Operational forecast weather forecast

(with a special look to ECMWF long-range forecasting and re-analysis)

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Road-map

ECMWF's...background and structure

NWP in a nutshell going from

deterministic to ensemble systems

Reanalysis

Background

- Convention establishing ECMWF entered in force on 1st Nov 1975, having been ratified by the following 13 Member states:

Denmark Spain Ireland Netherlands Switzerland Sweden

Belgium Germany France Yugoslavia Austria Finland United Kingdom

- Recognition of importance and potential to improve medium-range weather forecasts with benefits to the
  - European economy
  - Protection and safety of population
  - Development of meteorology in Europe / post university training
  - Development of European industry in the field of data-processing

- Recognition that resources are needed on a scale exceeding those normally practicable at national level

Today...

...ECMWF is an independent international organization, supported by 18 member states

Co-operating agreements:

World Meteorological Organization
A United Nations Specialized Age...
Working together in Weather, Climate a...

EUMETSAT

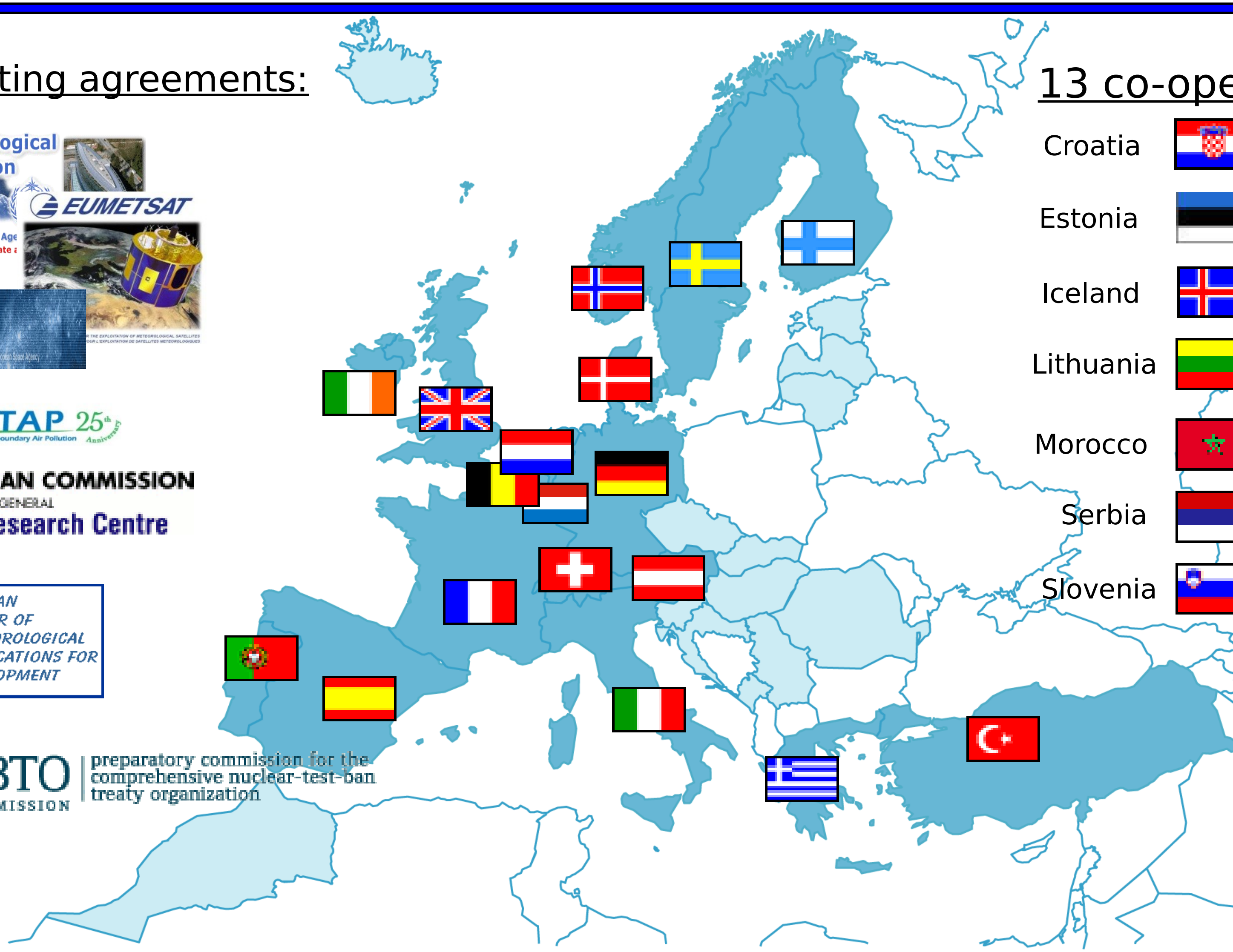
esa Multimedia Gallery

LRTAP 25th Anniversary
Long-range Transboundary Air Pollution

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

ACMAD
AFRICAN CENTER OF METEOROLOGICAL APPLICATIONS FOR DEVELOPMENT

CTBTO
PREPARATORY COMMISSION
preparatory commission for the comprehensive nuclear-test-ban treaty organization



13 co-operating states

Croatia	Czech Republic
Estonia	Hungary
Iceland	Latvia
Lithuania	Montenegro
Morocco	Romania
Serbia	Slovakia
Slovenia	

Goals

In addition to the principal goal of maintaining the current, rapid rate of improvements, the complimentary goals are:

To improve the quality and scope of **monthly** and **seasonal-to-interannual** forecasts

To enhance support to Member States national forecasting activities by providing suitable boundary conditions for limited-area models

To deliver **real-time analysis and forecasts of atmospheric composition**

To carry out climate monitoring through **regular re-analyses** of the Earth-system

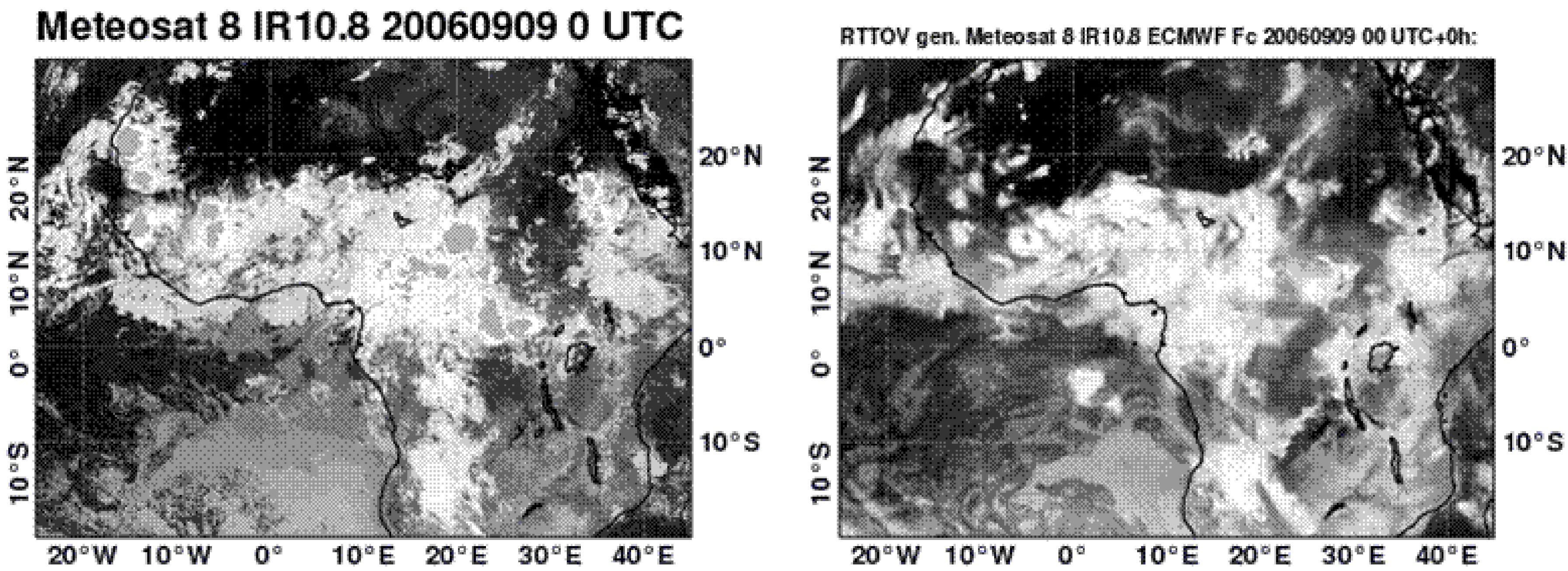
To contribute towards the optimization of the **Global Observing System**

- How do we produce a “good” forecast ?

The behavior of the atmosphere is governed by a set of physical laws which express how the air moves.

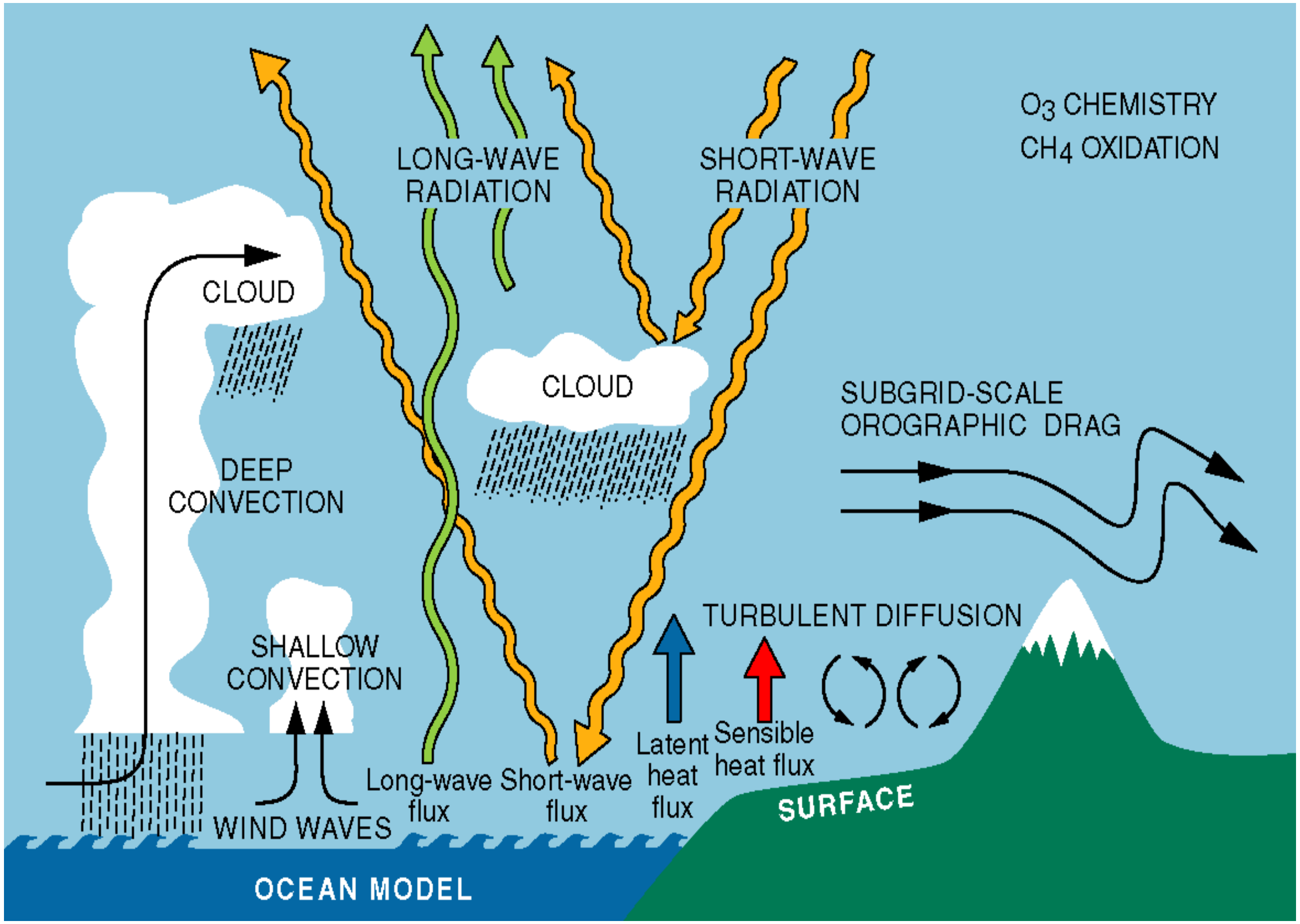
1st ingredient of good models (NWP and climate):

Good advection schemes that are a) numerically stable, b) conservative, c) non-diffusive



Additionally we must consider:
a) the process of heating and cooling
b) the role of moisture & clouds
c) Interactions between the atmosphere and the underlying land and ocean

The 2nd ingredient for skillful weather prediction or a good climate model is a good representation of the physical processes that are important for the timescales of concern



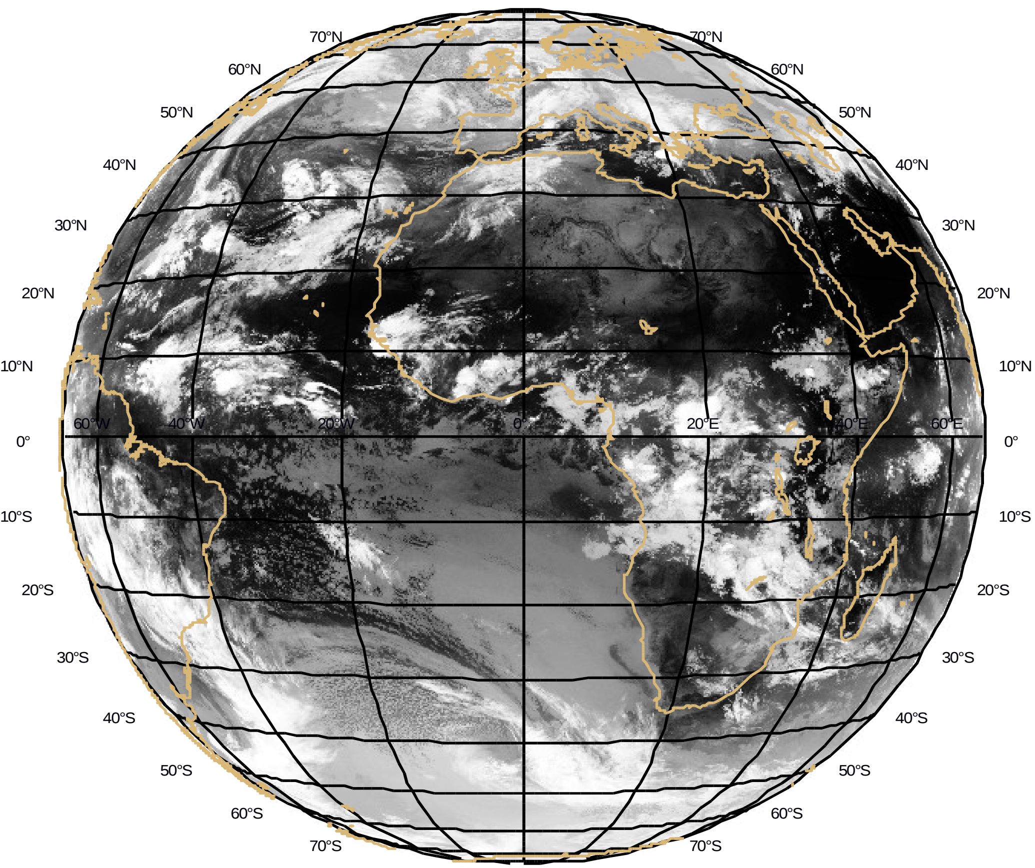
The ECMWF computers in 1978 and 2008

The 3rd ingredient for skilful weather prediction is computer power, that should be enough to estimate the initial state and to integrate the model equations in a reasonable amount of time.

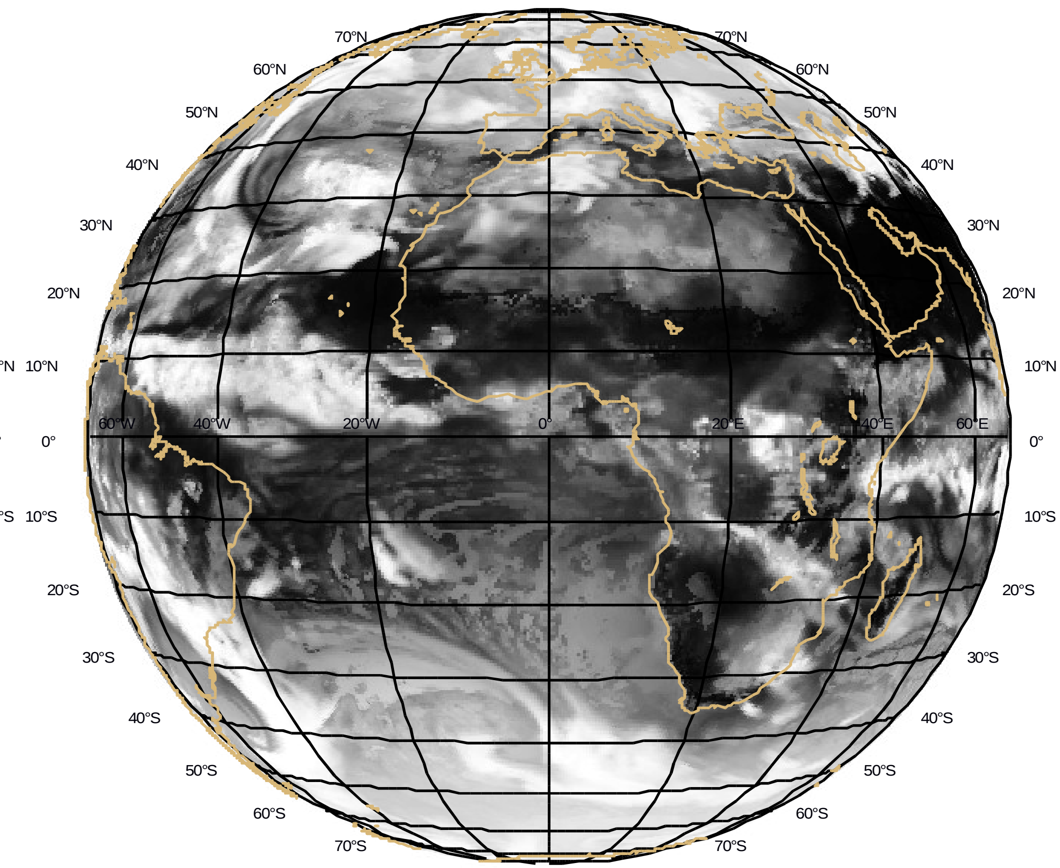
	1978	2008	Ratio
Specification	Cray 1A	IBM Power5+	
CPU	1	5000	5000
Clock speed (ns)	12.5	0.53	24
Peak perf (flops)	160 M	38 T	250,000
Sust perf (flops)	50 M	4 T	80,000
Disk space (bytes)	2.5 G	100 T	40,000

Verification of a 42h cloud forecast against Meteosat (using simulated BTs)

METEOSAT 7 First Infrared Band Thursday 14 October 2004 0600UTC

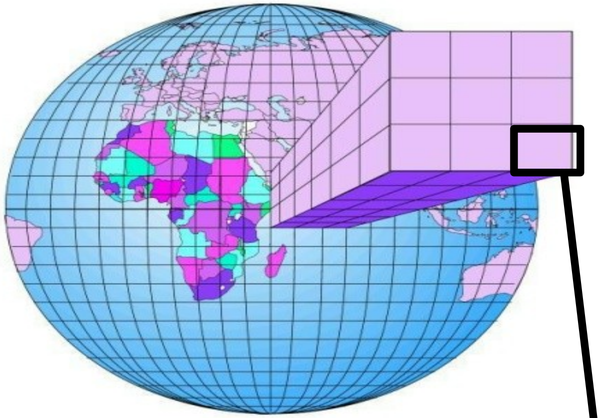


Tuesday 12 October 2004 12UTC ECMWF Forecast t+42 VT:Thursday 14 October 2004 06UTC
RTTOV generated METEOSAT 7 First Infrared Band (10 bit)

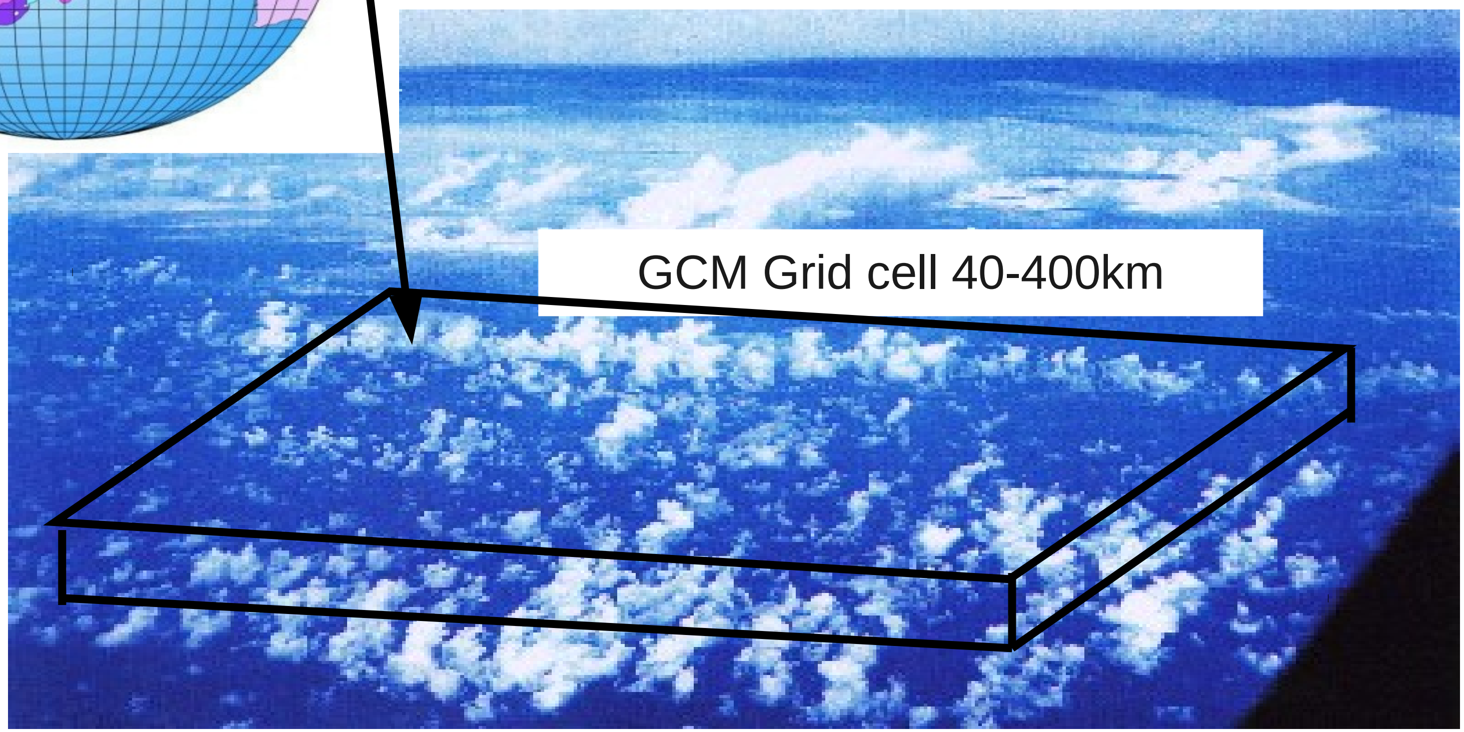


Conclusions: Models have errors!

