# Weather prediction in a world of uncertainties: should we care about model uncertainty?

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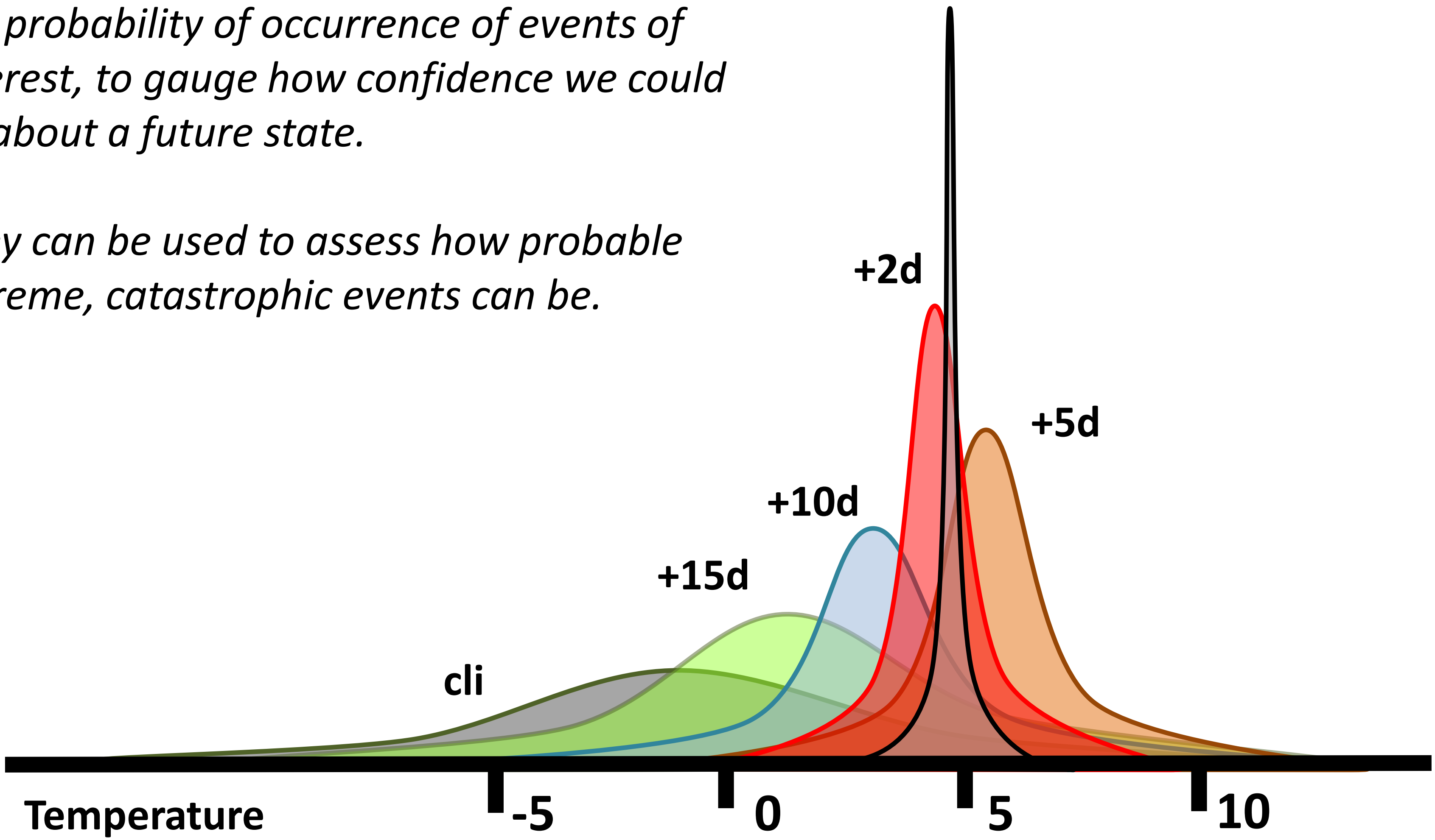
# Outline

1. The context: *'think ensemble'*
2. Should ensembles simulate model uncertainties?
3. Aiming for consistency in the ECMWF ensembles
4. Recommendations from past WSs (2005/2007/2011)
5. Conclusions

