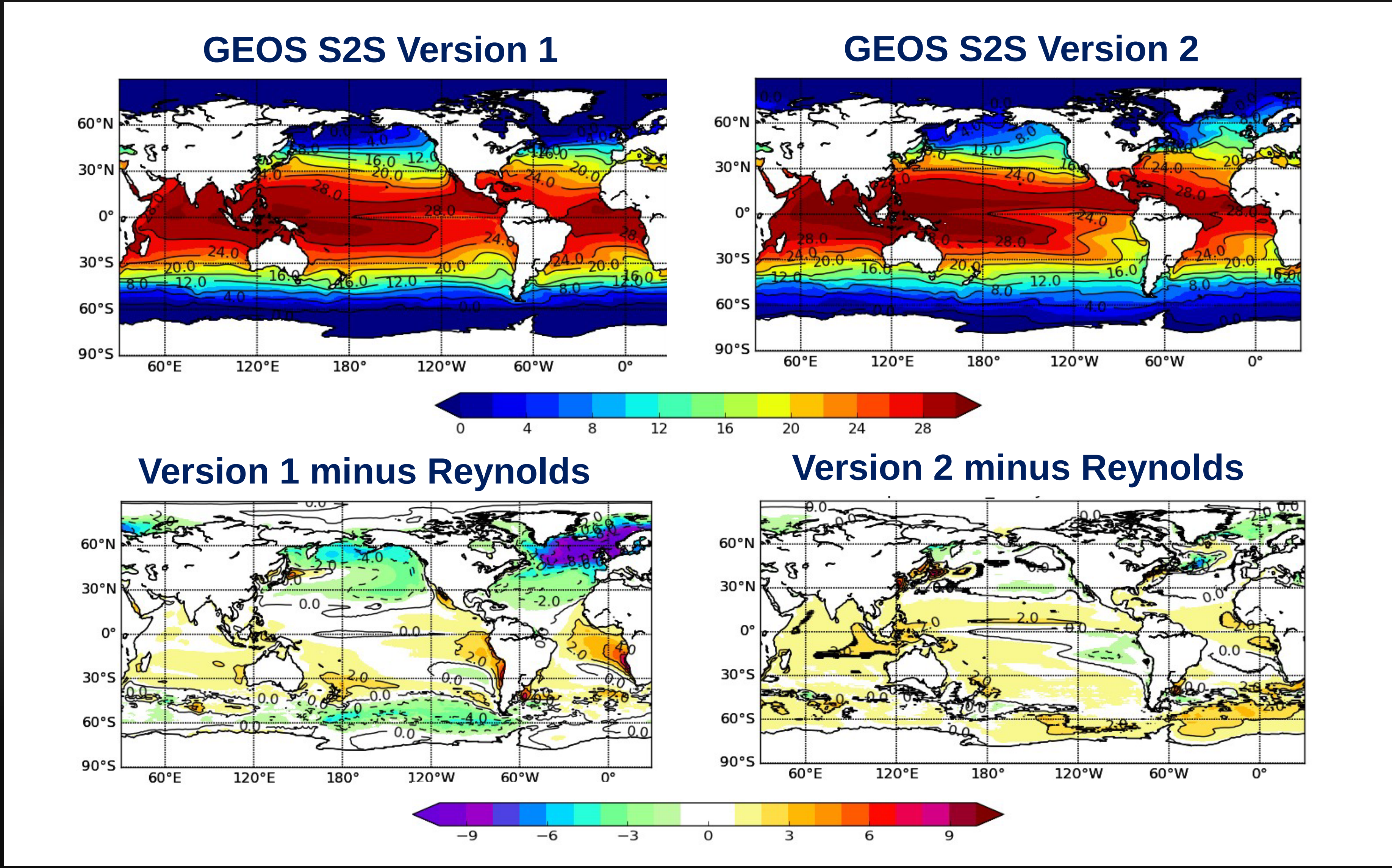
Coupled Ocean Data Assimilation System

- atmosphere is “replayed” to “FPIT” (like MERRA-2); precipitation correction over land;
- NCEP-like LETKF code/system, set here to behave as Ensemble OI;
- Forecasts: initialized from ODAS, perturbations from analysis differences;
- Hindcasts: re-initialized from 5-day run of ODAS, perturbations from analysis differences

Observations

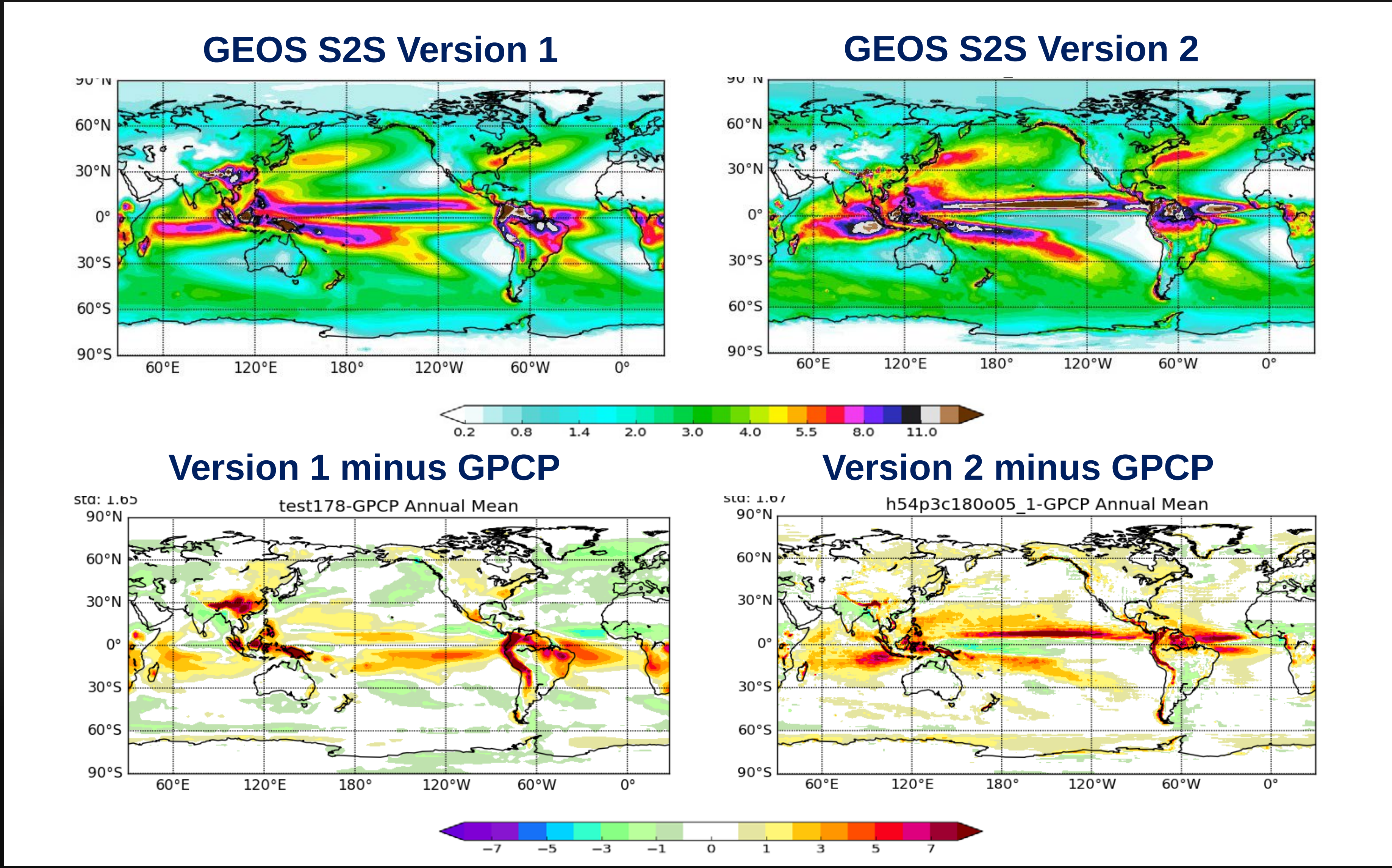
- nudging of SST and sea ice fraction from MERRA-2 boundary conditions;
- assimilation of *in situ* Tz and Sz including Argo, XBT, CTD, tropical moorings;
- assimilation of satellite along-track ADT (Jason, Saral, ERS, GEOSAT, HY-2A, CryoSat-2);
- sea ice concentration from the National Snow and Ice Data Center (NSIDC).

