Status and developments of the ECMWF ensemble

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Outline

1. Status of the ECMWF ensemble prediction system
    1.1 The operational VAriable Resolution Ensemble Prediction System (VAREPS)
    1.2 Performance of VAREPS in 2007
    1.3 Comparison of global ensemble systems using the TIGGE data-base
2. Developments
    2.1 VAREPS extension from 15 to 32 days
    2.2 Use of re-forecasts for calibration
    2.3 Simulation of initial uncertainties using a combination of ensemble data-assimilation methods and singular vectors
    2.4 Simulation of model uncertainties using a stochastic back-scatter scheme
3. Conclusions

1.1 The ECMWF operational VAREPS

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 evolved and initial SVs

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

$$de_j(d,0) = \sum_{area}\sum_{k=1}^{N_{SV}}[\beta_{j,k}\cdot SV_k(d-48,48) + \alpha_{j,k}\cdot SV_k(d,0)]$$

The unperturbed analysis $e_j(d,0)$ is the T_L399L62 truncation of the operational T_L799L91 analysis, generated with the 12-hour cycling, 4-dimensional variational assimilation system. (See [2], [5], [6], [9], [11] for more details).

1.1 The ECMWF VAriable Resolution EPS (VAREPS)

The key idea behind VAREPS ([5]) is to resolve small-scales only up to the time range when resolving them improves the forecast. VAREPS was implemented in September 2006 with the following configuration:

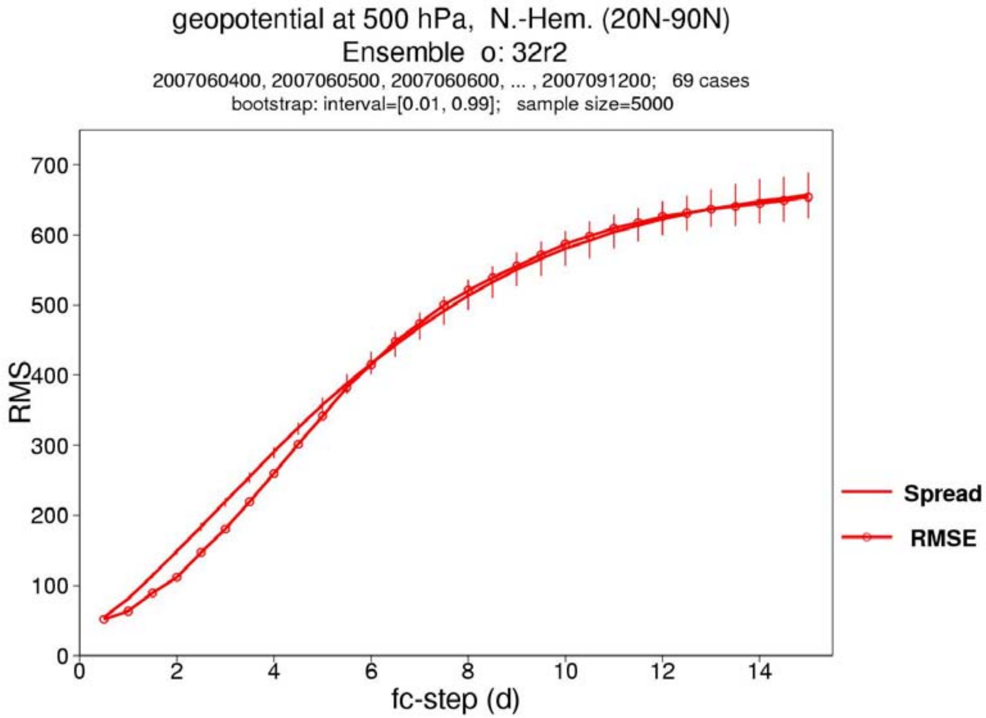
- T_L399L62 resolution from day 0 to day 10
- T_L255L62 resolution from day 10 to day 15

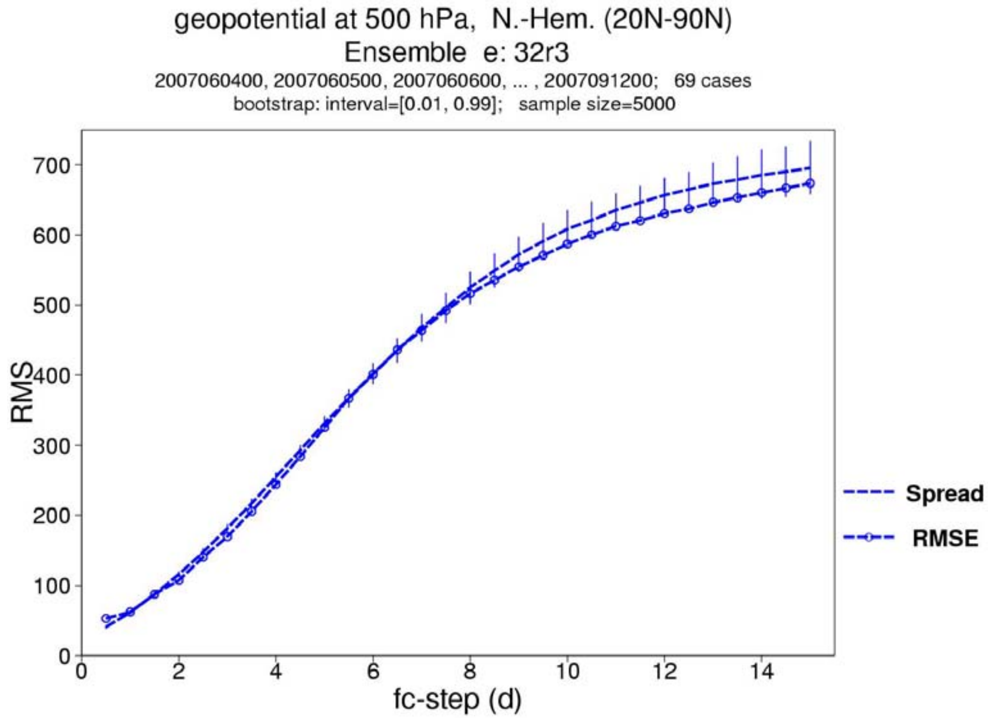
The implementation of VAREPS increased the value of the ensemble system in the short range, by providing more skilful predictions of the small scales, and in the medium-range, by extending the range of skilful products to 15 days.

On 6 November 2007, a new model cycle (32r3) has been introduced. The new model is more active, due to changes in the convection and vertical diffusion schemes. To compensate for the spread increase due to the model changes, the initial amplitude of the EPS perturbations has been reduced by 30%.

1.2 JA07: ECMWF o- & e-suites – Z500 NH

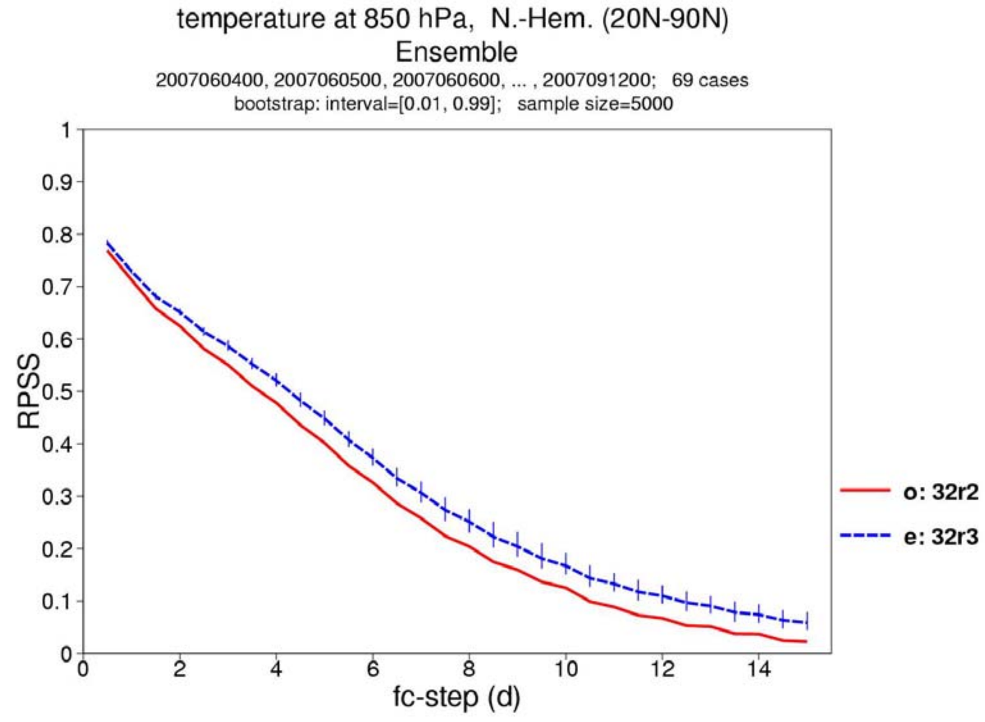
With the new model cycle (32r3, right panel), the ensemble has a better tuned spread. Between fc-day 1 and 4, the ensemble is not any more over-dispersive, and the ensemble spread is well tuned from fc-day 1 to fc-day 8. But after fc-day 8 the system is now slightly over-dispersive. Between fc-day 3 and 7 the ensemble-mean of the e-suite has a significantly smaller error.

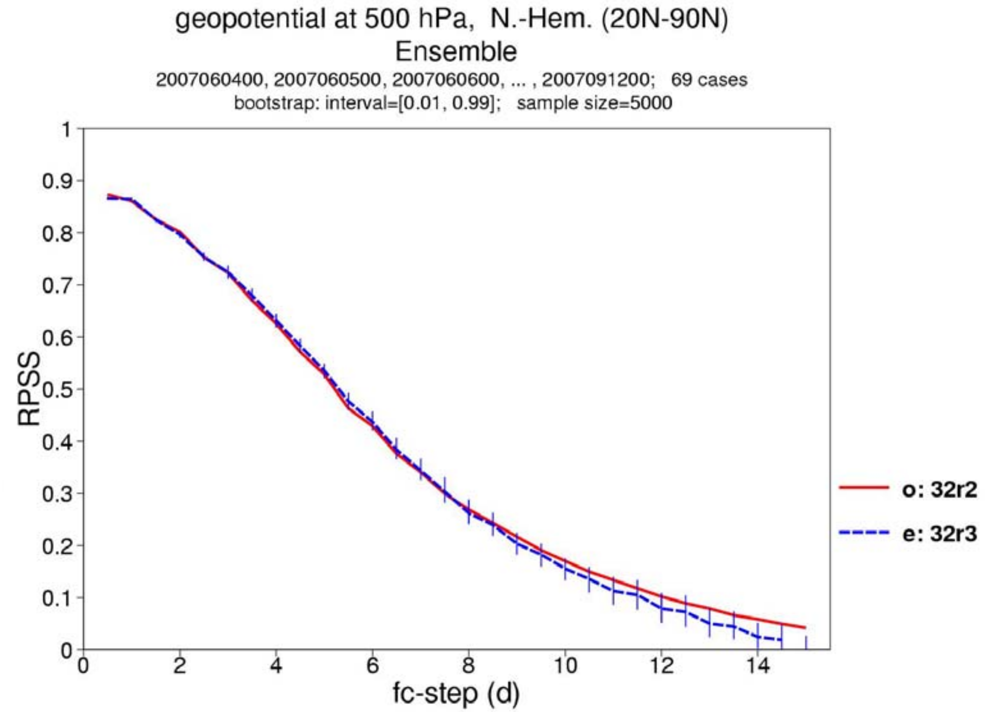




1.2 JA07: ECMWF o- & e-suites – T850 & Z500 NH

Over NH, the introduction of the new model cycle (32r3, right panel) improves the quality of the probabilistic prediction of T850, measured by the RPSS (left panel). But the difference in quality is very small and not statistically significant if one considers Z500 (right panel).