# 1. The context: *'think ensembles'*

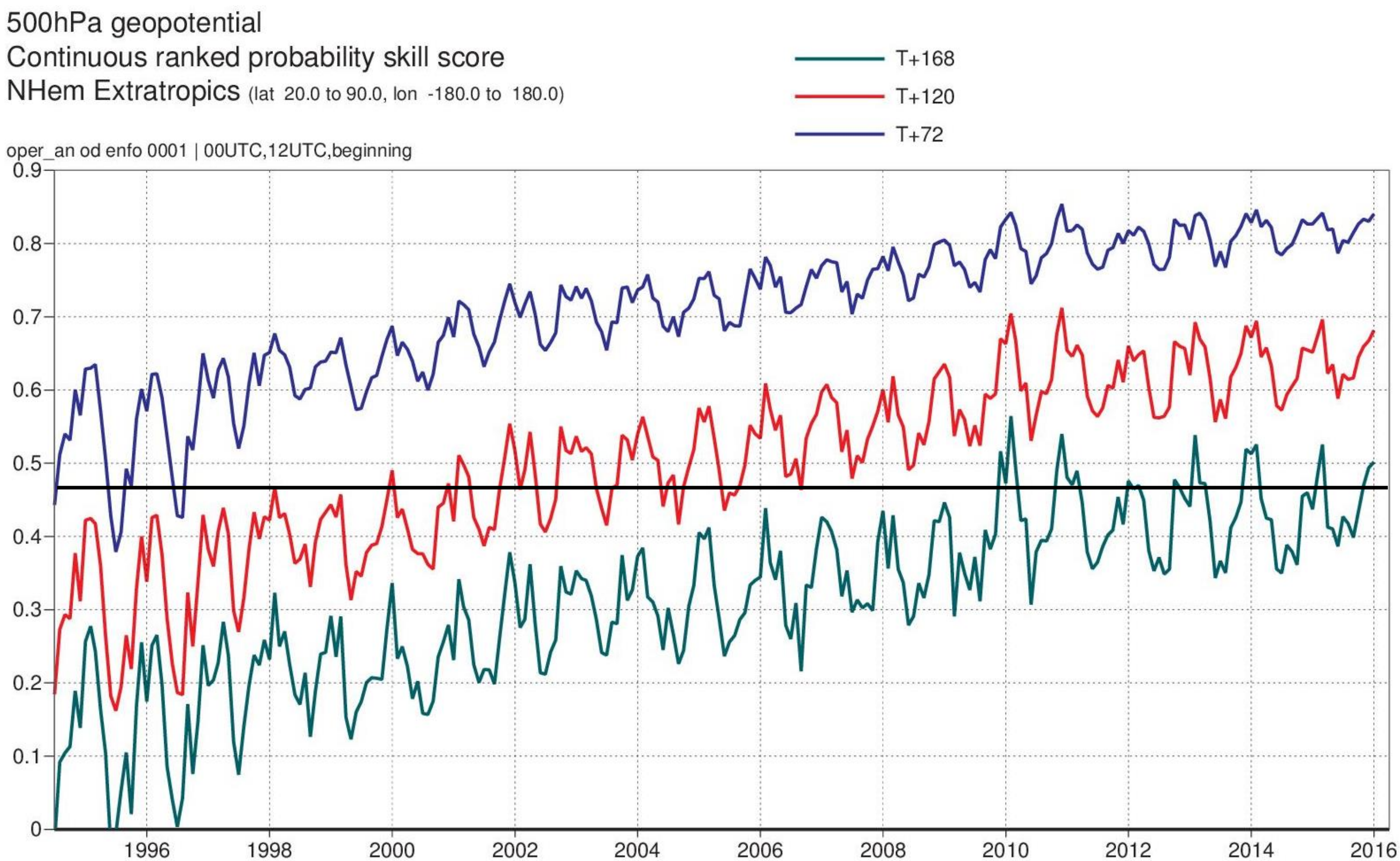
*Because ensembles can be used to estimate the probability of occurrence of events of interest, to gauge how confidence we could be about a future state.*

*They can be used to assess how probable extreme, catastrophic events can be.*



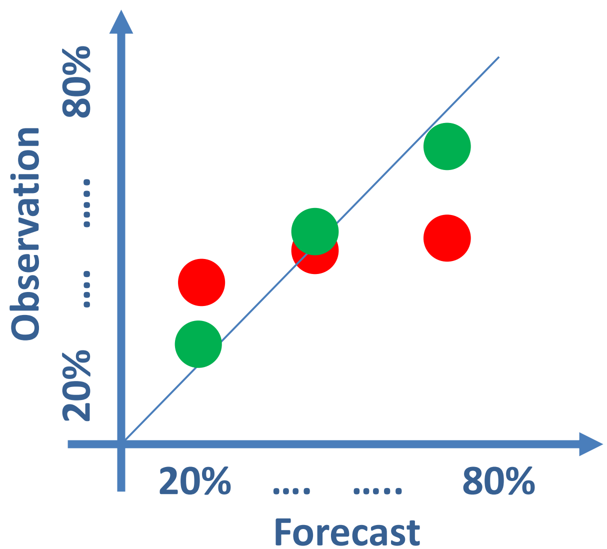
# 1. Ensembles are valuable if they are skilful and reliable

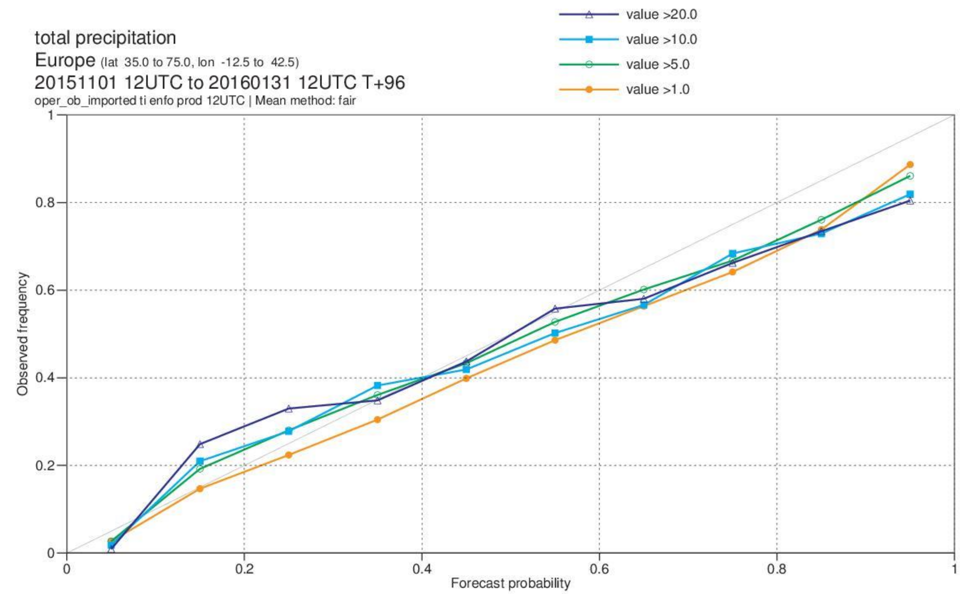
CRPSS is a measure of skill. Today, +7d fcs are as good as +3d fcs 20y ago!

