Ensemble Forecasting

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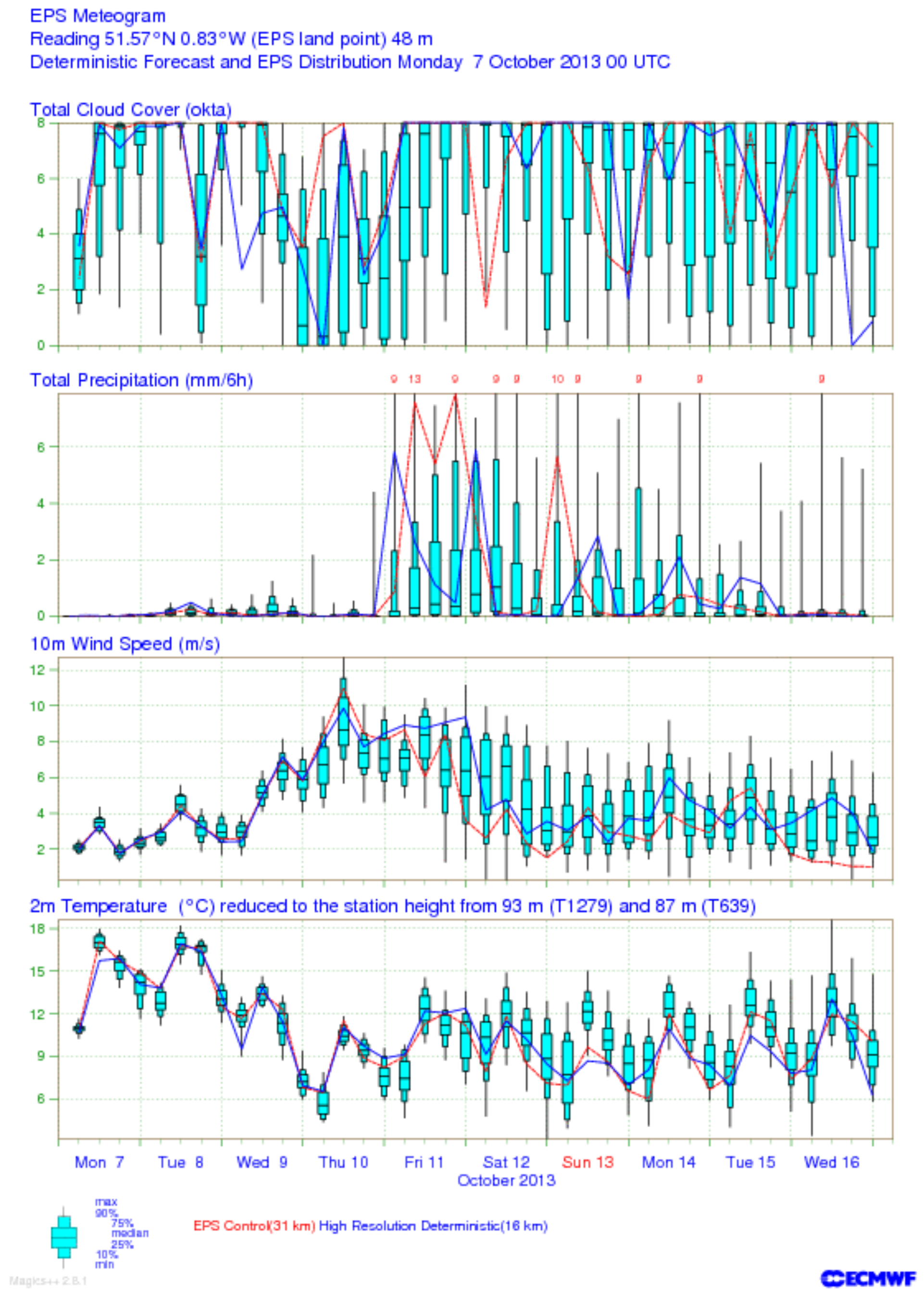
Outline

- Introduction
  - Why can’t we make perfect forecasts?
- The ECMWF ensemble
  - How does the ensemble represent uncertainties?
  - Configuration of the ensemble
- Ensemble products and their use
  - Very short overview – much more in rest of course


EPS Meteogram
Reading 51.57°N 0.83°W (EPS land point) 48 m
Deterministic Forecast and EPS Distribution Monday 7 October 2013 00 UTC
Total Cloud Cover (okta)
Total Precipitation (mm/6h)
10m Wind Speed (m/s)
2m Temperature (°C) reduced to the station height from 93 m (T1279) and 87 m (T639)
Mon 7
Tue 8
Wed 9
Thu 10
Fri 11
Sat 12
Sun 13
Mon 14
Tue 15
Wed 16
October 2013
max
90%
75%
median
25%
10%
min
EPS Control(31 km) High Resolution Deterministic(16 km)
ECMWF

Questions ...

- What are
  - the high-resolution forecast?
  - the control forecast?
  - the ensemble members?
- Why are they different (sometimes)?
- Which is best?
- How do we choose the "right" forecast?

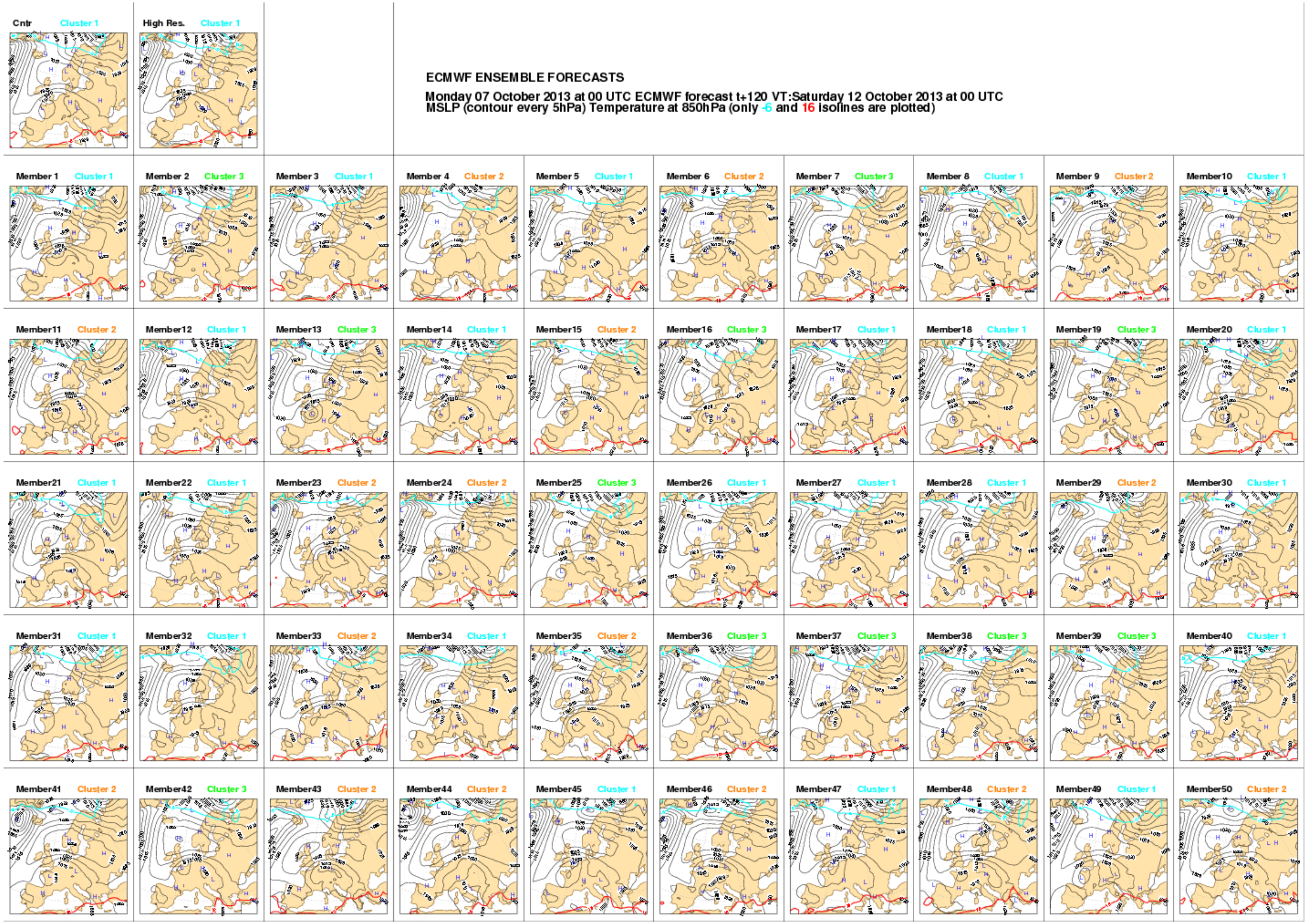
Why are forecasts sometimes wrong?

- **Initial condition uncertainties**
  - Lack of observations
  - Observation error
  - Errors in the data assimilation
- **Model uncertainties**
  - Limited resolution
  - Parameterisation of physical processes
- **The atmosphere is chaotic**
  - small uncertainties grow to large errors (unstable flow)
  - small scale errors will affect the large scale (non-linear dynamics)
  - error-growth is flow dependant
- **Even very good analyses and forecast models are prone to errors**

What is an ensemble?

- A set of forecasts run from slightly different initial conditions to account for initial uncertainties
  - At ECMWF perturbations are generated using singular vectors and an ensemble of data assimilations
- The forecast model also contains approximations that can affect the forecast evolution
  - Model uncertainties are represented using "stochastic physics"
- The ensemble of forecasts provides a range of future scenarios consistent with our knowledge of the initial state and model capability
  - Provides explicit indication of uncertainty in today's forecast

Ensemble: set of 50 forecasts



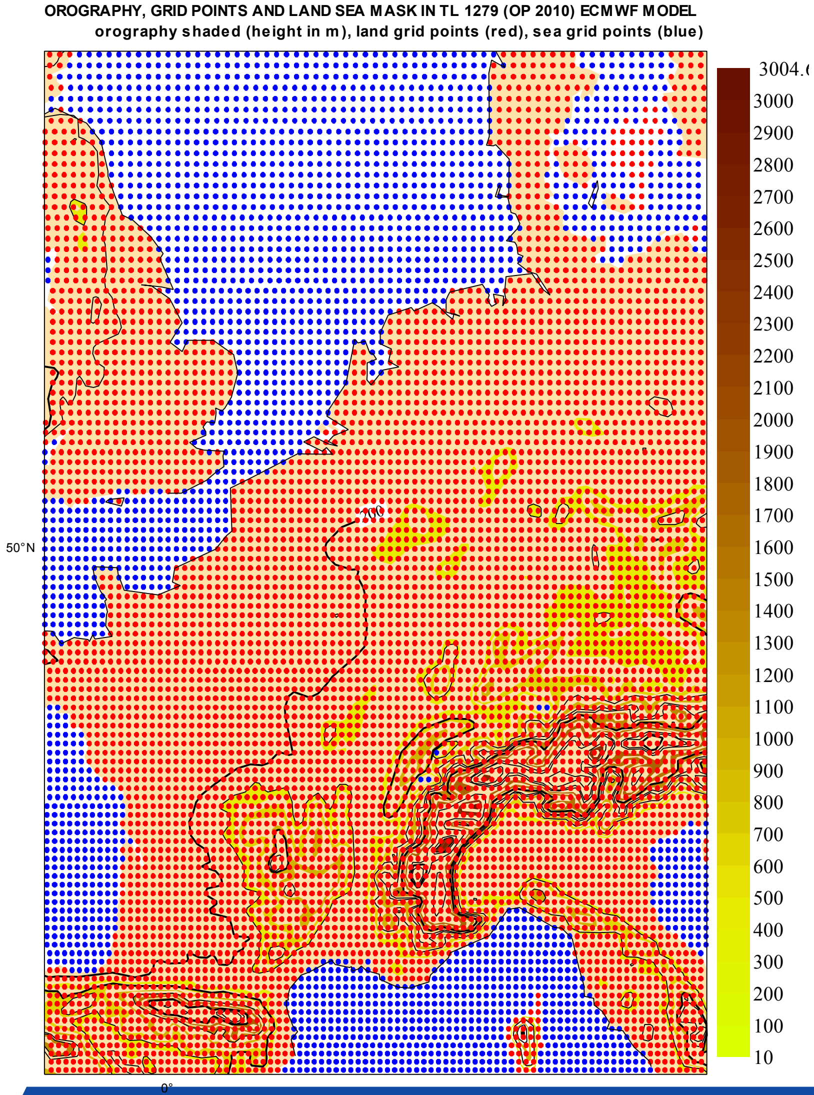
The ECMWF forecast system

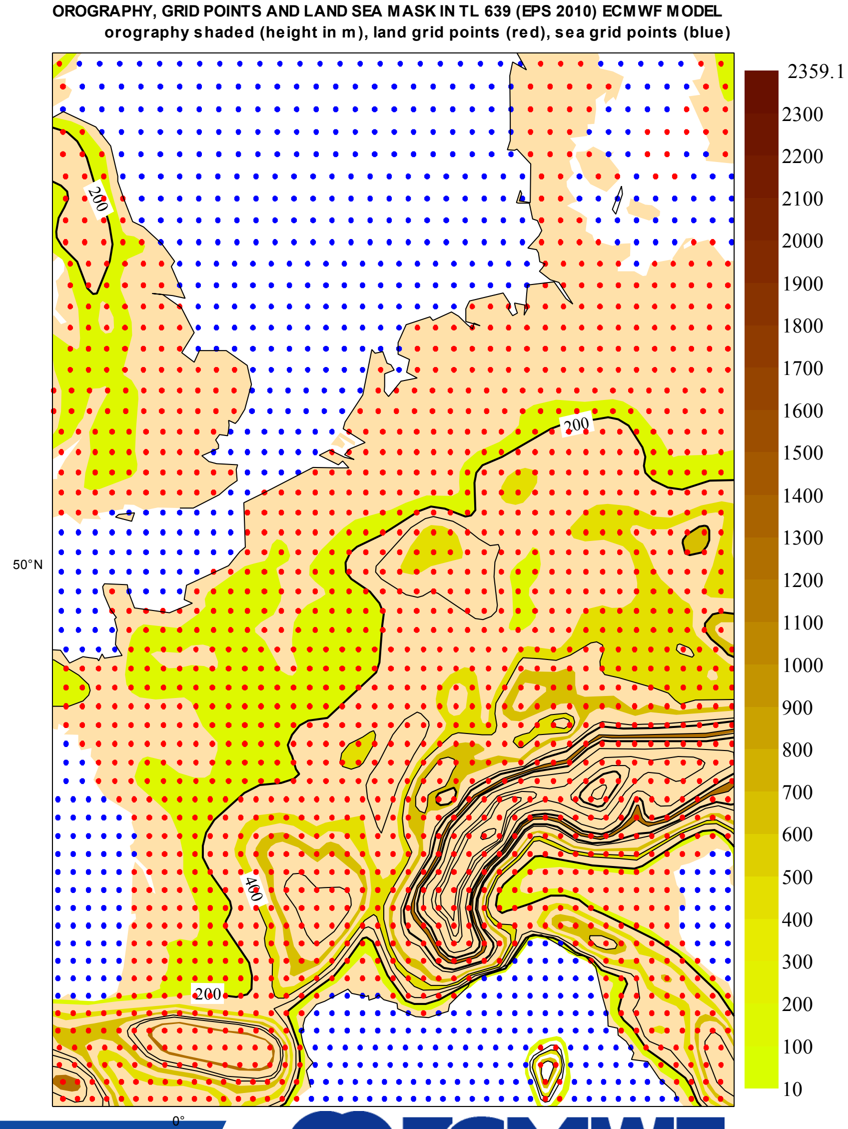
ECMWF medium-range forecasts

- High-resolution forecast (16 km grid, 91 levels) runs twice every day to 10 days
- Ensemble: same model but run at lower resolution (32 km, 62 levels; 64 km after day 10)
  - ensemble control (run from high-resolution analysis, no perturbation)
  - 50 perturbed members (account for initial and model uncertainties)

Model grids:

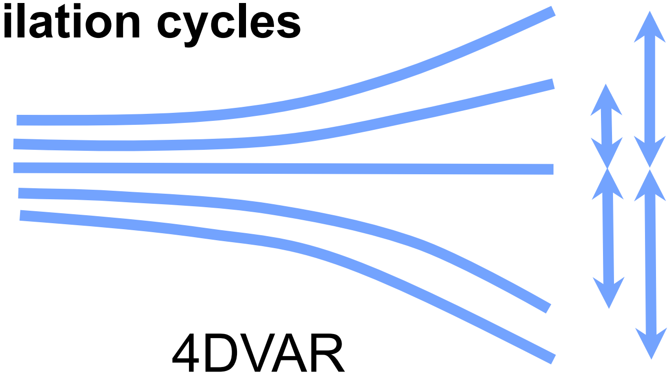
HRES (16km, T1279) ENS (32 km, T639)





Ensemble: initial uncertainties

- Combination of 2 types of perturbations
- Ensemble of data assimilations (EDA)
  - Randomly perturbed observations and SST fields
  - Run 10 independent data assimilation cycles



- Singular vectors: perturbations that grow quickly over the first 48 hours of the forecast

- Best approach given limited available computer resources

Ensemble of data assimilations (EDA)

- EDA (initial ENS perturbations since June 2010)
  - Control + 10 ensemble members using 4D-Var assimilations
  - T399 outer loop
  - T95/T159 inner loop (reduced number of iterations)
  - Model error: Stochastically Perturbed Parametrization Tendencies
  - Randomly perturbed observations and SST fields

- EDA perturbations are not sufficient by themselves
  - Additional initial perturbations based on “singular vectors”