Equilibrium-Climate Simulations: Annual Mean SST Improvements



Plots by Vikhliaev

Equilibrium-Climate: Annual Mean Precipitation Retains Double ITCZ



Plots by Vikhliaev

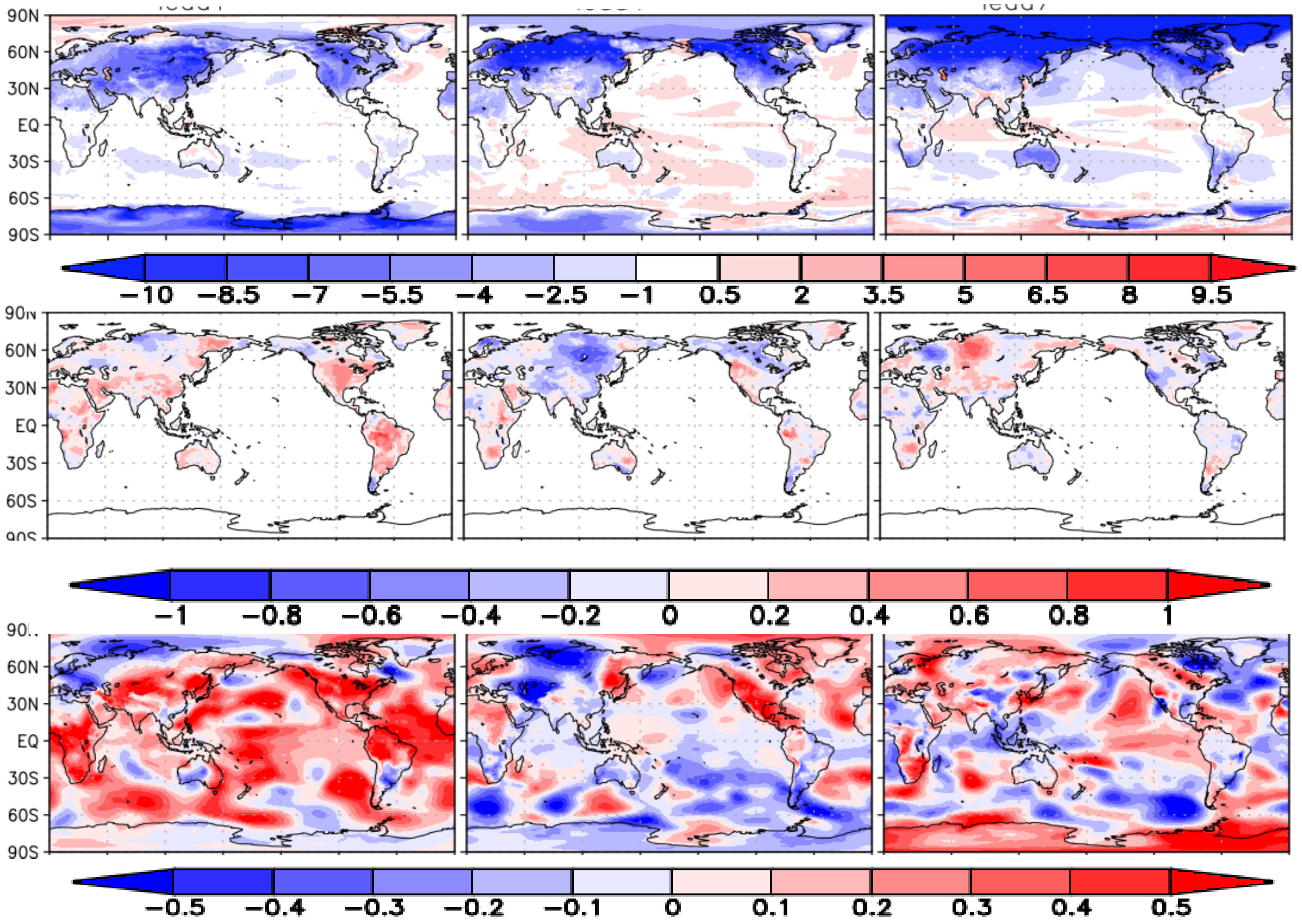
Forecast Mean Fields Show Overall Improvements

Lead 1 (Nov) | **Lead 4 (Feb)** | **Lead 7 (May)**

Absolute Difference

(blue → new system has less bias)

T2m Bias



T2m Anomaly Corr.

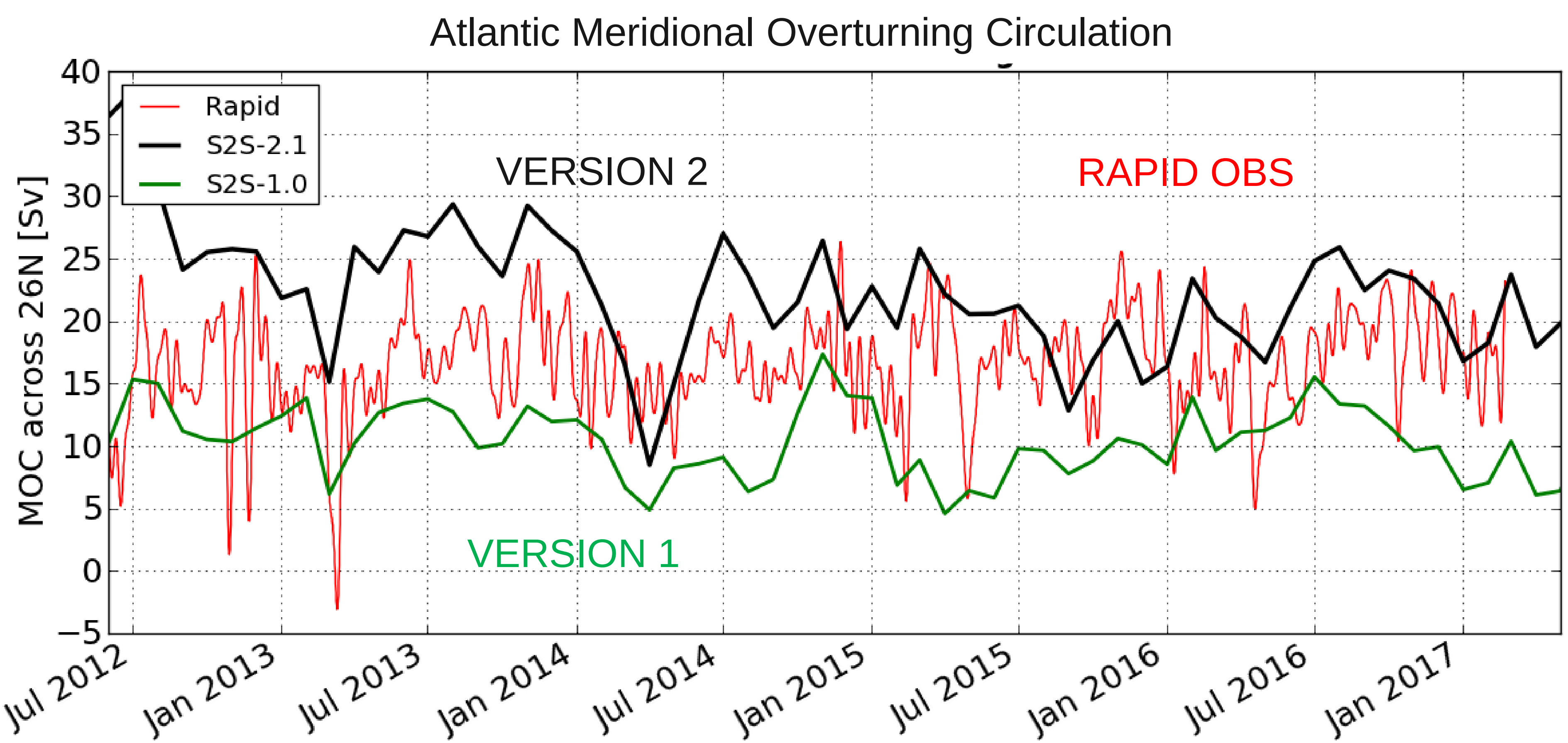
Anomaly Corr. Difference

(red → new system has higher corr.)

SLP Anomaly Corr.