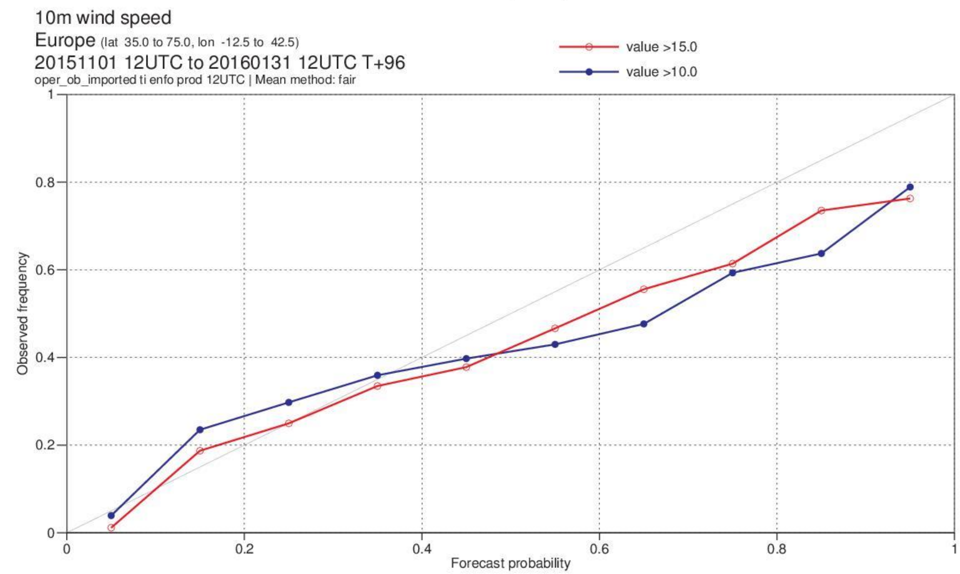


# 1. Ensembles are valuable if they are skilful and reliable

One way to check the ensemble reliability is to assess whether the average forecast and observed probabilities of a certain event are similar.



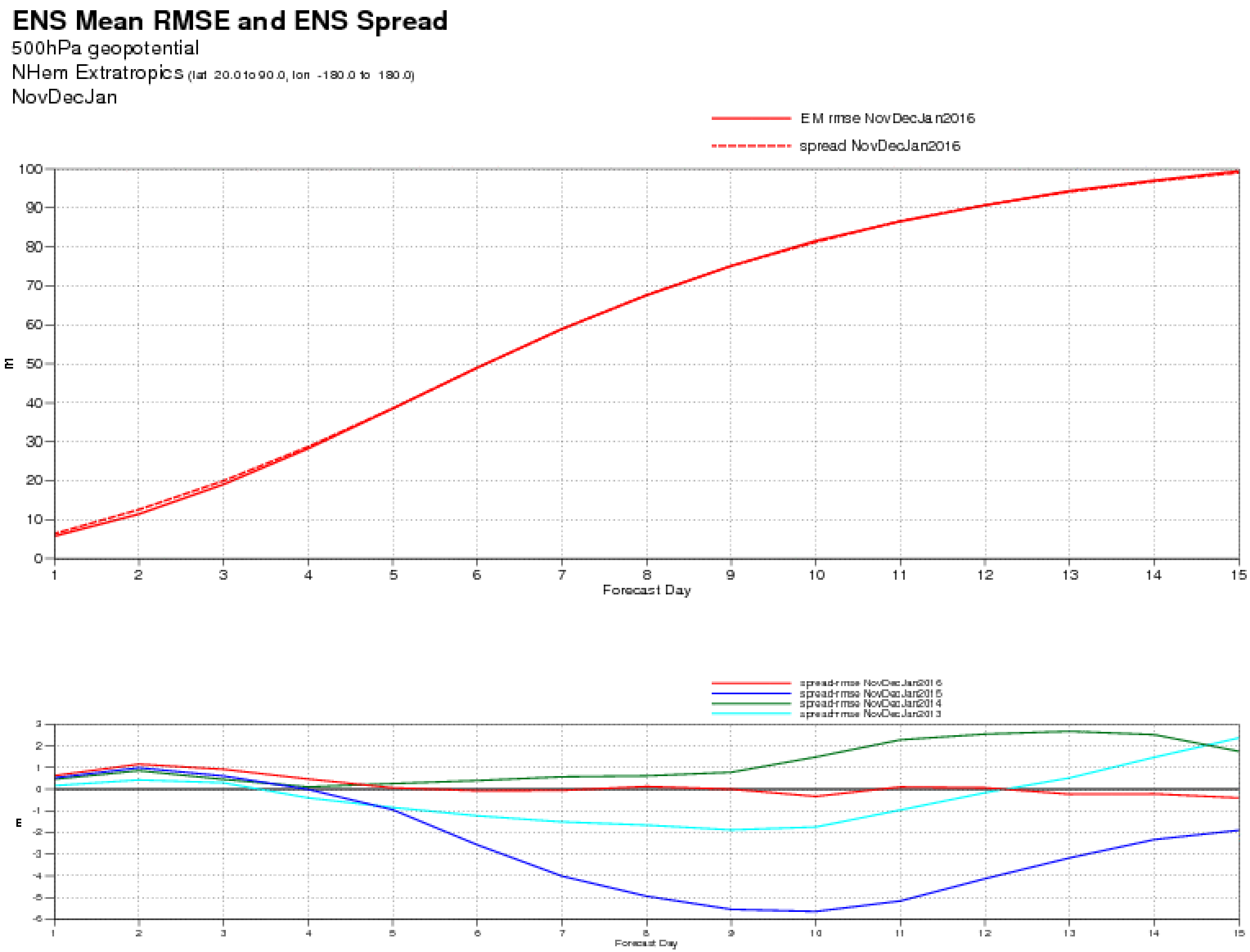



# 1. In a reliable ensemble, on average <spread>~<er(EM)>

In a reliable ensemble the average spread matches the average error of the ensemble mean.

This plot shows the two curves for Z500 over NH in ND15J16.



