The ECMWF ensembles

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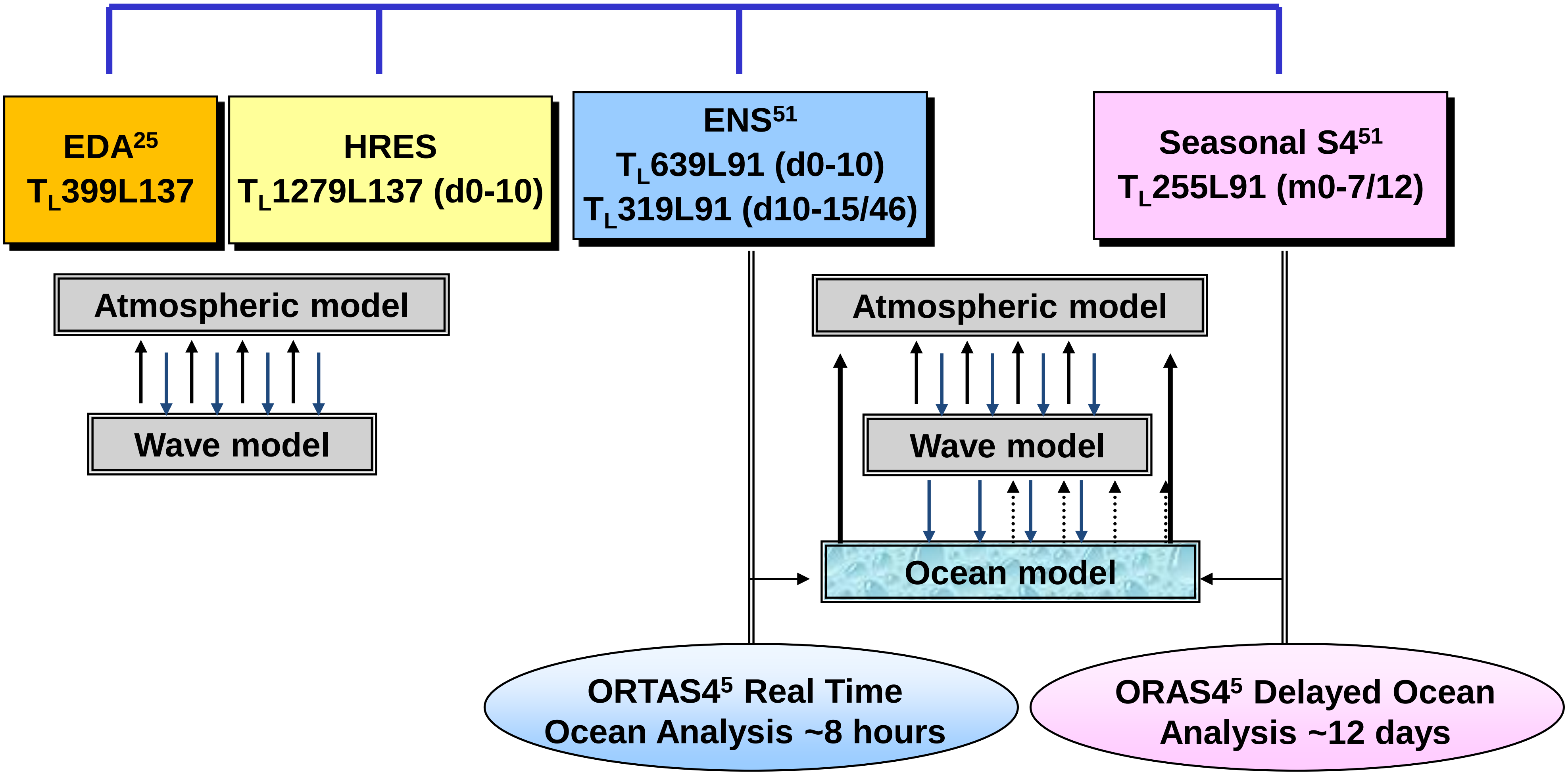
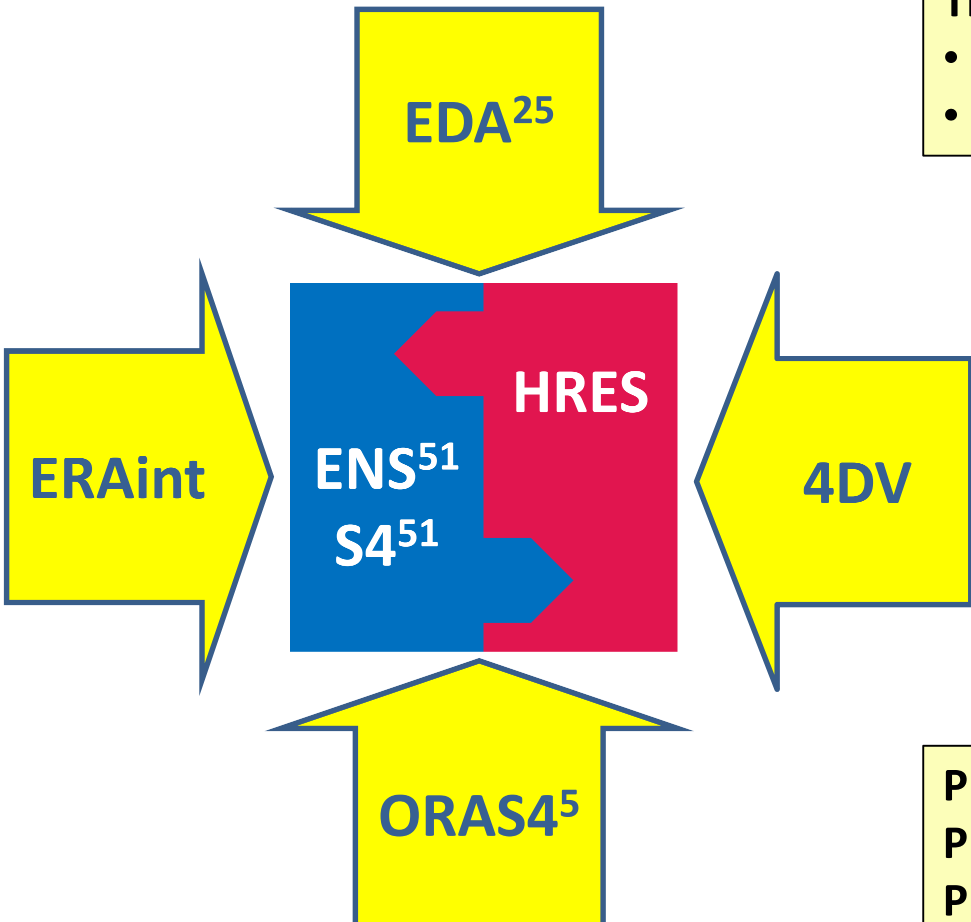
Outline

- Ensembles: the ECMWF way
- The Ensemble of Data Assimilations (EDA)
- The ensemble of ocean analyses (ORAS4)
- The medium-range/monthly ensemble (ENS)
- The seasonal ensemble (S4)
- Ensemble-based international projects: TIGGE, S2S, EUROSIP
- Conclusions: ongoing research and development

Ensembles: the ECMWF way



Ensembles: the ECMWF way



They simulate the effect of:
- **Observation/initial uncertainties**
- **Model uncertainties (2 stochastic schemes)**

PDF(0) << 4DV+EDA^{25}+ORAS4^{5}
PDF(0) << ERA+ORAS4^{5} (the past)
PDF(T) << HRES+ENS^{51}/S4^{51}

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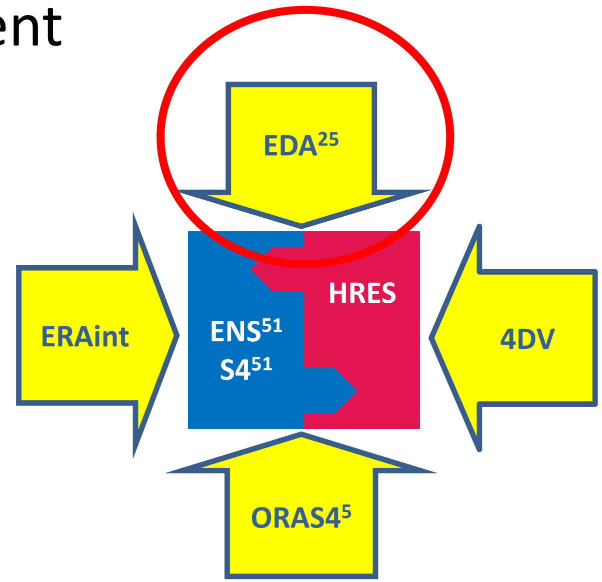
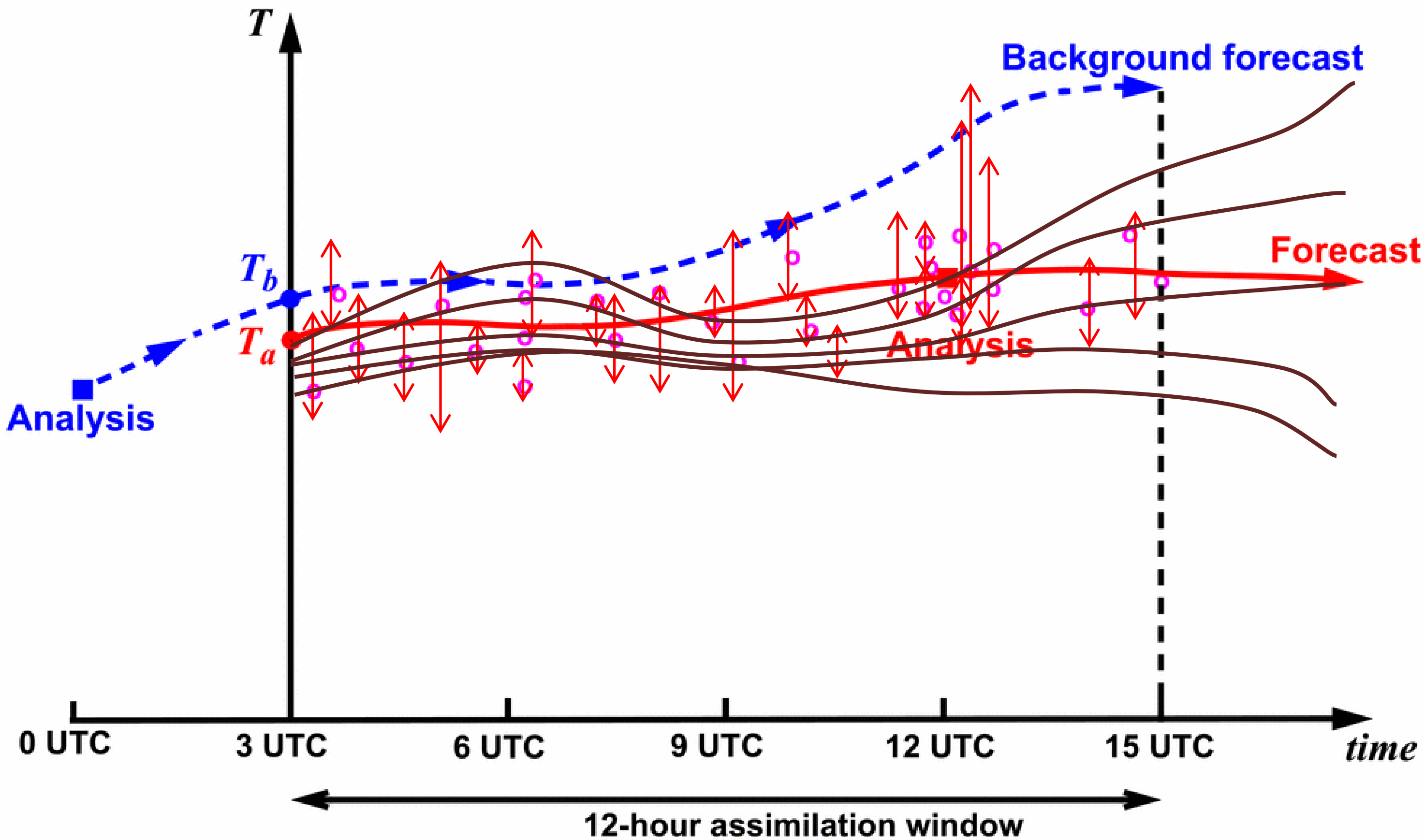


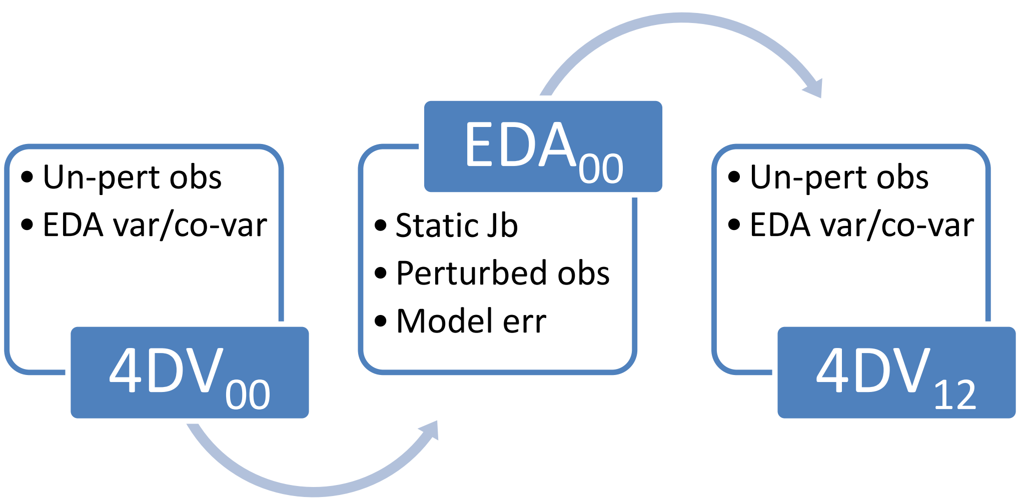
The ECMWF Ensemble Data Assimilation (EDA)

Each observation has an error (instrument, representativeness) and also each model trajectory should take model error into account. A way to generate a set of perturbations that take both these effects is to run an ensemble of analyses.

