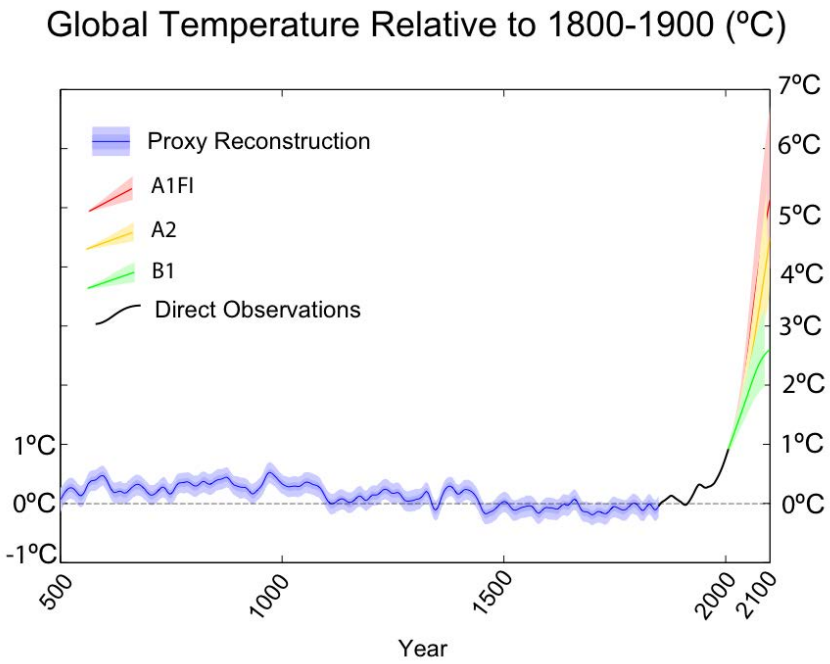
Modern reanalysis:

A framework for paleoclimate data assimilation?

Dick Dee, ECMWF

DAPS2017, Louvain-la-Neuve, 29 May 2017



ECMWF

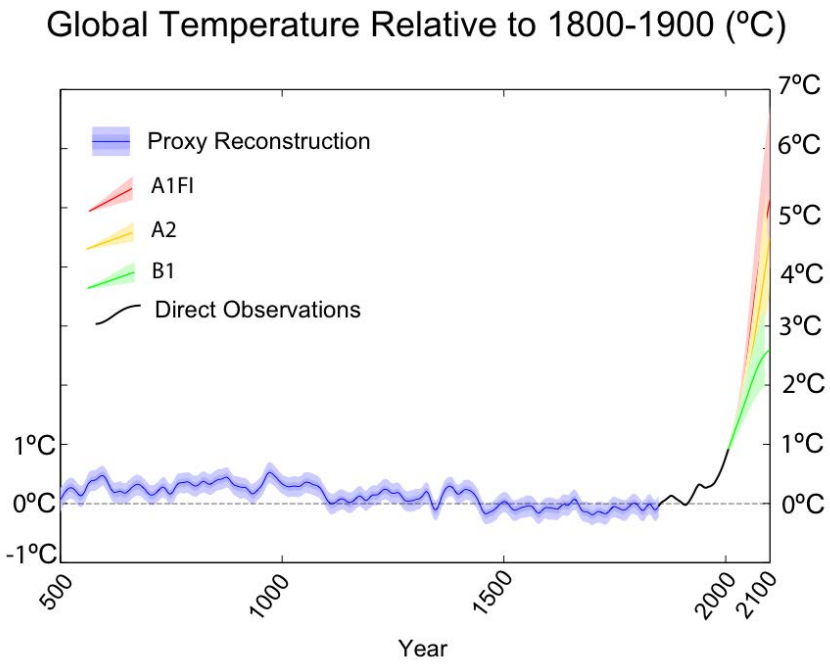
Modern reanalysis:

A framework for paleoclimate data assimilation?

Dick Dee, ECMWF

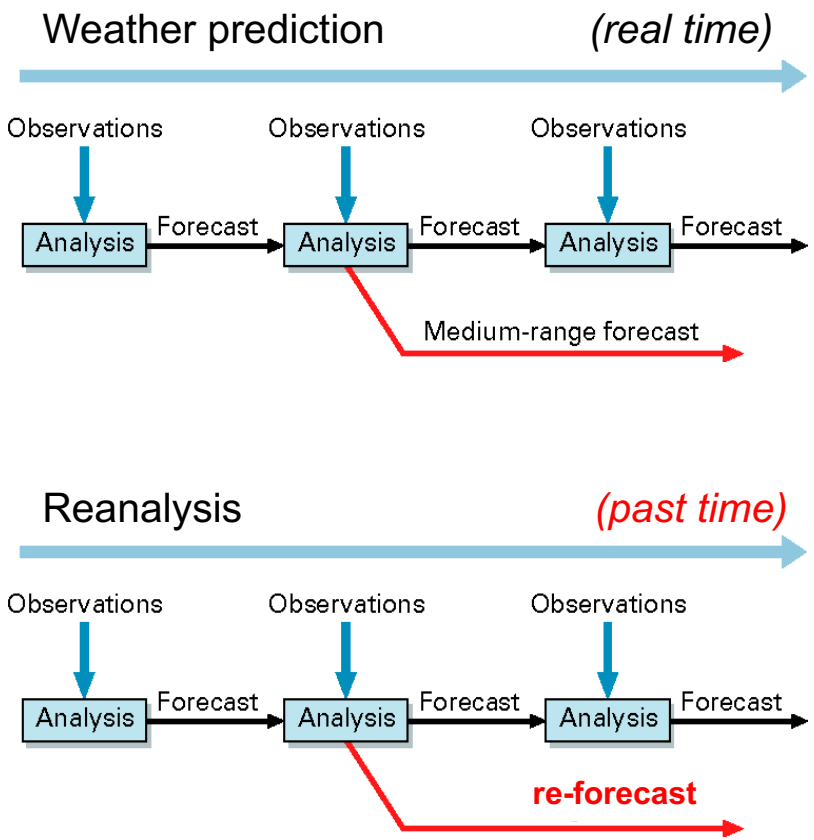
DAPS2017, Louvain-la-Neuve, 29 May 2017

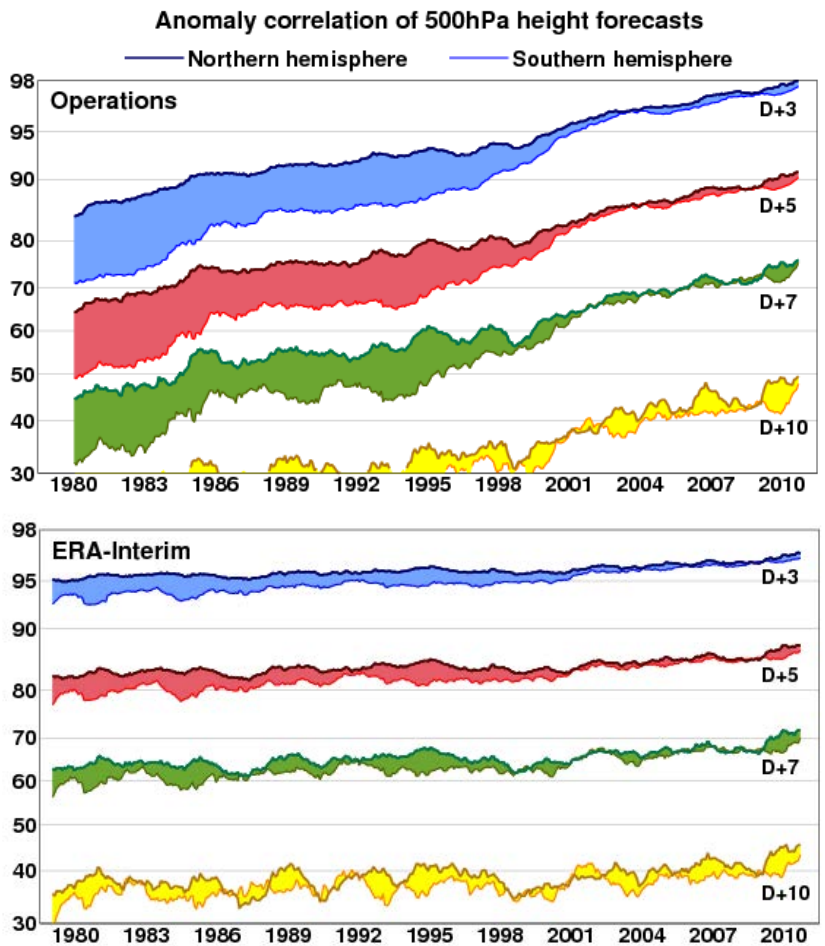
- Reanalysis at ECMWF
- Centennial reanalysis: ERA-CLIM
- A few thoughts on the title