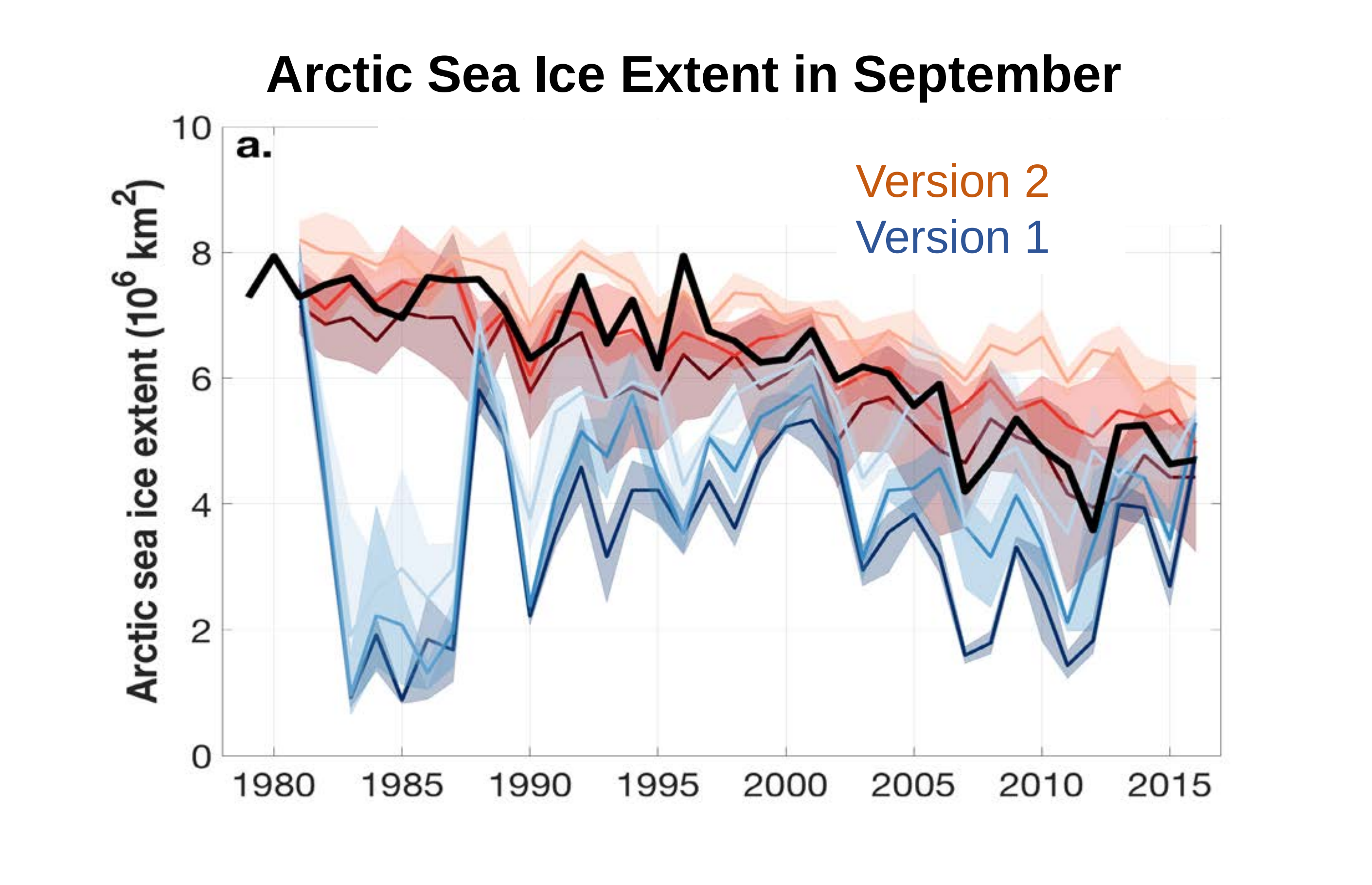
Plots by Li

AMOC in Versions 1 and 2 (Ocean analyses)



OBS = RAPID-WATCH MOC monitoring project

Forecast Mean Fields: Improvements in the Cryosphere

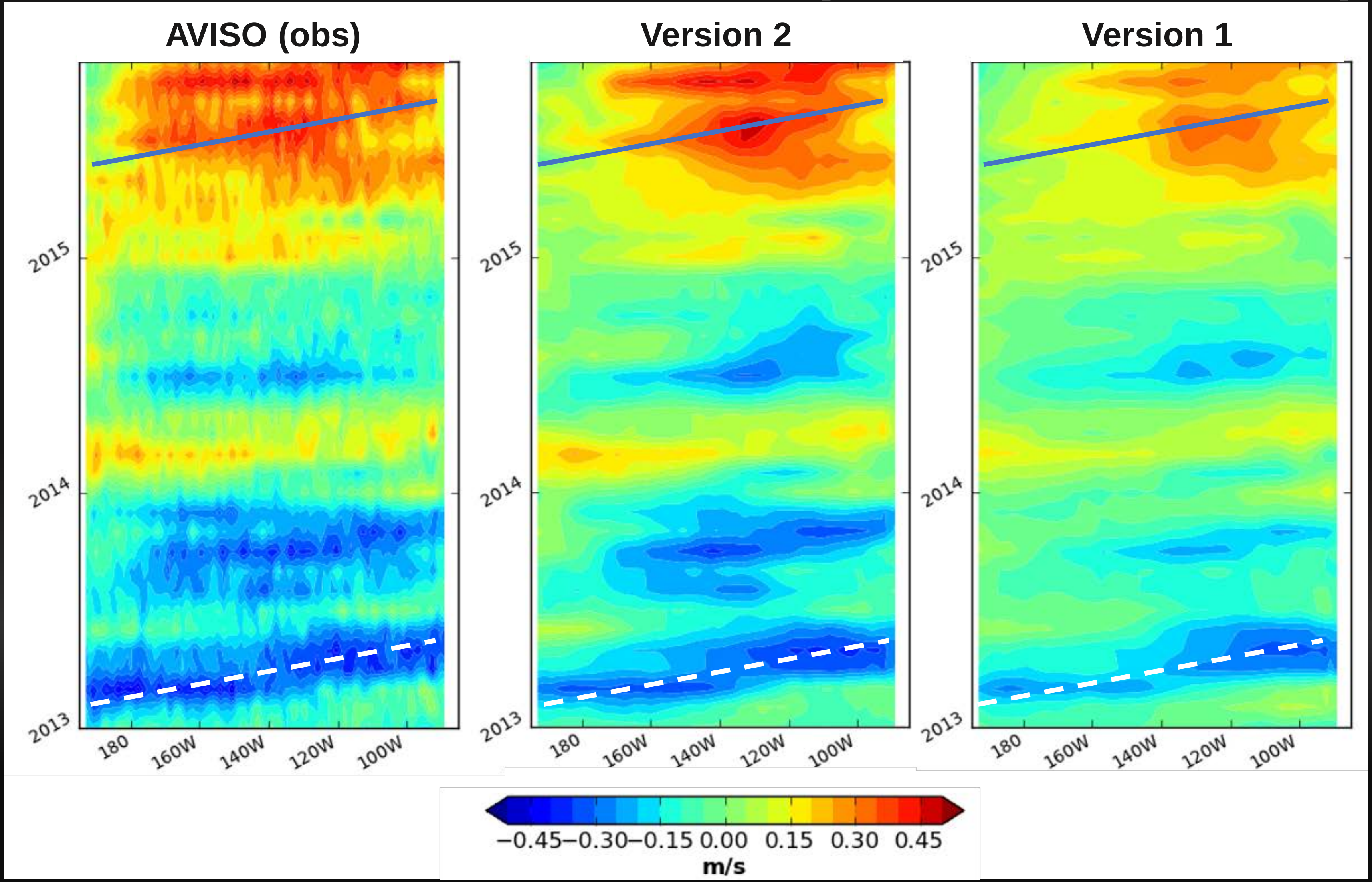


- Hemispheric ice extent is a widely used metric - area encompassed by 15% concentration contour.
- The S2S Version 2 hindcast system can explain up to 80% of September sea ice extent variance over the hindcast period.
- In large part, sea ice forecast skill arises from appropriately representing its long-term decline.
- Removing the long-term trend (following Bushuk et al., 2017) decreases skill

Plan is to use NASA observations of sea ice from NASA's IceSat platforms in future work. These improvements in GEOS-S2S Version 2 help pave the way for this , as well as for ice thickness data.

Plot by Andrews

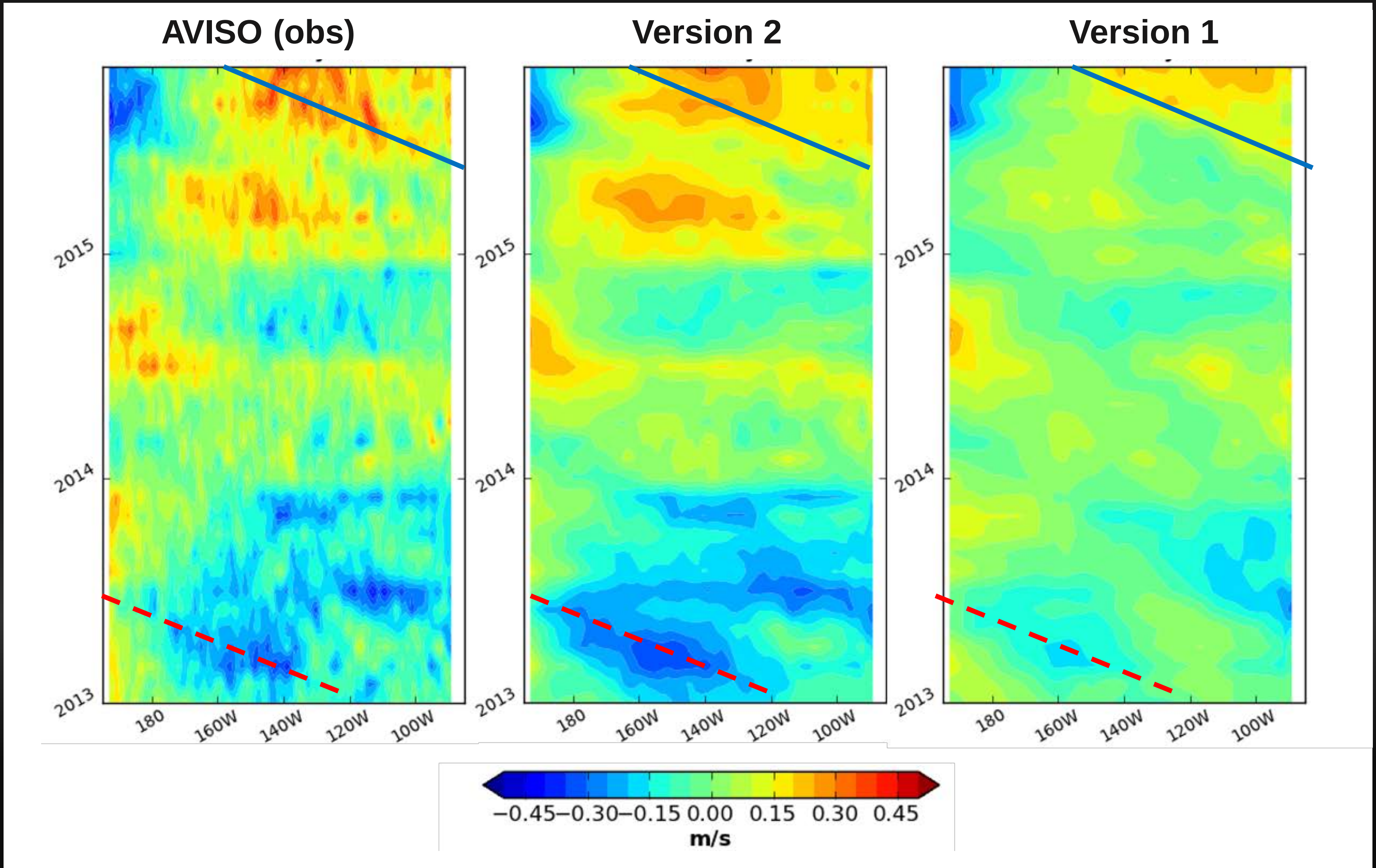
Kelvin Wave Decomposition in the Tropical Pacific