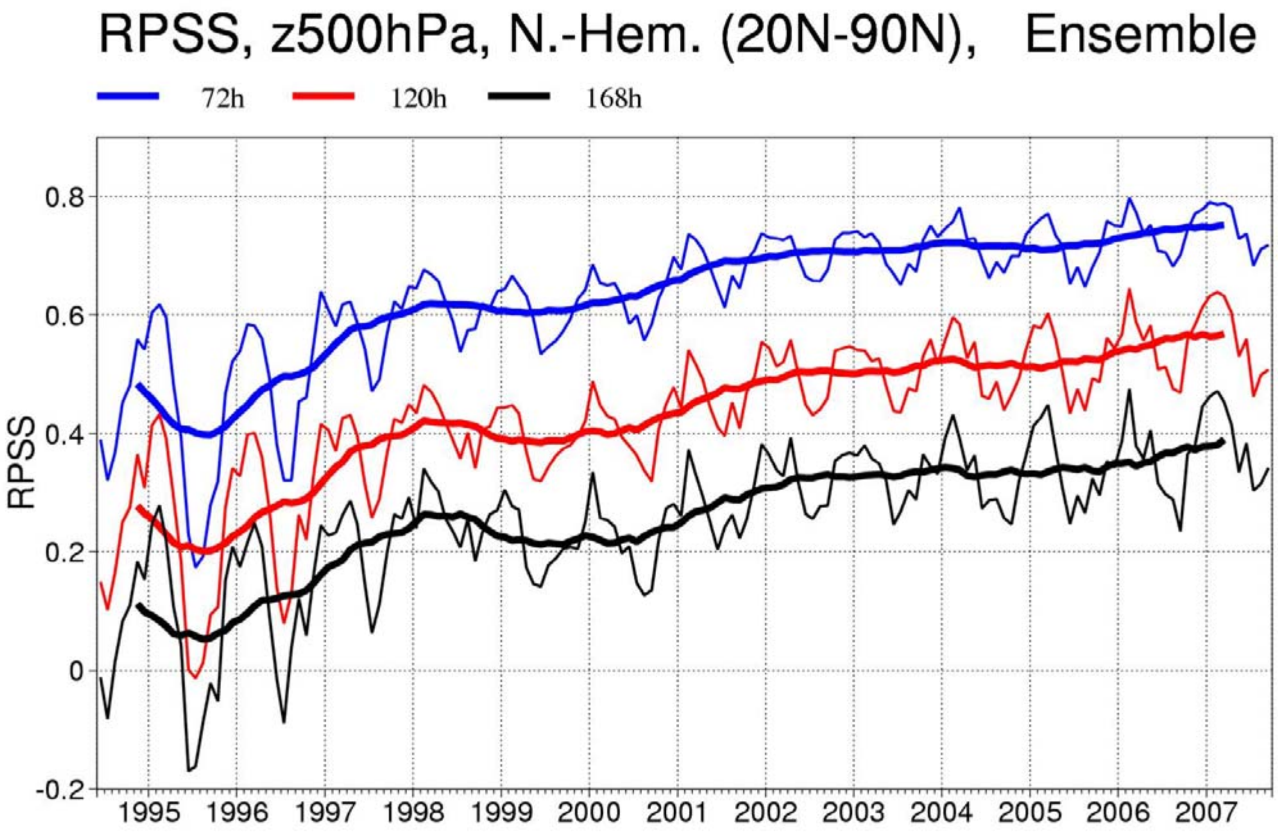


1.2 Trends in ensemble RPSS for Z500 & T850, NH

The RPSS for the probabilistic prediction of Z500 anomalies indicates that during the past 10 years ensemble predictability has increased.

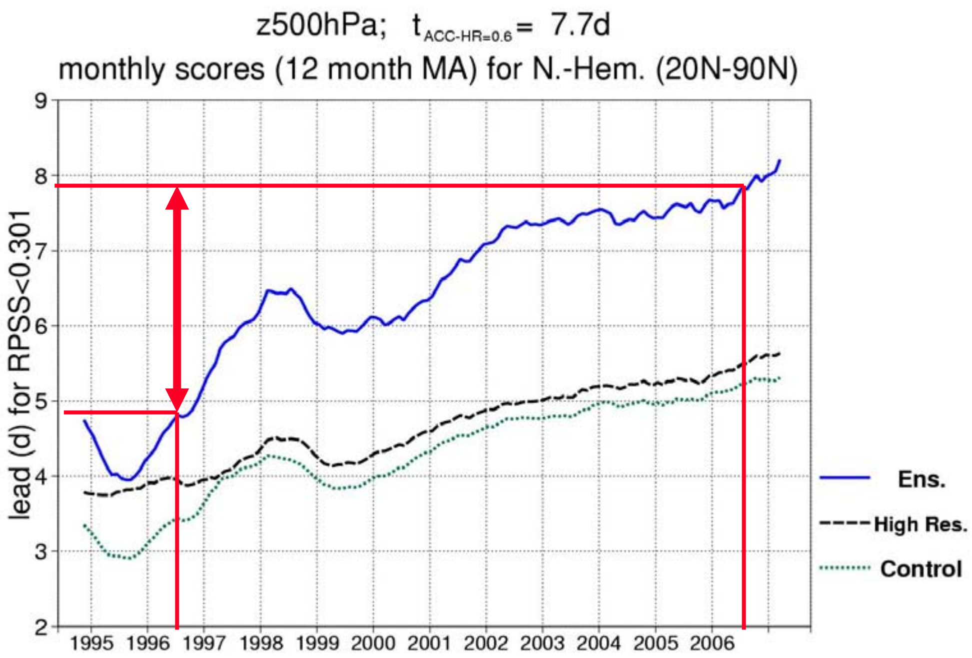
Over NH, the t+120h RPSS in 2006 was higher than the t+72h RPSS in 1996, indicating a gain in predictability of more than 2 days in a decade.

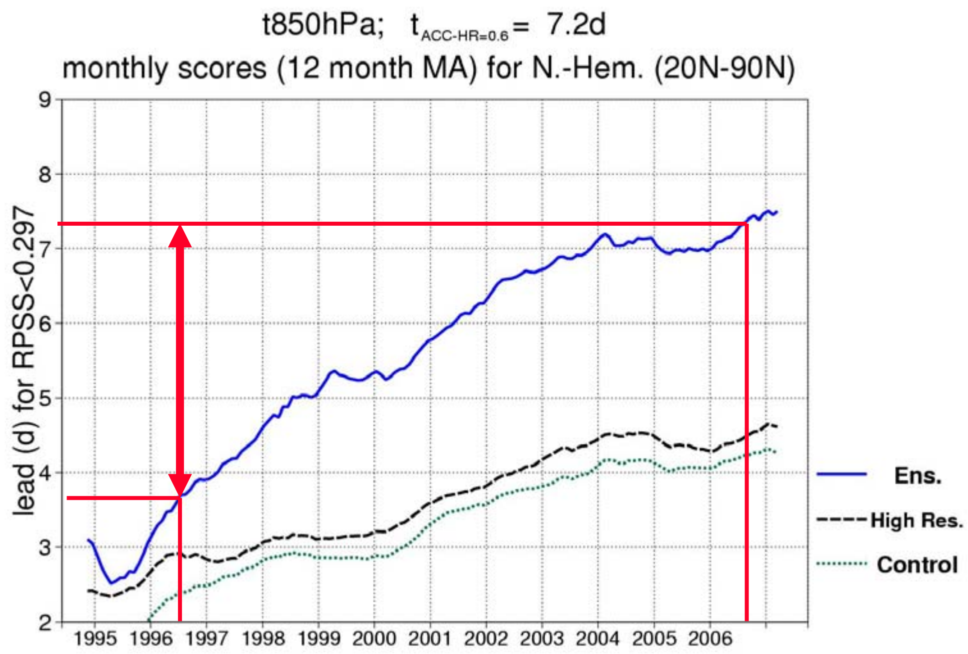
This increase is due to improvements in the quality of the analysis, in the model accuracy, and in the ensemble configuration.



1.2 Trends in ensemble RPSS for Z500 & T850, NH

The improvements in the accuracy of single and probabilistic forecasts can be assessed considering the lead time when a specified skill threshold is reached. These plots show the fc-time when the RPSS reaches a threshold that corresponds to the time the ACC of the HR forecast reaches 0.6 in 2006 (i.e. 0.301 for Z500 and 0.297 for T850). Results indicate for the EPS an increase in predictability of ~ 3 days for Z500 and ~ 3.75 days for T850 over NH.





