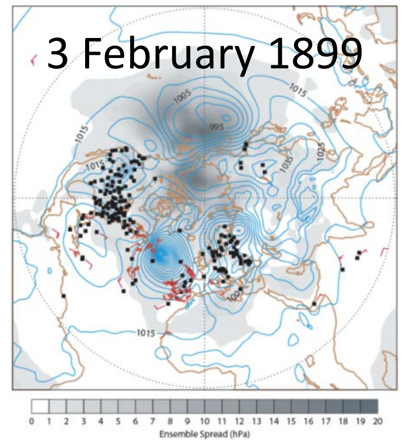
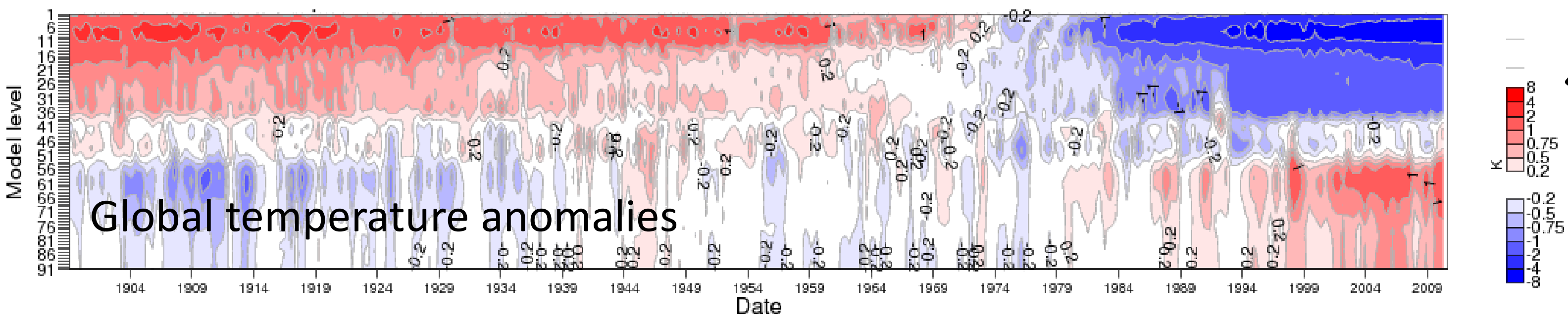
ECMWF ReAnalysis (ERA)
Data assimilation aspects





Paul Poli
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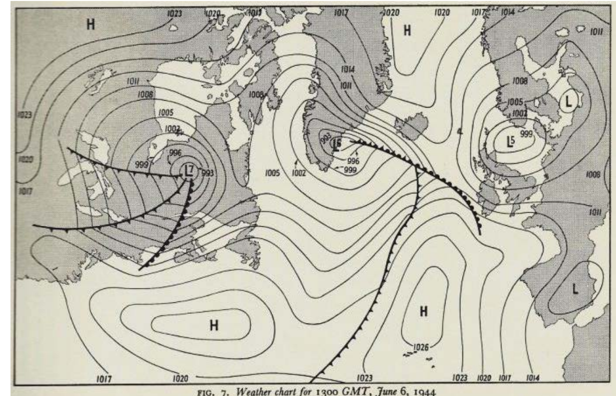
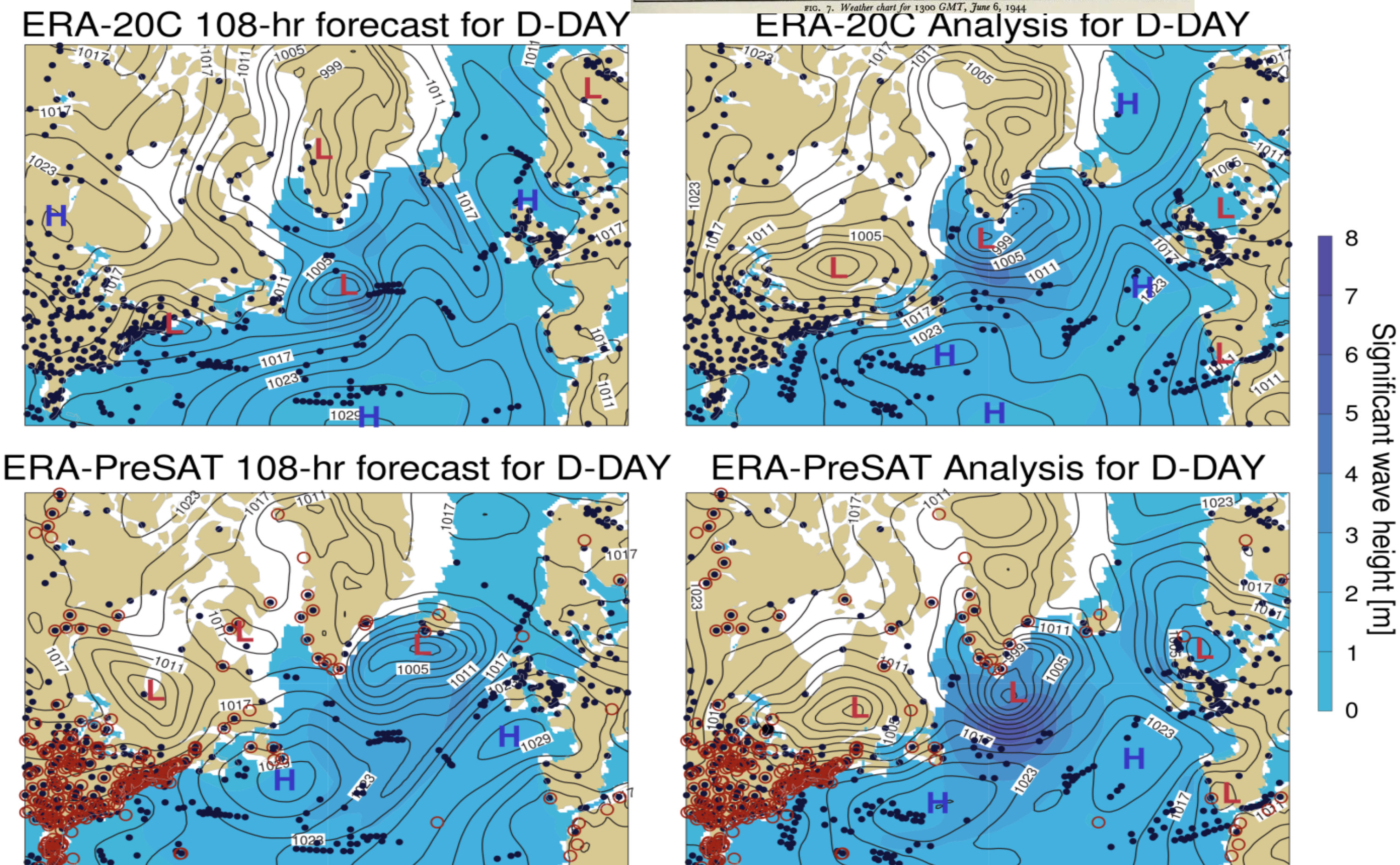
James Stagg,
Chief Meteorologist



Hand-drawn analysis for 13 UTC 6 June 1944



- **Surface observations**

o **Upper air (mostly pilot balloons)**

Reanalysis course outline

What is reanalysis?
- General concepts
- Goals of reanalysis

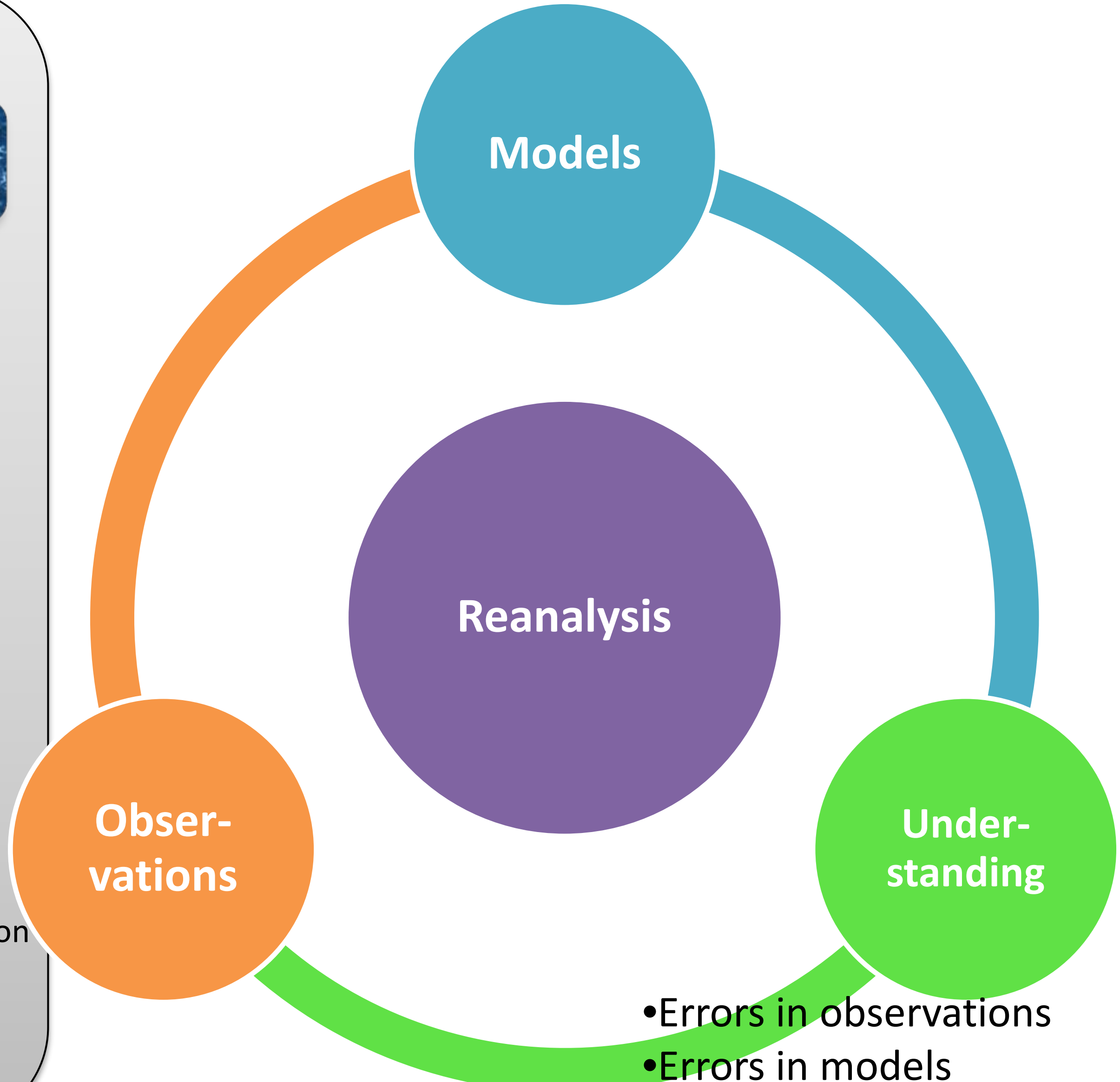
How are reanalyses made?
- Observations
- Model
- Data assimilation

Background errors | Observation errors

Reanalysis projects & applications
- Projects
- Users
- Applications

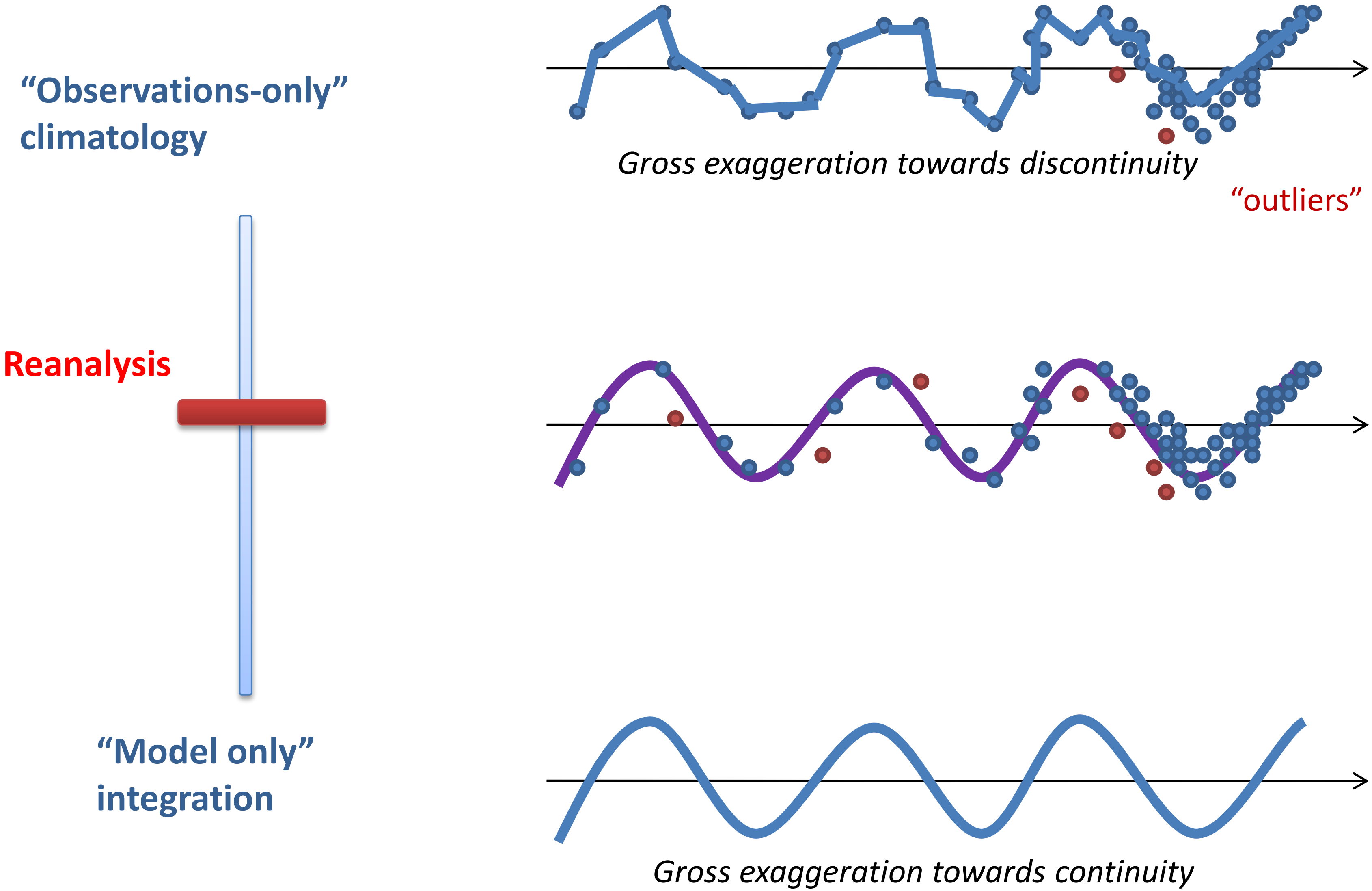
Conclusions
- Summary
- Challenges ahead