Initial uncertainties – singular vectors

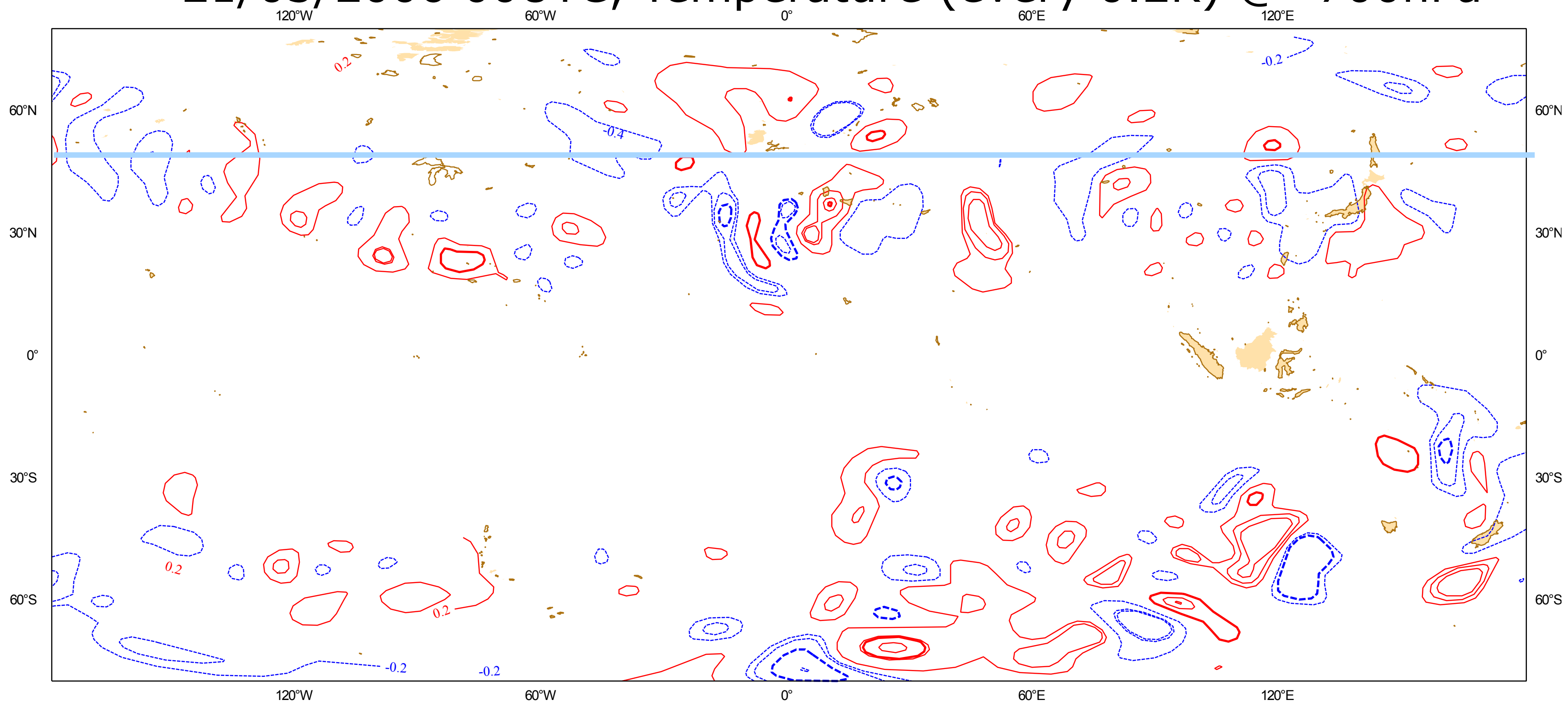
- The number of ensemble members is limited by available computer resources. How can we produce suitable perturbations?
- Look for perturbations that will grow fastest
- Singular vectors: perturbations that produce the greatest (linear) difference (total energy) over a fixed time interval (48 hours)
  - Uses the same tangent-linear and adjoint models as used for the 4D-Var analysis
- 50 perturbations generated by random (Gaussian) sampling from 50 singular vectors. Amplitude tuned to match error

Initial uncertainties – singular vectors

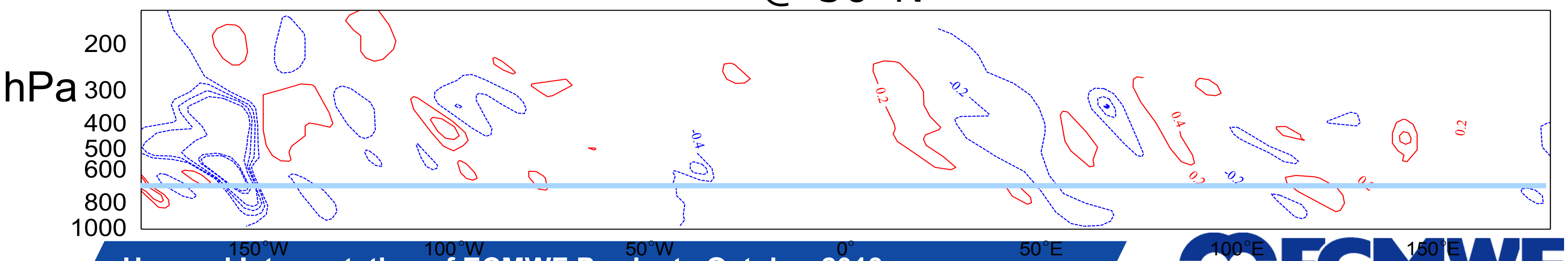
- Resolution: T42L62; optimisation interval: 48 h
- **Extra-tropics**
  - 50 SVs for N.-Hem. (30–90N) + 50 for S.-Hem.(30–90S).
  - Simple tangent-linear model (vert. diffusion and surf. friction only)
  - perturbations generated by random (Gaussian) sampling from 50 singular vectors. Amplitude tuned to match error
  - Perturbations from ensemble of data assimilations also used
- **Tropical cyclones:**
  - Up to 6 areas centred on existing tropical cyclones
  - 5 singular vectors per area, Gaussian (random) sampling
  - “moist SVs” – TL includes diabatic processes (large-scale condensation, convection, radiation, gravity-wave drag, vert. diff. and surface friction)

Example of initial perturbations

21/03/2006 00UTC, Temperature (every 0.2K) @~700hPa



@ 50°N



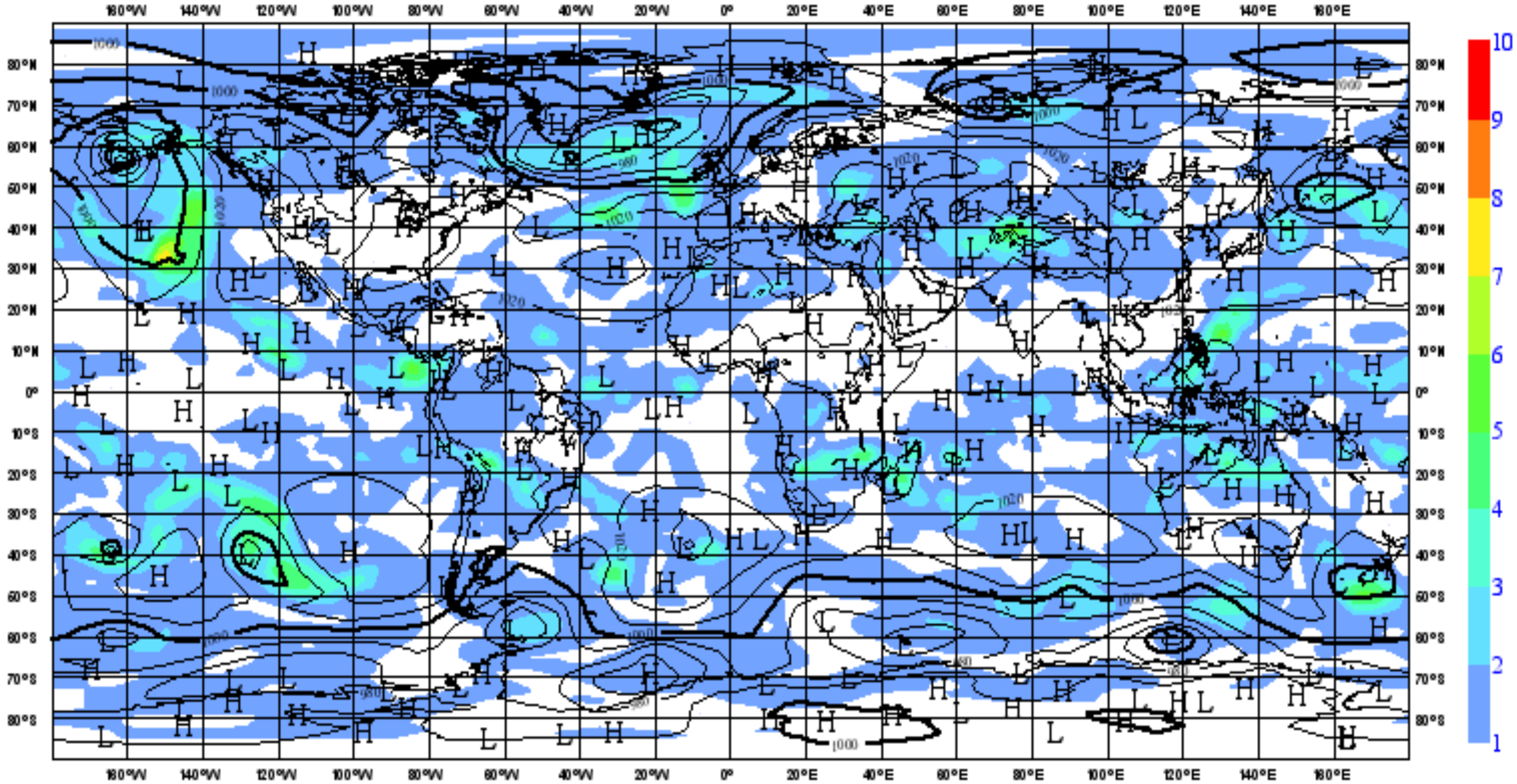
ECMWF

Ensemble initial perturbations

- **SV- and EDA-based perturbations have different characteristics:**
  - **EDA-based perturbations are less localized than SV-based perturbations. They have a larger amplitude over the tropics. EDA-perturbations are more barotropic than SV-based perturbations, and grow less rapidly.**
  - **At initial time, SV-based perturbations have a larger amplitude in potential than kinetic energy, while EDA-based perturbations have a similar amplitude in potential and kinetic energy**
- **Since June 2010 SV- and EDA-based perturbations are used together to construct the initial perturbations for the ENS**
- **The perturbations are constructed so that all perturbed members are equally likely**
- **All perturbations are flow-dependent: they are different from day to day**

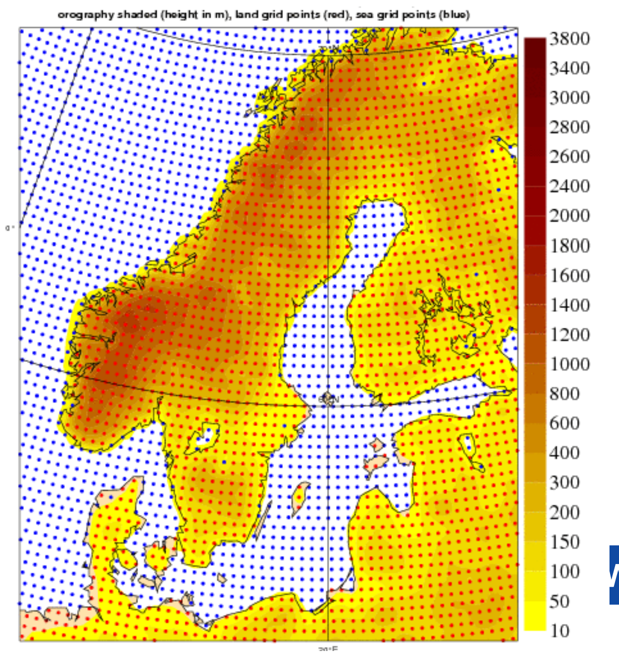
Ensembles of Data Assimilation (EDA)

The ensemble spread is flow-dependent but noisy. A filter is applied to remove it. This plot shows the EDA std in terms of vorticity at 500 hPa, +9h after filtering.

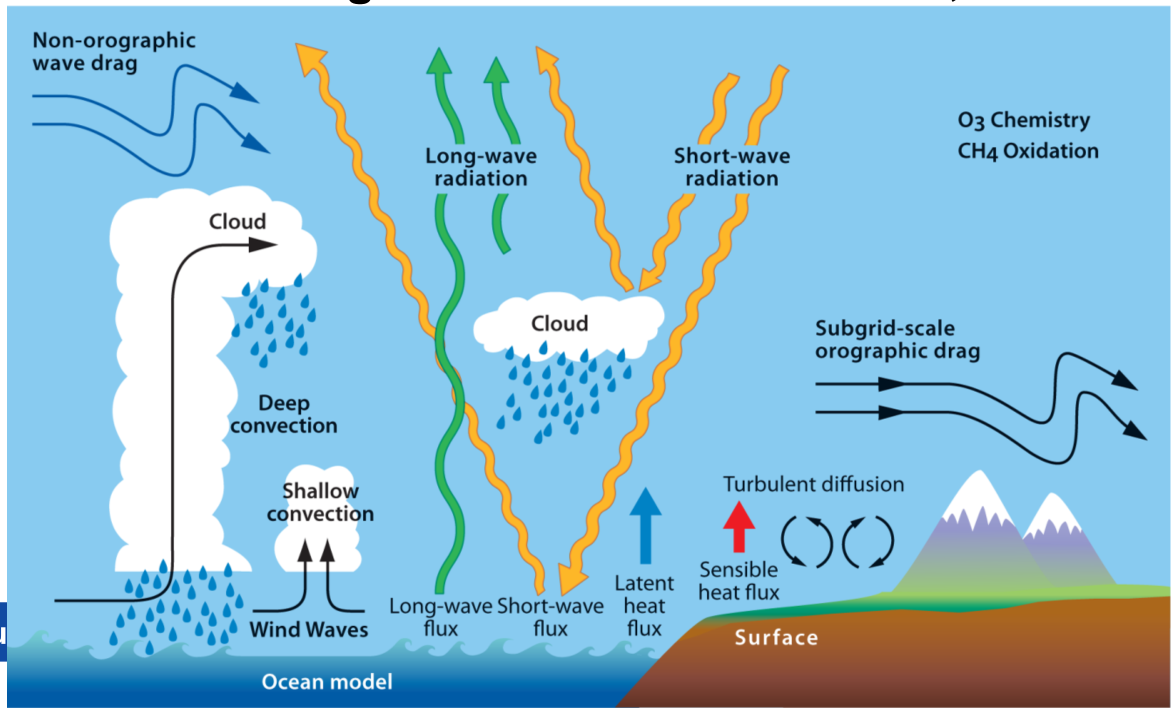


Model uncertainties – stochastic physics

- Parametrization – represent effects of unresolved (or partly resolved) processes on the resolved model state
- Statistical ensemble of sub-grid scale processes within a grid box; in equilibrium with grid-box mean flow
- Stochastic physics represents statistical uncertainty
  - allows for energy transfer from sub-grid scale to resolved flow, non-local effects

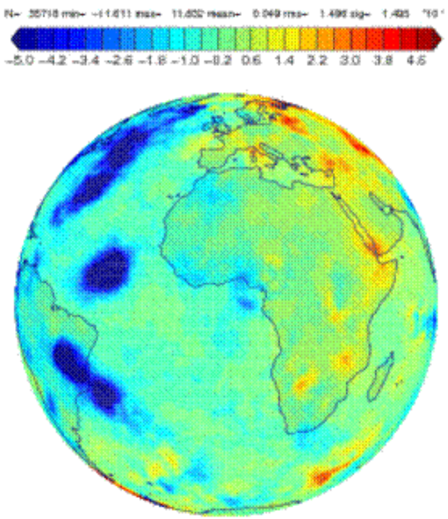


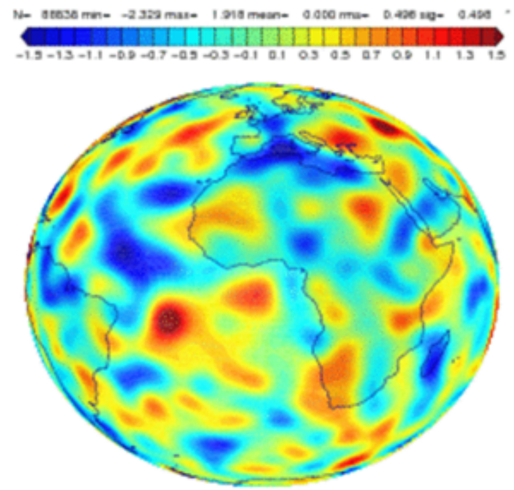
WF Produ



Model uncertainties – stochastic physics

- 2 components
- Stochastically Perturbed Parametrization Tendencies (SPPT)
  - Random pattern of perturbation to model fields
  - Initial scheme introduced 1999, revised 2009 (cycle 35r3)
- Spectral stochastic backscatter scheme (SPBS)
  - A fraction of the dissipated energy is backscattered upscale and acts as streamfunction forcing for the resolved-scale flow
  - Introduced in addition to SPPT in November 2010 (cycle 36r4)



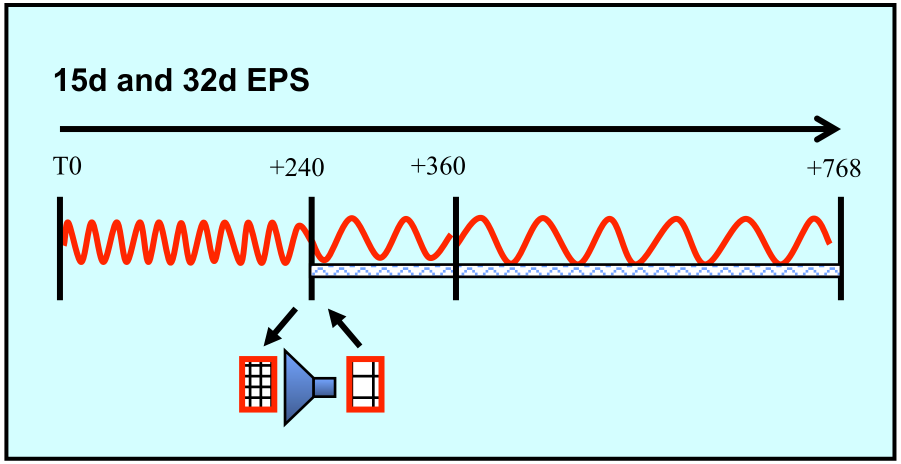


Stochastically Perturbed Parametrization Tendencies (SPPT)

