Data Assimilation

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Special acknowledgements to Jean-Noël Thépaut
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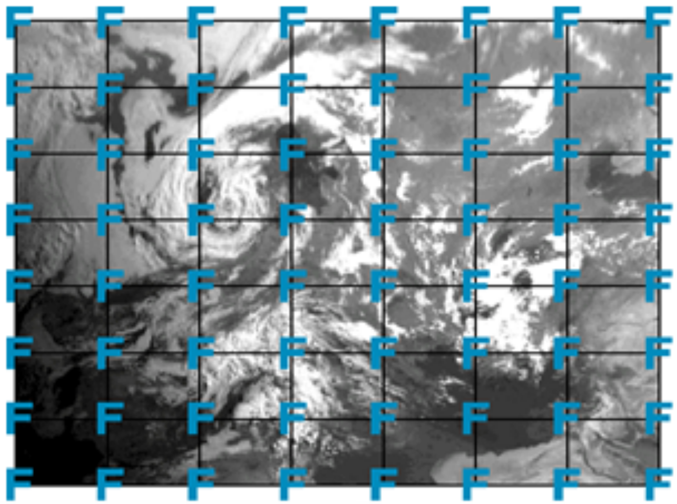
Data Assimilation

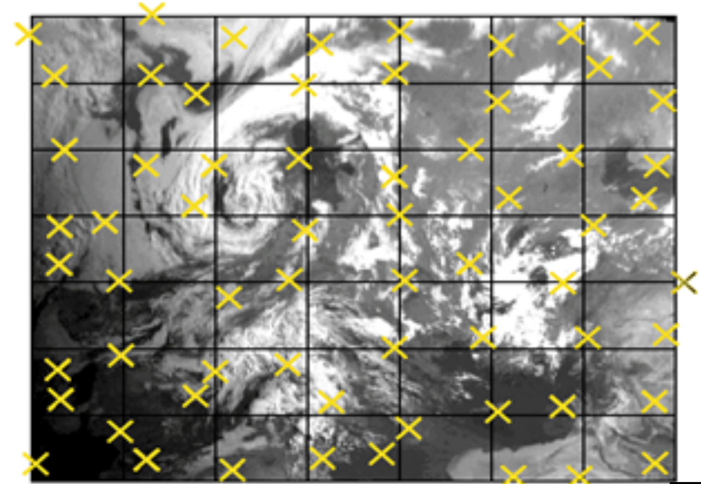
NWP definition: Process by which "optimal" initial conditions for numerical forecasts are defined.

- The best analysis (initial conditions) is the analysis that leads to the best forecast
- Makes "quickly" the best out of all information available

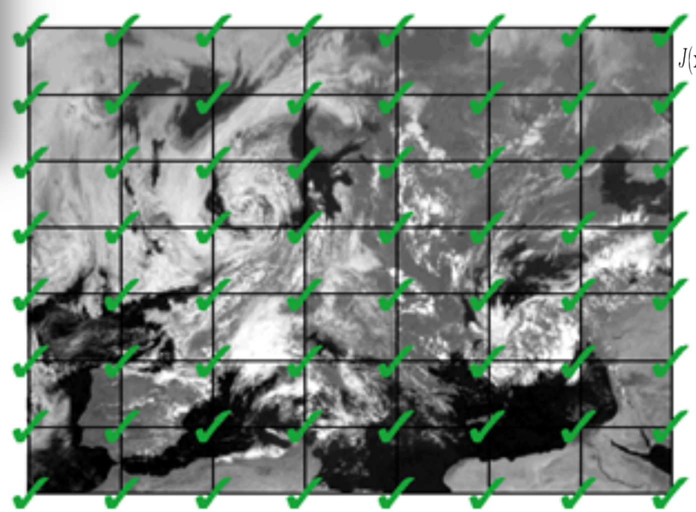
Model Forecast (with errors)

Observations (with errors)



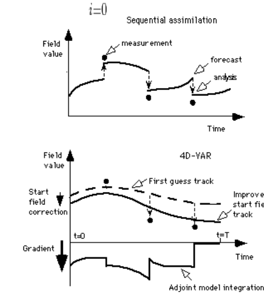


Computer (with a lot of CPUs)



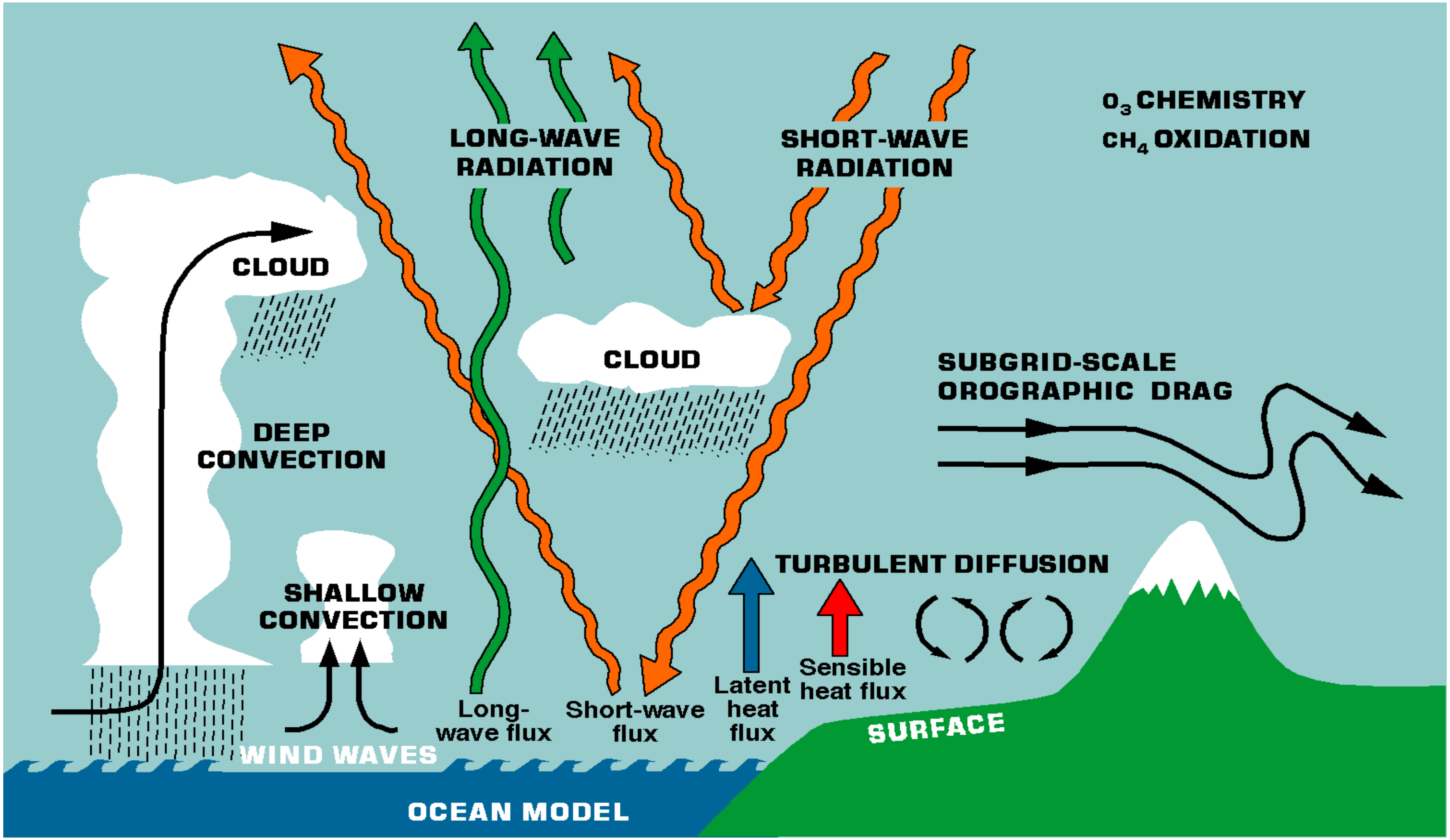
People (with a lot of good ideas)

$$J(x) = (x - x_b)^T B^{-1}(x - x_b) + \sum_{i=0}^{n} (y_i - H_i[x_i])^T R_i^{-1} (y_i - H_i[x_i])$$



Analysis (with - smaller – errors)

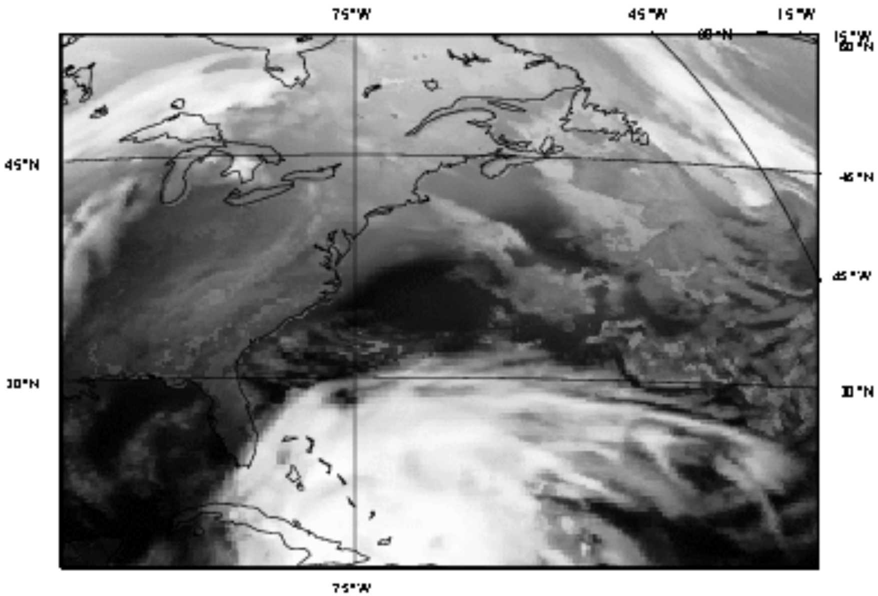
The forecast model is a very important part of the data assimilation system



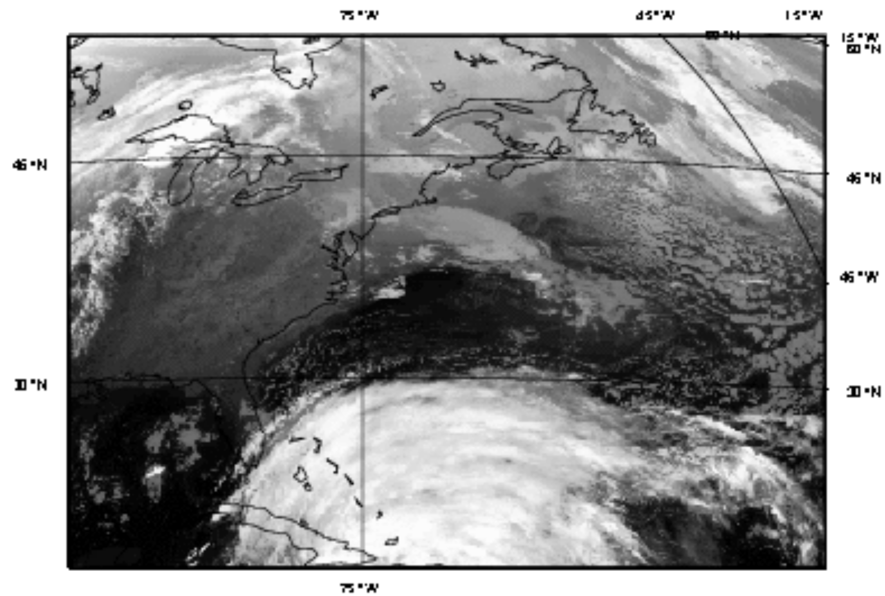
Most important physical processes in the ECMWF model

Models and observation operators have become much more realistic and accurate

ECMWF Fc 20121025 00UTC
Model simulated satellite images



GOES-13 IR10.8 20121025-20121030

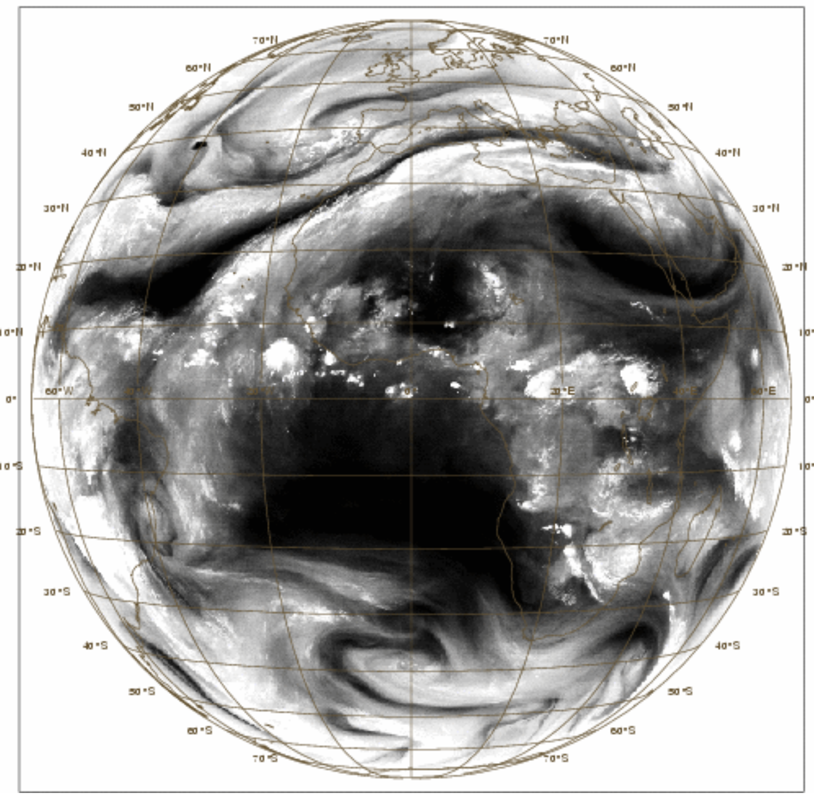


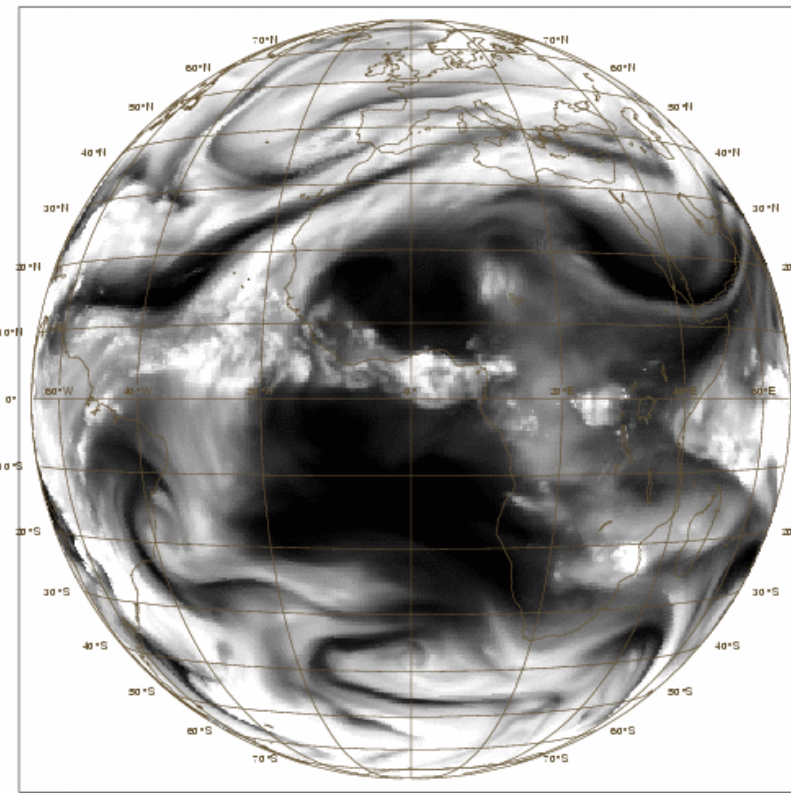
model

observation

Accurate radiative transfer models allows comparison of model and observed radiances

