MODERN ERA REANALYSIS FOR RESEARCH AND APPLICATIONS VERSION-2 (MERRA-2)

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Global Modeling and Assimilation Office

Overview

- Project Summary and Motivation
- Water Cycle and UTH
- Energy Budget and Temperature
- Weather
- Plans

Modern-Era Retrospective analysis for Research and Applications (MERRA)

- 1979-Present (will not continue, depending on radiance observations availability)
- ½° lat x ⅔° lon, 42 pressure levels (derived from 72 terrain following model levels)
- 1 hourly Surface/2D fields, 3 and 6 hourly 3D fields; over 300 variables
- NCEP GSI analysis (~2008)
- GEOS5 GCM (~2008)
- Offline land (MERRA-Land) and ocean reprocessing products
- Gridded Innovations and Observations (GIO)

MERRA-2 Motivation and Objectives

Produce an ongoing, intermediate reanalysis for the satellite era using a recent version of GEOS-5 to

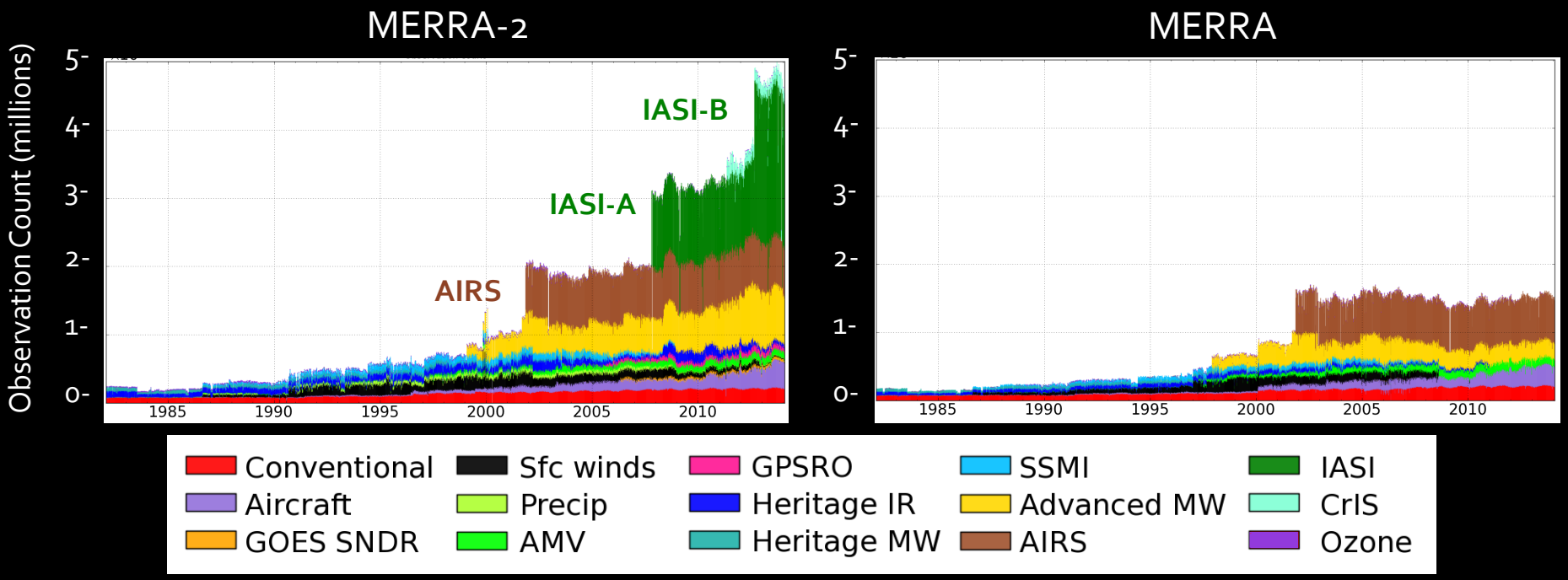
(1) address known limitations of MERRA (c. 2008), and

(2) provide a stepping stone to a *future coupled Earth system reanalysis.*

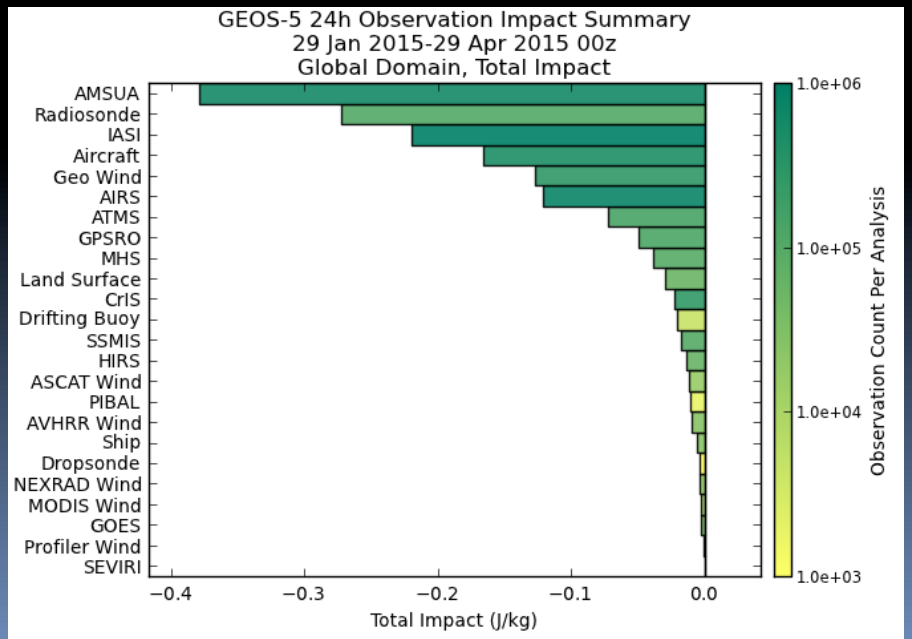
Specifics:

- Incorporate modern satellite observation types not available to MERRA
- Reduce spurious trends and jumps related to changes in the observing system
- Reduce biases and imbalances in the water and energy cycles
- Test coupling GOES-5 meteorology with other Earth system components

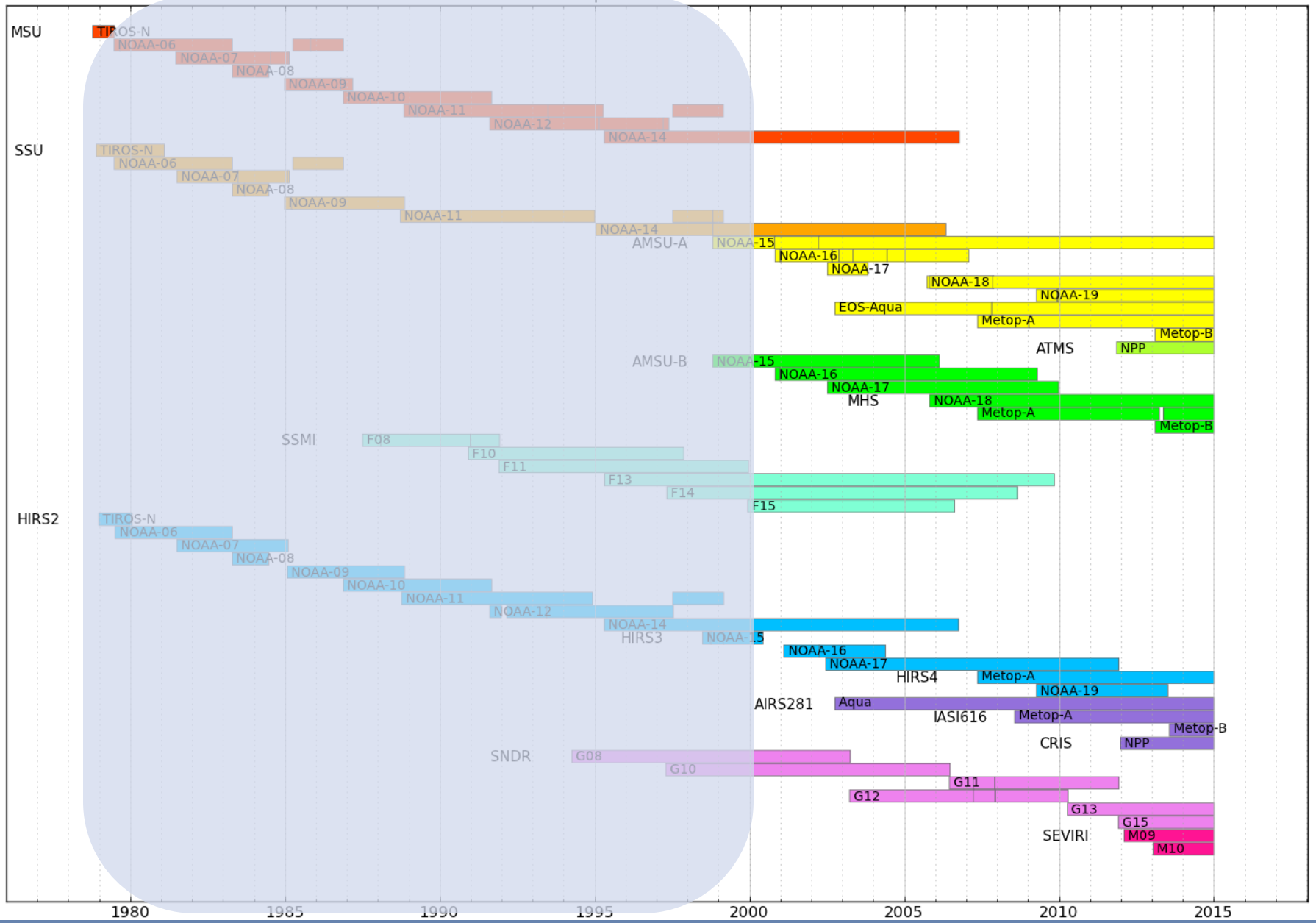
Observing system time series for MERRA and MERRA-2



- Data counts increase as more hyper-spectral sensors become active
- No microwave radiance data after NOAA-18 in MERRA
- Data counts for MERRA could decrease rapidly, especially if AIRS data were no longer available
- In MERRA-2, current, AMSUA, IASI, and AIRS provide most global impact from radiances



MERRA-2 Input Radiances



The MERRA-2 data assimilation system

GEOS-5.12.4 AGCM/GSI 3D-Var

0.5° x 0.625° x 72 hybrid-eta levels to 0.01 hPa

MERRA ⇨ MERRA-2 Evolution

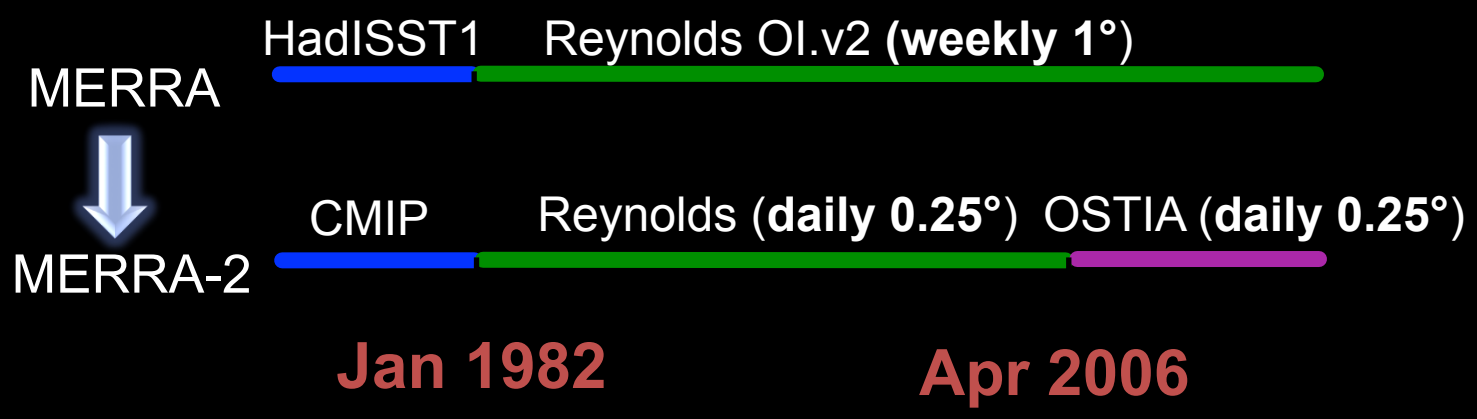
- **Updates to the AGCM and GSI**

  AGCM
  - *Cubed-sphere dynamics*
  - *Updated physics: limited deep convection, re-evap of rain, snow sublimation*
  - *Improved glacier model and cryosphere albedos*

  GSI
  - *Modern observations: GPSRO, NOAA-19, MetOp-A/B, S-NPP, SEVIRI, Aura OMI and MLS, capable for JPSS, MetOp-C*
  - *Updated moisture control variable and background errors*
  - *Bias correction for aircraft temperature observations*
  - *Balance constraint for noise*
  - *TC Relocation*
- **Aerosol assimilation with radiative coupling to AGCM (direct effects)**
- **Constraints on dry mass and globally integrated water**
- **Corrected precipitation for land surface forcing and aerosol deposition**

Surface boundary conditions and emissions

SST and Sea Ice Concentration

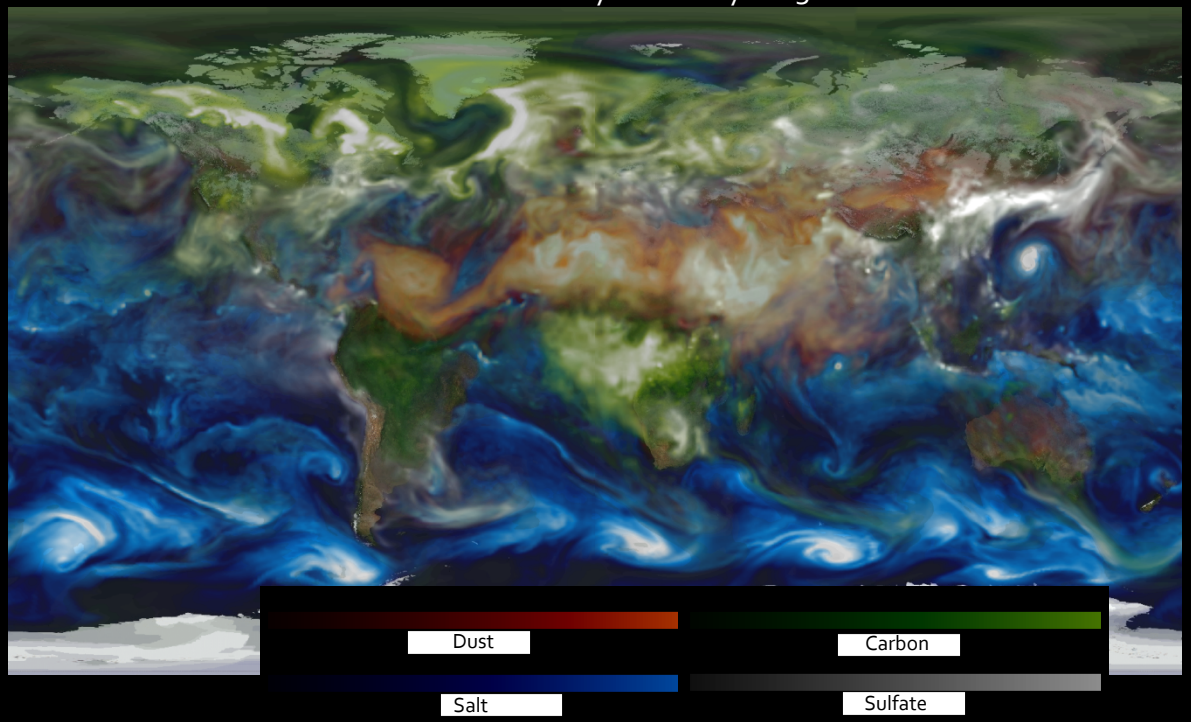


Aerosols and Trace Gasses

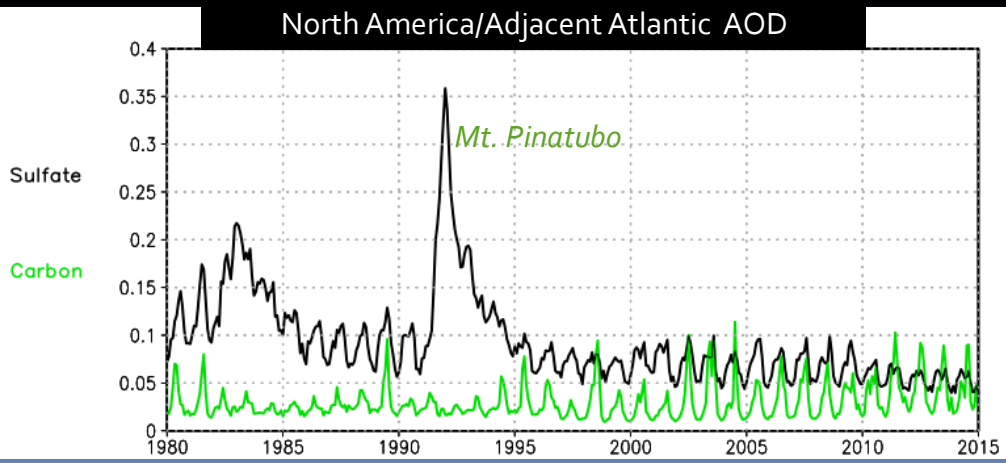
- CO fossil fuel emissions *(EDGAR inventory)*
- Biomass burning *(QFED after 2010, RETRO before)*
- Volcanic SO_2 *(AEROCOM emissions and injection heights)*