The three pillars of geosciences



- Errors in observations
- Errors in models
- Predictability
- Variability

Objective: Reconstruct the past



Reanalysis *products* and Reanalysis *process*

- Reanalysis *products*
  - Gridded fields of NWP model
    - Control variables: vorticity, divergence, temperature, humidity, ozone…
    - Derived variables: precipitation, radiation…
  - Fit to observations
    - Before, and after, assimilation
    - Before, and after, bias correction
- Reanalysis *process*
  - Integration of an invariant, modern version of
    a data assimilation system and numerical weather prediction model,
    over a long time period,
    assimilating a selection of observations

Differences with observations-only gridded datasets

1) How reanalysis deals with "missing data"

- Only assimilate observations when and where they exist
- In between, the "best model available" (from NWP!) is used to "fill in the blanks", from past and neighboring information

2) Reanalyses produce fields are space- and physically-consistent

- As specified by the underlying numerical model based on physical laws

3) Reanalyses use the widest variety of observations

- Not just temperatures, or winds, or humidities in isolation of each other,
- Also pressures, satellite observations, etc… = multi-variate approach
- In fact, reanalyses are the most data-rich products to date (30 billion obs. in ERA –Interim)

4) Reanalysis uses and evaluates all observations in a consistent way

- Accuracy (error bias) and precision (error std.dev.) explicitly taken into account
- Quality control (QC) procedures apply across all observation types
- The background prediction provides QC advantage w.r.t statistical reconstruction

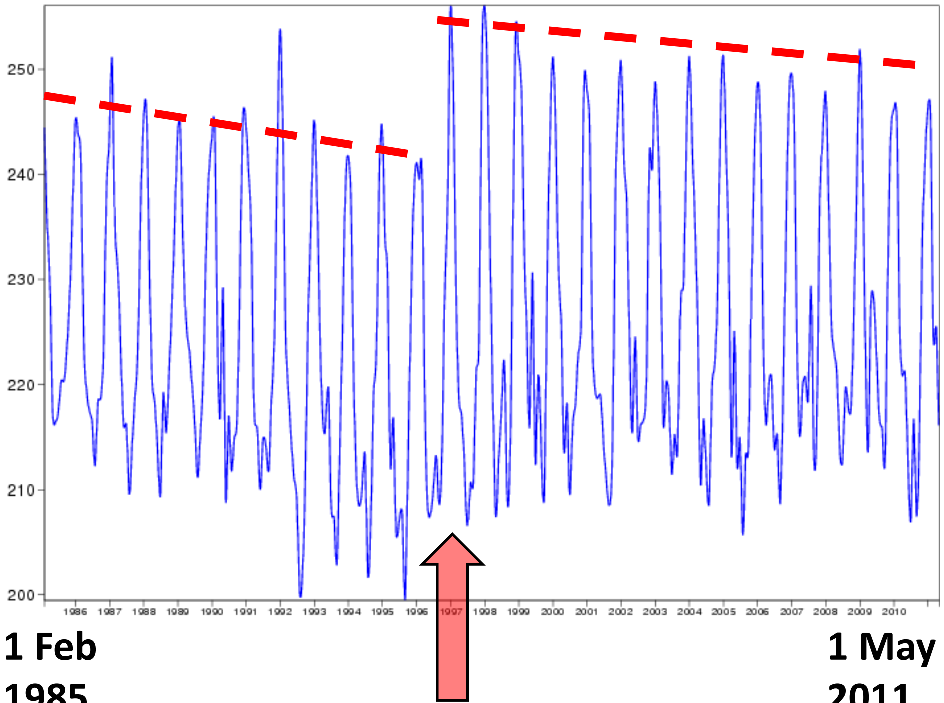
5) Observation quality and quantity changes over time are not easily dealt with

- LIKE ANY OTHER observations-based dataset.
- Reanalyses can adjust the observation influence to take account of how much information is already known (background errors). Example later with ERA-20C ensemble.

Observations-only datasets are the "observation limit" of reanalyses. They are extremely important for improving understanding.

Why re-analyze?
Overall aim is a greater time-consistency of the products

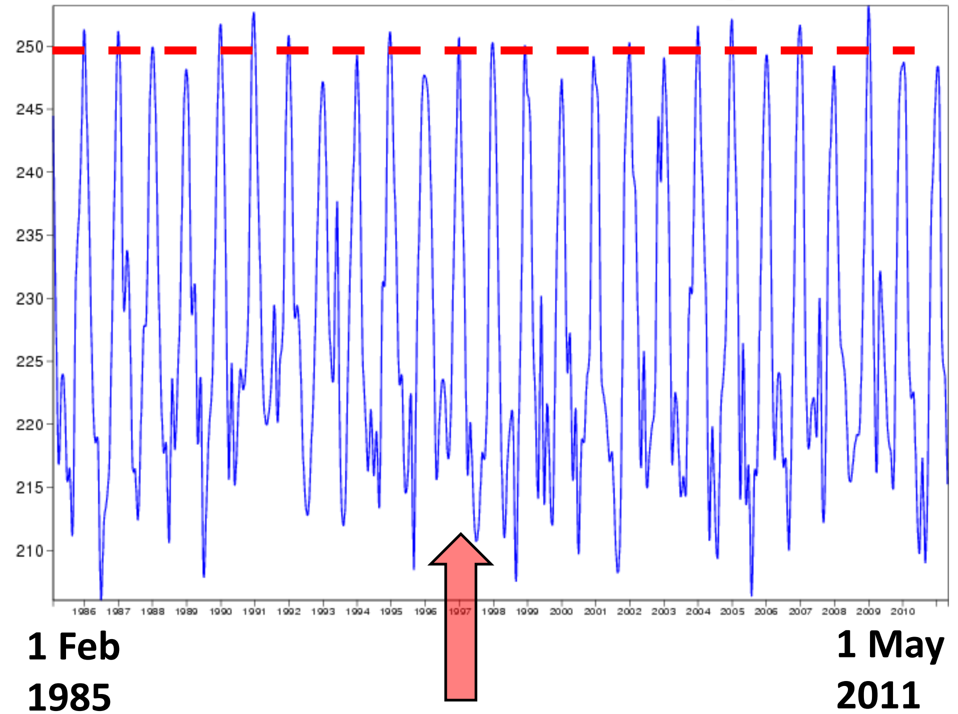
ECMWF Operations T2m at South Pole (average 88S-90S)



1 Feb 1985 **1 May 2011**

Was there a sudden change in South Pole summer variability in 1997?

ERA-Interim T2m at South Pole (average 88S-90S)



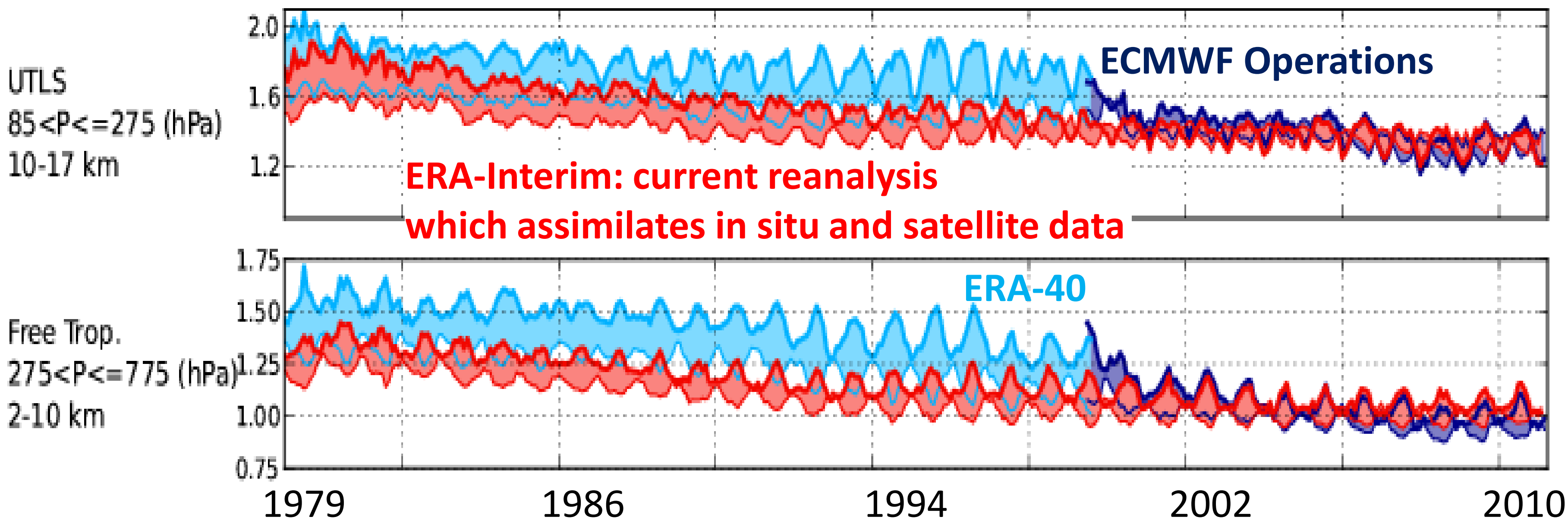
1 Feb 1985 **1 May 2011**

… probably not

Reconstructing the past more smoothly

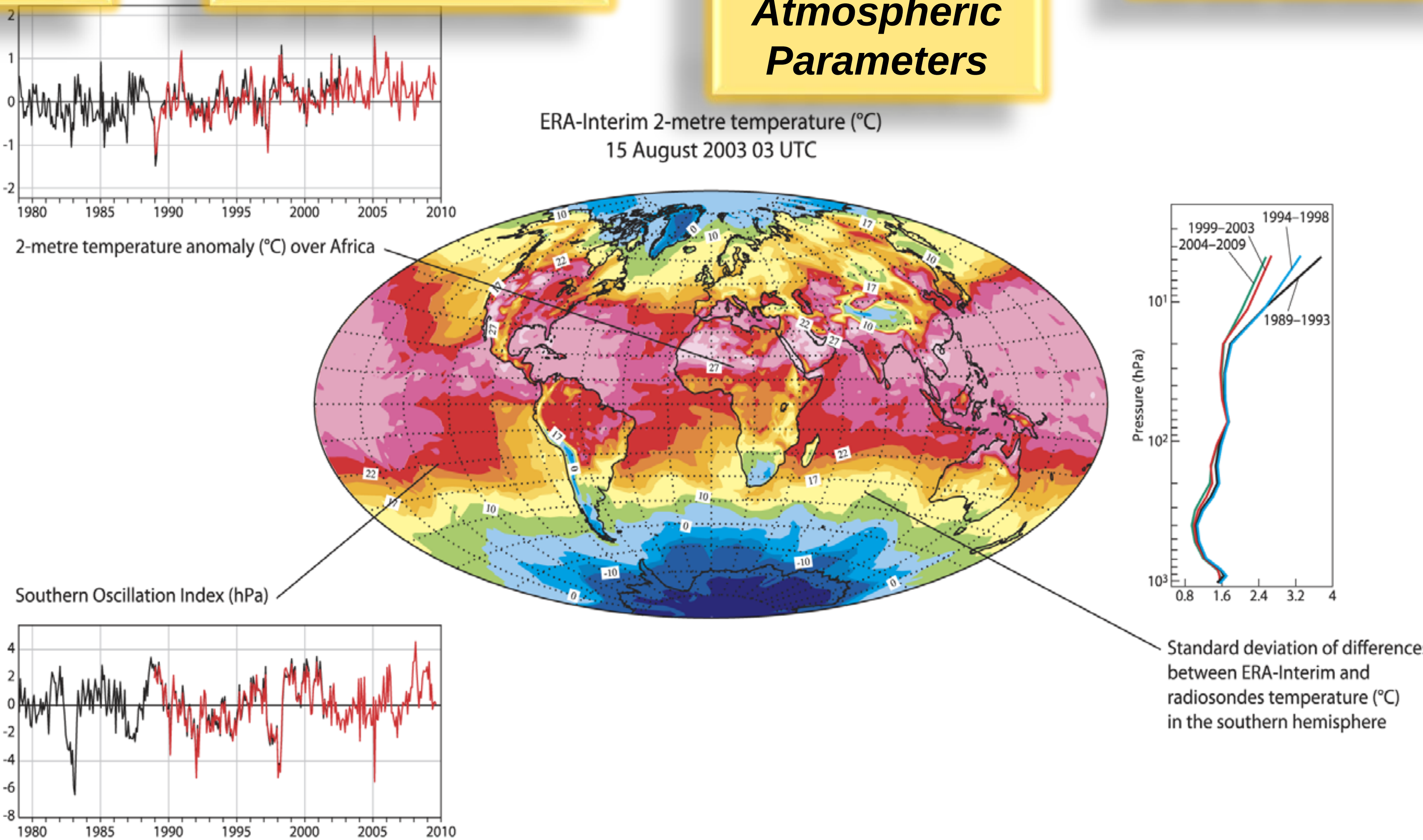
RMS of differences between observations from radiosondes and short-term forecast (background)

Thin line for Northern Hemisphere extratropics
Thick line for Southern Hemisphere, typically less well observed



Summary of the goals: reanalysis products should be consistent …

…in Time | **…in the Horizontal** | **…across Atmospheric Parameters** | **…in the Vertical**



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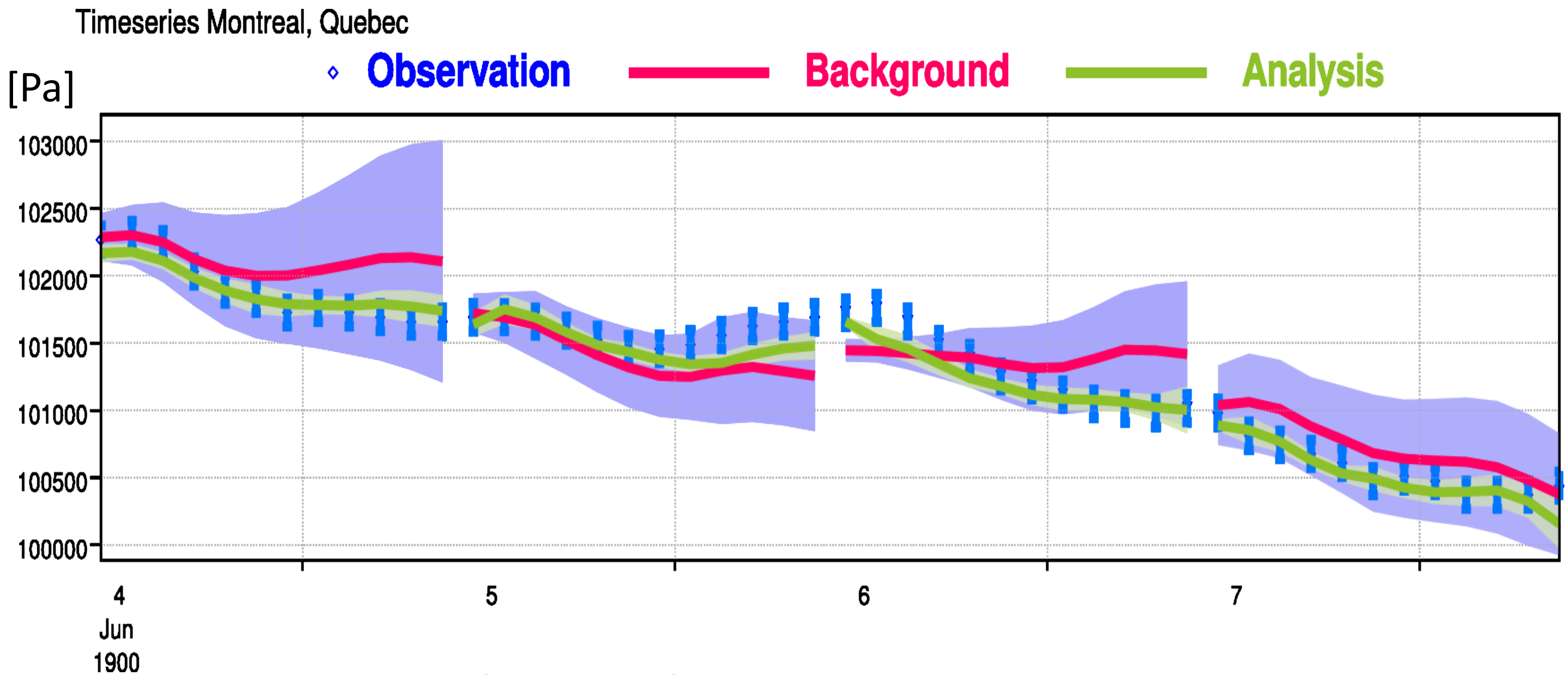
The ubiquitous data assimilation slide:

Constructing a history of the past with (24-hour) 4DVAR data assimilation



For each analysis, construct a cost function and find its minimum:

background constraint — observation constraint

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

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

$$\mathbf{J(z)} = (\mathbf{z_b} - \mathbf{z})^T \mathbf{B}_z^{-1} (\mathbf{z_b} - \mathbf{z}) + [\mathbf{y} - \tilde{\mathbf{h}}(\mathbf{z})]^T \mathbf{R}^{-1} [\mathbf{y} - \tilde{\mathbf{h}}(\mathbf{z})]$$

$$\mathbf{z}^T = [\mathbf{x}^T \boldsymbol{\beta}^T] \qquad \tilde{\mathbf{h}}(\mathbf{z}) = \mathbf{h}(\mathbf{x}) + \mathbf{b}(\mathbf{x}, \boldsymbol{\beta})$$

b simulates the observation biases

This produces the “most probable” atmospheric state *

* In a maximum-likelihood sense, which is equivalent to the minimum variance, provided that **background and observation errors are Gaussian**, **unbiased**, **uncorrelated with each other**; all error covariances are correctly specified; model errors are negligible within the analysis window

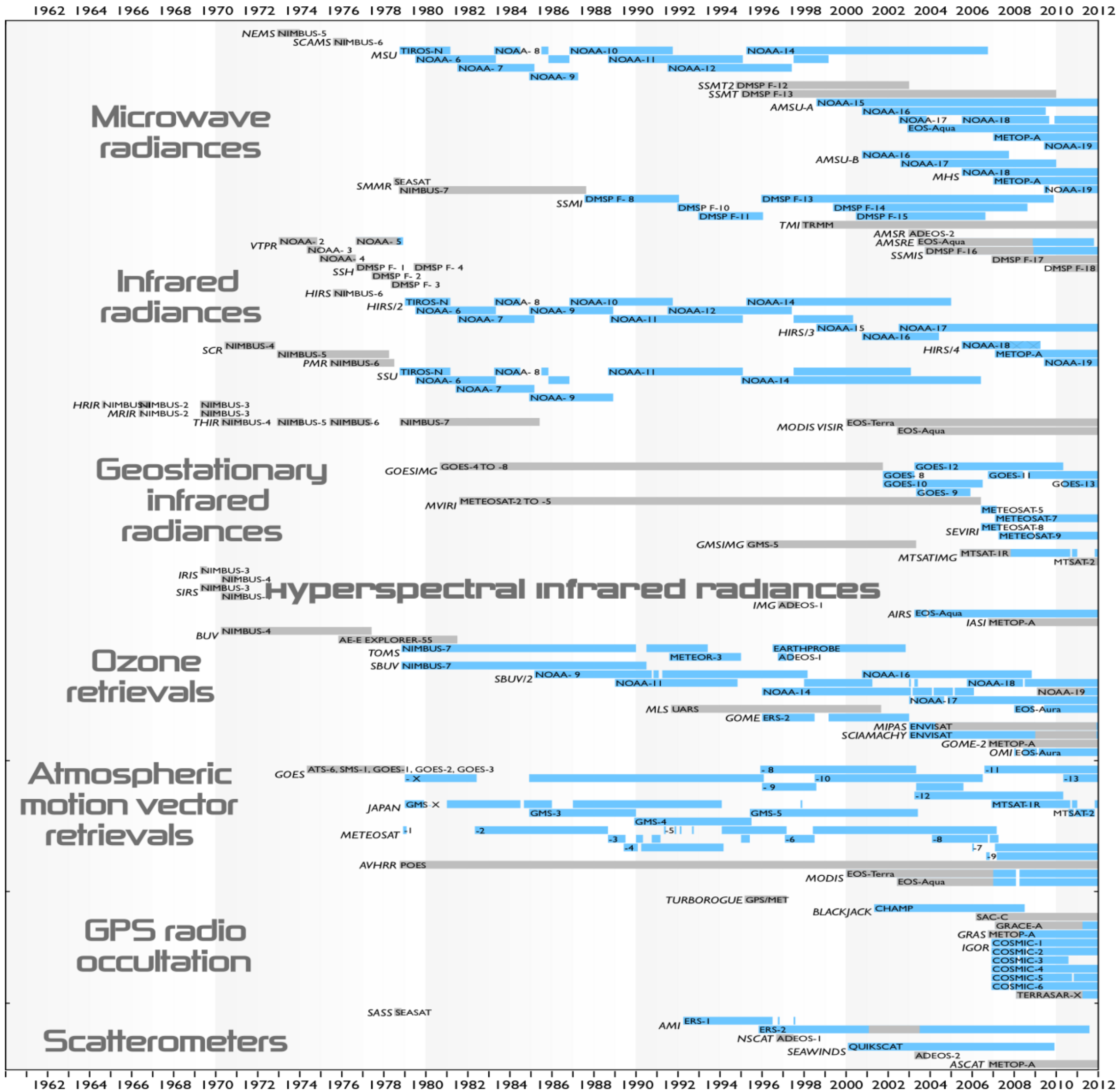
Reanalysis components
Part 1: Observations

Use as many observations as possible	• Goal being to produce the best estimate of the atmospheric state, at any given time and place • Question whether short datasets add long-lasting value
Use "good" observations	• Use corrected/reprocessed datasets when available • Focus efforts on long-term records • Consider the traceability of your sources

Keep track of what goes in/comes out	• Monitoring the key steps:
	  • observation ingest, blacklisting,
	  • thinning, assimilation

Keep that setup throughout	• A reanalysis production can take several years • Beware of large components of the observing system that suddenly disappear from the assimilation… bug?

Increased satellite observation diversity



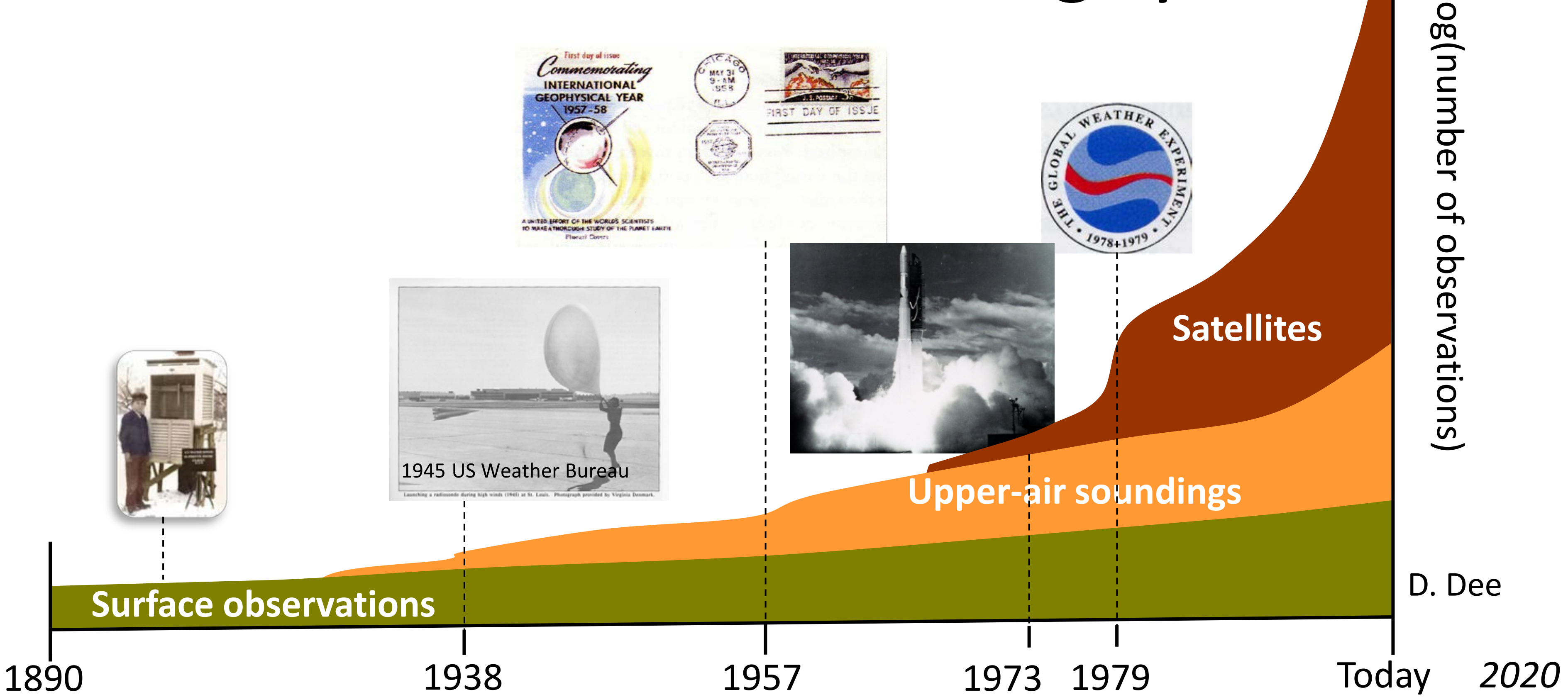
Observation timeline (atmosphere)

In blue: data that were assimilated in ERA-Interim

In grey: data that were not assimilated. …For future reanalyses…

Note the timeline starts in 1969

Evolution of the observing system



Manual stations, limited data exchange

First radiosonde networks, systematic soundings

International Geophysical Year: radiosonde network enhanced, especially in the Southern Hemisphere

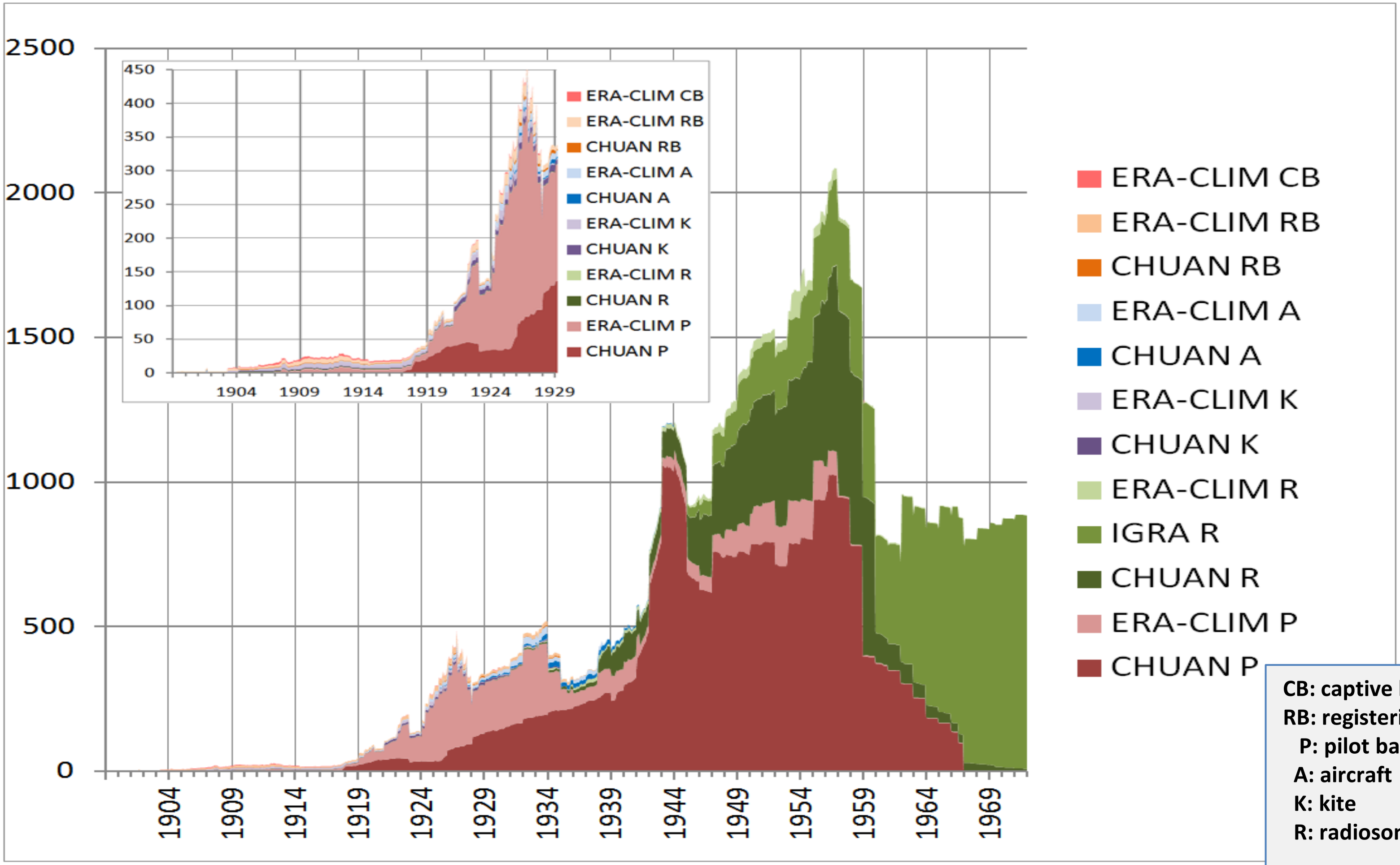
First operational satellite soundings (NOAA-2)

Improved sounding from polar orbiters; Winds from geostationary orbit; More data from commercial aircraft; First drifting buoys

More satellites, aircraft, buoys, ocean gliders and drifters. Fewer radiosondes, but probe higher. Better knowledge of instruments. More obs. per hour.