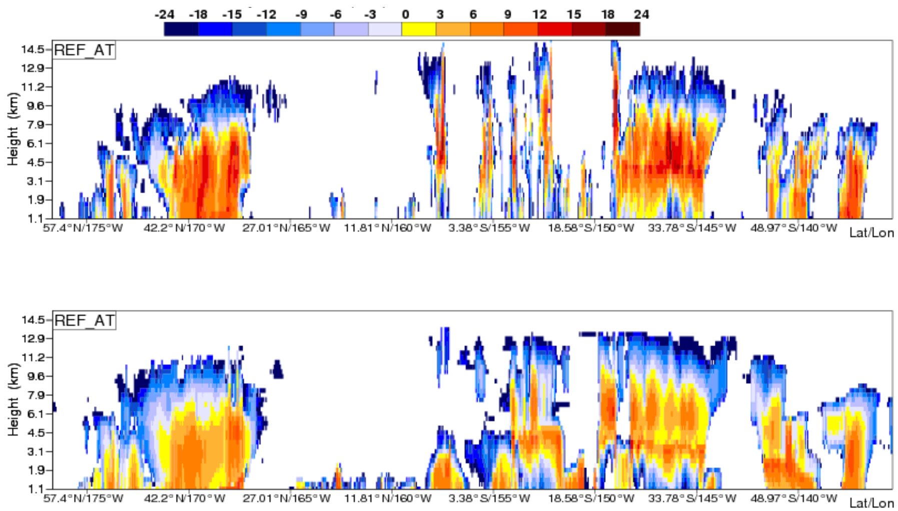
Observations Satellite Radiances ⟷ **compare** ⟷ **Model Radiances** ← **H** ← **Model T and q**

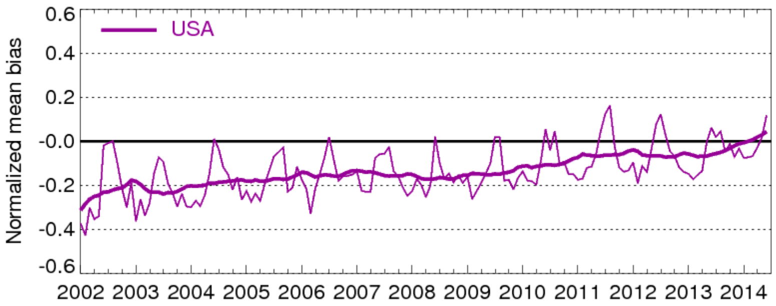




Models and observation operators have become much more realistic and accurate

C L O U D S A T





Continual improvement of ECMWF short-range precipitation forecasts with respect to ground-based radar data.

This widens opportunities to assimilate new data

Methodologies

Over the past decades, operational DA techniques have evolved from:

- Cressman type methods (1960/1970s)

to:

- Hybrid methods exploiting the best of both variational and ensemble worlds

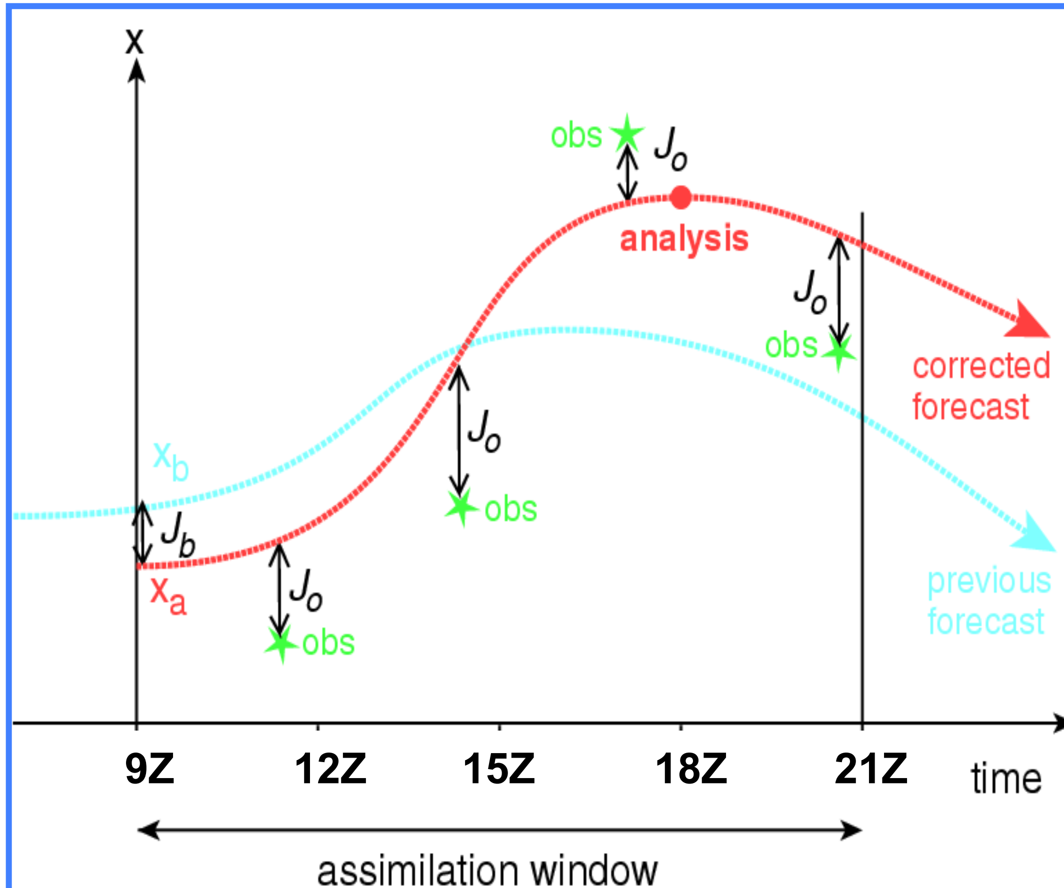
Choice remains application dependent

- Atmosphere, waves, sea-ice, ocean, composition, land…

ECMWF use a 4D Variational (4D-Var) Data Assimilation method

Around 13,000,000 observations within a 12-hour period are used simultaneously in one global (iterative) estimation problem

- "Observation – model" values are computed at the observation time at high resolution: 16 km
- 4D-Var finds the 12-hour forecast that take account of the observations in a dynamically consistent way
- Based on a tangent linear and adjoint forecast models, used in the minimization process at lower resolution
- 80,000,000 model variables (surface pressure, temperature, wind, specific humidity and ozone) are adjusted

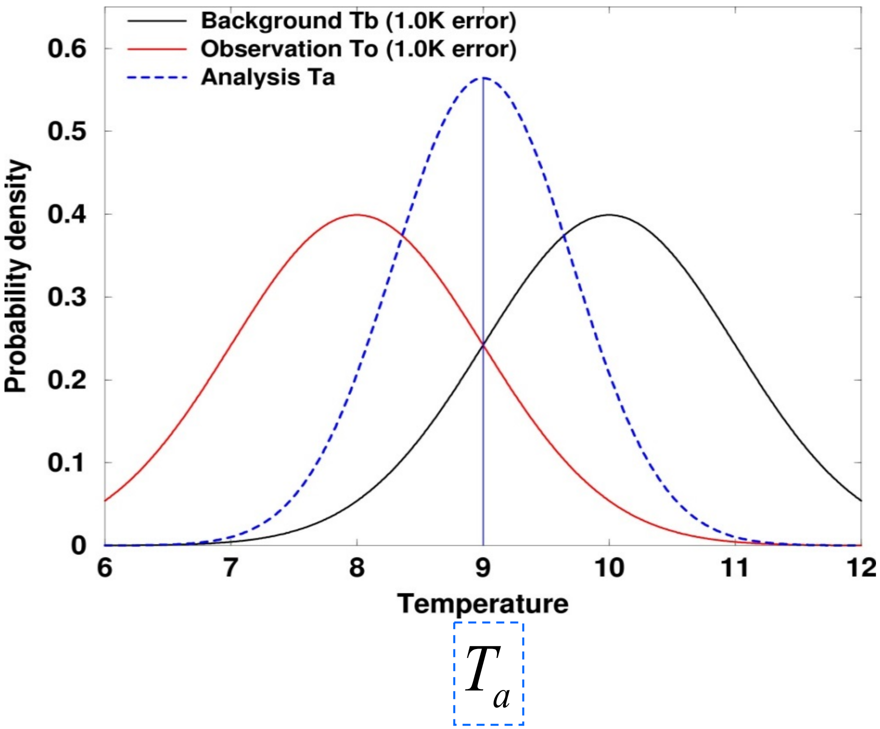


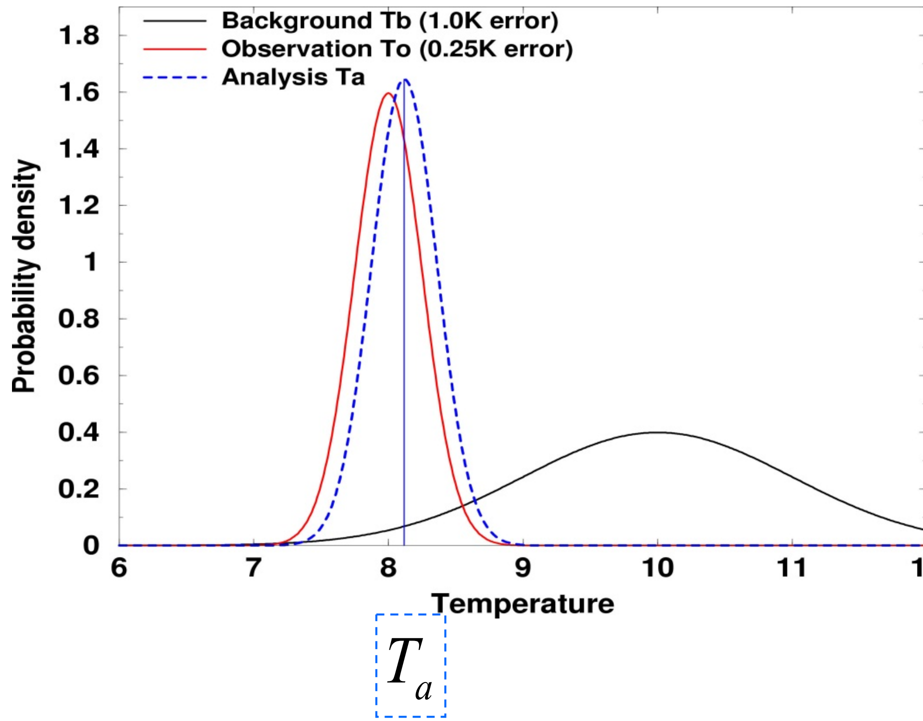
Observations and model background have errors
It is important to specify them accurately

