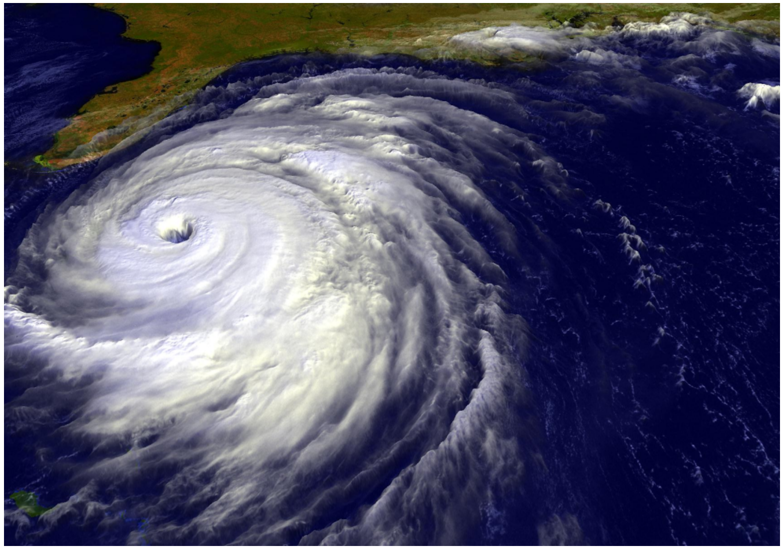

Approaches to ensemble prediction: the TIGGE ensembles

(EC/TC/PR/RB-L2)

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Abstract and key learning points

The aim of this session is to illustrate the key characteristic of the nine operational global, medium-range ensemble systems. These are the ensembles available also within the TIGGE (Thorpex Interactive Grand Global Ensemble) project data-base. Similarity and differences in the approaches followed to simulate the sources of forecast uncertainties will be discussed, and their relevance for forecast performance will be illustrated.

By the end of the session you should be able to:

- illustrate the main similarities and differences of the 9 TIGGE global ensembles
- link the performance differences of TIGGE ensemble to their design
- describe the main differences between singular vectors and EDA-based perturbations

Outline

1. Objectives and approaches to ensemble prediction
2. Comparison of the 2002 ECMWF, MSC and NCEP ensemble systems
3. The THORPEX/TIGGE global, medium-range ensembles

1. Ensemble prediction

Ensemble prediction aims to estimate the probability density function of forecast states, taking into account all possible sources of forecast error:

❖ Observation errors and imperfect boundary conditions

❖ Data assimilation assumptions

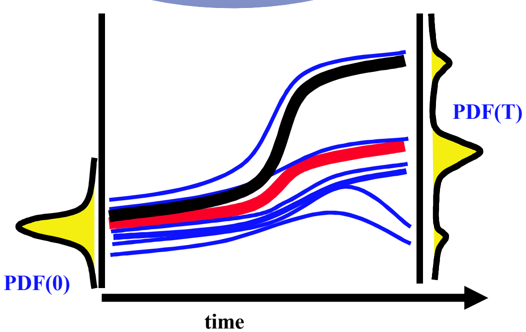
❖ Model errors

- Obs and BCs errors
- DA assumptions

Model unc

Model unc

- Obs and BCs errors
- DA assumptions



1. What should an ensemble prediction simulate?

Two schools of thought:

- Monte Carlo approach: sample all sources of forecast error, perturb any input variable and any model parameter that is not perfectly known. Take into consideration as many sources as possible of forecast error.

- Reduced sampling: sample leading sources of forecast error, prioritize. Rank sources, prioritize, optimize sampling: growing components will dominate forecast error growth.

There is a strong constraint: limited resources

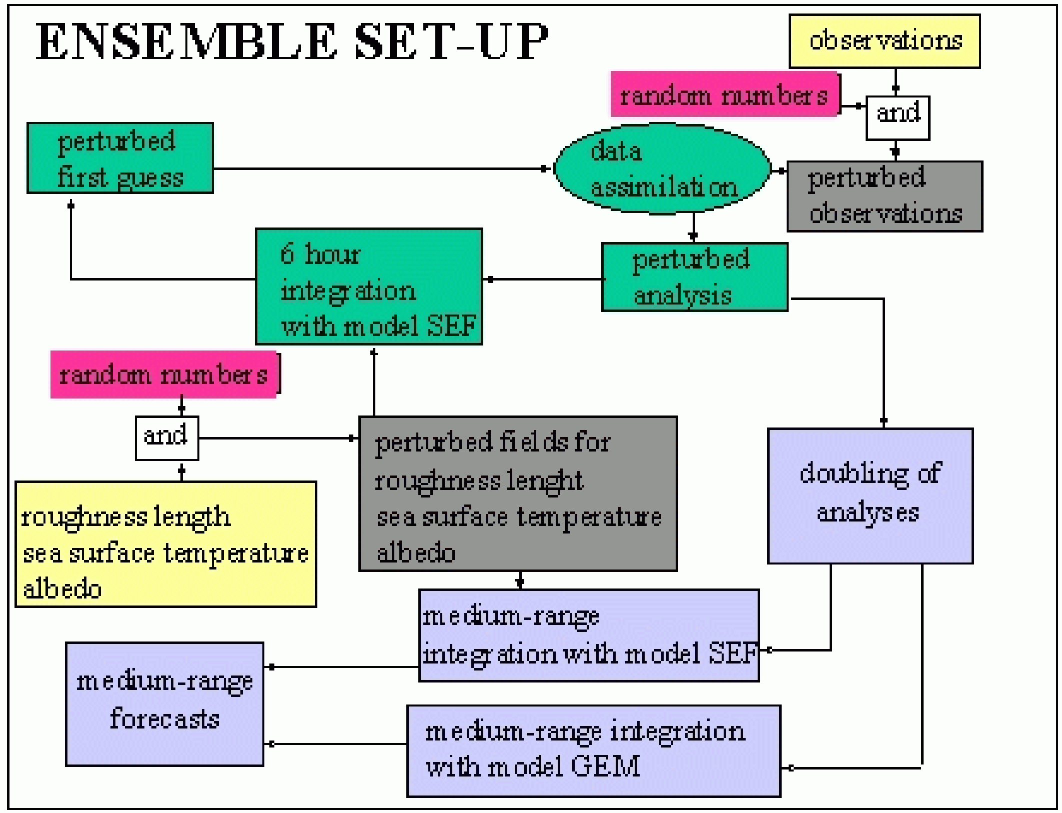
(man and computer power)!

1. Monte Carlo approach (MSC): all-inclusive design

The original (1995) MSC ensemble was designed following a Monte Carlo approach to simulate:

- observation errors (random perturbations);
- imperfect boundary conditions (perturbed surface fields);
- model errors (different parameterisations and originally also 2 models, random error component added to the initial perturbations).

The MSC ensemble



1. Simulation of init-unc: selective sampling

In the original ECMWF and NCEP ensembles (1992), the initial conditions are generated by adding perturbations to the unperturbed analysis.

The initial perturbations were designed to span only a subspace of the phase space of the system (selective sampling):

- ‘dynamically dominant’ directions at ECMWF
- ‘analysis dominant’ directions at NCEP

1. Selective sampling: singular vectors (ECMWF)

A perturbation time evolution is linearly approximated:

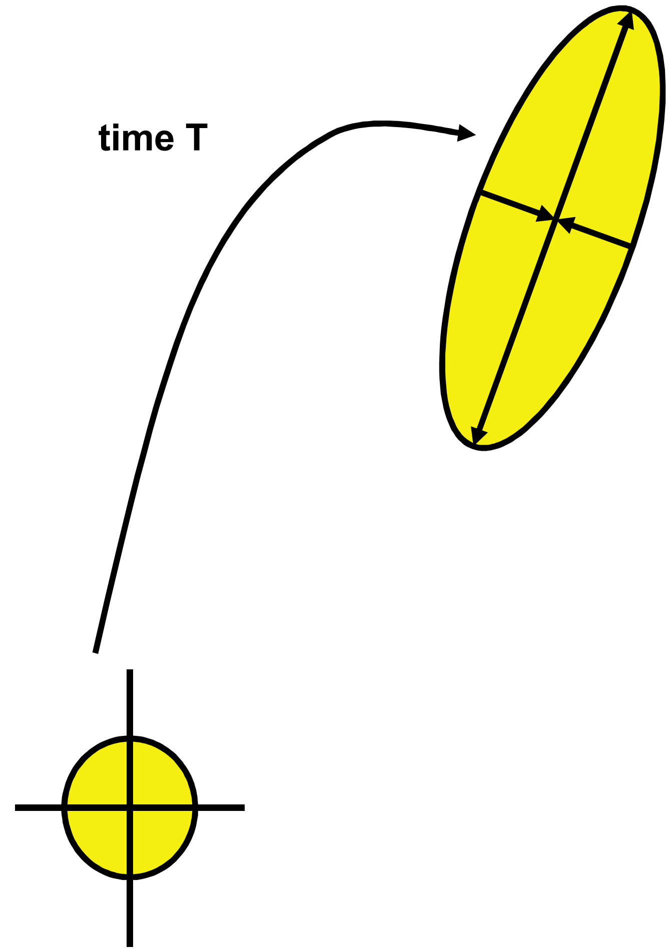
$$z'(t) = L(t,0)z'_0$$

The singular vectors, i.e. the perturbations with the fastest finite-time growth:

$$\left\|z'(t)\right\|^2 = < z'(t); Ez'(t) > = < L(t,0)z'_0; EL(t,0)z'_0 >$$

are computed by solving:

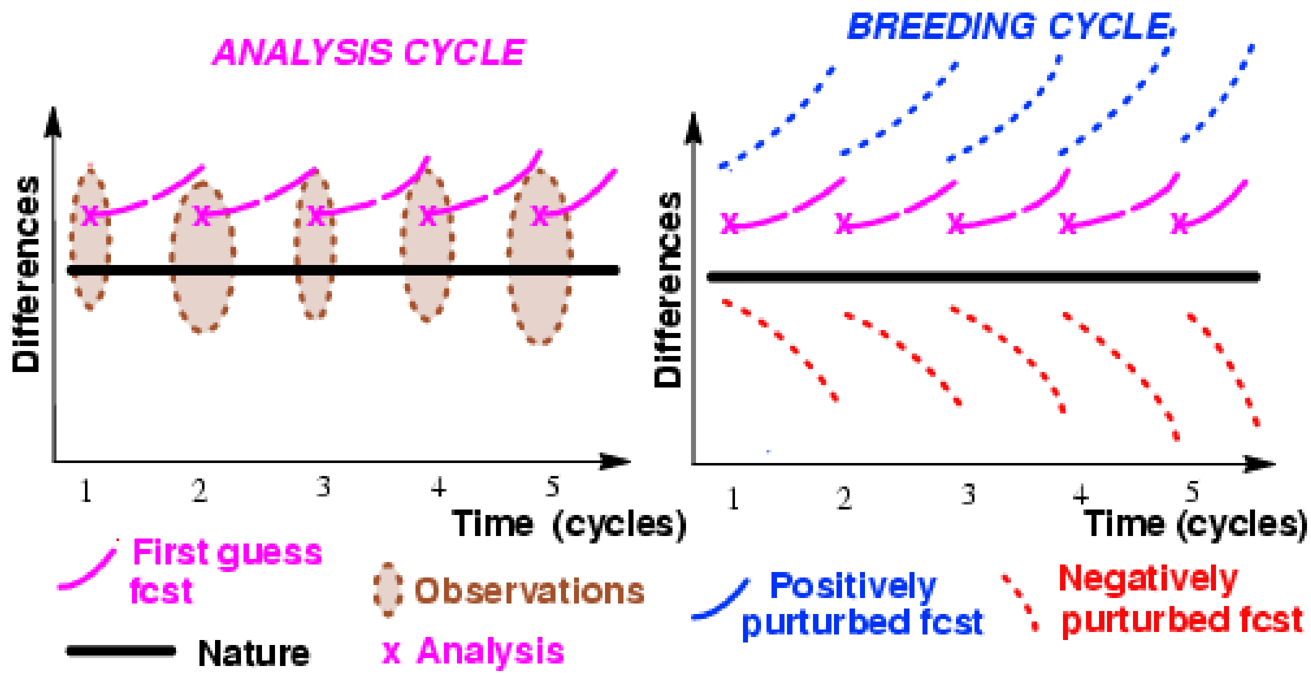
$$E^{-1/2}L^* ELE^{-1/2}v_j = \sigma_j^2 v_j$$



1. Selective sampling: breeding vectors (NCEP)

At NCEP a different strategy based on perturbations growing fastest in the analysis cycles (bred vectors, BVs) was followed

Each BV was computed by a cycle of (a) adding a random perturbation, (b) evolving and (c) rescaling it, and then repeat steps (b-c).



Outline

1. Objectives and approaches to ensemble prediction
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2. The 2002 ECMWF, MSC and NCEP systems

Results based on the 2002 operational systems are relevant since they highlight the relative impact of initial perturbation methods, analysis and model characteristics on ensemble performance.

In all ensembles, each member is given by integrating the following equation:

$$e_j(T) = e_j(0) + \int_{t=0}^{T} [P_j(e_j,t) + dP_j(e_j,t) + A_j(e_j,t)]dt$$

	MSC 2002	ECMWF 2002	NCEP 2002
Pj (model uncertainty)	Diff. Phys. Param.	Pj=P0 (single model)	Pj=P0 (single model)
dPj (random model error)	Diff. Phys. Param.	dPj=rj*Pj (stoch. physics)	dPj=0
Aj	2 models	Aj=A0 (single model)	Aj=A0 (single model)

2. The 2002 ECMWF, MSC and NCEP systems

The perturbed initial conditions can be defined directly by a perturbed analysis

$$e_j(0) = \aleph[e_j(-\tau), o_j(-\tau \div \tau), A_j, P_j]$$

or by adding a perturbation to the unperturbed analysis $e_0(0)$

$$e_j(0) = e_0(0) + de_j(0)$$

$$e_0(0) = \aleph[e_0(-\tau), o_0(-\tau \div \tau), A_0, P_0]$$

where $e_j(-\tau)$ is the DA starting point and $o_j(-\tau \div \tau)$ represents observations.