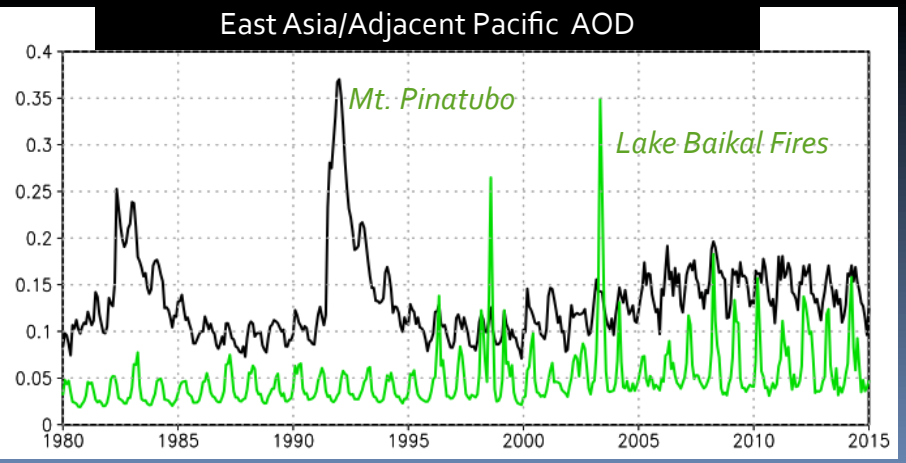
Aerosols and Trace Gases in MERRA-2

MERRA-2 Aerosol Analysis 10 July 2013 1200UTC



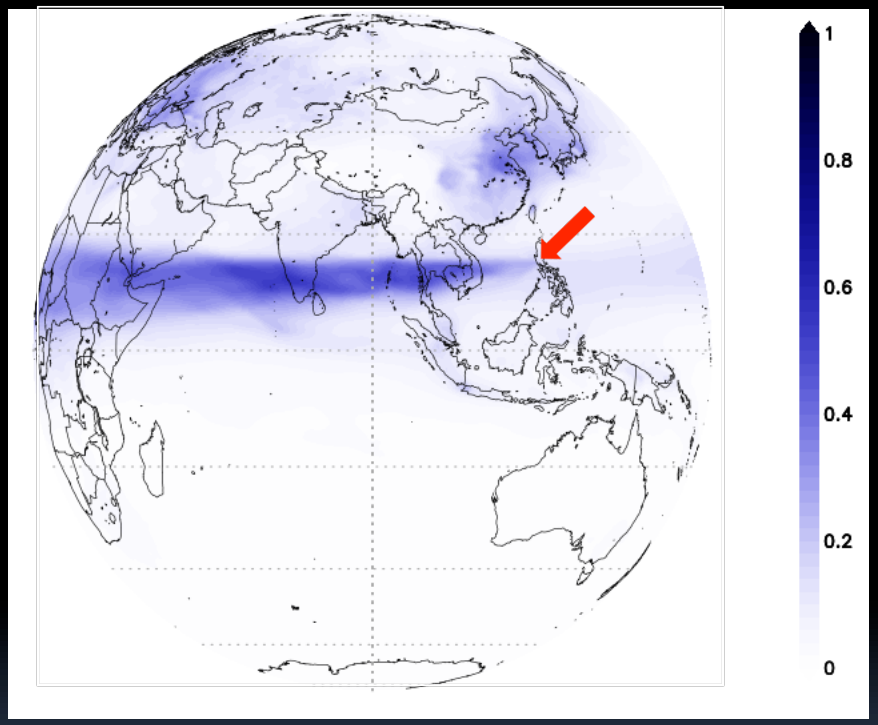
- **Black and organic carbon, dust, sea salt, sulfates**
- GOCART – mixing, chemistry and deposition
- Radiatively coupled with the dynamics
- Global 2-D AOD analysis with 3-D increments via local displacement ensembles
- Data: AVHRR 1979–2002; MODIS 2000–present; MISR; AERONET



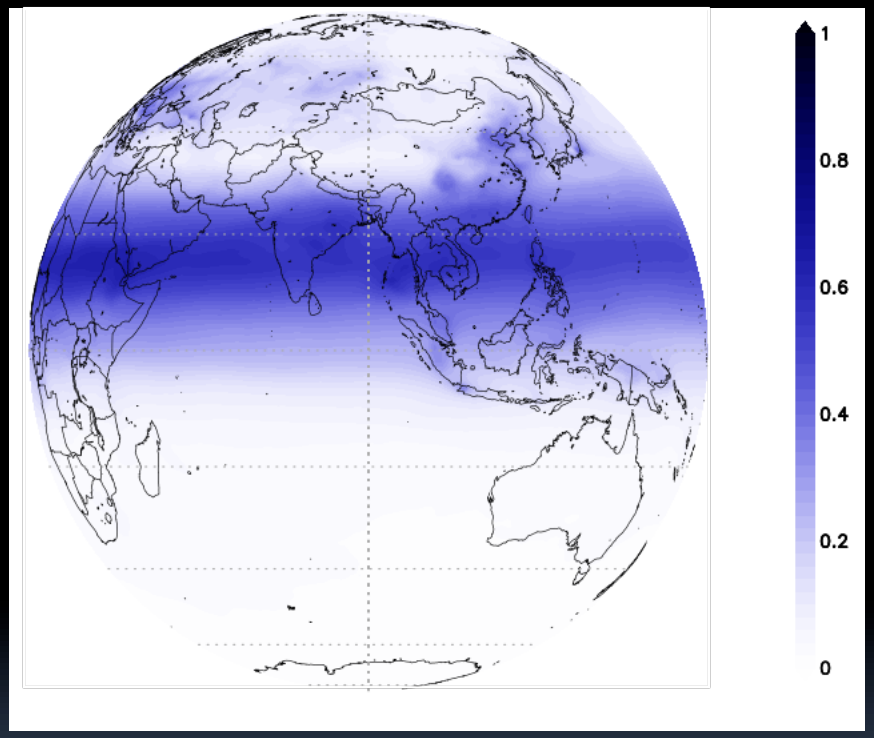


MERRA-2 depiction of Mt. Pinatubo eruption in June 1991

MERRA-2 **Sulfate AOD** June 1991



MERRA-2 **Sulfate AOD** July 1991

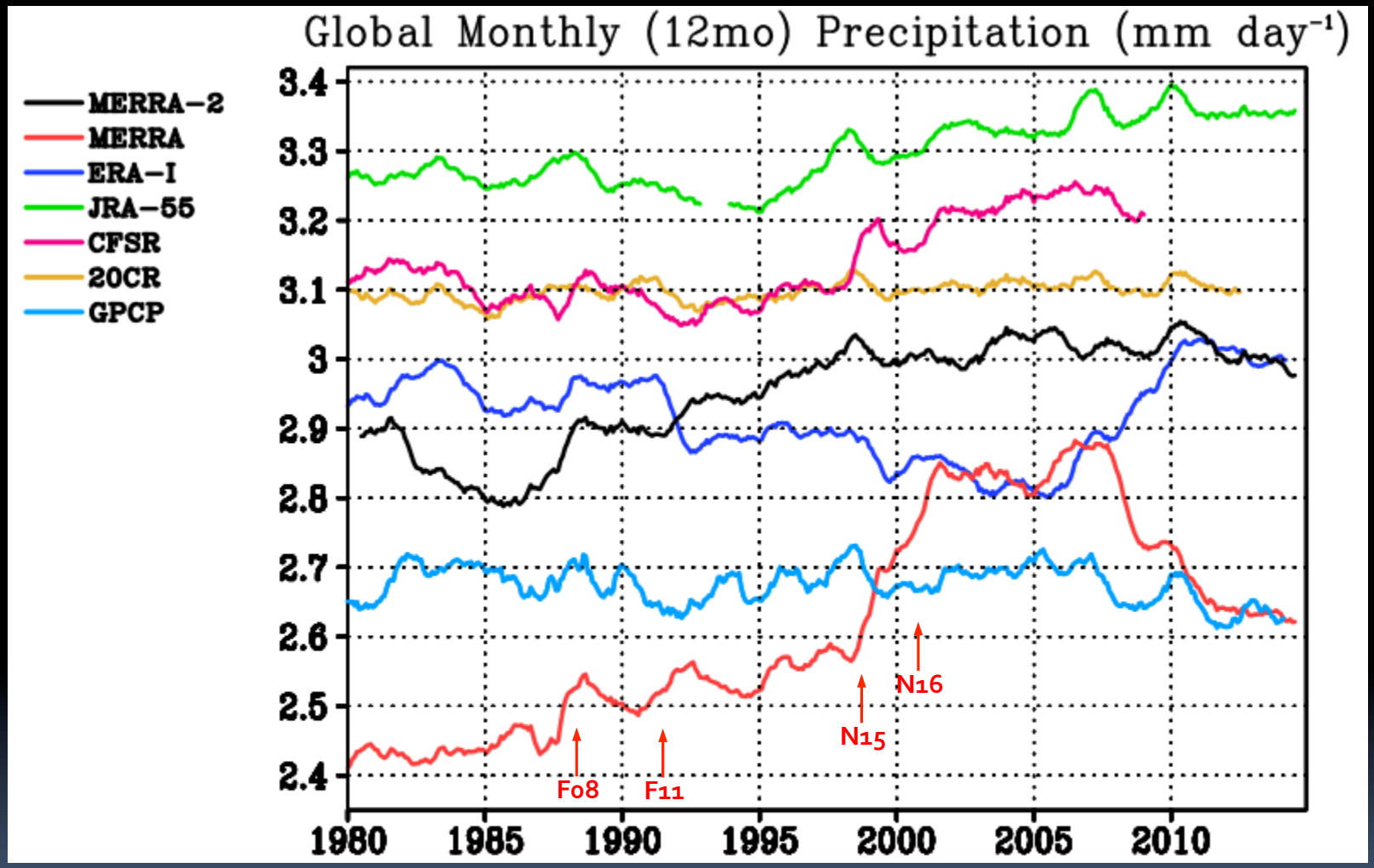


MERRA-2 captures the Mt. Pinatubo eruption in June 1991

The eruption sent a thick sulfate plume rapidly upwards into the stratosphere, which fanned out westward on the prevailing easterly winds aloft (left). By July 1991, the sulfate plume encompassed the tropics globally (right).

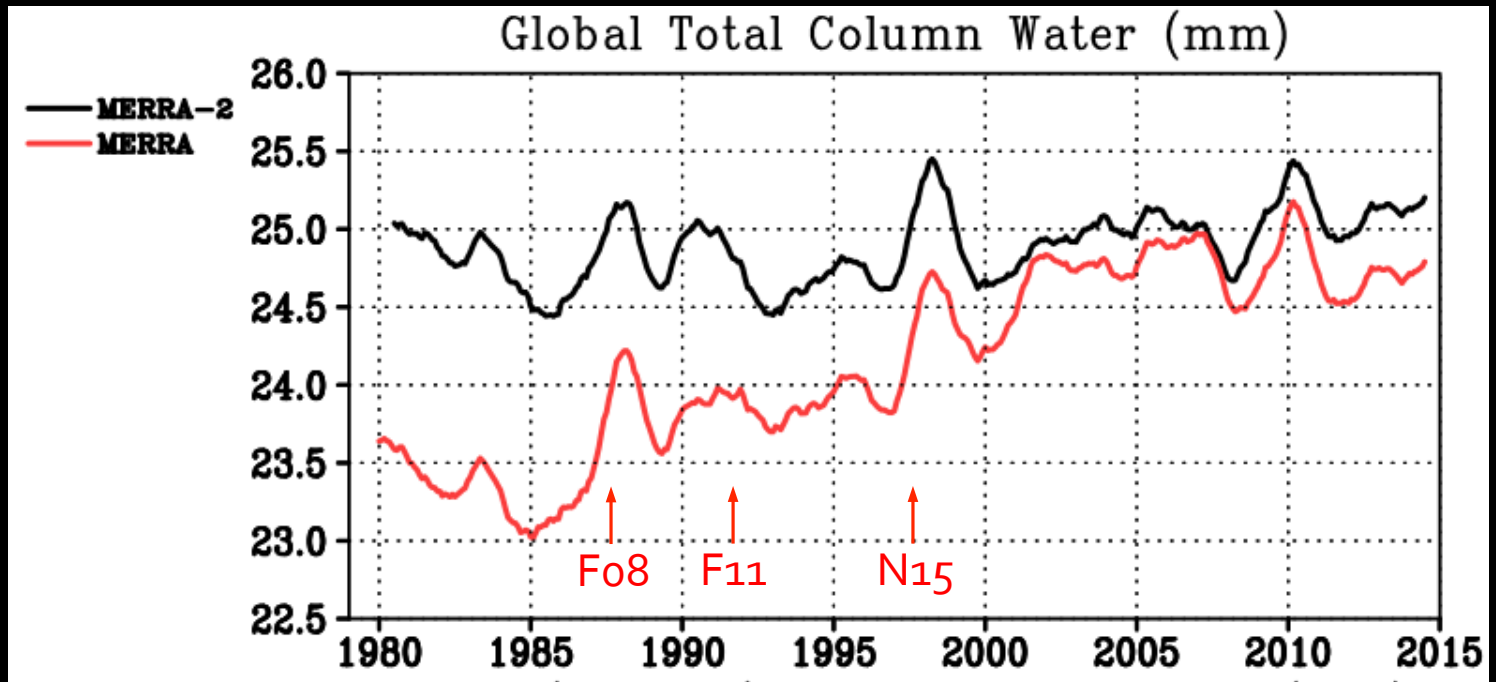
Water Cycle

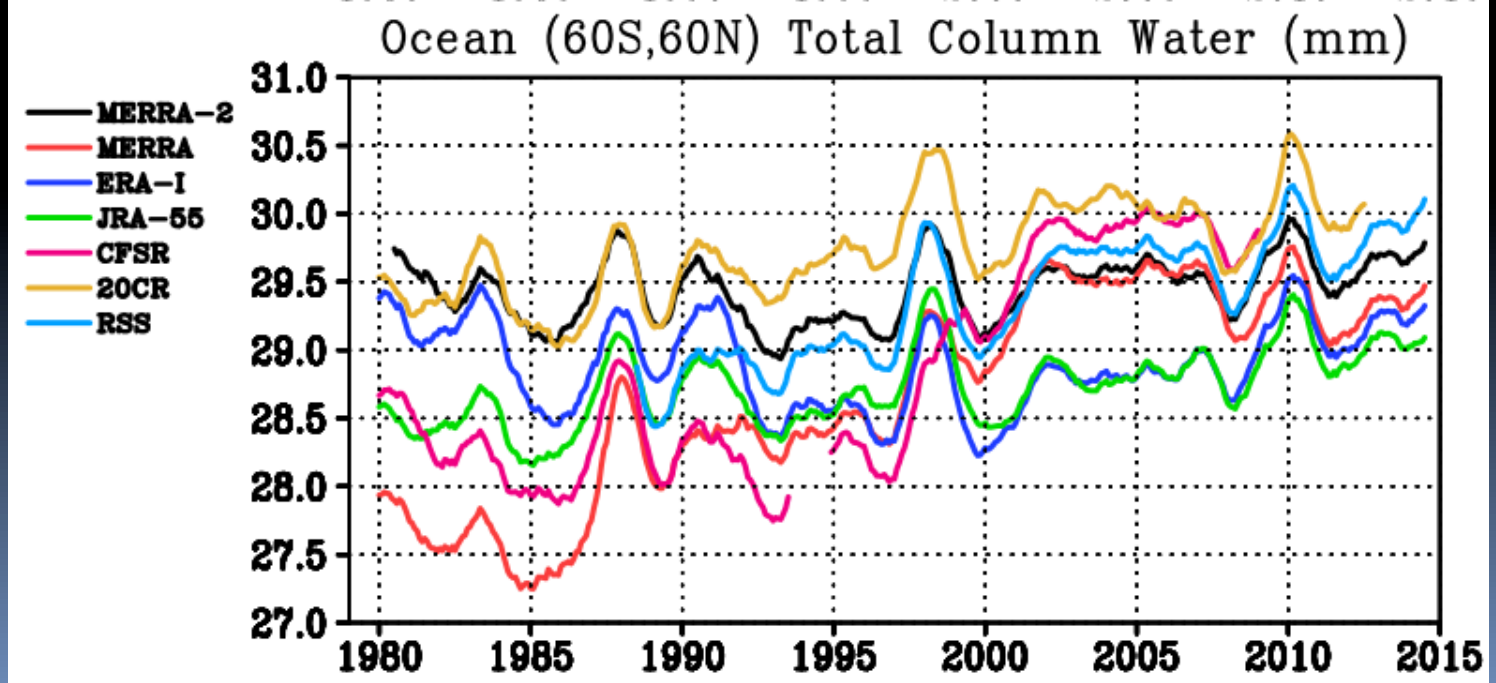
Time series of global precipitation



MW data sources with large impact on MERRA have somewhat less impact on MERRA-2 Precipitation

