4D-Var: From early results to operational implementation

Jean-Noël Thépaut, ECMWF

Acknowledements: Florence Rabier, Erik Andersson, Lars Isaksen, + many others

January 31, 2018

On what basis was the decision made?

Quoting Philippe Courtier “I’m still admiring that ECMWF took this decision”: David Burridge and Jean Pailleux were the most pushy at the time

What was the scientific evidence ?

one barotropic vorticity equation result
+
one shallow-water result
+
Experience with “physical retrieval” with model first-guess (Met.Office/Oxford) and ‘Peridot’ radiance assimilation in OI (France)

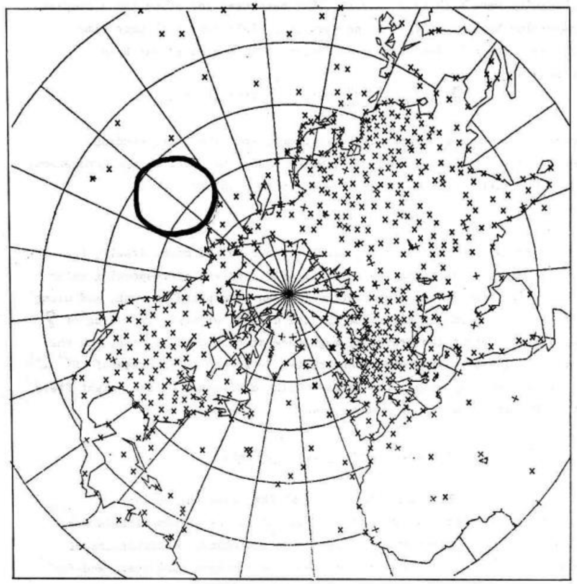


Figure 1. Distribution of radiosondes observations
26 April 1984

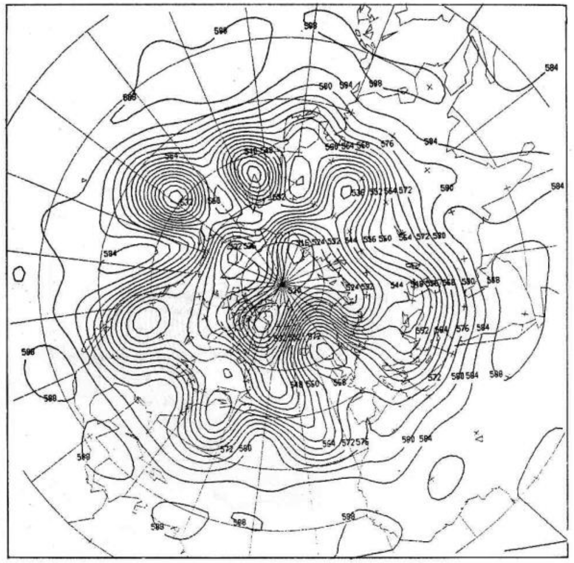


Figure 2. 500mb geopotential field of
Operational analysis, Paris.
26 April 1984 0.00Z

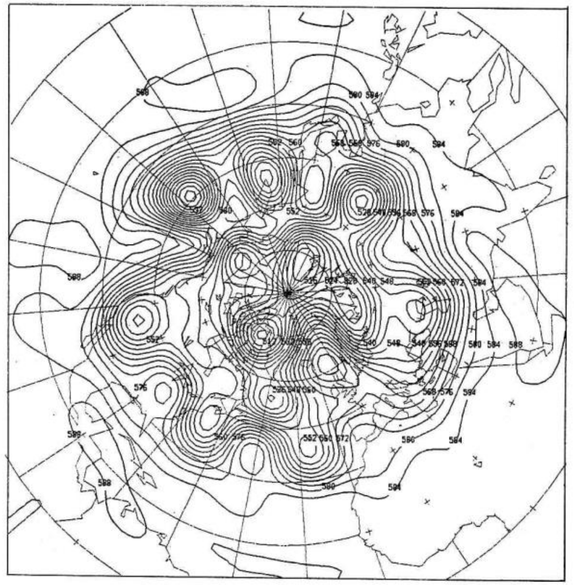
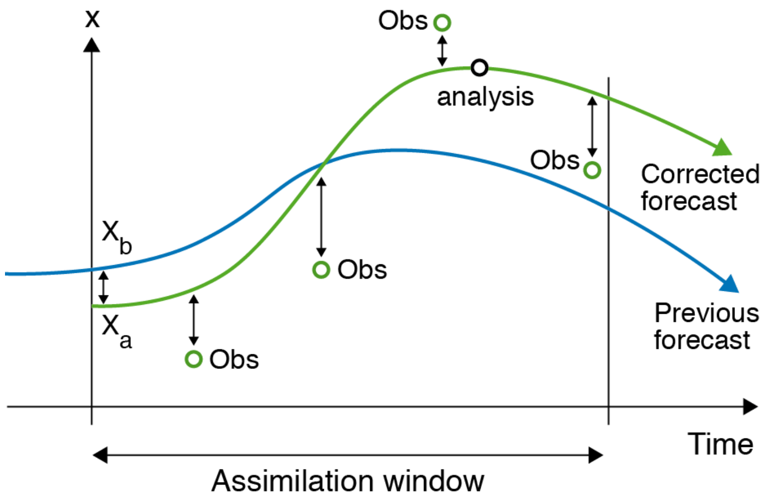


Figure 3. Same as figure 2 for
Variational analysis
26 April 1984 0.00Z

One! 24 hour 4D-Var with the barotropic vorticity eq.
(Courtier & Talagrand, 1987)

What are the ingredients needed to complete the last mile(s)?