Observed temperature: 8˚C

Short-range model background temperature: 10˚ C

Analysis: x˚C

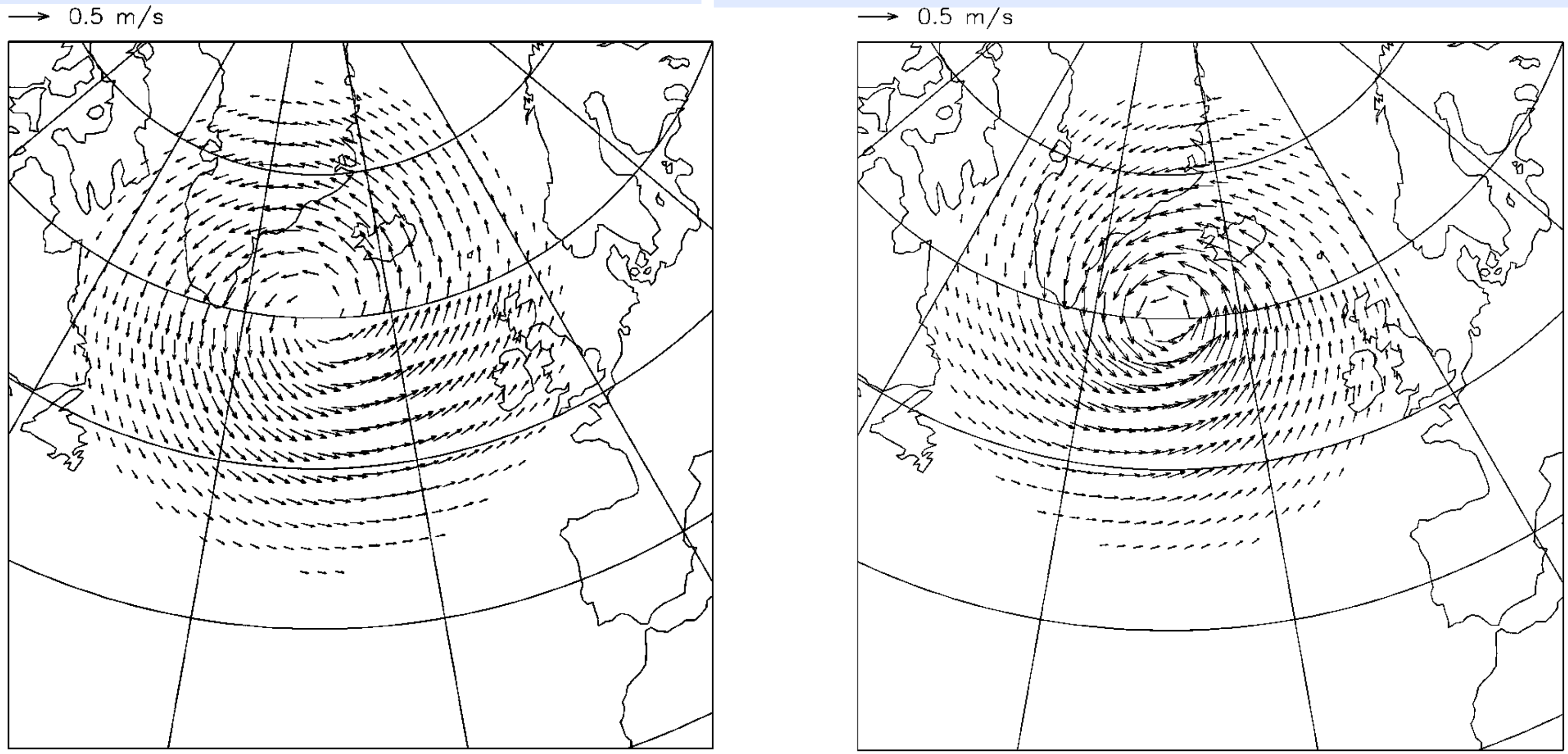




The Balance Operator ensures height/wind field approx. balance is retained in the extra-tropics

wind increments at 300hPa

wind increments 150 metre above surface



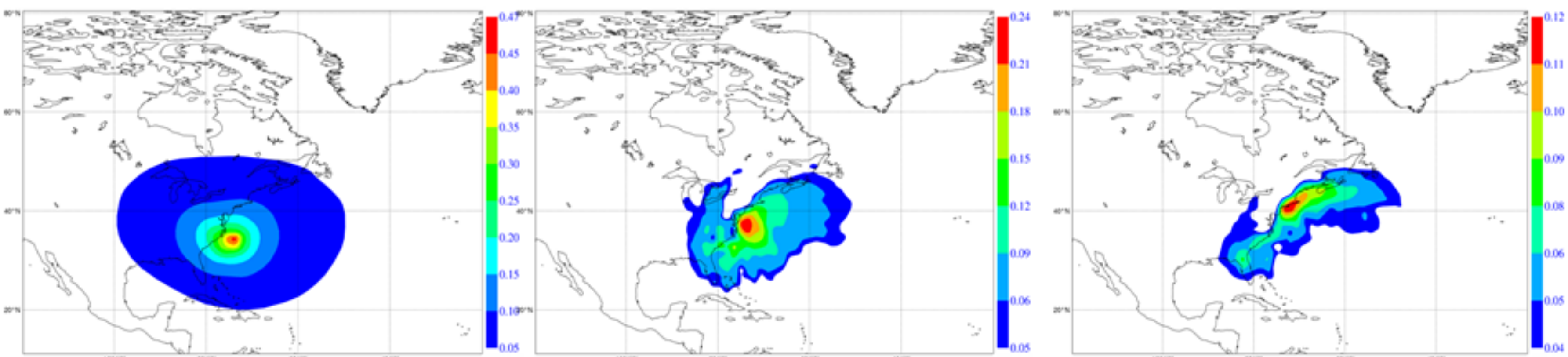
Wind increments obtained from a single surface pressure observation

4D-Var dynamically evolves increments

A useful property of 4D-Var is that it implicitly evolves the analysis increments *over the length of the assimilation window* (*Thépaut et al*.,1996) in accordance with the model dynamics

Temperature analysis increments for a single temperature observation at the start of the assimilation window:

$$x^a(t)-x^b(t) \approx MBM^T H^T(y-Hx)/(\sigma_b^2 + \sigma_o^2)$$



t=+0hours t=+3hours t=+6hours

More methodologies

Overarching considerations include:

- Seamless quantification of uncertainty estimation (analysis to long-range forecast)
- 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

Ensemble of Data Assimilations (EDA)

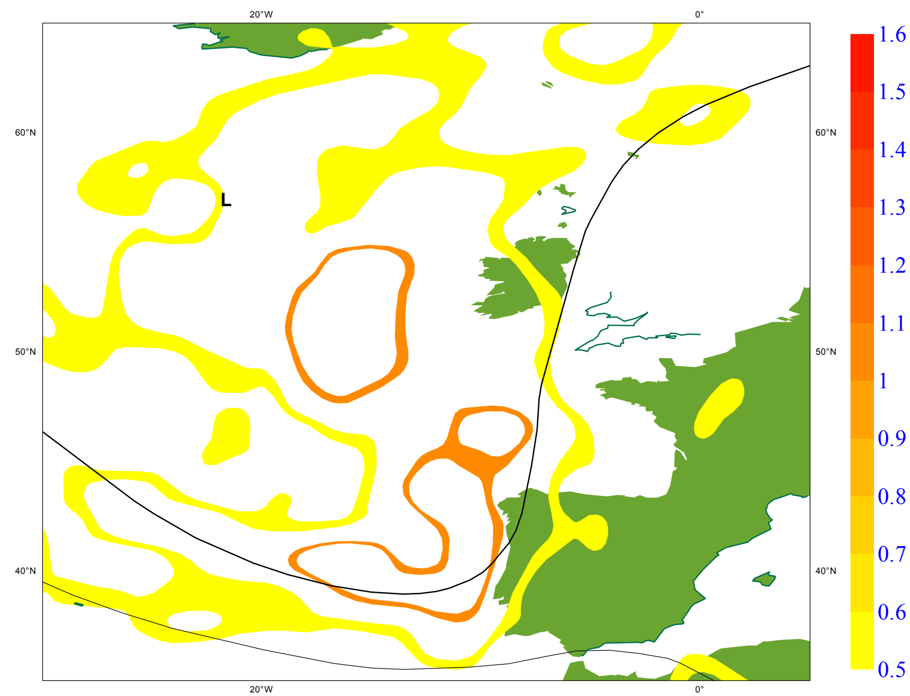
Run an ensemble of independent analyses with perturbed observations, model physics and Sea Surface Temperature fields.

25 EDA members plus a control at lower resolution.

Form differences between pairs of analyses (and short-range forecasts).

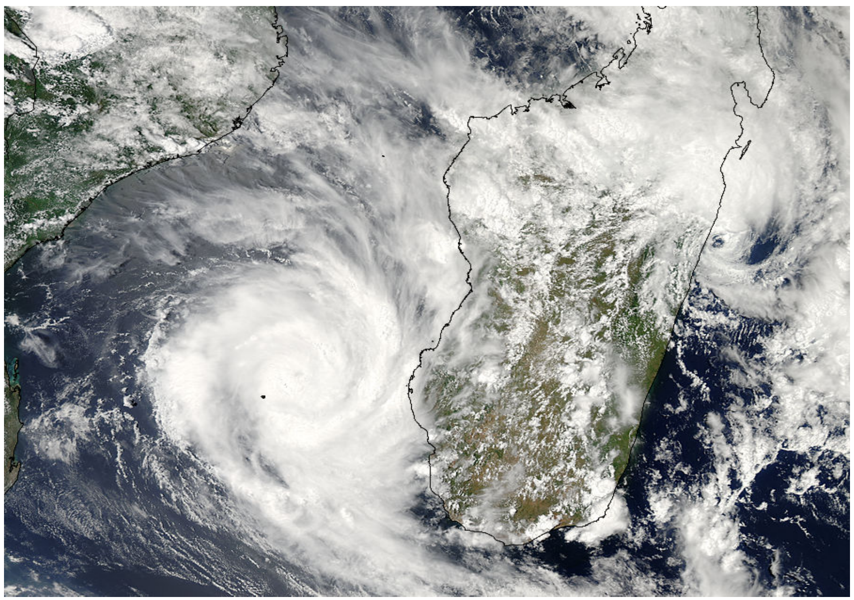
These differences estimates the statistical characteristics of analysis (and short-range forecast) error.

Yellow shading where the short-range forecast is uncertain →
give observations more weight in these regions.

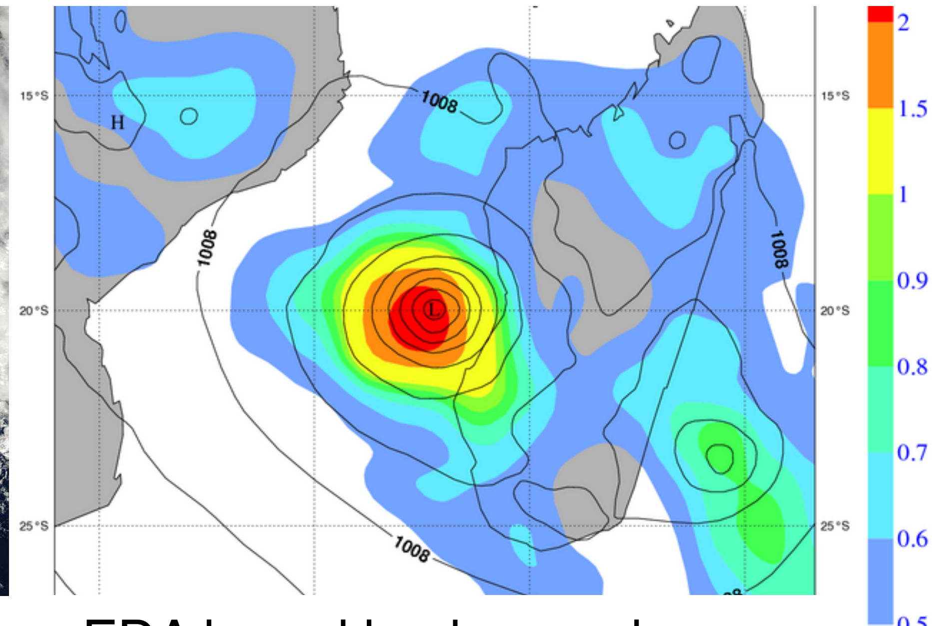


The EDA provides analysis and background uncertainty estimates

- To improve the initial perturbations in the Ensemble Prediction
- To calculate static and seasonal background error statistics
- To estimate flow-dependent background error covariances in 4D-Var
- To improve QC decisions and improve the use of observations in 4D-Var



Hurricane Fanele, 20 January 2009



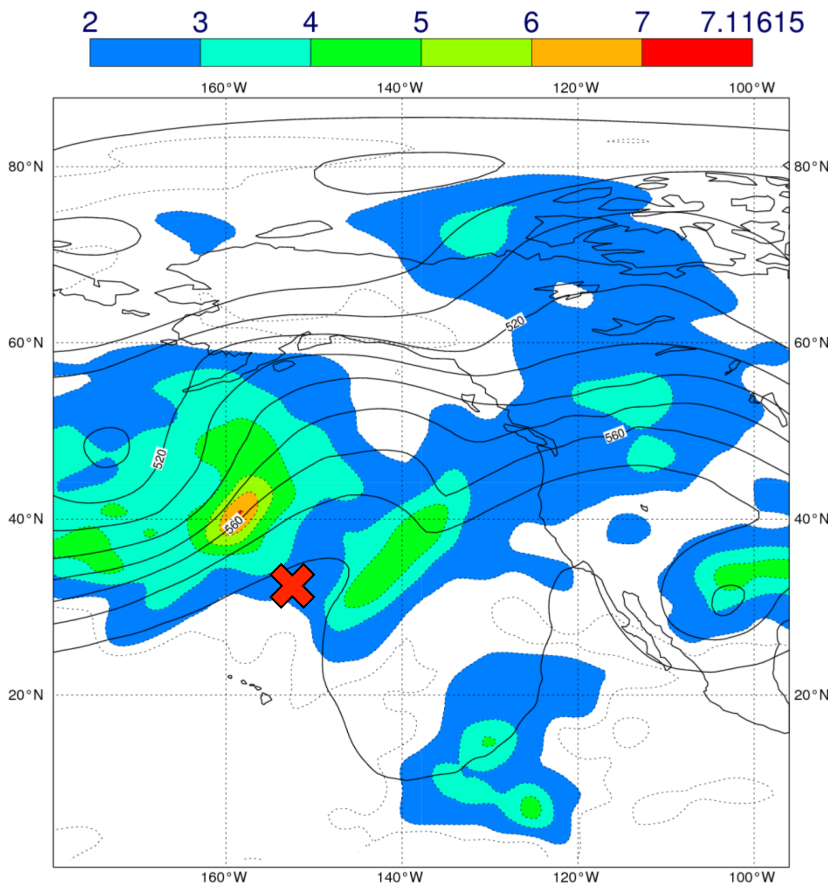
EDA based background error variance for Surface pressure

hPa

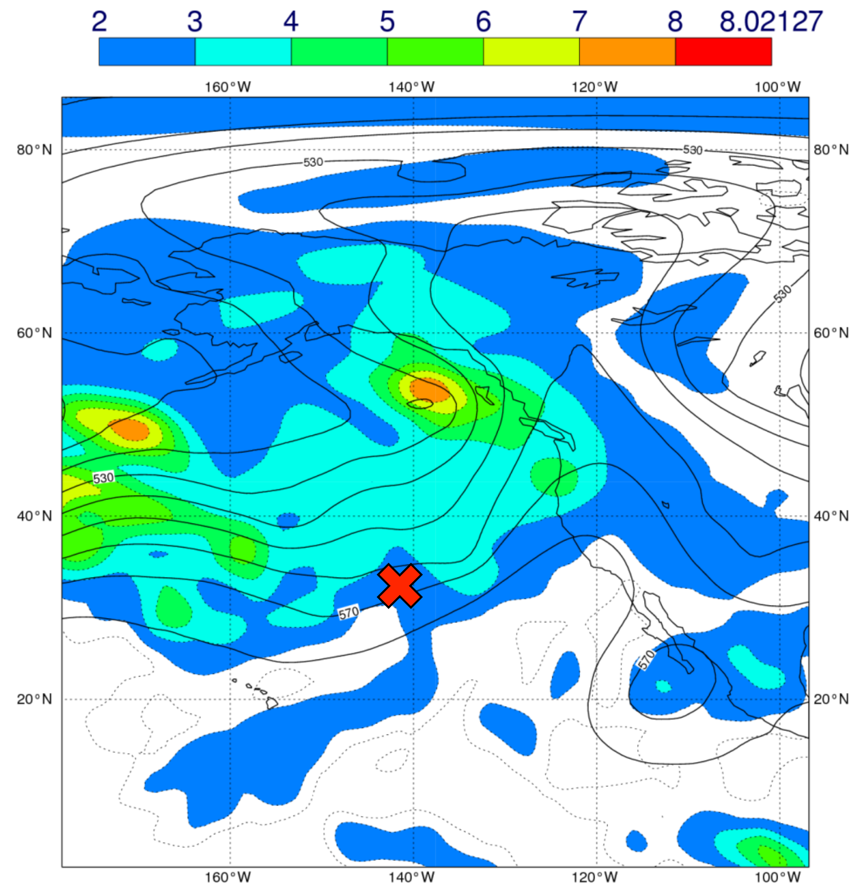
Why are flow-dependent covariances important?

