Development of the ECMWF forecasting system

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WEATHER PREDICTION BY NUMERICAL PROCESS

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Lewis F. Richardson
Cambridge University Press, 1922

PREFACE

“The scheme is complicated because the atmosphere is complicated.”

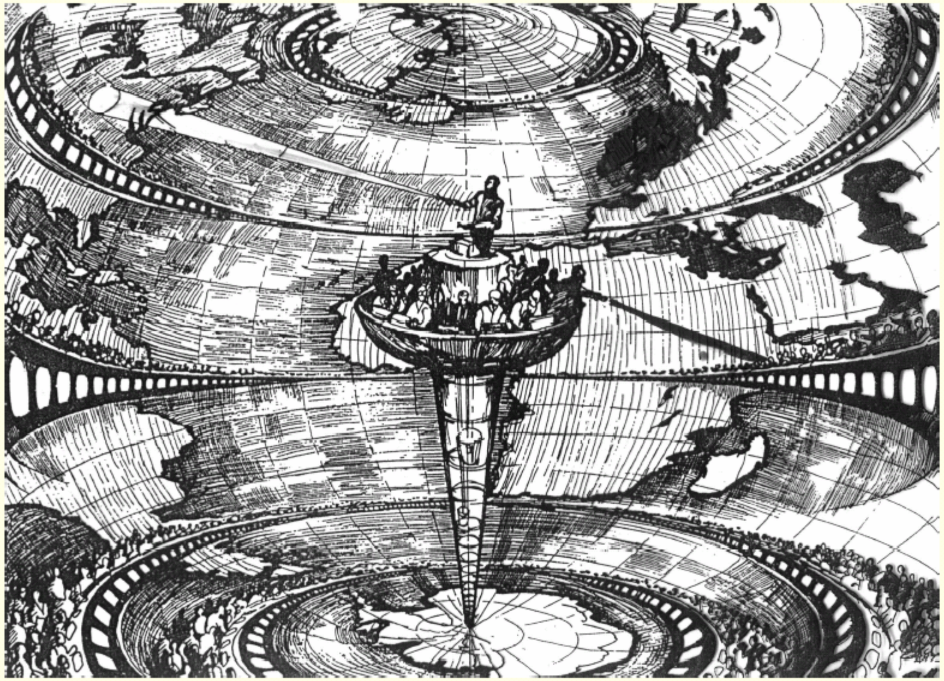
“Perhaps … in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained.”

“This investigation … first took shape in 1911 as the fantasy which is now relegated to Chapter 11.”

WEATHER PREDICTION BY NUMERICAL PROCESS

CHAPTER XI SOME REMAINING PROBLEMS

THE SPEED AND ORGANIZATION OF COMPUTING



Richardson's Forecast Factory (A. Lannerback).
Dagens Nyheter, Stockholm. Reproduced from L. Bengtsson, *ECMWF*, 1984

"… may one play with a fantasy?"

"Imagine a large hall, like a theatre …"

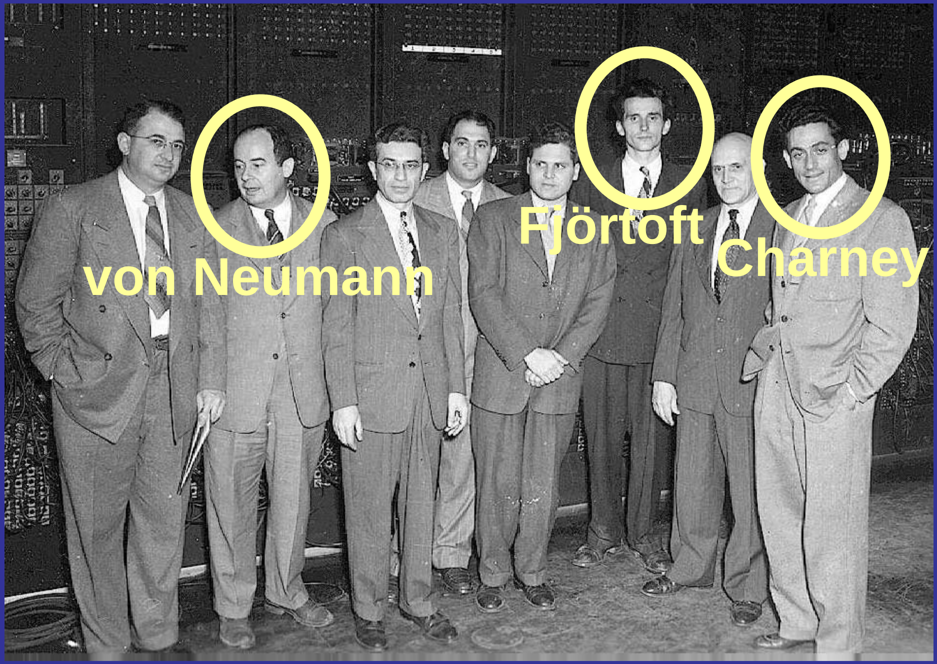
"A myriad [human] computers are at work upon the weather of the part of the map where each sits"

"Numerous little night signs display the instantaneous values so that neighbouring computers can read them"

"In a neighbouring building there is a research department, where they invent improvements"

1950 - The use of:

- the ENIAC electronic computer
- rational approximation of the governing equations



Charney, Fjörtoft and

von Neumann (1950):

Numerical integration of the barotropic vorticity equation

Tellus, **2,** 237-254

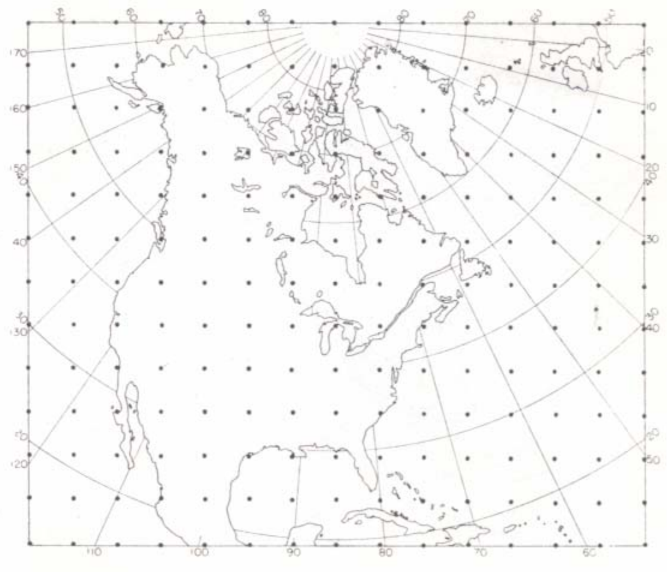


Fig. 1. A typical finite-difference grid used in the computations. A strip two grid intervals in width at the top and side borders and one grid interval in width at the lower border is not shown.

