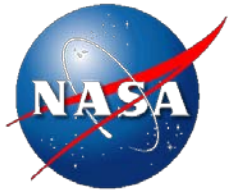



# MERRA & Beyond

## Towards the development of an Integrated Earth System Analysis at GMAO

Michael Bosilovich

Ron Gelaro, Steven Pawson, Michele Rienecker, Siegfried Schubert, Max Suarez

Arlindo da Silva, Rolf Reichle, Guillaume Vernieres

WCRP ICR4
May 7-11, 2012

# NASA and Reanalysis

## NASA's strategic goal
## "Advance Earth System Science to meet the challenges of climate and environmental change"

- Approach: characterize, understand, predict using NASA's observations and so acquire deeper scientific understanding of the components of the Earth system and their interactions.

- **Role of Reanalyses in NASA's mission:**
  - Long-term synthesis of data for a physically consistent climate research-quality data sets
  - Initial and boundary conditions for predictions
  - Validation and verification references, and internal and external constraints to models

# MERRA

- **GEOS-5 ADAS, 2008 version** – GEOS-5.2.0
  - 1/2° × 2/3° × 72L
  - 1979-present; cont. as a ~2-week delayed NRT climate analysis
  - **MERRA-Land** as an update to the land-surface collection

- Web site (FAQ, blog, issues found/resolved) **http://gmao.gsfc.nasa.gov/merra**
  - **MERRA Atlas** (**http://gmao.gsfc.nasa.gov/ref/merra/atlas/**)
  - Data online through the GES DISC (**http://disc.sci.gsfc.nasa.gov/mdisc/**)
    - > 1.1 PB distributed to date – Several access options
    - International by Volume: Canada, Japan, Germany, Spain
  - MERRA is online at PCMDI's ESG for CMIP5 model evaluations

- **MERRA Special Collection in *J. Climate***
  - *GMAO's* Overview paper – Rienecker et al. (2011)
  - 20 papers to date

# MERRA Acknowledgements


## System Development

**GMAO**: Ricardo Todling, Max Suarez, Julio Bacmeister, Emily Liu, Meta Sienkiewicz

Larry Takacs, Phil Pegion, Mike Bosilovich, Ron Gelaro, Michele Rienecker, Steve Bloom, Austin Conaty, Arlindo da Silva, Wei Gu, Randy Koster, Andrea Molod, Steven Pawson, Chris Redder, Siegfried Schubert

**Non GMAO**: Jack Woollen, Leo Haimberger, Joanna Joiner, Pete Robertson

## Input data:

NCEP, NESDIS, NCAR, NCDC, RSS (SSMI radiances and wind speed), JPL (QuikSCAT), CERSAT (ERS winds); TRMM project; GSFC SBUV team

## Production and Data Serving:

Rob Lucchesi, Tommy Owens, Doug Collins, Dana Ostrenga, Jerry Potter

## External Advisory Group:

Phil Arkin, Alan Betts, Robert Black, David Bromwich, John Roads, Jose Rodriguez Steven Running, Paul Stackhouse, Kevin Trenberth, Glenn White

# GEOS-5 Atmospheric Data Assimilation System

## AGCM

- Finite-volume dynamical core
- Hybrid vertical coord to 0.01 hPa
- Catchment land surface model
- Prescribed aerosols
- Interactive ozone
- Prescribed SST, sea-ice

## Analysis

- Grid Point Statistical Interpolation - GSI (co-developed with NCEP)
- Direct assimilation of satellite radiance data using JCSDA Community Radiative Transfer Model (CRTM)
- GLATOVS for SSU
- Variational bias correction for radiances

## Assimilation

- Implemented as an Incremental Analysis Update (IAU) to reduce shock of data insertion and improve utility for constituent transport – provides closed budgets.

$$\left(\frac{\partial q^n}{\partial t}\right)_{total} = dynamics(adiabatic) + physics(diabatic) + \Delta q$$

**Total Tendency** | **Model predicted change** | **Correction from DAS**

# Some data notes:

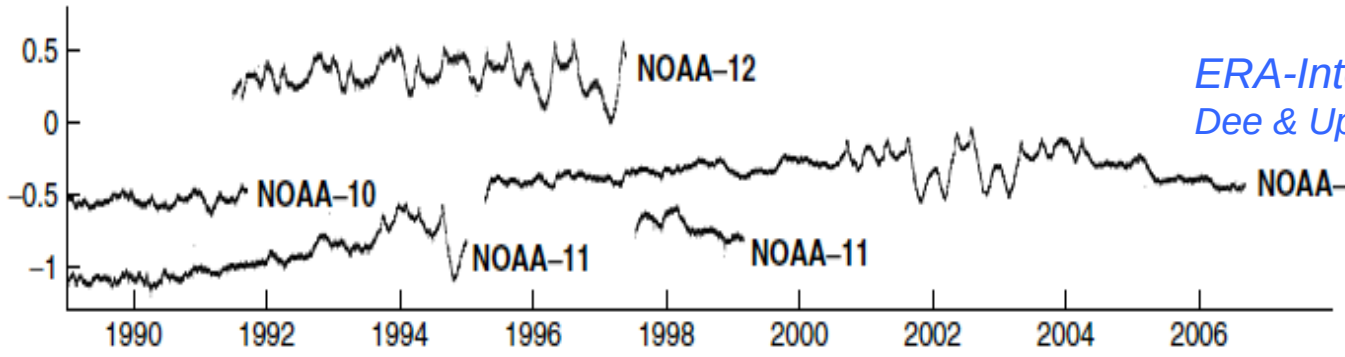
## Radiosonde Temperature Corrections

- **Vaisala RS-80 corrections:** Offline removal of large 00/12 UTC time-mean temperature differences - primarily in the stratosphere (Redder et al. 2004)
- **Homogenization:** Adjusted according to Haimberger (2007) updated for the Vaisala corrections
- **Radiation bias corrections:** Adjustments for the radiation bias of the thermistor

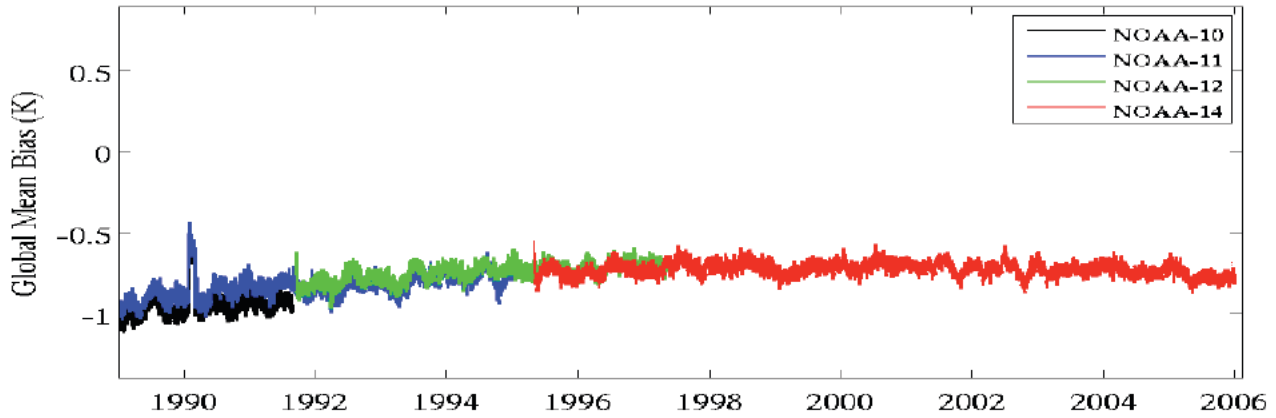
## Radiance Data

- **MSU**: Assimilated NESDIS cross-calibrated MSU [Ch 2-4].
- **MW**: Excluded channels with large surface sensitivities over snow, ice, and mixed surfaces [AMSU-A Ch 1-6 and 15; AMSU-B Ch 1, 2 and 5; MSU Ch 1 and 2].
- **IR**: Excluded surface-sensitive channels from analysis [e.g., HIRS Ch 8].