Opport-unity sensors : cell phones, UAVs, vehicles, rooftops, …

Efforts to improve the historical upper-air data record: “data rescue” a.k.a “data recovery”

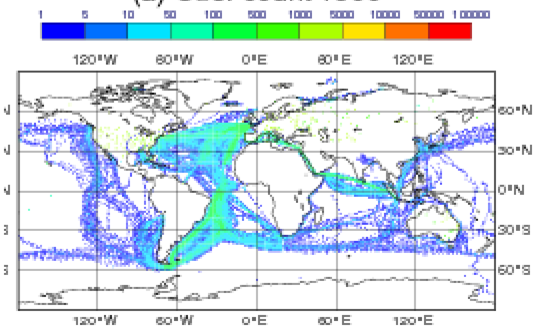


CB: captive balloon
RB: registering balloon
P: pilot balloon
A: aircraft
K: kite
R: radiosonde

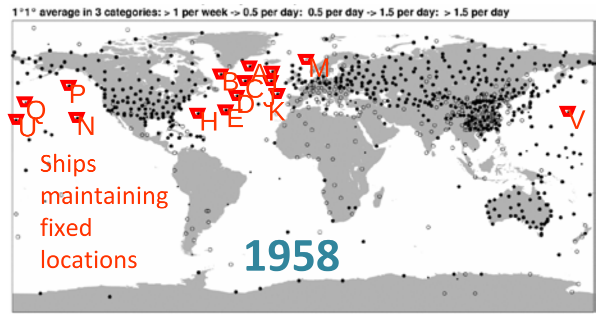
Stickler et al., 2014 : "ERA-CLIM: Historical Surface and Upper-Air Data for Future Reanalyses." *Bulletin of the American Meteorological Society*

Evolution of the observation coverage

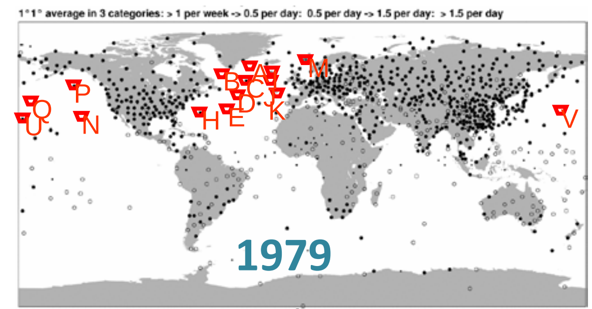
(a) Obs. count 1900



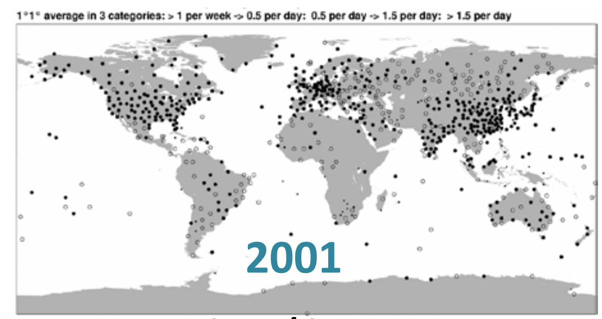
Surface pressure network



1609 soundings/day



1626 soundings/day

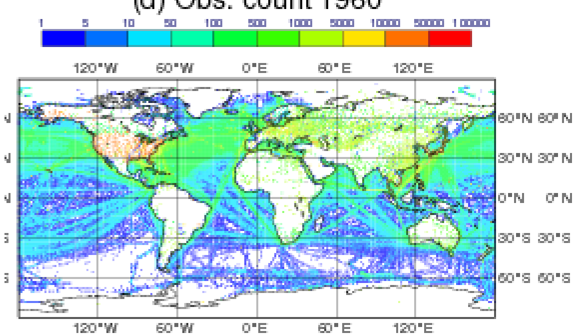


1189 soundings/day

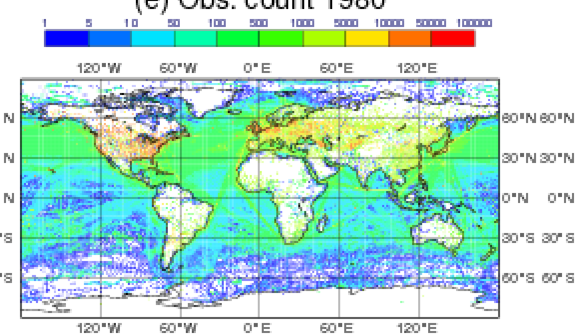
Radiosonde network

S. Uppala

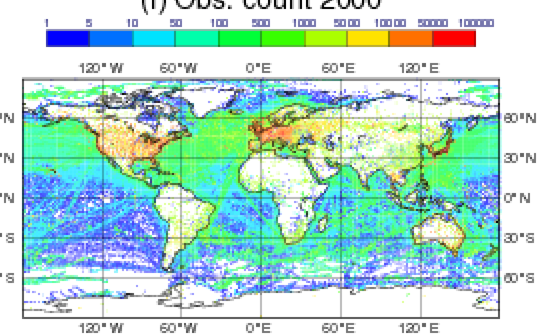
(d) Obs. count 1960



(e) Obs. count 1980



(f) Obs. count 2000



https://www.youtube.com/watch?v=NUfdFCHoxHM

Reanalysis components
Part 2: forecast model

Use a fixed version

- Dynamics, physics etc…
- Resolution must be computationally affordable
- Producing N decades in 1 year implies a factor N in run-time

Use the "best" model around

- Use the near-latest, stable, model version operational at some point
- Not the time to start experimenting with new, untested configurations

Shop around for forcing data

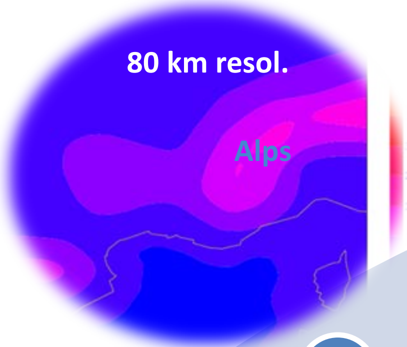
- Ideally, one dataset per forcing, to cover the whole time period
- Consider standards such as CMIP5

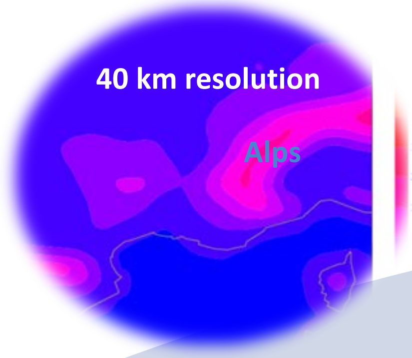
Keep that setup throughout the production

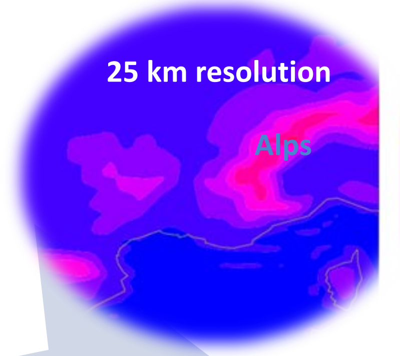
- Be extra careful with forcing data – any problem will map into products!
- Be extra careful when changing machine, compiler….

Illustration of resolution improvements

Orography of the Western Alps (500m contours)







Heritage

- **FGGE**
  1979
- **ERA-15:** 190 km resolution
  (1979-1993)
- **ERA-40:** 125 km resolution
  (1957-2002)

ERA-Interim
80 km resolution
(1979-present)

ERA-CLIM pilot reanalyses

- **ERA-20CM and ERA-20C**
  125 km resolution
  (1900-2010)
- **ERA-20C Land**
  25 km resolution
  (1900-2010)
- **ERA-SAT**
  40 km resolution
  (1979-onwards)

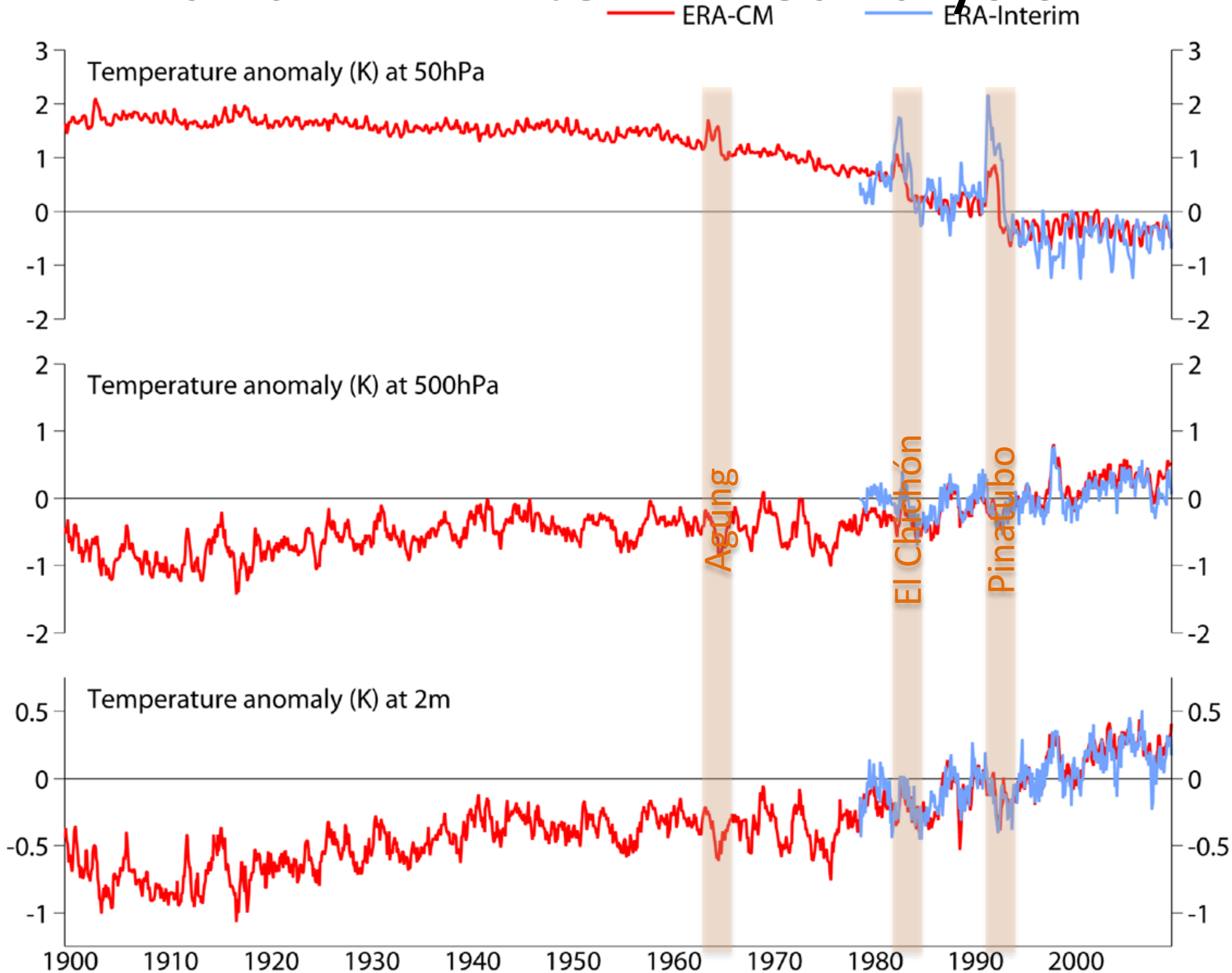
ERA-CLIM2 reanalyses

- **CERA-20C**
- **CERA-SAT**

Model forcings for reanalysis

- ERA-20CM integrates the ECMWF model, but without data assimilation
- So far, the previous ECMWF reanalyses did not attempt to use so many “historical forcing” datasets.
- ERA-20CM uses the following forcings:
  - Sea-surface temperature and sea-ice cover (Hadley Centre)
  - Solar irradiance (CMIP5)
  - Greenhouse gases (CMIP5)
  - Ozone for radiation (CMIP5)
  - Tropospheric aerosols (CMIP5)
  - Volcanic aerosols (CMIP5)

Comparison between “model-only” ERA-20CM and ERA-Interim reanalysis



Reanalysis components Part 3: Data assimilation & errors

Use a fixed data assimilation system (DAS)	• A blacklist to cover the entire reanalysis period • Observation handling for all: operators, thinning, etc… • Test the DAS with various amounts of observations
Errors in the background	• They change over time! • Need to account for this in one way or another
Errors in the observations	• Homework to find out Gross errors, Biases, and Random errors (std. dev. = specified as 'observation errors')
Keep that setup and monitor it	• Be extra careful during run-time etc… • Implement automated monitoring for all the key steps of the assimilation

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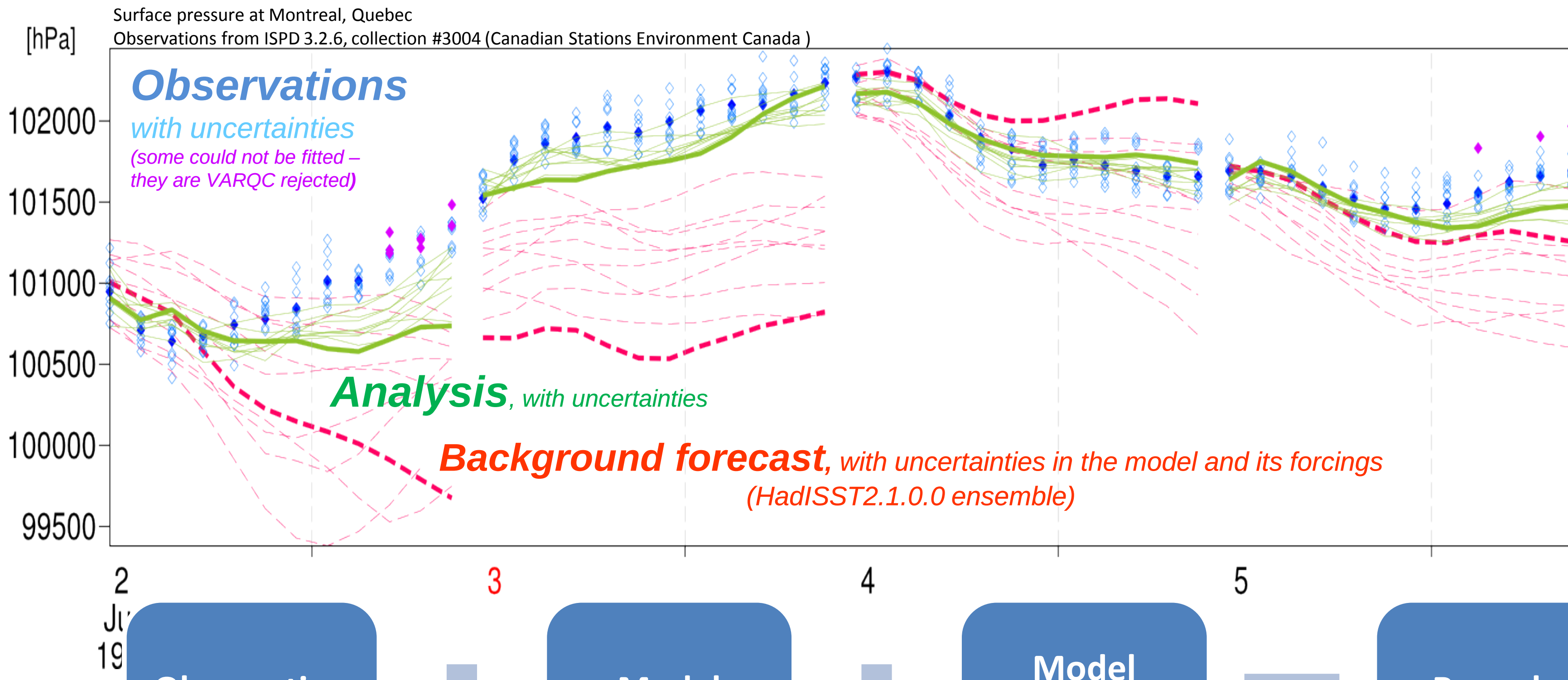
Ensemble of 4DVAR data assimilations: Discretization of the PDF of uncertainties