Vertical correlations

2012-01-01 00Z



2012-02-01 00Z

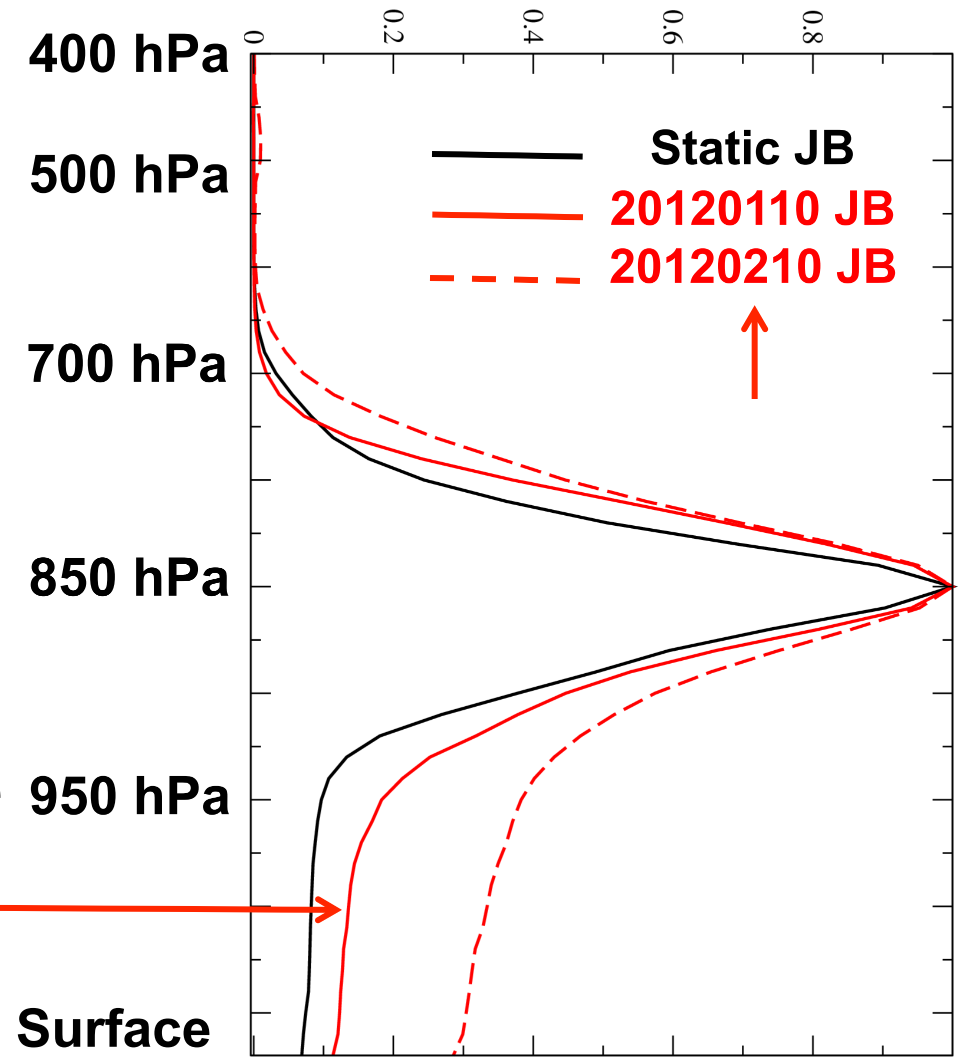


Why is flow-dependent JB better?

Vertical correlations at (30N,140W) at 850hPa

The 12-day averaging allows JB to cater for flow-regime changes

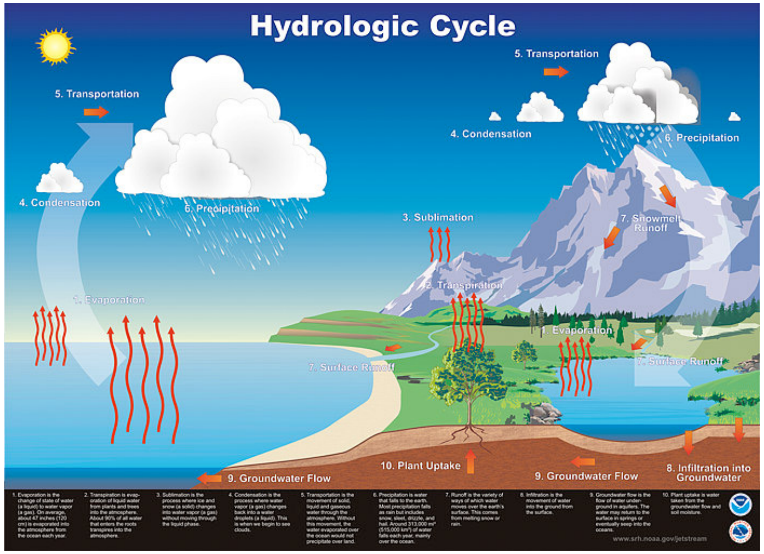
The vertical correlations between 850hPa and the boundary layer change significantly from 10th of January 2012 to 10th of February 2012.



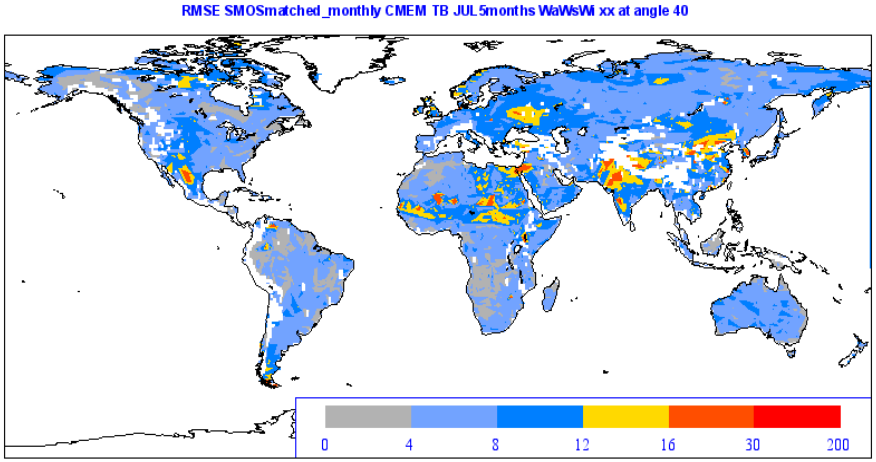
Land Data Assimilation

- Land surfaces: heterogeneities, range of spatial and time scales controlling the processes, reservoirs and fluxes.

- The Land Data Assimilation Systems (LDAS) make use of:
  - Processes and feedbacks represented with coupled land-atmosphere models (extension to carbon cycle available)
  - Data assimilation schemes, such as nudging, OI, EKF, EnKF, that update models states variables and/or surface parameters for NWP and climate applications
  - Routine Near Real Time observations with high information content about land surface variables (in-situ, SMOS, ASCAT, SMAP, etc.)

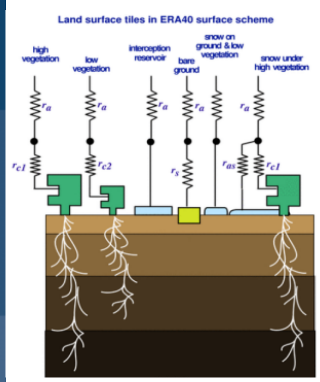


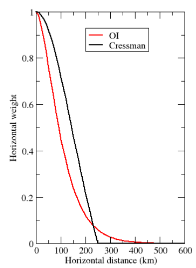
SMOS TB First Guess Departure (K) July 2012, RMSD=6.7K

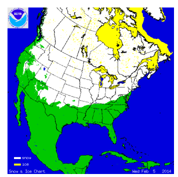


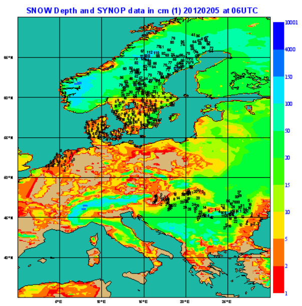
Snow in the ECMWF Data Assimilation System

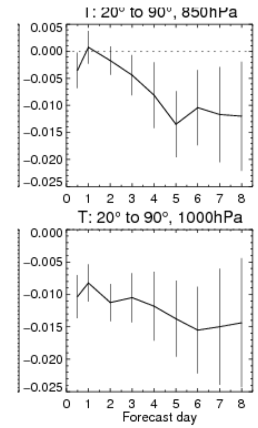
2009 2010 2011 2012 2013 2014 …











Snow Model

. Liquid Water
. Density
. Albedo
. Fraction

Snow Obs and DA

. Optimum Interpolation
. 4km IMS snow data
. Obs Quality Control
. IMS latency/acquisition

. Additional in situ obs
. WMO/SnowWatch action
. IMS data assimilation
. obs error revision

Snow Model & DA

. Multi-layer model
. Snow cover Fract
. BUFR SYNOP
. RT modelling
. Snow COST action

ECMWF Land Data Assimilation System:
https://software.ecmwf.int/wiki/display/LDAS/LDAS+Home

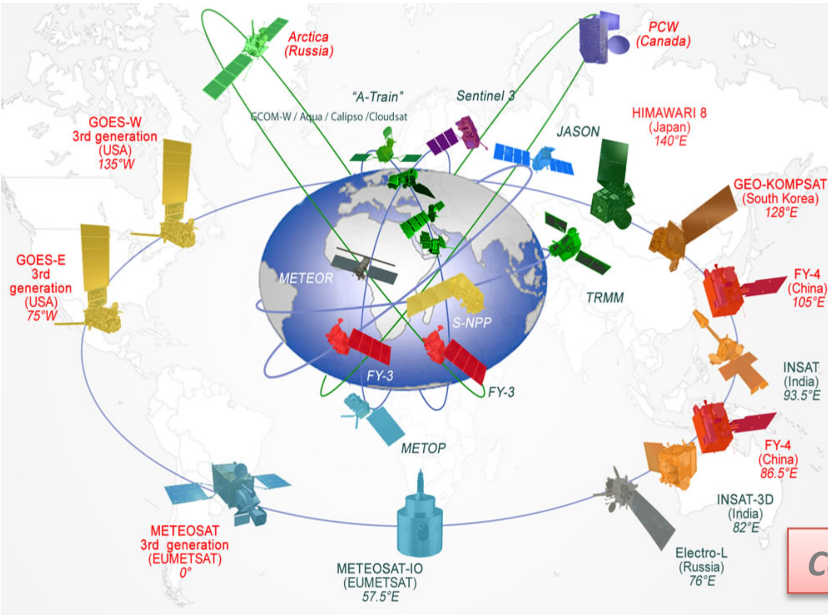
The Global Observing System

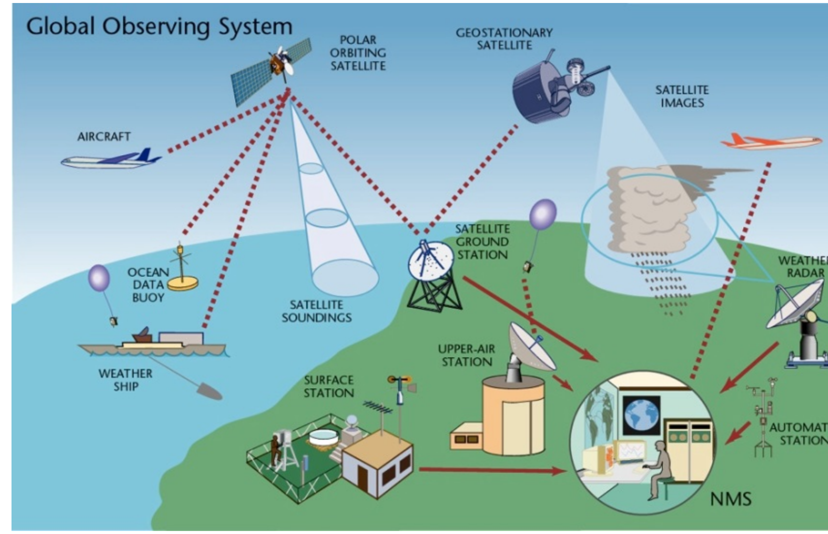
Maximizing the impact of new observations:

- Need to plan
- Need to assess
- Need to proof-of-concept
- Need to consolidate:
  - transfer from Research to Operations

Underpinning requirement: Full exploitation of new observations require sustained investments in model and data assimilation developments

