Data Assimilation in Numerical Weather Prediction models

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CERN, Geneva, February 20, 2014

University of Reading

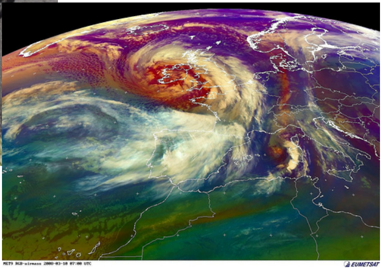
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Outline

Outline

Weather is Relevant

Plan Travel



Warn and Protect

Weather is Relevant

Logistics

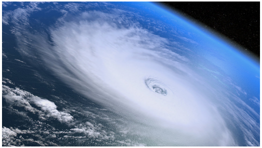
Rivers and Environment

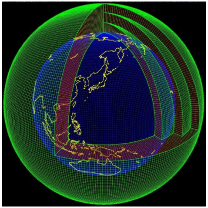
Air Control

Outline

Challenge

- **NWP** processes current weather observations through computer models to forecast the future state of weather.
- **Data Assimilation** computes the initial conditions for the NWP model.
  - the data available (10^5) is not enough to initialize current models with 10^7 degrees of freedom
  - need spatial and time interpolation
  - sometimes variables are not measured directly
  - we do not know the truth
- Our system is: 'a 3d grid of the atmosphere, with current data, and equations that describe atmosphere dynamics.'





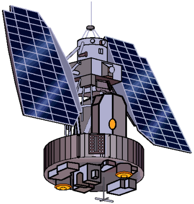
Remarks on the History of Weather Prediction I

- In 1901 Cleveland Abbe founded the United States Weather Bureau. He suggested that the atmosphere followed the principles of thermodynamics and hydrodynamics
- In 1904, Vilhelm Bjerknes proposed a two-step procedure for model-based weather forecasting. First, a analysis step of data assimilation to generate initial conditions, then a forecasting step solving the initial value problem.
- In 1922, Lewis Fry Richardson carried out the first attempt to perform the weather forecast numerically.
- In 1950, a team of the American meteorologists Jule Charney, Philip Thompson, Larry Gates, and Norwegian meteorologist Ragnar Fjörtoft and the applied mathematician John von Neumann, succeeded in the first numerical weather forecast using the ENIAC digital computer.