ECMWF

Numerical weather prediction and climate reanalysis





ECMWF

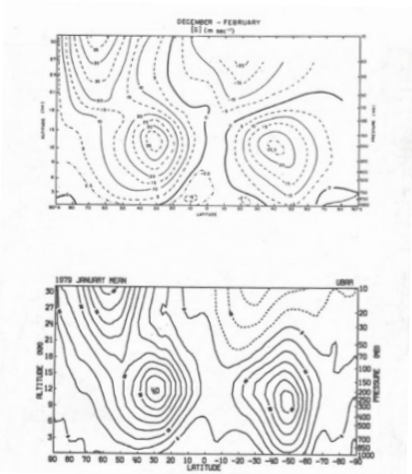
A brief history of atmospheric reanalysis productions at ECMWF

1980 1990 2000 2010

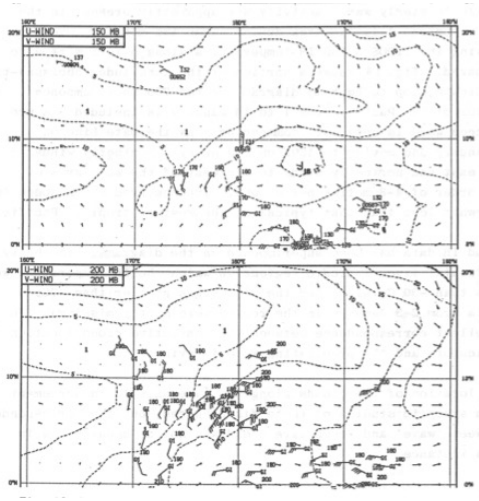
FGGE | ERA-15 | ERA-40 | ERA-Interim | ERA5

Atmosphere/land *Atmosphere/land/waves*

- The **FGGE** analyses provided the first global atmospheric dataset for scientific research
- Numerous seminal studies on atmospheric circulation
- Many case studies performed at ECMWF
- **FGGE** = First GARP Global Experiment
- GARP = Global Atmospheric Research Program



Kanamitsu 1980



Julian 1980

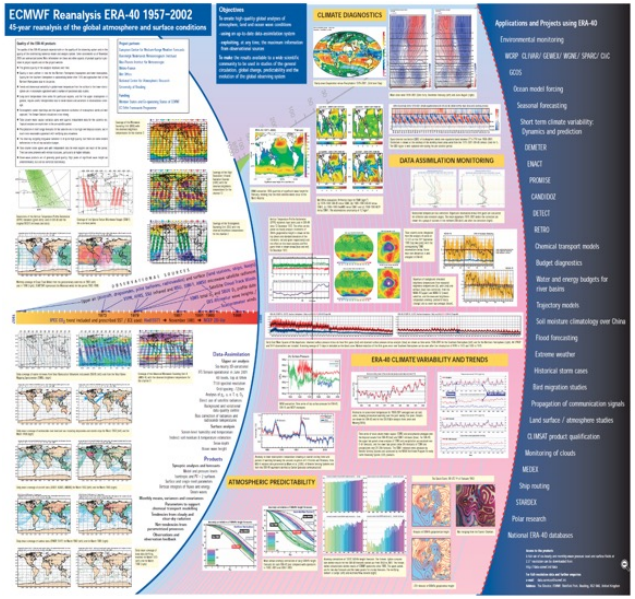
A brief history of atmospheric reanalysis productions at ECMWF

1980 — 1990 — 2000 — 2010

FGGE → ERA-15 → **ERA-40** → ERA-Interim → ERA5

Atmosphere/land — *Atmosphere/land/waves*

- **ERA-40**: Reanalysis data for 1957-2002
- Includes analyses of ocean wave height
- Use of radiance observations from satellites
- Improved SST and sea-ice data



QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY

Vol. 131 OCTOBER 2005 Part B No. 612

Q. J. R. Meteorol. Soc. (2005), **131**, pp. 2961–3012 doi: 10.1256/qj.04.176

The ERA-40 re-analysis

By S. M. UPPALA[1], P. W. KÅLLBERG[1], A. J. SIMMONS[1]*, U. ANDRAE[1], V. DA COSTA BECHTOLD[1], M. FIORINO[2], J. K. GIBSON[1], J. HASELER[1], A. HERNANDEZ[1], G. A. KELLY[1], X. LI[3], K. ONOGI[4], S. SAARINEN[1], N. SOKKA[1], R. P. ALLAN[5,11], E. ANDERSSON[1], K. ARPE[6], M. A. BALMASEDA[1], A. C. M. BELJAARS[1], L. VAN DE BERG[7], J. BIDLOT[1], N. BORMANN[1], S. CAIRES[8], F. CHEVALLIER[1], A. DETHOF[1], M. DRAGOSAVAC[1], M. FISHER[1], M. FUENTES[1], S. HAGEMANN[6], E. HÓLM[1], B. J. HOSKINS[9], L. ISAKSEN[1], P. A. E. M. JANSSEN[1], R. JENNE[10], A. P. MCNALLY[1], J.-F. MAHFOUF[1], J.-J. MORCRETTE[1], N. A. RAYNER[11], R. W. SAUNDERS[11], P. SIMON[12], A. STERL[8], K. E. TRENBERTH[10], A. UNTCH[1], D. VASILJEVIC[1], P. VITERBO[1] and J. WOOLLEN[13]

[1]*European Centre for Medium-Range Weather Forecasts, Reading, UK*
[2]*Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, USA*
[3]*Institute for Atmospheric Physics, Chinese Academy of Sciences, Beijing, China*
[4]*Japan Meteorological Agency, Tokyo, Japan*
[5]*Environmental Systems Science Centre, University of Reading, UK*
[6]*Max-Planck-Institut für Meteorologie, Hamburg, Germany*
[7]*European Organisation for the Exploitation of Meteorological Satellites, Darmstadt, Germany*
[8]*Koninklijk Nederlands Meteorologisch Instituut, De Bilt, the Netherlands*
[9]*Department of Meteorology, University of Reading, UK*
[10]*National Center for Atmospheric Research, Boulder, Colorado, USA*
[11]*Met Office, Exeter, UK*
[12]*Météo-France, Toulouse*
[13]*NOAA/NWS/National Centers for Environmental Prediction, USA*