Buizza et al 1999	Revised scheme (35r3)
$\Delta X_p = (1 + r_X)\,\Delta X_c$	$\Delta X_p = (1 + \mu r)\,\Delta X_c$
Random numbers r_X constant in 10° by 10° lat/lon boxes, and for 6 model time steps (3h in T399)	**Random pattern r based on multiple independent AR(1) processes in spectral space, with de-correlation scales 500 km and 6 h**
Uniform distribution between −0.5 and +0.5	**Gaussian distribution with stdev 0.5 (limited to ±3stdev)**
Independent random numbers r_X for X=T, q, u, v	**Same random number r for X=T, q, u, v**
Perturbations in entire column	**No perturbations in lowest 300 m and above 50 hPa ($0 \leq \mu \leq 1$)**

The ECMWF ensemble

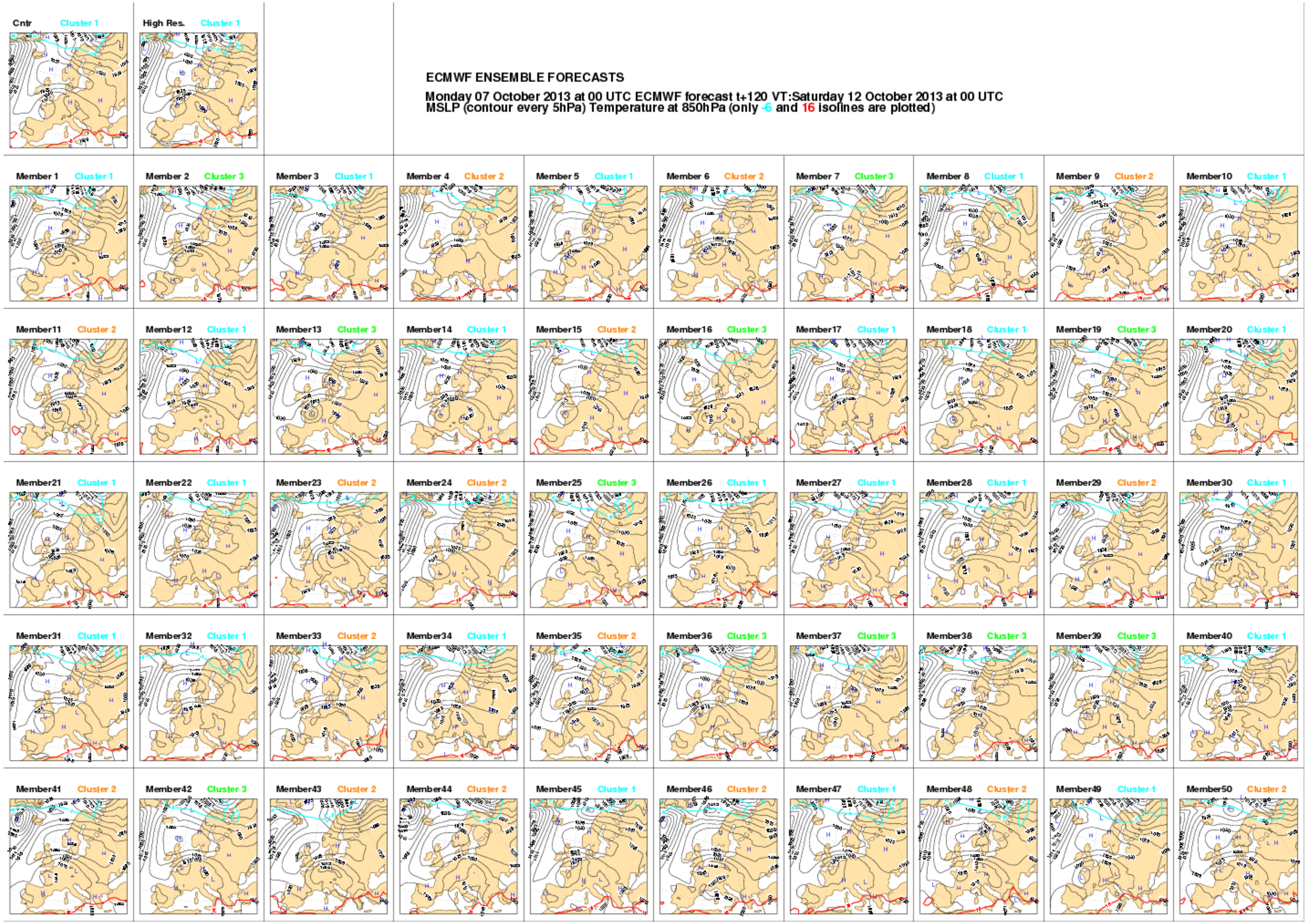
- 62 levels, 32km (T639) to day 10, then 65km (T319) to day 15
- 1 control + 50 perturbed members
- Runs twice per day (00 and 12)
- Coupled to ocean model from day 10
- Extended to 32 days twice per week for monthly forecast (00 Thursday, Monday)



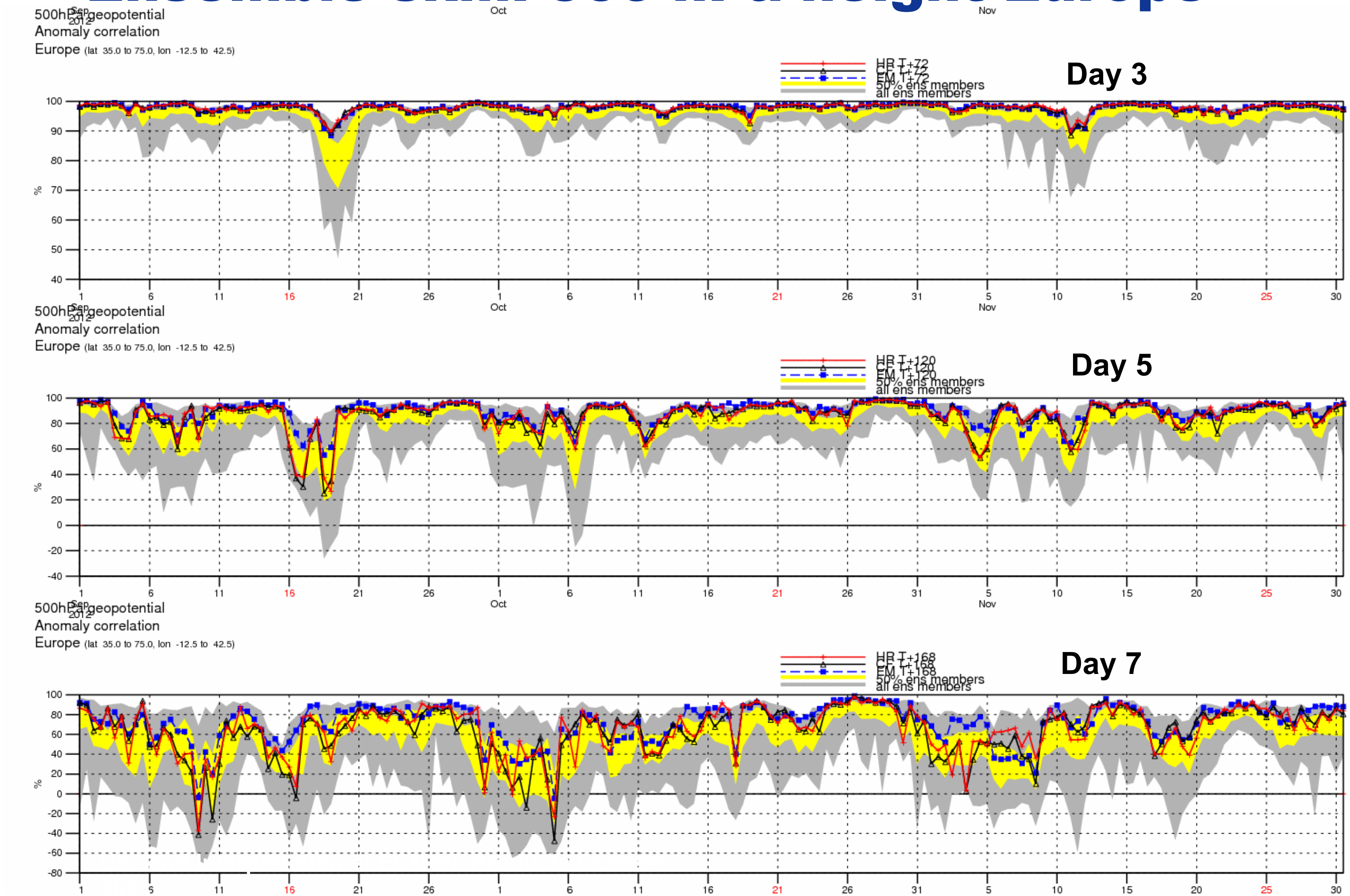
ensemble at variable resolution

- Small-scale features of the forecasts are wrong after a few days, so it makes sense to start the forecast at high resolution and then to decrease resolution
- For a given amount of computing resource, this allows to have higher resolution at the beginning, which makes the forecast better
- The additional skill can extend into the lower resolution segment (for some parameters, not all)
- Run EPS to day 10 at 32km resolution, then extend to day 15 at lower resolution (65km)

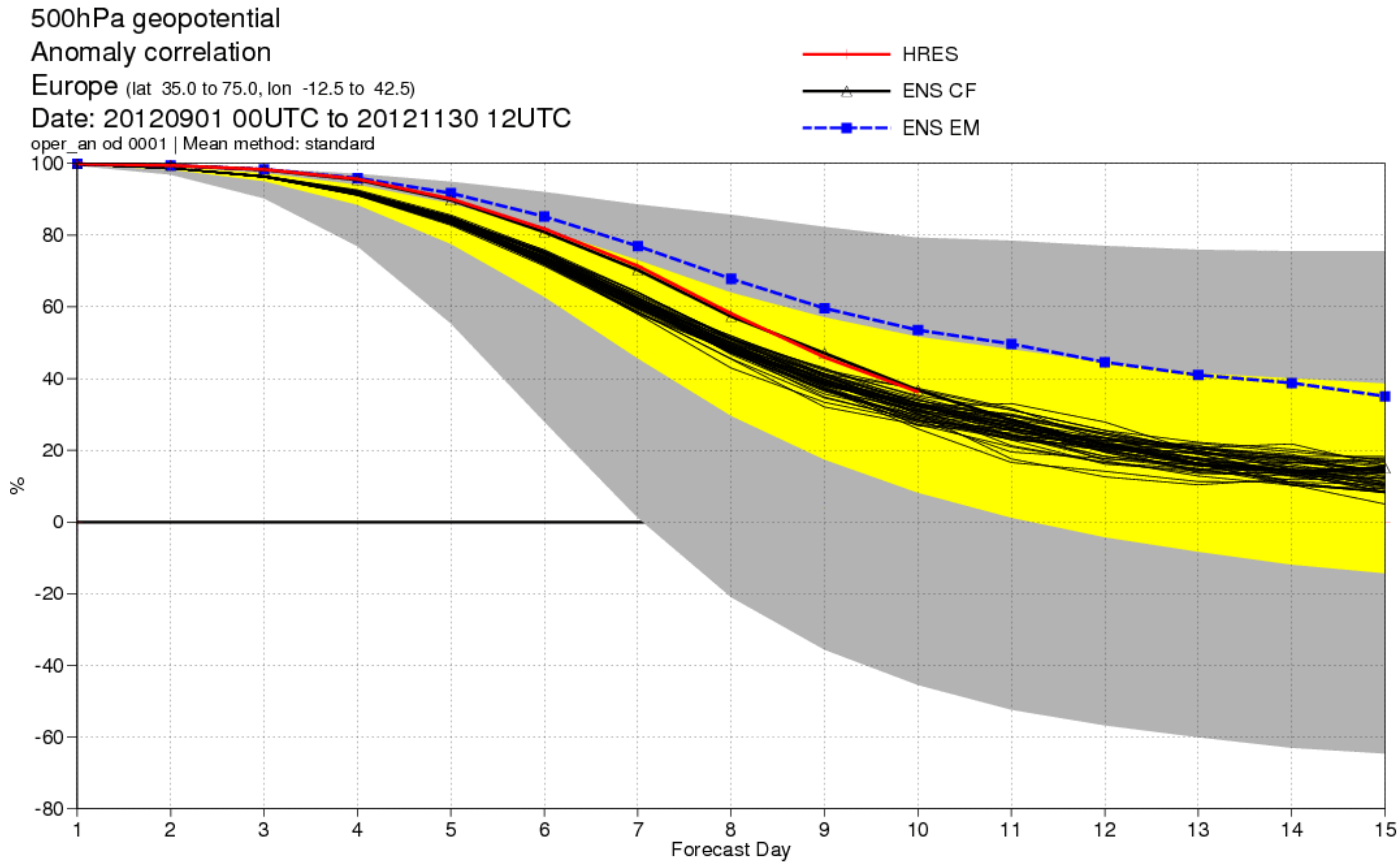
Ensemble


ECMWF ENSEMBLE FORECASTS
Monday 07 October 2013 at 00 UTC ECMWF forecast t+120 VT:Saturday 12 October 2013 at 00 UTC
MSLP (contour every 5hPa) Temperature at 850hPa (only -6 and 16 isolines are plotted)
Cntr Cluster 1
High Res. Cluster 1
Member 1 Cluster 1
Member 2 Cluster 3
Member 3 Cluster 1
Member 4 Cluster 2
Member 5 Cluster 1
Member 6 Cluster 2
Member 7 Cluster 3
Member 8 Cluster 1
Member 9 Cluster 2
Member10 Cluster 1
Member11 Cluster 2
Member12 Cluster 1
Member13 Cluster 3
Member14 Cluster 1
Member15 Cluster 2
Member16 Cluster 3
Member17 Cluster 1
Member18 Cluster 1
Member19 Cluster 3
Member20 Cluster 1
Member21 Cluster 1
Member22 Cluster 1
Member23 Cluster 2
Member24 Cluster 2
Member25 Cluster 3
Member26 Cluster 1
Member27 Cluster 1
Member28 Cluster 1
Member29 Cluster 2
Member30 Cluster 1
Member31 Cluster 1
Member32 Cluster 1
Member33 Cluster 2
Member34 Cluster 1
Member35 Cluster 2
Member36 Cluster 3
Member37 Cluster 3
Member38 Cluster 3
Member39 Cluster 3
Member40 Cluster 1
Member41 Cluster 2
Member42 Cluster 3
Member43 Cluster 2
Member44 Cluster 2
Member45 Cluster 1
Member46 Cluster 2
Member47 Cluster 1
Member48 Cluster 2
Member49 Cluster 1
Member50 Cluster 2

