ECMWF reanalyses:
Diagnosis and application

Dick Dee (ECMWF)

Contributions by P. Berrisford, P. Poli, S. Uppala, A. Simmons, P. Kållberg, and V. M. Others

Seminar on Diagnosis of Forecasting and Data Assimilation Systems
7-10 September 2009

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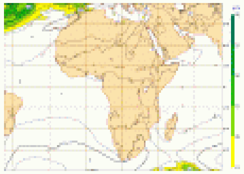


Free access to deterministic medium-range (3-6 days) weather forecasts including MSLP and 850mb

We are an international organisation supported by 31 States. We provide operational medium- and extended-range forecasts and a state-of-the-art super-computing facility for scientific research. We pursue scientific and technical collaboration with satellite agencies and with the European Commission.

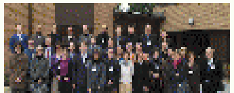
Paper on ERA 40 most highly cited in field of Geosciences

27 March 2009 The paper "The ERA-40 re-analysis", published in 2005, has been identified by Thomson Reuters Scientific's /Essential Science Indicators/ as one of the most highly cited papers in the field of Geosciences, and has been designated as a "Current Classic" for February.

ECMWF Newsletter survey

05 March 2009 An on-line survey is being carried out of readers of the ECMWF Newsletter. The responses will be carefully assessed with a view to further developing the content and presentation of the Newsletter.

EFAS Workshop



30 January 2009 The 4th Annual workshop of European Flood Alert System (EFAS) was held on 29 and 30 January at ECMWF. The workshop participants came from 24 national and regional

Hot Links
- Forecasts
- WMO
- EPSgrams
- TIGGE
- Seasonal Forecast
- GEMS Project
- Reanalysis
- Oceans
- Data
- ENSEMBLES
- Metview
- RMDCN
- DEISA
- SIMDAT

Outline

- Introduction to reanalysis
  - The basic idea
  - Products and applications
  - Quality requirements
  - The observations
- Diagnostics
  - Fit to data, forecast quality
  - Mass, energy, and water
  - Stratosphere
- Biases and trends

Introduction to reanalysis: The basic idea

- Reanalysis uses a modern data assimilation system to reprocess past observations

- It produces a detailed description of the atmospheric evolution over an extended period of time:

  - Gridded fields of observed meteorological parameters (ps, T, u, v, q)
  - Additional parameters generated by the model (rainfall, cloud parameters, boundary layer height, …)
  - Consistent with observations (through data assimilation)
  - Consistent with the laws of physics (from model equations)

Why not use archived analyses used for NWP?

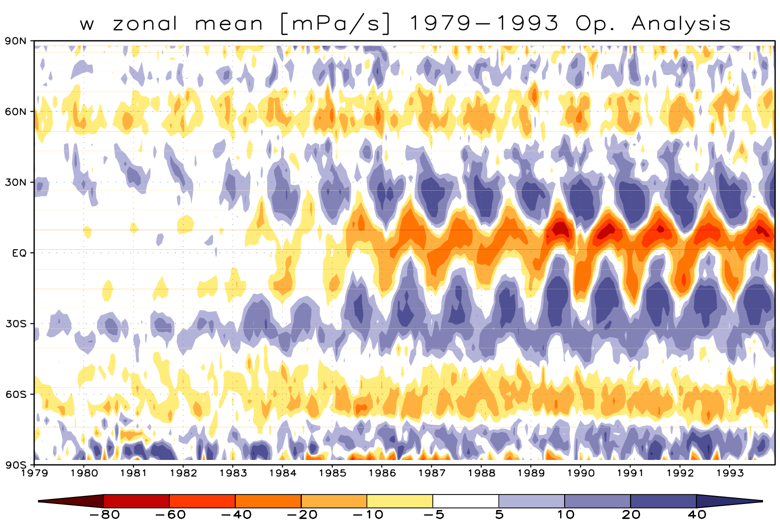
NWP systems are continuously upgraded:

- Improved resolution
- Changes in model physics
- Changes in forcing data (e.g. SST)

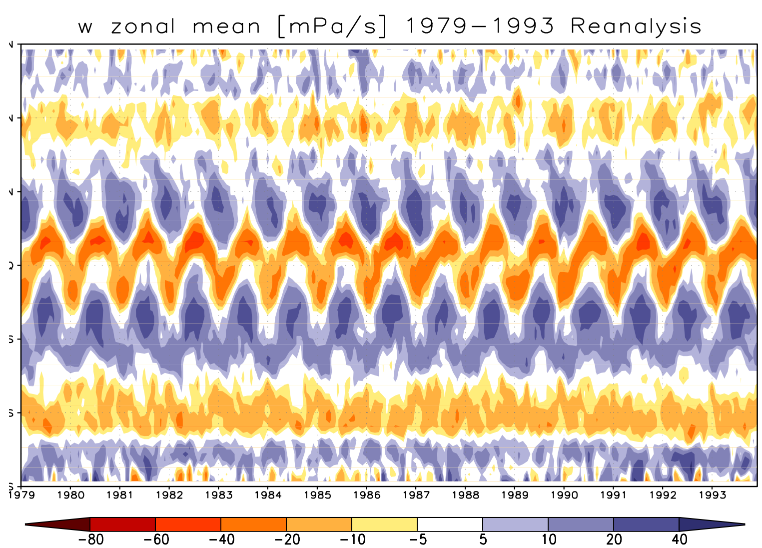
} Unphysical changes in operational analyses

Zonal mean vertical velocity at 500hPa:

From ECMWF Operations



From reanalysis (ERA-15)



Applications

- "Observations" for verification and diagnosis
  - Forecast model development, calibration of seasonal forecasting systems, climate model development; use of data assimilation increments for identifying model errors
- Input data for model applications
  - for smaller-scales (global→regional; regional→local), ocean circulation, chemical transport, nuclear dispersion, crop yield, health warnings, …
- Study of short-term atmospheric processes and influences
  - process of drying of air entering stratosphere, bird migration, …
- Providing climatologies
  - ocean waves, resources for wind and solar power generation, …
- Assessment of the observing system
  - providing feedback on observational quality, bias corrections and a basis for homogenization studies; contributing to data reprocessing activities
- Study of longer-term climate variability and trends
  - used with caution in conjunction with observational studies

Global atmospheric reanalysis products

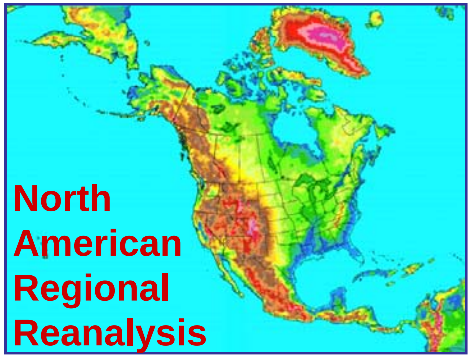
Organization	Time Period	Resolution	Analysis Method
NASA Data Assimilation Office (**DAO**)	**1980** to **1994**	2x2.5° lat/lon (Δx ~ **280km**) L20 (σ, top at 10hPa)	Optimal Interpolation (**OI**) with incremental analysis update
ECMWF (**ERA-15**)	**1979** to **1993**	T106 spectral (Δx ~ **125km**) L31 (σ-p, top at 10hPa)	Optimal Interpolation (**OI**) with nonlinear normal mode initialization
NOAA NCEP and NCAR (**R1**)	**1948** to present	T62 spectral (Δx ~ **200km**) L28 (σ, top at 3hPa)	Spectral Statistical Interpolation (**SSI**)
NOAA NCEP and DOE (**R2**)	**1979** to present	T62 spectral (Δx ~ **200km**) L28 (σ, top at 3hPa)	Spectral Statistical Interpolation (**SSI**)
ECMWF (**ERA-40**)	**1957** to **2002**	T159 spectral (Δx ~ **100km**) L60 (σ-p, top at 0.1hPa)	**3D-Var,** direct radiance assimilation
JMA and CRIEPI (**JRA-25**)	**1979** to **2004**	T106 spectral (Δx ~ **125km**) L40 (σ-p, top at 0.4hPa)	**3D-Var**, direct radiance assimilation
ECMWF (**ERA-Interim**)	**1989** to present	T255 spectral (Δx ~ **80km**) L60 (σ-p, top at 0.1hPa)	**4D-Var**, variational bias correction of radiance data (VarBC)

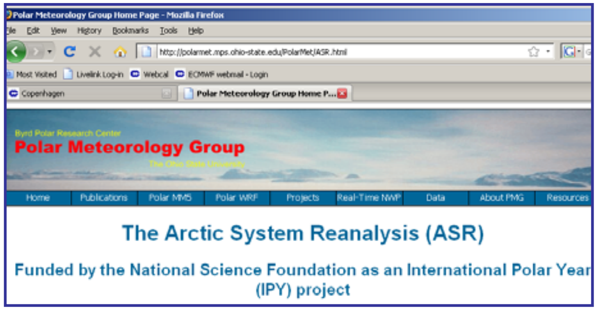
Soon to come:

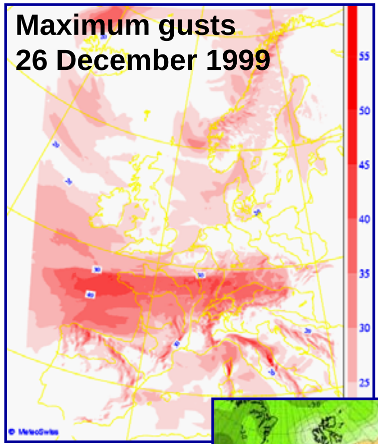
NCEP (**CFSRR**)	**1979** to **2009**	T382 spectral (Δx ~ **38km**) L64 **(**σ-p, top at 0.2hPa)	Grid-point Statistical Interpolation (**GSI**) *with weakly coupled ocean*
NASA GMAO (**MERRA**)	**1979** to present	0.5x0.67° lat/lon (Δx ~ **74km**) L72 (σ-p, top at 0.01hPa)	Grid-point Statistical Interpolation (**GSI**)
JMA (**JRA-55**)	**1958** to **2012**	T319 spectral (Δx ~ **63km**) L60 (σ-p, top at 0.1hPa)	**4D-Var**, variational bias correction of radiance data (VarBC)

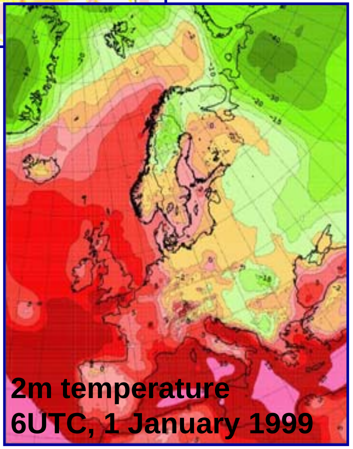
Other specialized atmospheric reanalysis activities

- Regional reanalysis and downscaling

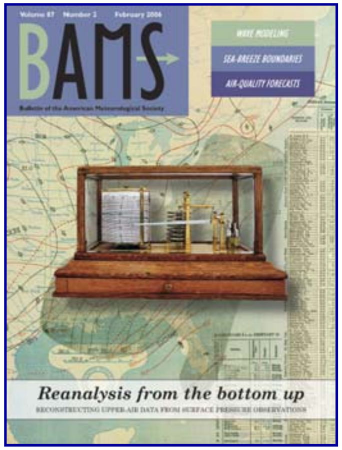




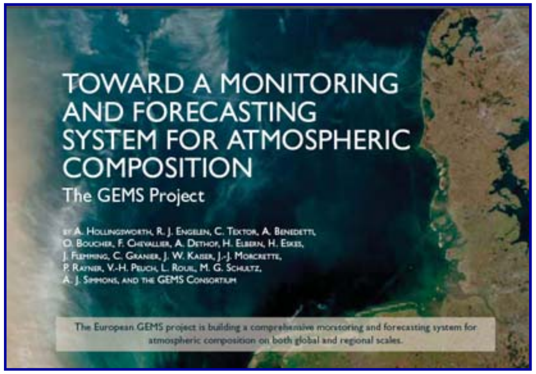




- Long-term reanalysis using only surface-pressure observations (20CR)



- Short-term reanalysis for chemical composition



Atmospheric reanalysis at ECMWF

	ERA-15	ERA-40	ERA-Interim	ERA-75 (target)
TIME PERIOD	*1979-1993*	*1957-2002*	*from 1989 onwards*	*from 1938 onwards*
USERS	Meteorologists and Atmospheric Scientists			
		Climate Scientists and Wider Earth Science Community		
			Additional "Environmental Users"	
				European Stakeholders **GMES Core & Downstream services**
INPUT DATA ACCESS	Mixed Observational Data Formats in Archive			Unified, Consolidated Database Facility
		Observation Quality Feedback Information		
				Internet Access
GRIDDED PRODUCTS	**Model Fields (GRIB format)**			
				Real-time Product Database **Essential Climate Variables** **Internet Access**
ATMOSPHERE	Assimilation OI 31 levels 150km	Assimilation 3DVAR 60 levels 125km	**Assimilation 4DVAR** **60 levels** **80km**	**Assimilation weak-constraint 4DVAR** **91 levels** **40 km** **Improved Observations**
LAND	Forcing	Model	**Improved Model**	**Improved Model & Assimilation** **Coupling**
OCEAN & SEA-ICE	SST/ice Forcing	**Improved SST/ice Forcing** **Wave Model**		**Improved SST/ice** **Coupling**
CHEMISTRY		Forcing	**Improved Forcing**	**Improved Interaction**
IMPACT	Enhance Understanding of Atmospheric Variability, Leading to Improved Models			
		Investigate Past Weather and Climate, Assess Observing System Impact		
			Monitor Near Real-time Climate with Traceability to Input Data	
				Facilitate Environmental Decisions, Enable New Applications of GMES, Assess Regional Climate Change & Risks via Regional Reanalyses, Improve Earth System Modeling, Maximize Benefits from Earth Observation Infrastructure

ERA-Interim

- 20+ years: 1989-2009, continuing near-real time
- Resolution: T255L60, 6-hourly (3-hourly for surface)
- Forecast model version late 2006 (Cy31r2)
- Analysis using 12-hourly 4D-Var
- Variational bias correction of radiance data (VarBC)

- Monthly updates of the product archive
- Member state users: full access via MARS
- All users: web access via ECMWF Data Server
- Copy of complete archive at NCAR (http:// dss.ucar.edu)

Please visit: http://www.ecmwf.int/research/era

Quality requirements for reanalysis products

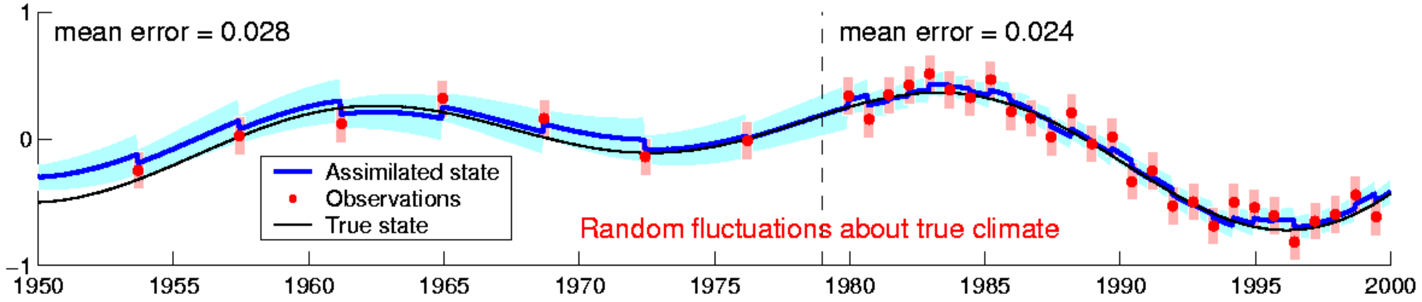
- Accurate representation of observations
  - Departures from assimilated data
  - Comparisons with independent data

- Physical coherence of analysed fields
  - Forecast quality
  - Validation of model-generated fields
  - Conservation properties

- Consistency in the time-dimension
  - Representation of climate signals
  - Assessment of trends

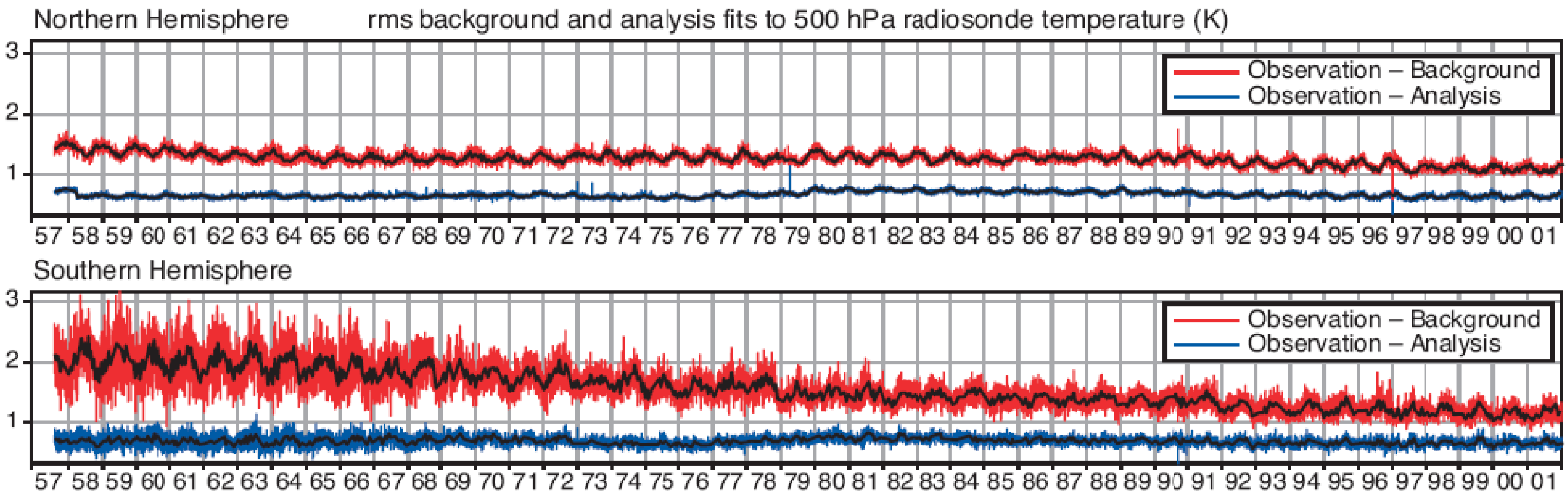
Reanalysis quality and the observing system