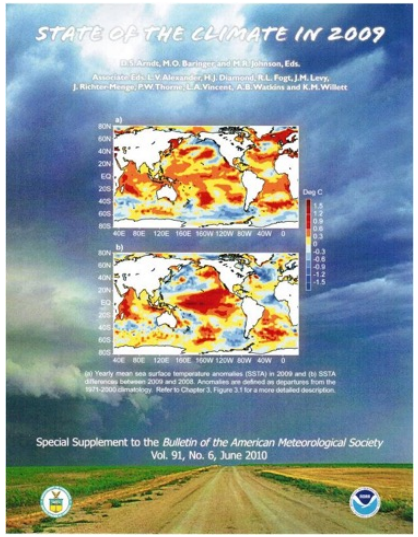
A brief history of atmospheric reanalysis productions at ECMWF

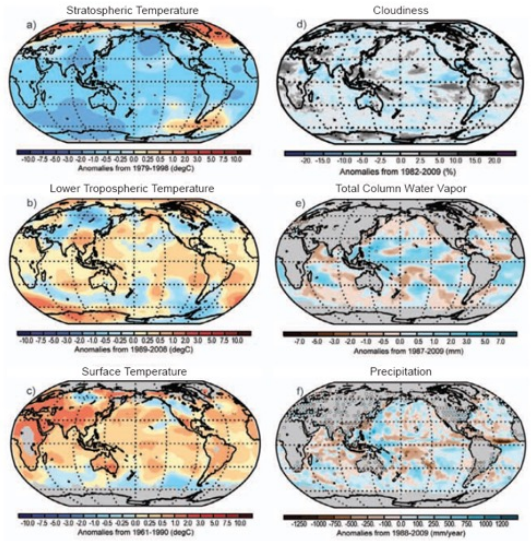
1980 1990 2000 2010

FGGE | ERA-15 | ERA-40 | **ERA-Interim** | ERA5

Atmosphere/land *Atmosphere/land/waves*

- **ERA-Interim**: Data from 1979 onward
- Continuously updated close to real time
- 4D-Variational data assimilation
- Improved use of satellite data
- Increasingly important for ECMWF research and operations
- ERA-Interim has a major role in Copernicus Services development





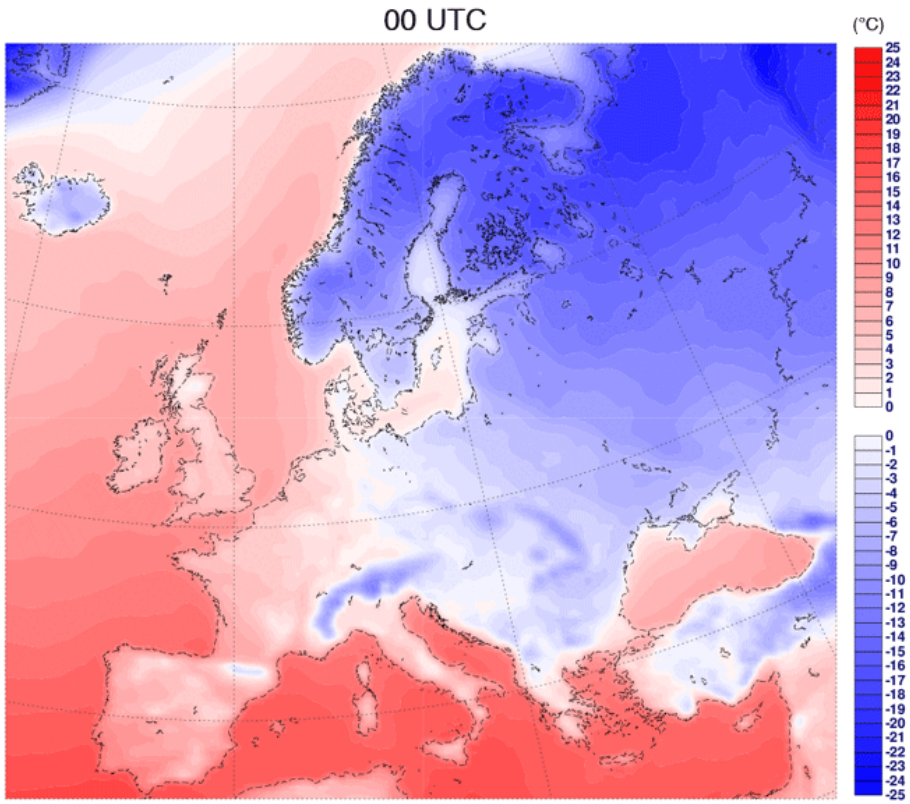
ERA5: The latest ECMWF reanalysis is now in production

- Atmosphere/land/wave parameters
- 31 km global resolution, 137 levels
- Hourly output from 1979 onward

- Based on IFS Cy41r2 (March 2016)
- Using improved input observations
- Ensemble data assimilation
- Providing uncertainty estimates

Public release plan:

Nov 2016	Test data (Jan-Feb 2016)
July 2017	Hourly data from 2010 - 2016
Aug 2017	Daily updates at short delay
Apr 2018	Complete from 1979 onward



ERA5 hourly temperatures for January 2016

Why does ECMWF invest in reanalysis?

Reanalysis provides an excellent testbed for data assimilation

- It reveals a great deal about the quality of the forecast model
- It leads to new ways to make better use of observations
- It exposes bugs and other technical problems in the Integrated Forecast System (IFS)

Reanalysis data are essential for ECMWF research and development

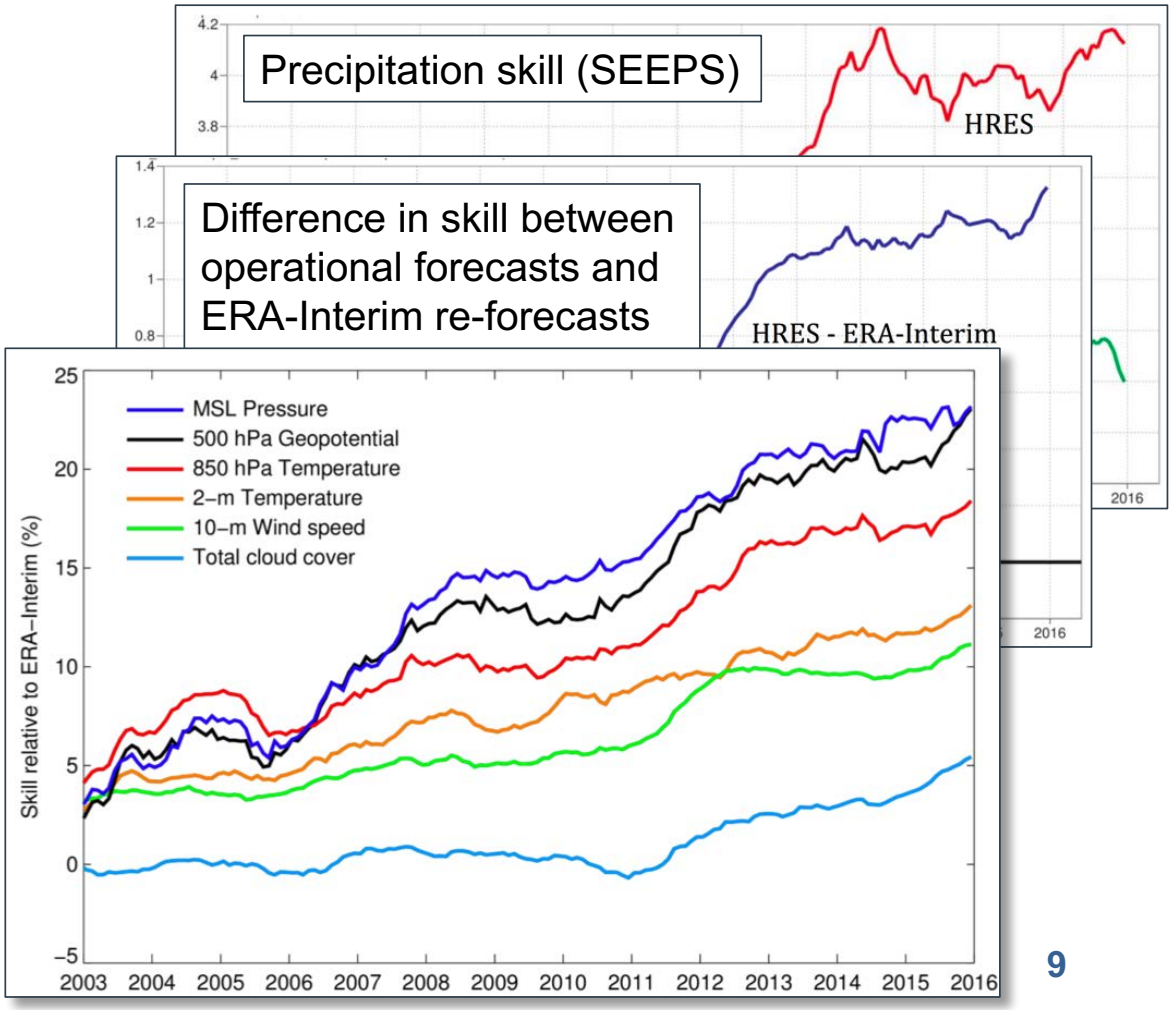
- It provides a comprehensive verification dataset for testing new model developments
- It allows development of new forecast products that rely on climatologies
- It is needed for calibration of monthly and seasonal forecasts