Bjerknes

Remarks on the History of Weather Prediction II

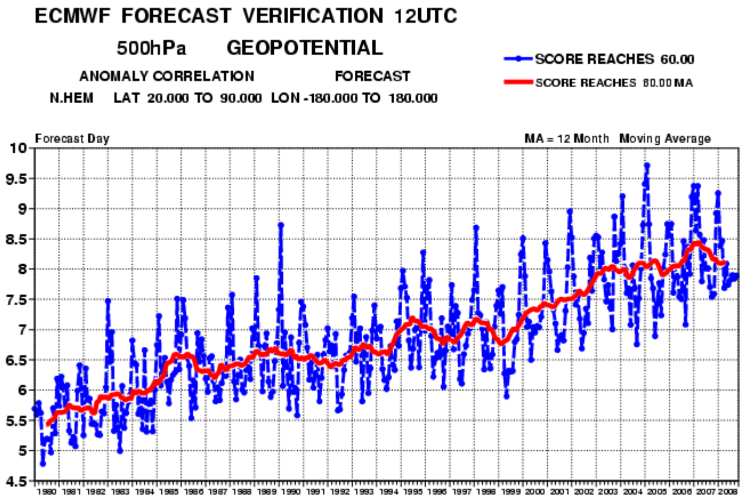
1962



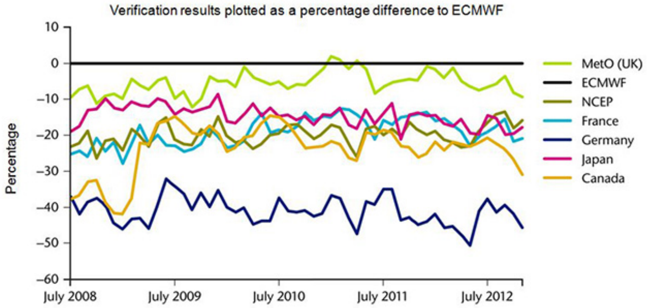
Nimbus 1: 1964

- In September 1954, Carl-Gustav Rossby's group at the Swedish Meteorological and Hydrological Institute produced the first operational forecast (i.e. routine predictions for practical use) based on the barotropic equation. Operational numerical weather prediction in the United States began in 1955 under the Joint Numerical Weather Prediction Unit (JNWPU), a joint project by the U.S. Air Force, Navy, and Weather Bureau.
- In 1959, Karl-Heinz Hinkelmann produced the first reasonable primitive equation forecast, 37 years after Richardson's failed attempt. Hinkelmann did so by removing high-frequency noise from the numerical model during initialization.
- In 1966, West Germany and the United States began producing operational forecasts based on primitive-equation models, followed by the United Kingdom in 1972, and Australia in 1977.

Skills and Scores

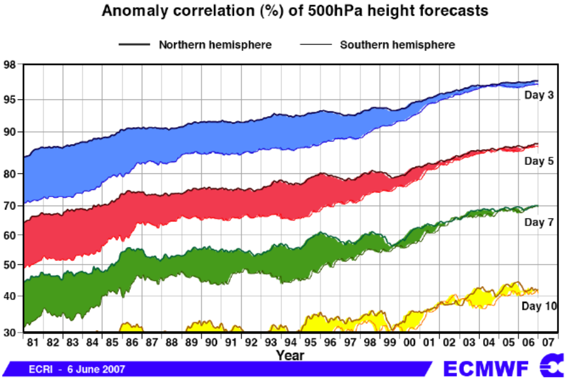


Operational Centers



Met Office

Comparison Northern and Southern hemispheres



Outline

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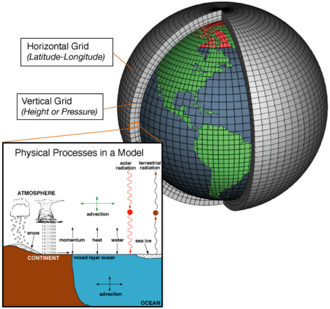
Numerical Weather Prediction

NWP modelling involves

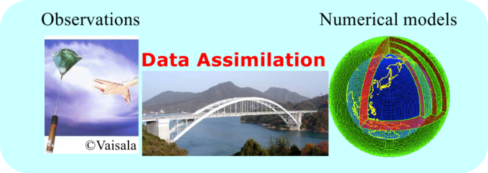
- a number of equations describing the fluid dynamics
- translated to numerical code
- combined with parametrization of other physical processes
- applied to certain domain
- integrated based on initial and boundary conditions



NWP is an initial-value problem

Outline

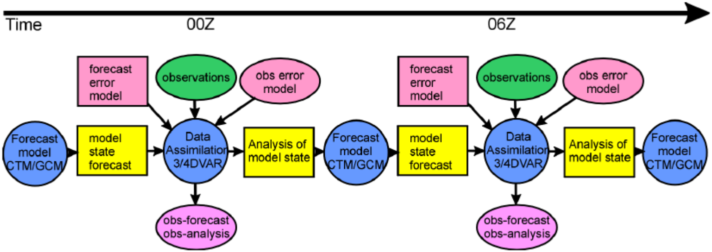
Data Assimilation



- DA gives the initial conditions for the Numerical Models.
- Produce a **regular**, physically consistent 4 dimensional representation of the state of the atmosphere from a heterogeneous array of in situ and remote instruments which sample **imperfectly and irregularly** in space and time. (Daley, 1991)

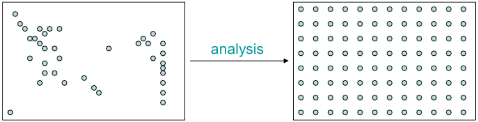
- **Inverse Problem**
- DA consists of using the actual result of some measurements to infer the values of the parameters that characterize the system. (A. Tarantolo 2005)

