An Overview of Atmospheric Analyses and Reanalyses for Climate

Kevin E. Trenberth

NCAR

Boulder CO

NSF

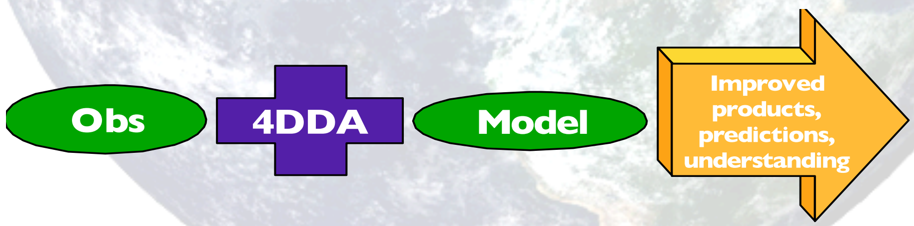
NESL

NCAR

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

$$\partial x/_{\partial t} = dynamics + physics + \Delta x$$

Observations of **state** and storage (***temperature, wind, soil moisture, etc***) are blended with the state of the system as forecast by a model based on the previous set of observations. 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 and land surface.

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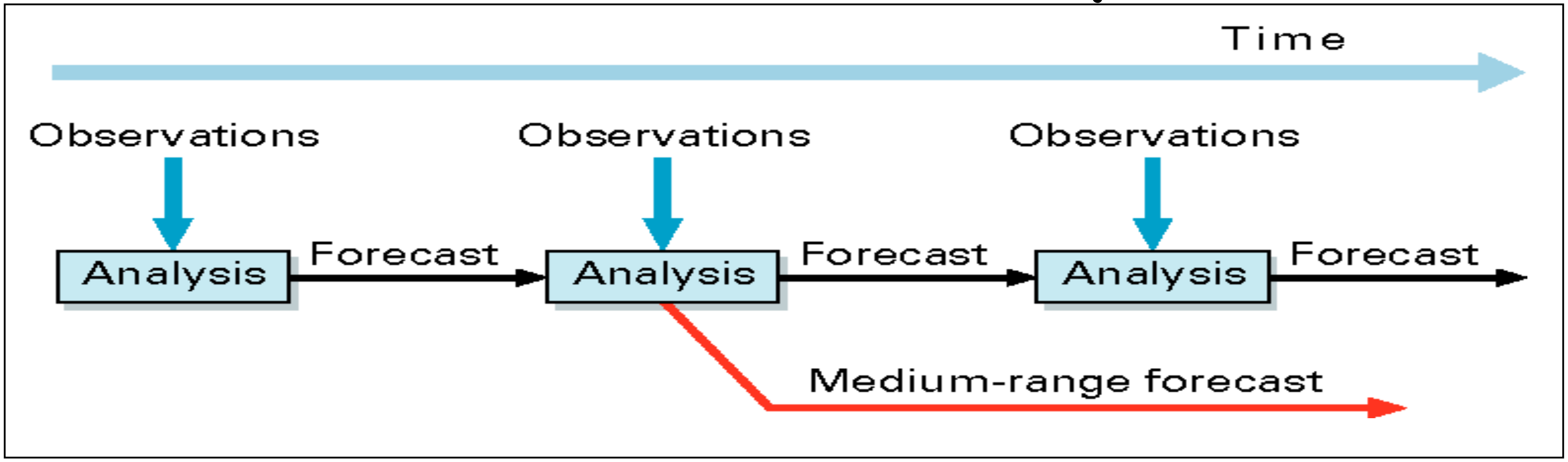
Data assimilation system



- 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

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".

1) Call for reanalysis:

Trenberth, K. E., and J. G. Olson, 1988: An evaluation and intercomparison of global analyses from NMC and ECMWF. *Bull.Amer.Meteor.Soc.*,69,1047-1057.

Bengtsson, L. and J. Shukla, 1988: Integration of space and in situ observations to study global climate change. *Bull. Amer. Meteor. Soc.*, 69, 1130-1143.

2) First generation

Schubert, S.D., R. B. Rood and J. Pfaendtner, 1993: An Assimilated Data Set for Earth Science Applications *Bull. Amer. Meteor. Soc.*, 74, 2331-2342.

Gibson, J.K., P. Kallberg, A. Nomura, and S. Uppala, 1994: The ECMWF re-analysis (ERA) project- Plans and current status. 10th Int. Conf. Interactive Inf. and Proc. Syst. Meteor., Oceanogr. and Hydrol., Nashville, TN, AMS, 164-167.

Kalnay,E., et al, 1996: The NMC/NCAR 40-year Reanalysis Project. *Bull.Amer.Meteor.Soc.*, 77,437-471.

Kanamitsu, M, W. Ebisuzaki, J. Woollen, S-K Yang, J .J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP-DOE AMIP-II Reanalysis (R-2),. *Bull. Amer. Met. Soc.*, 83, 1631-1643.

3) Second generation ERA40, JRA

4) Next generation: MERRA, ERA-interim, CFSR

Atmospheric Reanalyses

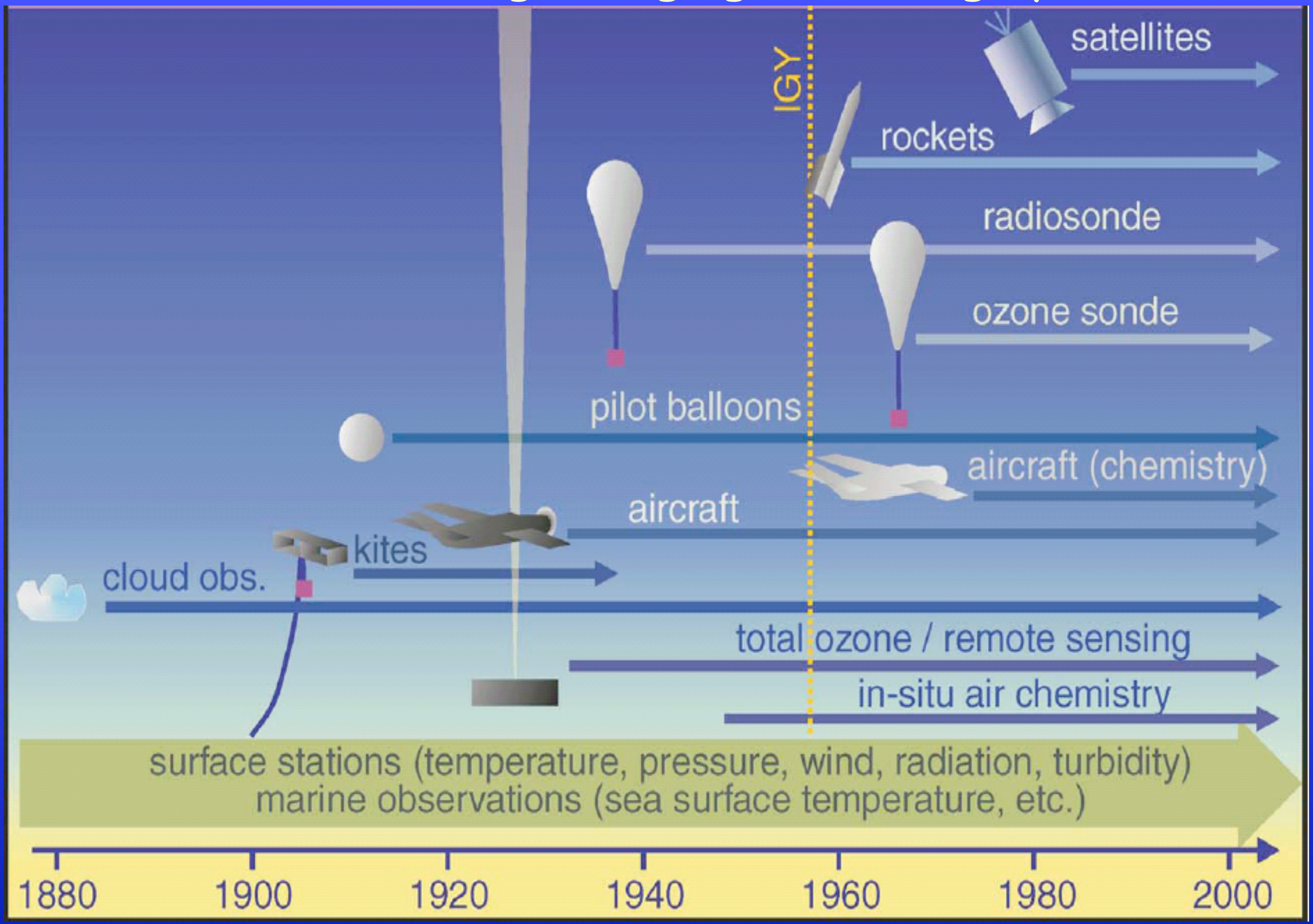
*Current **atmospheric reanalyses**, with the horizontal resolution (latitude; T159 is equivalent to about 0.8°), the starting and ending dates, the approximate vintage of the model and analysis system, and current status.*

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 2010, ongoing
C20r (NOAA)	T62	1875-2008	2009	Complete, in progress
ERA-40	T159	1957-2002	2004	done
ERA-Interim	T255	1979-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

Reanalysis

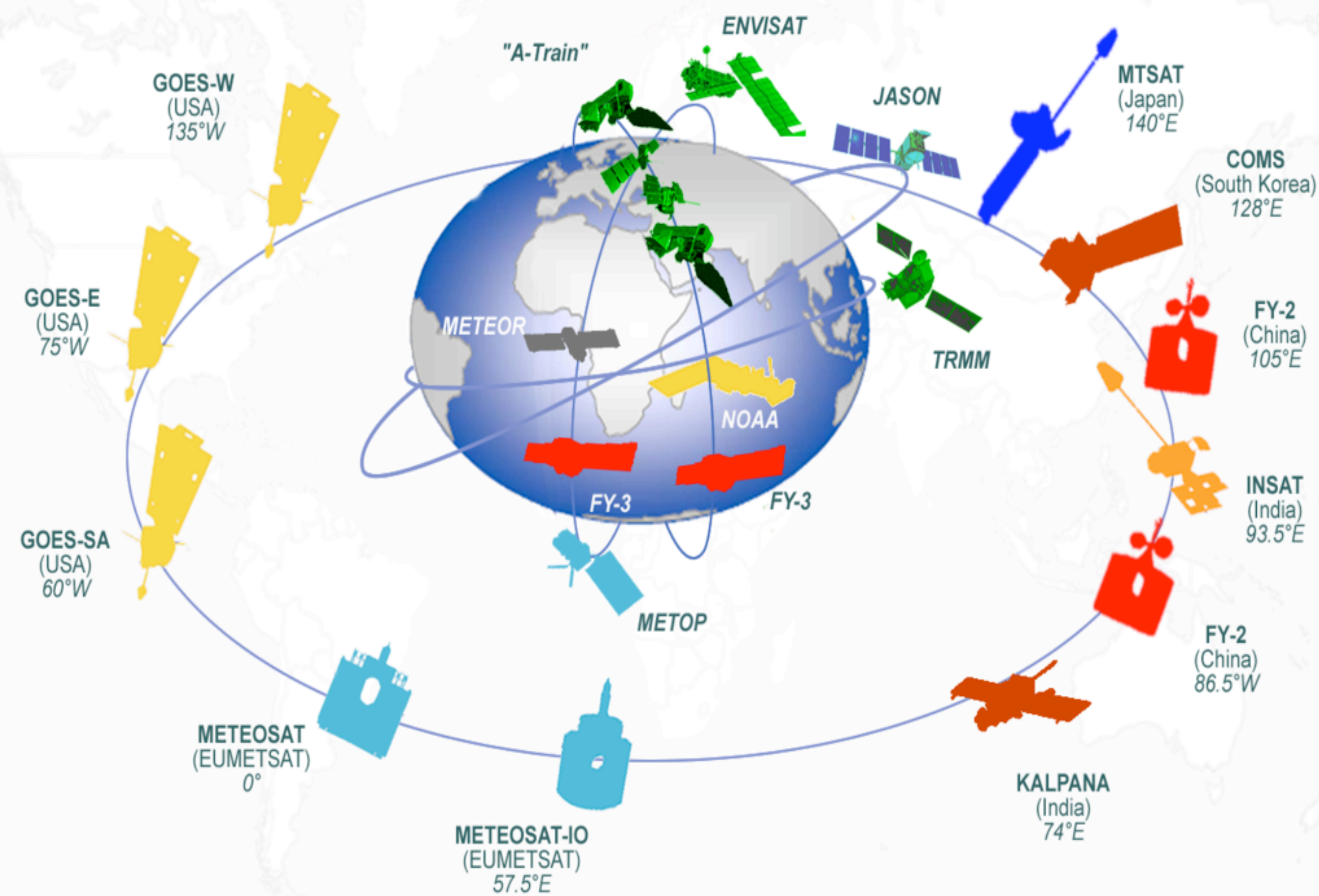
A MAJOR challenge remains the continually changing observing system in spite of substantial improvements in bias correction in the latest generation of reanalyses

The continuing changing observing system



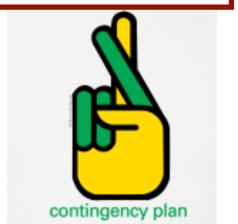
Courtesy, S. Brönnimann

Space-based Global Observing System Schematic



Information Value Chain

Satellites & sensors → Calibrated data sets → Quality-controlled products → Dissemination & access → Awareness & training → Users



GSICS Global Space-based Inter-Calibration System

SCOPE • CM

Internet
WMO IGDDS
GEONETCast
Delivering Environmental Data to Users Worldwide

VLab

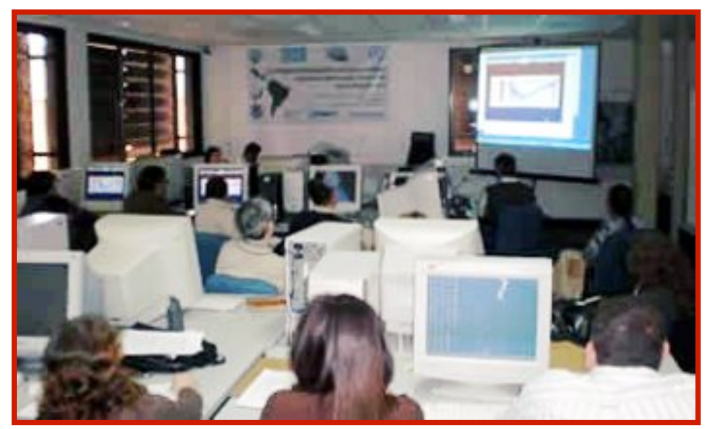
Components

GSICS: Global **S**pace-based **I**ntercalibration **S**ystem

IGDDS: WMO Integrated Global Data Dissemination Service

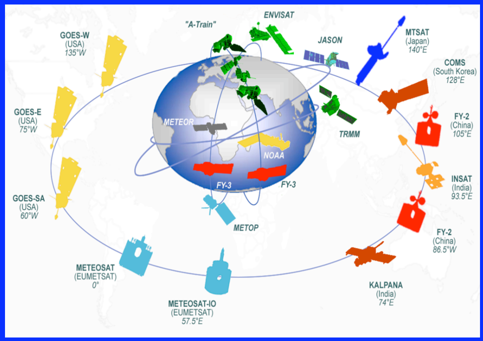
SCOPE-CM: Sustained Coordinated Processing of Environmental Satellite Data for Climate Monitoring

Vlab: Virtual Laboratory for Training in Satellite Meteorology



Given the observations:

Adequate **analysis**, **processing**, **meta-data**, **archival**, **access**, and **management** of the resulting data and the data products create further challenges in spite of the new computational tools.