Reanalysis data are extremely popular with external users

- Global datasets for research and education
- Input for downstream models and systems
- Essential data for services development

Use of reanalysis data to evaluate forecast performance

- Evolution of skill in operational forecasts is due to
  - model upgrades
  - changes in the observing system
  - atmospheric predictability
- ERA-Interim re-forecasts are produced using a fixed version of the IFS
- Forecast skill relative to ERA-Interim re-forecasts isolates the impact of specific model upgrades



Global EFI - multiple parameters

Forecasts homepage

Charts

Datasets

Quality of our forecasts

Documentation and support

Accessing forecasts

Back to charts

Related charts

EFI 2m temperature

EFI 2m minimum temperature

EFI 2m maximum temperature

EFI wind gust

EFI wind speed

EFI precipitation

EFI significant wave height

EFI snow fall

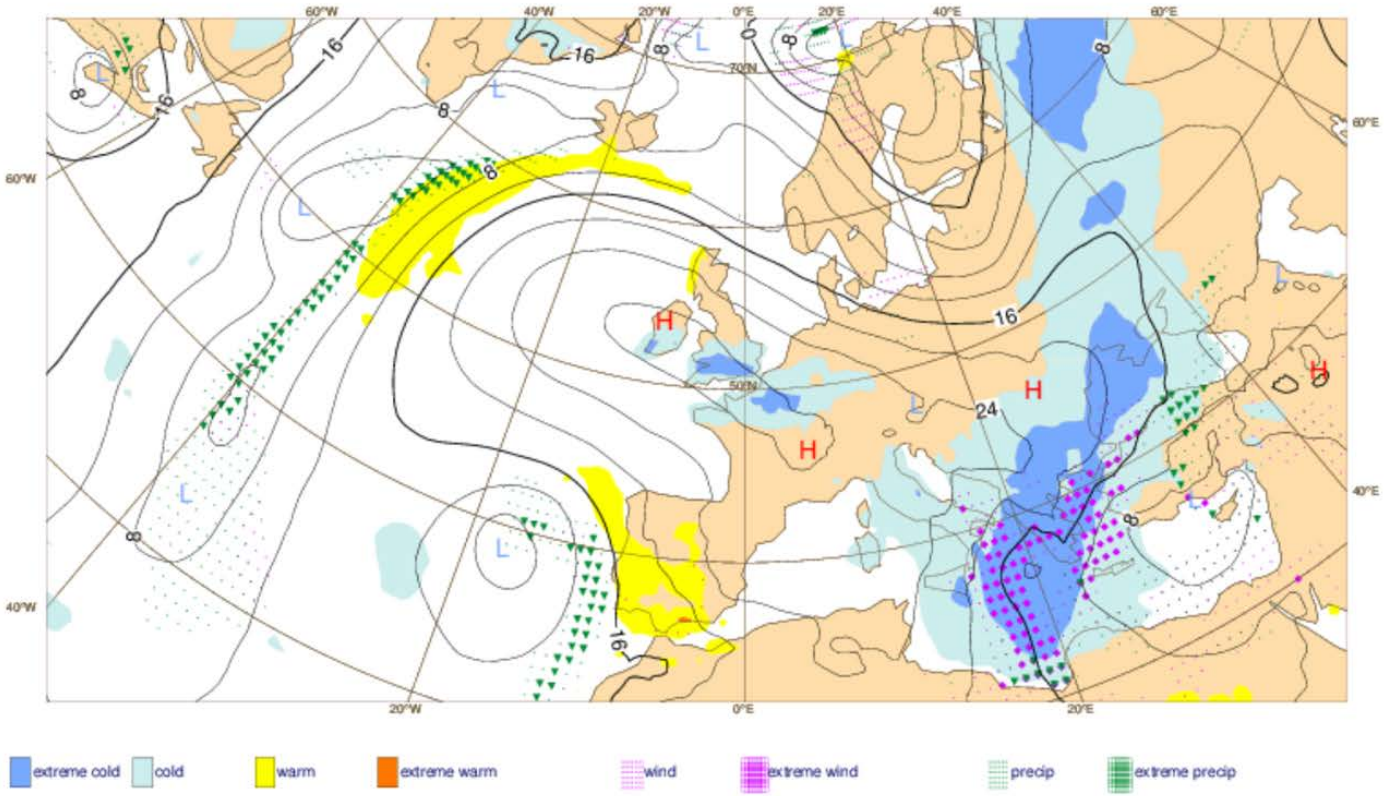
EFI cape

EFI cape shear

Global EFI - multiple parameters

Base time | Day | Area

Anomalous weather predicted by EPS:Wednesday 30 November 2016 0000 UTC
1000 hPa Z ensemble mean (Wednesday 30 November 2016 1200 UTC)
and EFI values for Total precipitation,maximum 10m wind gust and mean 2m temperature (all 24h)
valid for 24hours from Wednesday 30 November 2016 0000 UTC to Thursday 01 December 2016 0000 UTC



Toward a reanalysis of the coupled Earth system

1980 1990 2000 2010

FGGE ERA-15 ERA-40 ERA-Interim ERA5

Atmosphere/land *Atmosphere/land/waves*

Global ocean, using NEMO ocean model

ORAS3 ORAS4 ORAS5

Ocean *Ocean/sea ice*

Atmospheric composition, using satellite data from 2003

GEMS MACC CAMS

Atmospheric composition

Century-long reanalyses, using IFS coupled with NEMO

ERA-20C ORA-20C CERA-20C

Atmosphere/land/waves/ocean/sea ice

ECMWF

Development of century-long reanalyses (FP-7 funding)

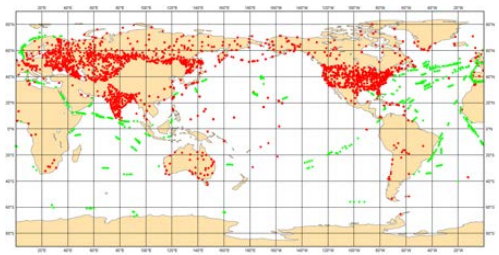
Weather observations have been collected systematically since the 18th century.