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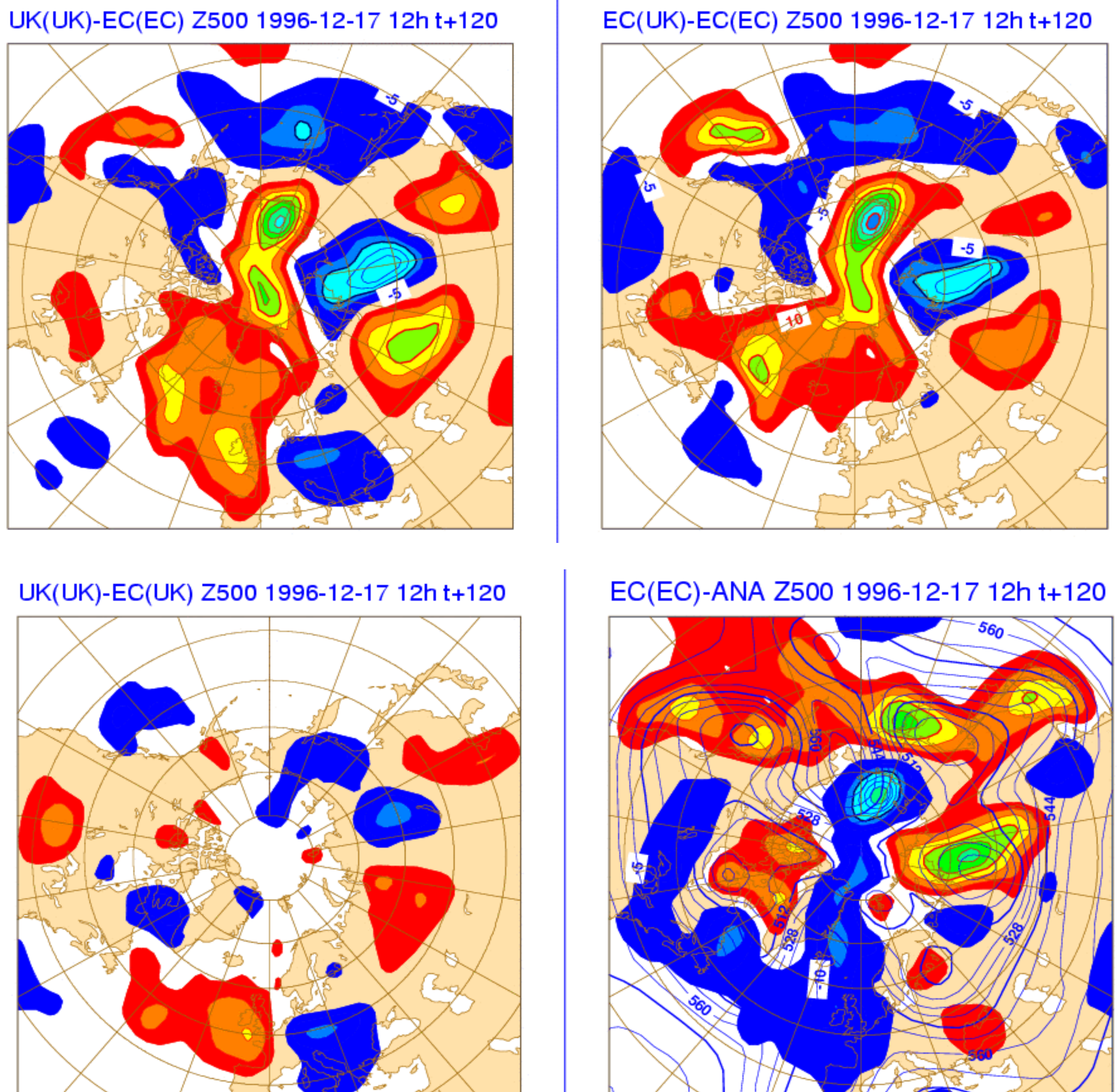
# 2. 1991/92: simulation of initial uncertainties

We started (in 1991) focusing on the simulation of the effects of initial uncertainties.

Indeed, works from the 1990s (see e.g. a figure from *Harrison et al* 1999) showed that initial differences explain most of the differences between ECMWF-from-ECMWF-ICs and UKMO-from-UKMO-ICs forecasts.