1.3 Comparison of the performance of TIGGE ensembles

				D06-JF07				AM07		JJA07				O07		
Center		'06 10	11	12	'07 1	2	3	4	5	6	7	8	9	10	11	12
ECMWF	00	1-, +	+ 15d													
	12	1-, +	+ 15d													
UKMO	00	1-, +		-1(17)	++											
	12	1-, +			++											
JMA	12	1-					+	+								
NCEP	00	12- ?		11→15m			5- 21m		-1(13)	-3(19,20,26)						
	06	12- ?		11→15m			5- 21m			-1(14) -3		-1(13)	-1(28)	-2(11,13)		
	12	11- ?		11→15m			5- 21m			-1(14) -3	-1(17)	-1(13)		-1(1)		
	18	11- ?		11→15m			5- 21m			-4(1,18-20)	-1(17)			-1(9)		
CMA	00						23-	21-	15-							
	12						22-	21-	15-	-1(11)						
MSC	00													3-		
	12													3-		
KMA	00															
	12											30-				
BMRC	00								21-	-2(5,7)			3-			
	12								21-				3-			
MetFr	18													26-		
CPTEC	00										19-					
	12										19-					

1-		+		-1		
start prod from	prod OK	new fields (date)	change in EPS (date)	missing fields (date)	no cycle (date)	test

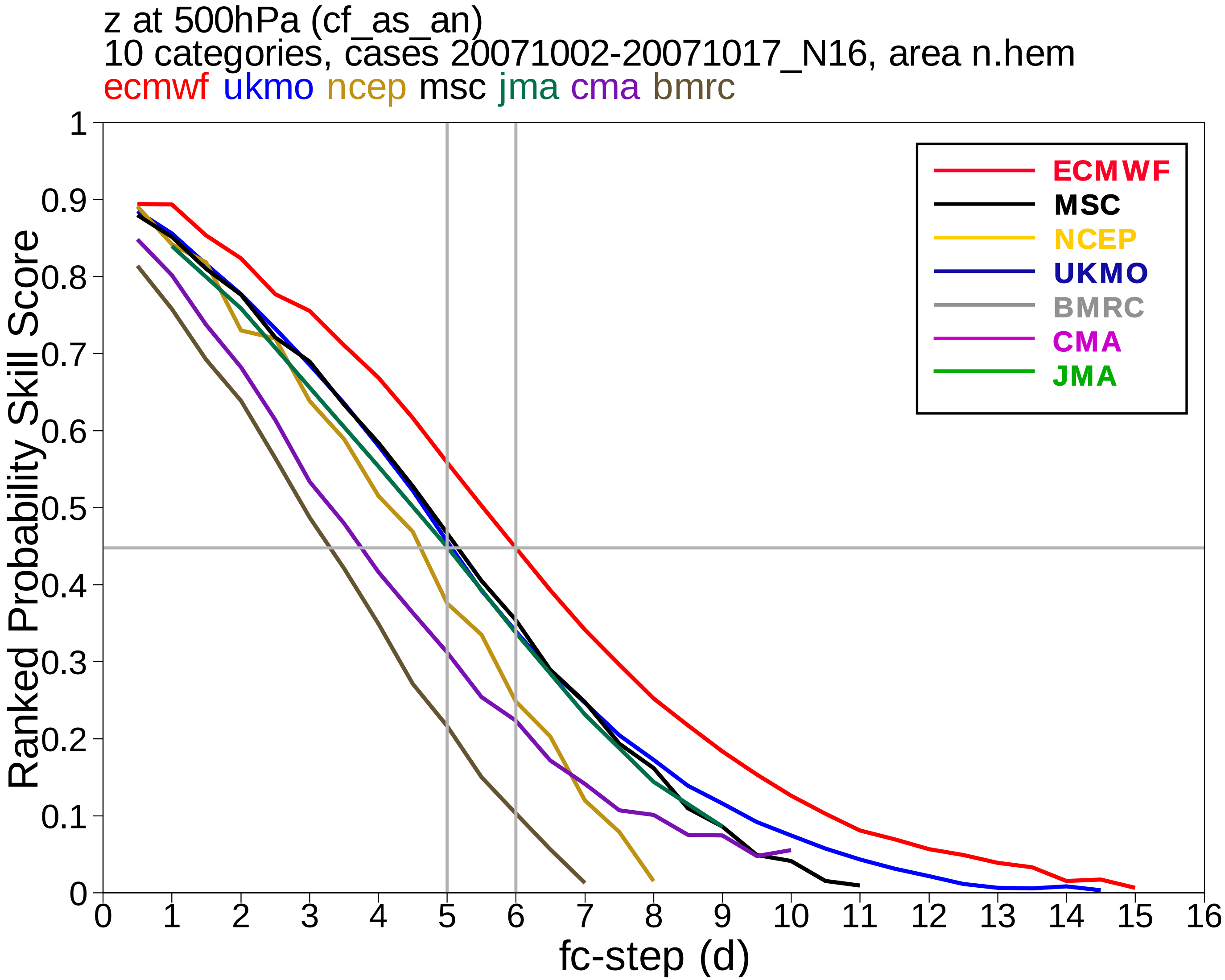
NOTE
1. NCEP
   - change in membership (-2006.12.14.06UTC:11m, 2006.12.14.12UTC-2007.03.27.12UTC:15m, 2007.03.27.18UTC:21m)
   - change in analysis from 1 may 07
2. ECMWF(28-11-2006): ECMWF implements Variable Resolution Ensemble Prediction System and extends the forecast range from 10 days to 15 days.

1.3 O07 (16c): EC/MSC/NCEP/UK/BMRC/CMA/JMA RPSS

Most recent TIGGE results: this figure shows the O07 average RPSS for Z500 over NH.

The EC ensemble outperforms the group of 2nd best ensembles (MSC, UKMO and JMA for this period) for the whole forecast period, with ~0.9d gain in predictability at t+5d.

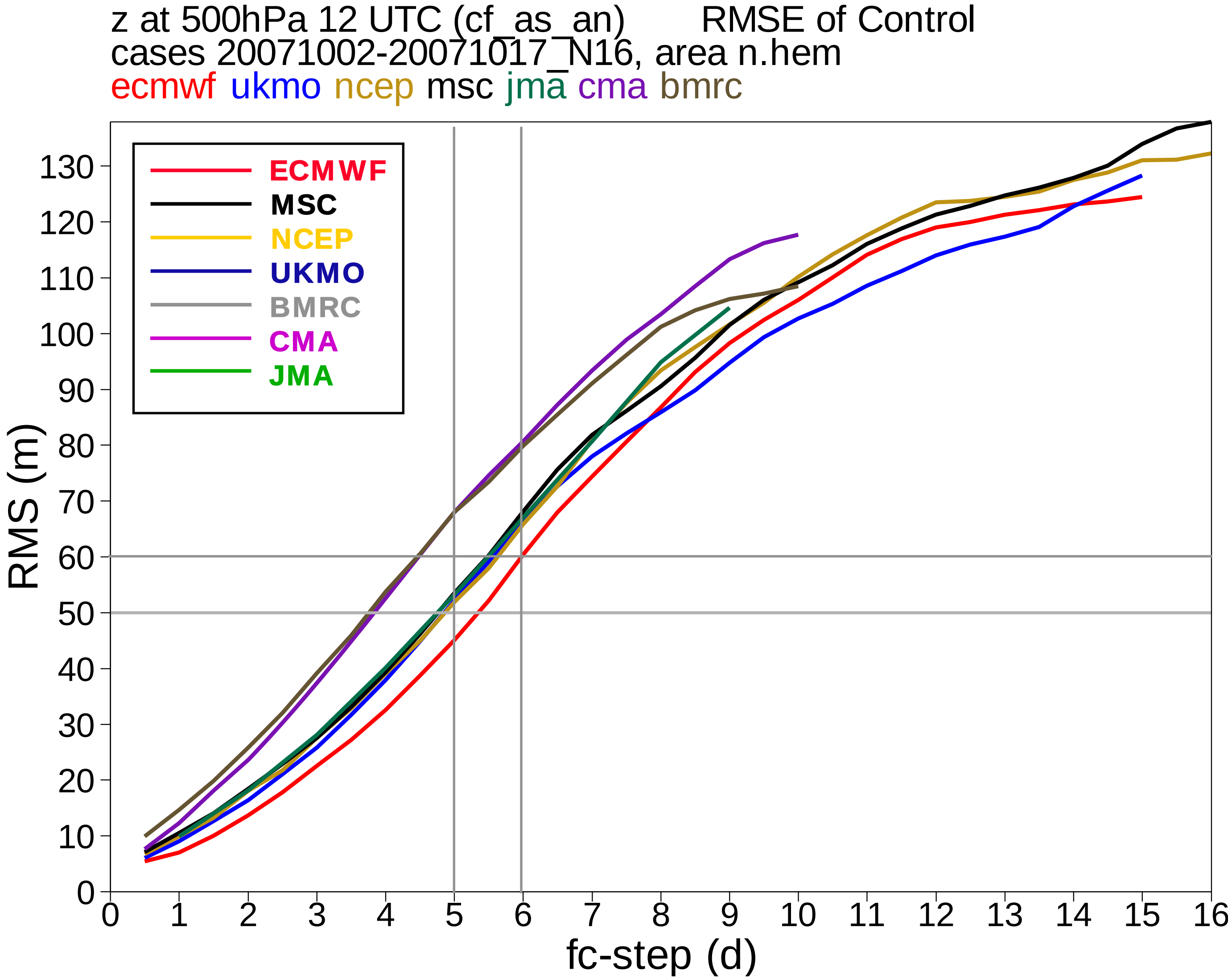
This result confirms a similar comparison performed for three other periods (total of ~240 cases).



1.3 O07 (16c): EC/MSC/NCEP/UK/BMRC/CMA/JMA CON

Most recent TIGGE results: this figure shows the O07 average RMSE of the control fc for Z500 over NH. The EC control outperforms the group of 2nd best ensembles (MSC, UKMO and JMA for this period) up to fc-day 8, with ~0.4d gain in predictability at t+5d.

This indicates that the differences in skill of the ensemble probabilistic forecasts is not only due to model/analysis, but also to the ensemble design (e.g. use of SVs).



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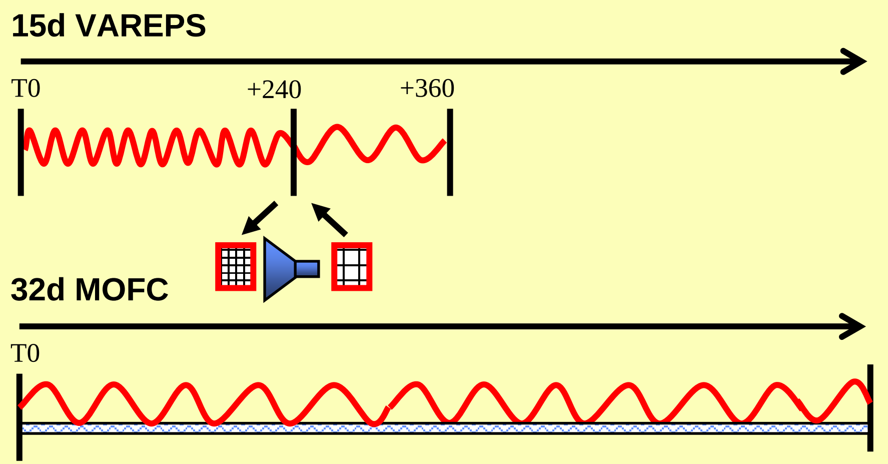
3. Conclusions