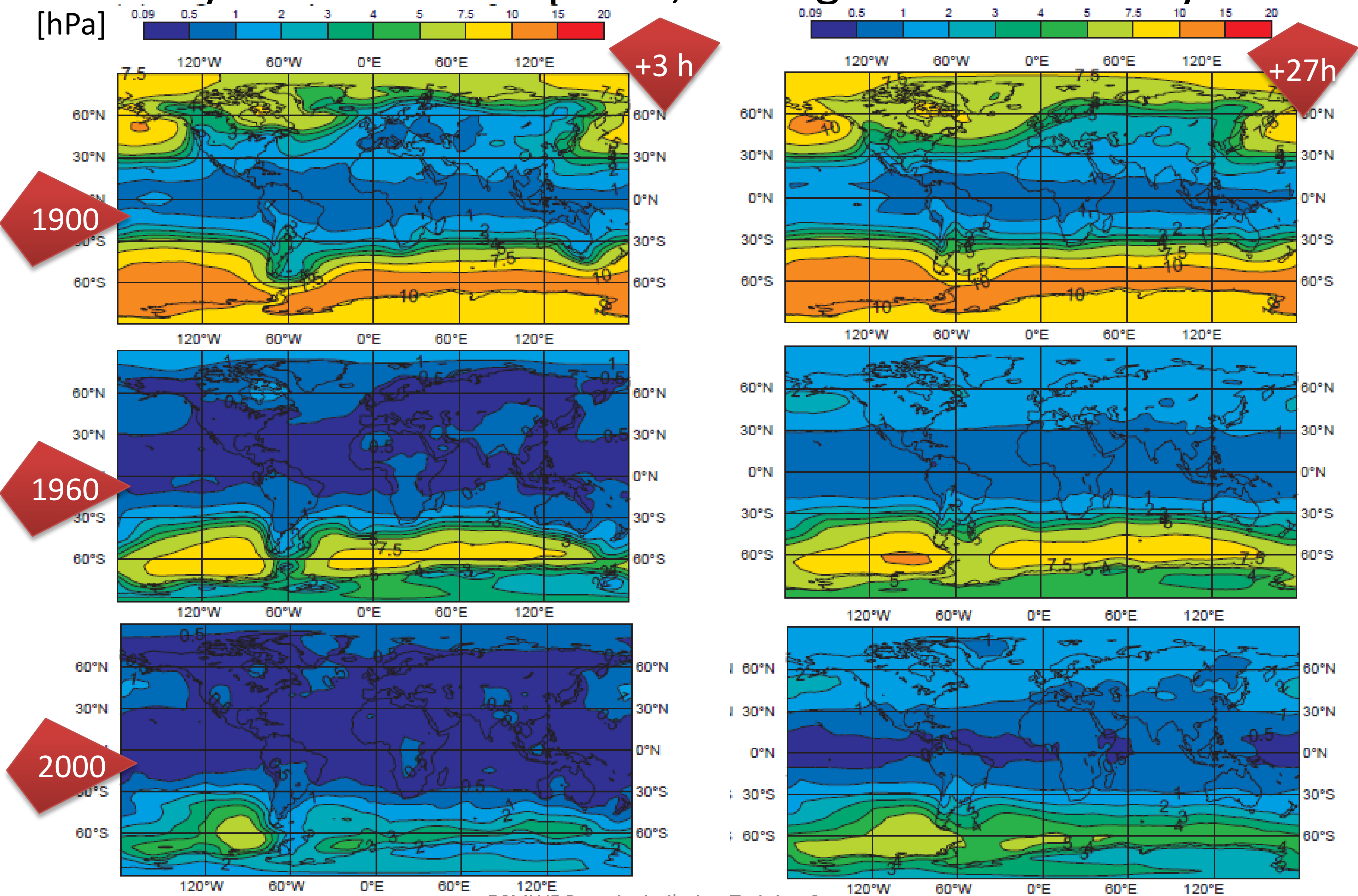


Observation uncertainties + **Model uncertainties** + **Model forcing uncertainties** = **Reanalysis uncertainties**

Benefits:

1. Estimate automatically our background errors, and update them
2. Provide users with uncertainties estimates (not perfect, but better than … nothing)

1-year ensemble spread, throughout the century

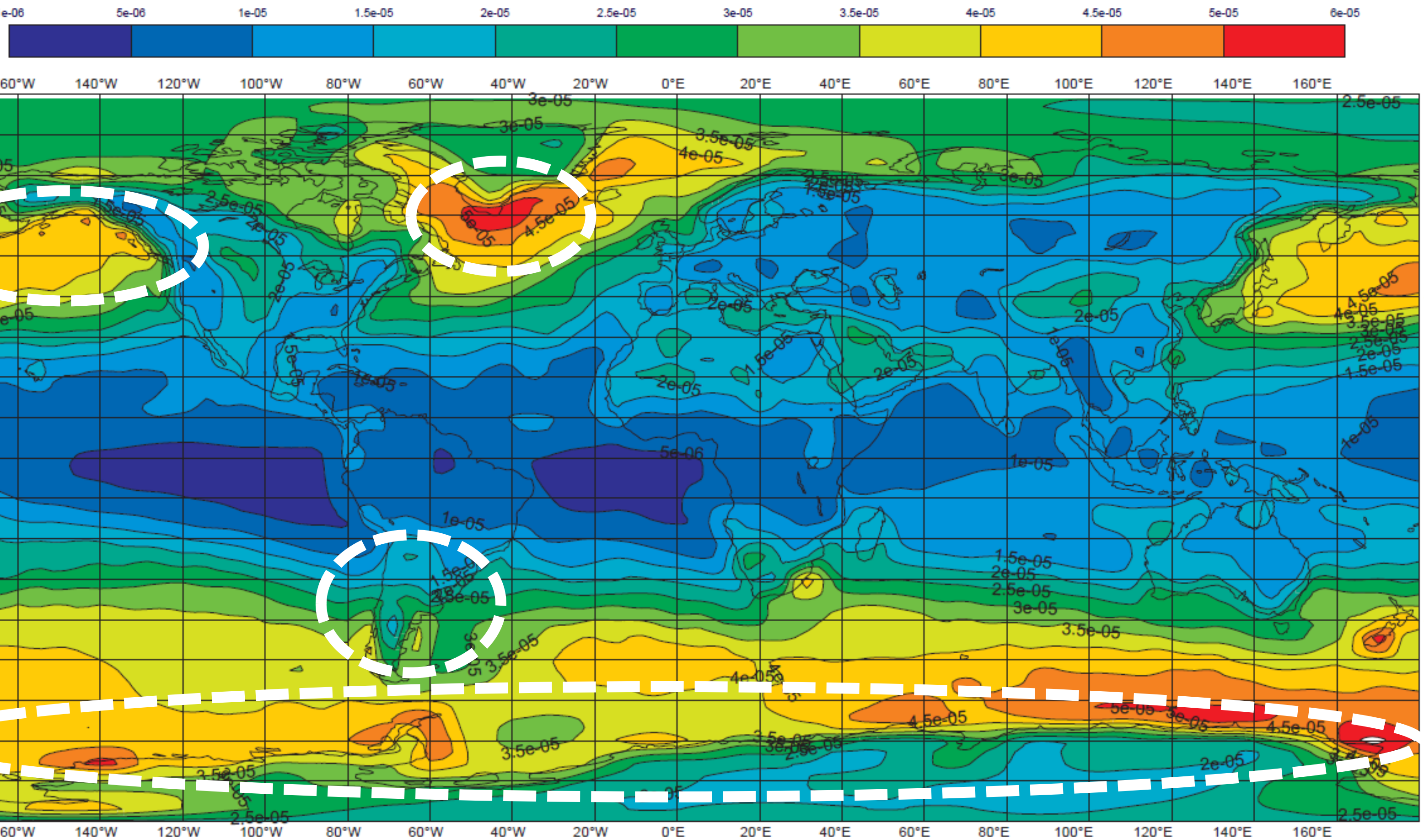


Background errors 2/6

From the ensemble spread, one can estimate background error variances

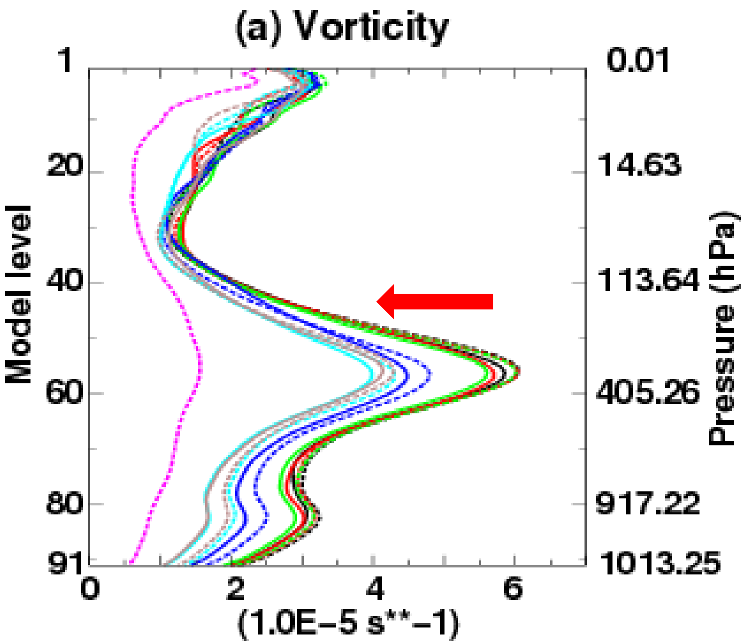
Estimate of bkg. error stdev. for vorticity at model level 89, for the year 1900

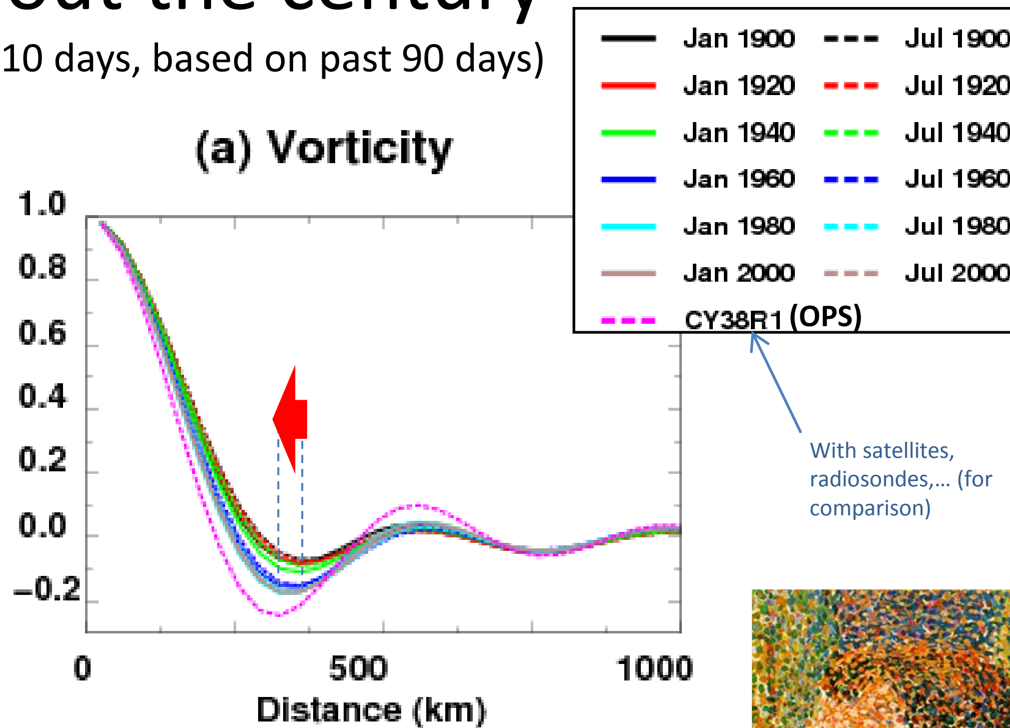
[s**-1]

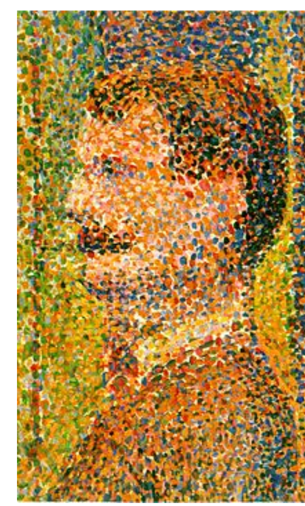


Self-updating background error covariances, throughout the century

(updated every 10 days, based on past 90 days)







Over the course of the century, more observations result in…

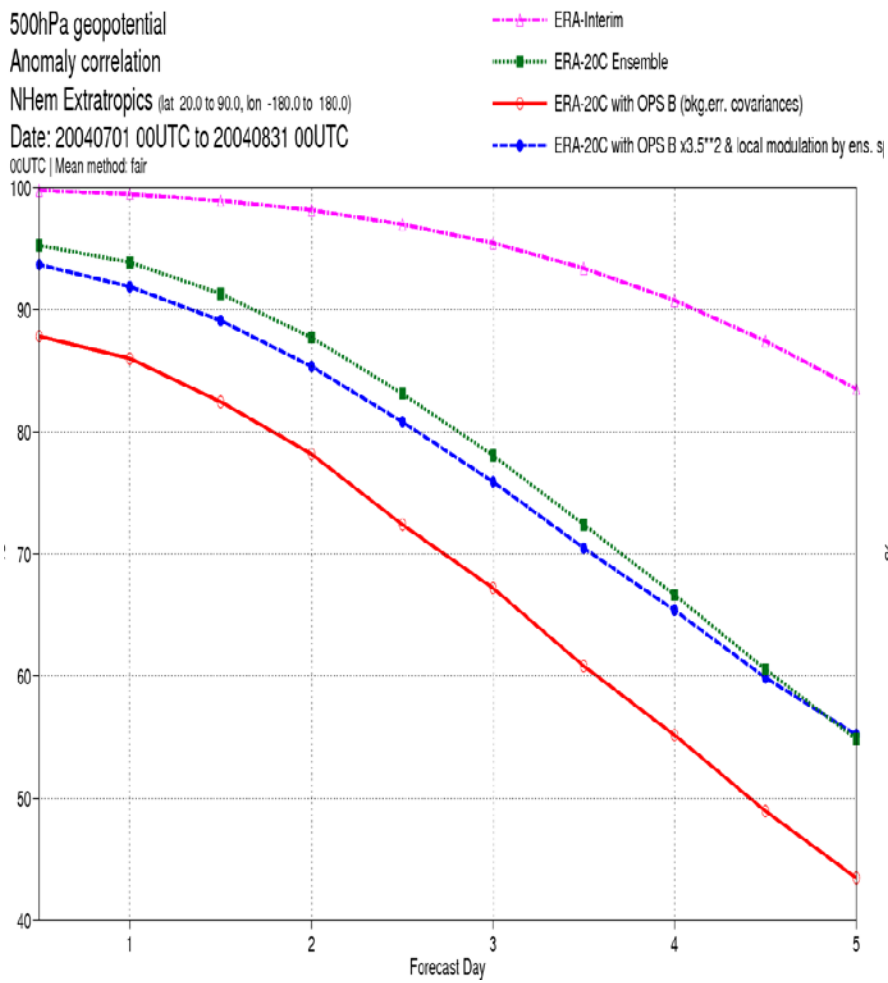
➔**Smaller** background errors, with **sharper** horizontal structures