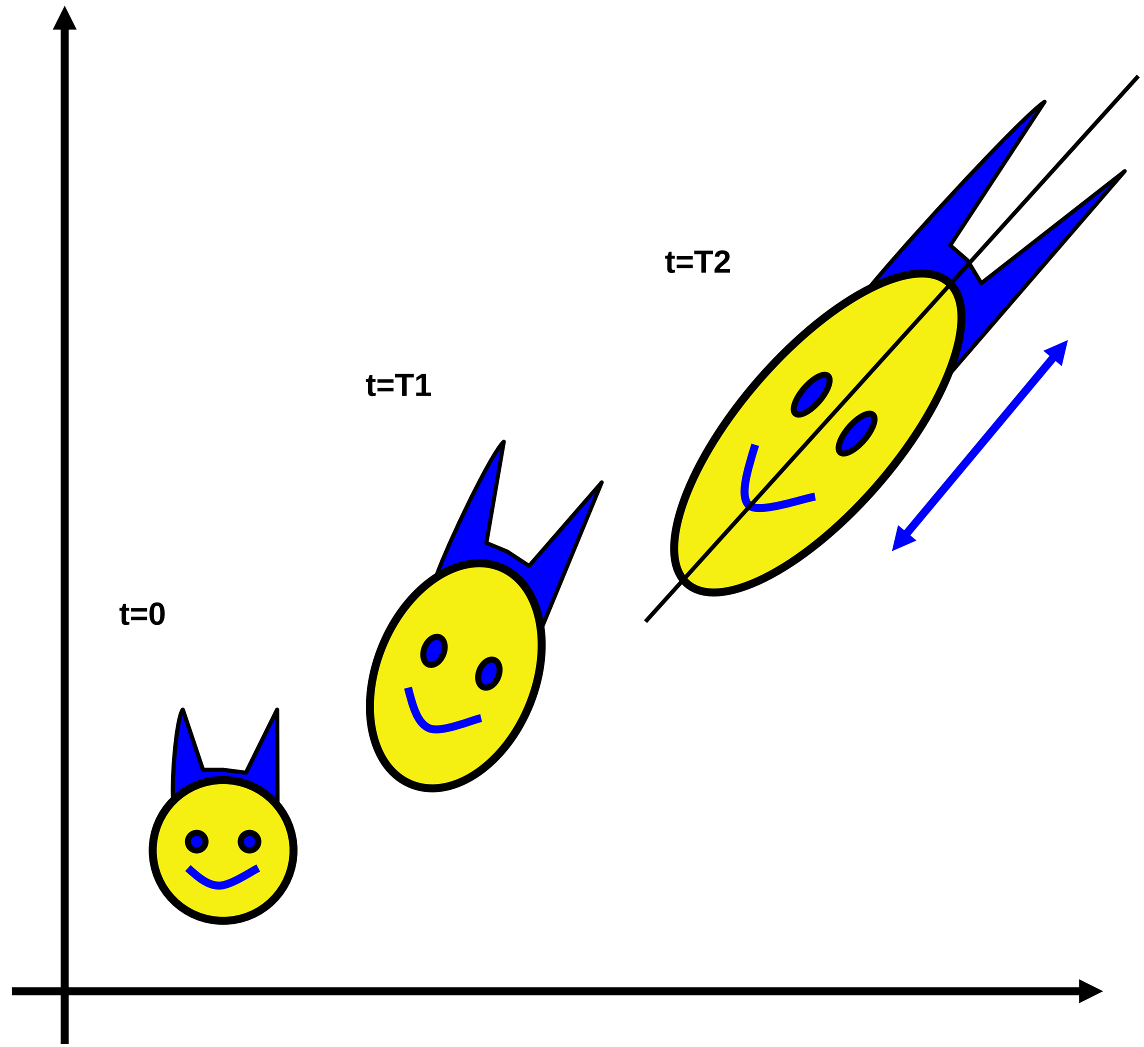


# 2. How should initial uncertainties be defined?

We did it following a 'singular vector' approach.

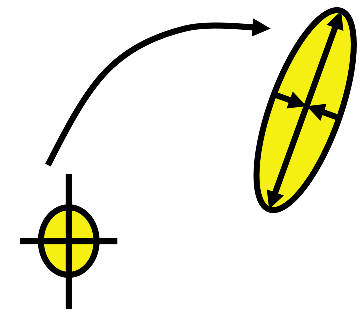
The idea was that initial perturbations' pointing along the directions of maximum potential growth, amplify the most. Thus if we knew them, we could estimate the potential maximum forecast error.



# 2. Singular vectors (SVs)

The directions of maximum growth were computed by solving an eigenvalue problem:

$$E_0^{-1/2} L^* E L E_0^{-1/2} \nu = \sigma^2 \upsilon$$

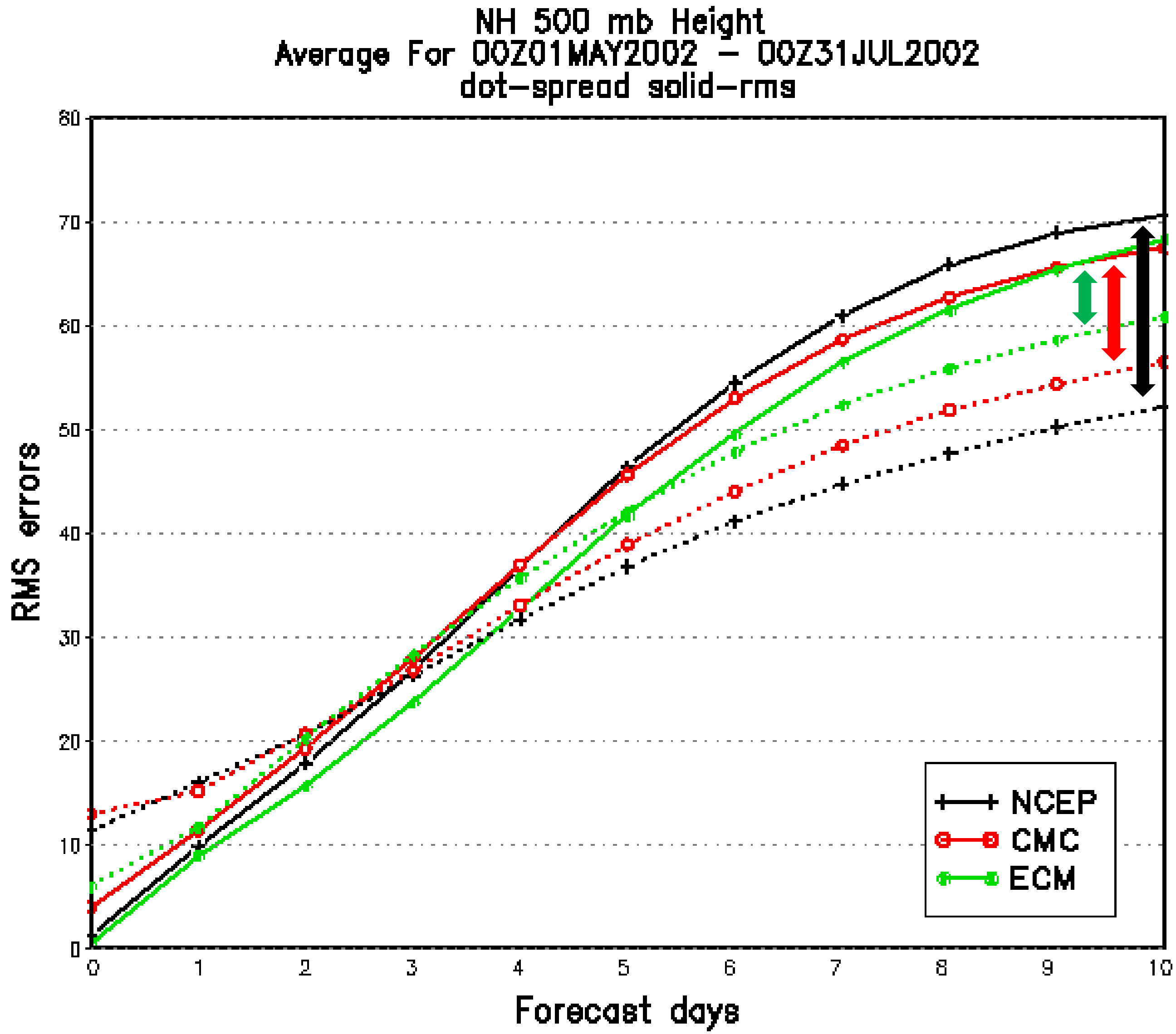


where:

- $E_0$ and $E$ are the initial and final time metrics
- $L(t,0)$ is the linear propagator, and L* its adjoint
- The trajectory is time-evolving trajectory
- $t$ is the optimization time interval

# 2. Should ensembles simulate model uncertainties?

Towards the end of the 1990s, it was clear that if we wanted to improve the accuracy and reliability of our ensembles, we needed to simulate also model uncertainties.