# Variational Bias estimates for MSU Channel 2




*ERA-Interim*
*Dee & Uppala 2009*

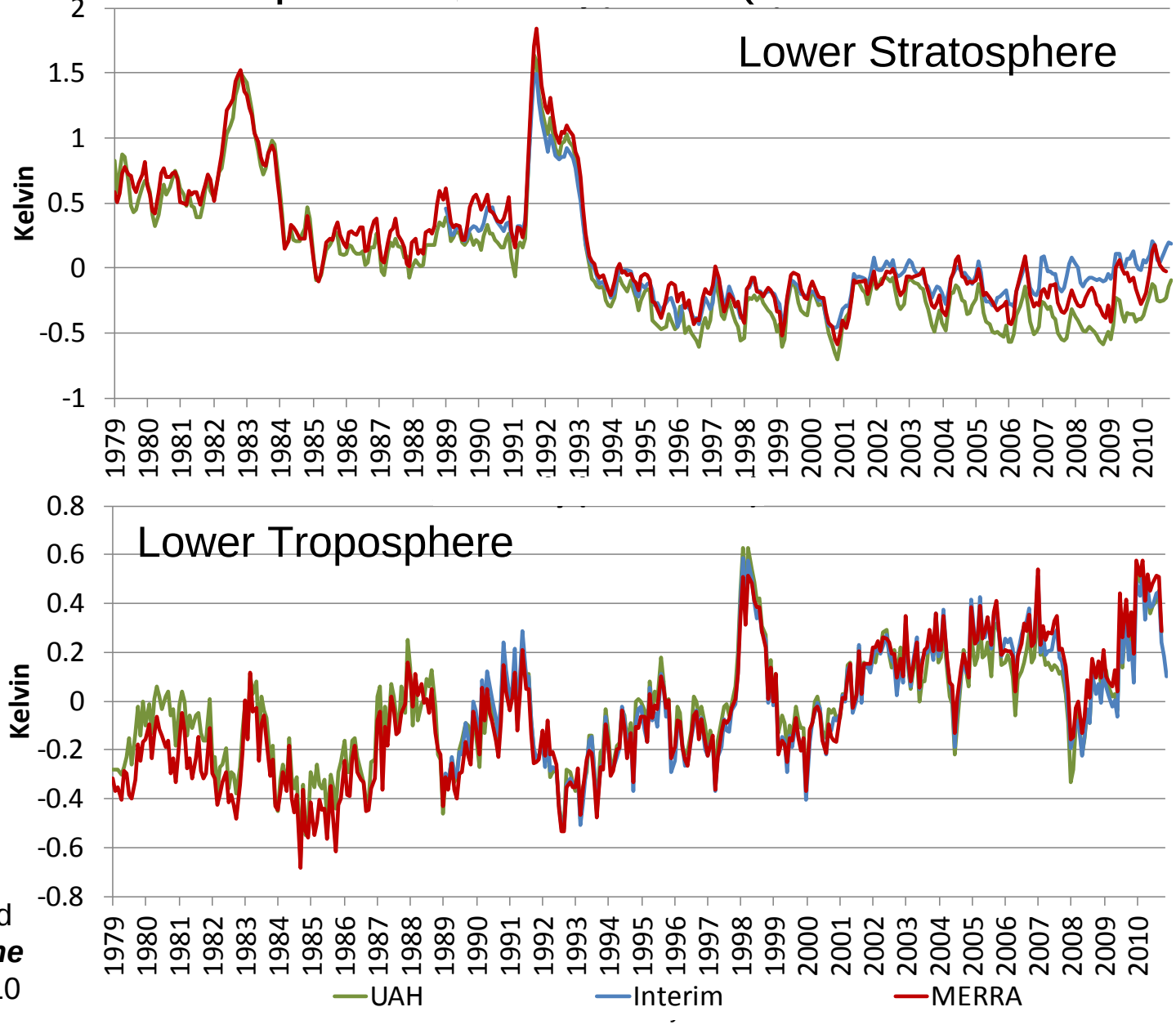



*MERRA system used intercalibrated data from NESDIS (SNO matchups, Zou et al. 2006)*

Q: Does use of inter-calibrated data (MERRA) vs non-calibrated data (ERA-Interim) impact the analysis? Or does VarBC take care of it?