AVISO is a multi-satellite gridded product of all available altimetry data

Version 2 of GEOS S2S contains Kelvin waves with more realistic amplitude and propagation than Version 1

Rossby Wave Decomposition in the Tropical Pacific

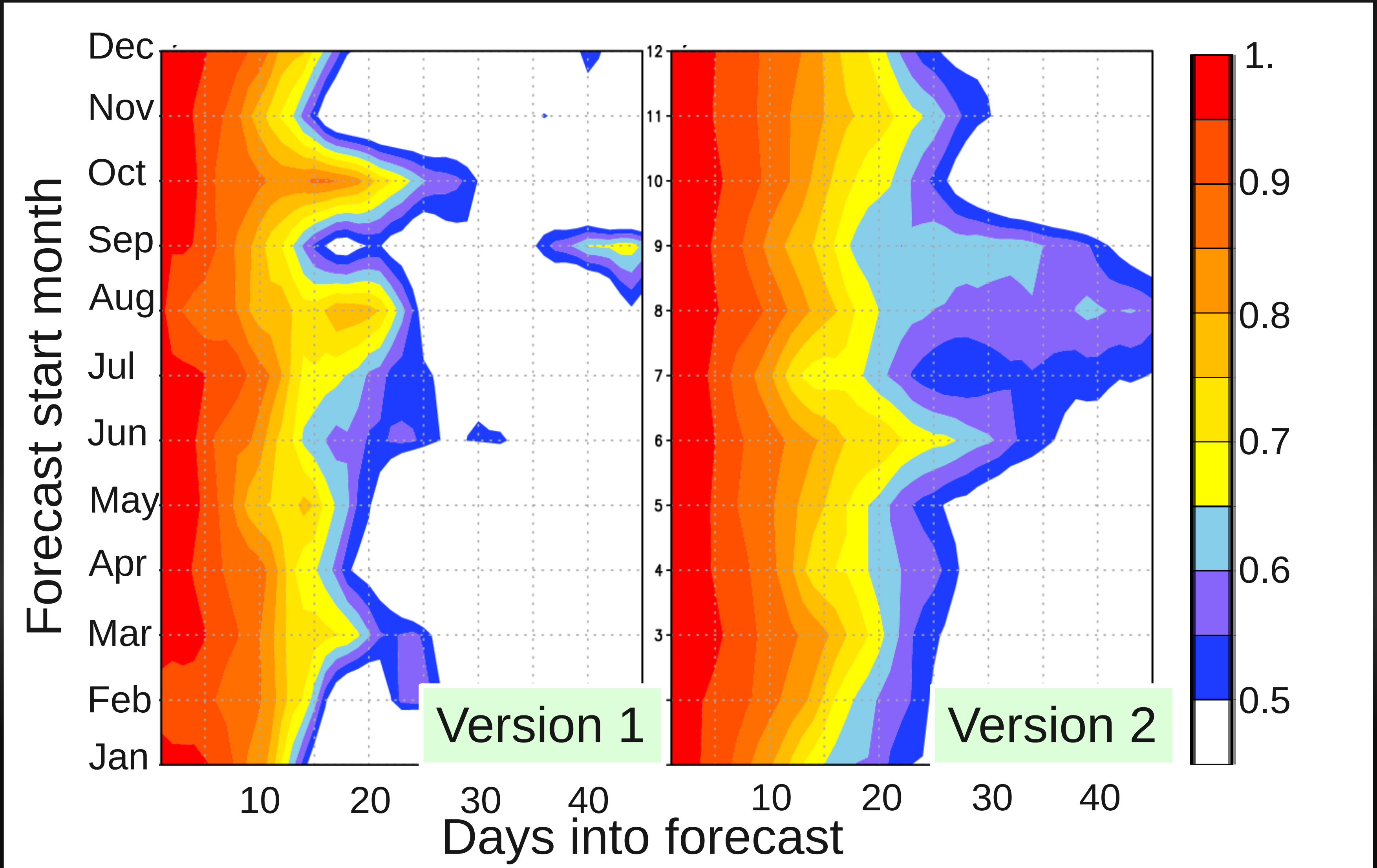


AVISO is a multi-satellite gridded product of all available altimetry data

Version 2 of GEOS S2S represents Rossby waves with more realism (strength and timing) than does Version 1.

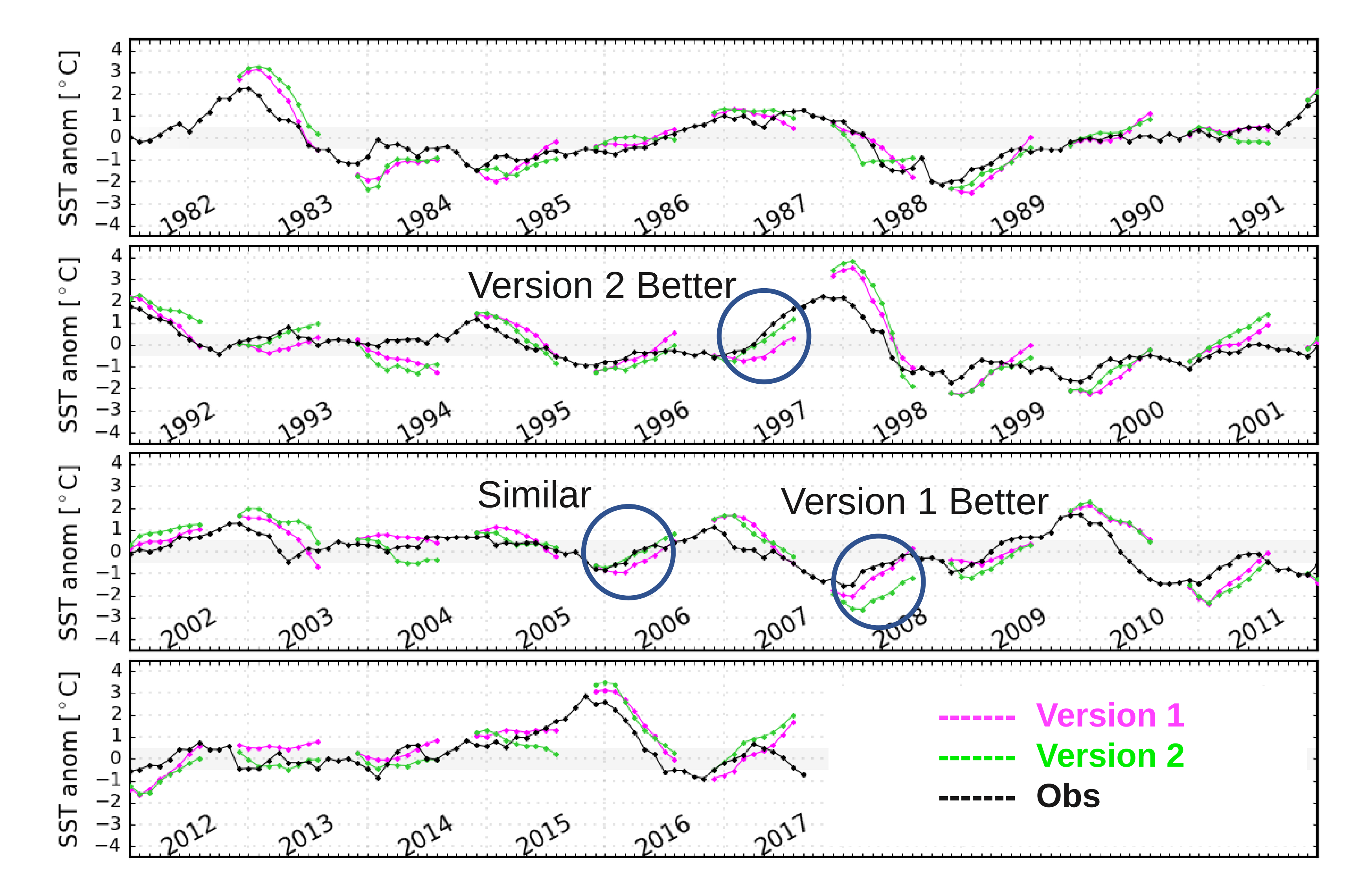
Improvements in the MJO Prediction Skill

