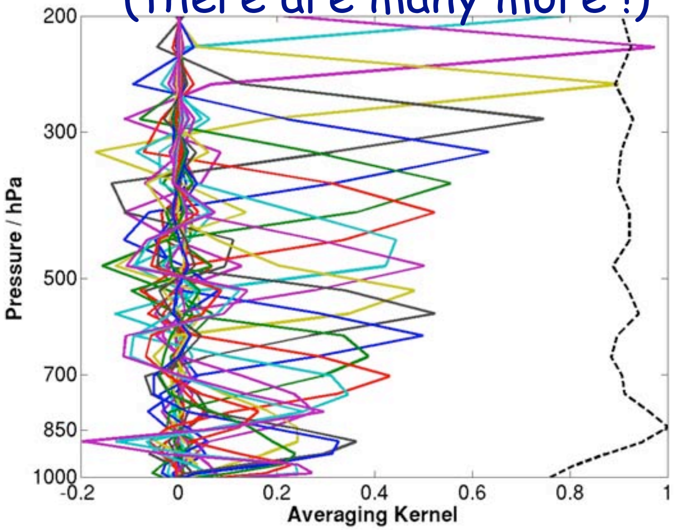
Observations 4: 4D-Var continued / Reanalysis

OUTLINE:

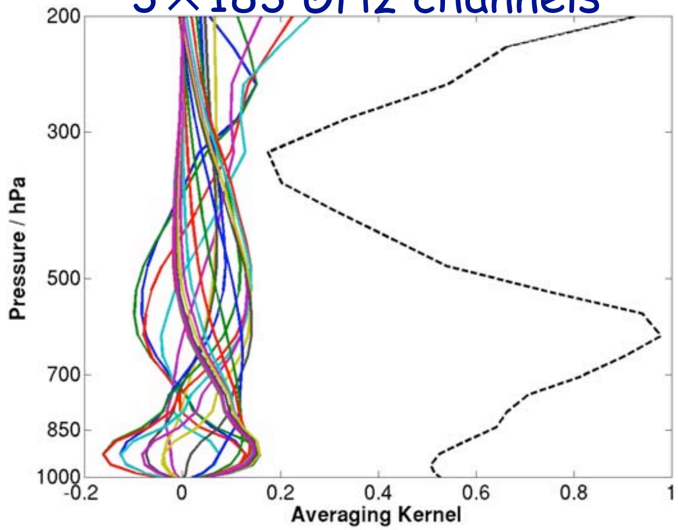
- IR vs MW impacts
- 4D-Var : Minimising the cost function
  - Example: Adjoint calculation for cloudy radiance assimilation
- Reanalysis

A comparison of moisture increments from MW vs IR

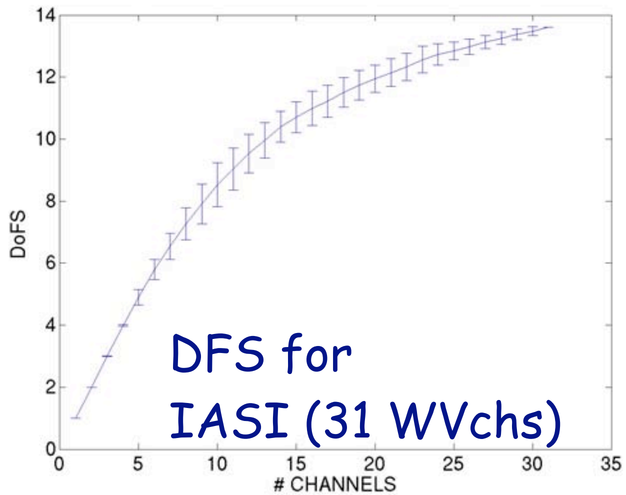
IASI – 31 WV channels
(there are many more !)



SSMIS SSMI-like channels +
3×183 GHz channels



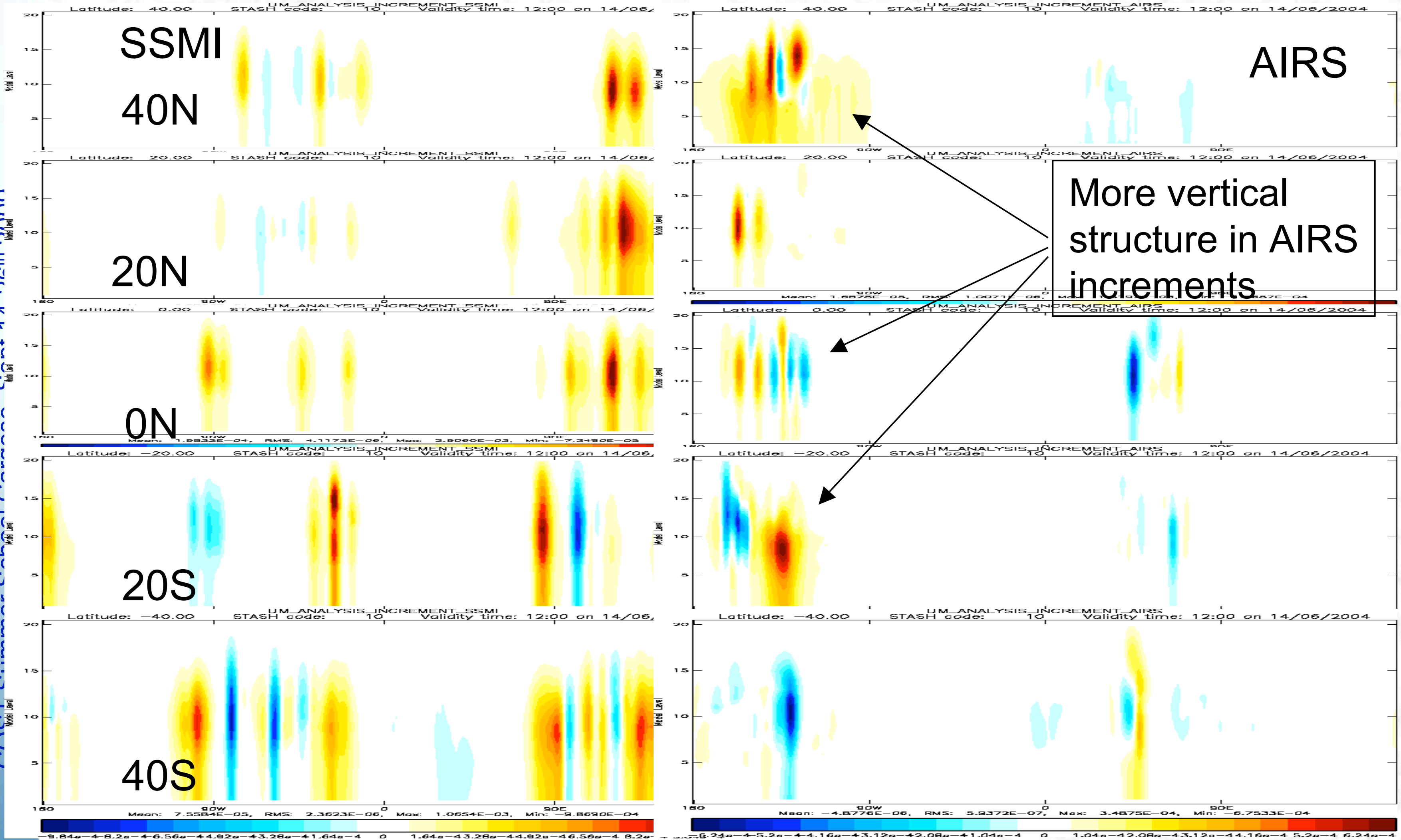
Averaging kernels
computed from
H, B and R matrices.
See Rodgers (2000)
- 'PSF' of retrievals



DFS for
IASI (31 WVchs)