	MSC 2002	ECMWF 2002	NCEP 2002
oj (obs error)	Random perturbations	-	-
ej (initial uncertainty)	ej directly from Anal. Cycles	ej=e0+dej(SV)	ej=e0+dej(BV)

2. The 2002 ECMWF, MSC and NCEP systems

The three ensembles differ also in size, resolution, daily frequency and forecast length. In 2002, the three systems had the following characteristics:

	MSC 2002	ECMWF 2002	NCEP 2002
Pj (model uncertainty)	1 model + Diff. Ph. Par.	Pj=P0 (single model)	Pj=P0 (single model)
dPj (random mod err)	dPj=rj*Pj (stoch. physics)	dPj=rj*Pj (stoch. physics)	dPj=0
Aj	Aj=A0 two models)	Aj=A0 (single model)	Aj=A0 (single model)
oj (obs error)	Random perturbations	-	-
ej (initial uncertainty)	ej from Anal. Cycles	ej=e0+dej(SV)	ej=e0+dej(BV)
hor-res HRES control	-	-	T170(d0-7.5)-T126(7.5-16)
hor-res control	TL149	TL255(d0-10)	T126(d0-3.5)-T62(3.5-16)
hor-res pert members	TL149	TL255(d0-10)	T126(d0-3.5)-T62(3.5-16)
vertical levels (c&pf)	23 and 41, 28	40	28
top of the model	10hPa	5hPa	3hPa
perturbed members	16	50	10
forecast length	10 days	10 days	16 days
daily frequency	00 UTC	12 UTC	00 and 12 UTC
operational impl.	February 1998	December 1992	December 1992

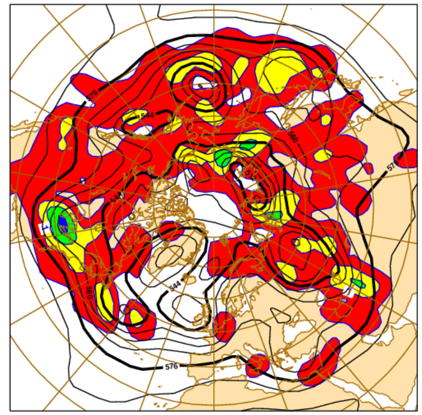
2. Similarities in EM & STD: 14/05/02 t=0

Due to the different methodologies, the ensemble initial states are different.

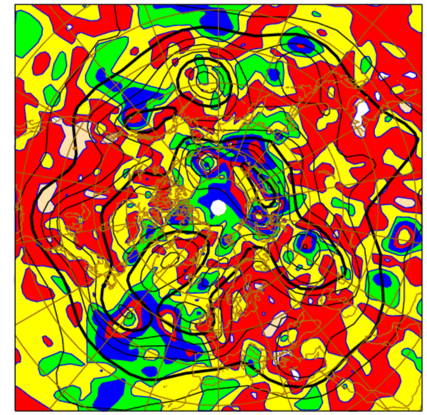
- Area: the ensembles’ put emphasis on different areas; EC has the smallest amplitude over the tropics.

- Amplitude: the ensembles’ stds are larger than the std of the 3-centers’ analyses (2 times smaller contour interval); EC has ~2 times lower values over NH.

Z500 - 00UTC 14 May 2002 t0
ECMWF EM (ci=8) and STD (ci=0.5)

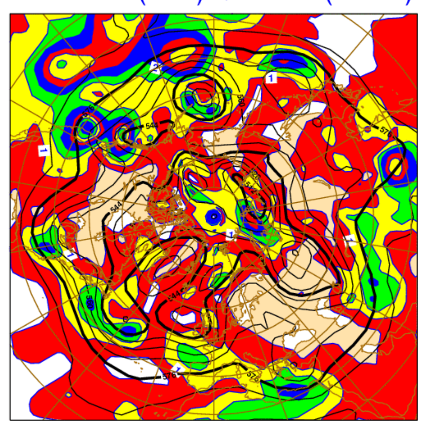


Z500 - 00UTC 14 May 2002 t0
MSC EM (ci=8) and STD (ci=0.5)

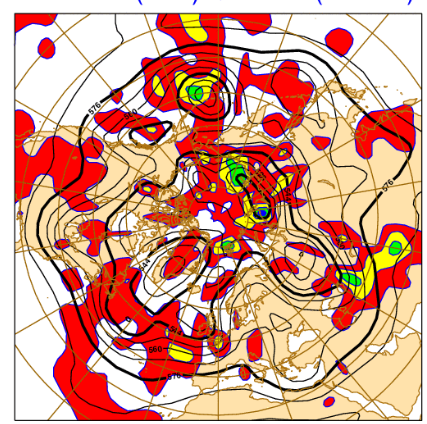


Ref=std(ANj)

Z500 - 00UTC 14 May 2002 t0
NCEP EM (ci=8) and STD (ci=0.5)



Z500 - 00UTC 14 May 2002 t0
3C MEAN (ci=8) and STD (ci=0.25)



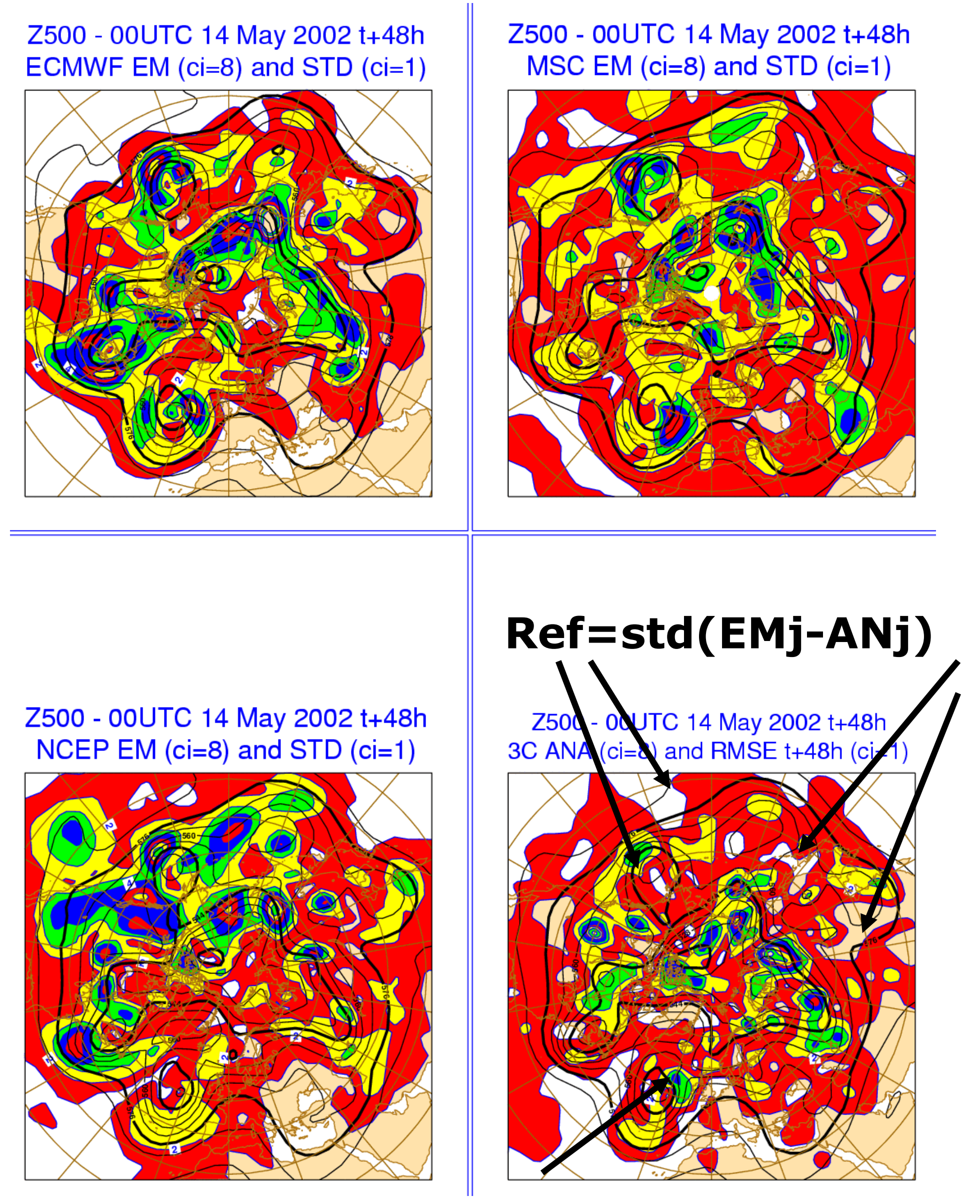
2. Similarities in EM & STD: 14/05/02 +48h

After 48h, the ensemble spreads are more similar, all identifying the main areas where the average of the ens-mean errors is larger.

- Area: there is some degree of similarity among the areas covered by the evolved perturbations.

- Amplitude: similar over NH; EC smaller over tropics.

- Std-vs-rmse: certain areas of large spread coincide with areas of large error.



2. Similarities in EM & STD: 14/05/02 +120h

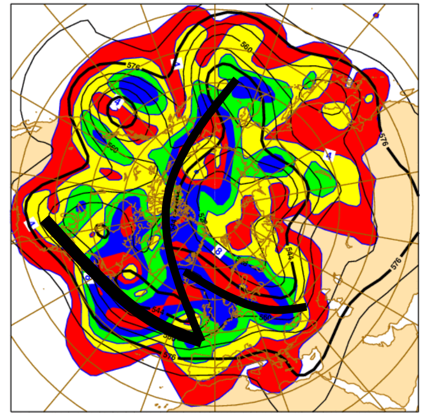
After 120h, ensemble spreads are even more similar, all identifying the main regions where the average of the ens-mean errors is larger.

- <u>Area</u>: perturbations show maximum amplitude in similar regions.

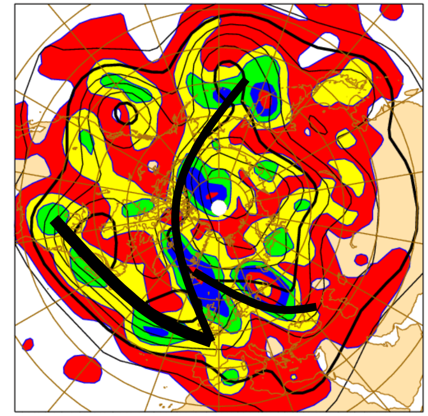
- <u>Amplitude</u>: EC perturbations have larger amplitude.

- <u>Std-vs-rmse</u>: there is a certain degree of agreement between areas of larger error and large spread.

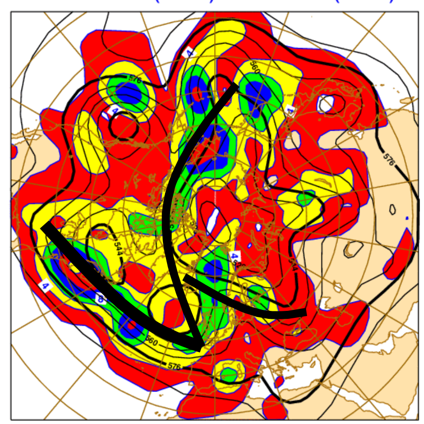
Z500 - 00UTC 14 May 2002 t+120h
ECMWF EM (ci=8) and STD (ci=2)



Z500 - 00UTC 14 May 2002 t+120h
MSC EM (ci=8) and STD (ci=2)

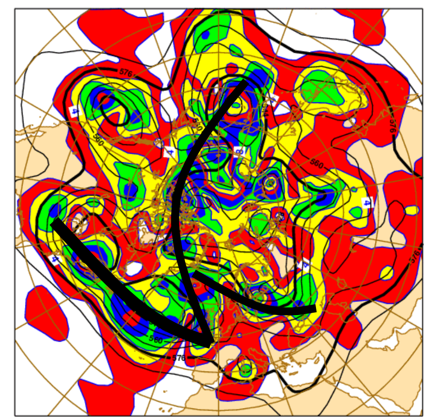


Z500 - 00UTC 14 May 2002 t+120h
NCEP EM (ci=8) and STD (ci=2)



Ref=std(EMj-ANj)

Z500 - 00UTC 14 May 2002 t+120h
3C ANA (ci=8) and RMSE t+48h (ci=2)



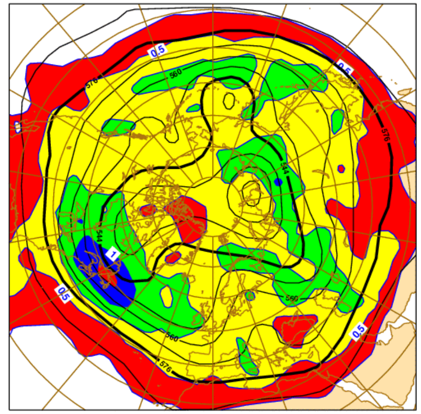
2. Similarities in EM & STD: May ‘02 t=0

Average results for May 2002 confirm that the three ensembles have different initial-time spread.

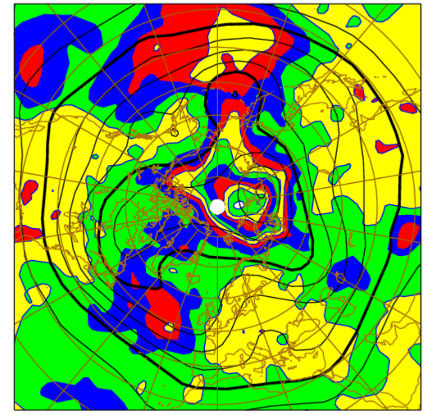
- Area: NCEP and MSC peak over the Pacific ocean and the Polar cap while EC peaks over the Atlantic ocean; MSC shows clear minima over Europe and North America.

- Amplitude: MSC and NCEP are ~2 times larger than the std of the 3 centres’ analyses (2-times larger contour interval); EC has amplitude similar to 3C-std over NH but has too small amplitude over the tropics.

Z500 - 00UTC May 2002 t0 (31d)
ECMWF EM (ci=8) and STD (ci=0.25)

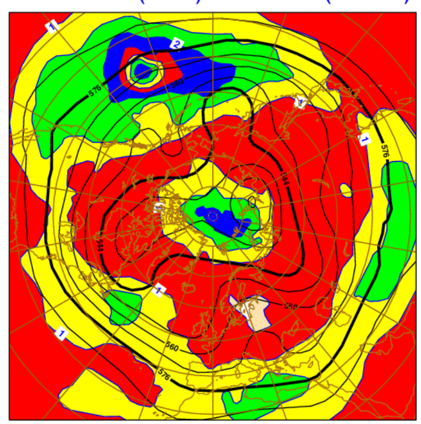


Z500 - 00UTC May 2002 t0 (31d)
MSC EM (ci=8) and STD (ci=0.5)

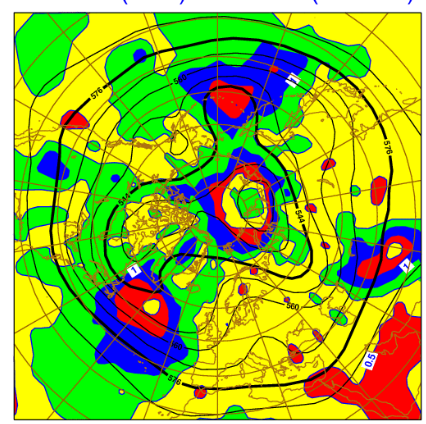


Ref=std(EMj-ANj)

Z500 - 00UTC May 2002 t0 (31d)
NCEP EM (ci=8) and STD (ci=0.5)



Z500 - May 2002 (31d) - t0
3C ANA (ci=8) and STD (ci=0.25)



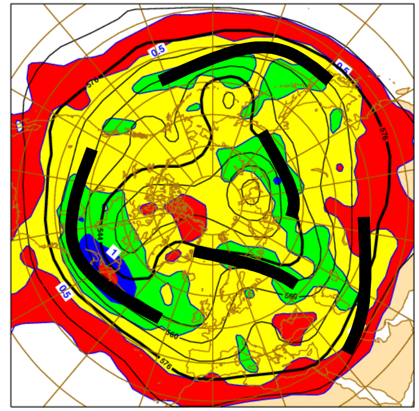
2. Similarities in EM & STD: May '02 t=0

The EC std shows a closer agreement with areas of baroclinic instability, as seen by comparing the stds with the Eady index (*Hoskins and Valdes* 1990:

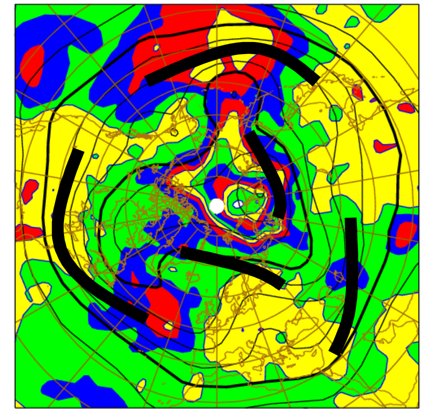
$$\sigma_E = 0.31 \frac{f}{N} \frac{du}{dz}$$

(with static stability N and wind shear computed using the 300- and 1000-hPa potential temperature and wind).