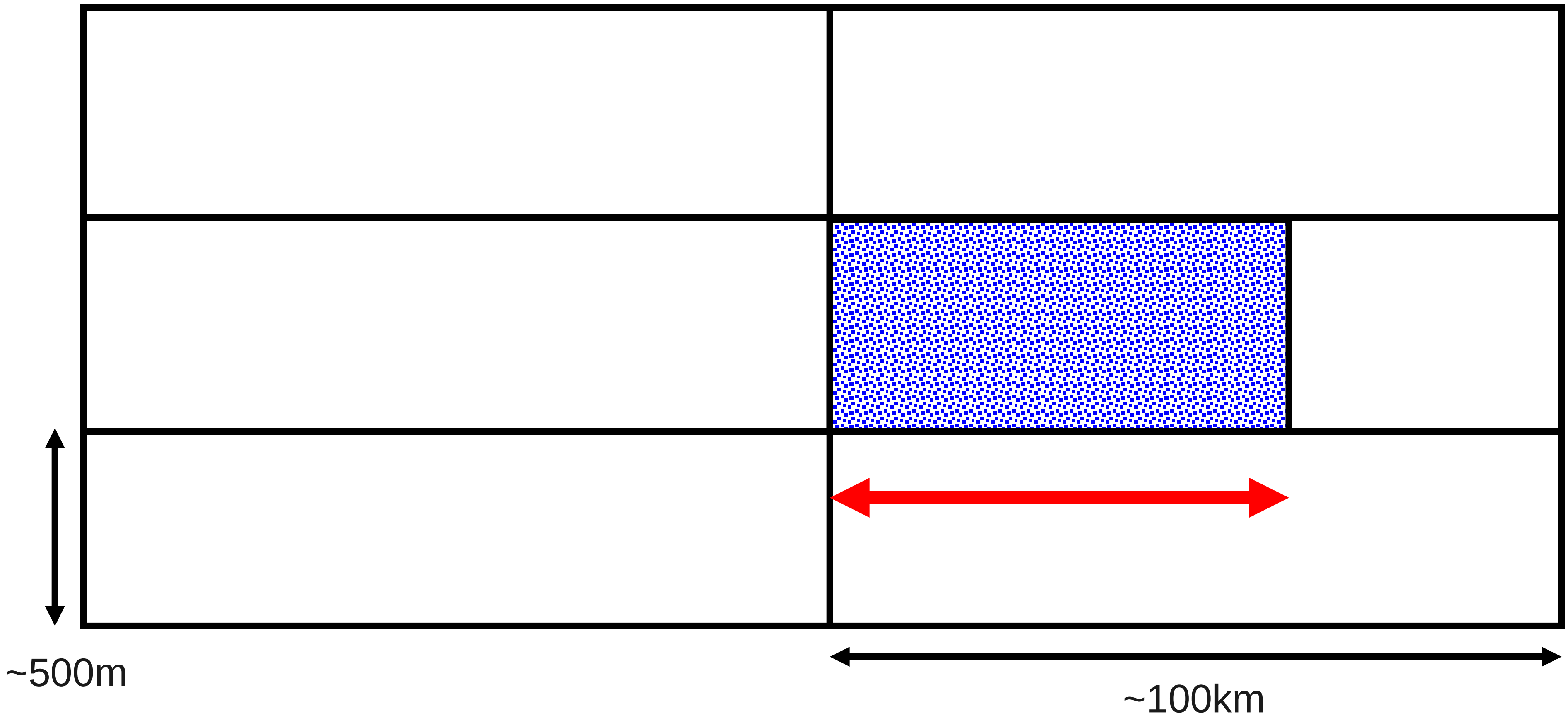
The problem of parametrization



Many of the observed clouds and especially the processes within them are of subgrid-scale size (both horizontally and vertically)

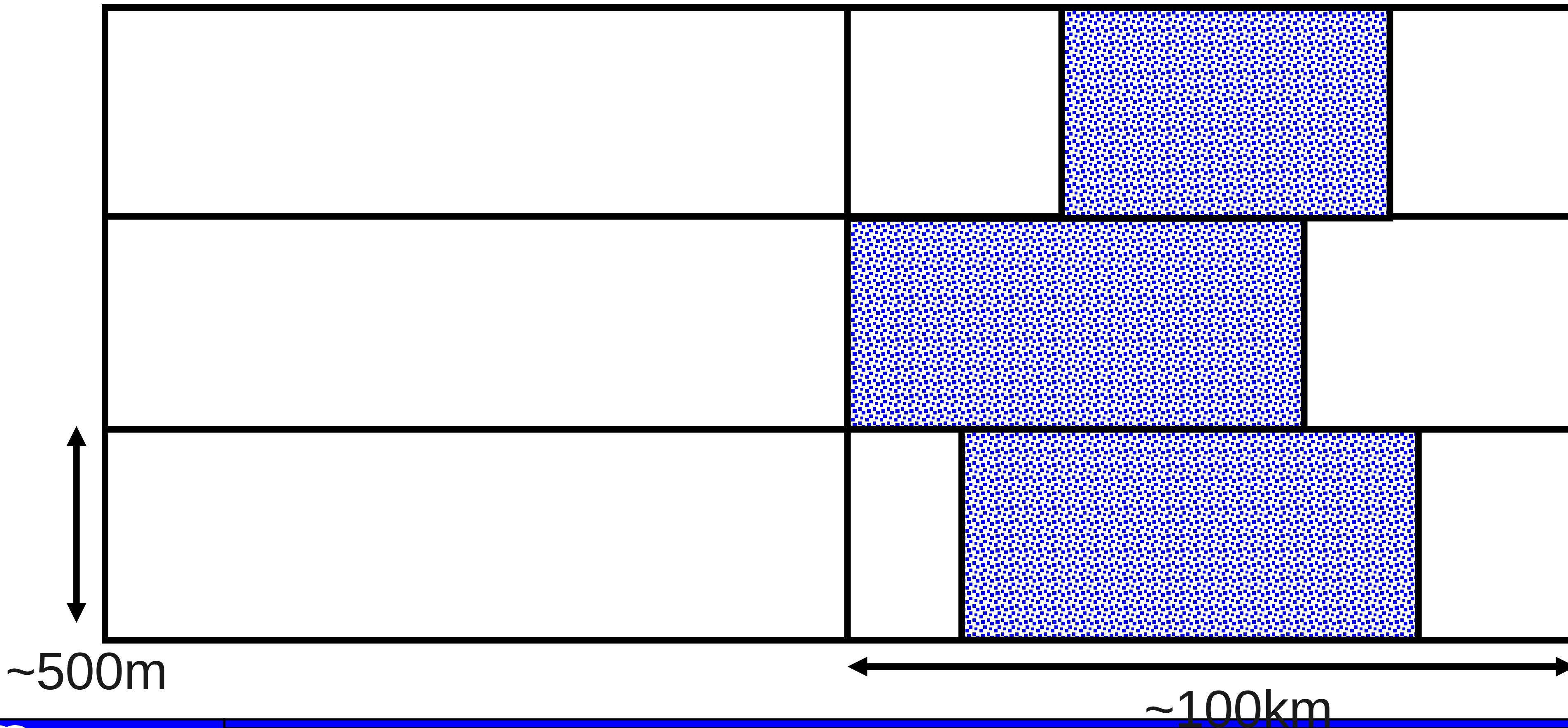


HORIZONTAL COVERAGE, a



Vertical Overlap of cloud

Important for Radiation and Microphysics Interaction



NWP: The initial value problem

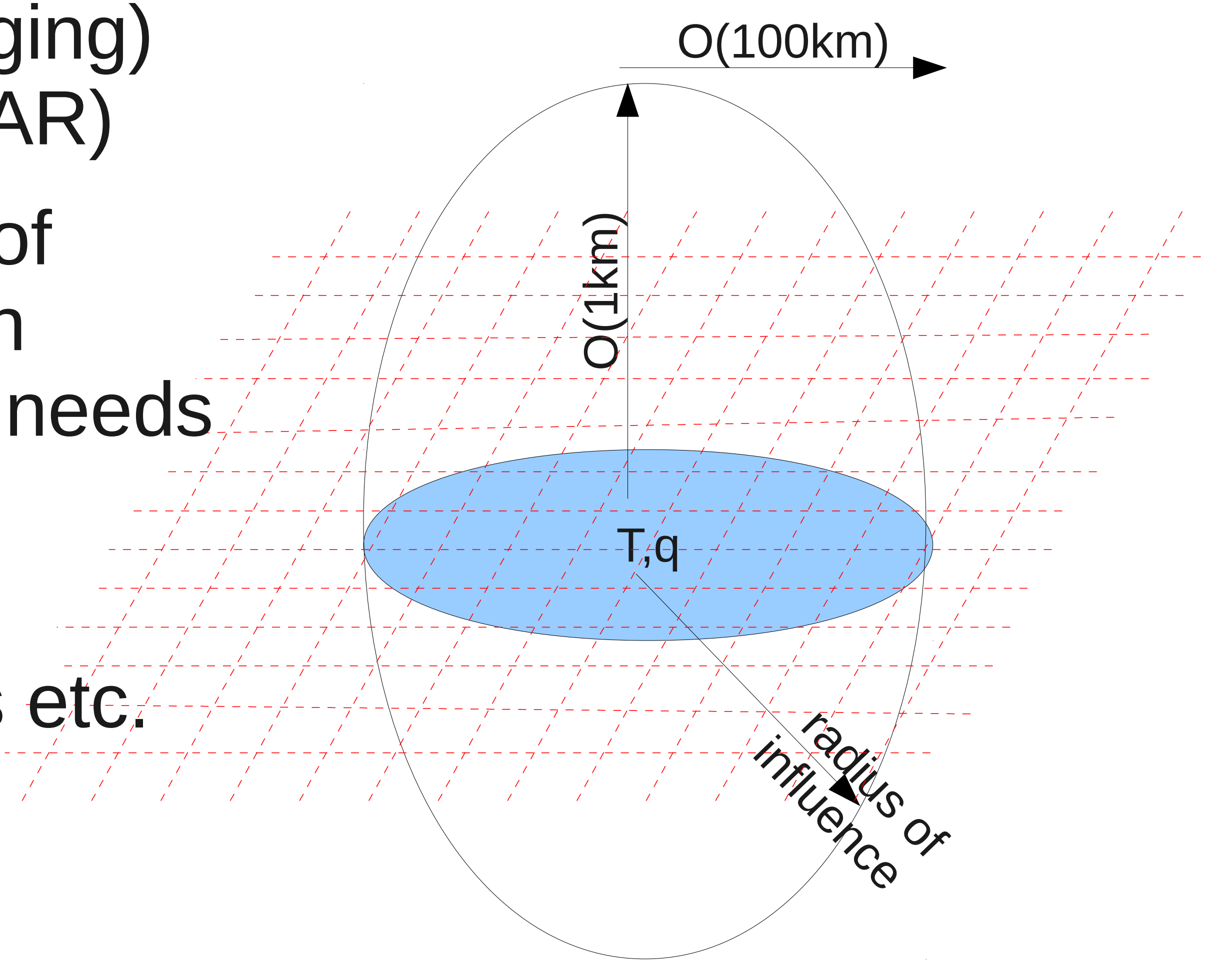
To make accurate forecasts it is important to know the current weather

Aim of “Data Assimilation” System

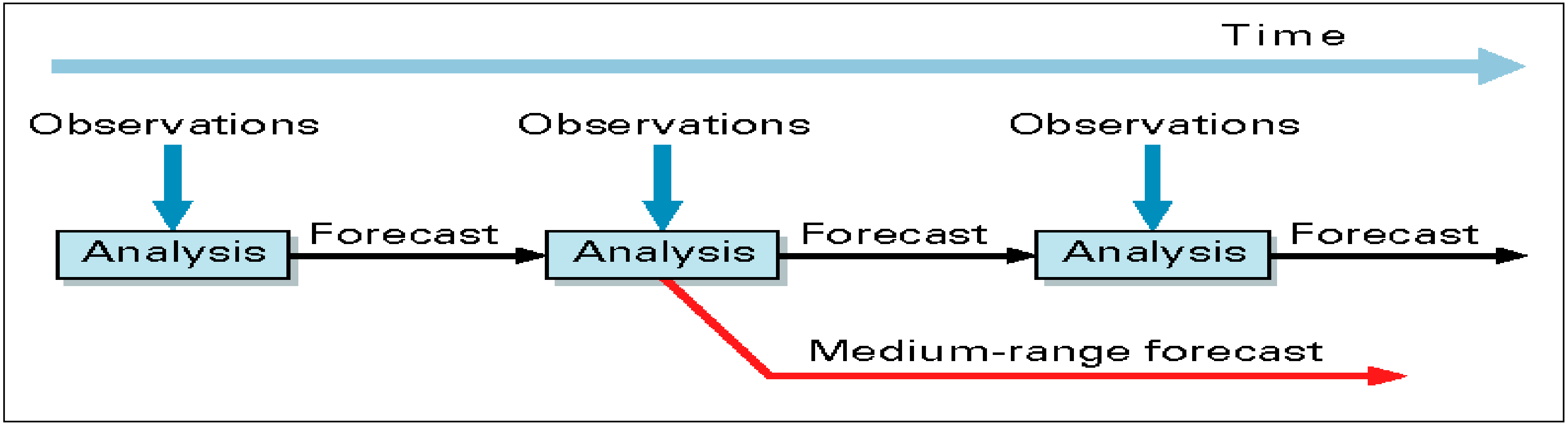
- To take a wide variety of variables (not necessarily model variables)...
- ...from a wide variety of instruments...
- ...with vastly different measurement densities...
- ...taking care to reject bad measurements...
- ...and combine them into an assessment of the atmospheric state, that is near balance with the forecast model “climate”
- Sounds Easy?

Data assimilation

- Methods range from very simple (nudging) to complex (4DVAR)
- Radius/distance of influence for each observation type needs to be defined
- Not obvious: e.g. Inversions, fronts etc.



Obs are assimilated to estimate the state of the atm



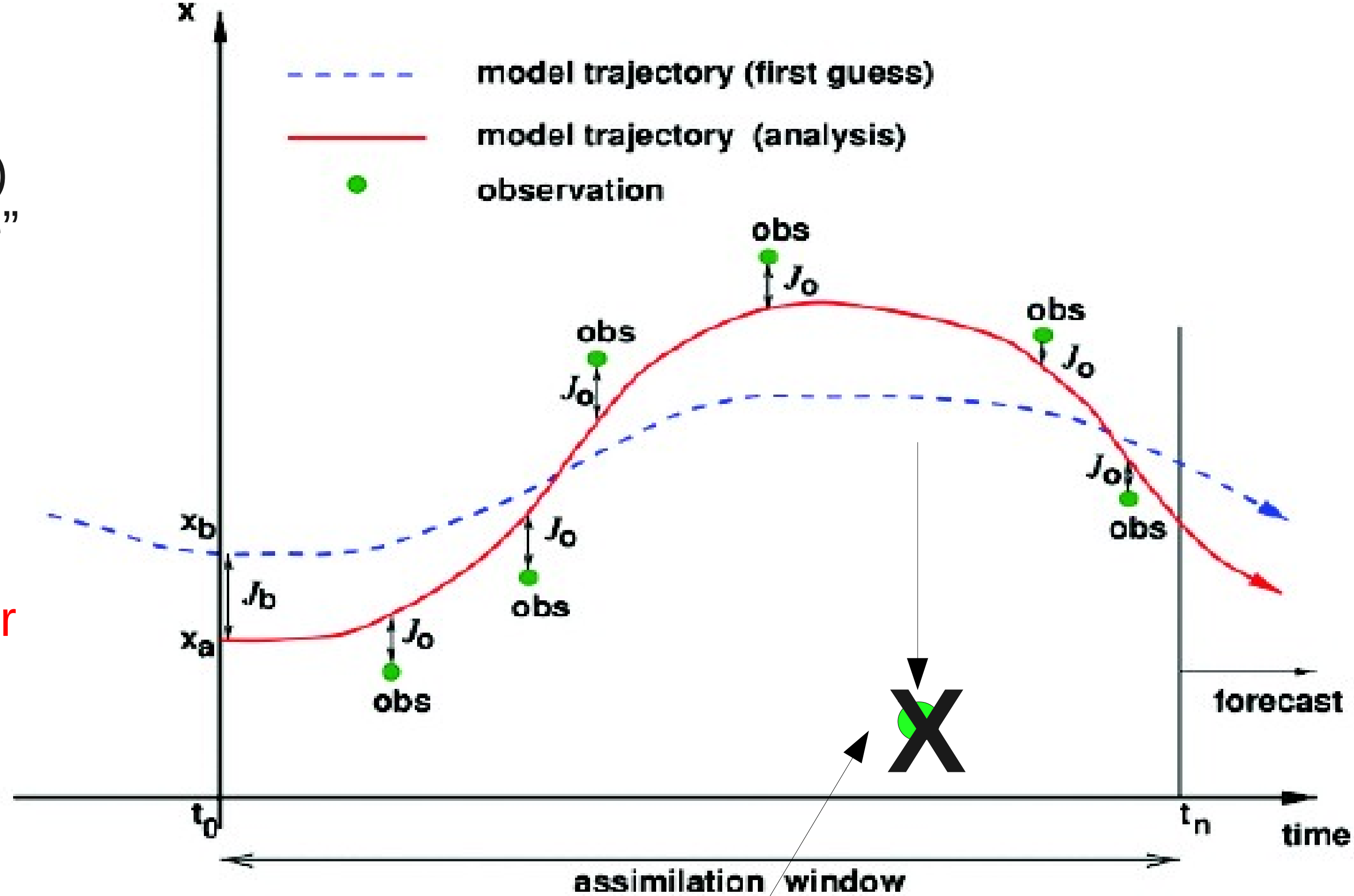
- Observations are used to “correct” errors in the short forecast from the previous analysis time.
- At ECMWF, every 12 hours 4 – 8,000,000 observations are assimilated

from Marta Janiskova

Goal: define atmospheric state x(t0) such that the “distance” between the model trajectory and observations is minimum over a given time period [t0, tn]

Requires tangent linear and adjoint of forecast model

Note that the quality of the forecast model is important for a good analysis!



Observations “too far” from the background forecast
are rejected as unreliable!!!