cf SSMIS DFS ~ 6

A comparison of moisture increments from MW vs IR

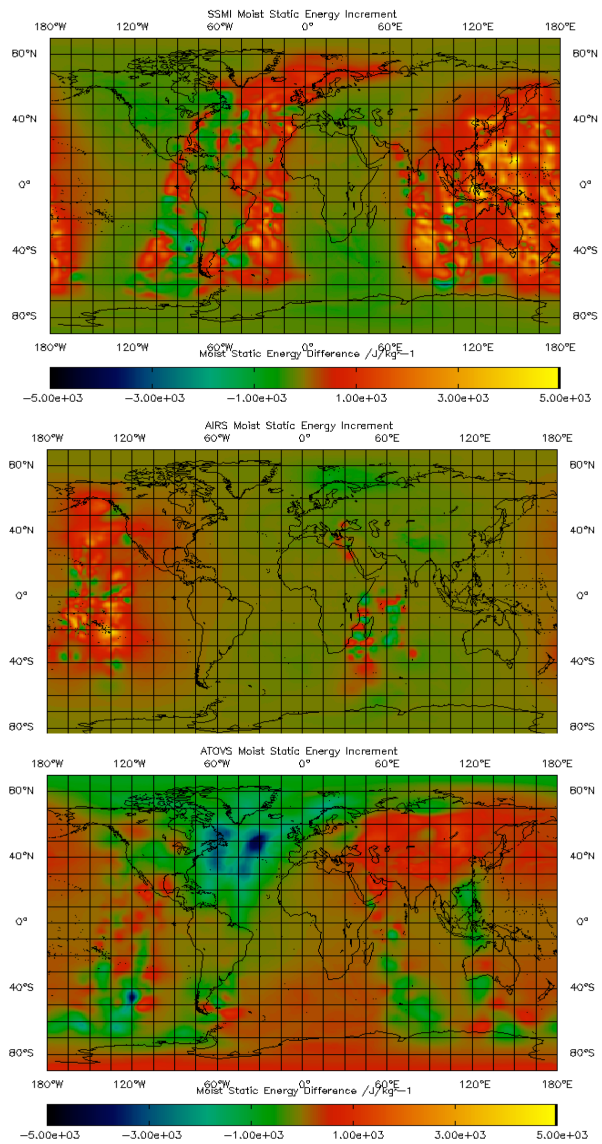


A comparison of MSE increments from MW vs IR

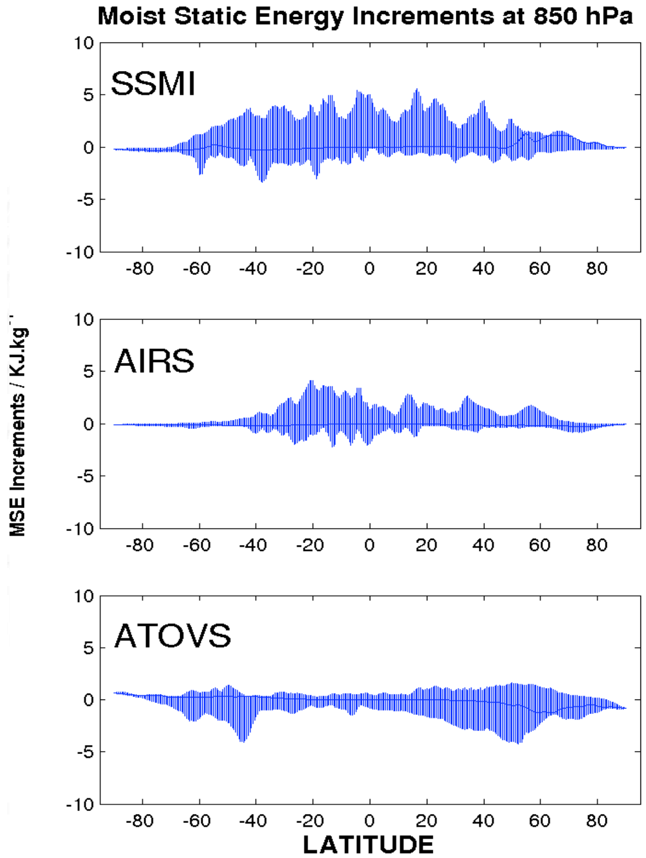
SSMI

AIRS

ATOVS



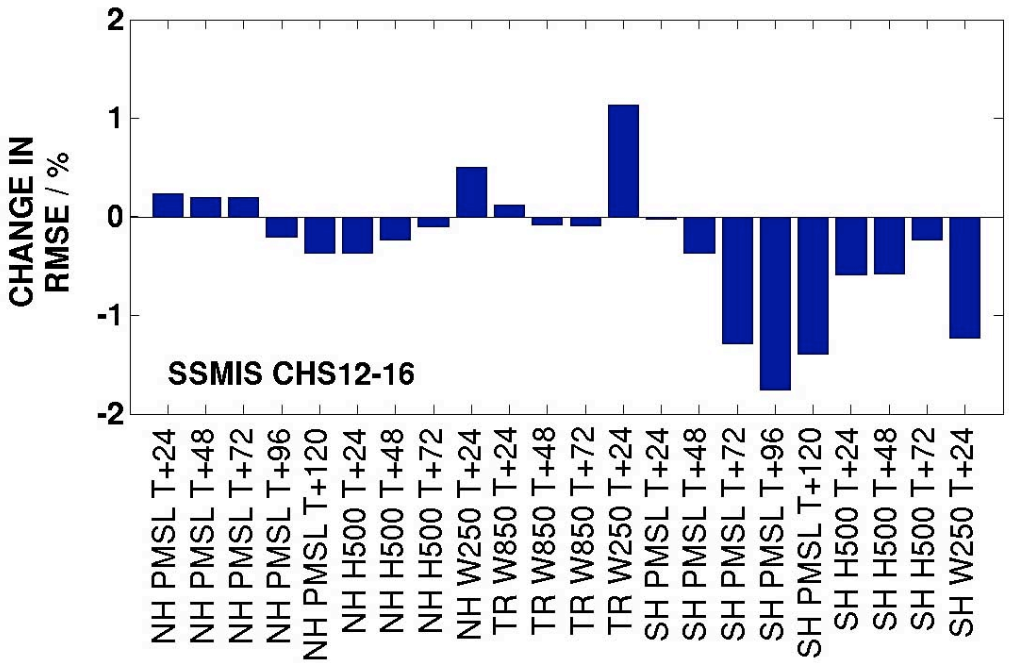
Moist Static Energy:



SSMI adds large 'energy' increments

The Impact of SSMIS window (SSMI-like) channels in NWP

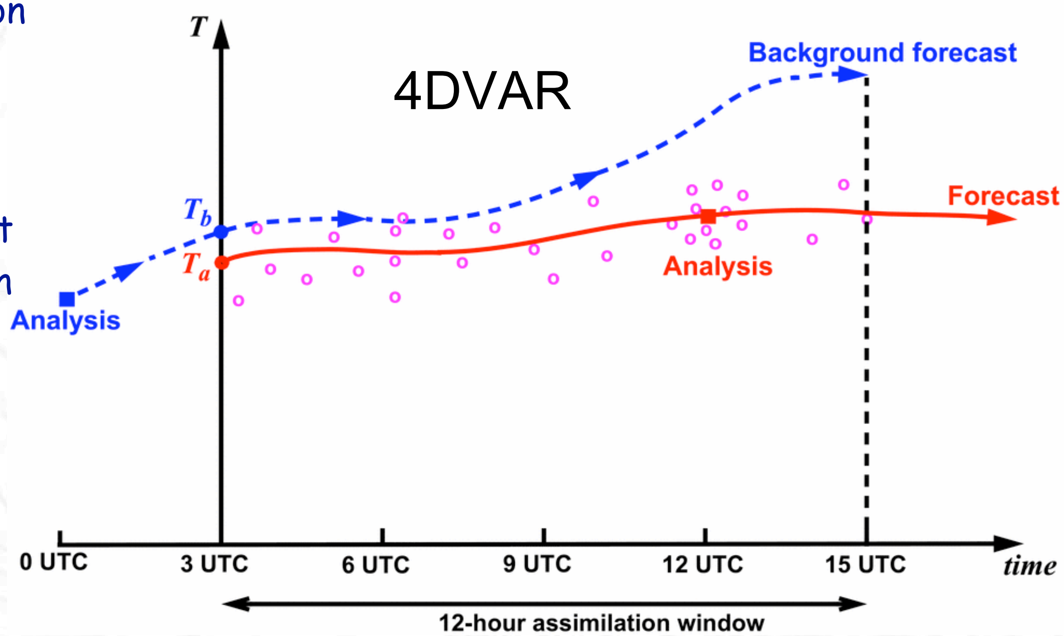
Met Office Global Model



Data Assimilation: 4D-Var

Data assimilation combines information from

- Observations
- A short-range "background" forecast that carries forward the information extracted from prior observations
- Error statistics
- Dynamical and physical relationships



This produces the "most probable" atmospheric state (maximum-likelihood estimate)***

***if background and observation errors are Gaussian, unbiased, uncorrelated with each other; all error covariances are correctly specified; model errors are negligible within the 12-h analysis window

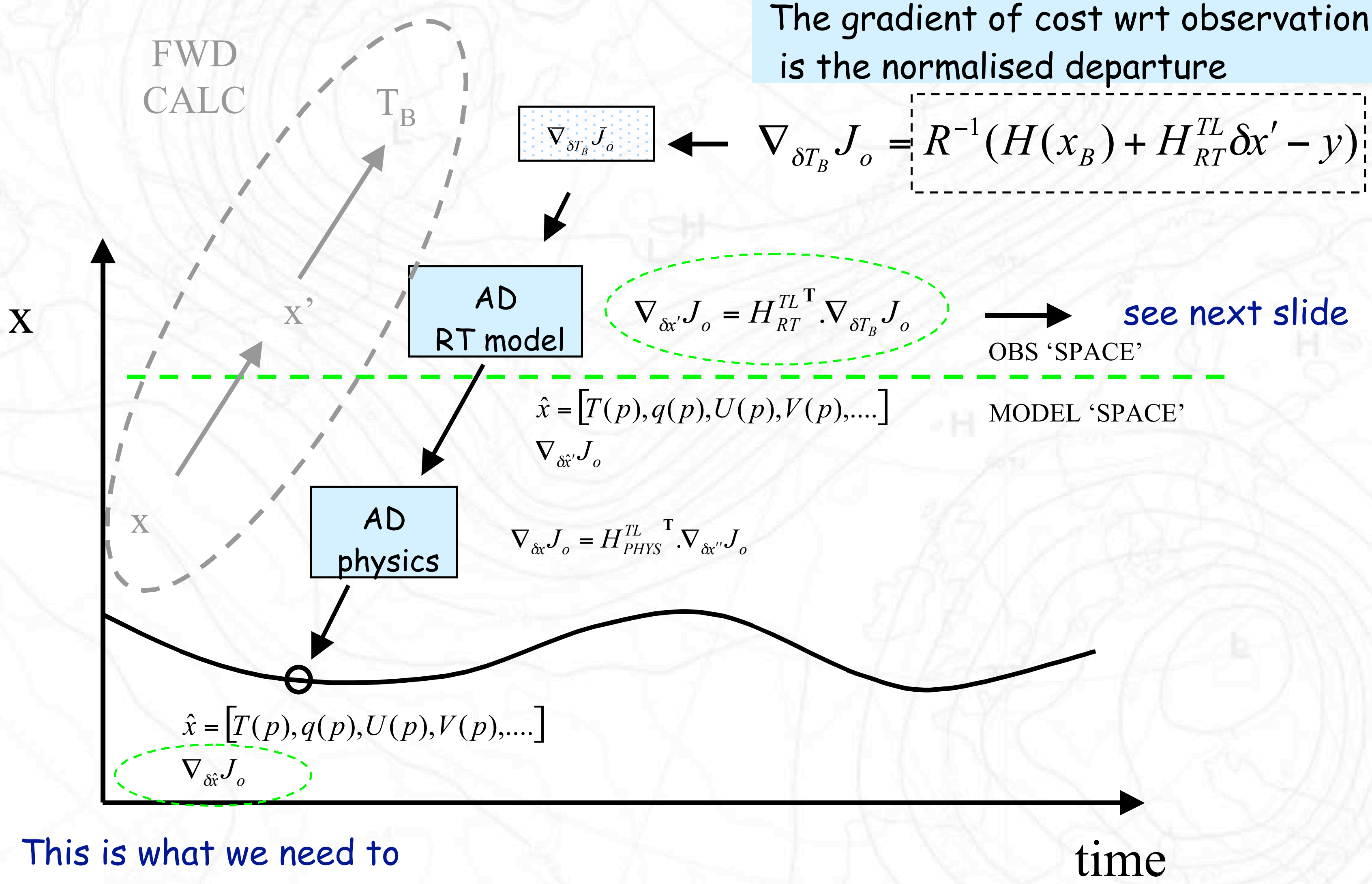
background constraint — observation constraint

$$J(\mathbf{x}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}^{-1} (\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1} [\mathbf{y} - \mathbf{h}(\mathbf{x})]$$

$$\mathbf{h}(\mathbf{x}) = \mathbf{h}[M(\mathbf{x})]$$ simulates the observations