Correlation of forecasted Real-time Multivariate MJO (RMM) index vs. that in MERRA-2



Plots by Achutavarier and Lim

Niño 3.4 Prediction is not Substantially Changed



Summary of Improvements with GEOS-S2S V2

- SST bias reduced (especially off the Equator)
- Assimilation of altimetry improves western boundary currents
- Global heat content improved (e.g. HC300 trend removed)
- Large scale meridional (AMOC) and zonal (ITF) heat transport improved in Version 2
- Kelvin and especially Rossby waves are significantly improved in the new system

(Impacts of) NASA Observations that Constrain the Physical State

NASA has numerous space-based observations of physical properties of the "slowly varying" components of the Earth. These can be used without adding complexity to the physical Earth System model, but do require new observation operators for the assimilation. These include:

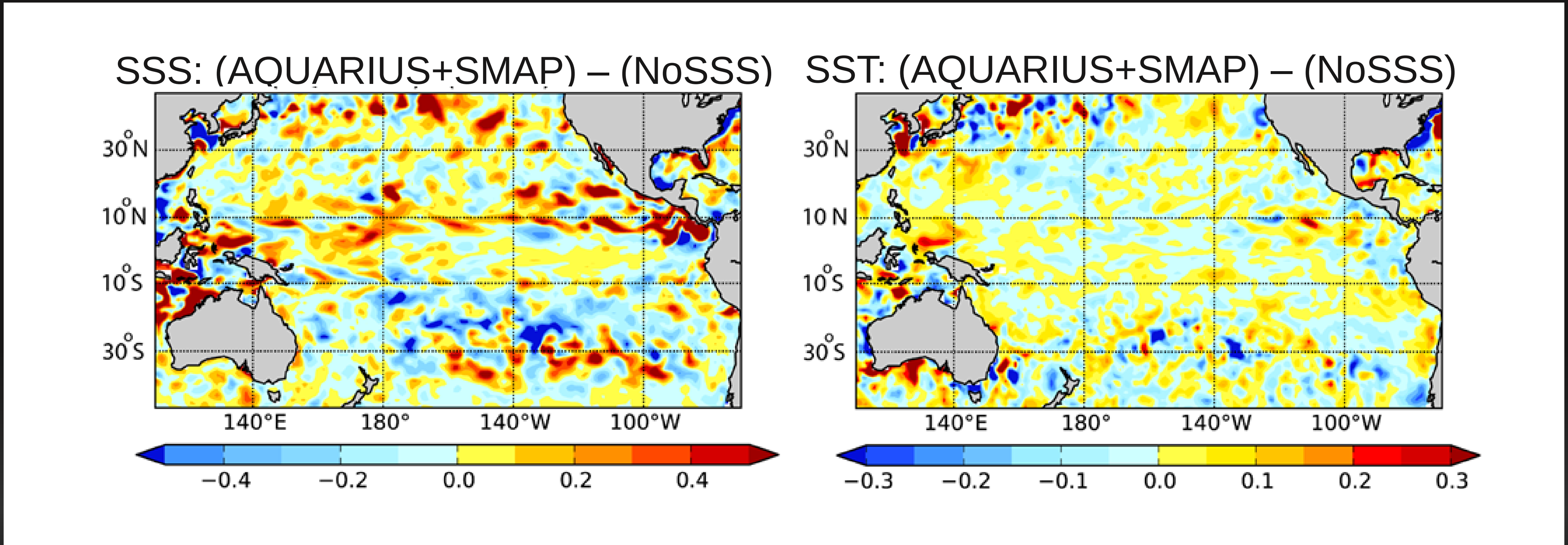
- Altimetry – passive altimetry is used routinely since 1993; active (e.g., IceSAT2) not yet used
- Soil Moisture (SMAP)
- Sea-Surface Salinity (Aquarius, SMAP, plus SMOS)
- …

Impacts of Sea-Surface Salinity

Experimental details:

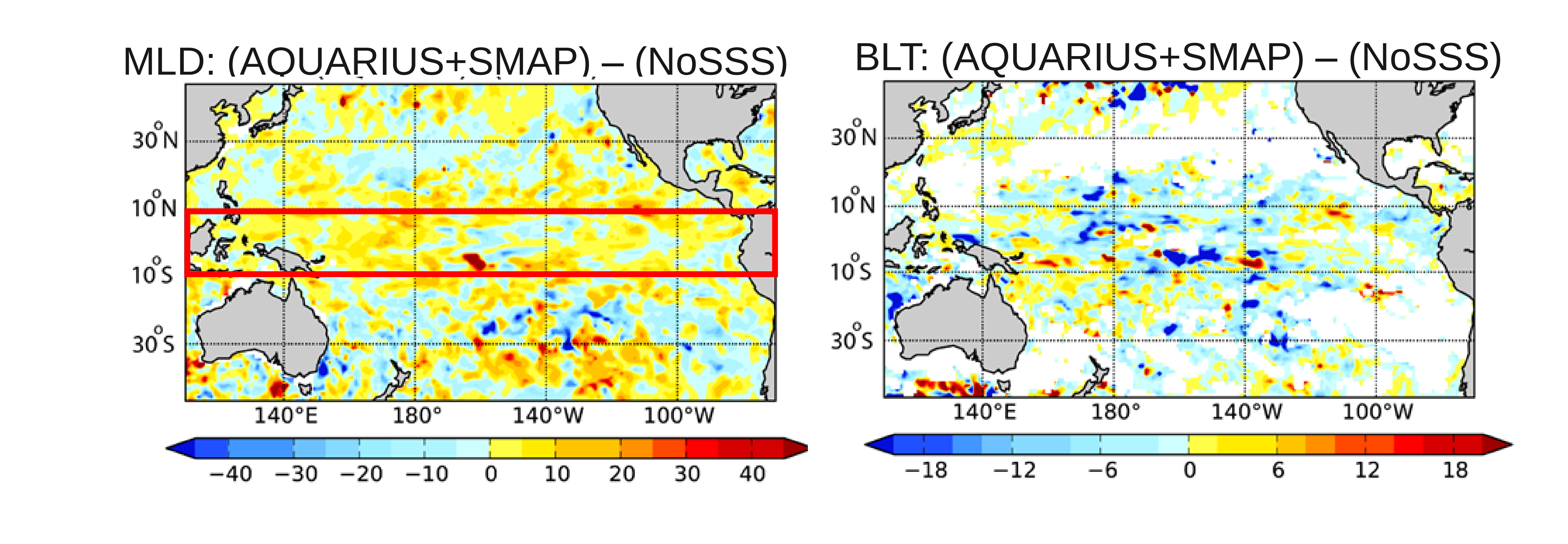
- Reference state: GEOS S2S production run
- Aquarius (2013 – May 2015) and SMAP (March 2015 – present) Sea Surface Salinity (SSS) assimilation has been added
- ESA SMOS (2009 onwards) data are also included
- Discernable improvement in predictions of Niño 3.4 SSTs when SSS data are included