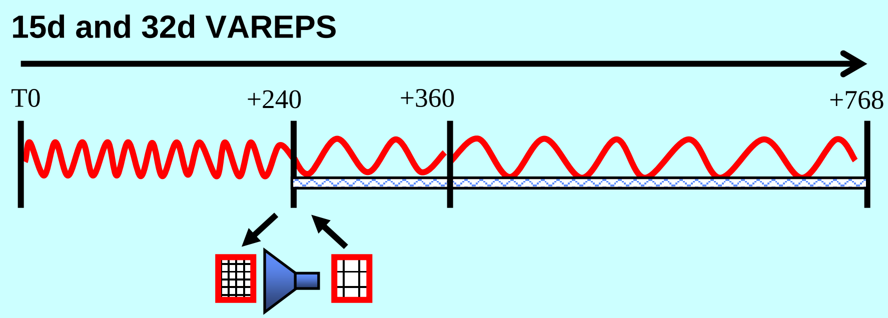
2.1 The 32-day unified VAREPS

The plan is to unify the 15d VAREPS and the 32d monthly ensemble systems into the unified 32d VAREPS:

- Twice-a-day (at 00 and 12 UTC):
  - d 0-10: T_L399L62 uncoupled
  - d 10-15: T_L255L62 uncoupled
- Once a week:
  - d 0-32: T_L159L62 **coupled**

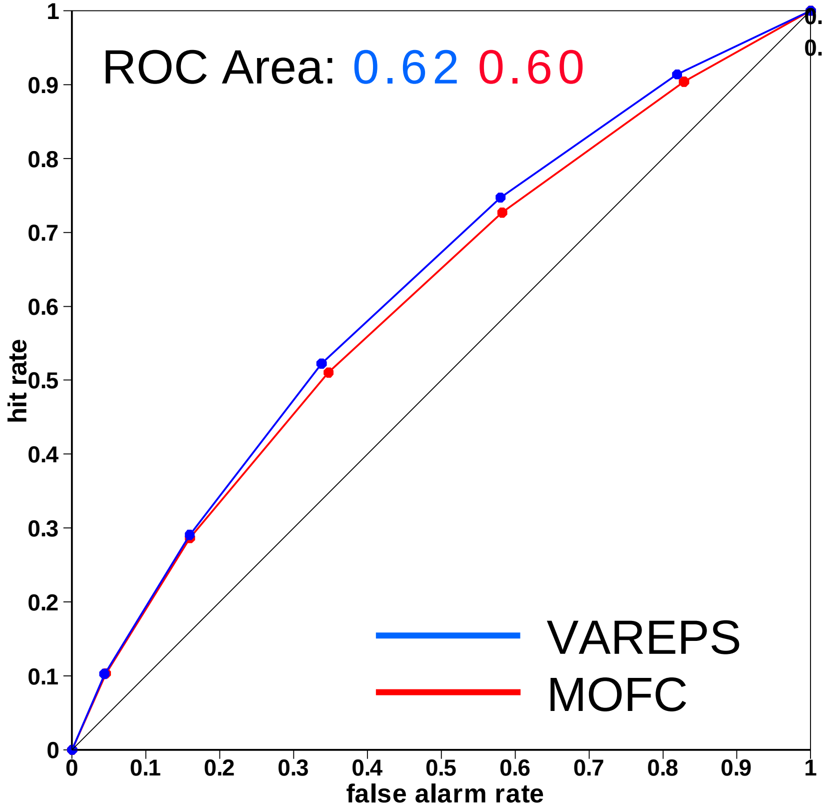


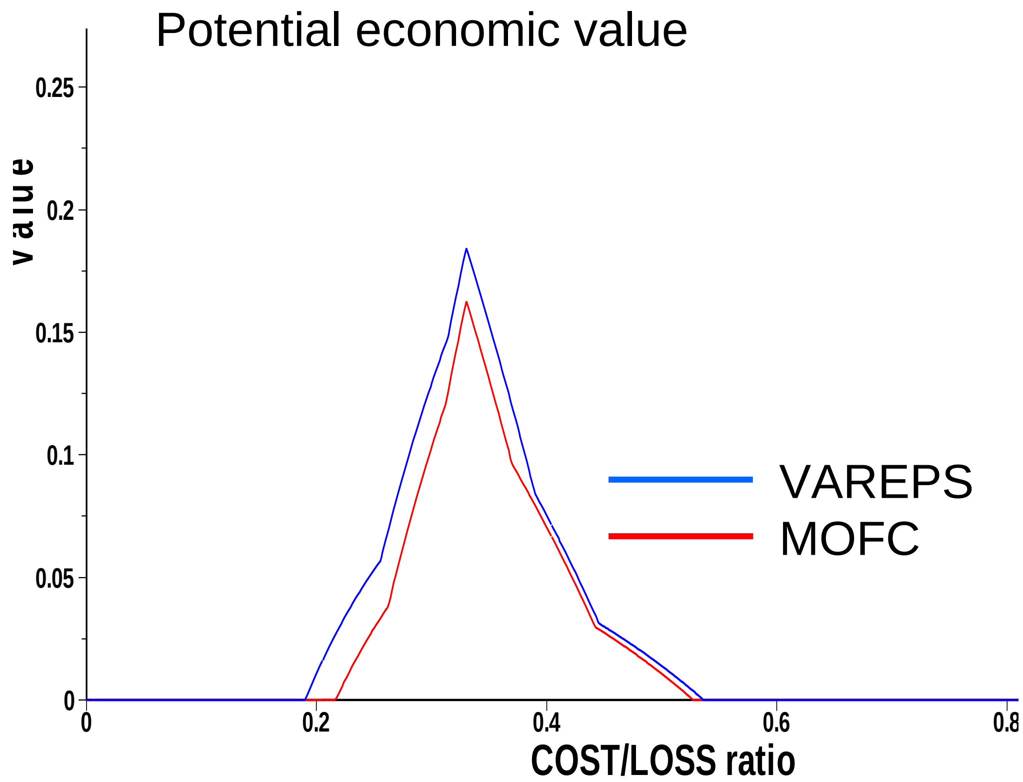
- Twice-a-day (at 00 and 12 UTC):
  - d 0-10: T_L399L62 uncoupled
  - d 10-15: T_L255L62 (**coupled at 00)**
- Once a week:
  - d 0-10: T_L399L62 uncoupled
  - d 10-32: T_L255L62 **coupled**



2.1 Planned unified VAREPS: ROCA and PEV, 2mT NH

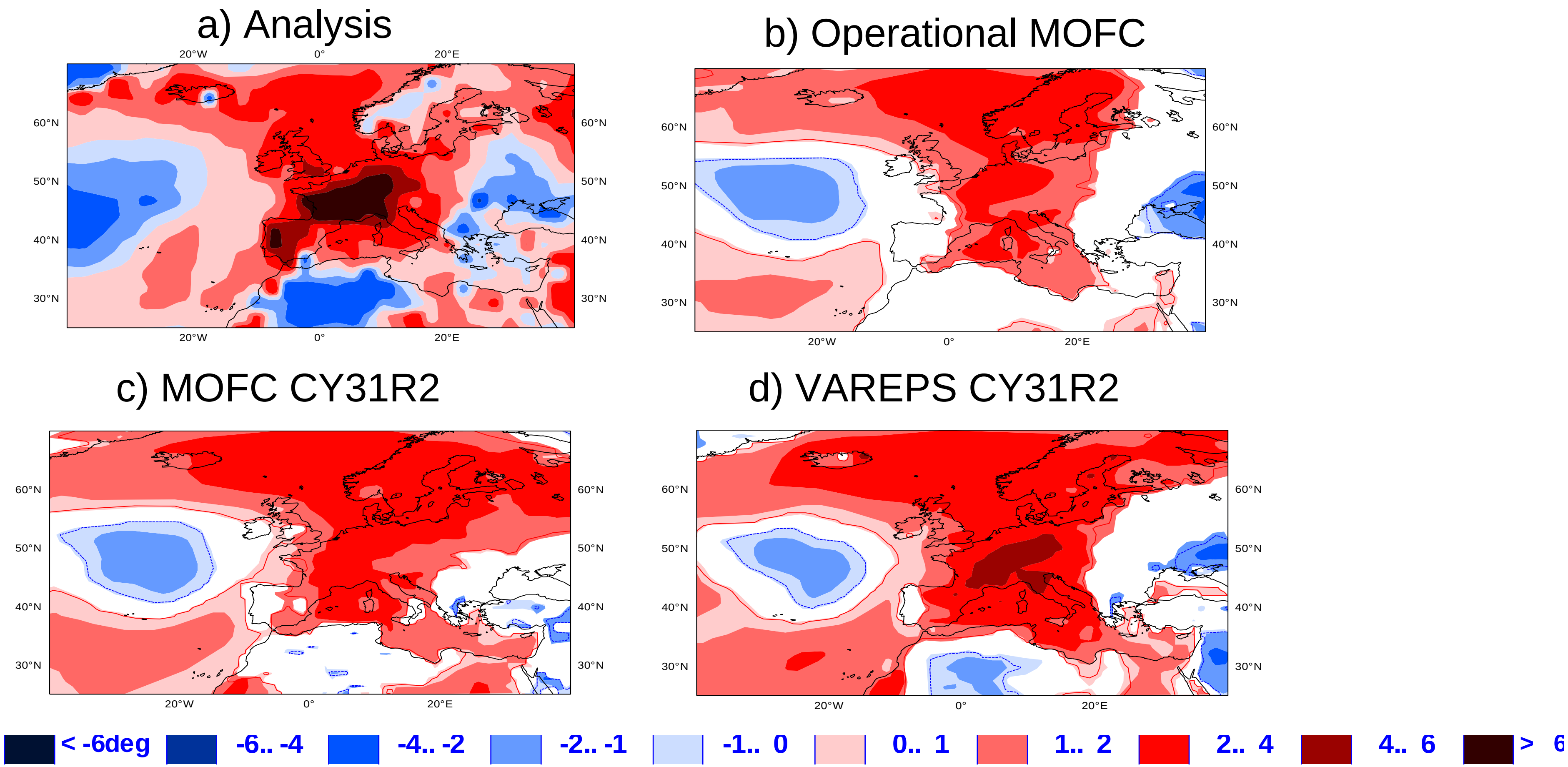
Results based on 5-member ensembles for 52-cases (13y, 4 dates per year, cy30r2), indicate that over NH the 32d VAREPS performs slightly better than the monthly. This figure shows the ROCA and the PEV for the probabilistic prediction of 2mT in upper tercile over NH for forecast days 12-18.





2.1 Planned unified VAREPS: summer 2003 heat wave

Forecasts started on 23 July 2003 for 2mT anomalies for 3-9 August 2003 (fc day 12-18): impact of model cycle and upgrade to 32-day VAREPS.



2.2 Use of reforecasts for calibration

With the implementation of the unified 32d VAREPS-Monthly forecast system, a new reforecast suite will be run operationally. The reforecasts from this suite can be used as training data to calibrate both medium-range and monthly forecasts.

The suite will run once a week and produce reforecasts for the last 18 years (1989-2006 of the respective operational date in 2007) and with 5 ensemble members.