Z500 - 00UTC May 2002 t0 (31d)
ECMWF EM (ci=8) and STD (ci=0.25)

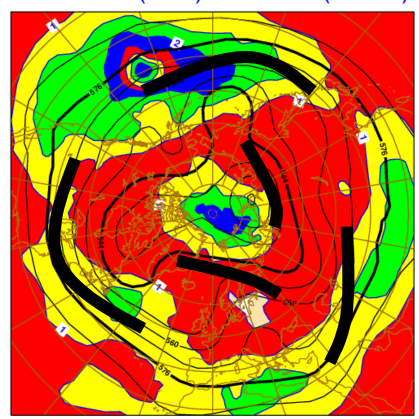


Z500 - 00UTC May 2002 t0 (31d)
MSC EM (ci=8) and STD (ci=0.5)

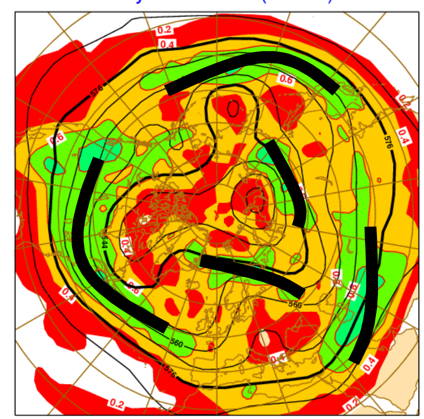


Ref=Eady index

Z500 - 00UTC May 2002 t0 (31d)
NCEP EM (ci=8) and STD (ci=0.5)



Z500 - May 2002 (31d) - EC ANA (ci=8)
Eady 300-1000 (ci=0.2)



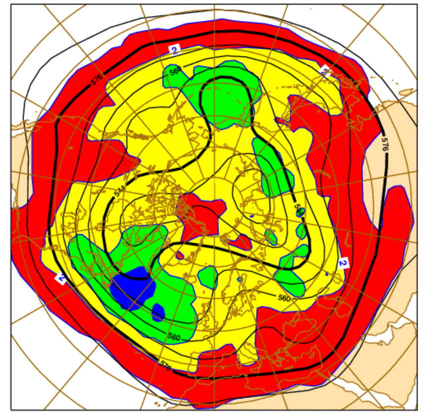
2. Similarities in EM & STD: May ‘02 +48h

After 48 hours, the ensemble spreads are more similar.

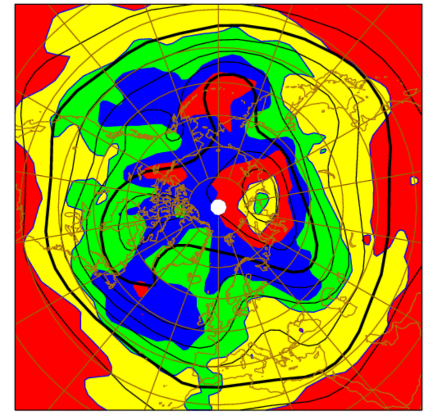
- <u>Area</u>: NCEP and MSC give more weight to the Pacific while EC gives more weight to the Atlantic; NCEP initial relative maximum over the North Pole cap has disappeared; MSC shows still a large amplitude north of Siberia.

- <u>Amplitude</u>: MSC has the largest amplitude over NH; EC has the smallest amplitude over the tropics.

Z500 - 00UTC May 2002 t+48h (31d)
ECMWF EM (ci=8) and STD (ci=1)

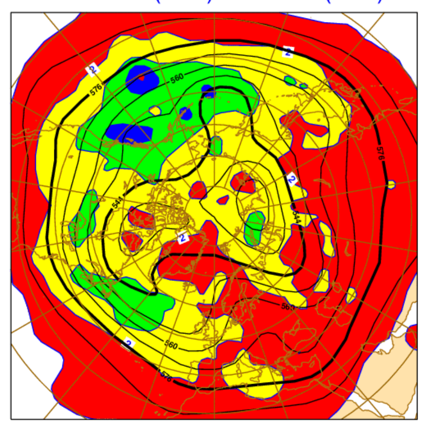


Z500 - 00UTC May 2002 t+48h (31d)
MSC EM (ci=8) and STD (ci=1)

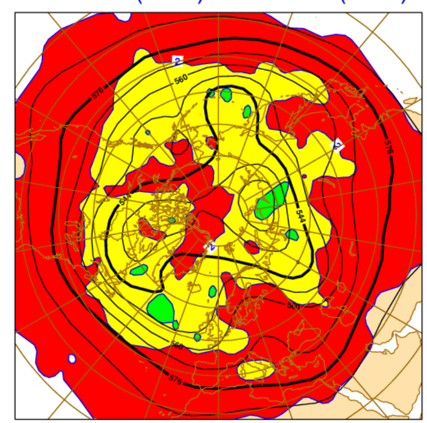


Ref=std(EMj-ANj)

Z500 - 00UTC May 2002 t+48h (31d)
NCEP EM (ci=8) and STD (ci=1)



Z500 - May 2002 (31d) - t+48h
3C ANA (ci=8) and STD (ci=1)



2. Main conclusions from the comparison

a) In terms of spread, the three systems differ substantially at initial time, while they are more similar after 2 days.

b) The spread of the ECMWF ENS grows faster than in the other two systems because of the combined effect of sustained SV-based perturbations' growth and the stochastic simulation of random model errors.

c) Skill has not been compared in this talk. *Buizza et al* (2005) concludes that ensemble performance depends on the quality of the data assimilation system used to generate the initial conditions, the model used to produce the forecasts, and the perturbation strategies. Overall, the ECMWF EPS was the most reliable and performed best.

Outline

1. Objectives and approaches to ensemble prediction
2. Comparison of the 2002 ECMWF, MSC and NCEP ensemble systems
3. The THORPEX/TIGGE global, medium-range ensembles

3. THORPEX/TIGGE objectives

THORPEX (THe Observing system Research and Predictability Experiment) was established in 2003 as a WMO World Weather Research Program to accelerate improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, the economy and the environment.

TIGGE (the THORPEX Interactive Grand Global Ensemble eXperiment), a key component of THORPEX, is a framework for international collaboration in ensemble prediction systems. It aimed 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).

3. TIGGE relies on existing ensemble systems

There are 10 operational global, medium-range ensemble systems (BMRC, CMA, CPTEC, ECMWF, FNMOC, JMA, KMA, MSC, NCEP and UKMO) with horizontal resolution ranging from T62 to T_L639 (~32km), and with forecast length ranging from 8 to 16 days.

9 of the 10 (all but FNMOC) medium-range ensembles, plus the short-range Meteo-France ensemble are archived in TIGGE. Today (Feb 2015), every day 436 forecasts generated by the 8 operational, global, medium-range TIGGE ensembles are shared, and archived in the TIGGE archive. They can be freely accessed by users with a 48-hour delay mode.

The TIGGE data-base includes many parameters from all contributing centres (see http://tigge.ecmwf.int/ for more information).

3. The TIGGE ensembles (updated Nov 2014)

The 9 TIGGE operational, medium-range, global ensembles use different methodologies to simulate initial-time and model uncertainties. Every day, the 7 ensembles that are still operational, put 436 forecasts into the TIGGE archive. These forecasts have horizontal resolution ranging from about 210 km to about 32 km, and forecast length between 10 and 16 days. They all simulate initial/observation and model uncertainties in different ways.

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)	91 (0.1)	0-10	50	2 (00/12)	102	Oct-06
			TL319 (0.56°; 65km)		15/32				
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)	28 (2.7)	0-8	20	4 (00/06/ 12/18)	84	Mar-07
			T190 (0.95°; 120km)		8-16				
UKMO (UK)	ETKF(globe)	YES	N216 (0.45°; 60km)	70 (0.1)	15	23	2 (00/12)	48	Oct-06/Jul-14

3. The SV-based ensembles: BOM, ECMWF, JMA, MF

In these ensembles, the perturbed initial conditions are defined by adding to the unperturbed analysis (the interpolated high-resolution analysis) perturbations defined by a linear combination of SVs:

- BMRC: initial-time SVs computed over NH and SH extra-tropics
- ECMWF: a combination of initial-time SVs, computed over NH and SH extra-tropics, and over few tropical regions , and perturbations generated from an Ensemble Data Assimilation (EDA) system
- JMA: initial-time SVs computed over the NH extra-tropics and the tropics
- MF: initial-time SVs optimized to grow over a European region plus EDA-based perturbations

3. The EnKF-based ensemble: MSC

The MSC ensemble uses an EnKF to generate the initial conditions (*Houtekamer & Mitchell* 2005). The perturbed initial conditions are defined by 20 EnKF members (randomly-selected from the 192 available members). The EnKF (*Evensen* 1994) is an approximation of the Kalman Filter that improves as the ensemble size increases.

The MSC EnKF uses a model error parameterization based on the forecast error description of the MSC 3D-Var. Thus, it should be considered as a hybrid scheme (*Hamill & Snyder* 2000). The EnKF runs with:

- a 6 hour cycle;
- four streams of 48 members;
- randomly perturbed observations, with random perturbations sampled from a normal distribution with obs-error statistics.

3. The BV-based ensemble: CMA

In these ensembles, the perturbed initial conditions are defined by adding to the unperturbed analysis (the interpolated high-resolution analysis) perturbations defined by BVs (*Toth & Kalnay* 1997), computed following the method that was used at NCEP from 1992 till recently.

Each BV is computed by adding a random perturbation to the starting analysis, evolving it for 24-hours and then rescaling it. BVs are grown non-linearly at full model resolution.

3. The ETKF-based ensemble: UKMO, KMA

The Ensemble Transform Kalman Filter (ETKF) method was first proposed by *Bishop et al* (2001) in targeted observation studies, and used in ensemble systems by *Wang & Bishop* (2003).

In the UKMO ETKF, perturbations are cycled and re-orthogonalized, and then 'transformed' using an estimate of the analysis error covariance matrix defined by observations and short-time forecast errors. ETKF perturbations can be considered as modified BVs, with BVs transformed using ETKF ideas. KMA uses the same system.

The perturbed initial conditions are defined by adding to the unperturbed analysis (the interpolated high-resolution analysis) perturbations defined by the difference of ETKF members.

3. The ETR-based (BV-inspired) ensemble: NCEP

The Ensemble Transform (ET) method was first proposed by *Bishop & Toth* (1999) in target observation studies. The ET with rescaling (ETR) method is an extension of breeding (*Wei et al* 2008).

Given a set of perturbations, in the ET method perturbations are 'transformed' using analysis error variances from the best possible data-assimilation system (instead of using an estimate of the analysis error covariance matrix defined by observations and short-time forecast errors, as it is done in the ETKF method). In the ETR method, the ET perturbations are re-scaled to have an initial spread distribution similar to an estimate of the analysis error variance.

As for ETKF perturbations, ETR perturbations can be considered modified BVs, with BVs transformed using the ET method and rescaled.

The perturbed initial conditions are defined by adding to the unperturbed analysis (the interpolated high-resolution analysis) perturbations defined by the difference of ETR members.

3. The EOF-based (BV-inspired) ensemble: CPTEC

The EOF-based method was developed by *Zhang & Krishnamurti* (1999) to apply an ensemble technique to hurricane forecasting:

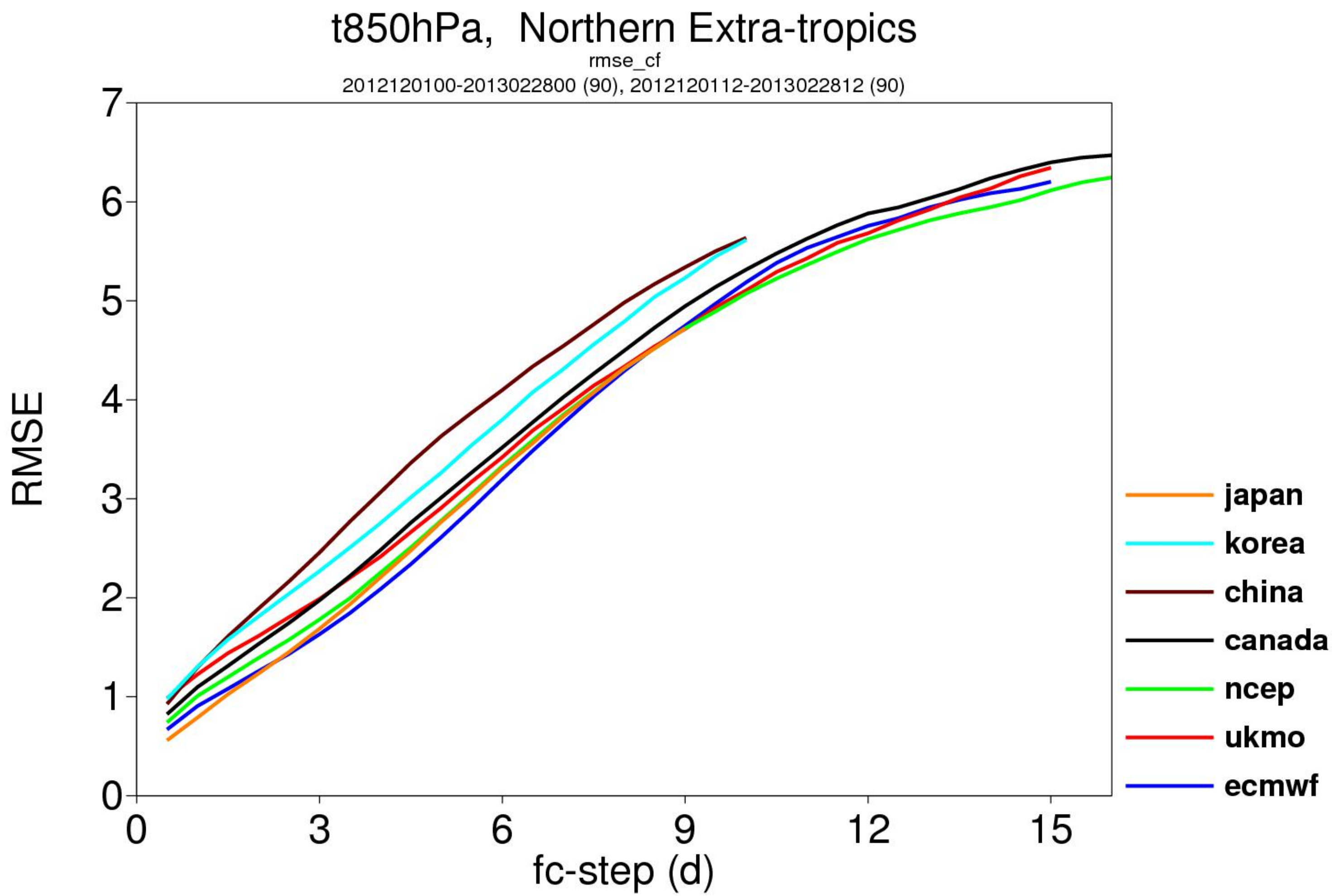
- an ensemble of forecasts is performed by adding random perturbations to the unperturbed analysis
- each model is integrated for 36 hours with full physics
- an EOF analysis is performed on the time series of the differences between the perturbed and the control forecast
- the modes whose EOF coefficients increase rapidly are used as initial perturbations

The perturbed initial conditions are defined by adding to the growing modes to the unperturbed analysis (the interpolated high-resolution analysis). EOF perturbations can be considered modified BVs, with BVs transformed using the EOF method

As for ETKF and ETR perturbations, these.