Data Assimilation cycle



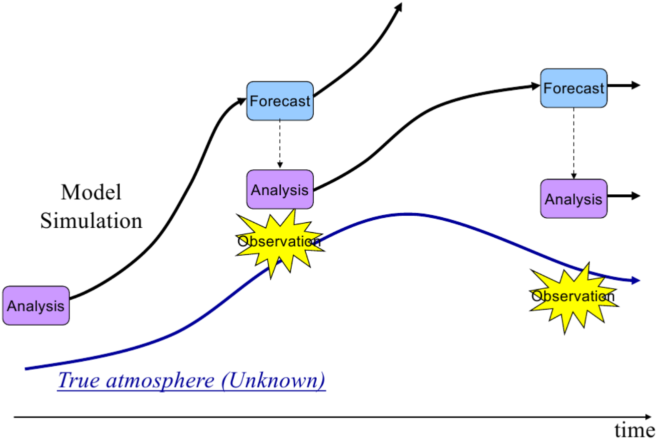
Soroja Polavarapu 2008

Data Assimilation



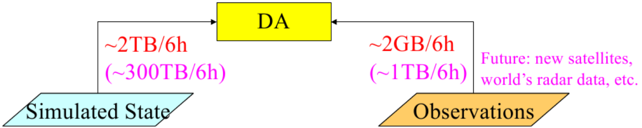
- Combine information from past observations brought forward in time by the NWP model, with information from current observations. Considering:
  - Statistical information on model and observation error.
  - physics captured in the model
- Observation errors
  - Instrument, calibration, coding telecommunication errors
- Model errors
  - 'representativeness', missing or wrong physical phenomena

Data Assimilation cycle



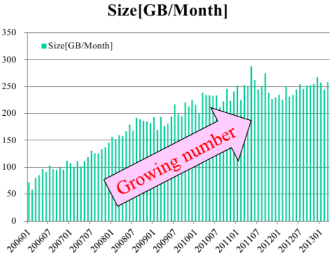
Courtesy of Takemasa Miyoshi

Data Assimilation size



28-km global mesh ~3GB
100 members for PDF ~300GB
7 time slots ~2TB

Extreme-scale Simulation:
3.5-km global mesh ~400GB
100 members ~40TB
7 time slots ~300TB