# MERRA, ERA-Interim & MSU (UAH)

## Global mean temperature anomalies (rel. to 1989-2008 mean)

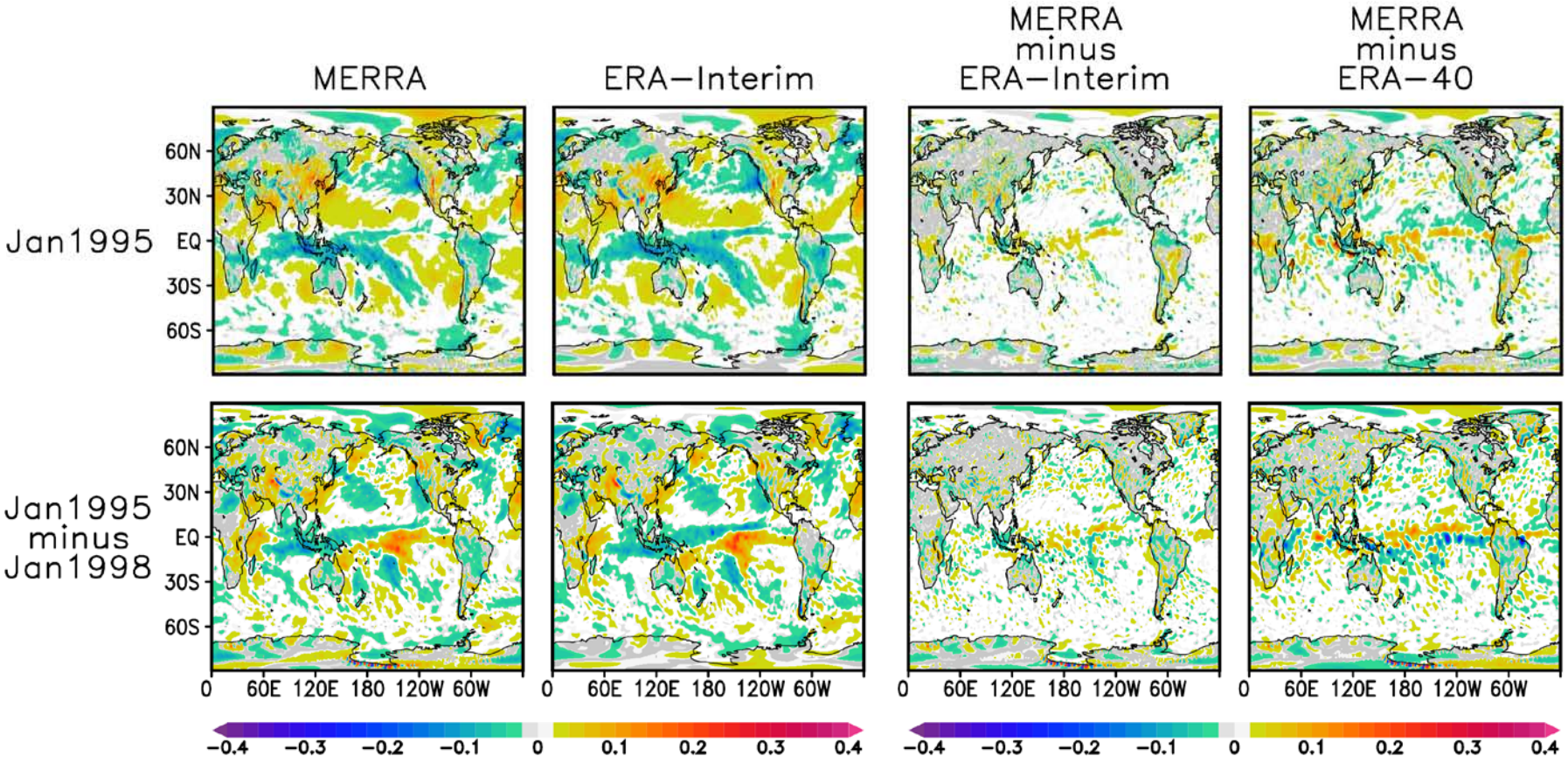



Data reported in ***State of the Climate***, 2010

# Agreement across Atmospheric Reanalyses

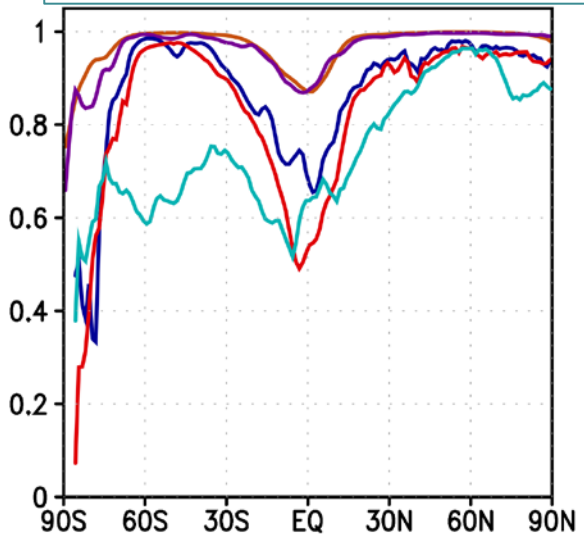
- Dynamical quantities agree well in the troposphere, even higher-order quantities such as vertical velocity, eddy transport of heat/momentum
- Give a consistent view of interannual climate variations

**500 hPa Vertical Velocity (Pa/s)**

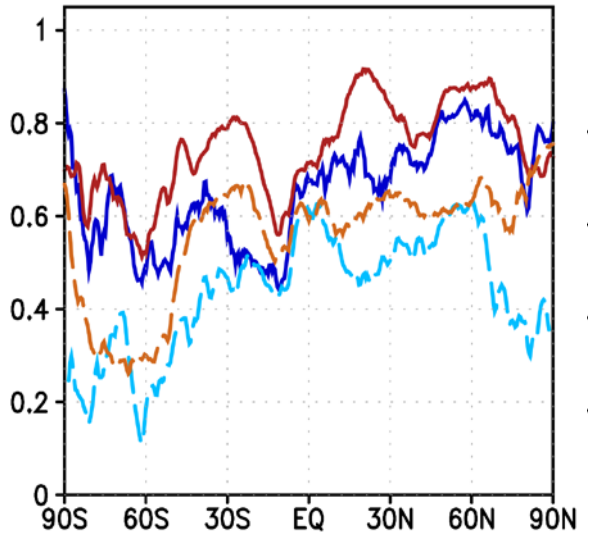


# Agreement across Atmospheric Reanalyses

**Zonal Mean of temporal correlations for January, 1990-2008**



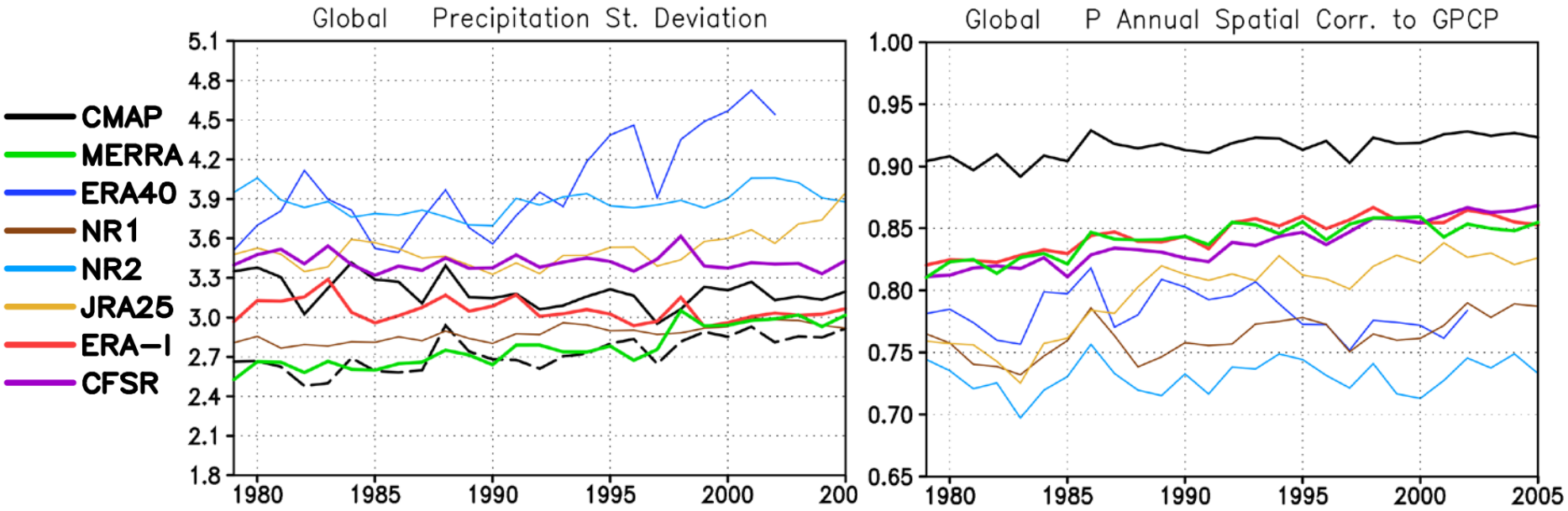

300mb Z-eddy: (MERRA versus ERA-Interim)
200mb U-wind: (MERRA versus ERA-Interim)
850mb U-wind: (MERRA versus ERA-Interim)
850mb V-wind: (MERRA versus ERA-Interim)
850mb Specific Humidity: (MERRA versus ERA-Interim)




PRECIPITATION: (MERRA versus ERA-Interim)
PRECIPITATION: (MERRA versus GPCPv2.1)
OLR: (MERRA versus ERA-Interim)
OLR: (MERRA versus NOAA)

# Annual Mean Precipitation

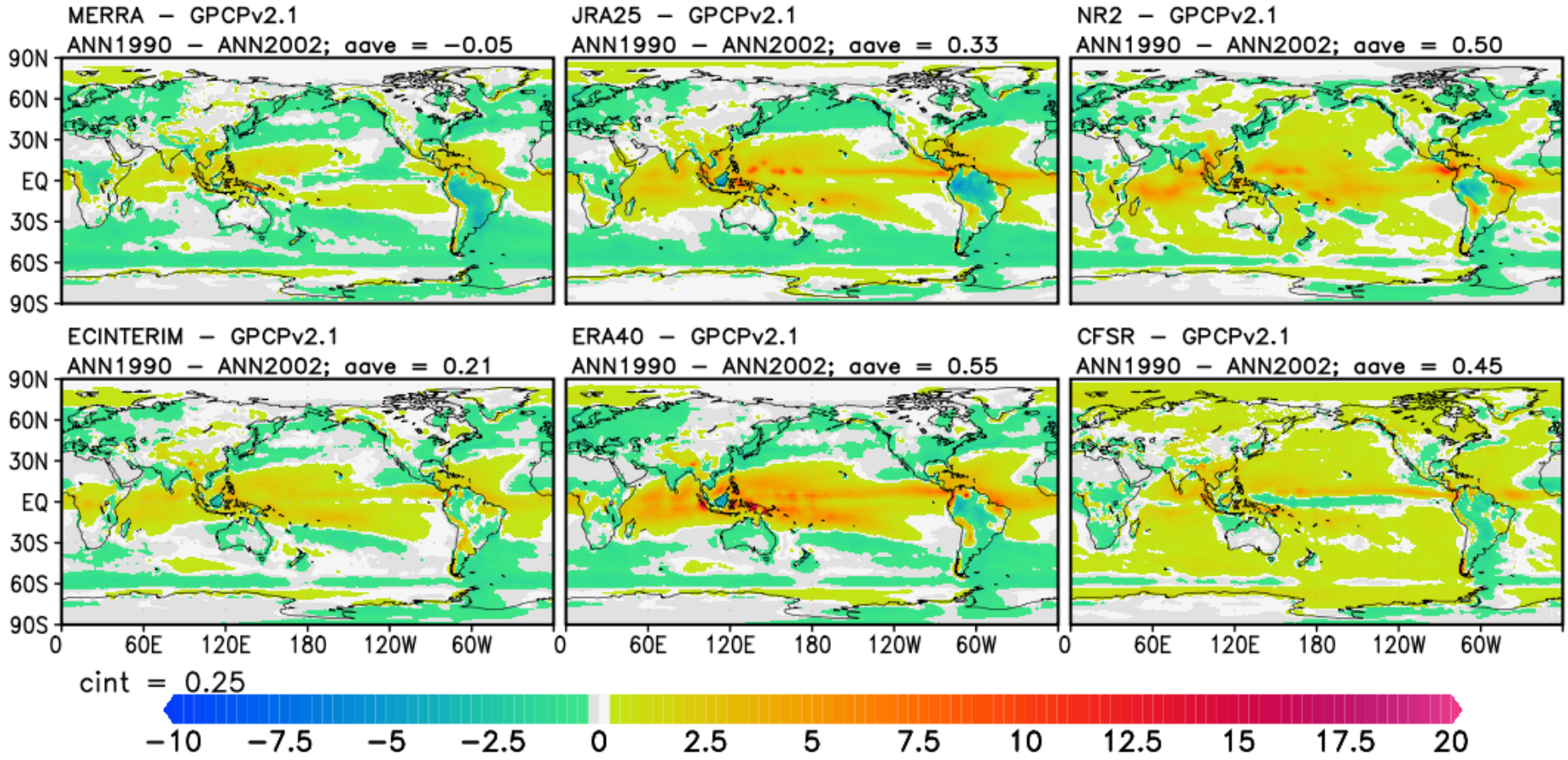
## Spatial standard deviation and spatial correlation to GPCP