Impacts on oceanic initial conditions in May 2015: surface fields



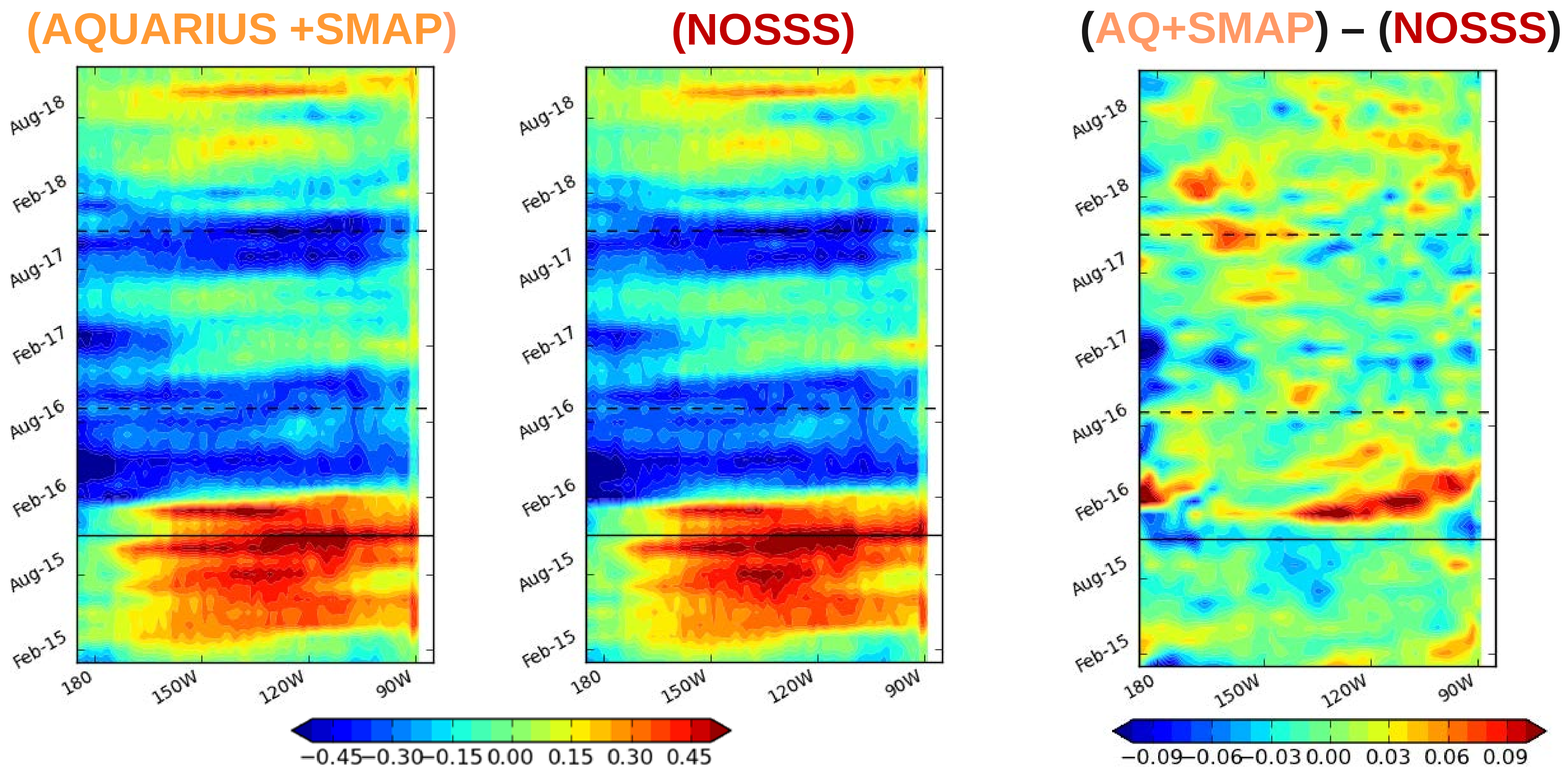
May 2015 differences between the experiment that assimilates both Aquarius and SMAP Sea Surface Salinity (SSS) minus the experiment that withholds SSS assimilation for (left) SSS and (right) SST. Improved (somewhat saltier) SSS, combined with SST, increase near-surface density within the equatorial waveguide

Impacts on oceanic initial conditions in May 2015: mixed & boundary layers



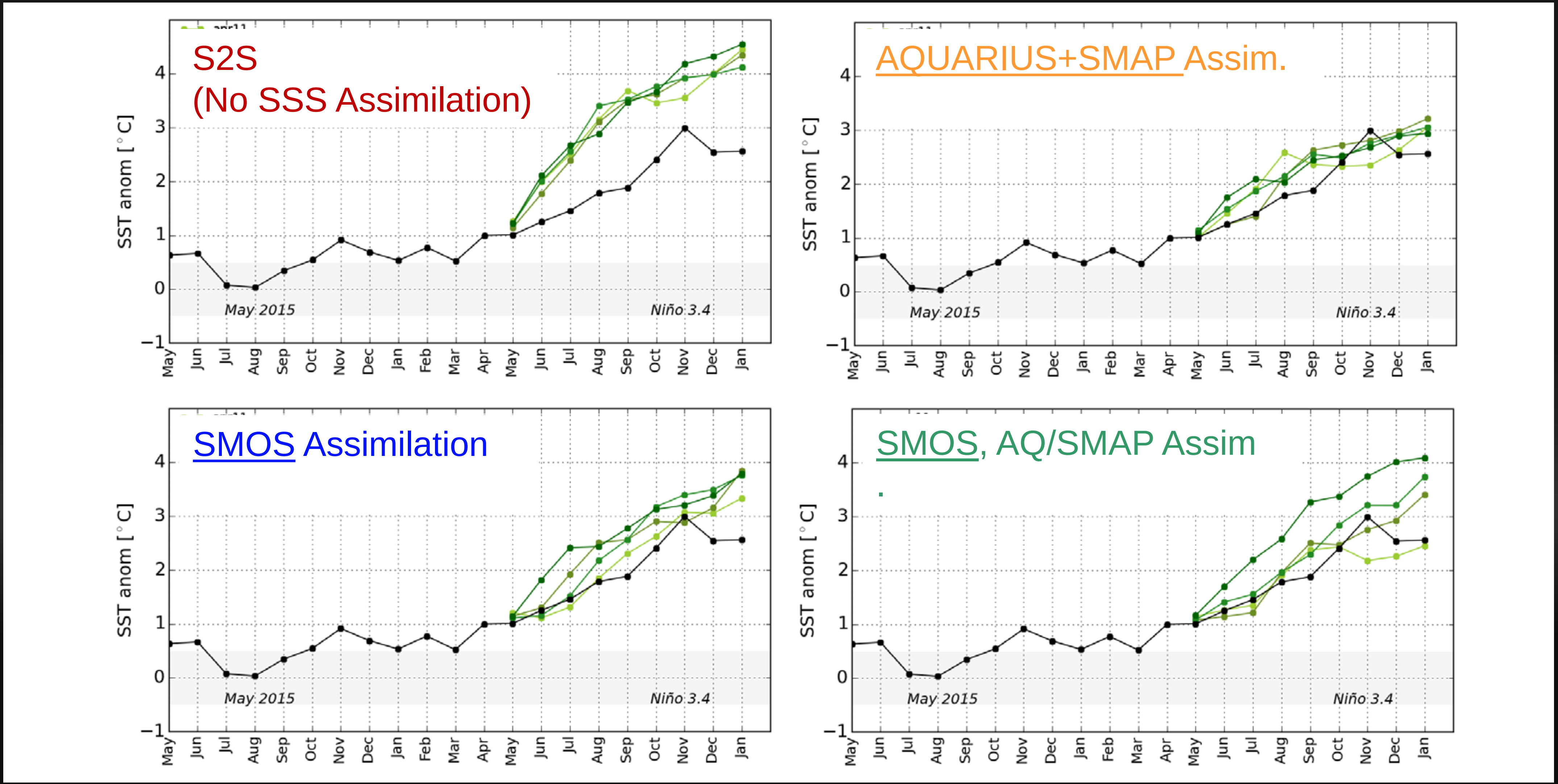
Increased density near the equator leads to deeper MLD (left) and shoaling of the barrier layer thickness (BLT – right). Increased MLD leads to damped ENSO response due to reduced efficiency of wind forcing on a relatively deeper MLD.

Impacts on oceanic initial conditions in 2015: Kelvin Waves

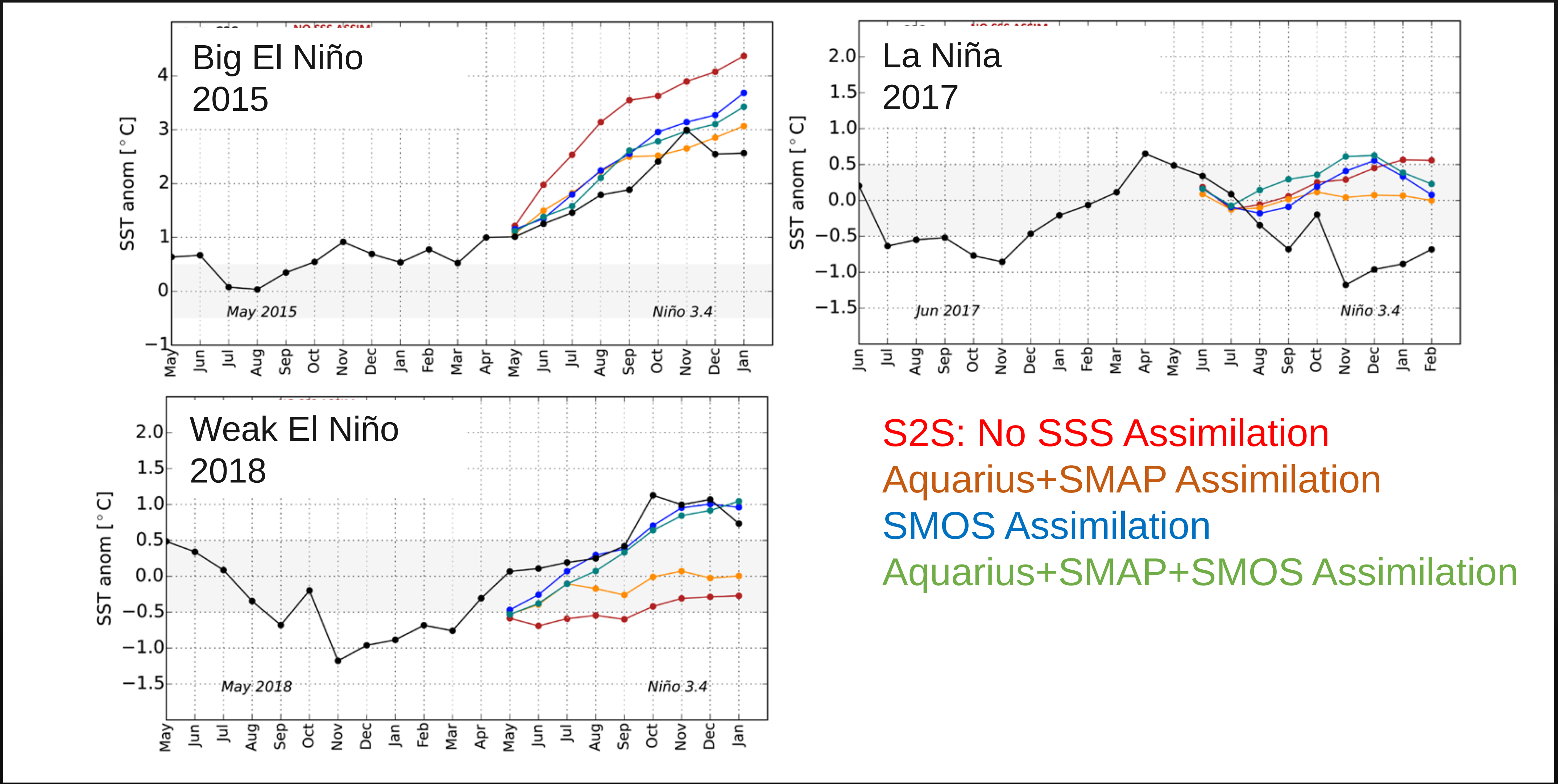


Note that the ENSO signal is generally damped due to SSS assimilation: the downwelling Kelvin wave is damped during the 2015 El Niño.

