An Overview of Atmospheric Analyses and Reanalyses for Climate

Kevin E. Trenberth

NCAR

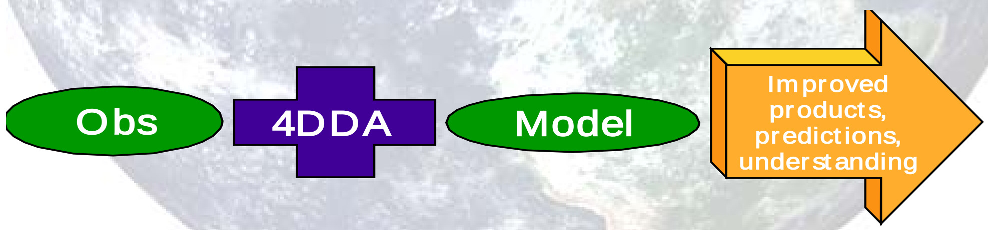
Boulder CO

Analysis

Data Assimilation merges observations & model predictions to provide a superior state estimate.

$$\partial x / \partial t = dynamics + physics + \Delta x$$

It provides a dynamically- consistent estimate of the state of the system using the best blend of past, current, and perhaps future observations.



Experience mainly in atmosphere; developing in ocean, land surface, sea ice.

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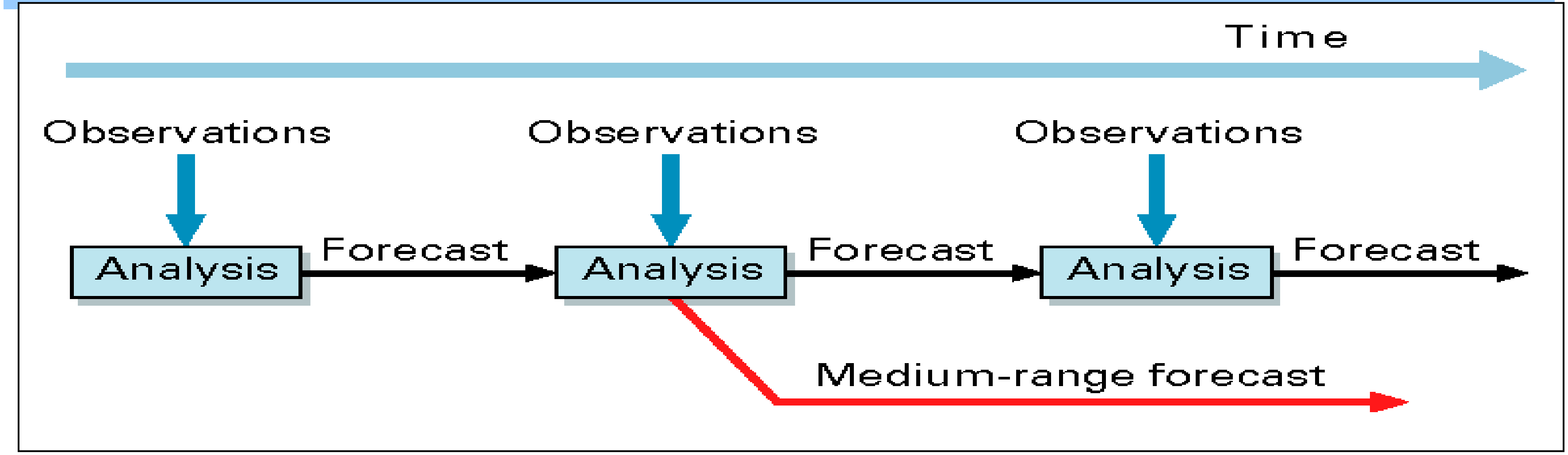
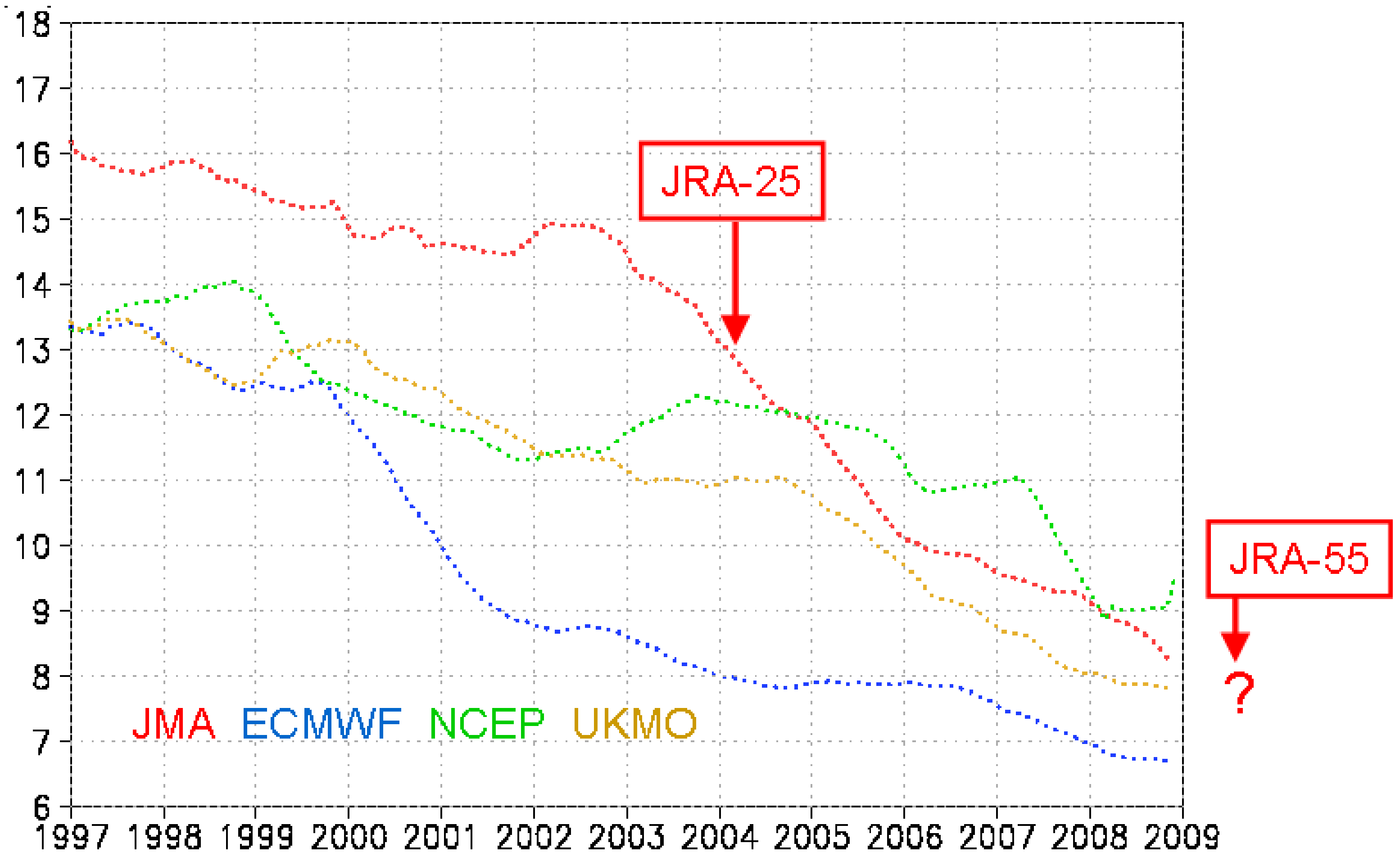
Data assimilation system



- The observations are used to correct errors in the short forecast from the previous analysis time.
- Every 12 hours ECMWF assimilates 7 – 9,000,000 observations to correct the 80,000,000 variables that define the model's virtual atmosphere.
- This is done by a careful 4-dimensional interpolation in space and time of the available observations; this operation takes as much computer power as the 10-day forecast.

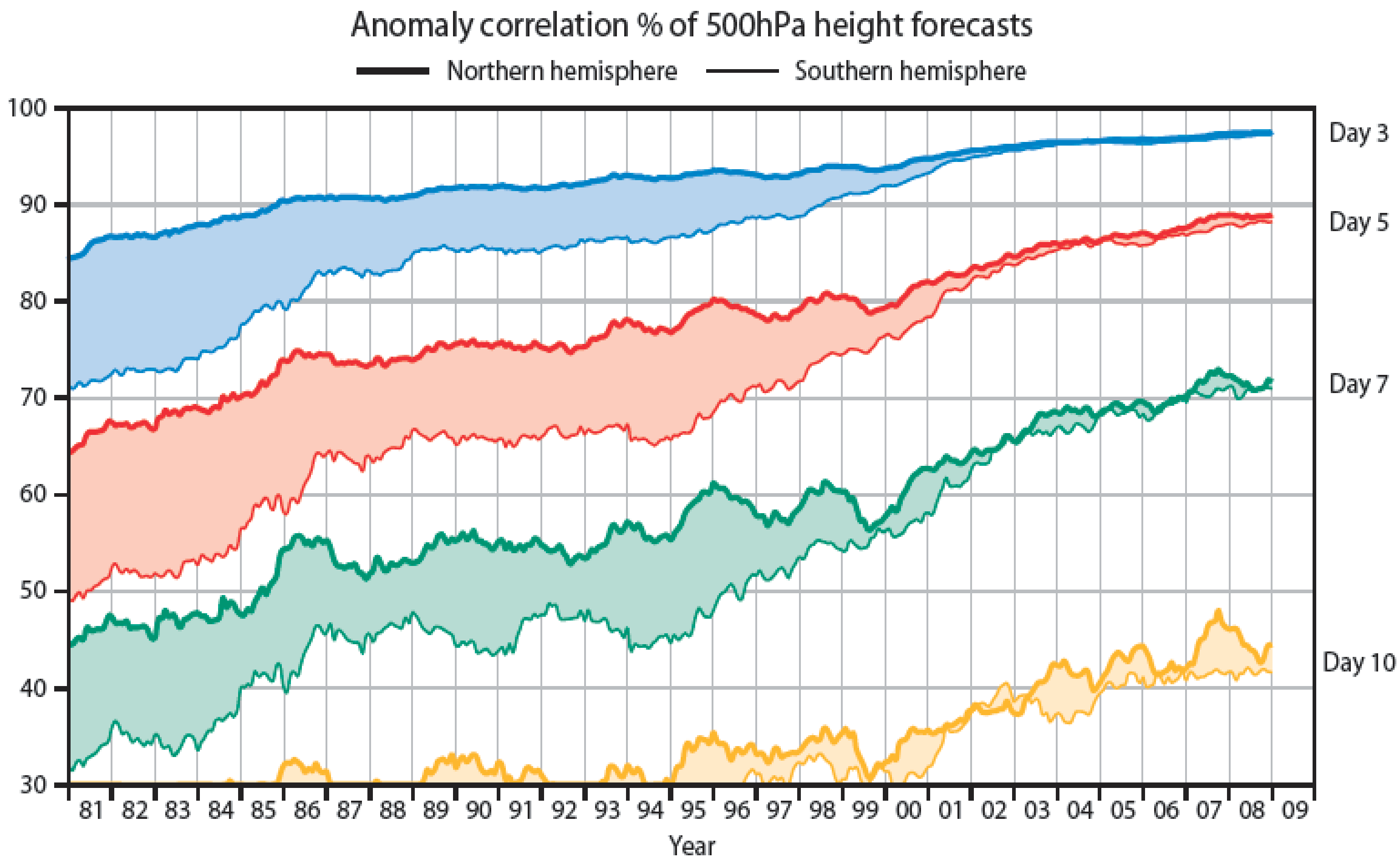
ECMWF 2009

NWP models and data assimilation continues to improve



Operational forecast scores of major NWP centers. RMSE of geopotential height at 500hPa in NH (m) for 24-hour forecasts are displayed. The scores of forecasts have improved over time.