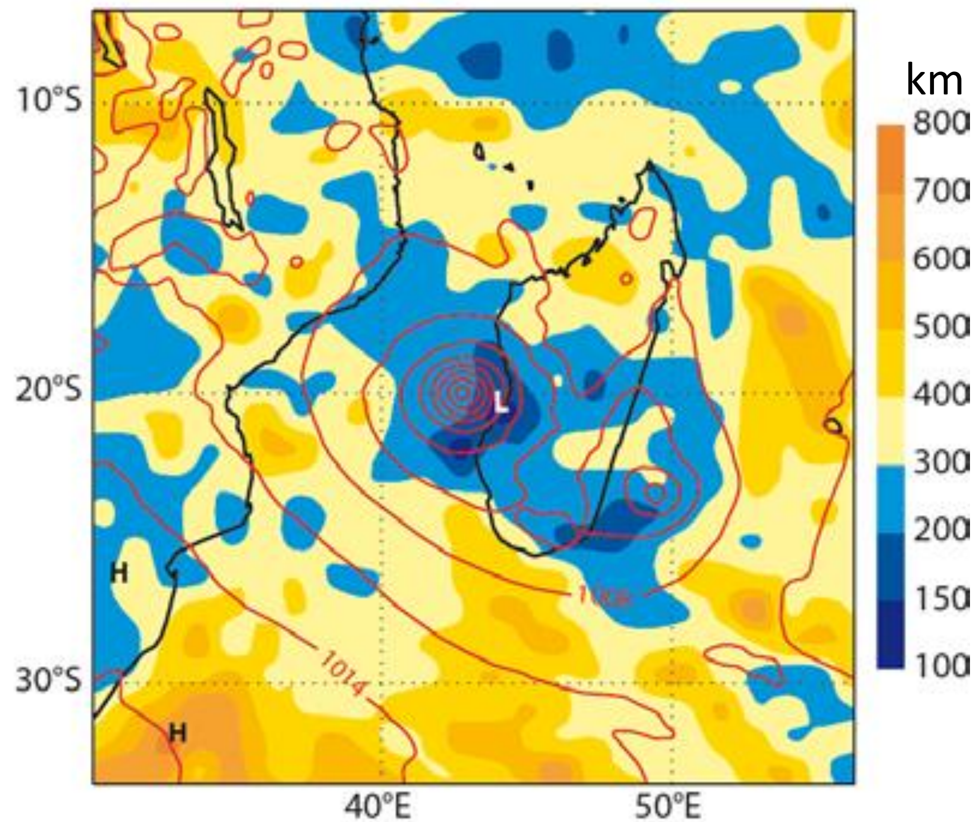


The EDA is used to estimate flow dependent stats

The 25-member **Ensemble of Data Assimilations** provides the 4DV-HRES with flow dependent background error statistics.



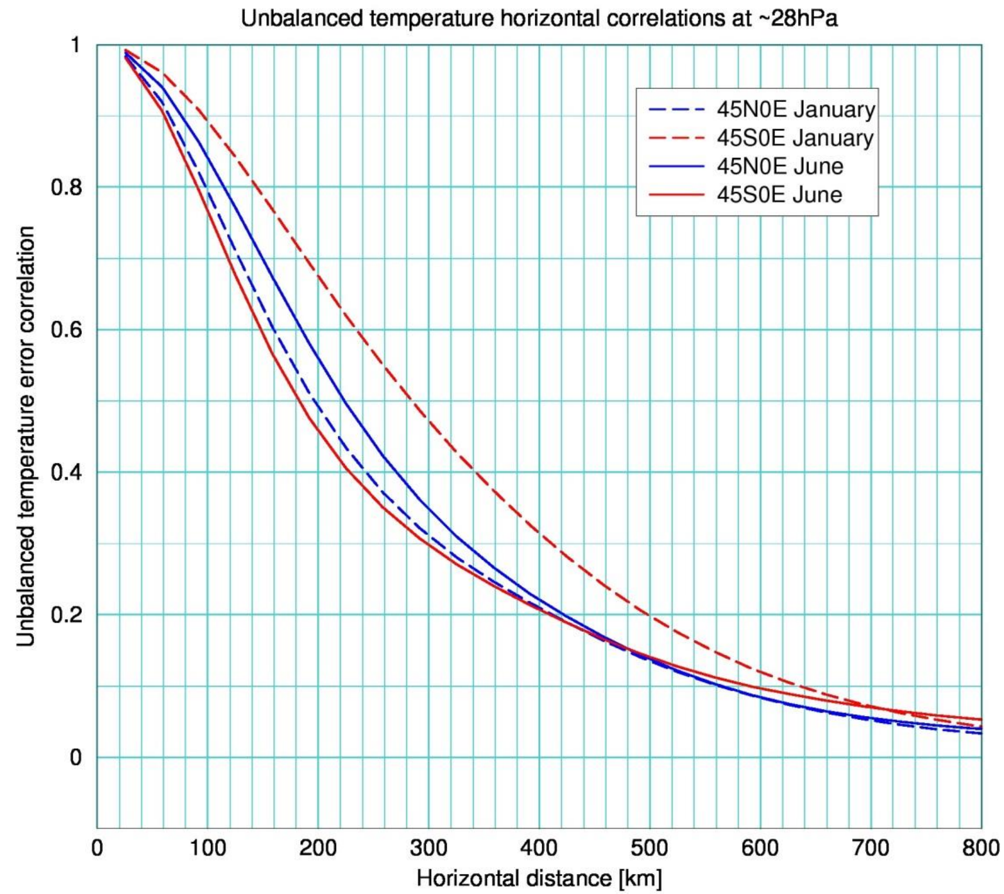
Background error correlation length scale for long(p_{msl}) and p_{msl}



EDA flow-dependent stats are key to assimilate obs

This figure shows the differences between EDA-based temperature correlations at ~28 hPa for two points, (45°N;0°E) (blue) and (45°S;0°E) (red) for a day in January (dashed) and June (solid).

The plot shows, e.g., that the SH winter (red solid) and summer (red dashed) temperature correlations are significantly different, a feature that cannot be accurately presented by climatological correlations.



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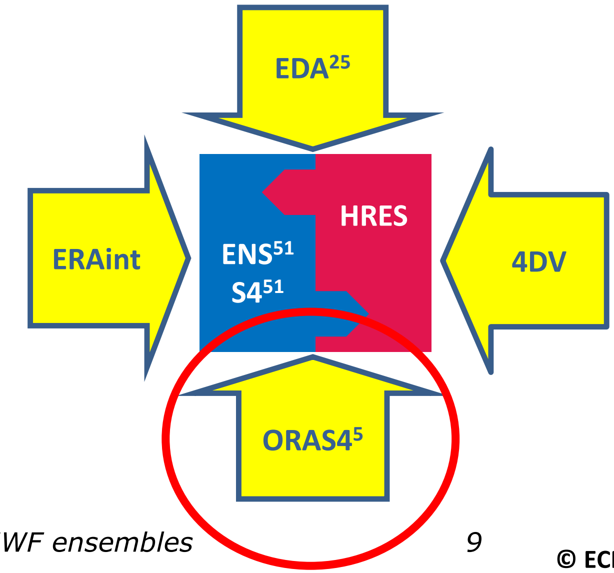
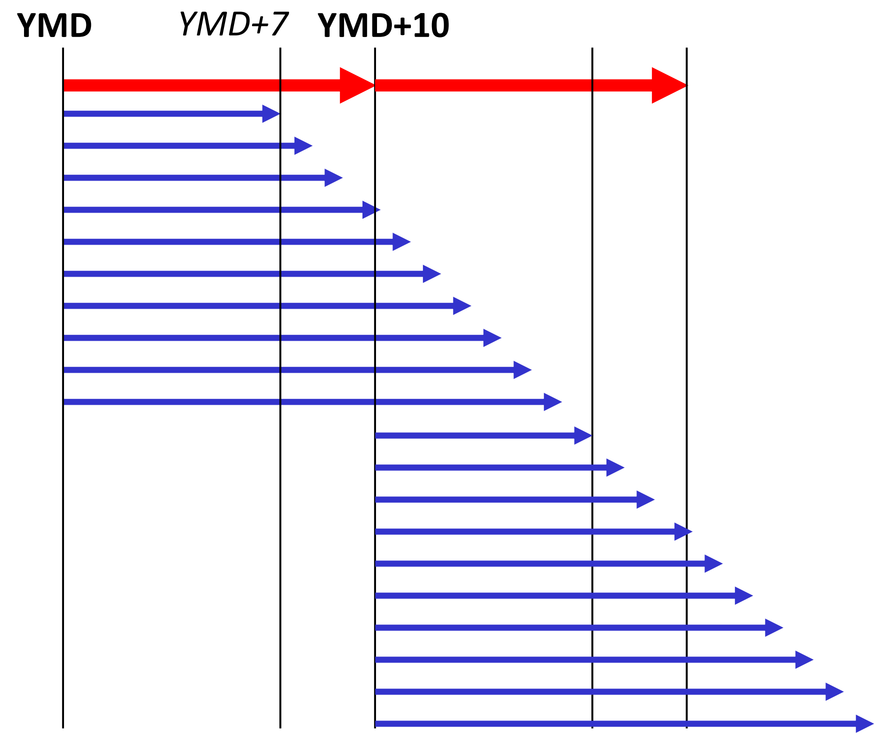


The real-time ensemble ocean analysis (ORTAS4)

ORTAS4 configuration:

- 6-day delay to allow for obs arrival, with an update every 10 days
- Resolution: ORCA_100_z42
- Members: 5 (1 control, 4 pert)
- SST: strong relaxation to gridded SST
- Perturbed atmospheric wind-stress
- Obs coverage unc simulated by rejecting 10% of argo obs and 5% or other obs