- Use of a fixed data assimilation system improves consistency
- Changes in accuracy reflect changes in the observing system

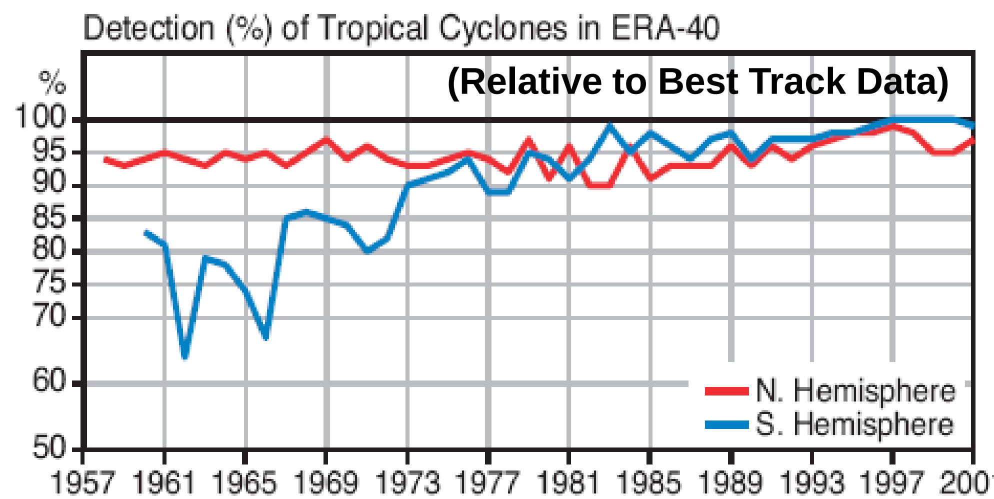


- Ideally, accuracy should improve with time as additional observations become available

ERA-40 fit to 500 hPa temperature observations from radiosondes

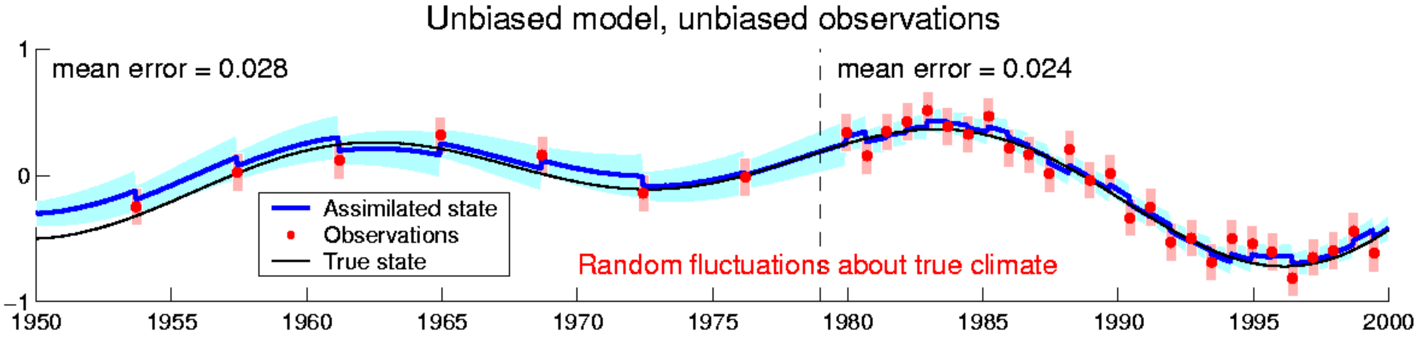


… and representation of Tropical Cyclones:

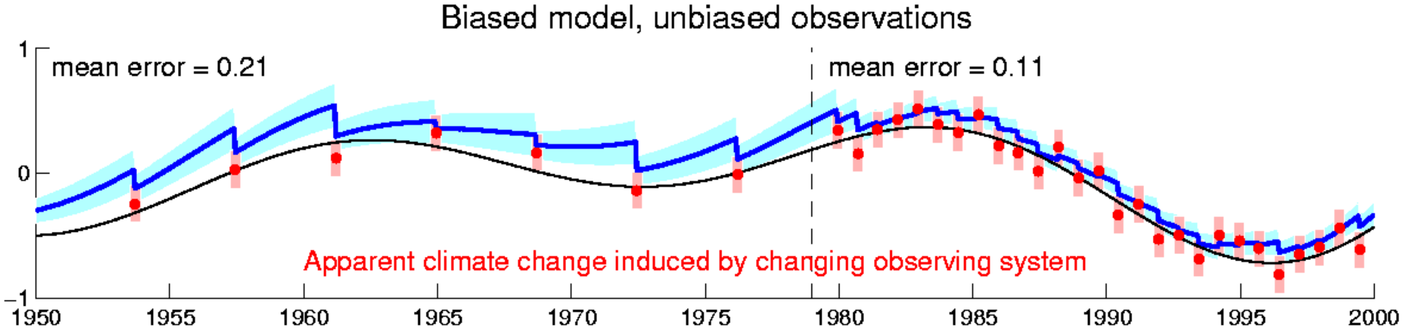


Reanalysis quality and the observing system

- Changes in accuracy reflect changes in the observing system

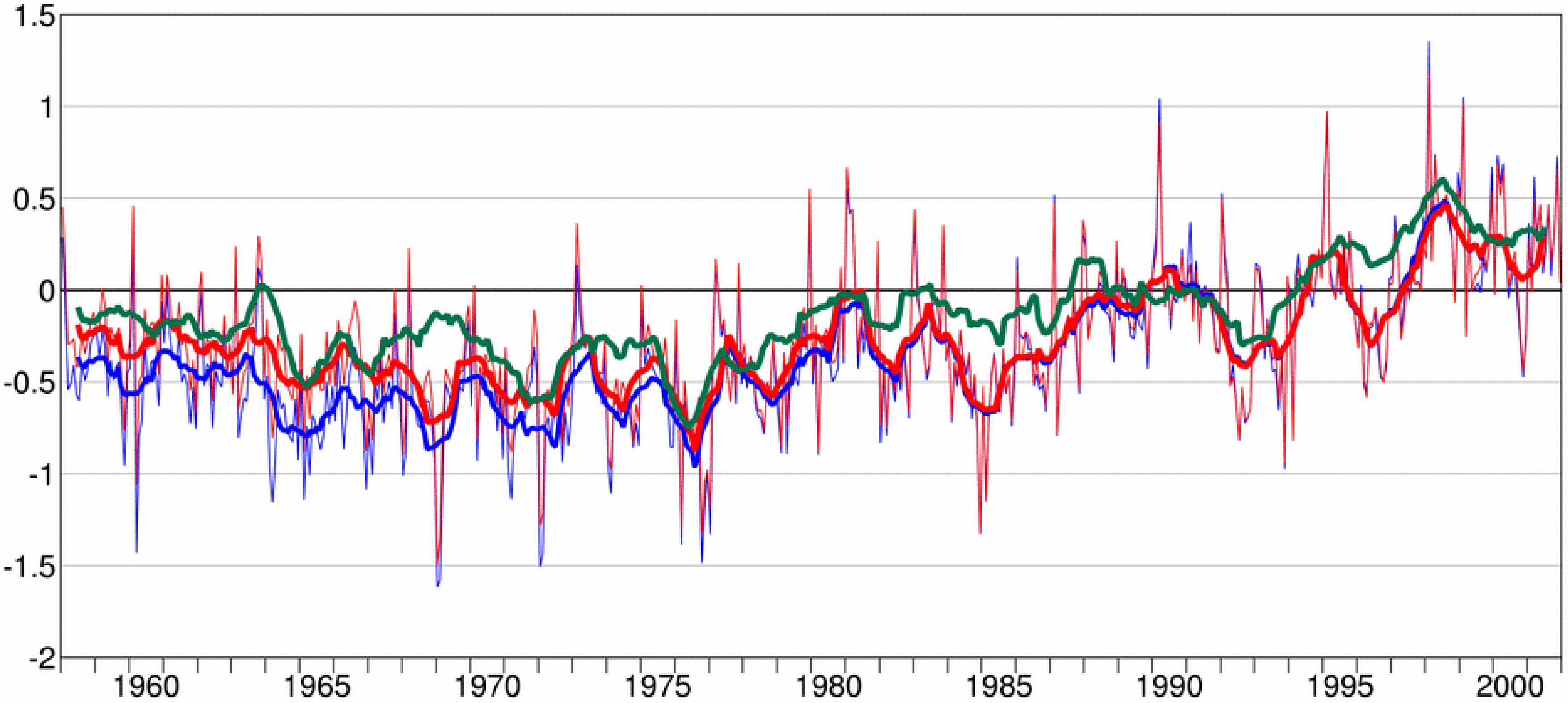


- **The other side of the coin:** Effect of bias in the system



ERA-40 mean fit to surface temperature observations from land stations (Simmons et al. 2004)

Surface air temperature anomaly (^{o}C) with respect to 1987-2001

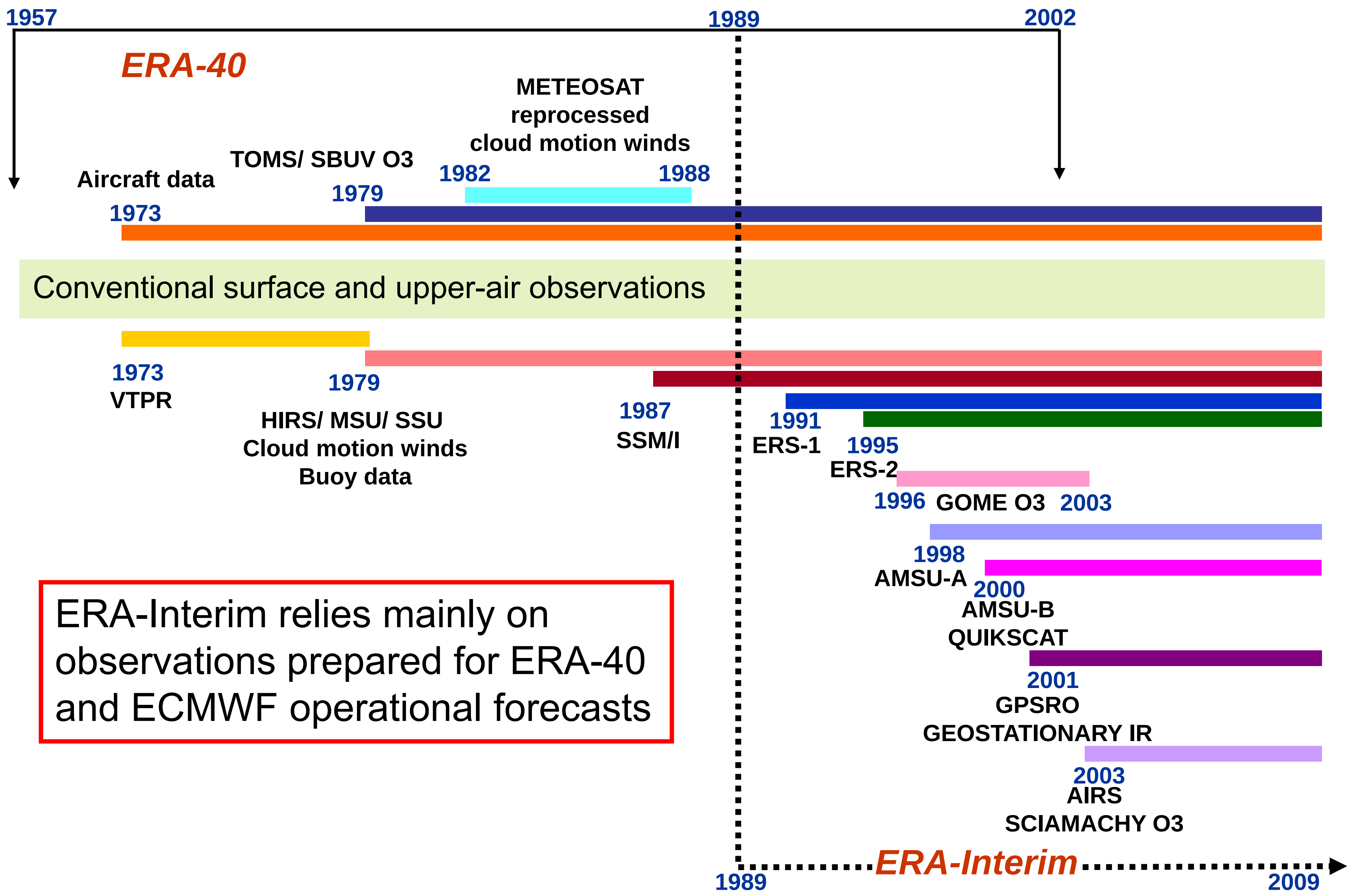


Based on monthly CRUTEM2v data (Jones and Moberg, 2003)

Based on ERA-40 reanalysis (including SYNOP data)

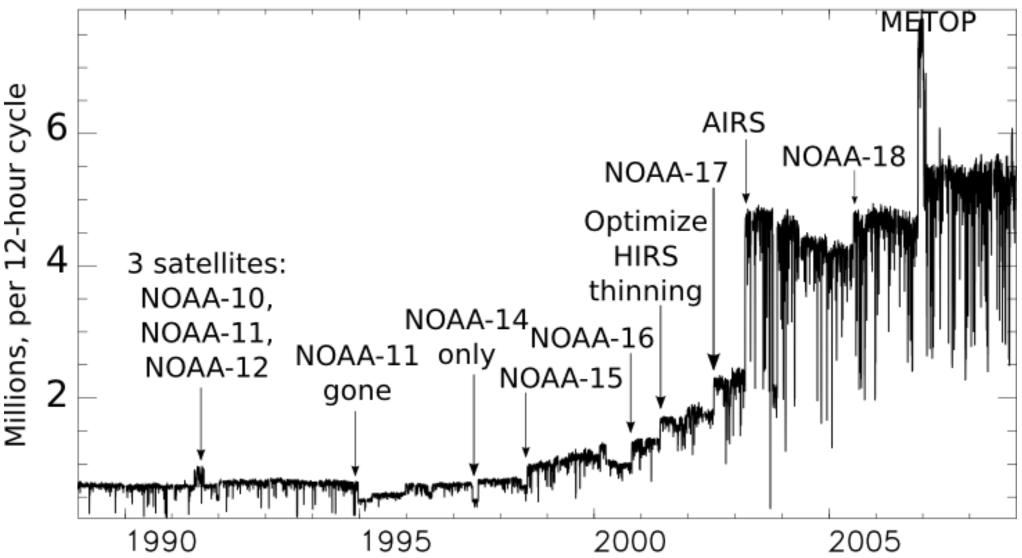
Based on ERA-40 model simulation (including SST/sea-ice data)

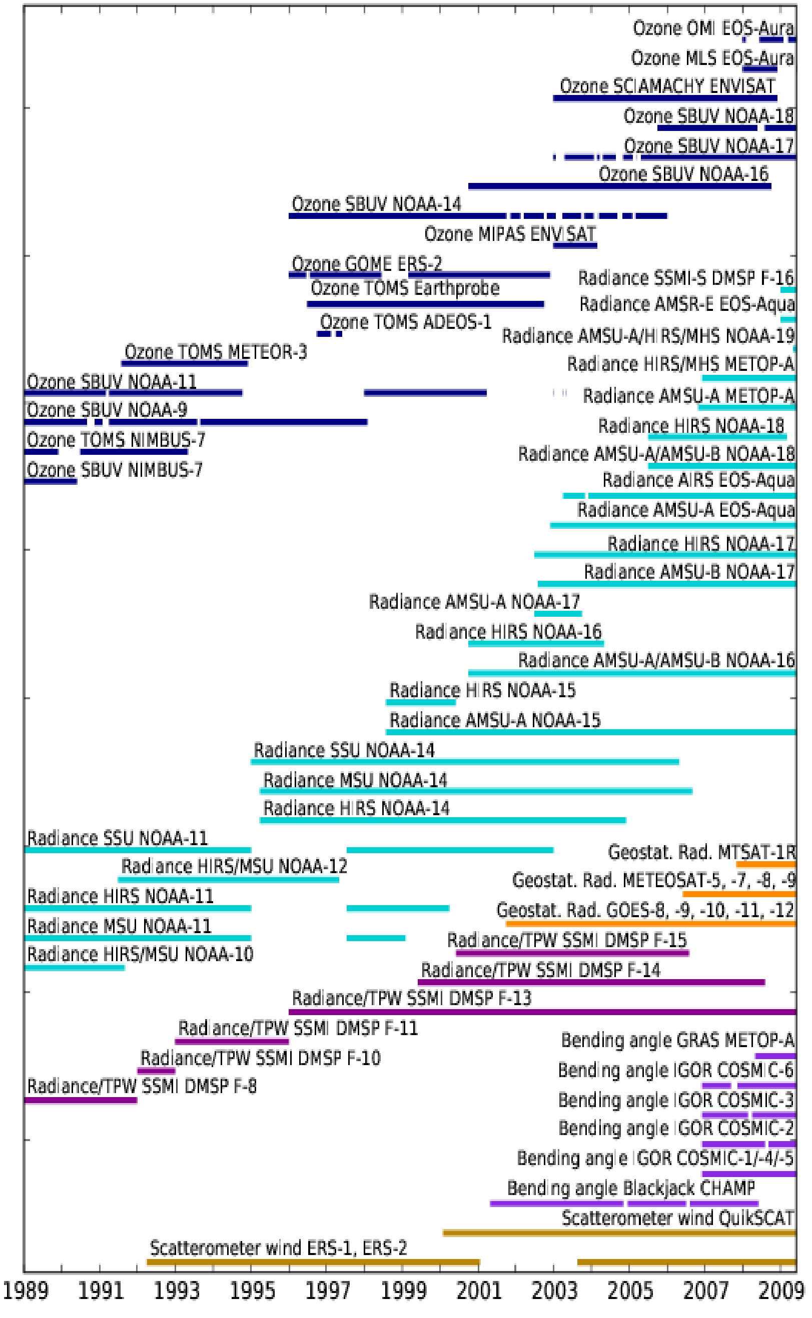
Observing systems used in ERA-40 and ERA-Interim



ERA-Interim relies mainly on observations prepared for ERA-40 and ECMWF operational forecasts

Data used in ERA-Interim

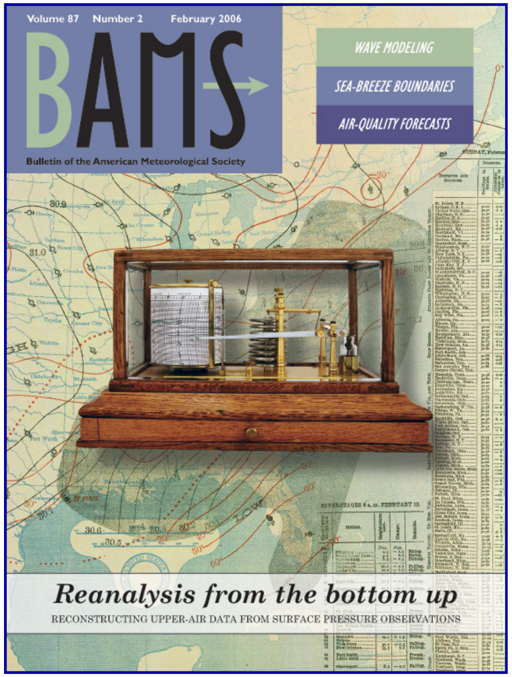




Understanding the effect of changes in the observing systems is key to understanding reanalysis quality

How far back can we go in time?