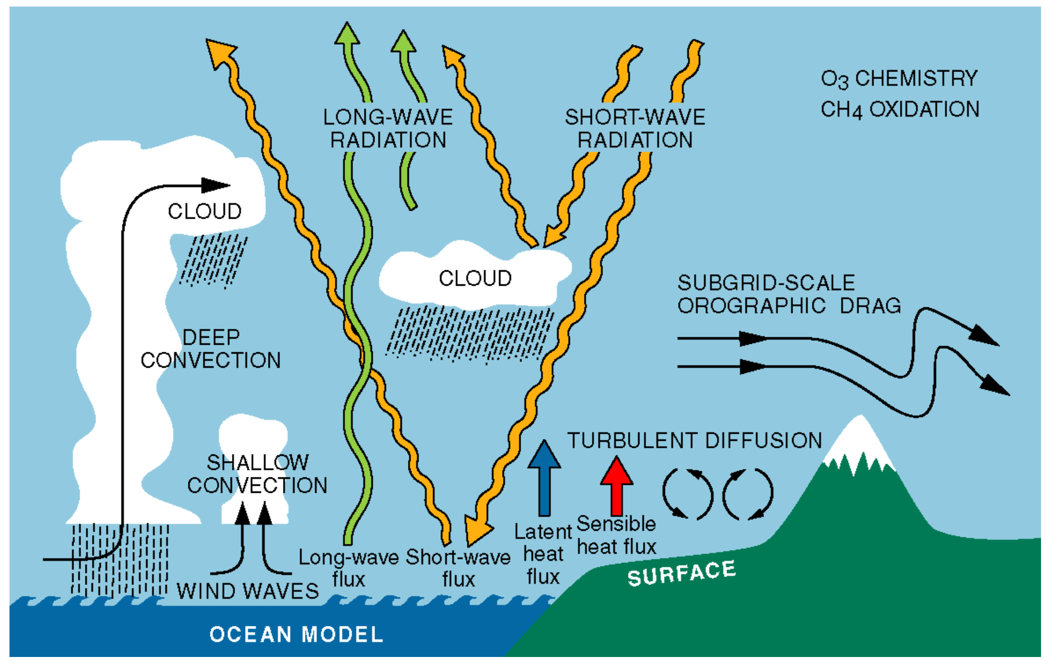
# 2. What are the sources of model uncertainties?

The reality is so complex that we can only describe its behavior in an approximate way.

We do it as best as we can, but approximations are made.

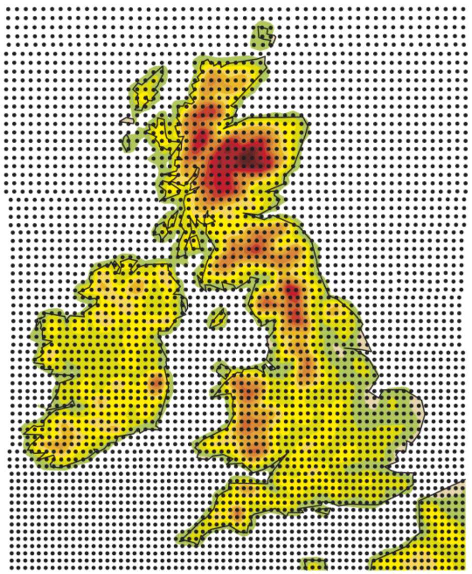
**ECMWF MODEL / ASSIMILATION SYSTEM**

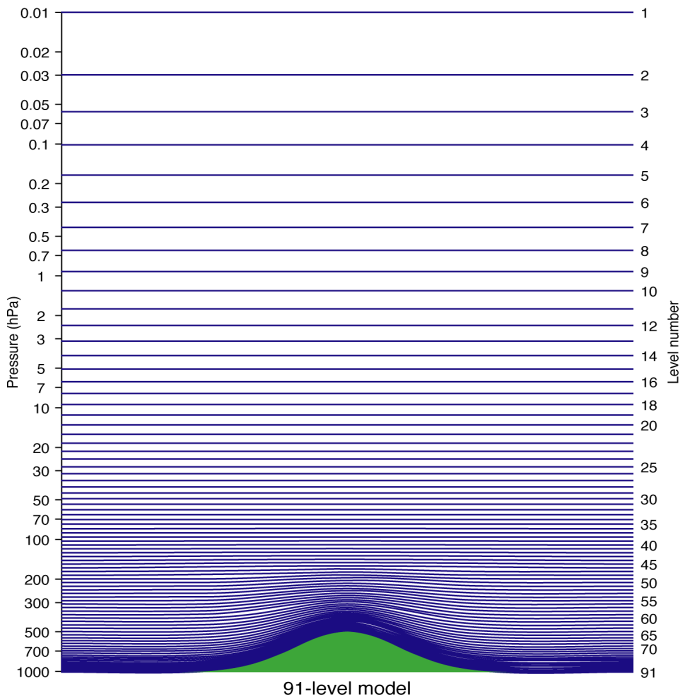
| | | | | |
|---|---|---|---|---|
| ATMOSPHERE | STRATOSPHERE | DYNAMICS–RADIATION–SIMPLIFIED CHEMISTRY | | |
| | TROPOSPHERE | DYNAMICS–RADIATION–CLOUDS–ENERGY & WATER CYCLE | | |
| OCEAN / LAND | | OCEAN | LAND HYDROSPHERE | LAND BIOSPHERE |
| | | OCEAN SURFACE WAVES<br>OCEAN CIRCULATION<br>SIMPLIFIED SEA ICE | SNOW ON LAND<br>SOIL MOISTURE FREEZING | LAND SURFACE PROCESSES<br>SOIL MOISTURE PROCESSES<br>SIMPLIFIED VEGETATION |



## 2. What are the sources of model uncertainties?

Furthermore, resources' availability limits the scales that models 'see'. In the ECMWF ENS, the atmosphere is seen as a mesh with 1.4 billion ($10^9$) cells with a grid of about 16 km and 91 levels.