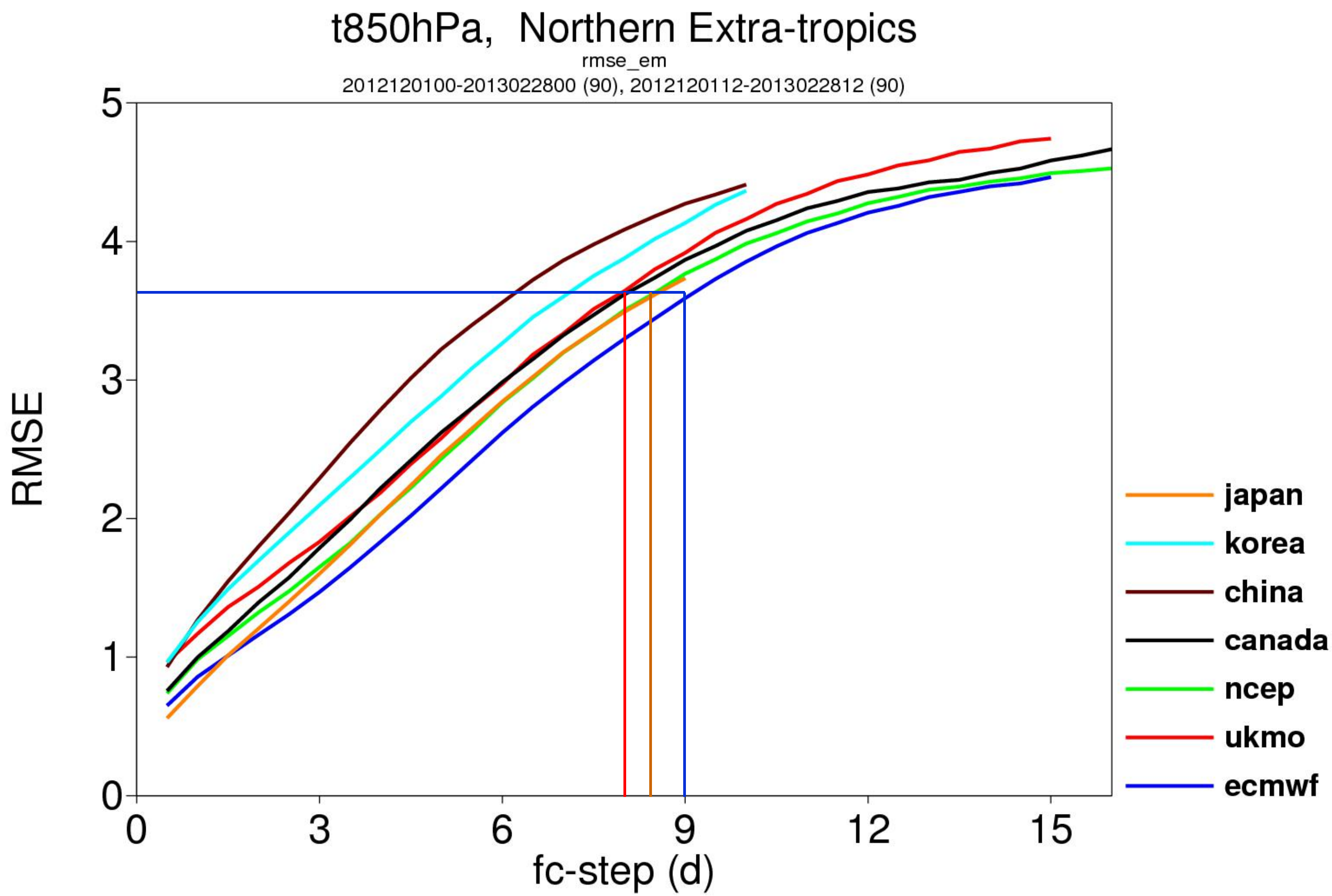
3. D12JF13 (90c): T850 rmse(CF) over NH

RMSE(control) for T850 over NH, for winter 2012-13 (90 cases).



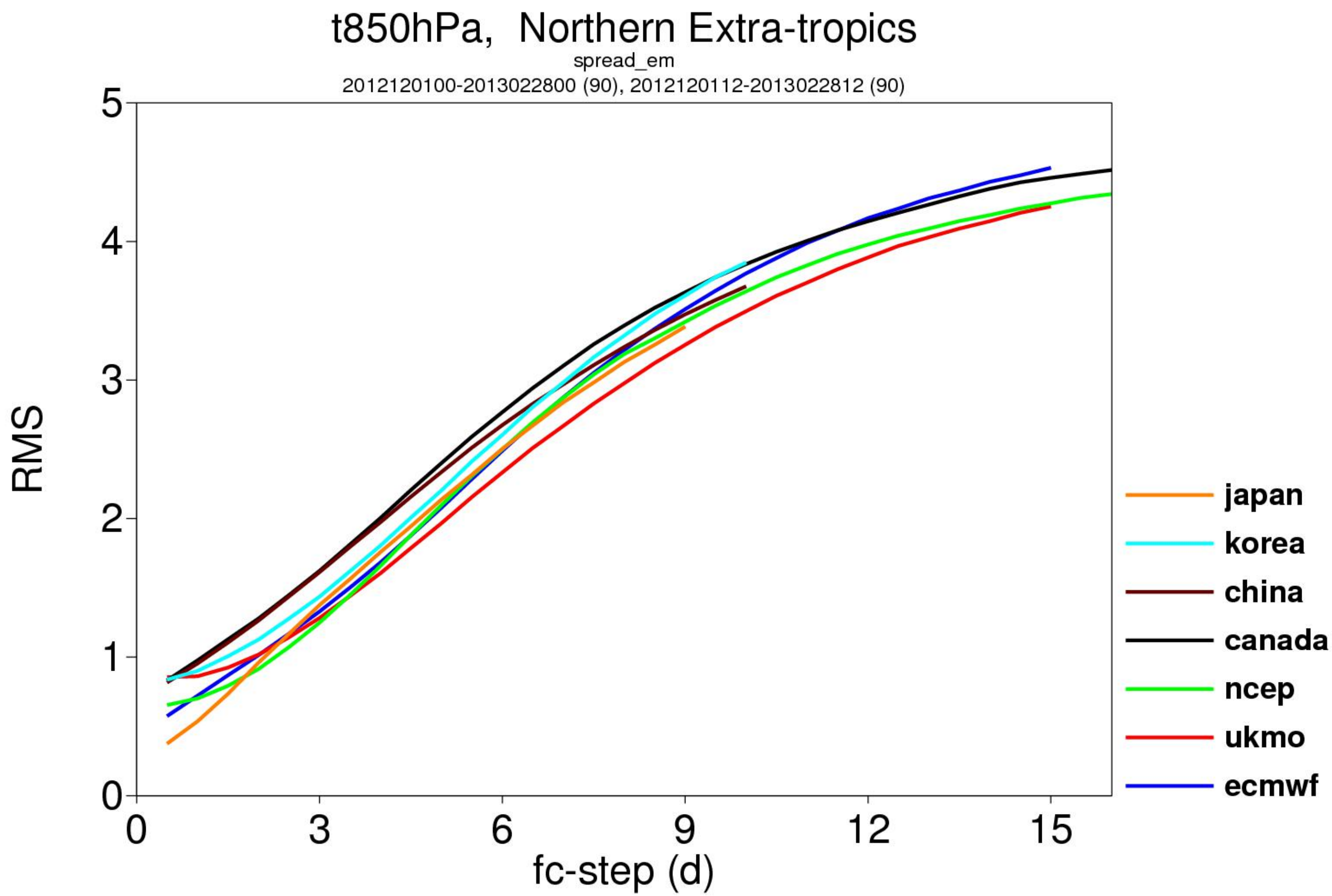
3. D12JF13 (90c): T850 rmse(EM) over NH

RMSE(ensemble-mean) for T850 over NH, for winter 2012-13 (90 cases).



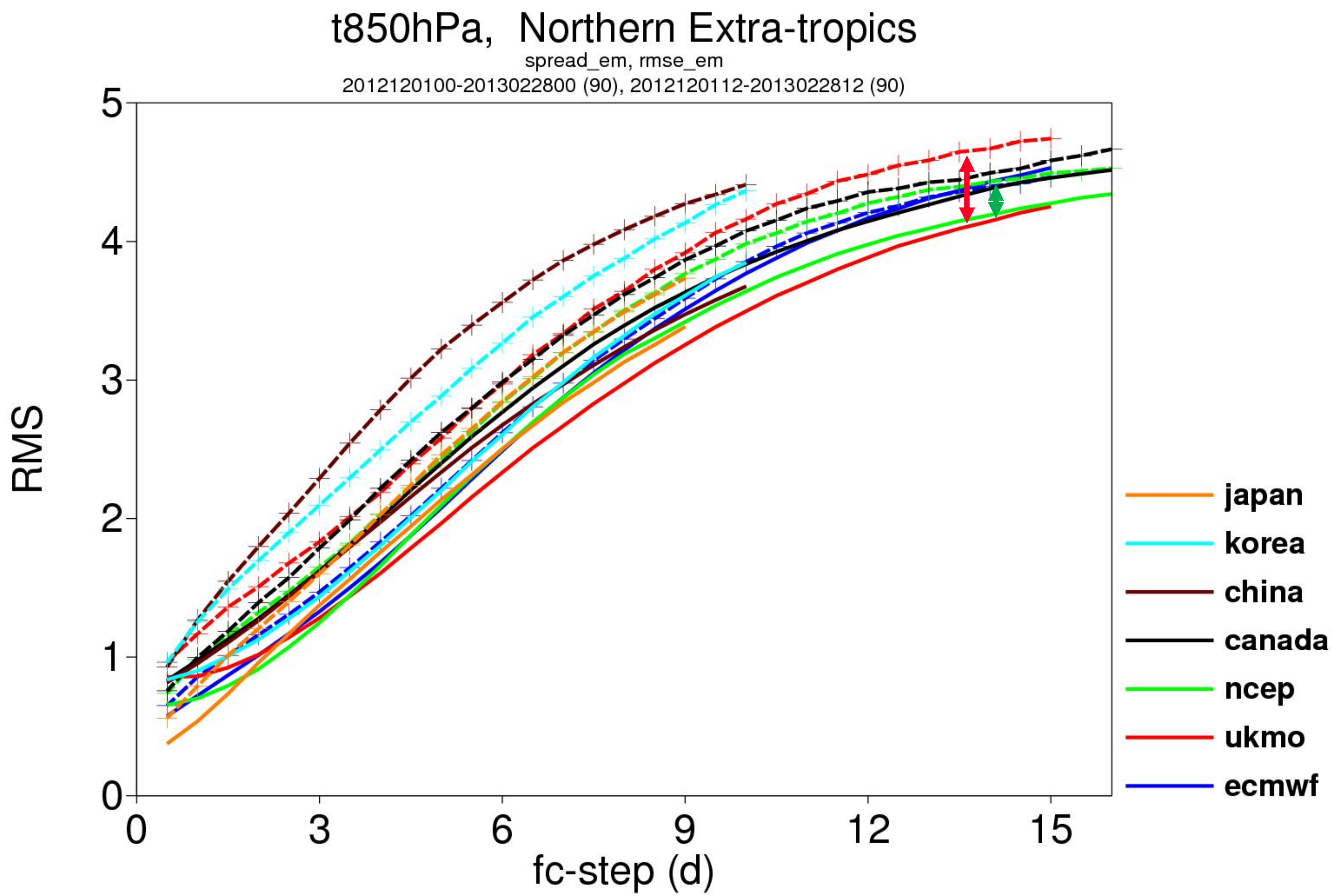
3. D12JF13 (90c): T850 std over NH

Spread (std) for T850 over NH, for winter 2012-13 (90 cases).