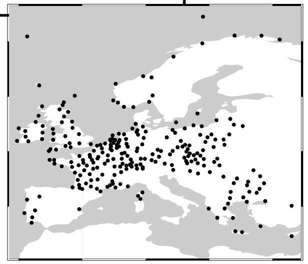
Results based on comparing ECMWF and GFS 10d-calibration ([7]) indicate that:

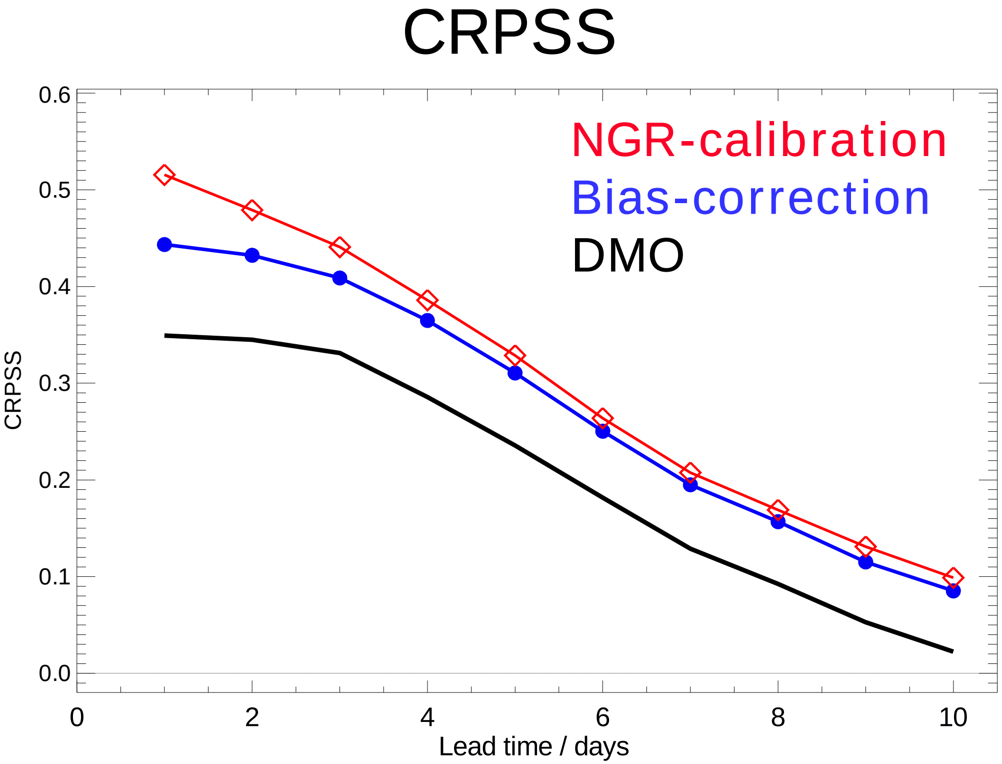
- ECMWF forecasts, though better than GFS forecasts, can be improved through calibration
- The main improvements are due to bias correction (60-80%), but advanced methods (e.g. NGR) lead to better calibrated ensemble spread, thus adding some extra improvements, in particular at early lead times
- Improvements occur mainly at locations with low skill

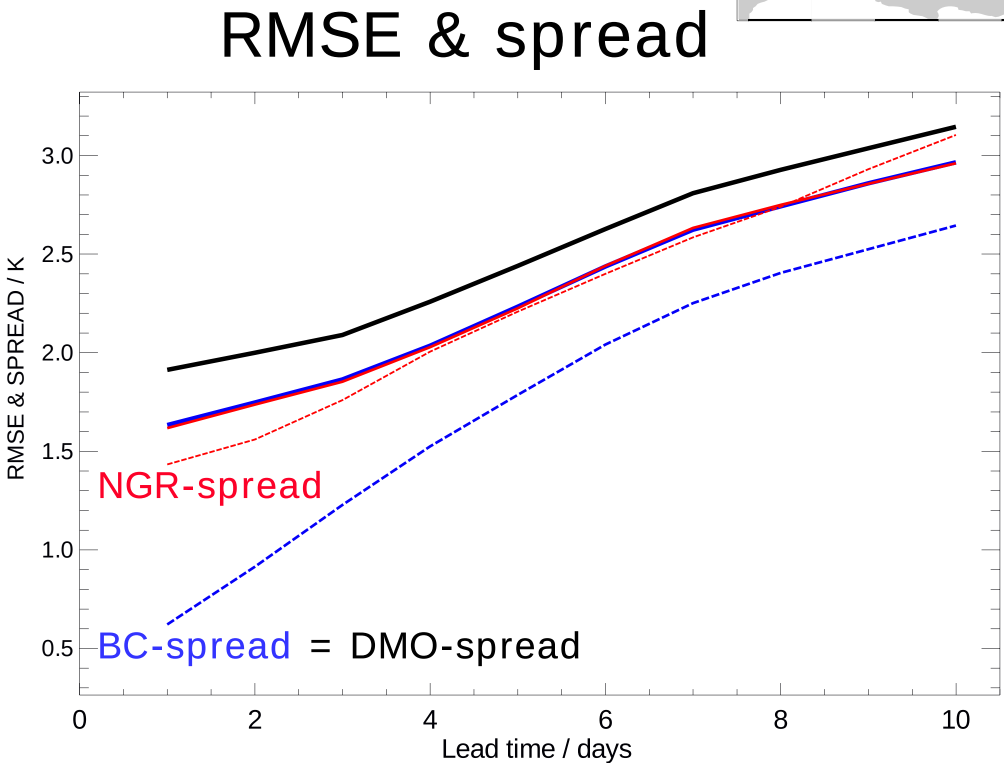
2.2 Use of reforecasts for calibration

2m temperature forecasts (1 Sep – 30 Nov 2005), 250 European stations

REFC-data: 15 members, 20 years, 5 week window







2.3 The EDA- and SV-based ensemble system

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 perturbed analyses (generated by an ensemble data-assimilation system, [2], [8], [10]) and initial SVs

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

$$PA_j(d,0) = A_{centre}(d,0) + [A_j(d-6h,6h) - A_{ref}(d-6h,6h)]$$

with the reference and center analyses defined by

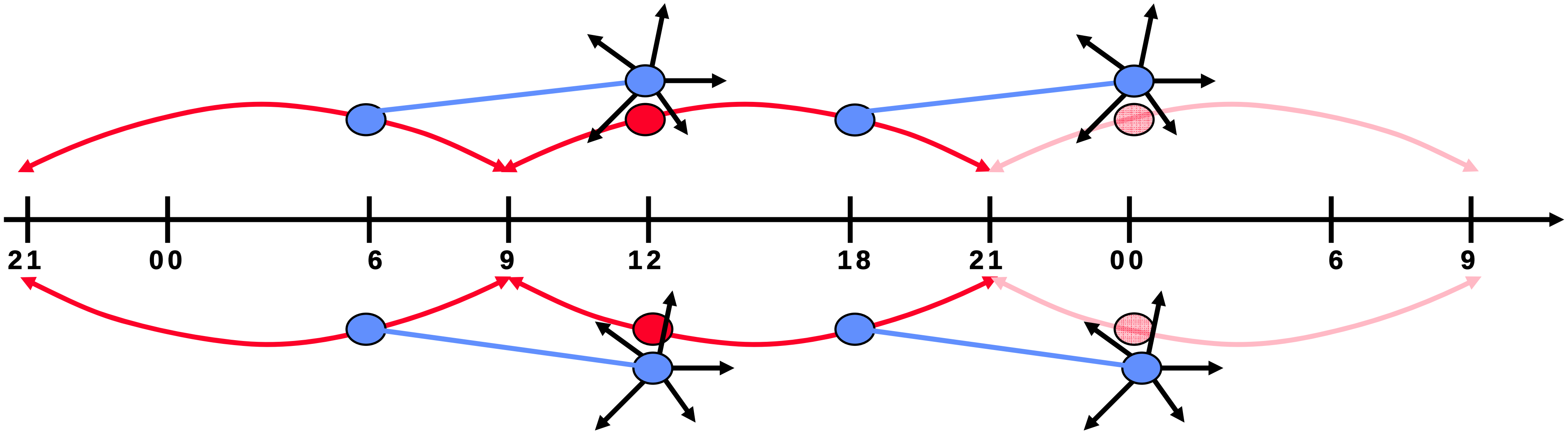
$$A_{centre}(d,0) = A_{T_L 799L91}(d,0)$$

$$A_{ref}(d-6h,6h) = \langle A_j(d-6h,6h) \rangle$$

2.3 The EDA- and SV-based ensemble system

Note that the EDA analyses are used at forecast step +6 hour:

$$PA_j(d,0) = A_{centre}(d,0) + f \cdot [A_j(d-6h,6h) - A_{ref}(d-6h,6h)]$$



This choice is consistent with data-assimilation practice followed when computing J_b statistics. In a future operational system, this choice will have the advantage that the EPS can start as soon as the 'centre' analysis (e.g. T_L799L91) is ready since the day *d* EDA-perturbations are generated using +6h forecasts started from the previous cycle.

2.3 Ensemble experiments

❖ The results discussed in this communication are based on the latest set of T_L399L62 experiments (model cycle 31r2) with the following characteristics:

- The EDA analyses have been generated with 12-hour cycling 4D-Var, resolution T_L399L91 in the outer-loop, and T_L255L91/T_L95L91 in the inner loops
- The SVs have been computed with a T42L62 resolution, a 48-hour optimisation time interval and a total energy norm (as in the operational system)
- The ensemble forecasts have been run up with a T_L399L62 resolution, 50 perturbed members, stochastic tendency perturbations and a 10-day forecast length.