## System improvements have aided the representation of spatial variations

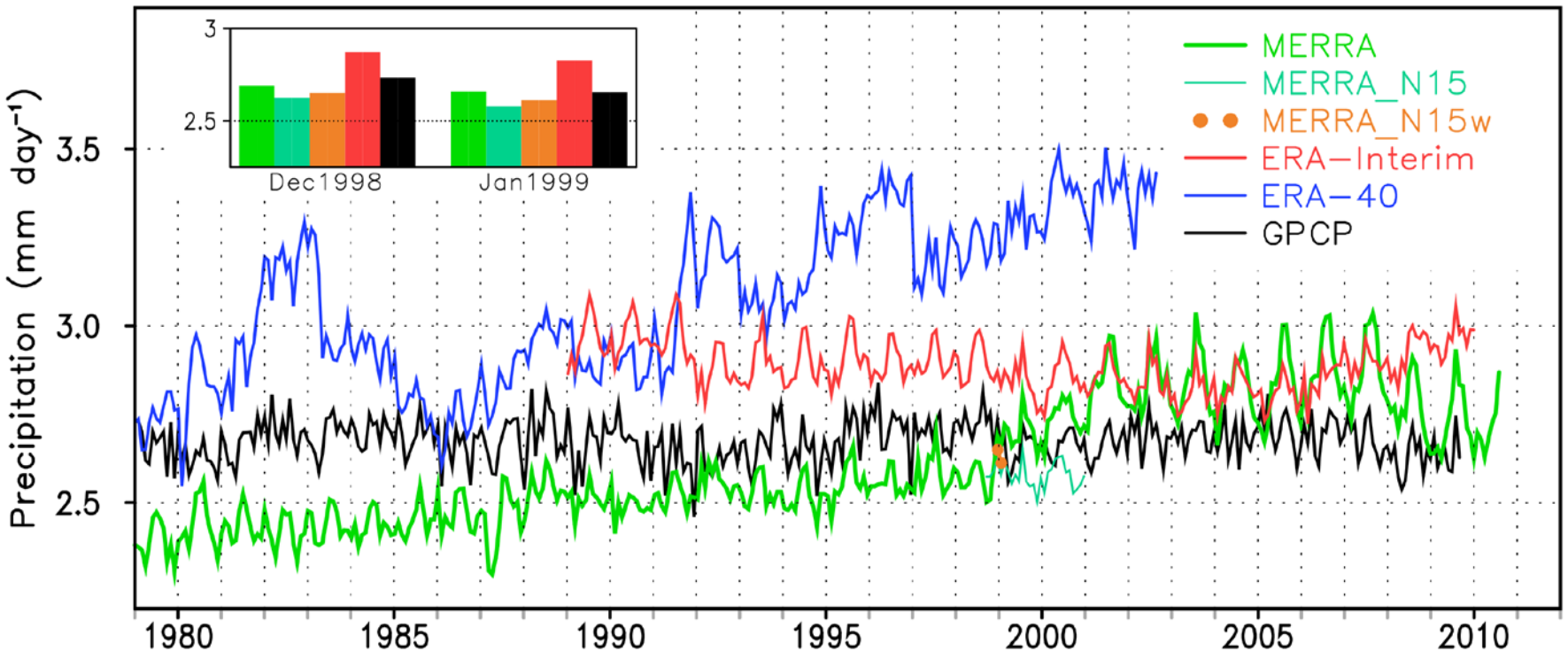
# http://gmao.gsfc.nasa.gov/ref/merra/atlas/

## Precipitation Comparisons from MERRA Atlas
## Annual mean (1990-2002) differences from GPCP

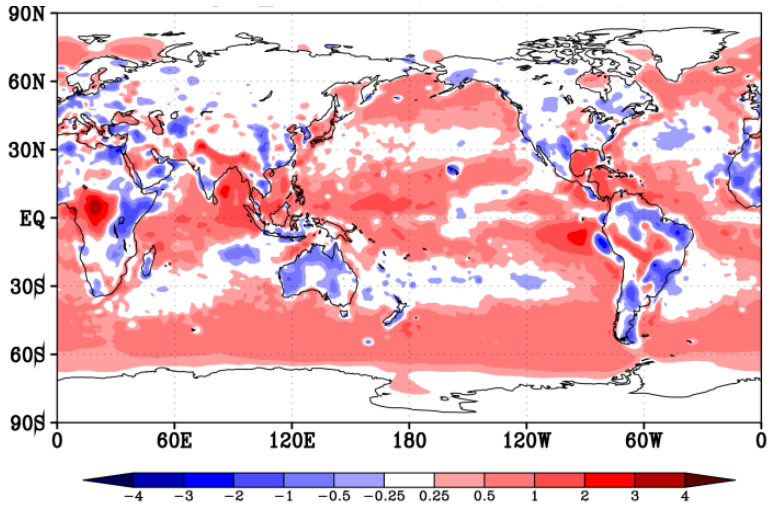


# System sensitivity to changes in the observing system

## Monthly Mean Global Precipitation



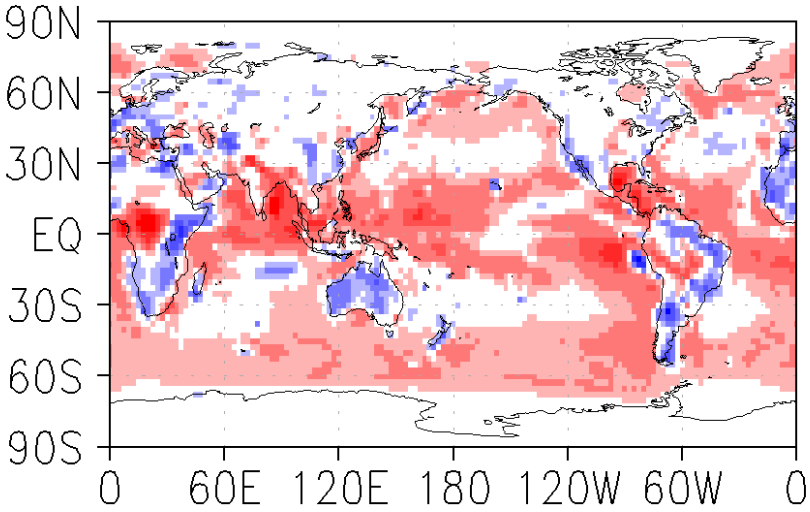
# MERRA Water Vapor Increment – observing system impacts