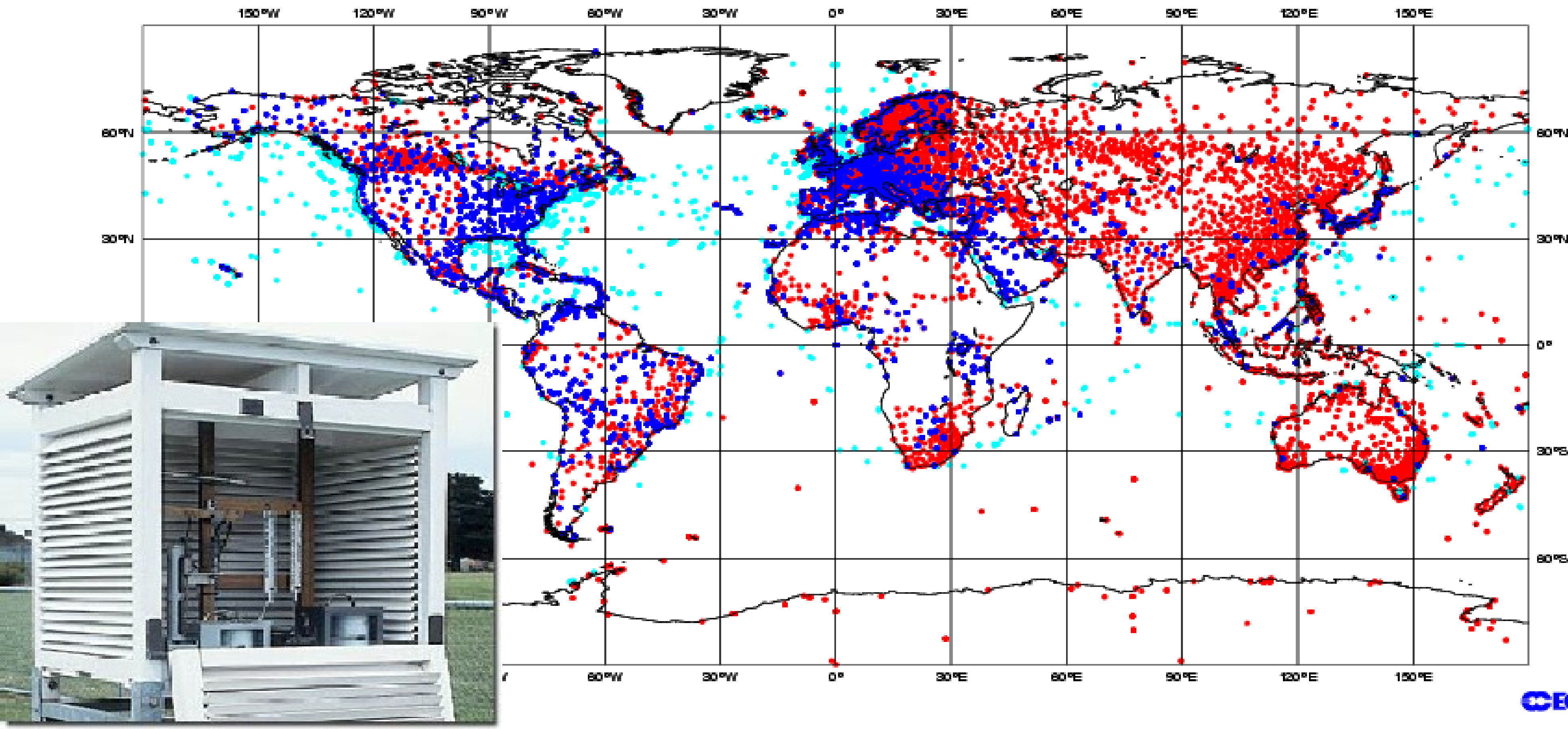
DATA USED: Pressure, humidity during day

SYNOP T,q also used for soil moisture analysis

Obs Type

17092 SYNOP | 2513 SHIP | 12011 METAR

ECMWF Data Coverage (All obs DA) - SYNOP/SHIP
20/JUL/2008; 12 UTC
Total number of obs = 31616

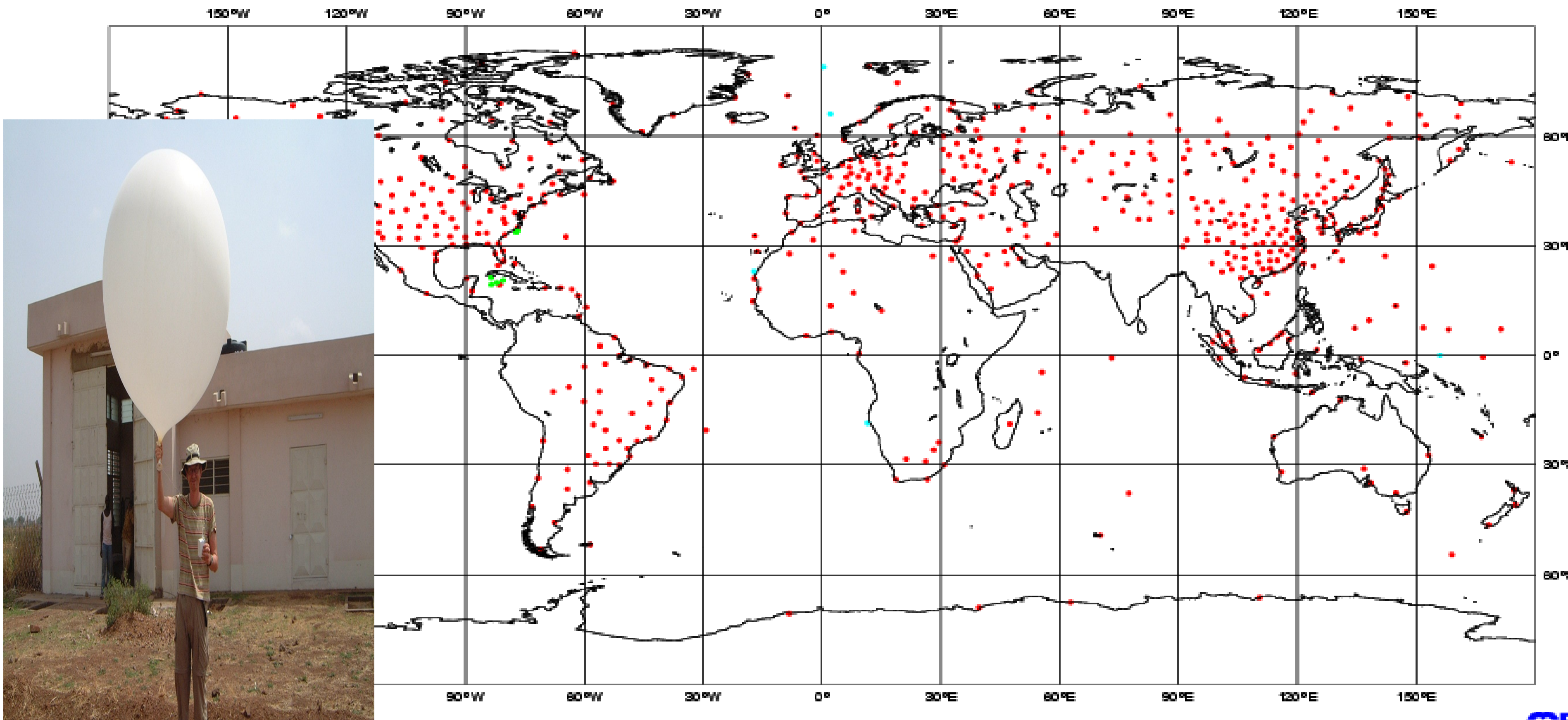


DATA USED: T,q,u,v – humidity to 300 or 100hPa

Obs Type

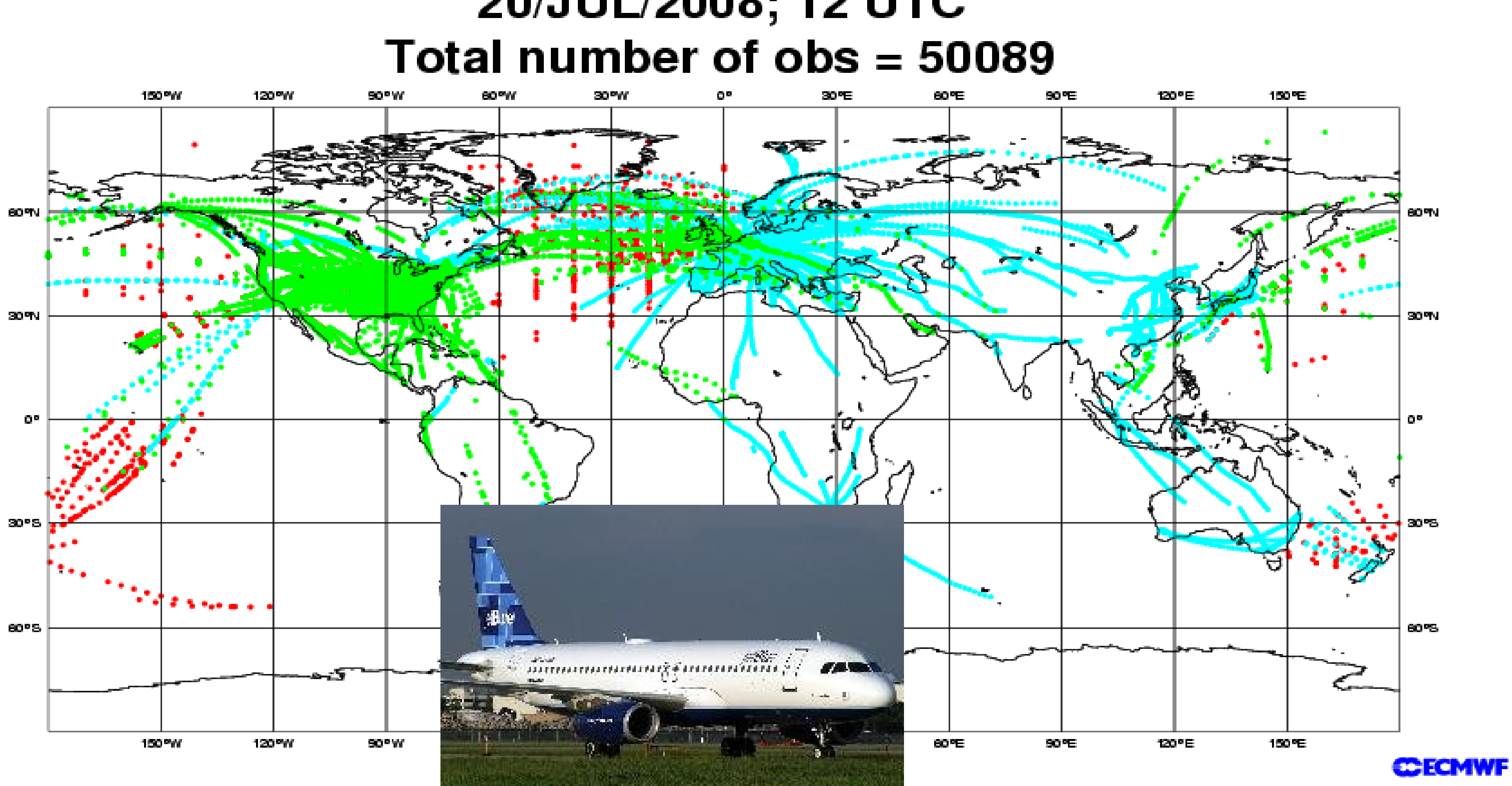
573 LAND · 5 SHIP · 7 DROPSONDE
0 MOBILE

ECMWF Data Coverage (All obs DA) - TEMP
20/JUL/2008; 12 UTC
Total number of obs = 585



ECMWF

DATA USED: Temperature, winds (mozaic humidity research product)



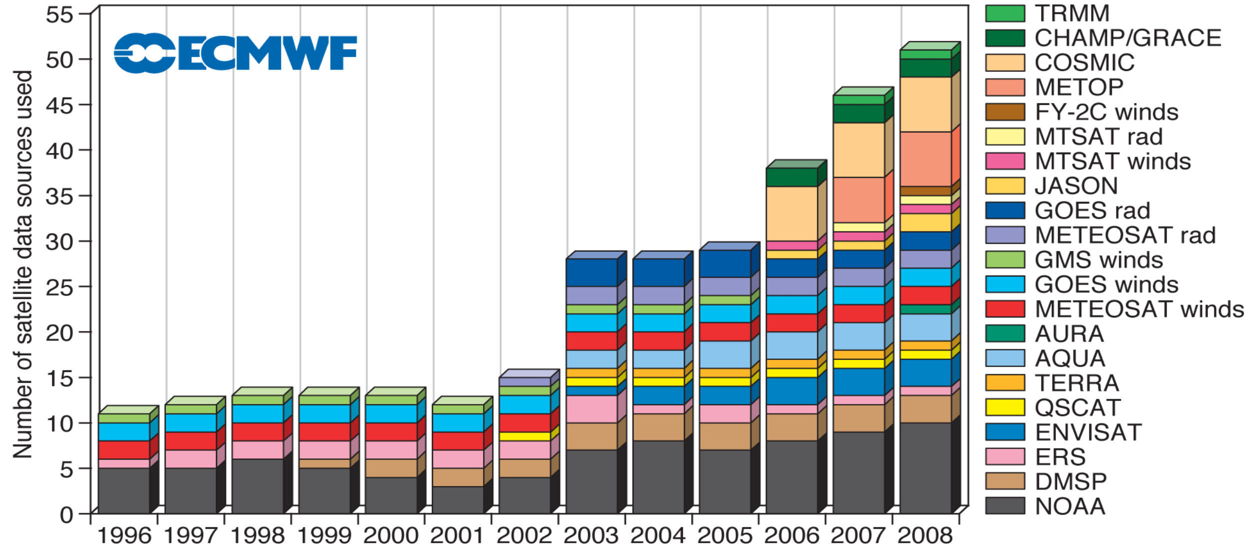
ECMWF

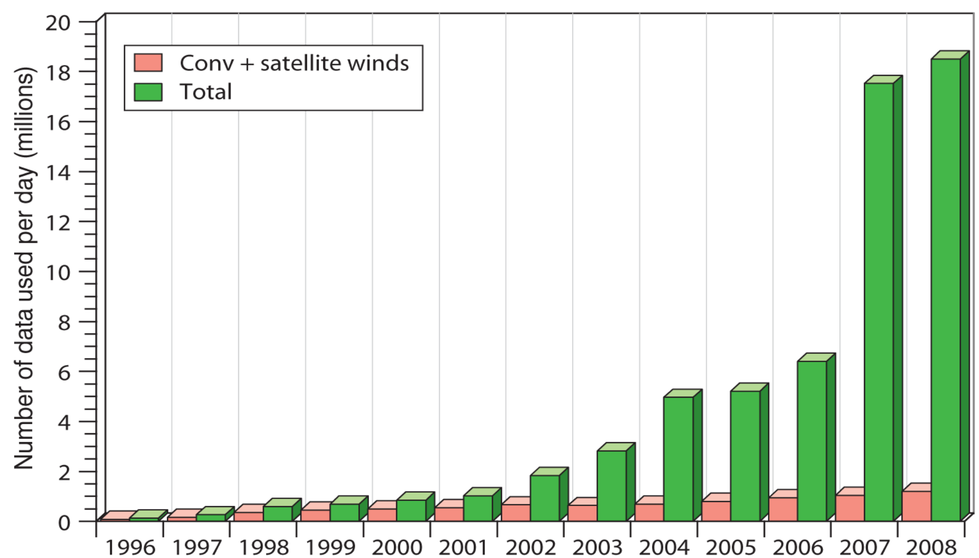
Satellite data used at ECMWF

A key factor for the advance in NWP is increase availability of satellite data.

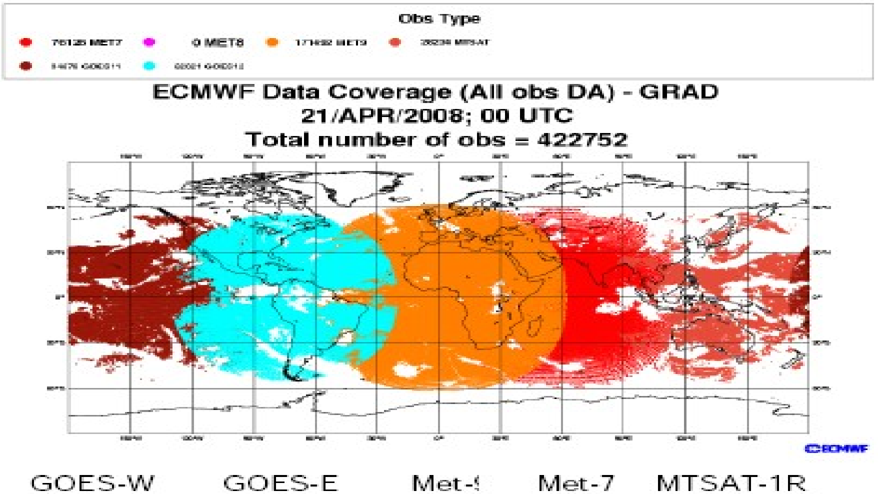
In 2008, ~ 300 million satellite observations from ~ 50 instruments have been received daily (top).

At ECMWF, ~ 6% of the available observations (~18 of the ~300 million) have been used daily (bottom).

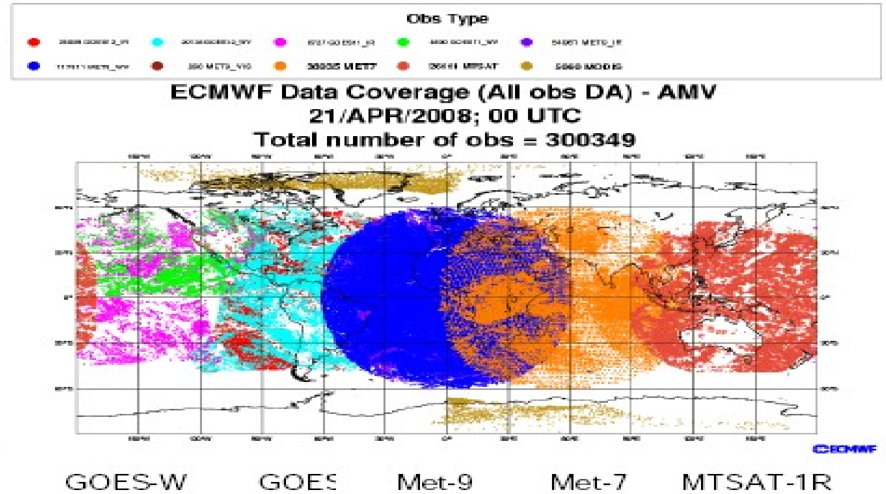




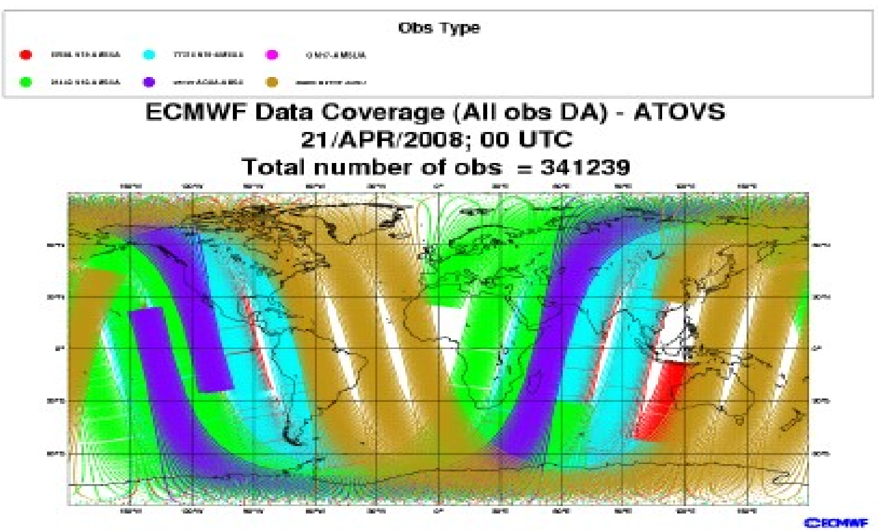
Clear-sky radiances



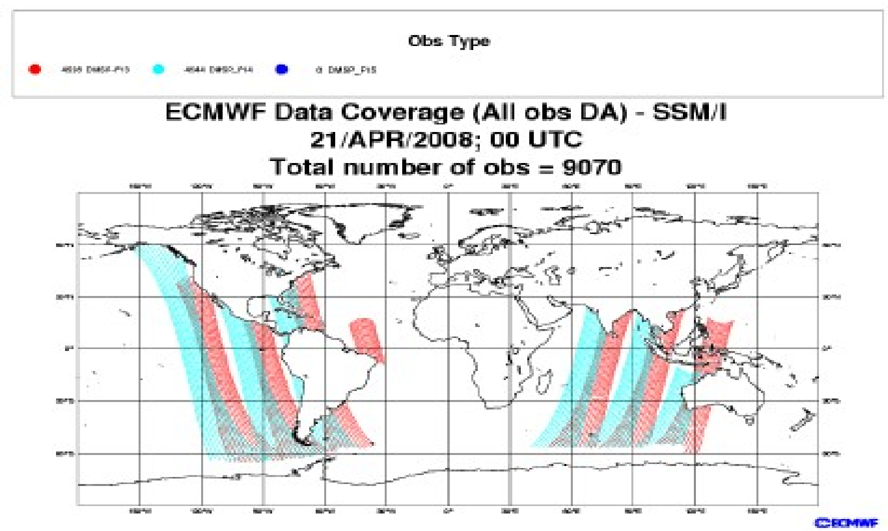
Atmospheric Motion Vectors



AMSU-A

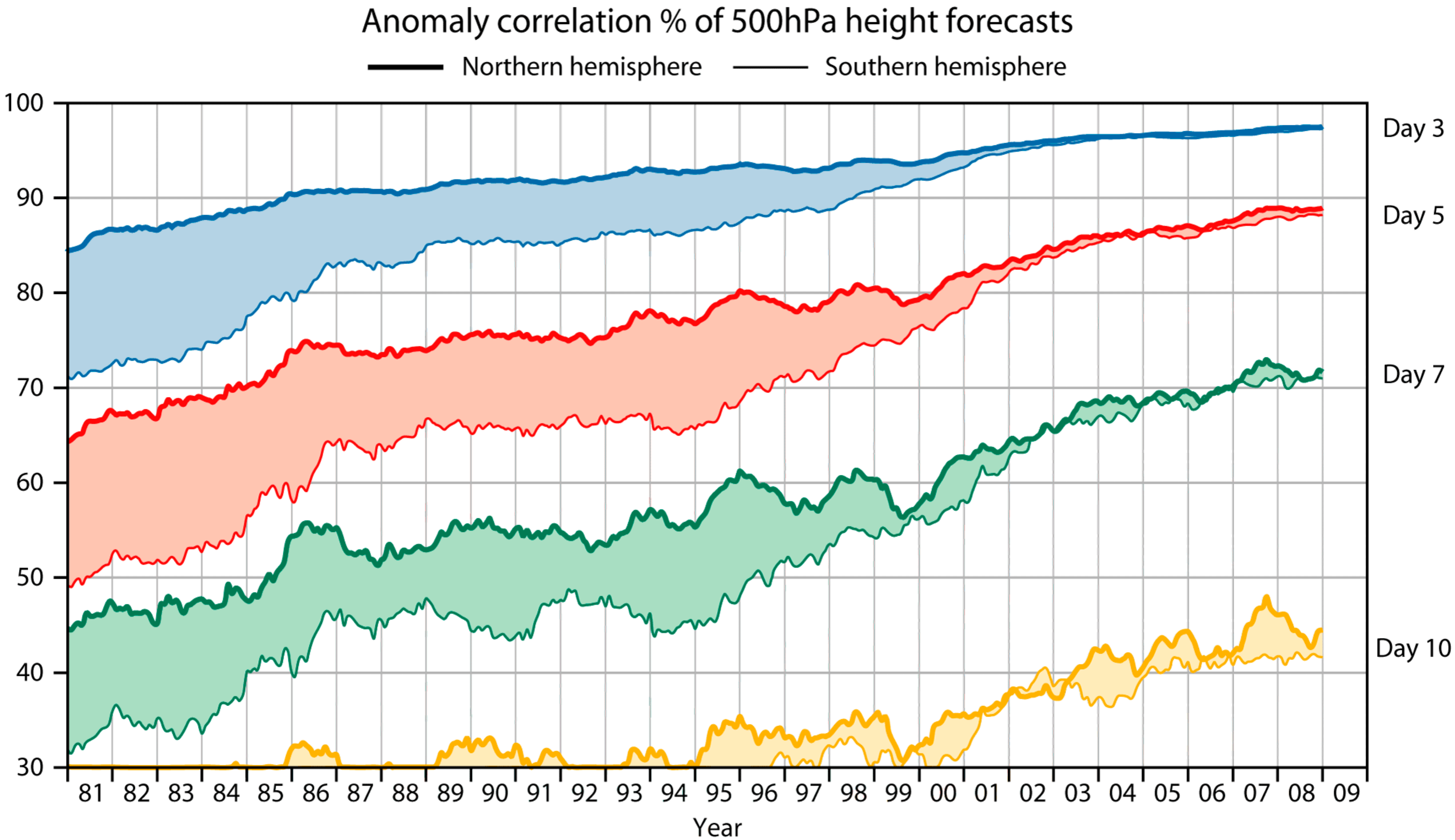


SSM/I



Evolution of ECMWF scores over NH and SH for Z500

- Over NH (SH) a day-7 single forecast of the upper-air atmospheric flow has the same accuracy as a day-5 in 1985 (day-3 in 1981).
- Note that Satellite data now implies equally good FC in NH and SH