Time Series of Total Precipitable Water

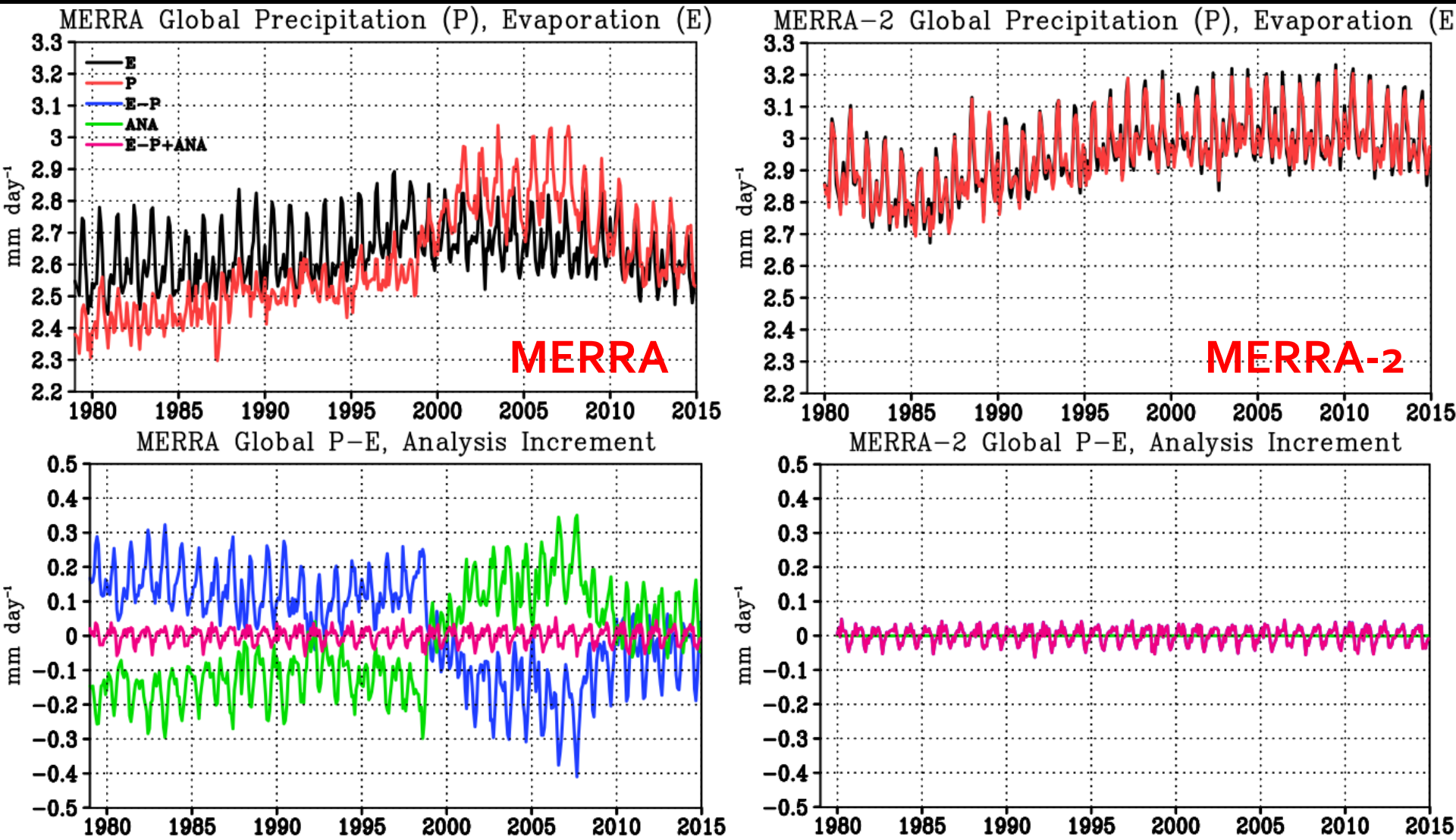




MW data sources with large impact on MERRA have much less impact on MERRA-2 Global TPW

Globally precipitation, evaporation and analysis forcing

Surface pressure and water vapor analyses are penalized for global imbalances (Takacs et al., *NASA GMAO Tech Memo, 2015)*

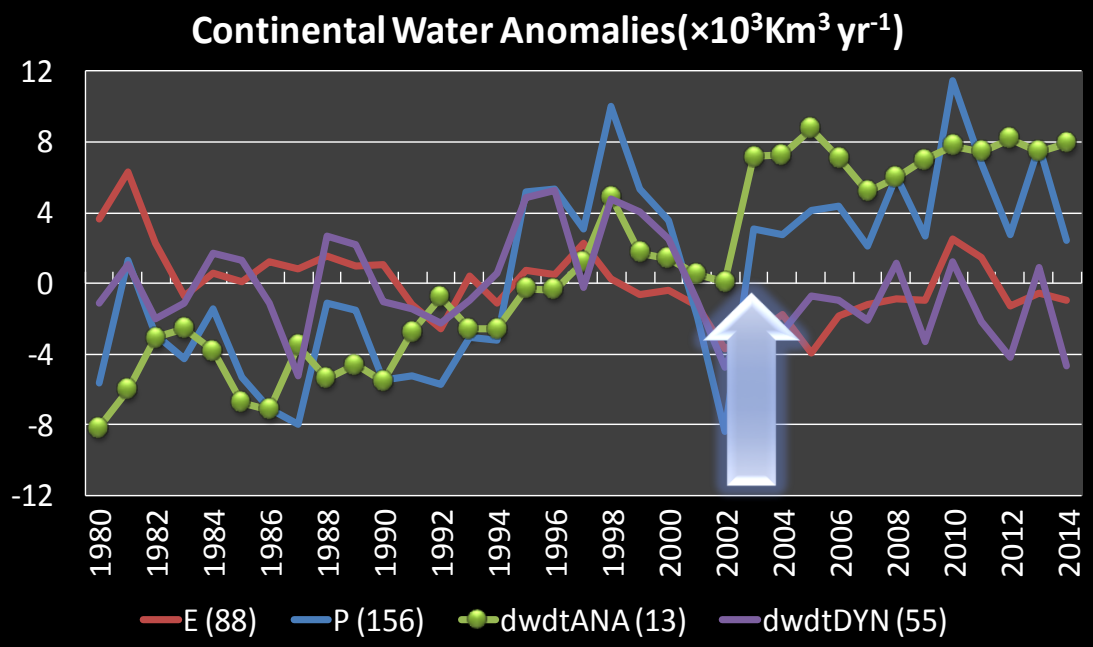


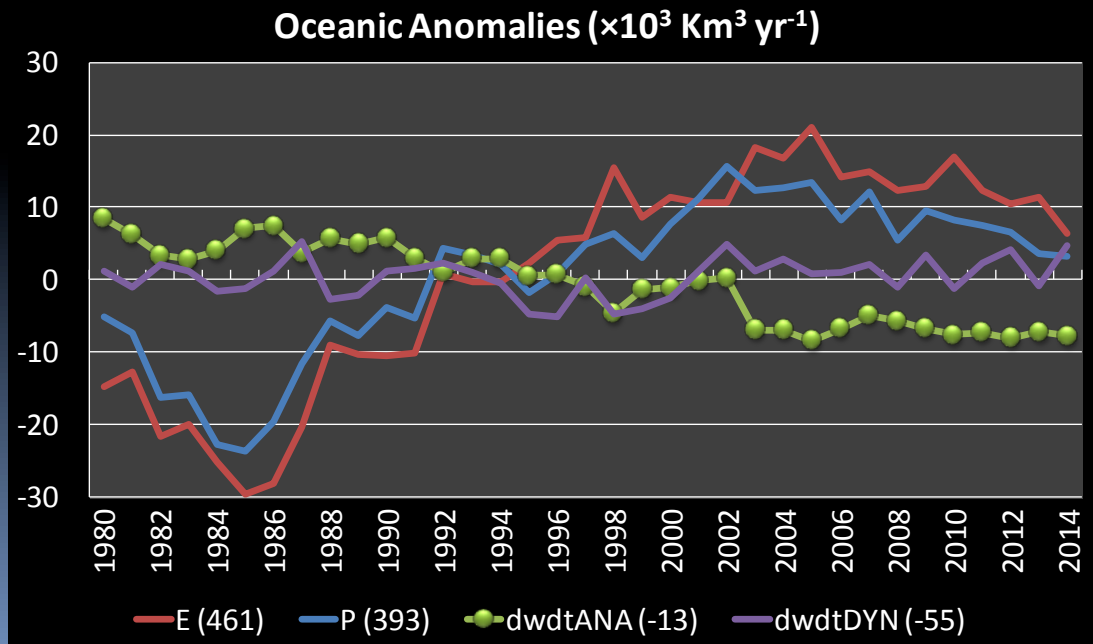
In MERRA, imbalances of P and E result from analysis adjustments, sensitive to changes in the observing system.

In MERRA-2, unphysical changes in total mass are ameliorated and global balance between P, E is maintained

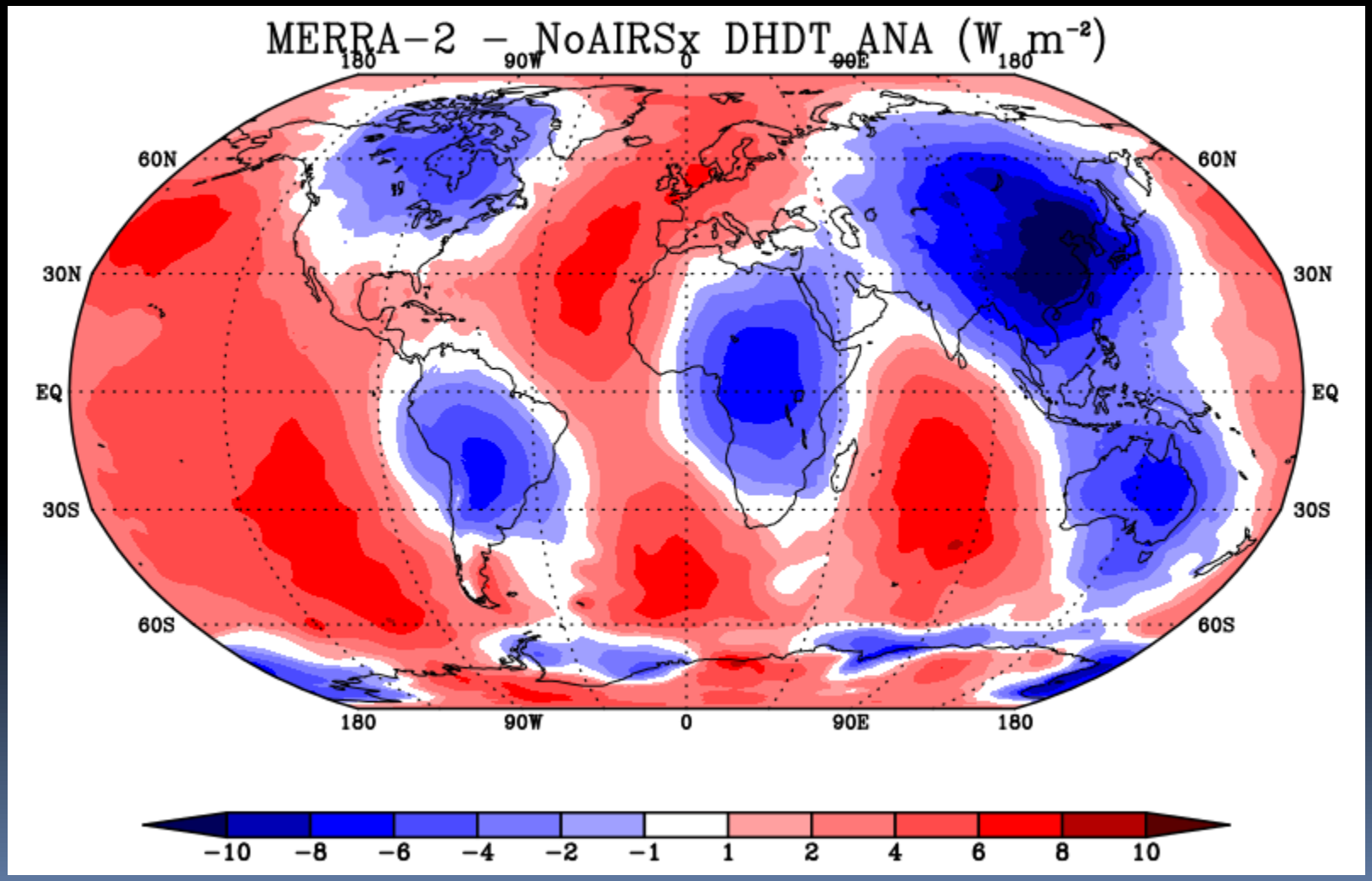
Land/Ocean Water Mass Budgets

- Ocean Precipitation and evaporation track each others variability, than the analysis increment
- Land evap follows the bias corrected precip. Land model precip follows the analysis increment trend
- Increment jump in 2003 due to AIRS?





Aside: AIRS Withholding Experiment



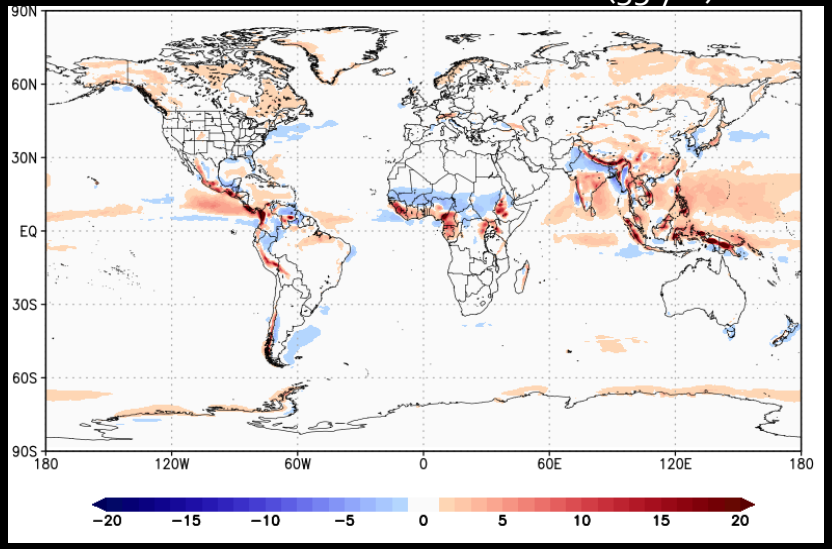
AIRS Withholding Experiment

W m^{-2}	Global	Land	Ocean
E	86.7 (0.5)	44.4 (0.0)	106.3 (0.8)
LPr	87.6 (0.5)	82.6 (-2.9)	89.9 (2.1)
HANA	-2.9 (-0.9)	-1.9 (2.4)	-3.4 (-2.4)
TOA(Net)	-4.5 (0.1)	-16.4 (0.4)	1.0 (-0.1)
Sfc(Lwnet)	-61.7 (-0.4)	-69.3 (-0.6)	-58.2 (-0.3)
Sfc(Swnet)	162.6 (0.4)	148.4 (0.9)	169.1 (0.2)

- 2003-2005 MERRA-2 without AIRS
- Land/Ocean offset in Latent Heat and Analysis Increment (~0.1 mm day^{-1} Pr)

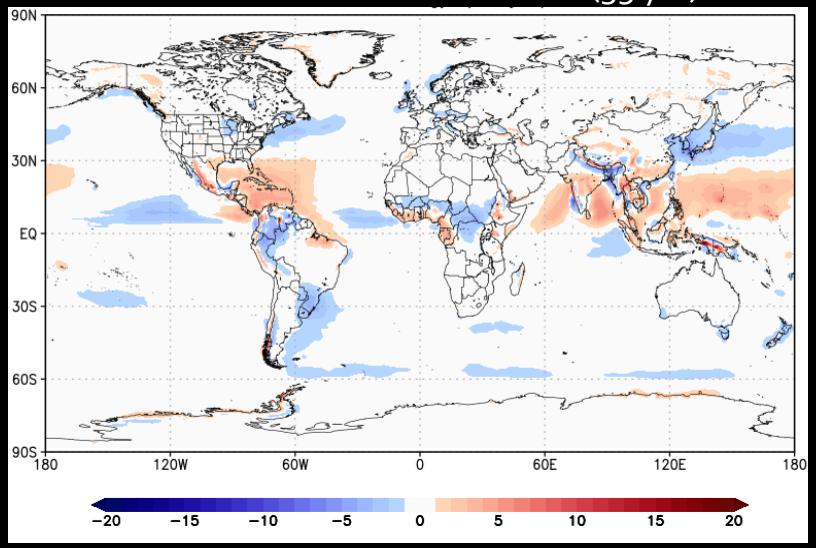
MERRA-2 Precipitation comparison with MERRA, GPCP

MERRA-2 minus GPCP JJA (35 yrs)



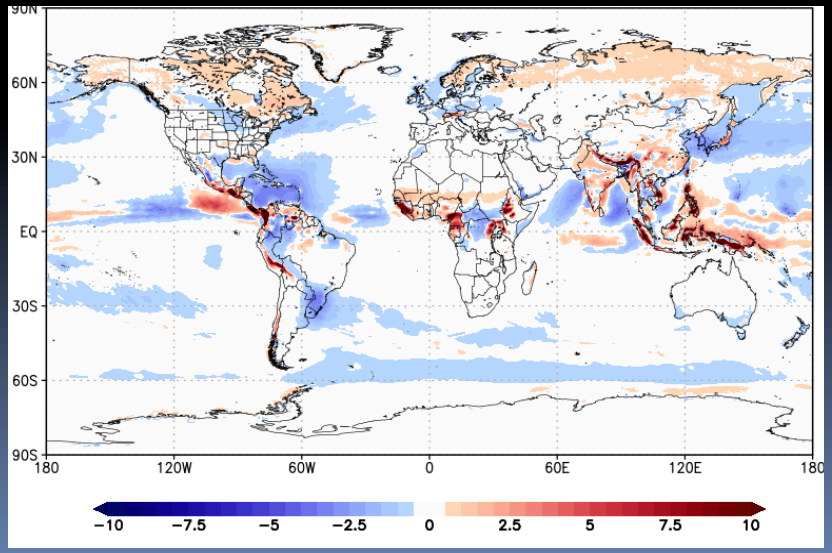
mm/day

MERRA minus GPCP JJA (35 yrs)



mm/day

ABS(MERRA-2, MERRA) vs. GPCP JJA (35 yrs)



mm/day

Blue shades imply MERRA-2 closer to GPCP than MERRA

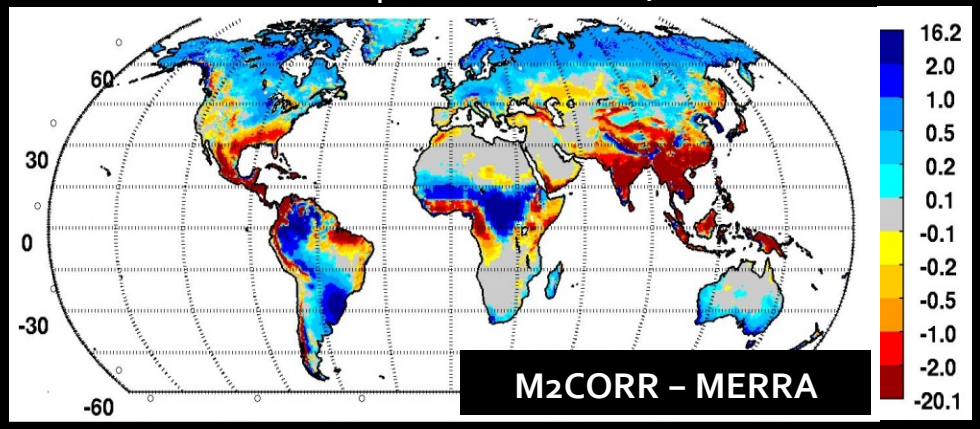
MERRA-2 improves over oceans, but rains excessively over tropical high terrain