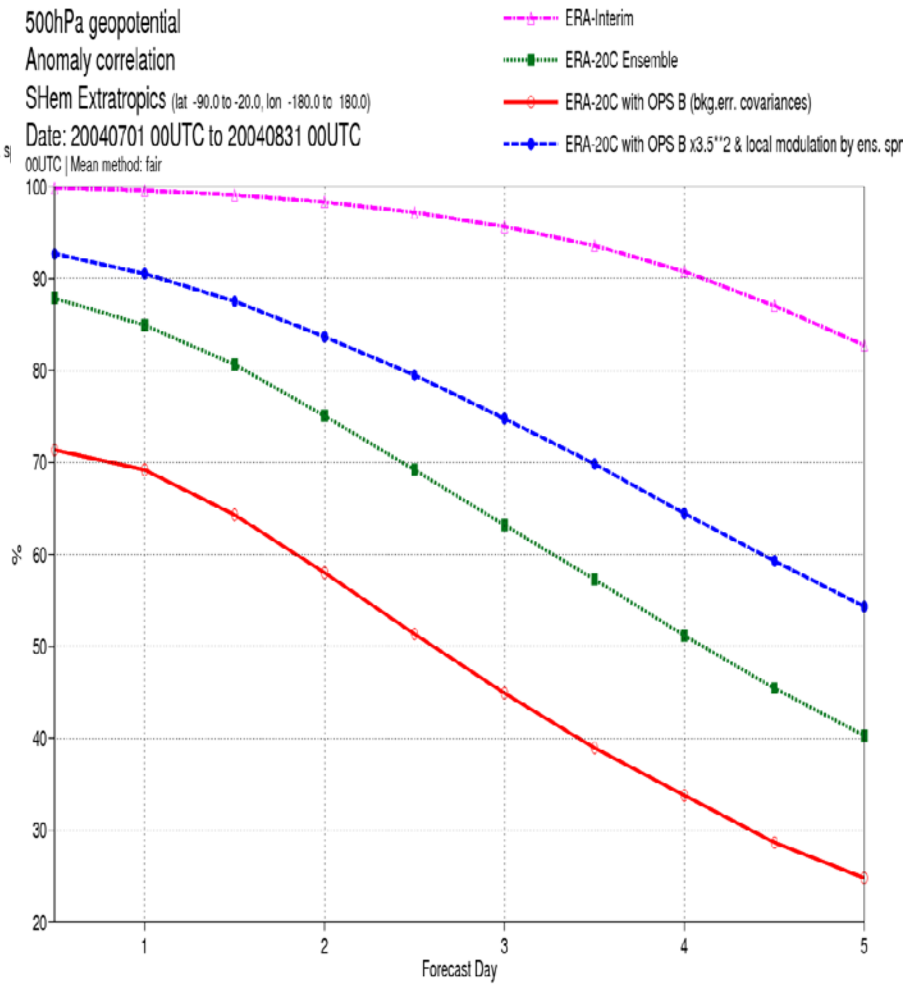
➔Analysis increments that are smaller, over smaller areas

= ERA-20C ensemble system adapts itself to the information available

Impact of background error assumptions

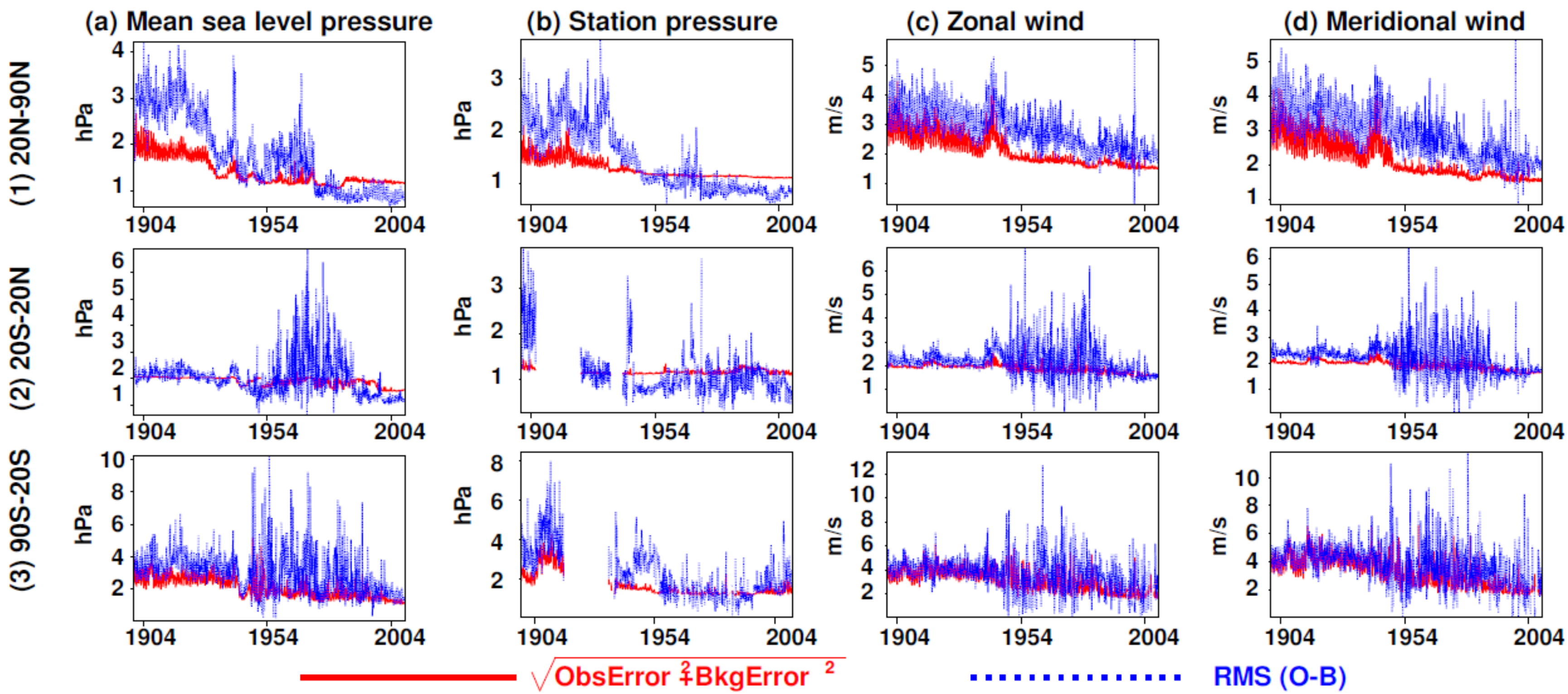
%





Background errors 5/6

Assimilation error assumptions: budget closure … or … “data assimilation reality check”



Assumed

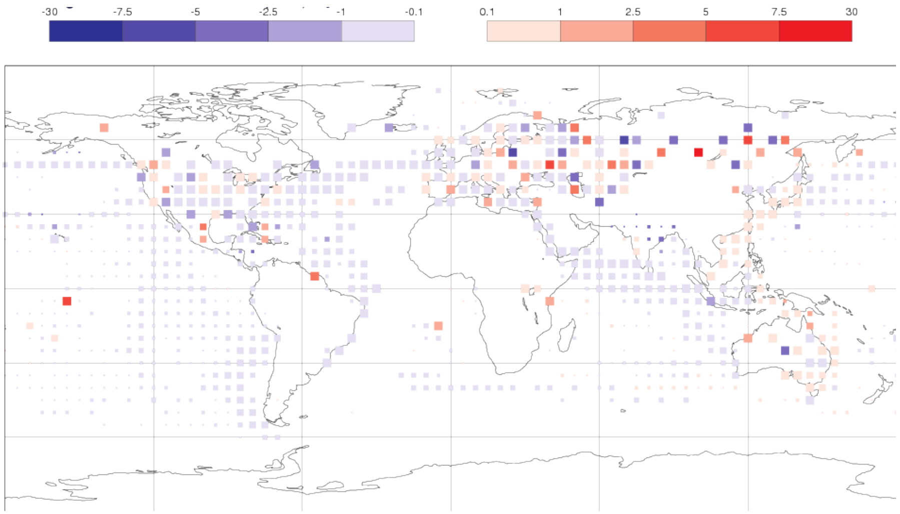
Actual

Showing only observations in the first 90 minutes of the 24-h window

Background errors 6/6

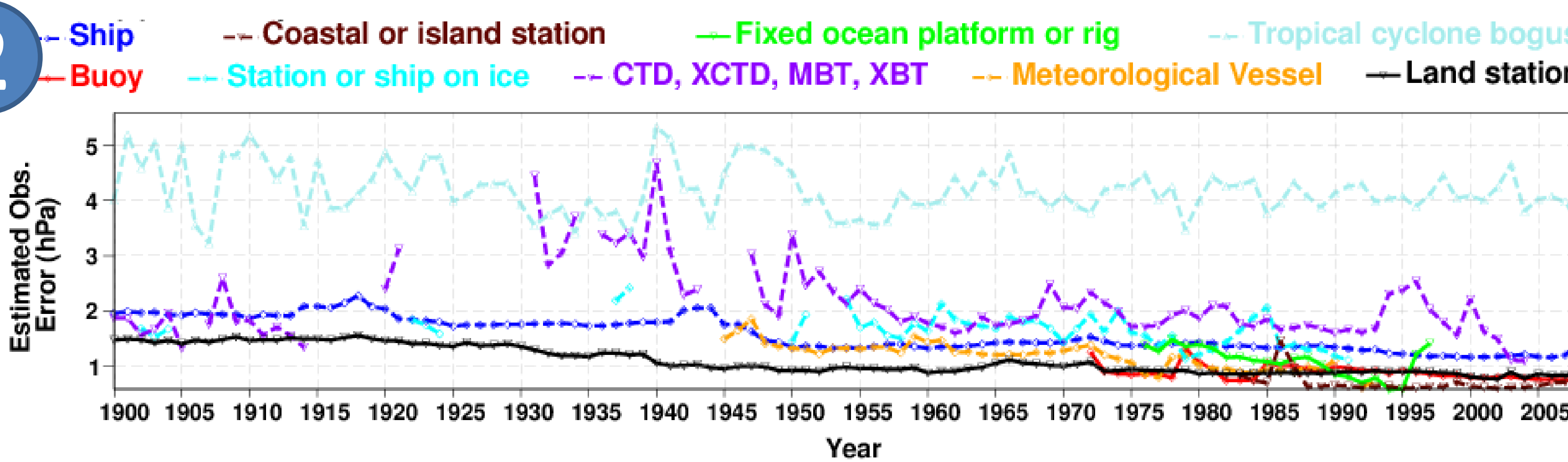
Estimates of observation errors

1



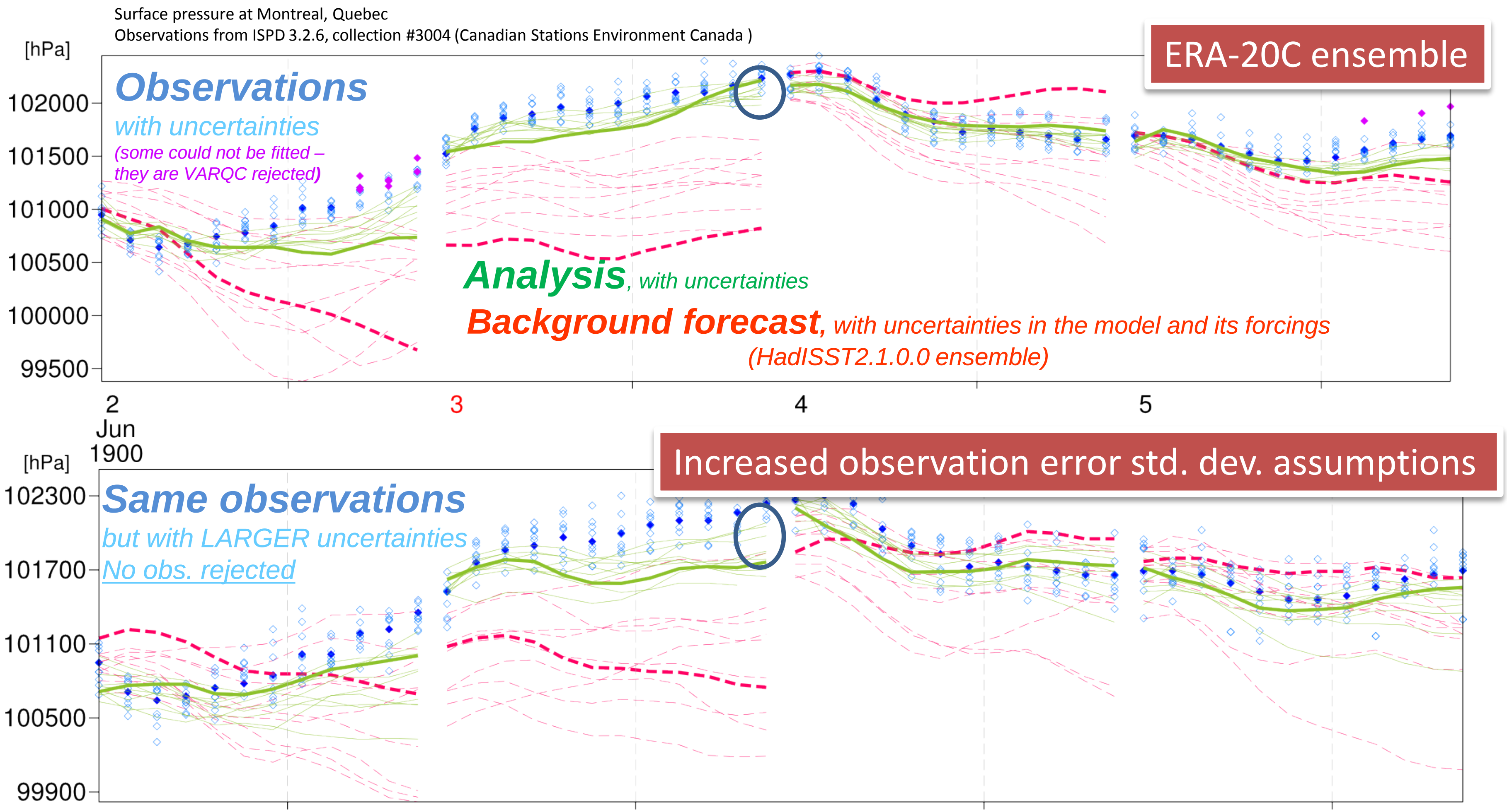
Map of surface pressure observation bias estimates in 1906 (VARBC)

2



ERA-20C assumed time invariant observation errors. This does not seem to be the case…

How useful are these revised (larger) observation error std. dev. estimates?