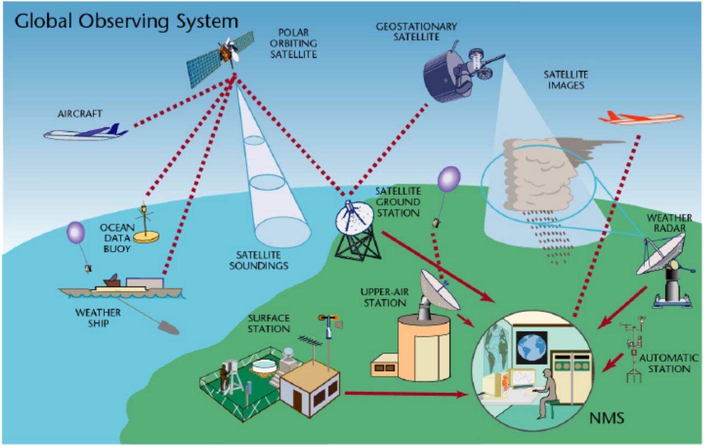


Courtesy of JMA

Courtesy of Takemasa Miyoshi

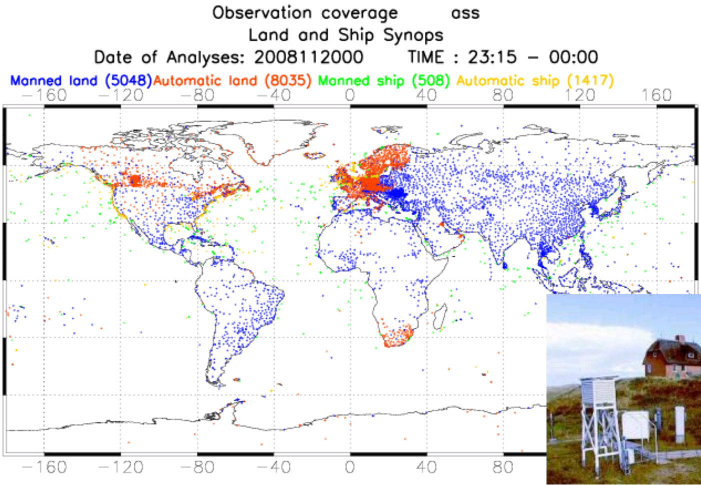
Outline

Data Survey

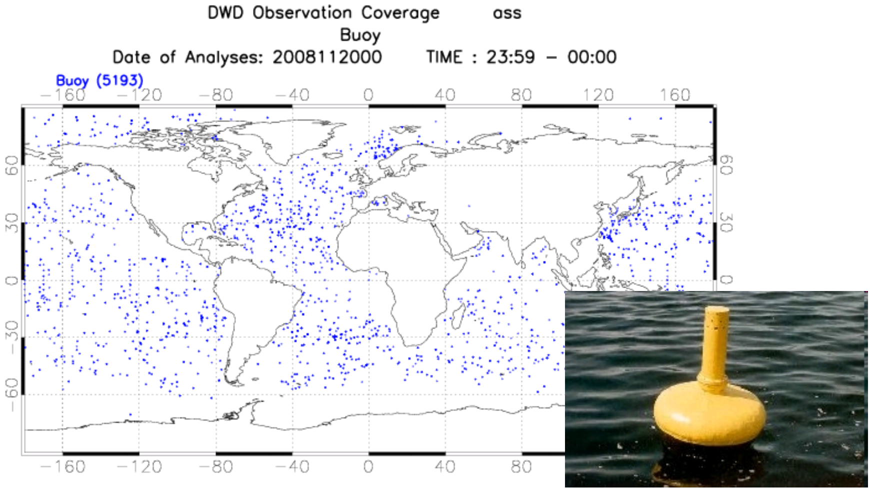


http://www.wmo.ch/web/www/OSY/GOS.html

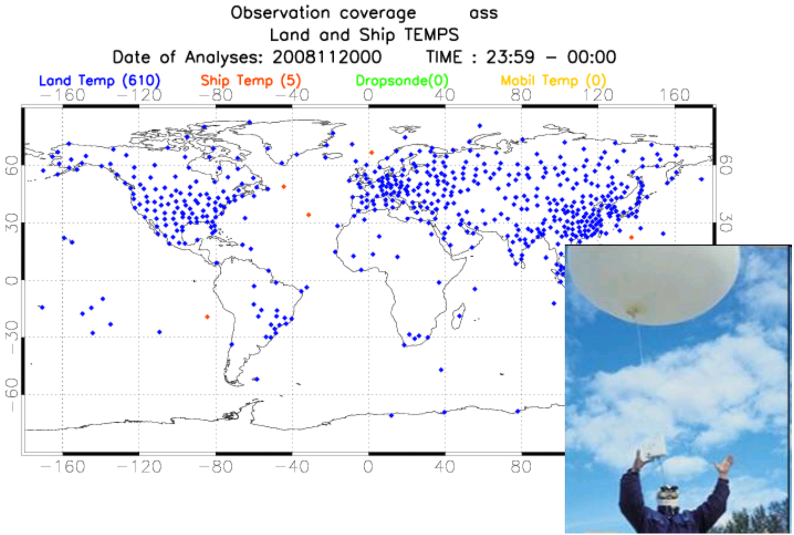
Synop


Observation coverage ass
Land and Ship Synops
Date of Analyses: 2008112000 TIME : 23:15 – 00:00
Manned land (5048)
Automatic land (8035)
Manned ship (508)
Automatic ship (1417)