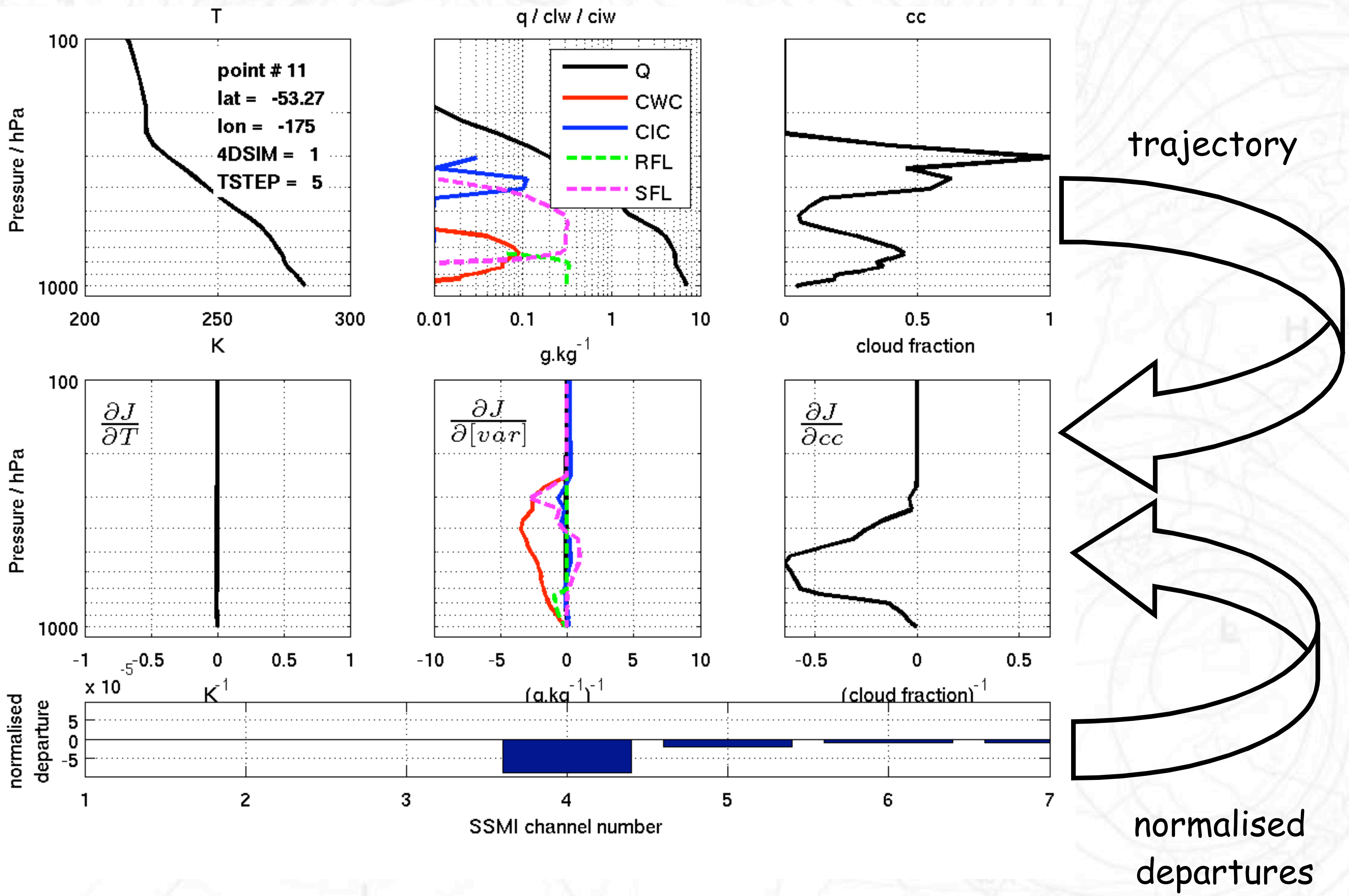
Cloudy & Precipitating Radiance Assimilation: Adjoint Calculation

The gradient of cost wrt observation is the normalised departure



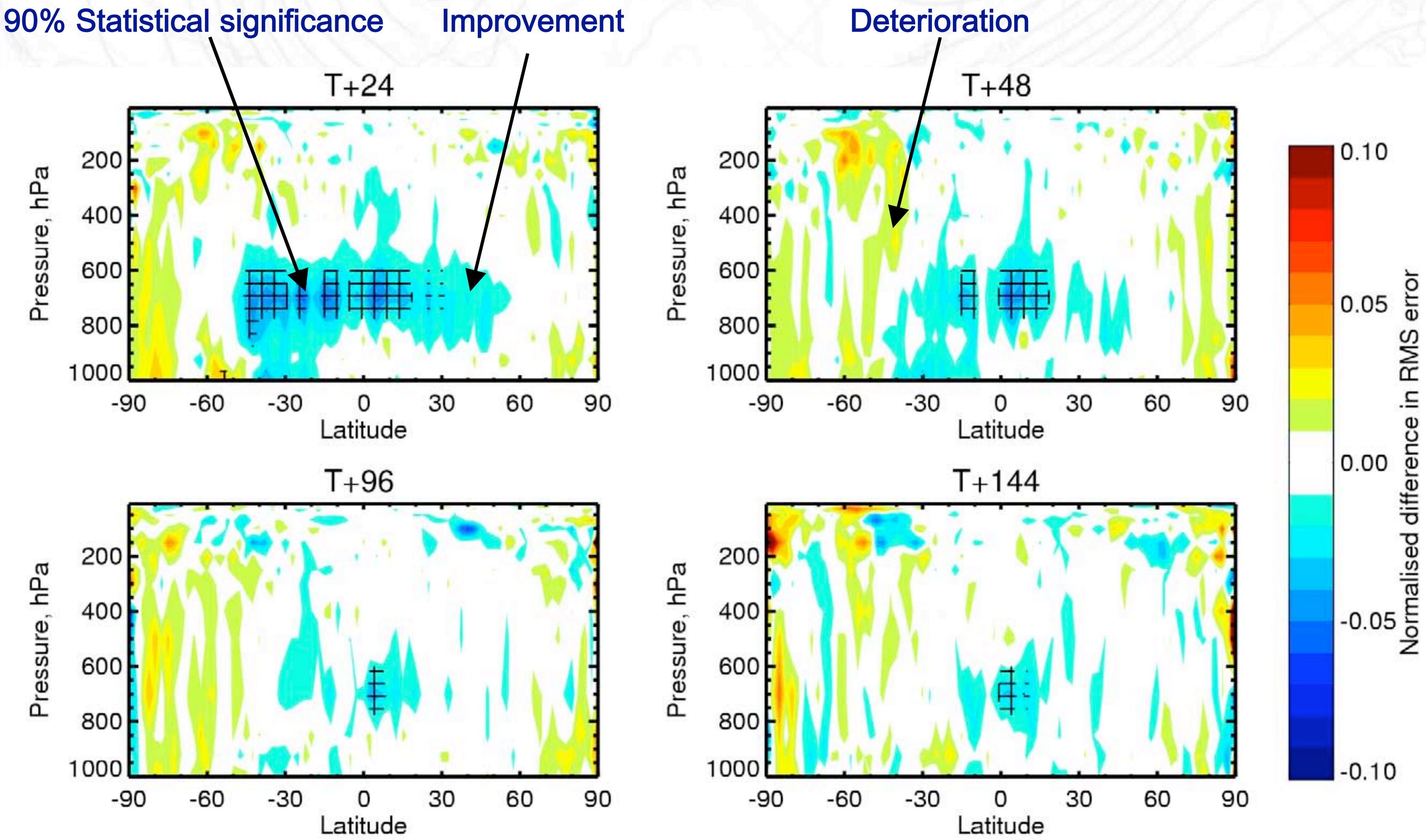
This is what we need to minimise the cost fn