NWP Forecast skill scores continue to improve



Extratropical NH and SH forecasts: 12 month means plotted at last month. Updated from Simmons and Hollingsworth 2002

SH skill became comparable to NH after about 2002!

Reanalysis

Operational four dimensional data assimilation continually changes as methods and assimilating models improve, creating huge discontinuities in the implied climate record.

Reanalysis is the retrospective analysis onto global grids using a multivariate physically consistent approach with a constant analysis system.

Reanalysis has been applied to atmospheric data covering the past five decades. Although the resulting products have proven very useful, considerable effort is needed to ensure that reanalysis products are suitable for climate monitoring applications.

From: Executive Summary of "The Second Report on the Adequacy of The Global Observing Systems for Climate in Support of the UNFCCC".

Atmospheric Reanalyses

*Current **atmospheric reanalyses**, with the horizontal resolution (latitude; T159 is equivalent to about 0.8°), the starting and ending dates, the approximate vintage of the model and analysis system, and current status.*

Reanalysis	Horiz.Res	Dates	Vintage	Status
NCEP/NCAR R1	T62	1948-present	1995	ongoing
NCEP-DOE R2	T62	1979-present	2001	ongoing
CFSR (NCEP)	T382	1979-present	2009	thru 2009, ongoing
C20r (NOAA)	T62	1875-2008	2009	Complete, in progress
ERA-40	T159	1957-2002	2004	done
ERA-Interim	T255	1989-present	2009	ongoing
JRA-25	T106	1979-present	2006	ongoing
JRA-55	T319	1958-2012	2009	underway
MERRA (NASA)	0.5°	1979-present	2009	thru 2010, ongoing

What have we gained and what are the benefits?

Prior to reanalyses, the analyzed climate record was beset with **major discontinuities** from changes in the data assimilation systems. It was difficult, if not impossible, to reliably infer anomalies and to analyze climate variability.

The use of a **stable data assimilation system** has produced fairly reliable records for monitoring, research and improved prediction that have enabled :

- climatologies to be established
- anomalies to be reliably established
- time series, empirical studies and quantitative diagnostics
- exploration of, improved understanding of processes
- model initialization and validation
- test bed for model improvement on all time scales, especially seasonal-to-interannual forecasts
- Greatly improved basic observations and data bases.

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What have we learned?

- Observing system changes affect variability
  - Trends and low frequencies unreliable
  - Exacerbated by model bias
- Budgets don't balance
  - Impacts many diagnostic studies
- Problems with hydrological cycle
  - Sensitivity to model physics (e.g., convection)
  - Exacerbated by insertion of observations
  - Problems with warm season continental climates
    - precipitation
    - diurnal cycle
- Unrealistic surface fluxes
  - Ocean (radiative, freshwater)
  - Land (precipitation, radiative)
  - Limits usefulness for offline forcing; e.g. ocean modeling
  - Limits ability to do coupled assimilation
- Quantities/regions not a priority for weather centers
  - Surface
  - Stratosphere
  - Polar regions
  - Many aspects of tropics

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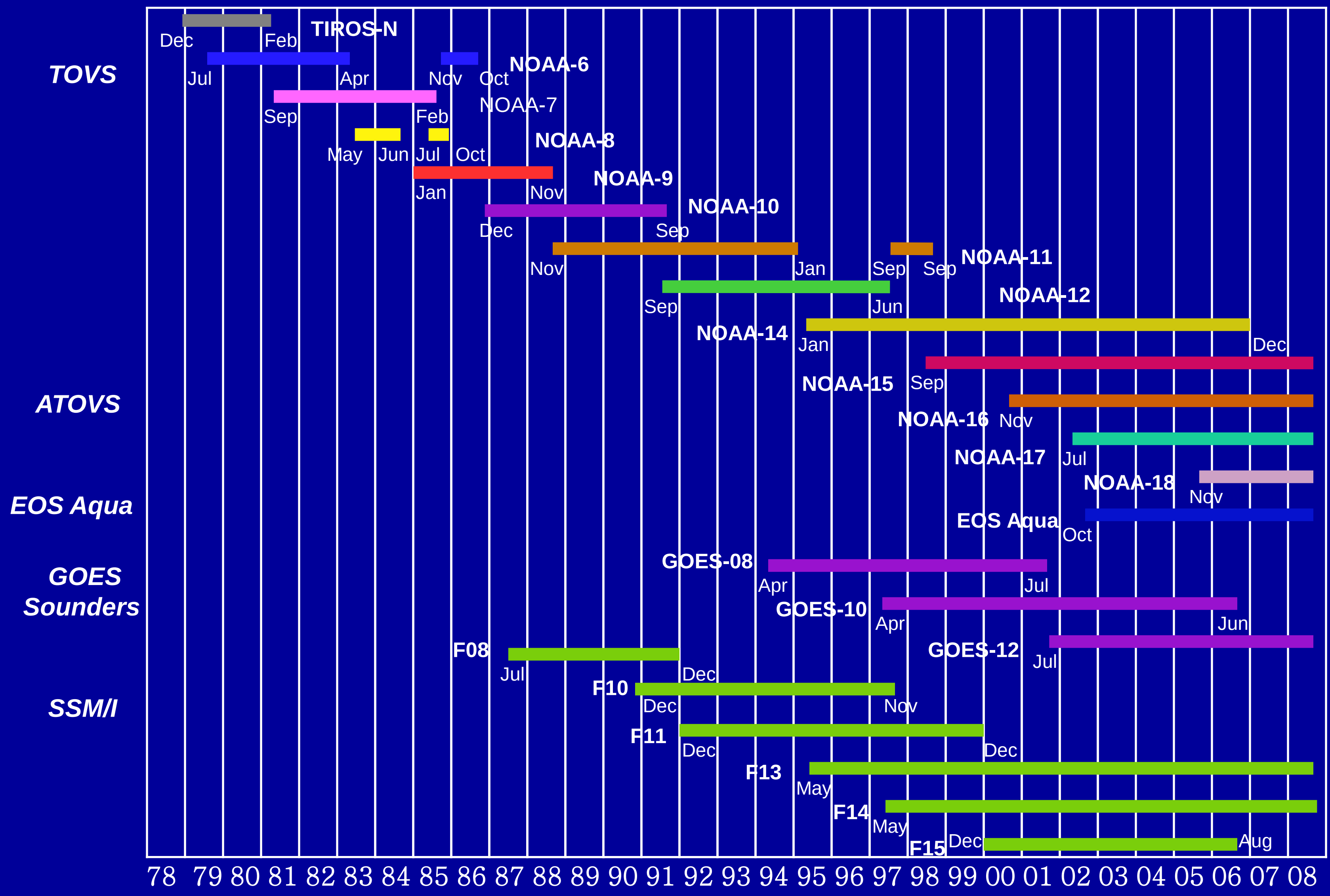
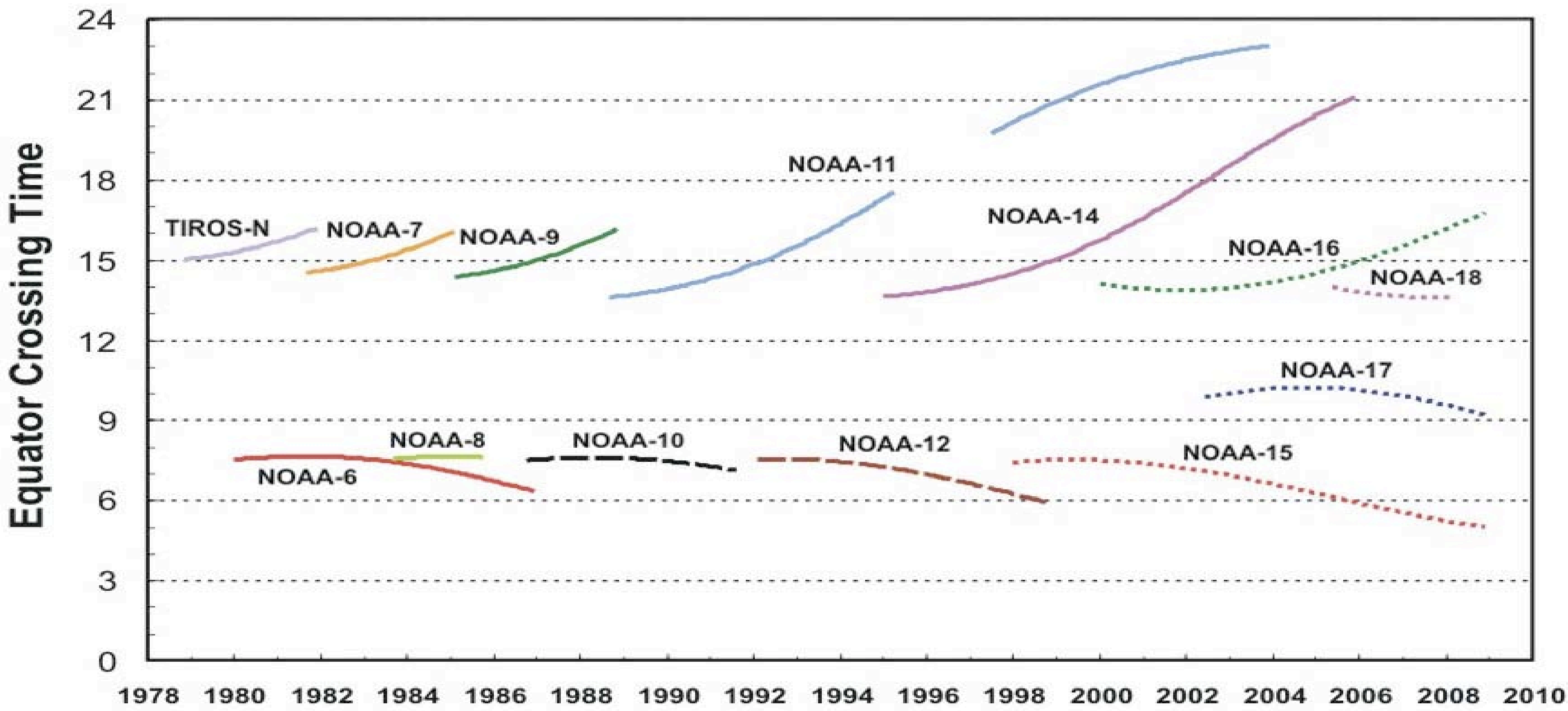
Reanalysis