Mflops, GFlops and Tflops at ECMWF

1979 Cray-1:

40-50 Mflops sustained on a single CPU

for a 10-day forecast with 200km grid resolution

1990 Cray YMP:

1 Gflops sustained on 8 CPUs

for a 10-day forecast with 125km grid resolution

2006 IBM P5-575:

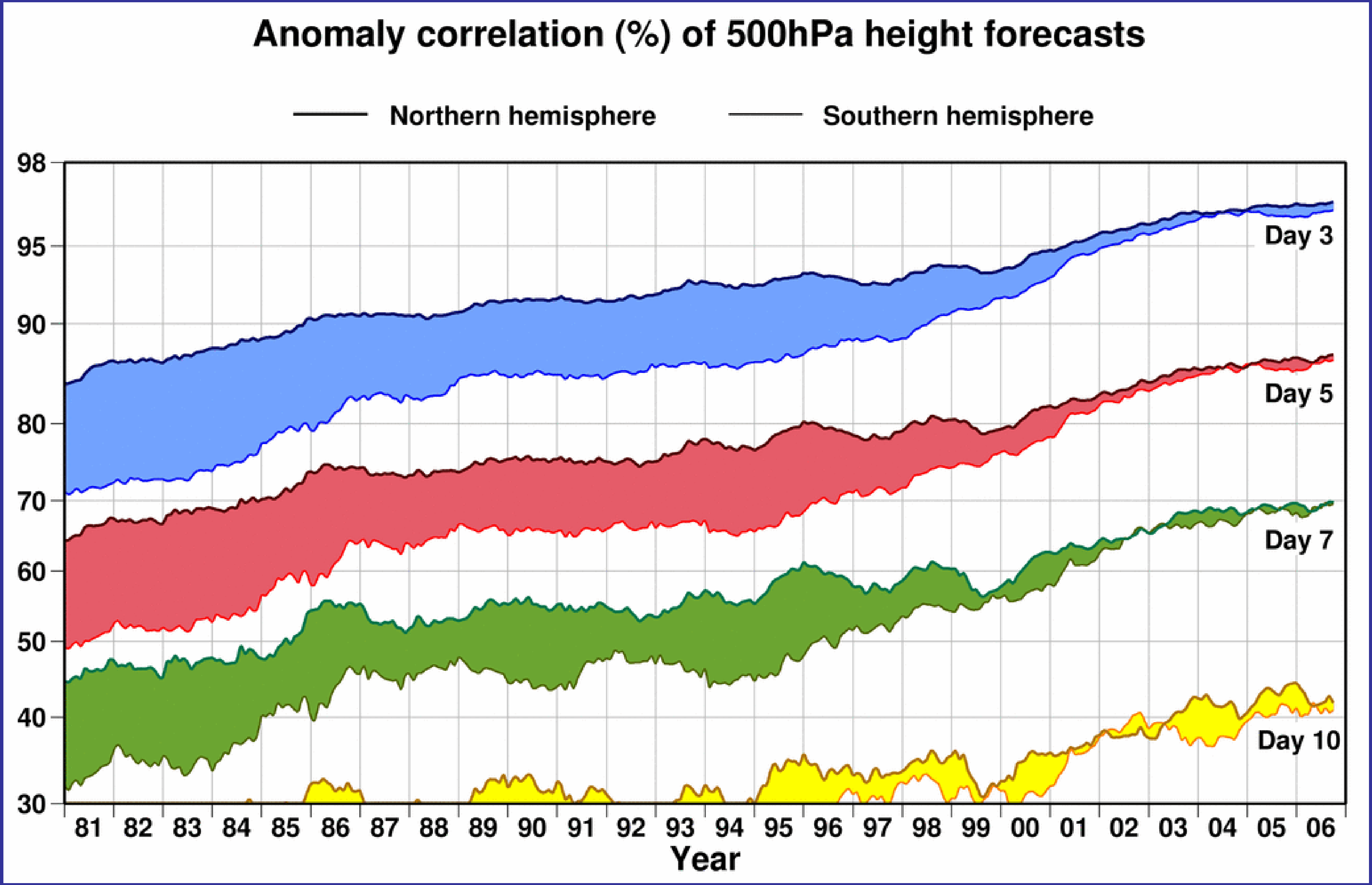
4 Tflops sustained overall on tasks run on 2 x 2240 CPUs

including a 10-day forecast with 25km grid resolution

Increases in computational power have enabled:

- **Increased vertical as well as horizontal resolution**
- **More sophisticated analysis of observations**
- **More realistic representations of atmospheric physics and land surfaces; coupling with ocean wave and circulation models**
- **More timely delivery of forecasts**
- **More comprehensive testing of forecasting-system changes**
- **Probabilistic forecasts based on ensemble methods**
- **An extended range of activities :**
  - monthly and seasonal prediction
  - reanalysis of multi-decadal observations for climate studies