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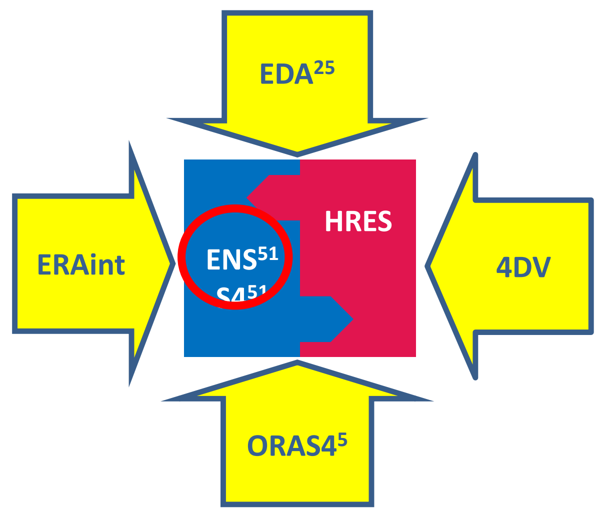
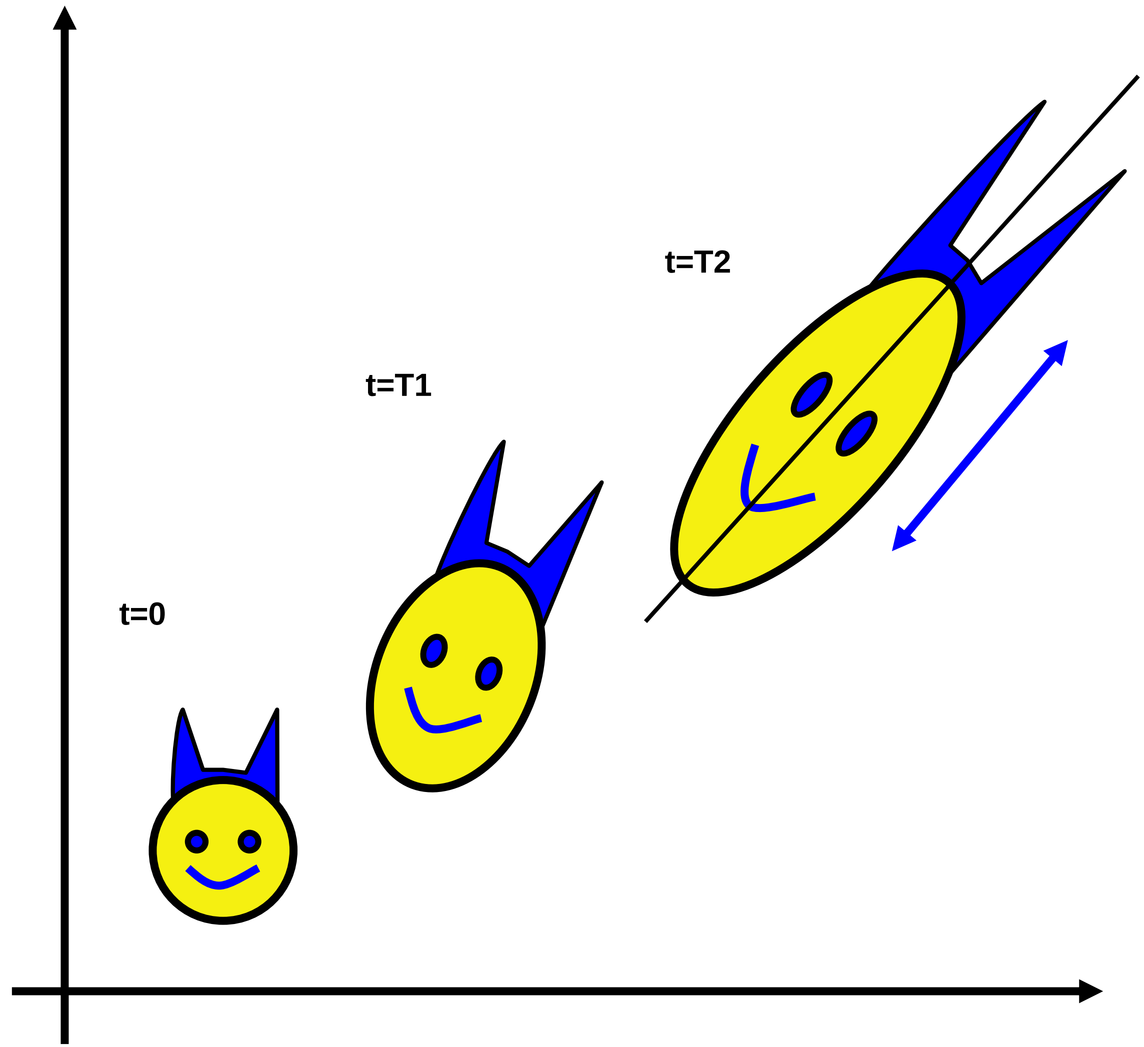


ENS initial perturbations: the singular vectors' component

Perturbations' components pointing along the directions of maximum growth amplify most.

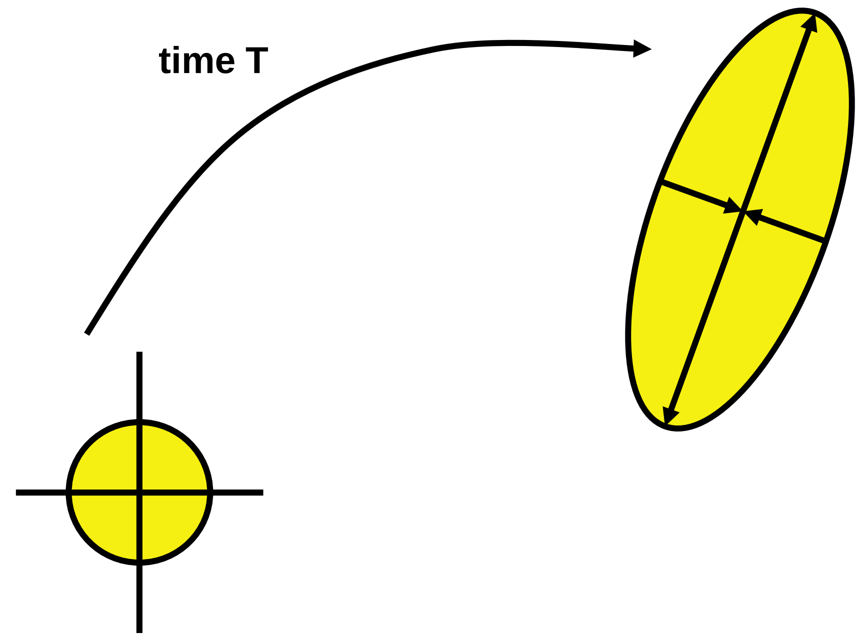
If we knew the directions of maximum growth we could estimate the potential maximum forecast error.



ENS initial perturbations: the singular vectors' component

To formalize the computation of the directions of maximum growth a metric (inner product) should be defined to 'measure' growth.

The metric used at ECMWF in the ensemble system is total energy.



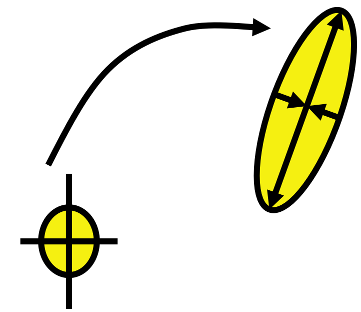
$$< x; E_{TE}\, y >= \frac{1}{2} \iint (\nabla\Delta^{-1}\zeta_x \cdot \nabla\Delta^{-1}\zeta_y + \nabla\Delta^{-1}D_x \cdot \nabla\Delta^{-1}D_y + \frac{C_p}{T_r} T_x T_y) d\Sigma \frac{\partial p}{\partial \eta} d\eta$$

$$+ \int (R_d \frac{T_r}{p_r} \ln \pi_x \ln \pi_y) d\Sigma$$

ENS initial perturbations: the singular vectors' component

The problem of the computation of the directions of maximum growth of a time evolving trajectory is solved by 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

ENS configuration: SVs & EDA & stoch-phys

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

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

$$\delta P_j(\lambda,\phi,p) = r_j(\lambda,\phi)P_j(\lambda,\phi,p)$$

Initial perturbations are defined using 25 perturbed analyses (generated by the ECMWF Ensemble of Data Assimilations) and initial singular vectors (SVINI)

$$e_j(d,0) = e_0(d,0) + PA_j(d,0) + \sum_{area}\sum_{k=1}^{N_{SV}}[\alpha_{j,k}\cdot SV_k(d,0)]$$

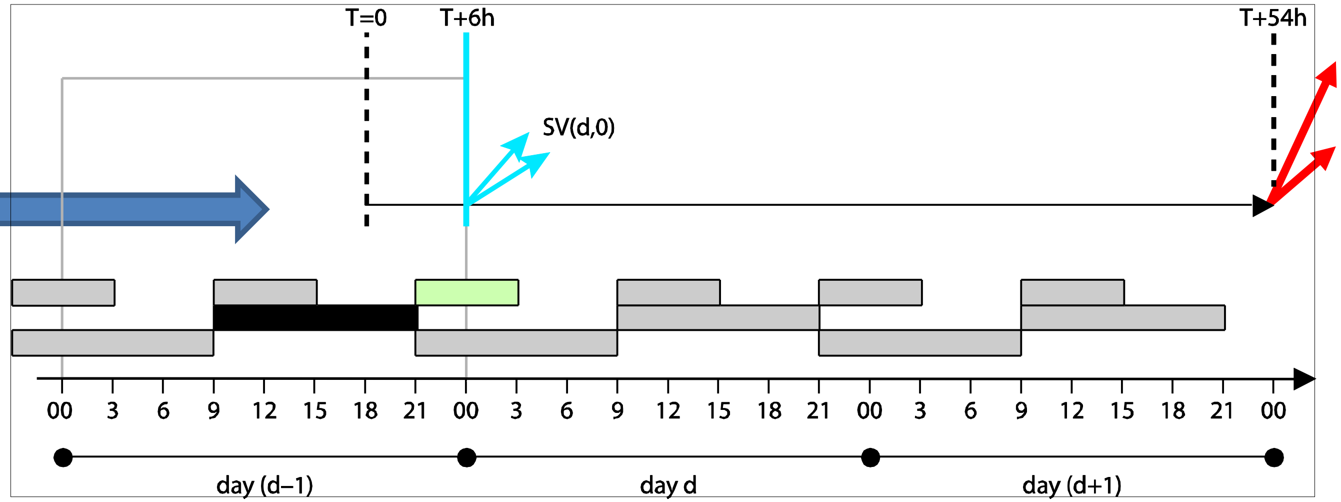
$$PA_j(d,0) = [A_j(d-6h,6h) - < A_j(d-6h,6h) >_{j=1,N_{EDA}}]$$

with the 'central' (unperturbed) analysis defined by

$$e_0(d,0) = A_{T_L 1279 L137}(d,0)$$

ENS forecasts

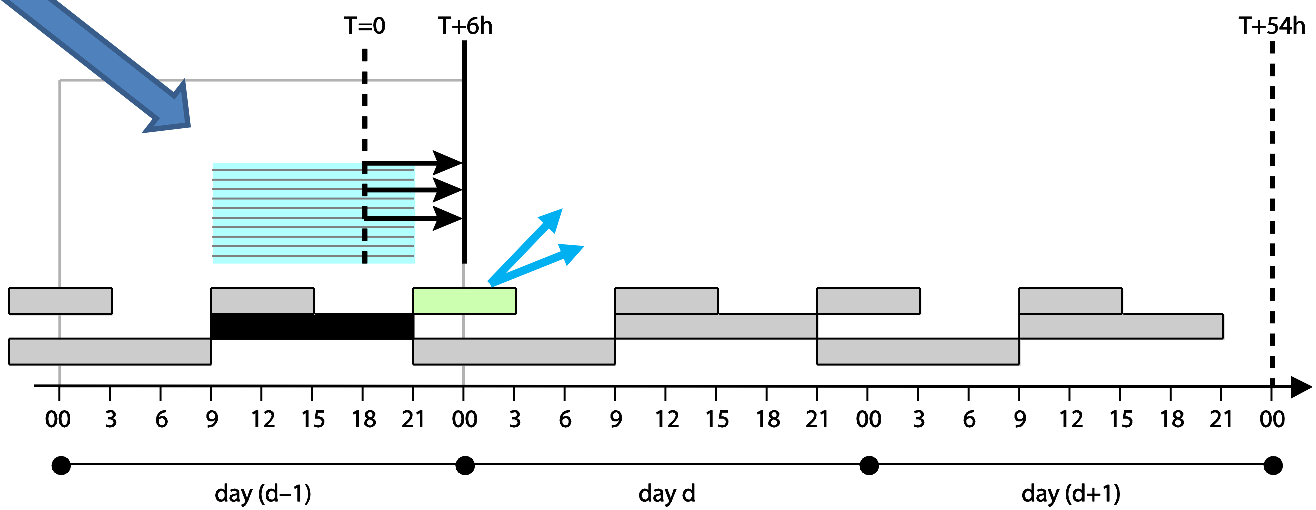
❖ SVs: at 00 and 12 UTC, they are computed along a forecast trajectory (6-54h)



❖ EDA: at 00 and 12 UTC, only the EDA run over the previous 12h window is available

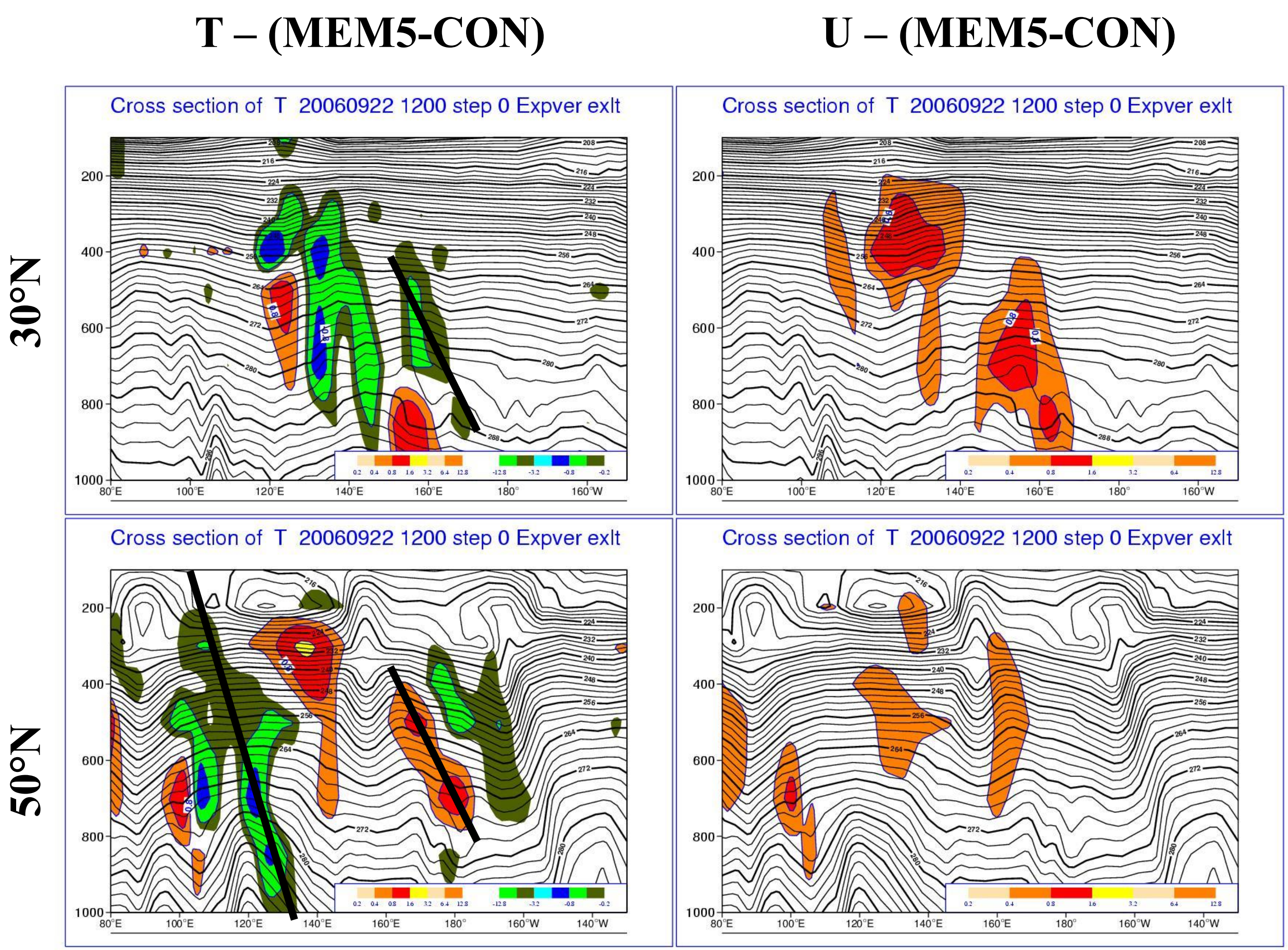
❖ ENS:

- The unperturbed (control) analysis is defined by the 6h HRES 4DVAR analysis (green box), with fg started from the previous DCDA analysis (black box).
- Initial perturbations are defined by a combination of SV- and EDA-based perturbations



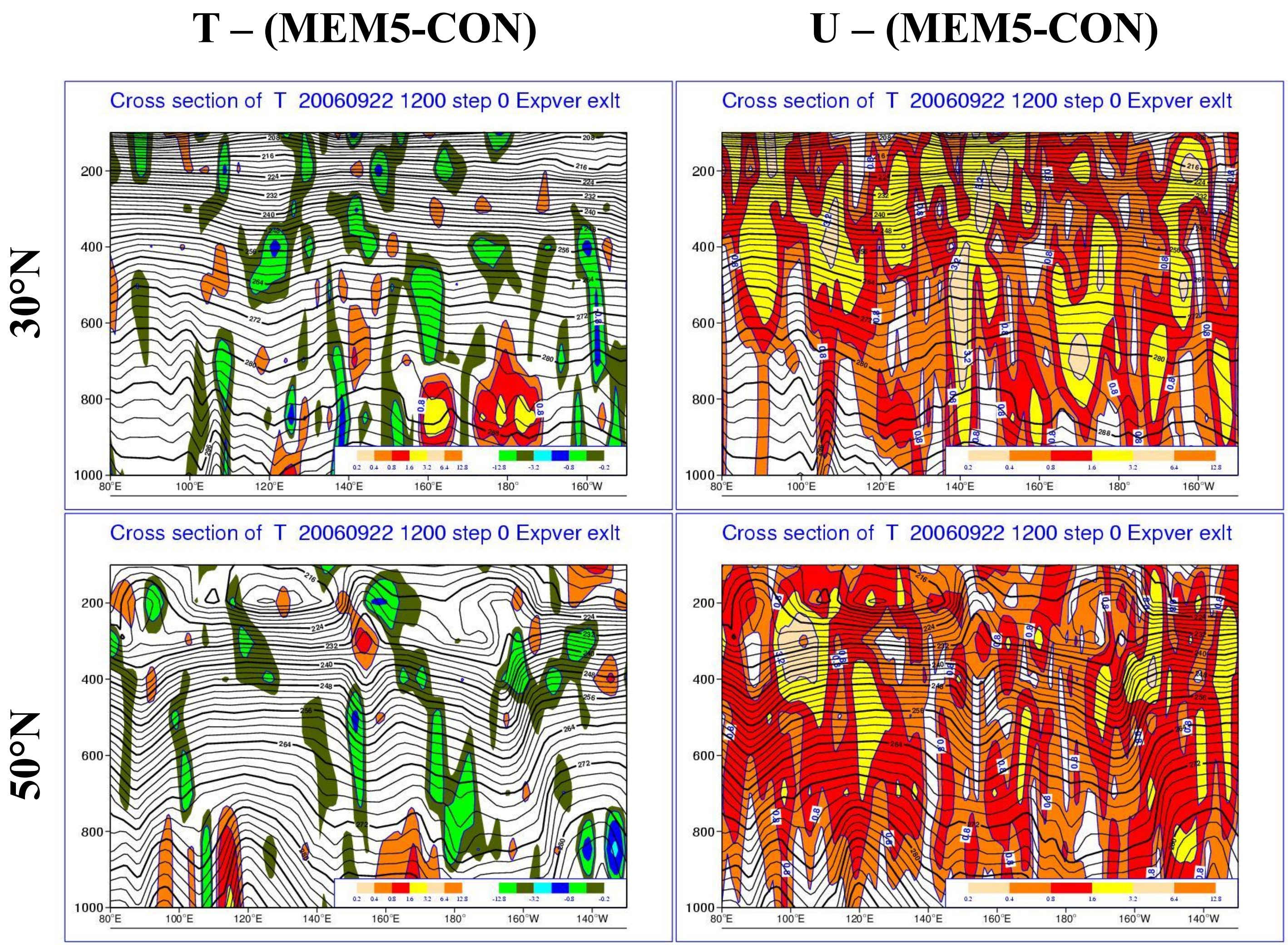
ENS SV component (22/09/2007 t=0)

At t=0, SVINI perturbations are more localized in space, and have a larger component in potential than kinetic energy. They also show a westward tilt with high, typical of baroclinically unstable structures.



ENS: EDA component (22/09/2007 t=0)

At t=0, EDA perturbations have a smaller scale than the SVINI perturbations, and are less localized in space. They have a similar amplitude in potential and kinetic energy. They tend to have more a barotropic than a baroclinic structure.



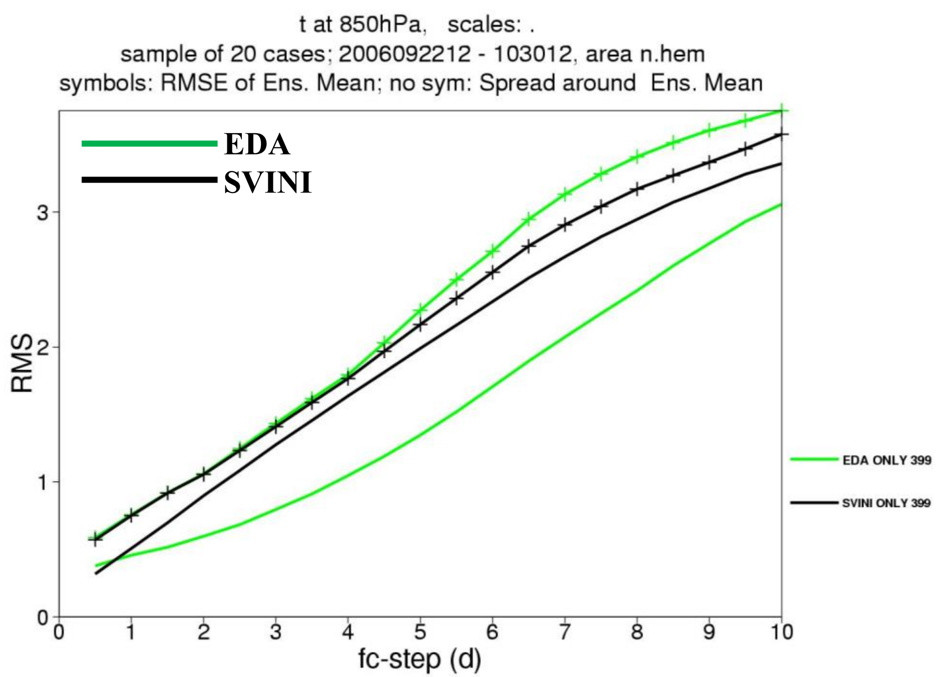
ENS: relative role of the EDA and the SV components

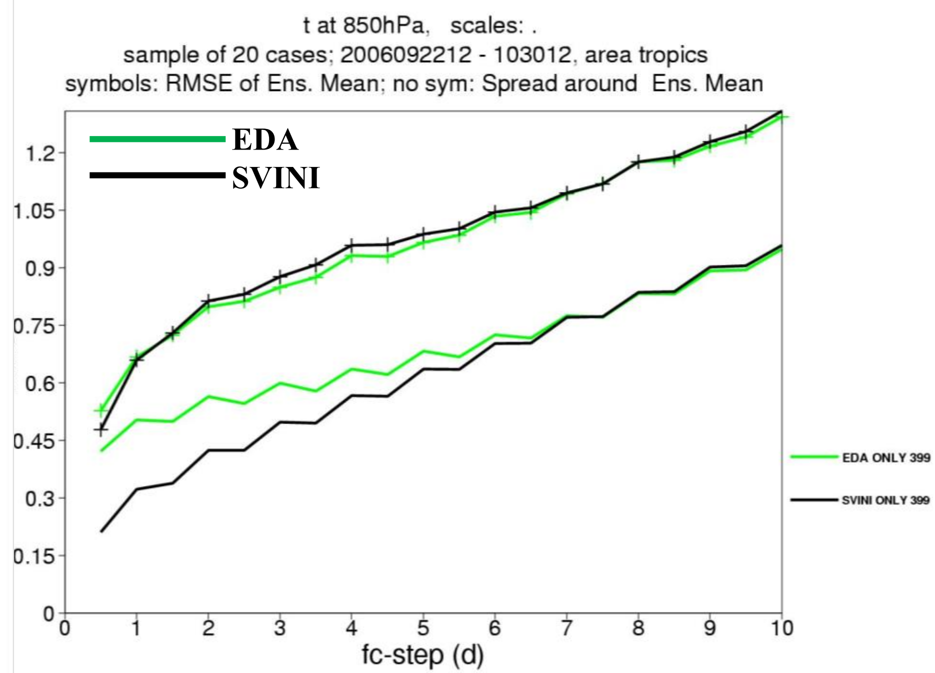
- Geographically: EDA-based perturbations are less localized. In particular, they have a larger amplitude over the tropics
- Vertically: EDA-perturbations are more barotropic than SV-based perturbations, while these latter show westward tilt with height typical of baroclinically unstable structures
- Spectrally: EDA perturbations are smaller in scale
- 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
- EDA perturbations grow less rapidly

ENS: relative role of the EDA and the SV components

Over the NH (left), the EDA ensemble have smaller spread, and a larger ensemble-mean error from forecast day 3.

Over the Tropics (right), the EDA ensemble has larger spread (in terms of T850), and this has a small positive impact on the error of the ensemble-mean, which is slightly smaller between forecast day 2 and 6.