Corrected precipitation forcing of the land surface

The **land surface** in MERRA-2 sees precipitation that is a mix of observations and model-generated precipitation.
(Reichle and Liu, *NASA GMAO Tech Memo, 2014)*

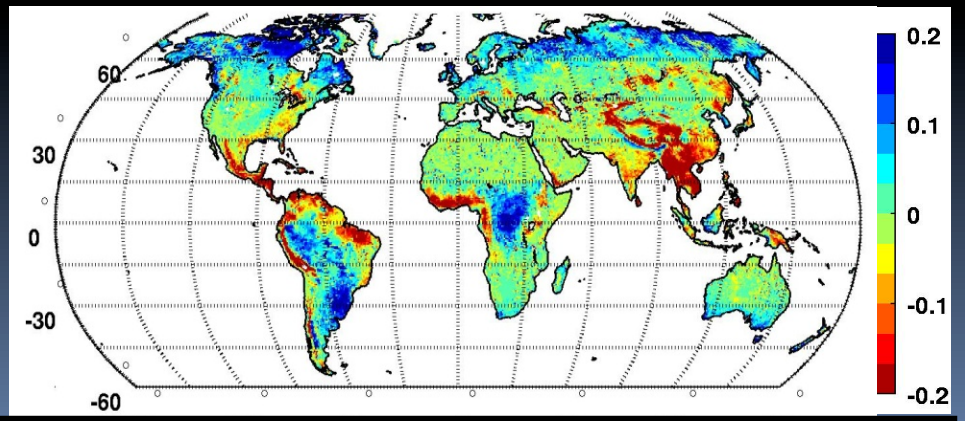
- Daily gauge-based **CPCU** data used over midlatitudes and tropics, except Africa
- Pentad gauge- and satellite-based **CMAP** data used over Africa
- Precipitation generated by **MERRA-2** itself used over high latitudes

Precipitation - JJA (27)



- MERRA-2 **root zone soil wetness** differs from that of MERRA due to differences in precipitation forcing and, to a lesser extent, differences in catchment model parameters.

Root Zone Soil Wetness – JJA (27)



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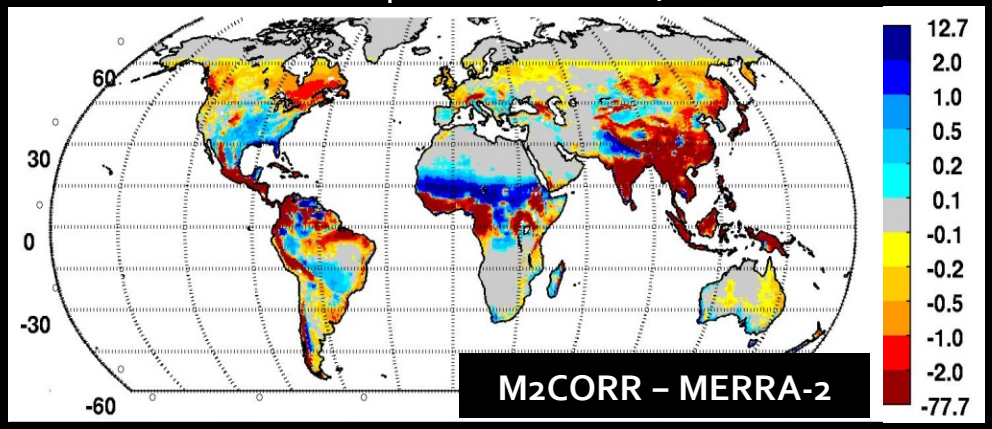
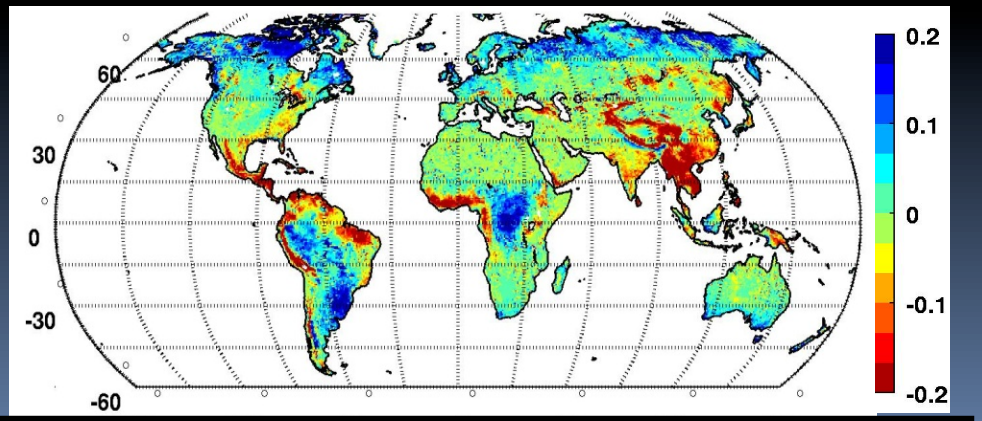


- MERRA-2 **root zone soil wetness** differs from that of MERRA due to differences in precipitation forcing and, to a lesser extent, differences in catchment model parameters.

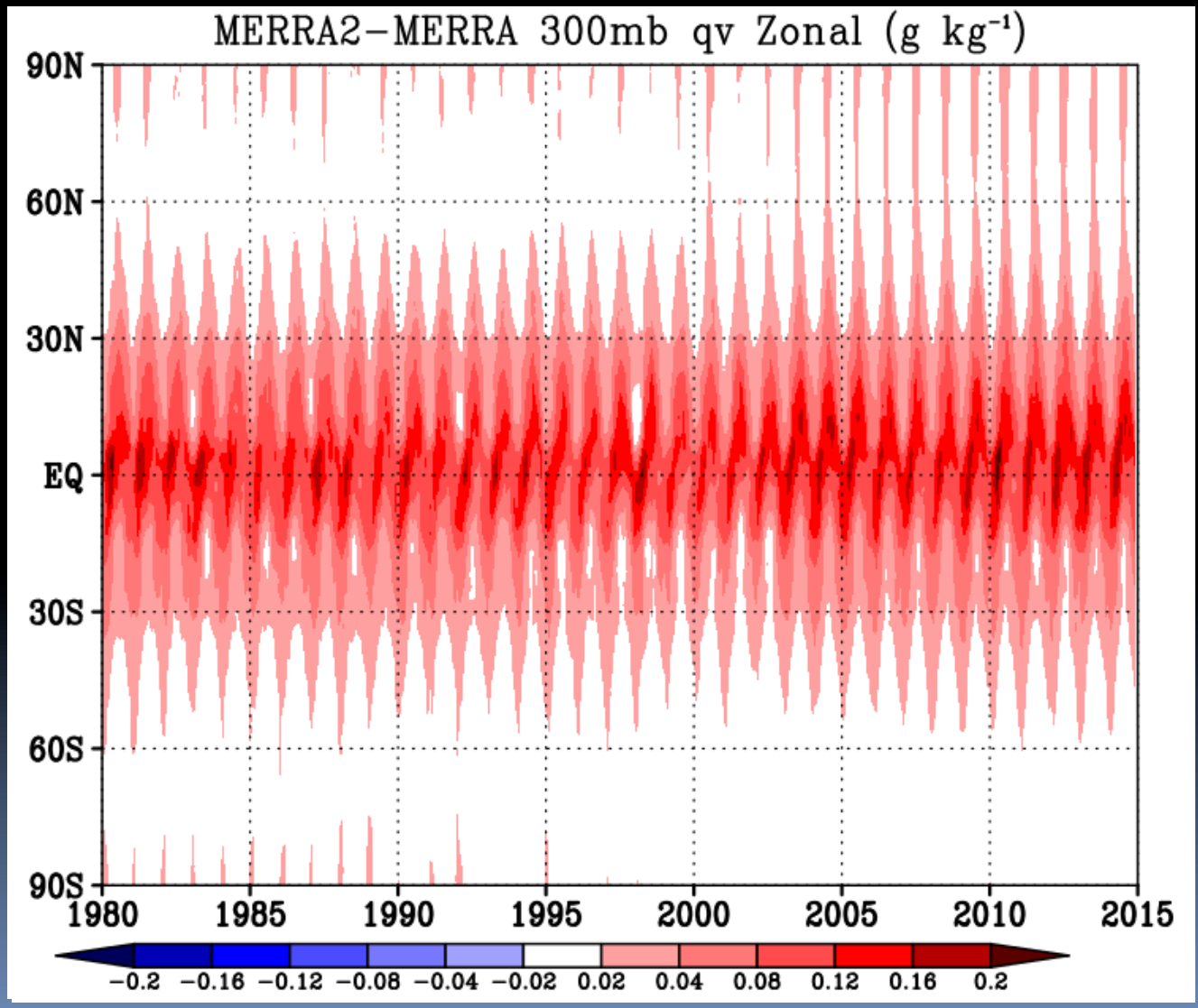
Root Zone Soil Wetness – JJA (27)



MERRA-2 – MERRA

Upper Tropospheric Humidity

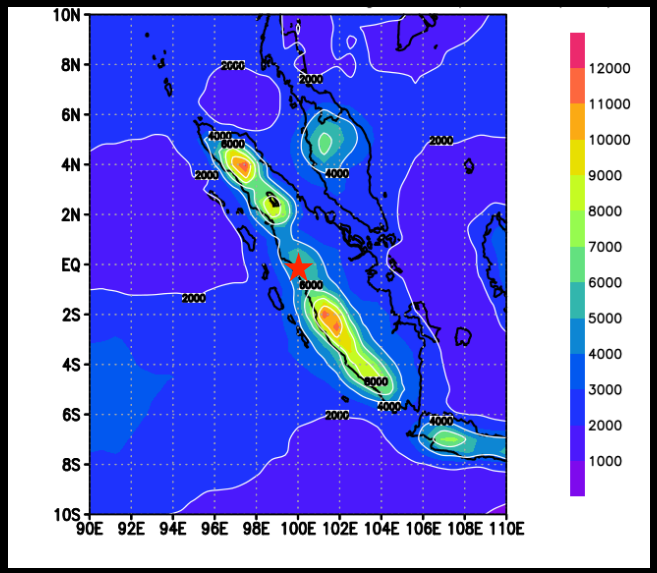
- MERRA lacking some data used in M2 and ERA after 2002
- MERRA-2 increase in qv model not observing system, primarily in the tropics



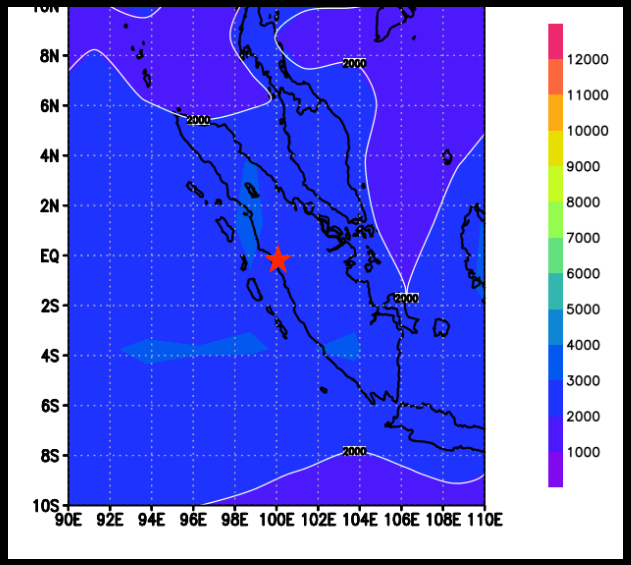
Energy Budget and Temperature

Precipitation comparison with Padang, Sumatra station data

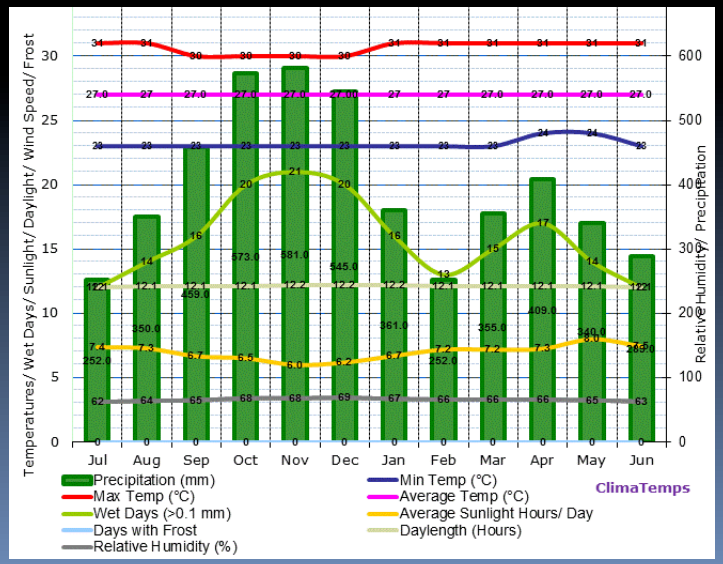
MERRA-2 Annual Average Precip (mm)



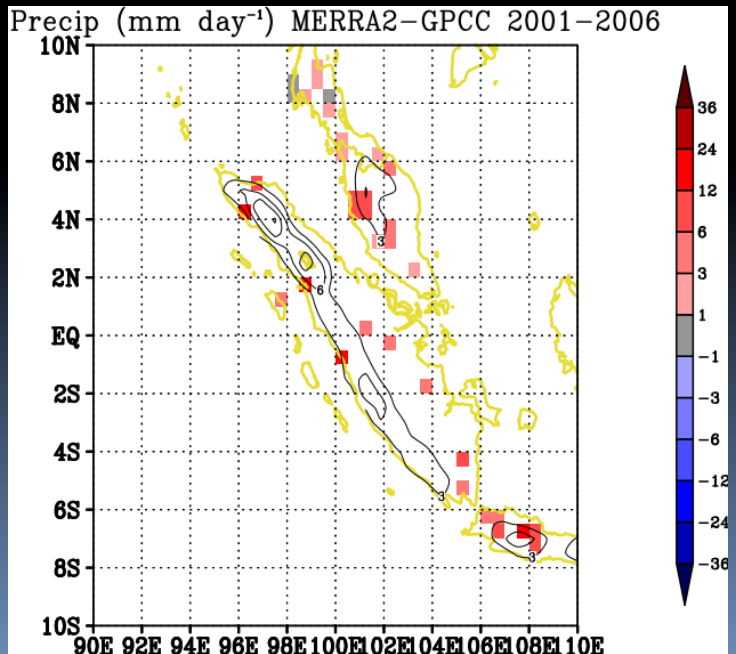
GPCP Annual Average Precip (mm)



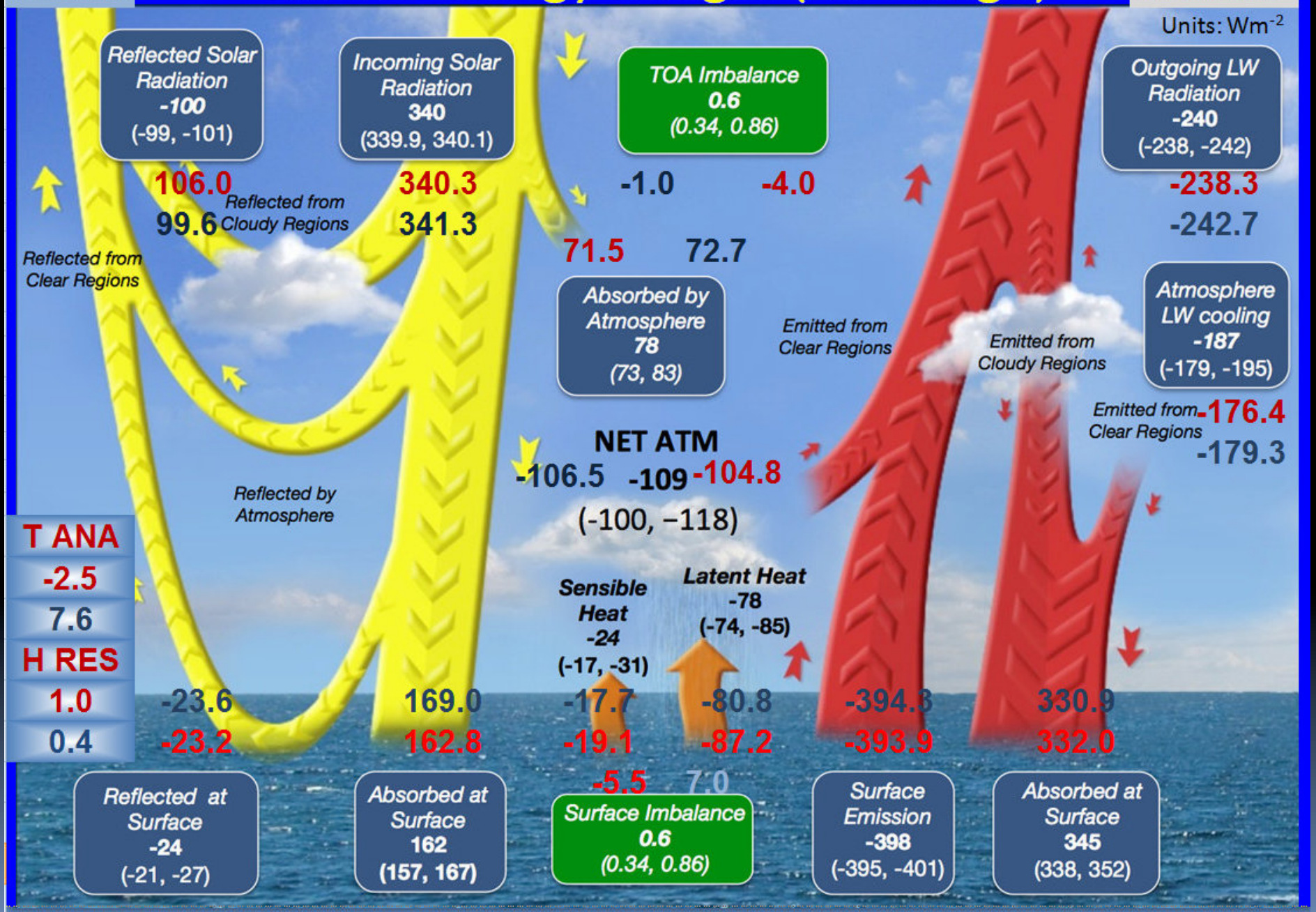
Padang, Sumatra Station Climate Graph (**Elev 7m**)