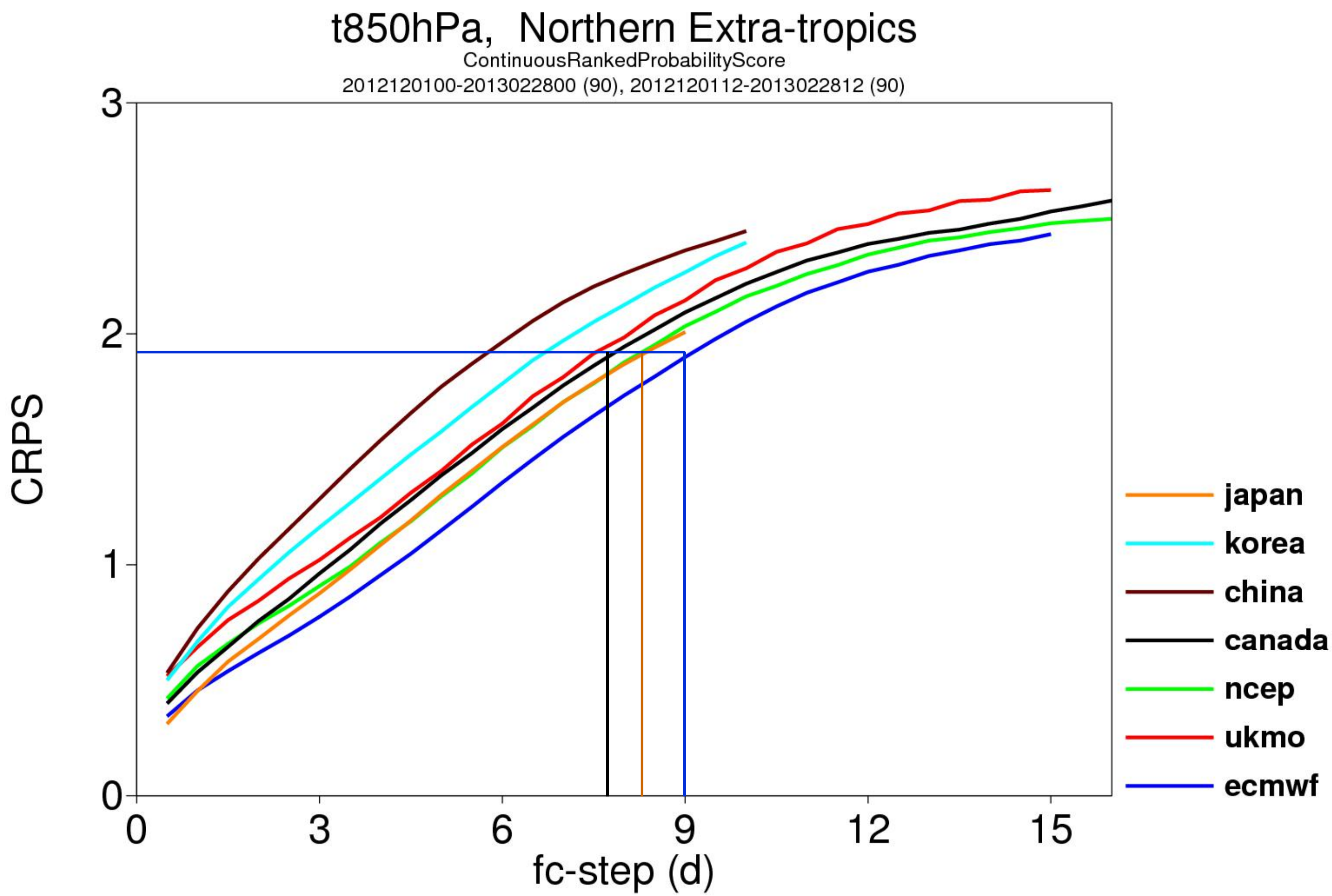
3. D12JF13 (90c): T850 std and rmse(EM) over NH

RMSE(ensemble-mean) and spread for T850 over NH, for winter 2012-13 (90 cases).



3. D12JF13 (90c): T850 CRPS over NH

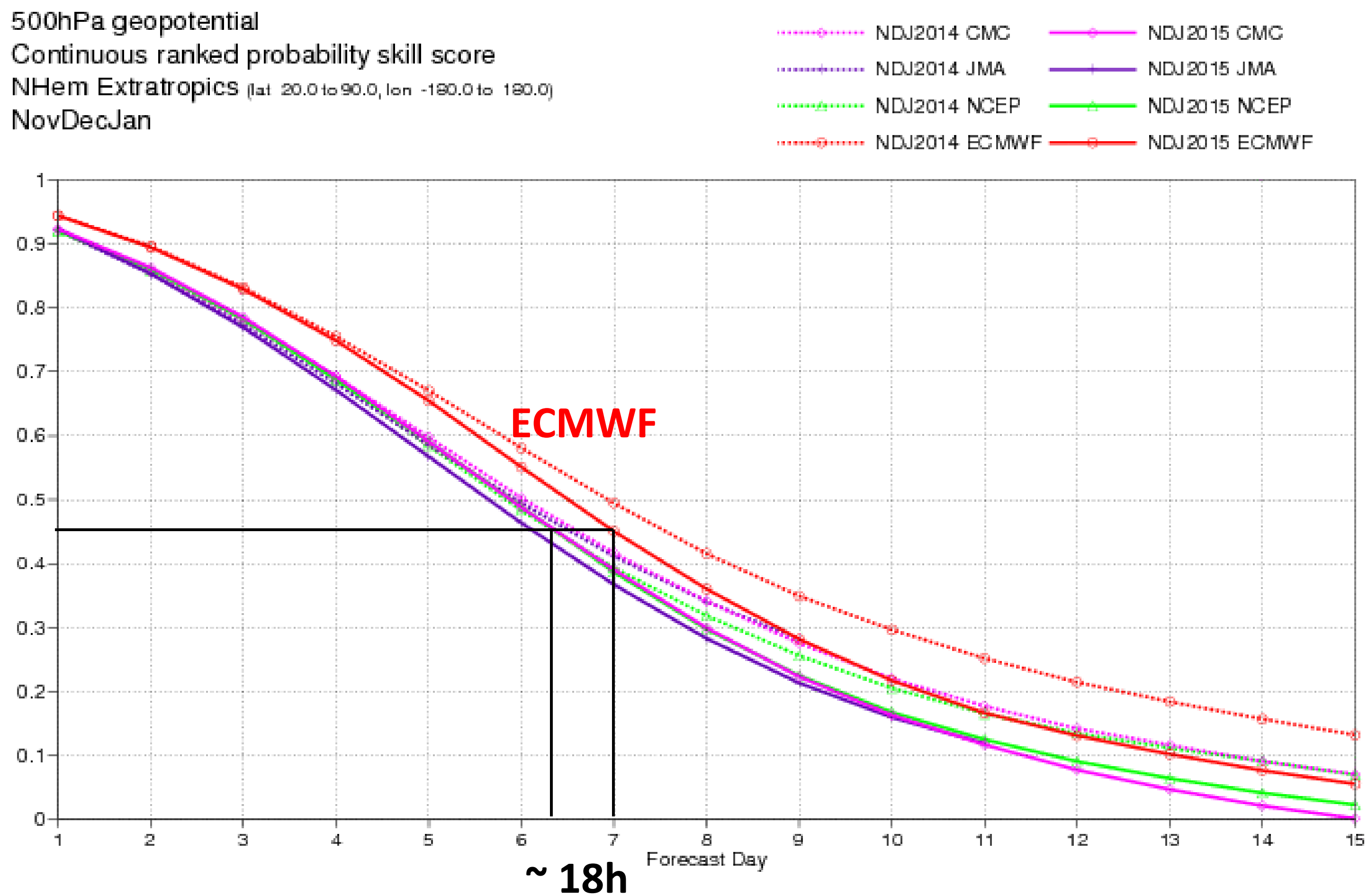
CRPS for T850 over NH, for winter 2012-13 (90 cases).



3. ND14J15: CRPSS(Z500,NH)

More recent results: average ND14J15 (solid) and ND13J14 (dashed) CRPSS for Z500 over NH for the 4 best TIGGE ensembles:

- ECMWF (red)
- JMA (violet)
- NCEP (green)
- CMC (pink)

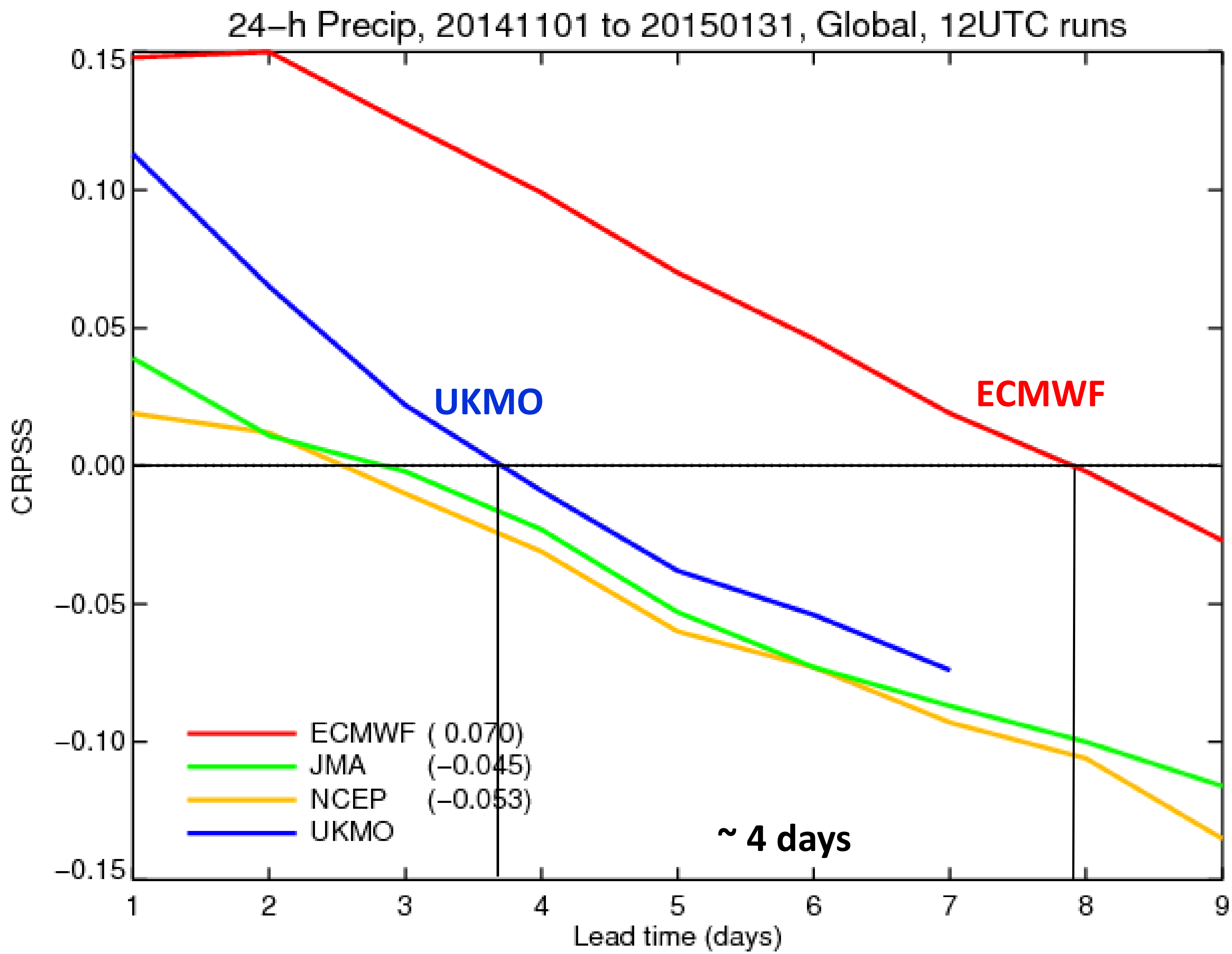


3. ND14J15: CRPSS(TP24,Global)

More recent results: average ND14J15 (solid) CRPSS for 24h precipitation over the globe for 4 TIGGE ensembles:

- ECMWF (red)
- JMA (green)
- NCEP (yellow)
- UKMO (blue)

Differences here between the best and the second best are about 4 days!

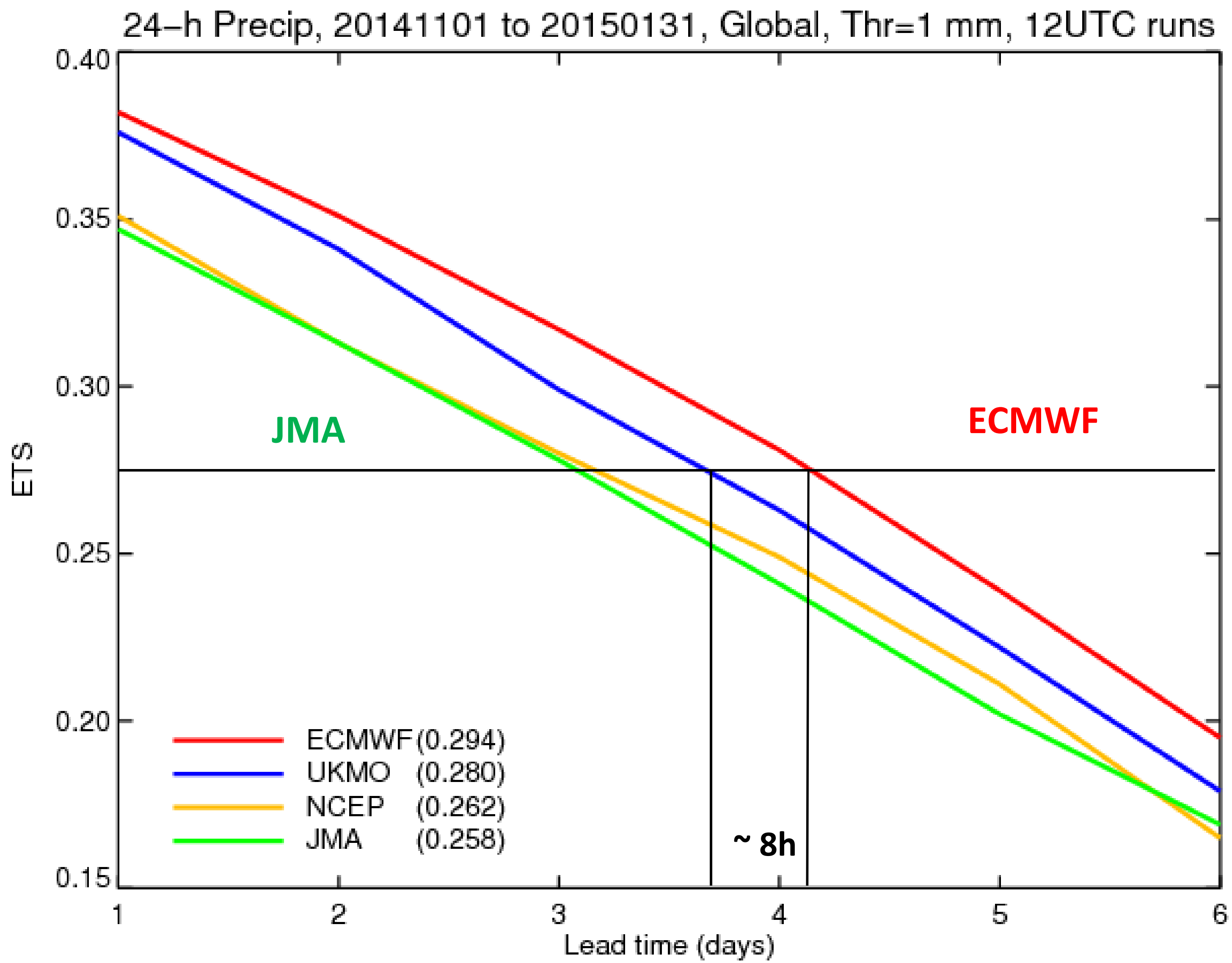


3. ND14J15: ETS(TP24>1mm,Global)

More recent results: average ND14J15 (solid) CRPSS for 24h precipitation over the globe for 4 single forecasts:

- ECMWF (red)
- JMA (green)
- NCEP (yellow)
- UKMO (blue)

Differences here between the best and the second best are about 8-10 hours.