RT Adjoint calculation : an example

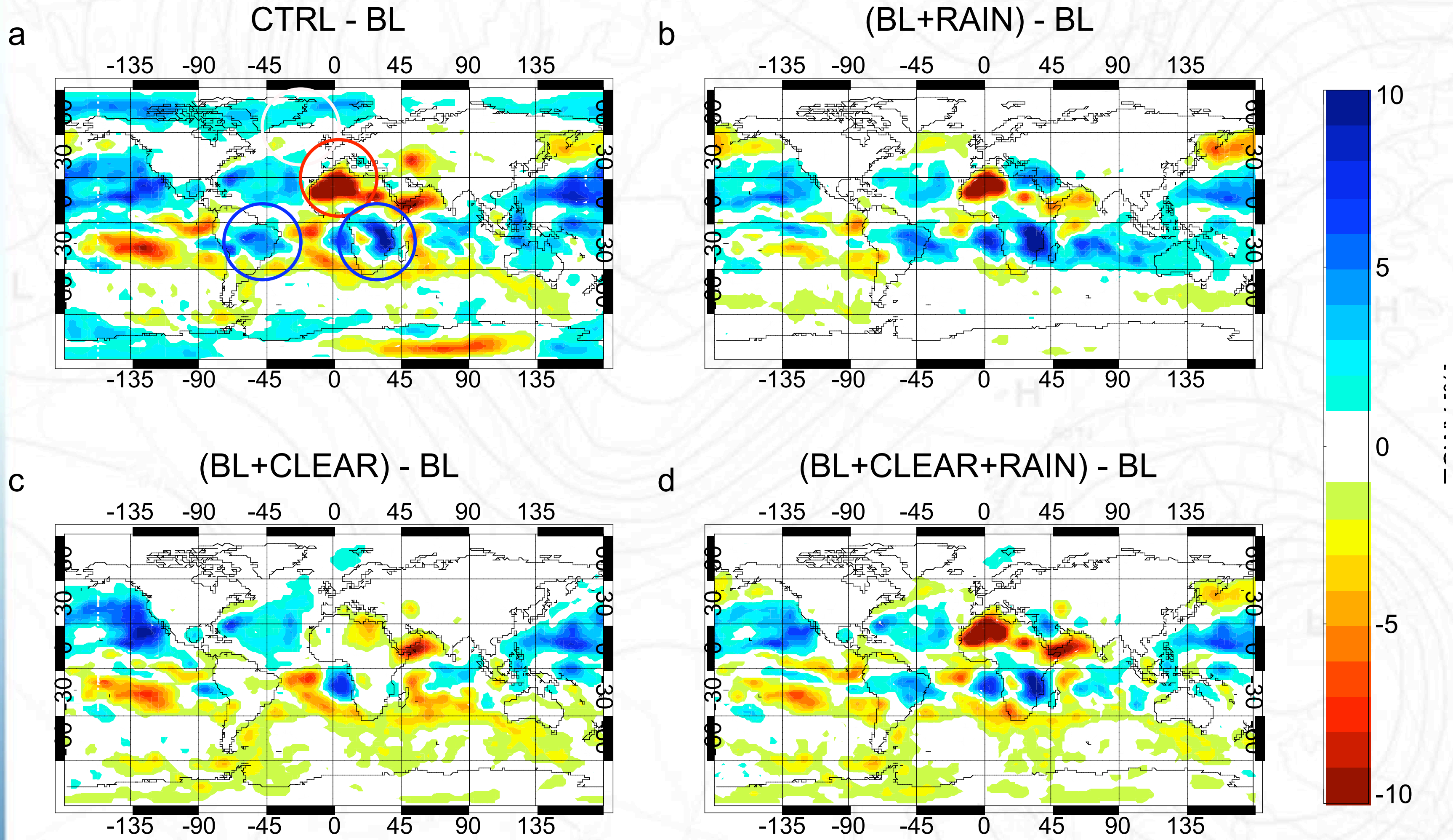


Mean Relative Humidity Forecast Score Difference 08-10/2004

Improvements in RMS forecast errors between "Rain" and "No Rain" experiments

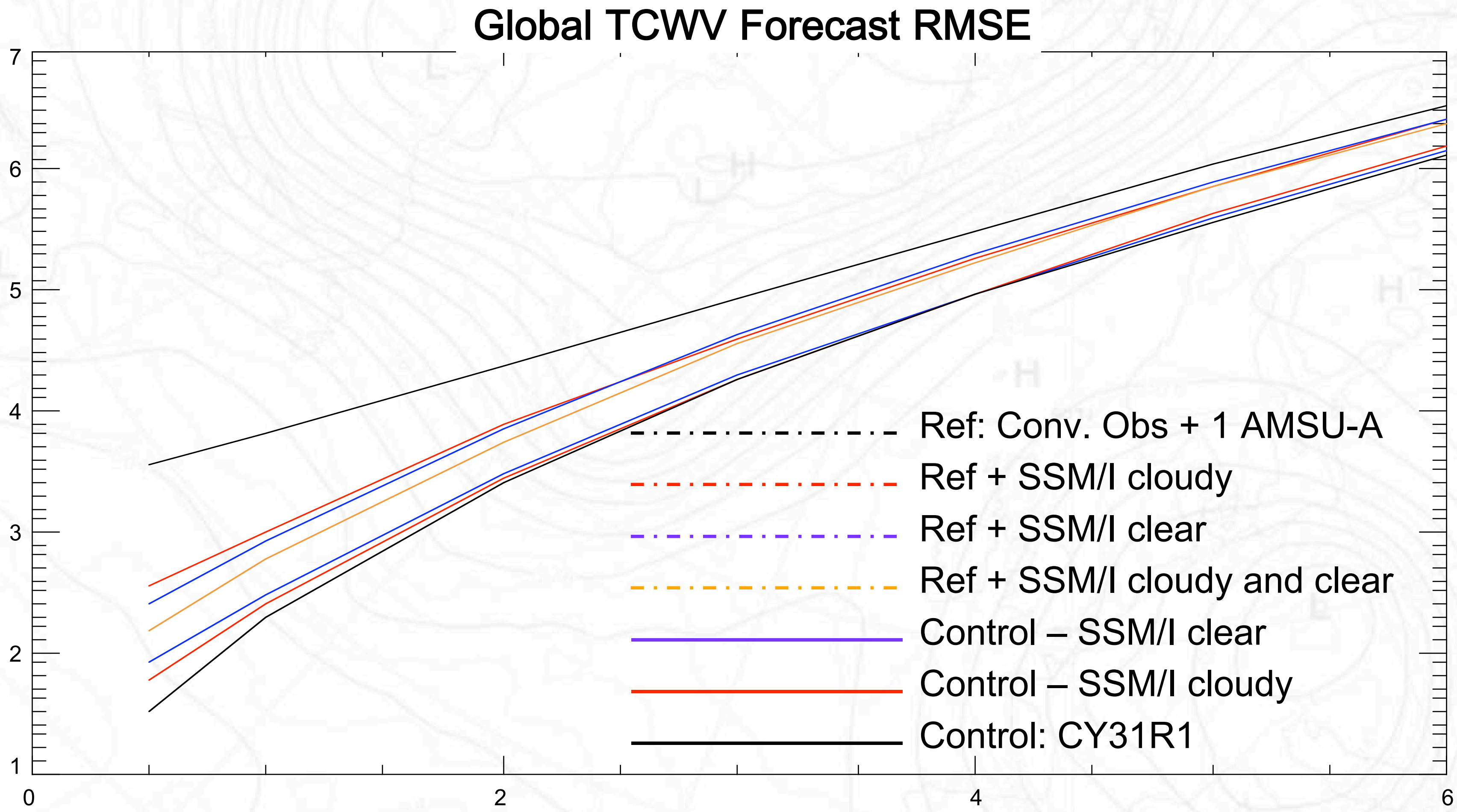


Dependence of moisture climate (TCWV) on satellite data usage



The impact of SSMI window channel radiance assimilation

ECMWF global model

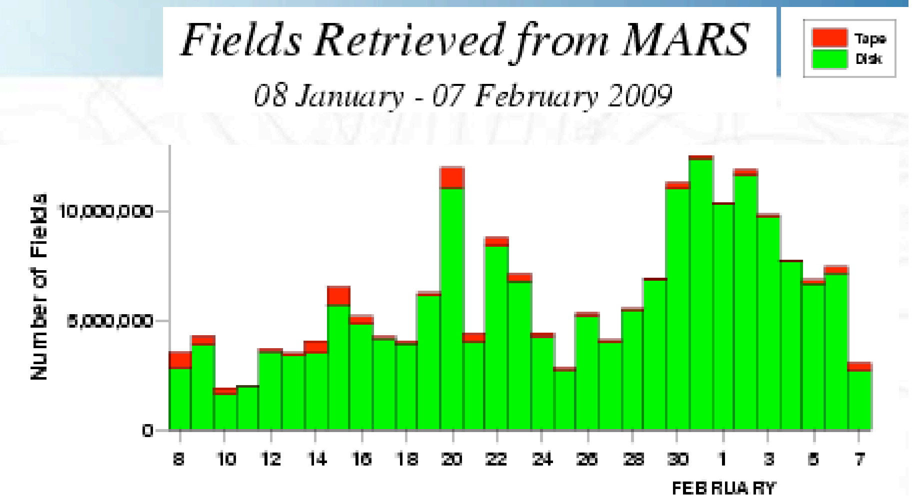


- **Rain assimilation operational since June 2005 at ECMWF with SSM/I data over global oceans**
- ***Observing System Experiments (OSE) for summer 2006 (Kelly et al. , EUMETSAT support)***

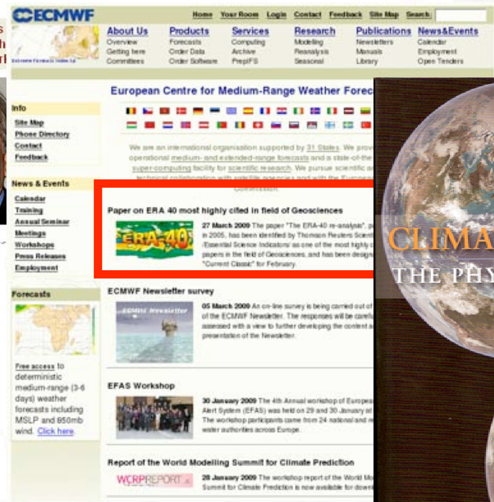
REANALYSIS

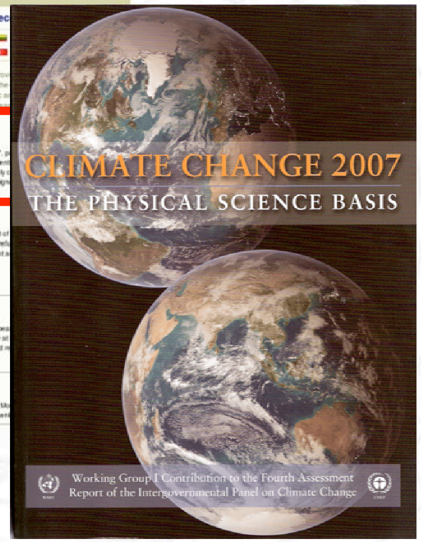
Atmospheric reanalysis: The user base

- Many users:
  - 12000 registered users of ERA public data server
  - _5M fields retrieved daily by ECMWF and Member-State users
  - National mirror sites for ERA in many countries

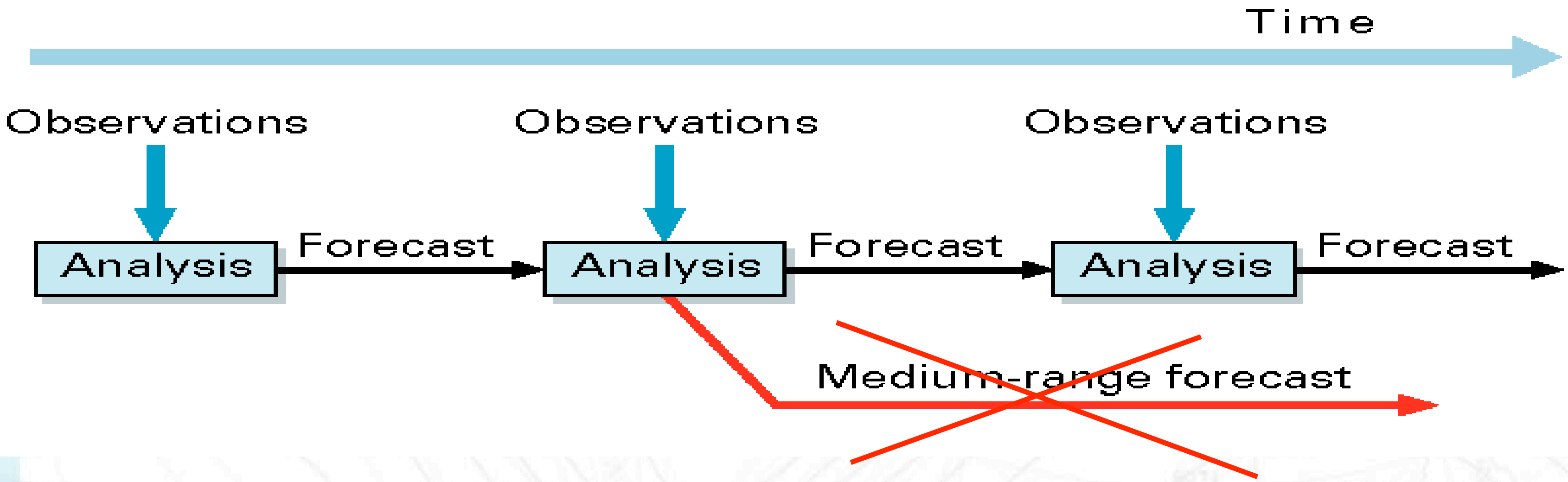


- And many citations:
  - Paper on NCEP/NCAR reanalysis is most cited paper in geosciences
  - Paper on ERA-40 is most cited recently in the geosciences
  - Many references in IPCC Fourth Assessment report





Reanalysis



- The observations are used to correct errors in the short forecast from the previous analysis time.
- Every 12 hours we assimilate 4 – 8,000,000 observations to correct the 100,000,000 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.