4400 mm average annual rainfall at 7-m elevation



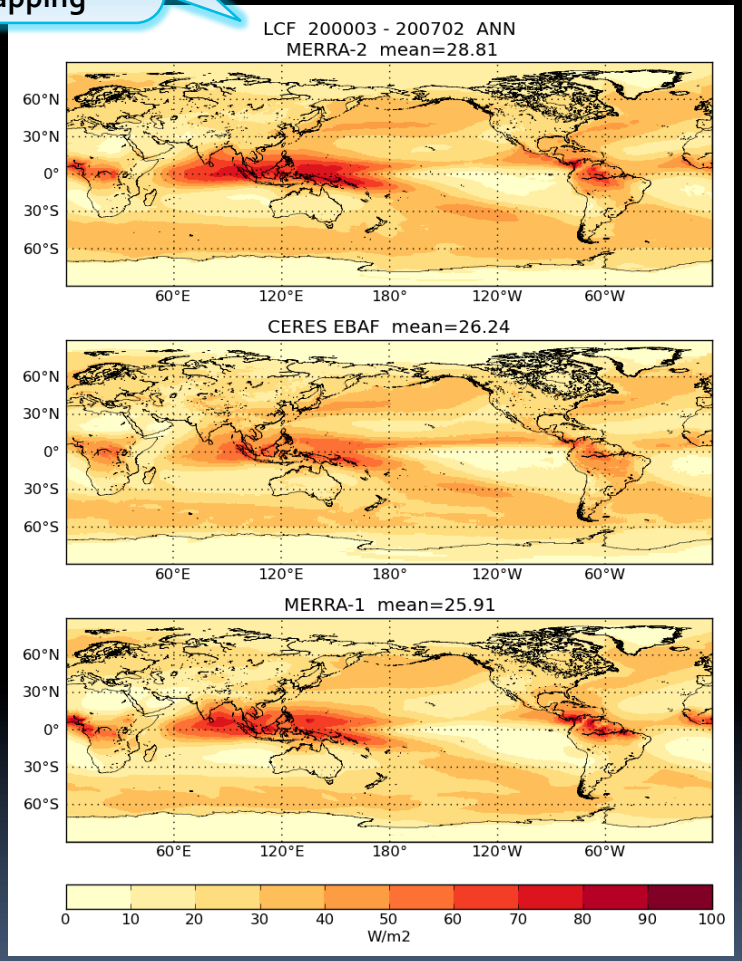
Earth's Energy Budget (1σ Range)

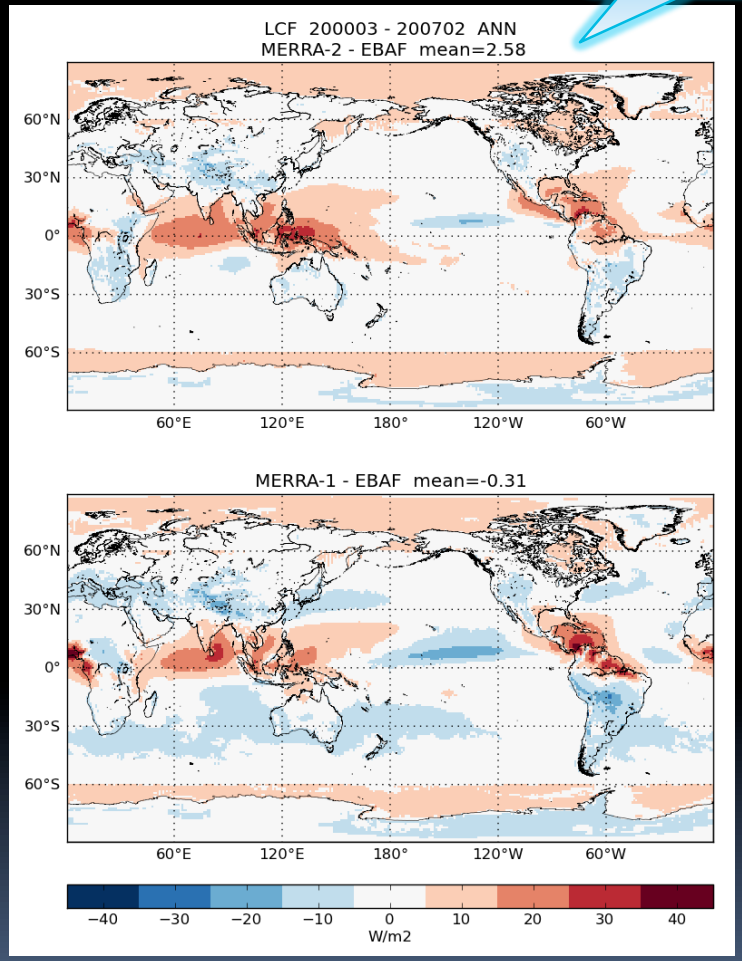


TOA Longwave Cloud Forcing Annual Average

LCF > 0. Clouds warm in LW by thermal trapping

LCF relative to EBAF





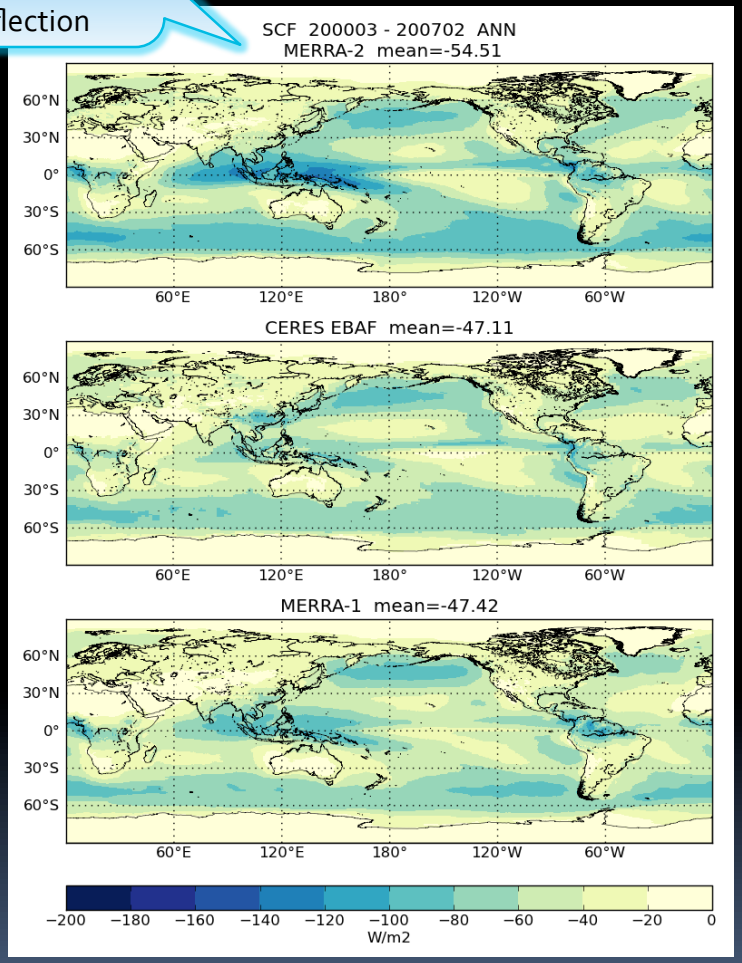
(1) Both MERRA-1 and -2 are very realistic, showing tropical convection, mid-/high-latitude cloud, and subtropical subsidence zones (cloud minima); (2) MERRA-2 does better over continents and in subsidence zones; (3) MERRA-2 has excessive Western Pacific convection.

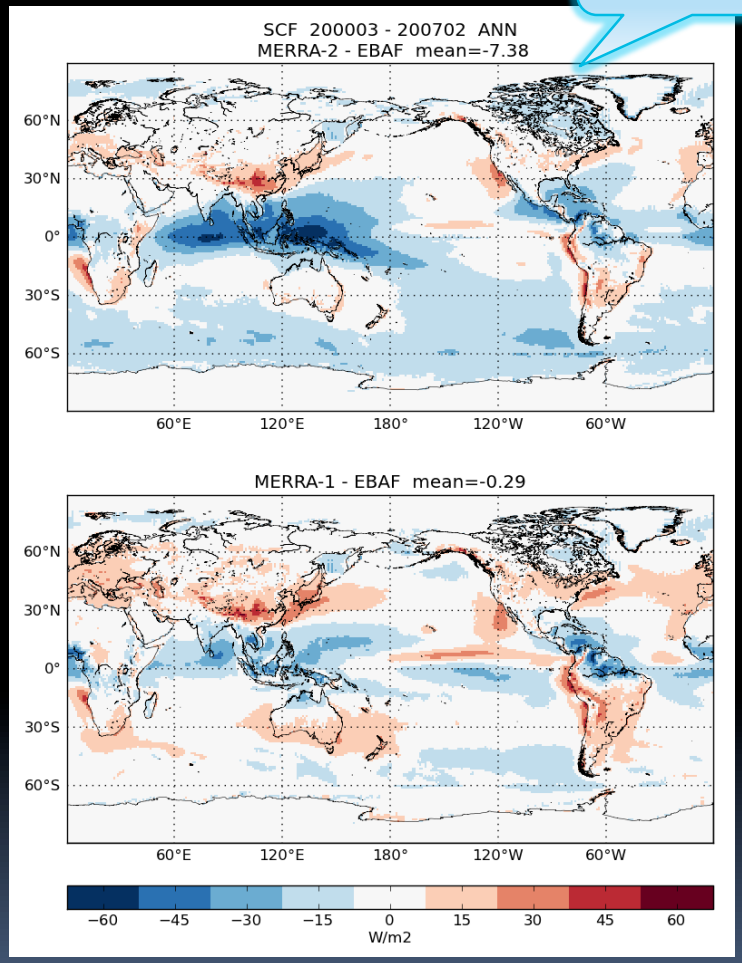
Courtesy Peter Norris

TOA Shortwave Cloud Forcing Annual Average

SCF < 0. Clouds cool in solar by reflection

SCF relative to EBAF

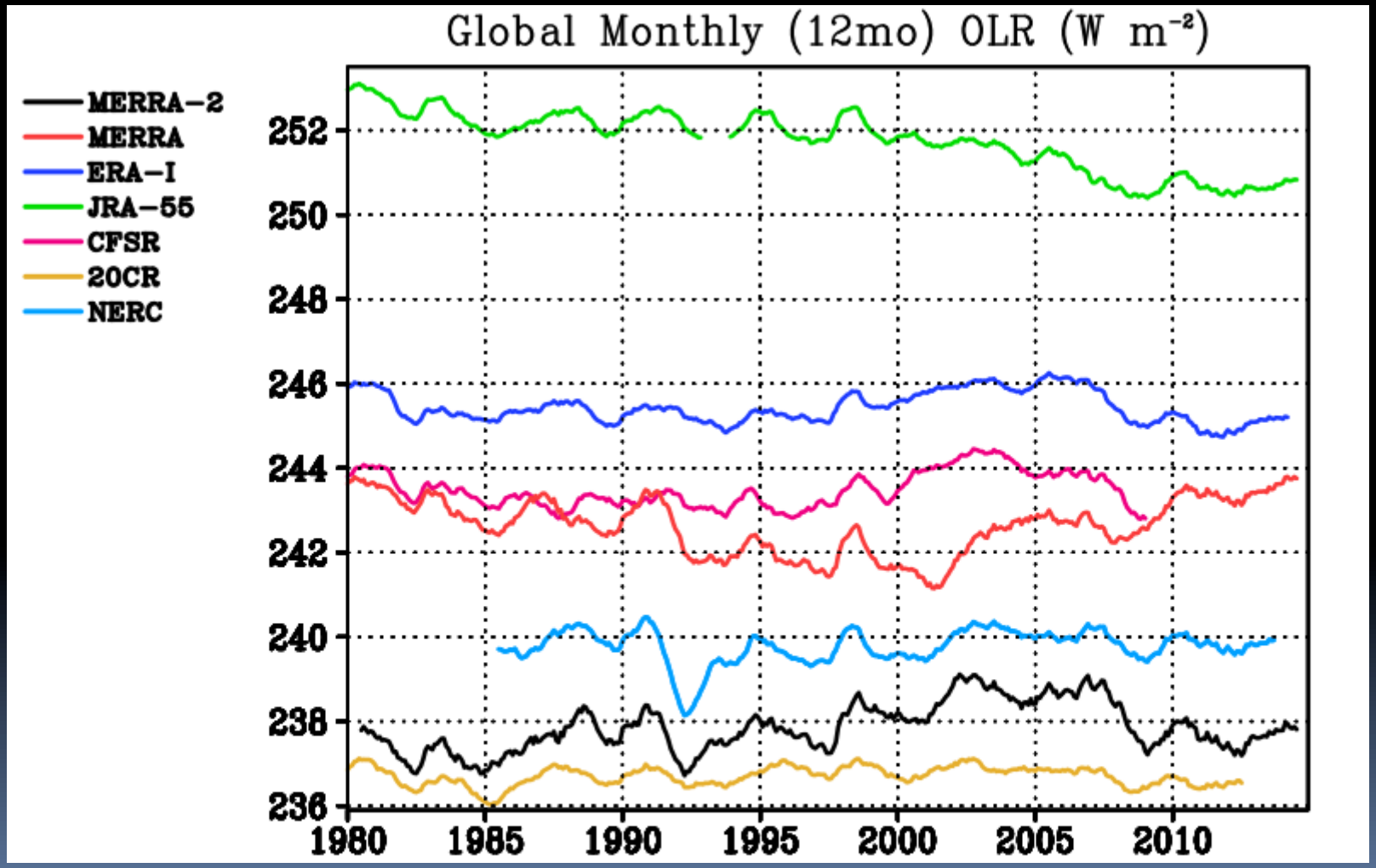




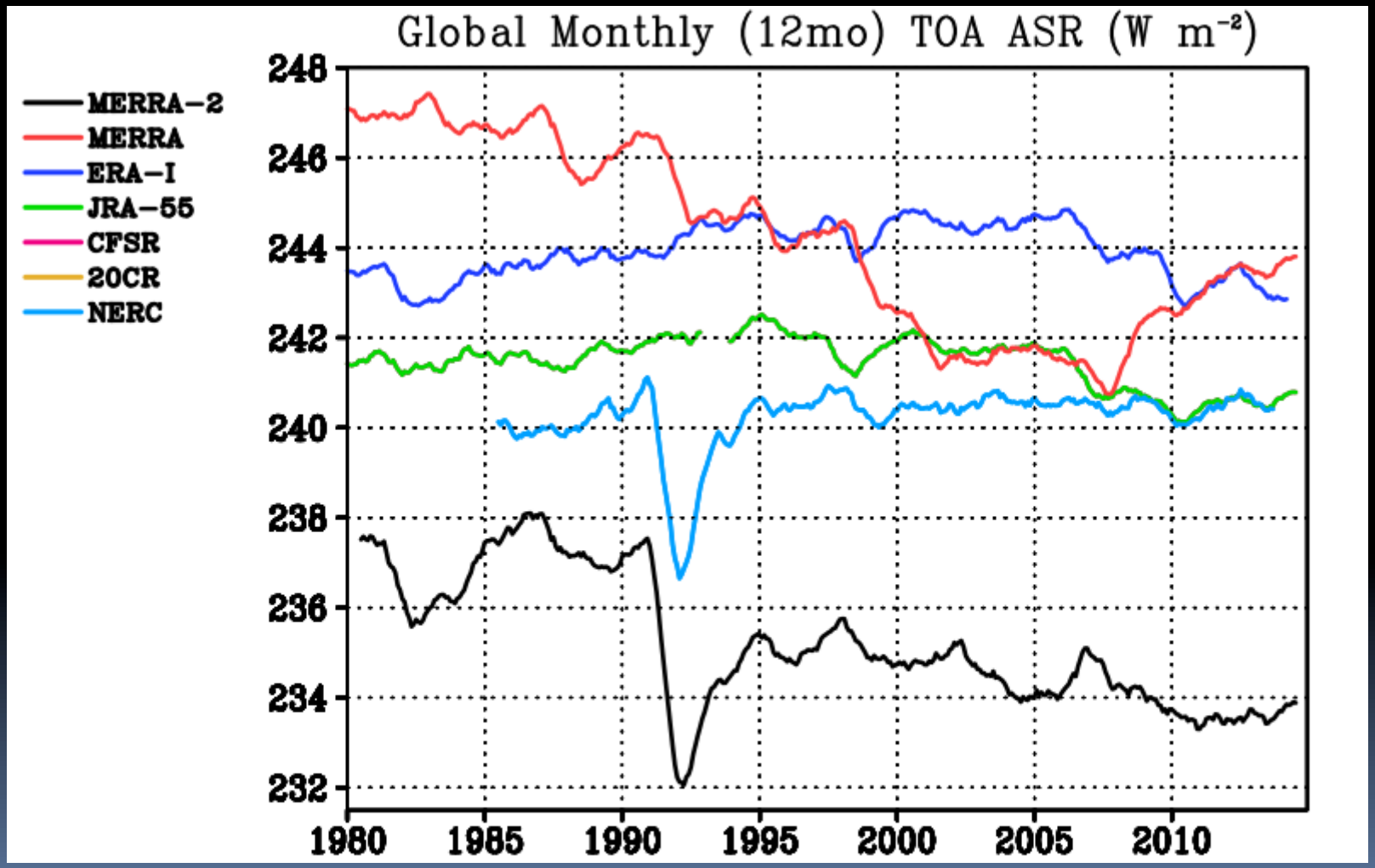
(1) MERRA-1 & -2 are both realistic, showing tropical convection, high-latitude stratus, and subtropical subsidence zones (cloud minima); (2) MERRA-2 does better than MERRA-1 over continents and in subsidence zones; (3) MERRA-2 has excessive Western Pacific & Southern Ocean cloud cooling (albedo).