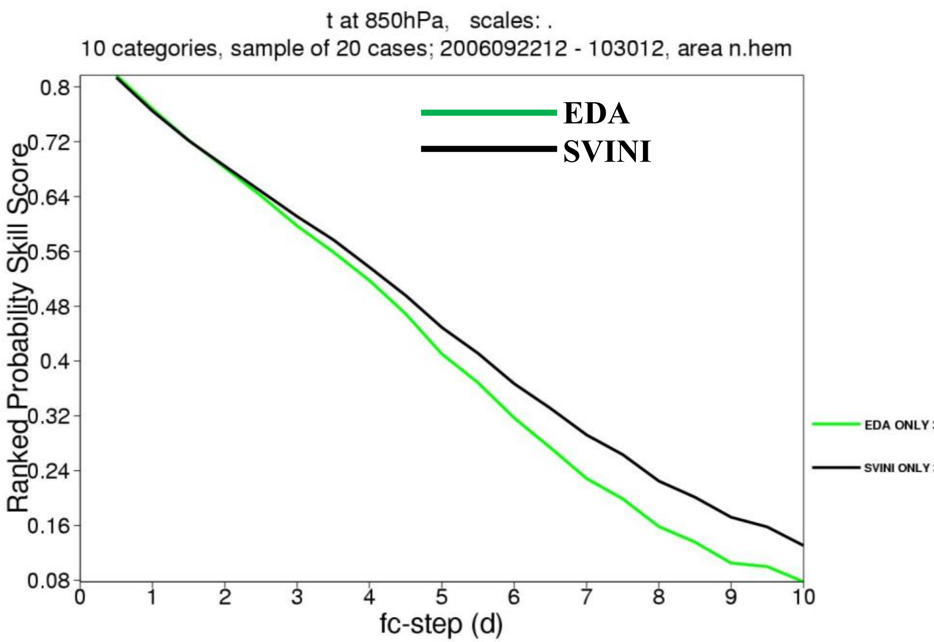


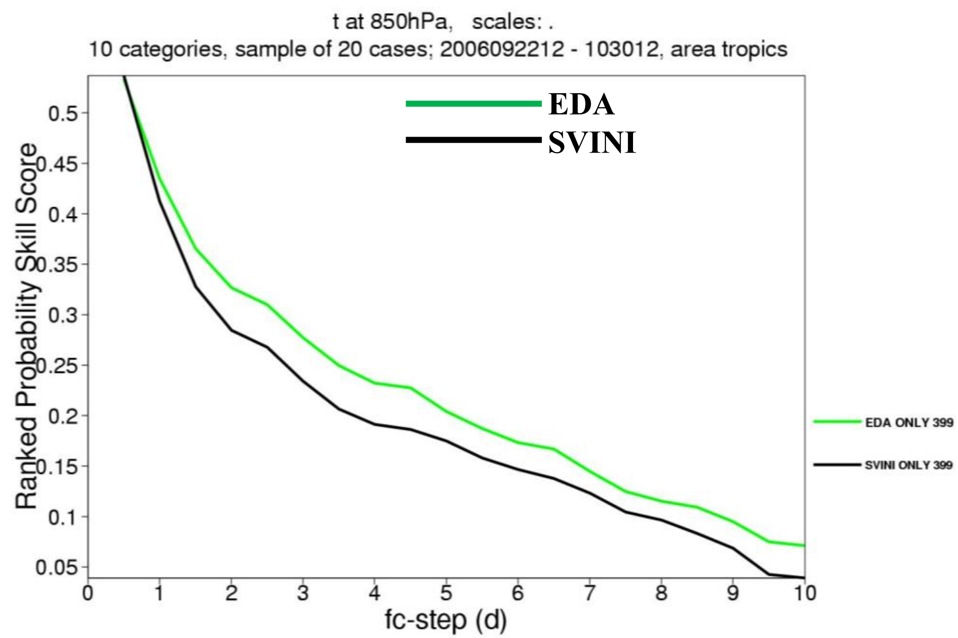


ENS: relative role of the EDA and the SV components

Over the NH (left), the EDA ensemble has a smaller RPSS for T850 probabilistic predictions from forecast day 3, while over the tropics it has a higher RPSS from day 1 (right panel).

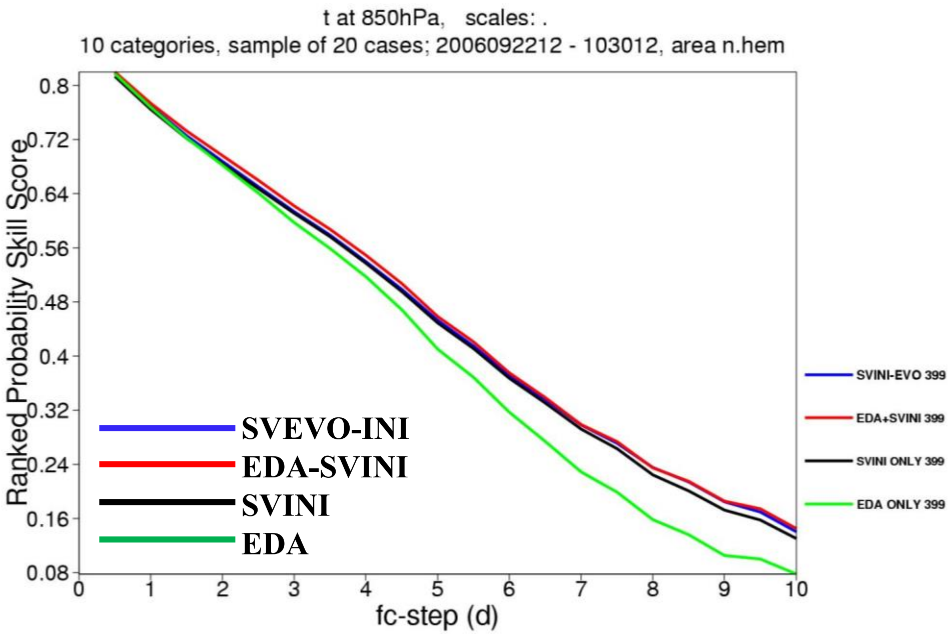
These results suggest that combining the ensemble of analysis and the initial singular vectors would lead to a better system.

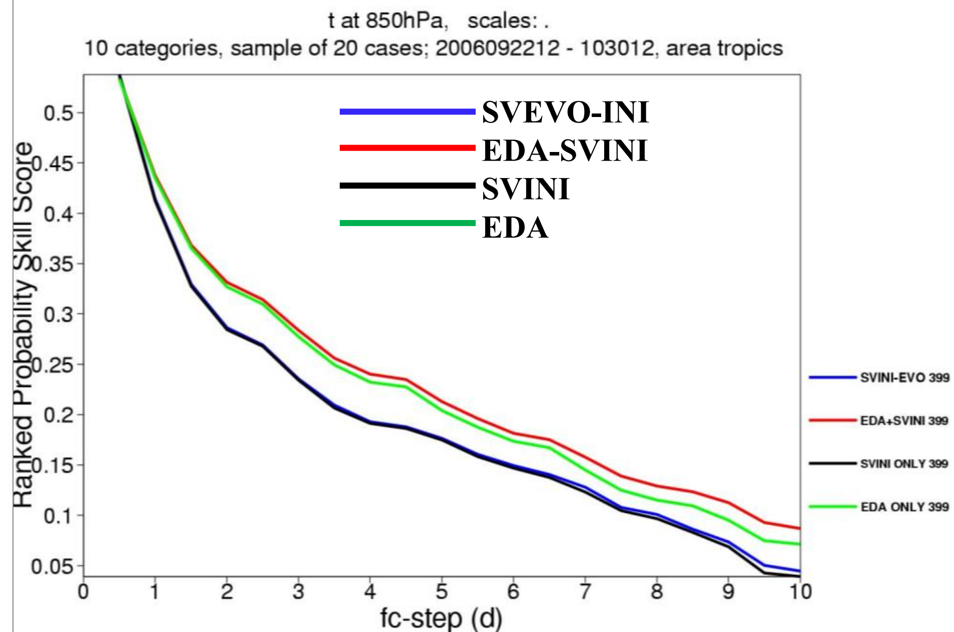




EDA, SVINI, EDA-SVINI & SVEVO-INI ENS

The EDA-SVINI ensemble combines the benefits of the EDA and the SV techniques. Over both the NH (left), the EDA-SVINI ensemble is only marginally better than the SVEVO-INI ensemble. But over the tropics (right), the EDA-SVINI ensemble has a higher RPSS. Note that the combination of EDA- and SVINI-based perturbations leads to an ensemble that outperforms one based on EDA-based perturbations only.

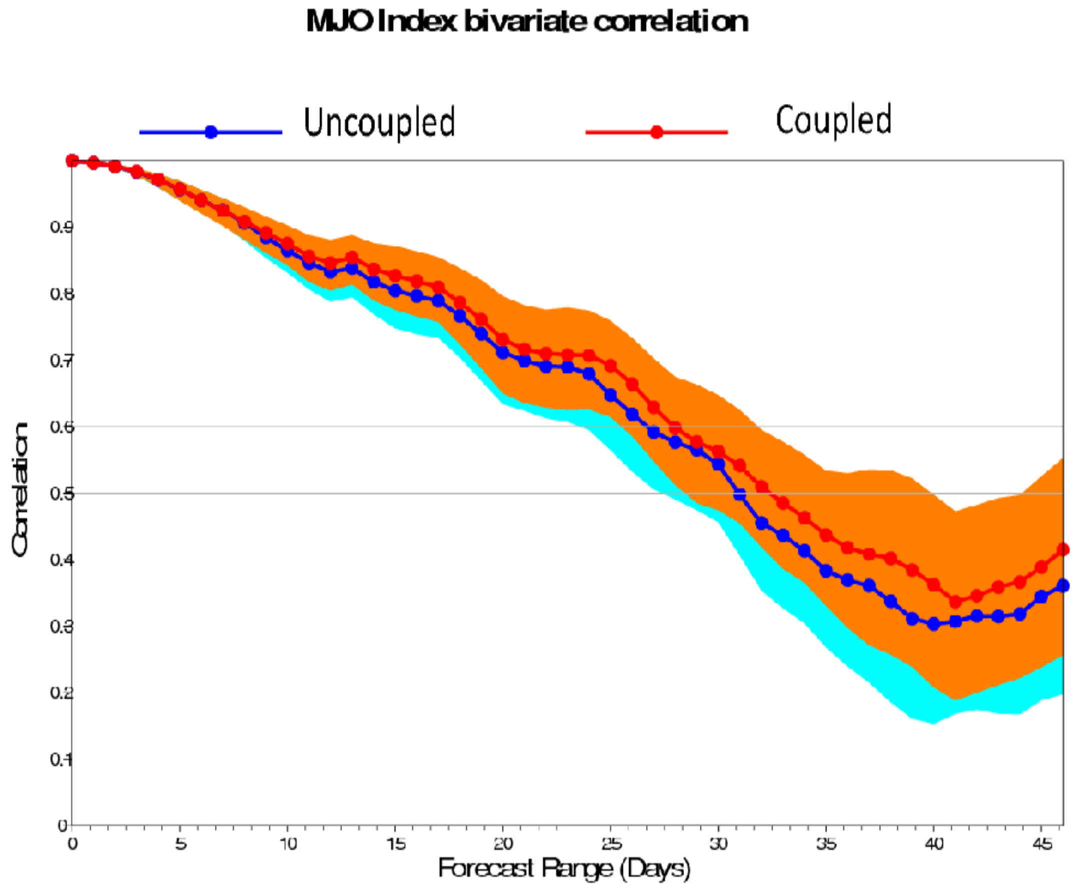




The importance of coupling to the NEMO ocean from d0

The **coupling from initial-time**, introduced in ENS in Nov 2013 with a new version of the ocean model (NEMO) and a 1-way wave-currents coupling, has improved skill, especially in the monthly time-range.

Work is progressing to introduce a better, unified wave-currents-sea-ice model (LIM). The new model based on NEMO is under testing at higher resolution, ORCA_025_Z75. It will be implemented in 2016.

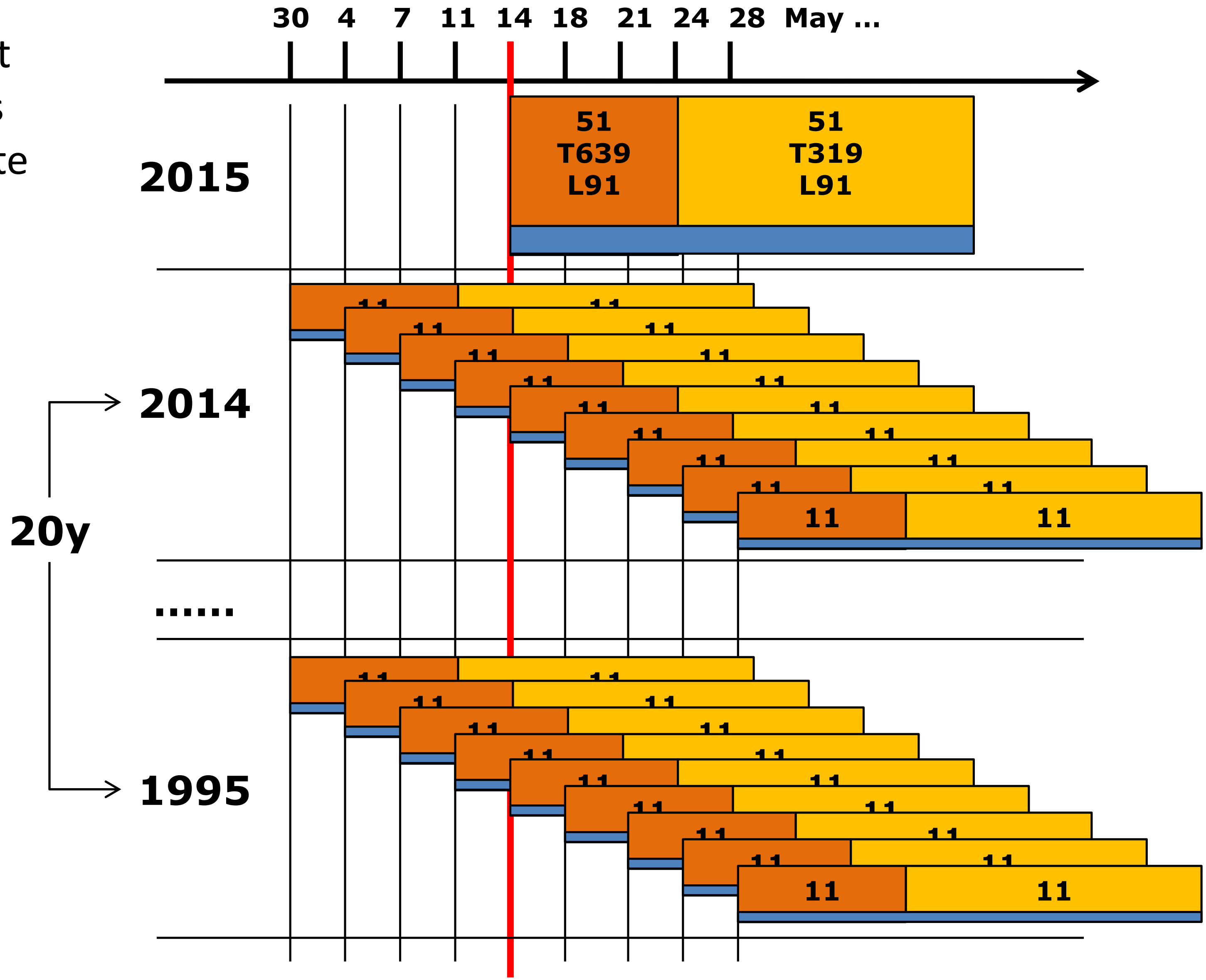


The ENS re-forecast suite to estimate the M-climate

A re-forecast suite is part of all ECMWF ensembles to estimate the M-climate for products such as the EFI and probabilities.