- NOAA-CIRES 20th Century Reanalysis V1: 1908-1958 (Compo *et al.* 2006; 2009)
- Uses NCEP's Climate Forecast System, T62 (~200 km) on 28 pressure levels
- HadISST-1.1 (Rayner *et al.* 2003)
- Ensemble Kalman Filter (EnKF) with 56 members
- Surface pressure data only (International Surface Pressure Databank 1.1 and ICOADS version 2.4)
- Version 2: 1892-2008



Key ideas:

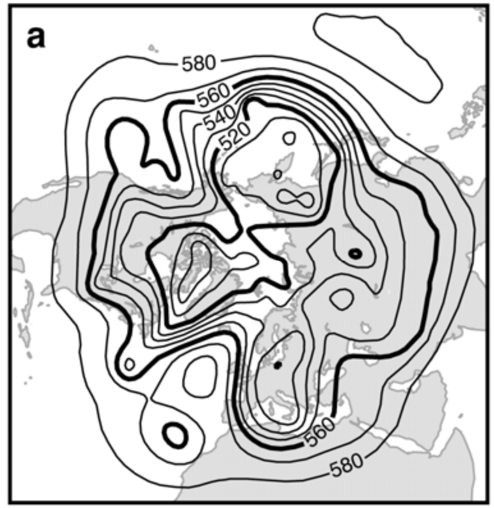
- Use of a stable observing system to prevent spurious trends
- Use of an ensemble to provide uncertainty information

Reanalysis of sparse observations

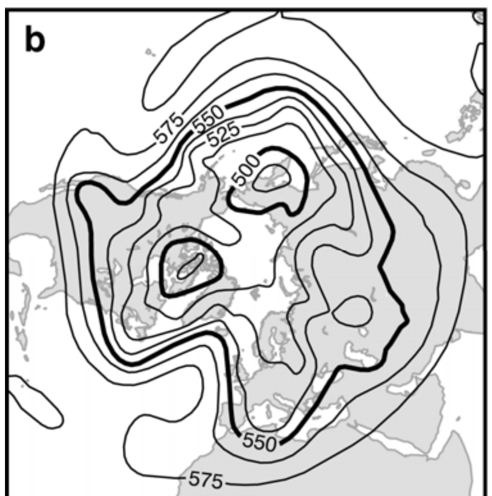
Whitaker, Compo,
and Thépaut 2009

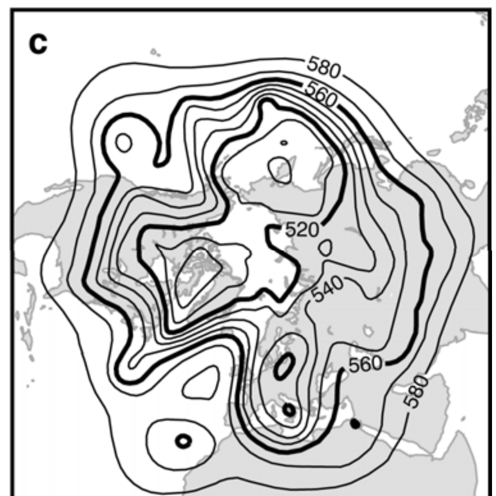
4D-Var CONTROL
All observations

(15 February 2005 00 UTC)



3D-Var
“Surface pressure observations only”

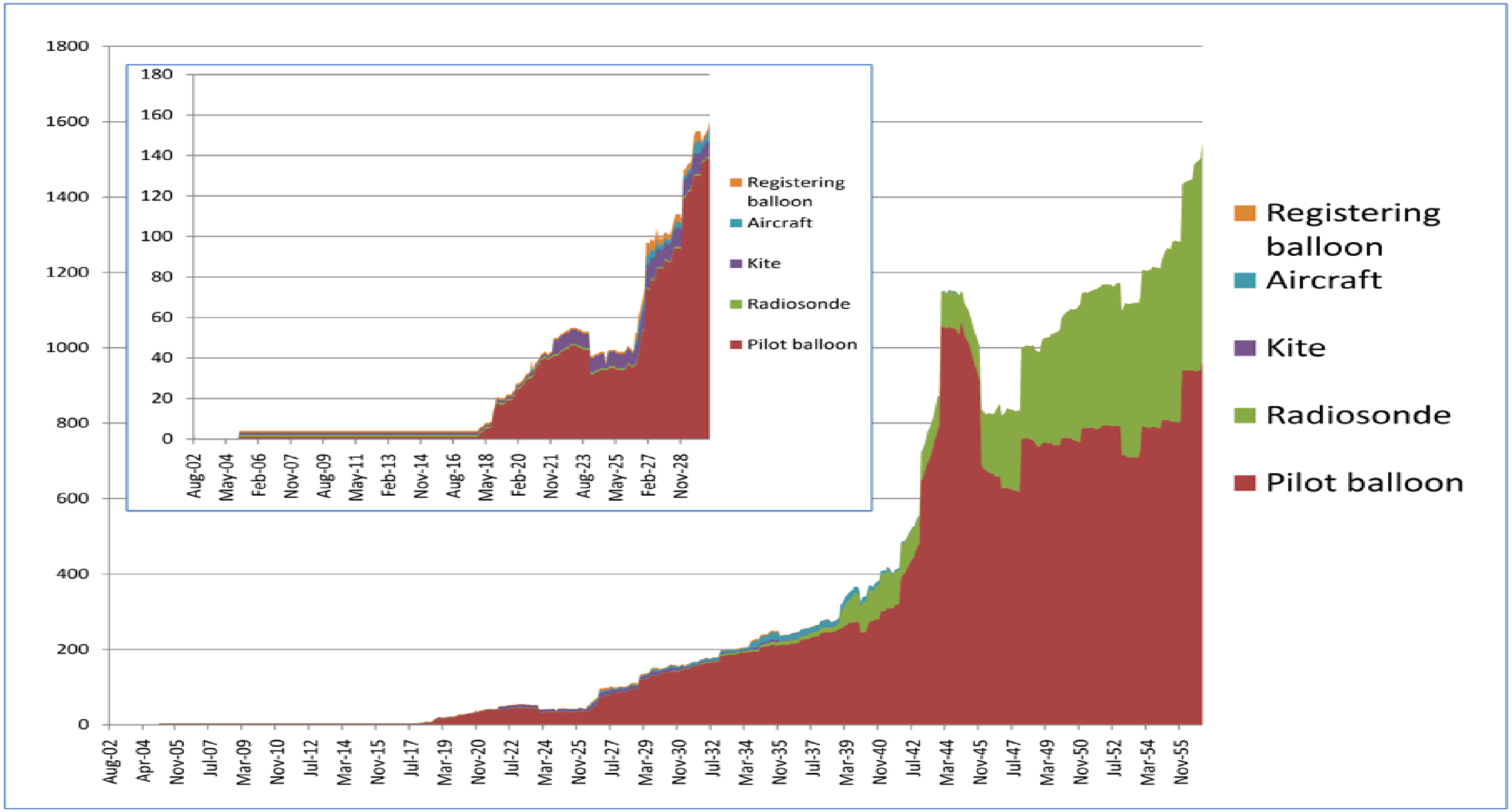




4D-Var
“Surface pressure observations only”

Upper-air observations pre-1957

The Comprehensive Historical Upper Air Network (CHUAN, Stickler et al. 2009)



Can we get *both* high accuracy *and* meaningful trend estimates?

Outline

- Introduction to reanalysis
  - The basic idea
  - Products and applications
  - Quality requirements
  - The observations
- Diagnostics
  - Fit to data, forecast quality
  - Mass, energy, and water
  - Stratosphere
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Quality requirements for reanalysis products

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- Physical coherence of analysed fields
  - Forecast quality
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- Consistency in the time-dimension
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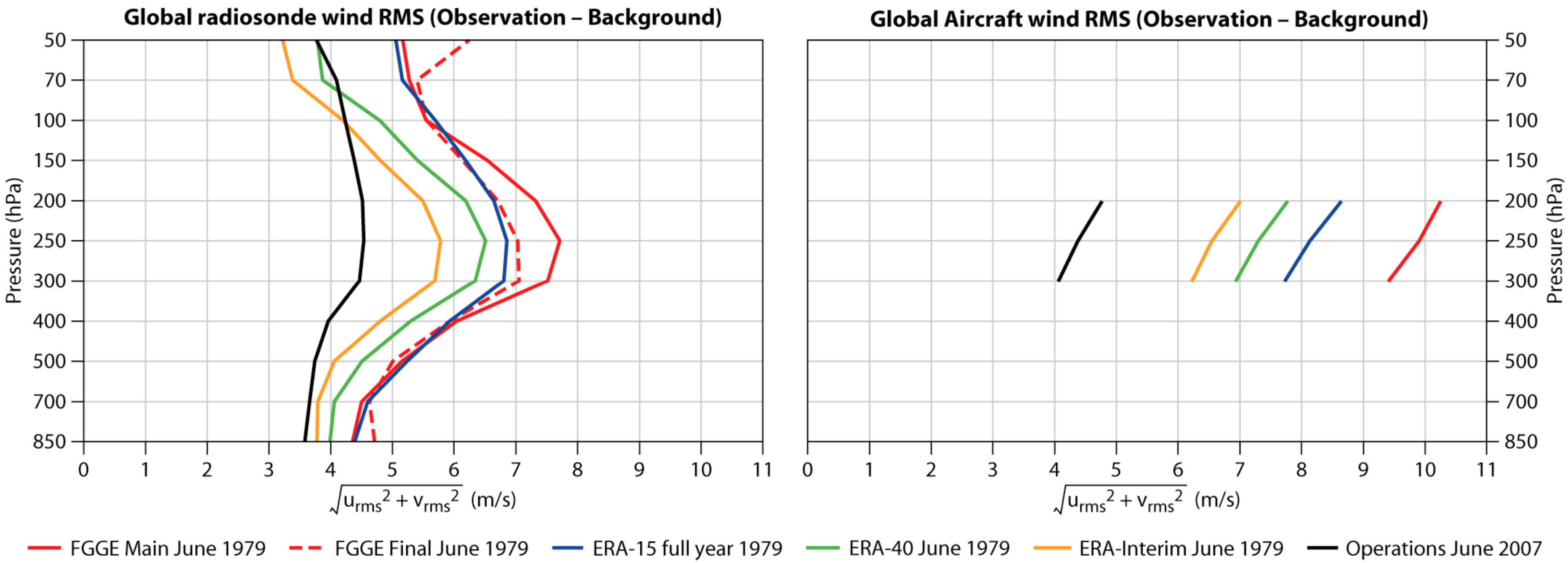
Fit to wind observations: Successive ECMWF reanalyses



- Increasing accuracy with successive reanalyses
- ECMWF Operations represent potential for improvement

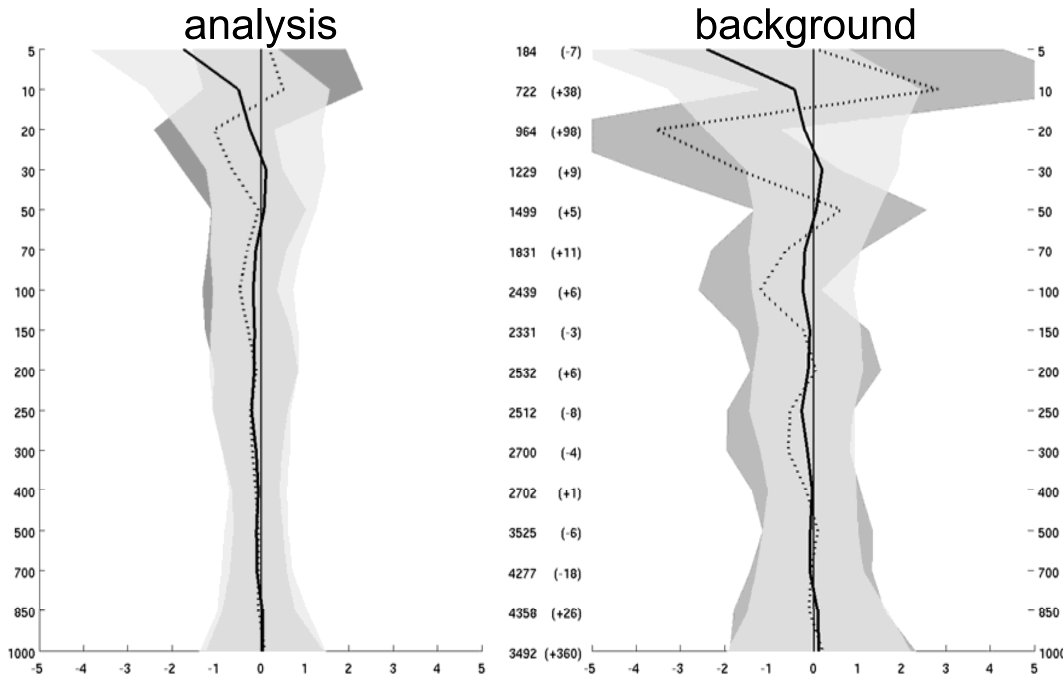
Upper-air temperatures in the Arctic (Jan 2000)

Reduced bias

Improved vertical consistency

Improved consistency between background and analysis

radiosonde temperature departures, mean and std dev



ERA-40 dark/dashed
ERA-Interim light/solid

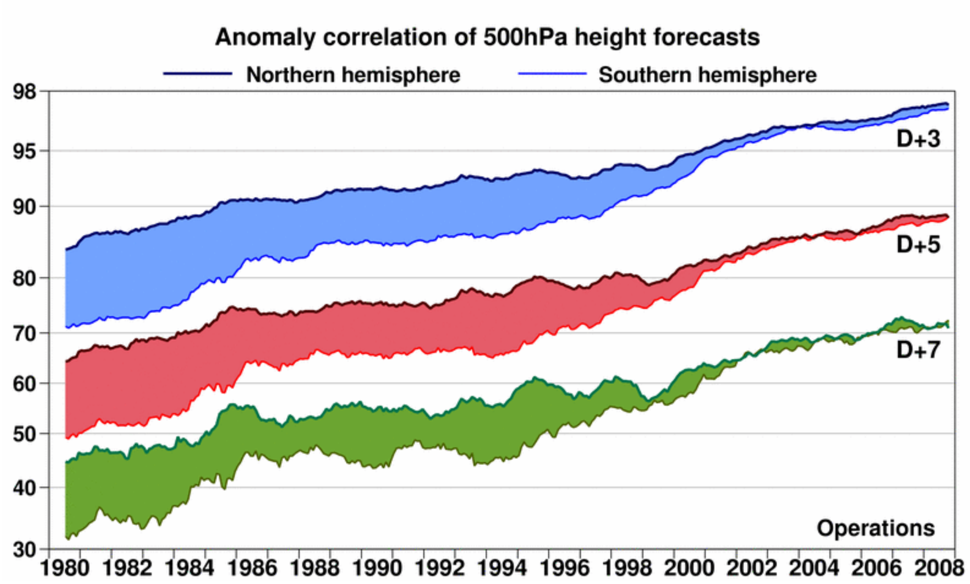
ERA-Interim achieves similar accuracy with smaller analysis increments

Quality of (re-)forecasts

Updated from
Simmons & Hollingsworth (2002)

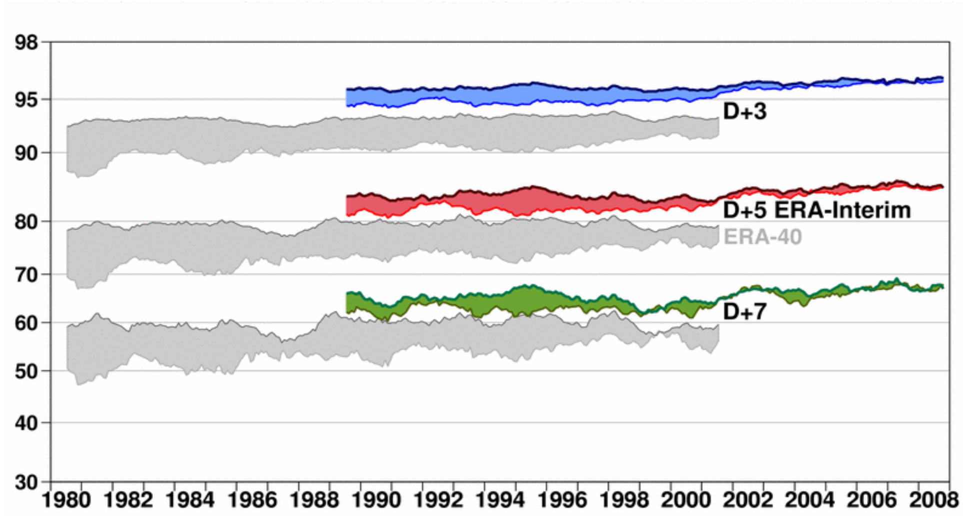
Operational forecasts from ECMWF:

- improvements over time due to system upgrades (model and data assimilation)



Re-forecasts produced with ERA-Interim:

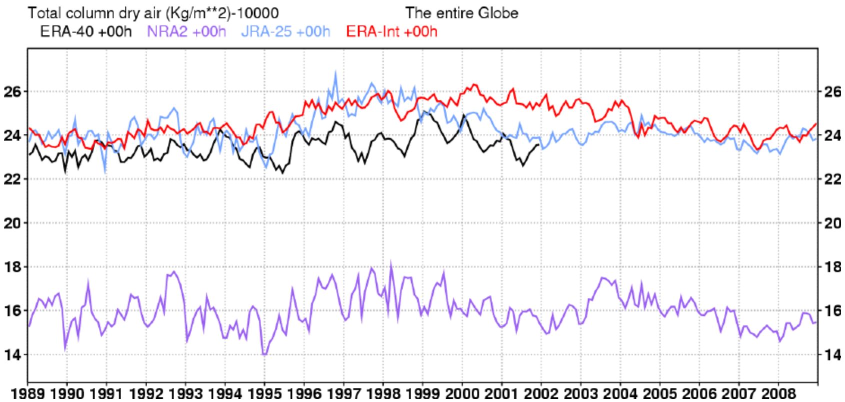
- quality is more uniform globally and in time
- improvements relative to ERA-40 reflect 5 years of IFS development



Mass budget

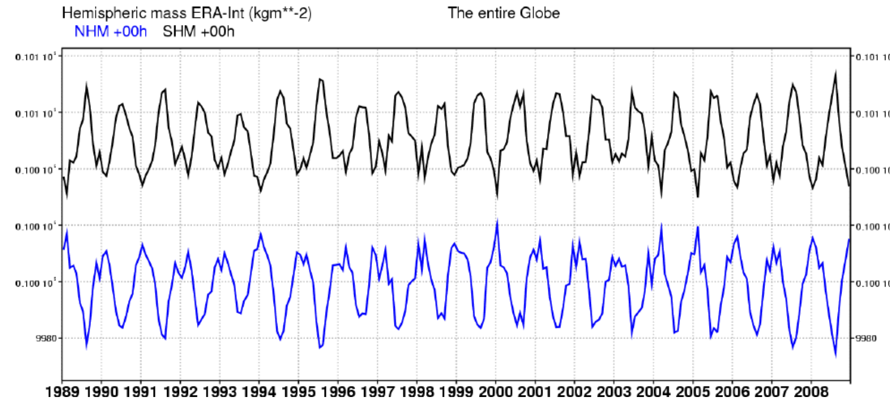
(P. Berrisford)

Global mass of dry air

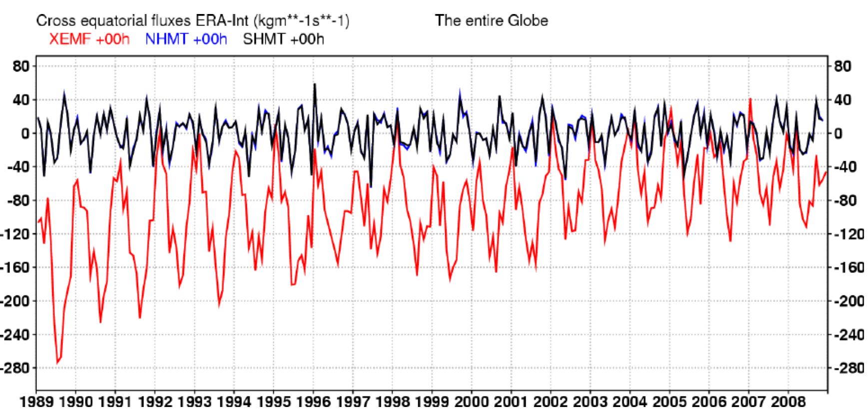


(Variations in mass all within 0.04%)

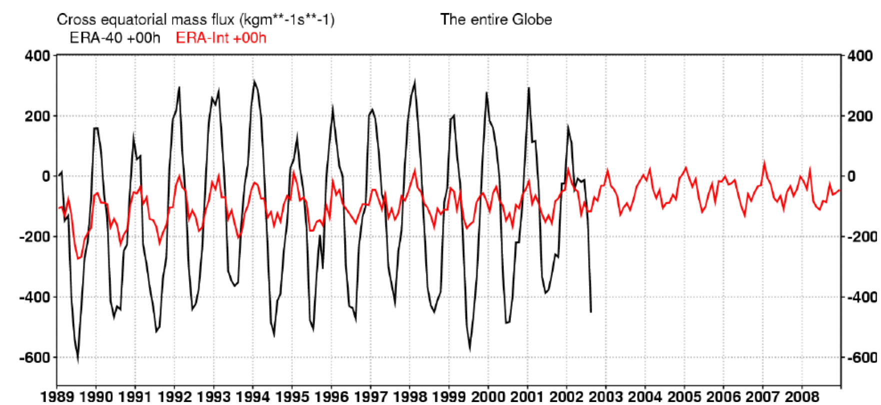
NH and SH mass in ERA-Interim



Cross equatorial mass flux in ERA-Interim

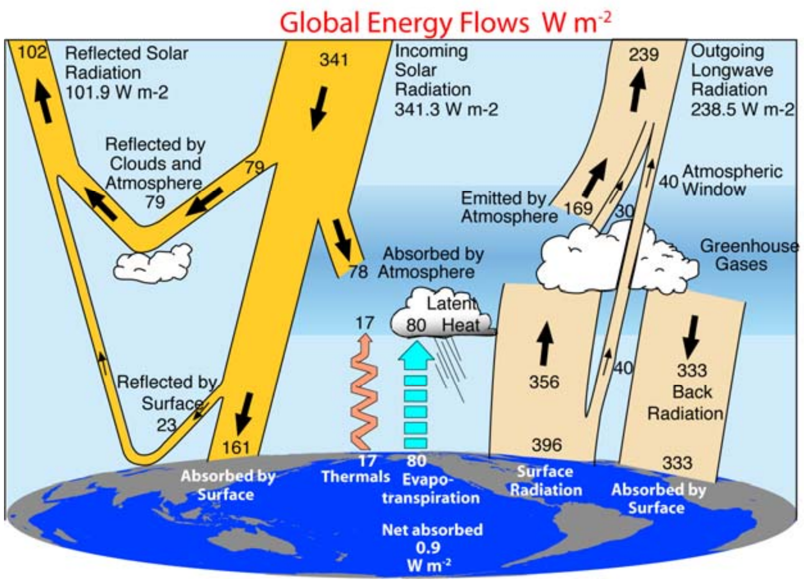


Cross equatorial mass flux in ERA-Interim and ERA-40

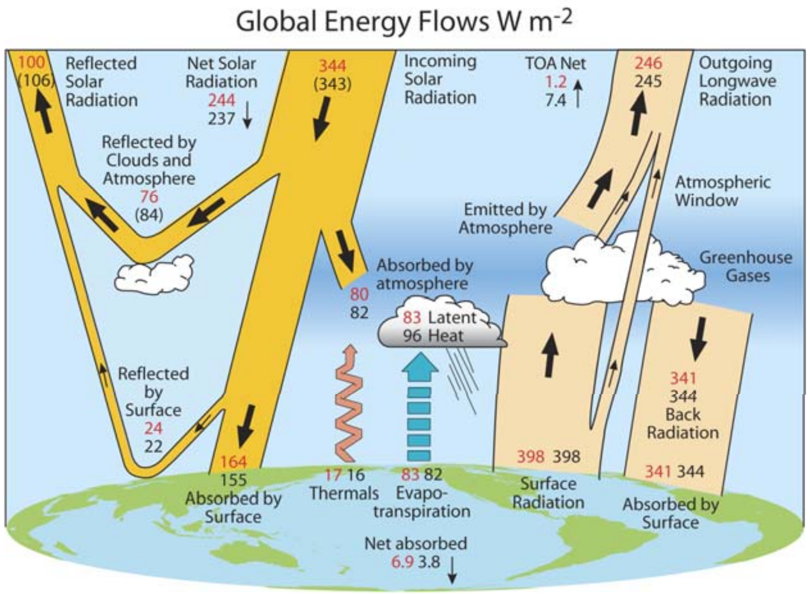


Energy budget

Trenberth *et al.* 2009:
Earth's global energy budget

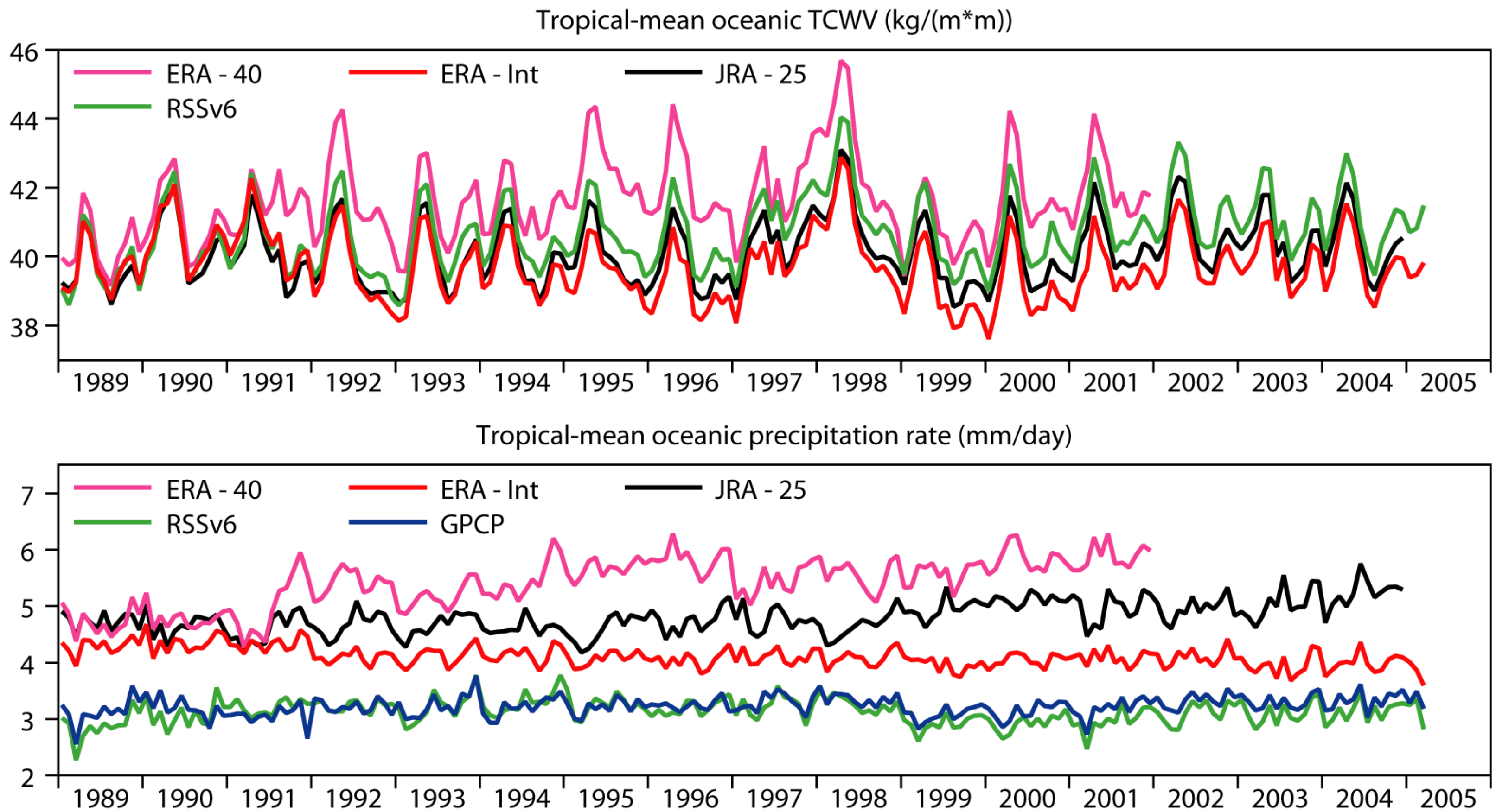


ERA-Interim 1989-2008 ERA-40 1989-2001



- TOA balance improved in ERA-Interim
- Surface energy balance worse, esp. over oceans

Water

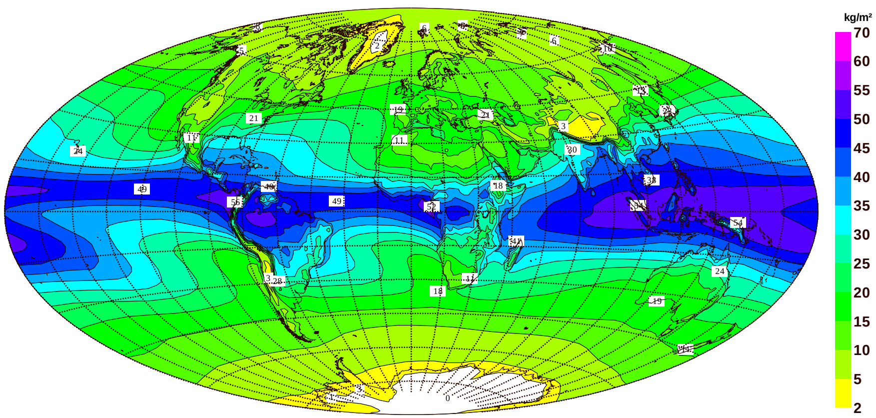


Improvements in ERA-Interim, due to:

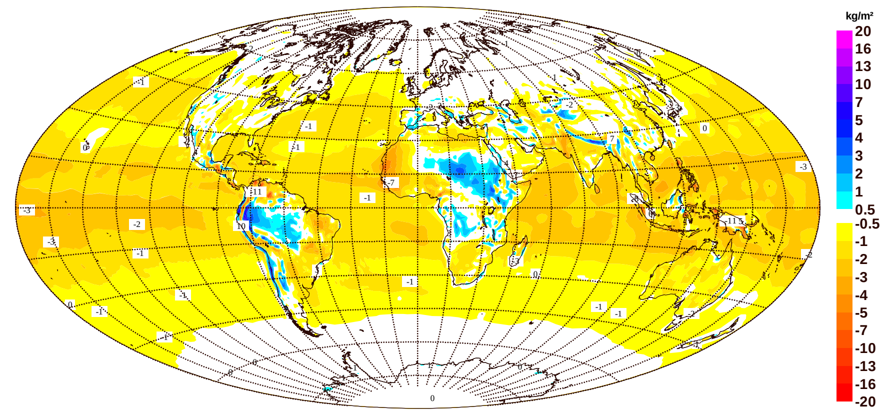
- Revised humidity analysis
- Better model physics
- 4D-Var
- Improved bias corrections for radiance data

Daily mean total column water vapour (1989-1998)

ERA-Interim

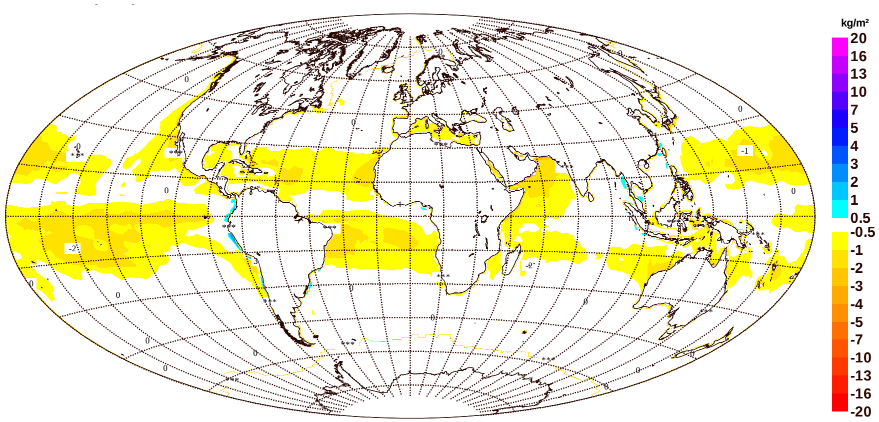


ERA-Interim – ERA-40



ERA group

ERA-Interim – SSM/I



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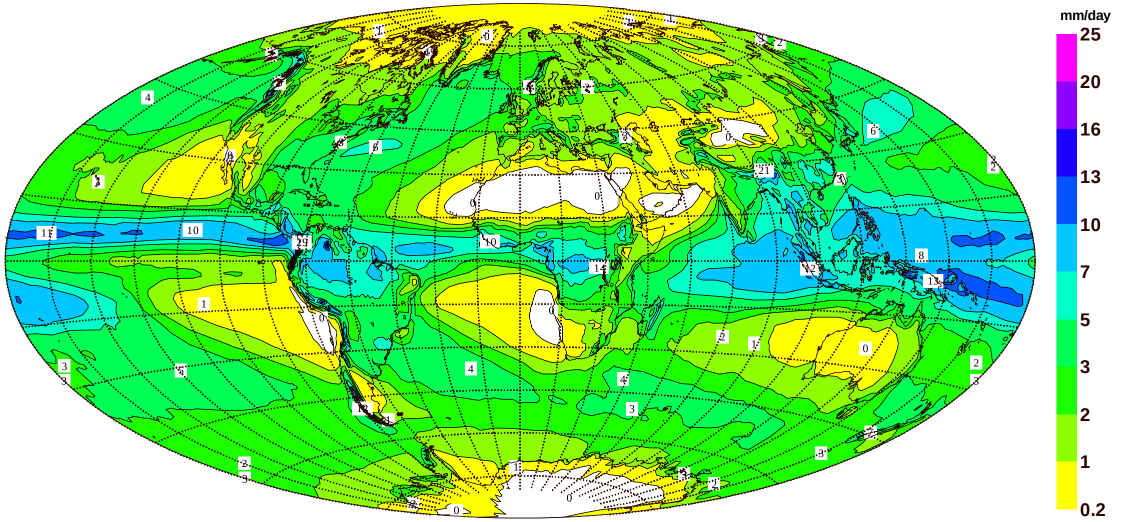
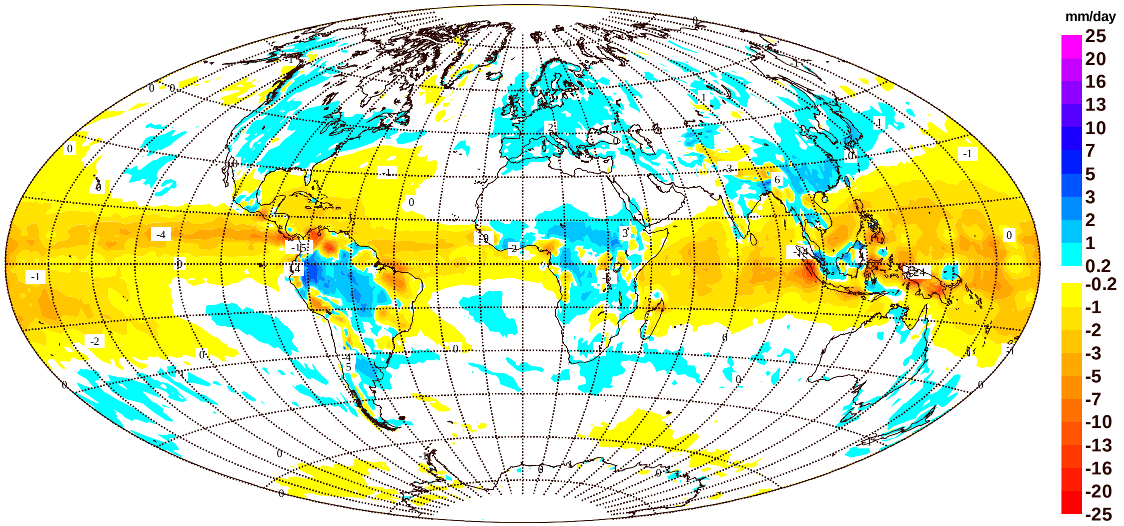
Mean daily precipitation (1989-1998)