Data sources: Conventional

SYNOP/SHIP/METAR:

- Meteorological/aeronautical land surface weather stations (2m-temperature, dew-point temperature, 10m-wind)
- Ships

→ temperature, dew-point temperature, wind (land: 2m, ships: 25m)

BUOYS:

- Moored buoys (TAO, PIRATA)
- Drifters

→ temperature, pressure, wind

TEMP/TEMPSHIP/DROPSONDES:

- Radiosondes
- ASAPs (commercial ships replacing stationary weather ships)
- Dropsondes released from aircrafts (NOAA, Met Office, tropical cyclones, experimental field campaigns, e.g., FASTEX, NORPEX)

→ temperature, humidity, pressure, wind *profiles*

PROFILERS:

- UHF/VHF Doppler radars (Europe, US, Japan)

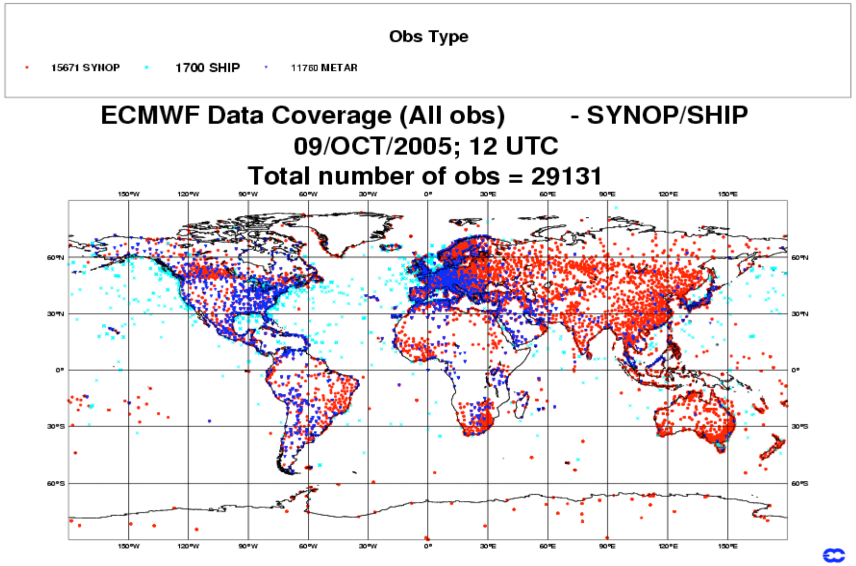
→ wind *profiles*

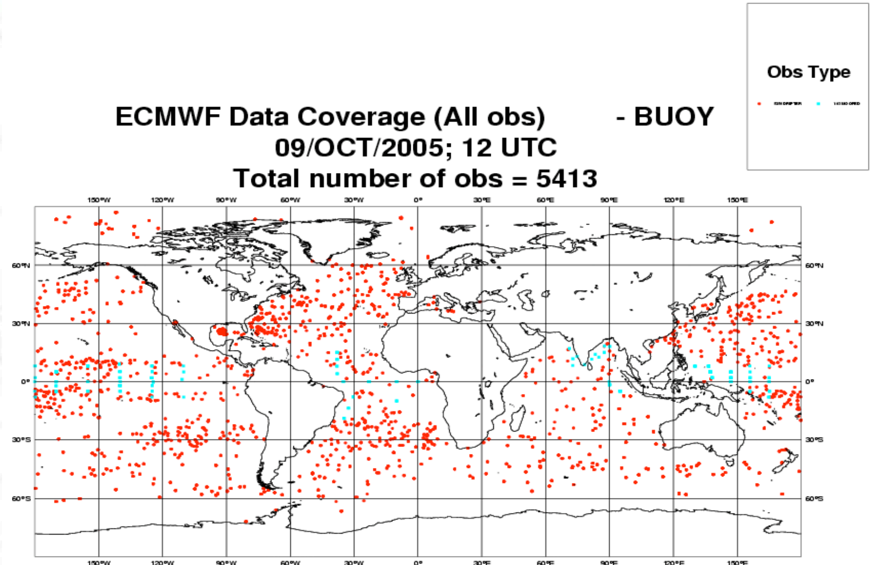
Aircraft:

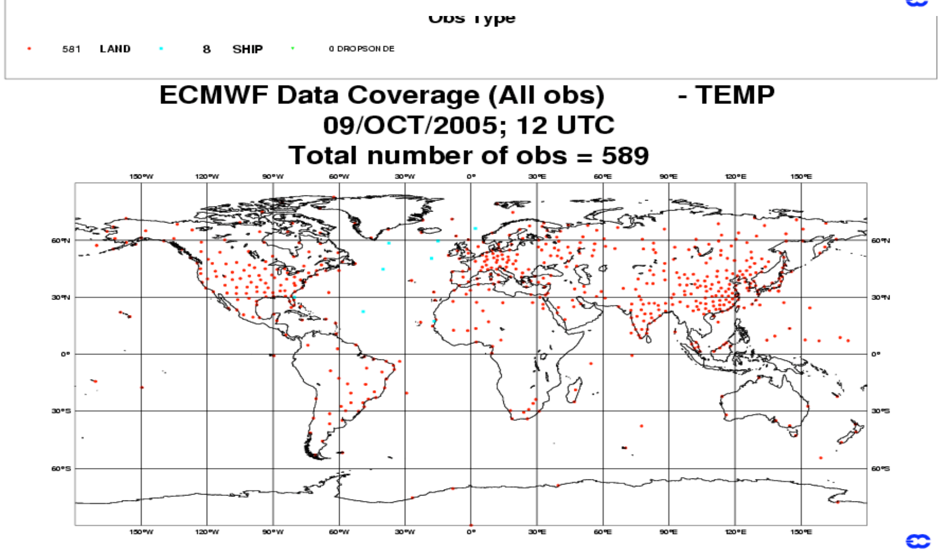
- AIREPS (manual reports from pilots)
- AMDARs, ACARs, etc. (automated readings)

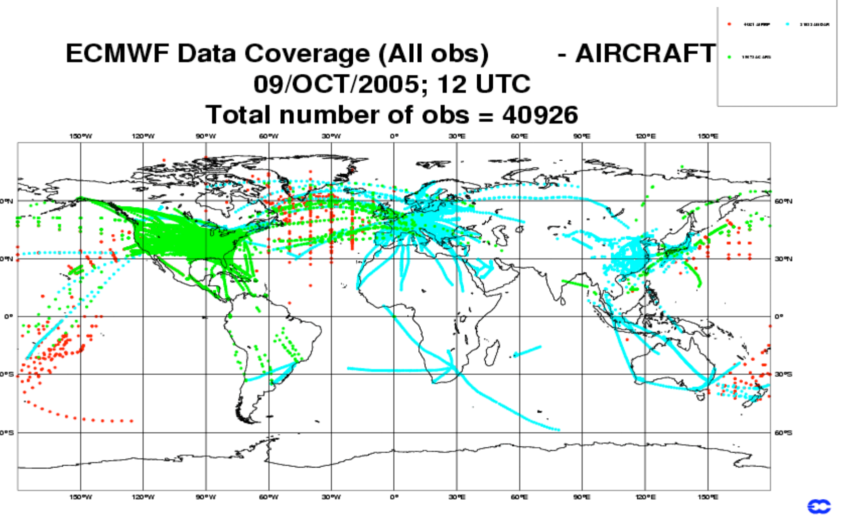
→ temperature, pressure, wind *profiles*

Example of conventional data coverage









Data sources: Satellites

Radiances (→ brightness temperature = level 1):
- AMSU-A on NOAA-15/16/17/18(/19), AQUA, Metop
- AMSU-B/MHS on NOAA-16/17/18(/19), Metop
- SSM/I on F-13, AMSR-E on Aqua
- HIRS on NOAA-17(/19), Metop
- AIRS on AQUA, IASI on Metop
- MVIRI on Meteosat-7, SEVIRI on Meteosat-9, GOES-11/12, MTSAT-1R imagers