Find the model trajectory that best fits the available observations

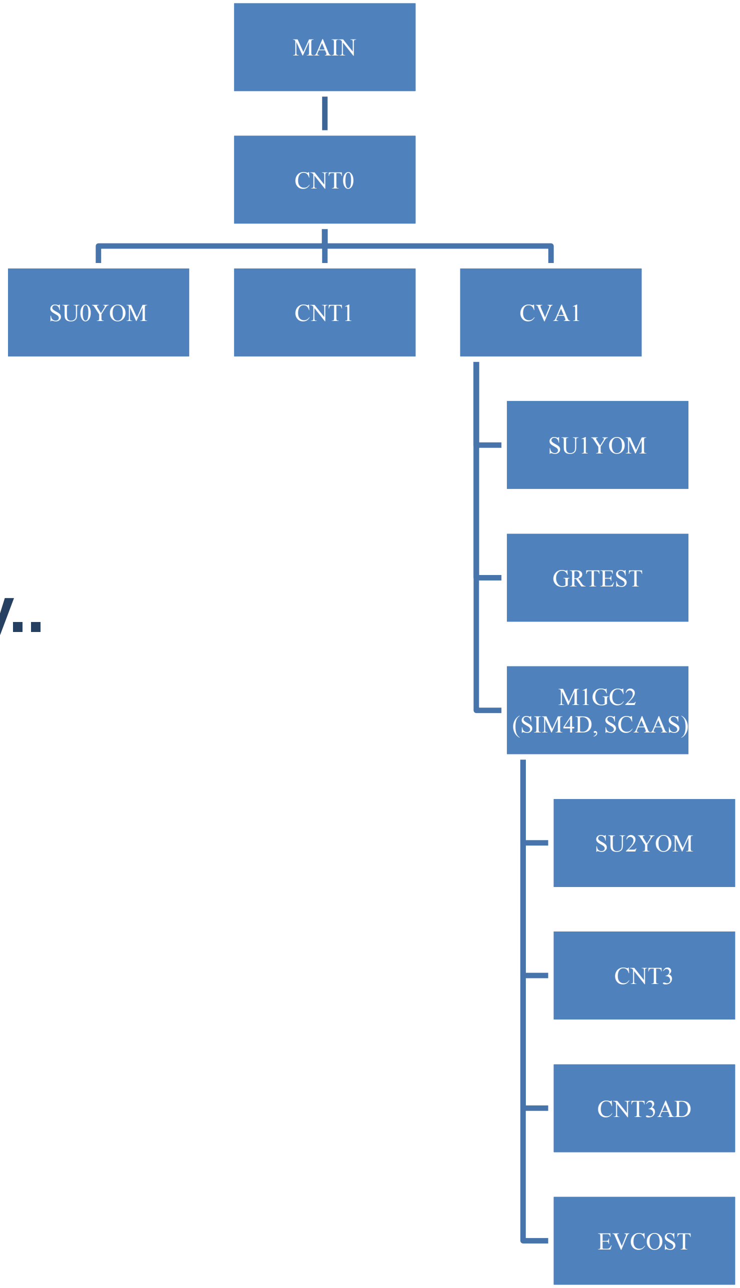


- A forecast model and its adjoint
- The observation operators, code to compute Jo and its gradient
- The first-guess operator, code to compute Jb and its gradient
- Mass/wind balance operators
- General minimization algorithm
- "Bulk of coding 1989-90. Debugging 1991-onwards"…

+ many « petits bras (et cerveaux) musclés »

+++ …

Very simple code, really..



1990-1991: First results with primitive equation model (T21/T42-L19) and simulated observations

Some of the (published) findings were:

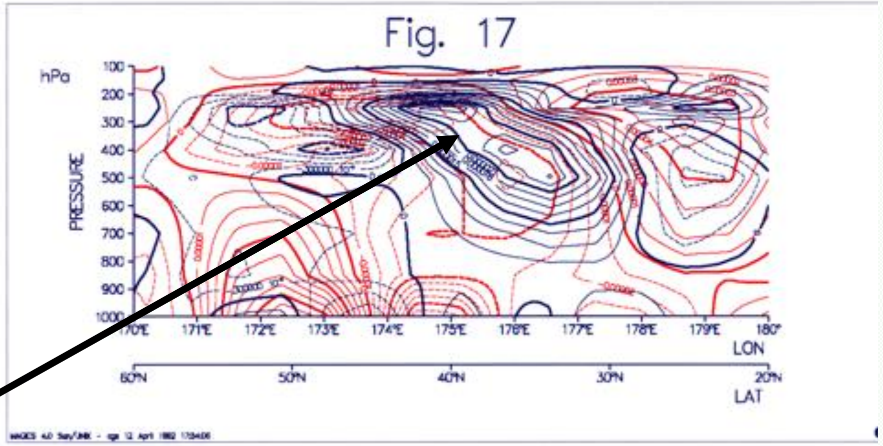
- The knowledge of the mass field evolution is sufficient to recover to a certain extent the vorticity field in the mid-latitudes
- The observation of the T21 evolution of the flow allows us to infer most of the higher resolution T21-T42 component of the flow
- The description of the atmosphere at one time (one location) can be obtained by observations at a different time (location), in a dynamically consistent way
- Conditioning is probably a key factor for operational implementation

Other (unpublished) findings:

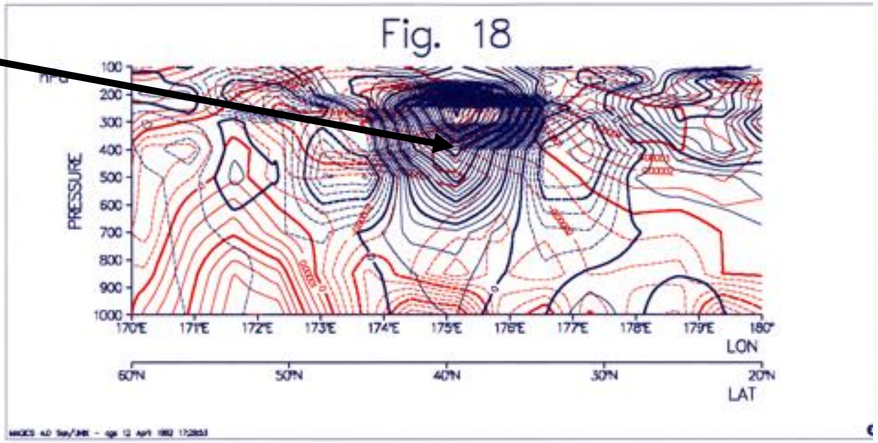
- Coding/debugging the TL and the Adjoint of the model is a pain in the … neck (part of the “bizutage” for new comers)!

1991-1992: What finally convinced Tony Hollingsworth about the potential of 4D-Var (1)

24h 4D-Var



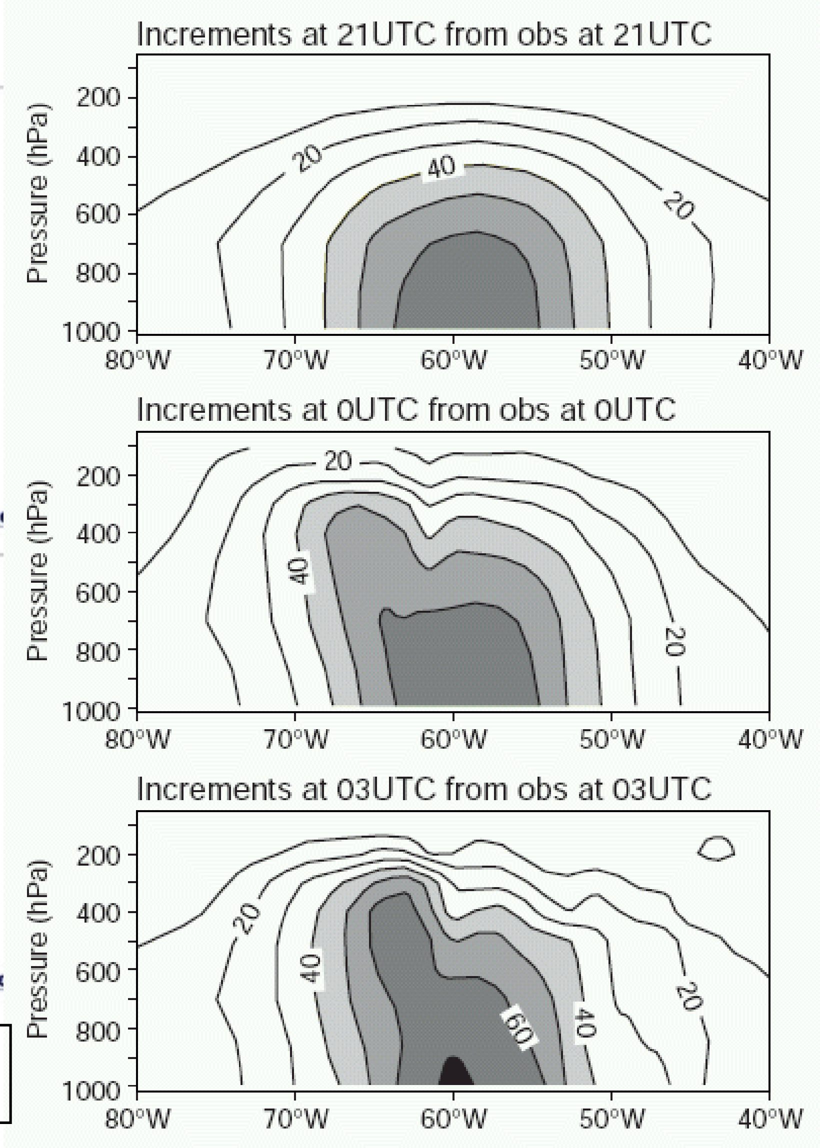
Impact of removing 200 hPa aircraft observations from the assimilation