From 12 May this will be changed to use **1980 re-forecasts**:

- 20y (1995 – 2014)
- 9 ICs (-2 to +2 weeks)
- 11 members per IC



ENS to predict the probability of severe weather

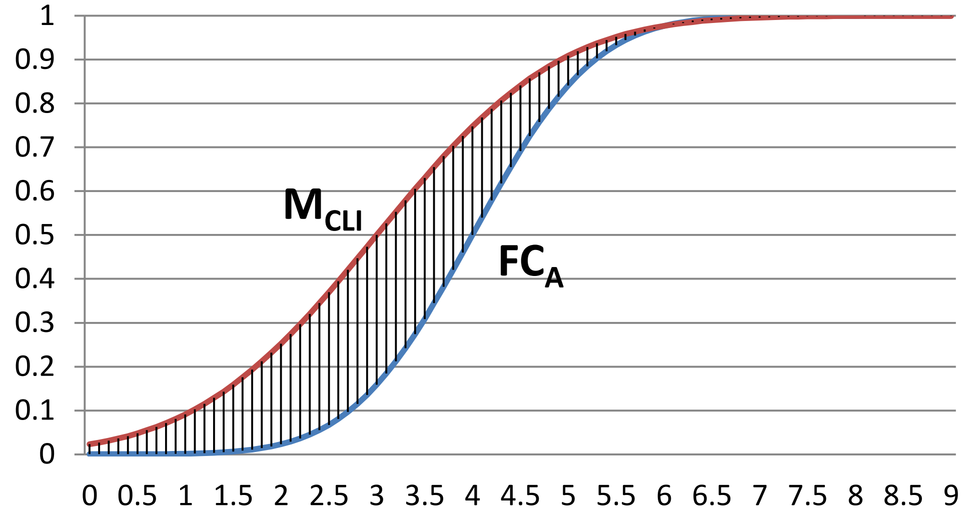
By comparing the model climate CDF^{MCLI} and the forecast CDFs (coloured lines), we can define the Extreme Forecast Index (EFI) and ***predict extremes as seen by the model***.

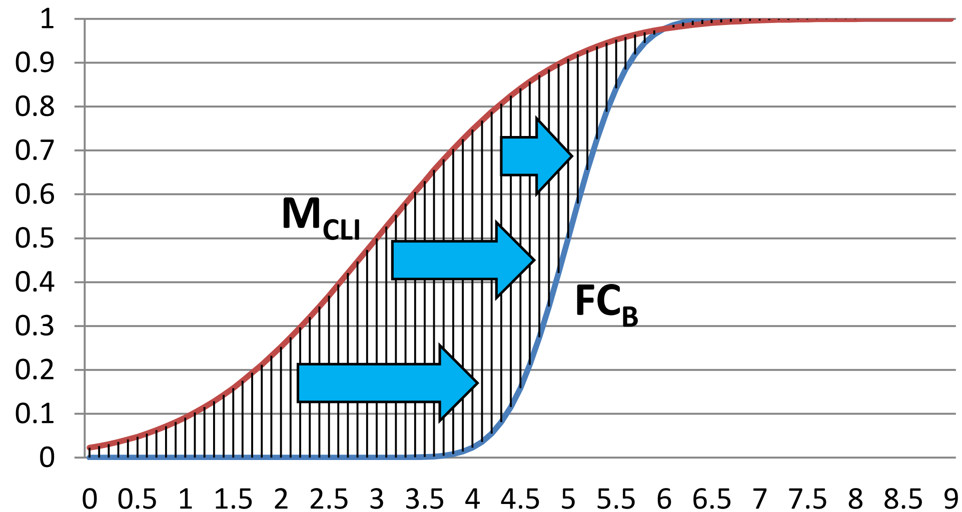
The EFI is the average difference between the CDF^{MCLI} and the fc CDF:

$$EFI = \frac{2}{\pi}\int_0^1 \frac{p - CDF(p)}{\sqrt{p(1-p)}}\,dp$$

The figure shows the following fc/obs PDFs:

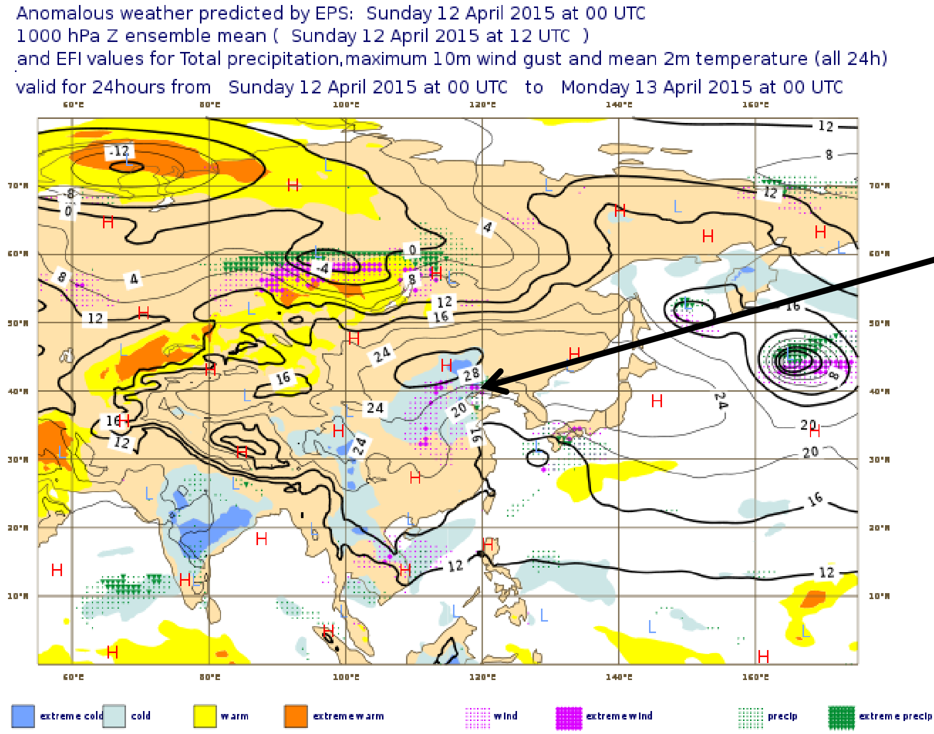
- *MCLI=N(3.0,1.5)*
- *FC_A=N(4.0,1.0) >> EFI_A=+40%*
- *FC_B=N(5.0,0.5) >> EFI_B=+59%*

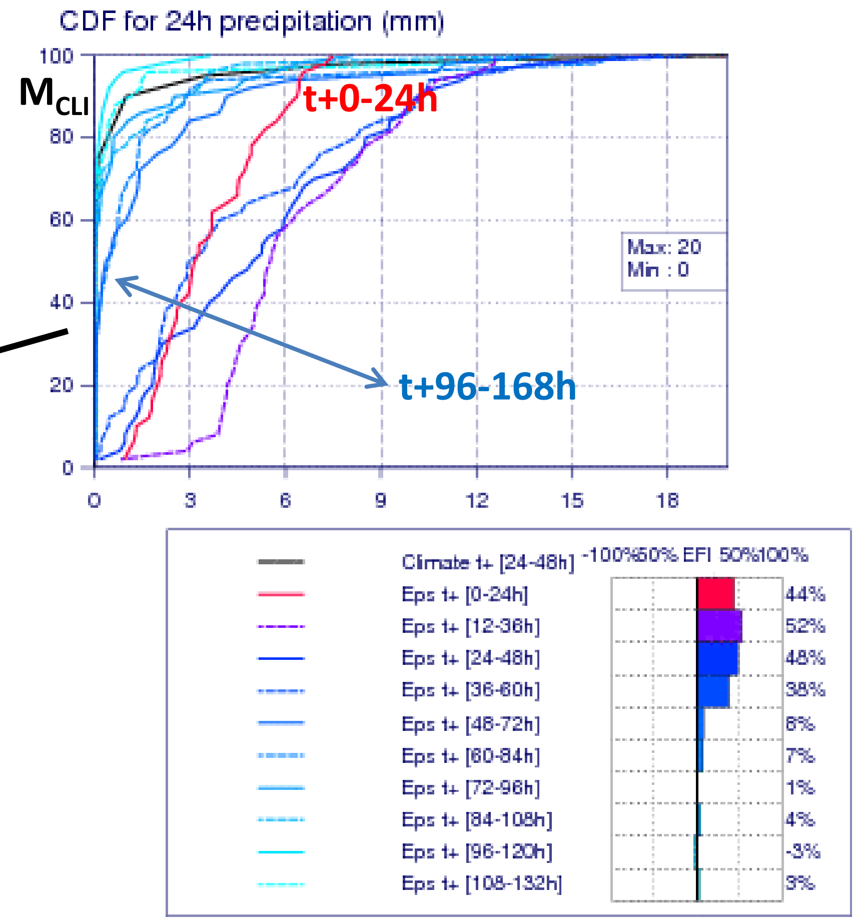




Beijing, ENS EFI for TP24 fcs vt Apr 12@00UTC-13@00UTC

ENS t+0-24h Extreme Forecast Index





EFI maps are used to identify regions where the ENS forecast distribution is significantly different from the model climate one.

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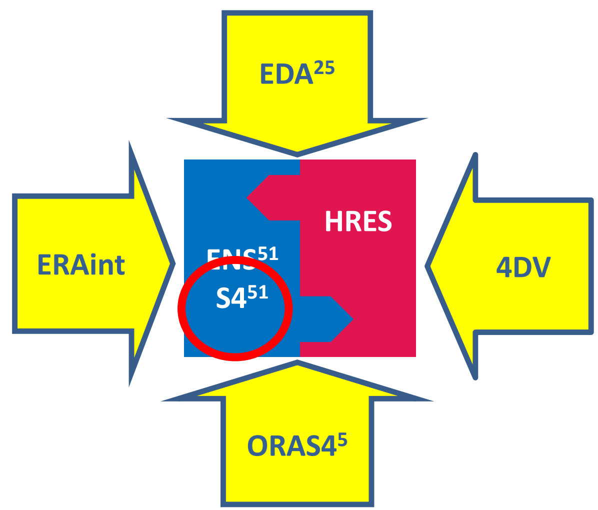