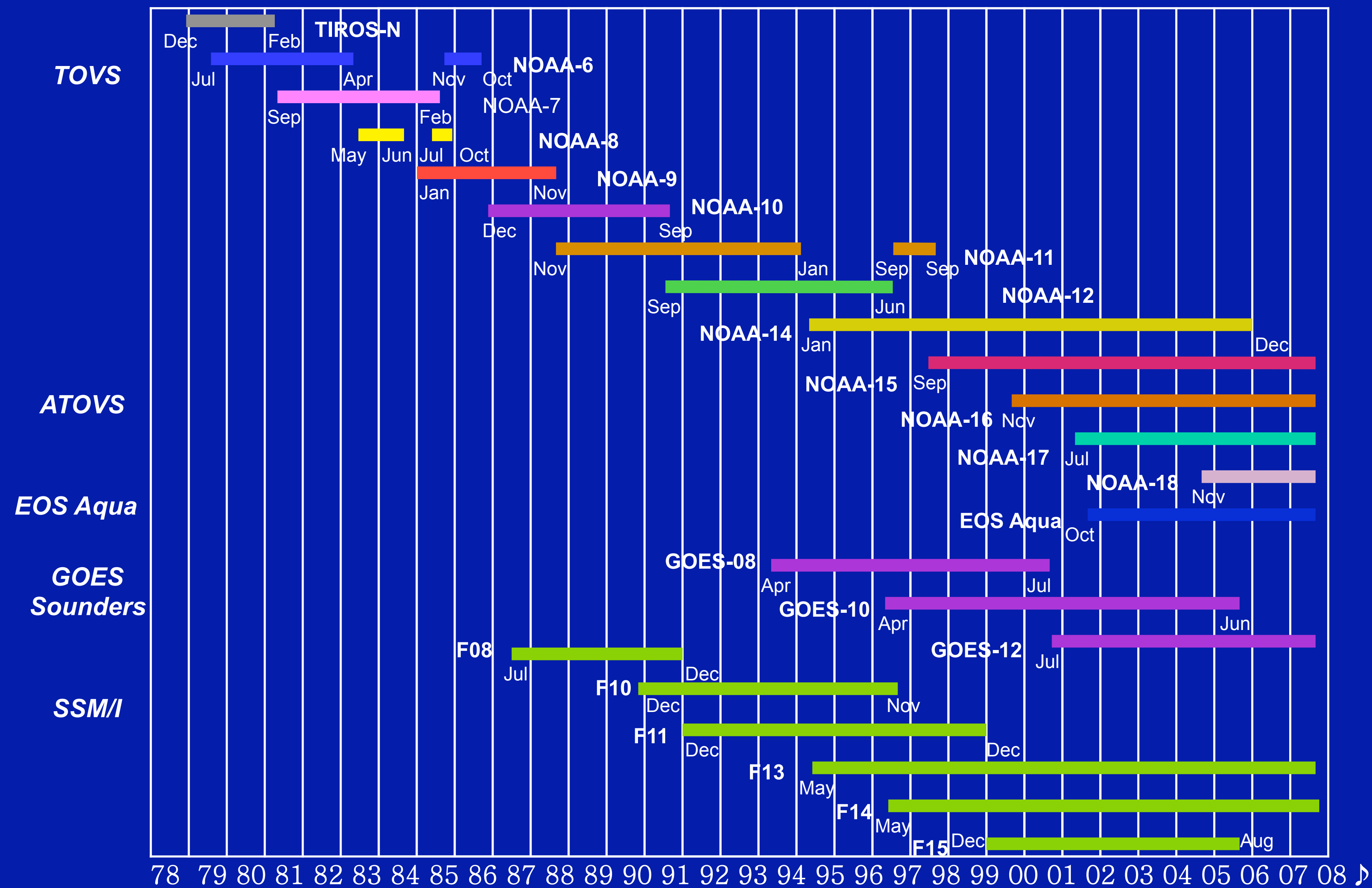


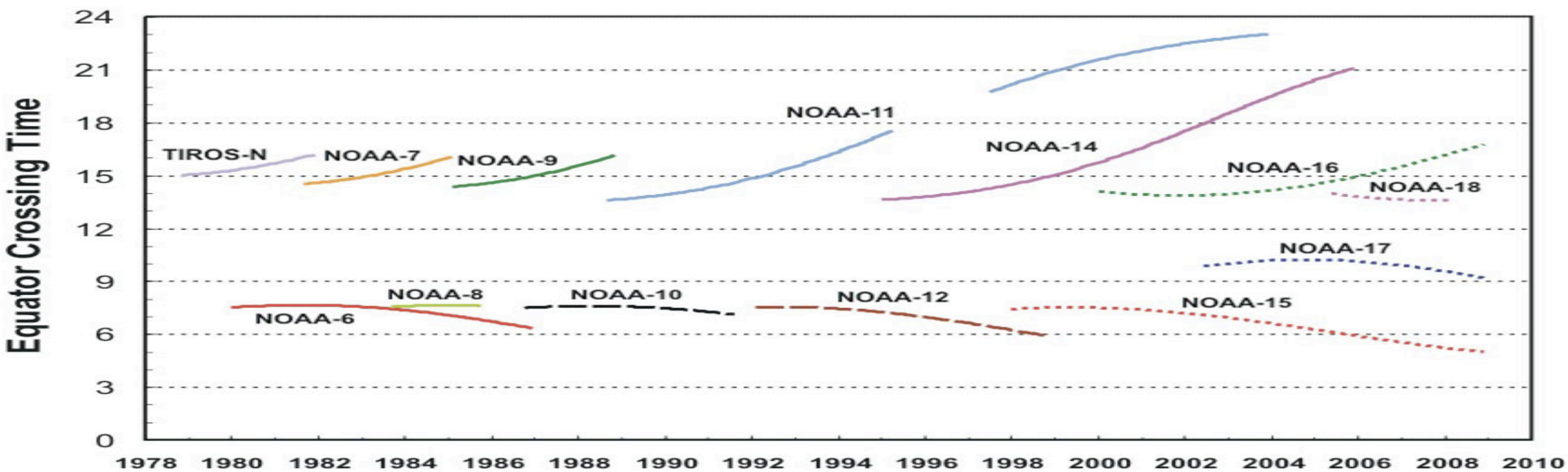
Volumes of data continue to grow and the challenge is to distill **information** out of the increasing **numbers**.

Known issues

- Nearly all satellite datasets contain large spurious variability associated with changing instruments/ satellites, orbital decay and drift, calibration, and changing methods of analysis
- Only 2 datasets (SSM/I water vapor; MSU satellite temps) were used in AR4 IPCC to examine trends
- Once, the issue was getting a single time series. Now there is a proliferation and multiple datasets purporting to be the "one". All differ, often substantially.
- Reprocessing is essential and should be the hall mark of any **climate** observing system

Satellite Data Streams assimilated





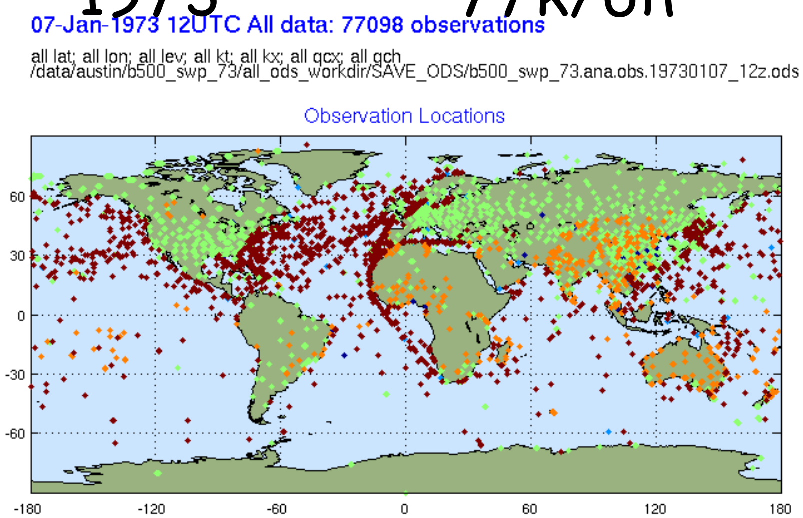
Example: Satellite based observations

- 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

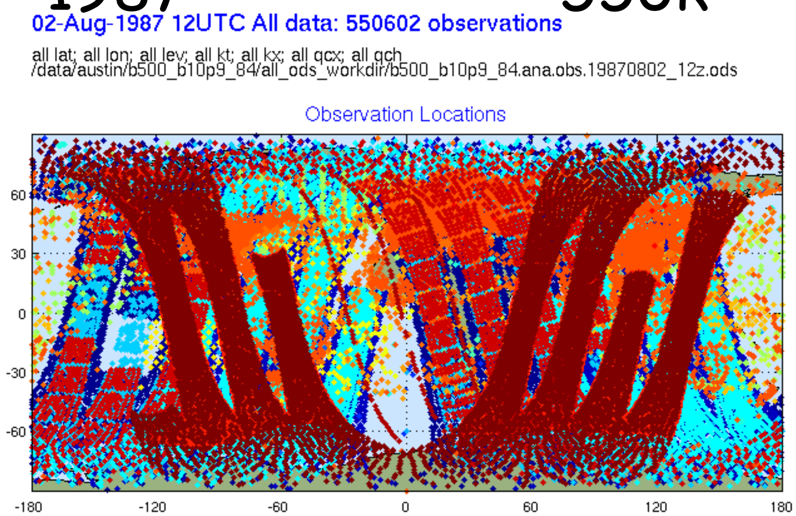
- Need is for stable orbits: has improved since 2002
- May require boosters
- Need sufficient sampling of diurnal cycle
- Launch on schedule, not on failure, to ensure overlap
- Calibrations required
- Ground truth validation required