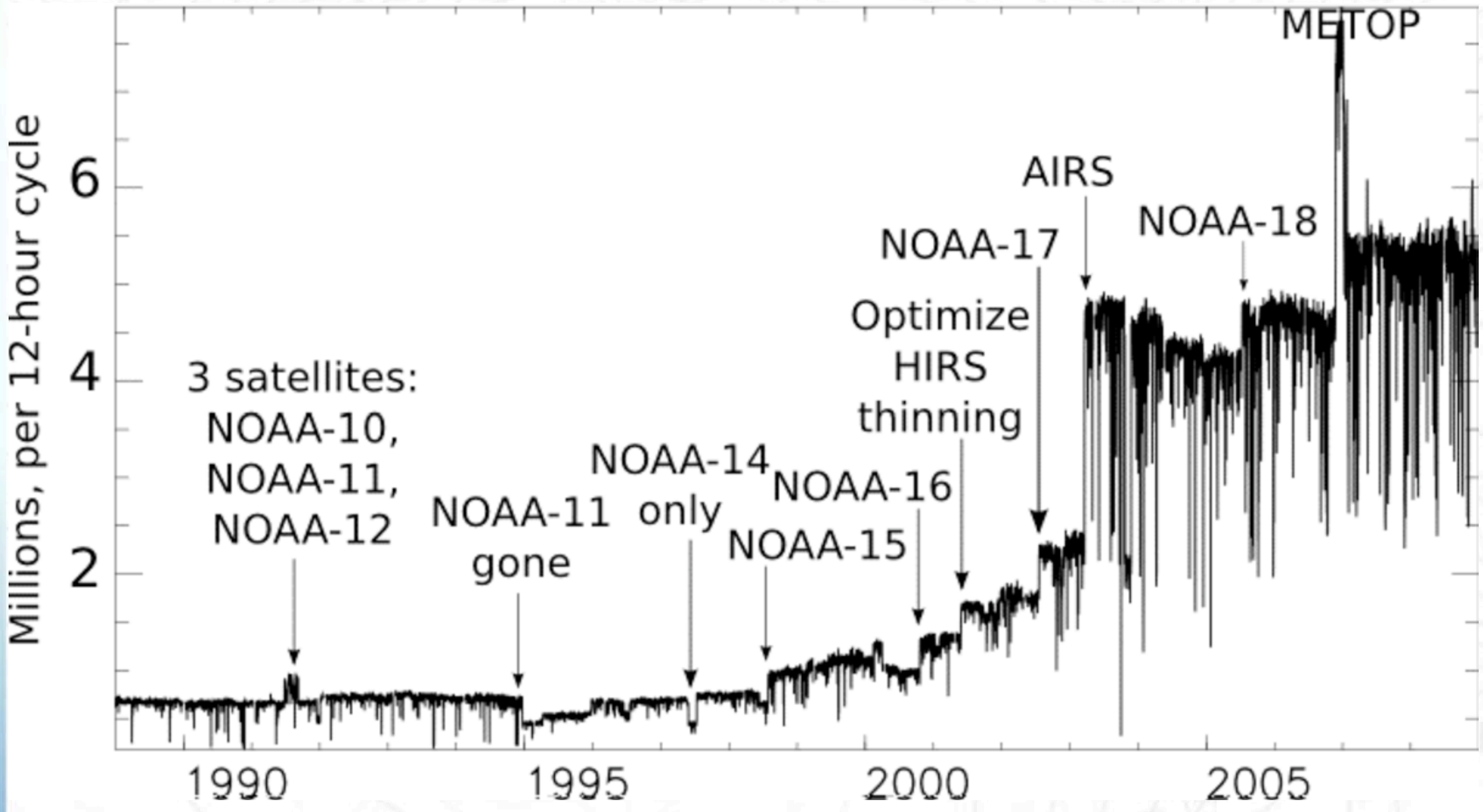
Ozone (→ total column ozone = level 2):
- Total column ozone from SBUV on NOAA-17/18, SCIAMACHY on Envisat, OMI on Aura, (GOME-2 on Metop)

Bending angles (→ bending angle = level 2):
- COSMIC (6 satellites), GRAS on Metop, (GRACE-A)

Atmospheric Motion Vectors (→ wind speed = level 2):
- Meteosat-7/9, GOES-11/12, MTSAT-1R(, FY-2C), MODIS on Terra/Aqua

Sea surface parameters (→ wind speed and wave height = level 2):
- Significant wave height from Seawinds on QuikSCAT, AMI on ERS-2, ASCAT on Metop
- Near-surface wind speed from RA-2/ASAR on Envisat, Jason altimeter

Observations assimilated in ERA-Interim 4DVAR



Total number of observations over 20 years: exceeds 30×10^9

Reanalyses have to deal with very large numbers of observations, whose quantity vary over time

Reanalysis in practical terms: bias correction

- Variational bias correction
  Aims at correcting observation and observation operator biases in an automatic, consistent and time-smooth manner
  - **Requires data that are considered not biased:**
    - All in situ: surface stations, radiosondes, aircraft
    - GPS radio occultation
    - So far, only applied to satellite radiance data in reanalysis
  - **Caveat: Not designed to handle model biases!**

Variational bias correction has become an important component of global reanalysis because it minimizes the impact of changes in radiance data (new instruments, re-calibration during flight…)

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?

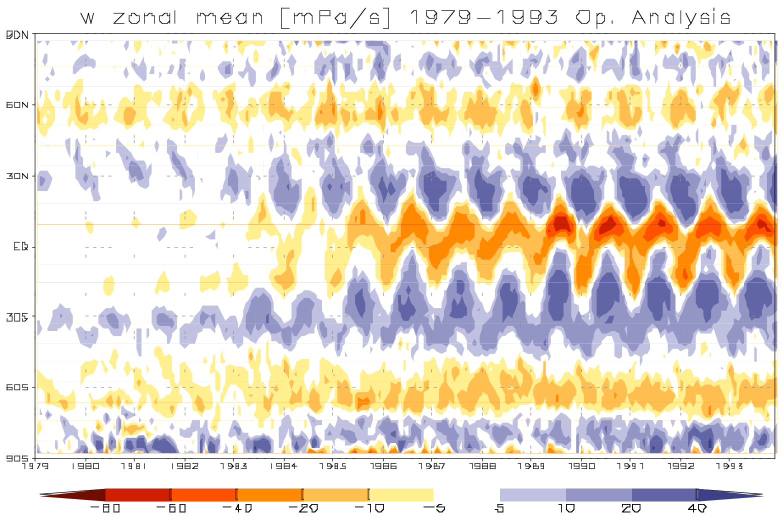
NWP systems are continuously upgraded:

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

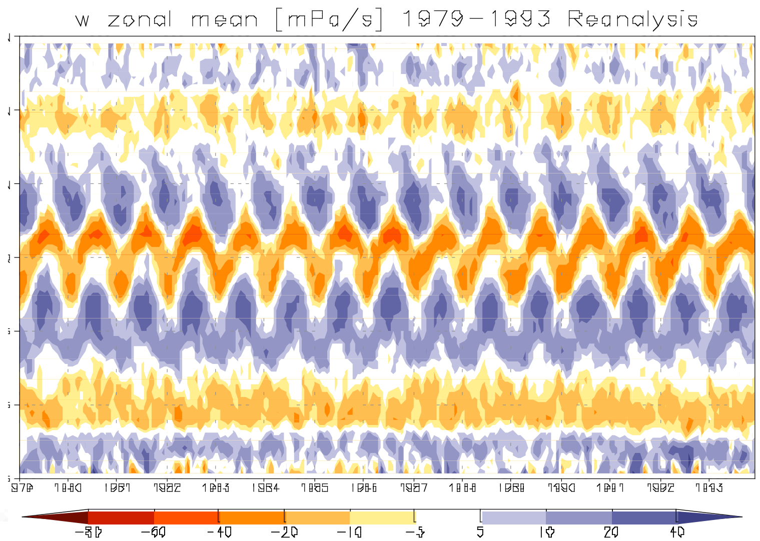
} Unphysical changes in operational analyses

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 (_, top at 10hPa)	Optimal Interpolation (**OI**) with incremental analysis update
ECMWF (**ERA-15**)	**1979** to **1993**	T106 spectral (Δx ~ **125km**) L31 (_-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 (_, top at 3hPa)	Spectral Statistical Interpolation (**SSI**)
NOAA NCEP and DOE (**R2**)	**1979** to present	T62 spectral (Δx ~ **200km**) L28 (_, top at 3hPa)	Spectral Statistical Interpolation (**SSI**)
ECMWF (**ERA-40**)	**1957** to **2002**	T159 spectral (Δx ~ **100km**) L60 (_-p, top at 0.1hPa)	**3D-Var**, direct radiance assimilation
JMA and CRIEPI (**JRA-25**)	**1979** to **2004**	T106 spectral (Δx ~ **125km**) L40 (_-p, top at 0.4hPa)	**3D-Var**, direct radiance assimilation
ECMWF (**ERA-Interim**)	**1989** to present	T255 spectral (Δx ~ **80km**) L60 (_-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 (_-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 (_-p, top at 0.01hPa)	Grid-point Statistical Interpolation (**GSI**)
JMA (**JRA-55**)	**1958** to **2012**	T319 spectral (Δx ~ **63km**) L60 (_-p, top at 0.1hPa)	**4D-Var**, variational bias correction of radiance data (VarBC)

ERA-Interim: after ERA-40 and before the next reanalysis

	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

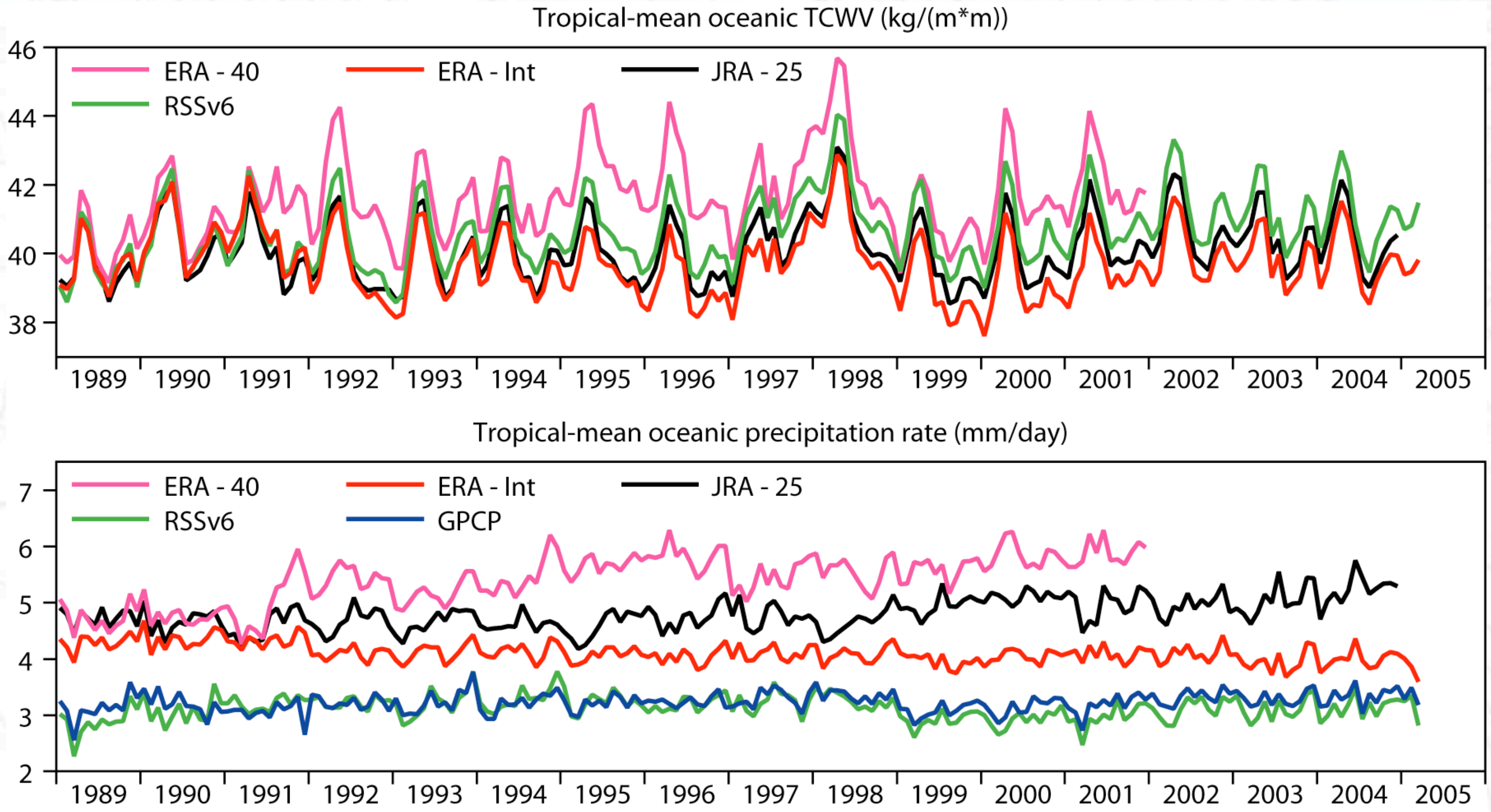
Quality requirements for reanalysis products