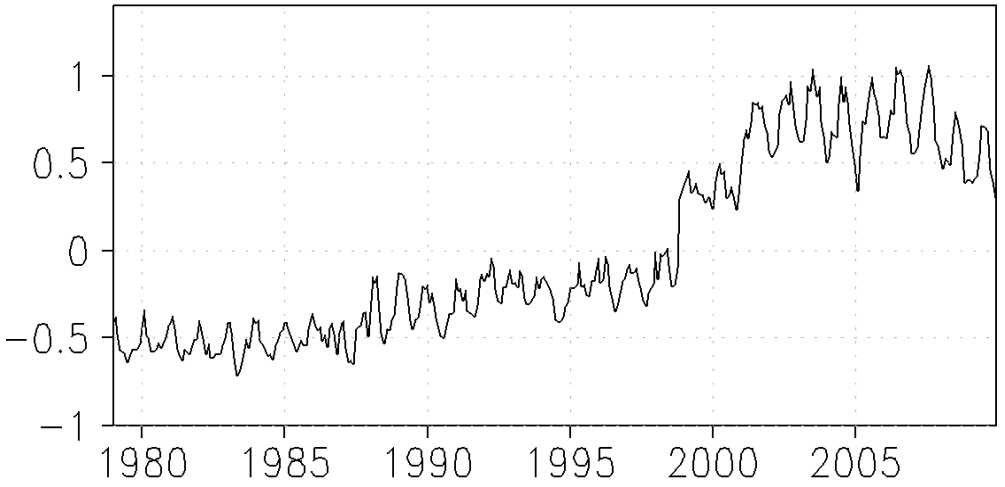



Water Vapor Increment Change
(mm day$^{-1}$)
2000-08 minus 1990-97

AMSU inst. in 1999 and 2001

1st EOF of vertically integrated $\Delta q_v^{ana}$ and its principal component



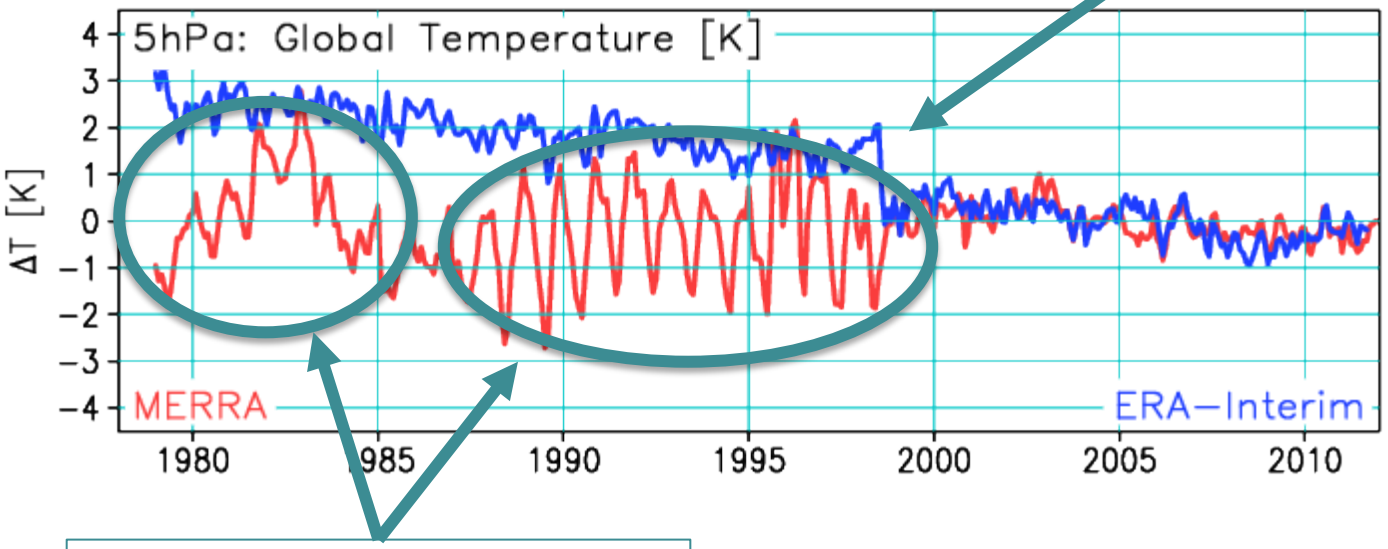

[*Robertson et al. 2011*]

# Issues to be Addressed: Changing Observing System

**5 hPa** global mean temperature anomalies
(rel. to 2000-2010 mean)

**MERRA, ERA-Interim**

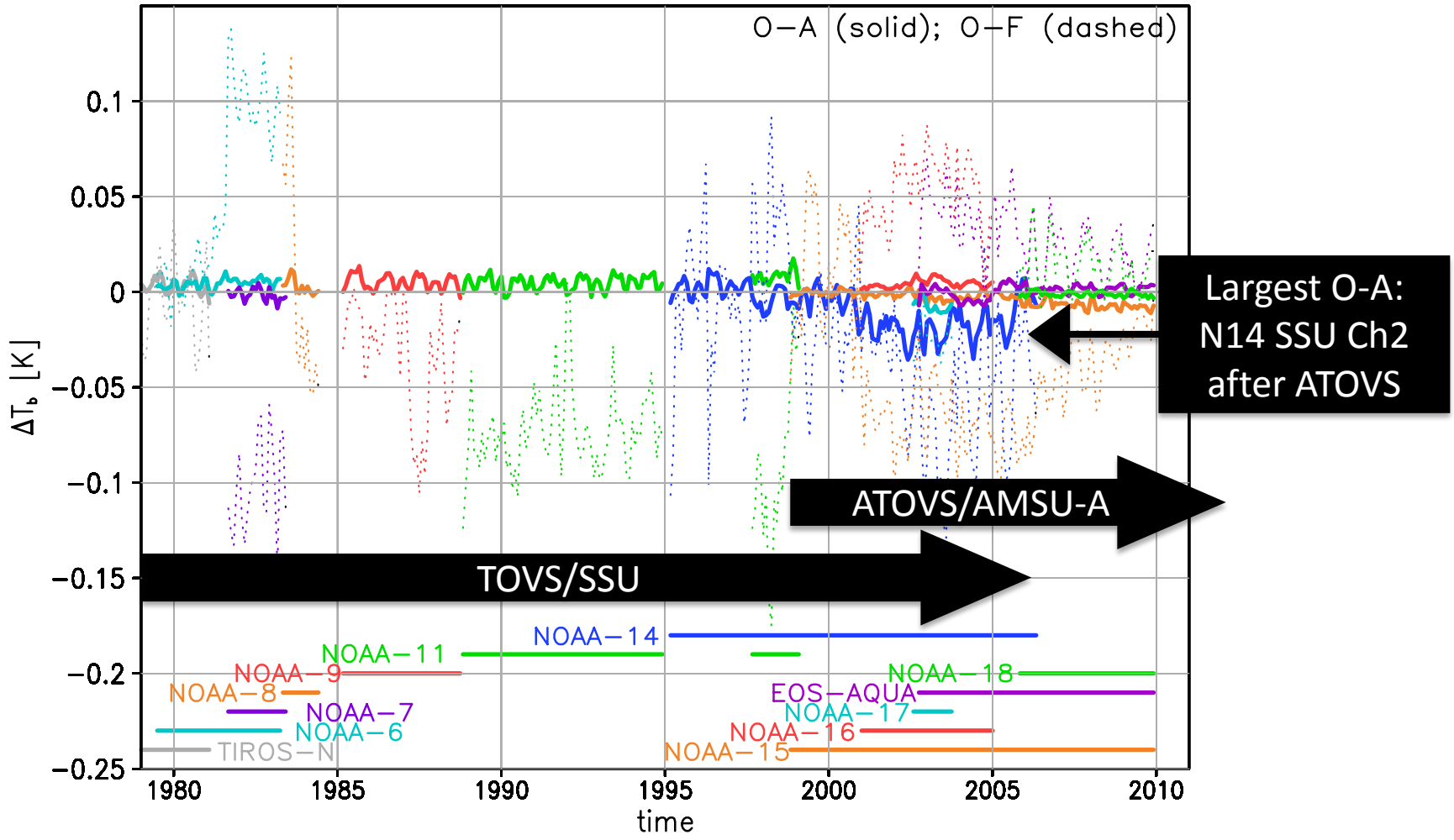
Arrival of AMSU-A, transition from SSU




Issue with handling of SSU RTM, bias corr., $CO_2$?