## 2. The ECMWF operational ensemble (ENS) today

Each ensemble forecast is given by the time integration of perturbed equations

$$e_j(d,T) = e_j(d,0) + \int_0^T [A(e_j,t) + P(e_j,t) + \underline{\delta P_j(e_j,t)}]dt$$

$$\delta P_j(\lambda,\varphi,p) = r_j(\lambda,\varphi)P_j(\lambda,\varphi,p) + F_\Psi(\lambda,\varphi,p)$$

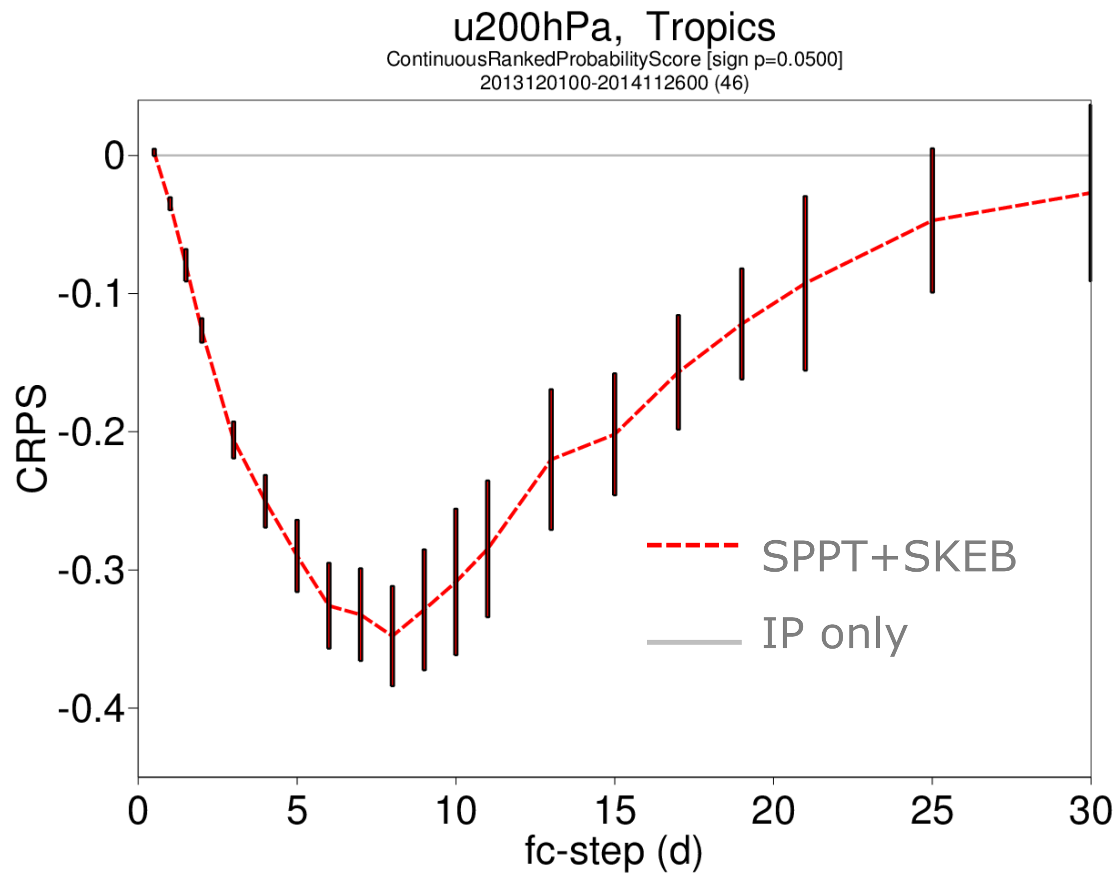
SPPT: Stochastically Perturbed Parameterized Tendencies
*(to represent uncertainty associated with parameterisations)*

SKEB: Stochastic Kinetic Energy Backscatter
*(to represent unresolved upscale energy transfer)*

# 2. Including model uncertainties improves ENS forecasts

Including model perturbations via the SPPT and SKEB schemes gives rise to better ensembles:

- The ensemble is **more reliable** (less under-dispersive);
- **Improved probabilistic skill** is observed at a range of lead times (e.g. see in plot improved CRPS for high-level winds in the Tropics)



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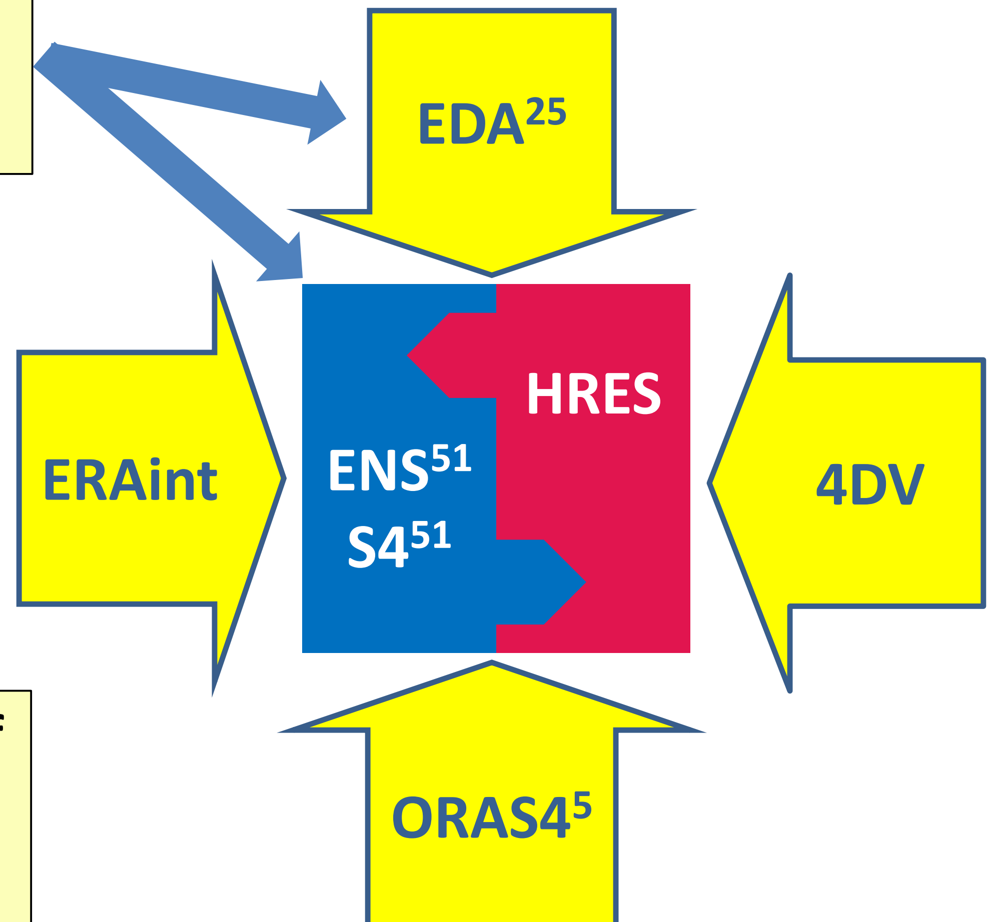
# 3. We aim to be consistent in our ensembles