OI cycled over 24h

Thépaut et al. 1993

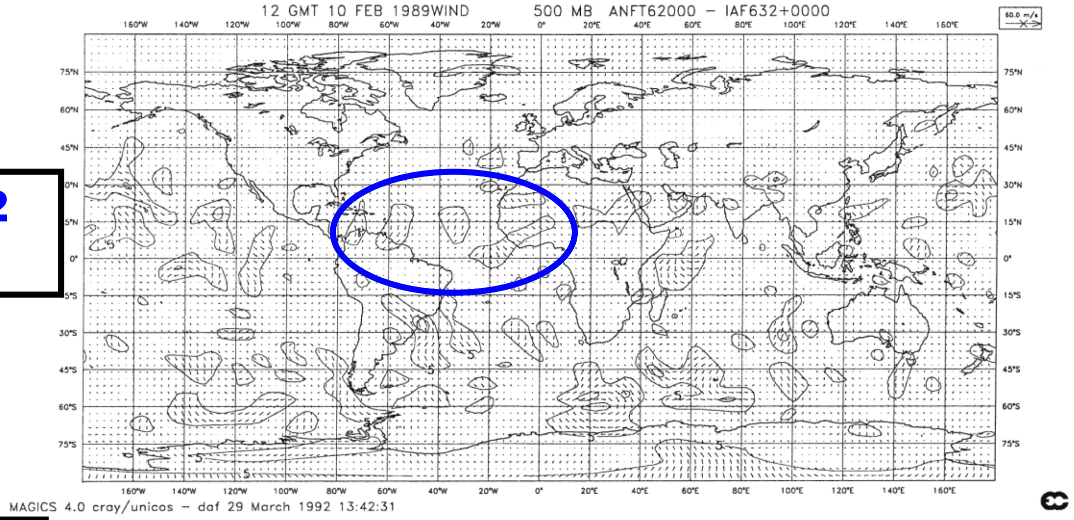
Rabier at al. 1993



The “legendary” 4D-Var pictures!

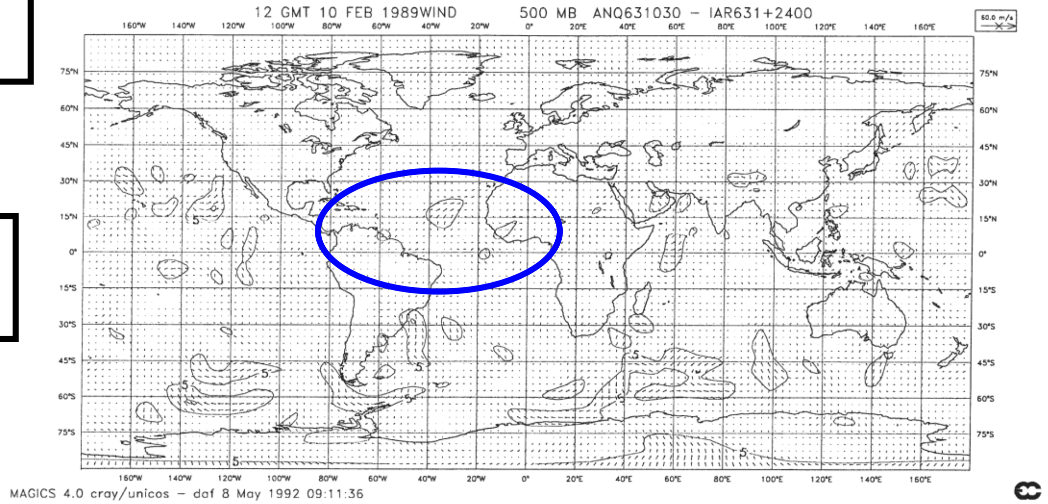
1992: What finally convinced Tony Hollingsworth about the potential of 4D-Var (2)

HIRS 11-12 included



Impact of TOVS radiances on the wind field

HIRS 11-12 excluded



Andersson et al., 1994

1993-1994: The incremental approach

Or chasing the CPUs .. with pragmatism and rigour

4D-VAR USING AN INCREMENTAL APPROACH 138

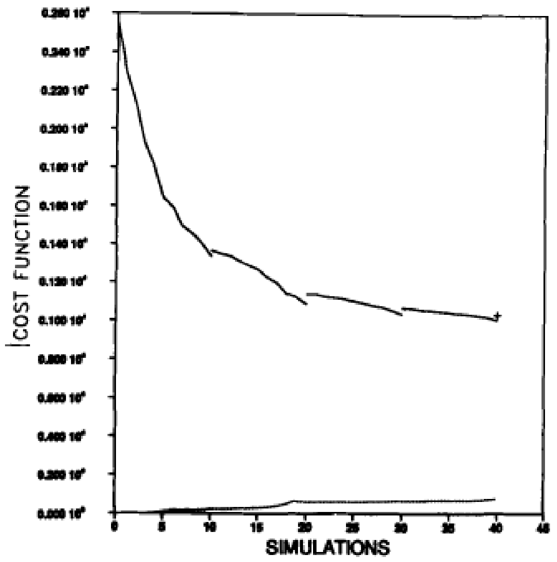


Figure 9. Same as Fig. 8, but with four updates of the trajectory.

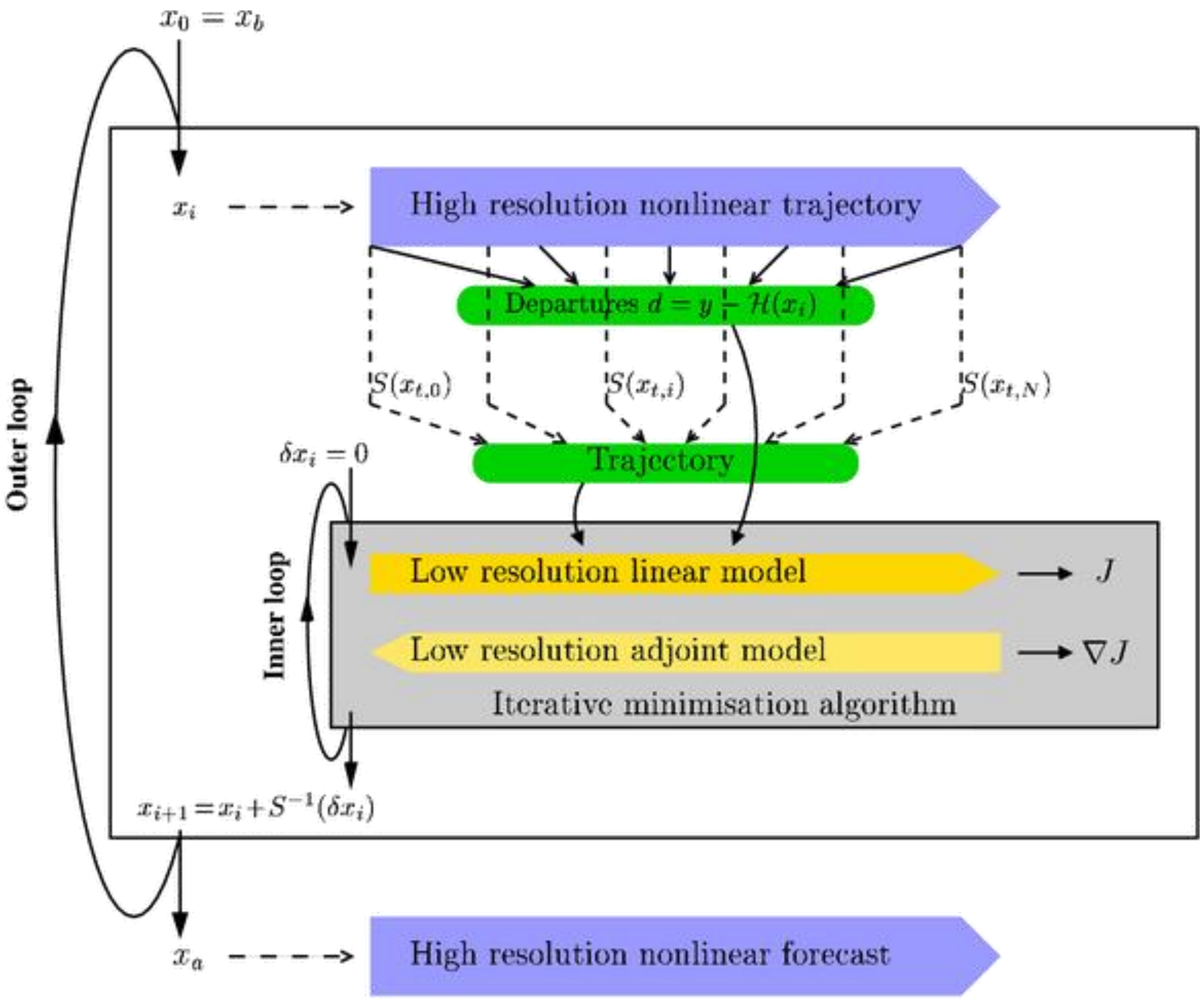
"Instead of using a full physical package and its adjoint (which leads to a non-differentiable minimization problem), we could use the tangent-linear adiabatic model, in the vicinity of the trajectory by the full model …(J. C. Derber, personal communication)"…this actually goes back to 1990.