- 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

Water

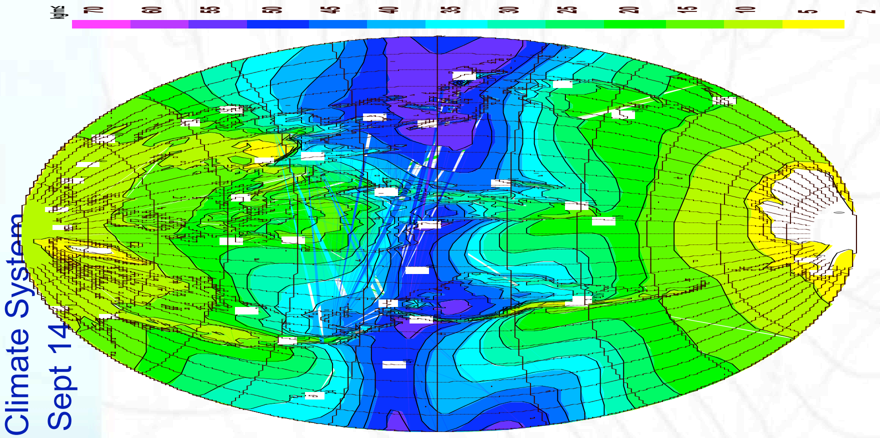


Improvements in ERA-Interim, due to:

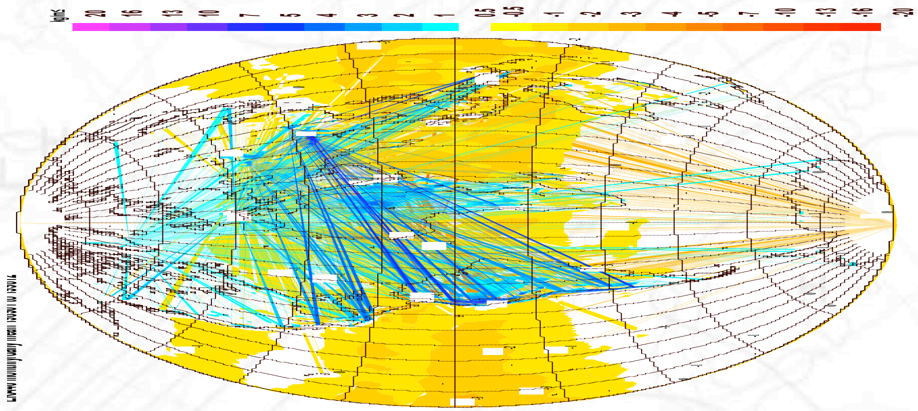
- Revised humidity analysis
- Better model physics
- 4D-Var
- Improved bias corrections for radiance data

Daily mean total column water vapour (1989-1998)

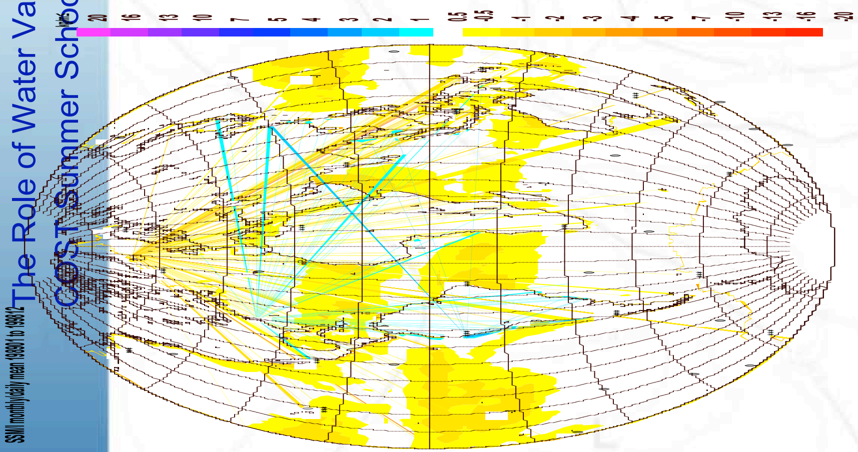
ERA-Interim



ERA-Interim – ERA-40

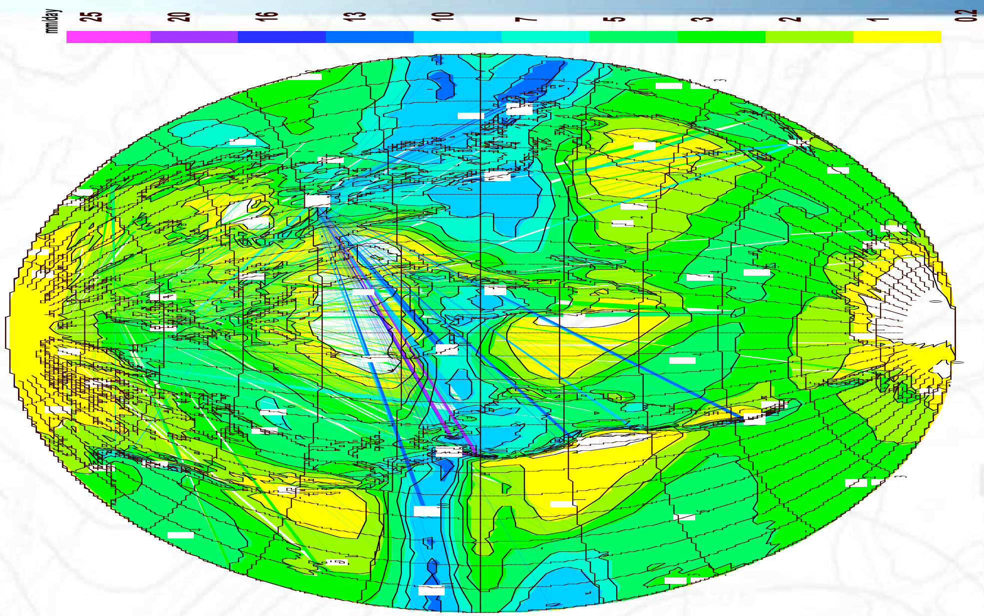


ERA-Interim – SSM/I

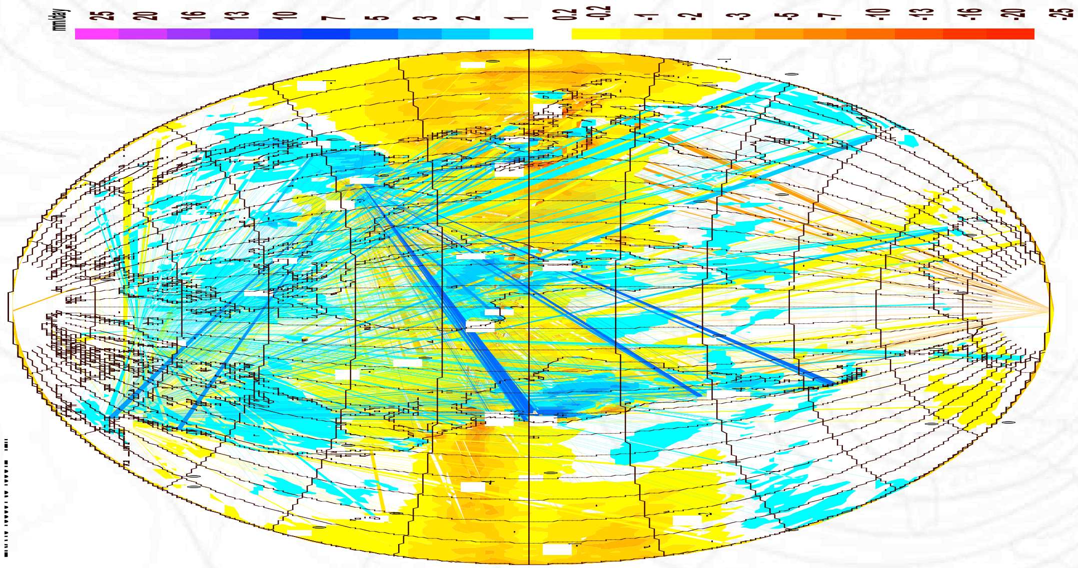


Mean daily precipitation (1989-1998)