The Changing Observing System

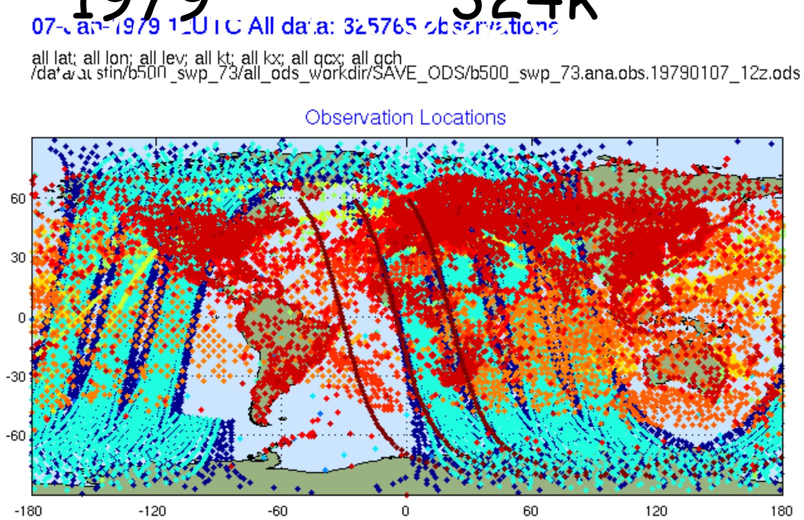
1973 77k/6h



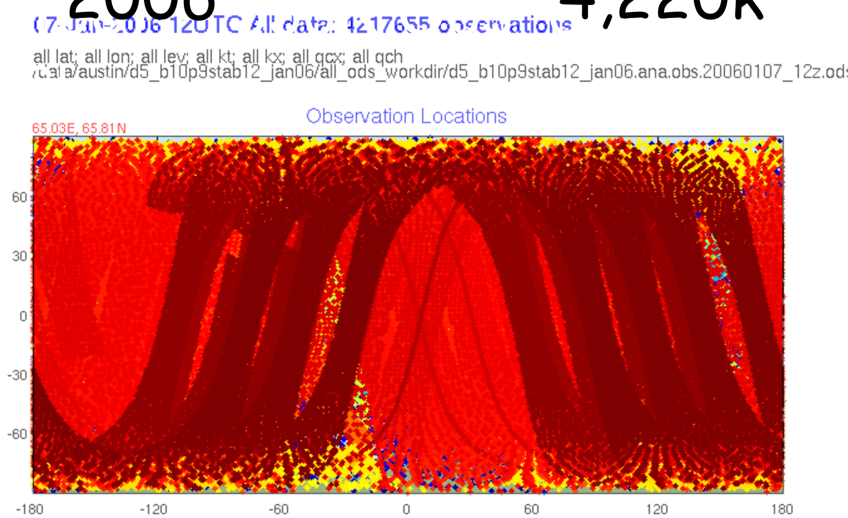
1987 550k



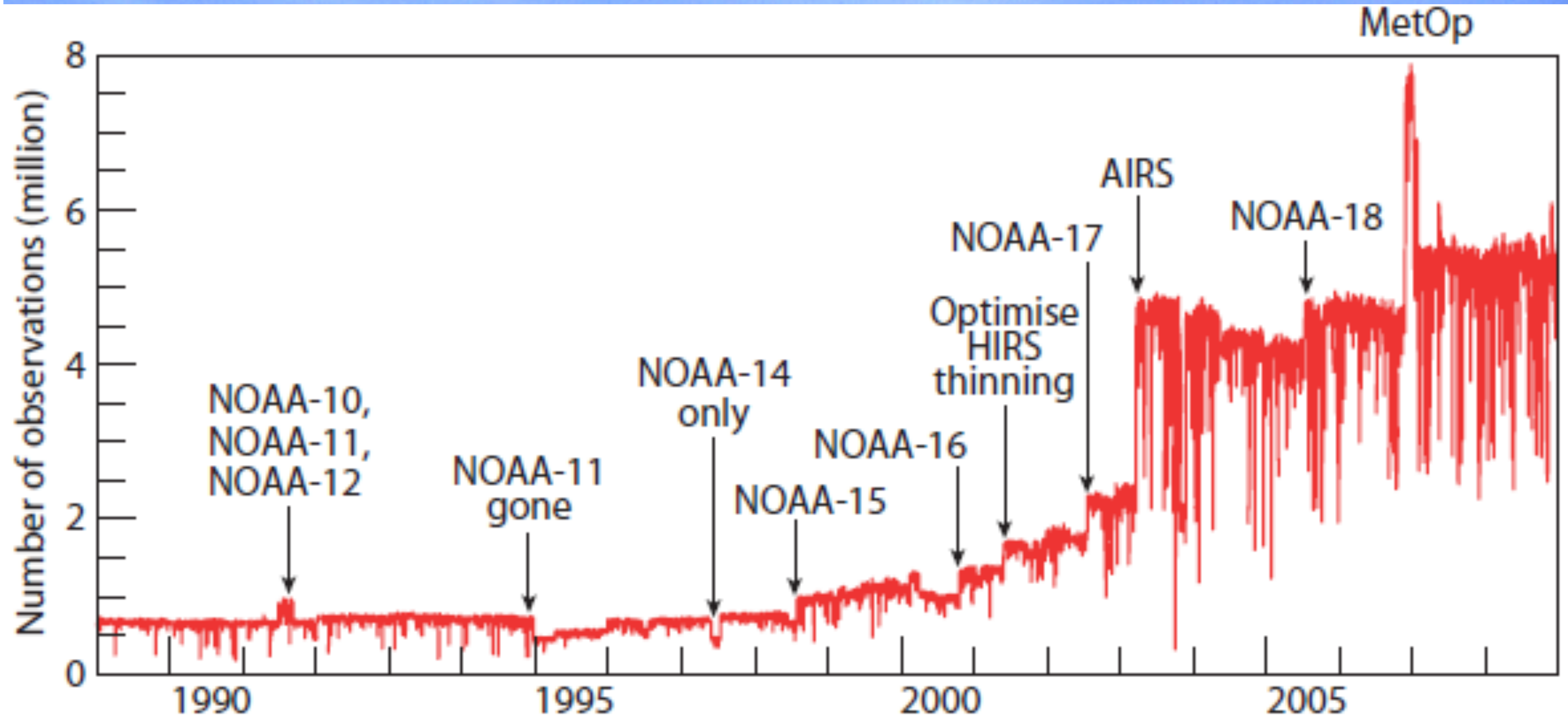
1979 324k



2006 4,220k



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



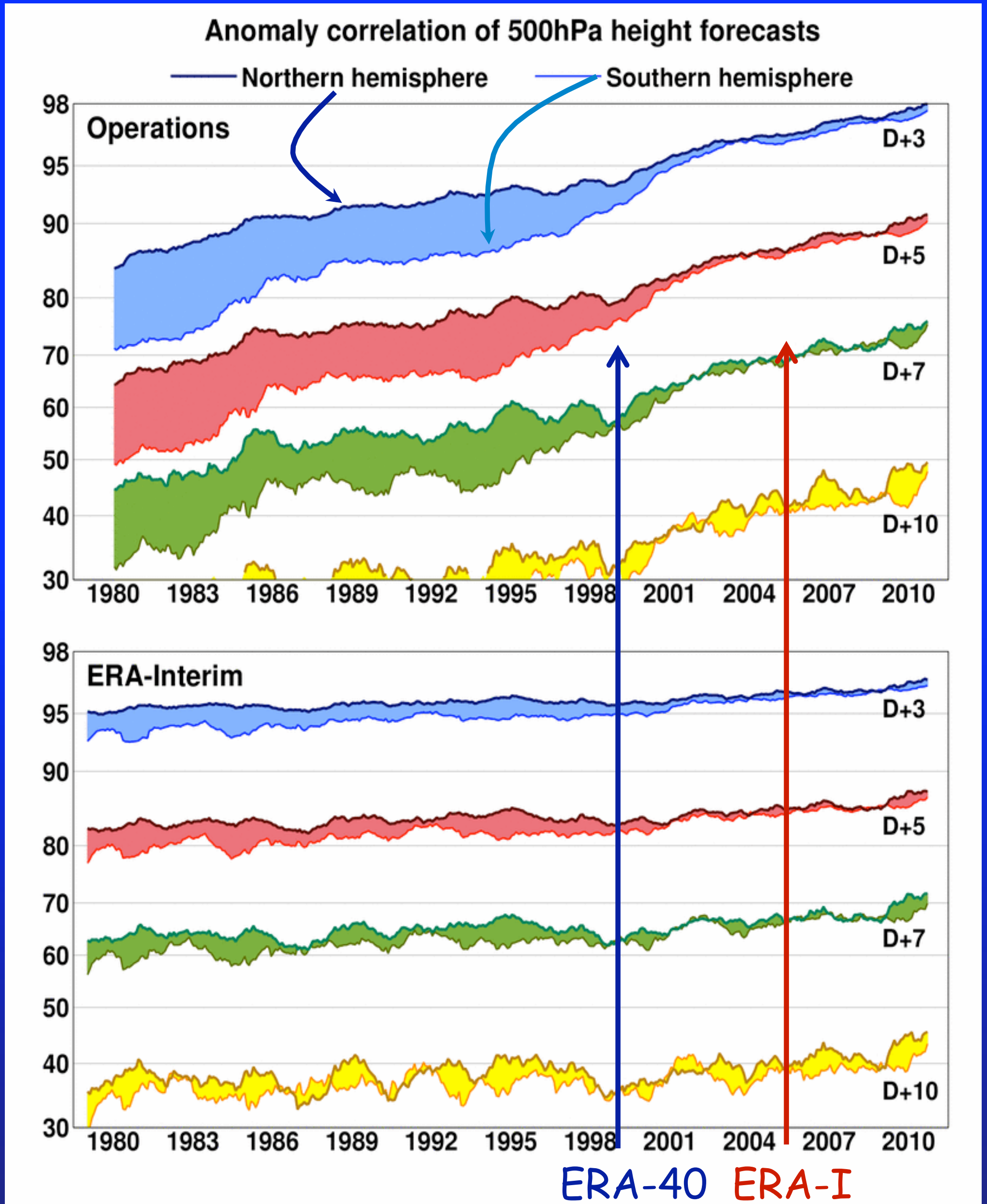
The total number of observations (satellite and conventional) used in the ERA-Interim 12-hourly variational analysis for the period 1989–2008 exceeds 29×10^9. This is mainly due to a large increase in the availability of satellite observations in the 20-year period.

ECMWF

Improvement in forecasts:

From 1980 to 2000 comes mostly from improvement to forecasting system

Correlation (%) of actual and predicted 500hPa height anomalies (12-month running means).

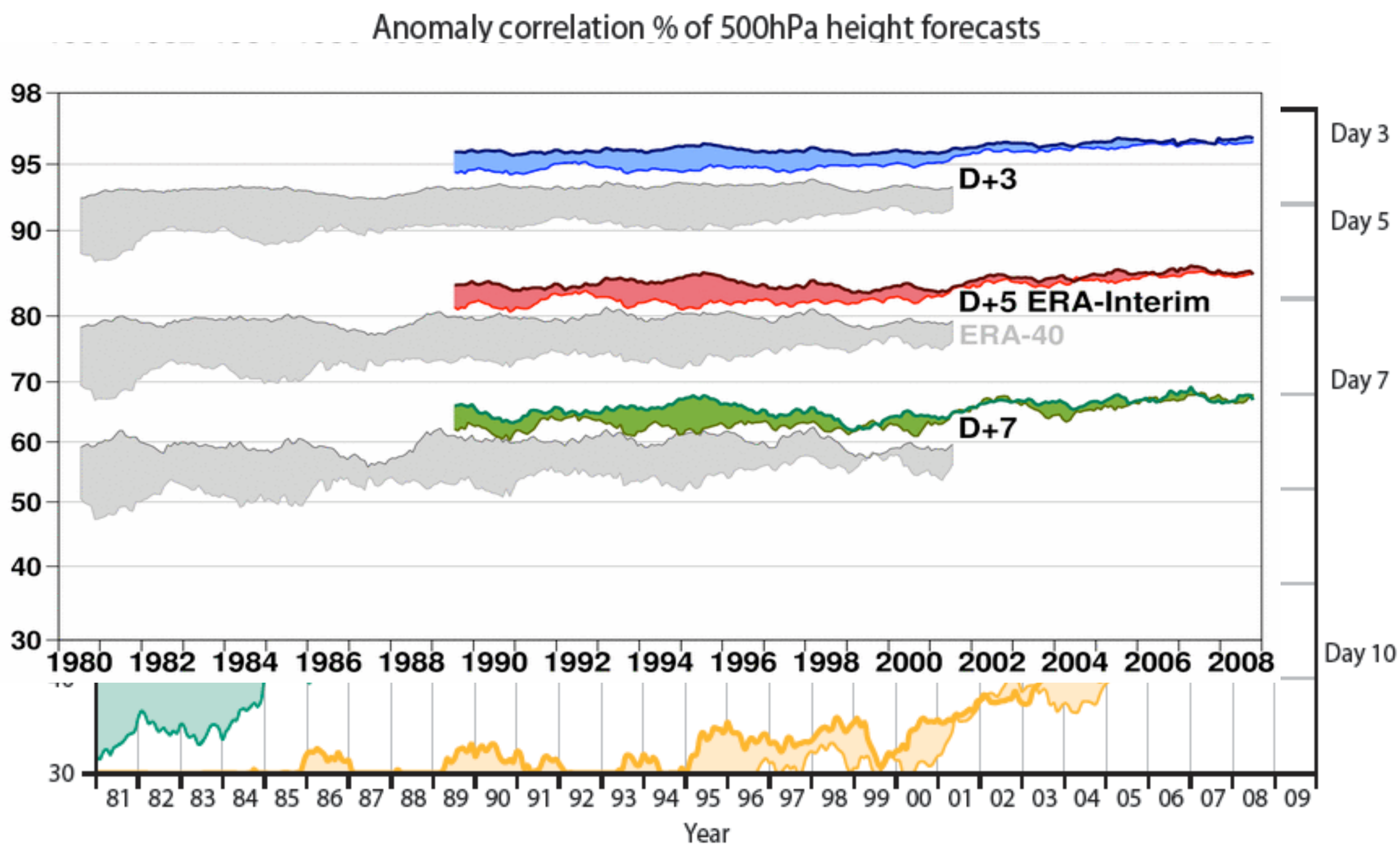


Reanalysis

Improvement since 2000 comes from both forecasting system and observations

Courtesy Adrian Simmons

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!

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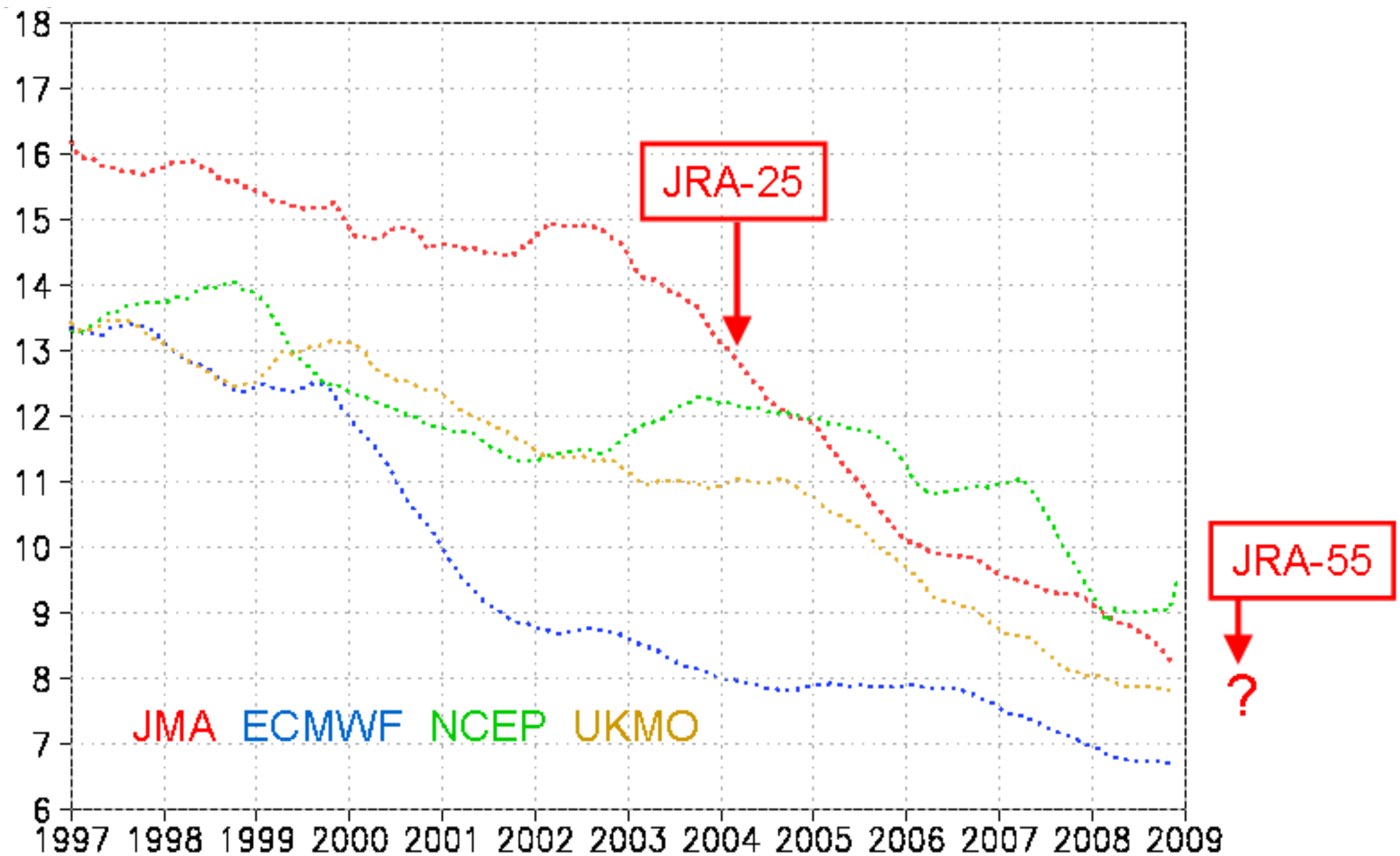


Operational forecast scores of major NWP centers. RMSE of geopotential height at 500hPa in NH (m) for 24-hour forecasts are displayed. The score of JMA forecast has improved rapidly in recent years.

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.

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

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

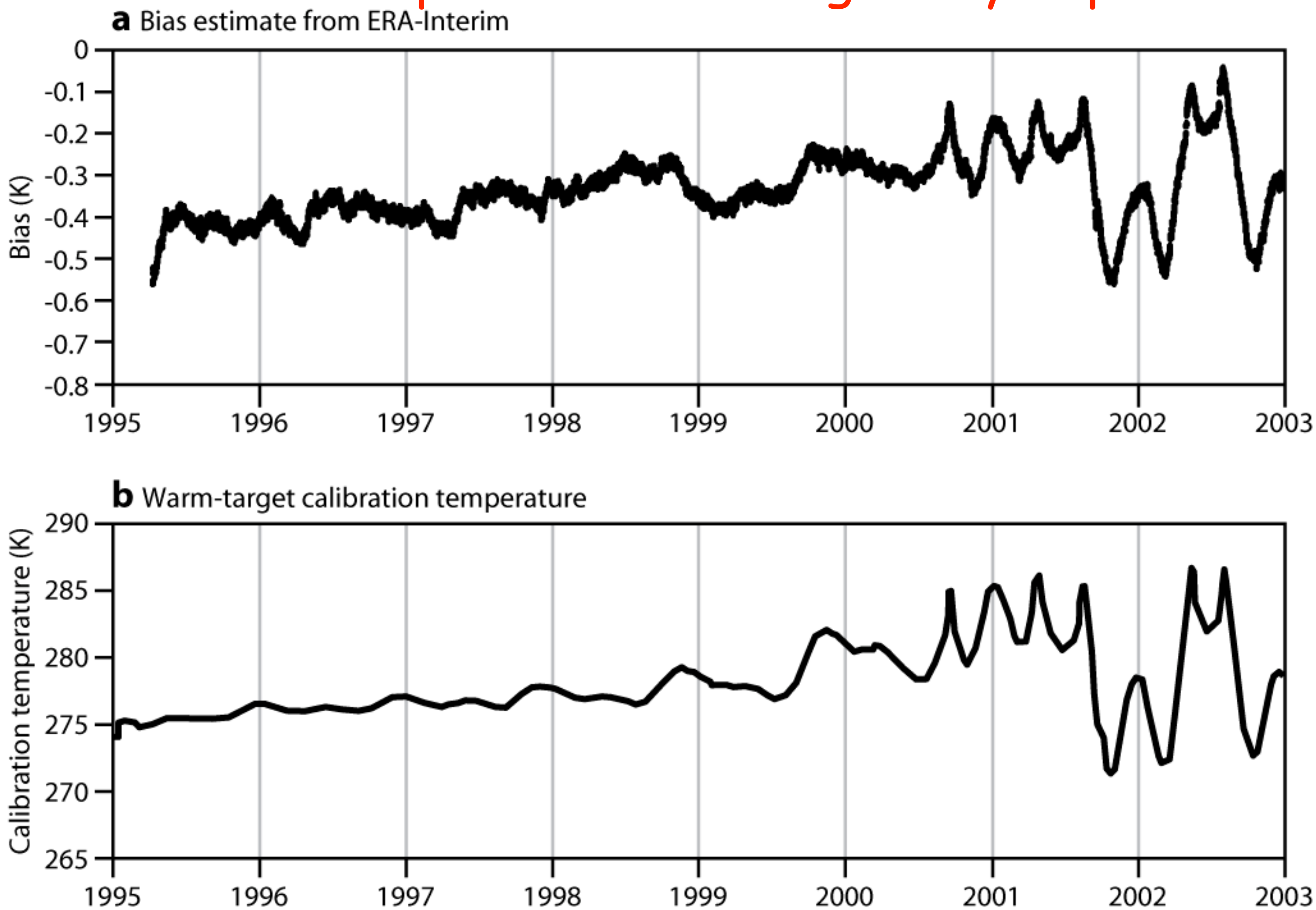
Bias corrections should be applied to satellite And radiosonde data.

Potential for unintended perturbations or bad data to be perpetuated.

- There is evidence from alpine summit observations that spurious trends may exist.
- Most radiosonde stations do NOT have adequate records of changes

Need to document bias correction changes to all observing systems.