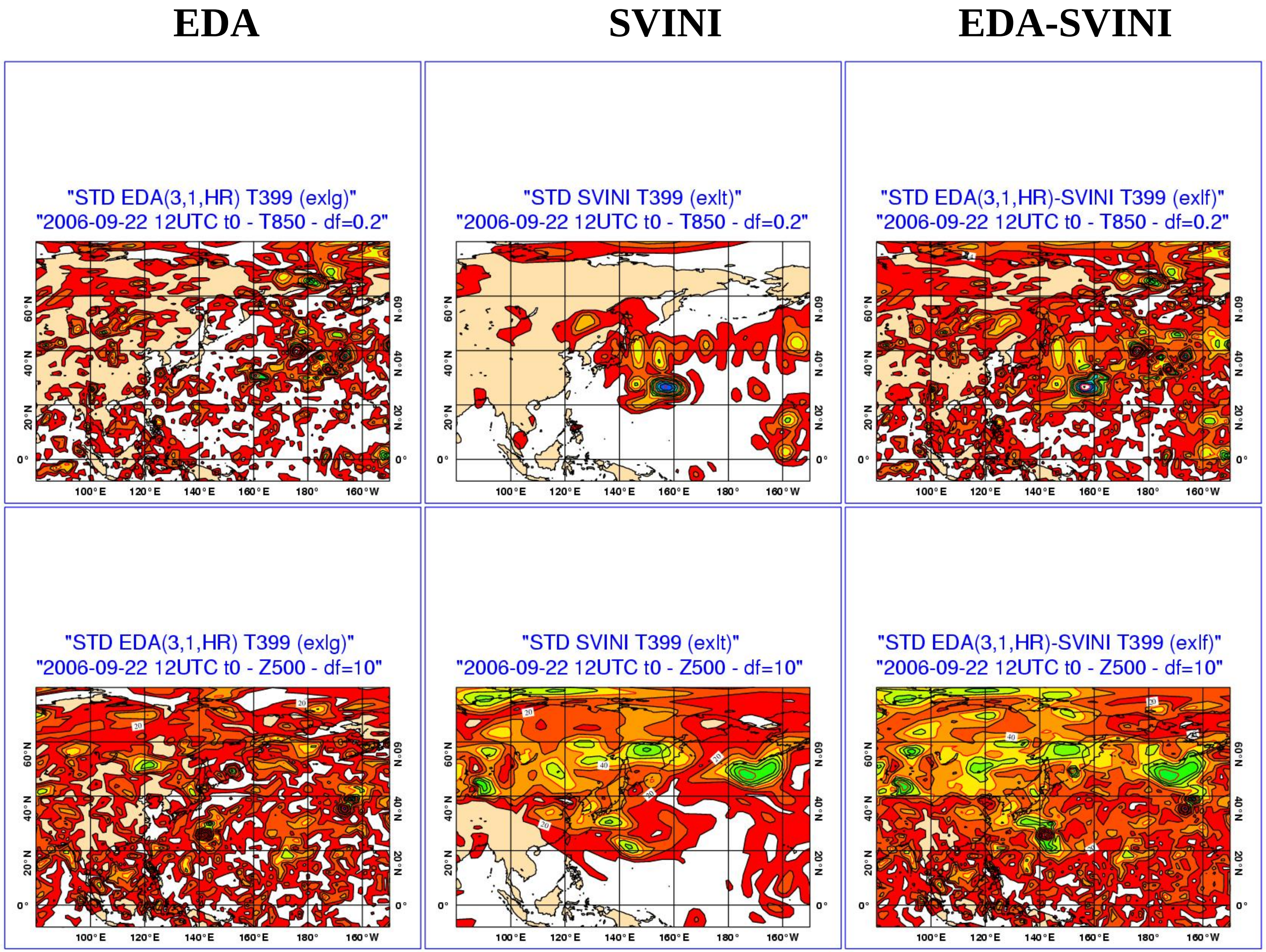
❖ The following 4 ensembles configurations are compared:

- **SVINI**: with initial uncertainties defined by initial SVs only
- **SVEVO-INI**: with initial uncertainties defined by evolved and initial SVs
- **EDA**: with initial uncertainties defined by EDA-only initial perturbations
- **EDA-SVINI**: with initial uncertainties defined by EDA- and initial SVs

2.3 std of EDA, SVINI & EDA-SVINI at t=0 – 22/09/07

EDA-only initial perturbations (left panels) are smaller in amplitudes and in scale than SVINI perturbations (middle panels), but are geographically more global.

The right panels show the effect of using both EDA and SVINI perturbations.

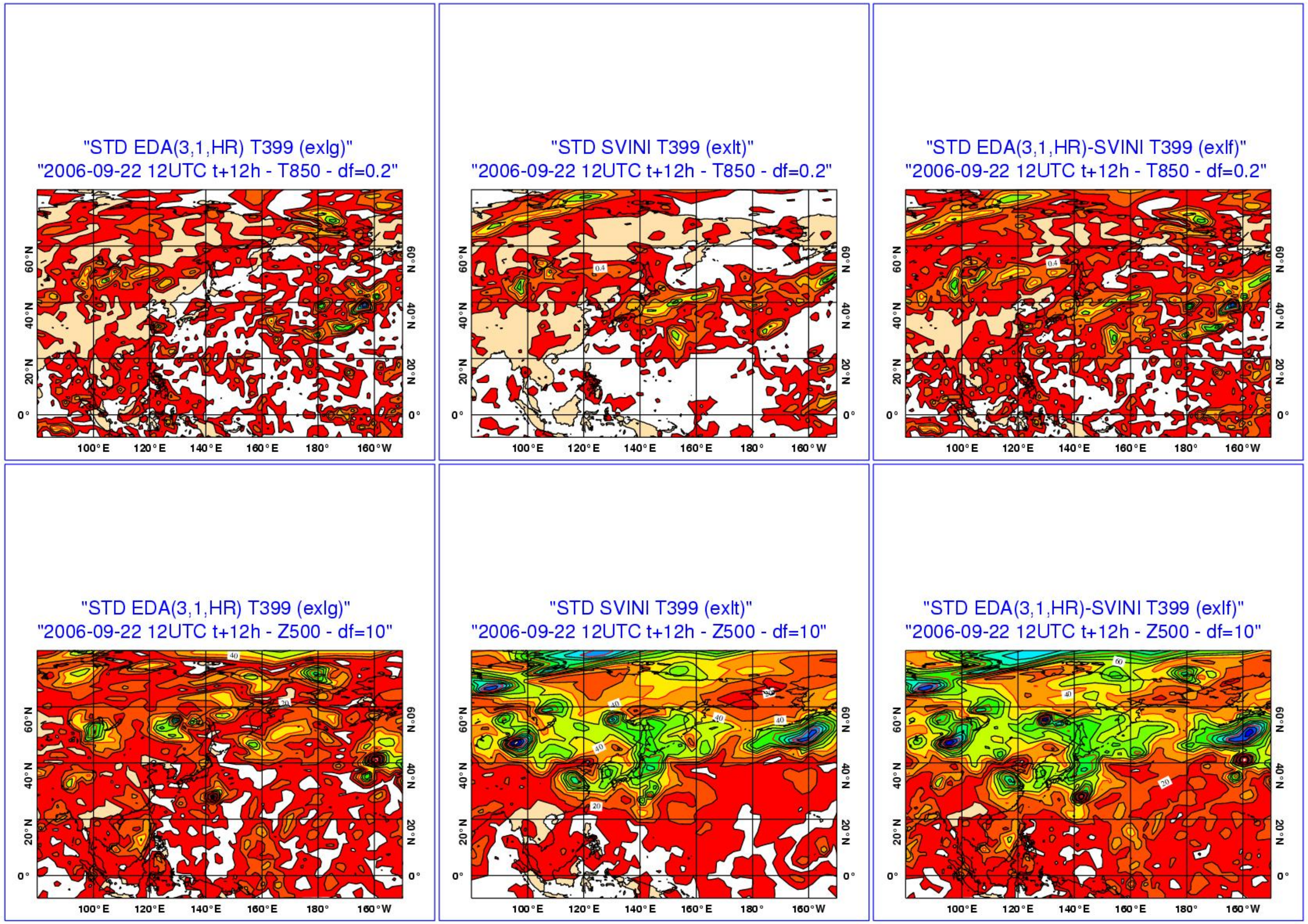


2.3 std of EDA, SVINI & EDA-SVINI at t+12h – 22/09/07

EDA perturbations (left panels) grow less rapidly than SVINI perturbations (middle panels).

In the combined EDA-SVINI ensemble, the SVINI component dominates the perturbations' growth.

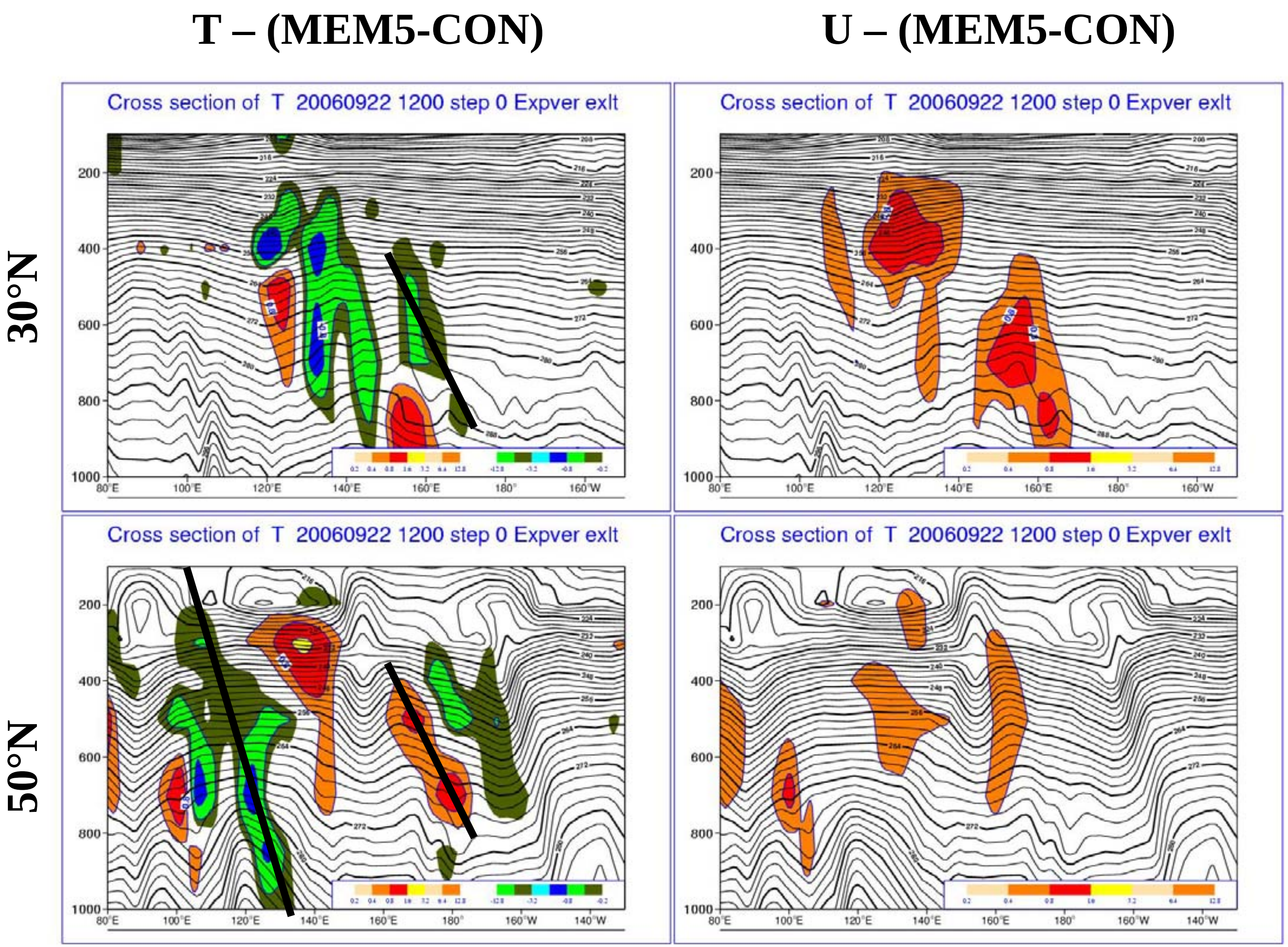
EDA **SVINI** **EDA-SVINI**



2.3 (MEM5-CON) SVINI EPS - 22/09/2007 t=0

At t=0, SVINI perturbations (defined by a combination of initial SVs) tend to be localized in space, and to have a larger component in potential than kinetic energy. They also show a westward tilt with high, typical of baroclinically unstable structures.