Conclusions

- TIGGE makes it easy to compare the performance of ensemble systems and to understand the impact of system's design on ensemble performance.

- Comparison have shown that the ECMWF ensemble continues to be the best of the single ensemble systems. Compared to a multi-model system, over the extra-tropics the ECMWF ensemble performs similarly to a TIGGE multi-model system, but over the tropics it performs worse.

- TIGGE data can be used to address fundamental predictability questions, e.g. which is the best way to simulate model error? Can a single-system ensemble outperform a multi-system ensemble? Which is the best way to combine ensemble members from different ensembles?

Acknowledgements

The success of the ECMWF EPS is the result of the continuous work of ECMWF staff, consultants and visitors who had continuously improved the ECMWF model, analysis, diagnostic and technical systems, and of very successful collaborations with its member states and other international institutions. The work of all contributors is acknowledged.

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On the different ensemble prediction systems

- <u>ECMWF (SV) system</u>

  See bibliography list in lecture 1.

- <u>MSC (EnKF) system</u>

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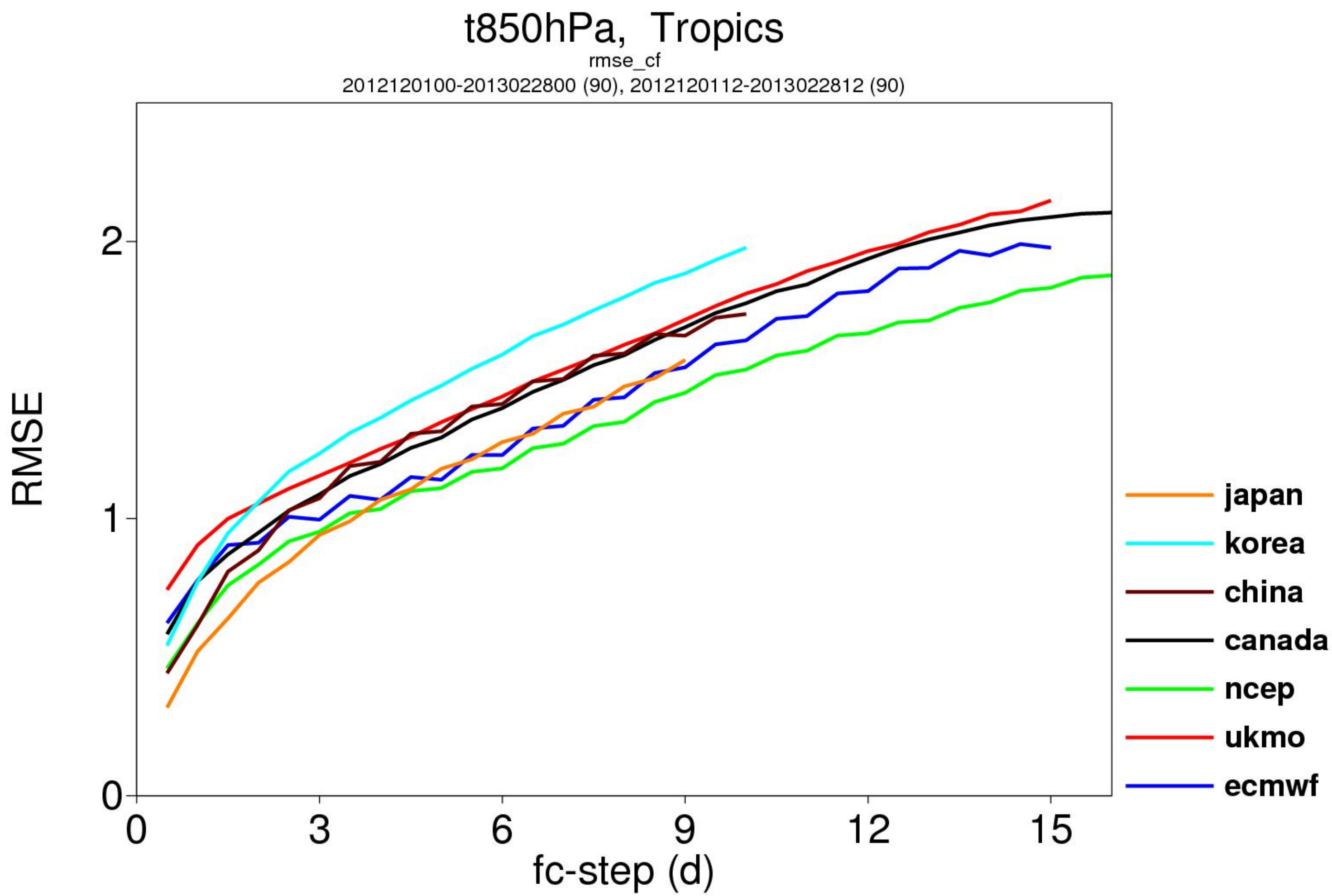
Buizza, R., Houtekamer, P. L., Toth, Z., Pellerin, G., Wei, M., & Zhu, Y., 2005: A comparison of the ECMWF, MSC and NCEP Global Ensemble Prediction Systems. *Mon. Wea. Rev.*, **133**, 5, 1076-1097.

… extra material …

3. J12FM13 (90c): T850 rmse(CF) over TR

RMSE(control) for T850 over the tropics, for winter 2012-13 (90 cases).



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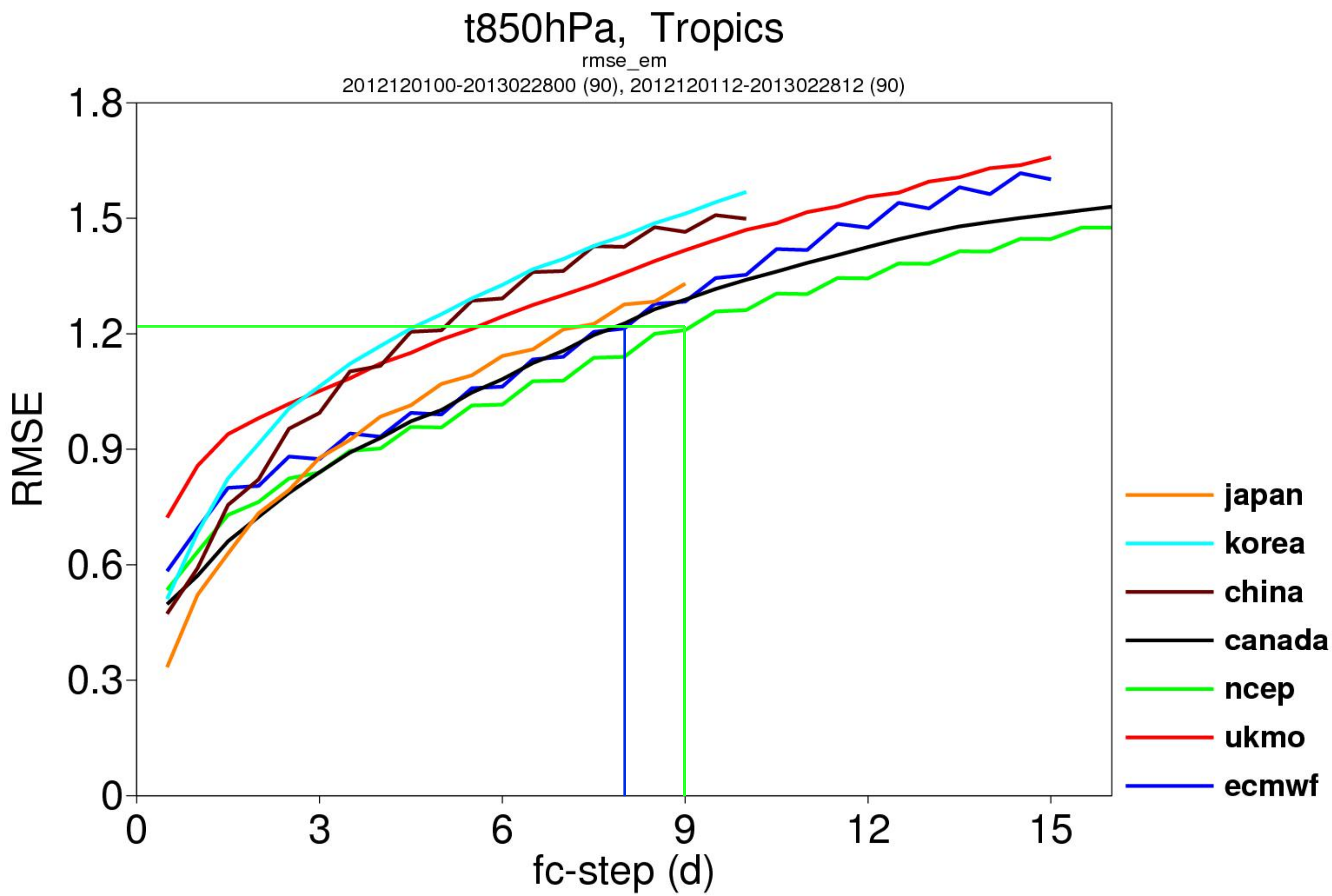
RMSE(ensemble-mean) for T850 over the tropics, for winter 2012-13 (90 cases).



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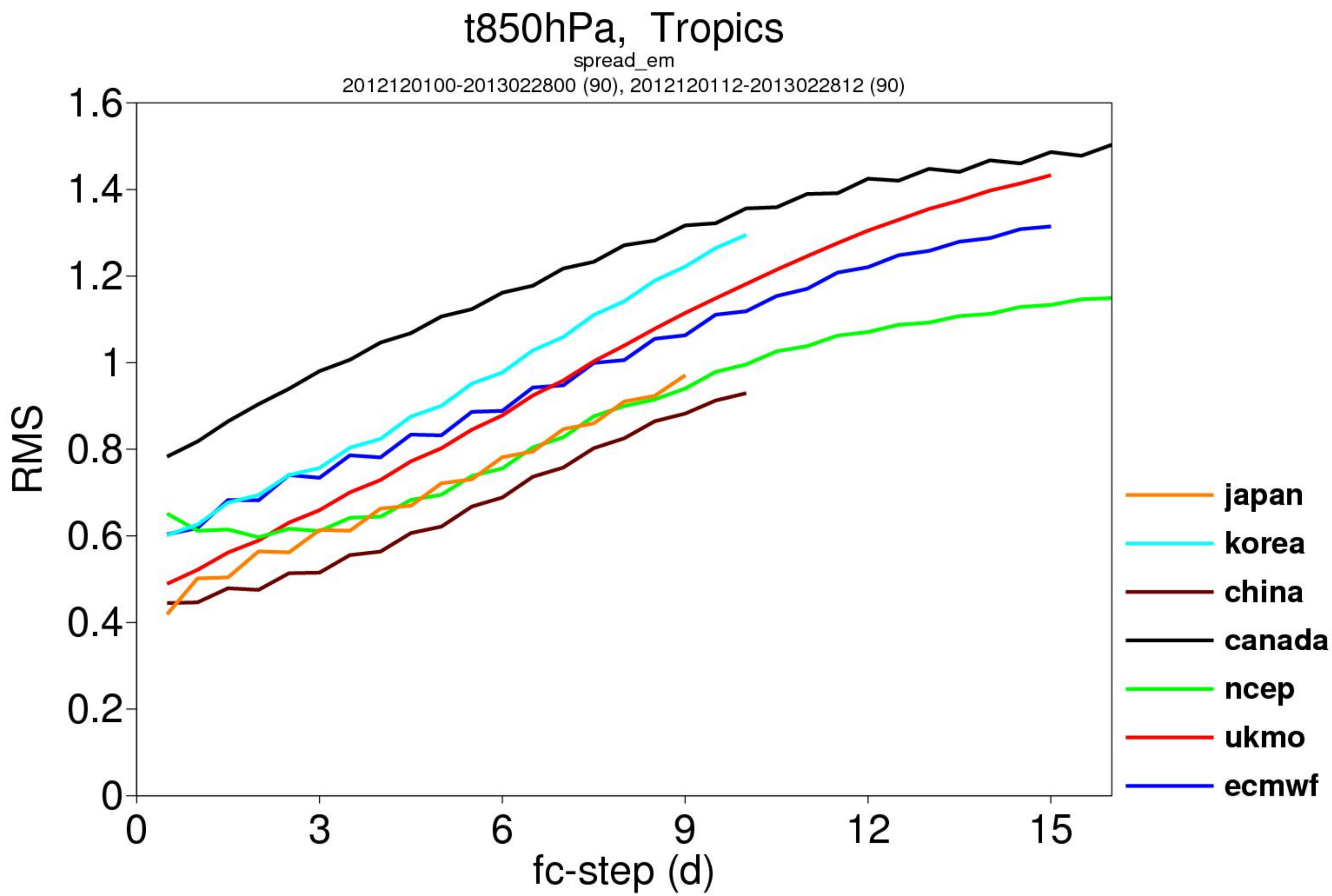