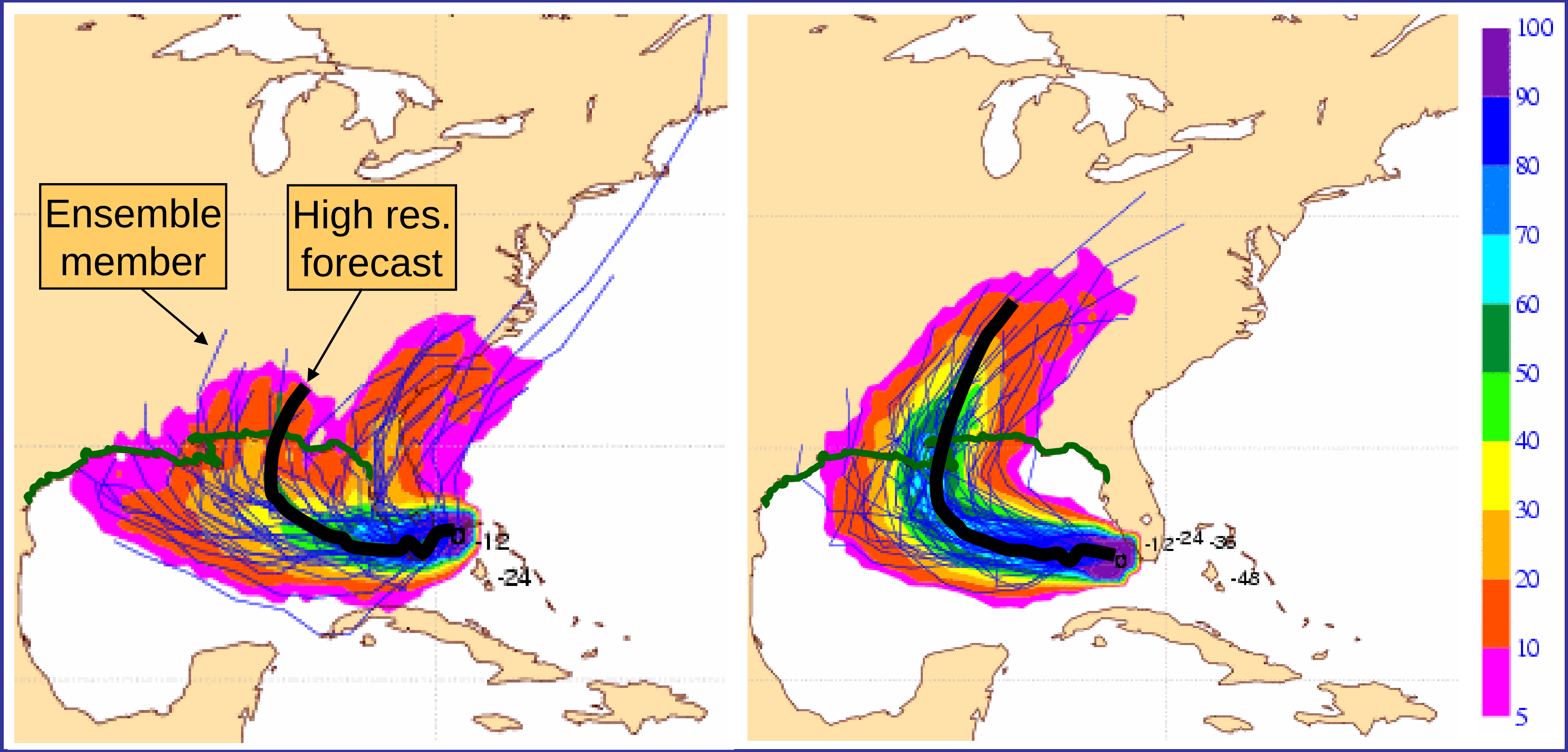
Improvement of operational ECMWF forecasts



Ensemble forecasts of hurricane Katrina

From 12UTC Thursday 25 Aug 2005

From 12UTC Friday 26 Aug 2005



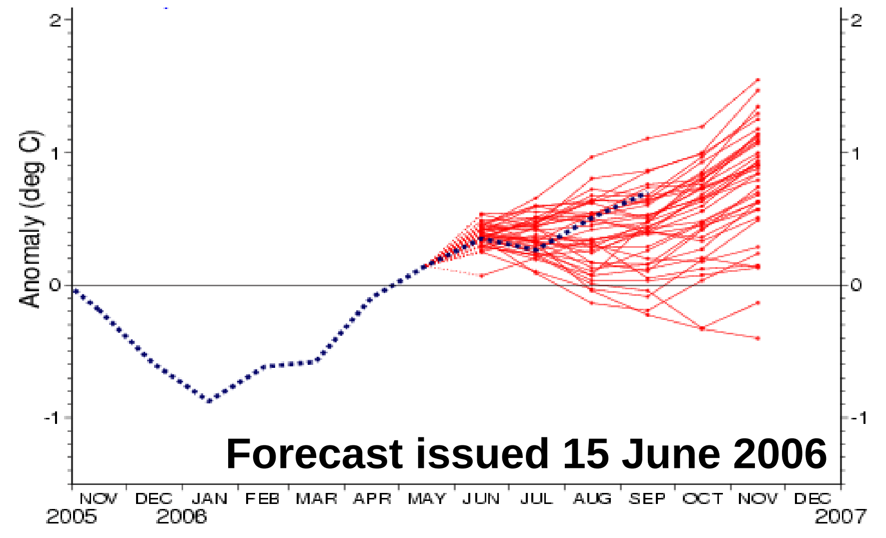
Ensemble member

High res. forecast

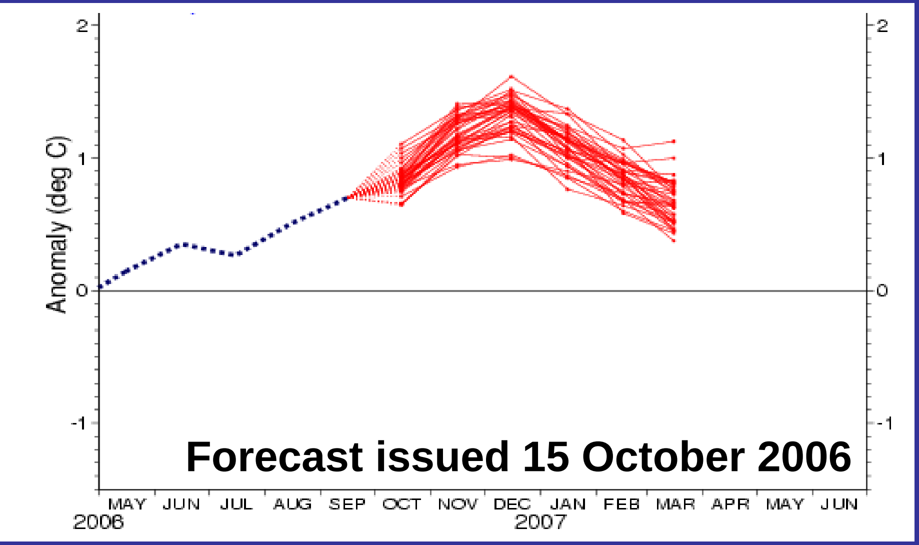
Shading: Probability that Katrina would pass within 120km