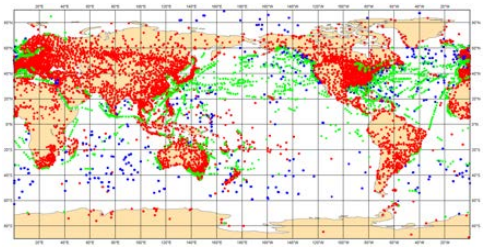
Can we develop a reanalysis extending back to the beginning of the instrumental record?

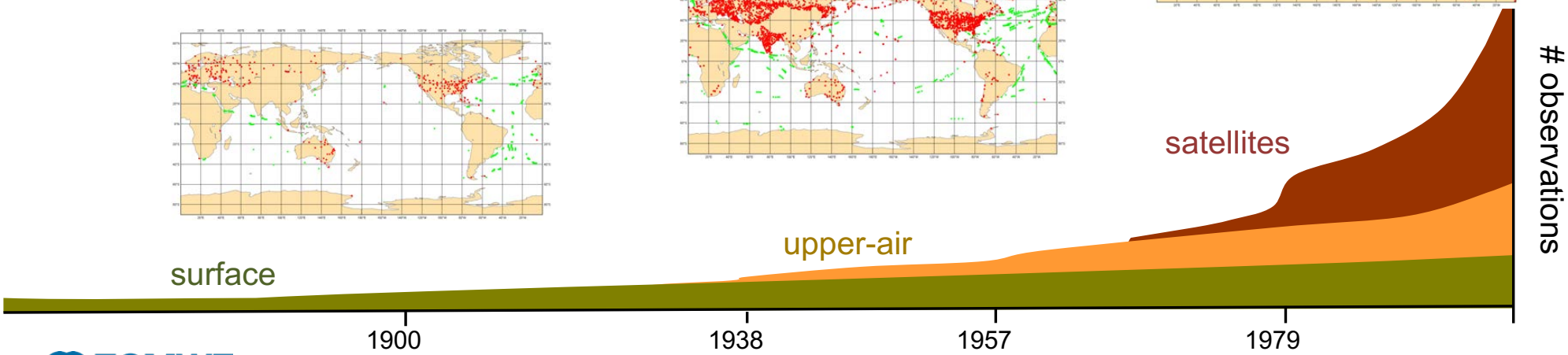
Where do we get the data? How accurate are the observations?

Surface pressure data coverage (ICOADS, ISPD)

Stations Ships Buoys

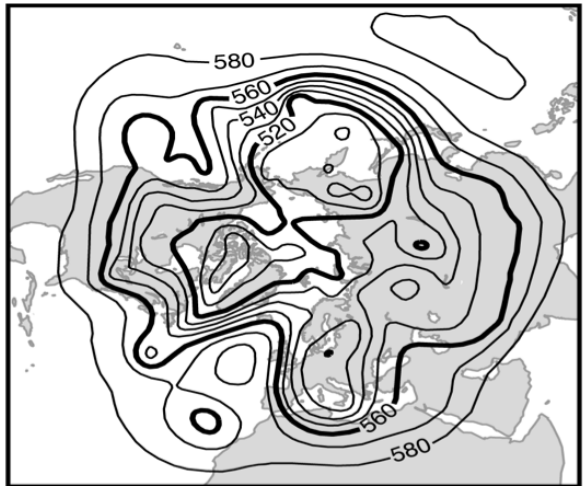




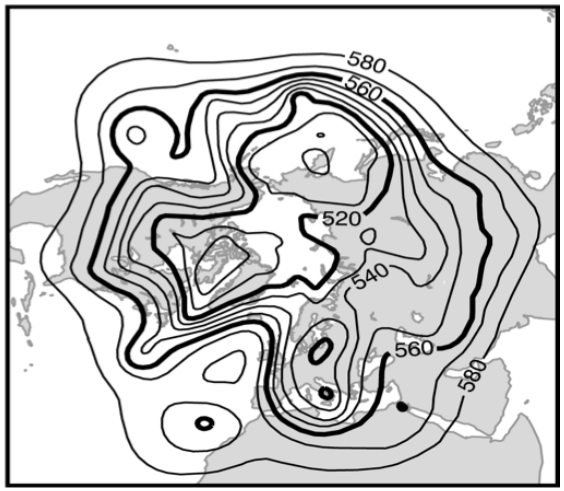


Making the best of early 20th-century weather observations

Two modern analyses of NH geopotential height at 500hPa

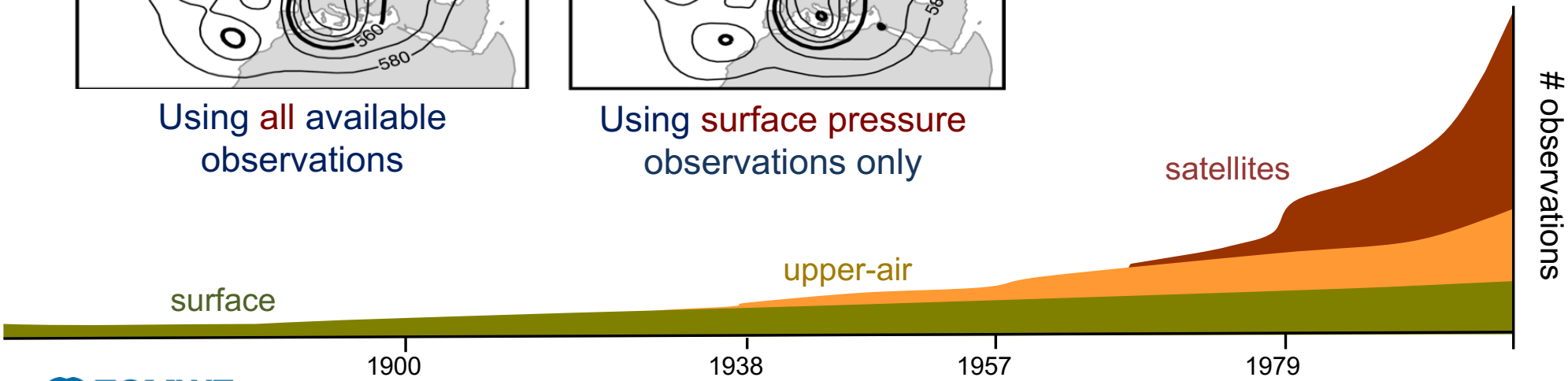


Using all available observations



Using surface pressure observations only

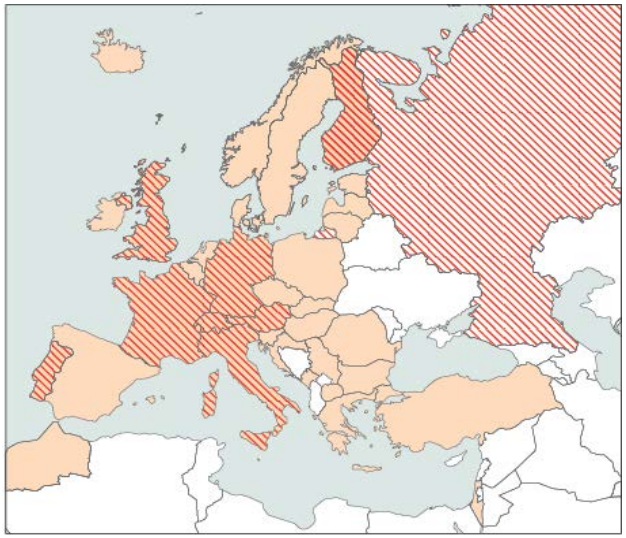
Whitaker, Compo, and Thépaut 2009



European collaborative research: The ERA-CLIM projects (2011-2017)