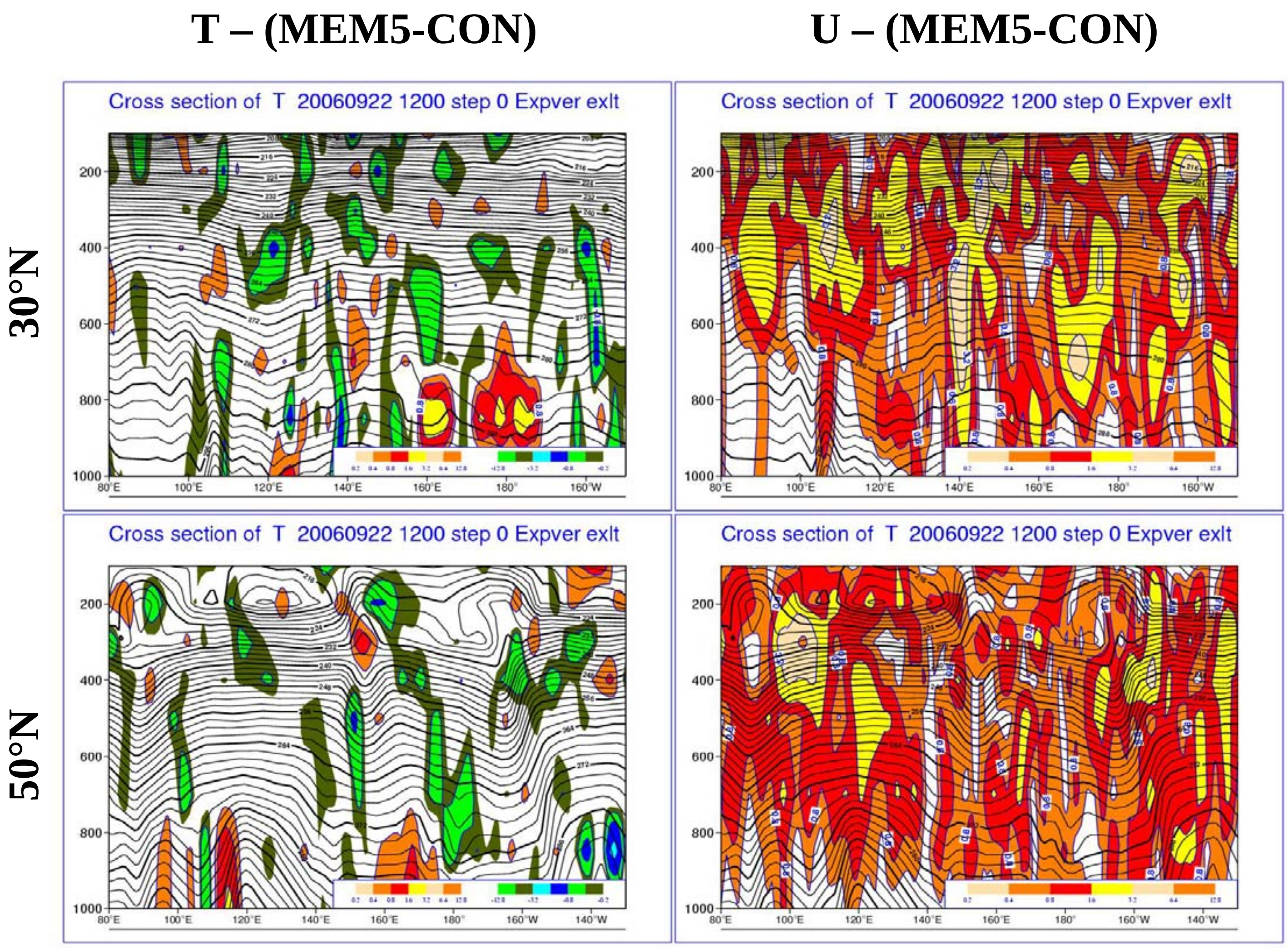
This figure shows two vertical cross sections of the temperature and zonal-wind components of the MEM5 perturbation.



2.3 (MEM5-CON) EDA EPS - 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.

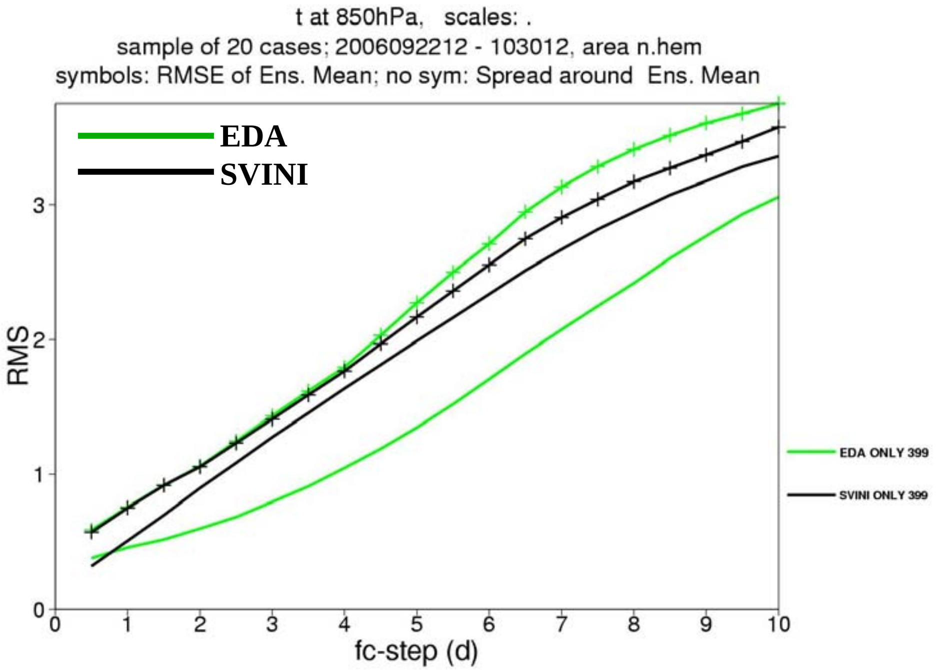
This figure shows two vertical cross sections of the temperature and zonal-wind components of the MEM5 perturbation.

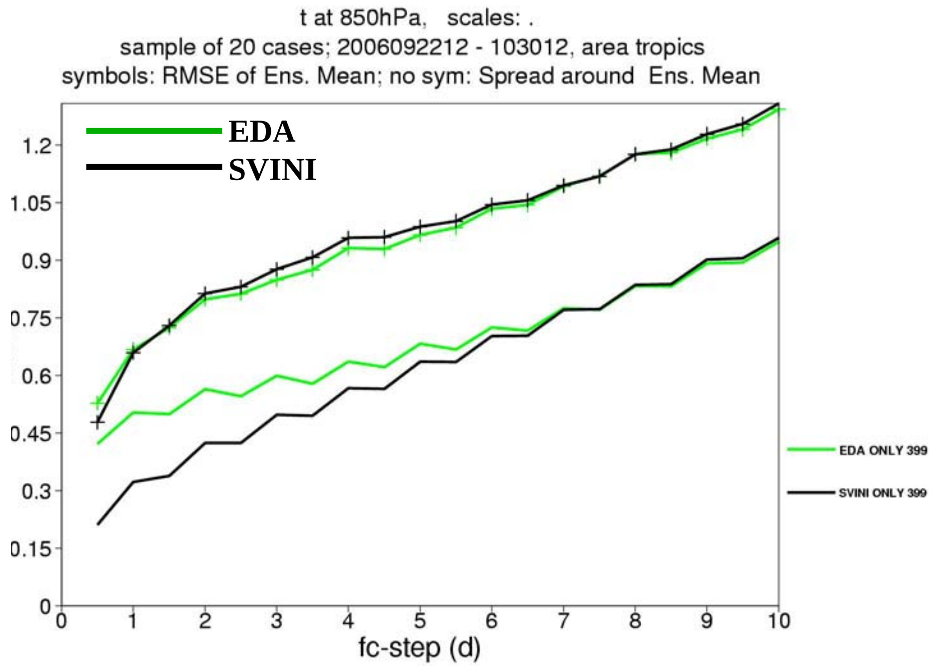


2.3 std/EM of EDA and SVINI EPS

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.