A MAJOR challenge remains the continually changing observing system in spite of substantial improvements in bias correction in the latest generation of reanalyses

Satellite Data Streams assimilated





Example: Satellite based observations

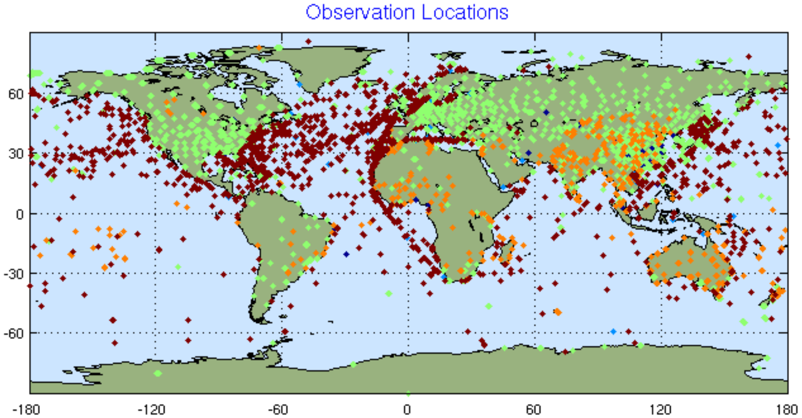
- Satellites typically last 3-5 years and have to be replaced
- Orbits decay
- Equator crossing times change
- New satellite orbits differ
- Instrument calibrations drift and can be changed by launch
- Interference can occur from other instruments

The Changing Observing System

1973 77k/6h

07-Jan-1973 12UTC All data: 77098 observations

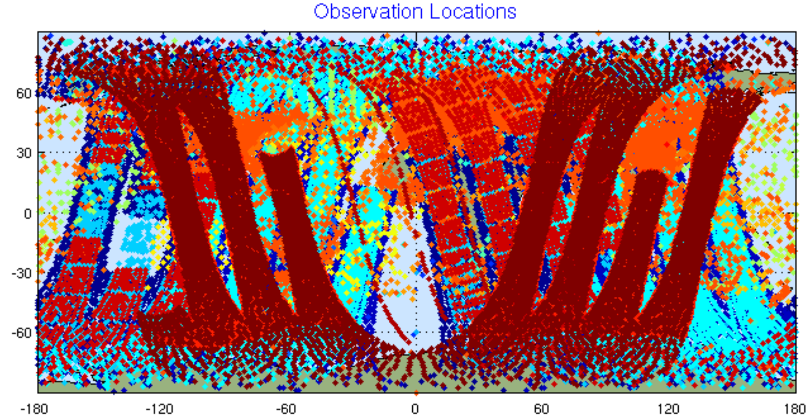
all lat; all lon; all lev; all kt; all kx; all qcx; all qch
/data/austin/b500_swp_73/all_ods_workdir/SAVE_ODS/b500_swp_73.ana.obs.19730107_12z.ods



1987 550k

02-Aug-1987 12UTC All data: 550602 observations

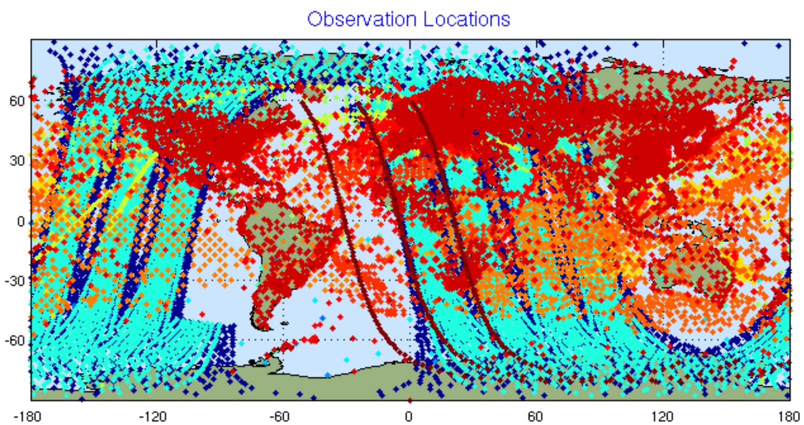
all lat; all lon; all lev; all kt; all kx; all qcx; all qch
/data/austin/b500_b10p9_84/all_ods_workdir/b500_b10p9_84.ana.obs.19870802_12z.ods



1979 324k

07-Jan-1979 12UTC All data: 325765 observations

all lat; all lon; all lev; all kt; all kx; all qcx; all qch
/data/austin/b500_swp_73/all_ods_workdir/SAVE_ODS/b500_swp_73.ana.obs.19790107_12z.ods



2006 4,220k

07-Jan-2006 12UTC All data: 4217655 observations

all lat; all lon; all lev; all kt; all kx; all qcx; all qch
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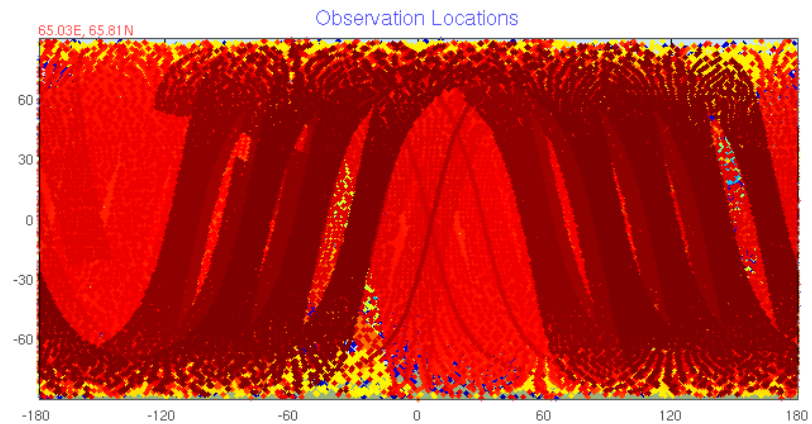

1979 – 325K Obs every 6hrs 2006 – 4.2M Obs every 6hrs

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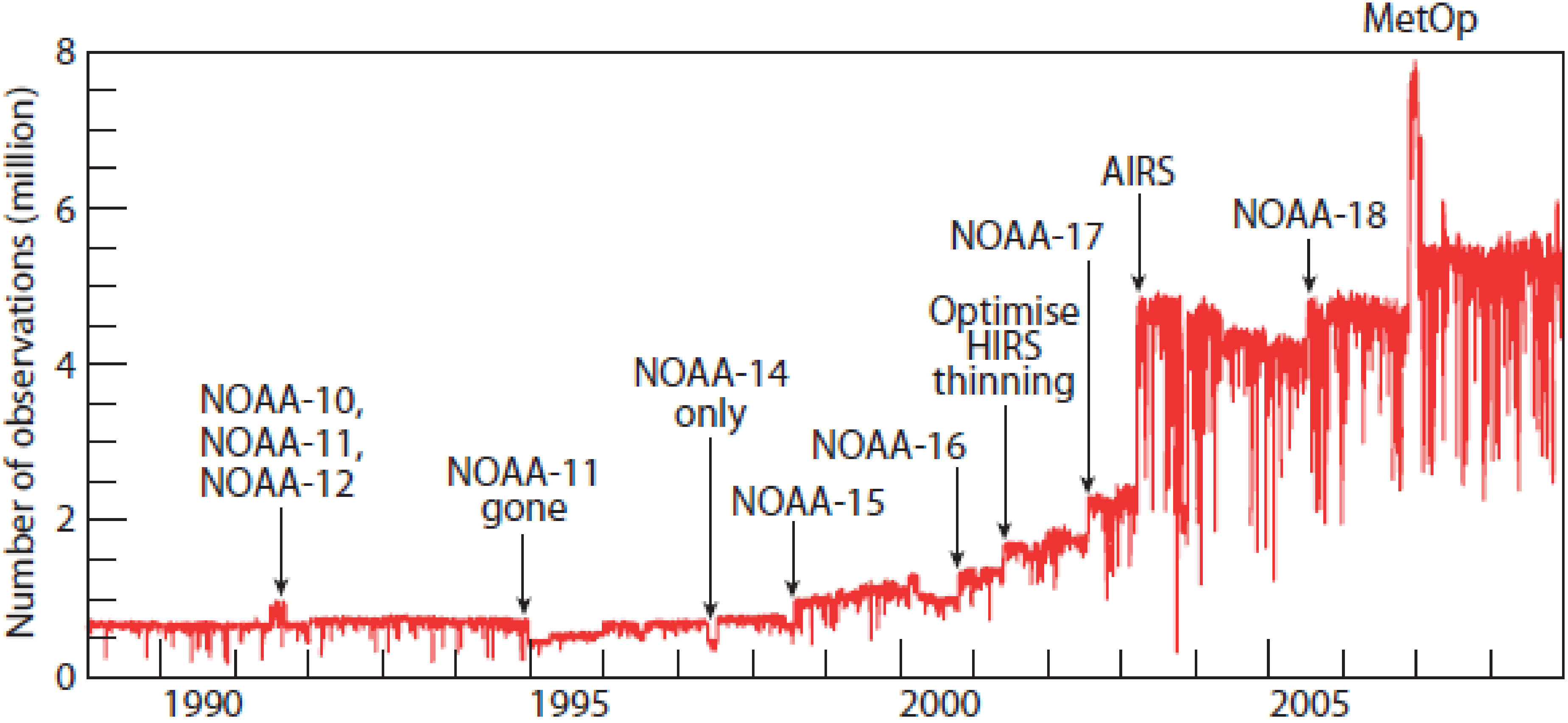


The total number of observations (satellite and conventional) used in the ERA-Interim 12-hourly variational analysis for the period 1989–2008 exceeds 29×10^9. This is mainly due to a large increase in the availability of satellite observations in the 20-year period.