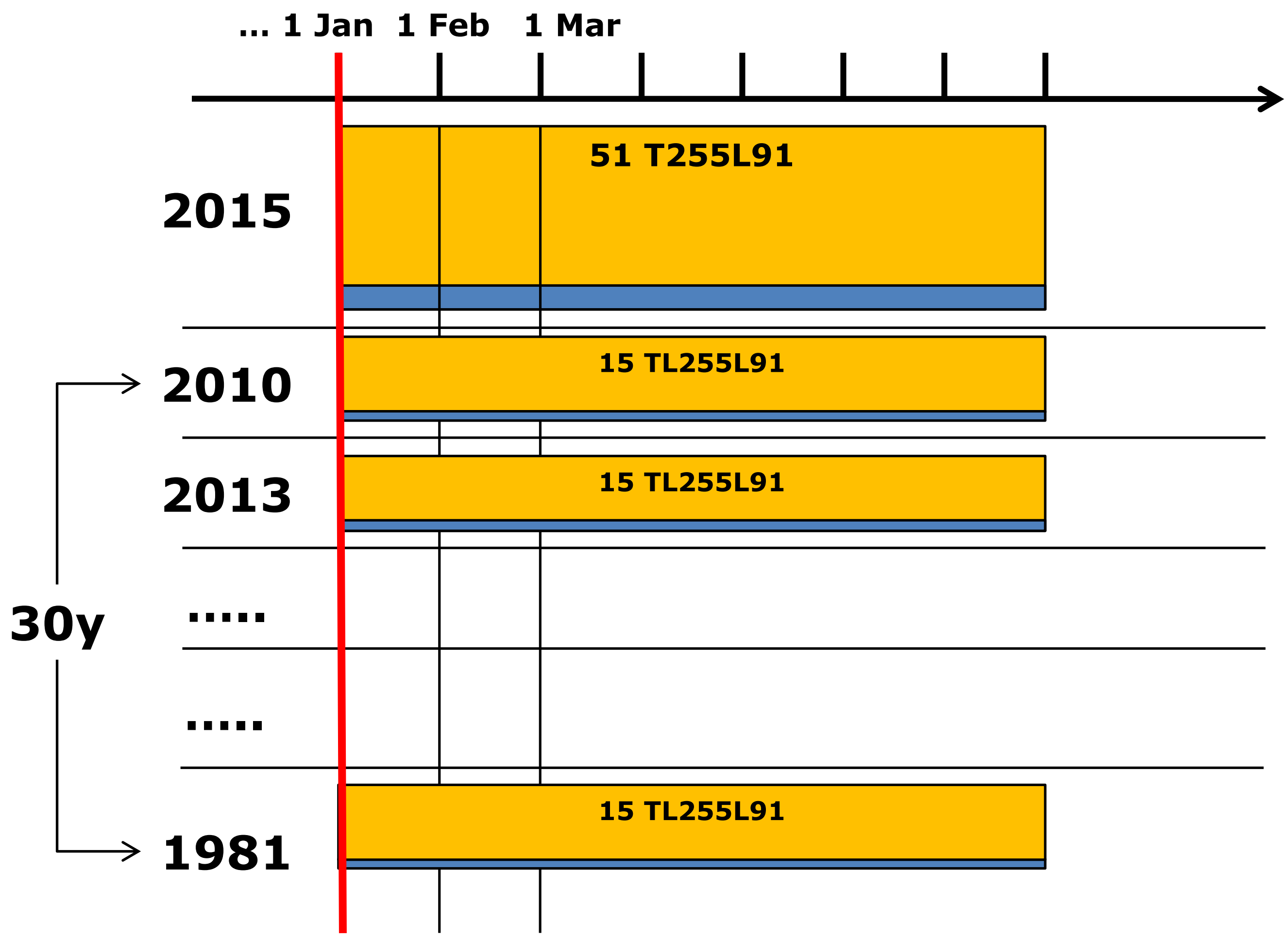
The seasonal ensemble (S4)

Each 1st day of the month, a 51-member ensemble is run up to 7 months (13 months every quarter, FMAN).

The M-climate is estimated using **450 re-forecasts**:

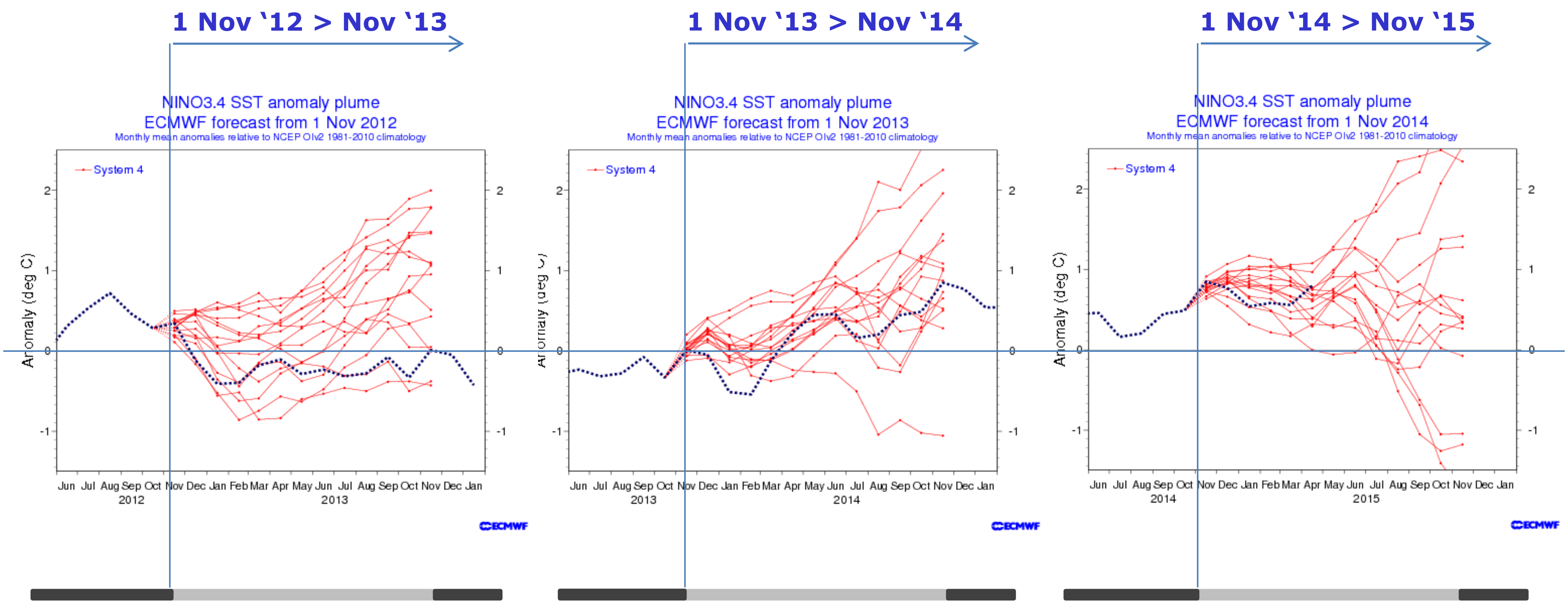
- 30 years (1981 – 2010)
- 15 members

The seasonal products (e.g. anomalies, probabilities) are bias corrected and/or calibrated using the model climate.



The seasonal ensemble S4 provides probabilities up to 1y

The tropics remain the area where seasonal prediction has the highest skill, as indicated e.g. by the accuracy of 1-year forecasts of SST anomaly in the Nino3.4 area.



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TIGGE: an international project in ensemble fc

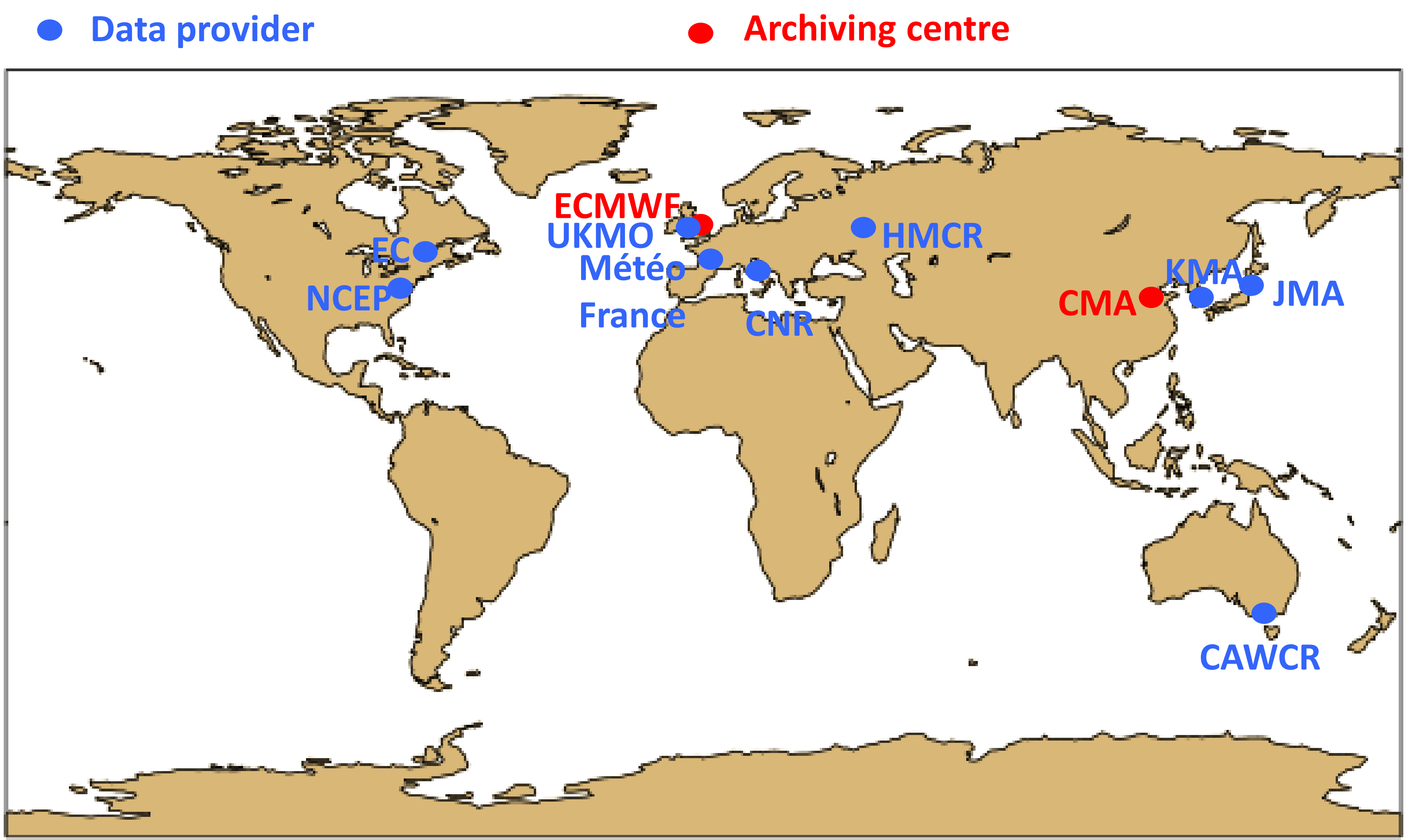
TIGGE (the THORPEX Interactive Grand Global Ensemble eXperiment), started in 2004 with the aim to enhance collaboration and to foster the development of new methods of combining ensembles from different sources and of correcting for systematic errors (biases, spread over-/under-estimation).

Every day, the 7 ensembles that are still running for at least up to 10 days operational, put 436 forecasts into the TIGGE archive. These forecasts are accessible with a 48h delay.

Centre	Initial unc. method (area)	Model unc.	Truncation (degrees, km)	# Vert Lev (TOA, hPa)	Fcst length (d)	# pert mem	#runs per day (UTC)	# mem per day	In TIGGE since
BMRC (AU)	SV(NH,SH)	NO	TL119 (1.5°; 210km)	19 (10.0)	10	32	2 (00/12)	66	Sep-07/Jul-10
CMA (CHI)	BV(globe)	NO	T213 (0.56°; 70km)	31 (10.0)	10	14	2 (00/12)	30	May-07
CPTEC (BR)	EOF(40S:30N)	NO	T126 (0.94°, 120km)	28 (0.1)	15	14	2 (00/12)	30	Feb-08
ECMWF (EU)	SV(NH, SH, TC) + EDA(globe)	YES	TL639 (0.28°; 32km) TL319 (0.56°; 65km)	91 (0.1)	0-10 15/32	50	2 (00/12)	102	Oct-06
JMA (JAP)	SV(NH, TR, SH)	YES	TL479 (0.38°; 50km)	60 (0.1)	11	25	2 (00/12)	52	Aug-11
KMA(KOR)	ETKF(globe)	YES	N320 (0.35°; 40km)	70 (0.1)	10	23	4 (00/06/12/18)	96	Dec-07
MSC (CAN)	EnKF(globe)	YES	600x300 (0.6°, 75km)	40 (2.0)	16/32	20	2 (00/12)	42	Oct-07
NCEP (USA)	ETR(globe)	YES	T254 (0.70°; 90km) T190 (0.95°; 120km)	28 (2.7)	0-8 8-16	20	4 (00/06/ 12/18)	84	Mar-07
UKMO (UK)	ETKF(globe)	YES	N216 (0.45°; 60km)	70 (0.1)	15	23	2 (00/12)	48	Oct-06/Jul-14

S2S: bridging the gap between weather and climate

The sub-seasonal to seasonal (S2S) WWRP/THORPEX/ WCRP joint research project aims to bridge the gap between weather and climate. Co-chaired by *F Vitart* (ECMWF) and *A Robertson* (IRI), it started in Nov 2013.