Benefits of SSS Assimilation on Niño-3.4 Prediction in 2015 (May Plumes)



Benefits of SSS Assimilation on Niño-3.4 Prediction in Three Cases



Summary of Impacts of SSS Observations

1) ASSIM SSS -> changes in SSS -> changes in near-surface density -> deepens MLD and shoals BLT

2) Deeper MLD acts to dampen ENSO (Kelvin) signal

3) Dampened ENSO -> cooling too-warm El Niño and adds improved uncertainty to La Niña forecasts

4) Assimilating satellite SSS -> improved ENSO forecasts. Often multiple satellite SSS outperform single satellite results.

Assimilation of satellite SSS improves ENSO Forecasts

Caveat: Hindcasts over Many Years

- Expensive – to run and to store/explore the output data
- Being used to compute anomalies in cases where climate change and long-term changes in the observing system might be creating similar changes
- Not conducive to data impact studies, when the observations are available for only a small number of years (as is typical with NASA observations, such as SSS)
- Not ideal for air pollution, ocean biology etc. where distributions are not Gaussian and bounded by zero
- Might slow down progress in enhancing physical insight, because we are implicitly accepting the existence of bias rather than addressing it (unacceptable in nuclear engineering, medicine, driving tests, …)
- Certainly slow down the "refresh" process for S2S systems
- We need to examine feasibility of new approaches that the community may be willing to adopt

Impacts of NASA Observations that Need a More Complex Model

NASA has numerous space-based observations of physical, chemical and biological components of the Earth system. These can be used in Earth System analysis and prediction by adding additional complexity to the physical Earth System model and new components to the assimilation code. These include:

- Aerosol properties (e.g., AOD)
- Stratospheric volcanic aerosols
- Ozone and other gaseous constituents
- Surface vegetation distributions
- Ocean color (phytoplankton)
- …

Stratospheric Pinatubo Aerosol Impacts on the 1991-1992 El Niño Forecasts

It is known that:

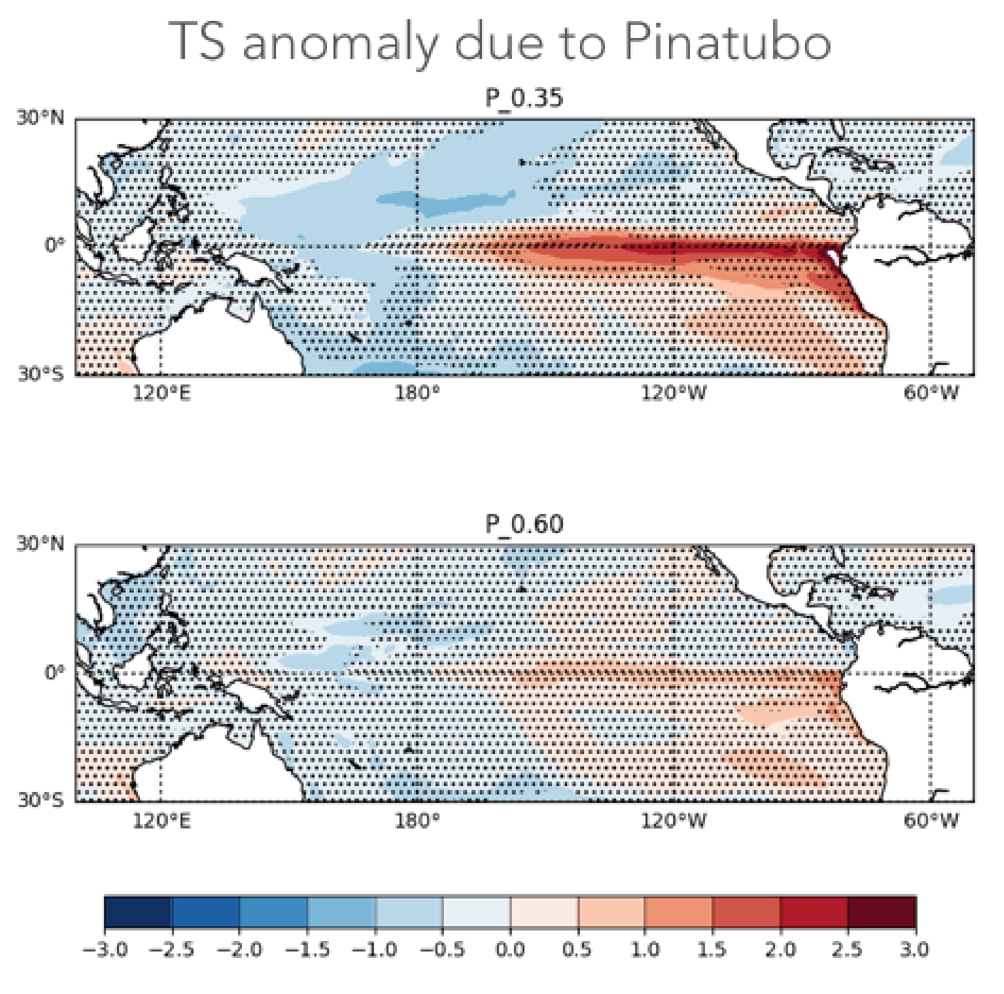
- Major eruptions such as El Chichon and Mt Pinatubo injected many tons of SO_2 into the stratosphere, where it converted to sulfate aerosol
- Stratospheric sulfate aerosol is long lived (years) and has impacts on surface temperature and stratospheric ozone-chemistry
- An El Niño was already developing when Pinatubo erupted in June 1991

GEOS-S2S study: did the Pinatubo event cause the 1991 El Niño event to become stronger than it would otherwise have been? (Work by Aquila et al.)

A stratospheric aerosol module was activated in GOCART for this study, to account for particle sizes of ~0.6microns as opposed to ~0.34microns, which is am appropriate size for tropospheric sulfate aerosols.

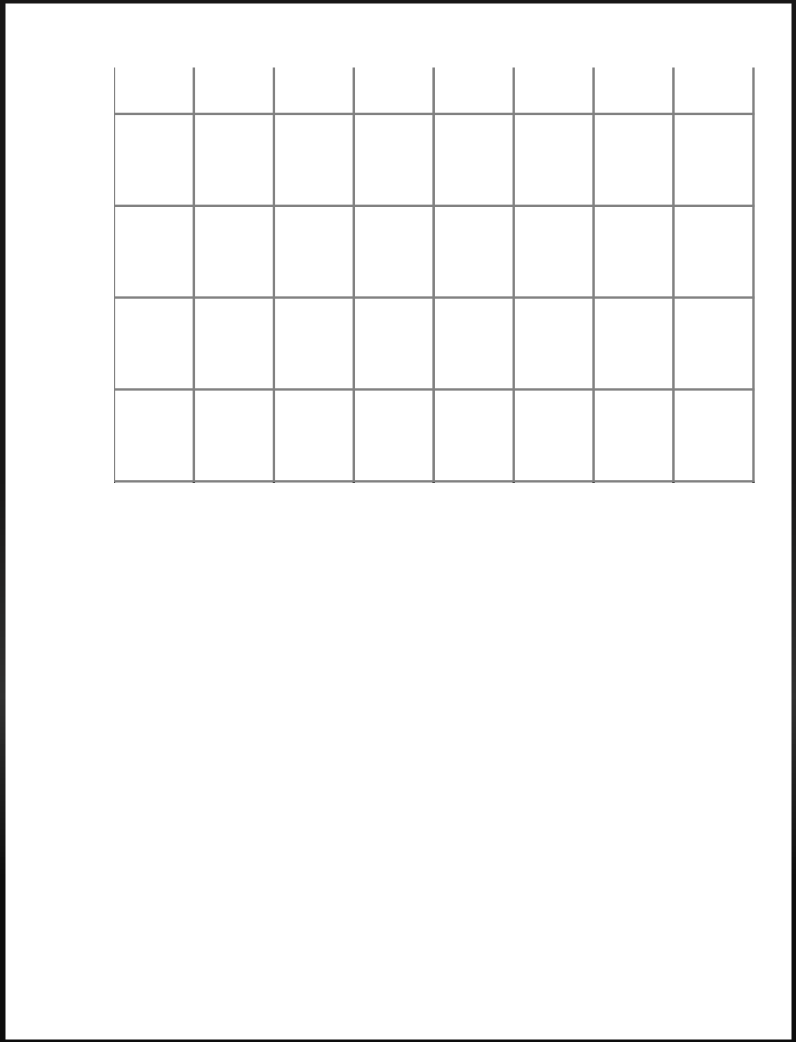
Pinatubo impacts in GEOS S2S: surface temperature in Feb 1992