Bias corrections are needed

But how good are they?
Is there a baseline to establish real trends?

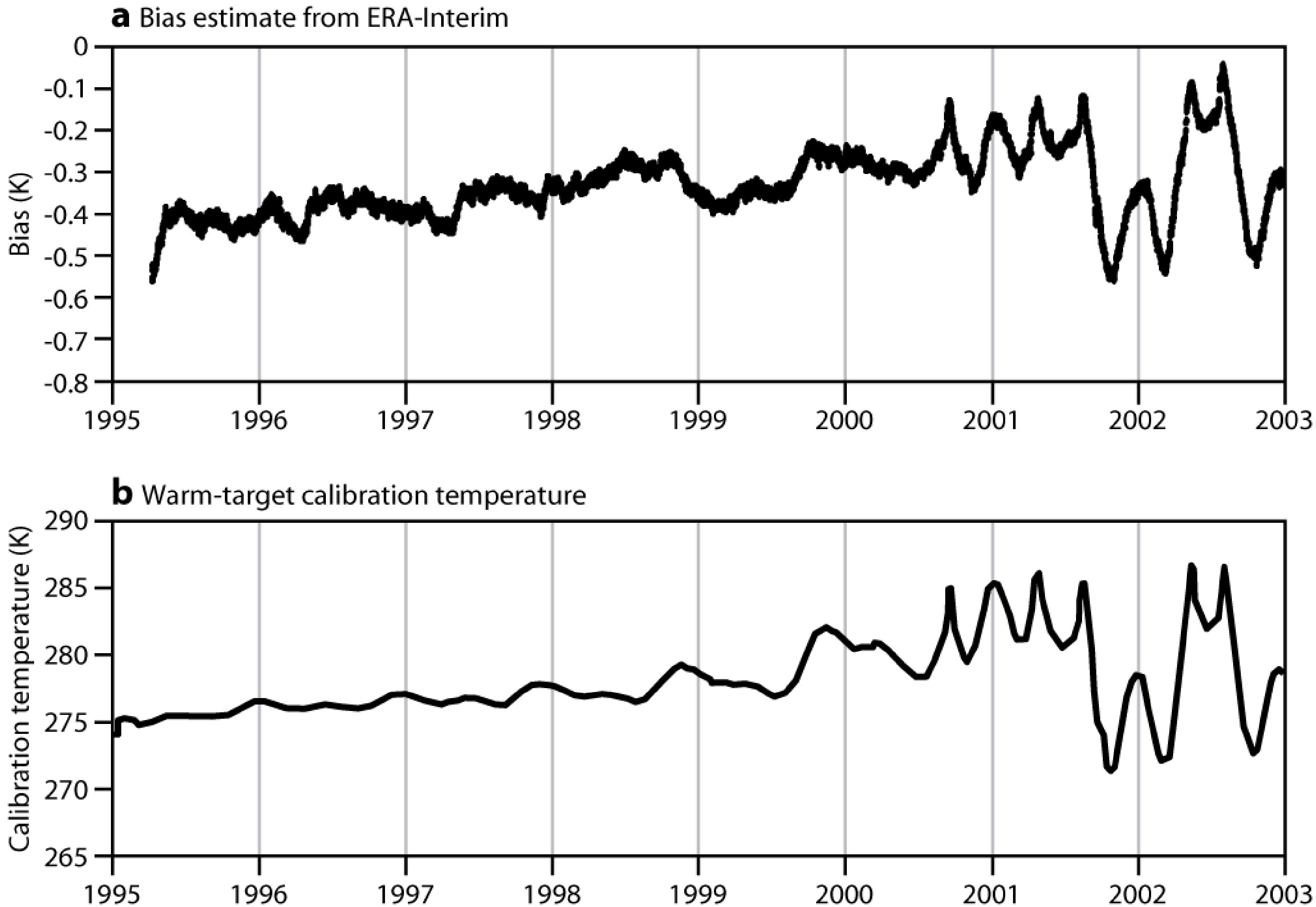
Bias corrections should be applied to satellite and radiosonde data.

Potential for unintended perturbations or bad data to be perpetuated.

Most radiosonde stations do NOT have adequate records of changes

Need to document bias correction changes to almost all observing systems.

Bias correction procedures have greatly improved

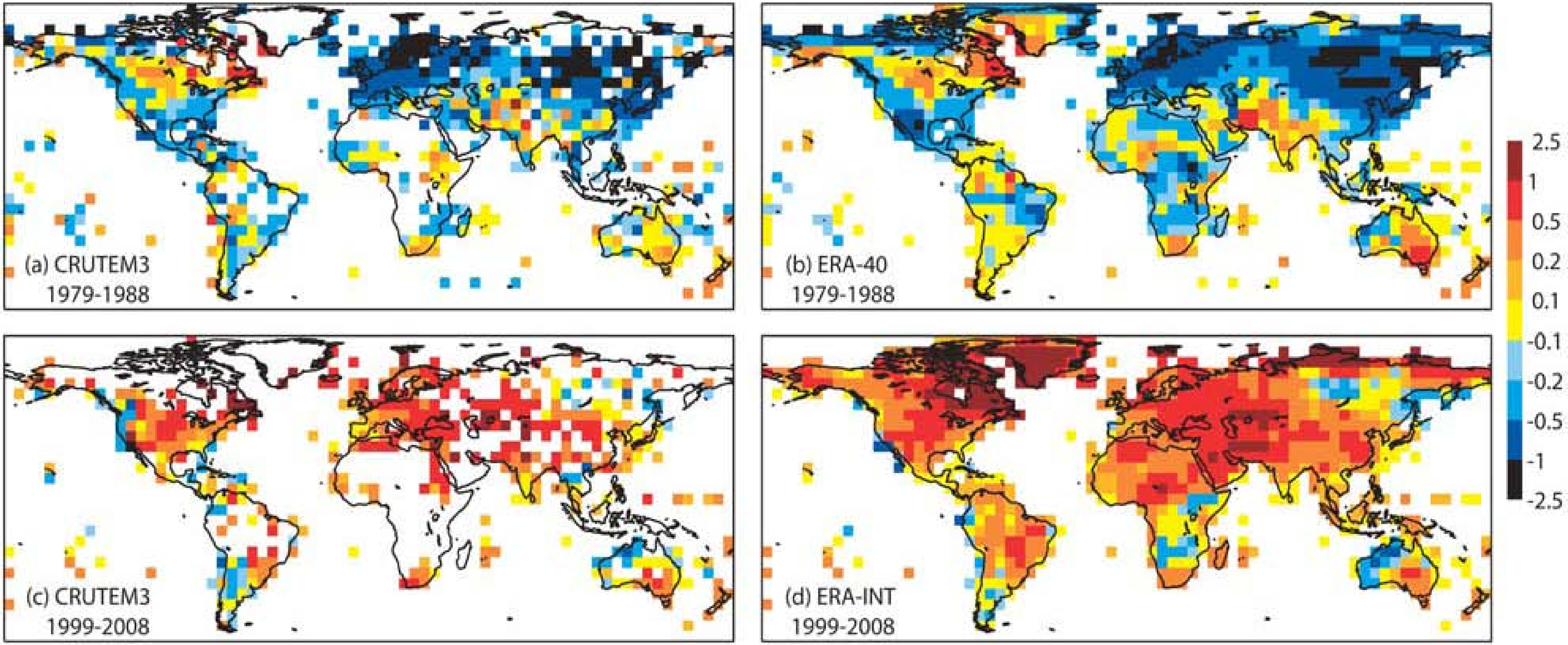


Top: Global mean bias estimates for MSU channel 2 computed in ERA-Interim using new bias correction procedures (top) and recorded warm-target temperatures used for on-board instrument calibration (bottom) show remarkable agreement

Dee et al 2009.

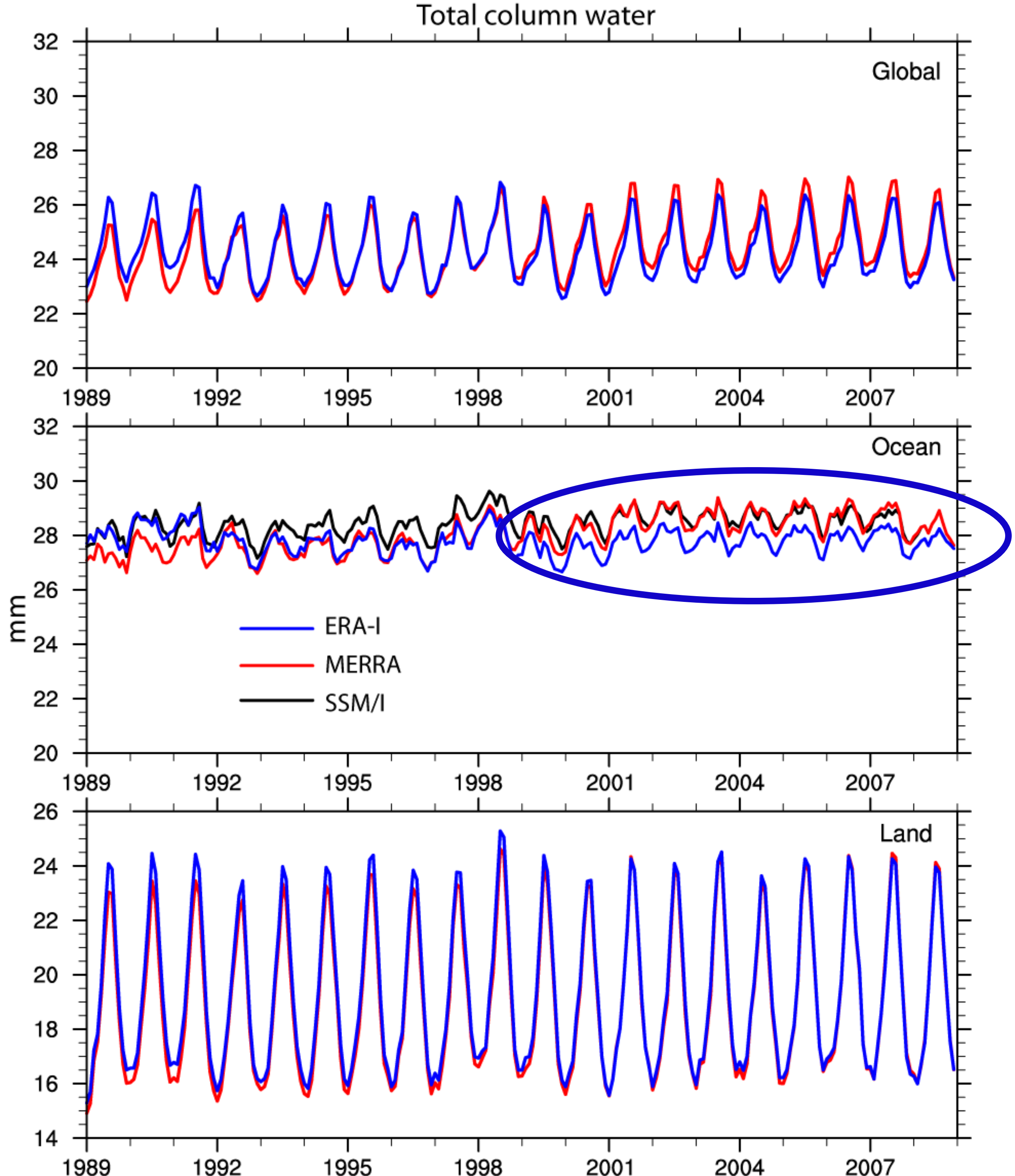
Examples of results from reanalyses with emphasis on problems

Surface Temperature: filled in gaps



Ten year mean anomalies in 2 m temperature (K) relative to the 1989–1998 mean for (a) CRUTEM3 for 1979–1988, (b) ERA-40 for 1979–1988, (c) CRUTEM3 for 1999–2008, and (d) ERA Interim for 1999–2008. Reanalysis values are plotted for all 5 grid squares for which there are CRUTEM3 data and for all other grid squares with more than 10% land. Simmons et al 2010.