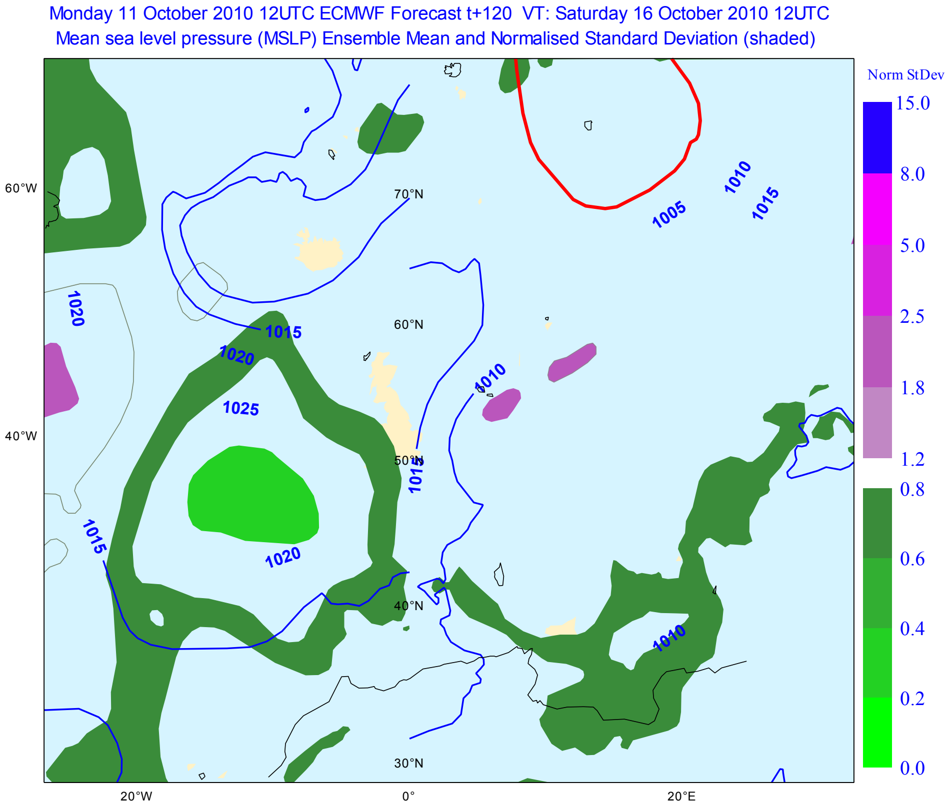
Ensemble skill: 500 hPa height Europe

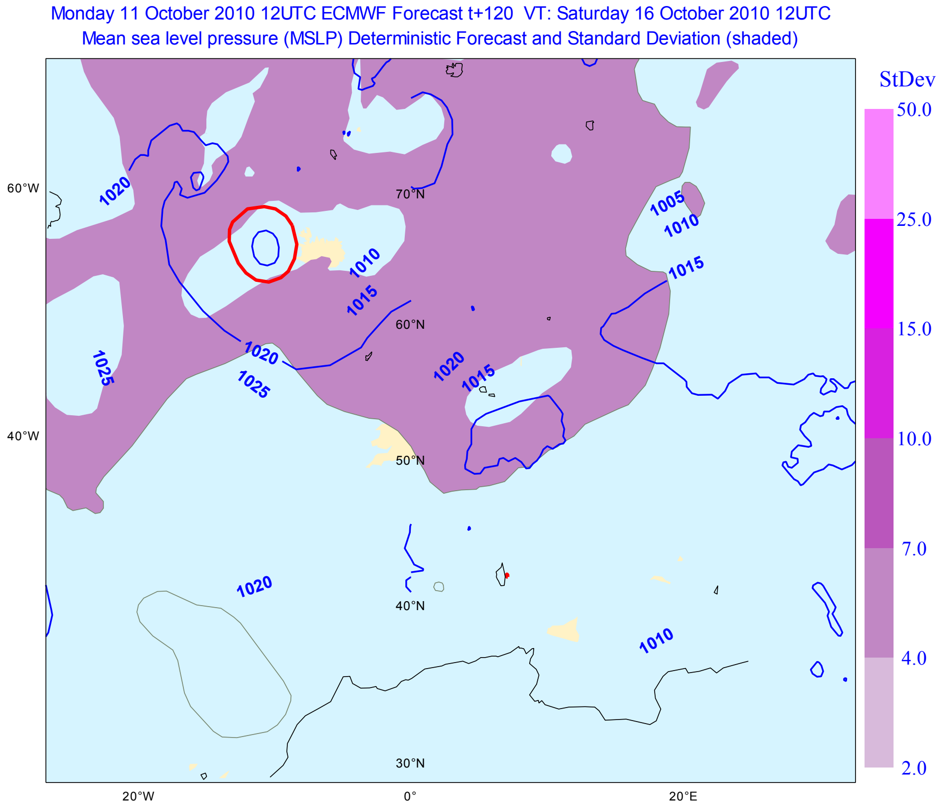


Ensemble skill: 500 hPa height Europe

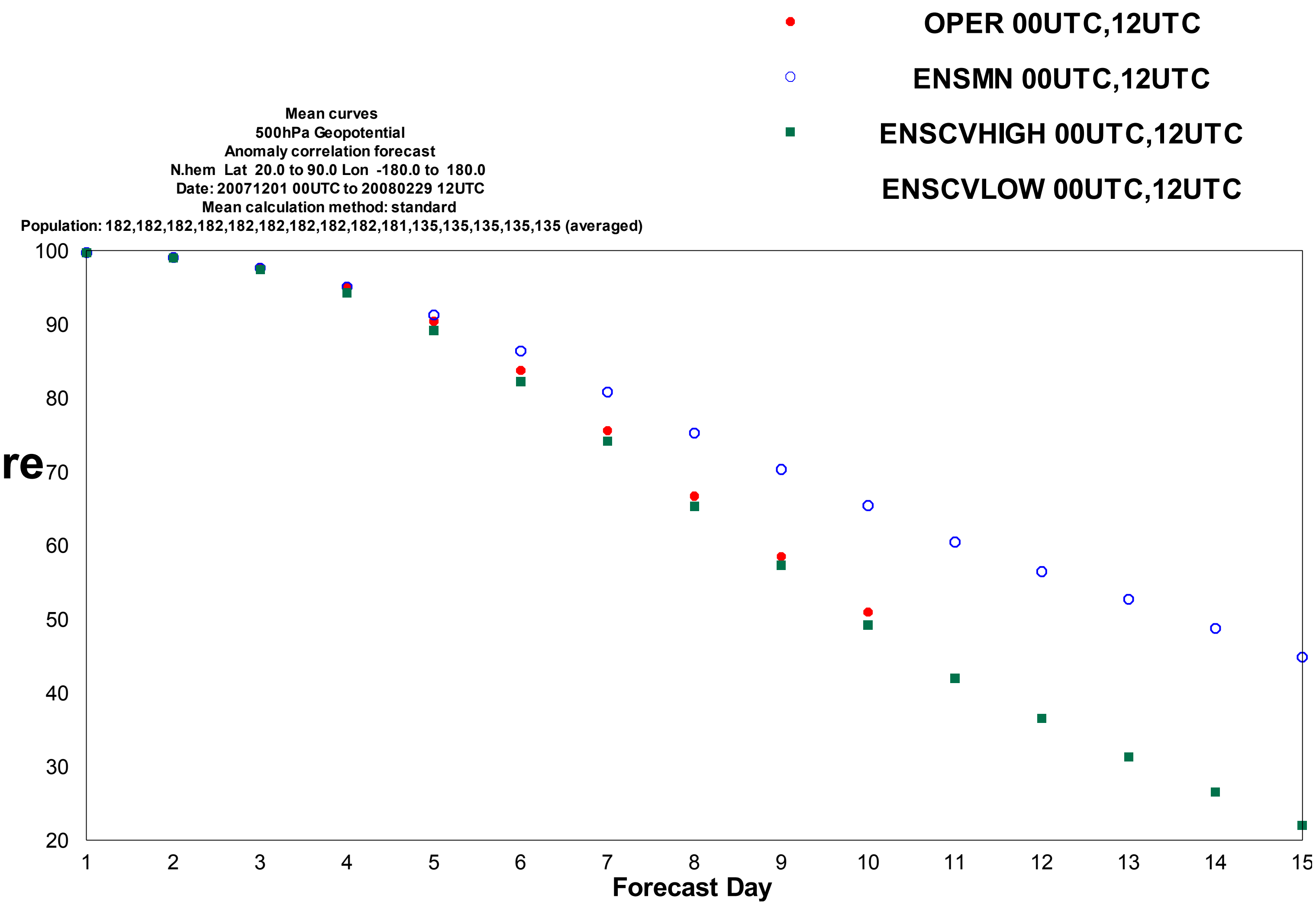


Ensemble mean and spread





Skill of the ensemble mean

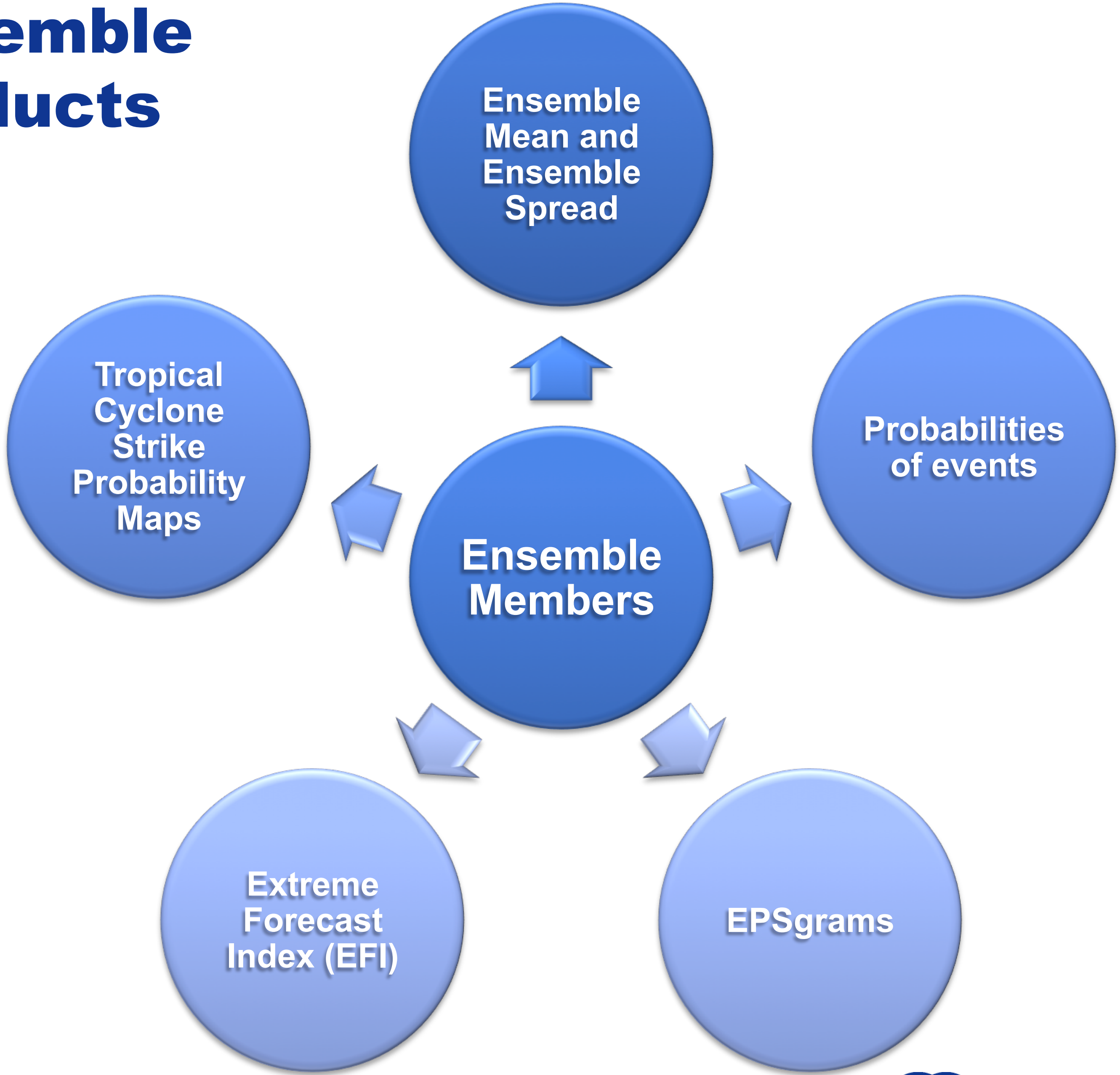


- Ensemble Mean is more skilful than single forecast

Deterministic use of the EPS

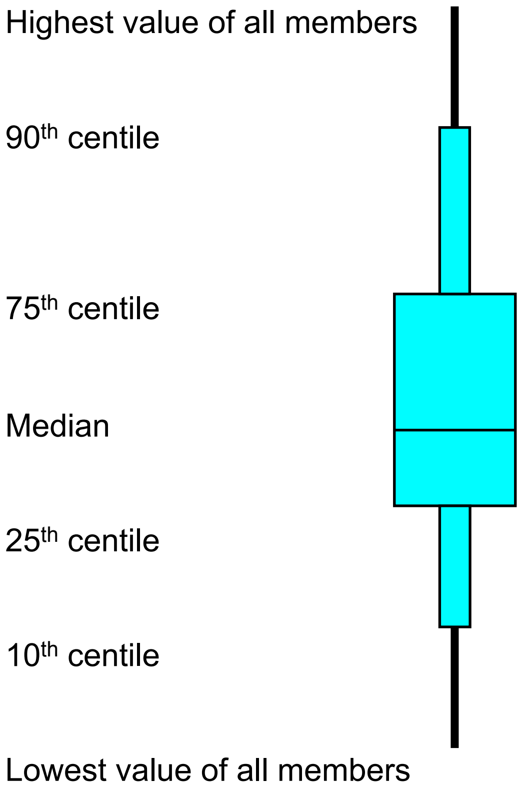
- The ensemble mean is the average over all ensemble members
- It smoothes the flow more in areas of large uncertainty (spread)
- This cannot be achieved with a simple filtering of a single forecast
- the ensemble mean is the best estimate for any parameter beyond D+3/D+4 (Z500, T2m, Precipitation)
- If there is large spread, the ensemble mean can be a rather weak pattern and may not represent any of the possible states
- The ensemble mean should always be used together with the spread

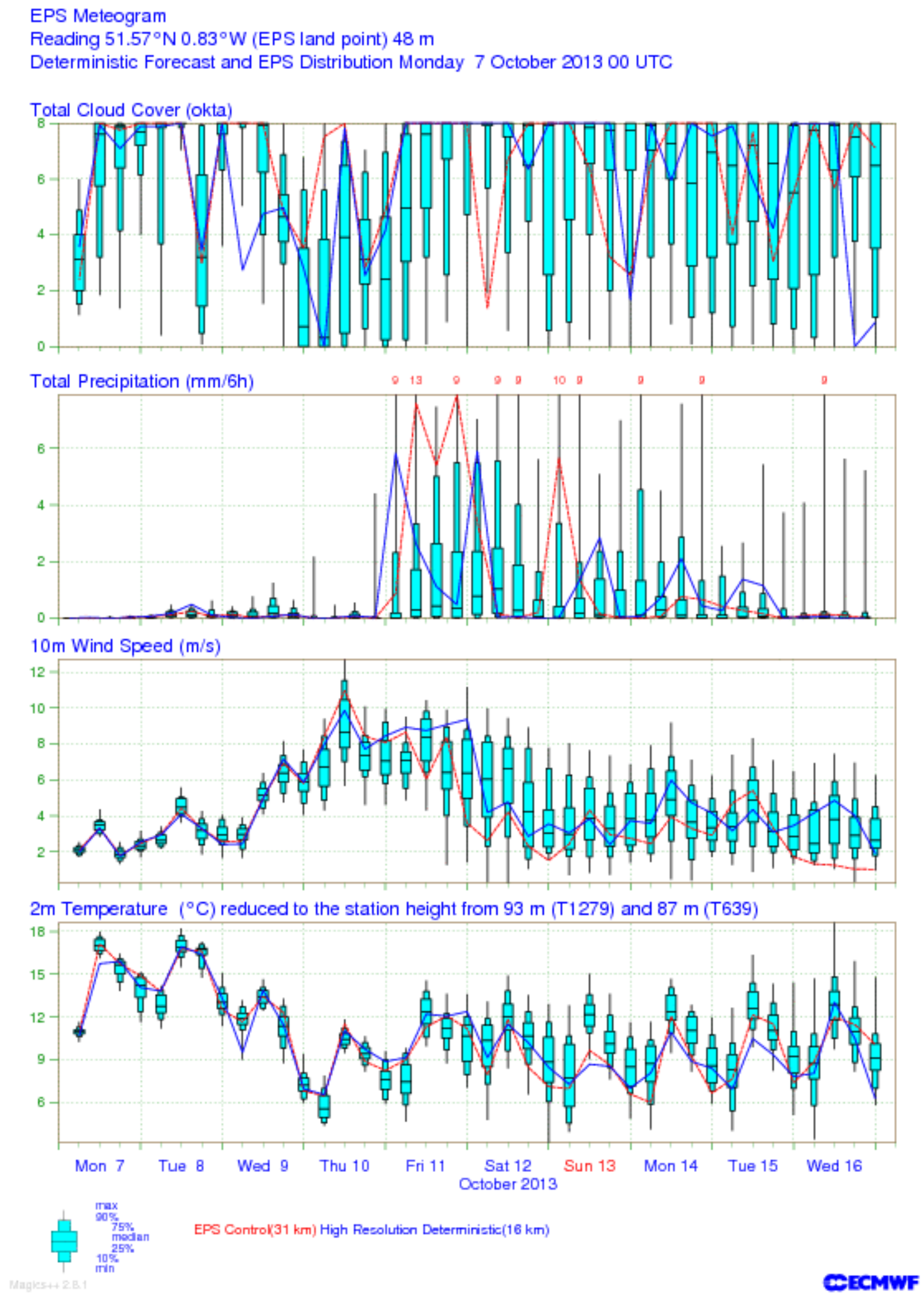
Ensemble products



ECMWF

ensemble forecasts: timeseries (EPSgram)