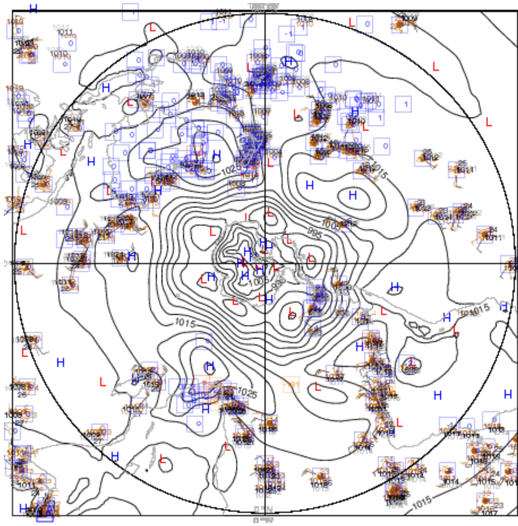
Analysis, presents LARGER uncertainties

Background forecast, Initial state (and subsequent ones) presents LARGER uncertainties

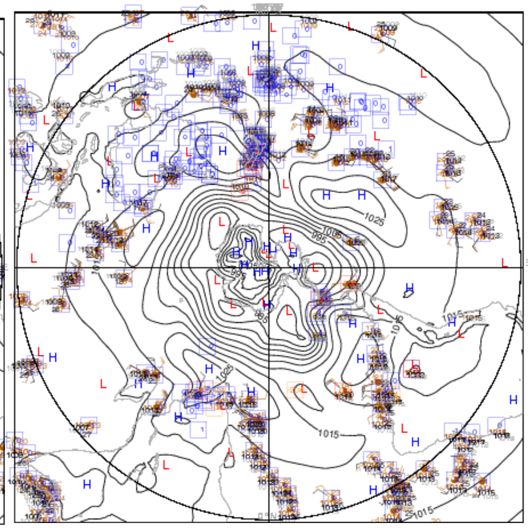
Impact of a single bad time-series

Southern Hemisphere

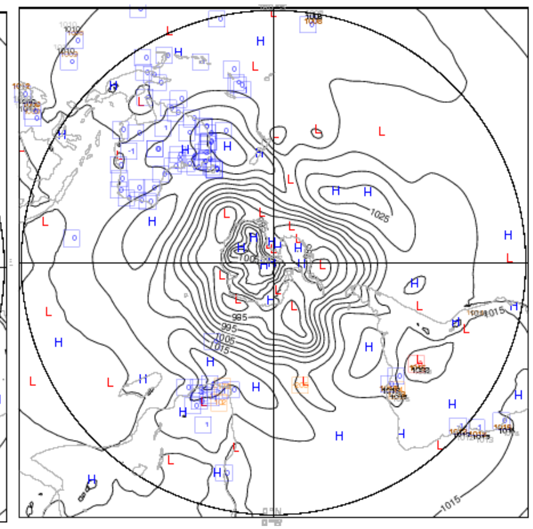
30 March 1954, 00 UTC



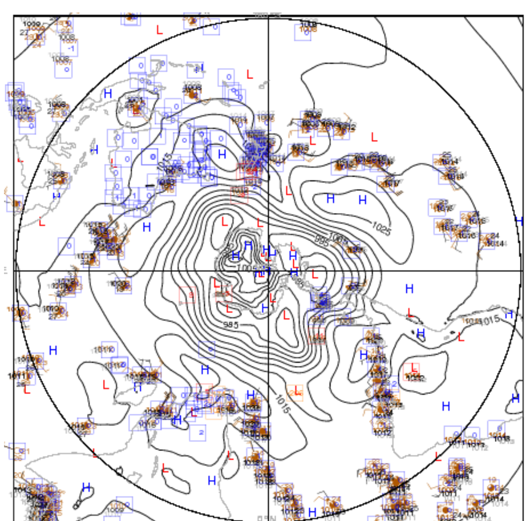
31 March 1954, 00 UTC



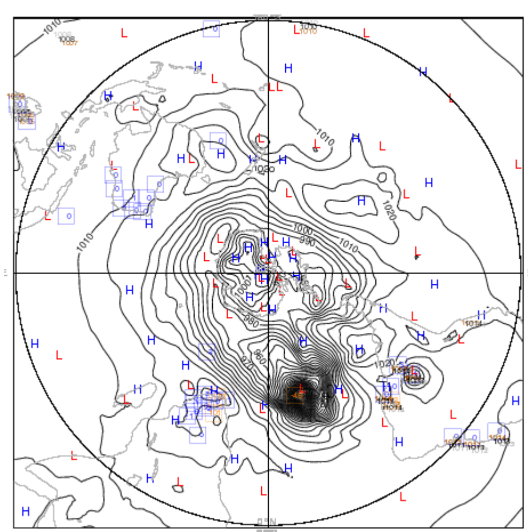
31 March 1954, 03 UTC



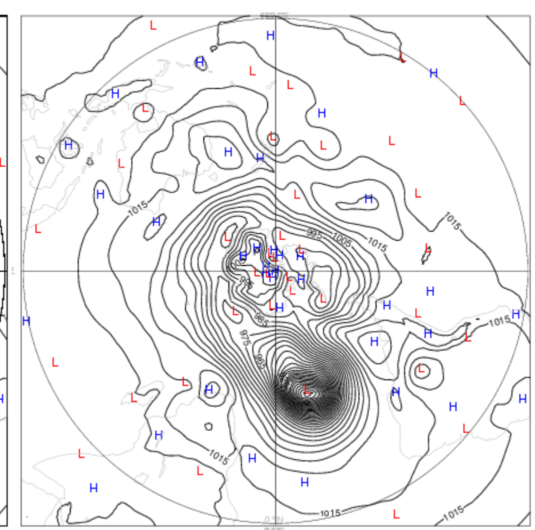
30 March 1954, 06 UTC



31 March 1954, 09 UTC



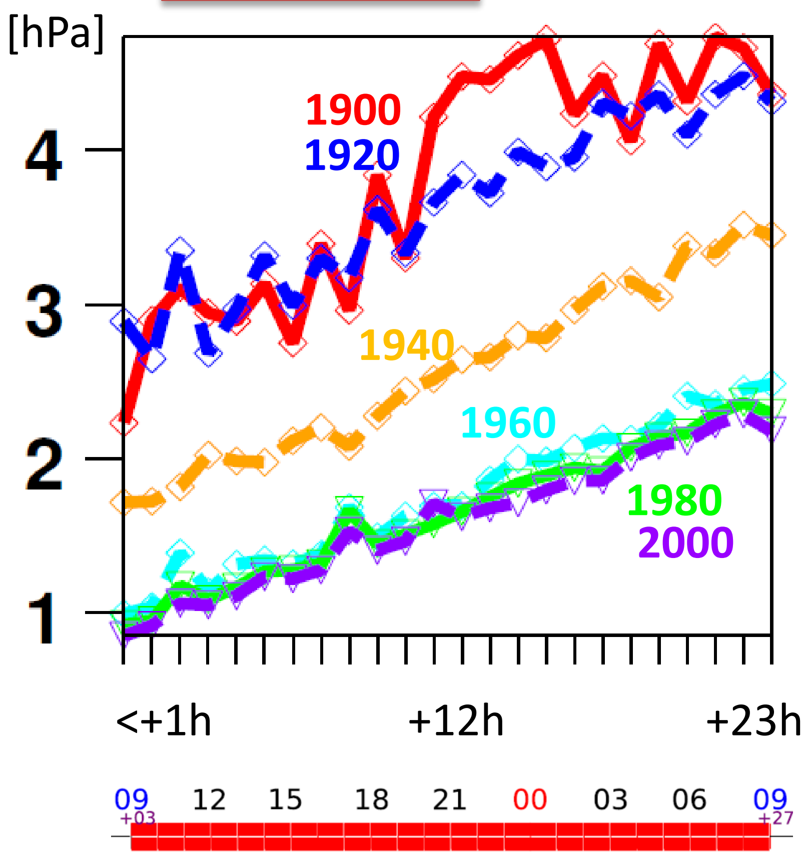
31 March 1954, 12 UTC



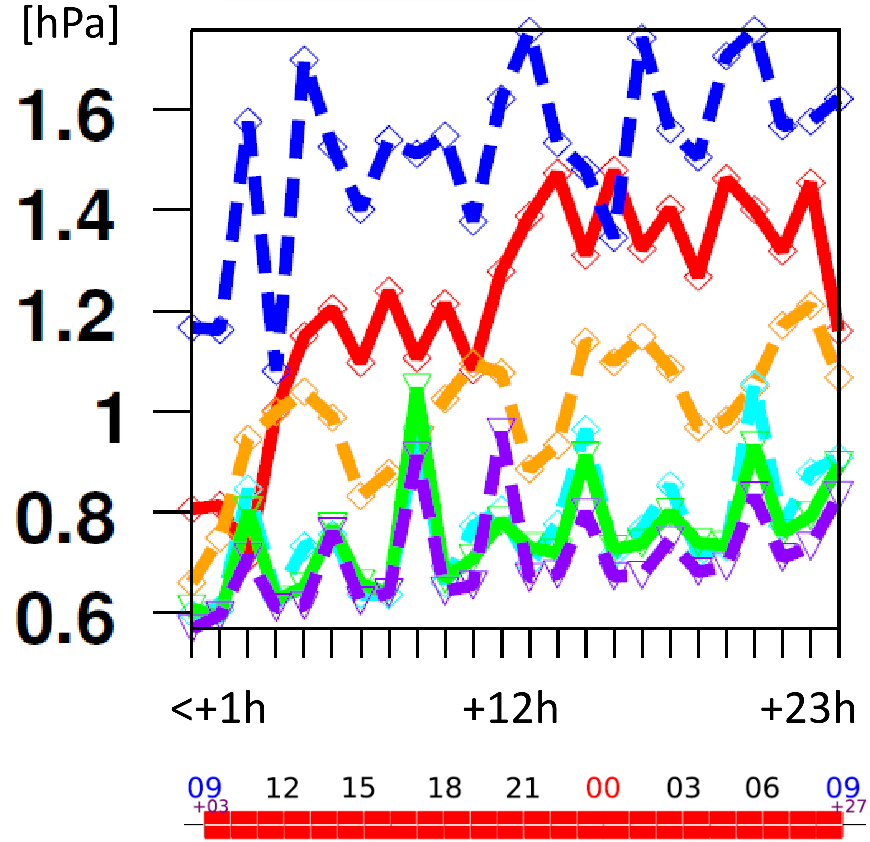
Observation errors 3/3

What about error growth within the 24-hour window?

RMS (O-B)



RMS (O-A)



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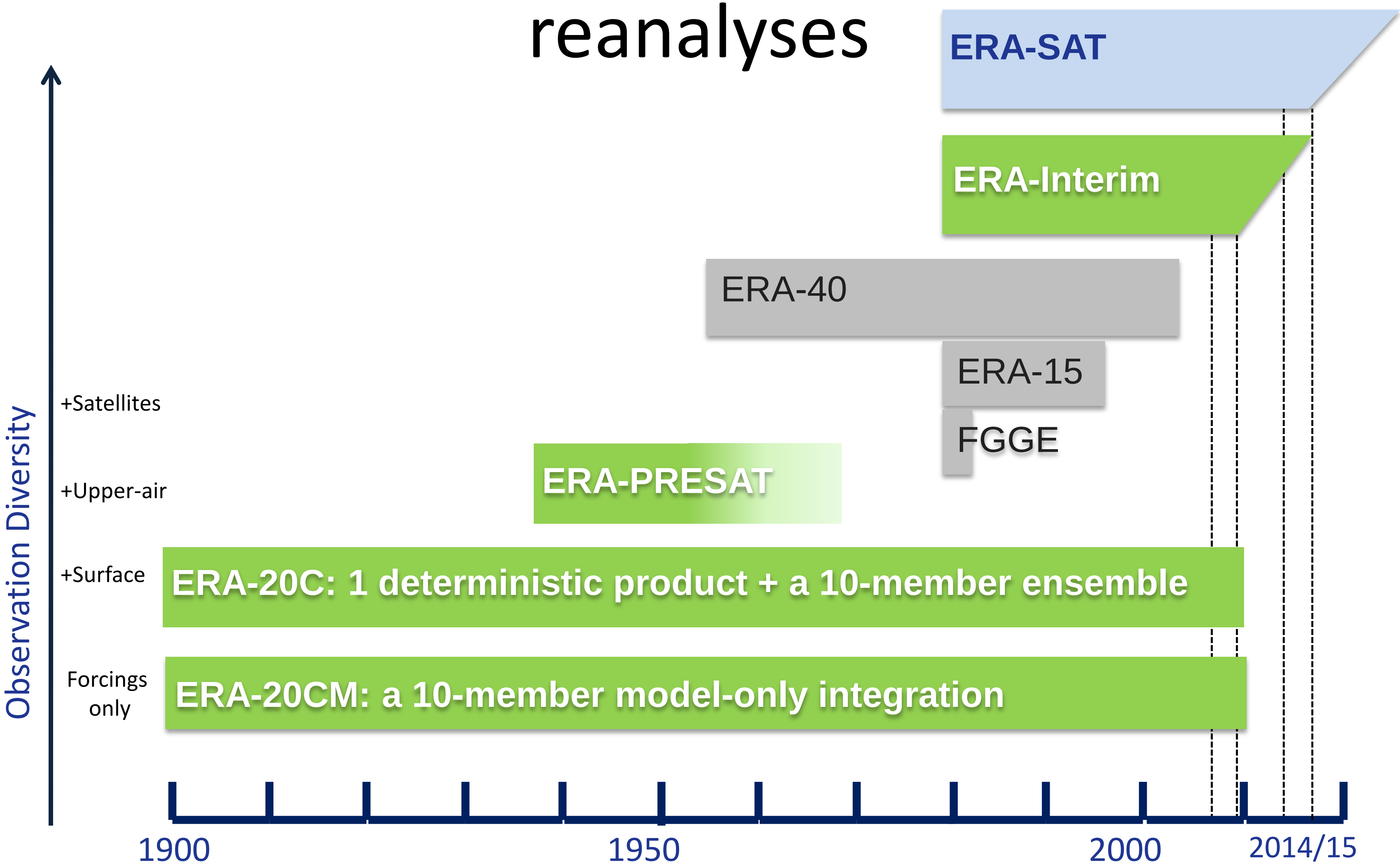
A (short) history of atmospheric reanalysis