Development of global climate reanalyses spanning the 20th century

Coordinated by ECMWF and involving many institutes across Europe

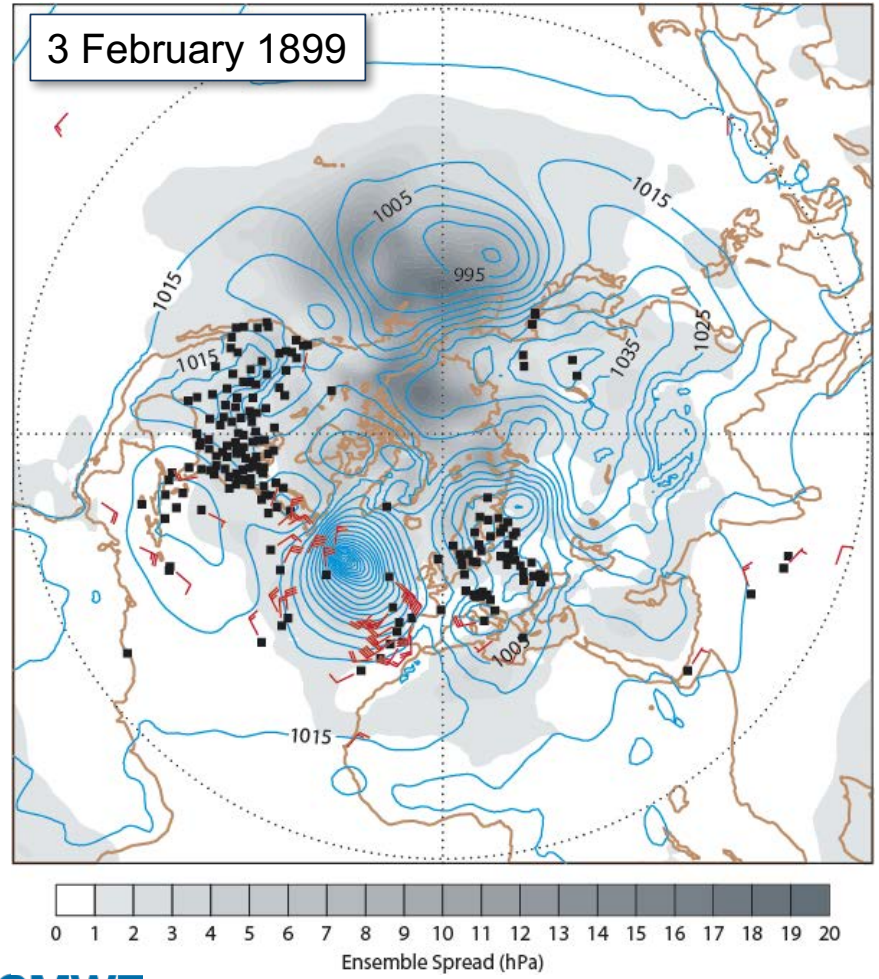


- Work on input observations and model data
- Data rescue for *in situ* and satellite observations
- Incremental development of new 20C reanalysis products
- Research in coupled data assimilation
- Progress toward a reanalysis of the coupled Earth system

ECMWF

ERA CLIM

ERA-20C: Reanalysis of an Atlantic storm



The New York Times
Published: February 16, 1899

TERRIFIC STORMS AT SEA

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of hurricane force, and seas swept her decks repeatedly. So fierce was the wind that the boat drifted before the gales and was barely able to keep steerage way. She anchored outside the bar late Sunday afternoon. The cable parted and she lost her anchor, together with 100 fathoms of chain. Then the great snowstorm drove her 150 miles off the shore. She succeeded in getting back late on Tuesday night.

The French liner La Bretagne, from Havre, came in a little before noon yesterday, with 58 cabin and 225 steerage passengers. She left Havre on Feb. 4, and two days later she encountered a fierce gale, which soon raised tremendous seas. This lasted until Feb. 12, and during this time the vessel had to be slowed down. The following day heavy head seas were encountered, but the steamship proved herself a

ECMWF

CERA-20C: ECMWF's first centennial coupled reanalysis

Atmosphere

Land

Wave

Ocean

Sea ice

Model: IFS/NEMO/LIM2 (CY41R2, March 2016)

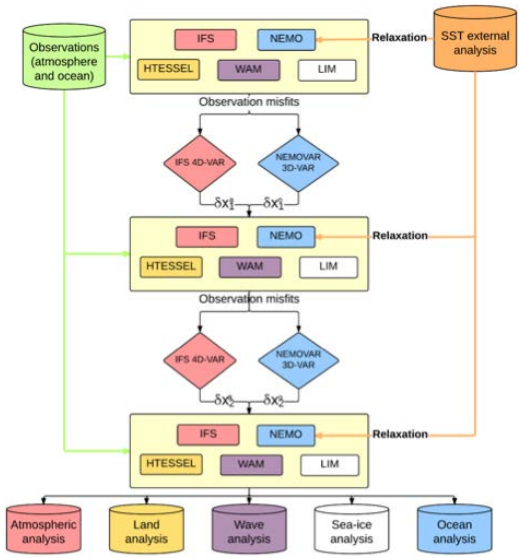
Forcing: HADISST2 for SST (nudged)

Observations: surface conventional, salinity and temperature profiles

Assimilation: new CERA system (10-member ensemble coupled DA)

Resolution: T159L91/ORCA1 Z42

Period: 1901-2010



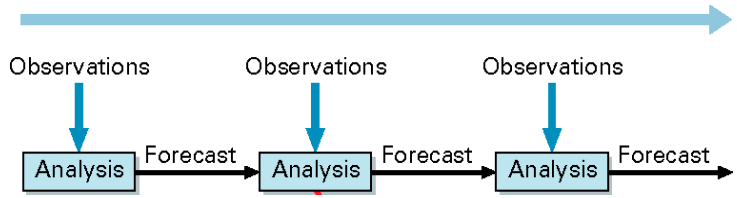
ECMWF

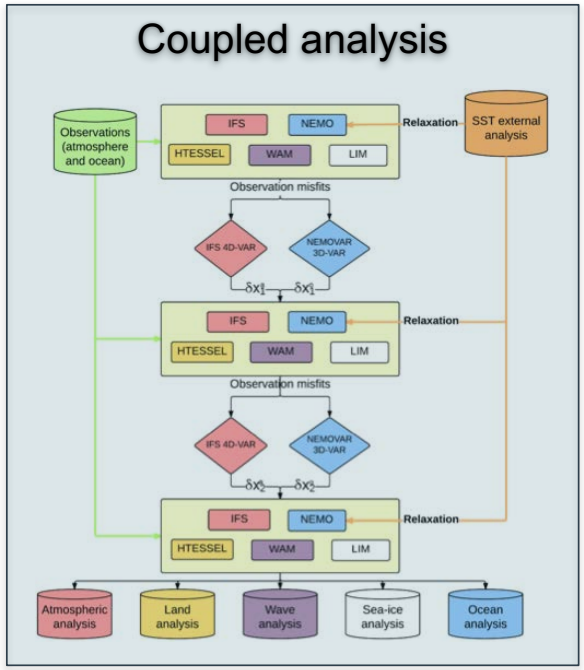
What do we mean by “Modern reanalysis” ?