Seasonal prediction

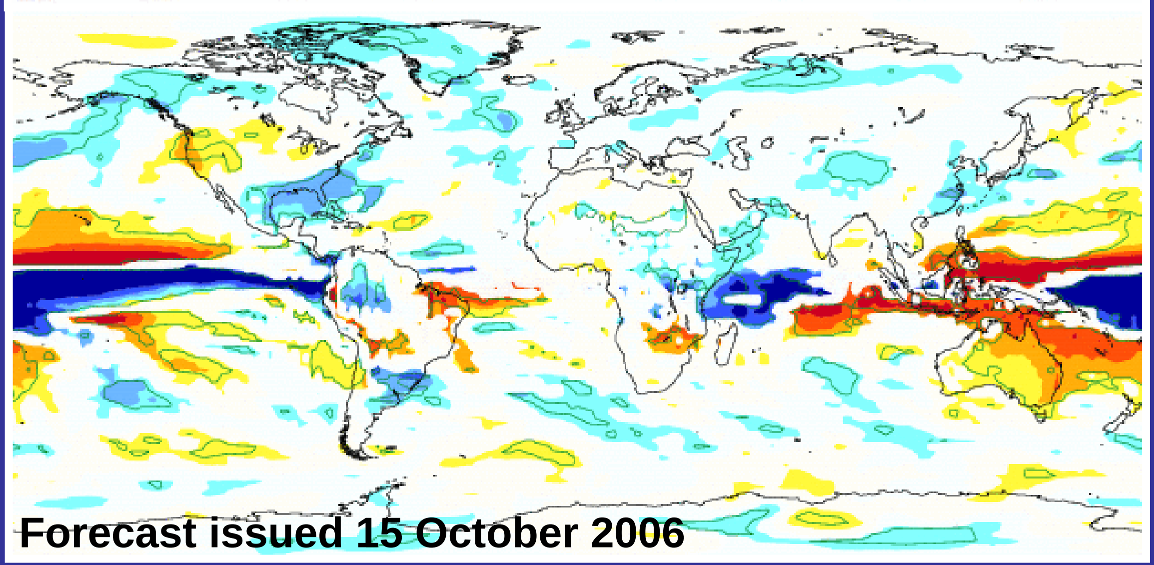
Temperature anomaly over tropical eastern Pacific



Forecast issued 15 June 2006



Forecast issued 15 October 2006



Forecast issued 15 October 2006

Predicted precipitation anomaly for Dec 2006 to Feb 2007

New directions: Analysis and prediction of aerosols, chemically reactive gases and greenhouse gases

Ships on the water between Singapore and Indonesia blanketed in haze from forest fires.
The Guardian, 6 October 2006

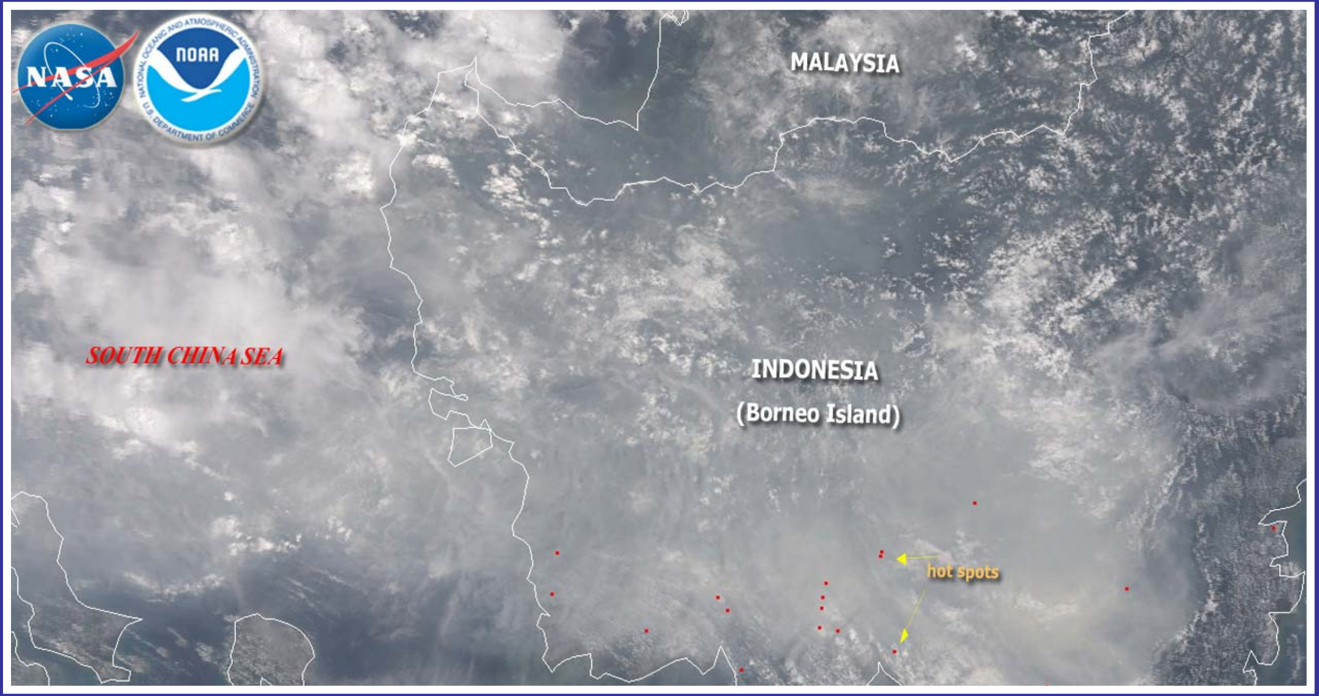


Image from MODIS instrument on NASA’s AQUA satellite
19 October 2006

Breakdown of core operational computer usage

	1979	1994	2006
24h data assimilation	20%	20%	22%
10-day deterministic forecast	80%	40%	17%
Ensemble forecasts		40%	61%