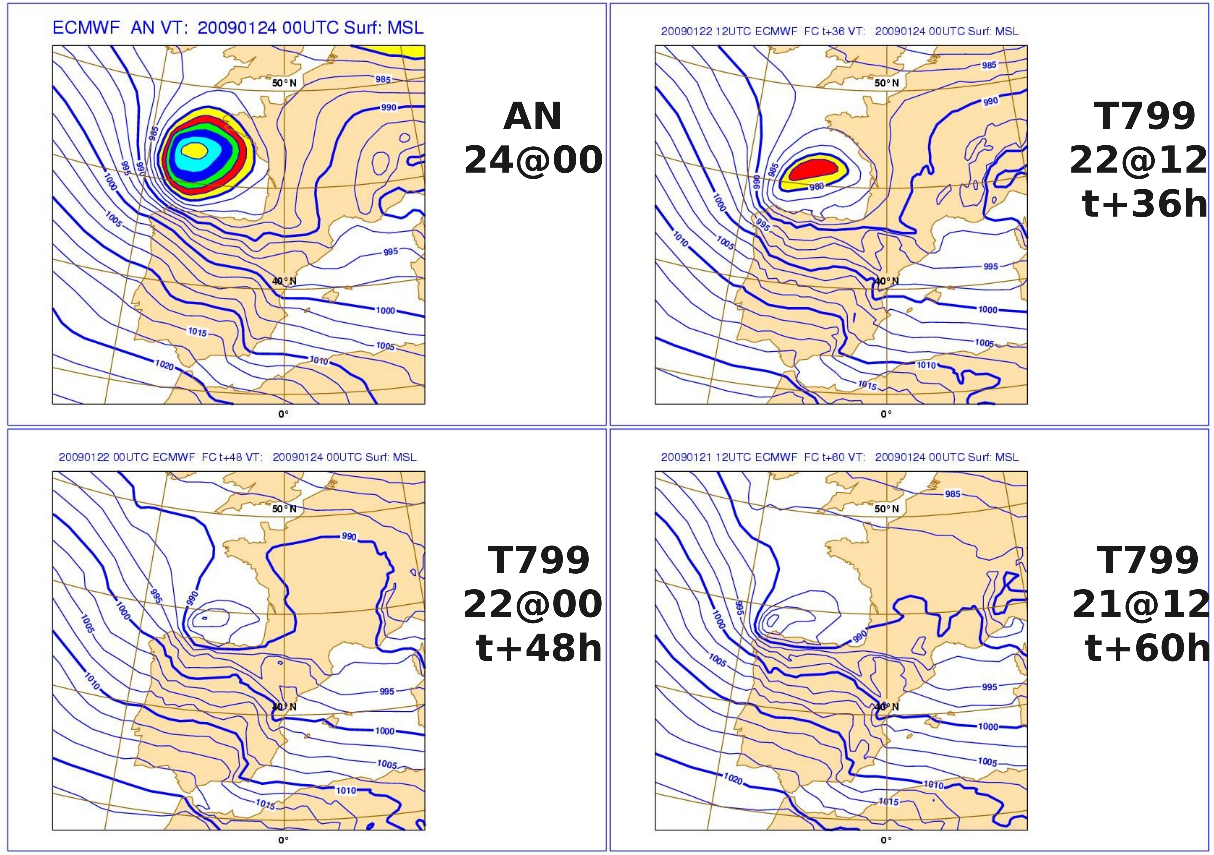
Can we estimate Errors in models?

Severe weather prediction: the storm of 24 Jan 2009

Ex 2: on 24 January, an intense storm hit Northern Spain and France.

Storm developed in the Atlantic and reached the coast of France at 6UTC of 24 Jan.

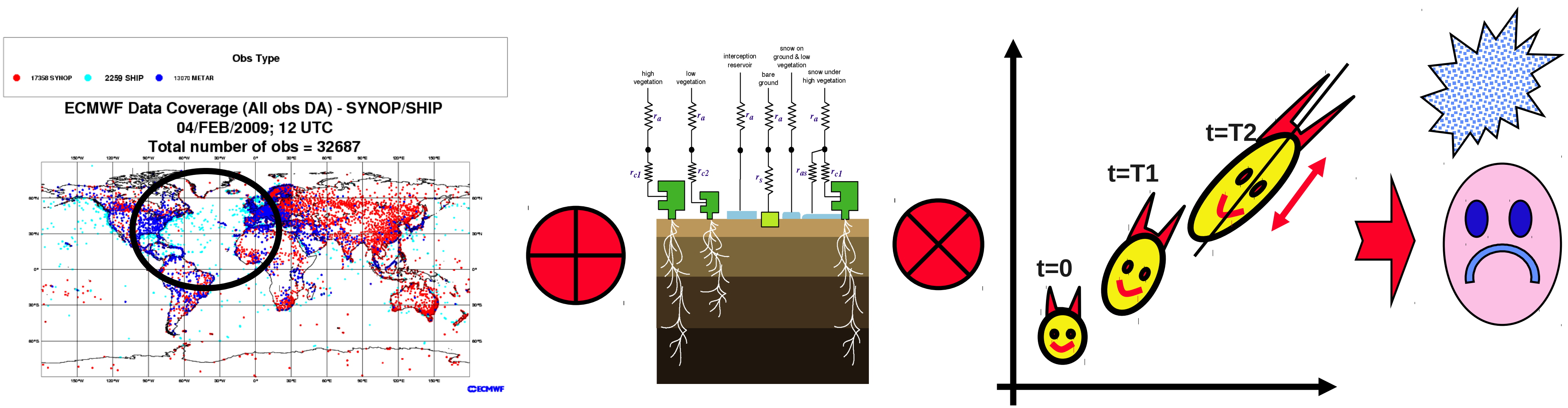
ECMWF T799 short range (+48h, +54h) forecasts had some difficulties in intensifying the storm.



Why do forecasts fail?

Forecasts can fail because:

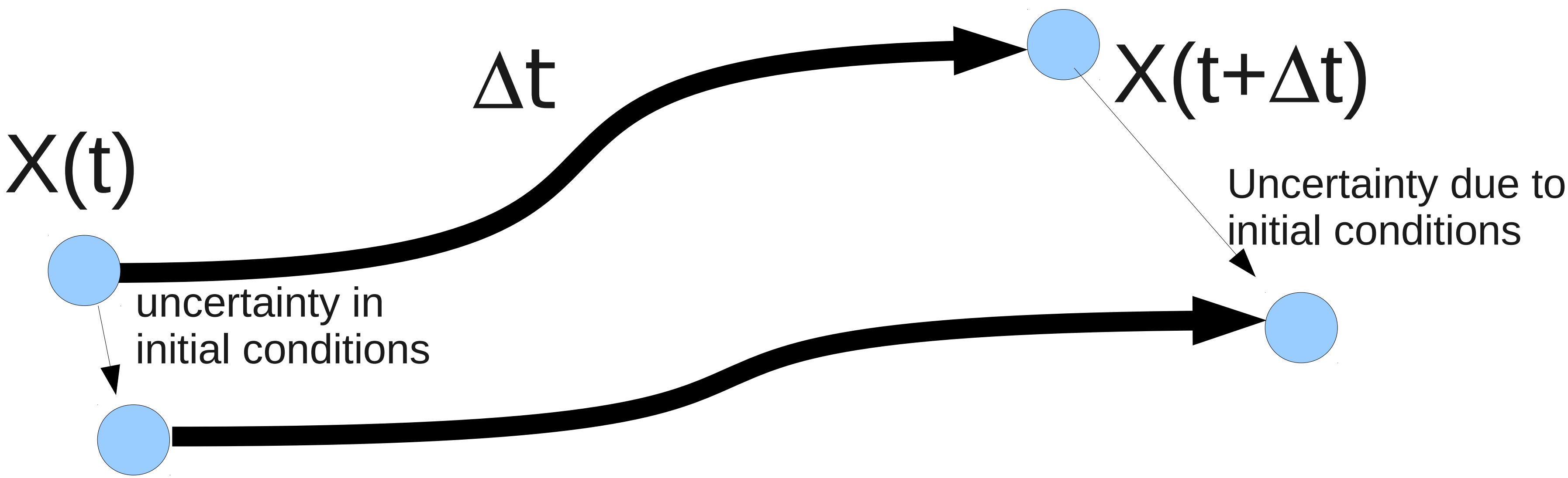
- The initial conditions are not accurate enough, e.g. due to poor coverage and/or observation errors, or errors in the assimilation (initial uncertainties).
- The model used to assimilate the data and to make the forecast describe only in an approximate way the true atmospheric phenomena (model uncertainties).
- A combination of the two phenomena



Uncertainty in NWP?

i. Imperfect model

ii. Uncertainty in initial conditions

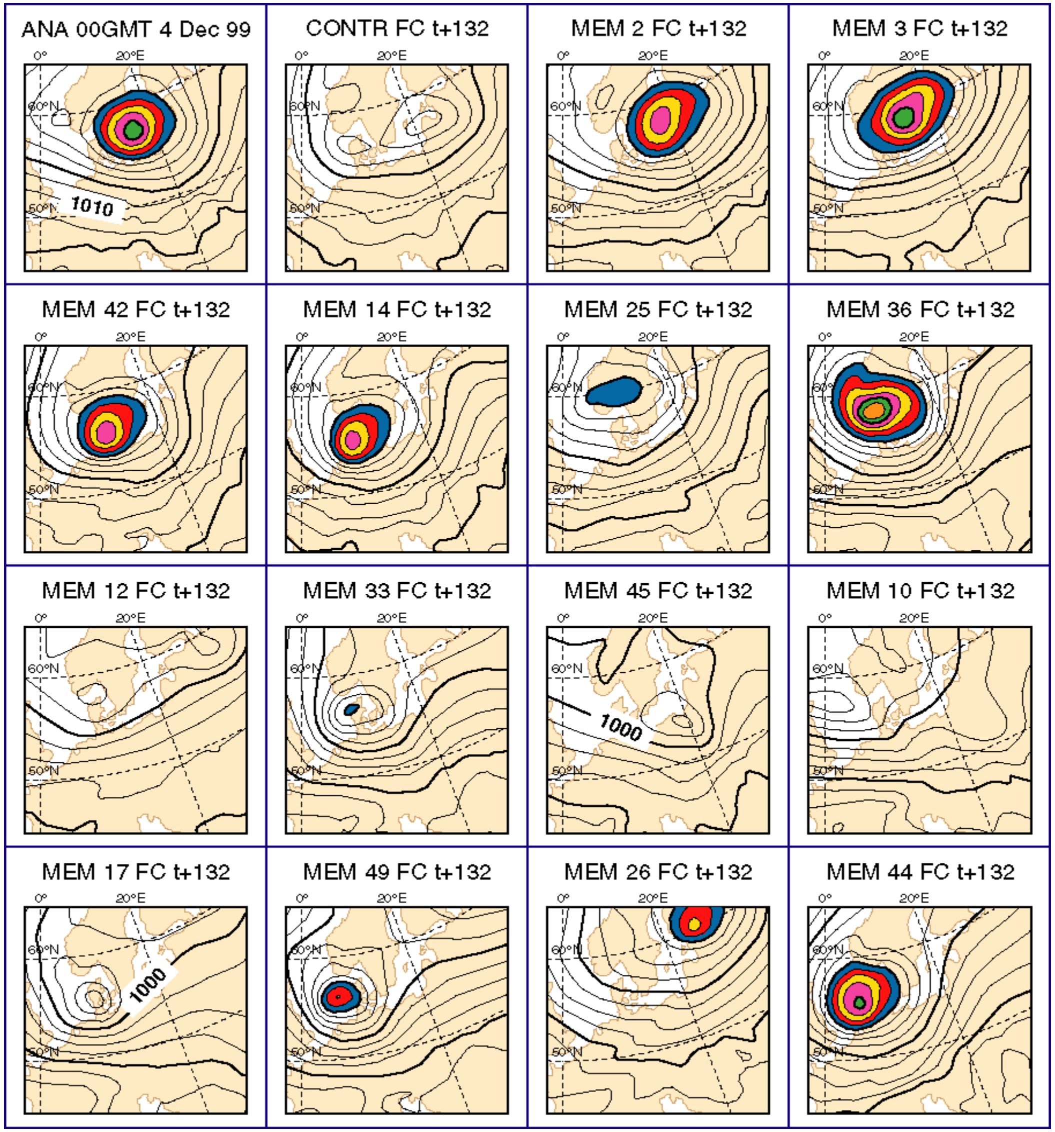


The atmosphere exhibits a nonlinear chaotic behavior

The chaotic behavior of the atmosphere is evident if one compares forecasts started from slightly different initial conditions.

Right: verifying analysis (top-left) and 15 132-hour forecasts of mean-sea-level pressure started from slightly different initial conditions

After 6 days Forecasts differ considerably



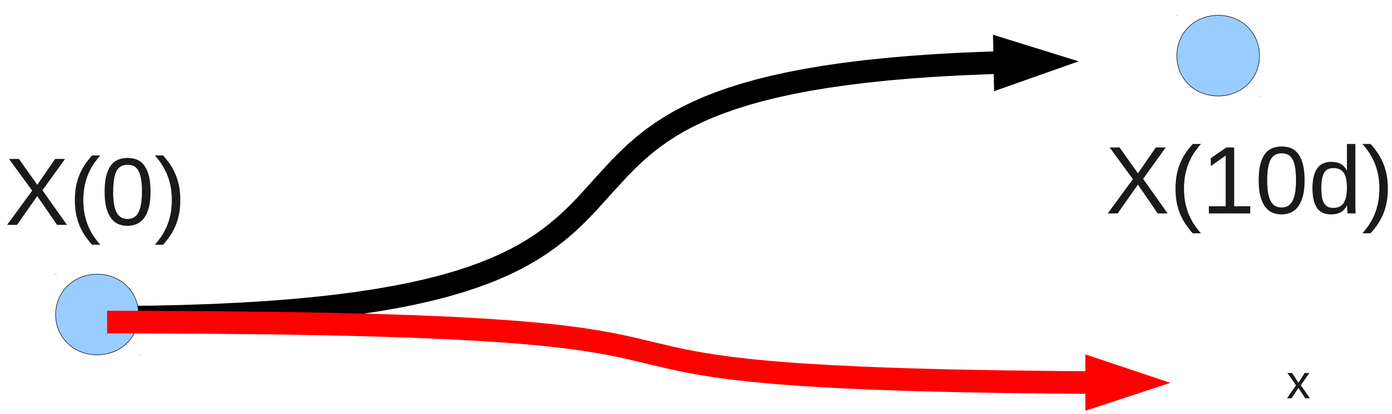
What do we want from a weather forecasting system?

We have seen that single forecasts fail due to a combination of initial and model uncertainties, and that the problem is made extremely complex by the chaotic nature of the atmosphere.

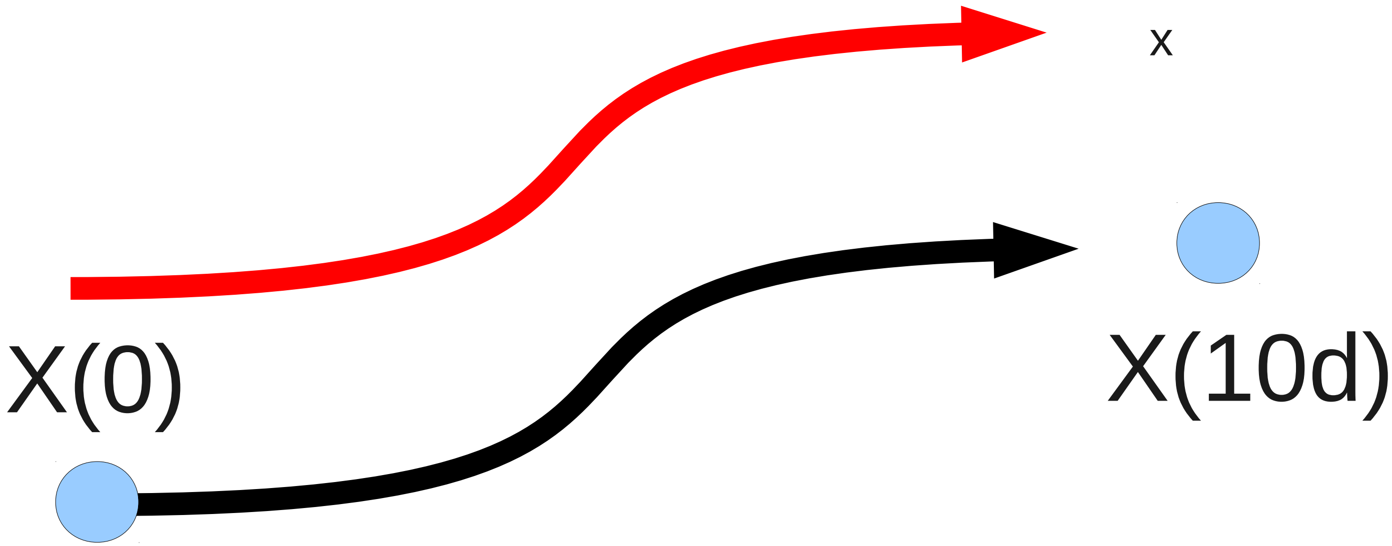
- How can we address this problem?
- Can something better than issuing single forecasts be done?

Ensemble prediction

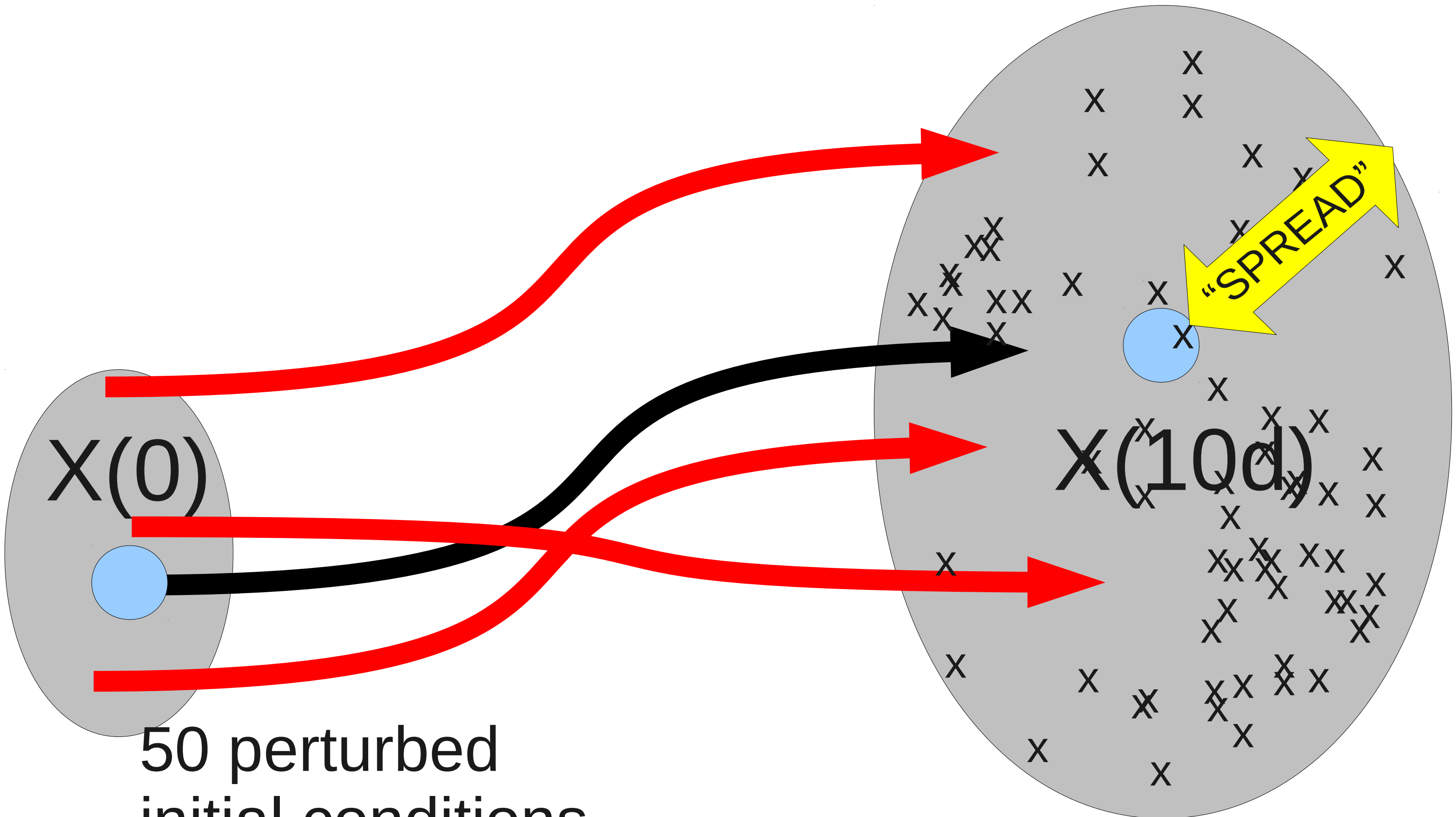
Can apply perturbations to model physics to account for model uncertainty