- **1979**: **Observation datasets collected for the First GARP Global Atmospheric Research Program Experiment (FGGE)**: used *a posteriori* for several years, to initialize models, track progress in NWP.
- **1983**: **Reanalysis concept proposed** by Daley for monitoring the impact of forecasting system changes on the accuracy of forecasts
- **1988**: **Concept proposed again, but for climate-change studies**, in two separate papers: by Bengtsson and Shukla, and by Trenberth and Olson
- **1990s**: **First-generation comprehensive global reanalysis** products ***(~OI-based)***
  - NASA/DAO (1980 - 1993) from USA
  - NCEP/NCAR (1948 - present) from USA
  - ERA-15 (1979 - 1993) from ECMWF – with significant funding from USA
- **Mid 2000s**: **Second-generation products *(~3DVAR)***
  - JRA-25 (1979 - 2004) from Japan
  - NCEP/DOE (1979 - present) from USA
  - ERA-40 (1958 - 2001) from ECMWF – with significant funding from EU FP5
- **Today: Third generation of comprehensive global reanalyses (*~better than 3DVAR*)**
  - NASA/GMAO-MERRA (1979 – present) from USA (IAU)
  - NCEP-CFSRR (1979 – 2008) from USA (land/ocean/ice coupling)
  - JRA-55 (1958 – 2012) from Japan (4DVAR)
  - 20-CR from USA (Ensemble Kalman Filter, surface pressure observations only)
  - ERA-Interim (1979 – present) from ECMWF (4DVAR)
  - ERA-20C (1900-2010) from ECMWF (4DVAR ensemble)

Overview of ECMWF atmospheric reanalyses



How (outside) users exploit reanalysis data

ERA-Interim: more than 15,000 users

- Monitor the observing system
  - Feedback on observational quality, bias corrections
  - Basis for homogenization studies of long data records
- Develop climate models
  - Use reanalysis products for verification, diagnosis, calibrating output,, …
- Drive users' models/applications
  - Use reanalysis as large-scale initial or boundary conditions for smaller-scale models (global→regional; regional→local), in various fields: wind energy, ocean circulation, chemical transport and dispersion, crop yield, health indicators, …
- Use climatologies derived from reanalysis for direct applications
  - Ocean waves, wind and solar power generation, insurance, …
- Study short-term atmospheric processes and influences
  - Process of drying of air entering stratosphere, bird migration, …
- Study of longer-term climate variability/trends
  - Requires caution due to changes in observations input
  - Lead to major findings in recent years in understanding variability

How ECMWF users exploit reanalysis data

- Baseline to track NWP score improvements
- Calibration for seasonal forecasting system
- Reference to diagnose changes brought by model improvements

Growing recognition for climate application

BAMS State of the Climate in 2008

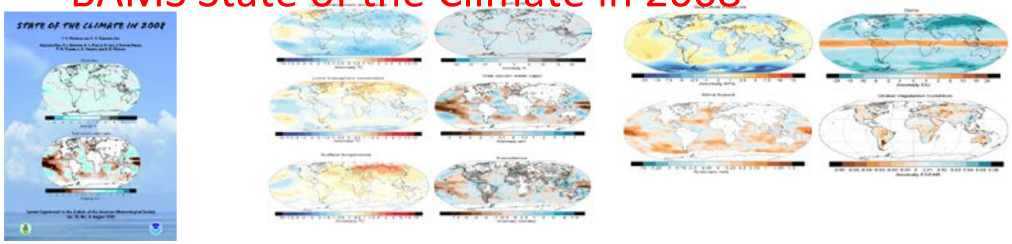


Plate 2.1. Global annual anomaly maps for those variables for which it was possible to create a meaningful anomaly estimate. Climatologies differ among variables, but spatial patterns should largely dominate over choices of climatology period. Dataset sources and climatologies are given in the form (dataset name/data source, start year–end year) for each variable. See relevant section text and figures for more details. Lower stratospheric temperature (RSS MSU 1981–90); lower tropospheric temperature (UAH MSU 1981–90); surface temperature (NCDC 1961–90); cloud cover (PATMOS-x 1982–2008); total column water vapor (SSM/I/GPS 1997–2008); precipitation (RSS/GHCN 1989–2008); mean sea level pressure (HadSLP2r 1961–90); wind speed (SSM/I1988–2007); total column ozone (annual mean global total ozone anomaly for 2008 from SCIAMACHY. The annual mean anomalies were calculated from 1° × 1.25° gridded monthly data after removing the seasonal mean calculated from GOME (1996–2003) and SCIAMACHY (2003–07)]; vegetation condition [annual FAPAR anomalies relative to Jan 1998 to Dec 2008 from monthly FAPAR products at 0.5° × 0.5° [derived from SeaWiFS (NASA) and MERIS (ESA) data].

BAMS State of the Climate in 2009

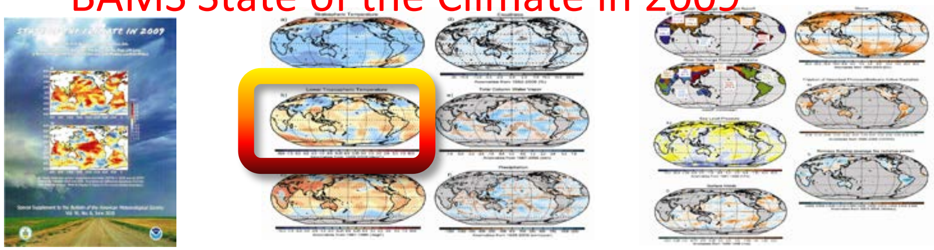


Plate 2.1. Global annual anomaly maps for those variables for which it is possible to create a meaningful 2009 anomaly estimate. Climatologies differ among variables, but spatial patterns should largely dominate over choices of climatology period. Dataset sources/names are as follows: lower stratospheric temperature (RSS MSU); lower tropospheric temperature (ERA-interim); surface temperature (NOAA NCDC); cloudiness (PATMOS-x); total column water vapor (SSM/I over ocean, ground based GPS over land); precipitation (RSS over ocean, GHCN (gridded) over land); river discharge (authors); mean sea level pressure (HadSLP2r); wind speed (AMSR-E); ozone (GOME2); FAPAR (SeaWIFS); Biomass Burning (GEMS/MACC). See relevant section text and figures for more details.

BAMS State of the Climate in 2010

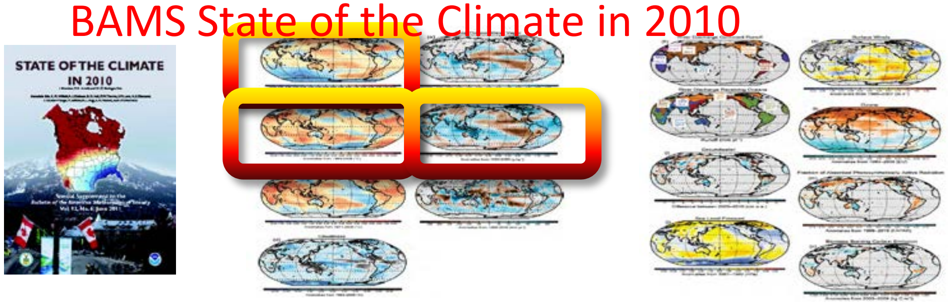


Plate 2.1. Global annual anomaly maps for those variables for which it is possible to create a meaningful 2010 anomaly estimate. Reference base periods differ among variables, but spatial patterns should largely dominate over choices of base period. Dataset sources/names are as follows: lower stratospheric temperature (ERA-Interim); lower tropospheric temperature (ERA-Interim); surface temperature (NOAA/NCDC); cloudiness (PATMOS-x); total column water vapor (AMSR-E over ocean, ground-based GPS over land); surface specific humidity (ERA-Interim); precipitation (RSS over ocean, GHCN (gridded) over land); groundwater 2010–2009 differences (the sum of groundwater, soil water, surface water, snow, and ice, as an equivalent height of water in cm) (GRACE); river discharge absolute values (authors); mean sea level pressure (HadSLP2r); surface wind speed (AMSR-E over ocean, authors in situ over land); ozone (SBUVs/OMI/TOMS/GOME1/SCIAMACHY/GOME2, base period data from the multi-sensor reanalysis, MSR); FAPAR [SeaWiFS (NASA) and MERIS (ESA) sensors]; biomass burning (GFAS). See relevant section text and figures for more details.

BAMS State of the Climate in 2011

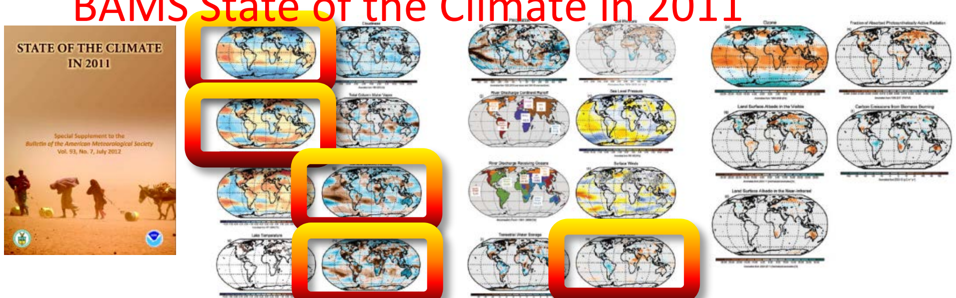


PLATE 2.1. (a) ERA-Interim 2011 anomalies of MSU Channel 4 equivalent for the lower stratospheric temperature; (b) ERA-Interim 2011 anomalies of MSU Channel 2LT equivalent for the lower tropospheric temperature; (c) NOAA-NCDC 2011 anomalies of surface temperature; (d) ARCLAKE 2011 summer season anomalies of lake surface temperature; (e) PATMOS-x 2011 anomalies of cloudiness; (f) SSMIS (Ocean) and radiosonde and ground-based GPS (circles) (Land) 2011 anomalies map of TCWV anomalies of total column water vapour; (g) ERA-Interim 2011 anomalies of surface specific humidity; (h) ERA-Interim 2011 anomalies of surface relative humidity; (i) RSS and GHCN precipitation; (j) Water Balance Model (WBM) analysis by authors showing 2011 anomalies of river discharge over continents and into oceans; (k) GRACE satellite observations of 2011 minus 2010 annual mean terrestrial water storage (the sum of groundwater, soil water, surface water, snow, and ice, as an equivalent height of water in cm); (l) WACMOS satellite observations of 2011 anomalies of soil moisture; (m) HadSLP2r 2011 anomalies of sea level pressure; (n) Satellite radiometer (ocean) and in situ (land; 1152 sites from ISD-Lite and Tim McVicar) 2011 anomalies of surface wind speed; (o) MACC reanalysis for 2011 anomalies of total aerosol optical depth; (p) GOME/SCIAMACHY/GOME2 2011 anomalies of stratospheric ozone; (q) MODIS White Sky broadband 2011 anomalies of land surface albedo from the visible spectrum; (r) MODIS White Sky broadband 2011 anomalies of land surface albedo from the near-infrared spectrum; (s) Combined SeaWiFS (NASA) and MERIS (ESA) 2011 anomalies of fraction of absorbed photosynthetically active radiation (FAPAR); (t) MACC GFAS processed MODIS observations for 2011 anomalies of biomass burning in terms of annual carbon emission per unit area.

Reanalysis course outline

What is reanalysis?	• General concepts • Goals of reanalysis
How are reanalyses made?	• Observations • Model • Data assimilation
Reanalysis projects & applications	• Projects • Users • Applications
Conclusions	• Summary • Challenges ahead

Summary of important concepts

- **Reanalysis does not produce "gridded observations"**
  - But it enables to extract information from observations in one, unique, theoretically consistent framework
- **Reanalysis sits at the end of the (long) meteorological research and development chain that encompasses**
  - observation and measurement collection,
  - observation processing and data exchange,
  - numerical weather prediction modelling and data assimilation
- **Unlike NWP, a very important concern in reanalysis is the consistency in time, over several years**
- **Reanalysis is bridging slowly, but surely, the gap between the "weather datasets" and the "climate datasets"**
  - Resolution gets finer
  - Reanalyses cover longer time periods, without gap
  - Helps different communities work together
  - Reanalysis has developed into a powerful tool for many users and applications

Current status of global reanalysis & Future outlook

- **Reanalysis is worth repeating as all ingredients continue to evolve**:
  - Models are improving
  - Data assimilation methods are improving
  - Observation (re-)processing is improving
  - Old observations (paper & microfilm records) are being rescued
  - The technical infrastructure for running & monitoring improves constantly
  - **With each new reanalysis we improve our understanding of systematic errors in the various components of the observing system**

- **Major challenges for a future comprehensive reanalysis project**:
  - Bringing in additional observations (not dealt with in ERA-Interim)
  - Dealing with changing background quality over time
  - Dealing with model bias, tied to problems with trends interpretation
  - Coupling with ocean and land surface
  - Making observations used in reanalysis more accessible to users
  - Providing first uncertainty estimates for the reanalysis products

ERA-CLIM2

ERA-20C

Further reading and on-line material

- Kalnay et al. (1996), "The NCEP/NCAR 40-Year Reanalysis Project", *Bull. Am. Meteorol. Soc.* **77** (3), 437-471
- Uppala et al. (2005), "The ERA-40 reanalysis", *Q. J. R. Meteorol. Soc.* **131** (612), 2961-3012, doi:10.1256/qj.04.176
- Bengtsson et al. (2007), "The need for a dynamical climate reanalysis", *Bull. Am. Meteor. Soc.* **88** (4), 495-501
- SciDAC Review (2008), "Bridging the gap between weather and climate", on the web at http://www.scidacreview.org/0801/pdf/climate.pdf with contributions from Compo and Whitaker
- Global and regional reanalyses twiki: http://www.reanalyses.org
- Dee et al. (2011), "The ERA-Interim reanalysis: configuration and performance of the data assimilation system ", *Q. J. R. Meteorol. Soc.,* **137** (656), 553-597
- Hersbach et al. (2013), "ERA-20CM: a twentieth century atmospheric model ensemble", ERA Report Series 16, http://www.ecmwf.int/publications/library/do/references/show?id=90989
- Poli et al. (2013), "The data assimilation system and initial performance evaluation of the ECMWF pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C)", ERA Report Series 14, http://www.ecmwf.int/publications/library/do/references/show?id=90833
- Simmons et al. (2014), "Estimating low-frequency variability and trends in atmospheric temperature using ERA-Interim". *Q.J.R. Meteorol. Soc.* doi: 10.1002/qj.2317

ECMWF data server

http://apps.ecmwf.int/datasets/

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- GRIB decoder

Downloadable datasets

- DEMETER Project
- ENSEMBLES project
- GEMS Reanalysis and Near Real-time
- MACC Reanalysis
- TIGGE
- TIGGE LAM
- YOTC

Global Reanalyses

- ERA-Interim (Jan 1979 - present)
- ERA-Interim/LAND (Jan 1979 - Dec 2010)
- ERA-40 (Sep 1957 - Aug 2002)
- ERA-15 (Jan 1979 - Dec 1993)
- ERA-20CM (Jan 1900 - Dec 2010): Climate Model Integration (experimental)

Observation Feedback

- ISPD v2.2
- ICOADS v2.5.1 with interpolated 20CR feedback

Coming in 2014:

- **ERA-Interim observation feedback**
- **ERA-20C & its observation feedback**
- **ERA-CLIM recovered upper-air data**

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