It turned out later that hoping to do completely without physics was a bit naïve…

(Courtier et al., 1994)

NB: This paper contains a lot about preconditioning too..
Collaboration with Jorge Nocedal (Argonne National Lab), and J.C. Gilbert (INRIA) was key… and a lot of fun!

Incremental formulation of 4D-Var



What had to be done to get 4D-Var into operations, 1994-97?

Device a good global Jb, that worked also in tropics!, + humidity

Evaluate direct radiance assimilation and use of scatterometer data

Implement 3D-Var!

Write new observation pre-processing and quality control software

New cycling of bg errors

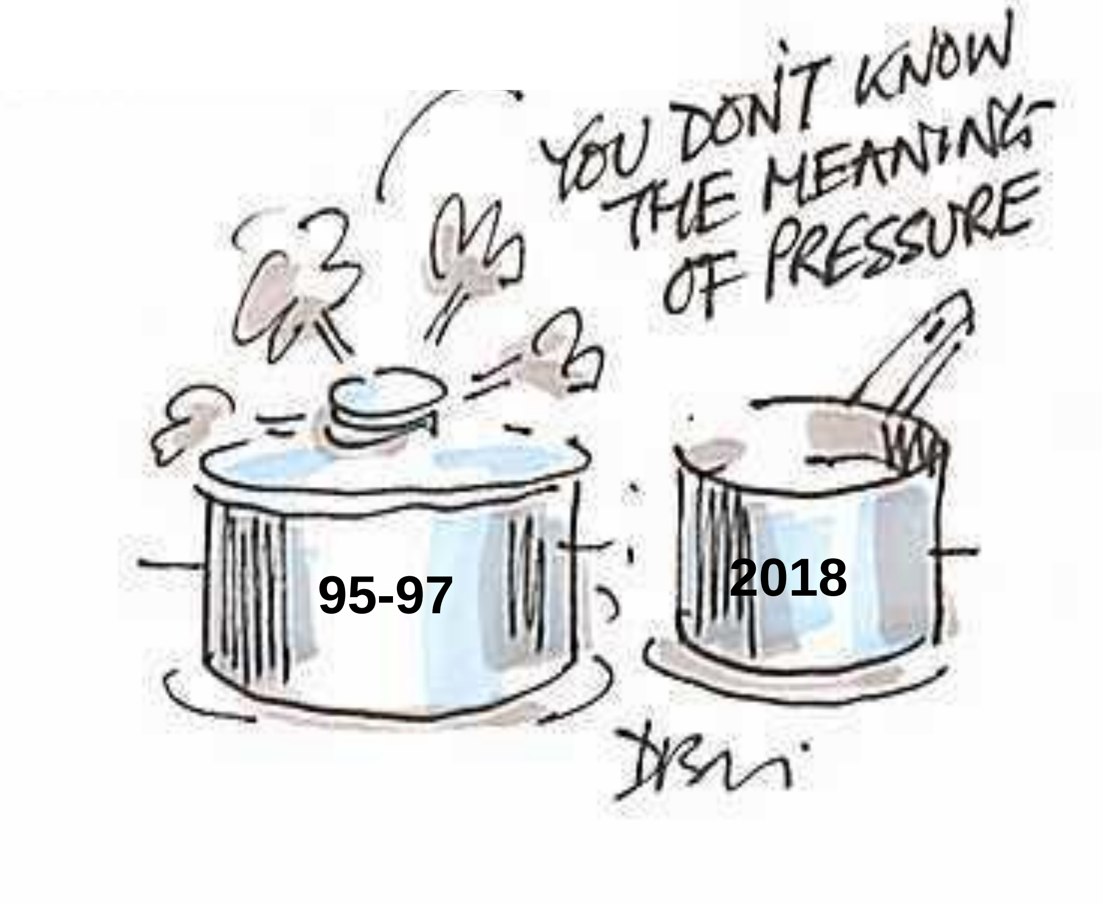
Switch to J. Derber's Jb

Parallelization of codes, and migration to Fujitsu

New joint OD/RD scripts for vpp700!

Evaluate use of NMI and TL-physics in 4D-Var

Implement 4D-Var!



Credit: Erik Andersson

From here….