Missing data for CRUTEM3 => underestimate trends vs full ERA

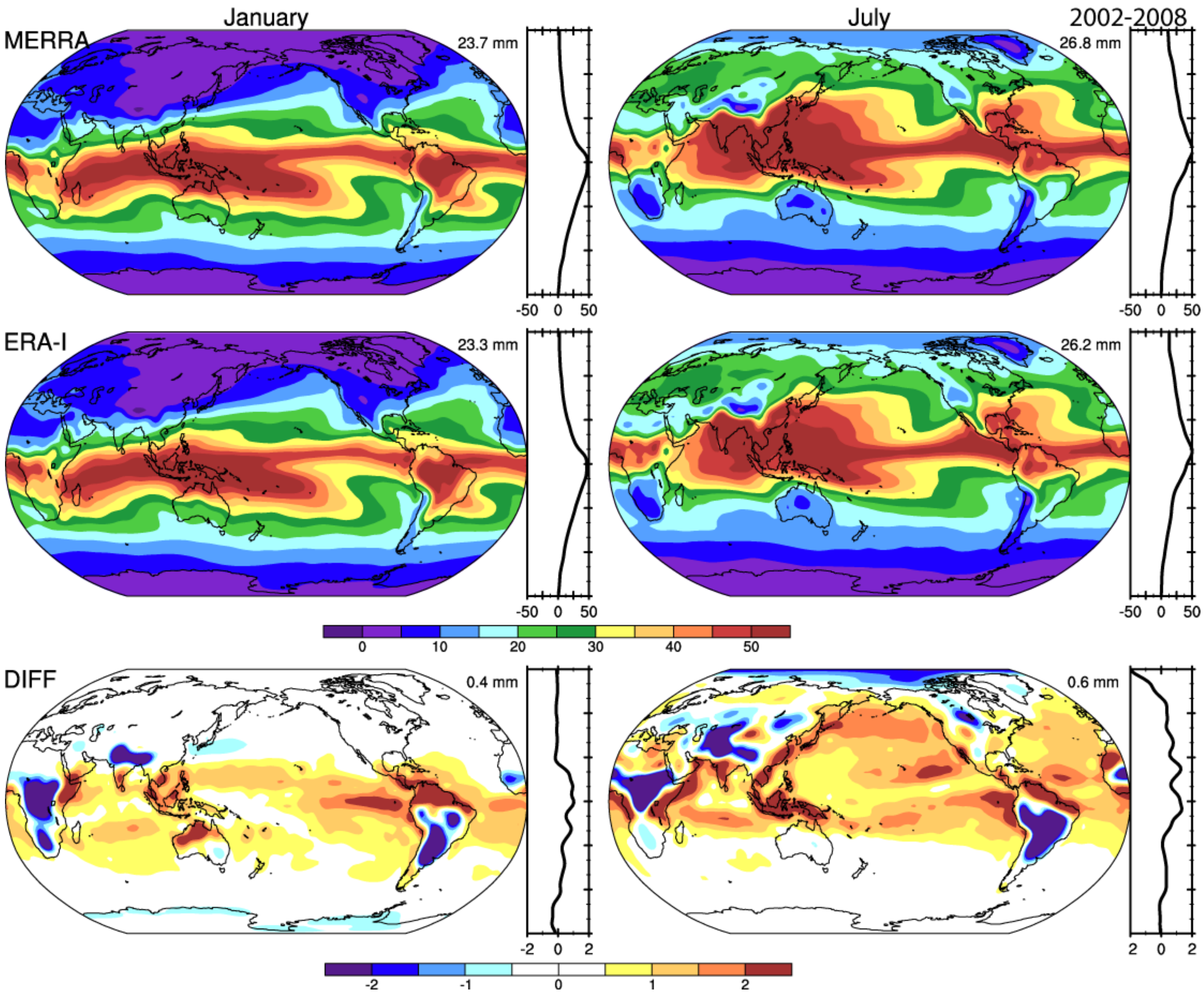


Focus on:
MERRA and
ERA-I

Which have smooth evolving moisture fields (no spinup):

- 4Dvar
- nudging

Precipitable water



Precipitation errors in reanalyses

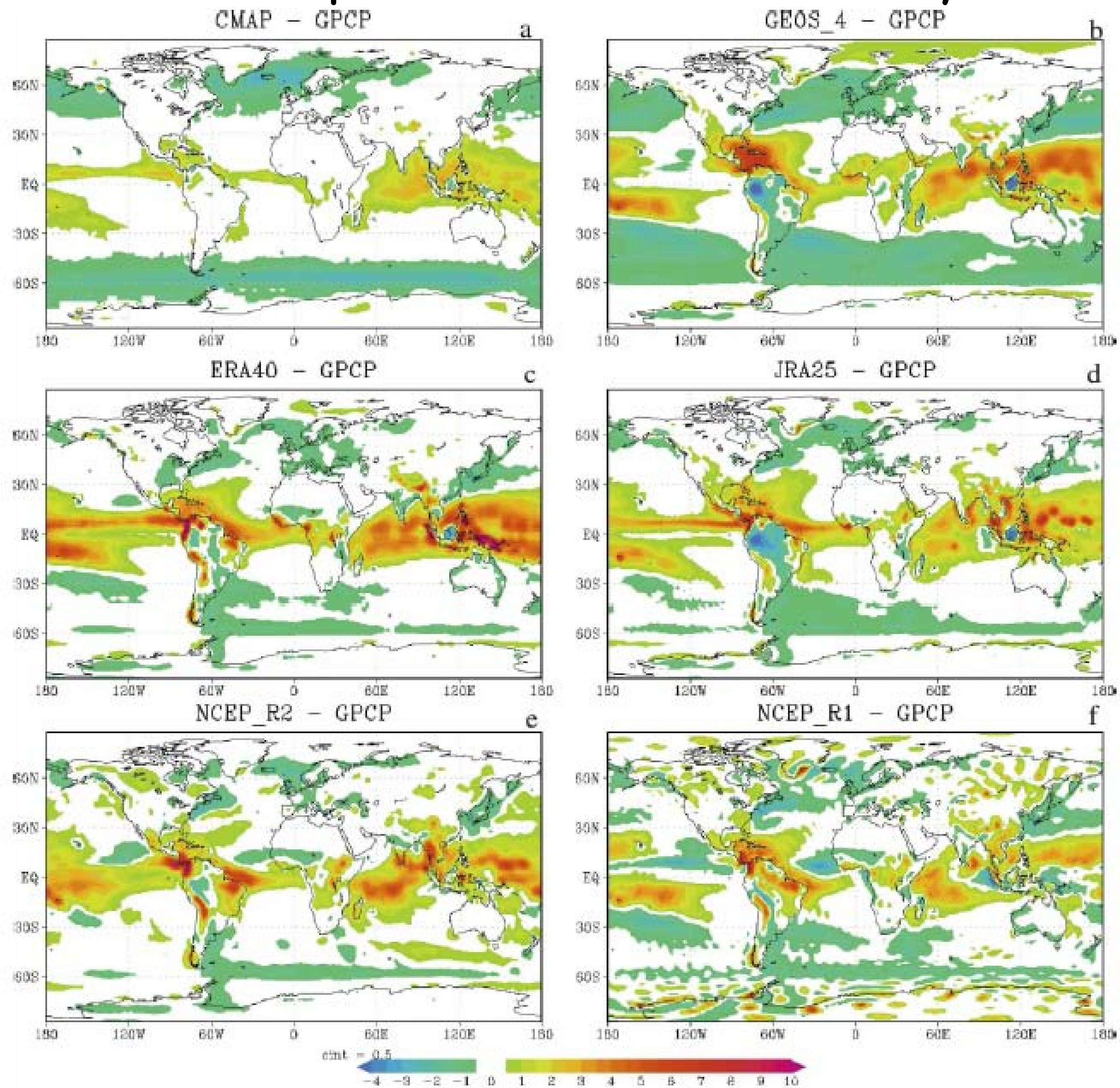


FIG. 2. Climate average (Jan 1979–Dec 2001) precipitation differences (mm day^{-1}) for the CMAP merged product and the