Ensemble prediction:
Can apply perturbations to initial conditions to account for initial condition uncertainty

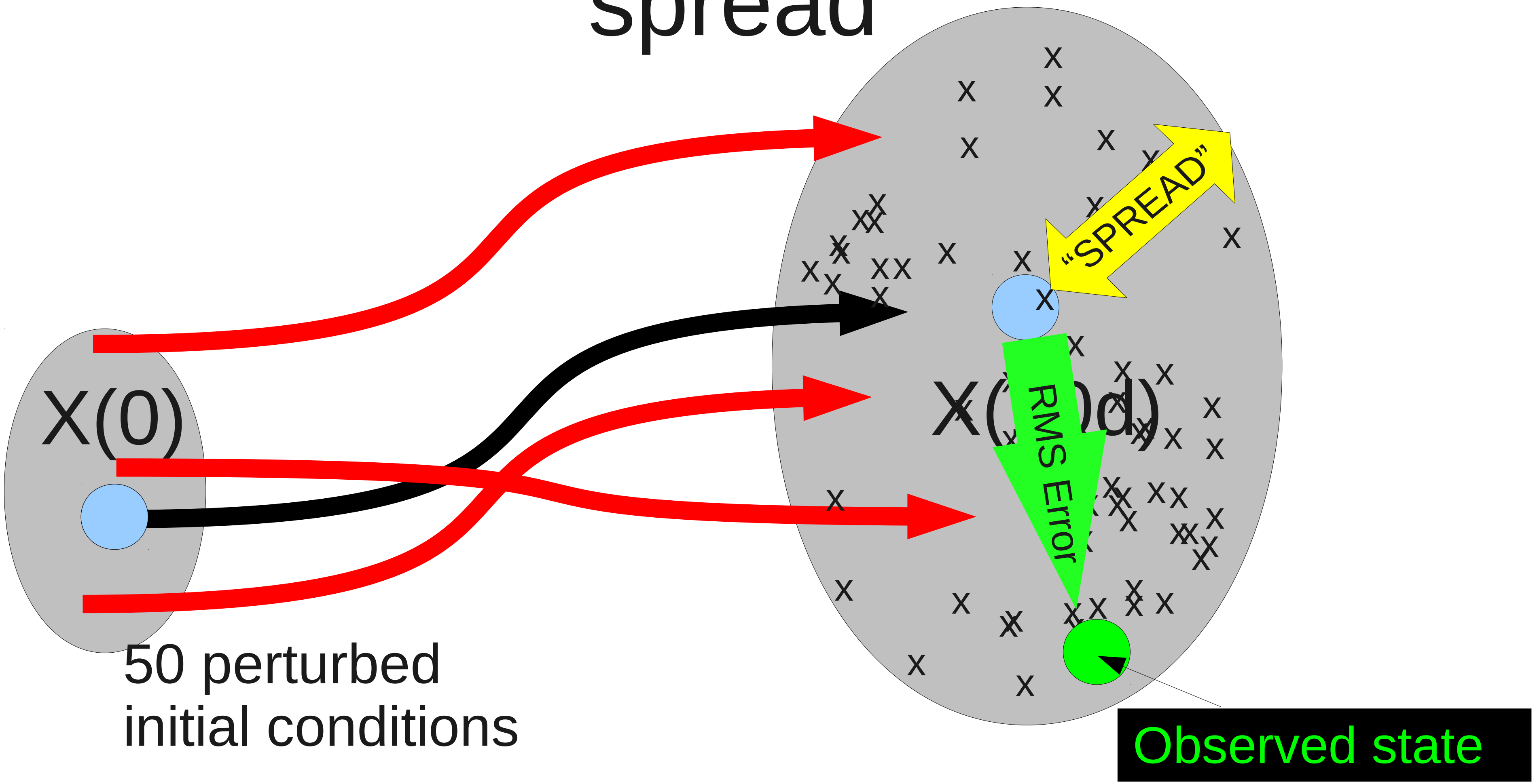


Result: clusters of possible outcomes

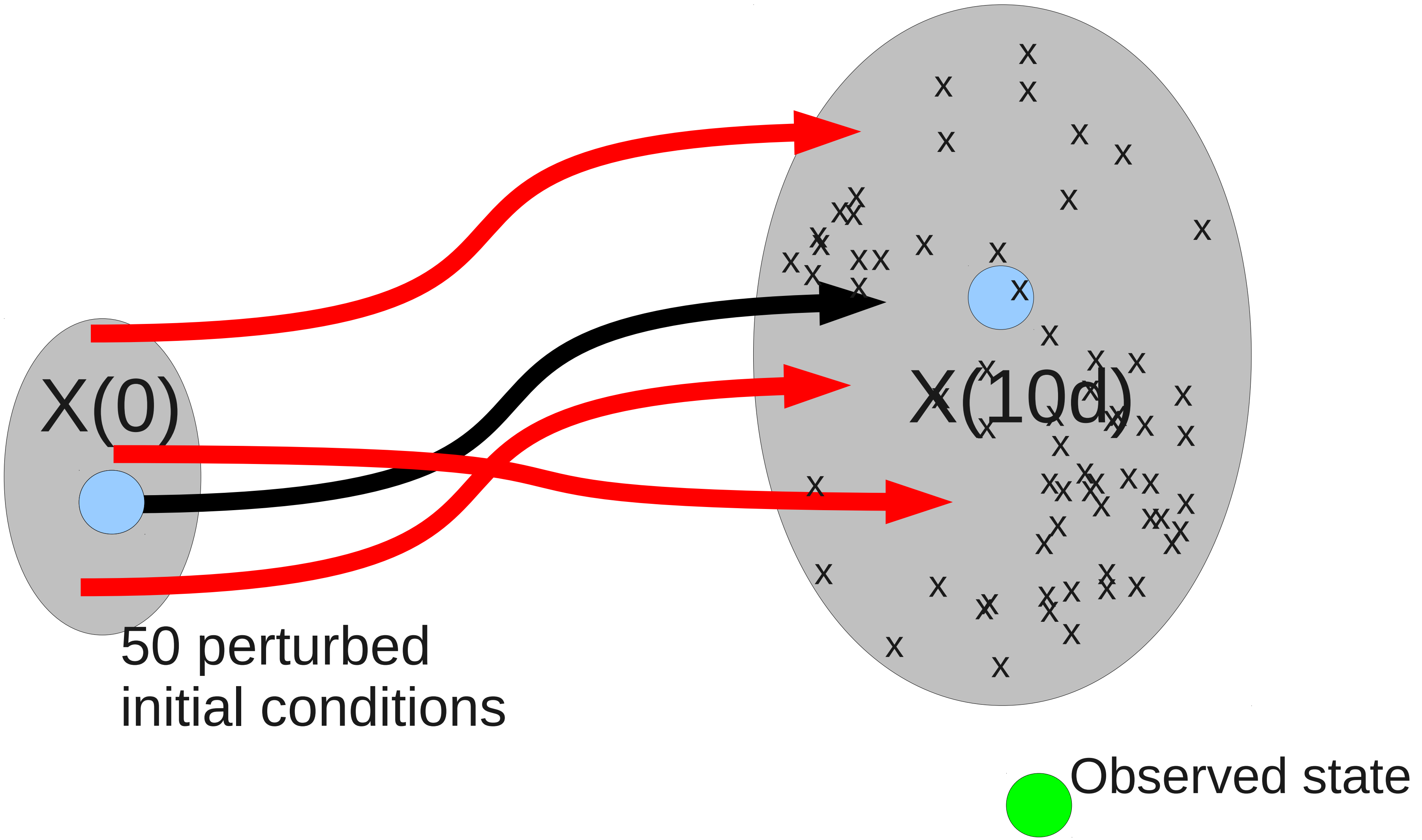


50 perturbed
initial conditions

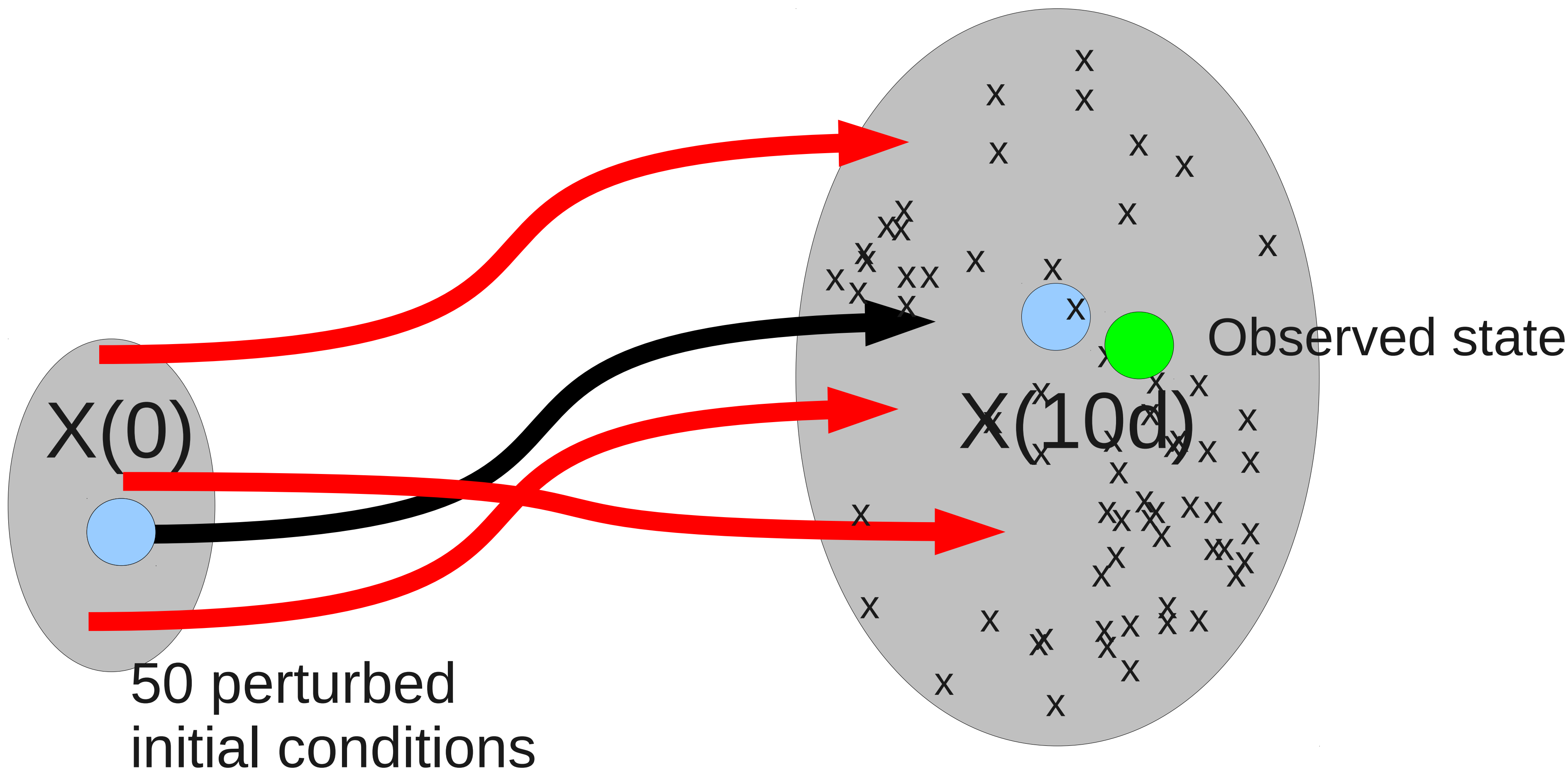
Desire: RMS forecast error to be = ensemble "spread"



Model over-confident: Spread too small and does not reflect error

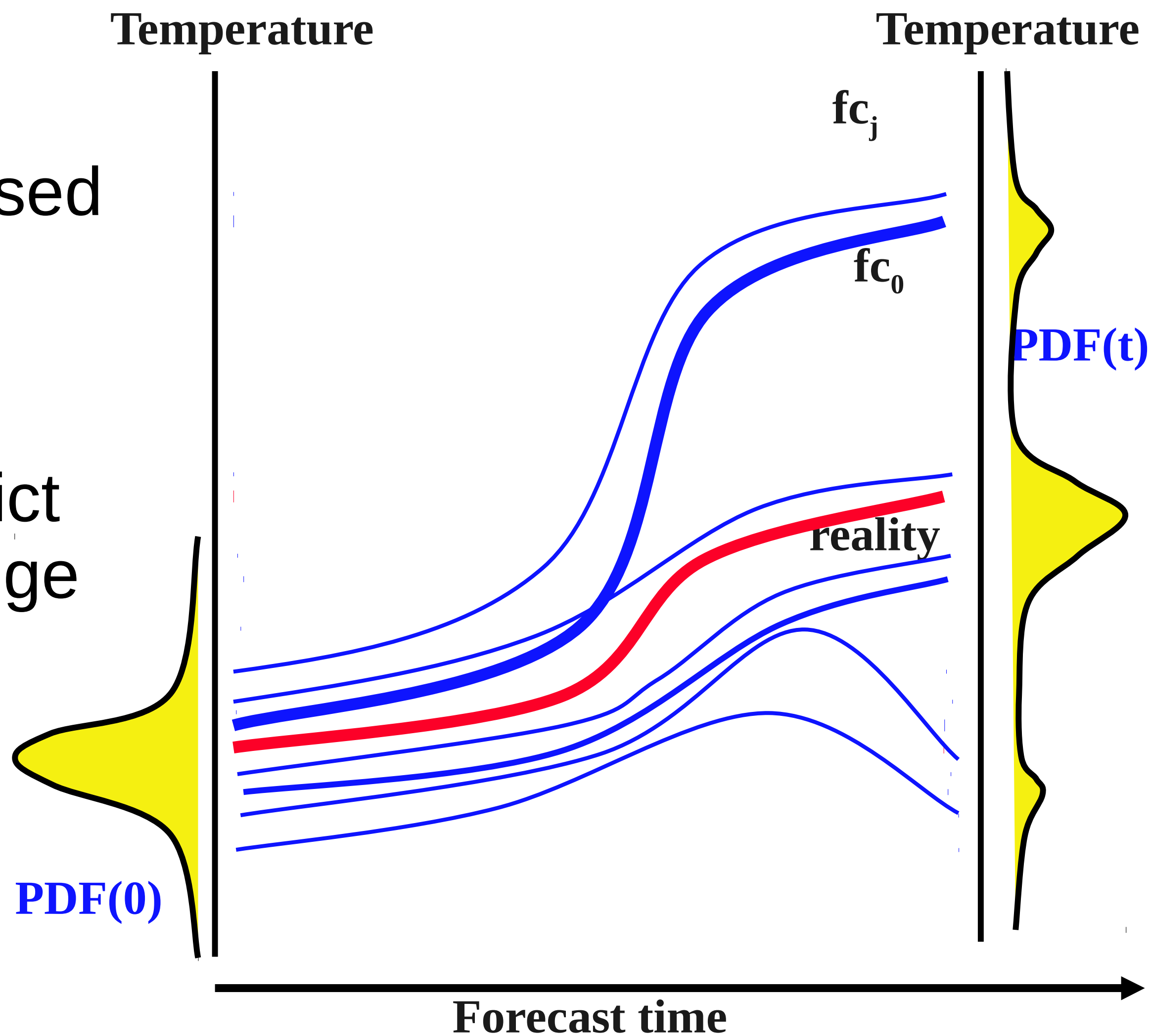


Model under-confident: Spread too large and ensemble forecast has low skill



Ensemble prediction systems

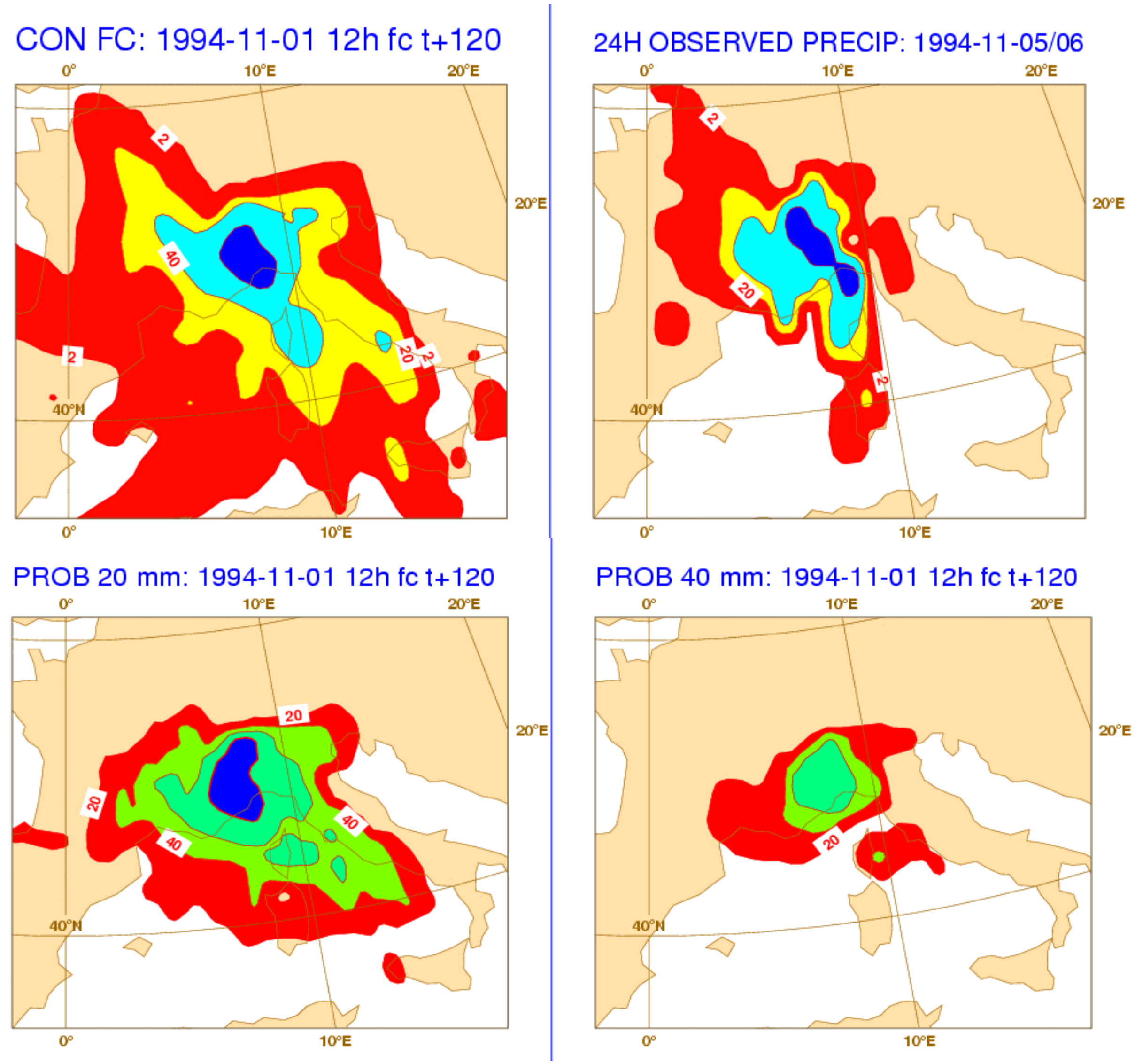
Ensemble prediction based on a finite number of deterministic integration appears to be the only feasible method to predict the PDF beyond the range of linear growth.



What does it mean to ‘predict the PDF time evolution’?

The EPS can be used to estimate the probability of occurrence of any weather event.

Floods over Piemonte (Italy), 6 Nov 94 (top right panel). The forecast skill of the single deterministic forecast given by the EPS control (top left) can be assessed by EPS probability forecasts (bottom panels).



The value of ensemble prediction

Ensemble predictions:

- can be used to evaluate predictability of the atmospheric flow (i.e. forecast the forecast skill): small “spread” **should (in theory!)** indicate high predictability (i.e. small error)

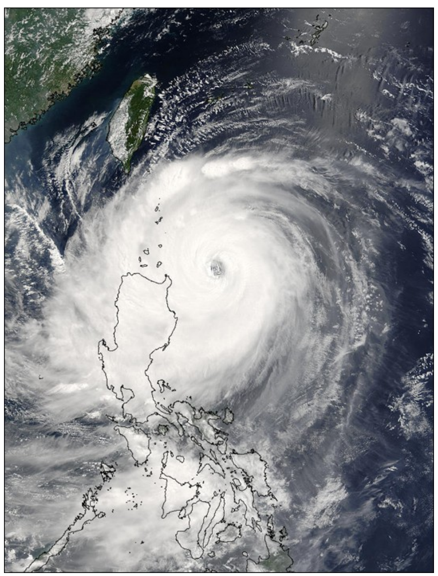
- can be use to estimate the whole probability distribution function of forecast states, and this distribution can be used not only to identify the most likely outcome, but also to assess the probability of occurrence of maximum acceptable losses.