- Multi-decadal output of a forecast (climate) model constrained by observations
- Can be formulated as a maximum-likelihood problem:

$$J(\mathbf{x}) = \overbrace{(\mathbf{x_b} - \mathbf{x})^T \mathbf{B}^{-1} (\mathbf{x_b} - \mathbf{x})}^{J_b\text{: background constraint}} + \underbrace{[\mathbf{y} - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1} [\mathbf{y} - \mathbf{h}(\mathbf{x})]}_{J_o\text{: observation constraint}}$$

- Background constraint: Short model predictions
- Observation constraint: Observations (or proxies)
- Need prior information on errors: B, R (Q, …)
- Other constraints and parameters can be added





ECMWF

Difficult problems with the use of “old” data in modern reanalyses

Data sparsity

- Spatial/co-variate impact of observations is largely determined by assumptions on background errors (B)
- Temporal impact dissipates rapidly (weather scales)
- Quality control and bias correction is very difficult

$$\mathbf{x}^{\mathrm{a}} - \mathbf{x}^{\mathrm{b}} = \mathbf{B}\left(\left.\frac{\partial \mathbf{h}}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^{\mathrm{a}}}\right)^{\mathrm{T}} \mathbf{R}^{-1}\{\mathbf{y} - \mathbf{h}(\mathbf{x}^{\mathrm{a}})\}$$

ECMWF

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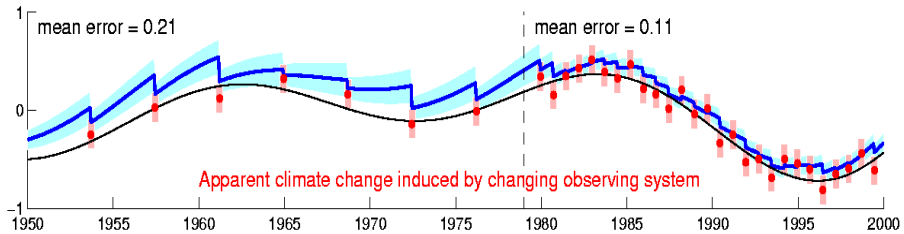
Model biases

- Are not sufficiently constrained by observations
- Changes in observing system result in false trends and variability
- Some work has been done on correcting model biases during data assimilation



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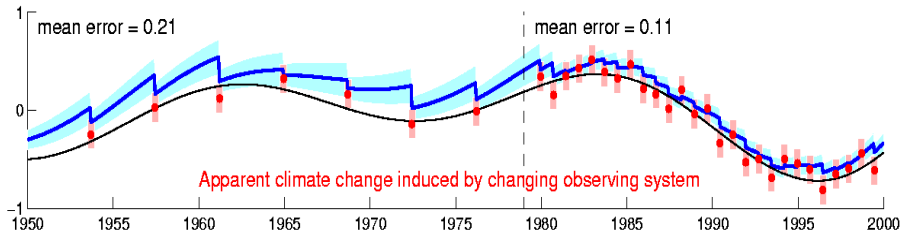
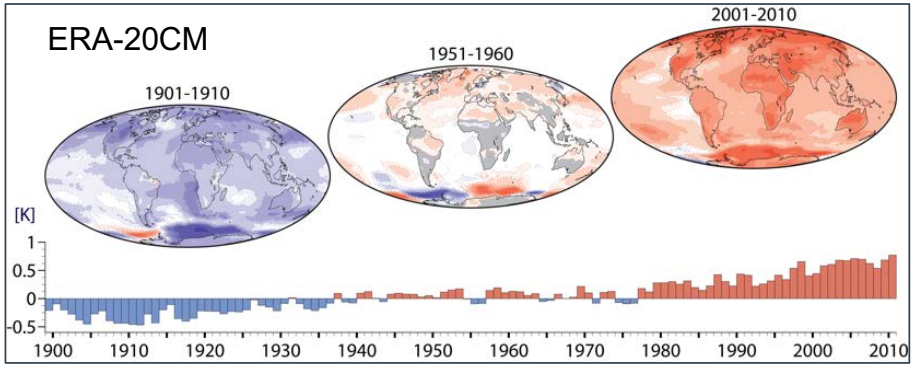


Accurate modelling of observations

- Not enough metadata
- Representativity issues: can the model represent what was measured?

ECMWF

~~Conclusions~~ Questions

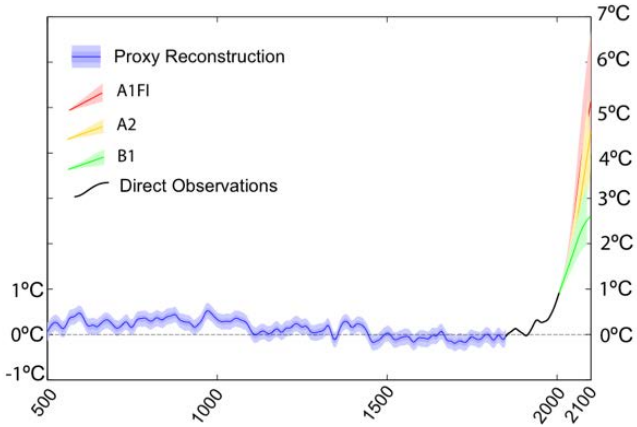


Modern reanalysis

- Developed in NWP context
- Data and models are compatible in terms of representing weather scales
- Is the methodology useful for paleoclimate reconstruction?

Model biases

- Biases in coupled climate models are considerable
- Should the data assimilation problem be re-formulated to constrain model bias parameters first of all?