ERA-Interim



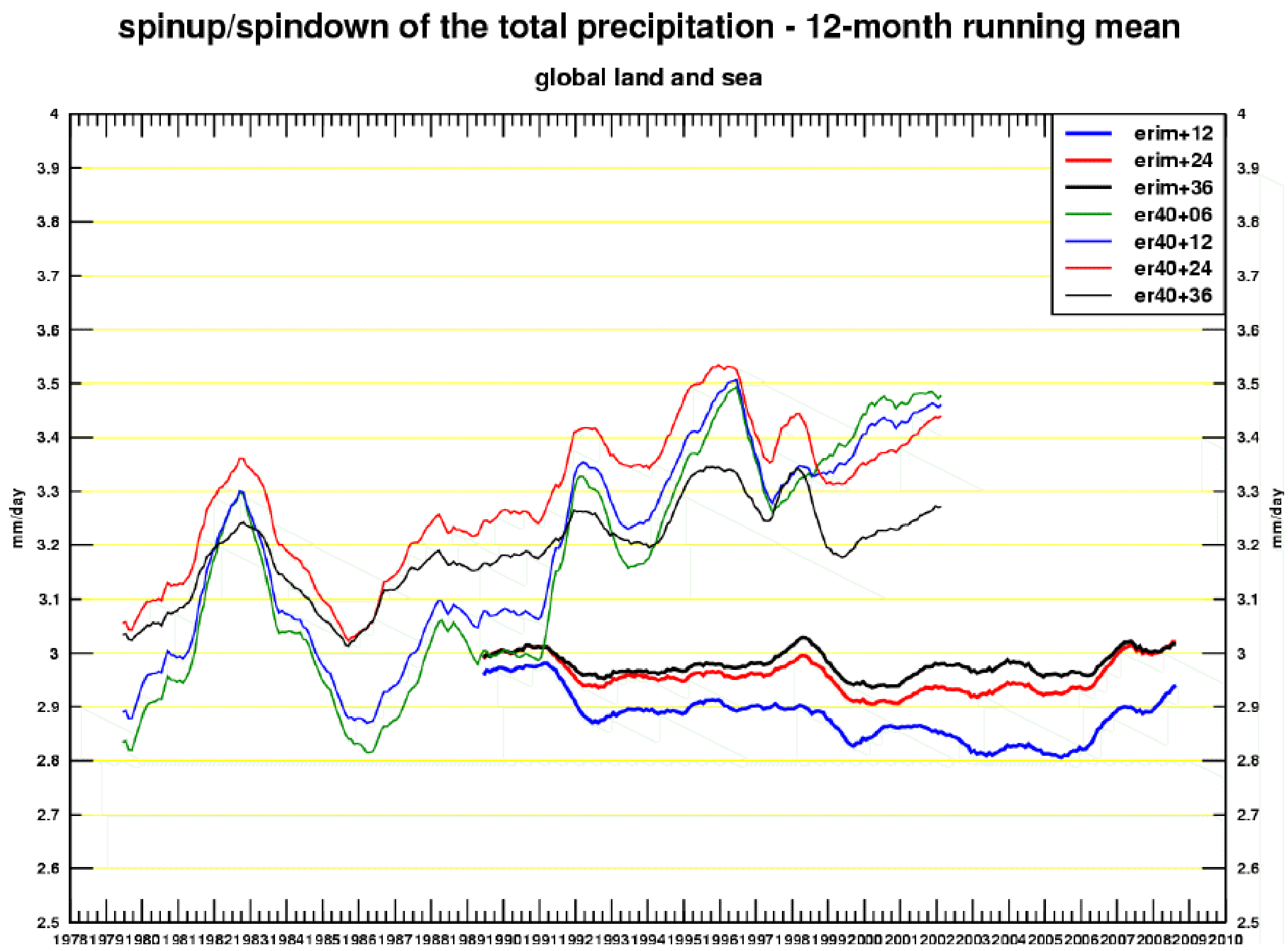
ERA group

ERA-Interim – ERA-40

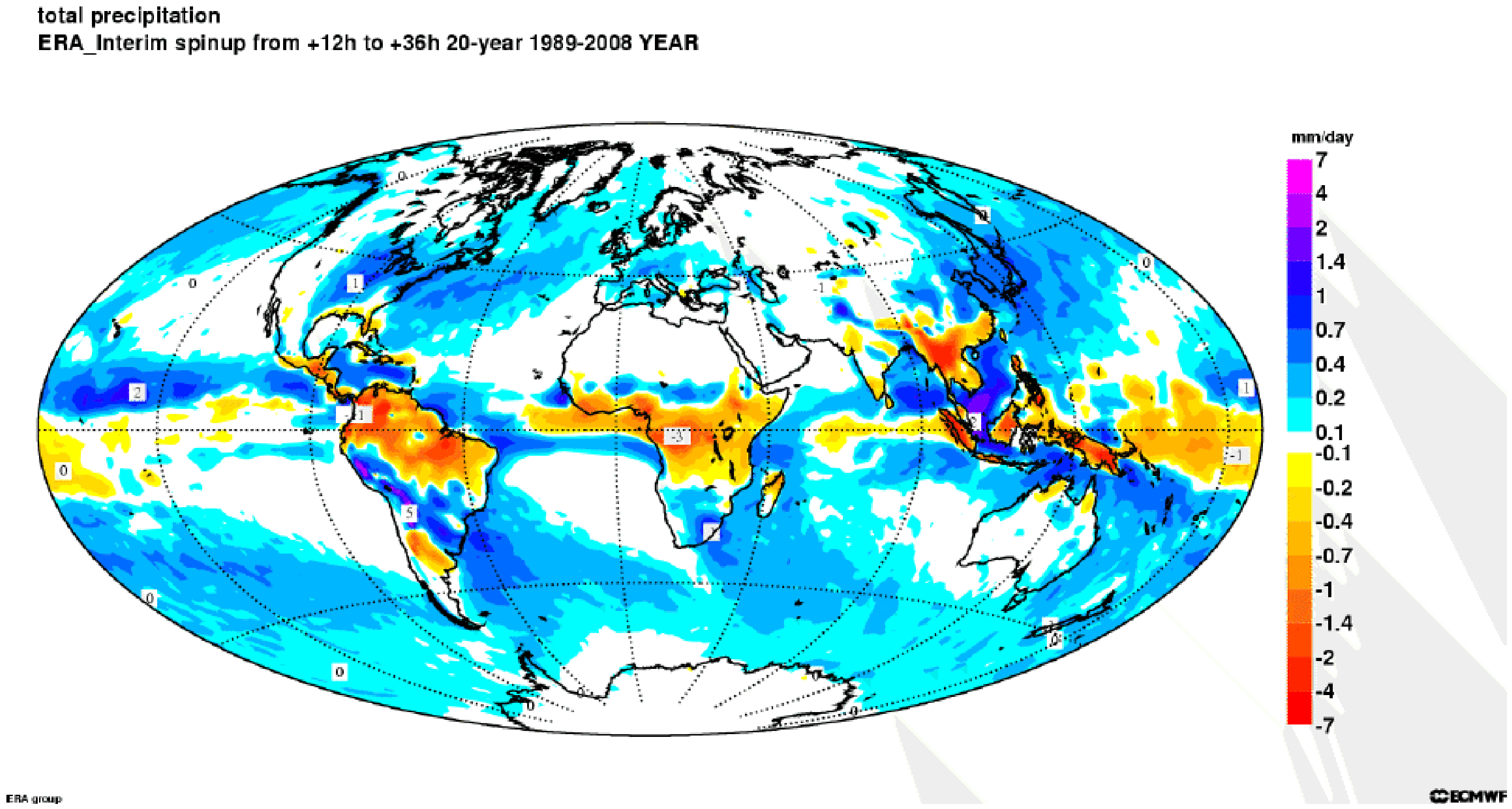


ERA group

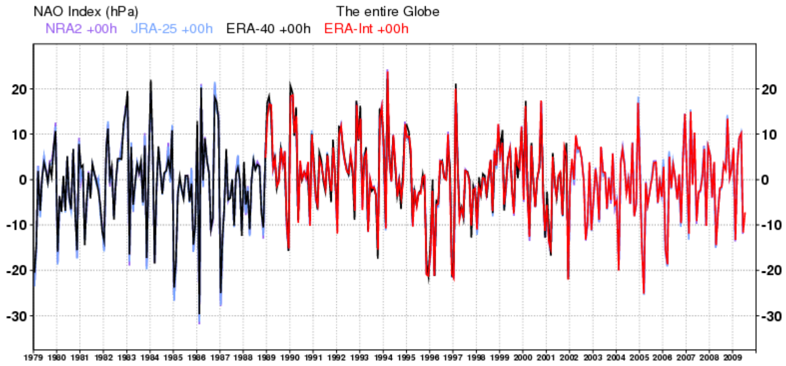
Precipitation spinup/spindown for ERA-40 and ERA-Interim

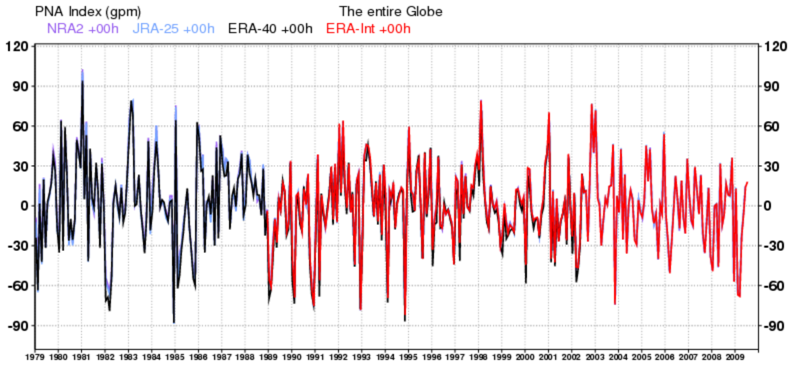


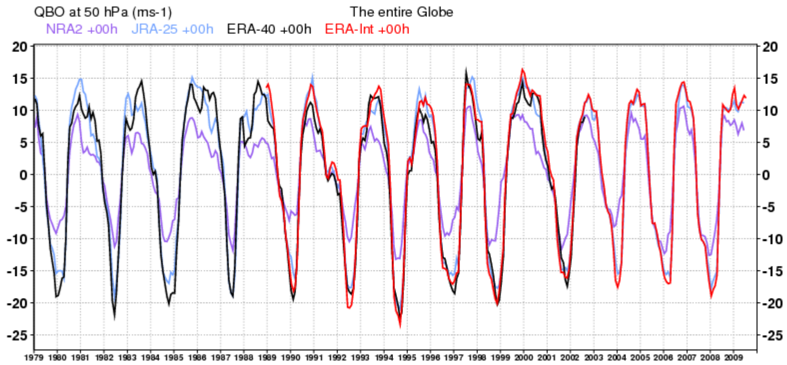
Precipitation spinup/spindown for ERA-Interim