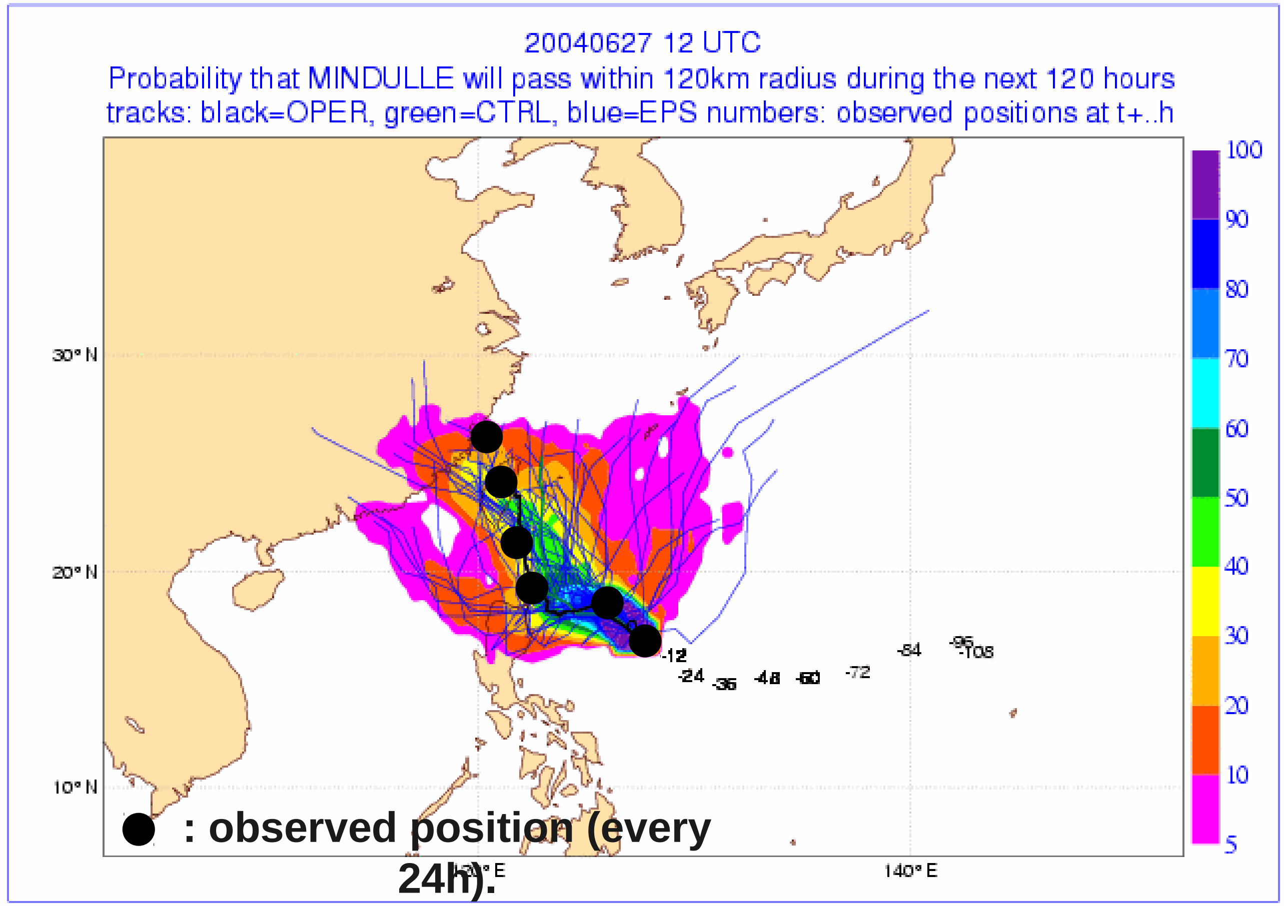
- are more consistent than single forecasts, i.e. ensemble-based successive forecasts verifying at the same time change less than single forecasts.

3. Track dispersion & predict: typhoon Mindulle (Jul ’04)

Typhoon Mindulle skirted along the coast of Eastern China in early July 2004, bringing torrential rain.

Dispersion of EPS tracks was relatively large: the +120h single HRES fc (black) had large errors.

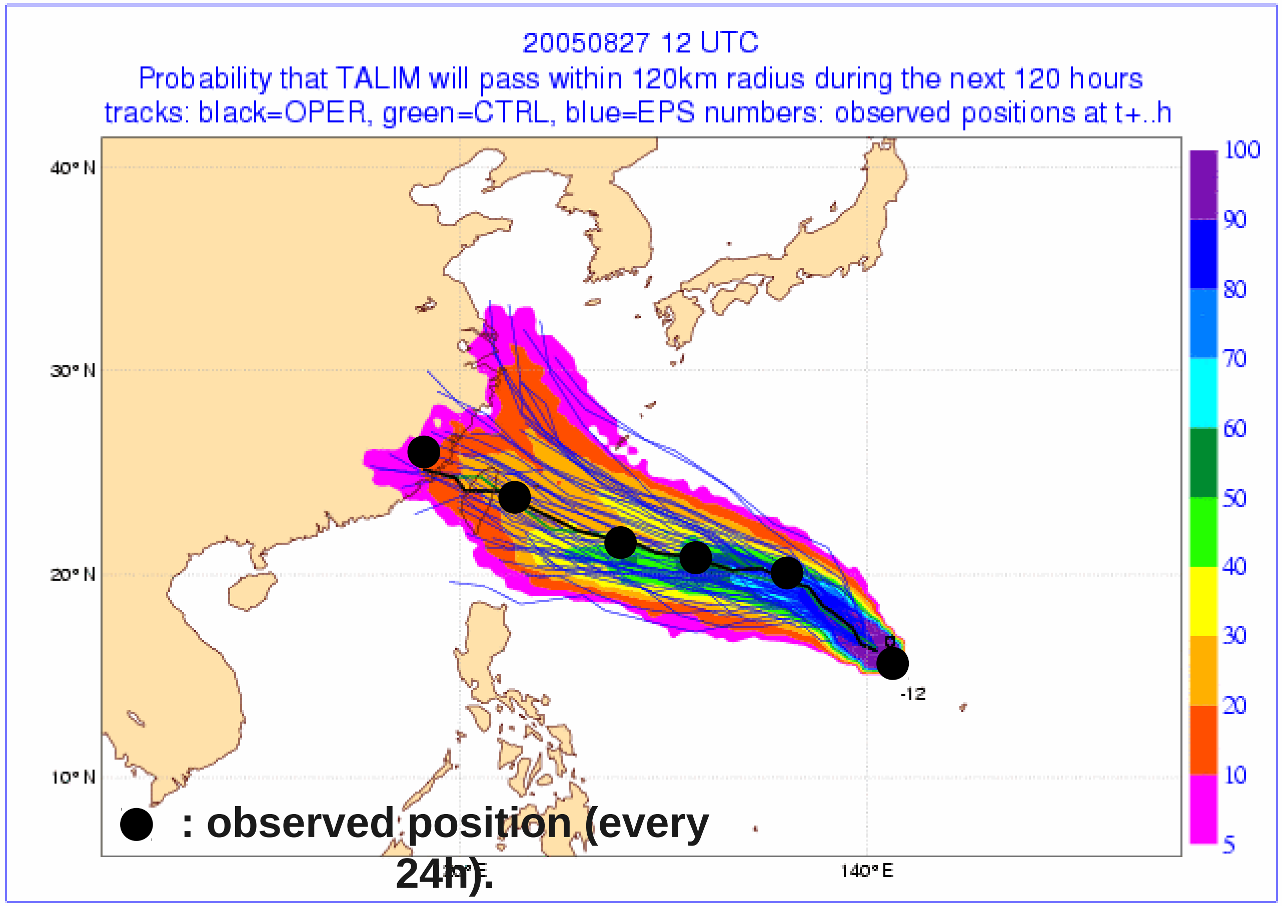




3. Track dispersion & predict: typhoon Talin (Sep ’05)

“Damages due to Typhoon Talin’s flooding and landslides are 7.8 billion yuan (US$960 million), at least 53 were killed.” (from the press).

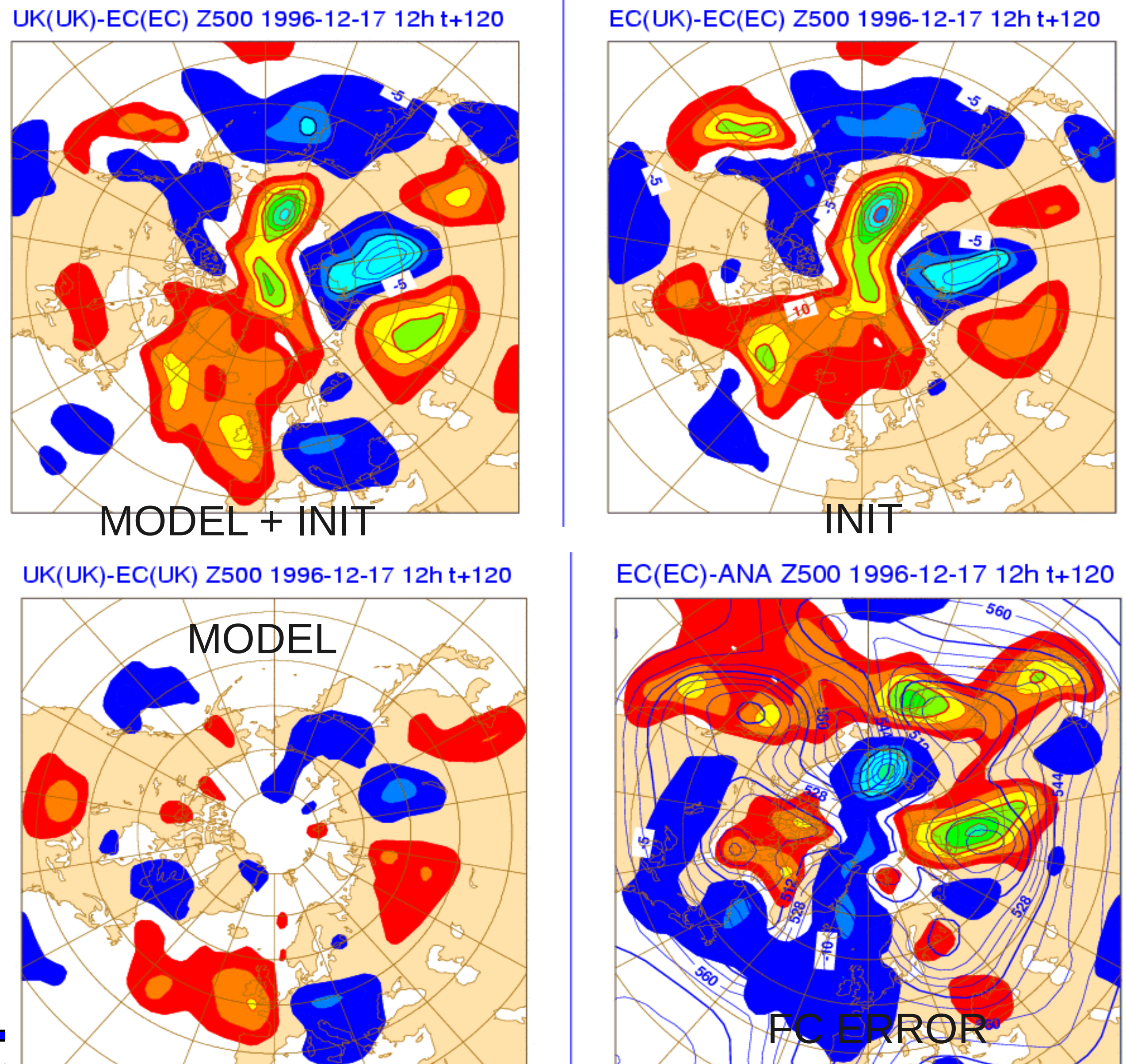
Dispersion of EPS tracks was relatively small: the +120h single HRES fc (black) had small errors.



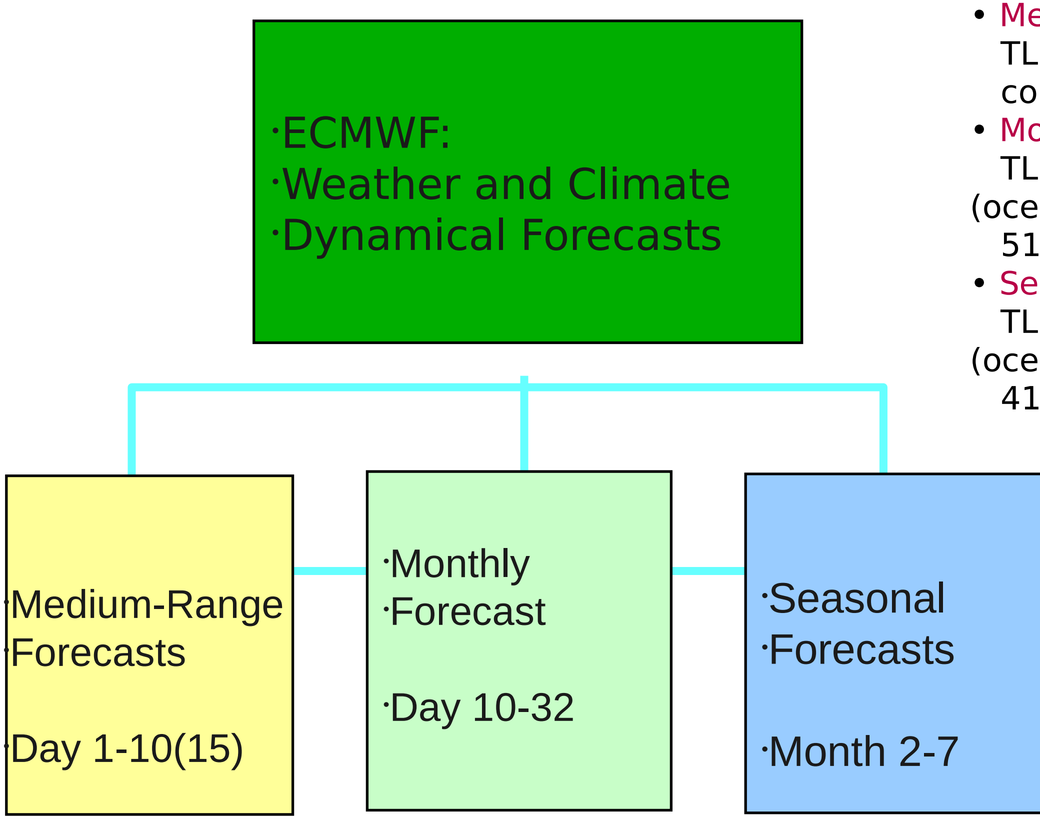
What is the relative contribution of initial and model uncertainties to forecast error?

Harrison et al (1999) have compared forecasts run with two models (UKMO and ECMWF) starting from either the UKMO or the ECMWF ICs.

Results have indicated that initial differences explains most of the differences between forecasts... *at short to medium range*

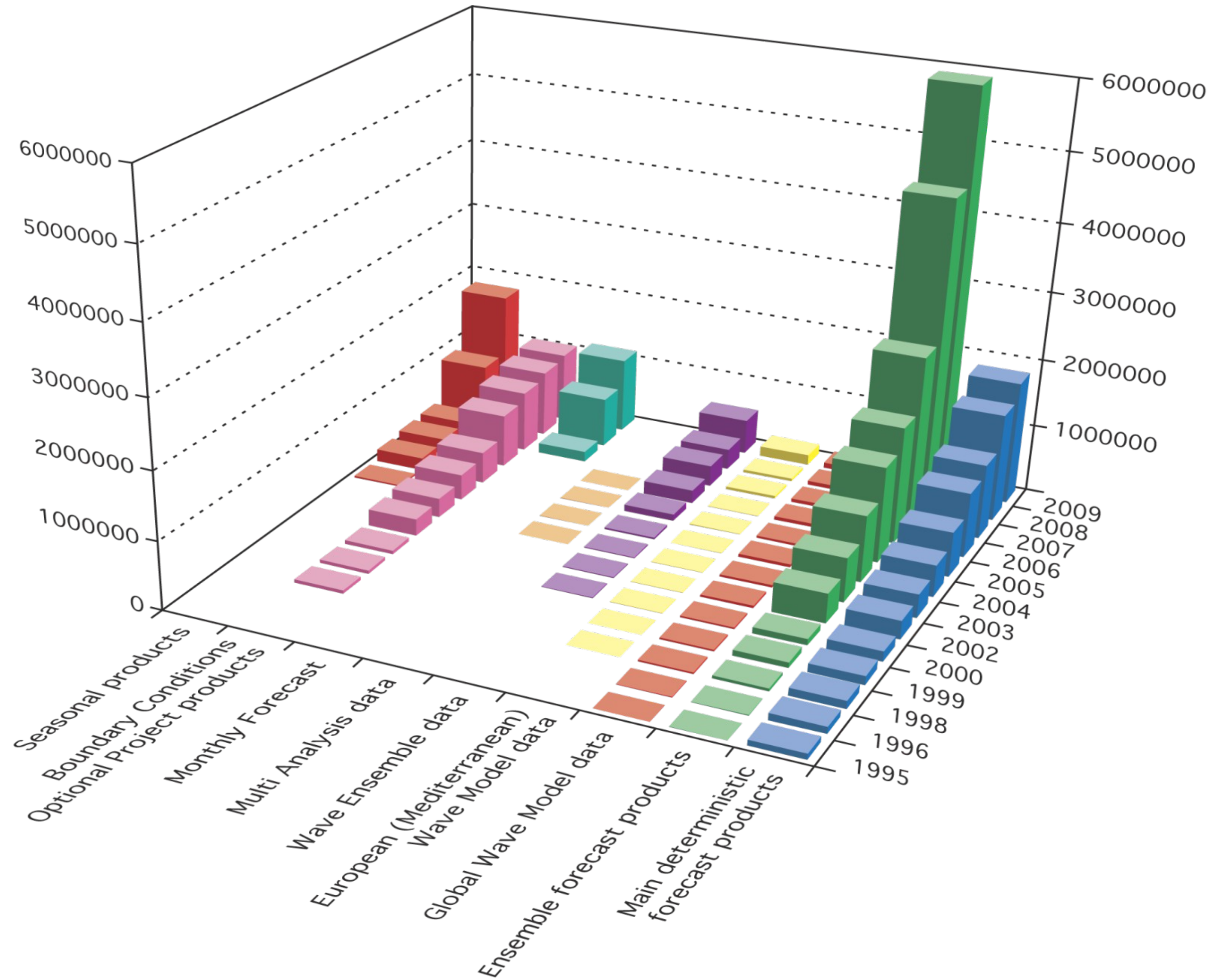


ECMWF model suites – Summary



- Deterministic high-resolution global atmospheric model
  TL1279 91 levels; range=10 days
- Medium-range ensemble prediction system
  TL639 / TL319 62 levels; range=15 days
  control + 50 perturbed members
- Monthly forecast system
  TL319 62 level (atm.), 1.4 º x 0.3-1.4º, 29 vertical levels (ocean)
  51-member ensemble; range=32 days
- Seasonal forecast system
  TL159 62 level (atm.), 1.4 º x 0.3-1.4º, 29 vertical levels (ocean)
  41-member ensemble; range=7 months

Data Dissemination(k bytes)



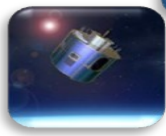
ECMWF Re-Analysis (ERA)

From Paul Poli aul.poli@ecmwf.int

·Simple concepts

·Polar-orbiting Satellite

·Argo Float



·Geostationary Satellite

·Bathythermograph

·Aircraf
t

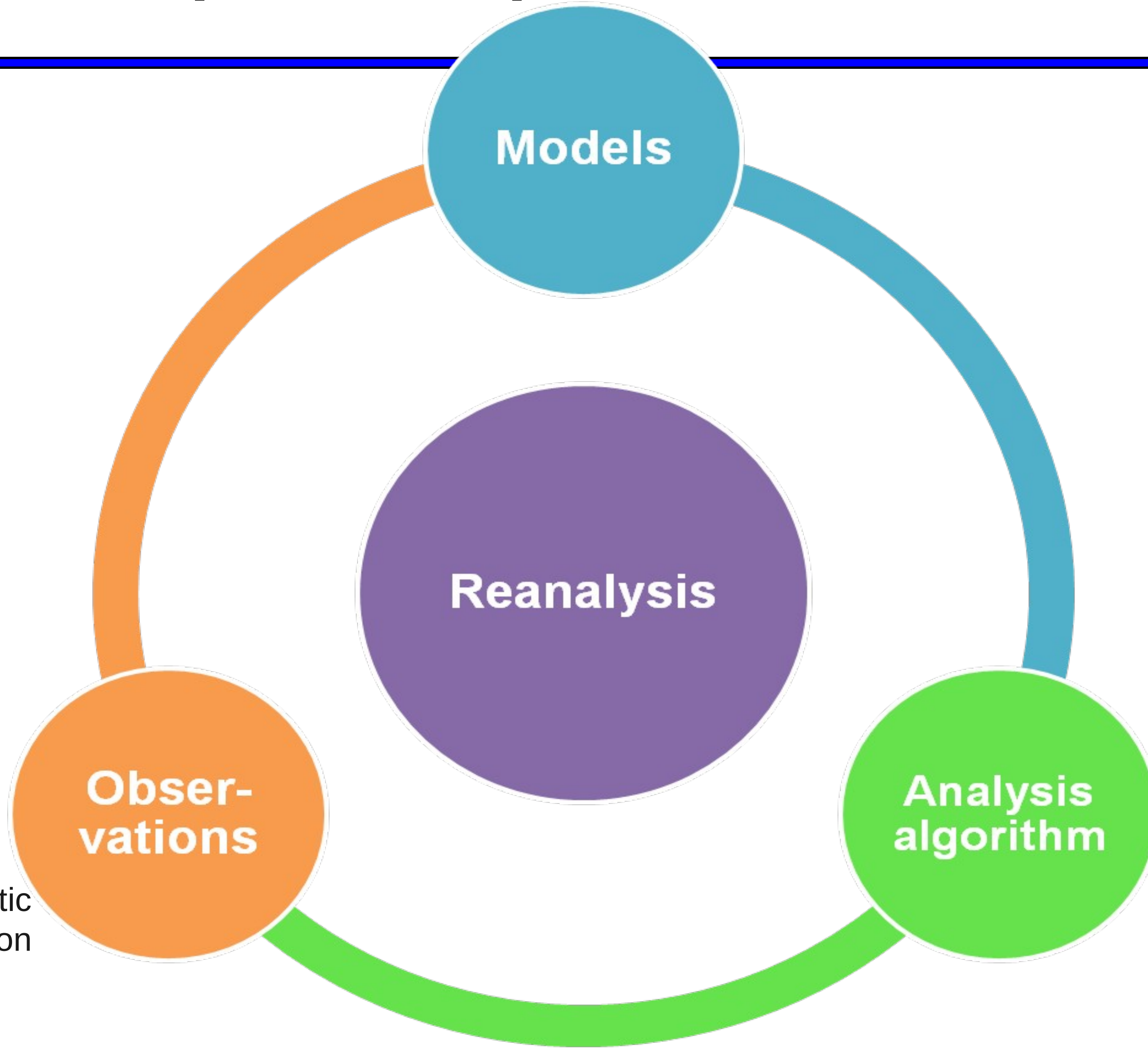
·Buoy

Balloon,
·radiosonde

·Ship

·(Semi-) Automatic
Station

·Observer



Why reanalysis?
Advantages against "observations-only" multi-decadal gridded datasets … for climate studies