Notes:

Deterministic and ensemble forecasts are now run twice per day, with the ensemble forecasts extended to day 15, at lower resolution beyond day 10

Cost of data assimilation relative to single forecast has increased more than ten-fold

Data assimilation takes major share of research usage, and accounts overall for ~40% of core usage

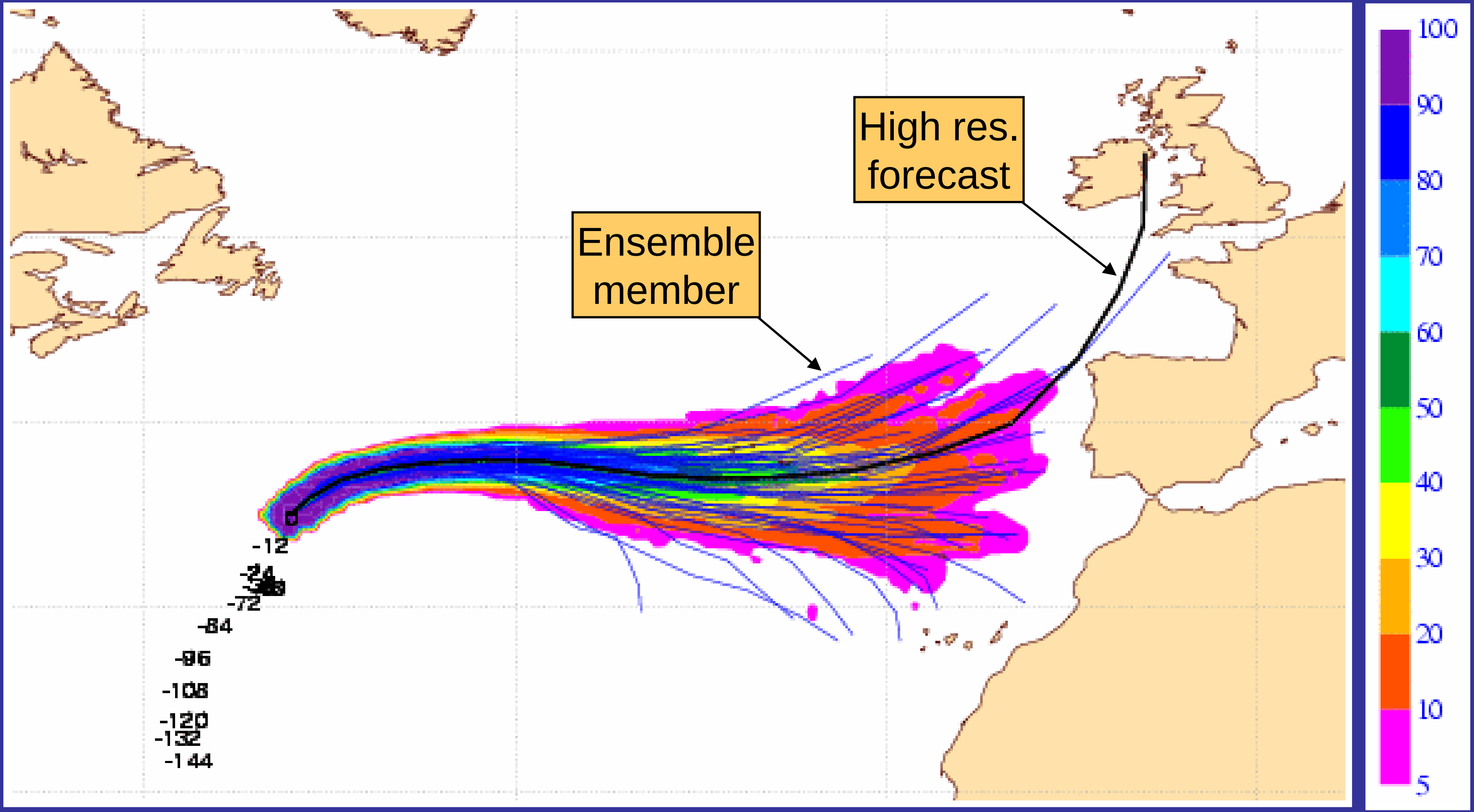
Other activities take 15-20% of net resources

Future developments

- **Better models**
  - with higher resolution
  - with improved representation of physical processes (radiation, …)
  - with more comprehensive dynamical equations
  - incorporating chemistry
  - incorporating sea-ice component
- **Better initial conditions for deterministic and ensemble forecasts**
  - increasing the utilization of satellite data
  - with an ensemble component to data assimilation
  - with longer-window (>12h) data assimilation
  - …
- **A more unified approach to prediction**
  - bringing more ocean into the earlier part of the forecast range
  - bringing more aspects of air quality into the core forecasting activity

Predictions for track of storm “Gordon”