# To improve reanalyses: diagnose how the observations are used
# Much is encapsulated in the innovations and analysis departures

## SSU Channel 2 $T_b$
## Global av. O-A (solid) and O-F (dotted)



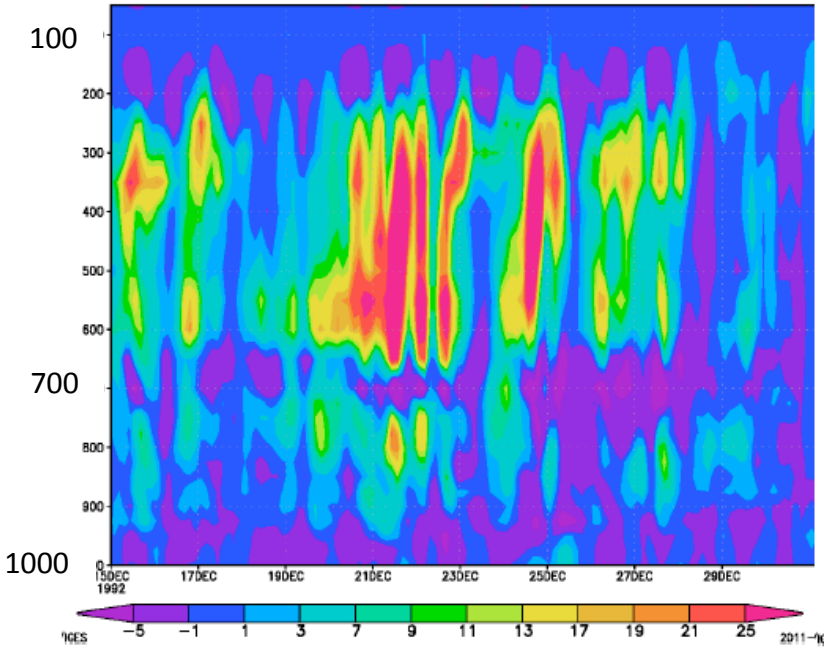
# MERRA Temperature Increment – diagnosing model biases

The assimilation increment is included in budgets as an *Analysis Tendency term*.

*Mapes and Bacmeister (J. Climate 2012) diagnosed tropical biases and the MJO using these Analysis Tendencies.*

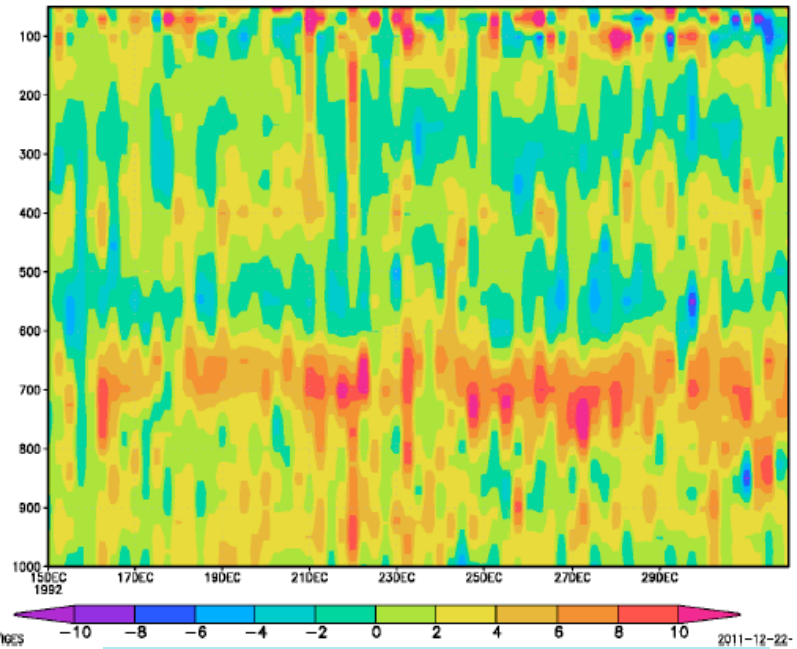
155.625E, 1.875S; 15-31 December 1992
(TOGA COARE Intensive Flux Array)

Total physical heating (K/day)




Cooling spikes at 700 hPa indicate misplaced melting, which should be at 550 hPa

Temperature analysis tendency (K/day)




Layered temperature structure disagrees with obs and leads to a correction by data assimilation.

# Atmospheric Reanalysis - beyond MERRA

April 2010, GSFC, Technical Workshop of Atmospheric Reanalysis Developers

Continuing to update reanalyses is still useful:

- To include improvements in data, using unused data (all-sky radiances, etc)
- To include improvements in models (e.g., **reduced biases**)
- As we develop the implementations to help deal with the changing observing system (e.g., changing B with the observing system)
- To provide fields needed for historical re-forecasts for short-term climate
- To make still further major improvements in the **water and energy cycle budgets**.

The main issues to be addressed for the next generation reanalyses:

- Improving the hydrological cycle
- Improving the quality of the reanalyses in the **stratosphere**
- Improving quality of the reanalyses over the **polar regions**
- Improving estimates of **uncertainty**
- Reducing spurious trends and jumps
- Reducing the size of the mean analysis increments

*Reanalysis.org* concept was born – implemented by Gil Compo - now active and growing

# Building an Integrated Earth System Analysis

GMAO strategy for IESA is stepwise, building on the GEOS-5 ADAS and assimilation systems for other components.

1. **MERRA+**
   MERRA u, v, T, q, $O_3$, $p_s$ drives
   Offline analyses Aerosols, Trace gases, ocean, land surface

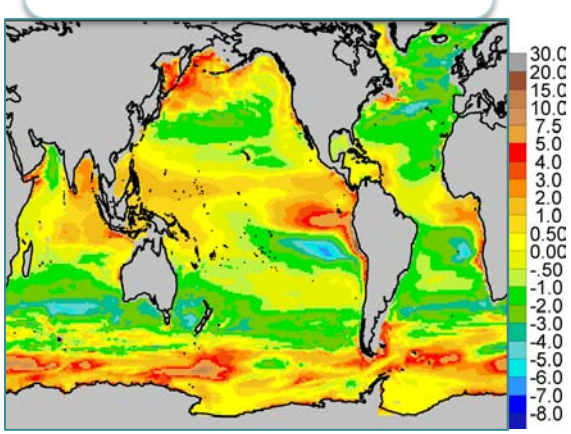
2. **Weakly coupled analysis**
   Atmosphere - Ocean analysis
   Atmosphere - Land analysis
   CO, $CO_2$ analysis
   Aerosol analysis

   } First guess from coupled system
   } Separate analyses

3. **GEOS IESA**
   More tightly coupled analyses
   Focused on the NASA EOS era

# MERRA-driven component reanalyses

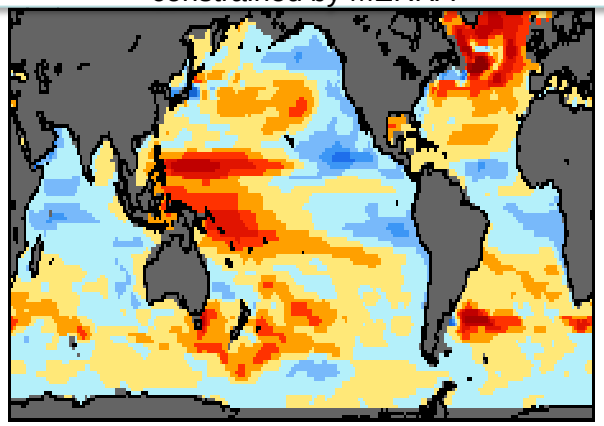
Annual Mean Air-sea $CO_2$ flux from ocean model (NOBM) forced with MERRA