1) How reanalysis deals with "missing data"

- Only assimilate observations when and where we have them!
- … instead of reverting to a crude, 2nd-order, unphysical interpolation to "fill in the blanks"

2) Produced fields are space- and physically-consistent

- As specified by the NWP model

3) Use the widest variety of observations

- Not just temperatures, or winds, or humidities in isolation of each other…
- … but also pressures, satellite observations, … multi-variate approach

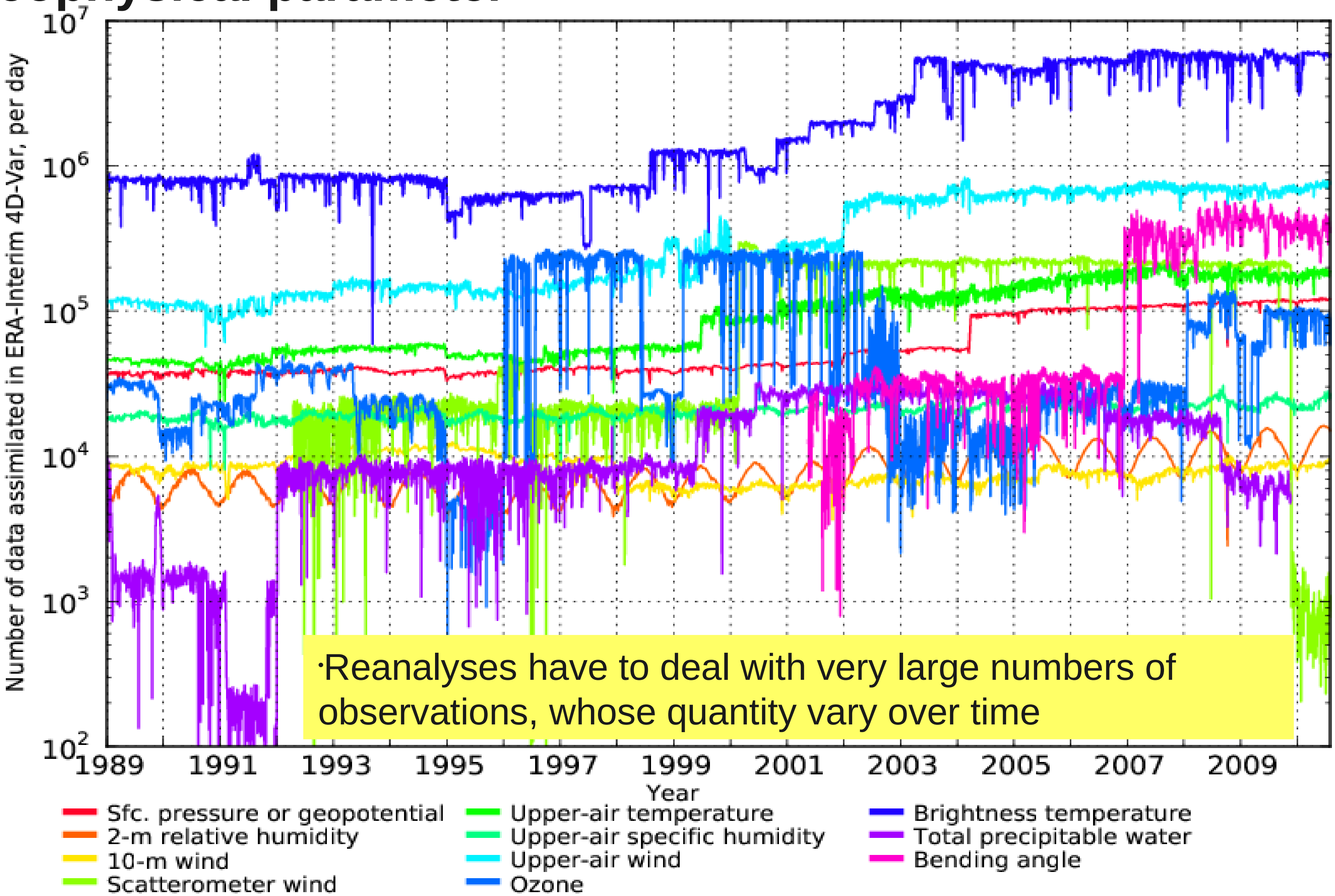
4) All observations are evaluated/used in a consistent way

- Accuracy and precision explicitly taken into account
- Seamless quality control (QC) procedures, across all observation types
- The background prediction provides a unique advantage for QC

Conclusion

- So, yes reanalysis combines lots of difficulties due to changes in observations input… but like with ANY OTHER observations-based dataset, the basic challenge is the same (change in observations' quality and quantity over time). The difference is, we try to do things in a consistent manner, by applying the same methodology of ***data assimilation*** for all observations

·Number of observations assimilated in ERA-Interim, by geophysical parameter



·Reanalyses have to deal with very large numbers of observations, whose quantity vary over time

·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 NWP models (= the first reanalyses!), to compare performances and progress
- **1983**: **Reanalysis concept first 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 byTrenberth 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 *(~4DVAR or IAU)***
  - JRA-55 (1958 - 2012) from Japan
  - NASA/GMAO-MERRA (1979 - present) from USA
  - NCEP-CFSRR (1979 - 2008) from USA
  - ERA-Interim (1979 - present) from ECMWF

·Summary of important concepts

- **Reanalysis does <u>not</u> 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 <u>consistency in time, over several years</u>**

- **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

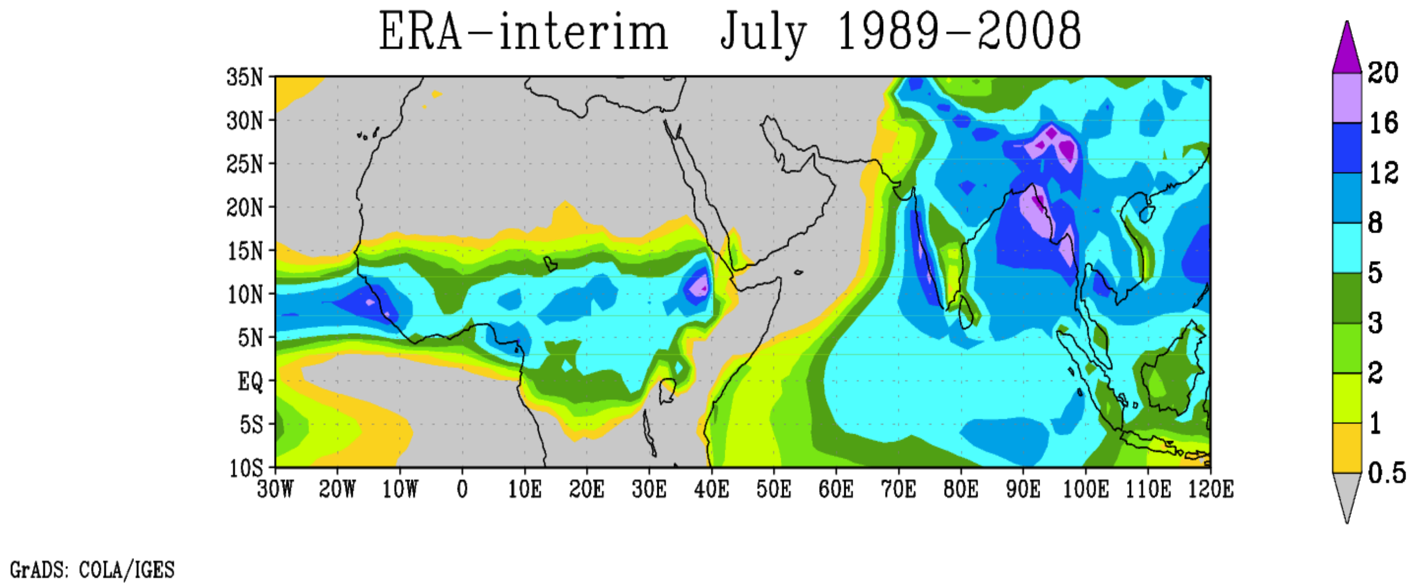
It is worth repeating as all ingredients continue to evolve:

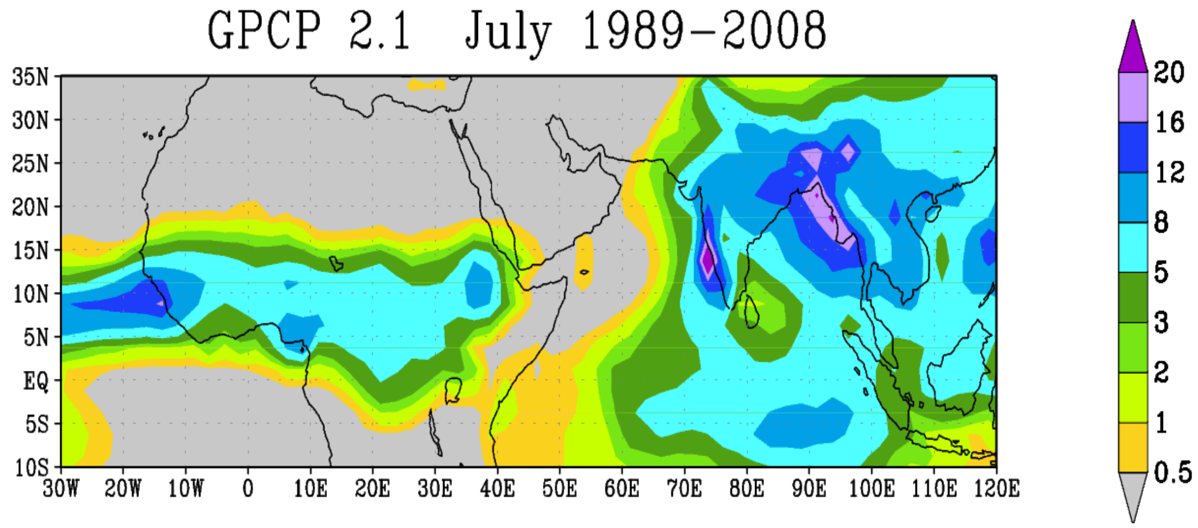
- Models are getting better
- Data assimilation methods are getting better
- Observation processing is improving
- Old observations (paper records) are being rescued
- The technical infrastructure for running & monitoring improves constantly
- **With each new reanalysis we improve our understanding of 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 model bias (ultimately responsible for problems with trends)
- Coupling with ocean and land surface
- Making observations used in reanalysis more accessible to users
- Providing meaningful uncertainty estimates for the reanalysis products