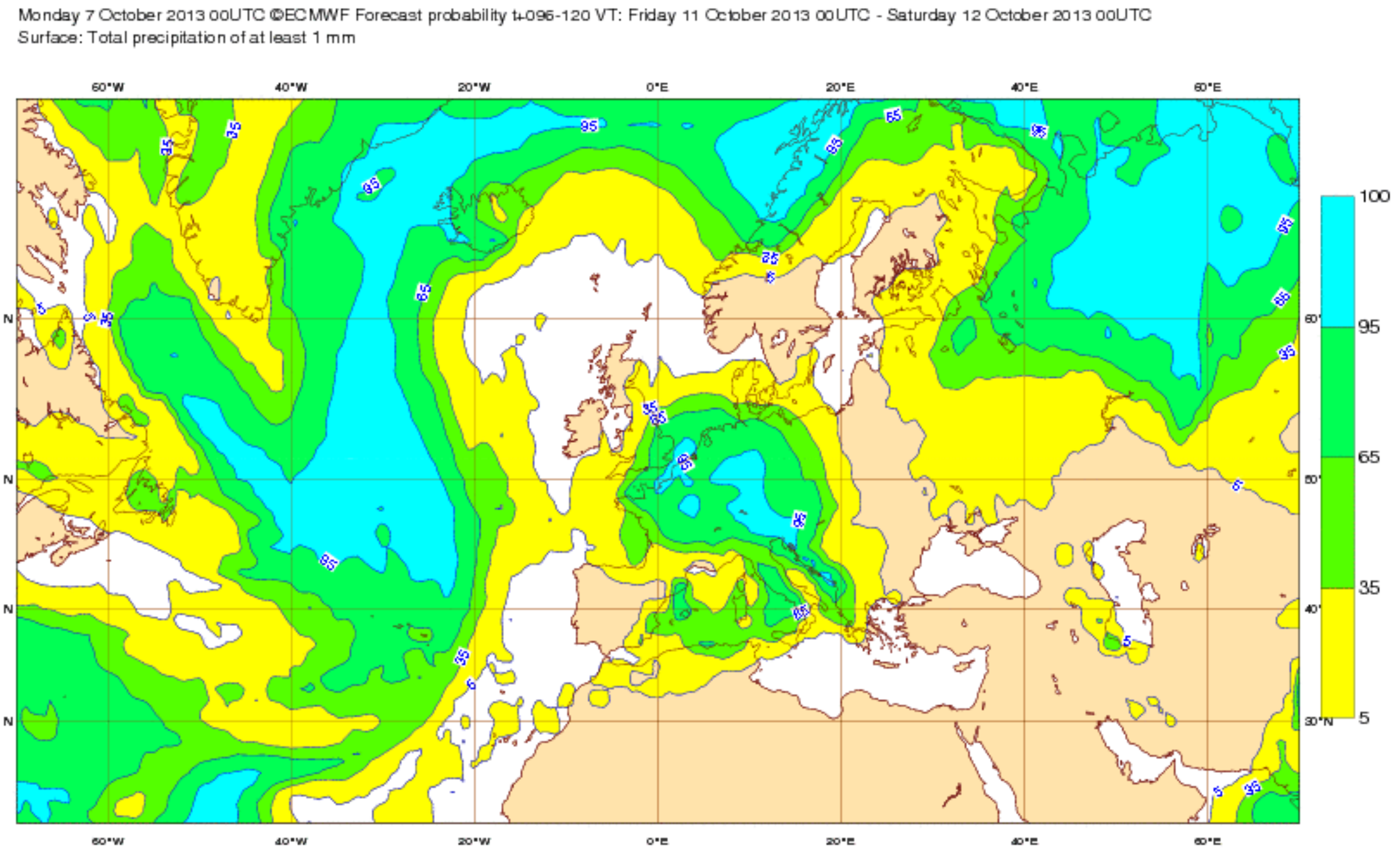


EPSgram for Reading

Base Monday 7/10/13 00 UTC

Probabilities of events

24h precipitation > 1 mm, forecast for Friday



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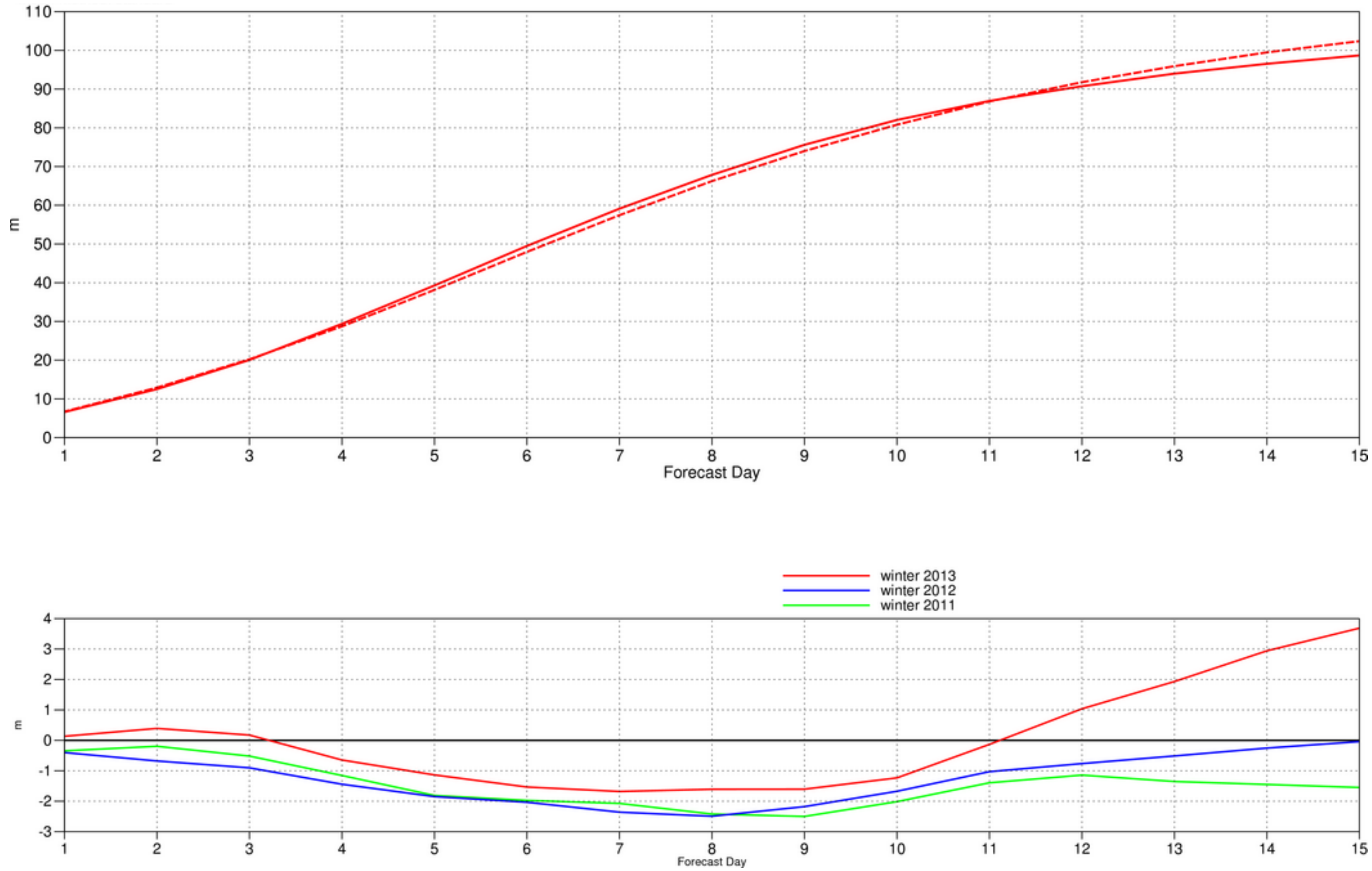
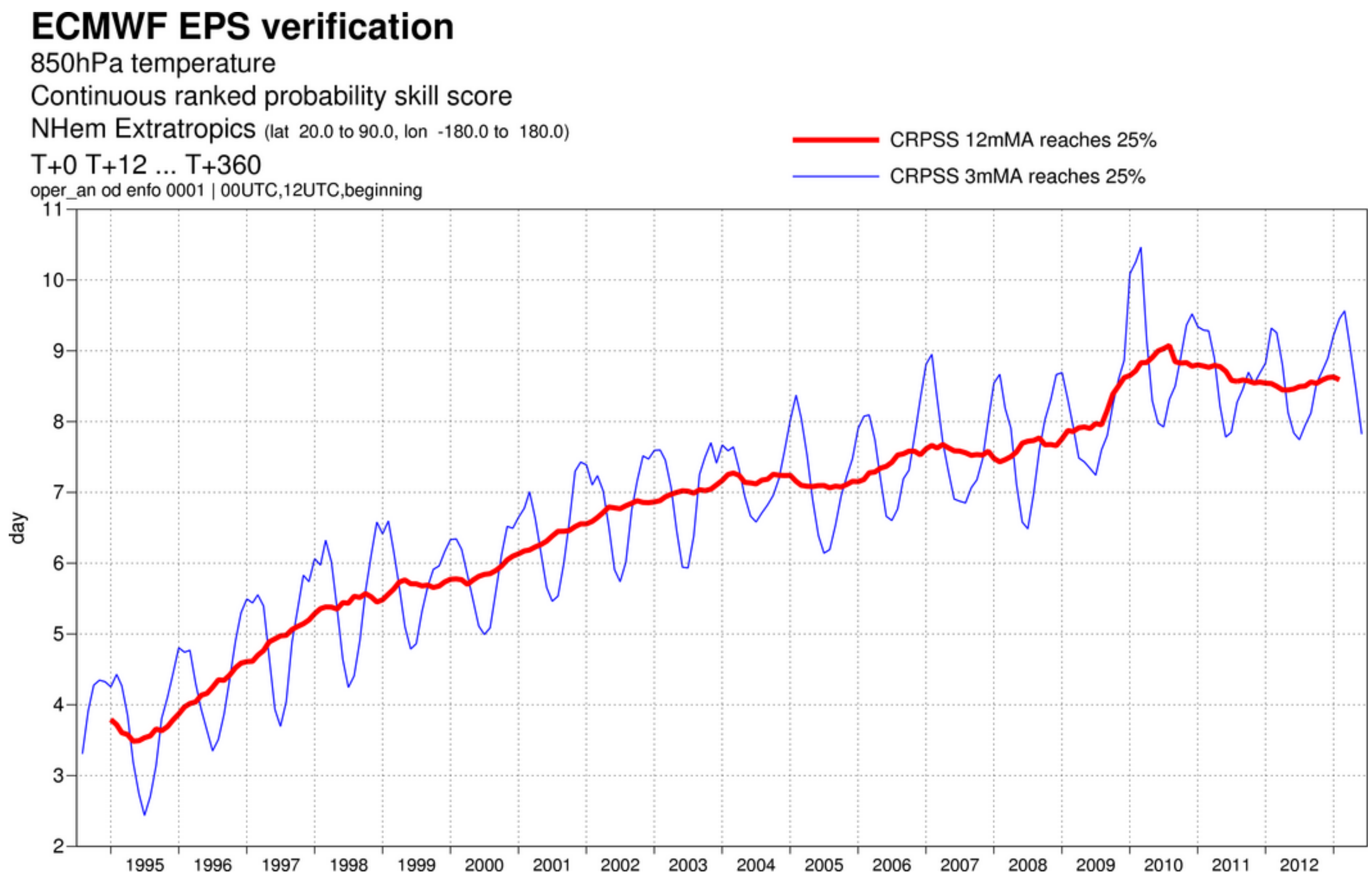
ENS spread and error, Z500, N.Hem



EPS spread (dashed), RMS error of ensemble-mean (full lines), and their difference (below) for Z500 hPa in winter 2010-11 (green), 2011-12 (blue) and 2012-13 (red).

ENS Probabilistic Score
CRPSS, Temperature at 850 hPa N hemisphere



Monthly score (blue), and 12-month running mean (red) of Continuous Ranked Probability Skill Score. Day at which score reaches 25%.

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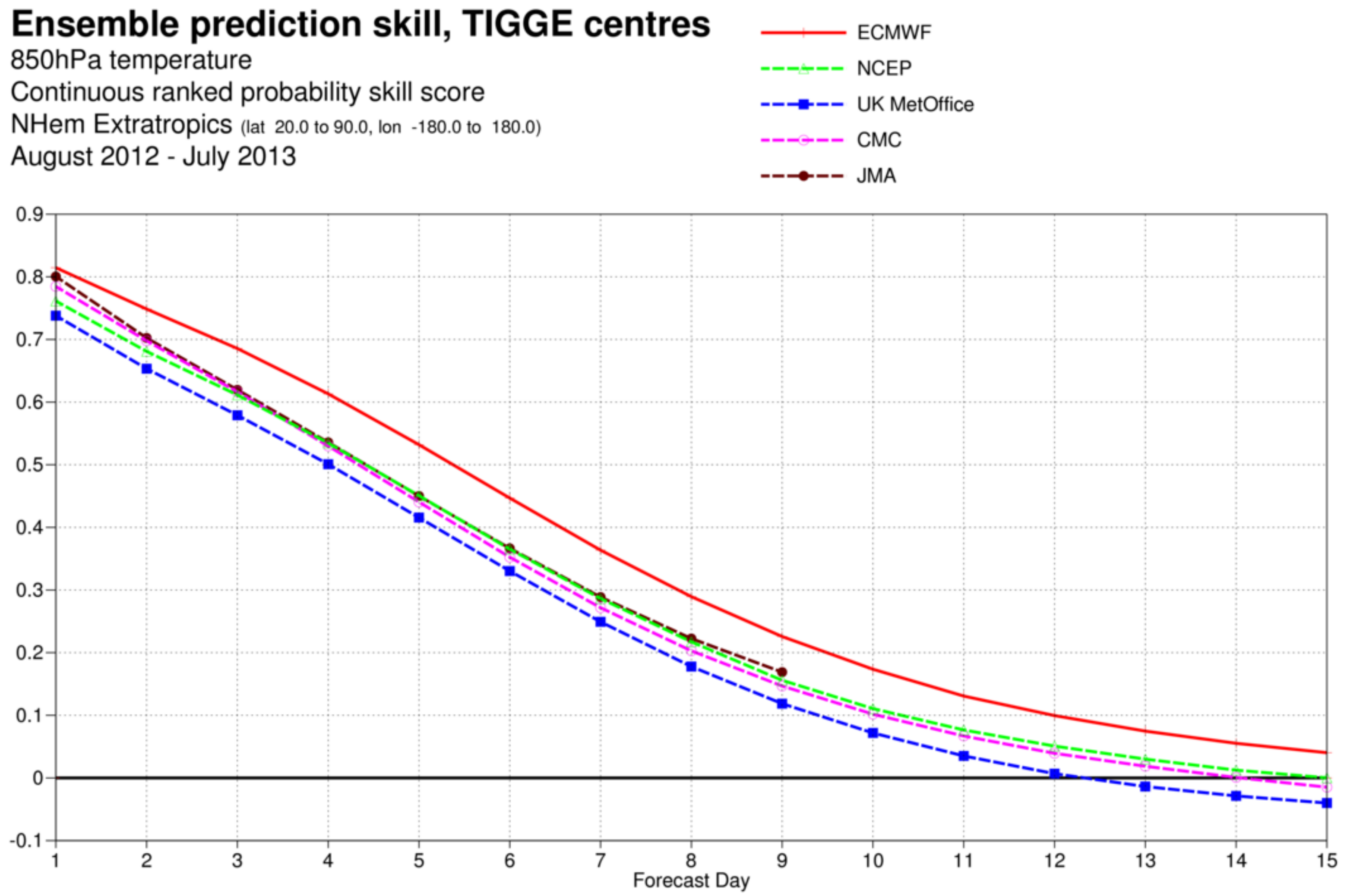
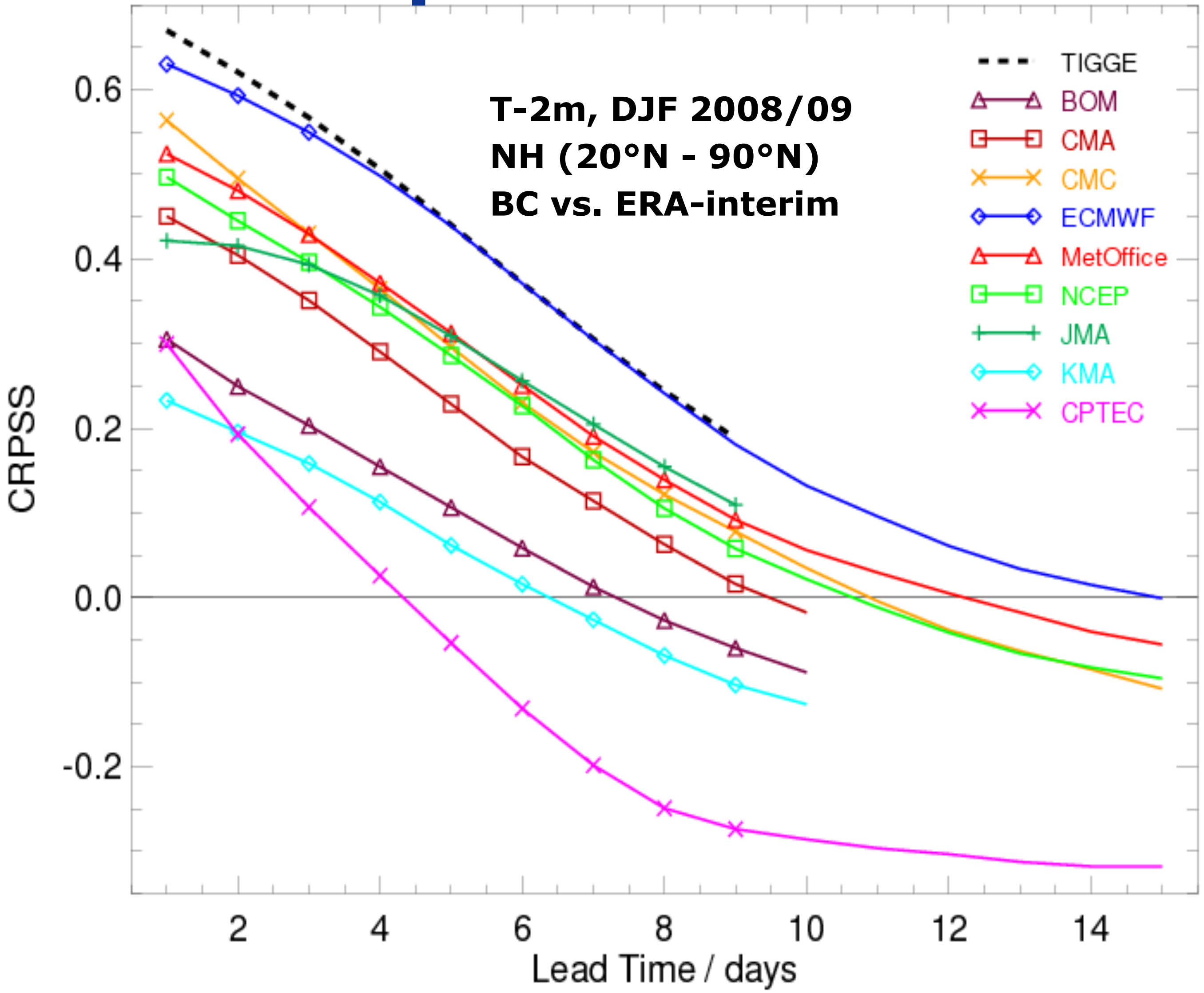
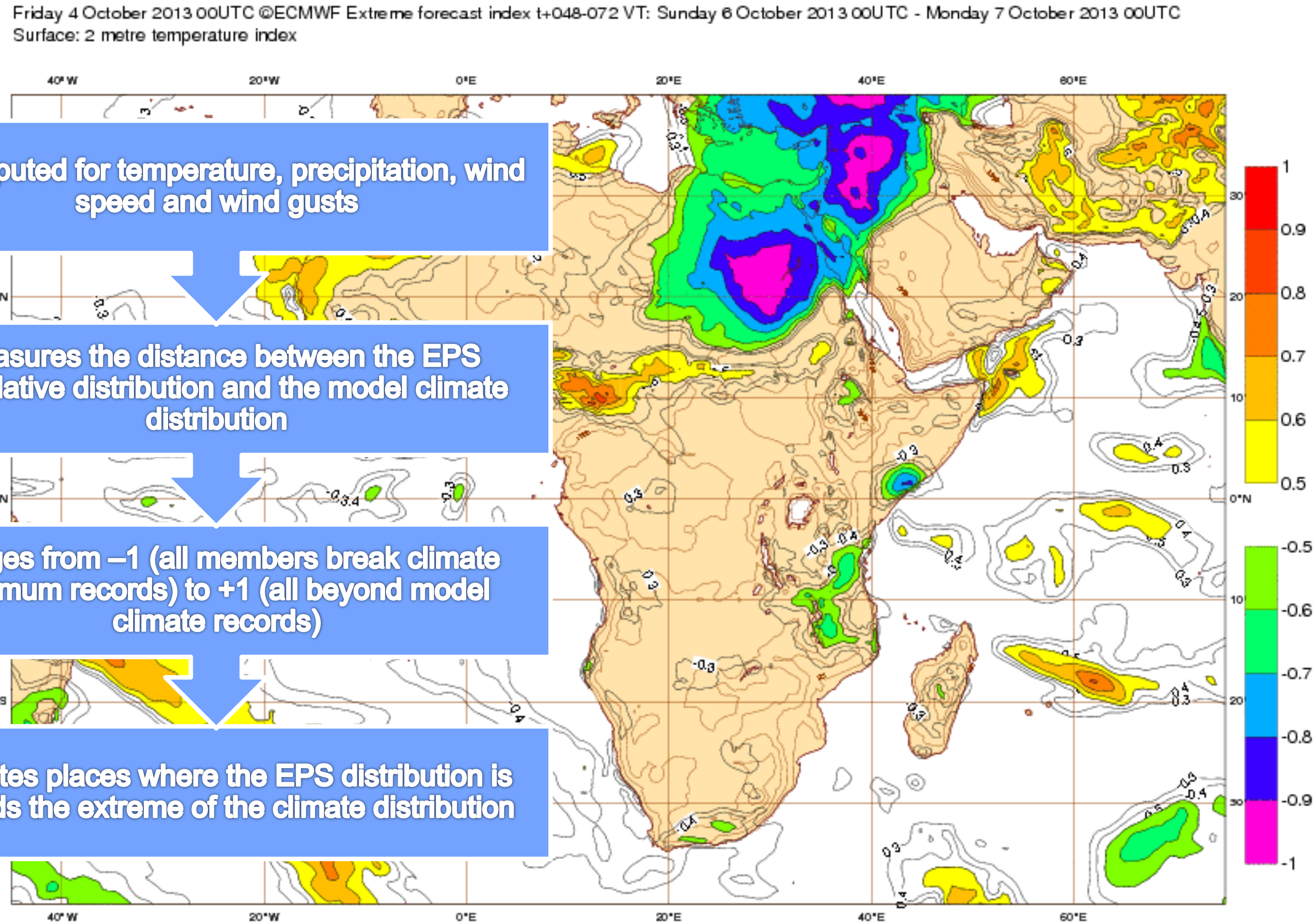
ENS Probabilistic Score
CRPSS, Temperature at 850 hPa N hemisphere