Courtesy Peter Norris

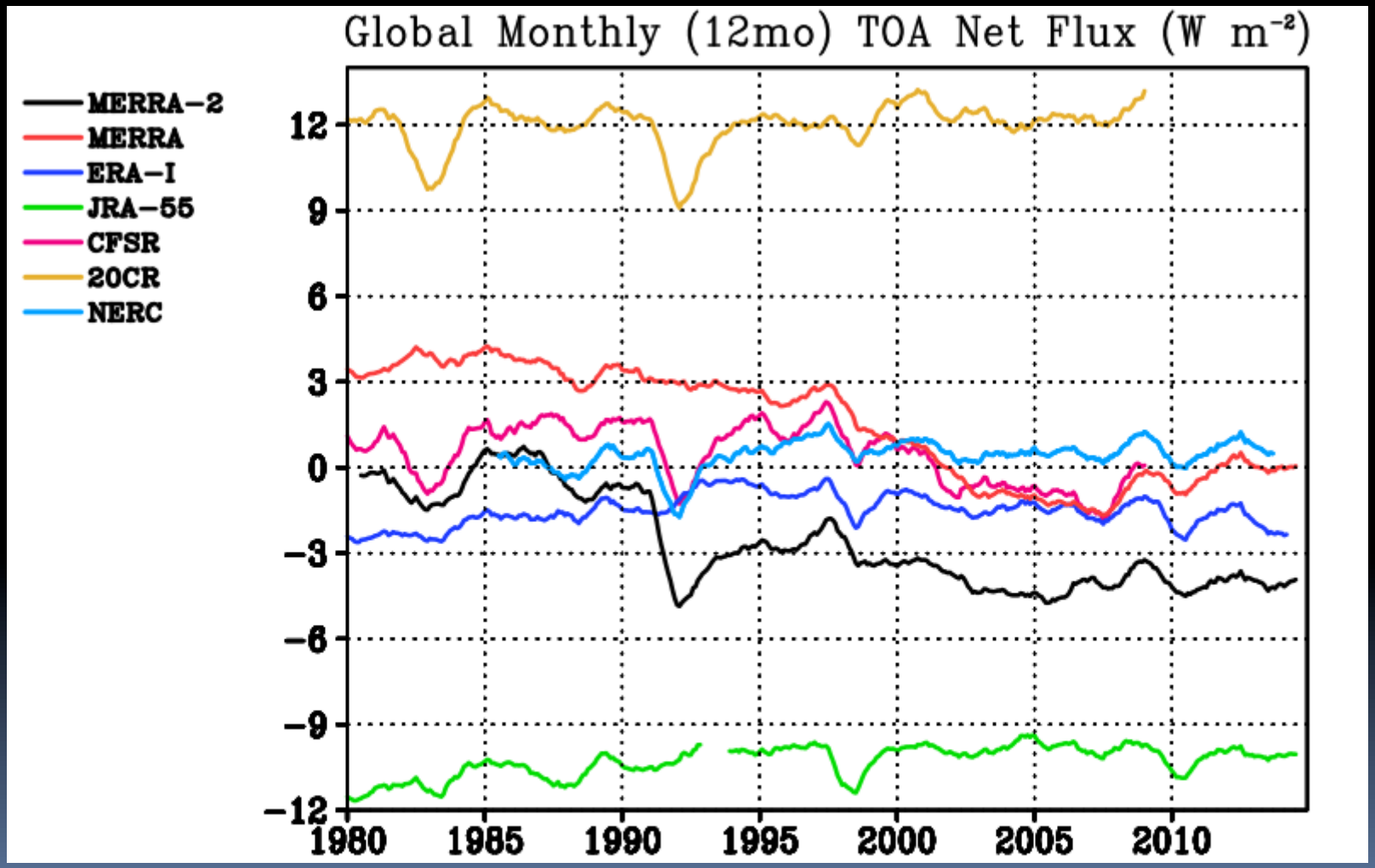
Global OLR


Global Monthly (12mo) OLR (W m⁻²)
MERRA-2
MERRA
ERA-I
JRA-55
CFSR
20CR
NERC
252
250
248
246
244
242
240
238
236
1980
1985
1990
1995
2000
2005
2010

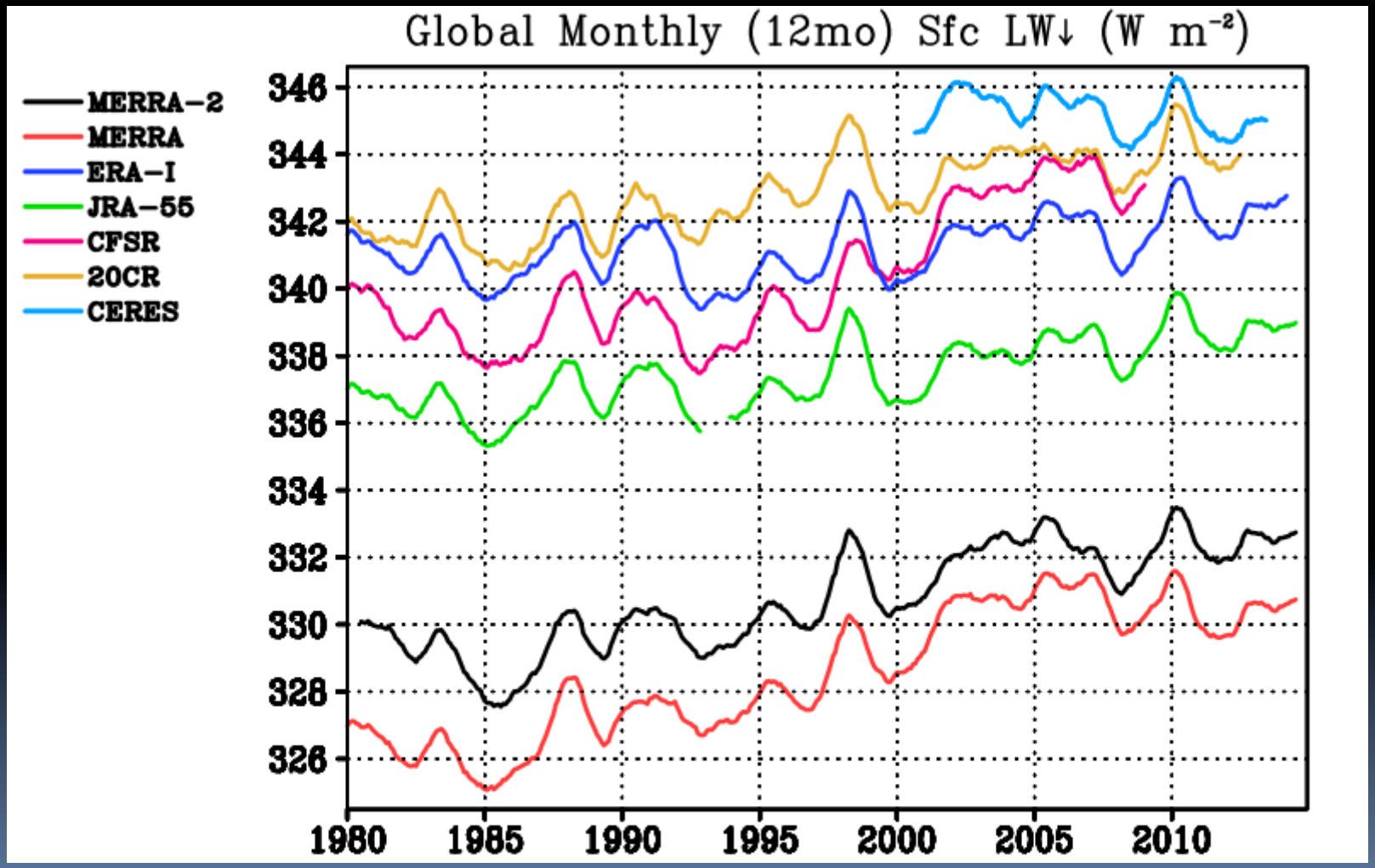
Global TOA Absorbed SW



Global TOA Net



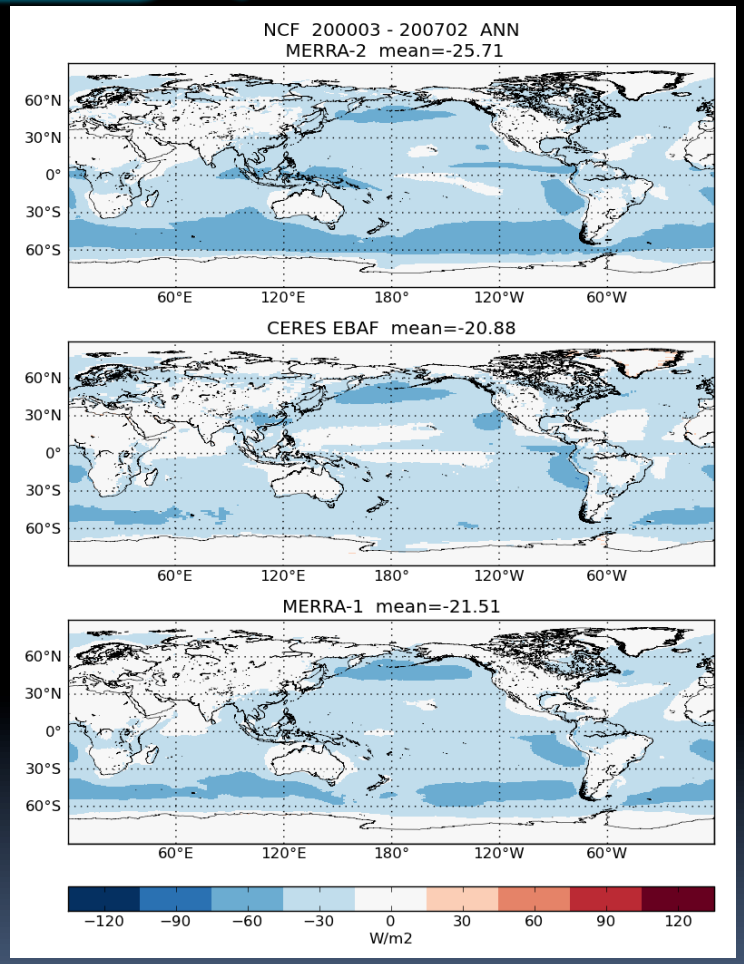
Global Surface Downward LW

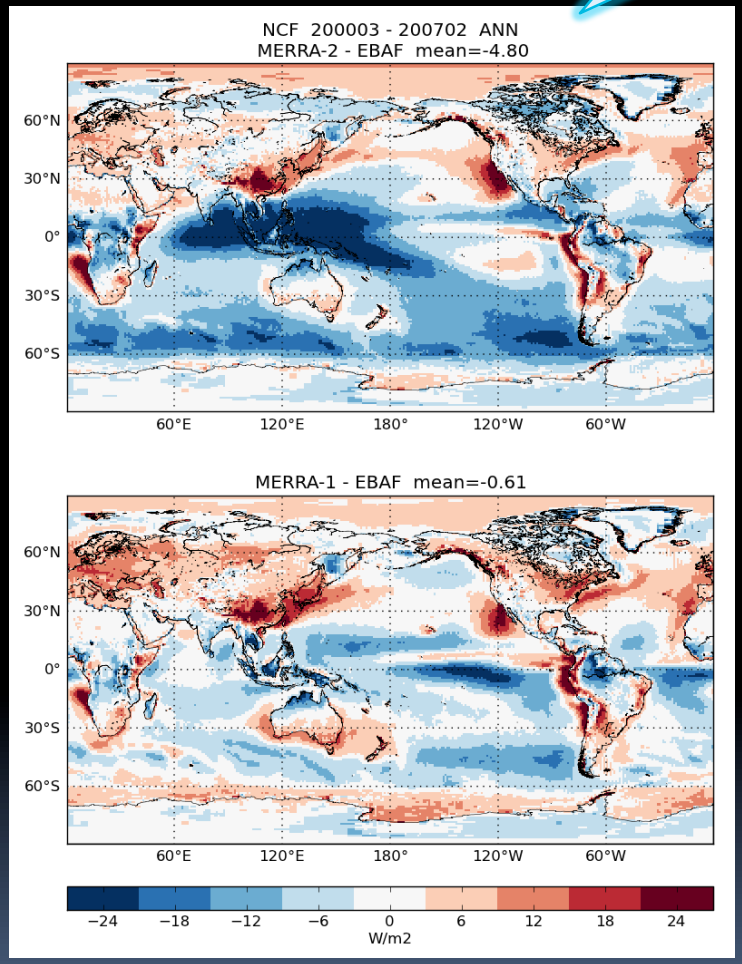


TOA Net Cloud Forcing Annual Average

Widespread negative shows net cooling due to clouds

NCF relative to EBAF

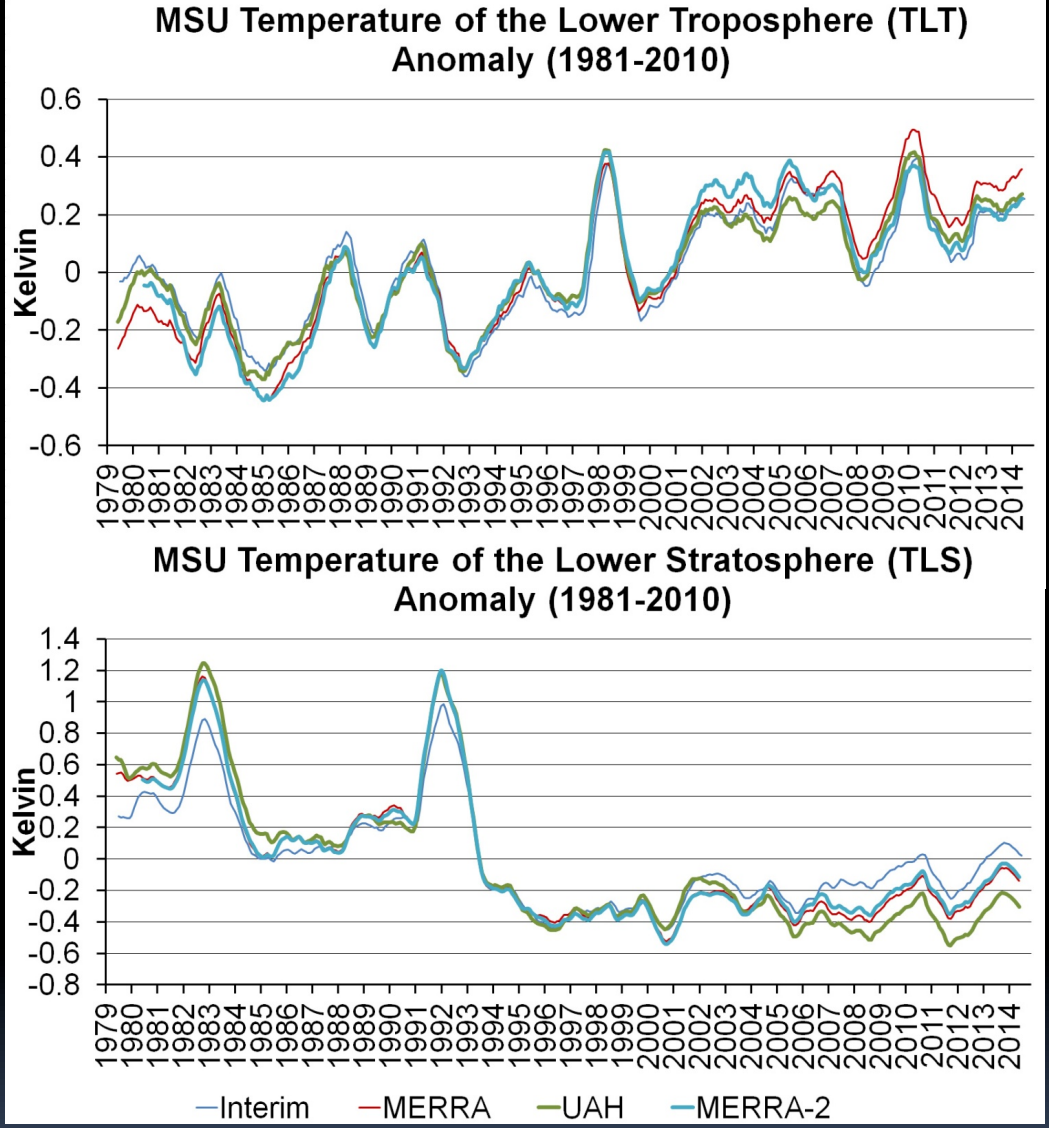




(1) Both MERRA-1 & -2 show general net negative cloud forcing, especially in stratus regions; (2) MERRA-2 does better over Eurasia and North America; (3) MERRA-2 has excessive Western Pacific and Southern Ocean cloud cooling.