·Rainfall climatology in July

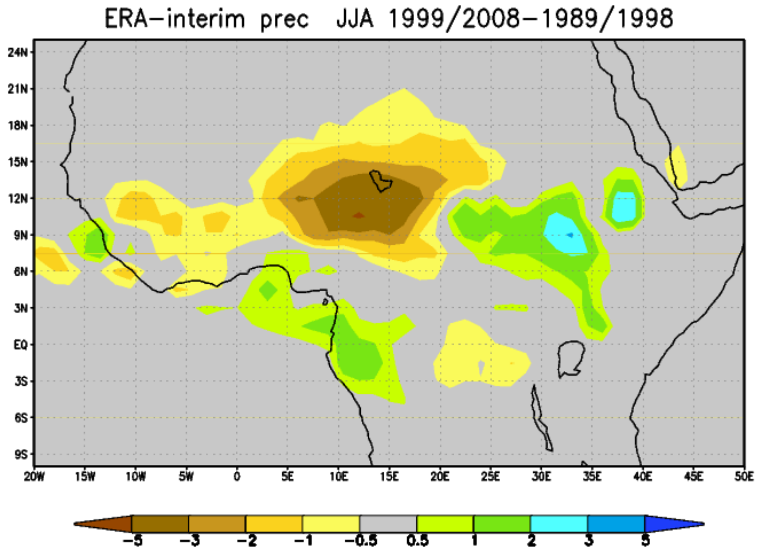




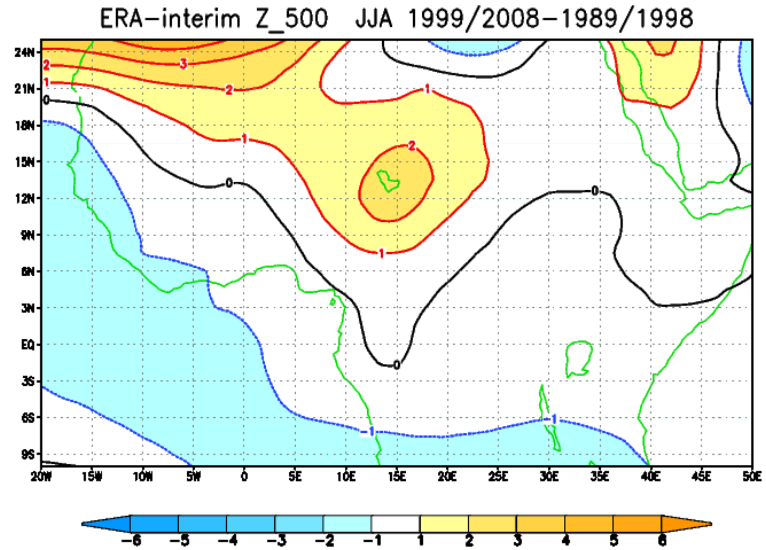
F Molteni

·ERA-interim: trends over Africa in JJA

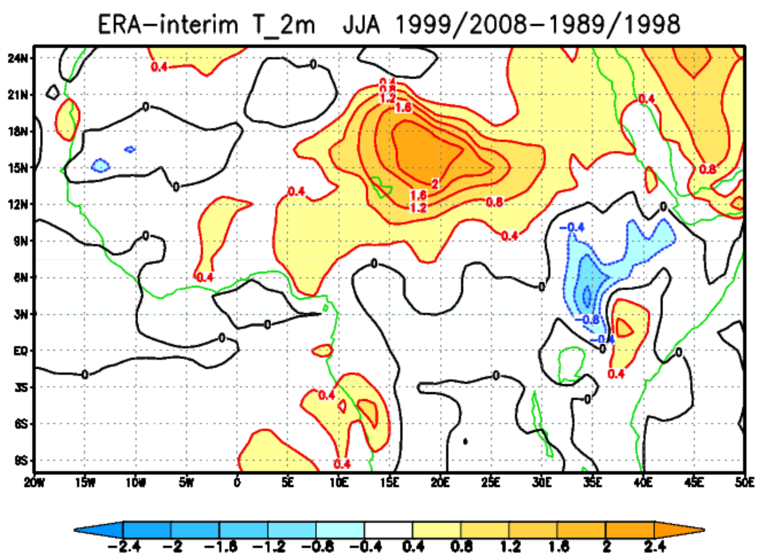
·Prec



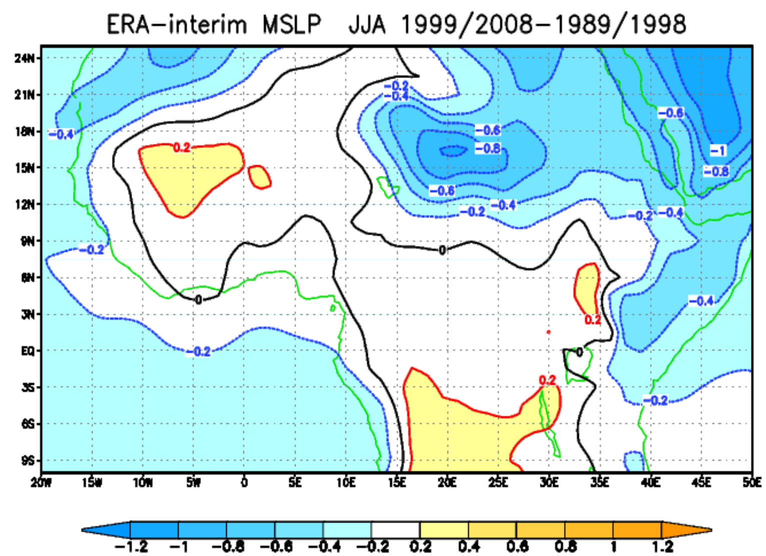
·Z 500



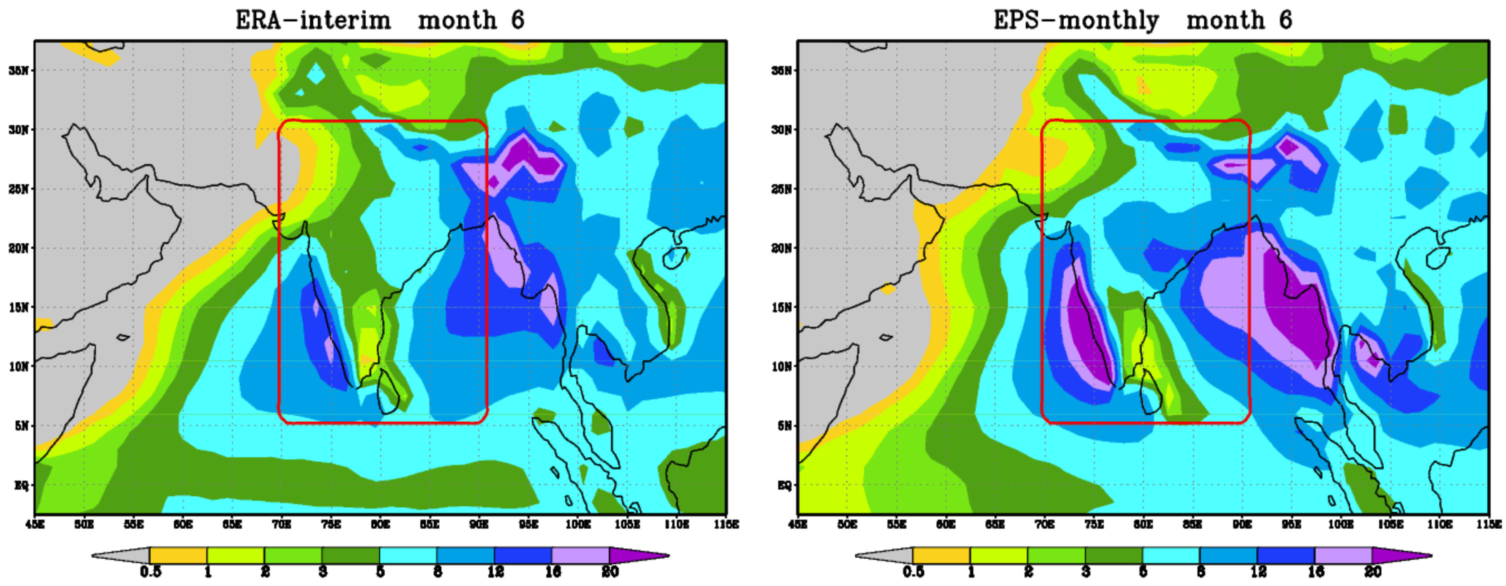
·T_2m



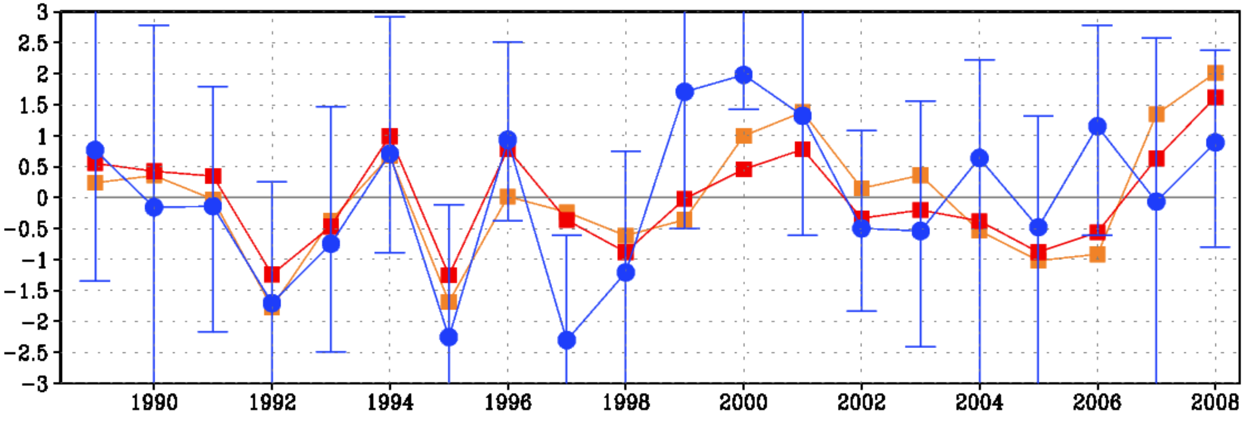
·SLP



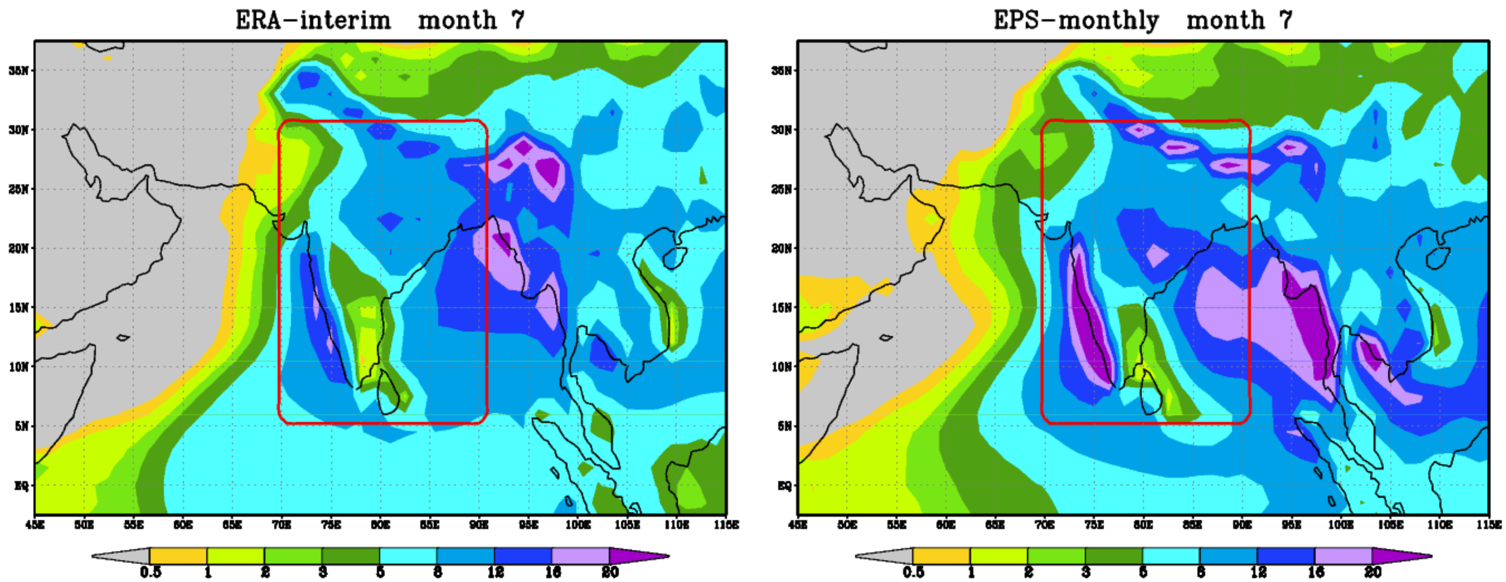
• 46-day EPS re-forecasts: India, June

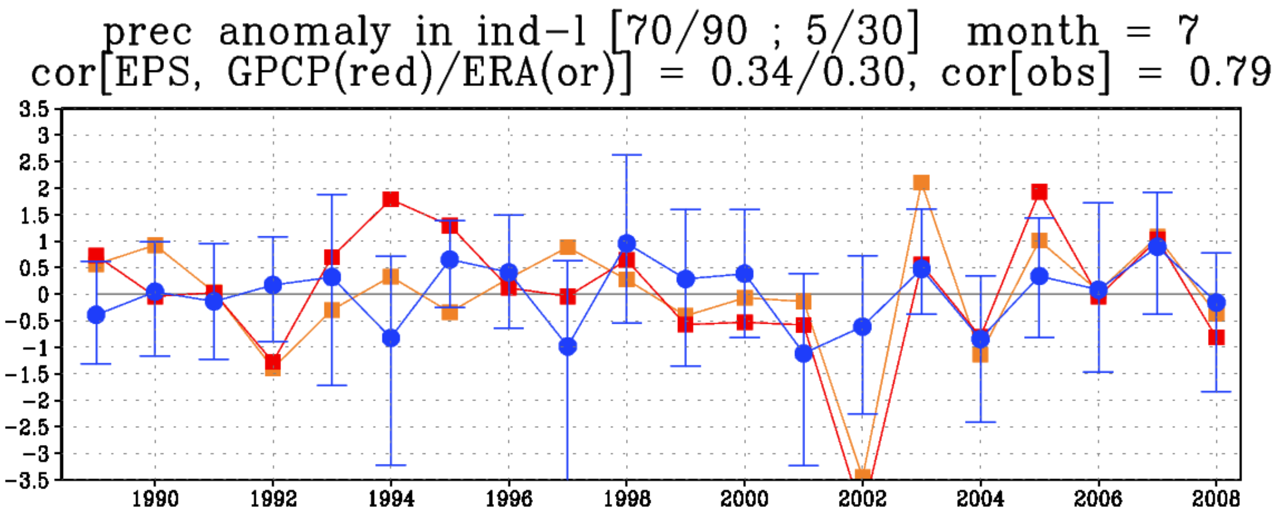


prec anomaly in ind−1 [70/90 ; 5/30] month = 6
cor[EPS, GPCP(red)/ERA(or)] = 0.65/0.55, cor[obs] = 0.90

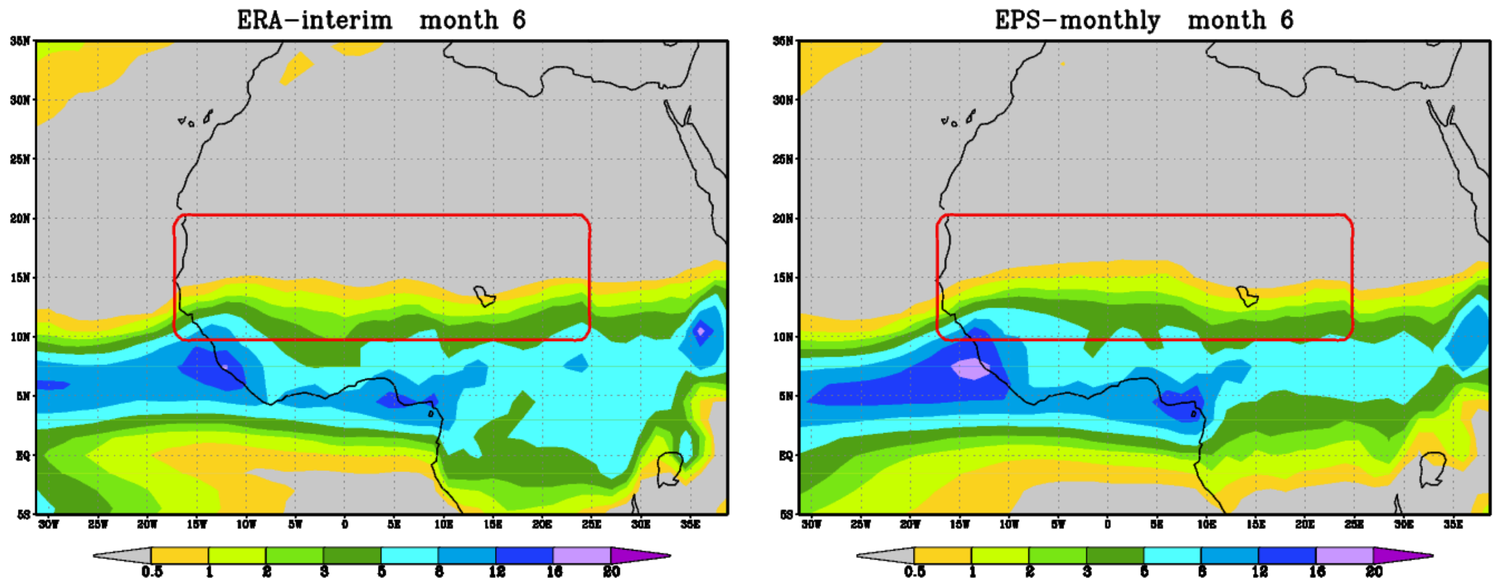


46-day EPS re-forecasts: India, July

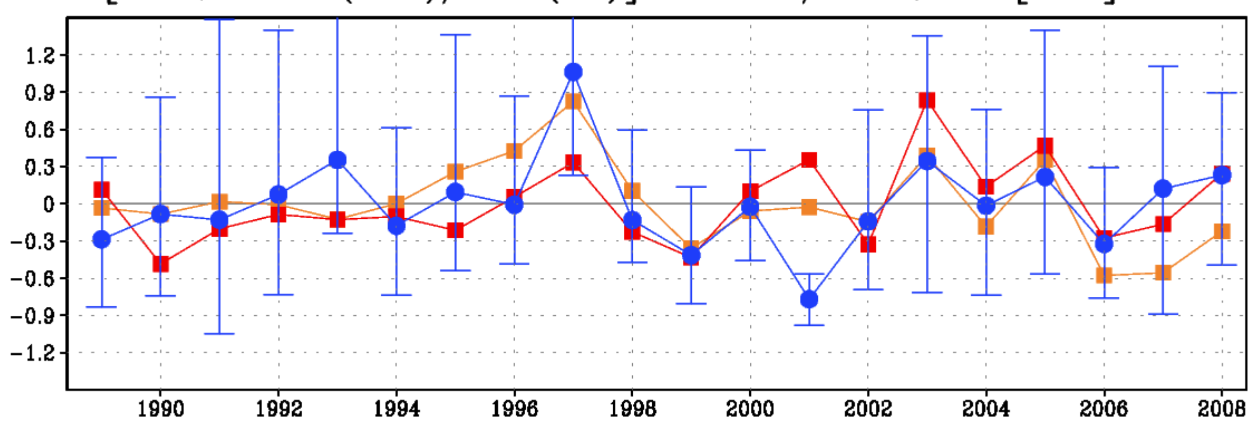




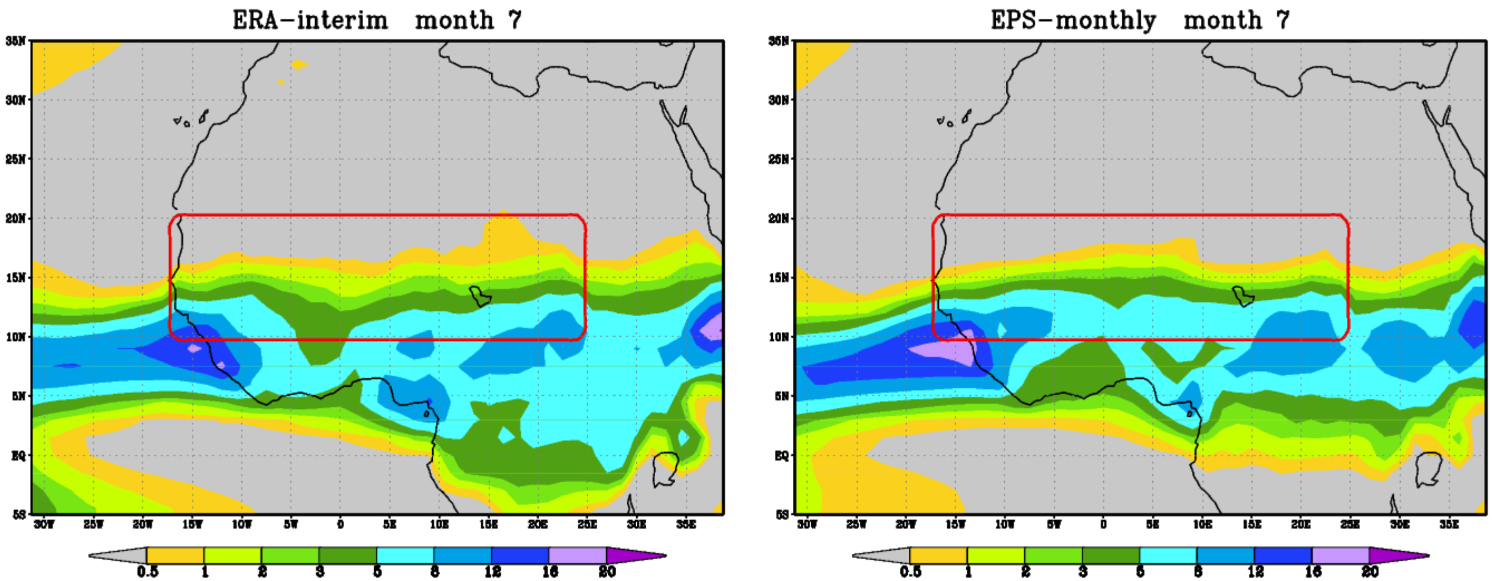
46-day EPS re-forecasts: Sahel, June

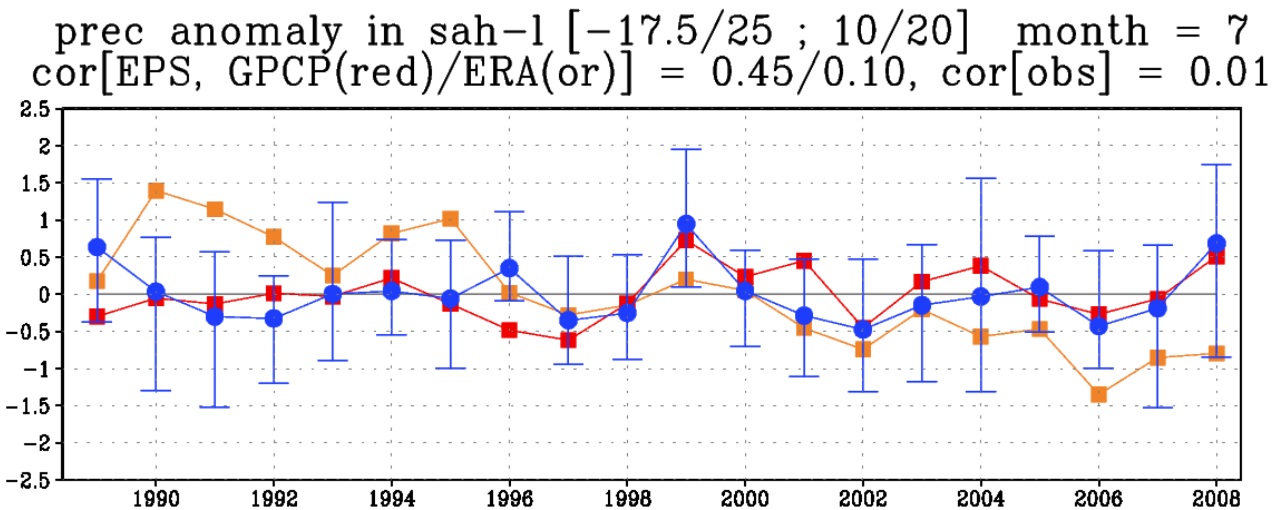


prec anomaly in sah−l [−17.5/25 ; 10/20] month = 6
cor[EPS, GPCP(red)/ERA(or)] = 0.36/0.57, cor[obs] = 0.53



• 46-day EPS re-forecasts: Sahel, July





Bibliography

On normal modes and baroclinic instability

Birkoff & Rota, 1969: *Ordinary differential equations*. J. Wiley & sons, 366 pg.

Charney, J. G., 1947: The dynamics of long waves in a baroclinic westerly current. *J. Meteorol.*, **4**, 135-162.

Eady. E. T., 1949: long waves and cyclone waves. *Tellus*, **1**, 33-52.

On SVs and predictability studies

Buizza, R., Gelaro, R., Molteni, F., & Palmer, T. N., 1997: The impact of increased resolution on predictability studies with singular vectors. *Q. J. R. Meteorol. Soc.*, **123**, 1007-1033.

Gelaro, R., Buizza, R., Palmer, T. N., & Klinker, E., 1998: Sensitivity analysis of forecast errors and the construction of optimal perturbations using singular vectors. *J. Atmos. Sci.*, **55**, 6, 1012-1037.

Harrison, M. S. J., Palmer, T. N., Richardson, D. S., & Buizza, R., 1999: Analysis and model dependencies in medium-range ensembles: two transplant case studies. *Q. J. R. Meteorol. Soc.*, **126**, 2487-2515.

On the validity of the linear approximation

Buizza, R., 1995: Optimal perturbation time evolution and sensitivity of ensemble prediction to perturbation amplitude. *Q. J. R. Meteorol. Soc.*, **121**, 1705-1738.

Gilmour, I., Smith, L. A., & Buizza, R., 2001: On the duration of the linear regime: is 24 hours a long time in weather forecasting? *J. Atmos. Sci.*, **58**, 3525-3539 (also EC TM 328).

Bibliography

On the ECMWF Ensemble Prediction System

- Buizza, R., & Hollingsworth, A., 2002: Storm prediction over Europe using the ECMWF Ensemble Prediction System. *Meteorol. Appl*., **9**, 1-17.
- Buizza, R., Bidlot, J.-R., Wedi, N., Fuentes, M., Hamrud, M., Holt, G., & Vitart, F., 2007: The new ECMWF VAREPS. *Q. J. Roy. Meteorol. Soc*., **133**, 681-695 (also EC TM 499).
- Buizza, R., 2008: Comparison of a 51-member low-resolution (TL399L62) ensemble with a 6-member high-resolution (TL799L91) lagged-forecast ensemble. *Mon. Wea. Rev.*, **136**, 3343-3362 (also EC TM 559).
- Leutbecher, M. & T.N. Palmer, 2008: Ensemble forecasting. *J. Comp. Phys.*, **227**, 3515-3539 (also EC TM 514).
- Molteni, F., Buizza, R., Palmer, T. N., & Petroliagis, T., 1996: The new ECMWF ensemble prediction system: methodology and validation. *Q. J. R. Meteorol. Soc.*, **122**, 73-119.
- Palmer, T N, Buizza, R., Leutbecher, M., Hagedorn, R., Jung, T., Rodwell, M, Virat, F., Berner, J., Hagel, E., Lawrence, A., Pappenberger, F., Park, Y.-Y., van Bremen, L., Gilmour, I., & Smith, L., 2007: The ECMWF Ensemble Prediction System: recent and on-going developments. A paper presented at the 36th Session of the ECMWF Scientific Advisory Committee (also EC TM 540).
- Vitart, F., Buizza, R., Alonso Balmaseda, M., Balsamo, G., Bidlot, J. R., Bonet, A., Fuentes, M., Hofstadler, A., Molteni, F., & Palmer, T. N., 2008: The new VAREPS-monthly forecasting system: a first step towards seamless prediction. *Q. J. Roy. Meteorol. Soc.*, **134**, 1789-1799.

Bibliography

On SVs and targeting adaptive observations

- Buizza, R., & Montani, A., 1999: Targeting observations using singular vectors. *J. Atmos. Sci.*, **56**, 2965-2985 (also EC TM 286).
- Palmer, T. N., Gelaro, R., Barkmeijer, J., & Buizza, R., 1998: Singular vectors, metrics, and adaptive observations. *J. Atmos. Sci.*, **55**, 6, 633-653.
- Majumdar, S J, Aberson, S D, Bishop, C H, Buizza, R, Peng, M, & Reynolds, C, 2006: A comparison of adaptive observing guidance for Atlantic tropical cyclones. *Mon. Wea. Rev*., **134**, 2354-2372 (also EC TM 482).
- Reynolds, C, Peng, M, Majumdar, S J, Aberson, S D, Bishop, C H, & Buizza, R, 2007: Interpretation of adaptive observing guidance for Atlantic tropical cyclones. *Mon. Wea. Rev.,* **135**, 4006-4029.
- Kelly, G., Thepaut, J.-N., Buizza, R., & Cardinali, C., 2007: The value of observations - Part I: data denial experiments for the Atlantic and the Pacific. *Q. J. R. Meteorol. Soc.*, **133**, 1803-1815 (also EC TM 511).
- Buizza, R., Cardinali, C., Kelly, G., & Thepaut, J.-N., 2007: The value of targeted observations - Part II: the value of observations taken in singular vectors-based target areas. *Q. J. R. Meteorol. Soc*., **133**, 1817-1832 (also EC TM 512).
- Cardinali, C., Buizza, R., Kelly, G., Shapiro, M., & Thepaut, J.-N., 2007: The value of observations - Part III: influence of weather regimes on targeting. *Q. J. R. Meteorol. Soc.*, **133**, 1833-1842 (also EC TM 513).

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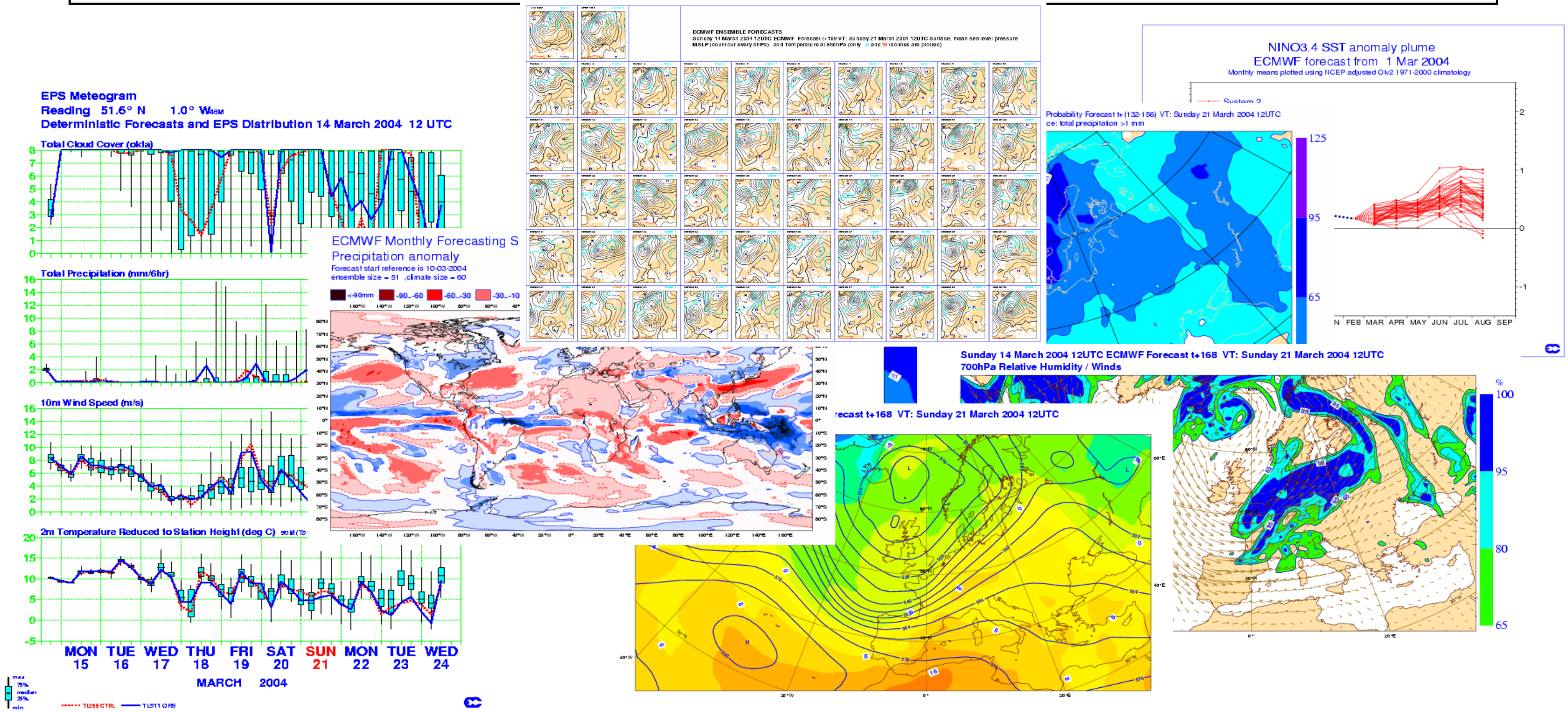

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