ENS skill compared to other centres



Extreme forecast index (EFI)



Is computed for temperature, precipitation, wind speed and wind gusts

Measures the distance between the EPS cumulative distribution and the model climate distribution

Ranges from –1 (all members break climate minimum records) to +1 (all beyond model climate records)

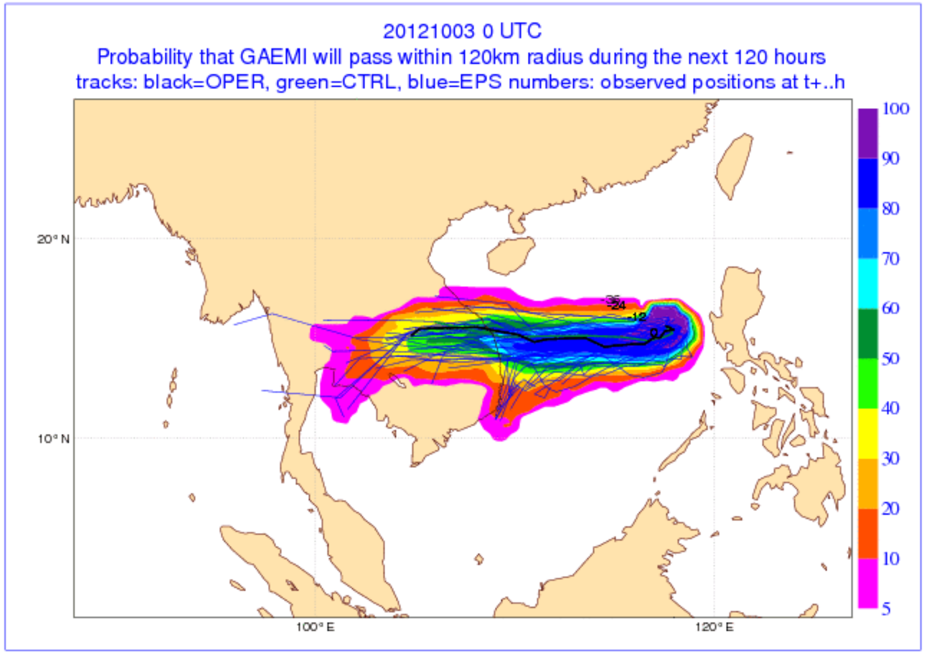
Indicates places where the EPS distribution is towards the extreme of the climate distribution

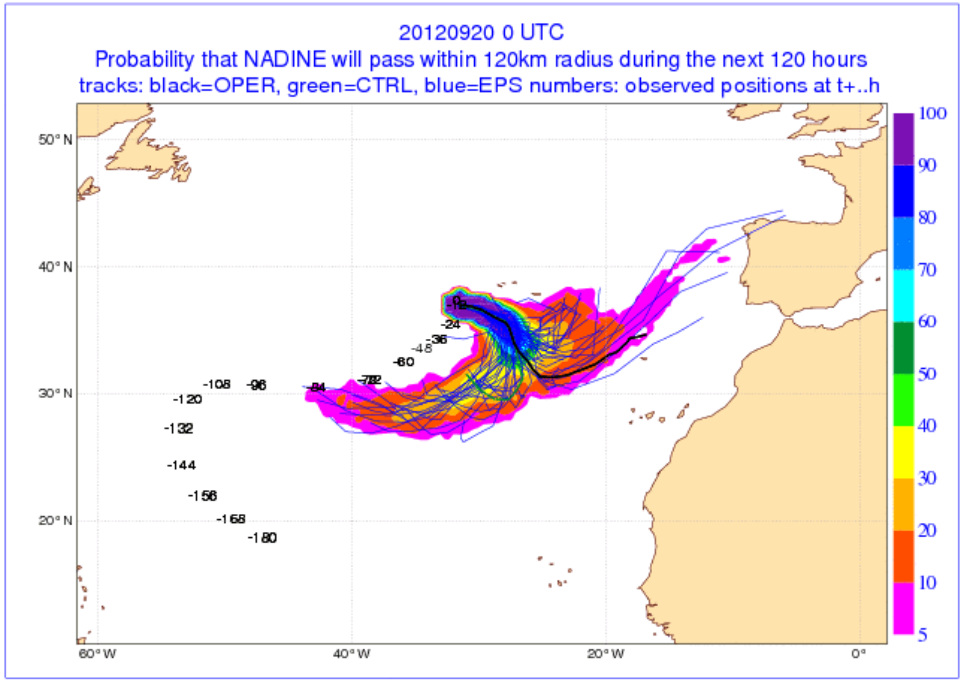
ECMWF

Tropical cyclone tracks

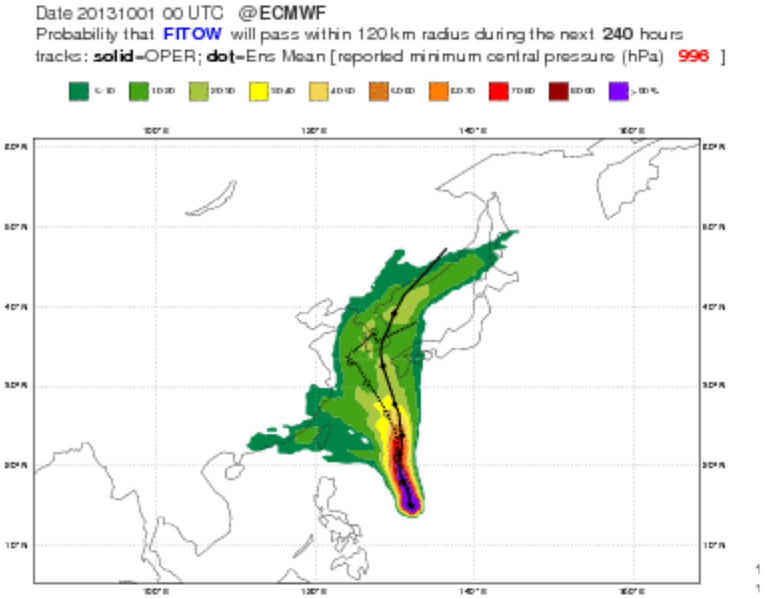
Gamei

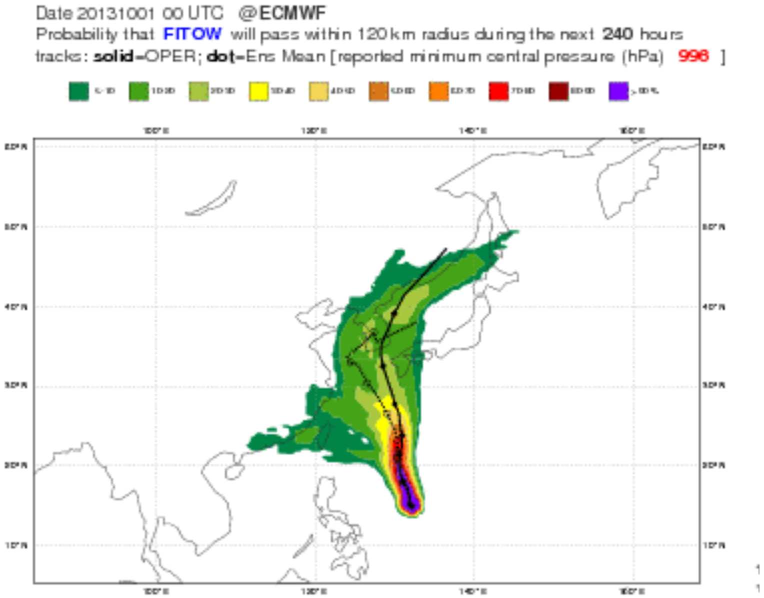
Nadine





strike probability


Date 20131001 00 UTC @ECMWF
Probability that FITOW will pass within 120 km radius during the next 240 hours
tracks: solid=OPER; dot=Ens Mean [reported minimum central pressure (hPa) 996]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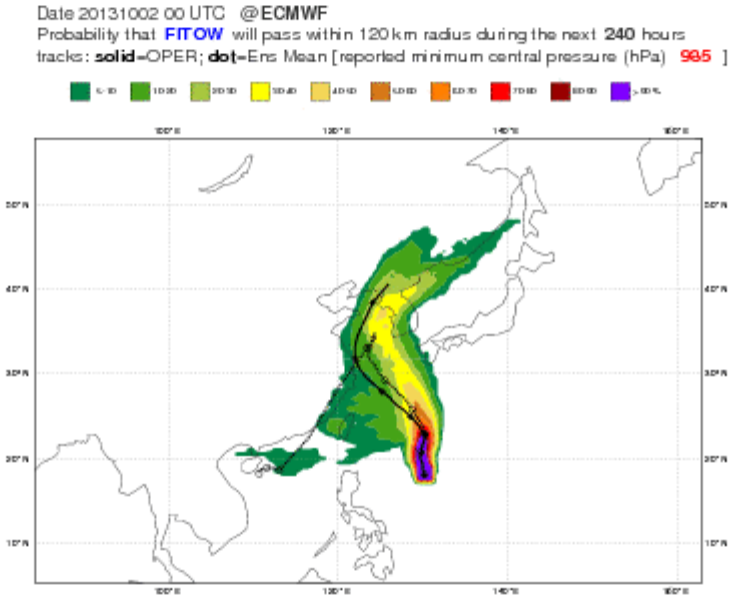
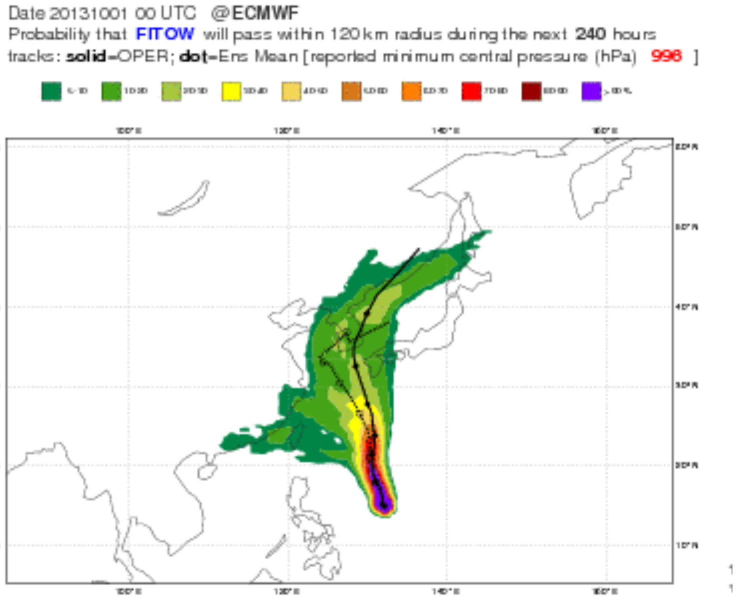

Date 20131002 00 UTC @ECMWF
Probability that FITOW will pass within 120km radius during the next 240 hours
tracks: solid=OPER; dot=Ens Mean [reported minimum central pressure (hPa) 985]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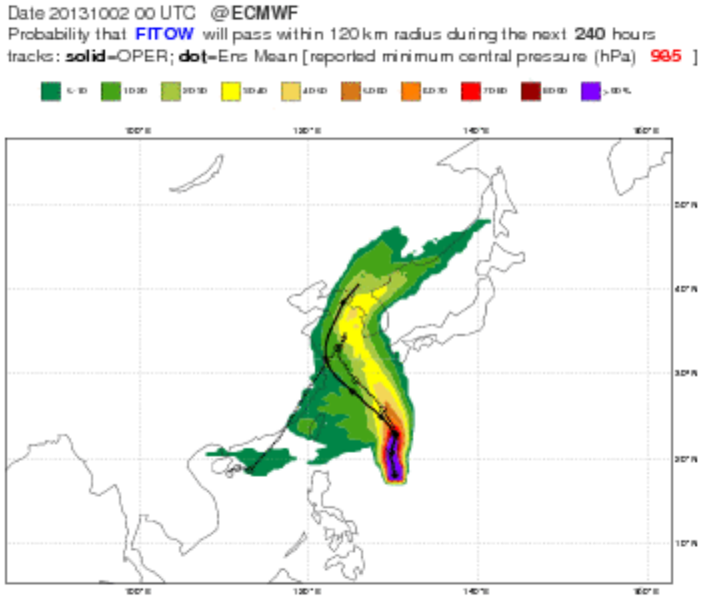
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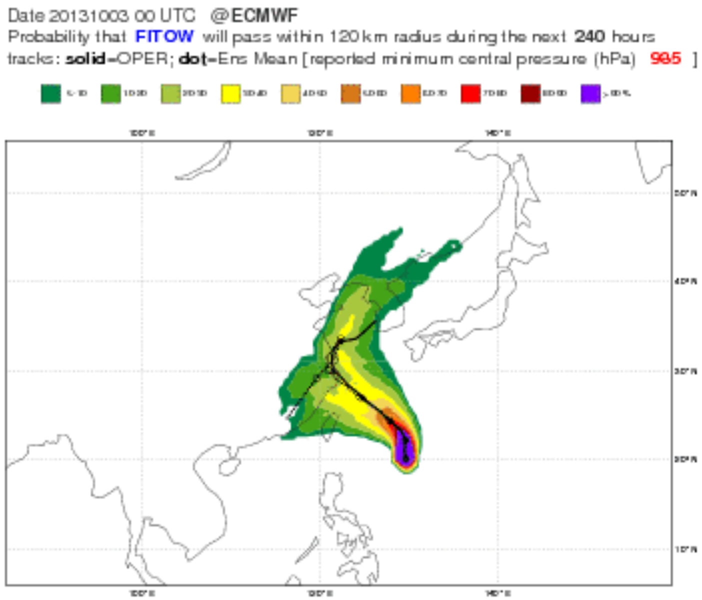
Date 20131003 00 UTC @ECMWF
Probability that FITOW will pass within 120km radius during the next 240 hours
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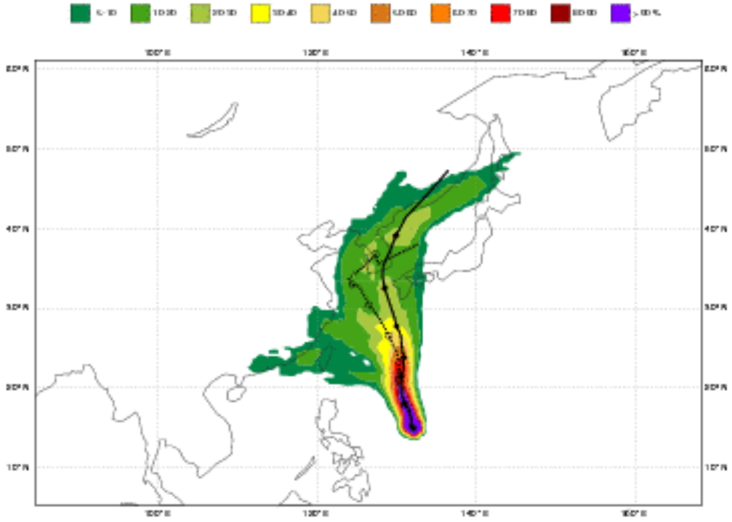
Date 20131001 00 UTC @ECMWF
Probability that **FITOW** will pass within 120km radius during the next **240** hours
tracks: **solid**=OPER; **dot**=Ens Mean [reported minimum central pressure (hPa) 996]



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Probability that **FITOW** will pass within 120km radius during the next **240** hours
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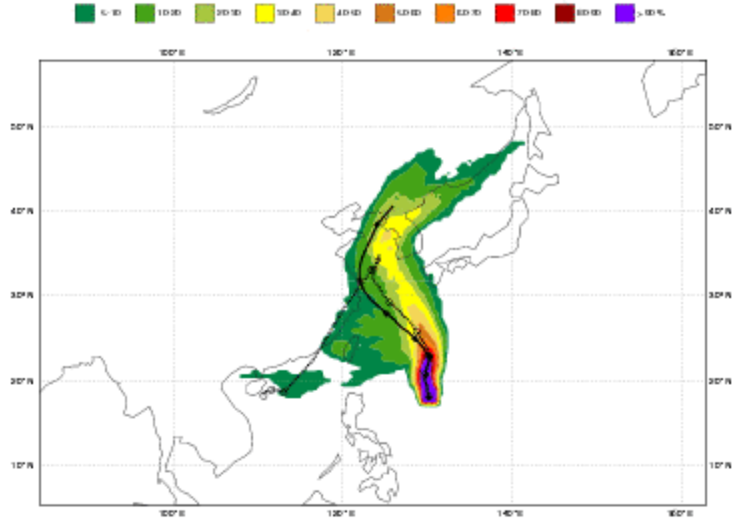