Bosilovich et al 2008

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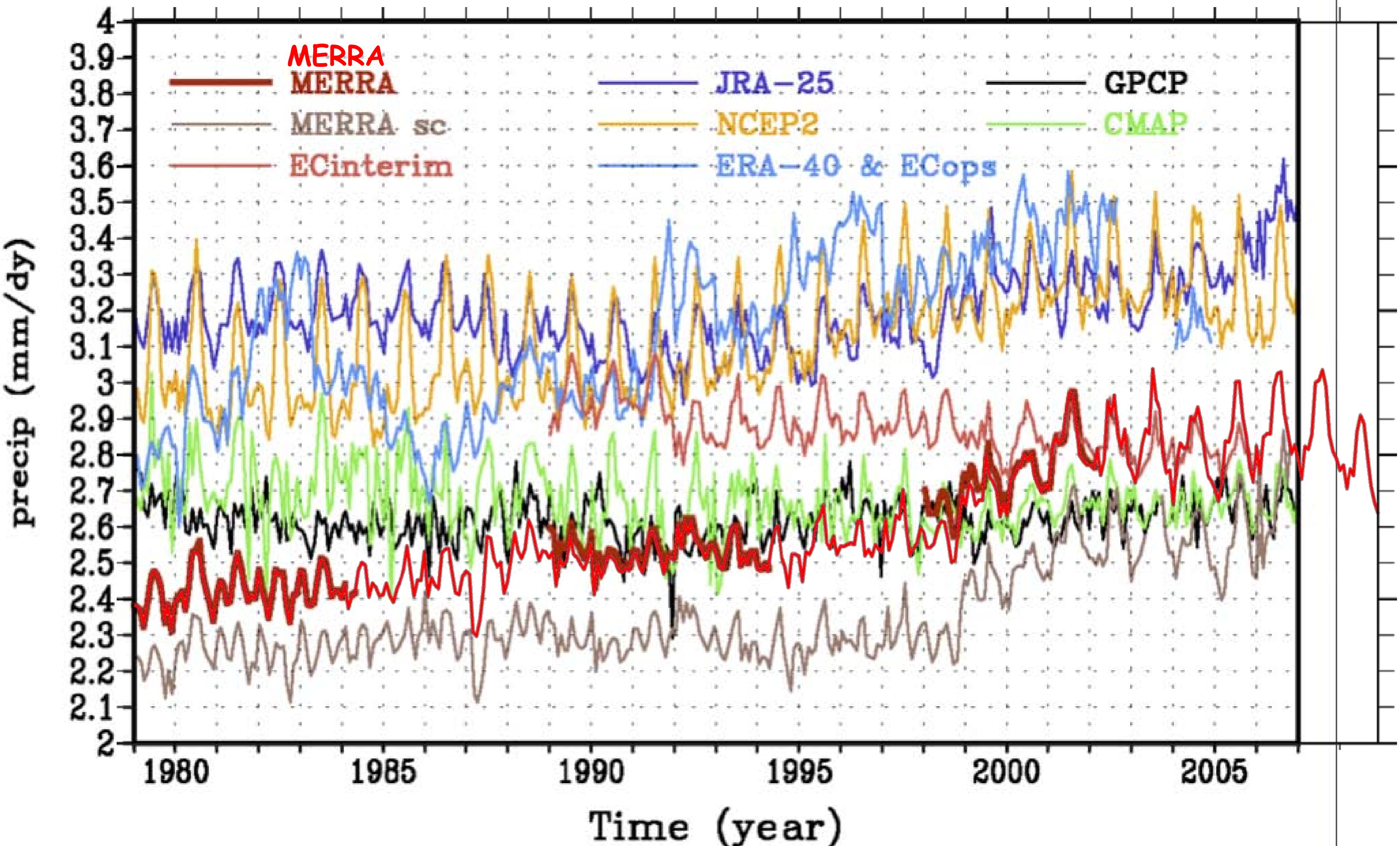
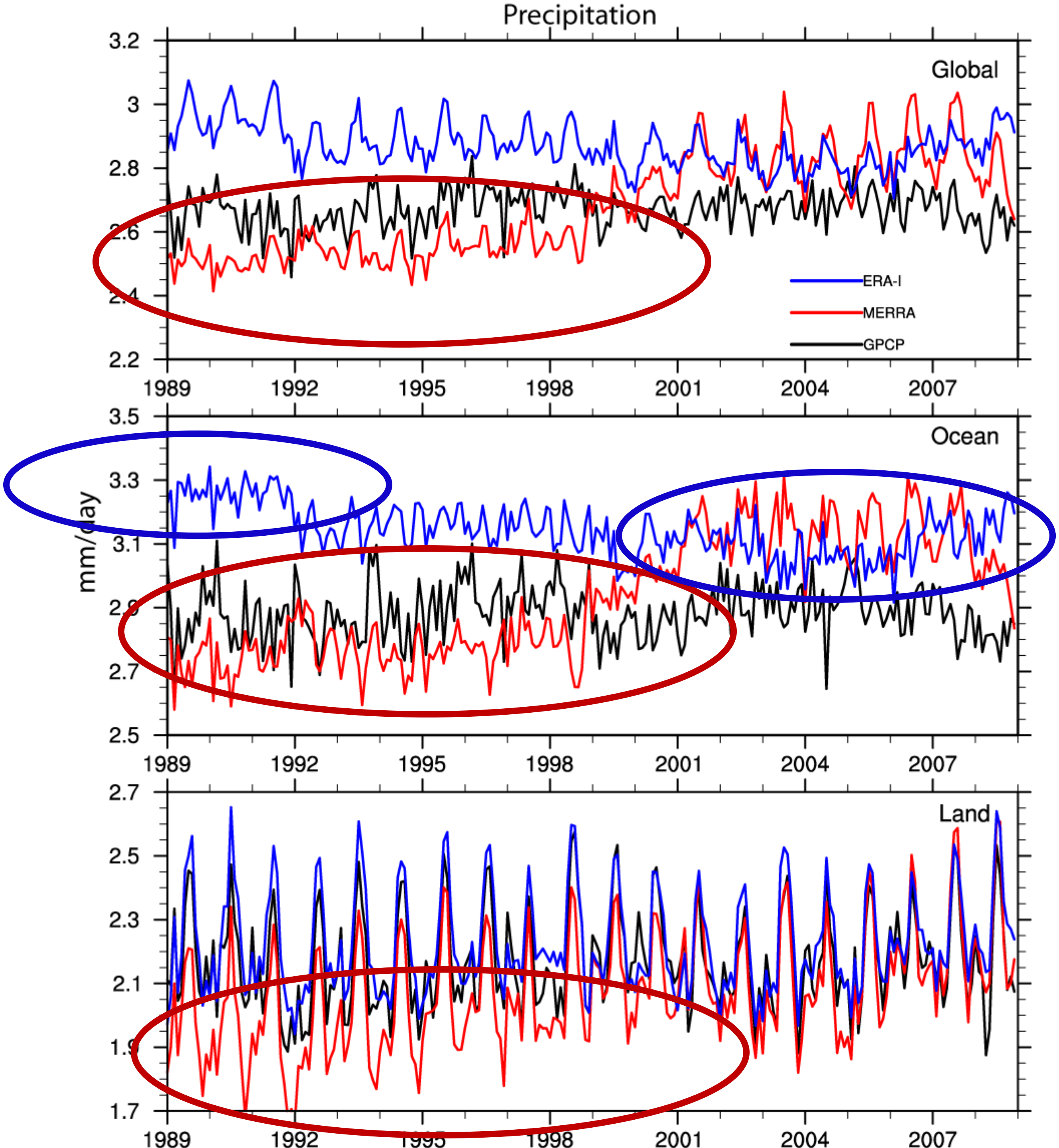
Global mean precipitation



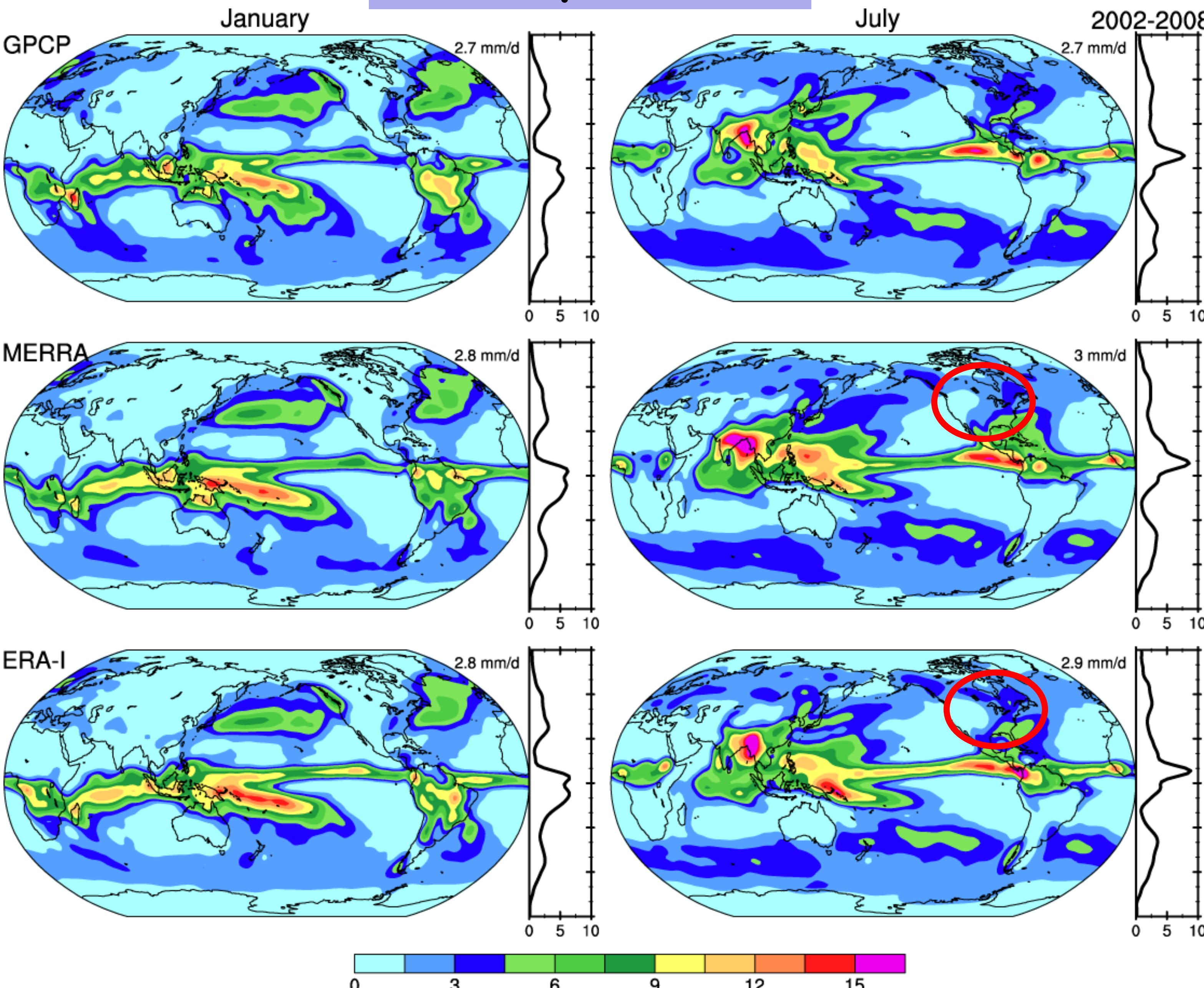


Identifiable discons:

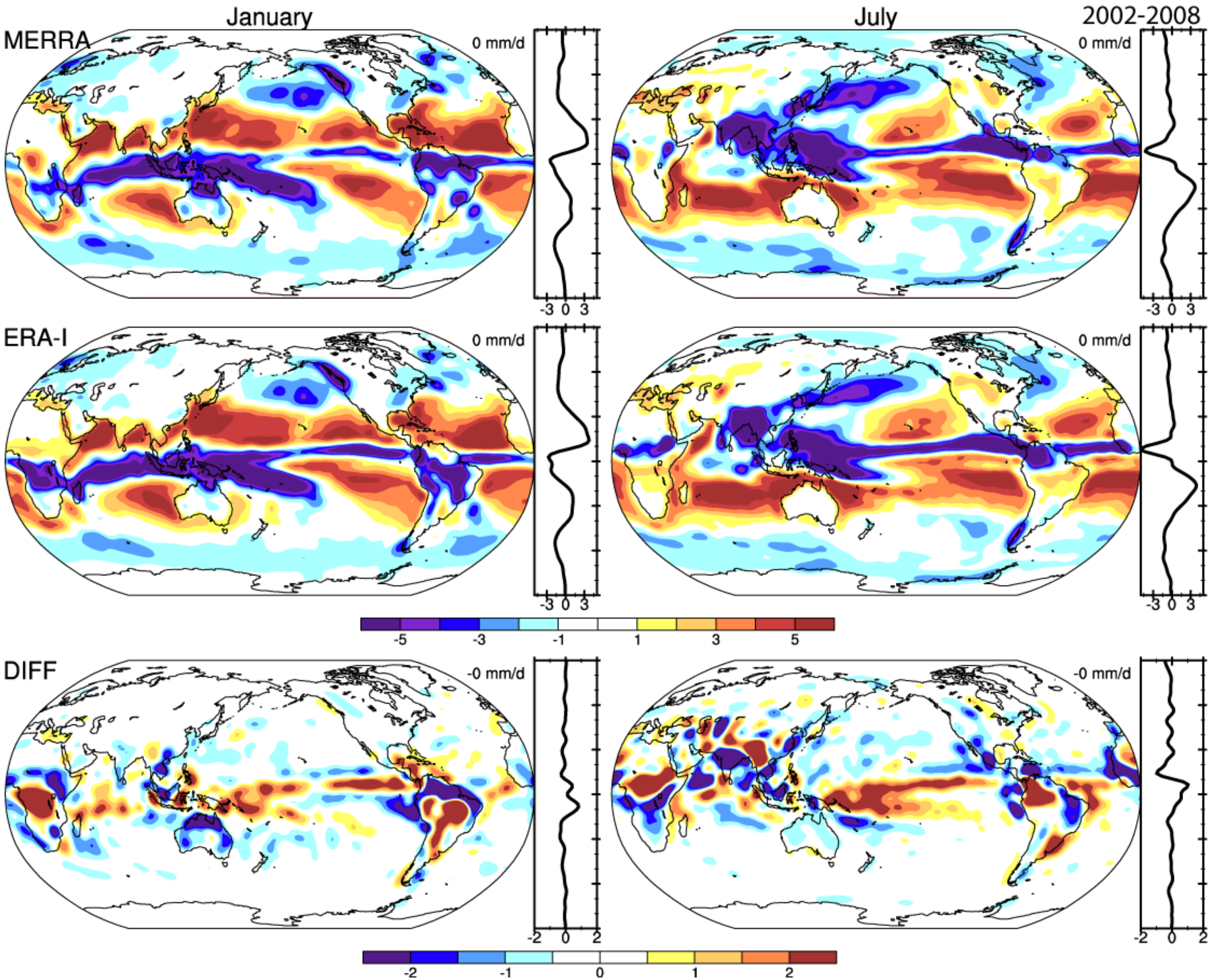
•SSM/I mid-1987,
•TOVS to ATOVS: AMSU-A,AMSU-B
late 1998 to 2001
(NOAA 15 =>NOAA 12
NOAA 16 => NOAA 14, March 20, 2001),

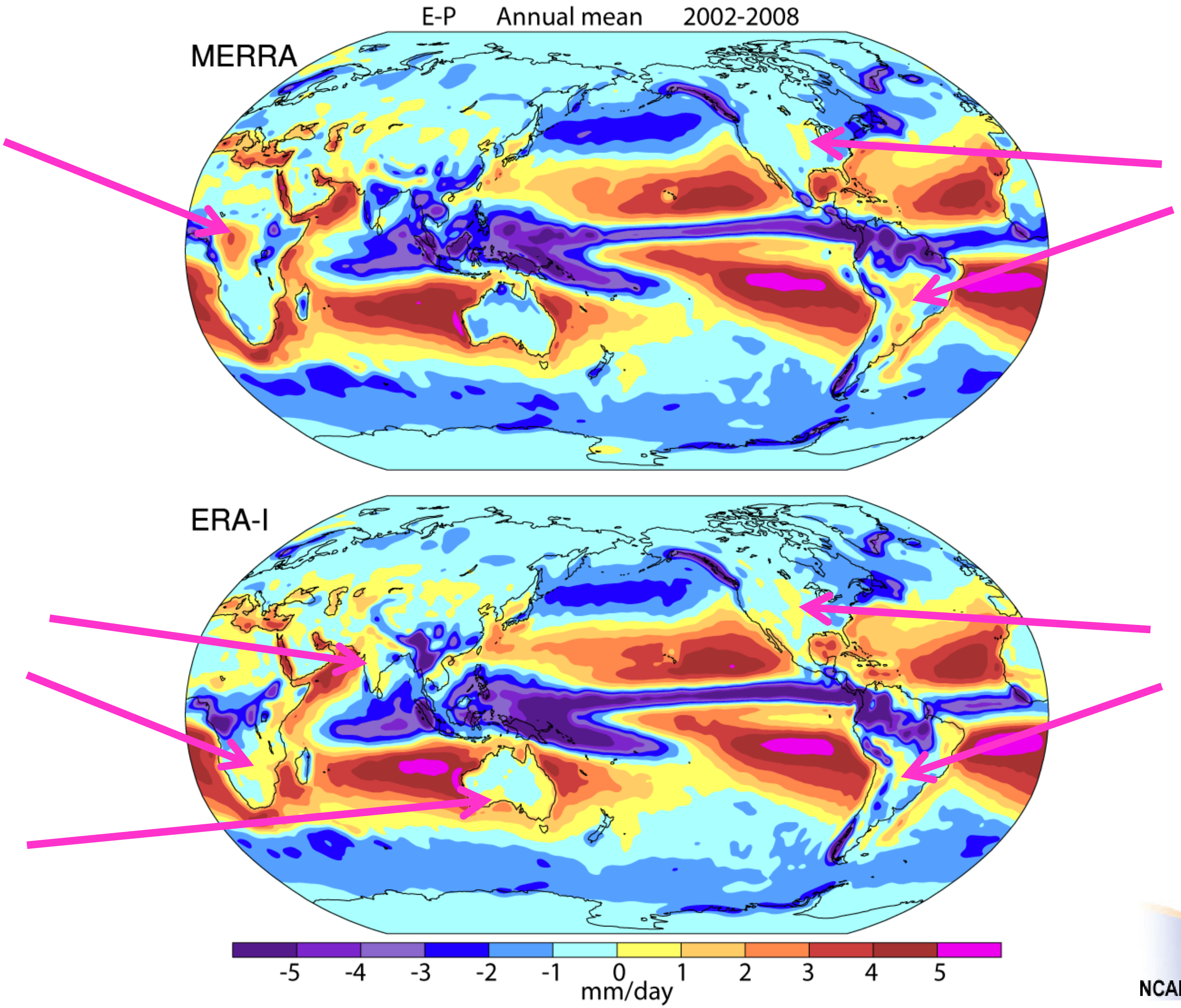
AIRS late 2002,
GPS RO 2002 on,
COSMIC April 2006.