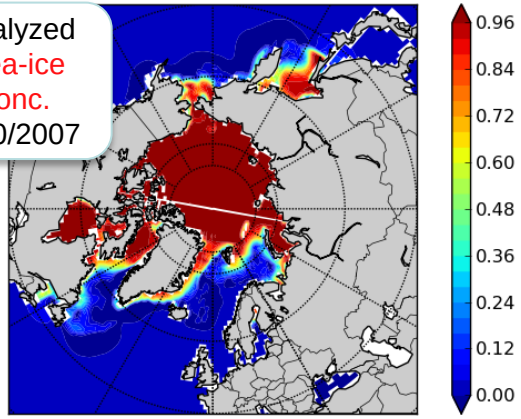

**Underway**:

- $CO_2$ (AIRS, AVHRR, MODIS)
- Aerosols (MODIS, MISR)
- Ocean (JASON, Argo, in situ)
- Sea-ice (ice concentration)
- Ocean biology (SeaWIFS, MODIS)
- Land surface (AMSR-E, ASCAT, SMOS, MODIS, GRACE)

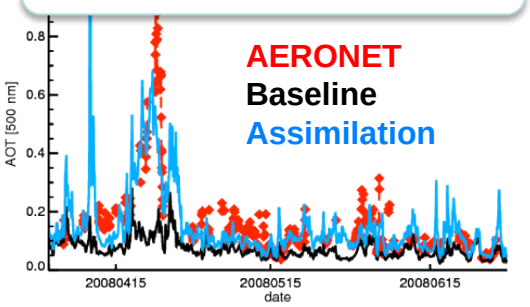
Linear trends of HC300, 1993–2009 from GMAO Ocean Reanalysis (°C/decade) constrained by MERRA



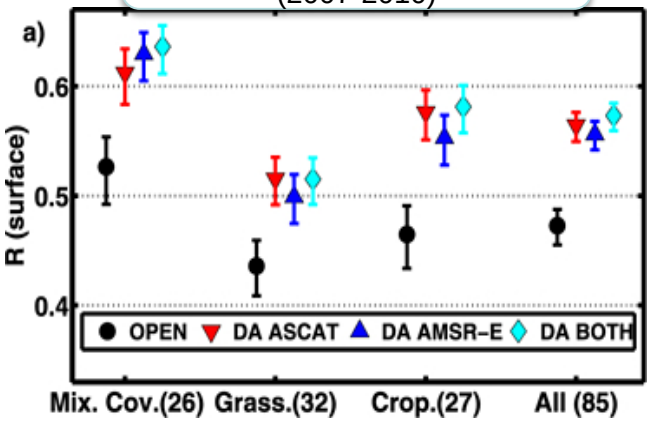
Analyzed Sea-ice conc. 2/20/2007




AOT (500 nm) at Bonanza Creek
Assimilation of MODIS data



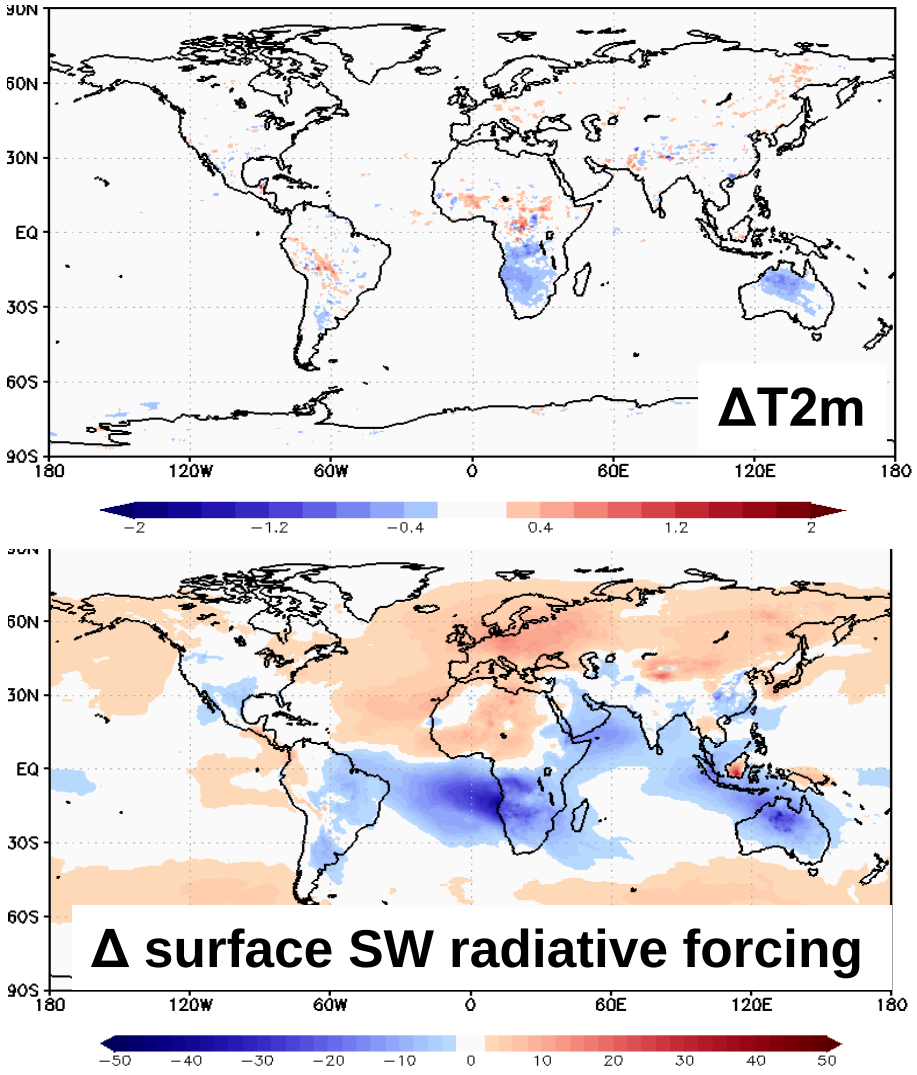

Improvements in soil moisture skill (R) from data assimilation (2007-2010)