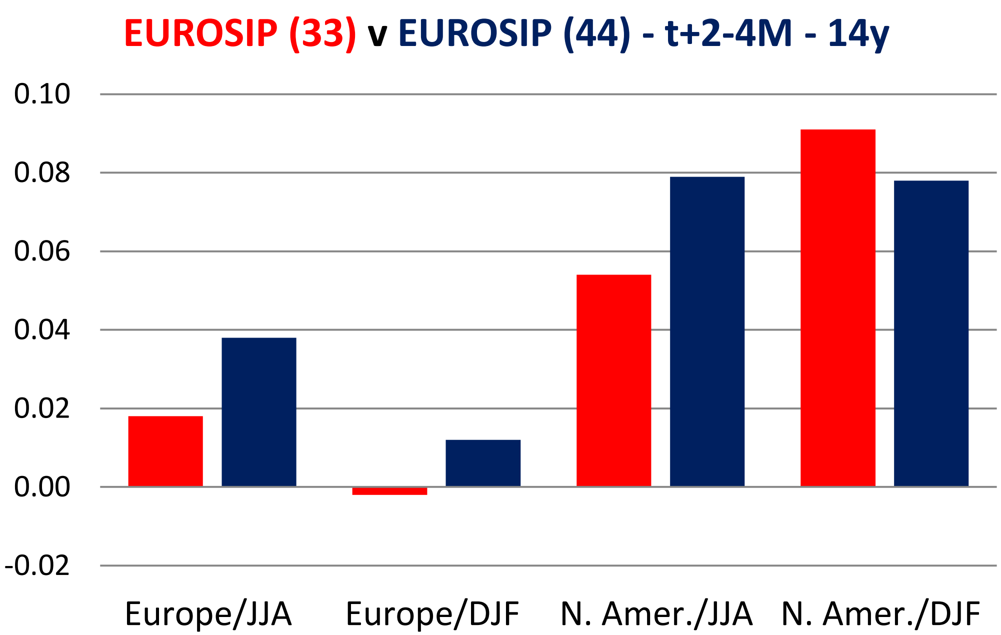


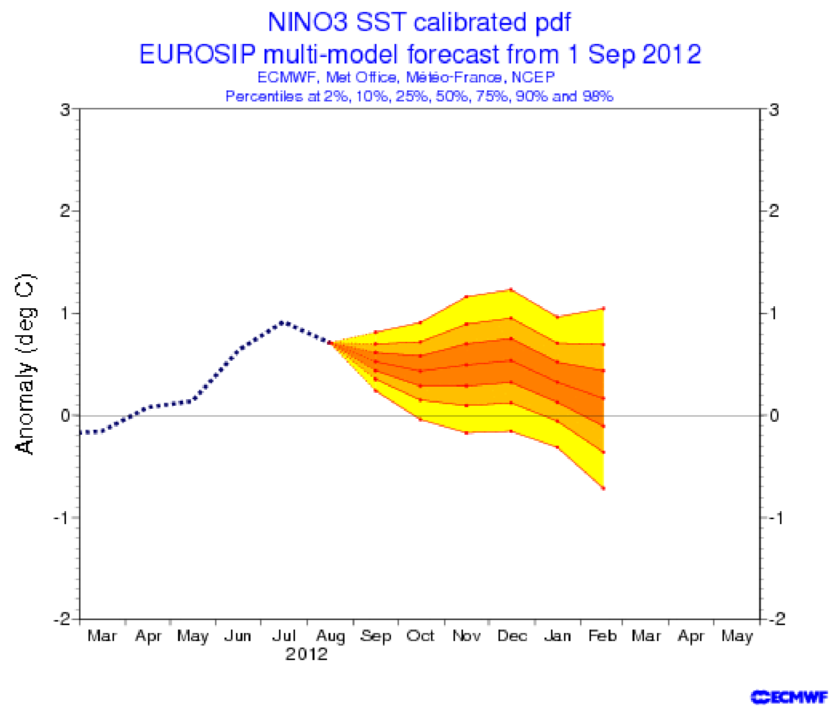
S2S: bridging the gap between weather and climate

	Time-range	Resol.	Ens. Size	Freq.	Hcsts	Hcst length	Hcst Freq	Hcst Size
ECMWF	D 0-46	T639/319L91	51	2/week	On the fly	Past 20y	2/weekly	11 (>22)
NCEP	D 0-45	N126L64	4	4/daily	Fix	1999-2010	4/daily	1
JMA	D 0-34	T159L60	50	weekly	Fix	1979-2009	3/month	5
CAWCR	D 0-60	T47L17	33	weekly	Fix	1981-2013	6/month	33
CMA	D 0-45	T106L40	4	daily	Fix	1992-now	daily	4
CNR	D 0-32	0.75x0.56 L54	40	weekly	Fix	1981-2010	6/month	1
EC	D 0-35	0.6x0.6L40	21	weekly	On the fly	Past 15y	weekly	4
HMCR	D 0-63	1.1x1.4 L28	20	weekly	Fix	1981-2010	weekly	10
KMA	D 0-60	N216L85	4	daily	On the fly	1996-2009	4/month	3
Met.Fr	D 0-60	T127L31	51	monthly	Fix	1981-2005	monthly	11
UKMO	D 0-60	N96L85	4	daily	On the fly	1989-2003	4/month	3

EUROSIP: a multi-system approach for the seasonal range

In 2012, for the first time, European (ECMWF, Meteo France and UK Met Office) and American (NCEP) ensemble systems are used to generate operational products. This follows research that has shown that better and more reliable seasonal forecasts can be created by combining the output from several systems.





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How can we keep improving the ensembles?

Work is progressing on many areas to further improve the ECMWF ensembles:

1. **Modelling** (including model uncertainty simulation): improve all model components (land, atmosphere and ocean) and increase resolution; upgrade the stochastic schemes used to simulate model uncertainty

2. **Initial Conditions** estimation: integrate further the analysis and forecast ensembles (EDA and ENS) and re-assess the potential benefit of starting ENS directly from EDA analyses; assess the impact of using a more strongly coupled DA

3. **Predictability:** identify sources of predictability, and ways to extract predictable signals for the ensemble PDF

4. **Ensemble methods**: assess whether different ensemble configurations (IC/model unc, membership, truncation, refc suite, …) could lead to more accurate and reliable PDF fcs

…. extra slides ..

Forthcoming upgrades and changes

1. The ECMWF Seasonal System-4 (S4):
   - Work has started to define S5 configuration (higher resolution, new atmosphere and ocean models, dynamical sea-ice)
   - Production of new ocean re-analysis (ORAS5) has started (5 members, ¼ degree z75, new NEMO model, dynamical sea-ice, 1975-date)
   - H2-2016: re-fc production
   - H1-2017: implementation of S5

2. The ECMWF medium-range/monthly ensemble (ENS):
   - On 12 May (a) the forecast length was extended from 32 to 46 days, and (b) the re-fc suite will be extended from 5 to 22 members per week
   - H1-2016: higher atmosphere resolution (~18 km to d10, 36 km afterwards)
   - H2-2016: higher-resolution (¼ degree, z75) and new version of NEMO (with dynamical sea-ice) in ENS

Forthcoming resolution increase: all IFS components

	Operational suite	Future resolution (preferred option)
HRES	T_L1279 / L137	T_{CO}1279 / L137
4DVAR	T_L1279+3xT_L255 / L137	T_{CO}1279+T_{CO}255/319/399 / L137
EDA	T_L399 / L137 (25 members)	T_{CO}639 / L137 (25 members)
ENS/MOFC IFS: OCEAN:	51 members TL639 (0 - 10days) +T_L319 (10 - 32days) / L91 NEMO ORCA100z42	51 members T_{CO}639 (0 - 10days) +T_{CO}319 (10 - 32days) / L91 NEMO ORCA025z75

T_{CO} – Cubic octahedral Gaussian reduced grids

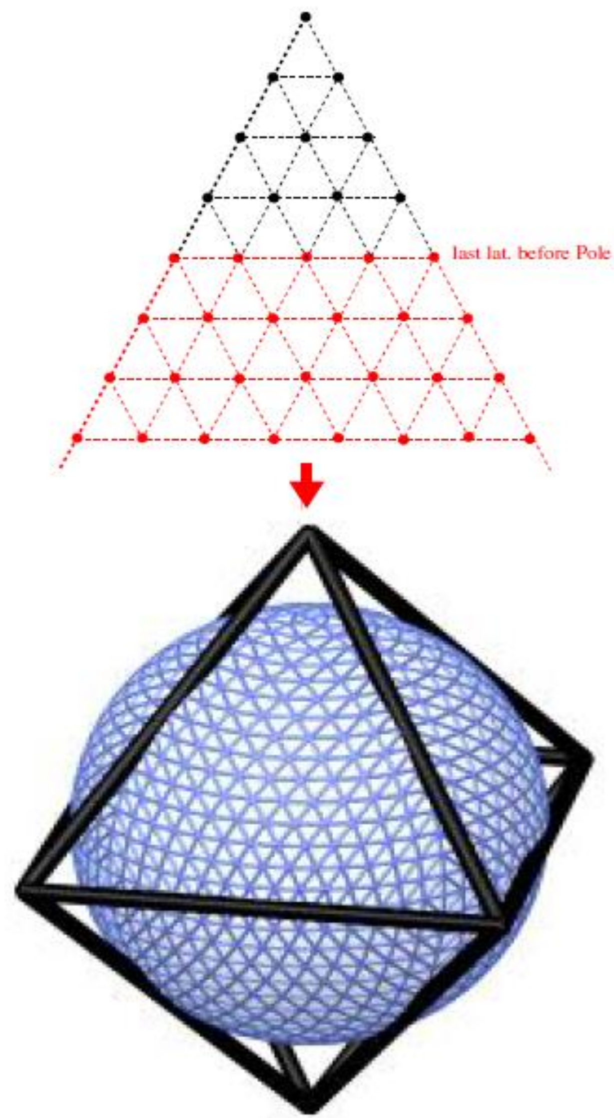
Forthcoming resolution upgrade: octahedral cubic grids

It is a reduced Gaussian grid with the same number of latitude circles (*NDGL*) than the standard Gaussian grid (↔ Gaussian weights) but with a new rule to compute the number of points per latitude circle.

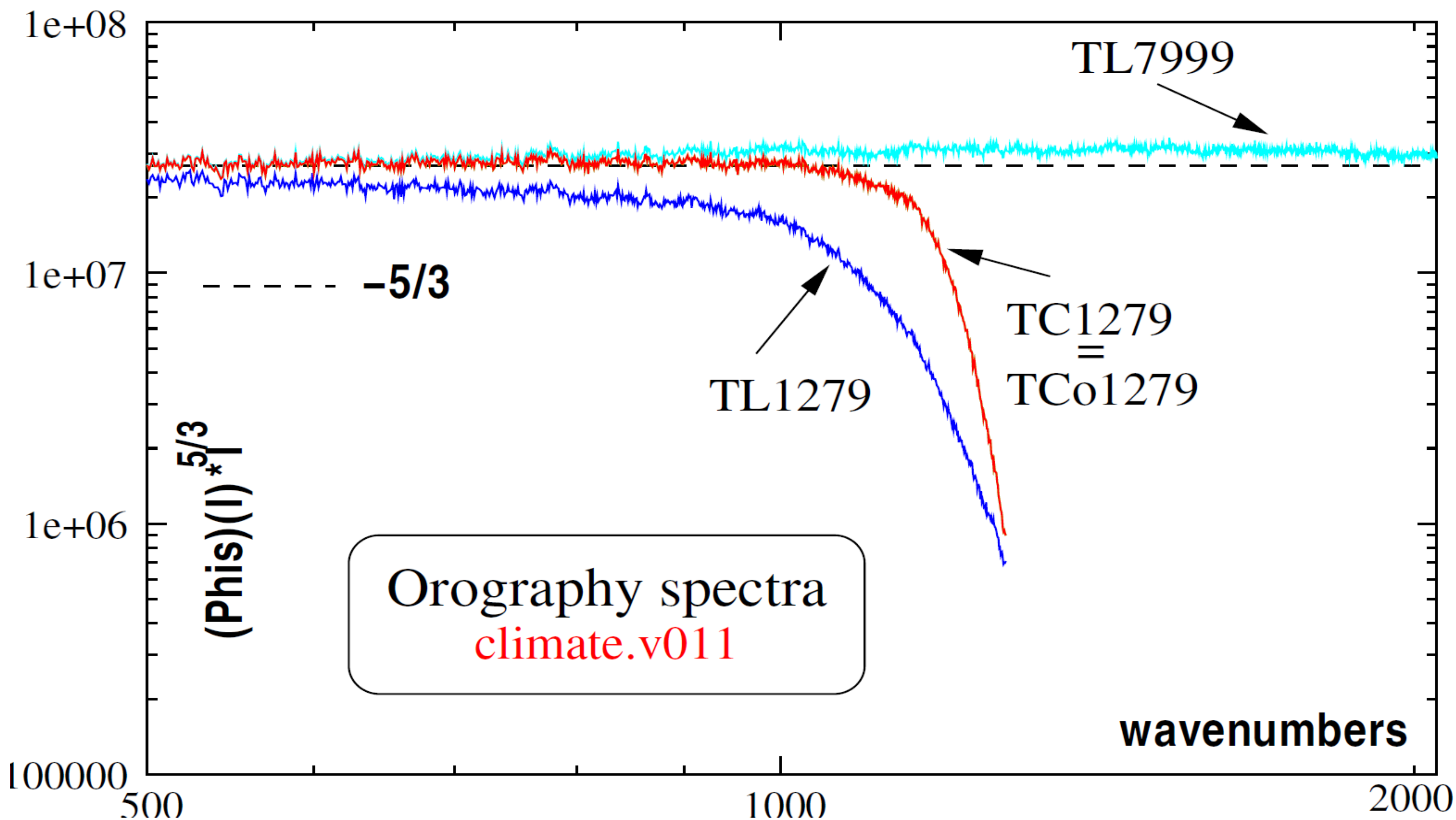
Number of points per latitude

NLOEN(lat_N)=20 → Poles
NLOEN(lat_i)=NLOEN(lat_{i-1})+4

TL1279 :2.14 Mpoints
TC1023 :5.45 Mpoints
TC1279 :8.51 Mpoints
TCo1279 :6.59 Mpoints



Forthcoming resolution increase: orographic variance



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