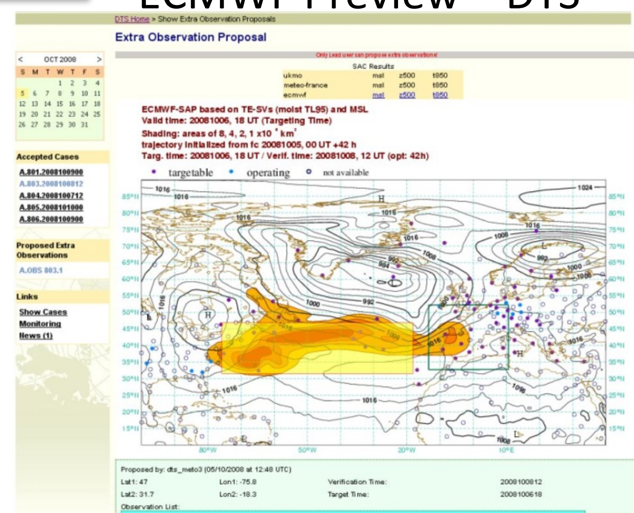
WMO Integrated Global Observing System



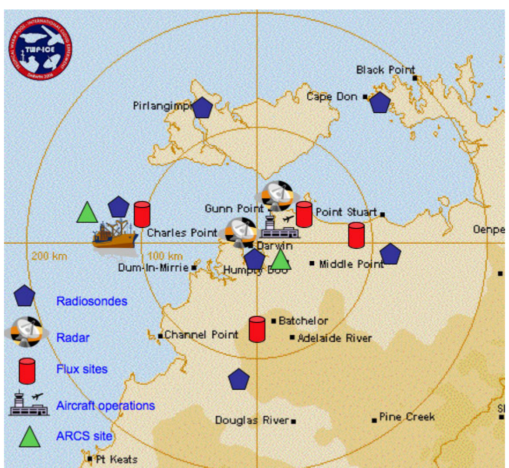


Courtesy: WMO

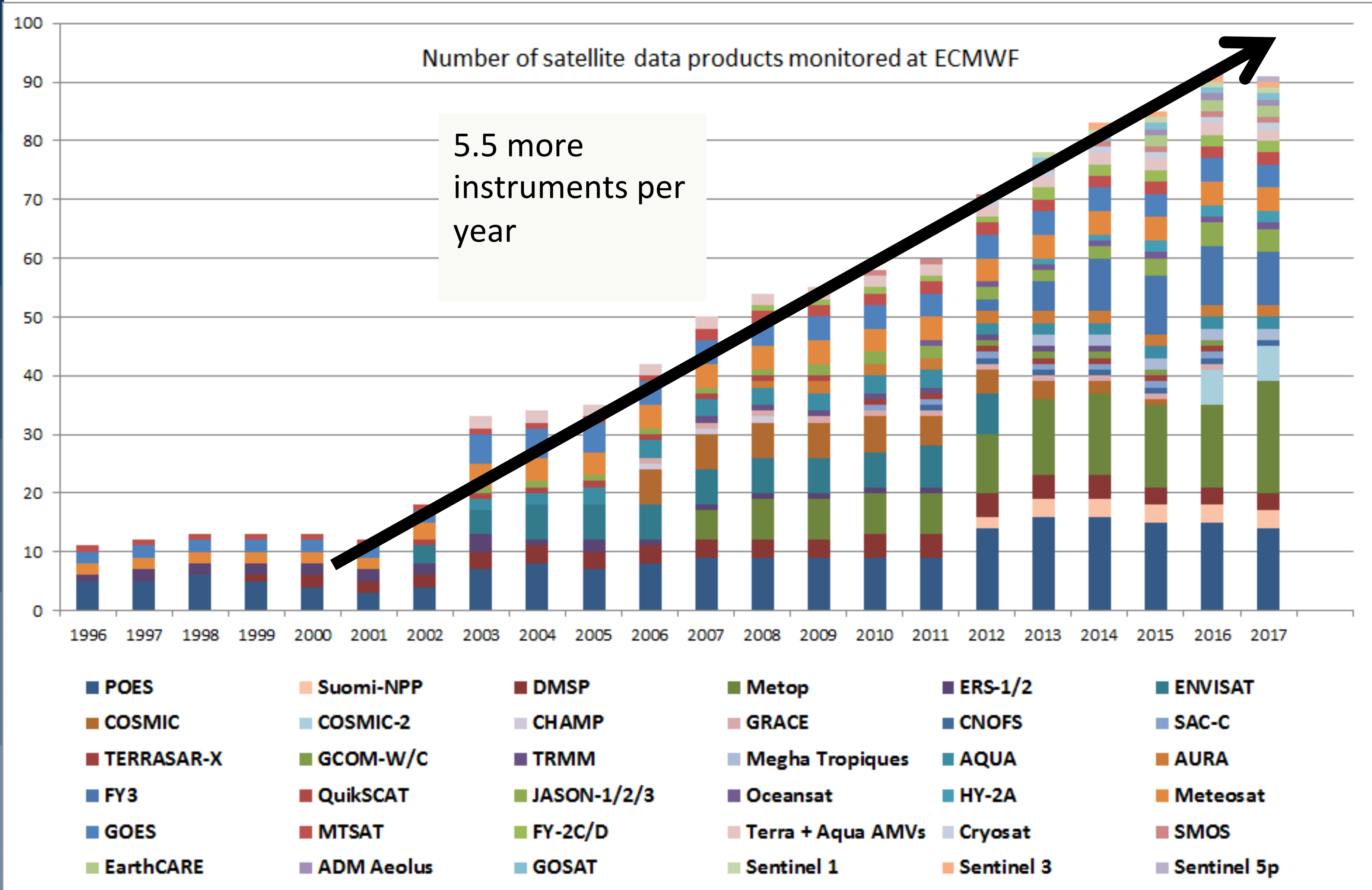
ECMWF Preview – DTS



T W P - I C E

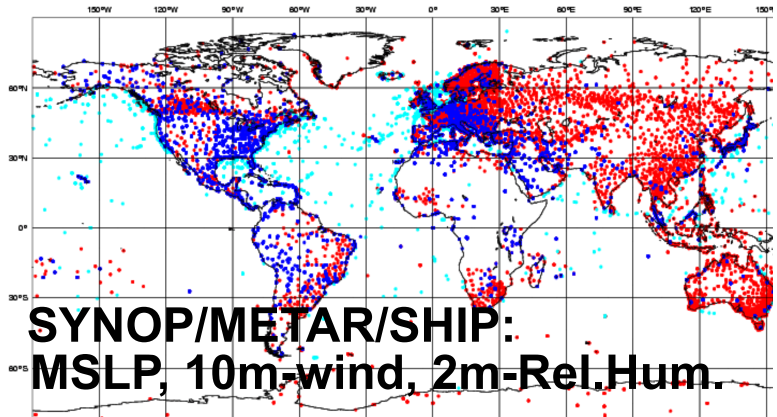


Supported by field campaign experiments, Data targeting studies, etc.

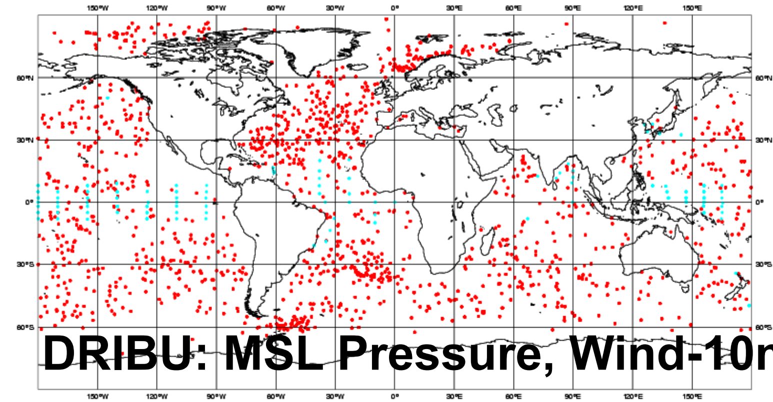


Number of satellite data products monitored at ECMWF
5.5 more instruments per year
100
90
80
70
60
50
40
30
20
10
0
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
POES
Suomi-NPP
DMSP
Metop
ERS-1/2
ENVISAT
COSMIC
COSMIC-2
CHAMP
GRACE
CNOFS
SAC-C
TERRASAR-X
GCOM-W/C
TRMM
Megha Tropiques
AQUA
AURA
FY3
QuikSCAT
JASON-1/2/3
Oceansat
HY-2A
Meteosat
GOES
MTSAT
FY-2C/D
Terra + Aqua AMVs
Cryosat
SMOS
EarthCARE
ADM Aeolus
GOSAT
Sentinel 1
Sentinel 3
Sentinel 5p

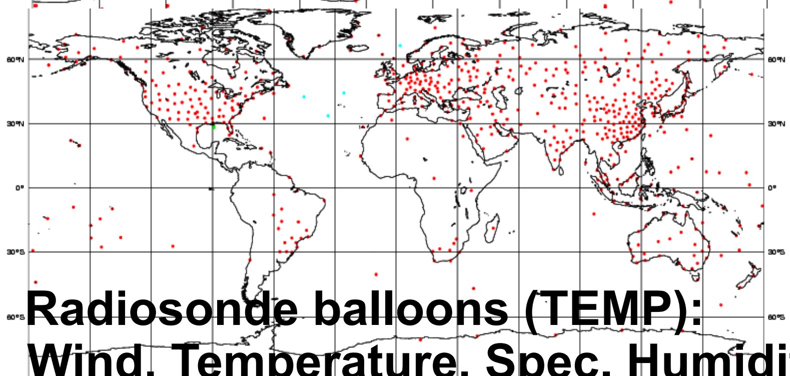
Conventional observations used by ECMWF's analysis



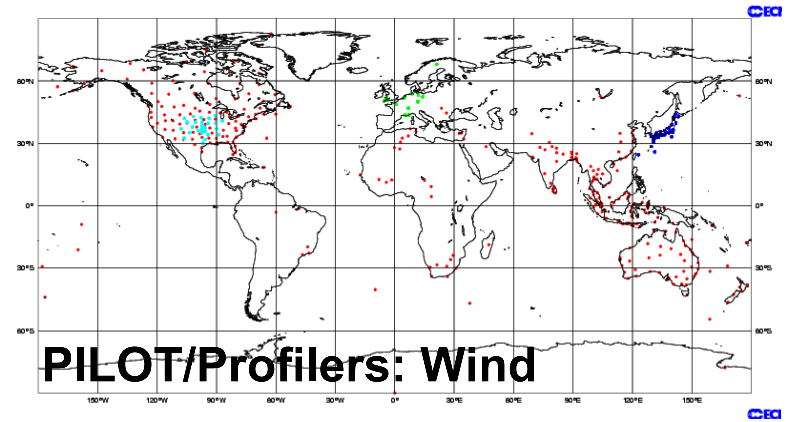
SYNOP/METAR/SHIP: MSLP, 10m-wind, 2m-Rel.Hum.



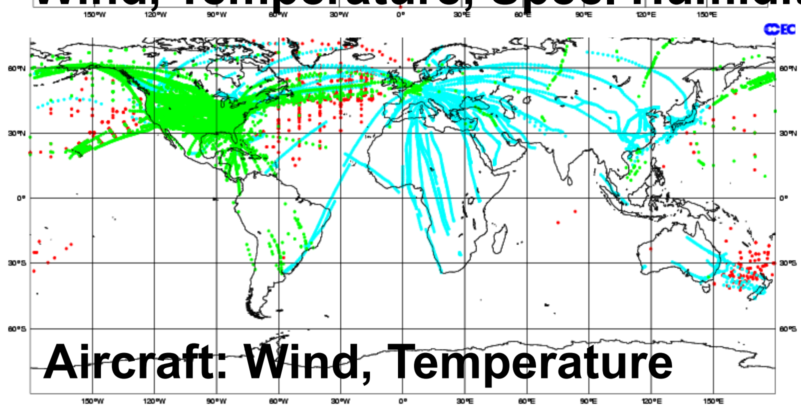
DRIBU: MSL Pressure, Wind-10m



Radiosonde balloons (TEMP): Wind, Temperature, Spec. Humidity



PILOT/Profilers: Wind

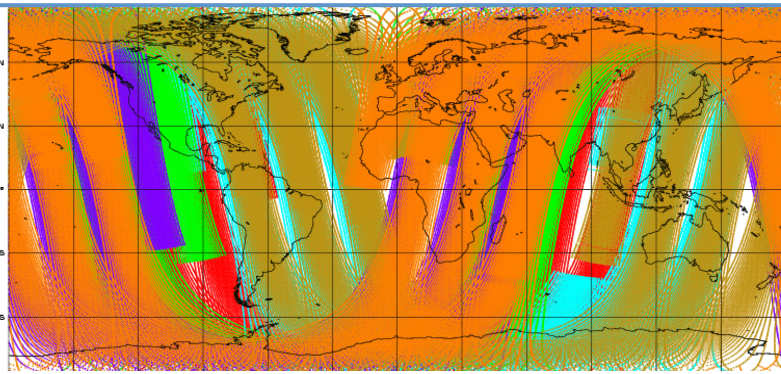


Aircraft: Wind, Temperature

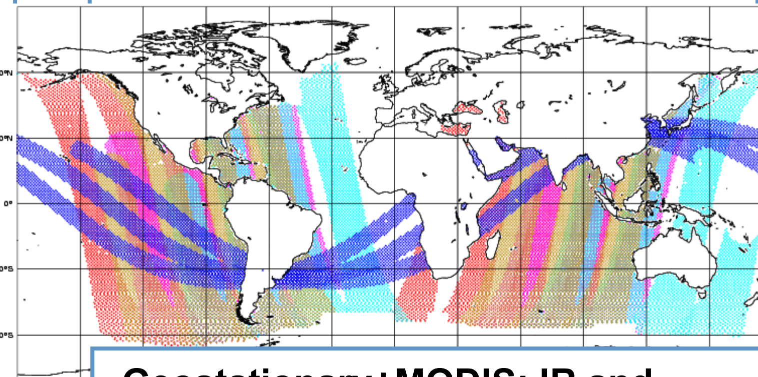
Note: We only use a limited number of the observed variables; especially over land.