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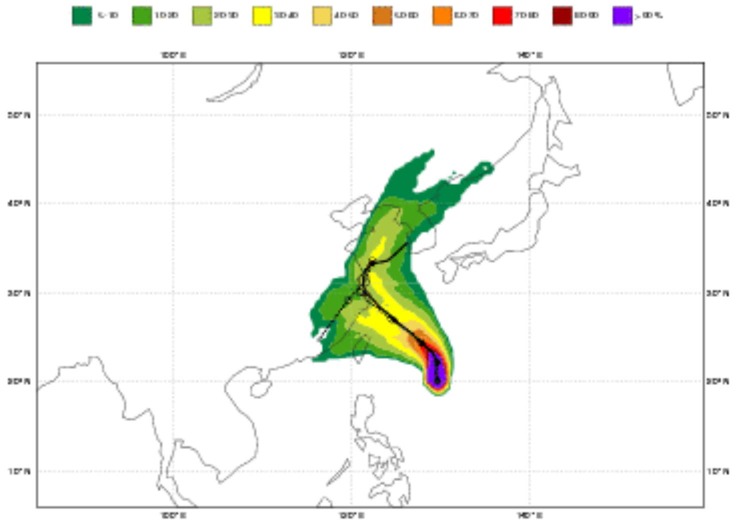
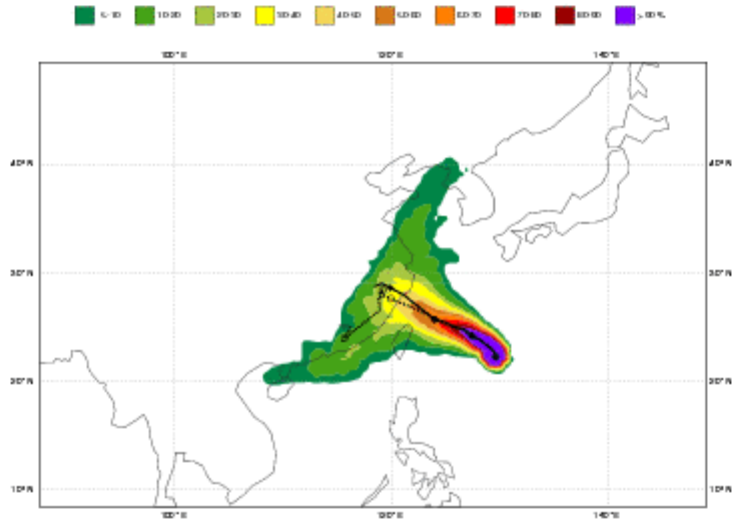
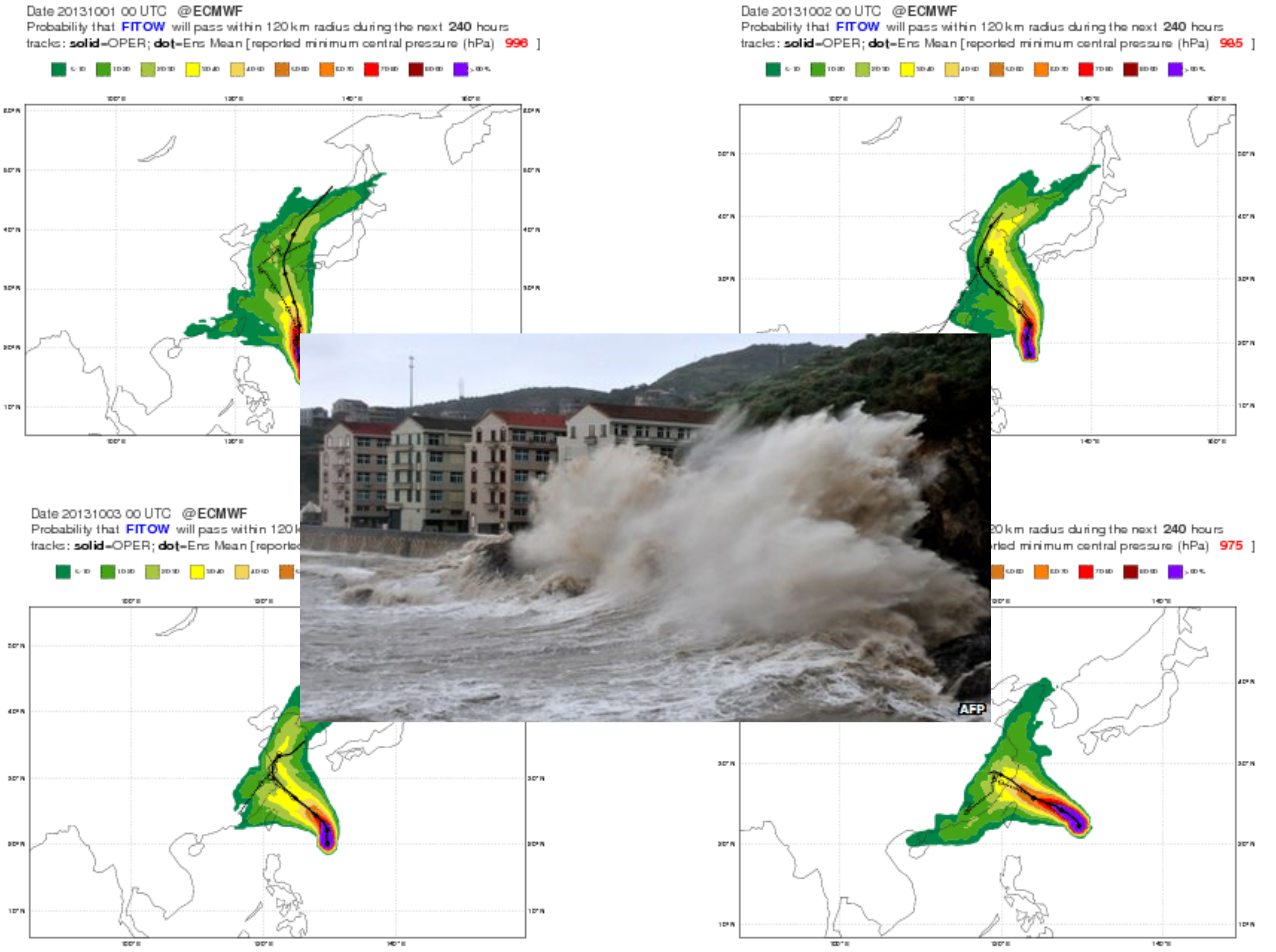


Date 20131004 00 UTC @ECMWF
Probability that **FITOW** will pass within 120km radius during the next **240** hours
tracks: **solid**=OPER; **dot**=Ens Mean [reported minimum central pressure (hPa) 975]



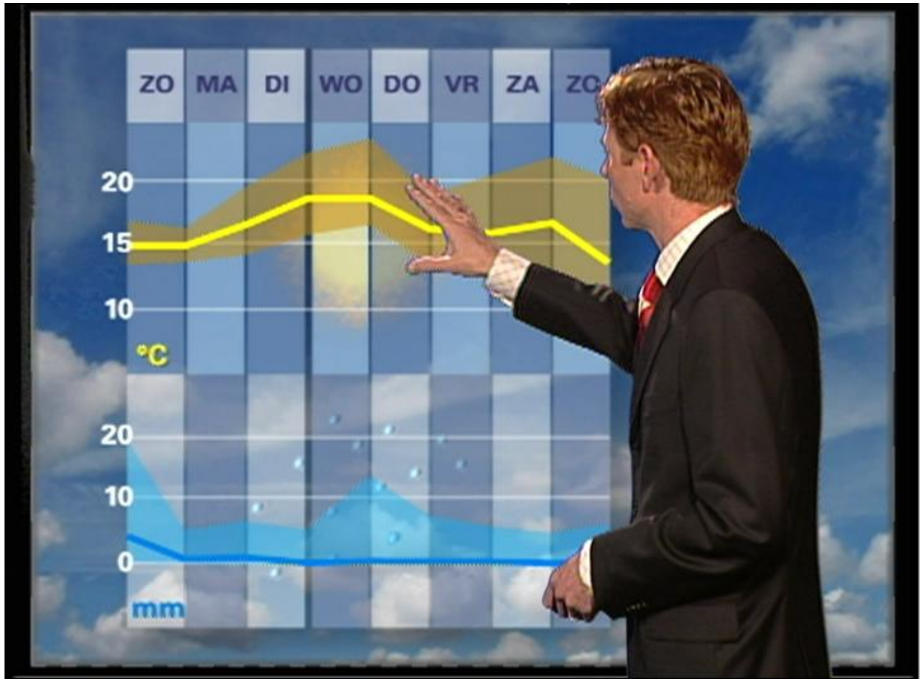


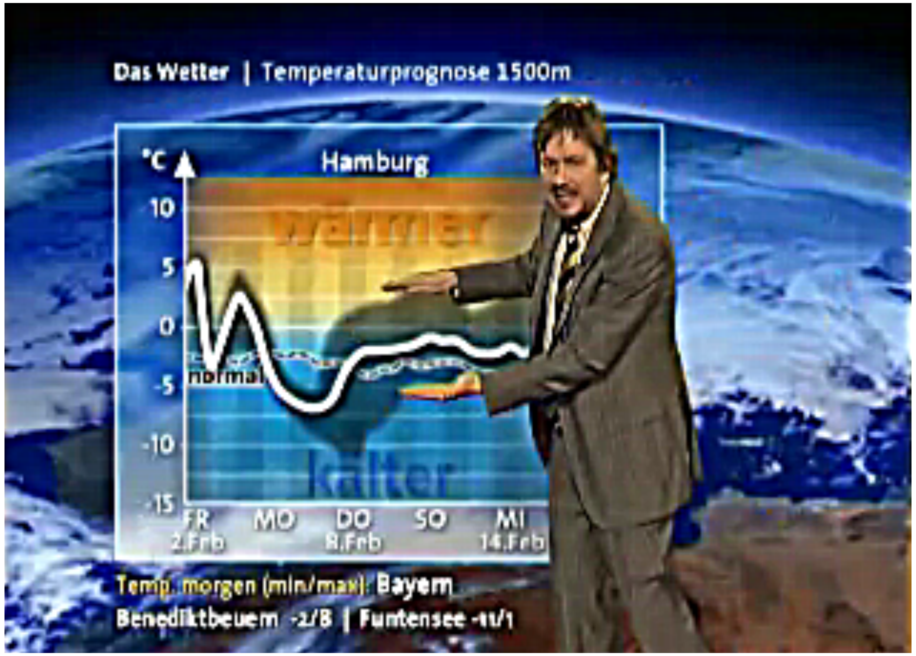
Date 20131001 00 UTC @ECMWF
Probability that FITOW will pass within 120 km radius during the next 240 hours
tracks: solid=OPER; dot=Ens Mean [reported minimum central pressure (hPa) 996]
Date 20131002 00 UTC @ECMWF
Probability that FITOW will pass within 120 km radius during the next 240 hours
tracks: solid=OPER; dot=Ens Mean [reported minimum central pressure (hPa) 985]
Date 20131003 00 UTC @ECMWF
Probability that FITOW will pass within 120 k
tracks: solid=OPER; dot=Ens Mean [reporte
20 km radius during the next 240 hours
rted minimum central pressure (hPa) 975]
AFP

ENS – communicating uncertainty

- All forecasts have errors
- It can be important for the user to know about the uncertainty in a forecast
  - what else could happen? what is the worst possibility?
- This is not a new idea
  - Forecasters are used to adjusting their forecast with their experience of model errors (flow dependence, forecast range dependency)
  - Inconsistency of the forecasts (in time, from one model to the other) were used as indication of the (un-)predictability of scenarios
- Ensembles give more information – they provide an explicit, detailed representation of model uncertainties, and potential of unusual events

Uncertainty information to public





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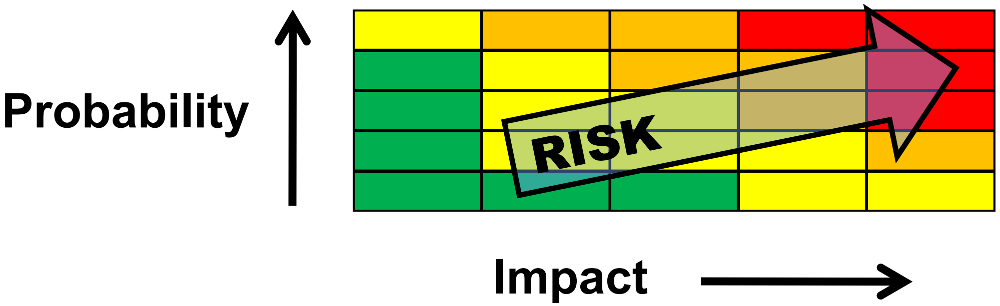
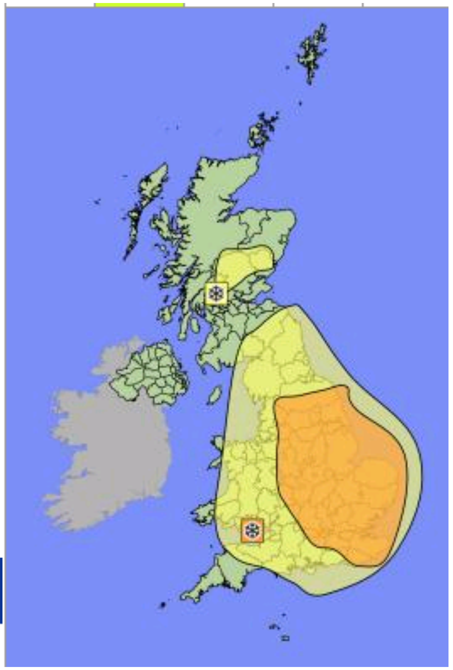
Uncertainty information to public

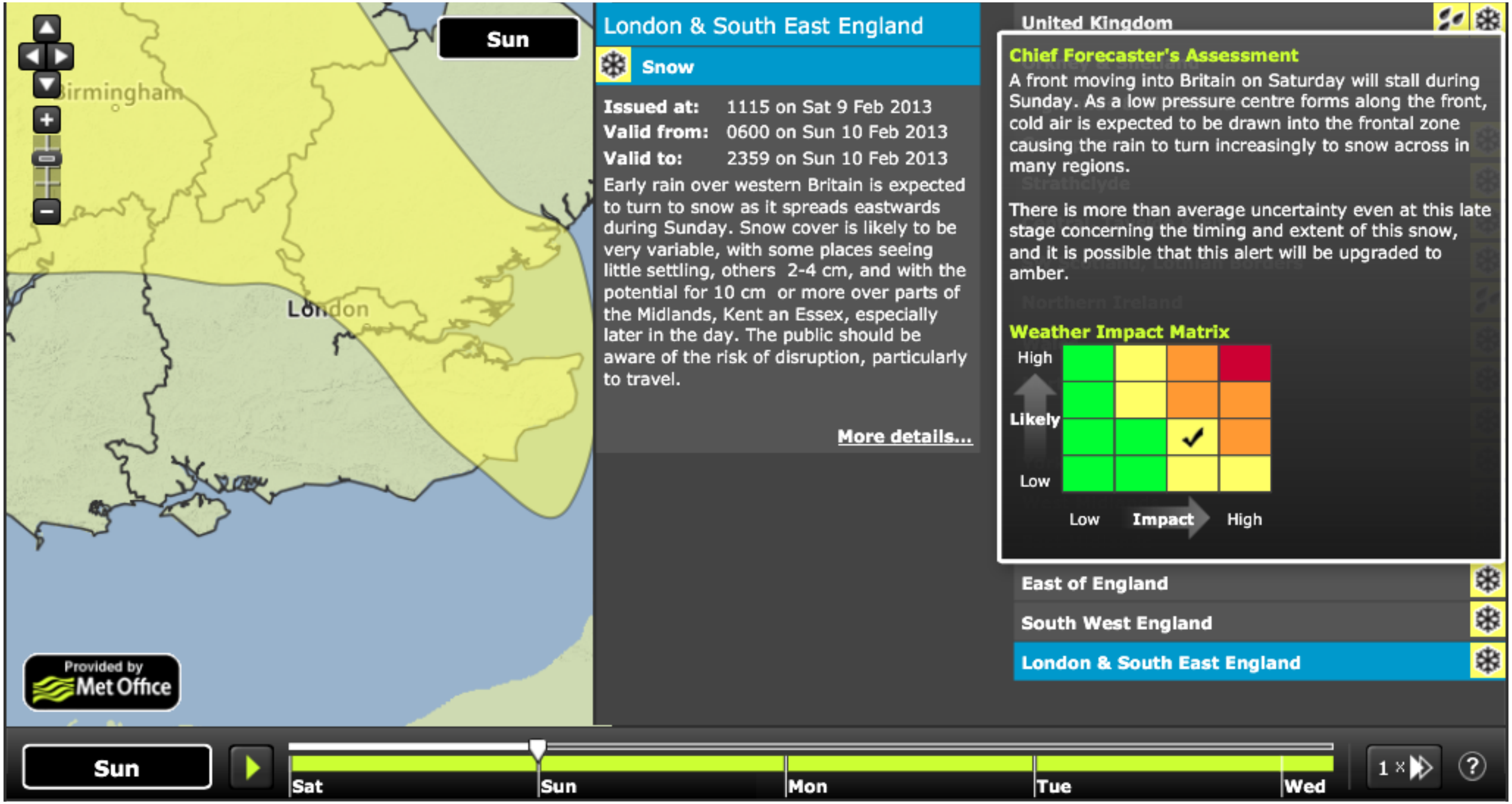
Value: the economic or societal worth of forecasts

- Forecasts only have value if people use them
  - make a decision or take an action which would not otherwise have been made
- Decisions can be based on deterministic forecasts, but …
- Decisions involve assessment of risk
- Risk = probability x impact
- To make a good decision need to know the probability and the impact (consequence to the individual user)