From 00UTC Monday 18 September 2006



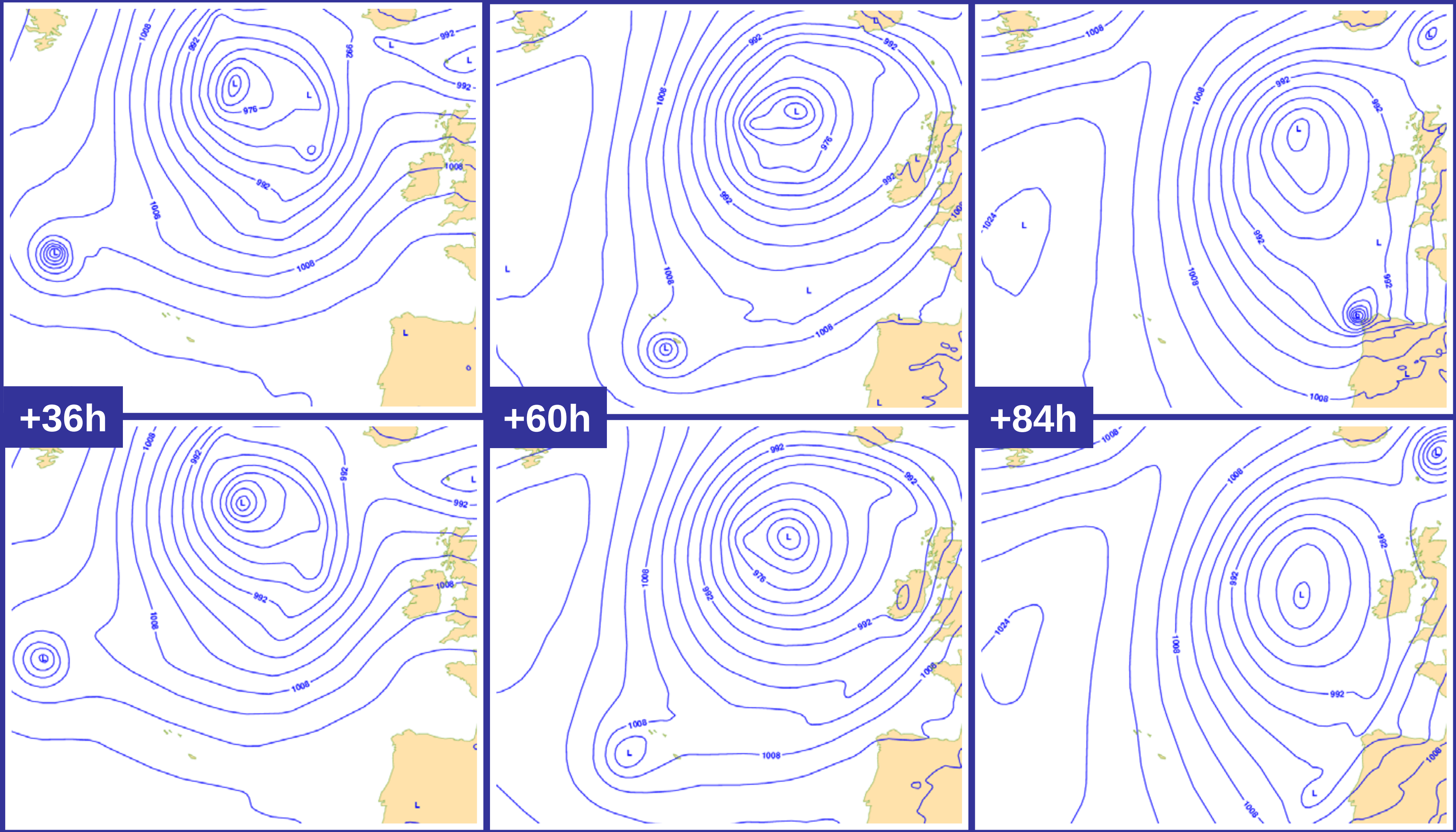
Ensemble member

High res. forecast

Shading: Probability that Gordon would pass within 120km

Forecasts for “Gordon” from 00UTC 18 September