Bias correction procedure 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

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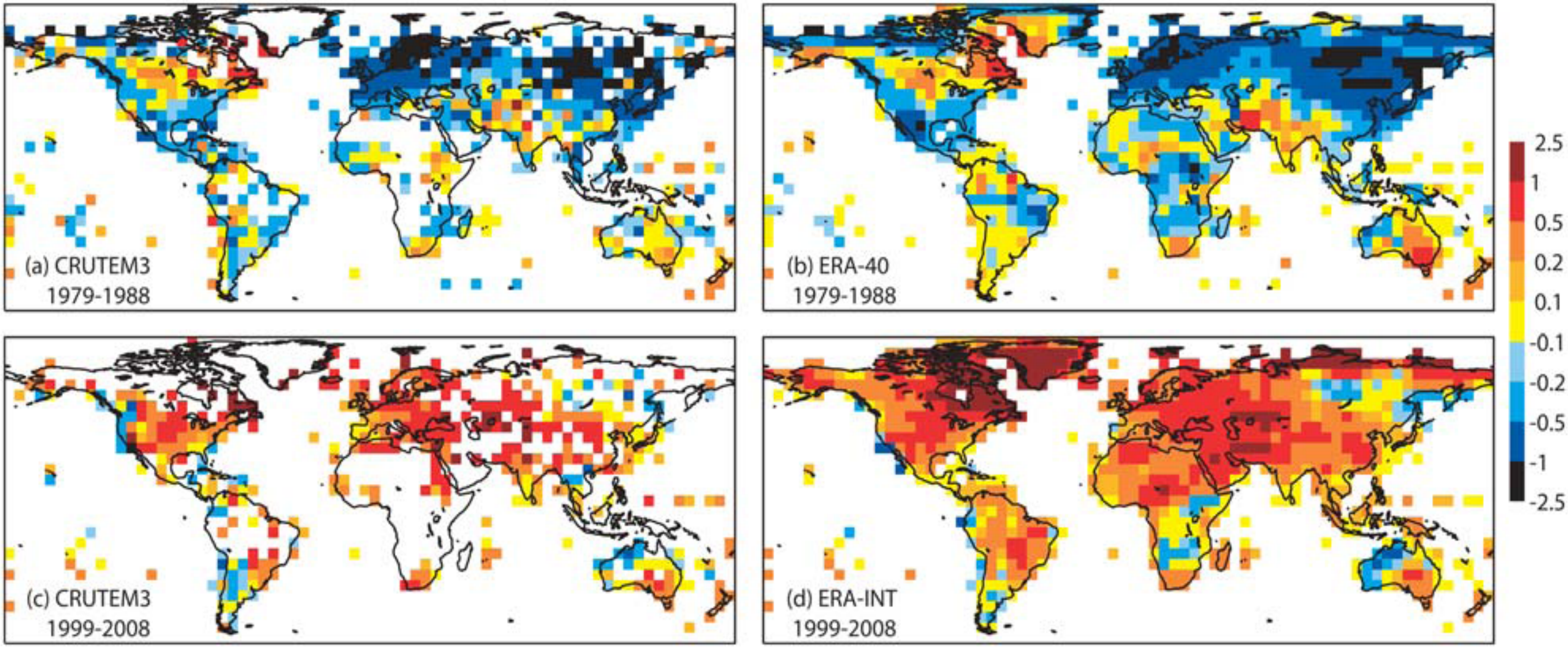
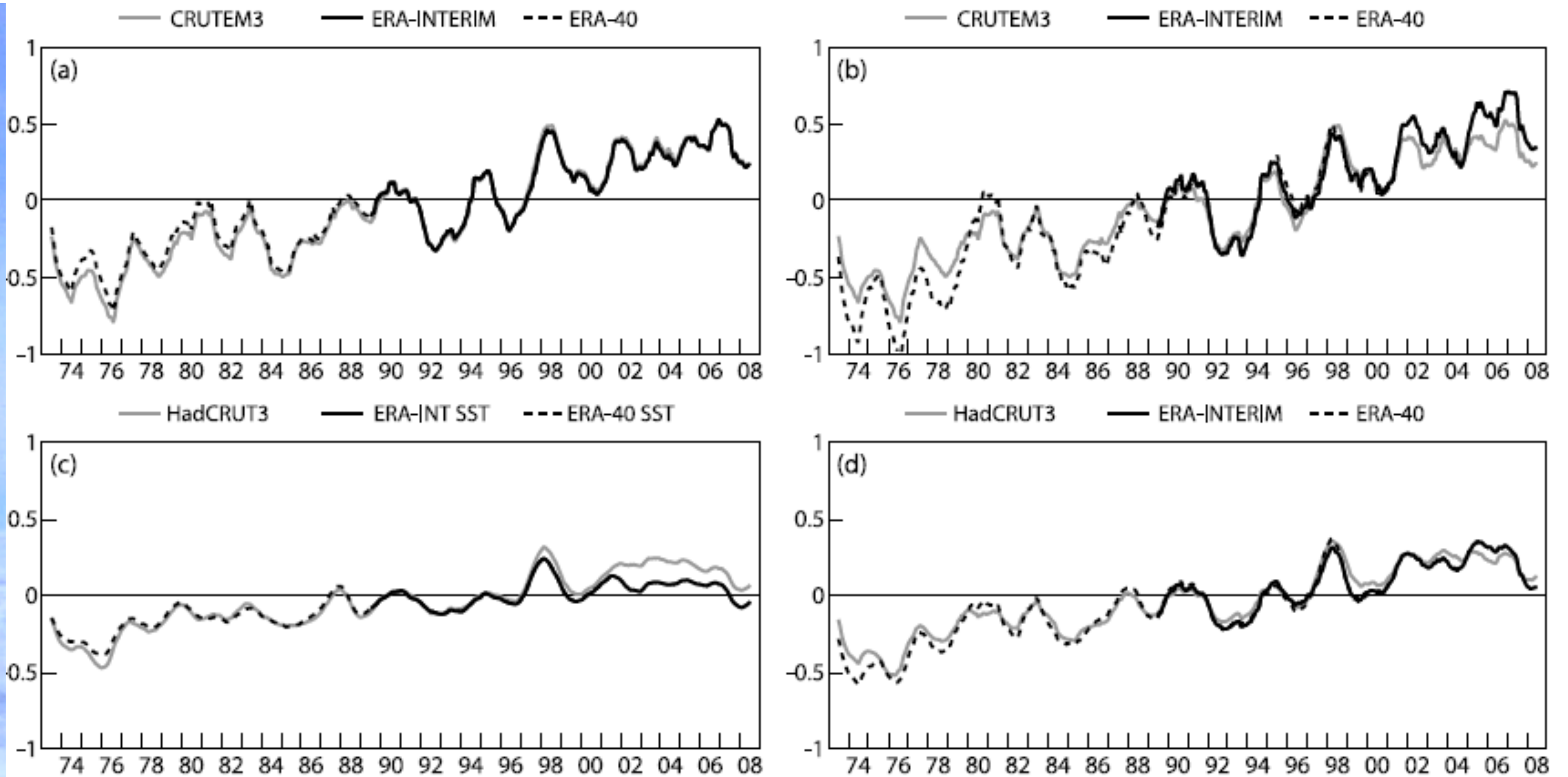
Surface Temperature: filled in gaps



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



Twelve month running means of temperature anomalies (K) (a) 2mtemperatures land with the reanalyses sampled with the same coverage as CRUTEM3. (b) Same as a but with reanalyses averaged over for land. (c) SSTs, with reanalyses sampled with the same coverage as HadCRUT3. (d) Global ERA 2 m temperatures vs all HadCRUT3 values.

Time series are adjusted to have zero mean from 1989 to 1998, except ERA SSTs are adjusted the same as HadCRUT3.

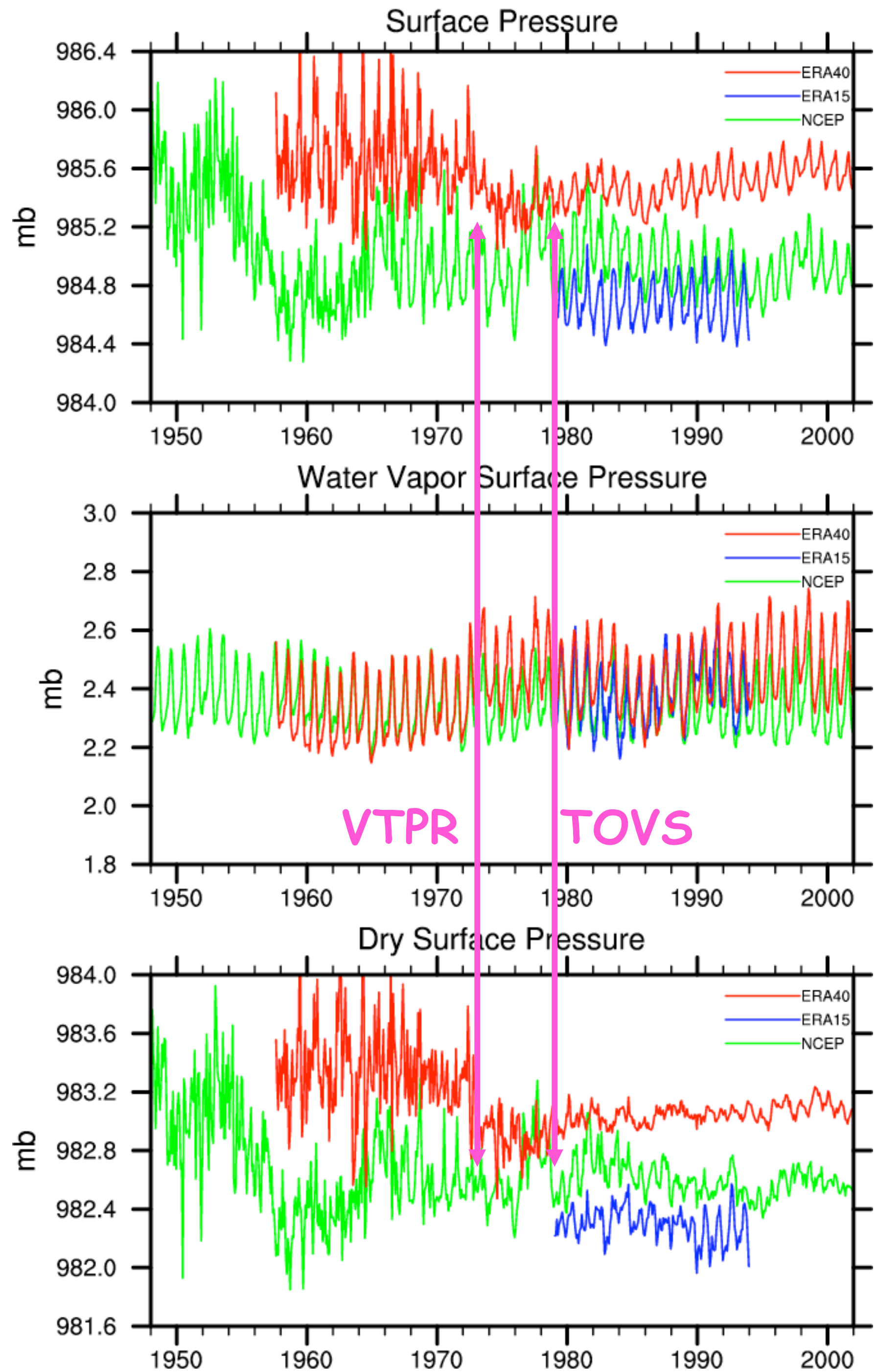
Simmons et al 2010

Conservation of mass of dry air.

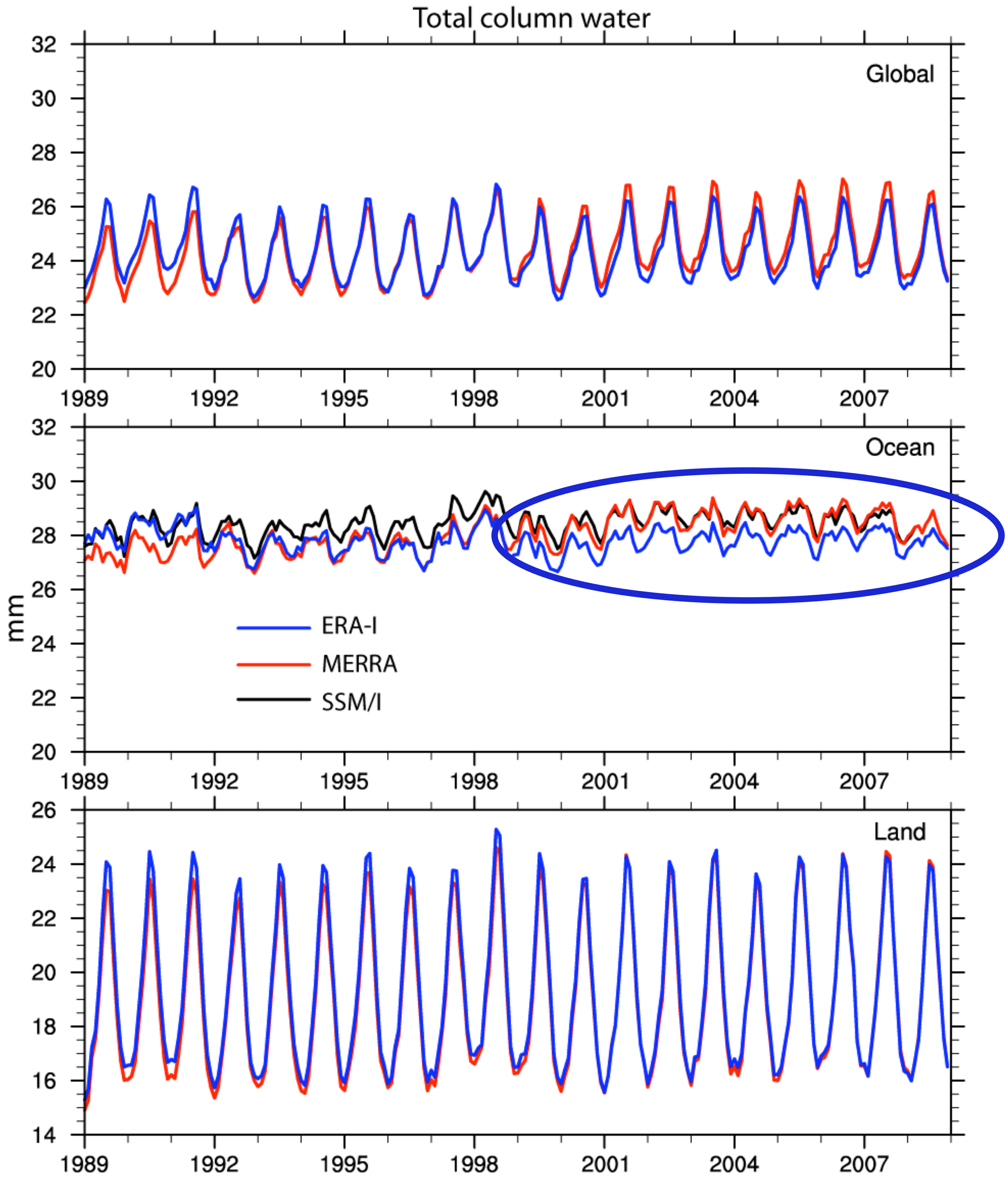
Both total surface pressure p_s and that due to moisture p_w are independent measures of the water vapor contribution. Their difference p_d should be constant.

Mean annual cycle is similar for p_s and p_w, except NCEP before 1966 and ERA-15 after 1989.

ERA40 offset from global topography 5.5 m lower, mostly Antarctica.



Examples of results from reanalyses with emphasis on problems

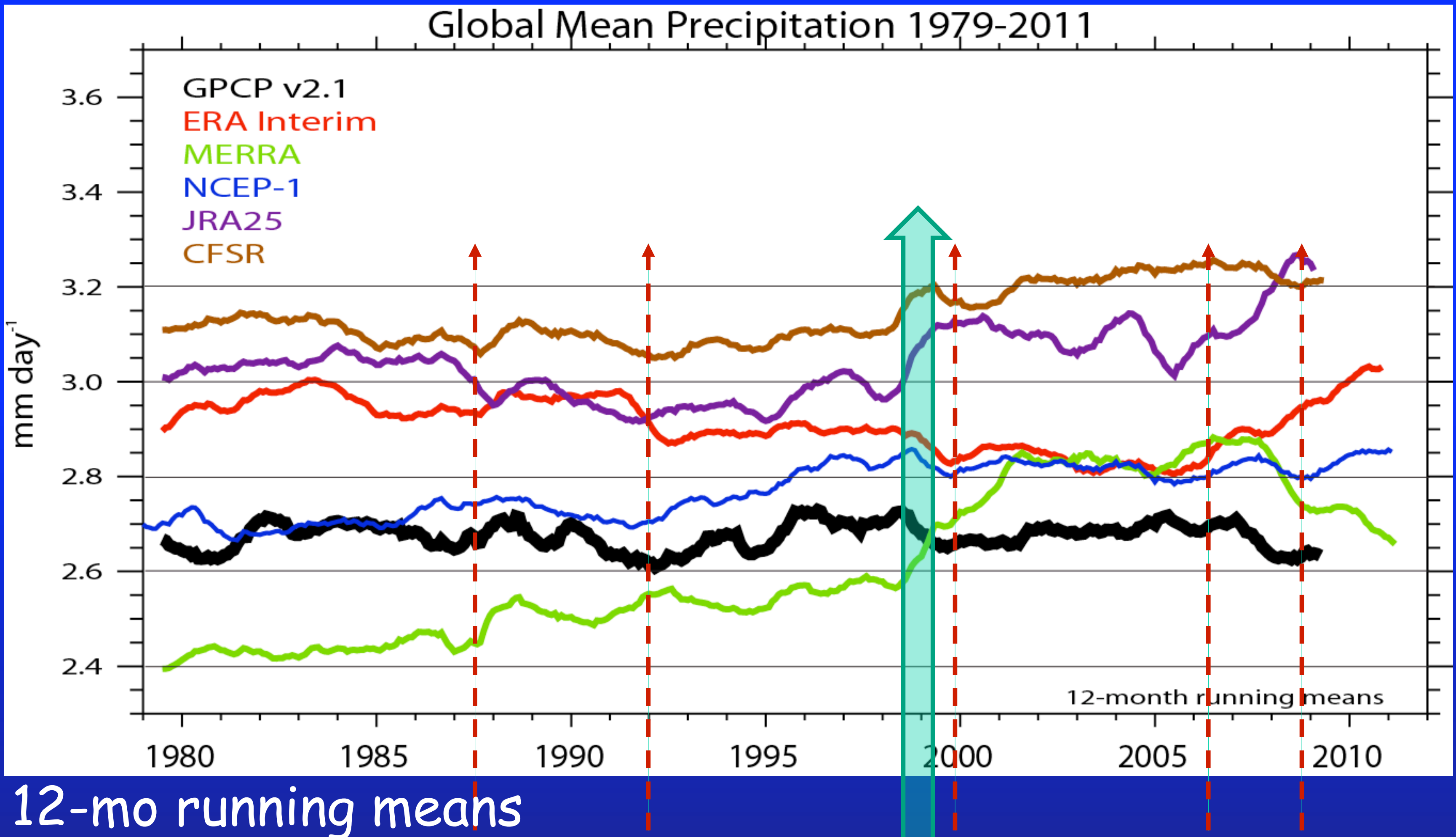


Focus on:
MERRA and
ERA-I

Which have smooth evolving moisture fields (no spinup):