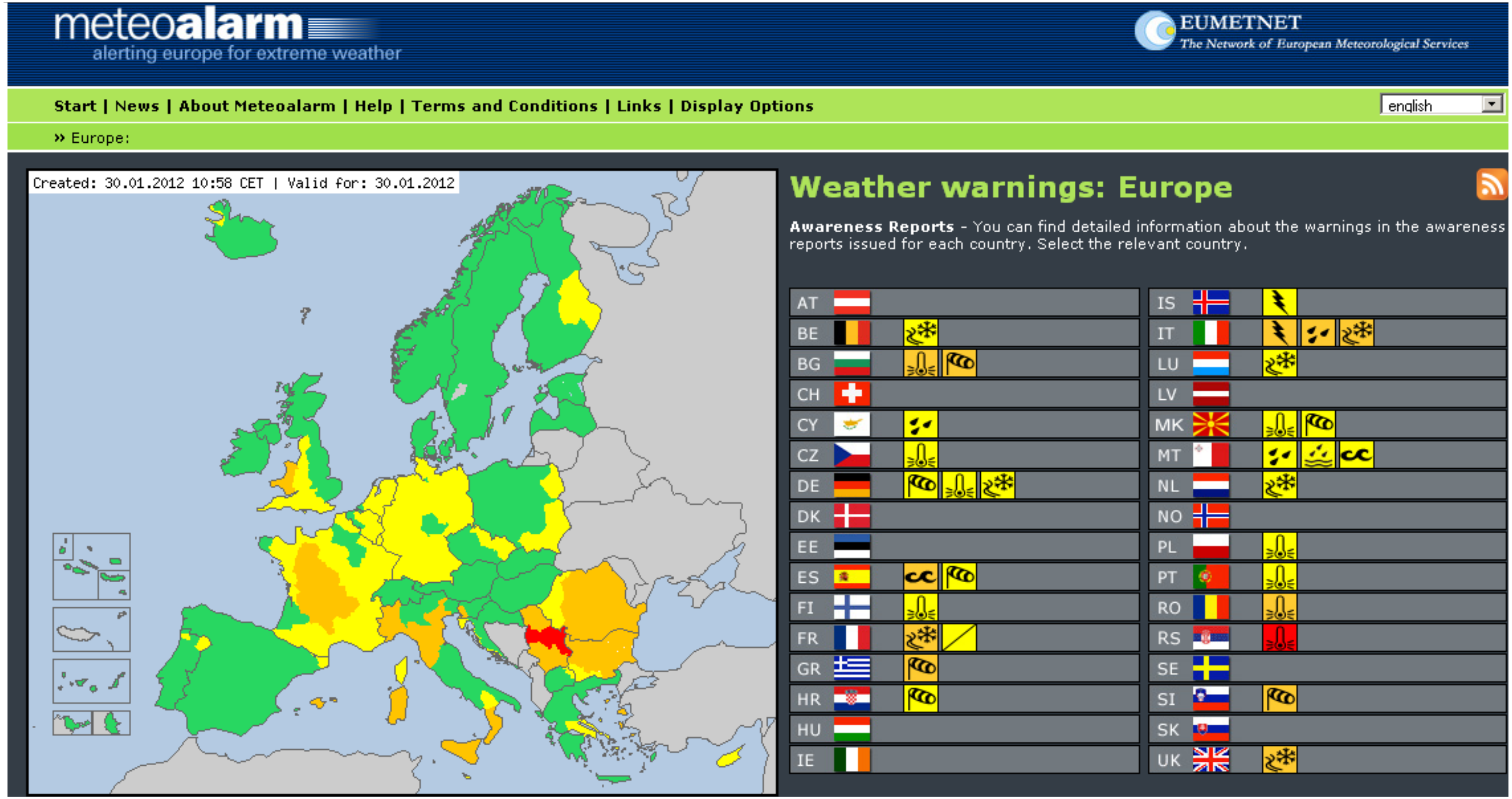




Met Office


Sun
Birmingham
London
Provided by Met Office
London & South East England
Snow
Issued at: 1115 on Sat 9 Feb 2013
Valid from: 0600 on Sun 10 Feb 2013
Valid to: 2359 on Sun 10 Feb 2013
Early rain over western Britain is expected to turn to snow as it spreads eastwards during Sunday. Snow cover is likely to be very variable, with some places seeing little settling, others 2-4 cm, and with the potential for 10 cm or more over parts of the Midlands, Kent an Essex, especially later in the day. The public should be aware of the risk of disruption, particularly to travel.
More details...
United Kingdom
Chief Forecaster's Assessment
A front moving into Britain on Saturday will stall during Sunday. As a low pressure centre forms along the front, cold air is expected to be drawn into the frontal zone causing the rain to turn increasingly to snow across in many regions.
There is more than average uncertainty even at this late stage concerning the timing and extent of this snow, and it is possible that this alert will be upgraded to amber.
Weather Impact Matrix
High
Likely
Low
Low
Impact
High
East of England
South West England
London & South East England
Sun
Sat
Sun
Mon
Tue
Wed
1 ×
?

MeteoAlarm



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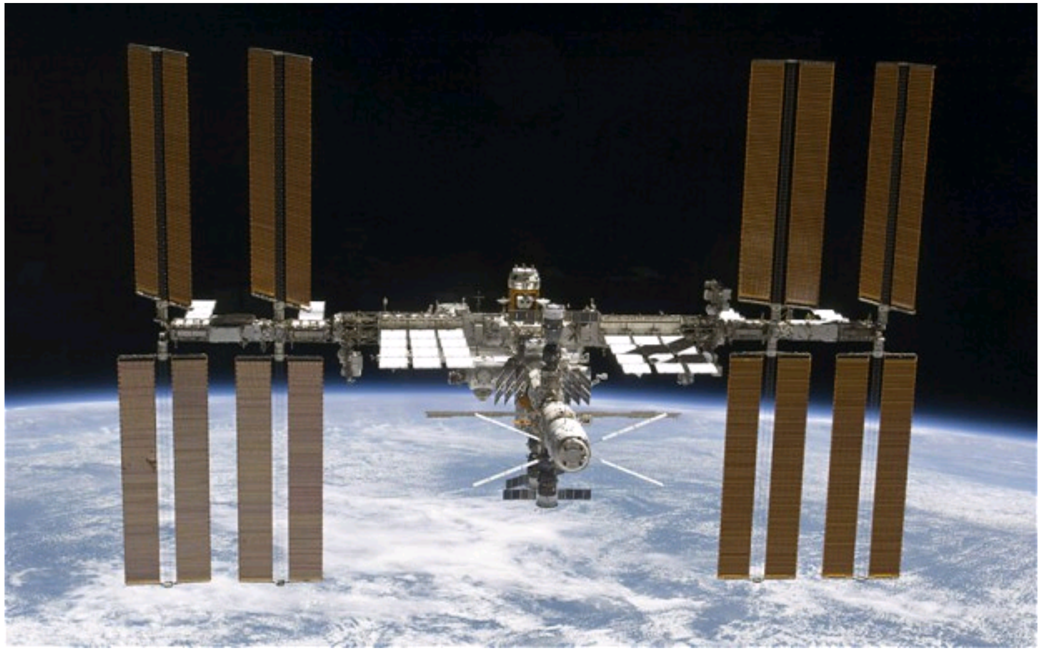
Summary - why do we run an ensemble?

- The best method we have to produce flow-dependent probabilistic weather forecasts
- The ensemble of forecasts provides a range of future scenarios consistent with our knowledge of the initial state and model capability
  - Provides explicit indication of uncertainty in today's forecast
  - Range of ensemble based products for different users
- Learn more about the ECMWF forecast products in the rest of the course
- Read more in the ECMWF products User Guide
  - http://www.ecmwf.int/products/forecasts/guide/

ECMWF

Ensemble forecasts support decision making

- The International space station is threatened by space debris
- An avoidance maneuver will be conducted if the probability of collision is greater than 1 in 10,000



- Do you have to make important decisions?
- The ensemble gives you the information you need to help you make these decisions

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Decision analysis - the cost-loss model

- Simplest possible case - but shows many important features
- There are only two important weather types: weather is either “good” or “bad”
- A particular user or decision maker will be affected by bad weather - they have a choice of two actions
  - If they do nothing and bad weather occurs they suffer a loss L
  - However, they can decide to take some protective action to prevent this possible loss, but it will cost C

Why is the probability forecast better?

- If the cost of protection is high wait until event is more certain
  - False alarms are more important
- If the loss is greater then protect even at low probability
  - Missed events are more important
- Changing the probability threshold at which to take action gives different hit rates and false alarm rates
- The optimal probability threshold depends on the user: p_t=C/L
- Using the probabilities allows decision makers to take decisive action according to their own risks – these are different for each user
- Even if the user does not have an explicit cost/loss they are still aware of the relative importance of false alarms and missed events

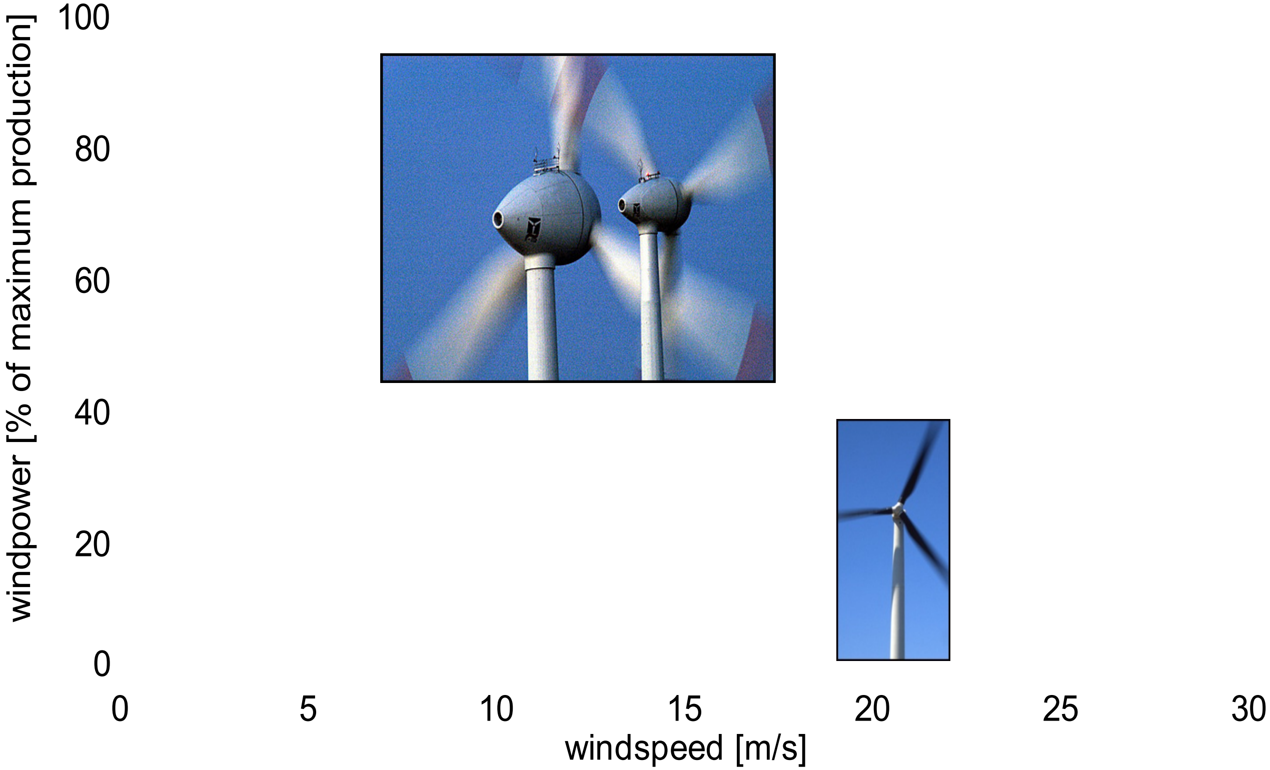
Wind farm example

turbines must be stopped in high winds

Must continue to supply electricity even if not generating

So may need to buy extra energy

Cheaper to buy in advance



Decision to make:

Should I buy extra energy to protect against ff>25 m/s, yes or no?

Financial costs to wind farm manager

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 €	200 €
Protection: NO	1000 €	0 €

Value of deterministic forecasts

- If no forecast just use climatological information
  - Always protect (if often occurs)
  - Never protect (if rarely occurs)
- Using forecast: protect when event is forecast
  - Can save money compared to using climate
- Value

$$V = \frac{\text{saving from using forecast}}{\text{saving from perfect forecast}}$$

- V = 0 forecast is no better than climate
- V = 1 forecast is perfect (no misses, no false alarms)

Value of deterministic forecast

Protect when event is forecast

Value of using forecast = saving compared to not using forecast

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Forecast: YES Protect: YES	Hit Cost = 200 €	False alarm Cost = 200 €
Forecast: NO Protect: NO	Miss Loss = 1000 €	Correct reject 0 €

Value, forecast quality and the user

Value can be written in terms of hit rate (H), false alarm rate (F) and the "cost-loss ratio" of the user (C/L):

$$V = (1-F) - \left(\frac{1-C/L}{C/L}\right)\left(\frac{\bar{o}}{1-\bar{o}}\right)(1-H) \text{ if } C/L < \bar{o}$$

$$V = H - \left(\frac{C/L}{1-C/L}\right)\left(\frac{1-\bar{o}}{\bar{o}}\right)F \text{ if } C/L > \bar{o}$$

- **Value depends on forecast quality: H and F**
- **but value also depends on the user (C/L)**
- **and on the weather event ($\bar{o}$)**

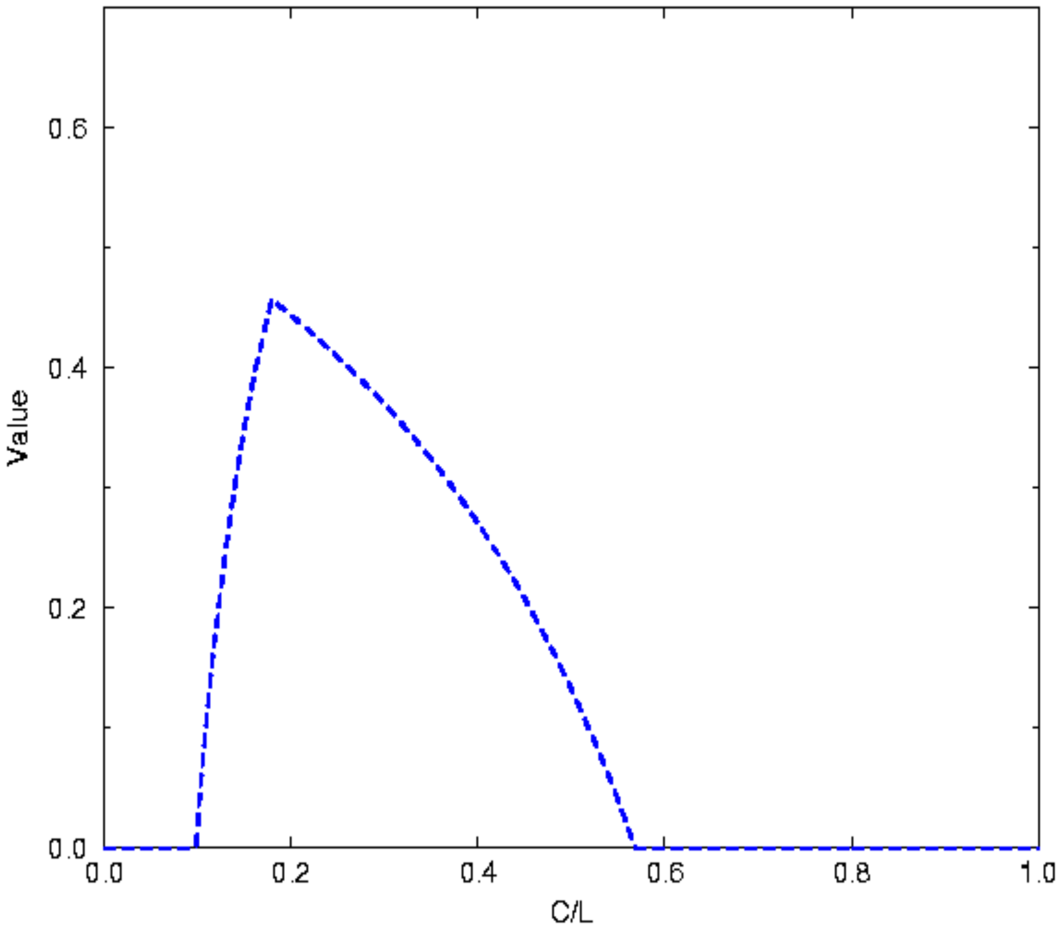
Cost-loss wind farm manager

Cost-loss ratio = 200/1000

= 0.2

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 €	200 €
Protection: NO	1000 €	0 €

Value for different users



High loss from missed event (hit rate important)

High cost to protect (false alarm rate important)

Value of probability forecasts

- Using a deterministic forecast is straightforward: take action if bad weather is forecast, otherwise do nothing
- What if the forecast is given as a probability of bad weather?
- To make a decision the probability forecast must be converted to a yes/no action
- Choose a probability threshold p_t
  - if $p>p_t$ then take action
  - if $p<p_t$ then do nothing
- Which probability threshold to choose?

ECMWF

Financial costs to wind farm manager

Probability is 30%

30

70

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 €	200 €
Protection: NO	1000 € 30,000 €	0 €

Financial costs to wind farm manager

Probability is 30%

30

70

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € **6,000 €**	200 € **14,000 €**
Protection: NO	1000 €	0 €

Financial costs to wind farm manager

Probability is 30%

30  70 

Better to protect (costs €20000) than not protect (costs €30000)

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € 6,000 €	200 € 14,000 €
Protection: NO	1000 € 30,000 €	0 €

ECMWF

Financial costs to wind farm manager

Probability is 10%

10  **90** 

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 €	200 €
Protection: NO	1000 € 10,000 €	0 €

Financial costs to wind farm manager

Probability is 10%

10  **90** 

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € **2,000 €**	200 € **18,000 €**
Protection: NO	1000 €	0 €

Financial costs to wind farm manager

Probability is 10%

10  **90** 

Better to NOT protect (costs €10000) than protect (costs €20000)

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € **2,000 €**	200 € **18,000 €**
Protection: NO	1000 € **10,000 €**	0 €

ECMWF

Financial costs to wind farm manager

Probability is 20%

20  **80** 

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 €	200 €
Protection: NO	~~1000 €~~ **20,000 €**	0 €

Financial costs to wind farm manager

Probability is 20%

20  **80** 

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € **4,000 €**	200 € **16,000 €**
Protection: NO	1000 €	0 €

Financial costs to wind farm manager

Probability is 20%

20  **80** 

Same to protect as not protect (€20000)

	event occurs i.e. ff ≥ 25 m/s	event does NOT occur i.e. ff < 25 m/s
Protection: YES	200 € **2,000 €**	200 € **18,000 €**
Protection: NO	1000 € **20,000 €**	0 €

Probability threshold depends on user

- If the cost of protection is expensive wait until event is more certain (higher probability)
  - False alarms are more important
- If the loss is greater then protect even at low probability
  - Missed events are more important
- The threshold depends on the user: p_t=C/L

Value of probability and deterministic forecasts compared