- Three ensemble forecasts (no Pinatubo, with 0.34 micron and 0.6 micron aerosols) run.
- All three show that the El Niño continues to develop
- The El Niño is stronger with aerosols, but not significantly
- Using the inappropriate aerosol size in the stratosphere does lead to an event that is significantly stronger (top)



Pinatubo impacts in GEOS S2S: Niño 3.4 index

- All nine-months forecasts predict an El Niño event that was stronger than observed.
- Using the small aerosol size forced an extremely strong ENSO event, peaking at more than 3K, compared to more than 2K with no aerosols (top)
- The larger (appropriate) aerosol loading led to a warming some tenths of one degree warmer than with no aerosols (bottom)



Tropospheric aerosol class

Significantly Stronger El Niño

Stratospheric aerosol class

Insignificantly Stronger El Niño

Summary of Pinatubo Study

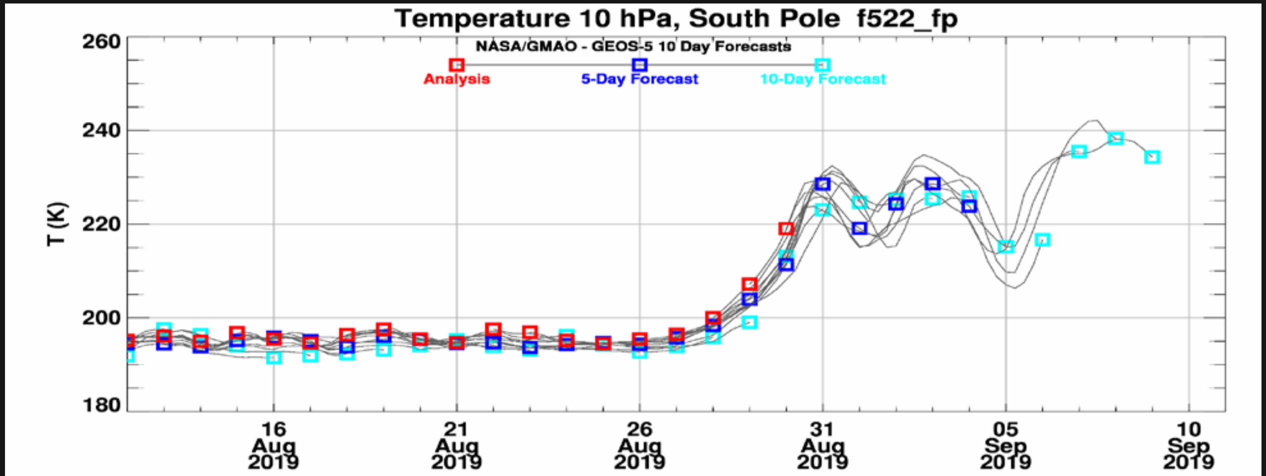
- Radiative impacts of volcanic aerosols in the stratosphere did not have a significant impact on the development of the 1991-1992 El Niño event
- This does not rule out the potential impacts of eruptions that are much stronger than Pinatubo
- This not address the health/aviation (etc.) impacts of ash or tropospheric sulfates from such volcanic eruptions
- Also does not address impacts on ozone that persist for at least 2-3 years following the eruption and can have impacts on the high-latitude circulation
- The work highlights the importance of using a model of suitable complexity (distinguishing among stratospheric and tropospheric sulfate aerosol sizes)

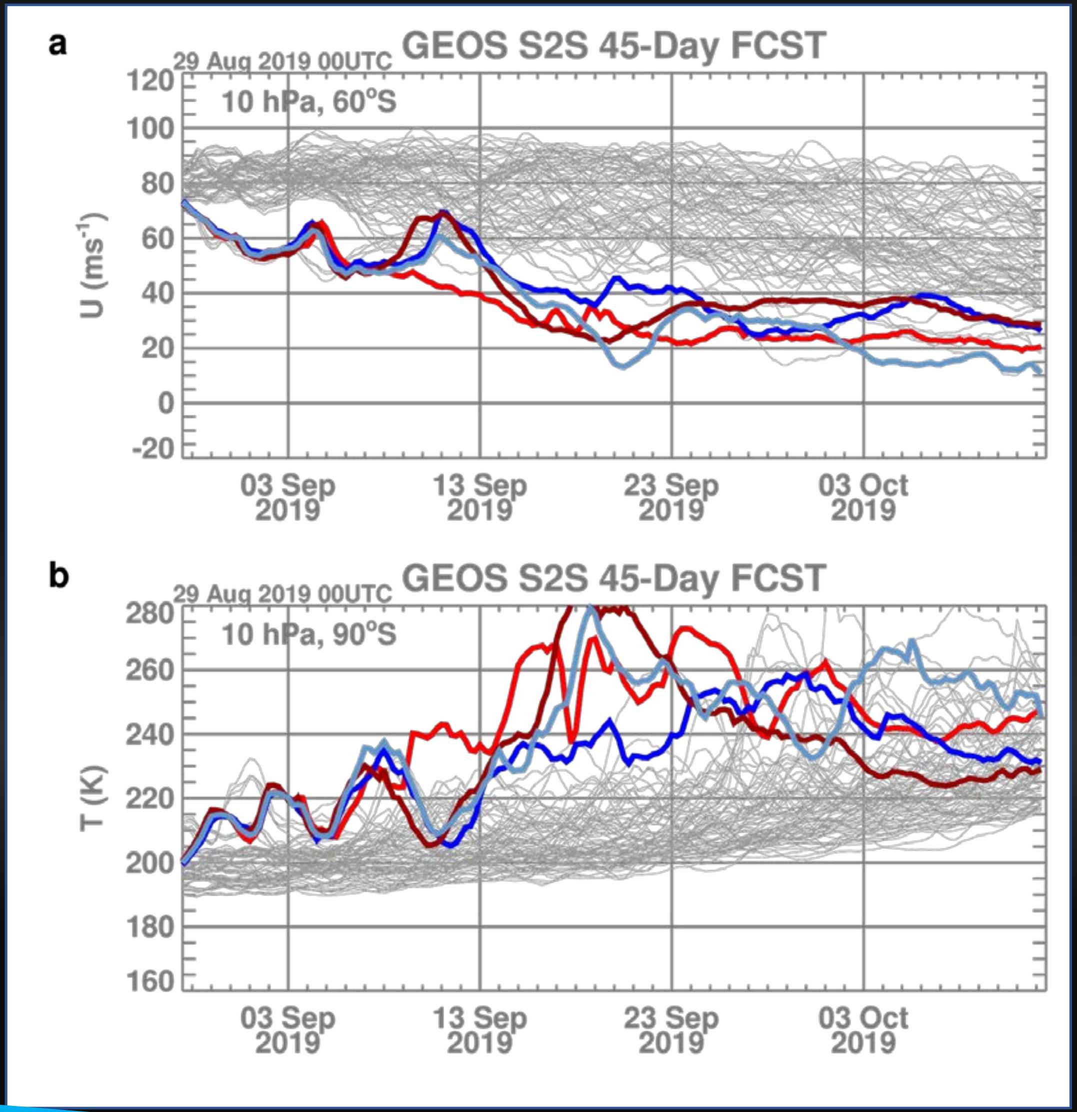
A Teaser to End With …

- The Antarctic stratosphere is poised to undergo a minor (wavenumber 1) warming in the next few days
- Exemplified by the PV animation, a forecast from Friday August 30 to Monday September, 2019
- GEOS-S2S forecasts are consistently projecting a very warm Antarctic stratosphere over the next weeks.

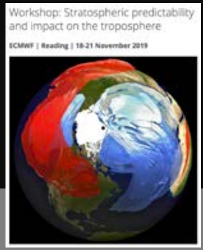
Animation by Coy

… and this Persists beyond 10 days





- Consistent forecasts in GEOS "weather" system
- All ensemble members of GEOS-S2S show warmer temperatures and weaker winds than in entire hindcast record, persisting over 45 days



Plots by Coy

Summary and Discussion Points

- Version 2 of GEOS-S2S is a positive step along GMAO’s development pathway
- Complexity of process, spatial resolution, and ensemble size compete for compute resources – after-the-fact cost is also substantial (data storage/access)
- GMAO’s focus on NASA’s mission helps guide such decisions
- Overall, more basic research is needed to make definitive decisions on the system configuration used in all applications
- GEOS is highly modular and scale aware, making it relatively straightforward to configure the system for specialized applications
- Planning substantial science investigations using V2 and V3 of GEOS-S2S to guide formulation of V4 (resolution, ensemble, complexity)