T799 (~25km grid) deterministic forecast

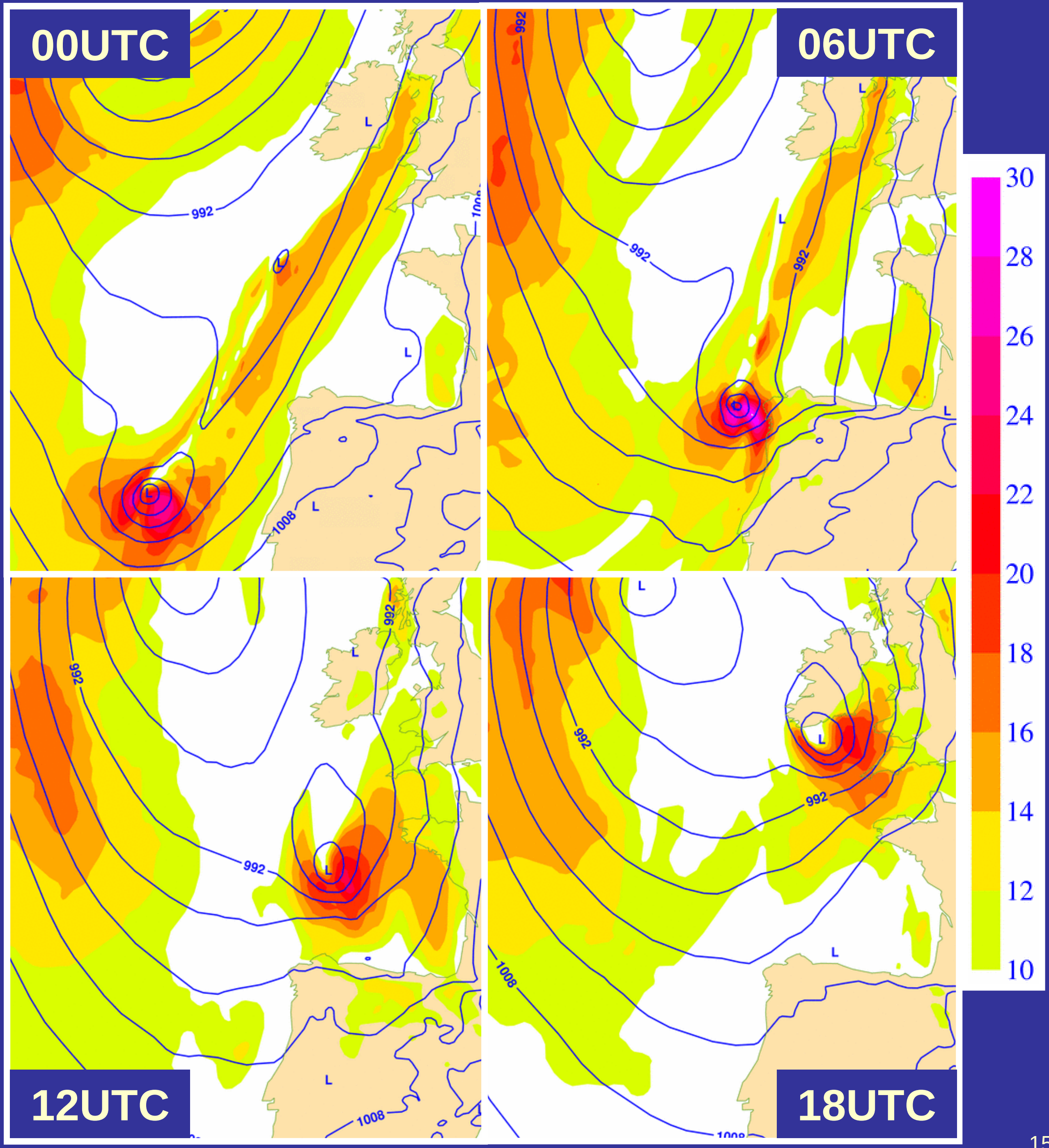


T399 (~50km grid) control forecast from Ensemble Prediction System

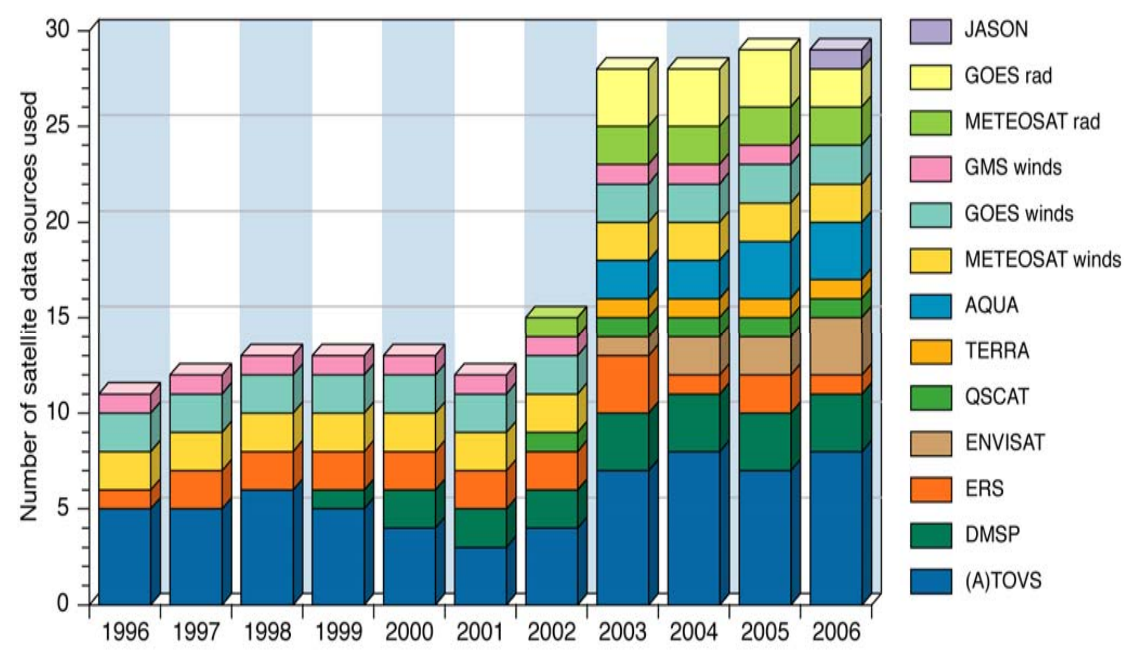
“Gordon”