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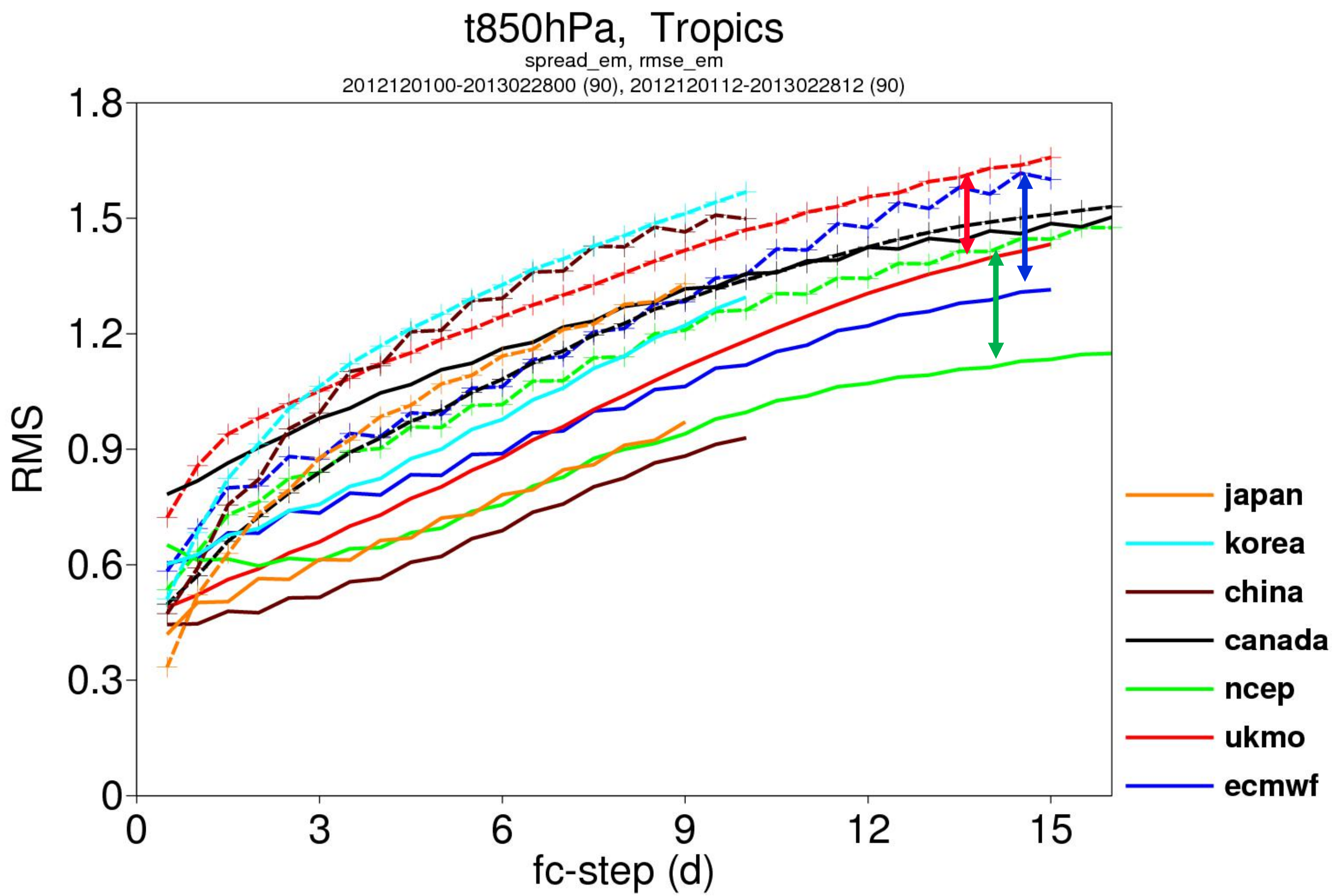

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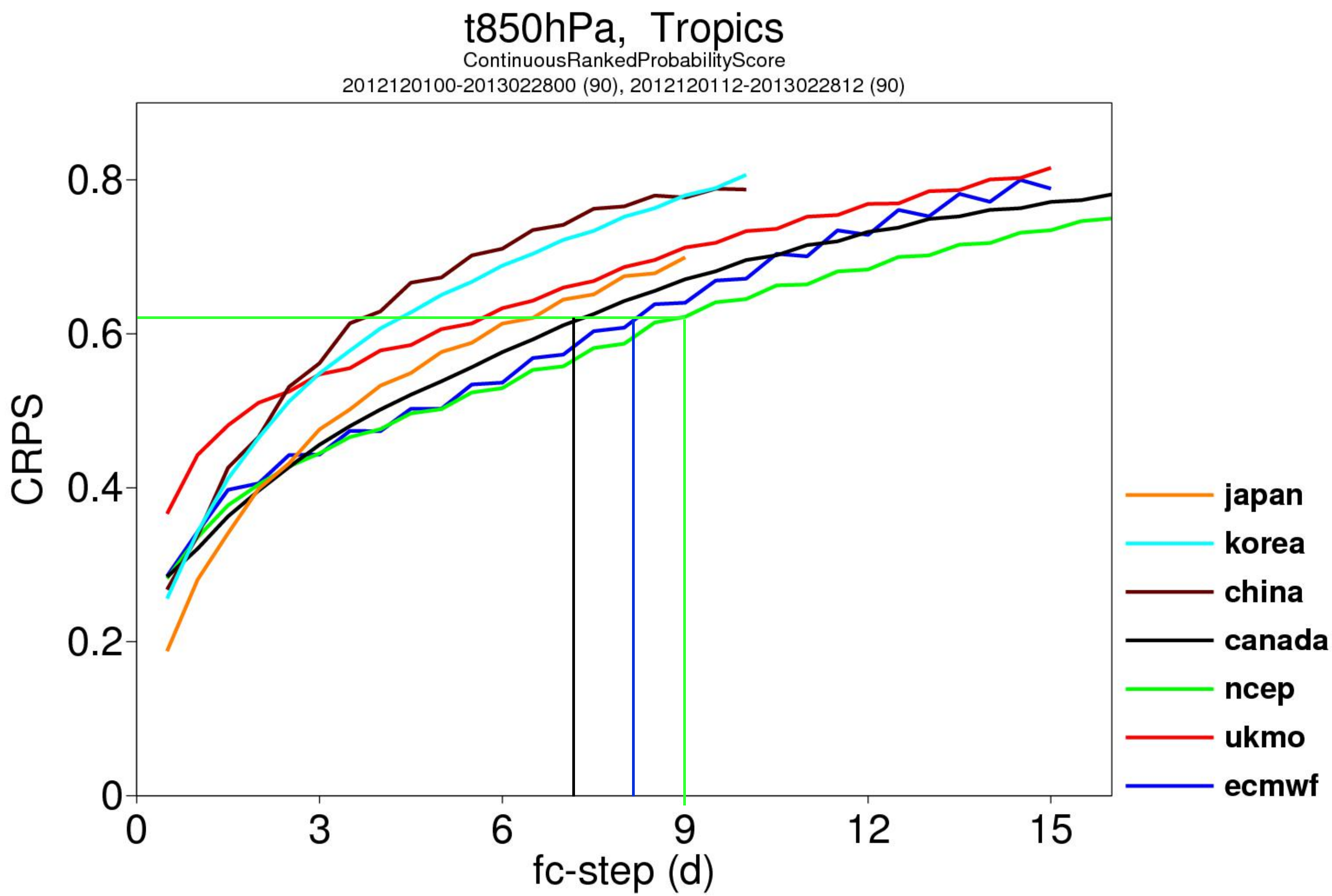

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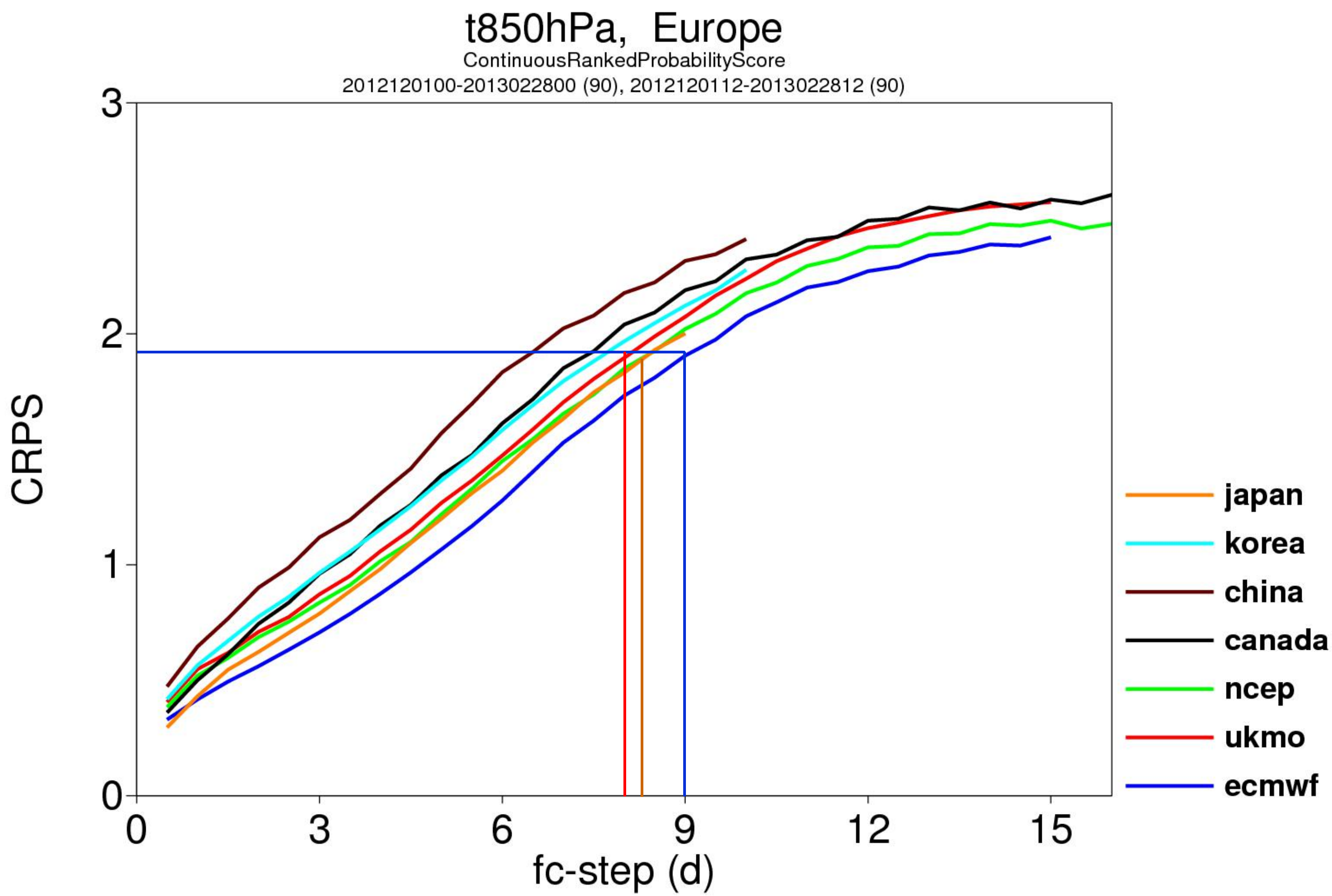
CRPS for T850 over Europe, for winter 2012-13 (90 cases).



3. J12FM13 (90c): U850 CRPS over NH

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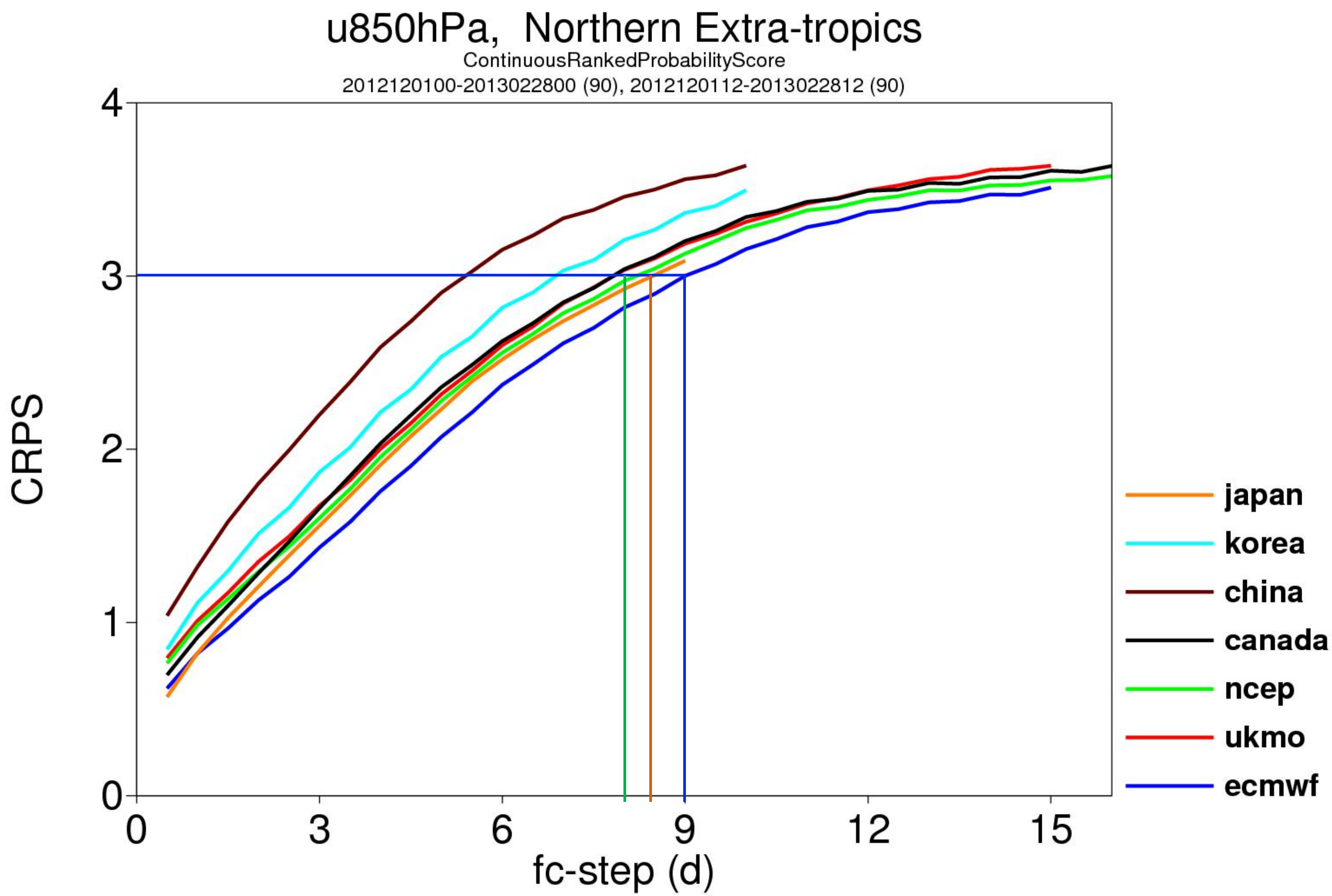