# IESA: Impact of improved Aerosols
# Aerosols in the NRT GEOS-5 system

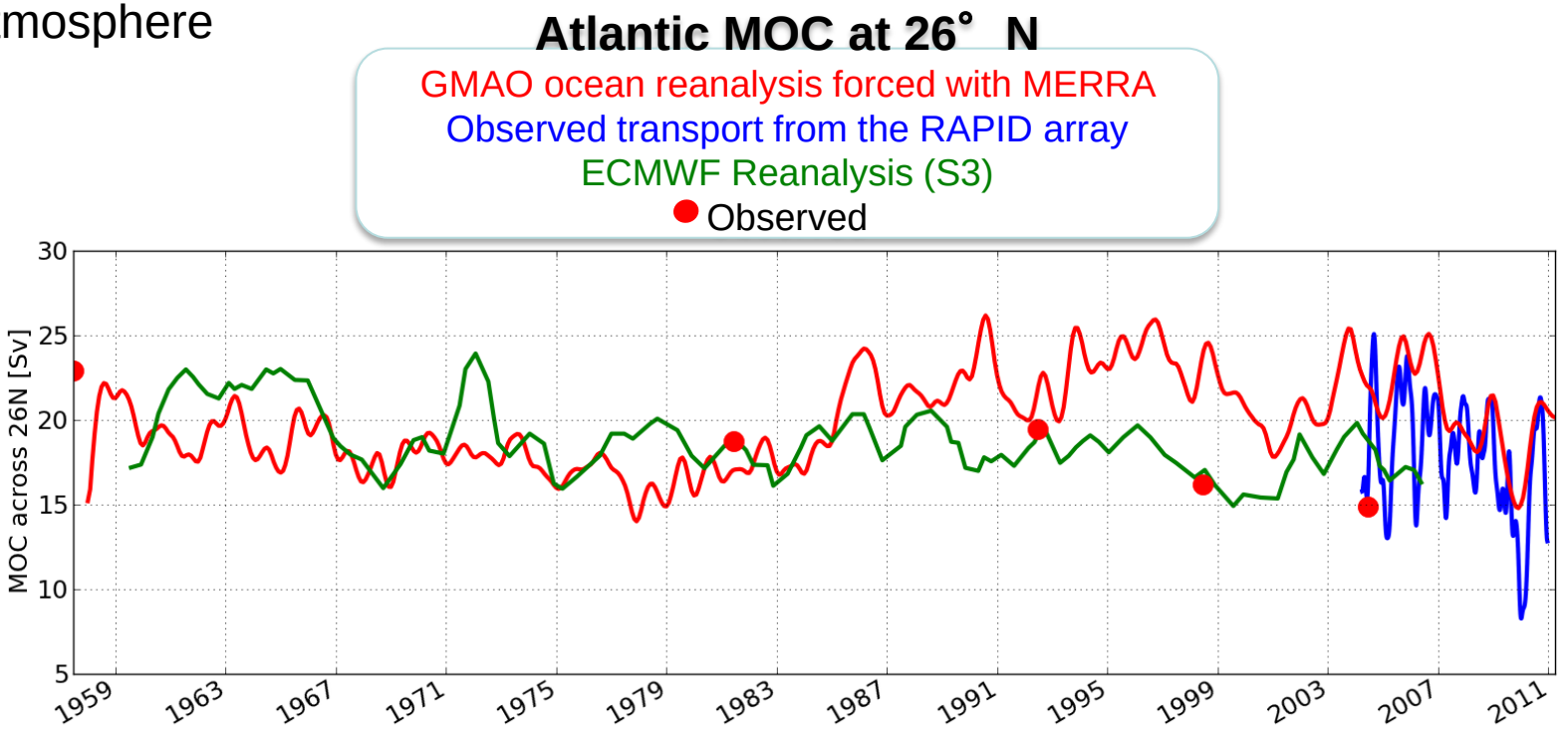
- Time-dependent aerosols modeled with GOCART
- Aerosol analysis implemented offline
- Updated aerosol fields provided to the model every 6 hours
- Impacts shown for Sept 2011
- Plots Δ (analysis with RT aerosols) - (analysis with prescribed climatological aerosols).

*See Arlindo Da Silva's presentation on Tuesday morning*



# IESA: Other Interactions
## Ocean and sea-ice data assimilation in GEOS-5 AOGCM constrained by MERRA

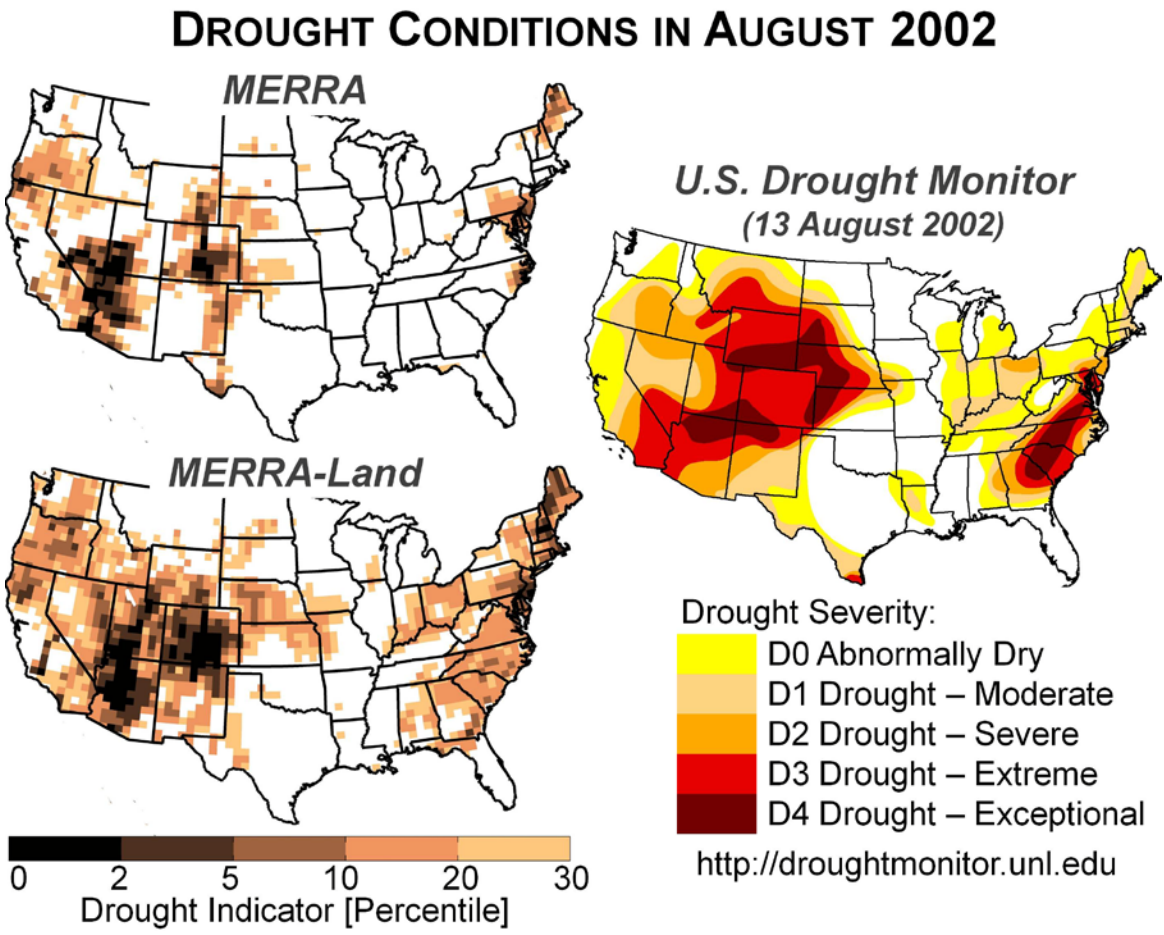
- MOM4 coupled to GEOS-5 AGCM and CICE
- Ocean observations assimilated daily, including corrected XBT data
- XBT, CTD, Satellite altimetry, Argo, sea-ice concentration
- Analyses used to initialize CMIP5 decadal predictions
- Observing system changes are just as problematic for the ocean as for the atmosphere



# IESA: Other Interactions
## Importance of improving precipitation in analyses – MERRA-Land

- Catchment LSM driven offline with MERRA and corrected precipitation
- Global gauge-based precipitation data from CPC used to correct MERRA
- MERRA-Land collection is served at the GES DISC
- Underway: assimilation of soil moisture, snow water equivalent, skin temperature, water storage

*See Rolf Reichle's presentation on Wednesday morning*




**http://gmao.gsfc.nasa.gov/merra/merra-land.php**

# Summary

- MERRA and other current reanalyses represent an advance on the previous generation (ERA-40, NR1, NR2, …)
  - Interannual tropospheric variability is now almost indistinguishable in directly analyzed fields and getting closer in some aspects of the divergent flow, but still problematic in moisture-related fields.
  - Issues also remain in the stratosphere in the TOVS era
- Problems lie partly in model biases and partly in the treatment of observations
  - *Attention needed on how observations are used – an area that still remains to be mined; an area for which international coordination and collaboration are needed*.
- MERRA products include information on increments and observation feedback files
  - Analysis tendency terms are useful in diagnosing issues with how observations are used and model biases
  - Gridded observation files (O-F and O-A) that are available for further diagnostics
- Phased approach to IESA is being used to identify issues that need to be addressed in a truly integrated analysis.

# MERRA On-line Resources

- **http://gmao.gsfc.nasa.gov/merra**
  - **MERRA Atlas** (**http://gmao.gsfc.nasa.gov/ref/merra/atlas/**)
  - **MERRA-Land** as an update to land-surface collection **http://gmao.gsfc.nasa.gov/merra/merra-land.php**
  - MERRA is online at PCMDI's ESG for CMIP5 model evaluations

- Data Access: GES DISC (**http://disc.sci.gsfc.nasa.gov/mdisc/**)