**The ensembles simulate the effect of:**

- **Observation/initial uncertainties**
- **Model uncertainties (2 stochastic schemes)**




**The ensembles give us estimates of the PDF of analyses and forecast states:**
**PDF(0) << 4DV+EDA$^{25}$+ORAS4$^{5}$**
**PDF(0) << ERAint+ORAS4$^{5}$ (the past)**
**PDF(T) << HRES+ENS$^{51}$/S4$^{51}$**

# 3. Full consistency in the ensembles is not there yet

| | Operational suite | Uncertainty sources | | |
|---|---|---|---|---|
| | | Obs | ICs | Model |
| HRES | $T_{CO}1279$ (~9 km) L137 (0-10d) | -- | -- | -- |
| 4DVAR | $T_{CO}1279$ (inner $T_{CO}255/319/399$) L137 | -- | -- | -- |
| EDA | 25 members: $T_{CO}639$ (~18km) L137 | δo | -- | SPPT(1L) |
| ENS | 51 members: $T_{CO}639$ (~18km) L91 (0-15d)<br>$T_{CO}319$ (~36km) L91 (15-46d)<br><br>- Ocean: NEMO ORCA100z42 *(to 025z75 in Q4)* | --<br><br><br>-- | $EDA^{25}$ & $SVs^{50*Nareas}$<br><br>$ORAS4^{5}$ | SPPT(3L) & SKEB<br><br><br>-- |
| SEA S4 | 51 members: $T_L255$ (~80km) L91<br>*(to $T_{CO}319L137$ in 2017)*<br><br>- Ocean: NEMO ORCA100z42 *(to 025z75 in 2017)* | --<br><br><br>-- | SVs<br><br><br>$ORAS4^{5}$ | SPPT(3L) & SKEB<br><br><br>-- |

$T_{CO}$ – Cubic octahedral Gaussian reduced grid
$T_L$ – Gaussian linear grid

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# 4. WSs' recommendations: diagnostic and validation

- 2005 - WS on *'Representation of sub-grid scales'*:
  - Develop a methodology to **diagnose** the spectral energy transfer
  - Increase the **validation** work
  - Consider using coarse-graining strategies (with a factor of 10 difference in resolution) to determine the statistics that an effective stochastic scheme should generate

- 2007 WS on *'Ensemble Prediction'*:
  - More emphasis should be given to **understanding** model error
  - Experiments should be designed and performed to **diagnose** and **isolate** model error

- 2011 WS on *'Model uncertainty'*:
  - Initial tendencies/analysis increments can be used to **determine** model error statistics
  - Use Cloud Resolving Models and observational data to **evaluate** stochastic-based parameterisations (e.g. of clouds and convection)

# 4. WSs' recommendations: <u>physical basis</u>

- 2005 - WS on '*Representation of sub-grid scales':*
  - Identify and explore the **physical basis** of the stochastic schemes
  - Target improvements in the statistics of specific **physical phenomena**
- 2007 WS on '*Ensemble Prediction*':
  - Link more the future efforts with developments in **physical parameterisations**
  - A multi-model approach is very pragmatic and useful, but it should not be used to avoid the difficult problem of improving the modelling of model uncertainties
  - There should be **closer interaction** between scientists developing parameterisation schemes and 'models of model error'
- 2011 WS on '*Model uncertainty*':
  - Establish a firm **physical basis** for stochastic perturbations
  - Apply 'falsification concepts': does the scheme invalidate **physical constraints**?
  - Develop physical parameterisations where the **physical basis for uncertainty is made explicit**, and include in them explicitly uncertainty treatments (like stochastic ones)
  - Include uncertainty resulting from the **dynamical** core and **physics-dynamics** interactions

# 4. WSs' recommendations: comparison and testing

- 2005 - WS on *'Representation of sub-grid scales'*:
  - **Compare** 'in a clean environment' ECMWF's approaches with others
  - Investigate a **hierarchy of models** and approaches
  - Interact more with the academic community

- 2011 - WS on *'Model uncertainty'*:
  - **Test** existing and new formulations (**taking cost into account**)
  - Statistical post-processing techniques based on hindcasts should be used as a **benchmark** strategy for assessing model uncertainty schemes
  - Start a stochastic parameterisation **inter-comparison project**
  - To assess the impact of model error schemes on the low-frequency variability of the model, **run forecasts that span several years**
  - **Test** model error schemes **across a range of resolutions**

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# 5. Conclusions: few comments on the process to follow

A. Model uncertainty schemes should be included in the ensembles to simulate the effects (on the resolved scales) of model approximations and of missing processes

B. They should make the ensembles more reliable and accurate, and should be judged by looking at how they change the forecast PDF

C. Model uncertainty schemes should be incorporated into the development of the physical parameterisation schemes

D. Cost (human, CPU) should be taken into account

E. Relevant diagnostics should be applied to compare schemes

F. Consistency across ensembles of DA and FCS should be favoured