Precipitation



Freshwater flux E-P
From moisture budget





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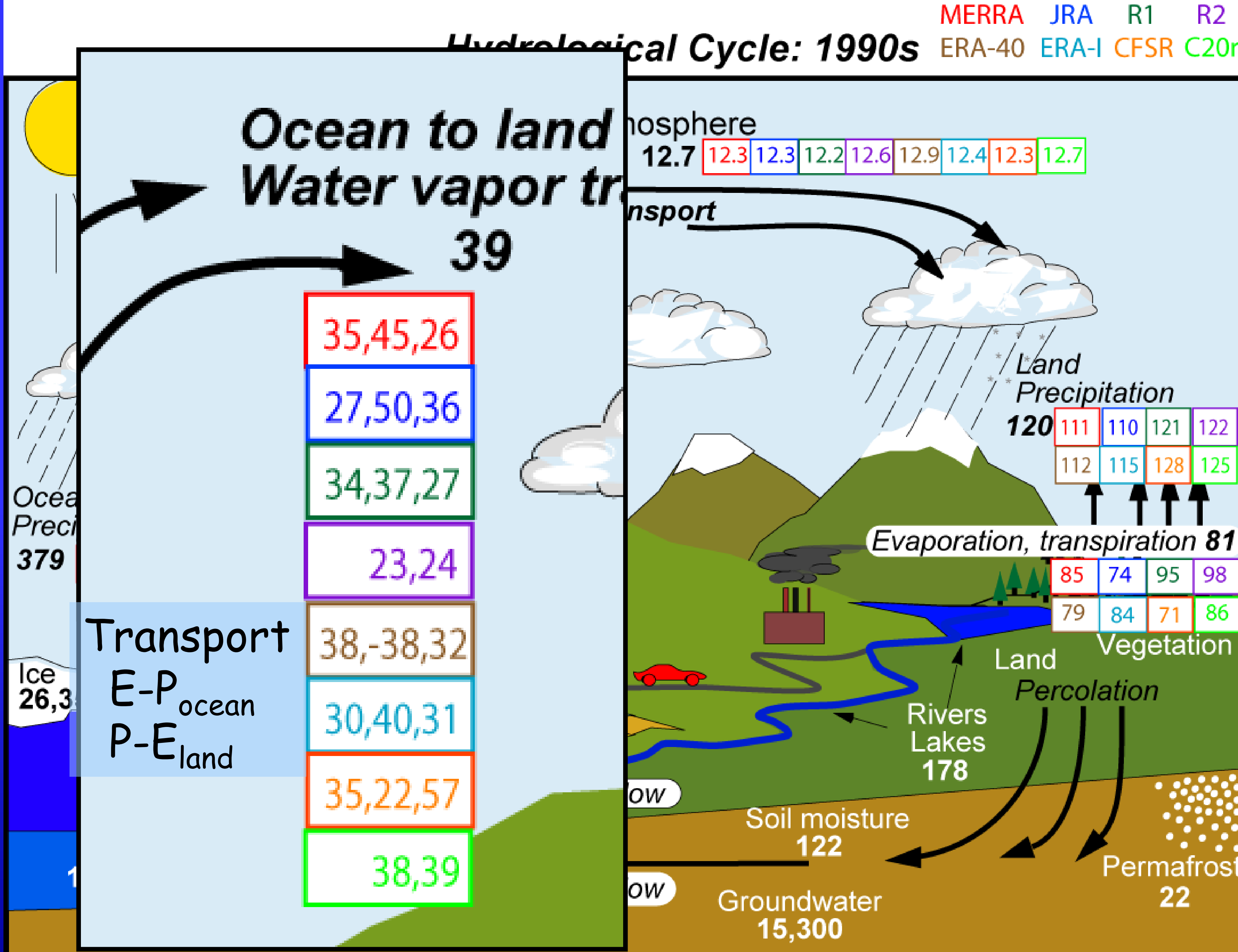
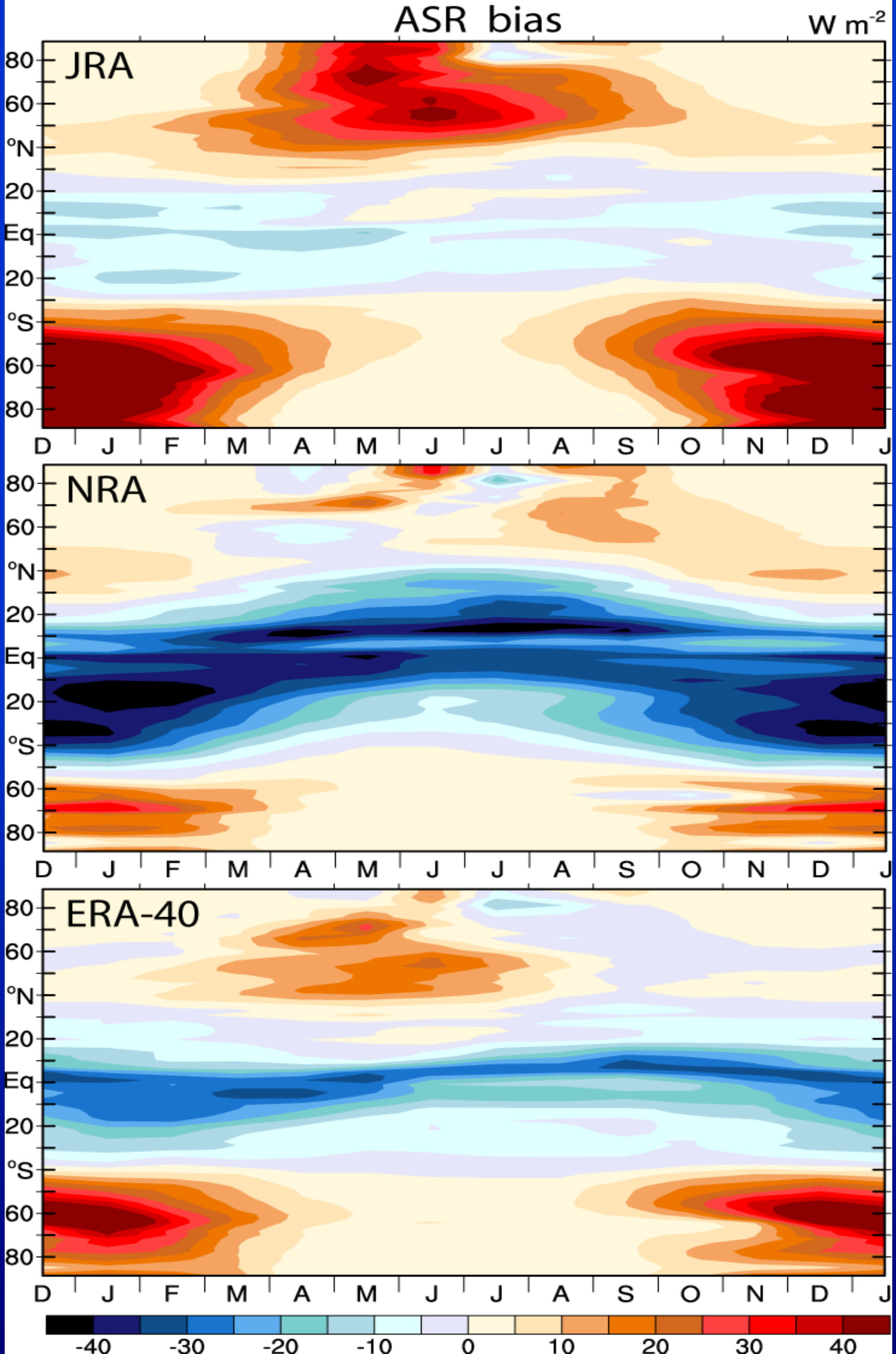


Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges



Energy budget: Reanalyses

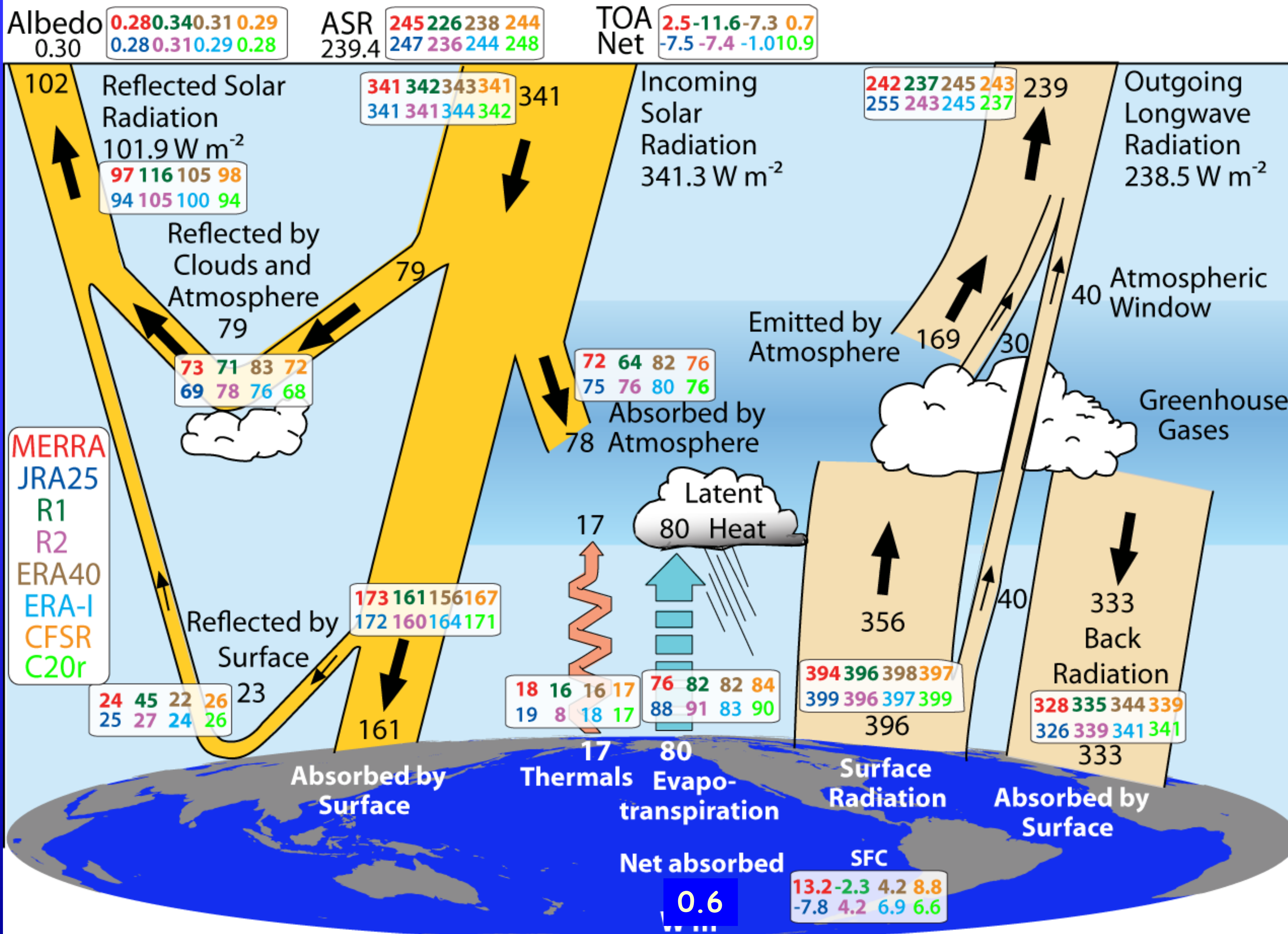
ASR bias 1990s

Biggest in summer

- All reanalyses have too much incoming solar radiation in southern oceans
- Caused by too few clouds
- Implies too much heating of ocean which should diminish poleward heat transports when models are coupled
- Has implications for storm tracks and ocean transports

Trenberth and Fasullo 2010

Global Energy Flows W m^{-2} : 1990s



Energy budget: Reanalyses

- At TOA, most climate models are tuned to get balance or replicate ERBE/CERES
- Depends on equilibrium simulation
- No longer works in reanalyses
  - Specified SSTs
- Global imbalances (hide even bigger local)

	R1	ERA-40	ERA-I	JRA	MERRA	CFSR	
Resolution	1.9°	0.8°	0.5°	1.1°	0.5°	0.5°	
ASR	-13	-1	+5	+8	+6	+5	W m^{-2}
OLR	-2	+6	+6	+16	+3	+4	
Net(TOA)	-12	-8	-2	-8	+2	0	
Net (sfc)	-3	+4	+6	-8	+13	+8	

For 1990s vs climatology

Reanalyses

- Even if the assimilating model has a balanced energy budget, when SSTs are specified there is an infinite heat and moisture source or sink
- There is no feedback on the SSTs from surface fluxes
- The result is potentially large energy imbalances at TOA and at surface
- The TOA and surface energy balances can be strong diagnostics of model bias problems

Reanalysis

1. The next (4th) International reanalysis conference is planned to be in April 2012 in Washington DC area.
2. There is not a problem with lack of reanalyses, indeed there is a proliferation. The problems are:
   1. lack of an end to end program with adequate evaluation of products (and the funding), and
   2. Reanalysis is all done in a research domain and not sustained, so that key personnel can be lost.
   3. Lack of adequate vetting and diagnosis
3. Reanalysis is an essential part of climate services, especially in monitoring, attribution and prediction