Initialisation issues

and

tropical performance

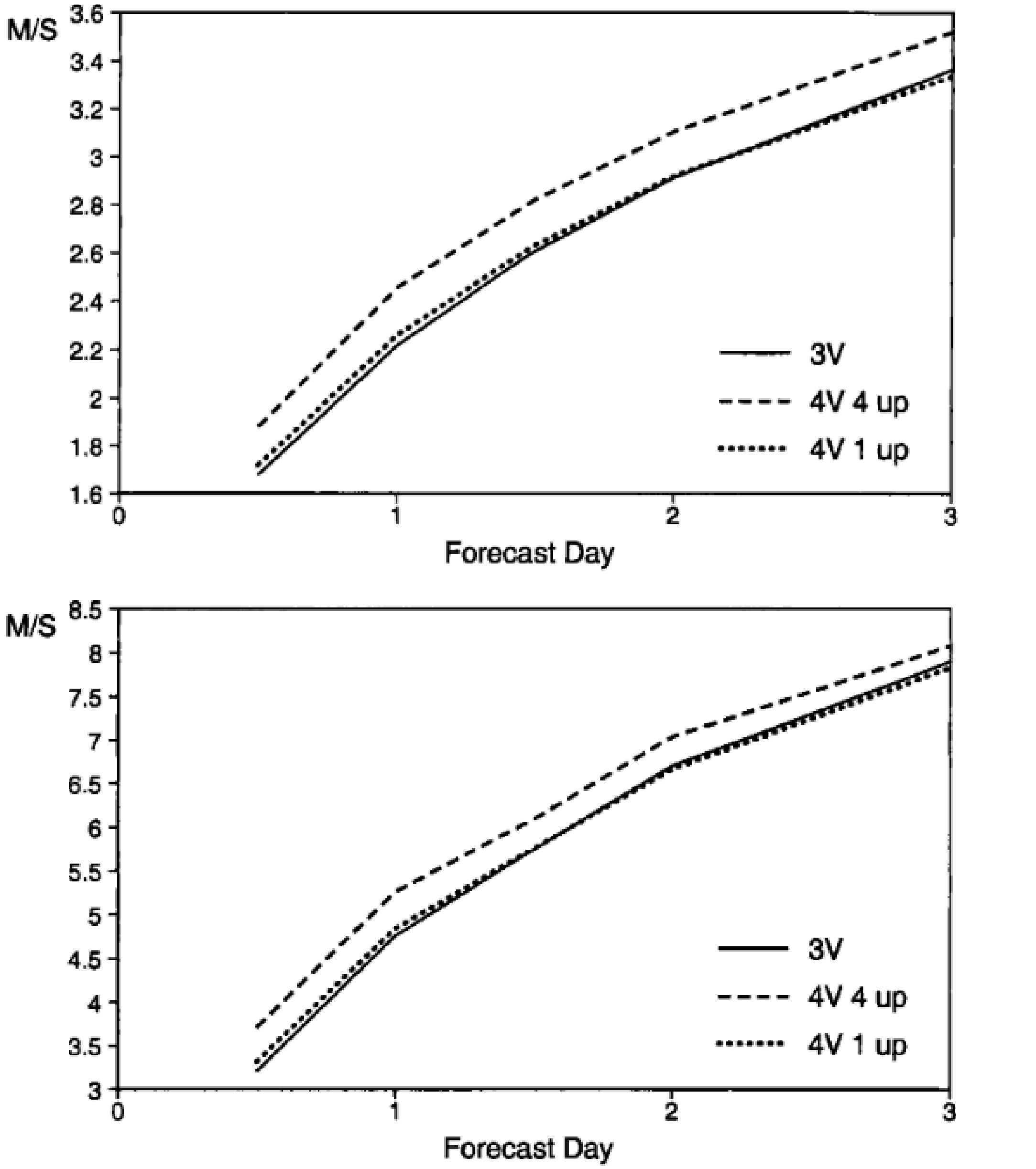
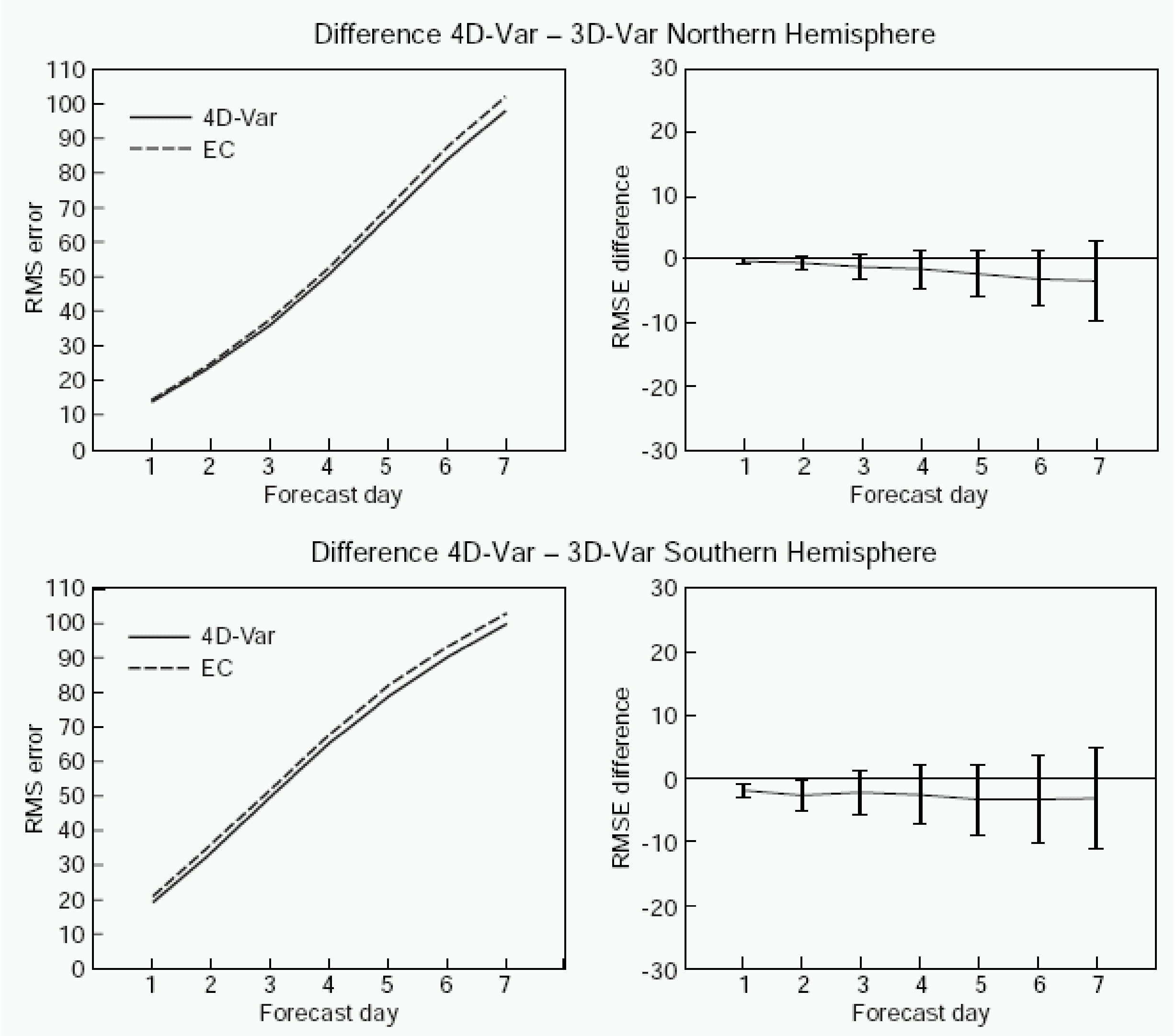


Figure 5. Tropical wind scores (root-mean-square errors in m s^{-1}) verified against own analysis at 850 (top) and 200 hPa (bottom). 3D-Var is shown as a solid line, 4D-Var with 4 outer-loops as a dashed line, and 4D-Var with one outer-loop as a dotted line.