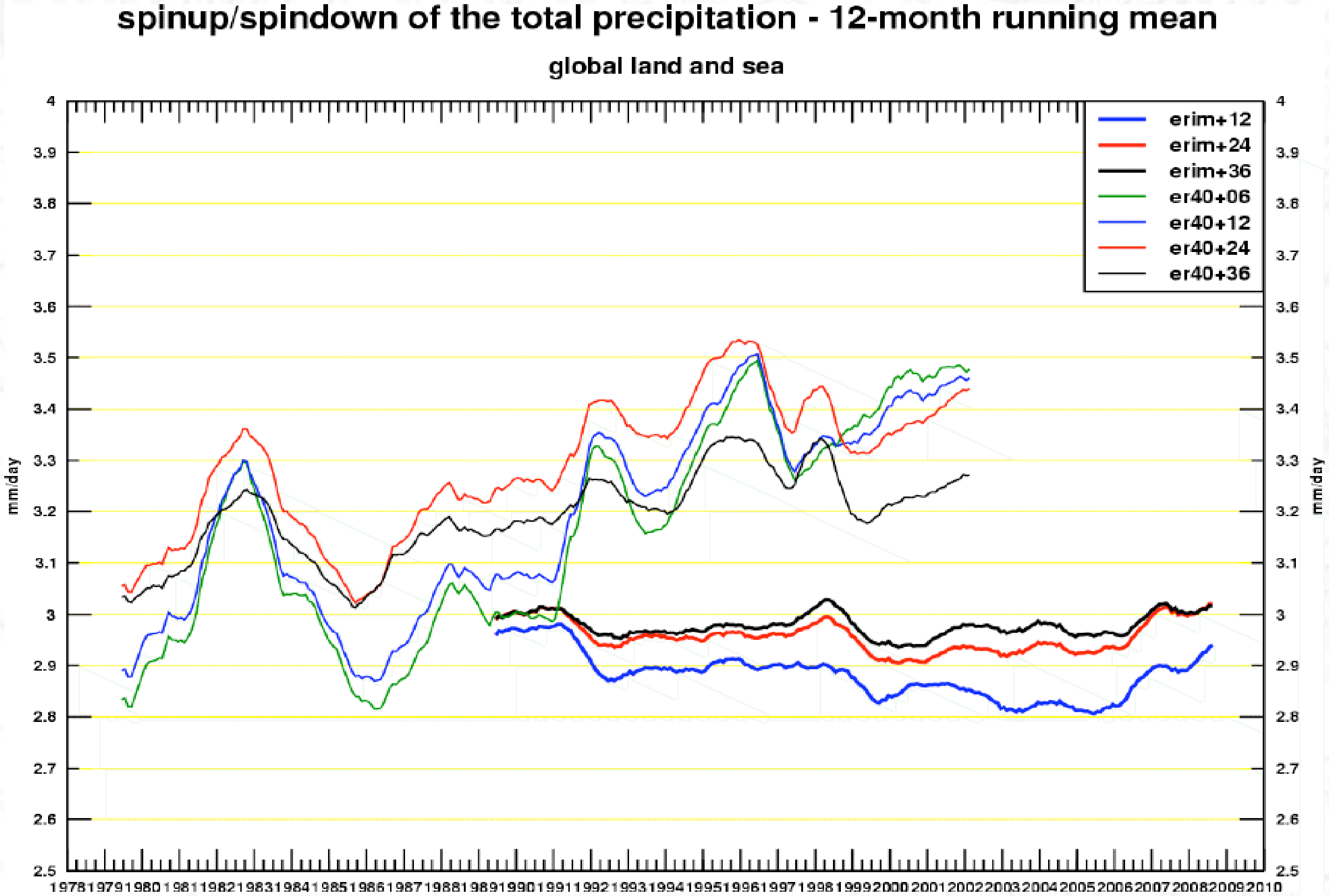
ERA-Interim



ERA-Interim – ERA-40

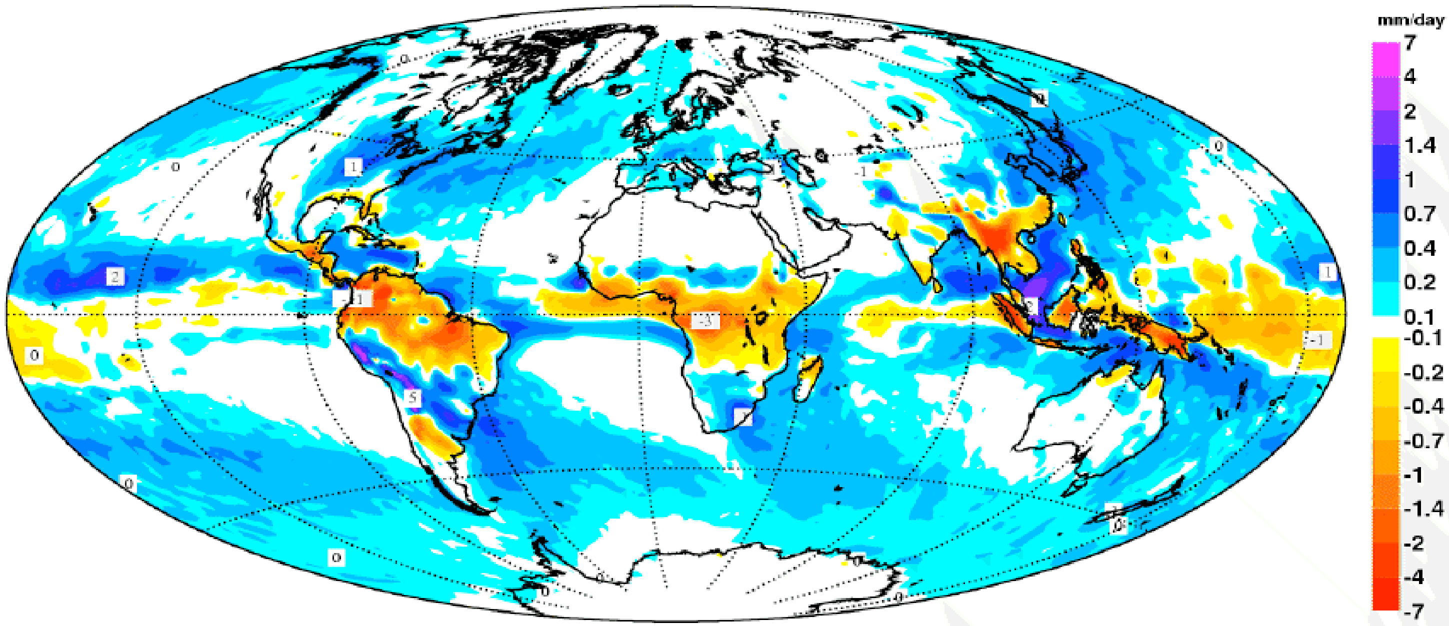


Precipitation spinup/spindown for ERA-40 and ERA-Interim



Precipitation spinup / spindown for ERA-Interim

total precipitation
ERA_Interim spinup from +12h to +36h 20-year 1989-2008 YEAR



ERA group

ECMWF

Reanalysis and climate monitoring

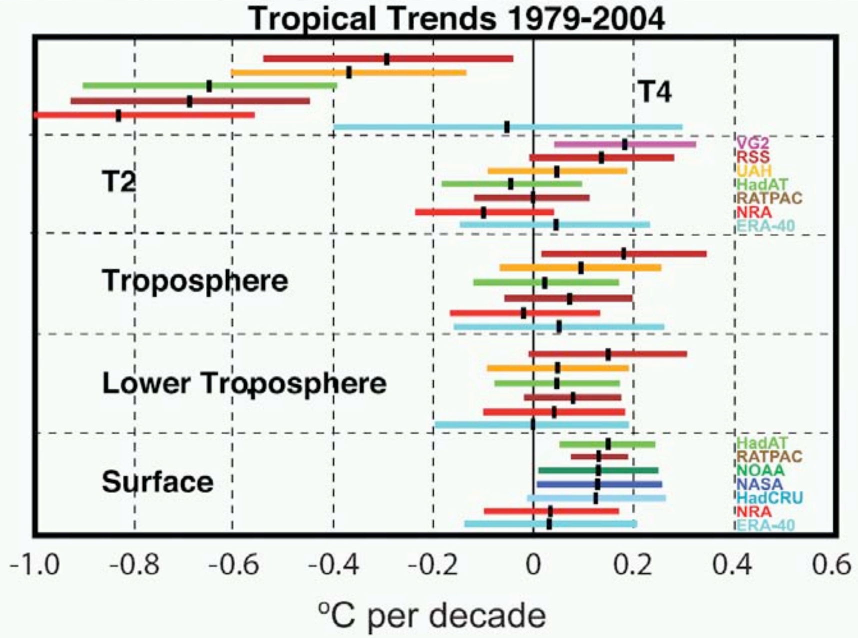


Figure 3.18. *Linear temperature trends (°C per decade) for 1979 to 2004 for the globe (top) and tropics (20°N to 20°S; bottom) for the MSU channels T4 (top panel) and T2 (second panel) or equivalent for radiosondes and reanalyses; for the troposphere (third panel) based on T2 with T4 used to statistically remove stratospheric influences (Fu et al., 2004a); for the lower troposphere (fourth panel) based on the UAH retrieval profile; and for the surface (bottom panel). Surface records are from NOAA/NCDC (green), NASA/GISS (blue) and HadCRUT2v (light blue). Satellite records are from UAH (orange), RSS (dark red) and VG2 (magenta); radiosonde-based records are from NOAA RATPAC (brown) and HadAT2 (light green); and atmospheric reanalyses are from NRA (red) and ERA-40 (cyan). The error bars are 5 to 95% confidence limits associated with sampling a finite record with an allowance for autocorrelation. Where the confidence limits exceed –1, the values are truncated. ERA-40 trends are only for 1979 to August 2002. Data from Karl et al. (2006; D. Seidel courtesy of J. Lanzante; and J. Christy).*

Benefits of reanalysis products as a proxy for observations are well established

Reanalysis for climate monitoring: physically consistent ECVs (essential climate variables)

In the climate community, reanalysis is still regarded as unsuitable for trend estimation (IPCC)

This view evolves as reanalyses become more consistent and rely on more observations

Summary & Important concepts

- Reanalysis does not produce "gridded fields of observations"
  - But it enables to extract information from observations in one, unique, theoretically consistent framework
- Reanalysis sits at the end of the meteorological research and development chain that encompasses
  - observation collection [measurement],
  - observation processing,
  - numerical weather prediction modelling, and
  - data assimilation
- Unlike NWP, a very important concept in reanalysis is the consistency in time
- Reanalysis is bridging slowly, but surely, the gap between the "weather scales" and the "climate scales"
  - Resolution gets finer
  - Covers longer time periods

Current status of reanalysis & Future outlook

- **Reanalysis has developed into a powerful tool for many users and applications**
  - It relies on the combined expertise of a large user community and feedback
  - An extended reanalysis project such as ERA-40 takes 7-10 years to complete

- **It is worth repeating as all ingredients continue to evolve**:
  - Models are getting better
  - Data assimilation methods are getting better
  - Observation processing is improving
  - The technical/scientific infrastructure for running & monitoring improves constantly

- **With ERA-Interim, we made good progress in key problematic conceptual areas**:
  - Dealing with biases and changes in the radiance observing system

- **Major challenges for a future reanalysis project**:
  - Bringing in additional observations (not dealt with in ERA-Interim)
  - Dealing with model bias (ultimately responsible for problems with trends)
  - Coupling with ocean and land surface
  - Providing meaningful uncertainty estimates for the reanalysis products