Satellite data sources used by ECMWF’s analysis

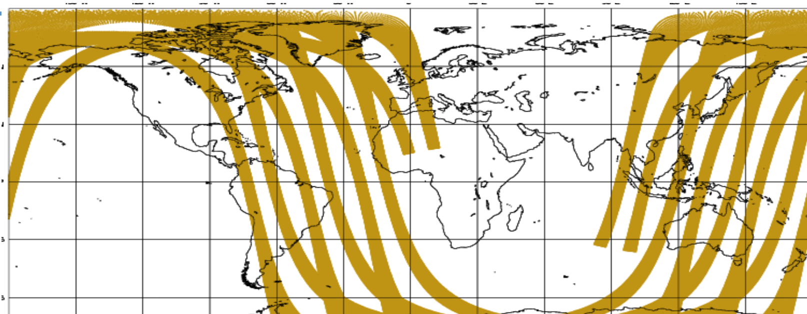
Sounders: NOAA AMSU-A/B, HIRS, AIRS, IASI, MHS



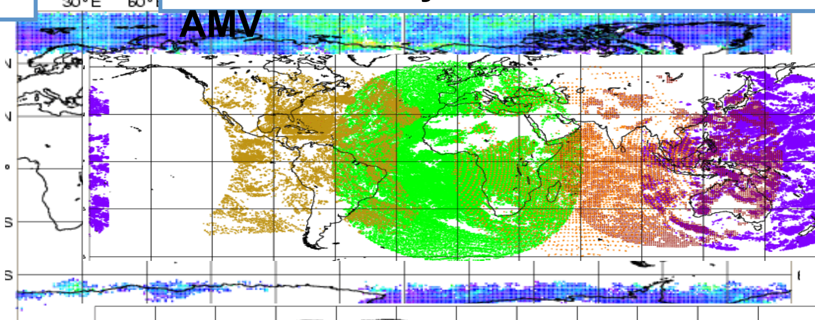
Imagers: SSMI, SSMIS, AMSR-E,



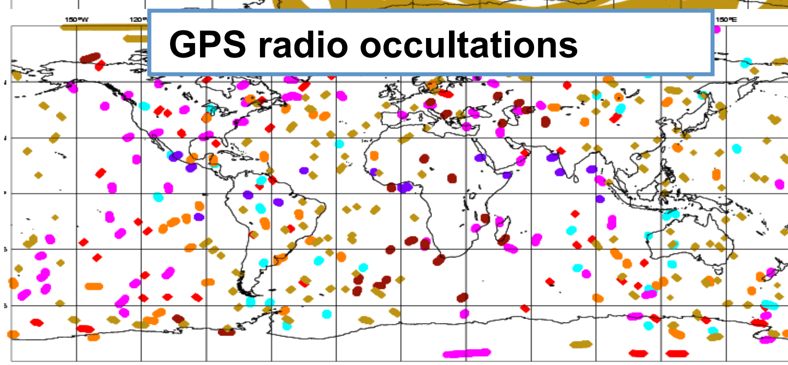
Scatterometer ocean low-level winds: ASCAT



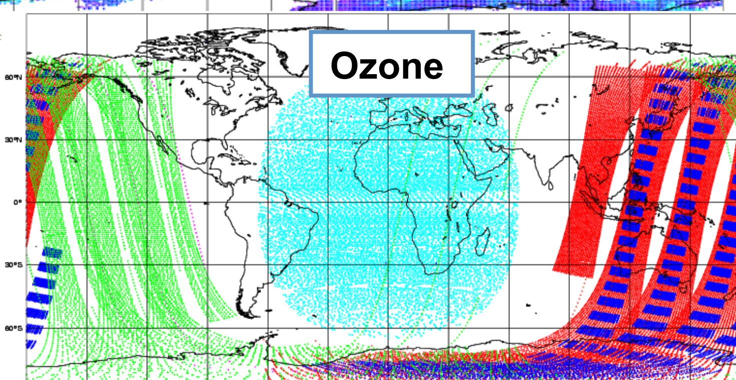
Geostationary+MODIS: IR and AMV



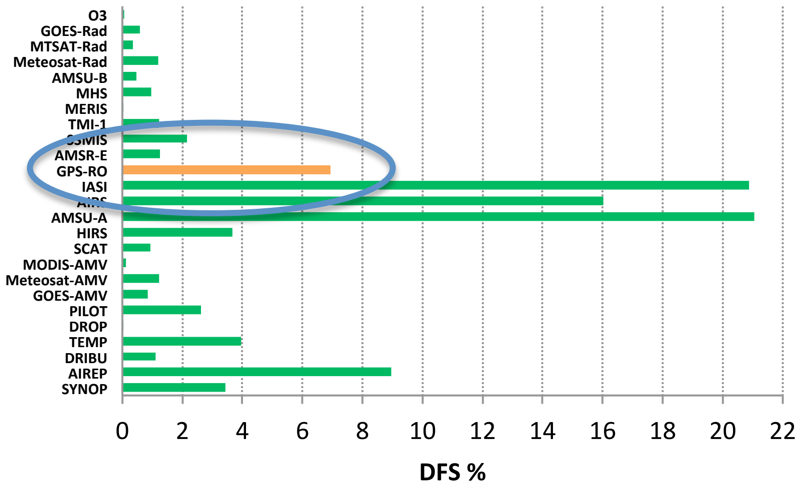
GPS radio occultations

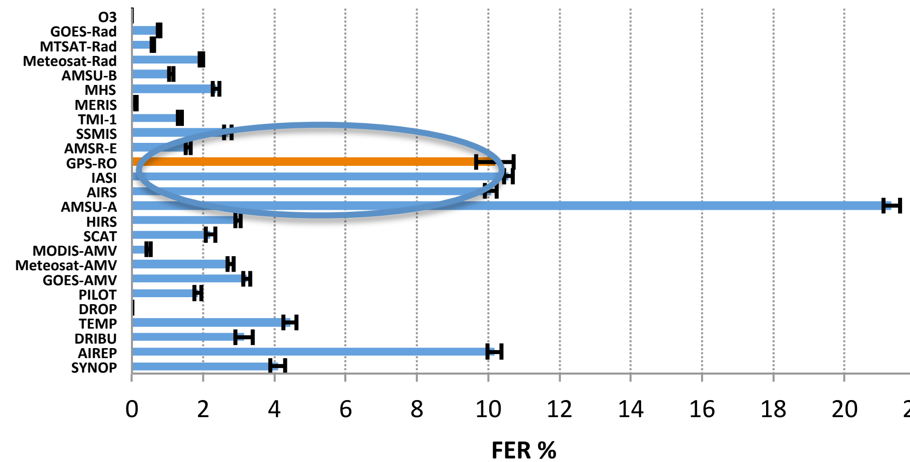


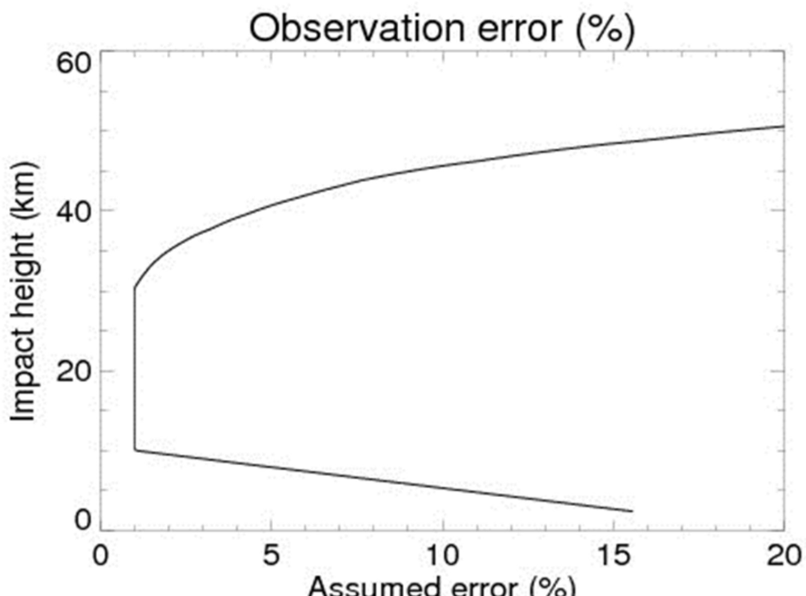
Ozone

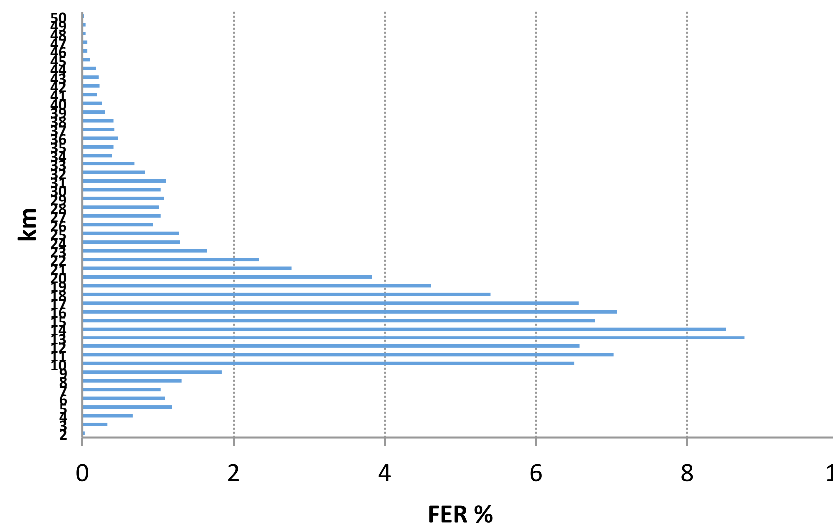


Observation Impact at ECMWF









Possible zoom on observation type, level, geographical area, etc.

Quality control of observations is very important

Data extraction

- Check out duplicate reports
- Ship tracks check
- Hydrostatic check

Thinning

- Some data is not used to avoid over-sampling and correlated errors
- Departures and flags are still calculated for further assessment

Blacklisting

- Data skipped due to systematic bad performance or due to different considerations (e.g. data being assessed in passive mode)
- Departures and flags available for all data for further assessment

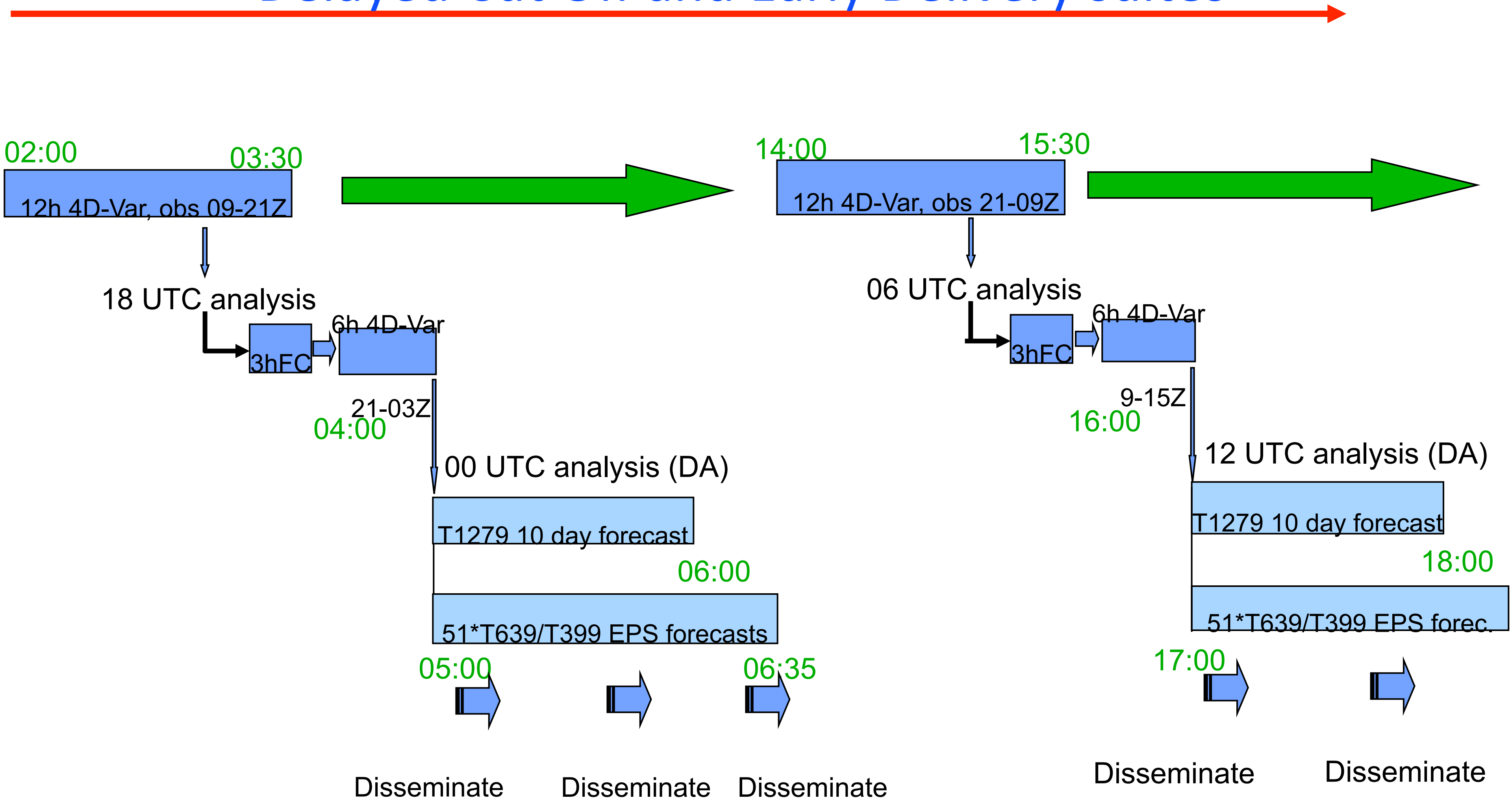
Model/4D-Var dependent QC

- First guess based rejections
- VarQC rejections

Used data → Increments

Analysis

Operational schedule
Delayed Cut Off and Early Delivery suites



Methodologies

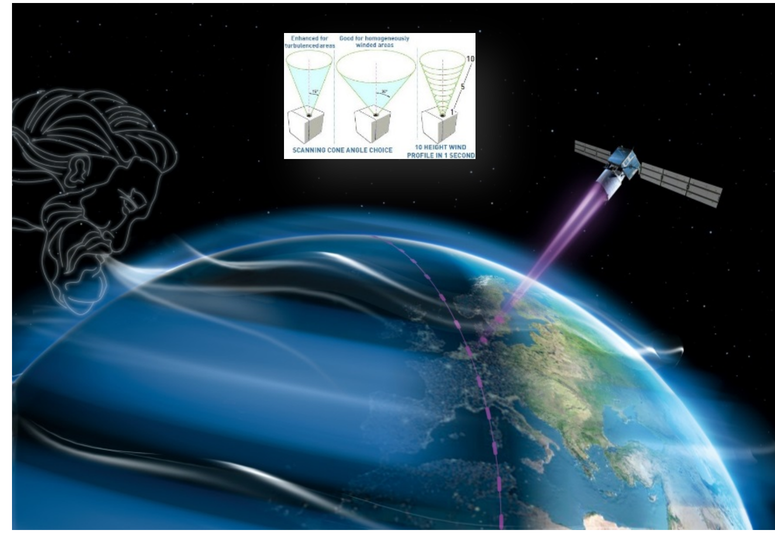
More specific challenges and opportunities

- Preparing for novel observing systems
- Scalability
- Meso-scale Data Assimilation
- Climate Monitoring Applications

ADM–AEOLUS: A new perspective for wind distribution understanding and data assimilation

An ESA Earth-explorer mission

Doppler wind lidar
Measures Doppler shift (due to wind) of backscattered UV laser light from the atmosphere