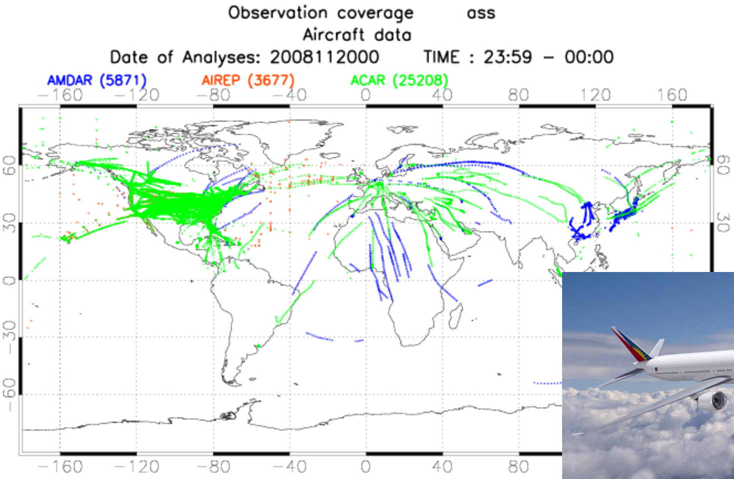
Buoys


DWD Observation Coverage ass
Buoy
Date of Analyses: 2008112000 TIME : 23:59 – 00:00
Buoy (5193)
−160 −120 −80 −40 0 40 80 120 160
60 30 0 −30 −60

Radio-Sondes

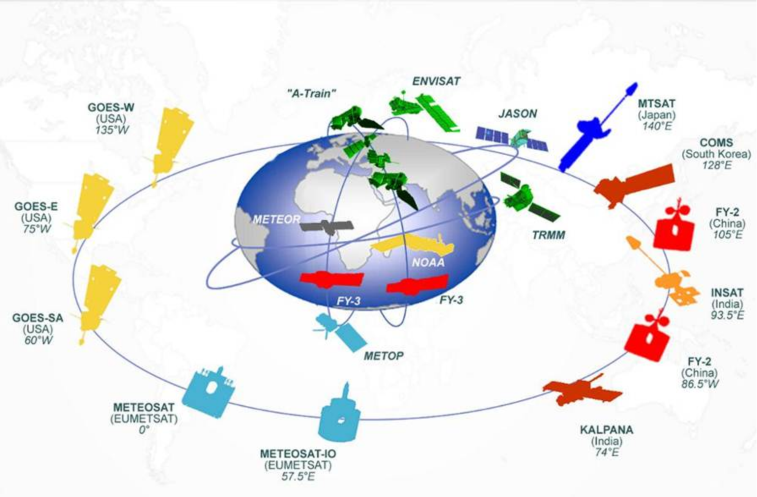


Aircrafts


Observation coverage ass
Aircraft data
Date of Analyses: 2008112000 TIME : 23:59 – 00:00
AMDAR (5871)
AIREP (3677)
ACAR (25208)
−160 −120 −80 −40 0 40 80 120 160
60 30 0 −30 −60