Courtesy Peter Norris

MSU Temperature



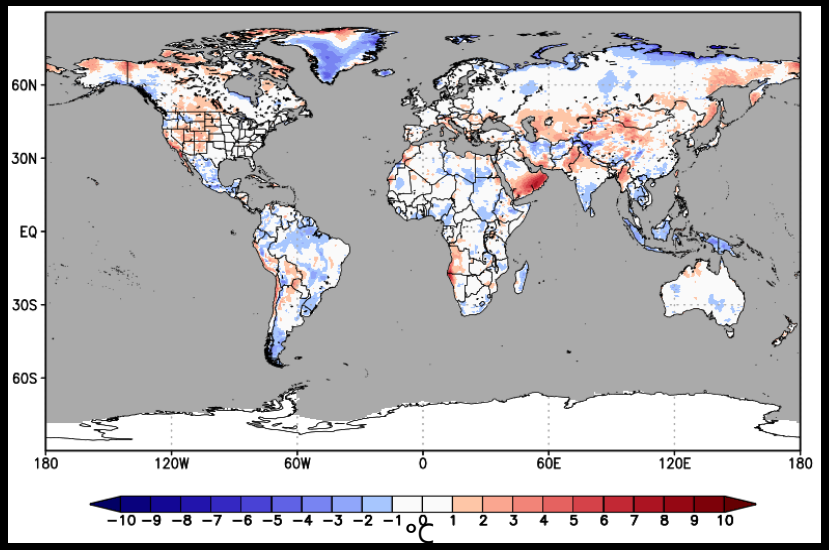
	TLT		TLS	
	Mean (K)	Trend (K/10yr)	Mean(K)	Trend (K/10yr)
UAH	268.7	0.14	211.9	-0.35
MERRA-2	270.1	0.17	210.9	-0.27
MERRA	270.1	0.19	211.0	-0.28
ERA-I	267.3	0.13	210.9	-0.18

- Mean from 1981-2010
- MERRA-2 leans warm in early 2000s, following SST
- MERRA-2 Lower Trop trend improved from MERRA

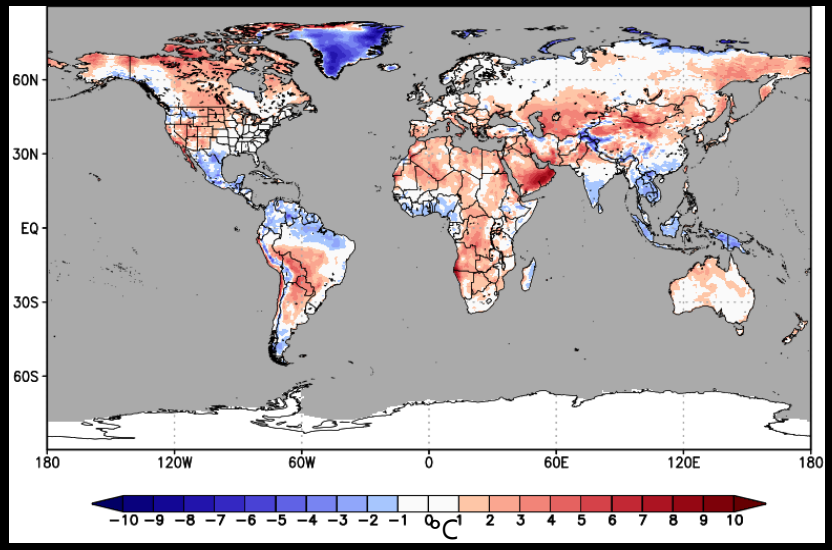
Trend computed over 1980-2014

MERRA-2 Surface air temperature comparison with MERRA, HadCRU

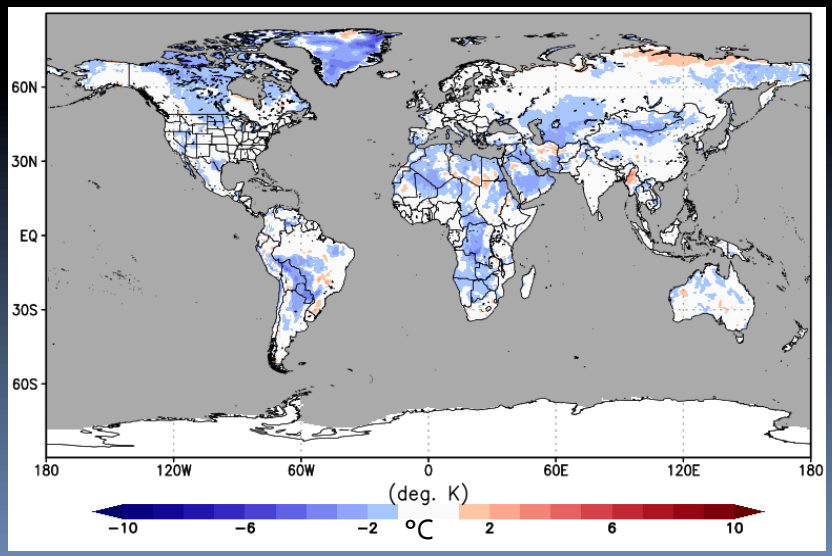
MERRA-2 T_{2m} minus HadCRU July (34yrs)



MERRA T_{2m} minus HadCRU July (34yrs)



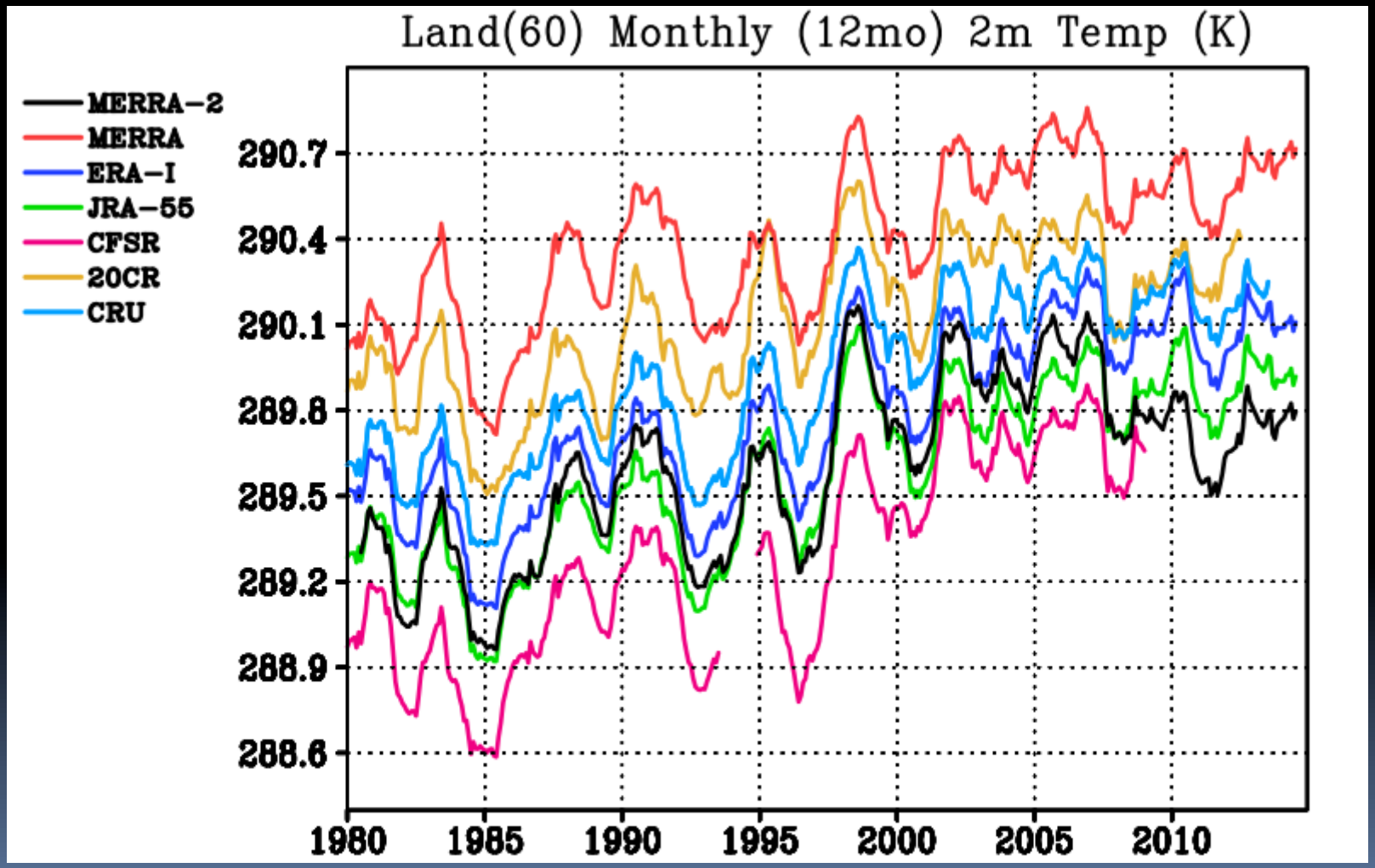
ABS(MERRA-2, MERRA) T_{2m} vs. HadCRU July (34yrs)



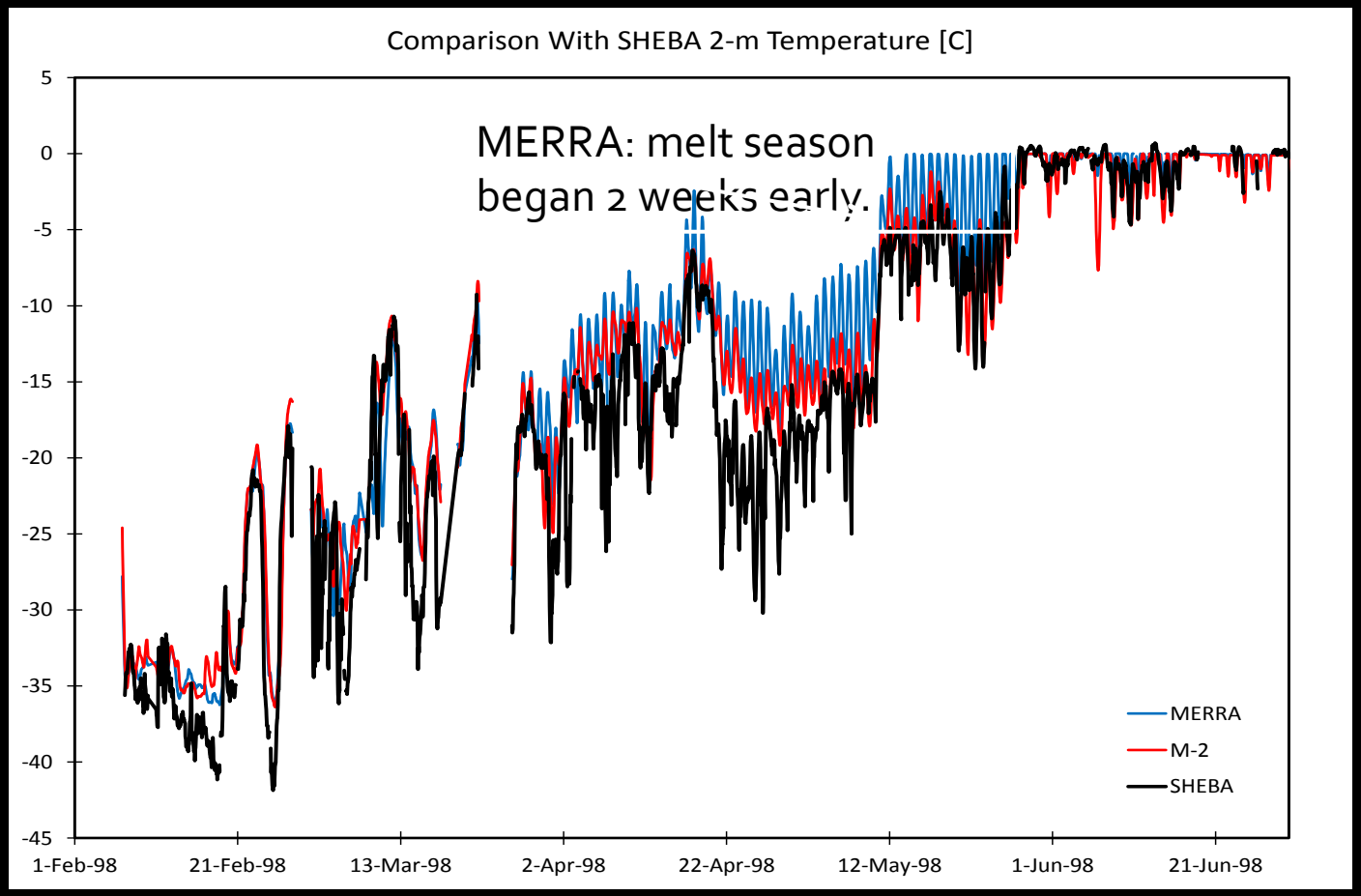
Blue shades show MERRA-2 closer to HadCRU data than MERRA

Results for January show smaller overall improvement

Land 2m T Time Series



Polar Meteorology

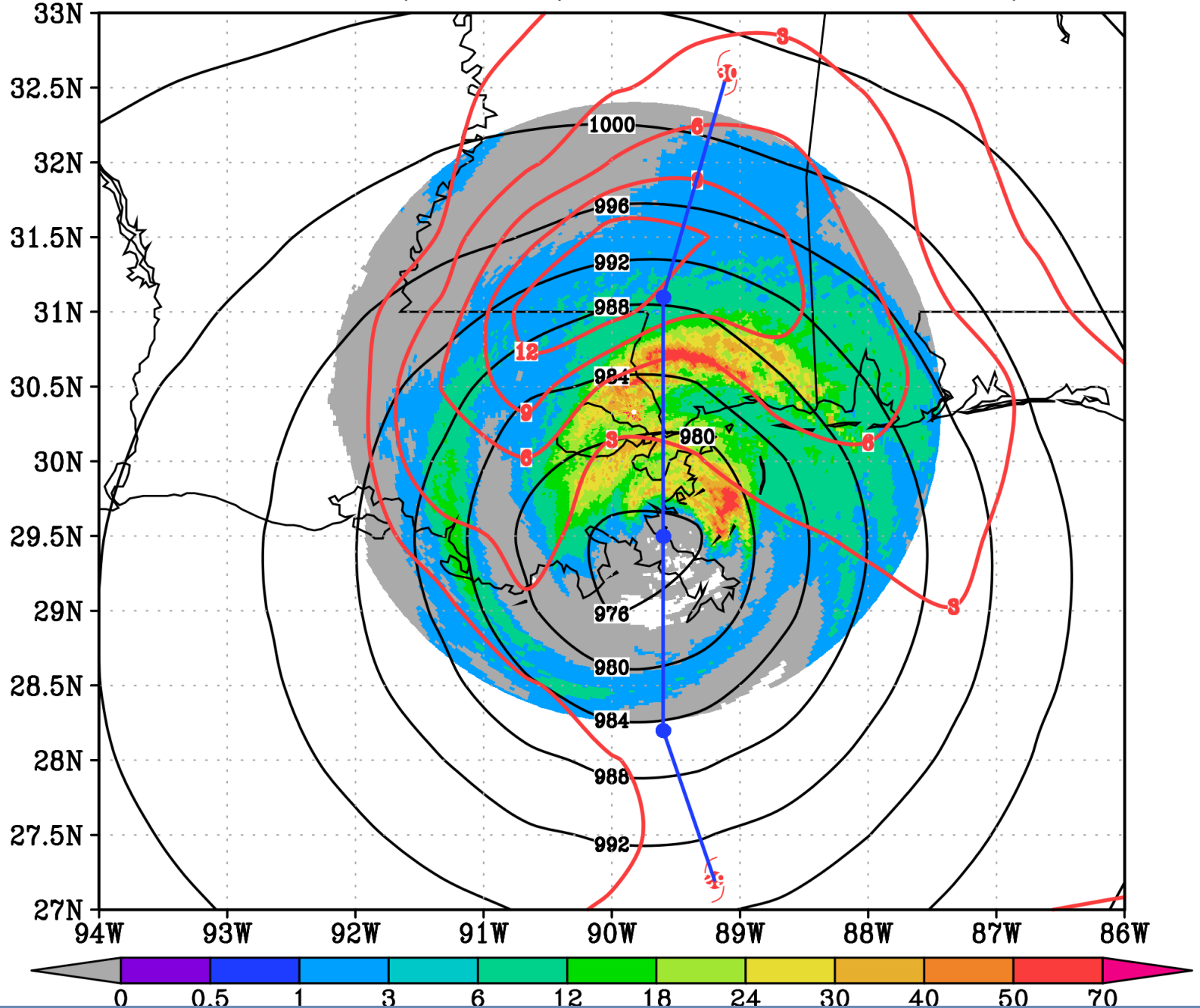


- Temperature over sea ice is significantly affected by <u>surface albedo</u>. Other processes can be important (clouds!).
- In MERRA, ice albedo was fixed constant (0.6).
- In MERRA-2, Arctic ice albedo is seasonally prescribed (monthly).
- MERRA: ~10°C May bias., MERRA-2: reduced Bias, differences remain.