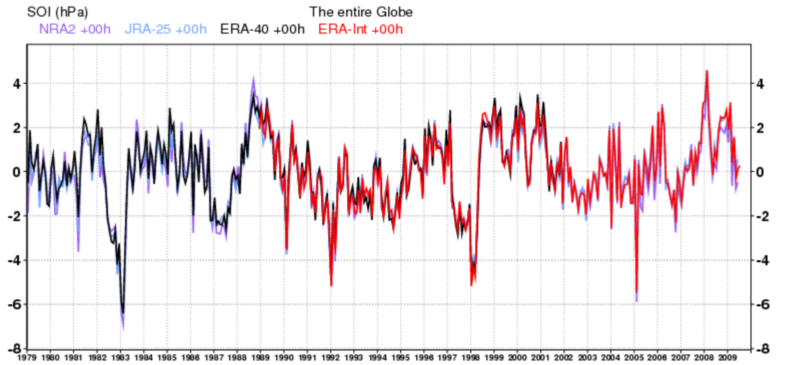


Climate indices



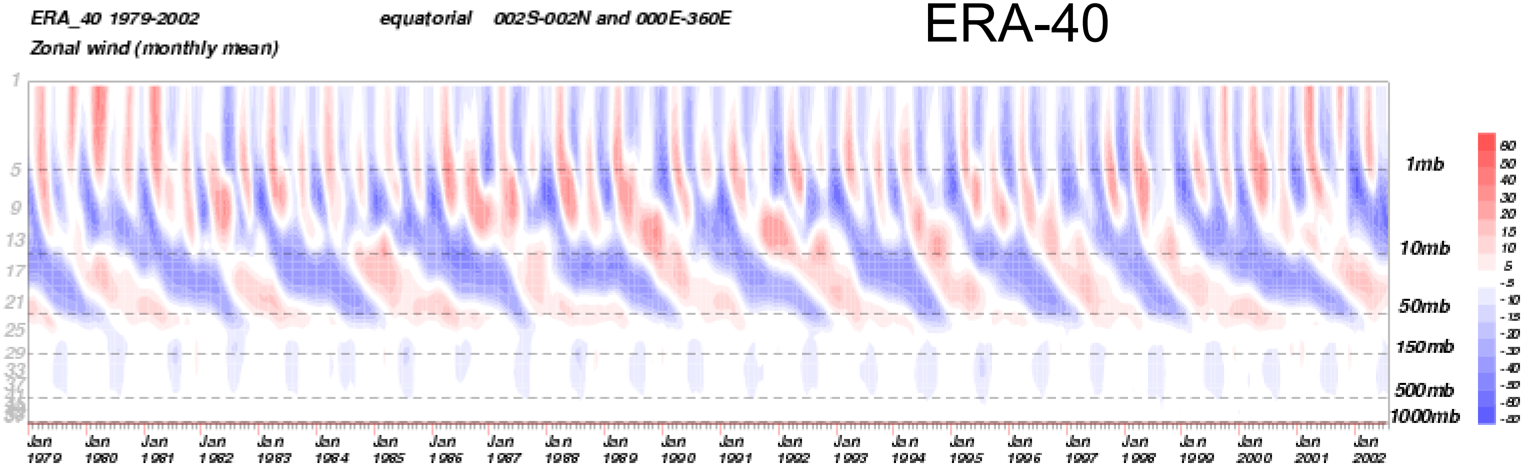




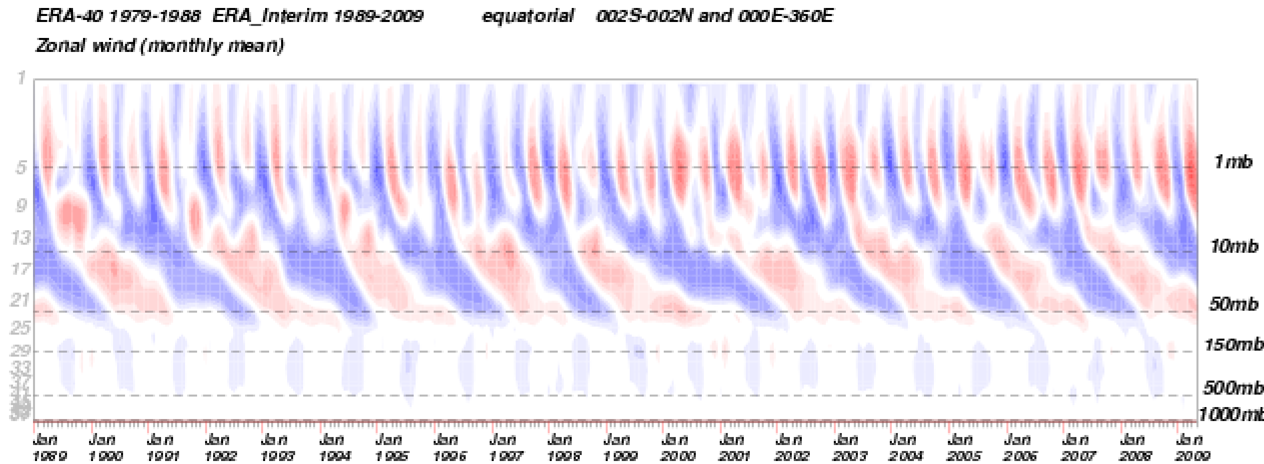


Stratospheric circulation: Representation of QBO

ERA-40



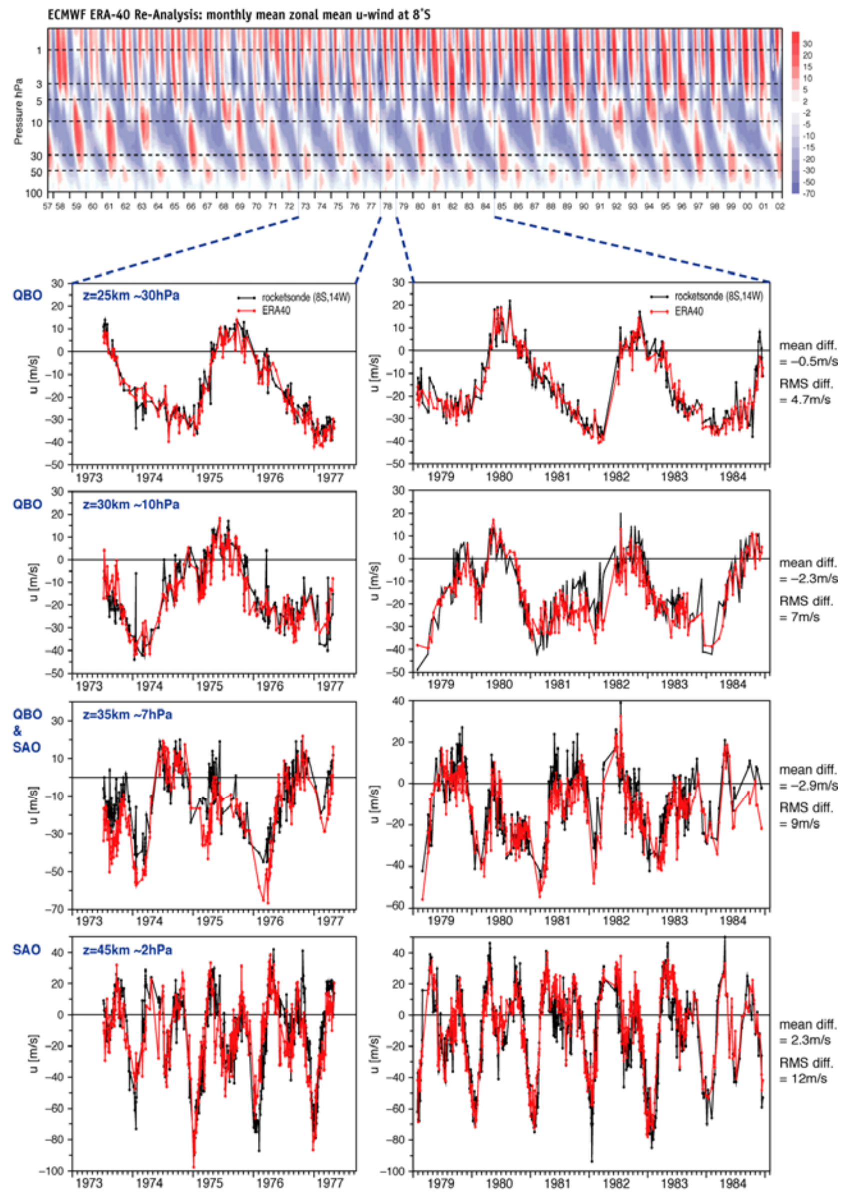
ERA-Interim



ERA-40 compared with rocketsondes

(A. Untch)

ERA-40 monthly mean zonal wind at 8S



25km

30km

35km

45km

QBO

SAO

Particle dispersion

Are stratospheric winds produced by data assimilation good enough for long-term transport calculations?

(Schoeberl *et al.* 2003)

Particle distributions after 50 days of backward kinematic trajectories using TOMCAT CTM

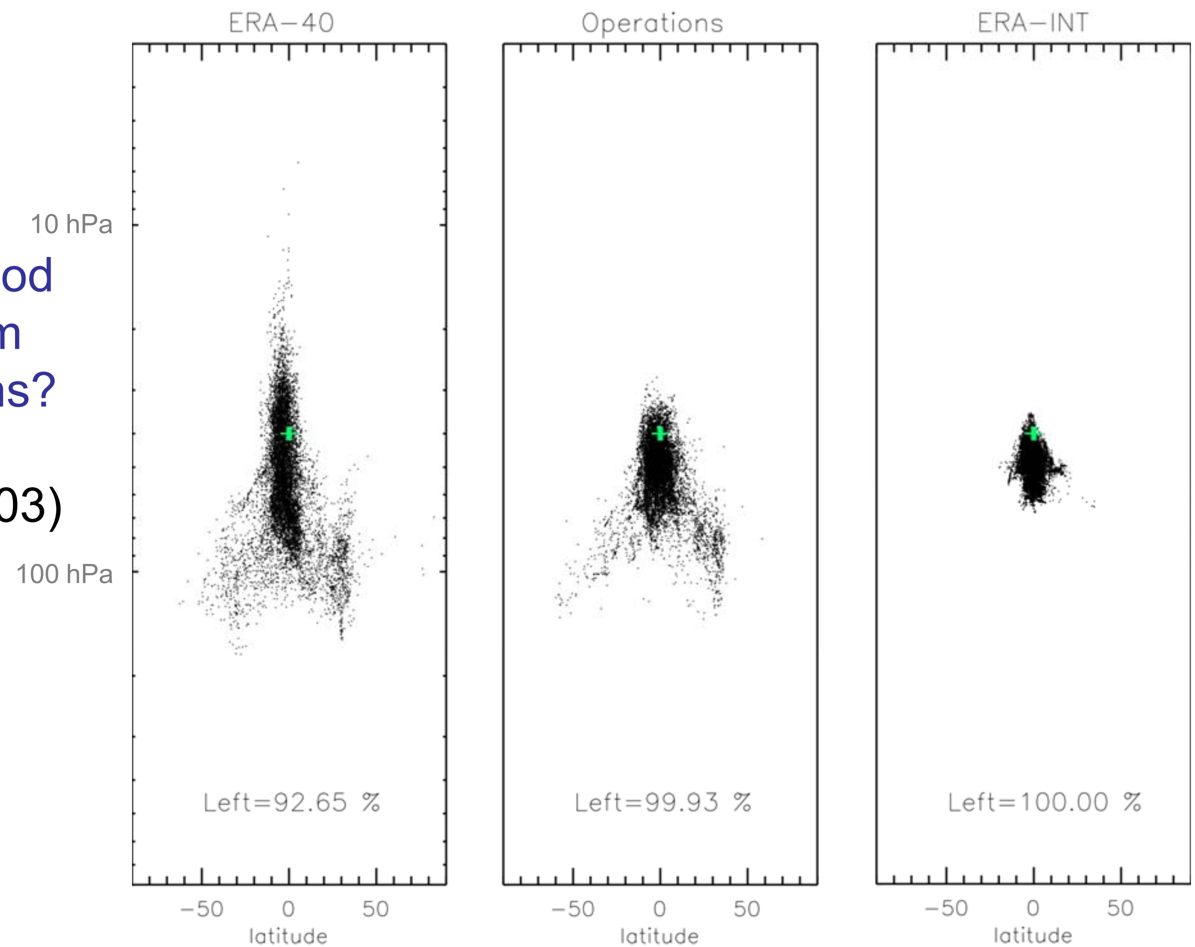


Figure updated from Monge-Sanz *et al.* 2007

Mean age of air in the lower stratosphere

Based on 20-year CTM runs, using reanalysed winds from ERA-40 and ERA-Interim

Observational estimates derived from ER-2 aircraft measurements of CO_2 and SF_6

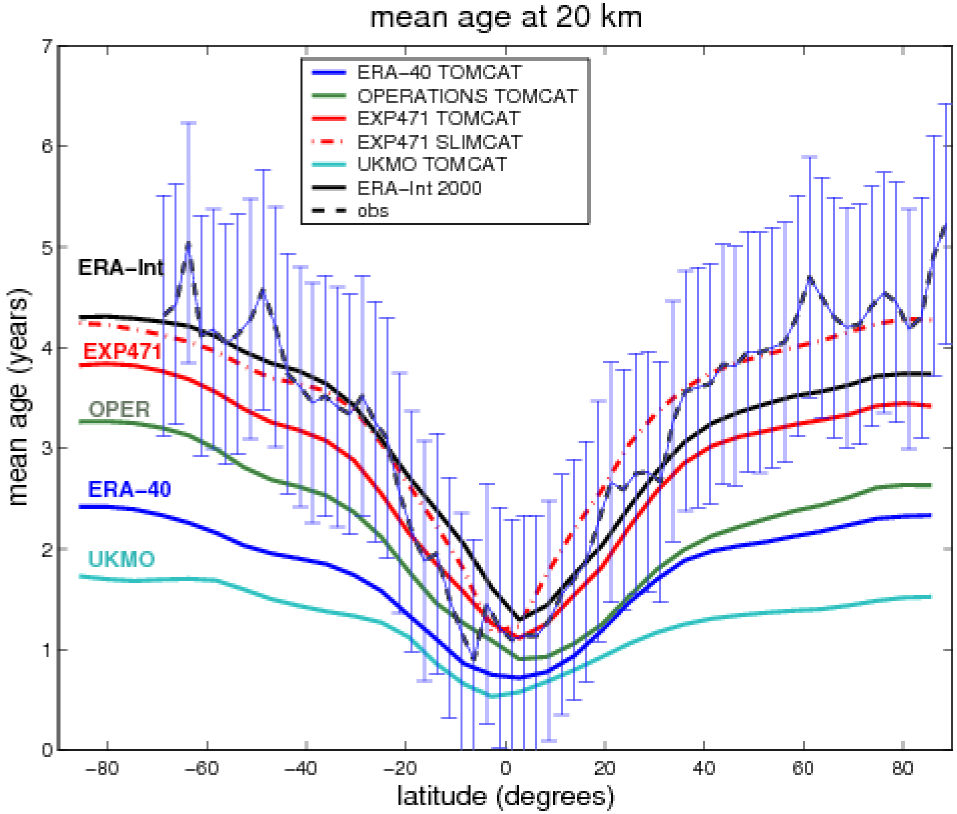
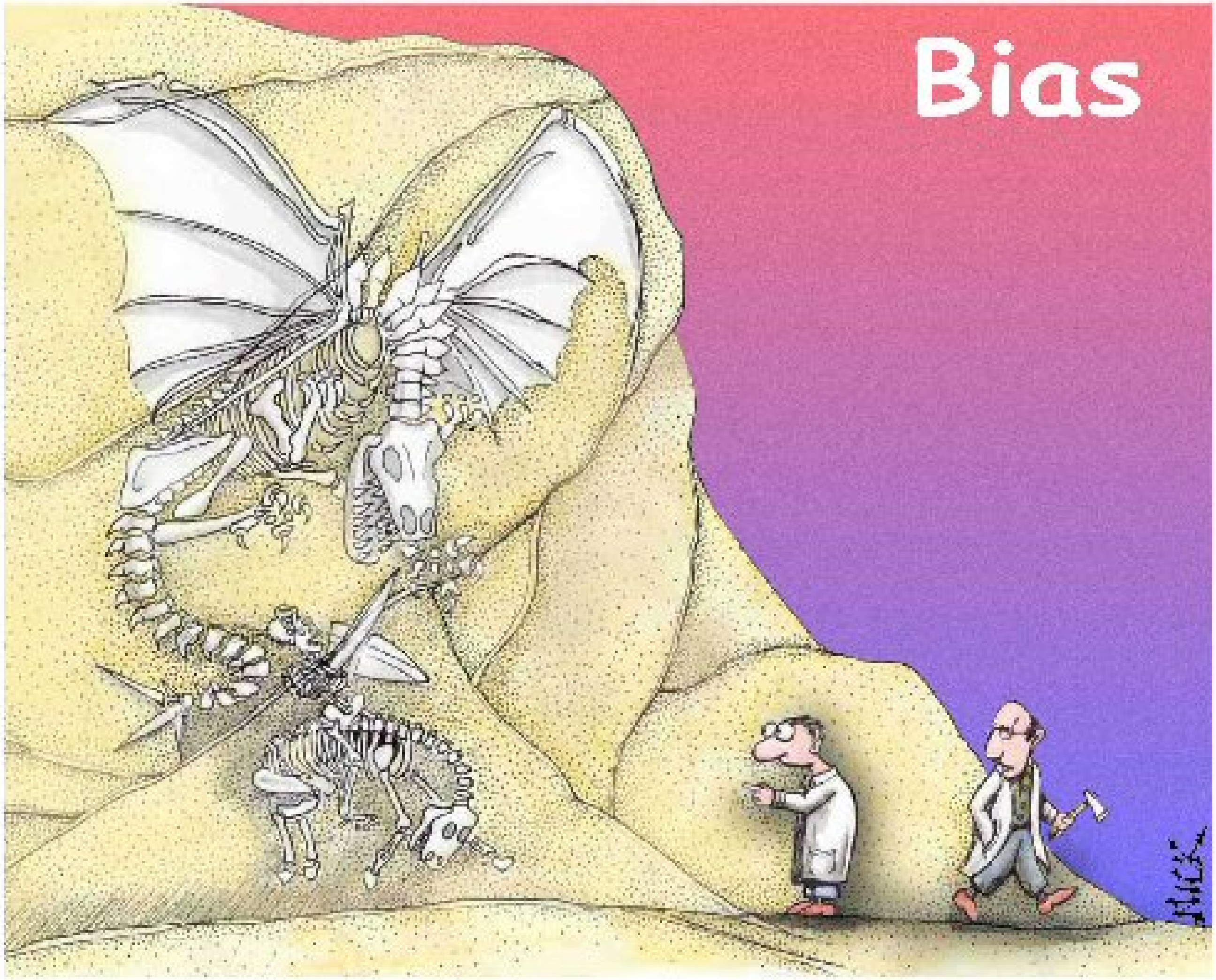


Figure updated from Monge-Sanz *et al.* 2007

Outline

- Introduction to reanalysis
  - The basic idea
  - Products and applications
  - Quality requirements
  - The observations
- Diagnostics
  - Fit to data, forecast quality
  - Mass, energy, and water
  - Stratosphere
- Biases and trends



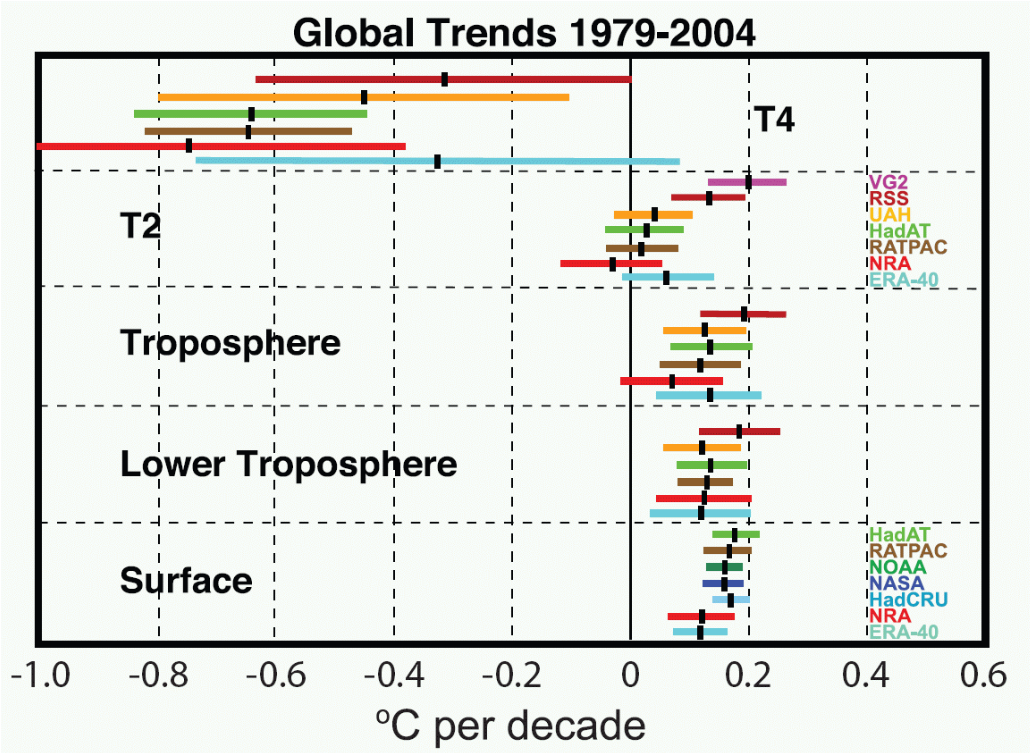
"Ignore it, Jeffries. It's unscientific."