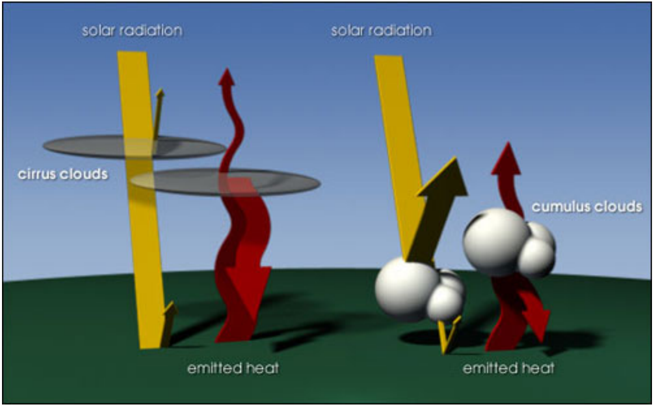

Philippines

Satellites

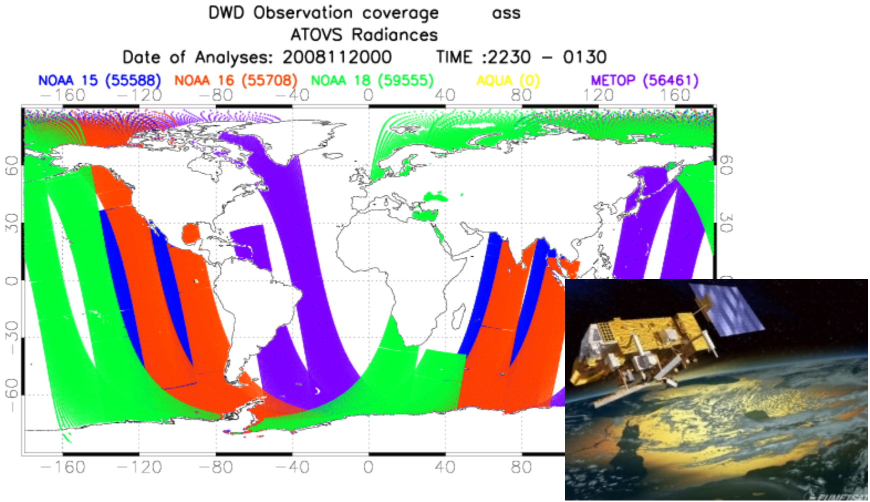


GOES-W
(USA)
135°W
GOES-E
(USA)
75°W
GOES-SA
(USA)
60°W
"A-Train"
ENVISAT
JASON
MTSAT
(Japan)
140°E
COMS
(South Korea)
128°E
METEOR
TRMM
FY-2
(China)
105°E
NOAA
INSAT
(India)
93.5°E
FY-3
FY-3
METOP
FY-2
(China)
86.5°W
METEOSAT
(EUMETSAT)
0°
METEOSAT-IO
(EUMETSAT)
57.5°E
KALPANA
(India)
74°E

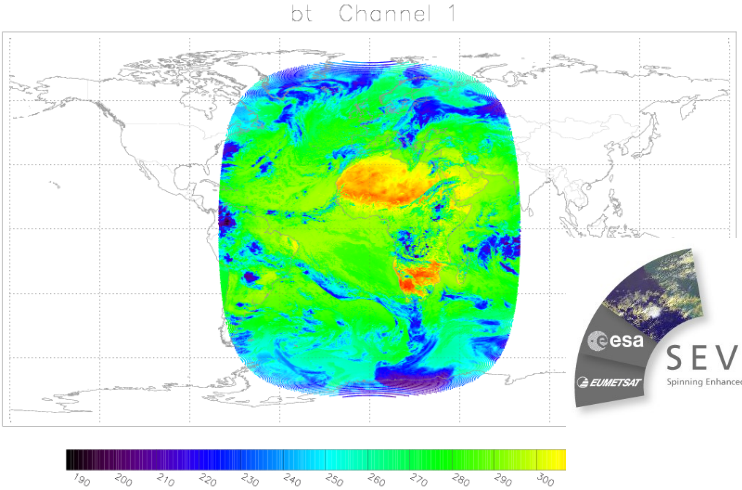
Radiances


solar radiation
solar radiation
cirrus clouds
cumulus clouds
emitted heat
emitted heat

Radiances

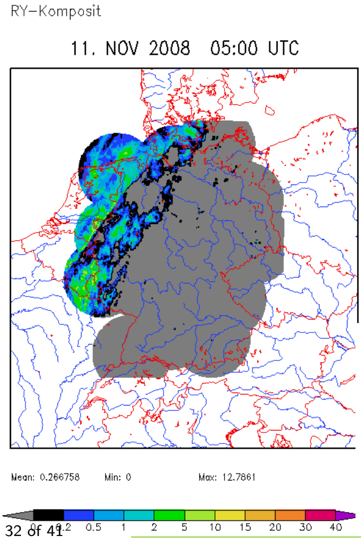

DWD Observation coverage ass
ATOVS Radiances
Date of Analyses: 2008112000 TIME :2230 – 0130
NOAA 15 (55588) NOAA 16 (55708) NOAA 18 (59555) AQUA (0) METOP (56461)
−160 −120 −80 −40 0 40 80 120 160
60 30 0 −30 −60