… to there…

With compromises in
- assimilation length,
- resolution,
- number of updates,
- physics…

and positive scores

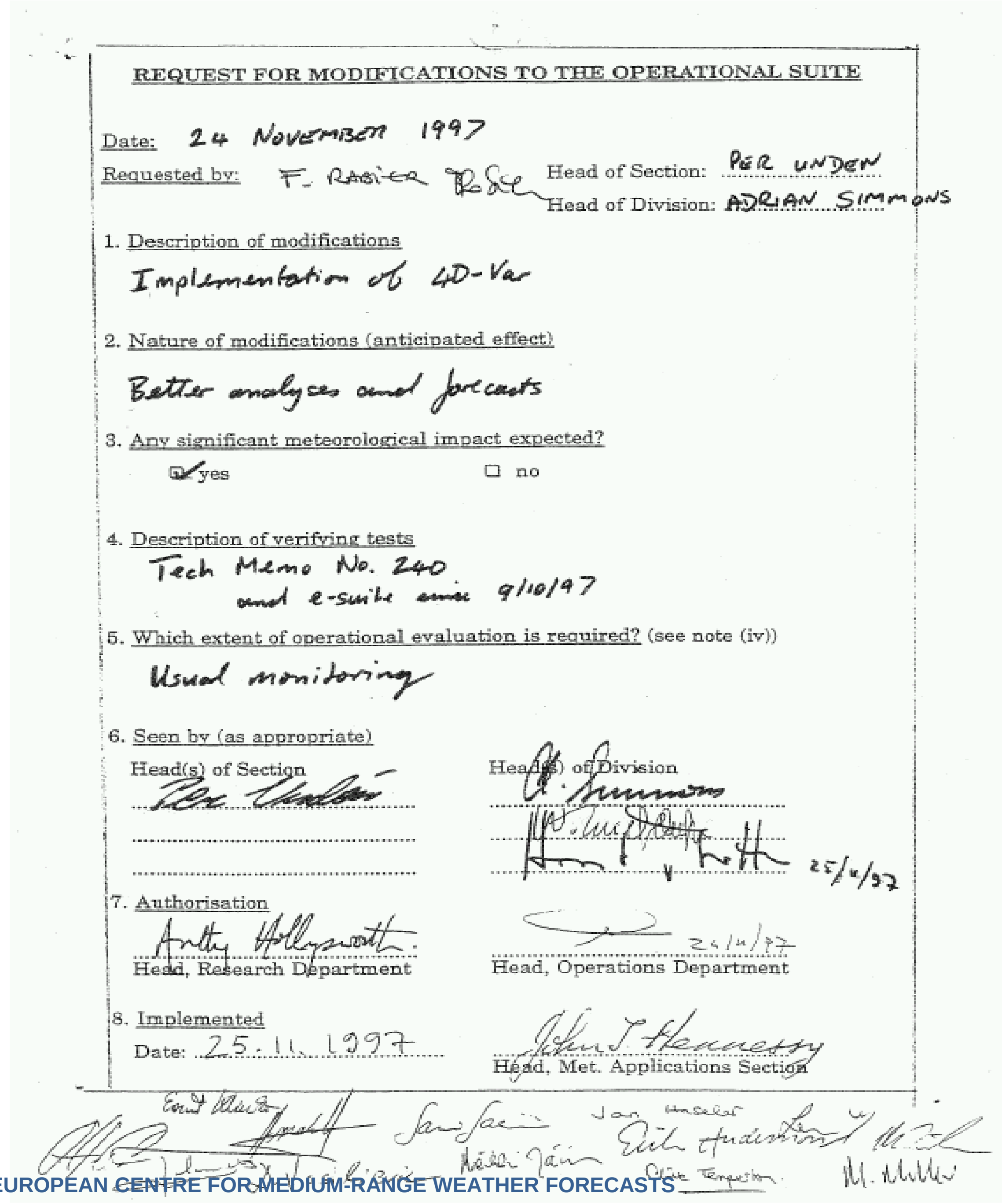


Rabier et al., 1998, 2000
Bouttier and Rabier, 1998

4D-Var implemented at ECMWF
25 November 1997

Who officially signed?

F. Rabier
P. Undén
A. Simmons
W. Zwieflhofer
H. Böttger
A. Hollingsworth
M. Capaldo
J. Hennessy



REQUEST FOR MODIFICATIONS TO THE OPERATIONAL SUITE

Date: 24 November 1997

Requested by: F. Rabier

Head of Section: Per Undén

Head of Division: Adrian Simmons

1. Description of modifications

Implementation of 4D-Var

2. Nature of modifications (anticipated effect)

Better analyses and forecasts

3. Any significant meteorological impact expected?

☑ yes ☐ no

4. Description of verifying tests

Tech Memo No. 240
and e-suite since 9/10/97

5. Which extent of operational evaluation is required? (see note (iv))

Usual monitoring

6. Seen by (as appropriate)

Head(s) of Section

Head(s) of Division

25/11/97

7. Authorisation

Head, Research Department

24/11/97

Head, Operations Department

8. Implemented

Date: 25.11.1997

Head, Met. Applications Section

And many others!

P. Courtier
J-N. Thépaut
J. Pailleux
D. Burridge
J. Eyre
E. Andersson
M. Fisher
J. Haseler
M. Hamrud
L. Isaksen
H. Järvinen
E. Klinker
F. Lalaurette
J-F. Mahfouf
M. Miller
O. Pesonen
S. Saarinen
C. Temperton
D. Vasiljević
T. McNally
G. Kelly
F. Bouttier …

The 4DVar has also been part of a truly collaborative effort between ECMWF and Météo-France

Chasing the CPUs … with agressivity!



- IFS – ARPEGE Collaboration

- Météo-France has benefited enormously from the IFS-ARPEGE collaboration
    - 3D-Var development and implementation (1997)
    - 4D-Var implementation (2000)




- Quite a few specific new developments were necessary (some of which fed back to the ECMWF system)

+ …

- Requirements: another bunch of “p’tits bras (et cerveaux) musclés”

The 4DVar has also been part of a truly collaborative effort between ECMWF and Météo-France

1. Why doing it cheap when we can do it cheaper?

2. We need a (not so) simple physics to keep up with the nonlinear model!

3. Let's get rid of the fast (and noisy, and very annoying waves), and let's do it elegantly and cheaply!

4. Oops, the grid is stretched!

5. …

6. and a few years later, pioneering collaborative work on EDA

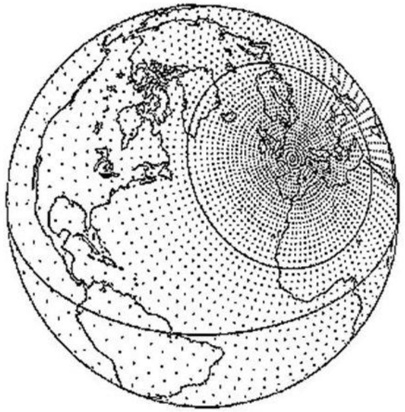
F. VEERSÉ and J.-N. THÉPAUT

TABLE 4. THE 'ROUGH TIME RATIO'.

Experiment	Rough time ratio (%)
Std T95	100
Inc. T95/T63	36.61
Inc. T95/T79	74.46
Multi-trunc. Inc.	31.09
QC Inc. T95/T63	23.20
QC Inc. T95/T79	47.72
QC Multi-trunc. Inc.	27.14

The 'rough time ratio' is the execution time of the experiment divided by the execution time of the Std T95 experiment, excluding the time spent in post-processing activities.

Grille du modèle ARPEGE



Following Gustafsson (1992) and Polavarapu et al. (2000), the digital filter can be introduced as a weak constraint through a penalty cost function $J_c(\delta\mathbf{X}_0)$ defined as

$$J_c(\delta\mathbf{X}_0) = \frac{1}{2}\langle \delta\mathbf{X}(t_{N/2}) - \delta\bar{\mathbf{X}}(t_{N/2}), \delta\mathbf{X}(t_{N/2}) - \delta\bar{\mathbf{X}}(t_{N/2})\rangle, \quad (3.2)$$

With another group of talents!