Analysed mean sea-level pressure (hPa) and windspeed (ms^{-1}) at 10m

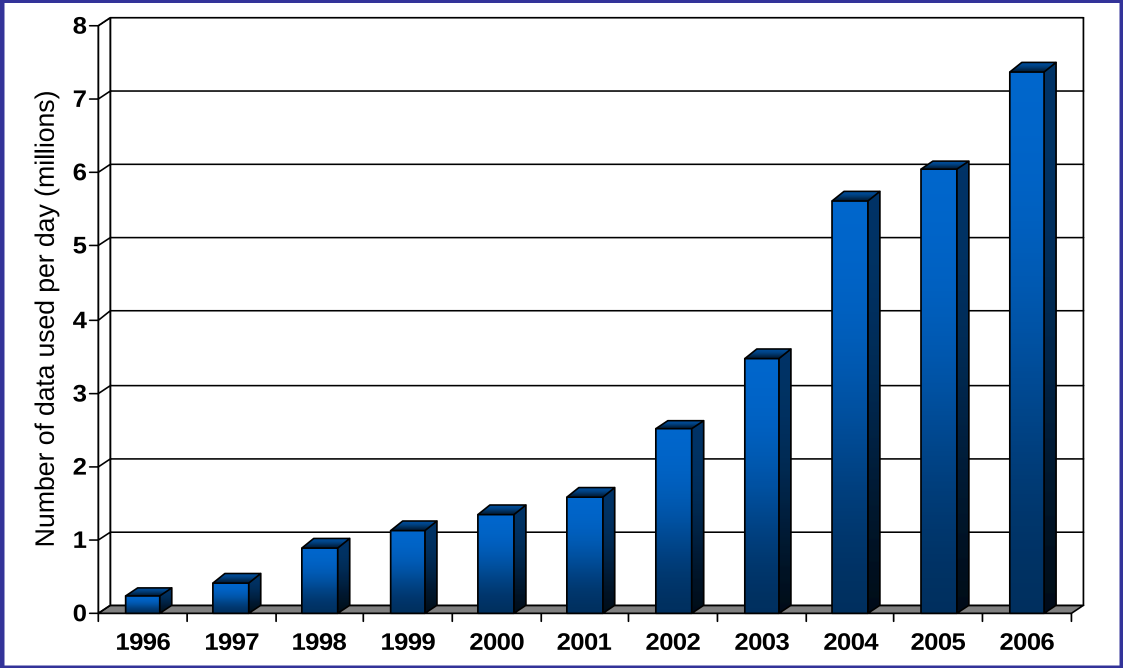
Thursday 21 September 2006



Data from almost 30 satellite-borne instruments used daily



Large increase in number of data used daily



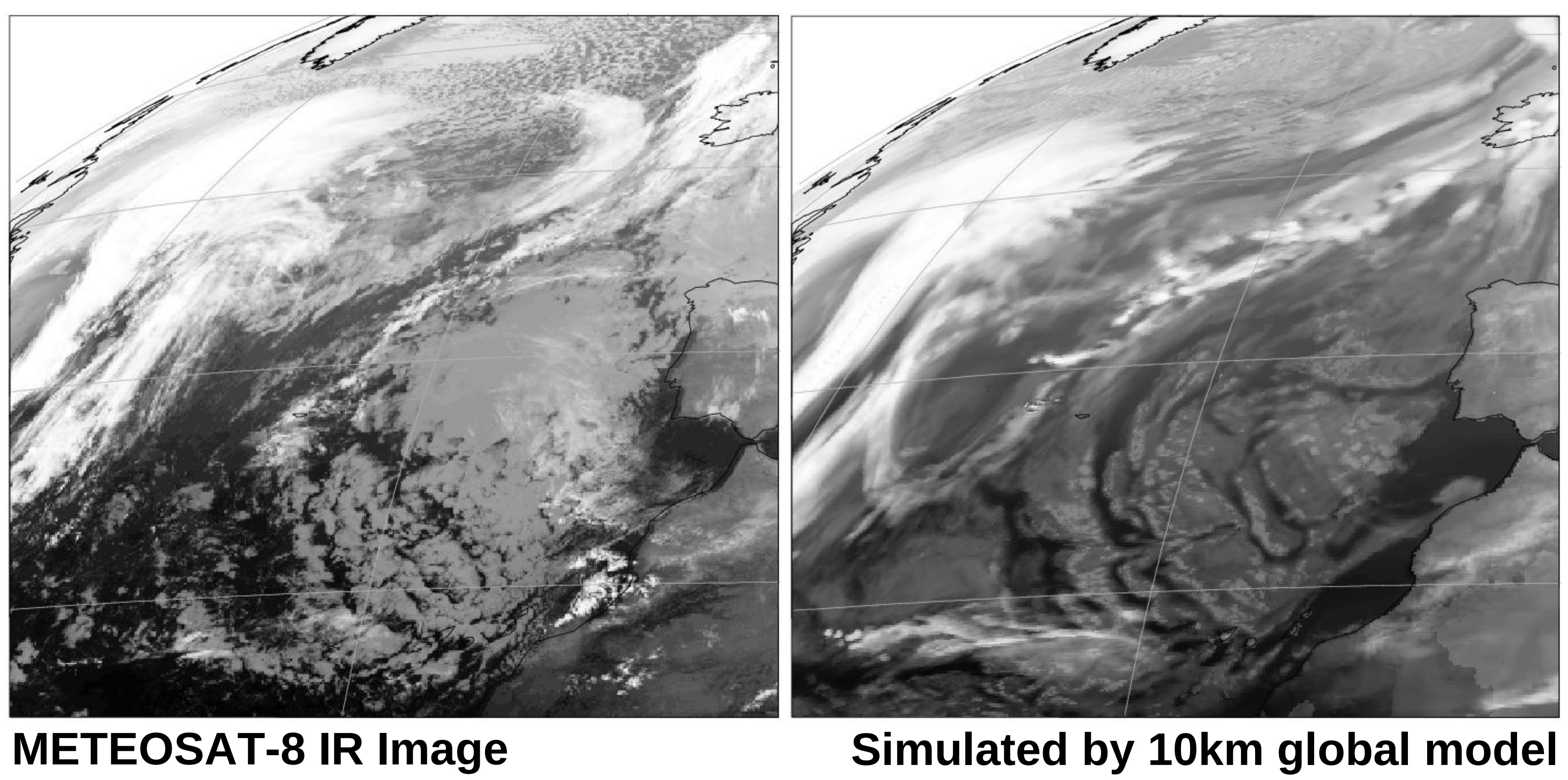
Observation data count for one 12h 4D-Var cycle 0900-2100 UTC 26 March 2006

	Screened	Assimilated
Surface (land, ship, buoy)	409,000	66,000
Aircraft	362,000	179,000
Balloons	243,000	115,000
Satellite sea-surface winds	269,000	122,000
Satellite upper winds	2,811,000	127,000
Satellite radiances	74,825,000	2,646,000
TOTAL	78,918,000	3,253,000

35% of screened in-situ data are assimilated

<4% of screened satellite data are assimilated

Simulation of radiances measured by satellite



METEOSAT-8 IR Image

Simulated by 10km global model

Utilization of satellite data

- ~25% of cost of data assimilation is accounted for by satellite data
- Only a small fraction of the available data is currently assimilated
- Use of radiances affected by cloud and rain is a key challenge
- Radiative transfer calculations needed to simulate these radiances are particularly expensive
- The new generation of instruments will provide a considerable amount of additional data

Launch of METOP-A
19 October 2006

Carrying eight instruments from which data should be used

What are the technical challenges?

- **Effective utilization of increasing numbers of processor cores**
  - **larger problem sizes help, but number of model points per core decreases as resolution increases for given execution time**
    - a problem also for ensemble forecasts due to memory constraints
    - increases communication and load-imbalance overheads
  - **load balancing also becomes more challenging as models include a wider range of processes**
  - **assimilation of observational data poses substantial additional challenges:**
    - involves repeated mapping between observation and model space
    - iteratively adjusts model at a lower resolution than primary forecast
    - has higher IO demands

What are the technical challenges?

- **Ensuring continued effectiveness of algorithms**
  - that today balance accuracy and efficiency (at expense of lower ratio of sustained to peak flops)
  - with scope for refinements in design and implementation, and perhaps for more radical change
  - but that nevertheless are subject to limits imposed by physical laws and the nature of remotely-sensed observations

- **Ensuring continued effectiveness of long-lived codes in which there has been major investment**
  - The joint ECMWF / Météo-France code originated in 1987
  - has run operationally on
    - CRAY C90 vector shared memory
    - Fujitsu VPP vector distributed memory
    - IBM scalar SMP clusters
  - and will run operationally on
    - NEC SX vector SMP cluster
    - ….?