Radiances

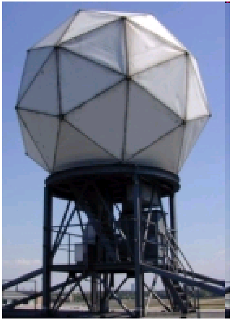


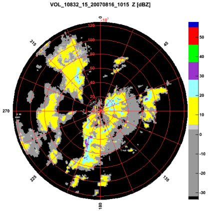
esa
EUMETSAT
SEVIRI
Spinning Enhanced Visible and Infrared Imager

Radar

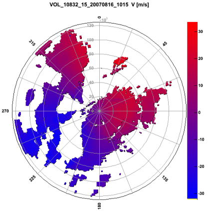


RY–Komposit
11. NOV 2008 05:00 UTC
Mean: 0.266758
Min: 0
Max: 12.7861
0.5 1 2 5 10 15 20 30 40





VOL_10832_15_20070816_1015 Z [dBZ]



VOL_10832_15_20070816_1015 V [m/s]

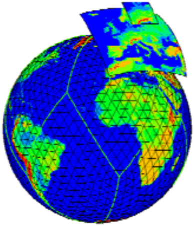
Outline

DA in DWD

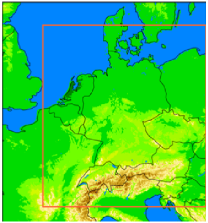
- Research and Development
- Section on Modelling:
  - Unit Num. Modelling
  - Unit Data Assimilation
  - Unit Physics
  - Unit Verification

Model and Assimilation Systems at DWD

- Current:
  - GME 30Km 3DVar
  - COSMO-EU 7Km Nudging
  - COSMO-DE 2.8Km Nudging



- Next Future (2014):
  - **ICON** Global, Regional grid refinement, non-hydrostatic, deterministic: 13Km EPS:20Km
    Hybrid 3DVar-LETKF
  - **COSMO-DE** both deterministic and EPS: 2km
    LETKF



Outline

Data Assimilation Analysis

In order to find out φ we should minimize the functional

$$J(\varphi) := \left\|\varphi - \varphi^{(b)}\right\|^2 + \left\|f - H\varphi^{(b)}\right\|^2.$$

The normal equations are obtained from first order optimality conditions

$$\nabla_{\varphi} J = 0.$$

Usually, the relation between variables at different points is incorporated by using covariances/weighted norms:

$$J(\varphi) := \left\|\varphi - \varphi^{(b)}\right\|_{B^{-1}}^2 + \left\|f - H\varphi^{(b)}\right\|_{R^{-1}}^2,$$

The update formula is now

$$\varphi^{(a)} = \varphi^{(b)} + BH^*(R + HBH^*)^{-1}(f - H\varphi^{(b)})$$

Ensemble Kalman Filter

- In the KF method B evolves with the model dynamics: $B_{k+1} = MB_k M^*$.
- EnKF[1] is a Monte Carlo approximation to the KF.
- EnKF methods use reduced rank estimation techniques to approximate the classical filters.
- The ensemble matrix $Q_k := \left(\varphi_k^{(1)} - \overline{\varphi}_k^{(b)}, ..., \varphi_k^{(L)} - \overline{\varphi}_k^{(b)}\right)$.
- In the EnKF methods the background covariance matrix is represented by $B := \frac{1}{L-1} Q_k Q_k^*$.
- Update solved in a low-dimensional subspace

$$U^{(L)} := \text{span}\{\varphi_k^{(1)} - \overline{\varphi}_k^{(b)}, ..., \varphi_k^{(L)} - \overline{\varphi}_k^{(b)}\}.$$

[1] Evensen 1994

Outline

Summary and open questions

- Data assimilation combines information of observations and models and their errors to get a best estimate of atmospheric state and give the initial condition to the NWP model.
- The DA problem is underdetermined. There are much less observations than is needed to compute the model equivalent.
- Data assimilation methods have contributed much to the improvements in NWP.
- Challenge: full use of satellite data and forecast in presence of clouds.
- Big data problem.

Thank you for your attention!

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- Data Assimilation Unit

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