Biases and trends

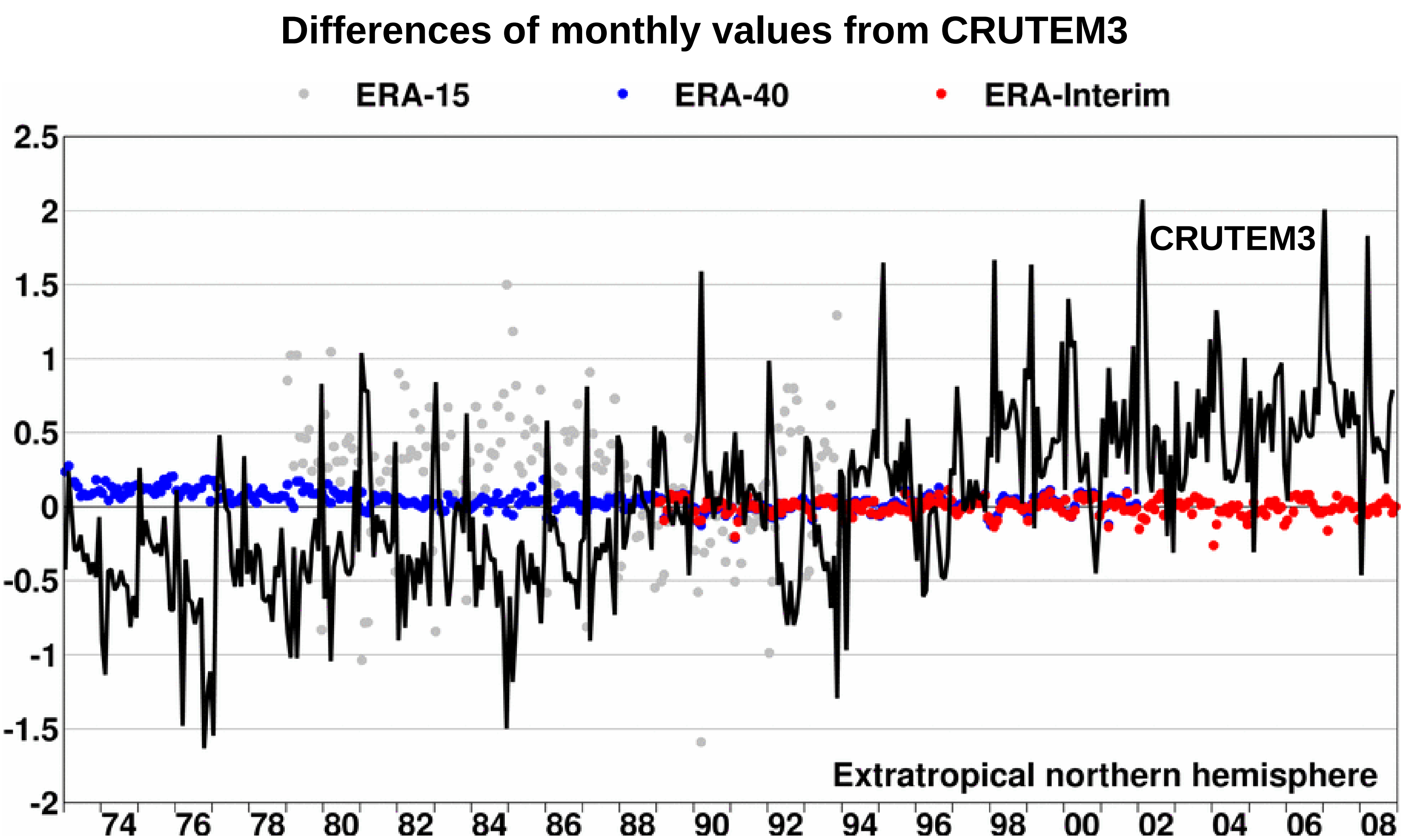
Reanalysis is considered unsuitable for trend estimation (IPCC AR4)

In theory, temperature trends from reanalysis should be superior

In practice, this requires dealing with biases in models and observations



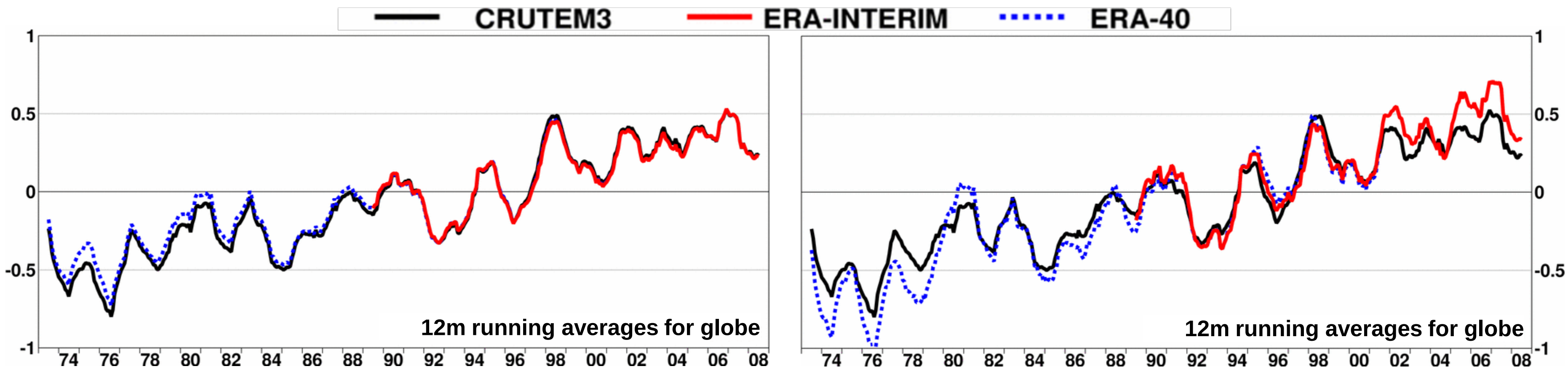
Time series of 2m land temperature anomalies (K)

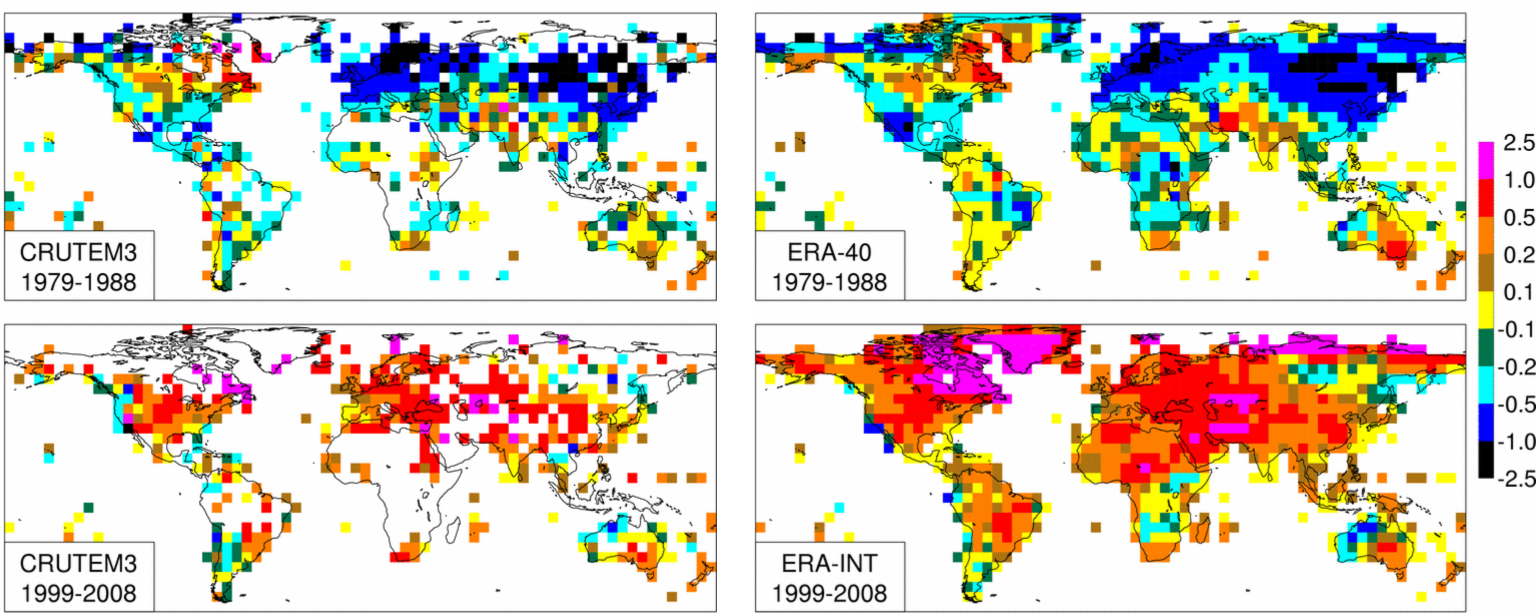


ERA sampled as CRUTEM3 (Brohan et al., 2006) following Simmons et al. (2004)

2m temperature anomalies (K) relative to 1989-1998

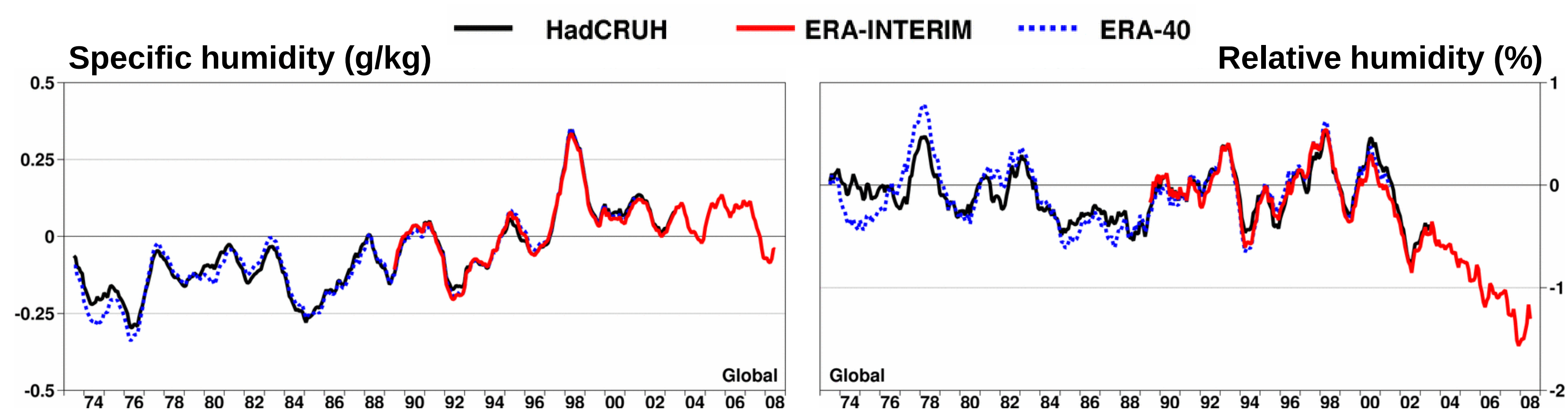
ERA sampled as CRUTEM3 (Brohan et al., 2006) | **ERA over land, not sampled**



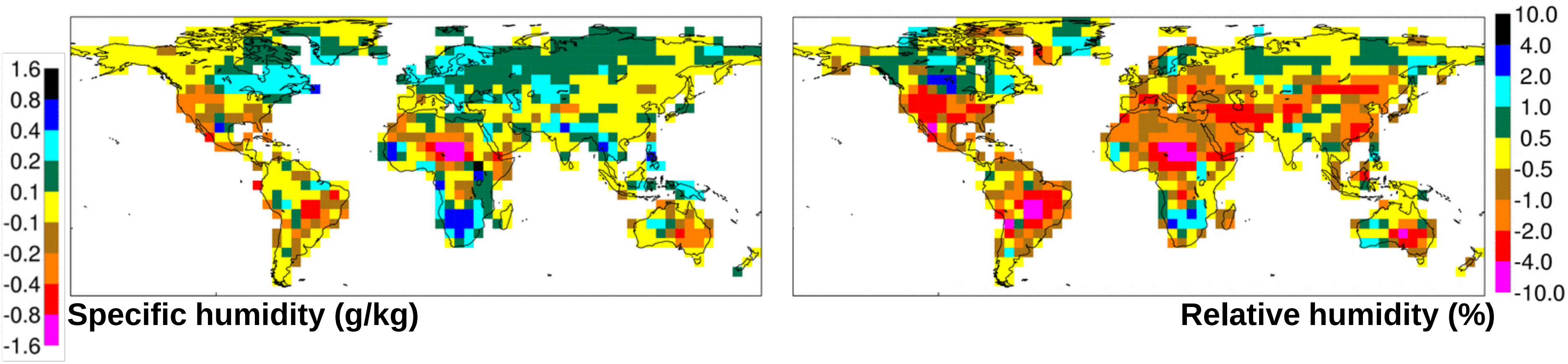


Time series of 2m land humidity anomalies

12m running averages, with ERA sampled over land as HadCRUH (Willett et al., 2008)



ERA-Interim: Difference between (1999-2008) and (1989-1998)

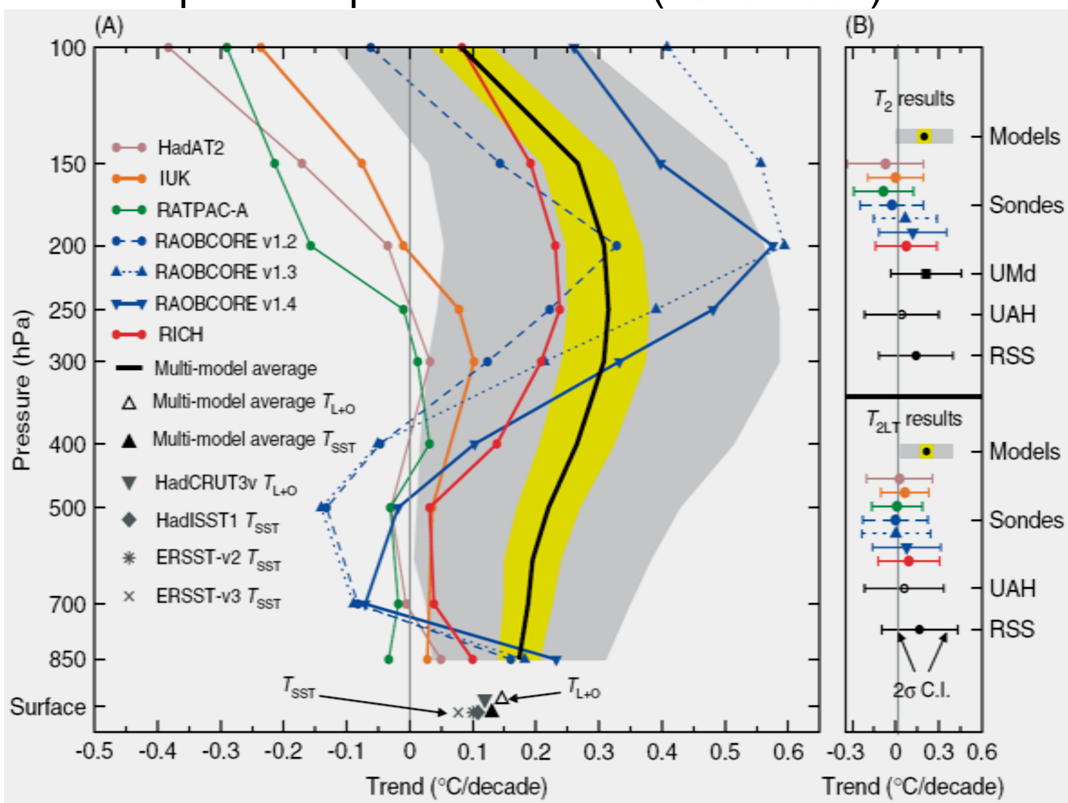


Simmons et al. 2009 (JGR, in press)

Can we do as well for upper-air trends in reanalysis?

Problem: There is no single true reference data set

Tropical temperature trends (1979-1999)



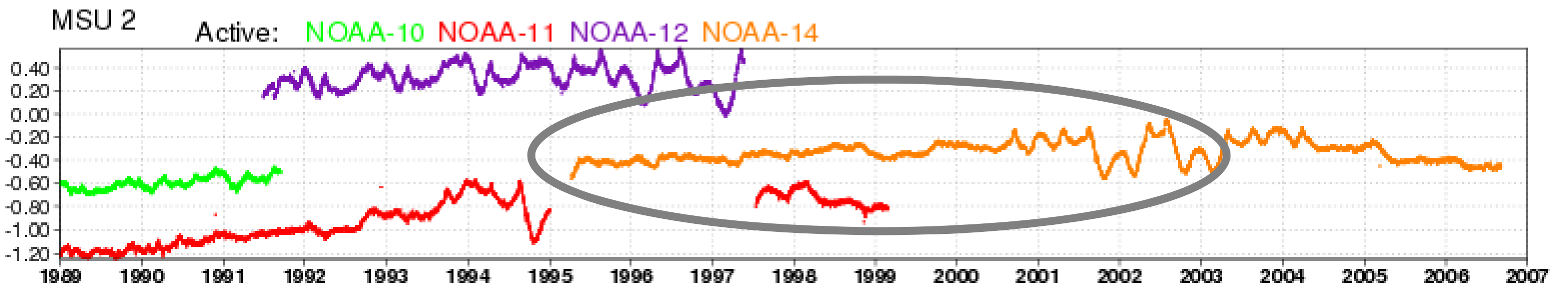
Santer *et al.* 2008, Int. J. Climatology

Reanalysis can be used to remove biases from observations

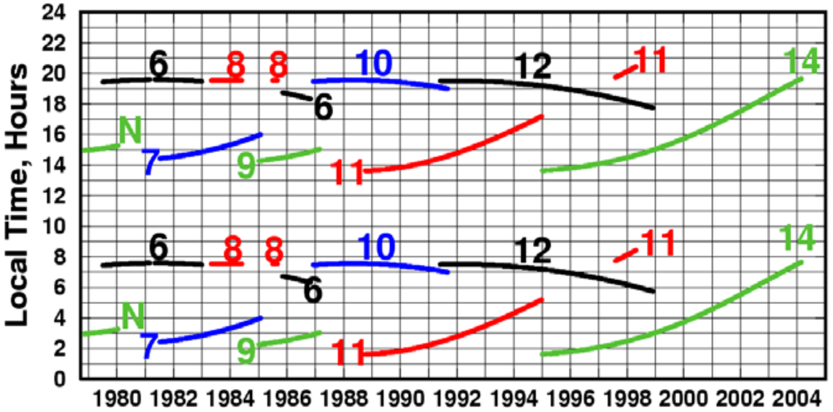
Variational bias correction of satellite radiances in ERA-Interim

Dee and Uppala 2009 (QJRMS, in press)

Global mean bias corrections for MSU channel 2 (lower troposphere)