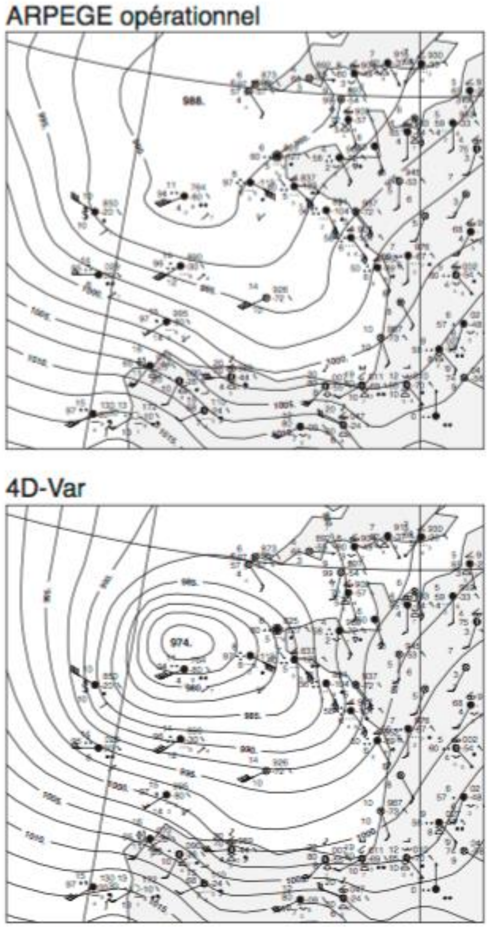
+ …

Certainly a big boost towards 4D-Var implementation at Météo-France

Lothar – December 1999

Thank you 3DVar!

FIGURE 2
COMPARAISON ANALYSE / OBSERVATIONS
le 27 Décembre 1999 à 12h



Comparison between the mean sea level pressure analyses of the ARPEGE operational (3D-Var) system at the time and a pre-operational 4D-Var test (all other things equal) for 27/12/99 12 UTC. The syndrome of a dedoubling of the structure between the guess and the observations (leading to the rejection of crucial information and hence to a weakening and ill-positioning of the analysed low) disappears when the full sequence of observations can be taken into account continuously.

This collaborative work spread to the Arpege/Aladin and Arome community
as well as within the Hirlam-Aladin (Harmonie) initiative

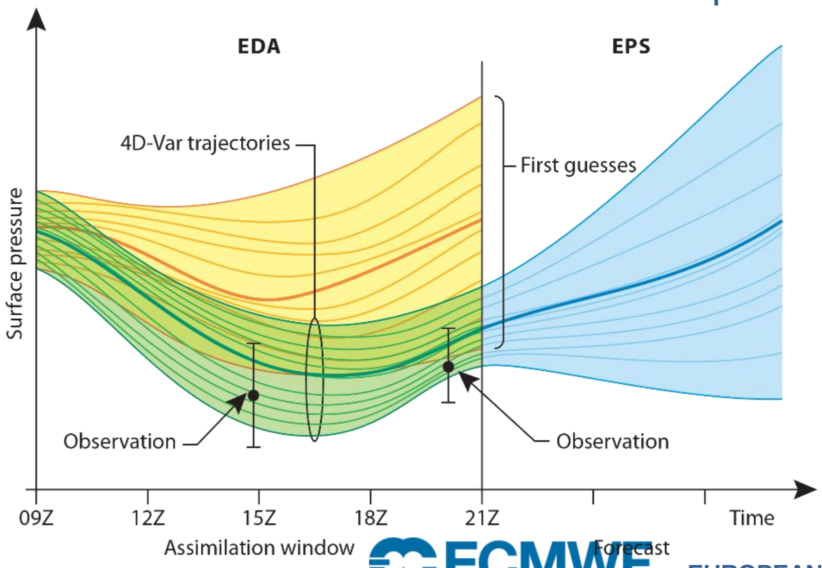
- Code sharing for basic infrastructure
- Adaptations to LAM configurations (extension zones, control variable, JB, additional observation operators, ..)
- Strong momentum towards operational 3DVar assimilation schemes
- Many papers on 4DVar LAMs
  - … but not operational configurations yet..
- Collaboration continues actively today around the OOPS (Object Oriented Prediction System)

+ many others…

Things have moved on since initial implementation(s)…

Overarching considerations include:

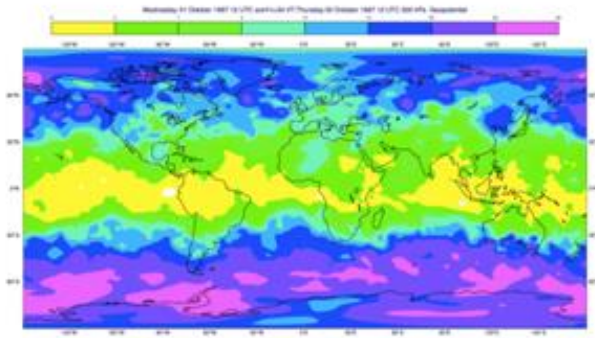
- Seamless quantification of uncertainty estimation (present to future)
- Improved specification of a priori errors
  - Model, background, observations - systematic and random
  - Errors of the day
- Covariance modeling
  - More variables (aerosols, trace gases, clouds)
  - Non gaussianity
  - Higher resolution
- Data Assimilation for a coupled earth system



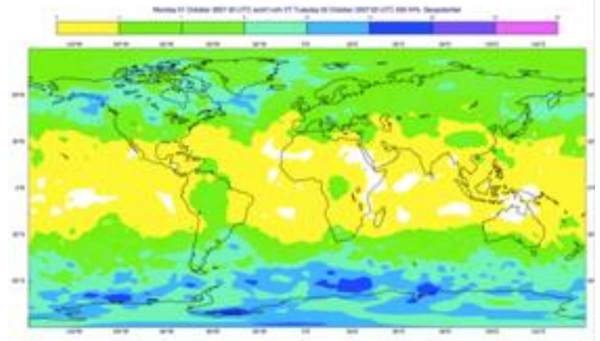
Many new schemes:

- Hybrid 4DVar
- Weak-constraint 4DVar
- 4D-en-Var
- Hybrid 4D-en-Var
- 4DVar Benkf
- …