Courtesy: ESA

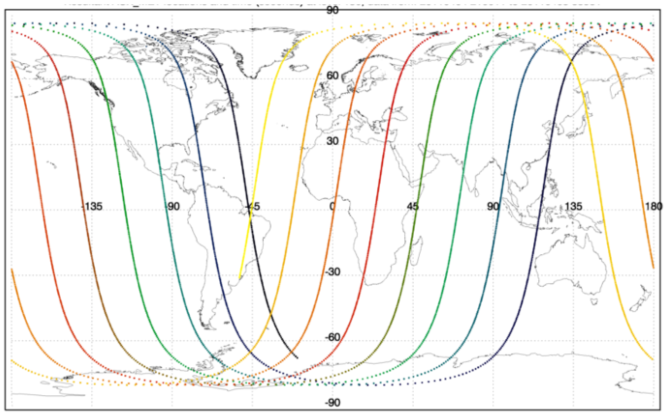
Main application is to improve global analyses and forecasts
Profiles of horizontal line-of-sight (HLOS) wind components

Launch expected mid 2016

More wind profiles would greatly benefit the Global Observing System

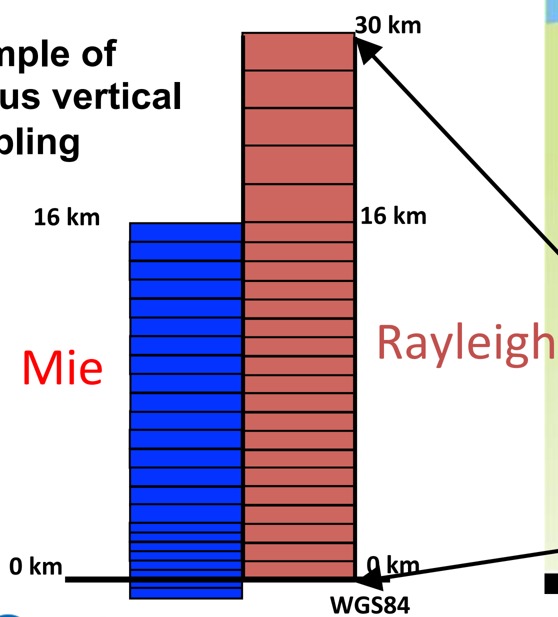
Sourc

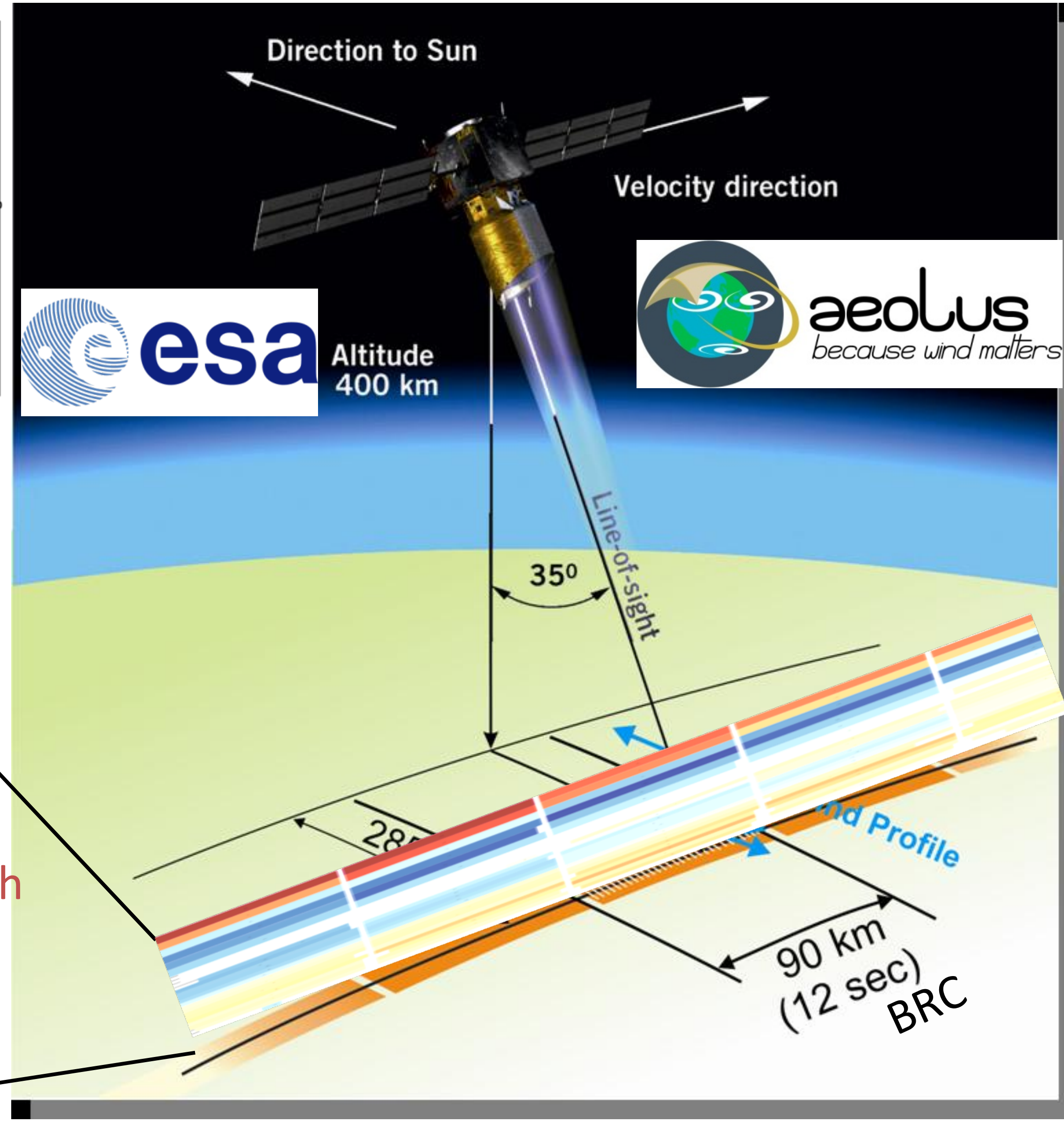
Aeolus measurement principle



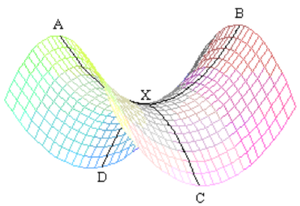
12 hrs coverage, ~92K winds

Example of Aeolus vertical sampling



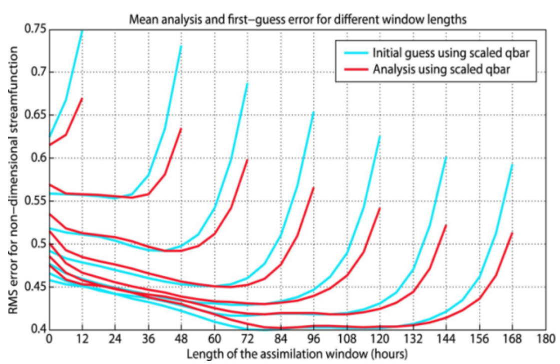


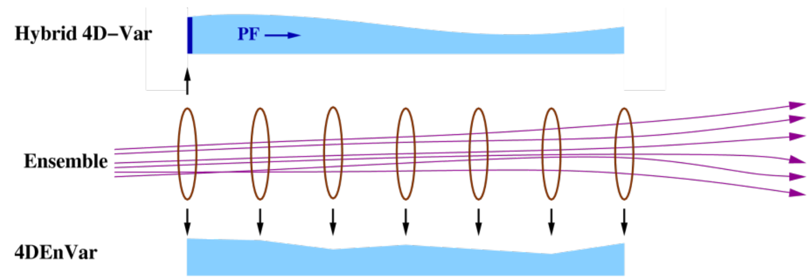
DA has to remain efficient on massively parallel computers



Long window weak-constraint 4D-Var (saddle point algorithm)

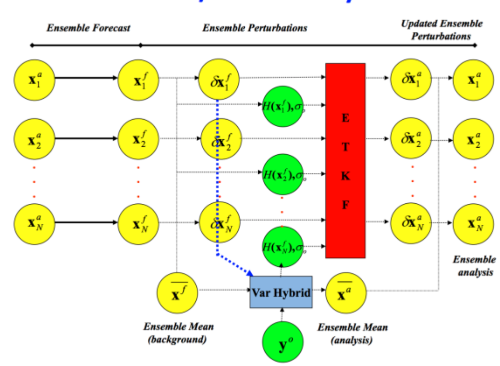
Lagrangian: $\mathcal{L}(\delta\mathbf{x}, \delta\mathbf{p}, \delta\mathbf{w}, \lambda, \mu)$





4D-en-Var (no TL/AD needed, ensembles run in parallel, I/O costs to be managed)

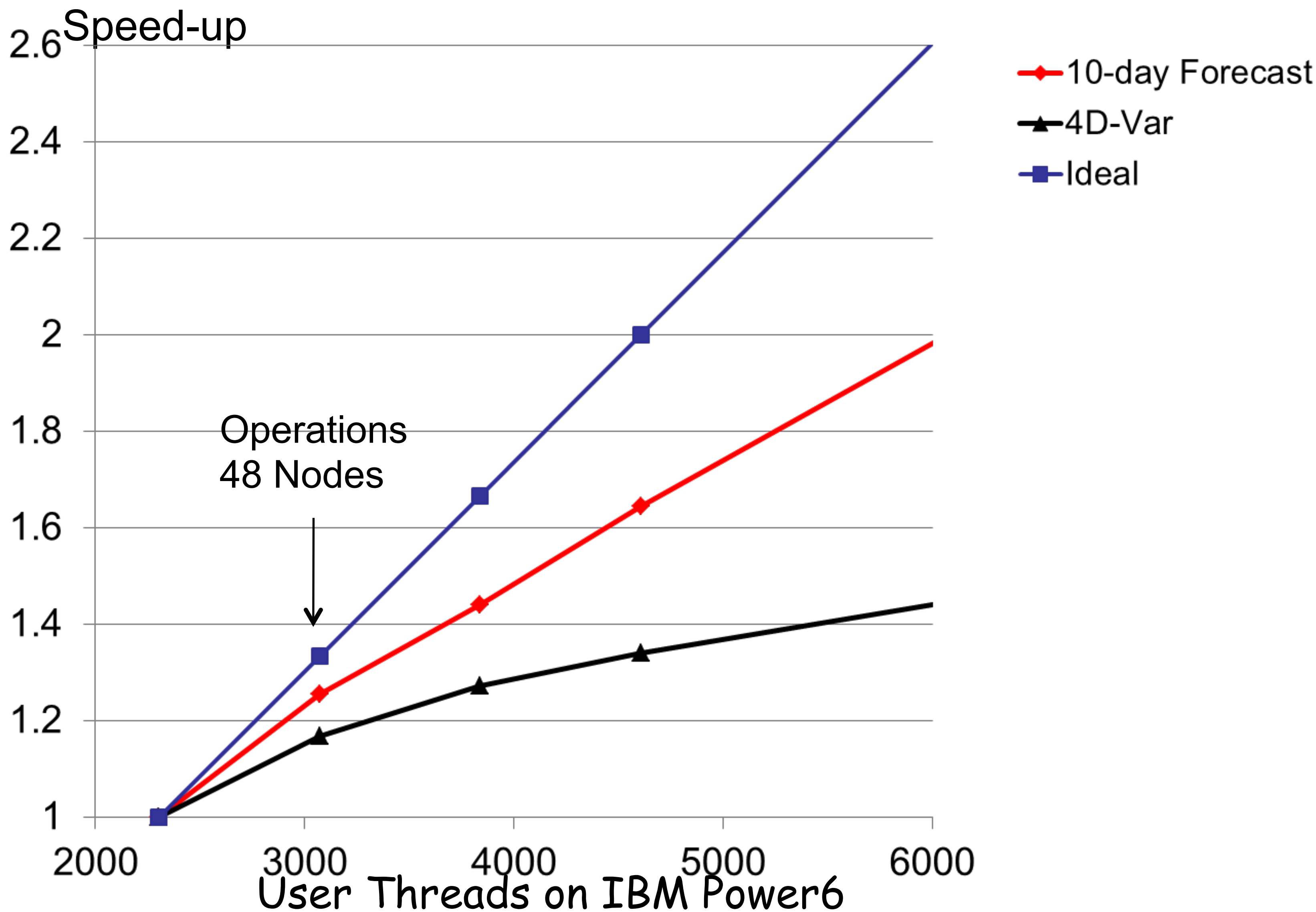
Variational/Ensemble Hybrid DA



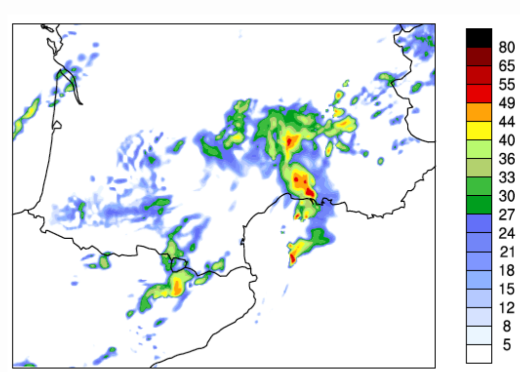
EnKF ("embarrassingly parallel") and various hybrid EDA/VAR methods

Pre- and Post-processing of big data are part of the story!