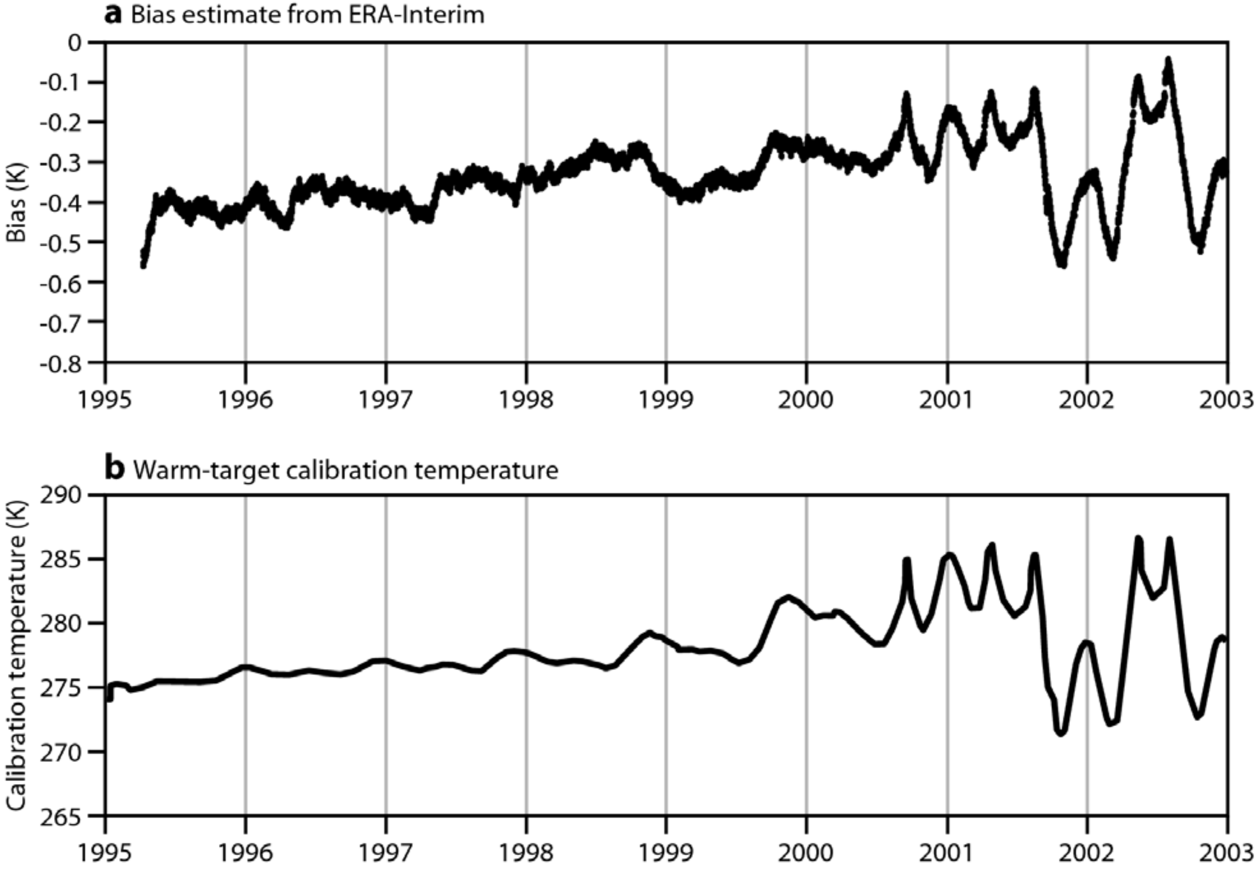


Equator crossing times for NOAA Polar Orbiting satellites



- Drift in polar orbit causes changes to the total heat budget of the satellite
- This affects instrument self-calibration

MSU instrument bias due to warm-target fluctuations



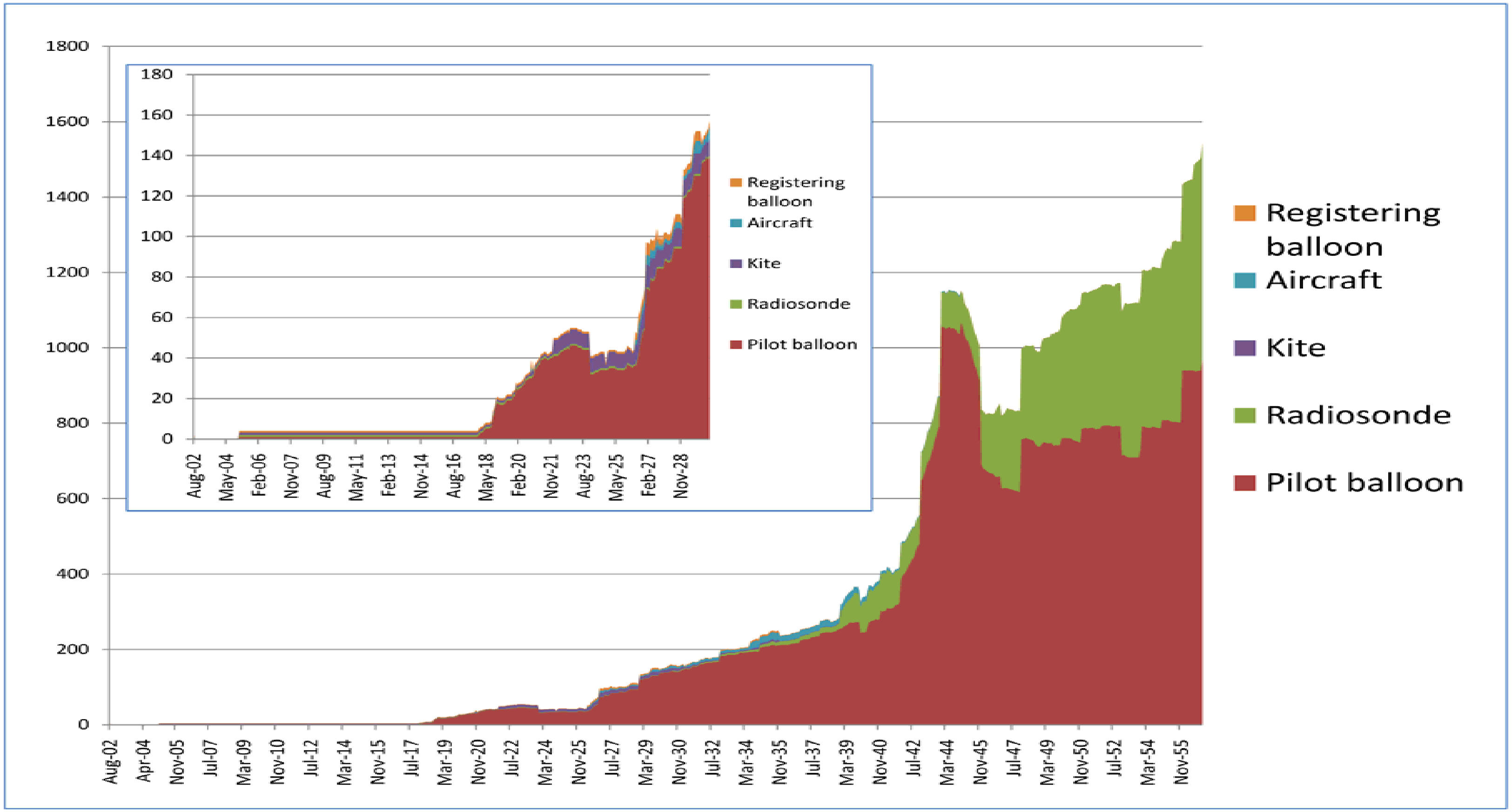
Variational bias estimates for NOAA-14

Actual warm-target temperatures on board NOAA-14 (Grody *et al.* 2004)

MSU instrument errors are identified based on all information available to the reanalysis

Upper-air observations pre-1957

The Comprehensive Historical Upper Air Network (CHUAN, Stickler et al. 2009)



Can we get *both* high accuracy *and* meaningful trend estimates?

Can satellite radiance data be anchored to radiosondes?

Control:

Assimilate surface pressure and radiosonde temperature data only

Experiment 1:

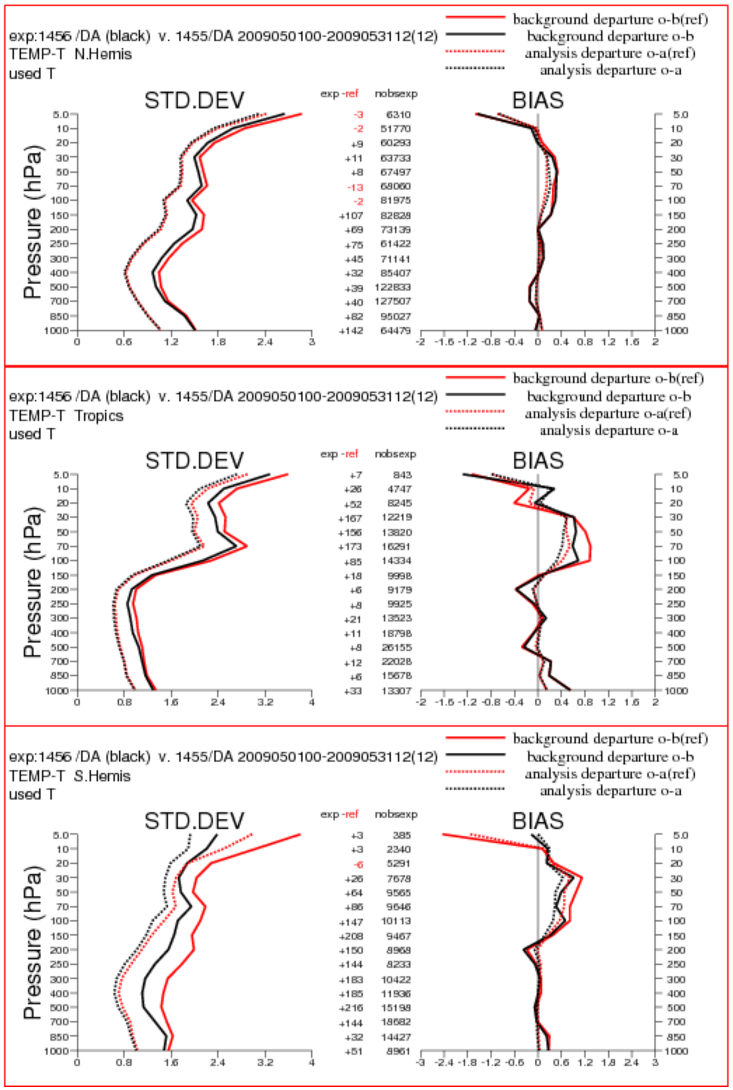
Add AMSU-A radiance data from a single satellite, subject to variational bias correction

Experiment 2:

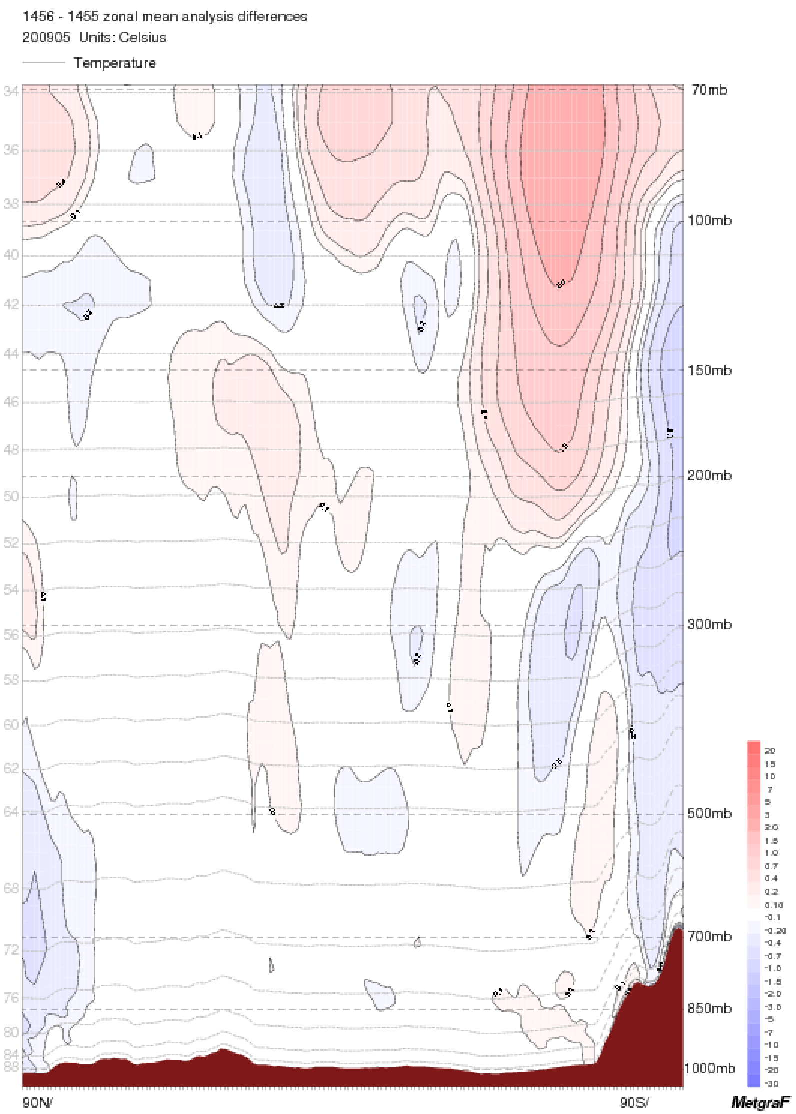
Add 4 more AMSU-A instruments

Experiment 1: A single AMSU-A instrument

Radiosonde departures

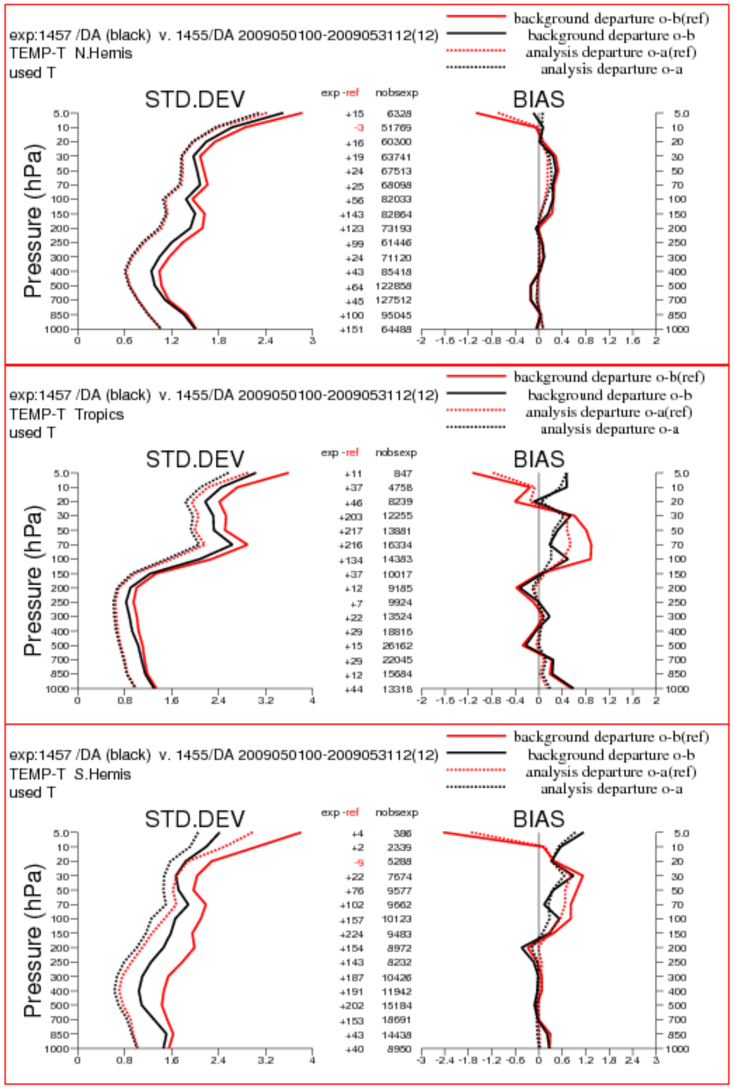


Mean analysis differences

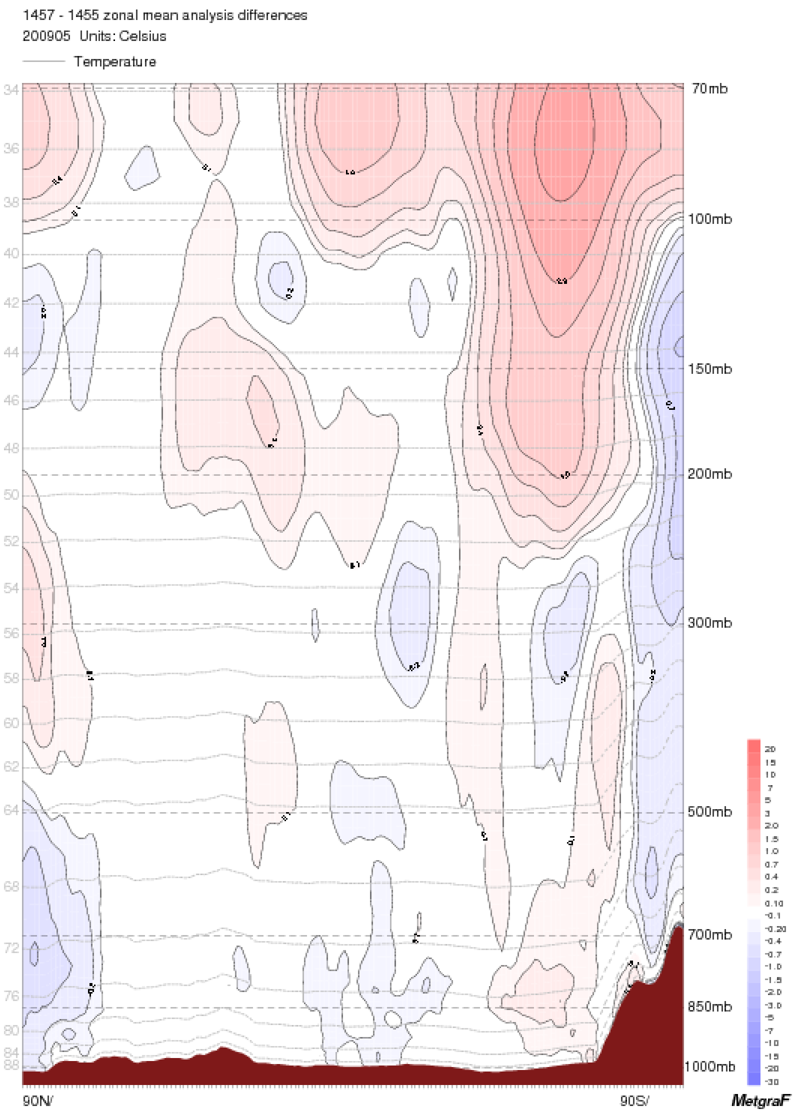


Experiment 2: Five AMSU-A instruments

Radiosonde departures



Mean analysis differences



Conclusions

- Historic observations are our most important resource for understanding the atmospheric circulation, predictability, and climate
- Reanalysis presents this information in an accessible and physically coherent form
- The major challenge in data assimilation for reanalysis is to properly manage changes in the observing system
- Accurate representation of climate signals and trends is the ultimate goal and the most difficult to attain
- We are learning how to do it..