- 4Dvar
- nudging

Global mean precipitation



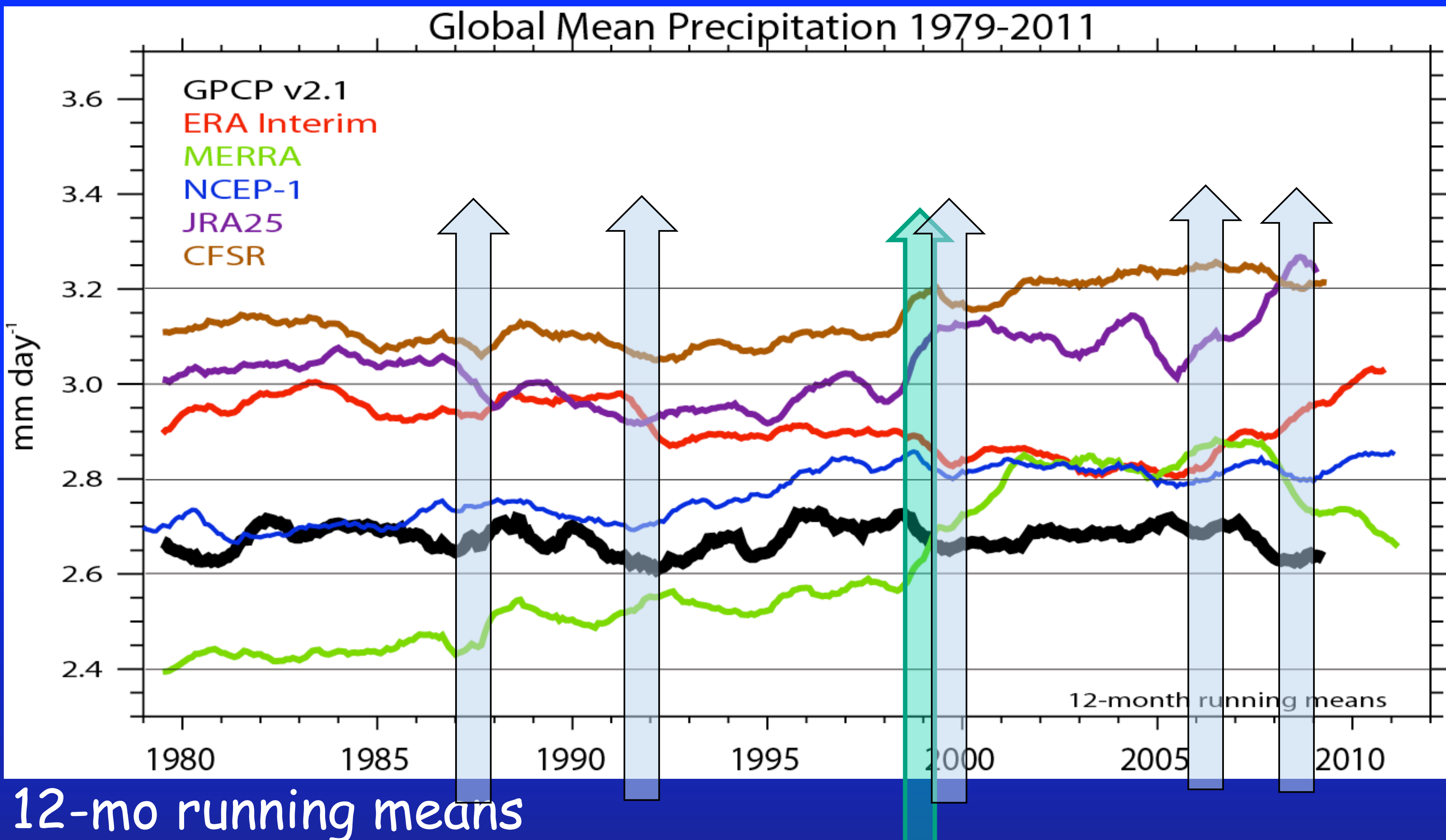
12-mo running means

TOVS to ATOVs Nov 1998

Changes in SSM/I

Courtesy J Fasullo

Global mean precipitation



12-mo running means

TOVS to ATOVs Nov 1998

Changes in SSM/I

Courtesy J Fasullo

Precipitation errors in reanalyses

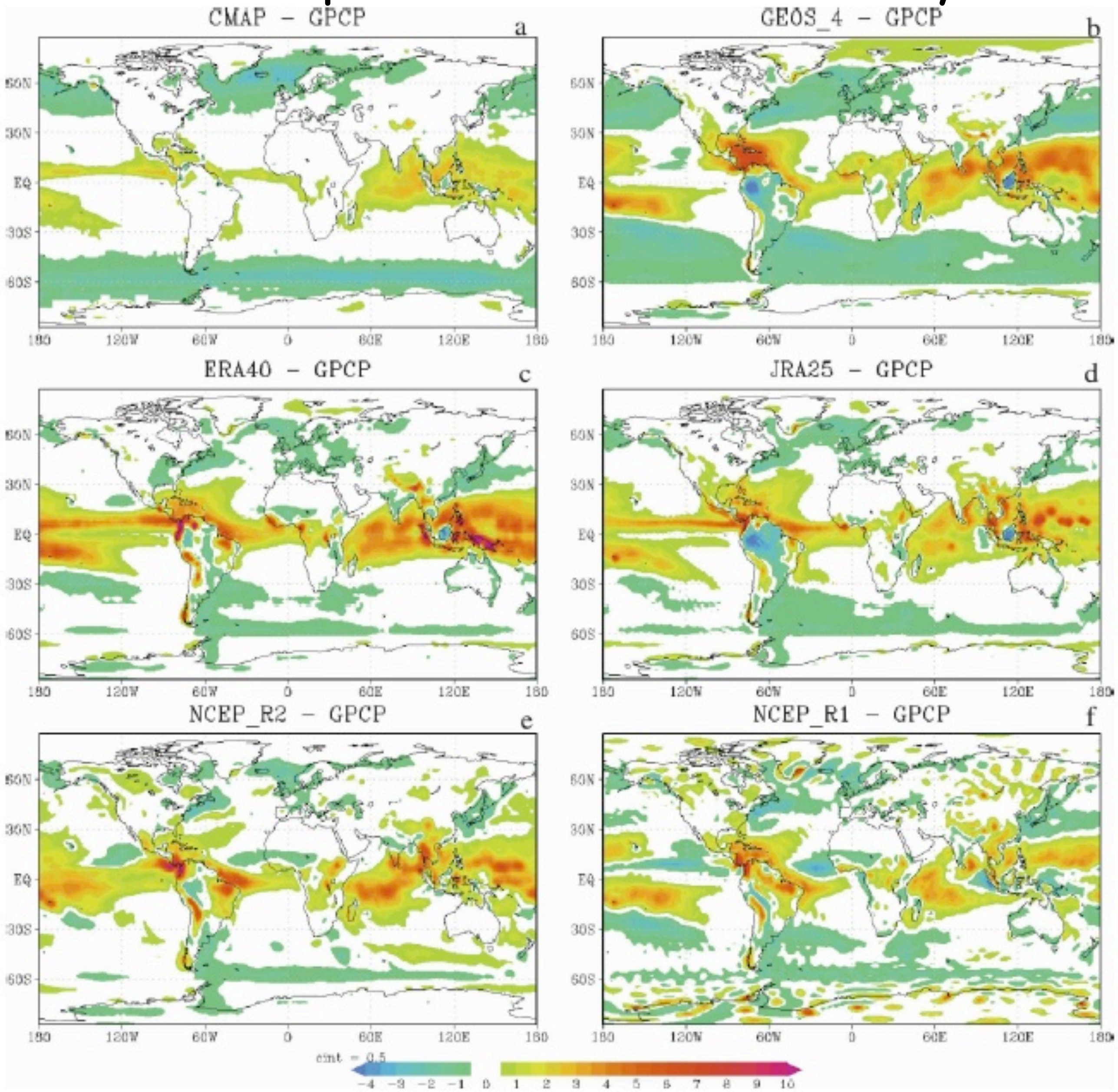
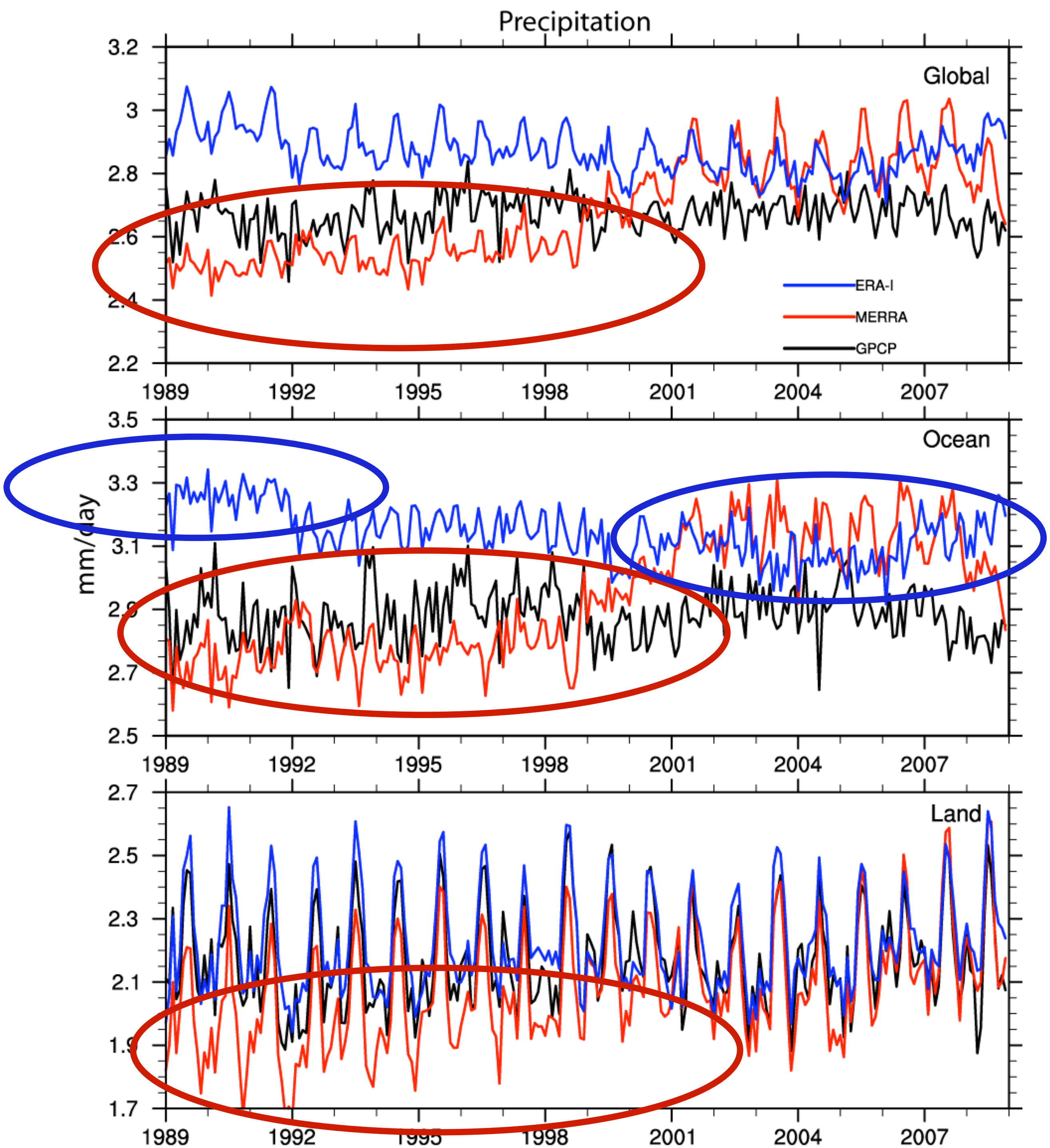


FIG. 2. Climate average (Jan 1979–Dec 2001) precipitation differences (mm day^{-1}) for the CMAP merged product and the

Bosilovich et al 2008

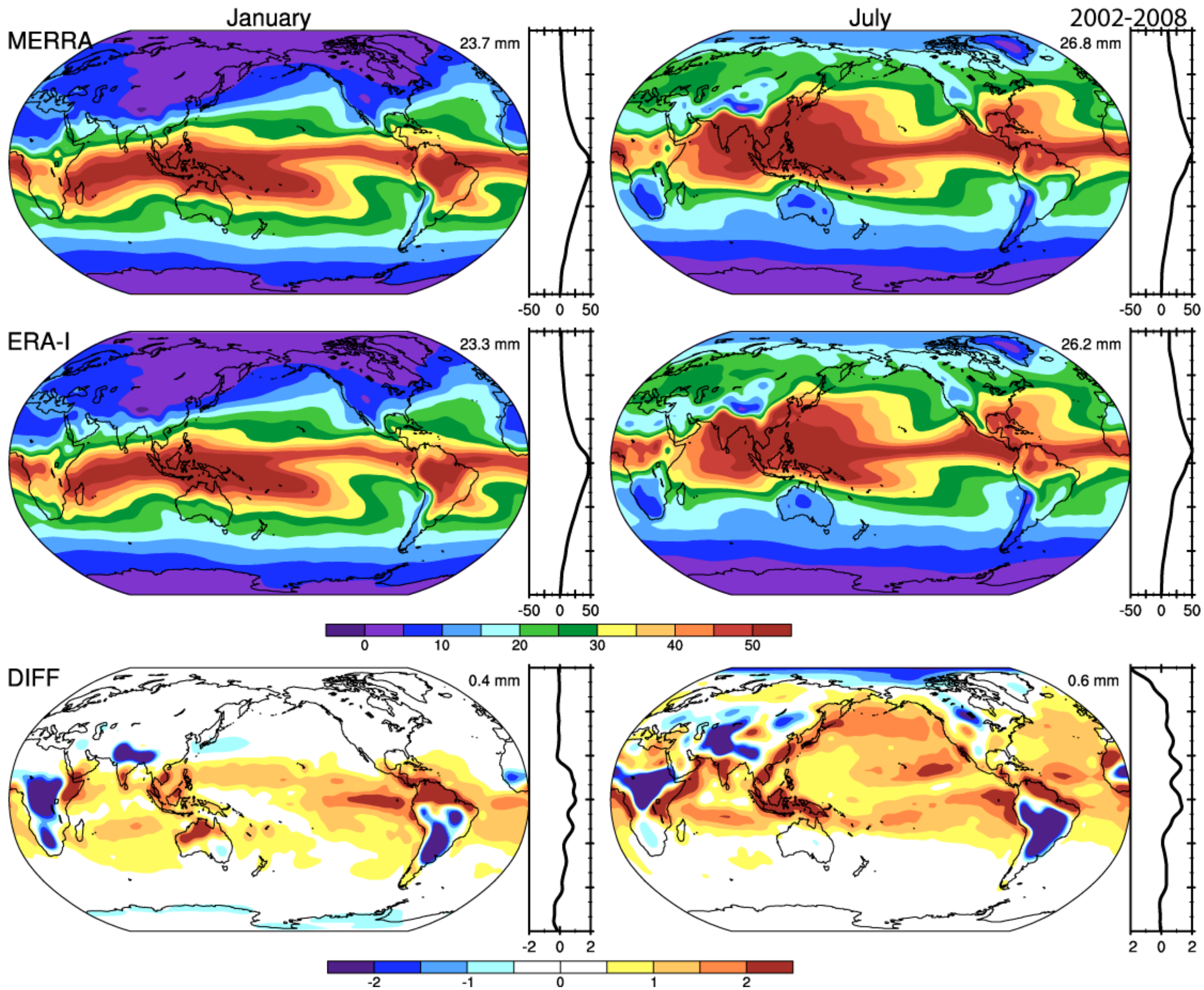


Identifiable discons:

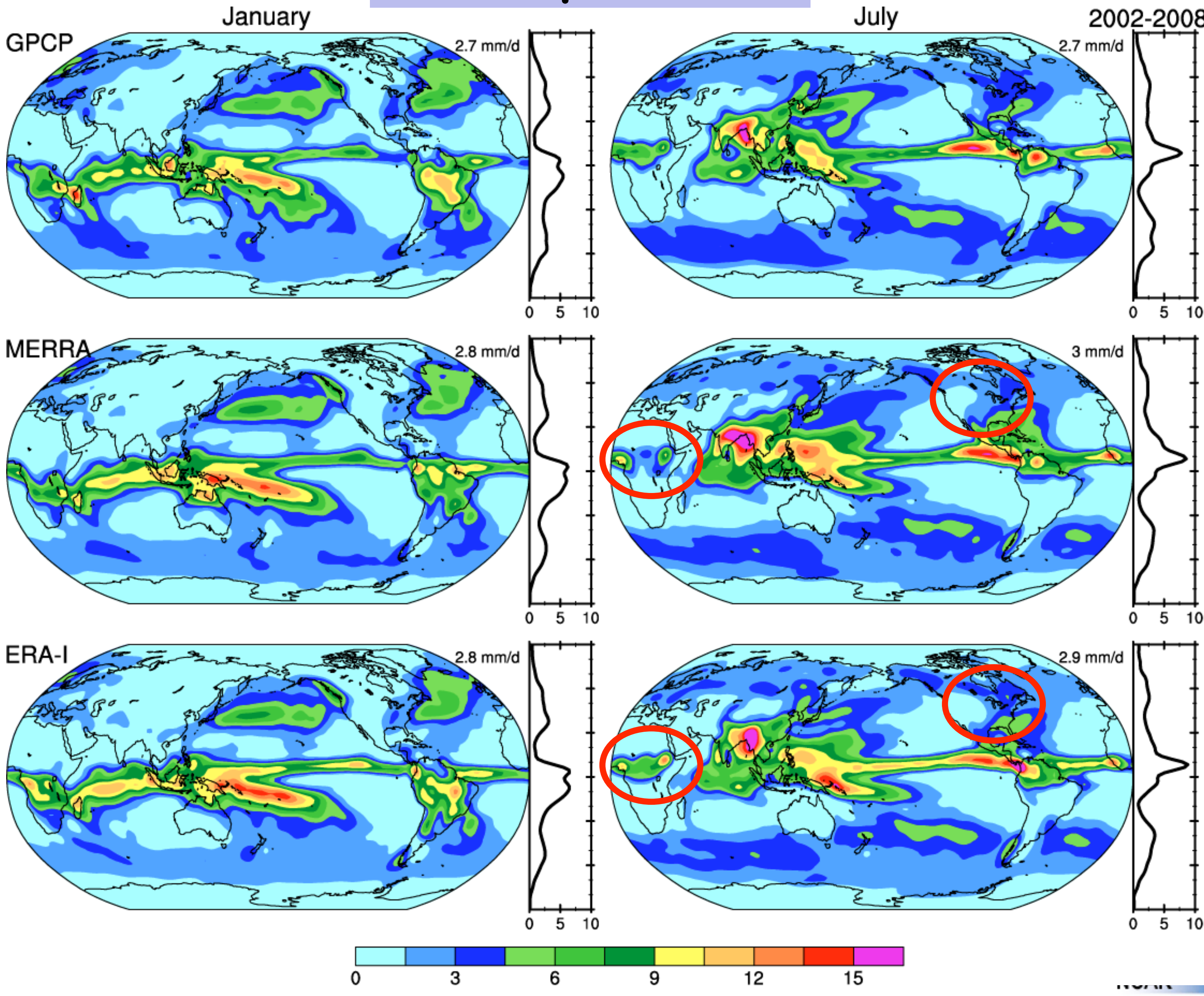
•SSM/I mid-1987,
•TOVS to ATOVS: AMSU-A,AMSU-B late 1998 to 2001 (NOAA 15 =>NOAA 12 NOAA 16 => NOAA 14, March 20, 2001),

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

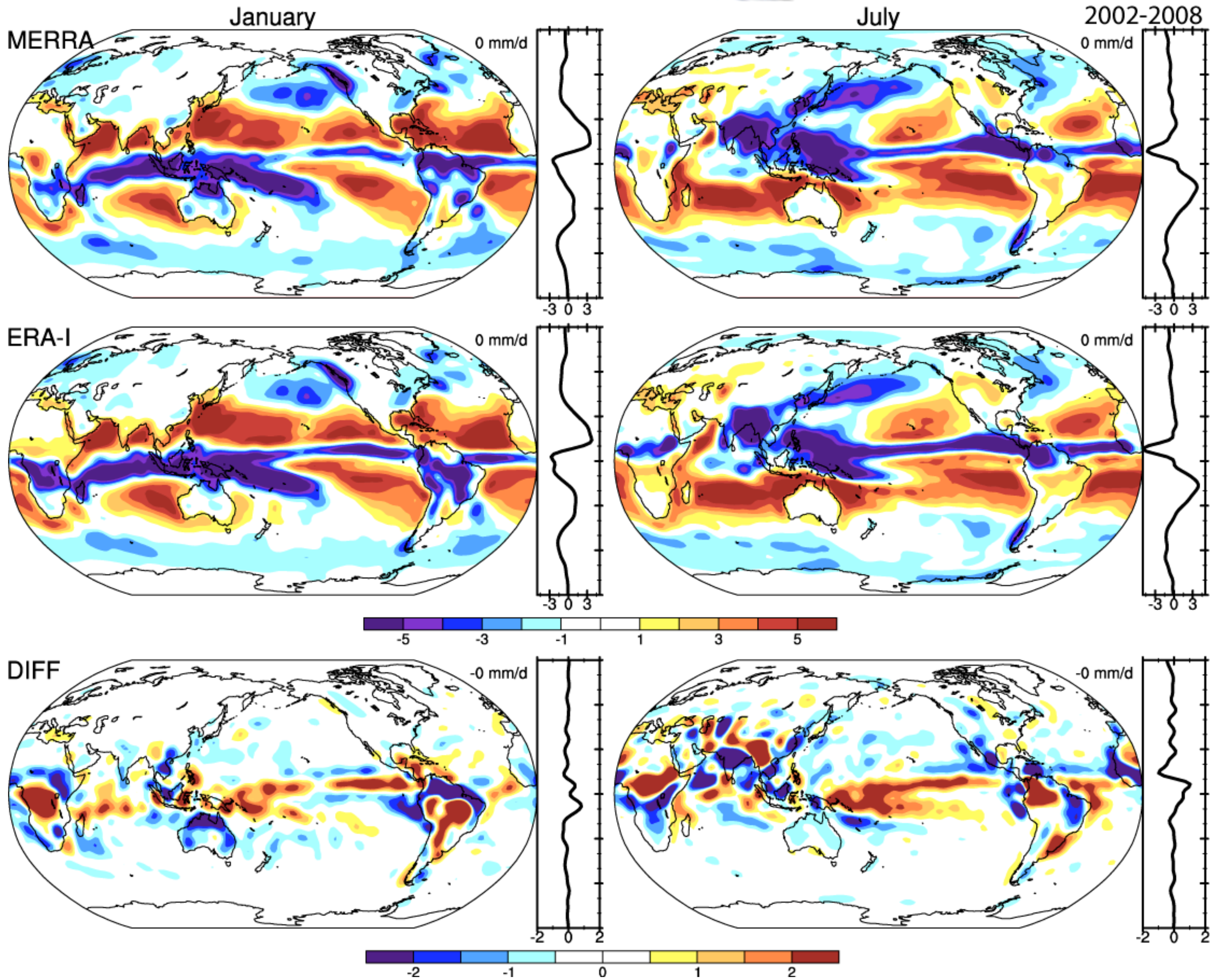
Precipitable water



Precipitation



Freshwater flux E-P
From moisture budget



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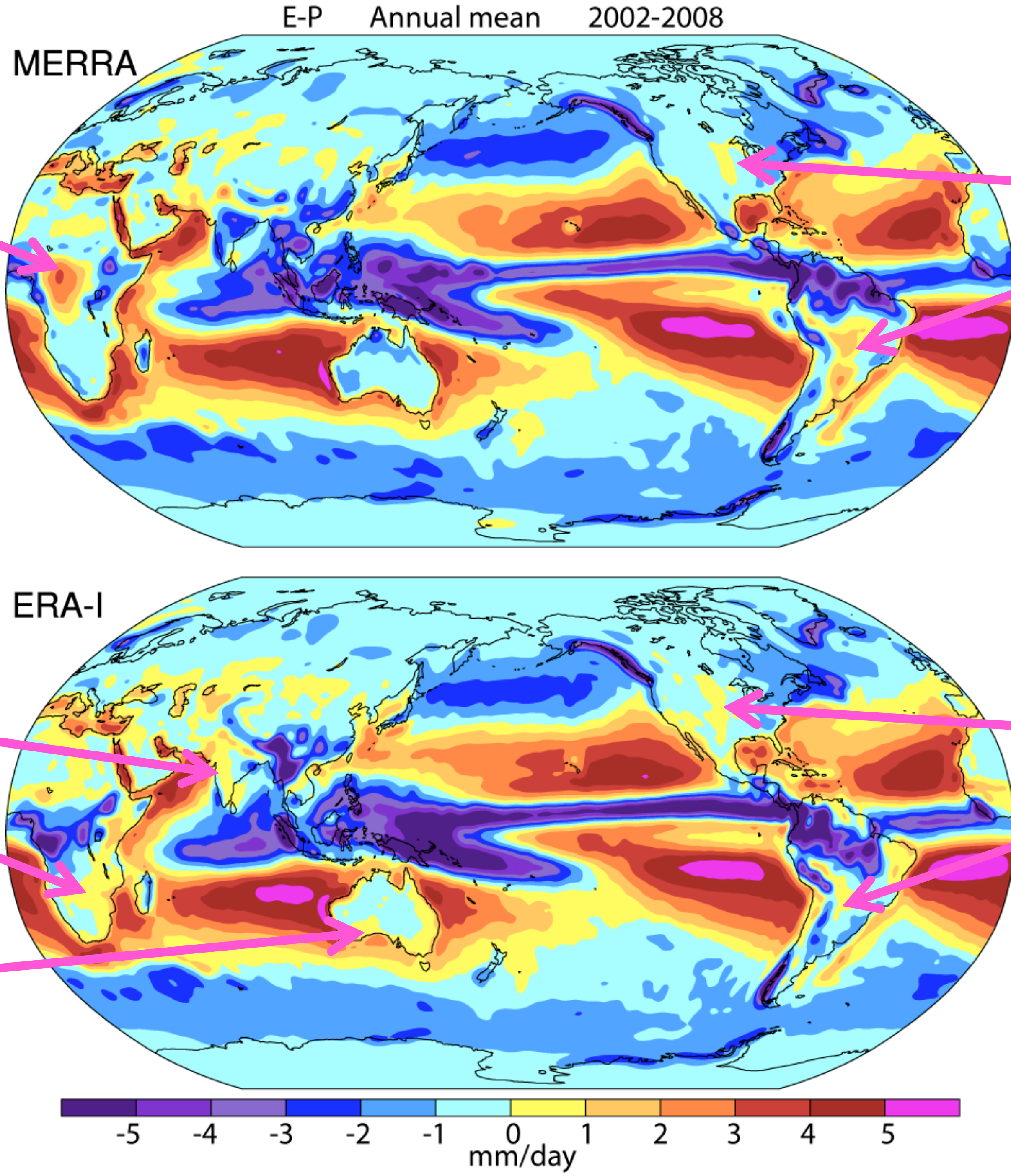

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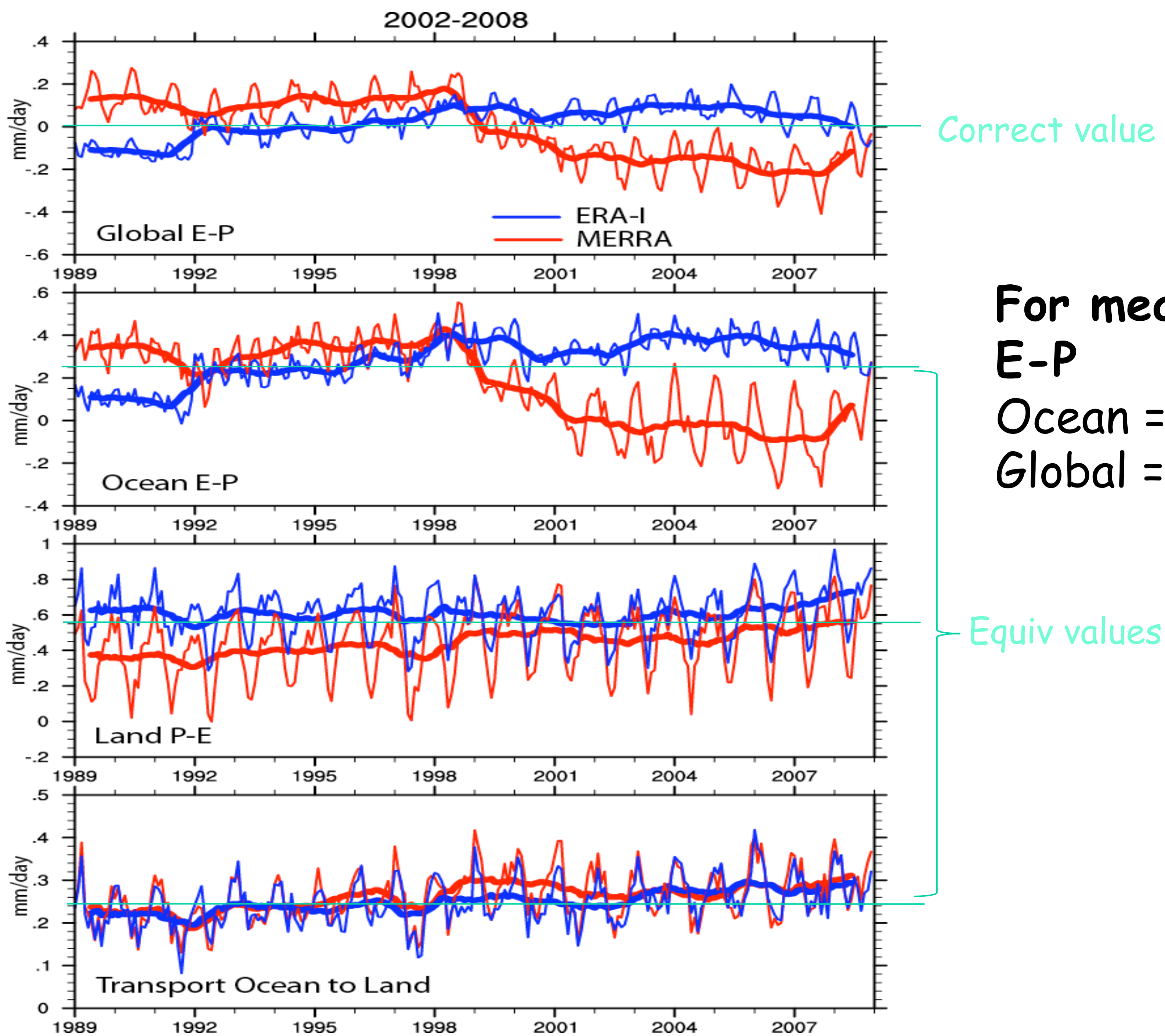
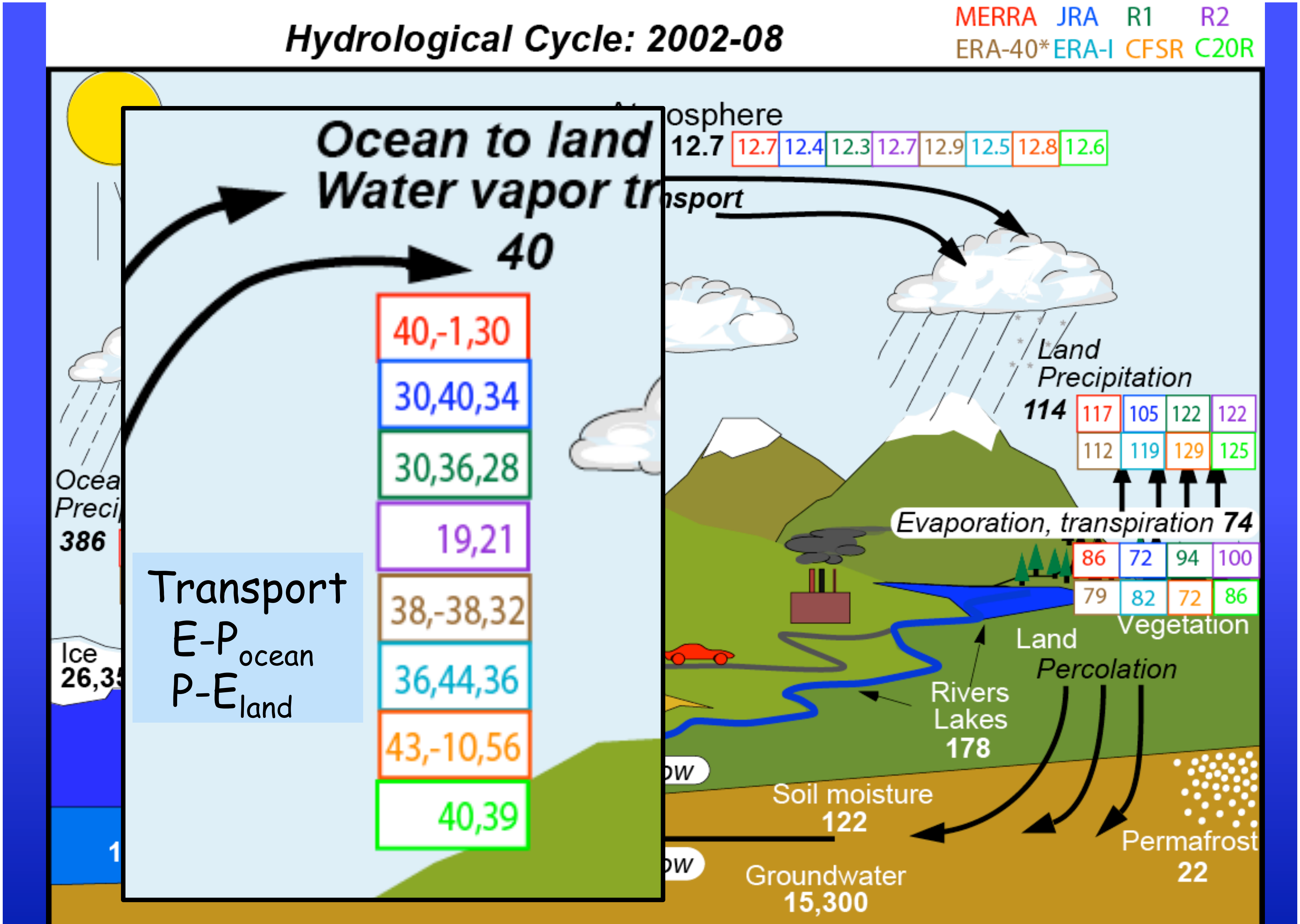