Scalability of T1279 Forecast and 4D-Var

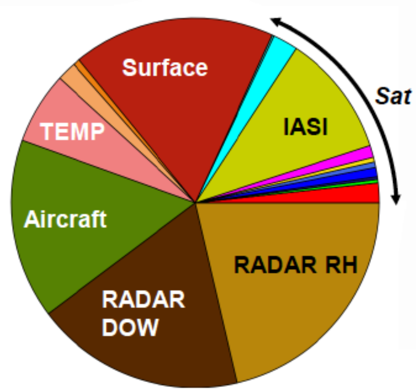


Challenges with Meso-scale Data Assimilation



Radar reflectivity simulated by AROME

Source: Thibaut Montmerle, Météo-France



Active obs in AROME for one rainy day

General

- Quick evolving processes
- Rapid updates requires (hourly or sub-hourly)
- Uncertainties and predictability

Remote sensing observations

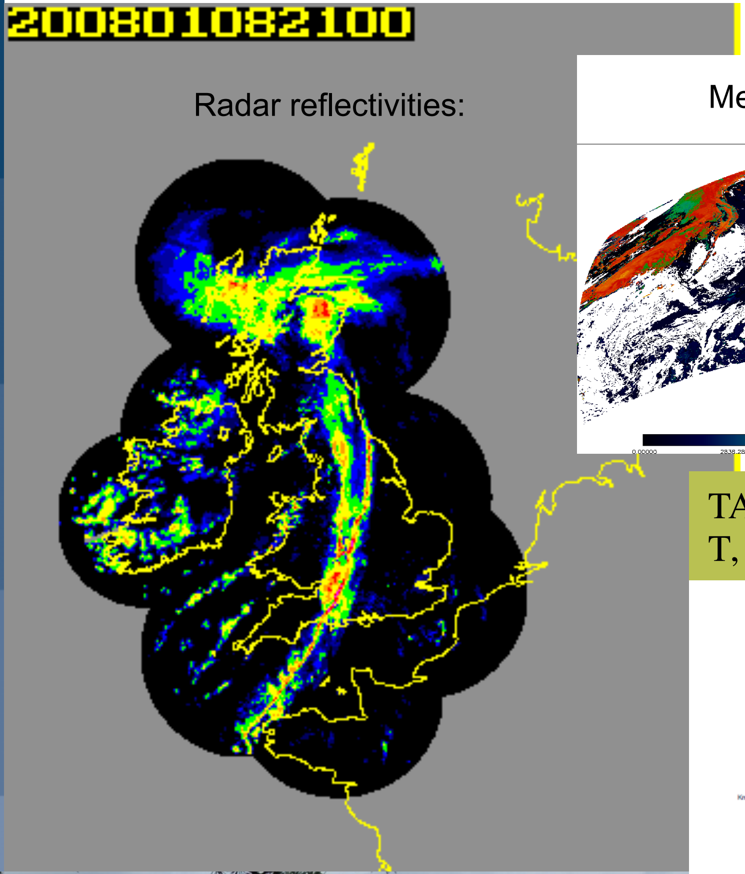
- More timely use of information from GEO satellites
- Novel observations for convective scale DA
- Assimilate cloud-affected radiances
- Non-linear observation operators
- Accuracy and efficiency of radiative transfer in all-sky

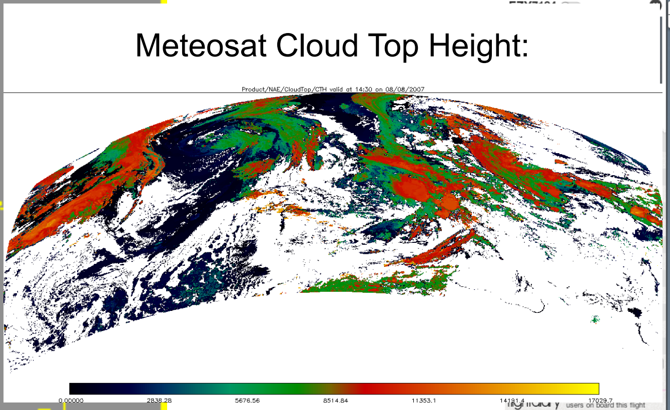
Covariance modeling

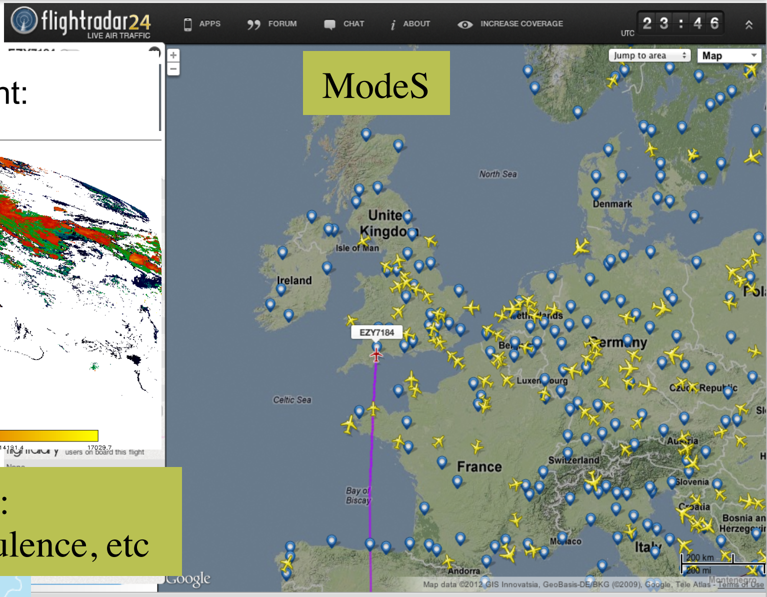
- Traditional balance (e.g. geostrophic & hydrostatic) not applicable at high-resolution
- Impact on ensemble size
- Complex, non-linear, flow-dependent relationship between model variables
- Significant model error (in phase and amplitude)

Novel observations for convective-sale DA

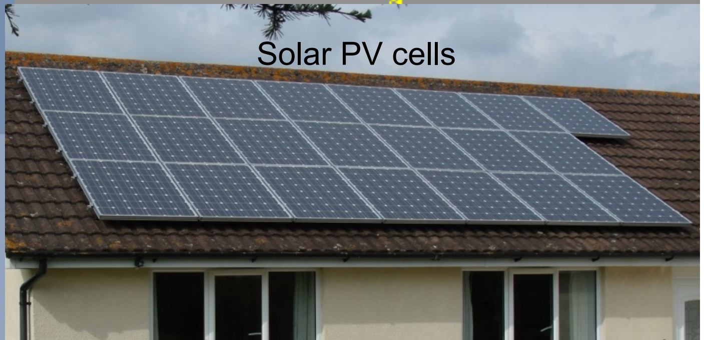
Source: Tom Hamill and WMO DA symposium 2013

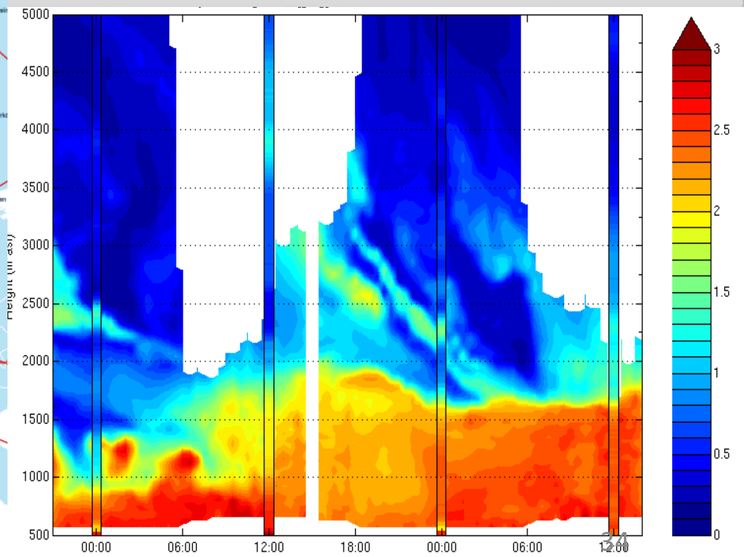






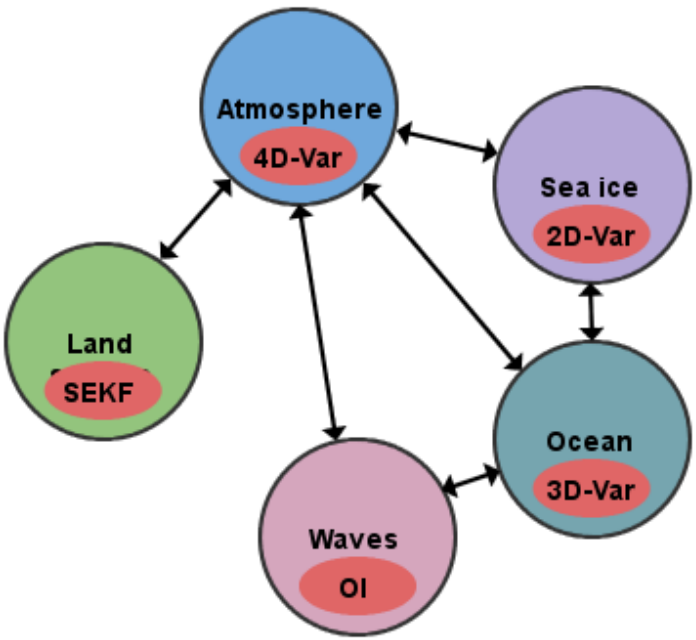
TAMDAR Observations:
T, wind, RH, icing, turbulence, etc

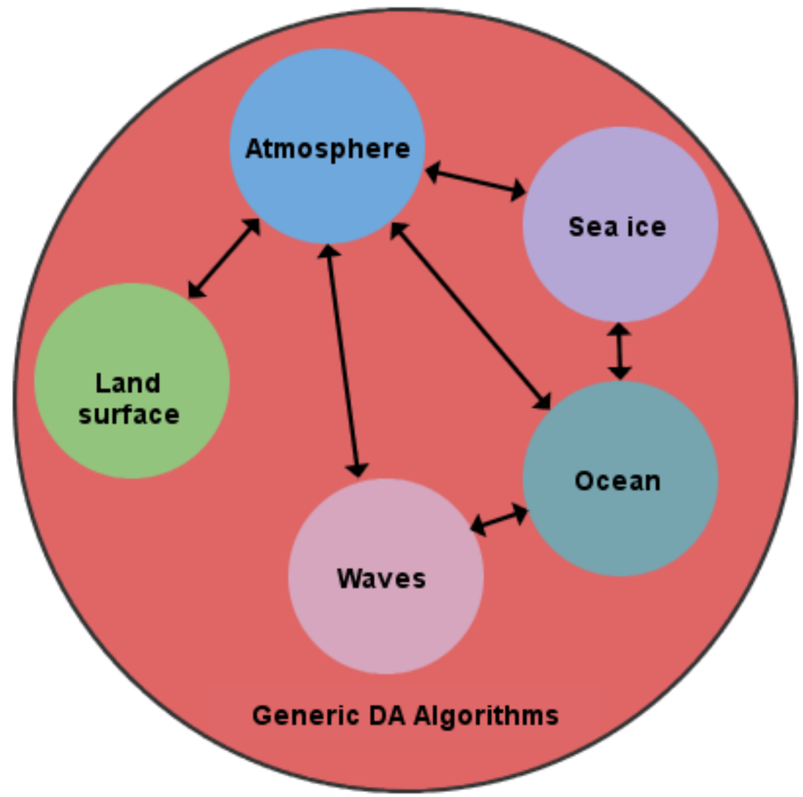




High resolution water vapour from lidar:

Positioning Data Assimilation at the heart of weather modeling

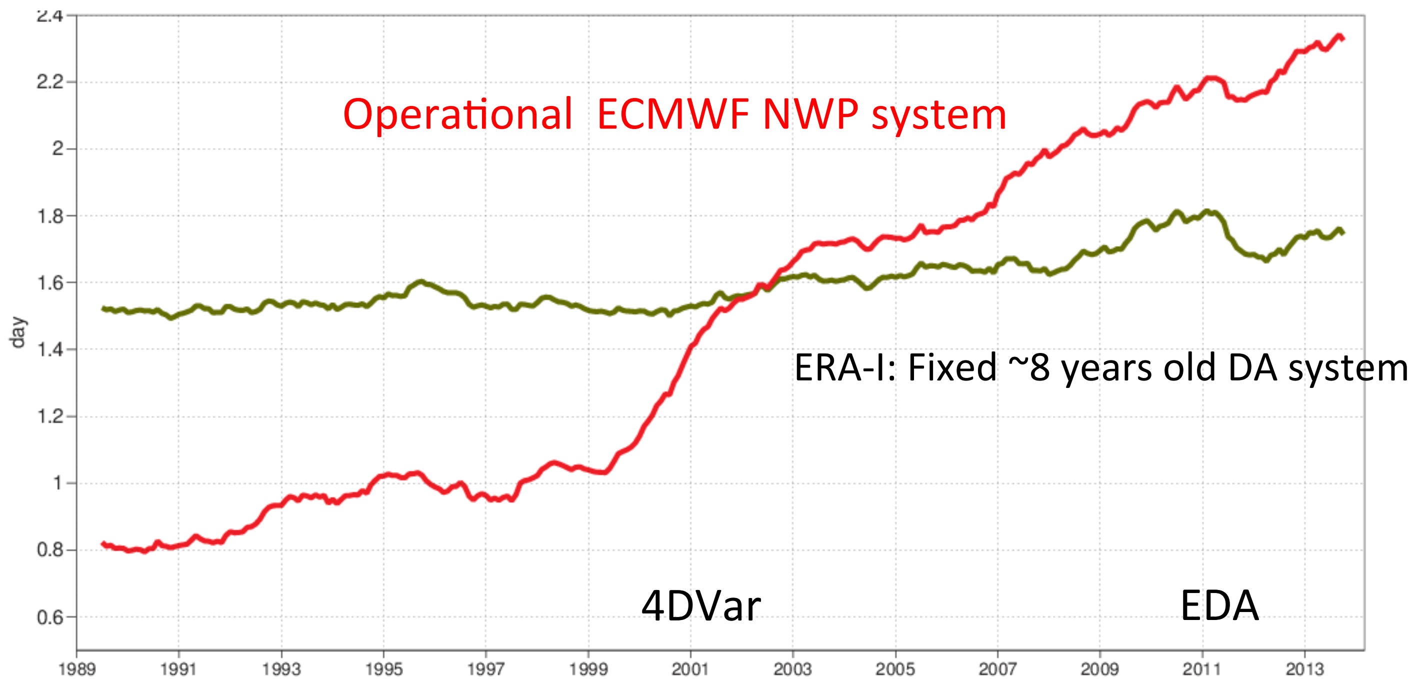




Where are we today?

Short range forecast skill: We are still progressing

500hPa geopotential height forecast skill
Lead time of anomaly correlation reaching 99%



This is also the case for medium-range forecast skill!

Conclusions

- Prospects of reducing further initial condition errors are great (improved models and observations)
- Data assimilation is the natural vehicle to confront models and observations, and contribute to a seamless quantification of uncertainty estimation
- Full exploitation of the GOS needs:
  - Careful planning and coordination with data providers
  - Sustained investment in model and DA developments
- We expect a lot of NWP impact from the Aeolus DWL
- Efficiency on future HPCs will be a fundamental driver
- Specific challenges and opportunities for meso-scale data assimilation

Thank You!