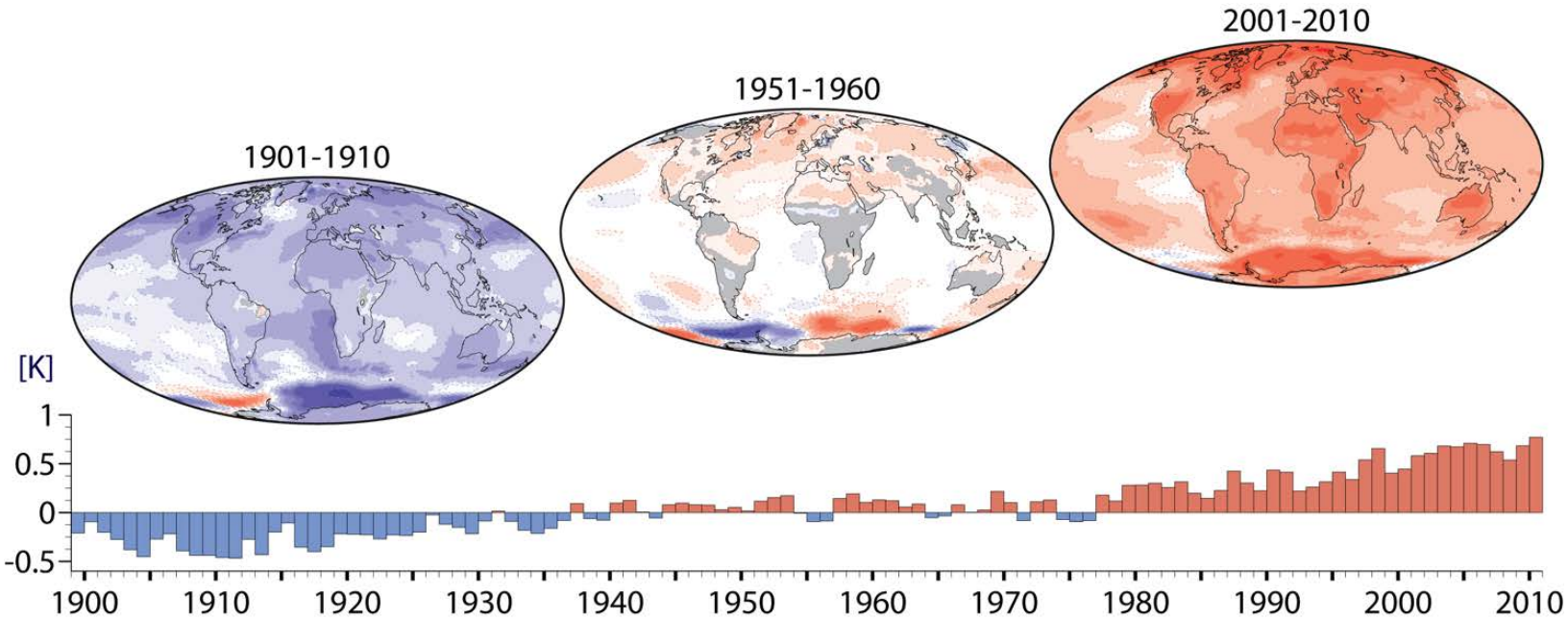


Accurate modelling of observations

- Are current-generation climate models good enough to accurately simulate available proxy data?

ECMWF

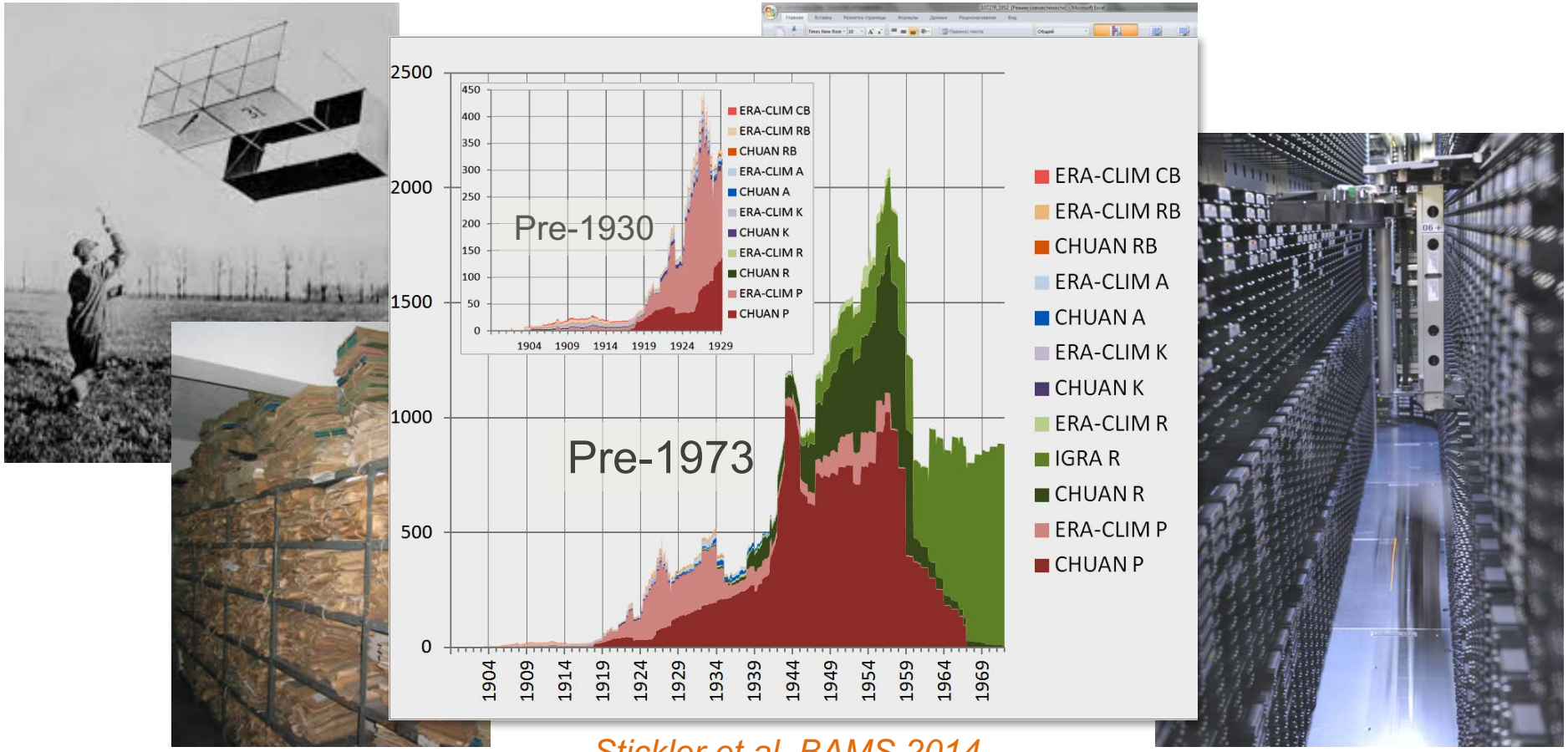
ERA-20CM: Annual and decadal temperature change (ensemble mean)



ERA-20CM data available at www.ecmwf.int/research

Hersbach et al, QJ 2015

Data rescue: Early 20th-century upper-air weather observations



Stickler et al, BAMS 2014

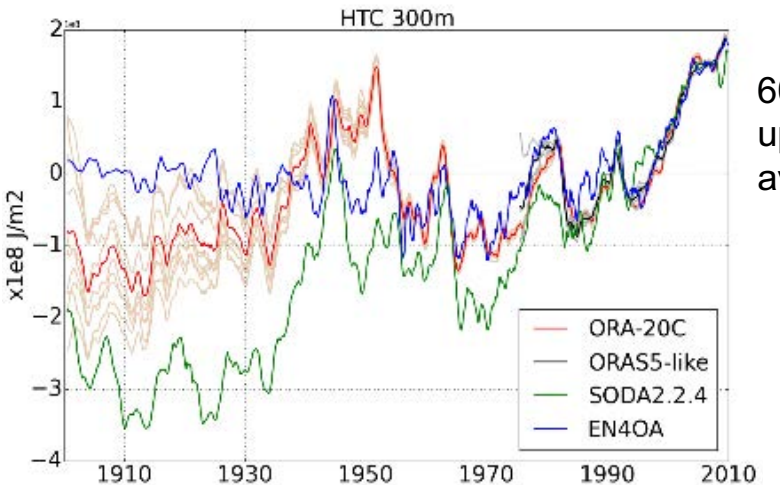
ORA-20C: ECMWF's first centennial ocean reanalysis

Ocean

Sea ice

Model: NEMO/LIM2 (CY41R2, Mar 2016)
Forcing: HADISST2 for SST (nudged) and ERA-20C
Observation: salinity and temperature profiles
Assimilation: 3D-Var (10-member ensemble)
Resolution: ORCA1 Z42
Period: 1900-2010

Initial conditions from previous ocean runs based on different configurations were used to sample the uncertainty of the ocean state in 1900



60˚S - 60˚N heat-content anomalies for the upper ocean with respect to the EN4OA average for 1970-2000

E. de Boisseson *et al*. (2016) An ensemble of 20th century ocean reanalyses for providing ocean initial conditions for CERA-20C coupled. ERA Report Series, 24

Diversification: MACC, ORAS and ERA/Land