For mean

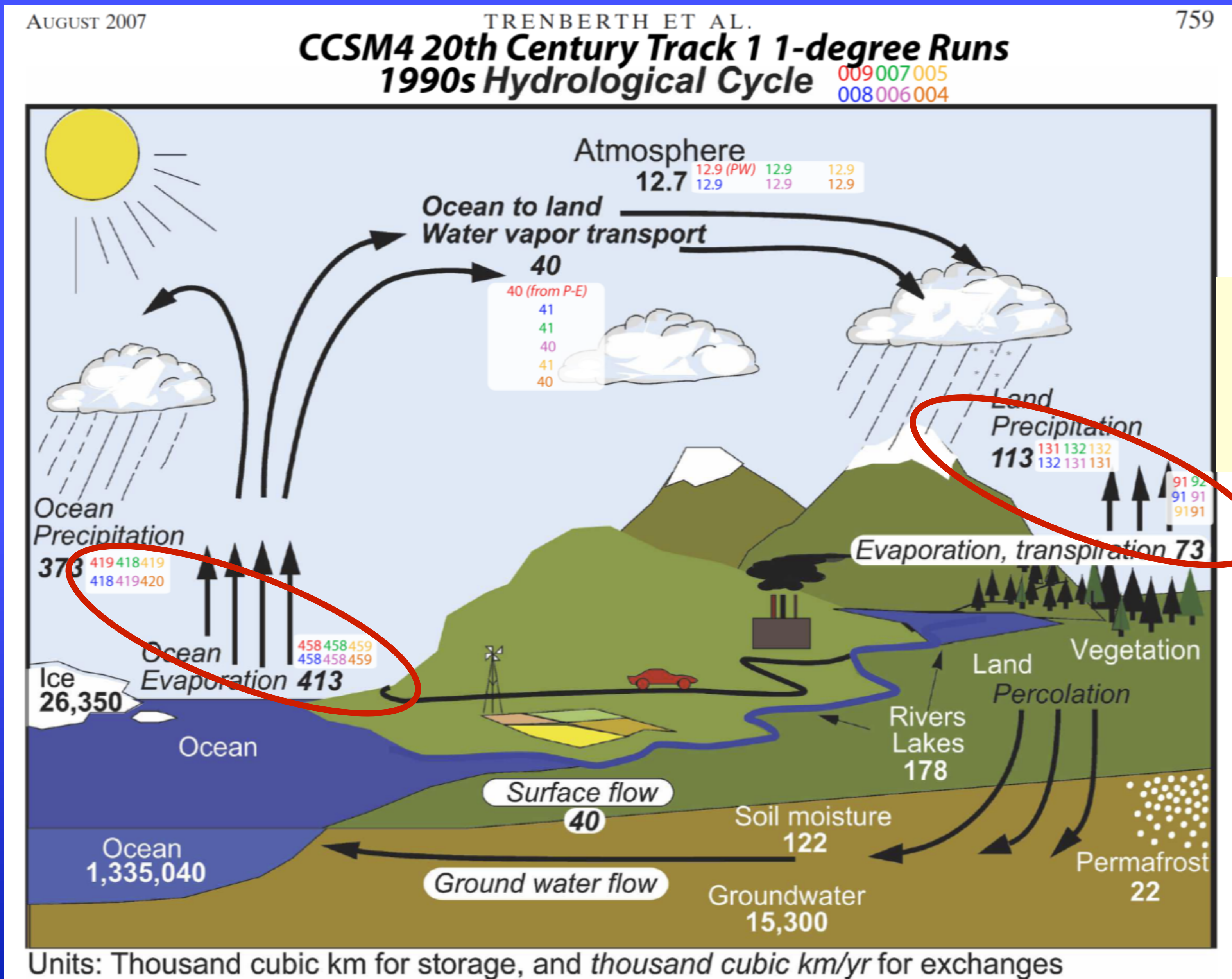
E-P

Ocean = -Land

Global = 0



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges *1990s



Much too high

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)

	NRA	ERA-40	ERA-I	JRA	MERRA	CFSR	
Resolution	1.9°	0.8°	0.5°	1.1°	0.5°	0.5°	
ASR	-14	-2	+4	+5	+4	+3	W m^{-2}
OLR	-2	+6	+6	+15	+3	+4	
Net(TOA)	-14	-8	-2	-9	+1	-1	
Net (sfc)	+2	+3	+6	-9	+12	+8	

Mostly for 1979-2001 vs climatology

TOA Radiation

CCSM4

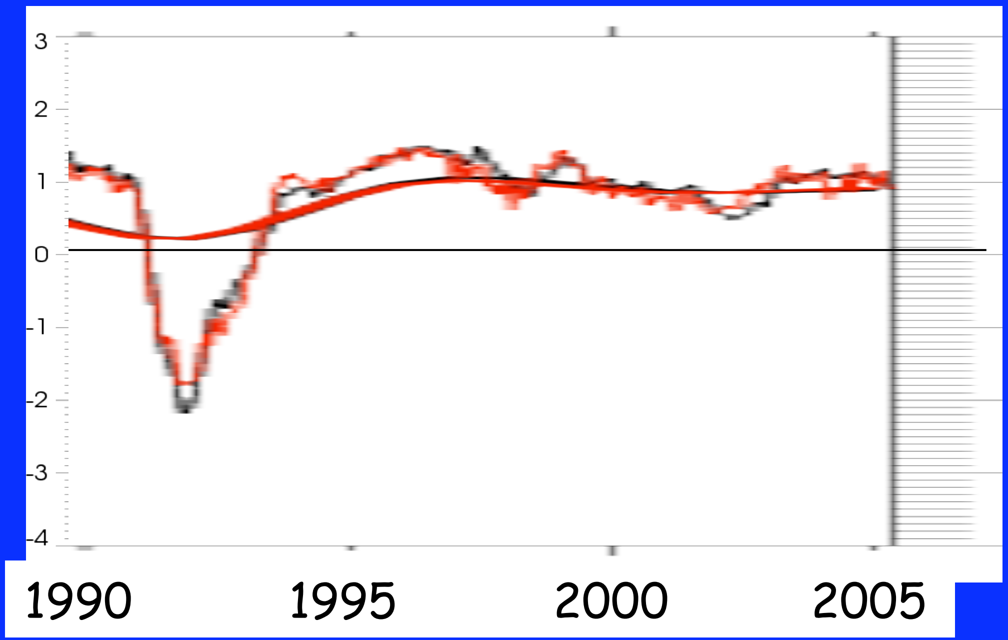
TOA radiation and surface flux over ocean;

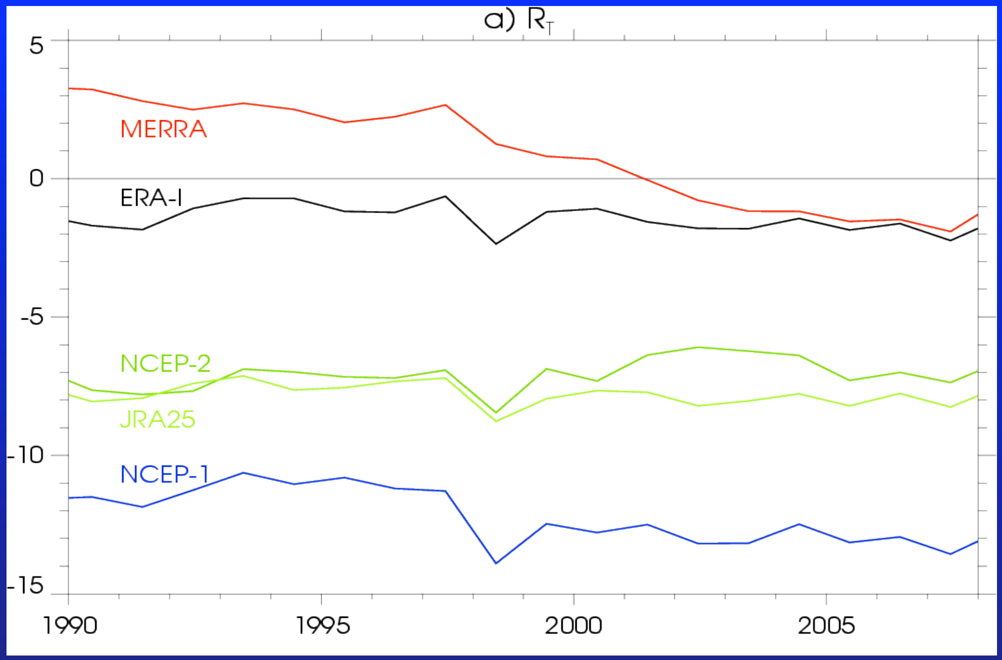
Net 1990s 0.6 W m^{-2}

(Pinatubo knock down)

Net 2000s 0.9 W m^{-2}

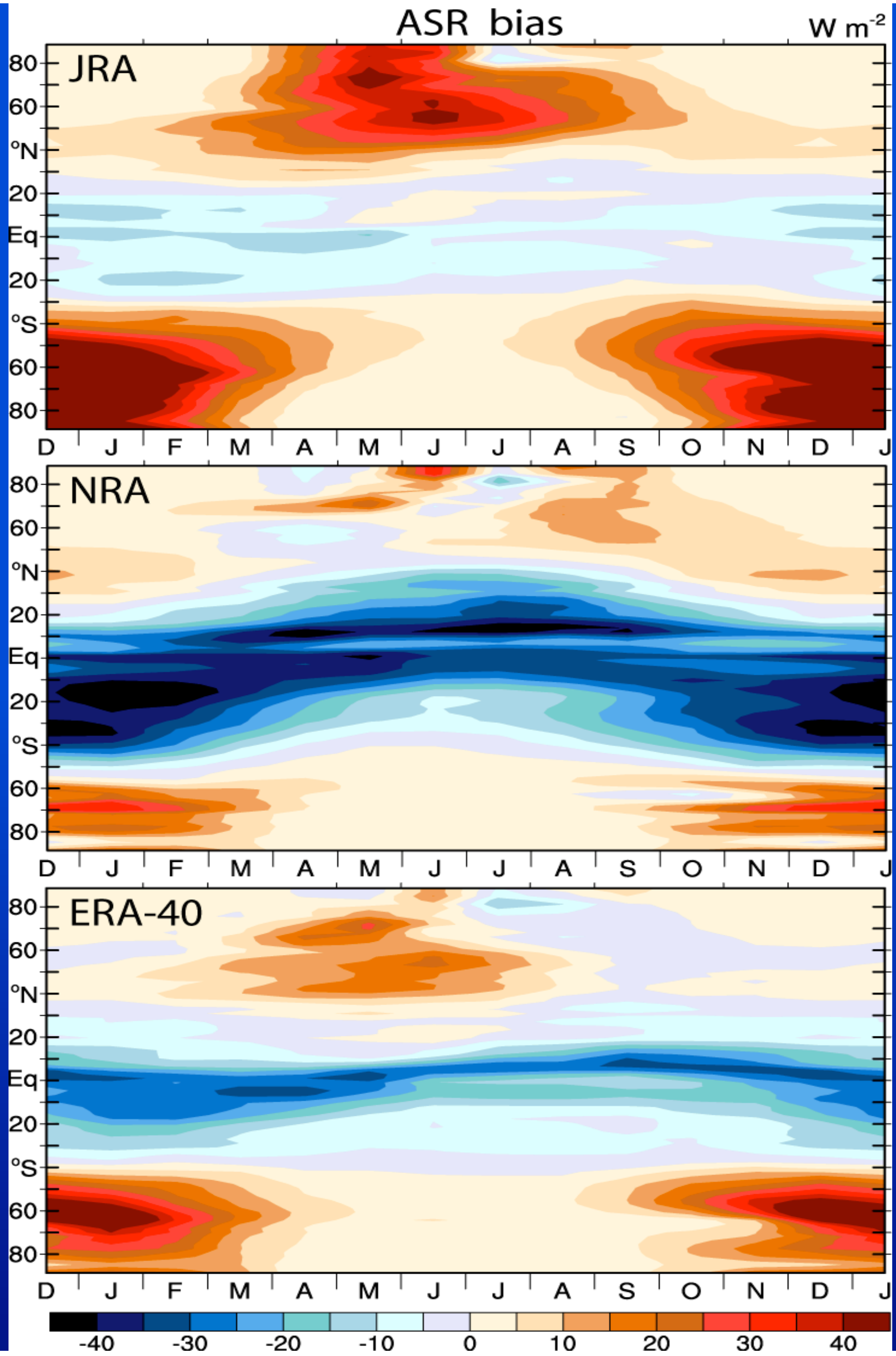
In a good model, the water and energy are conserved.