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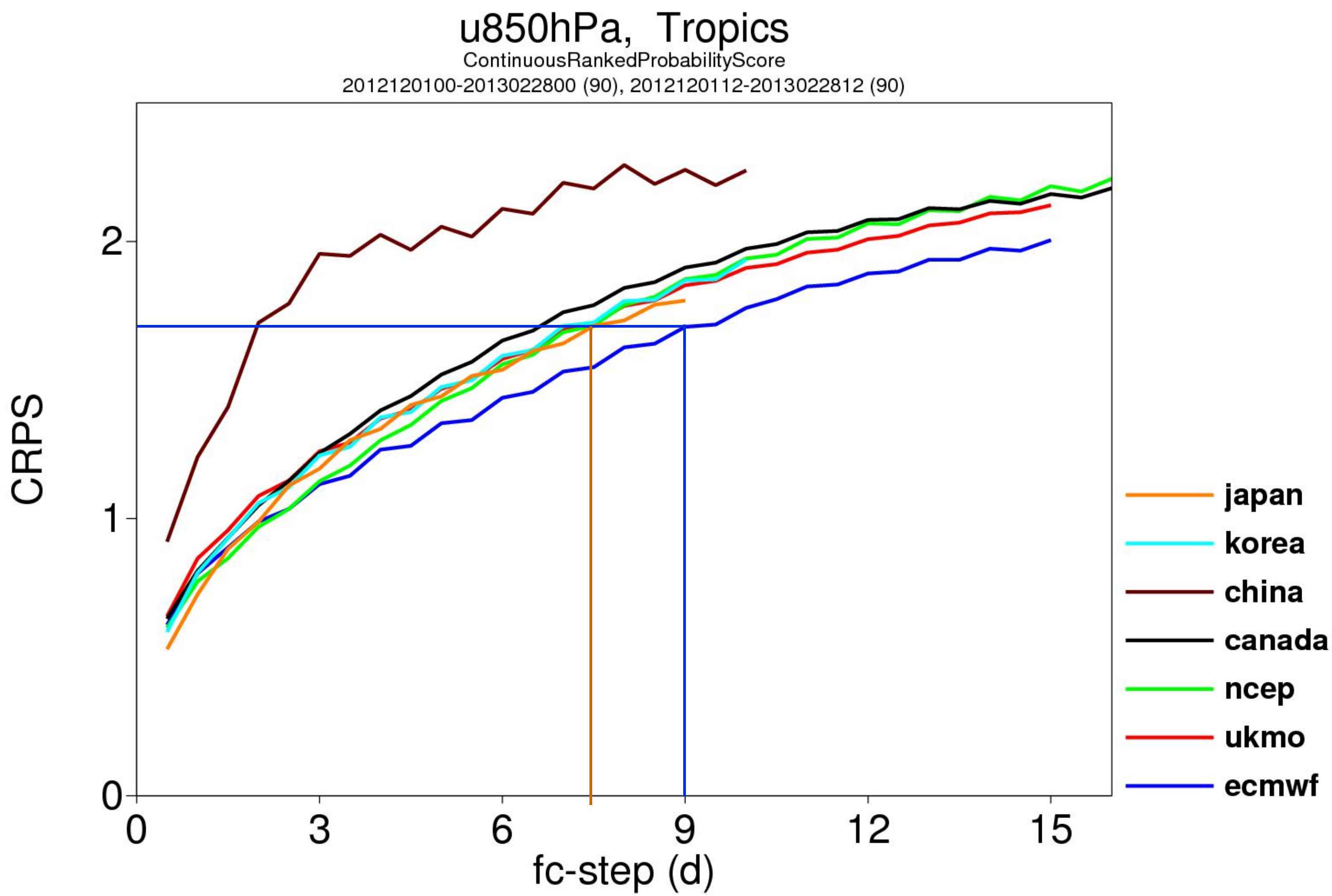

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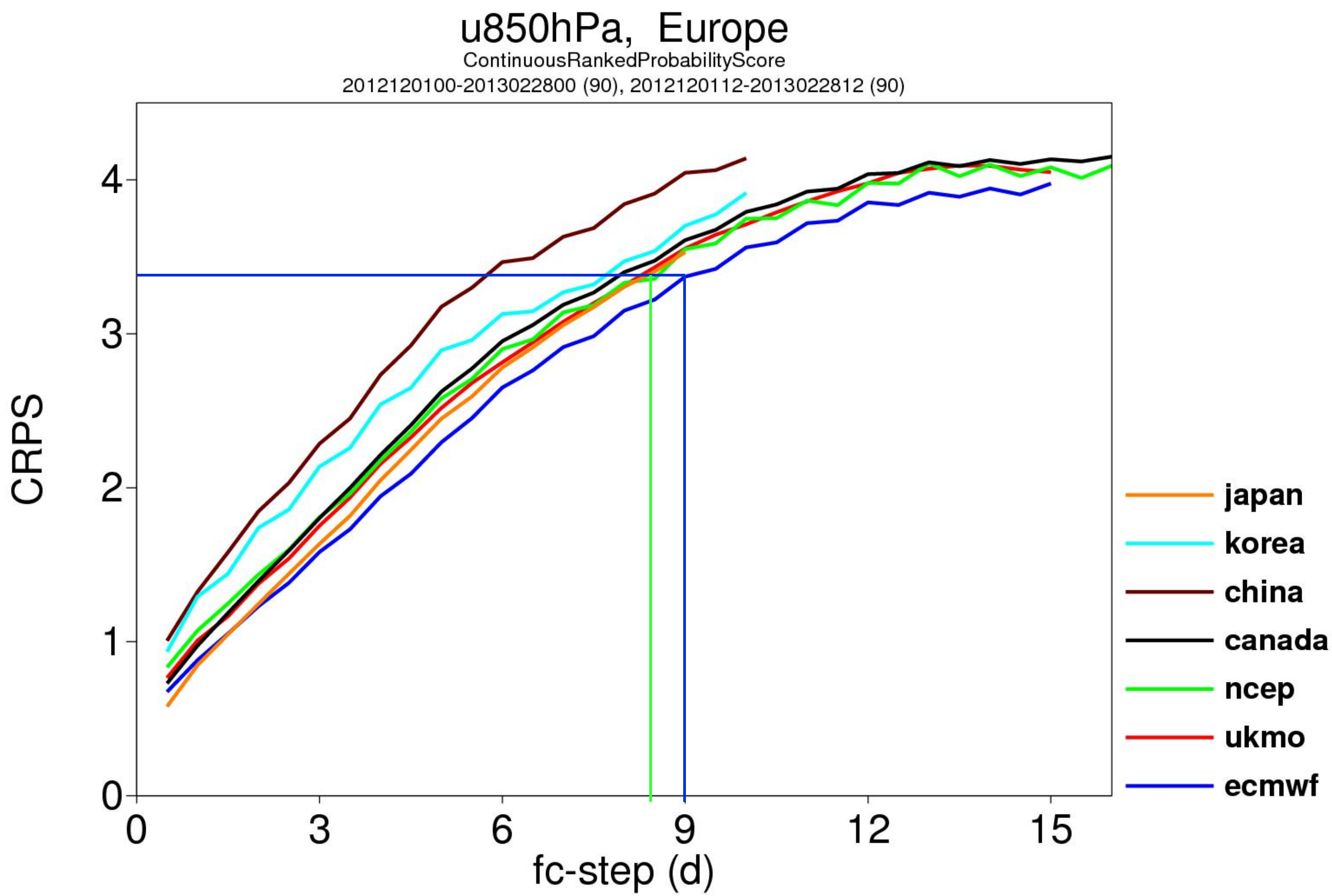
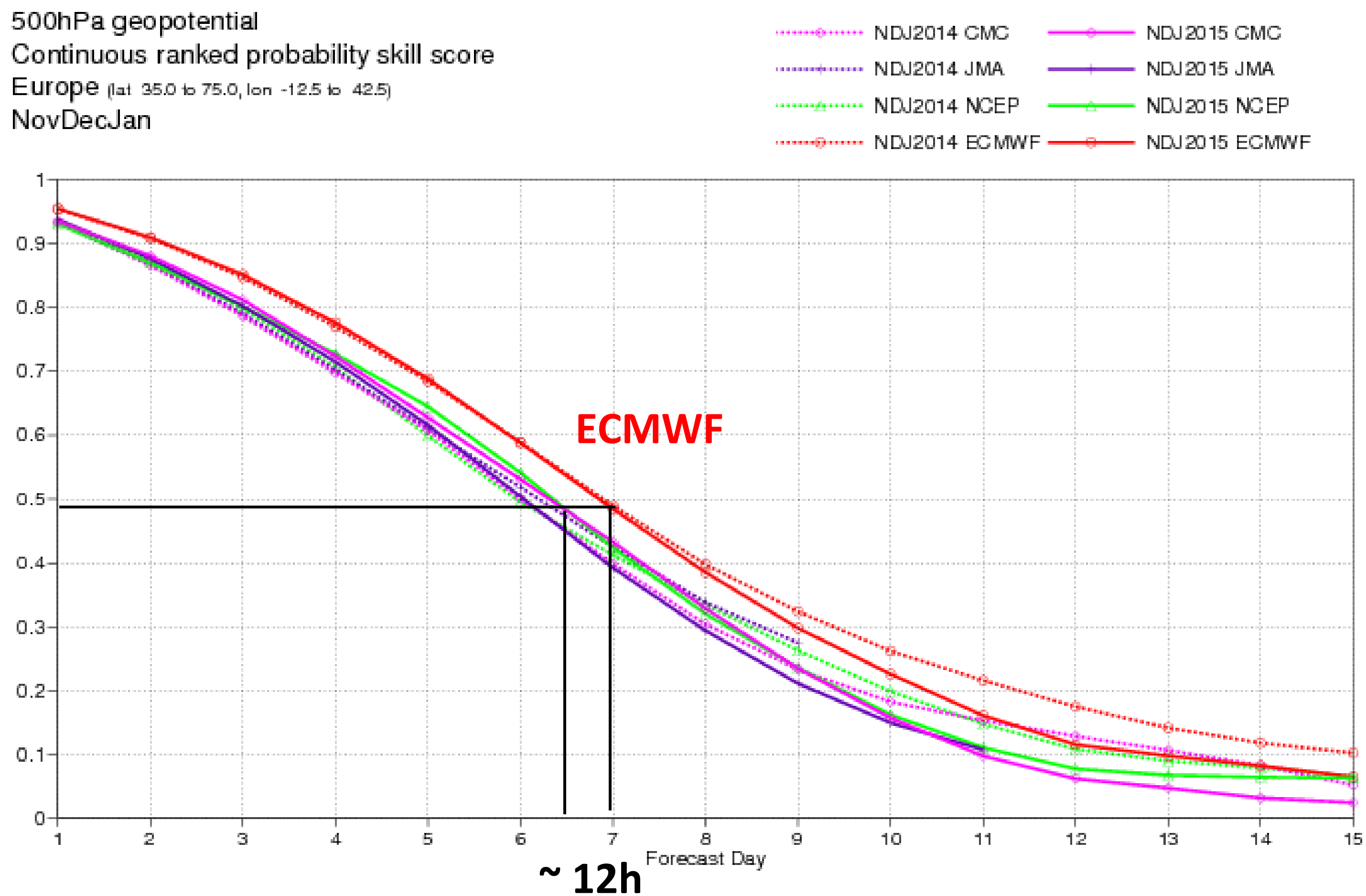


3. D13JF14: CRPSS(Z500,EU)

More recent results: average D13JF14 (solid) and D12JF13 (dashed) CRPSS for Z500 over Europe for the 4 best TIGGE ensembles:

- ECMWF (red)
- JMA (violet)
- NCEP (green)
- CMC (pink)



3. ND14J15: CRPSS(TP24,Europe)

More recent results: average ND14J15 (solid) CRPSS for 24h precipitation over Europe for 4 TIGGE ensembles:

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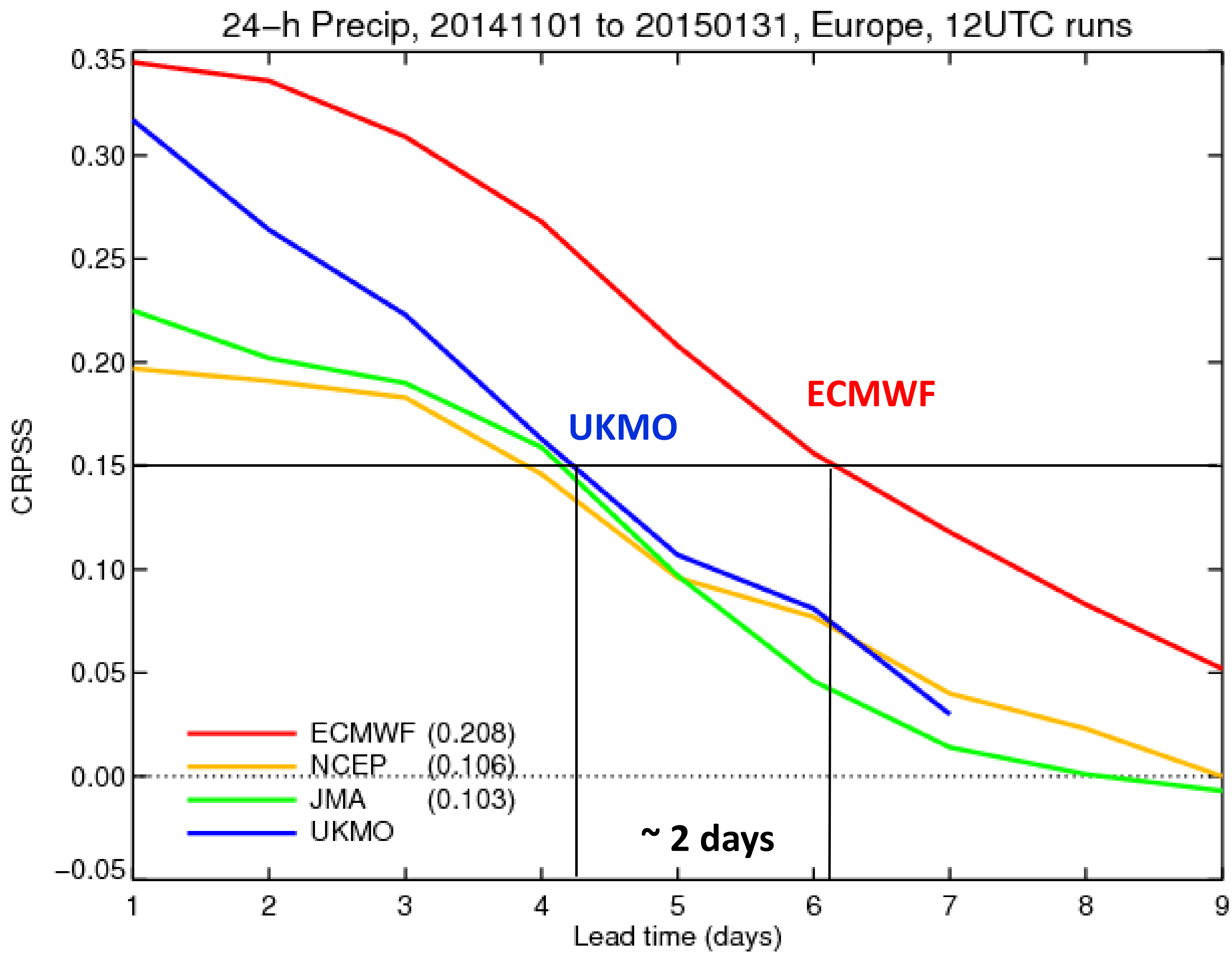
- JMA (green)
- NCEP (yellow)
- UKMO (blue)

Differences here between the best and the second best are about 2 days!



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More recent results: average ND14J15 (solid) CRPSS for 24h precipitation over Europe for 4 single forecasts:

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- JMA (green)
- NCEP (yellow)
- UKMO (blue)

Differences here between the best and the second best are about 18 hours.