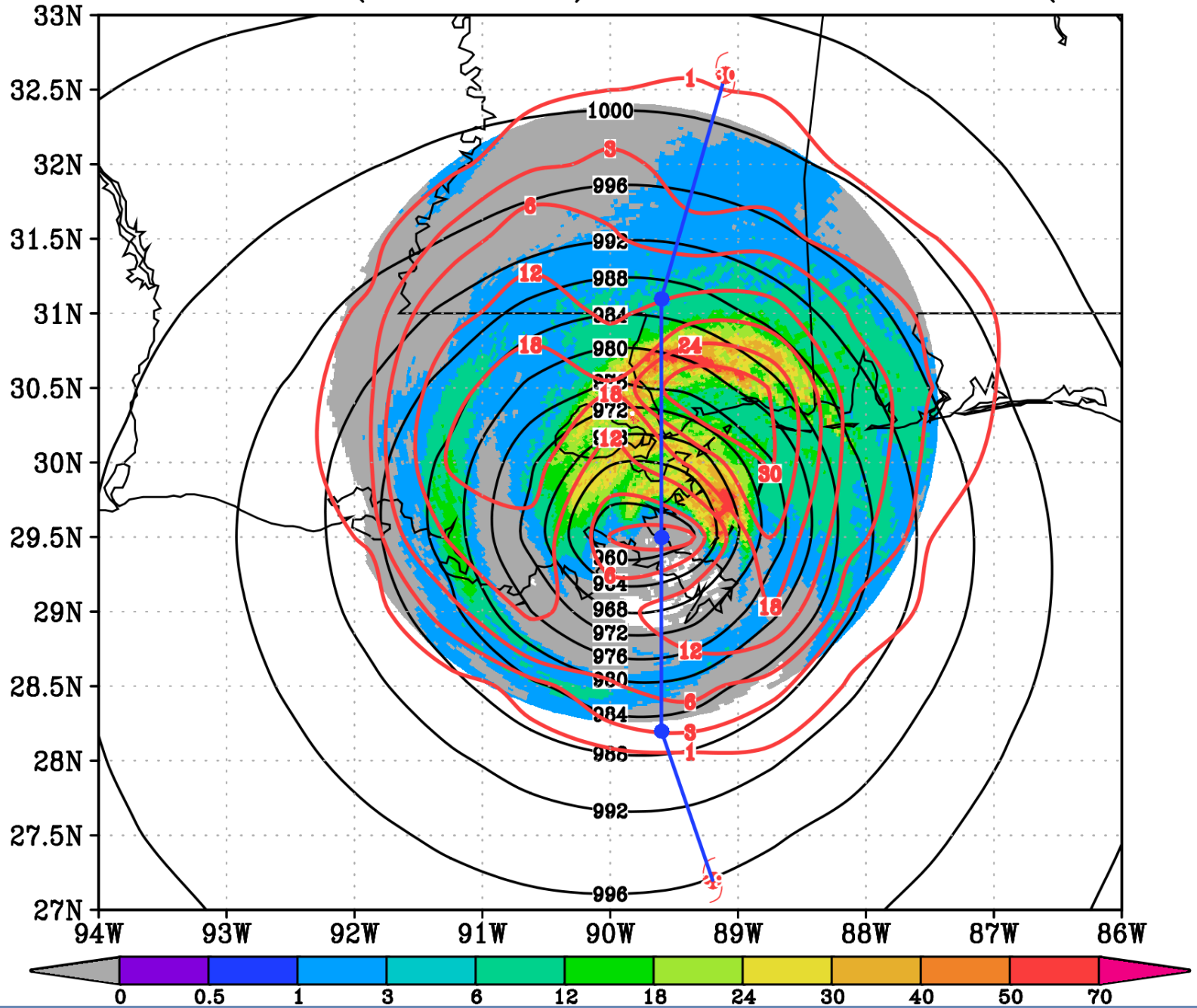
Courtesy Richard Cullather

Weather

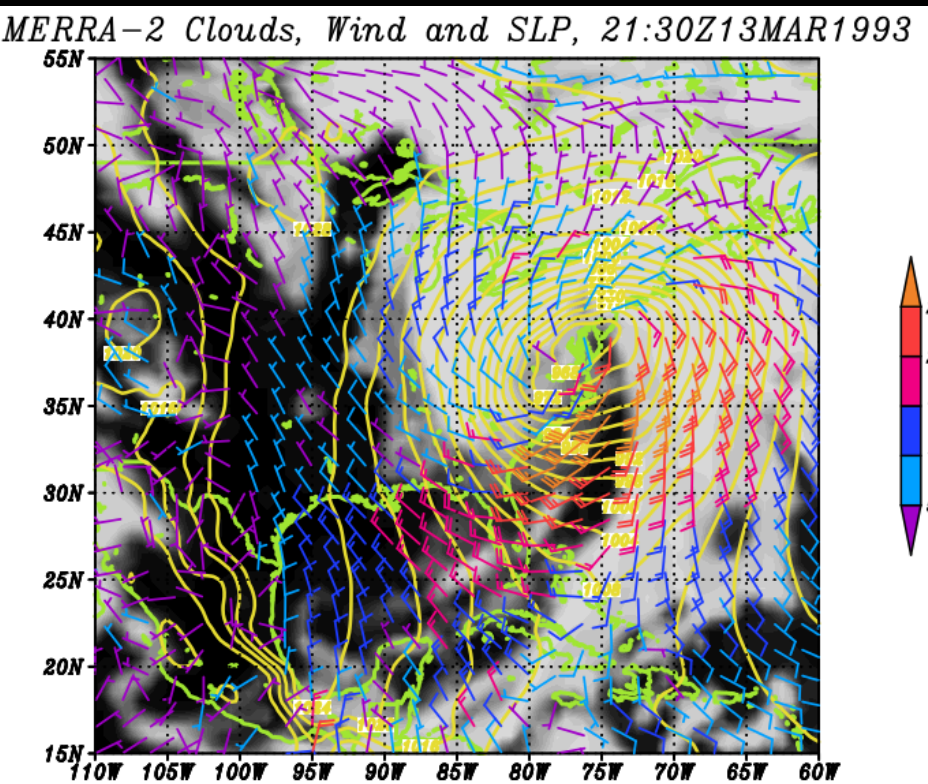
Katrina Landfall (MERRA) 1230Z29AUG2005 (mm hr^{-1})

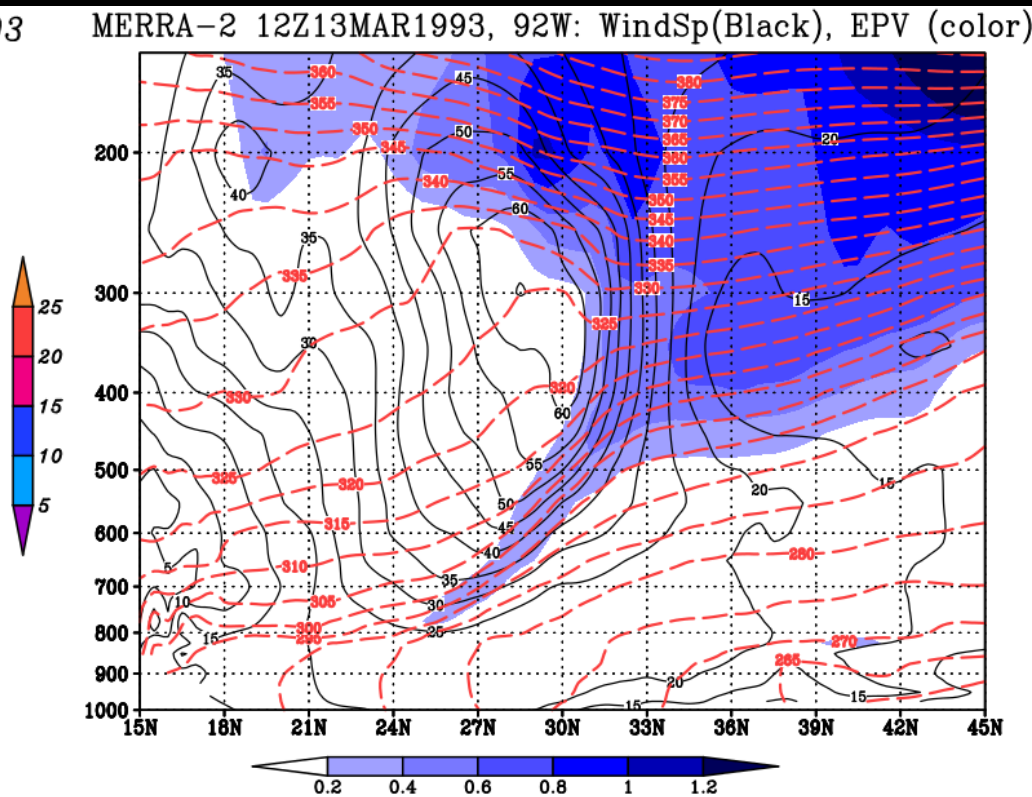


Katrina Landfall (MERRA-2) 1230Z29AUG2005 (mm hr^{-1})



Storm of The Century





- ~2ft snow depth over large portion of the East
- Vertical cross section shows a textbook depiction of the tropopause fold (in blue), jet stream (black contour and temperature gradients (red dash)

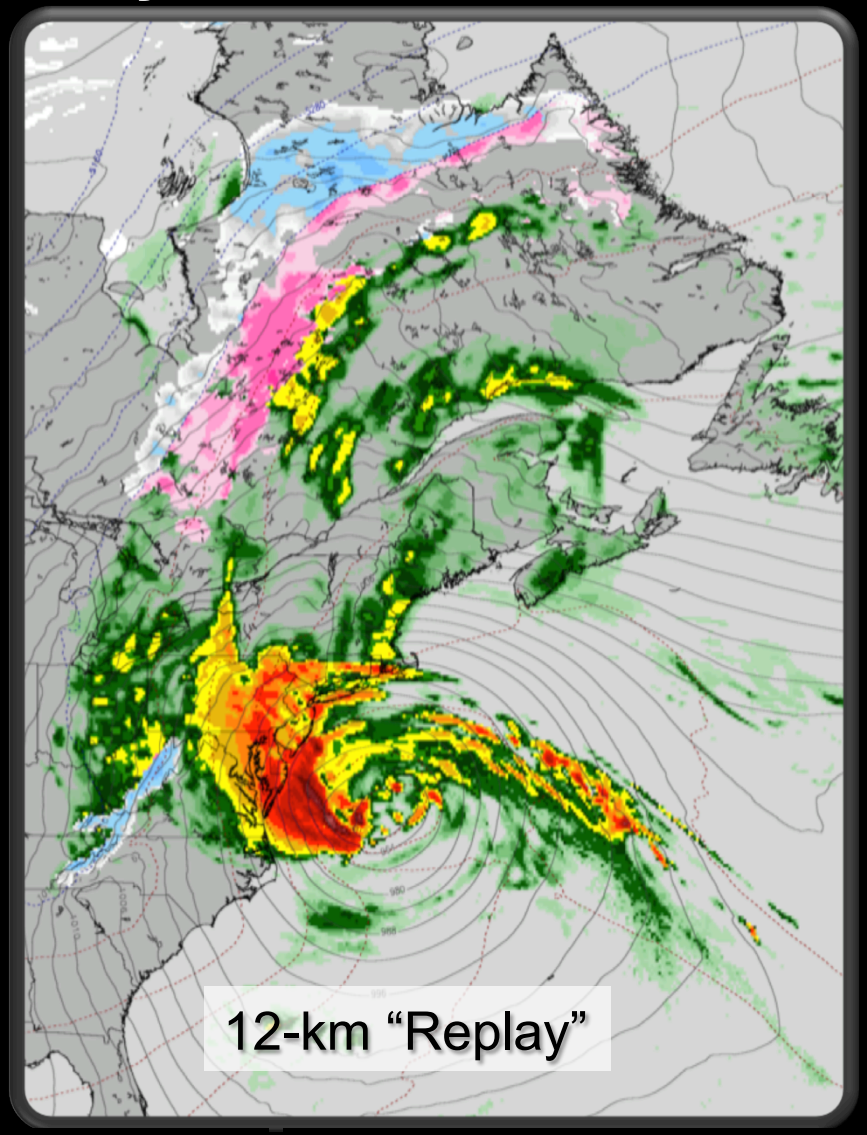
Plans

Bill Putman, Global Modeling and Assimilation Office

MERRA-2 12km Dynamical Downscaling: Hurricane Sandy 2012

12-km "Replay"

- Replay to 50-km MERRA2 Increments
- 12-km Horizontal Resolution
- 72 Vertical levels
- Non-Hydrostatic FV3 Dynamics
- Full Aerosol Reanalysis (MERRA2-aero)
- Including CO_2
- Initially Two Streams
  - Dec-1999 – May-2005
  - May-2005 – Nov-2010
- Eventually 30+ years 1979-present



Snowfall Rate [inches/hour]
0.010 0.025 0.050 0.075 0.100 0.250 0.500 1.000 2.000 3.000 4.000

Mixed Precipitation Rate [inches/hour]
0.010 0.050 0.100 0.500 2.000 4.000

Rainfall Rate [mm h-1]
0.00 0.05 0.15 0.40 0.80 3.20 12.80 30.00 50.00 100.0

MERRA-2 Products and Ancillary Applications

Completed 1980-present, now running as a continuing climate analysis with 2-3 week latency

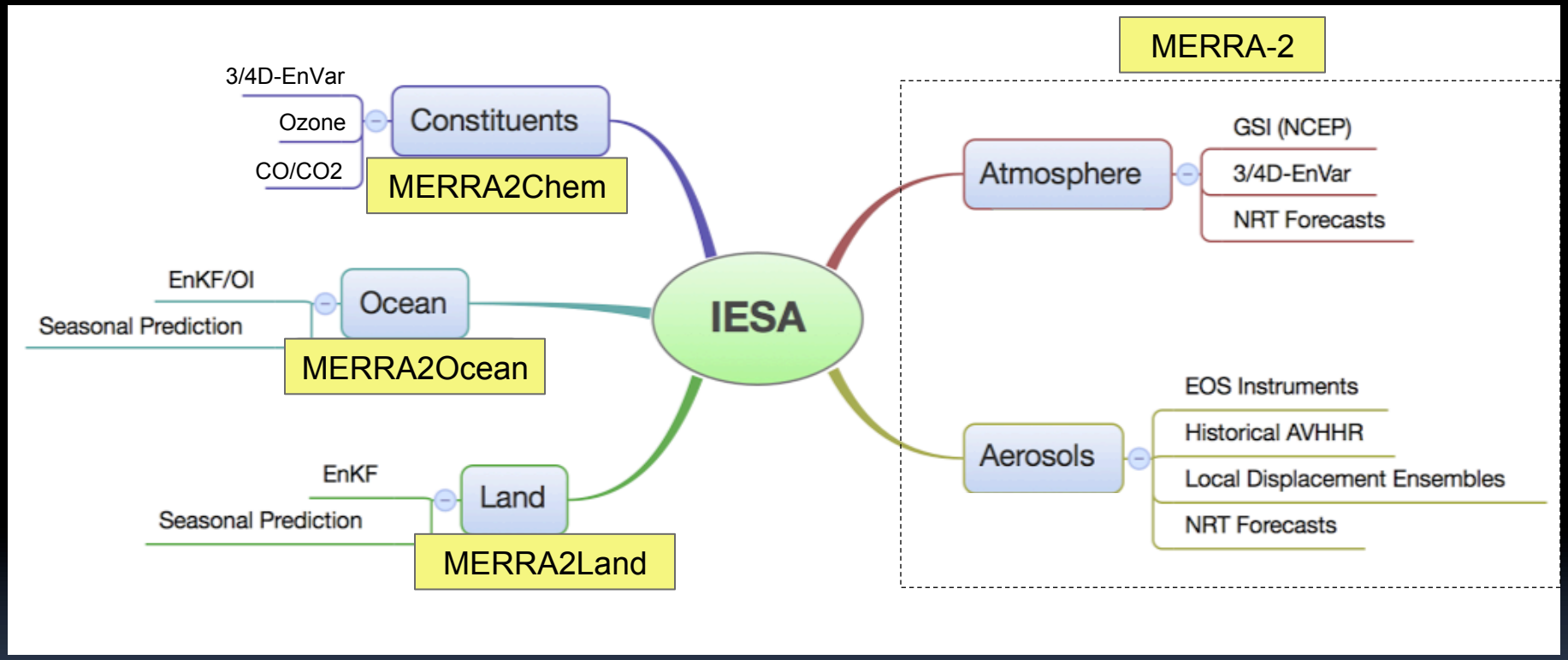
Data release expected to begin in July 2015 via the NASA Goddard Earth Sciences (GES) Data Information Services Center (DISC)

- 1-hourly surface/2D fields, 3- and 6-hourly 3D fields
- Daily Products ~25 GB/day (9.1 TB/yr)
- Monthly Products ~34 GB/mo (408 GB/yr)

Ensemble of (initially) 10 AMIP integrations using the MERRA-2 model configuration

MERRA-2-driven analyses of ocean state (physics and biogeochemistry), atmospheric chemistry (EOS period), and carbon cycle.

Toward an Integrated Earth System Analysis



Coupled and MERRA2-driven component reanalyses

Reanalysis Progression

	MERRA	MERRA-2	Next Target
System vintage	2008	2014	2017
Release	2009	mid 2015	late 2018
Scope	Atmosphere	Atmosphere, including aerosols and land correction	Atmosphere-ocean-ice-land
Resolution	0.5°×0.66° L72	0.5°×0.625° L72 (C180 cubed sphere)	0.25°×0.3125° L137 (C360 cubed sphere) + 25-km ocean
Analysis	3D-Var atmos	3D-Var atmos	4D EnsVar atmos + EnKF land + EnOI ocean

Thanks!