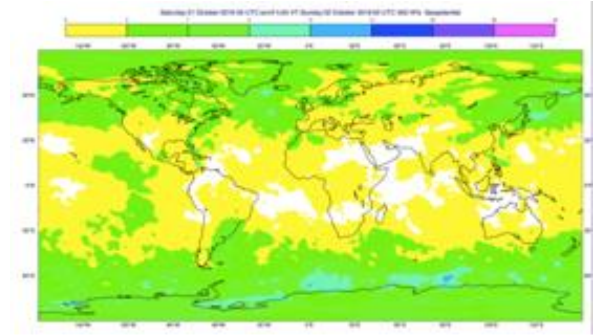
24h Fc error 1997



24h Fc error 2007



24h Fc error 2016

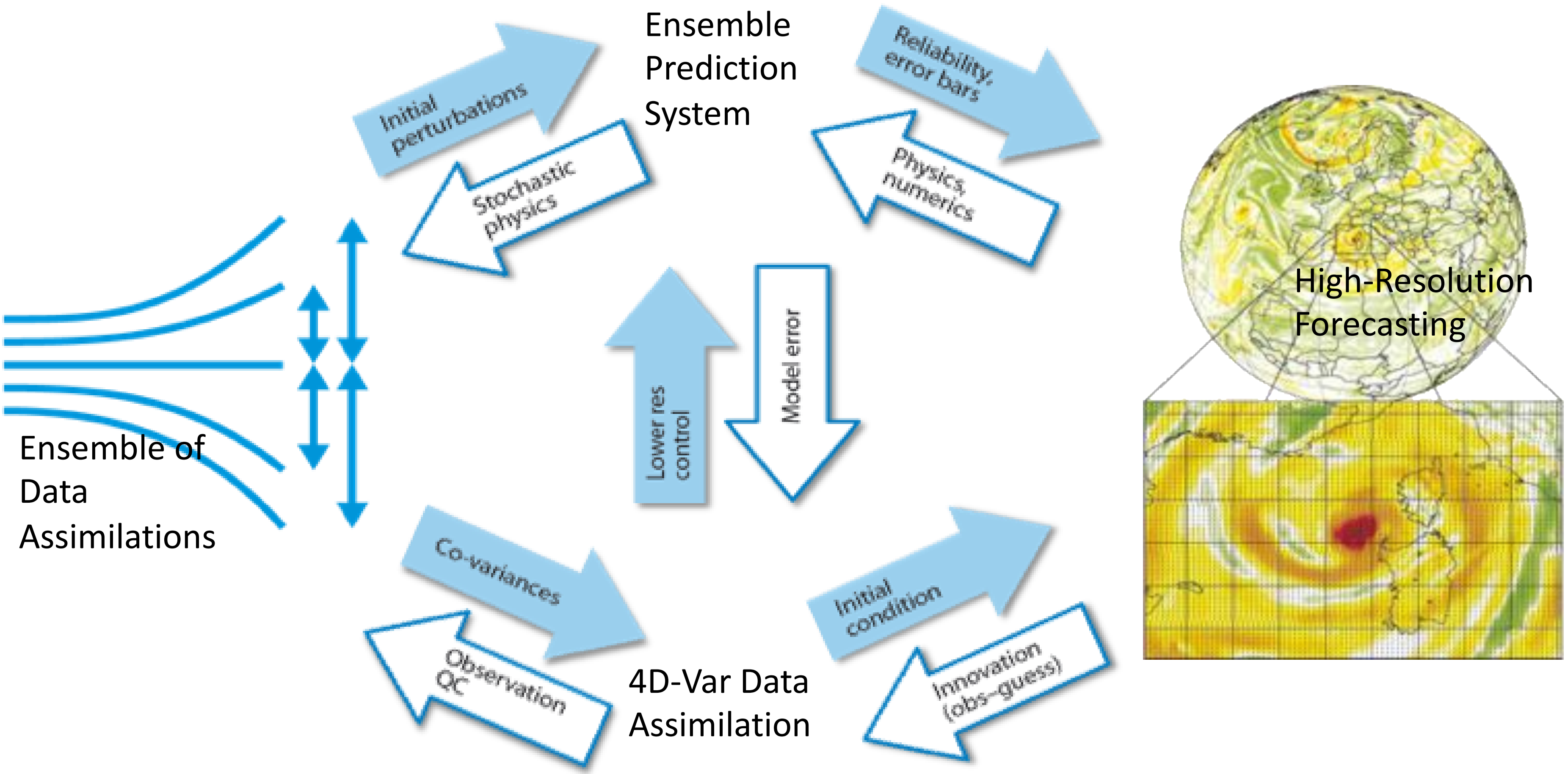


Credit: Lars Isaksen

See Massimo's talk!

… and 4DVar has certainly contributed to framing a new way of thinking and designing NWP

Inter-dependent analysis & forecasting system



Last but not least..

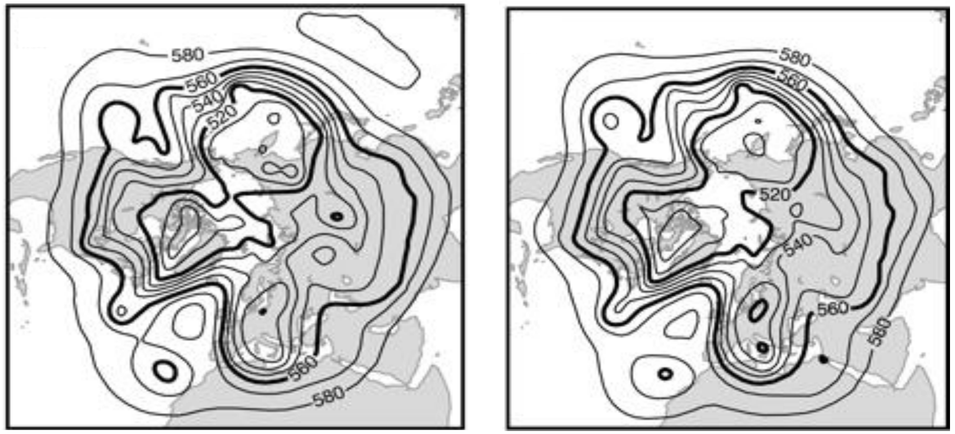
4DVar has been and is still an essential tool for reanalyses activities at ECMWF

Method of choice for assimilating sparse observations

Reanalysis is a flagship monitoring product of the Copernicus Atmosphere Monitoring (CAMS) Service and Copernicus Climate Change (C3S) Services

4DVar is expected to remain the vehicle for future coupled reanalyses envisaged for the Copernicus Services evolution

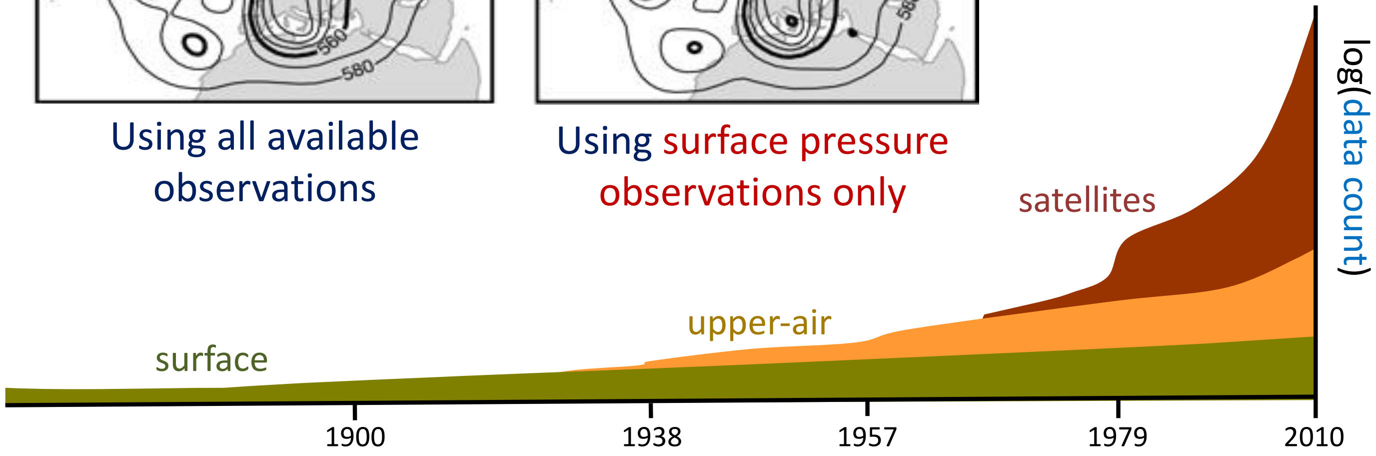
Two modern analyses of geopotential height at 500hPa



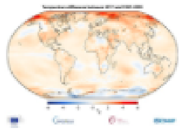
Using all available observations

Using surface pressure observations only

Whitaker, Compo, and Thépaut 2009



2017 extends period of exceptionally warm years, first complete datasets show



Thu, 04/01/2018 - 13:09

The first complete temperature datasets for 2017 show that last year was the third in a row of exceptionally warm years, the Copernicus Climate Change Service (C3S) implemented by the European Weather Centre (ECMWF) can announce.

Read more

Thank You