Reanalyses:
TOA 1990-2008
Net radiation

Trenberth et al 2009:
0.9 W m^{-2} for 2000s

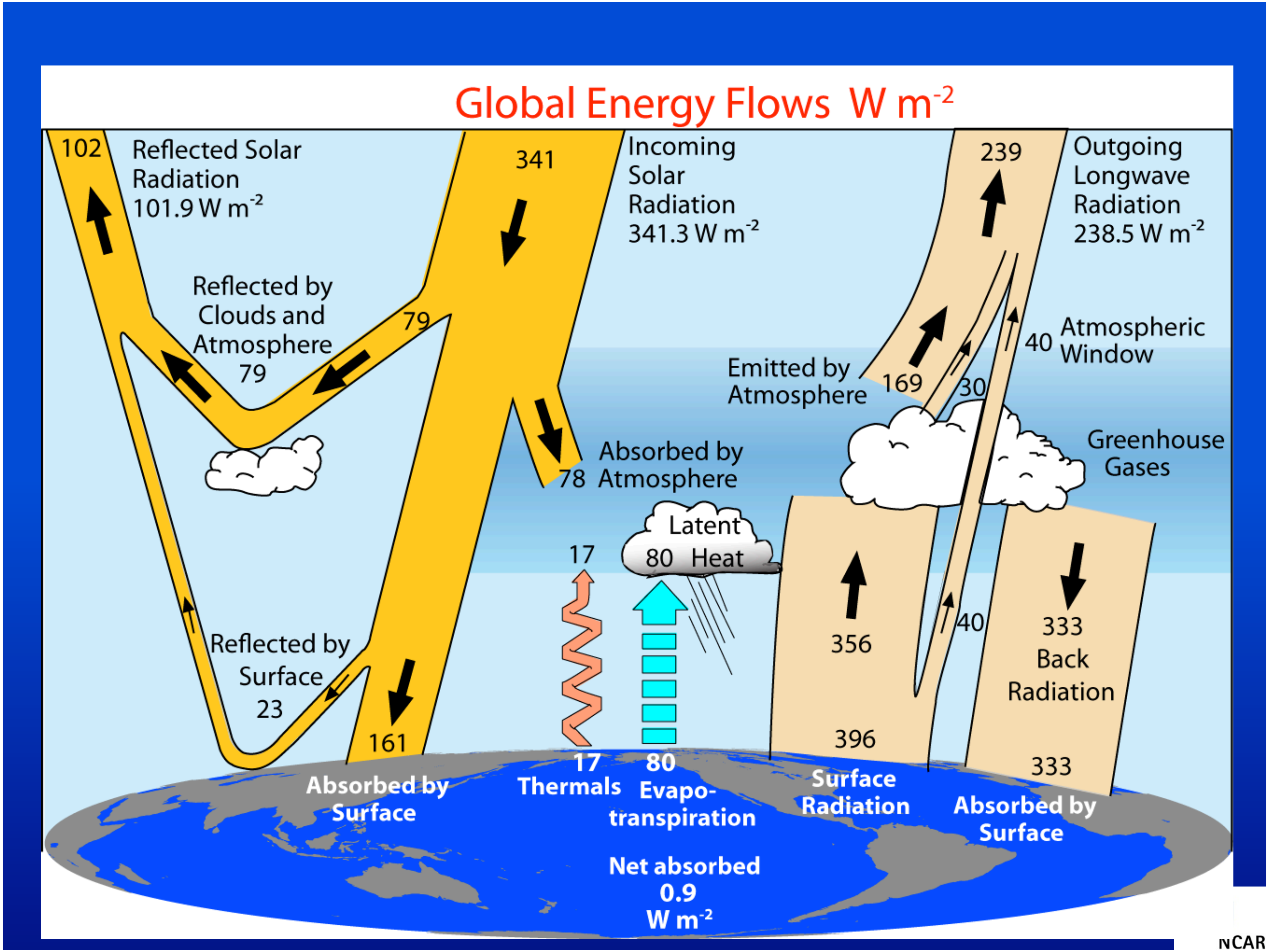


Reanalyses

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


Global Energy Flows W m-2
102
Reflected Solar Radiation 101.9 W m-2
341
Incoming Solar Radiation 341.3 W m-2
239
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
Emitted by Atmosphere
169
30
40
Atmospheric Window
Absorbed by Atmosphere
78
Greenhouse Gases
Latent Heat
80
17
356
40
333
Back Radiation
396
333
Reflected by Surface 23
161
Absorbed by Surface
17 Thermals
80 Evapo-transpiration
Surface Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2

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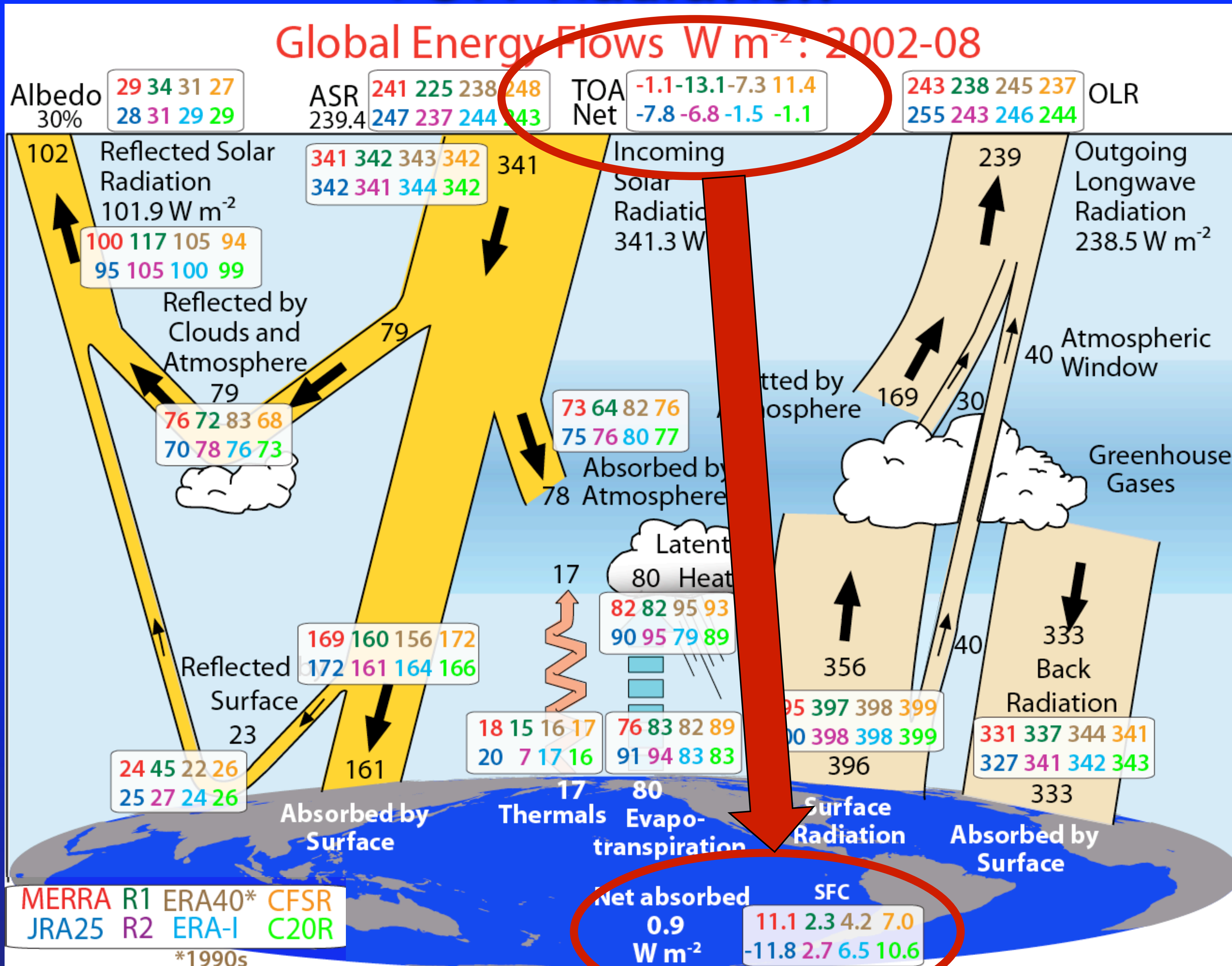
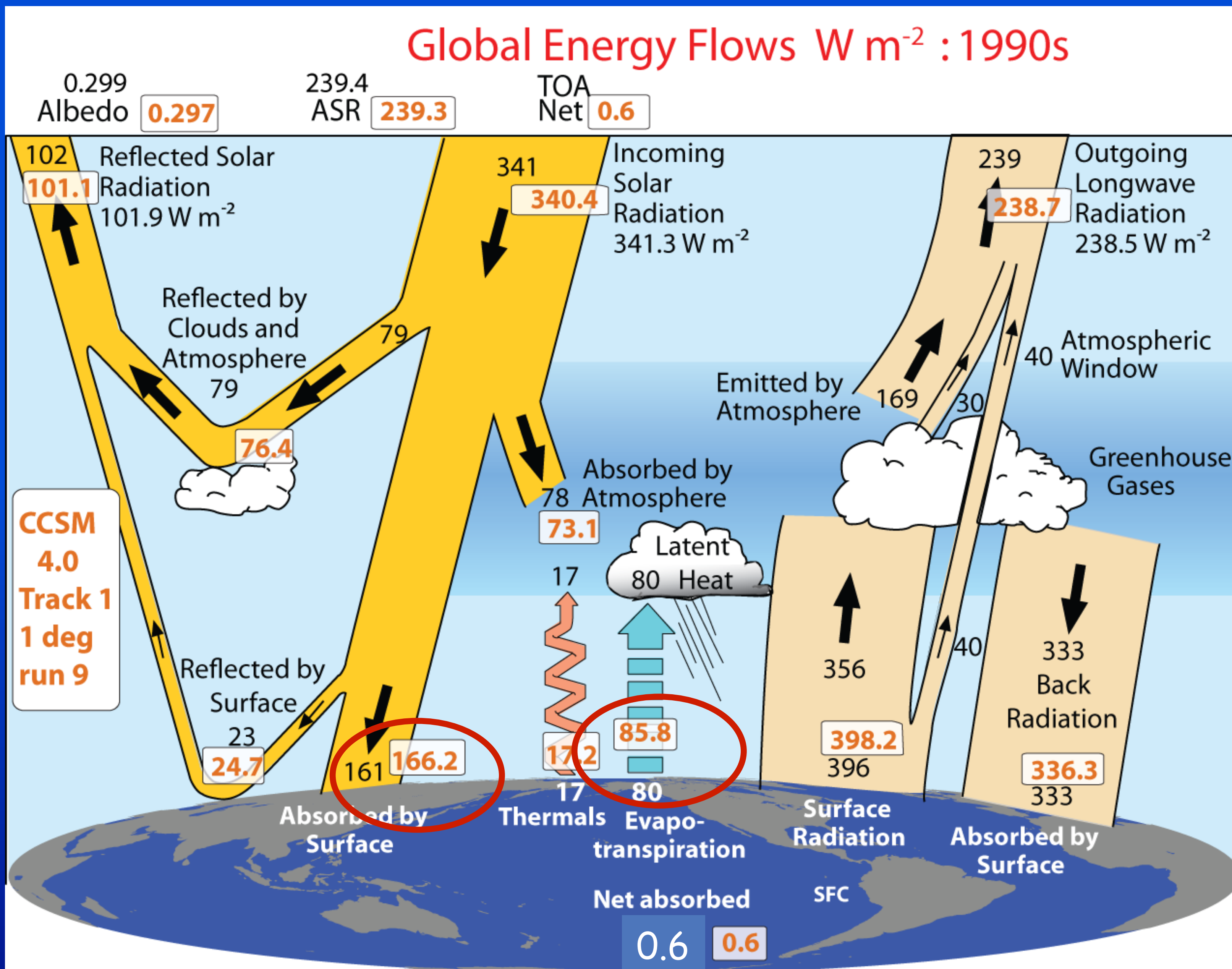
TOA Radiation



Trenberth et al 2011 J Climate

CCSM4



Global Energy Flows W m-2 : 1990s
0.299
Albedo 0.297
239.4
ASR 239.3
TOA
Net 0.6
102
101.1
Reflected Solar Radiation 101.9 W m-2
341
340.4
Incoming Solar Radiation 341.3 W m-2
239
238.7
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere
79
79
76.4
40 Atmospheric Window
Emitted by Atmosphere
169
30
Absorbed by Atmosphere
78
73.1
Greenhouse Gases
Latent Heat
80
17
CCSM 4.0 Track 1 1 deg run 9
Reflected by Surface
23
24.7
161
166.2
17.2
85.8
356
398.2
396
40
333 Back Radiation
336.3
333
17 Thermals
80 Evapo-transpiration
Absorbed by Surface
Surface Radiation
Absorbed by Surface
Net absorbed
SFC
0.6
0.6

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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. 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 vetting and evaluation of products (and the funding for that), and
   2. Reanalysis is done in a research domain and not sustained, so that key personnel can be lost.
   3. Lack of adequate vetting and diagnosis
2. Reanalysis is an essential part of climate services, especially in monitoring, attribution and prediction

Implications

Reanalyses

- Ocean E is generally too large, and P is too large except for MERRA
- The low value of P-E over land is consistent with the view that E is too large and P occurs prematurely, so that the role of advection from afar is too low.
- The lifetime of moisture is too short in models.
- In CFSR, the main balance is between the analysis increment and P, and the model can't stand having the observed amount of moisture, so it rains it out.
- The moisture budget provides better estimates and more stable estimates of E-P than model fluxes or E and P.

CCSM4

- Transport onto land of water is about right.
- Absorption in atmosphere of energy low=> too much at surface => too much E.

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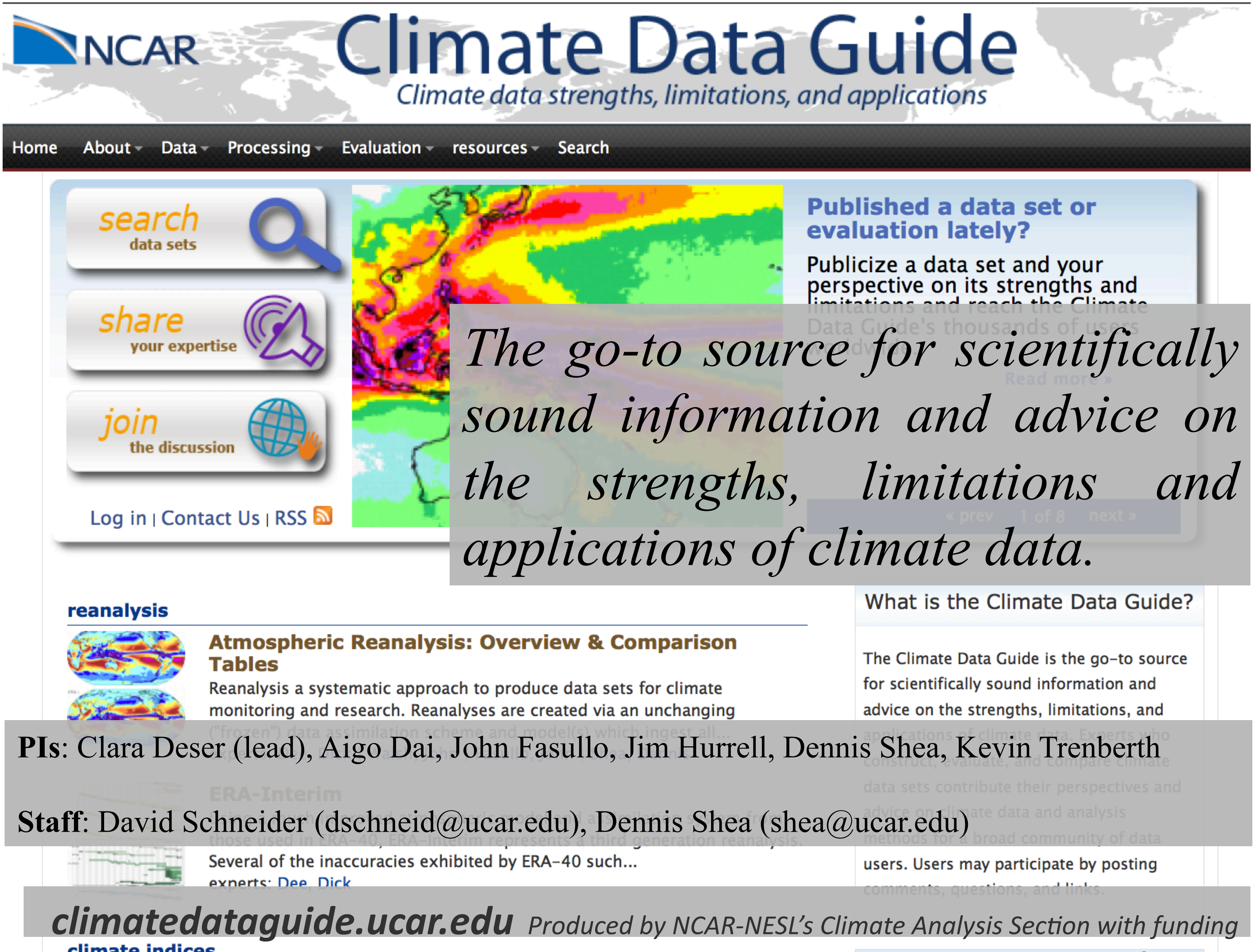

The go-to source for scientifically sound information and advice on the strengths, limitations and applications of climate data.

PIs: Clara Deser (lead), Aigo Dai, John Fasullo, Jim Hurrell, Dennis Shea, Kevin Trenberth

Staff: David Schneider (dschneid@ucar.edu), Dennis Shea (shea@ucar.edu)

climatedataguide.ucar.edu *Produced by NCAR-NESL's Climate Analysis Section with funding from NSF*