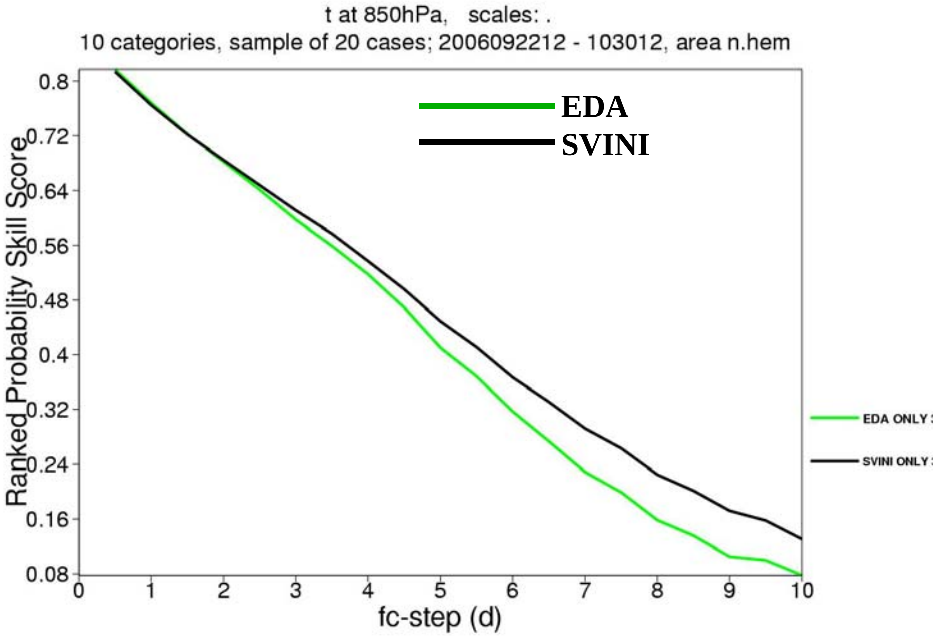


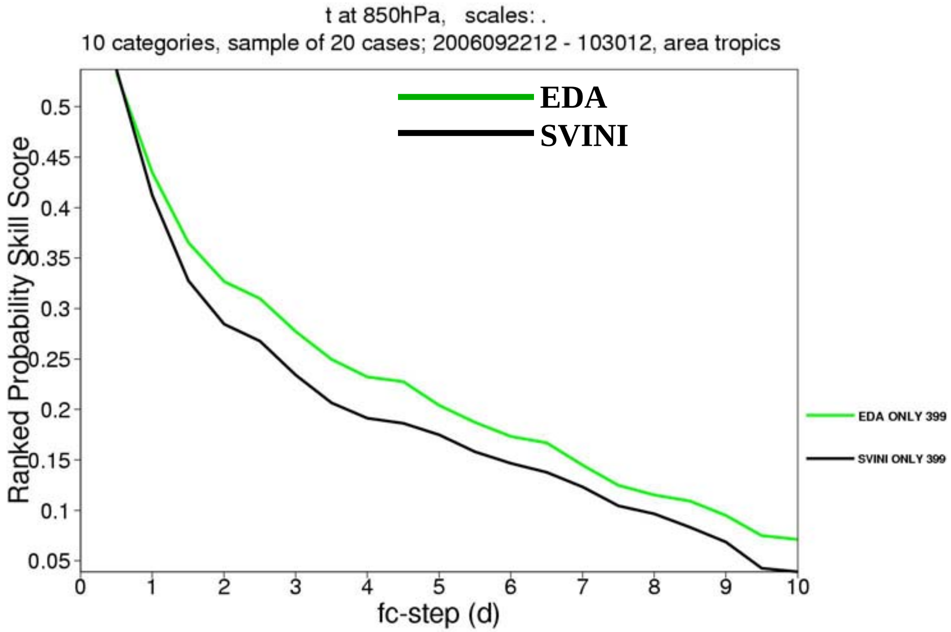


2.3 RPSS of EDA and SVINI EPS

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).

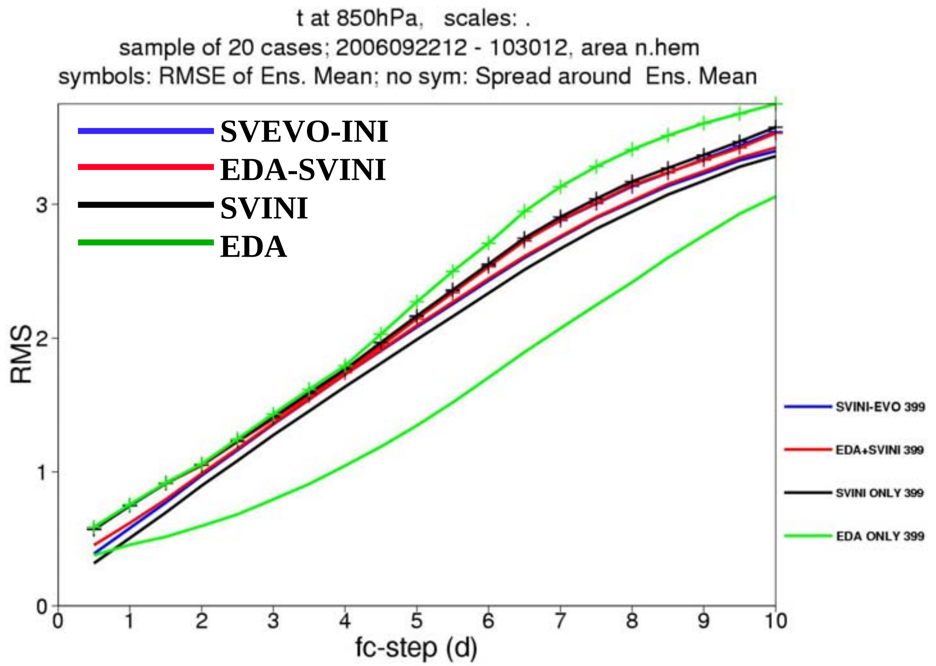
These results suggest that combining the ensemble of analysis and the initial singular vectors would lead to a better system.

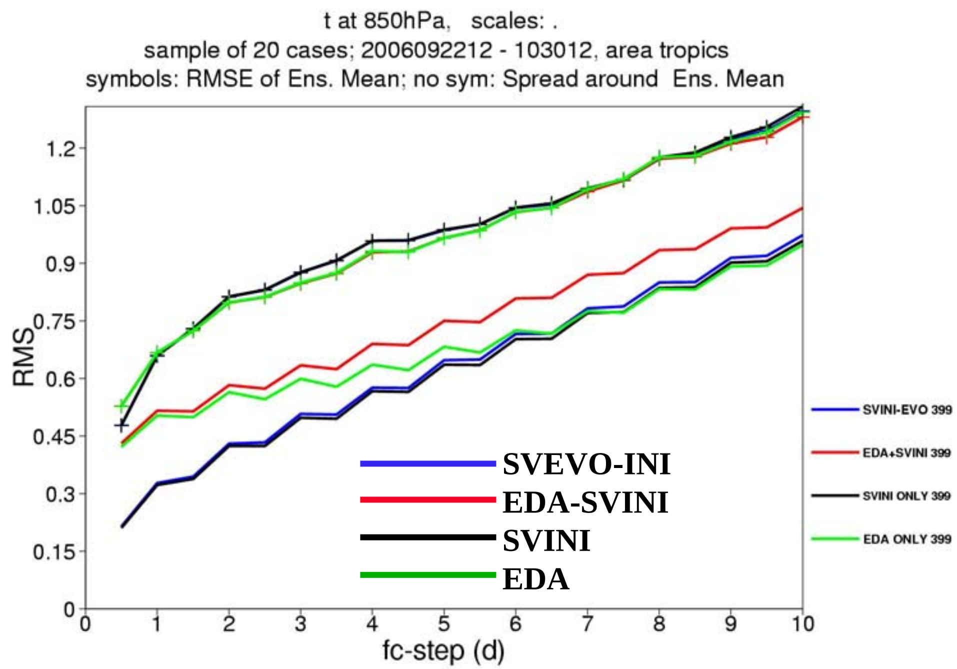




2.3 std/EM of EDA, SVINI, EDA-SVINI & SVEVO-INI EPS

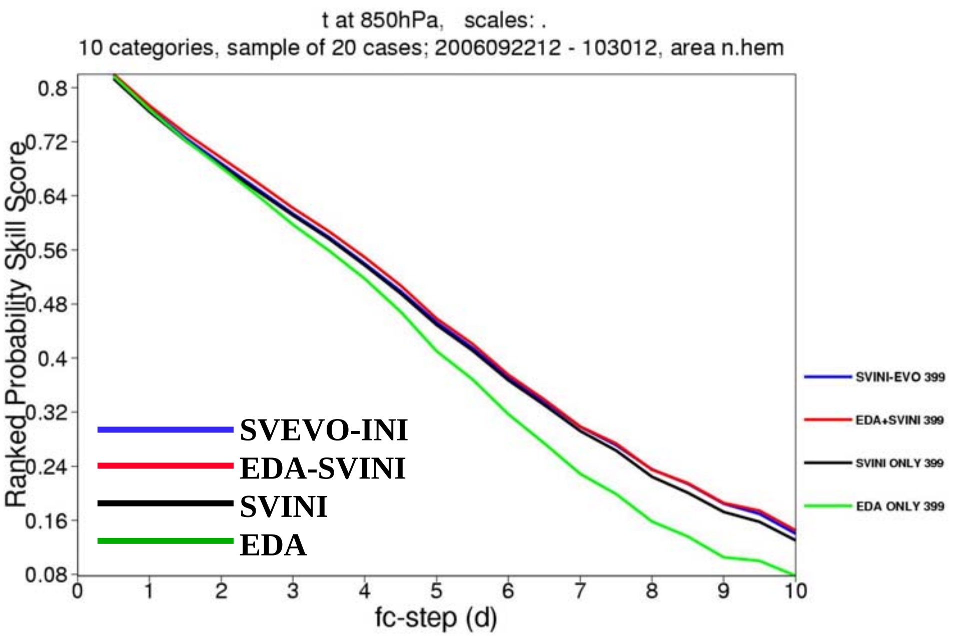
The EDA-SVINI ensemble combines the benefits of the EDA and the SV techniques. Over both the NH (left) and the tropics (right), the EDA-SVINI ensemble has a better tuned spread, and the smallest ensemble-mean error (in terms of T850). In the extra-tropics, compared to the SVINI the EDA ensemble severely underestimates the spread, but over the tropics the EDA ensemble has initially a larger spread.

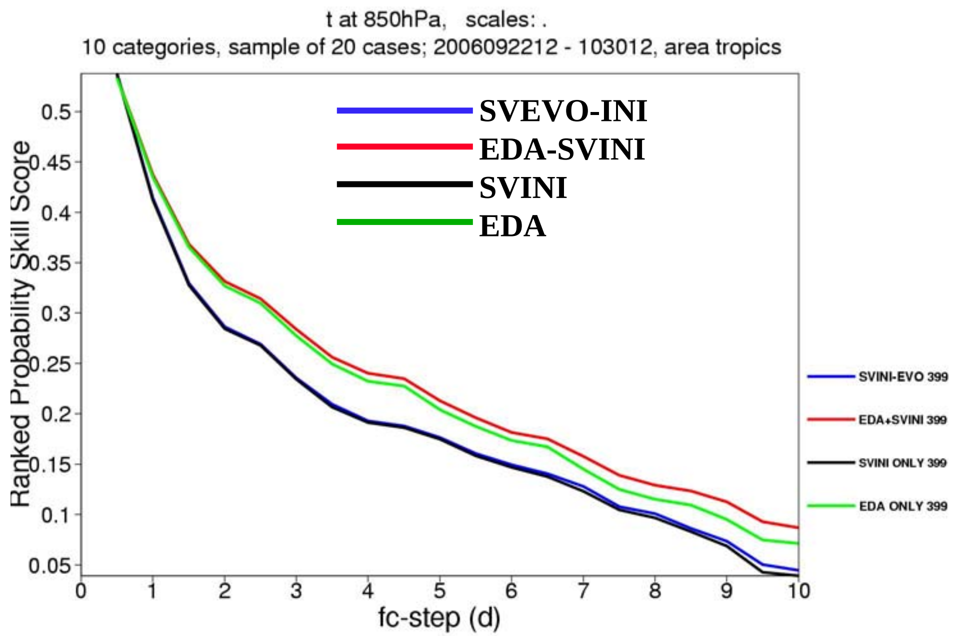




2.3 RPSS of EDA, SVINI, EDA-SVINI & SVEVO-INI EPS

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.

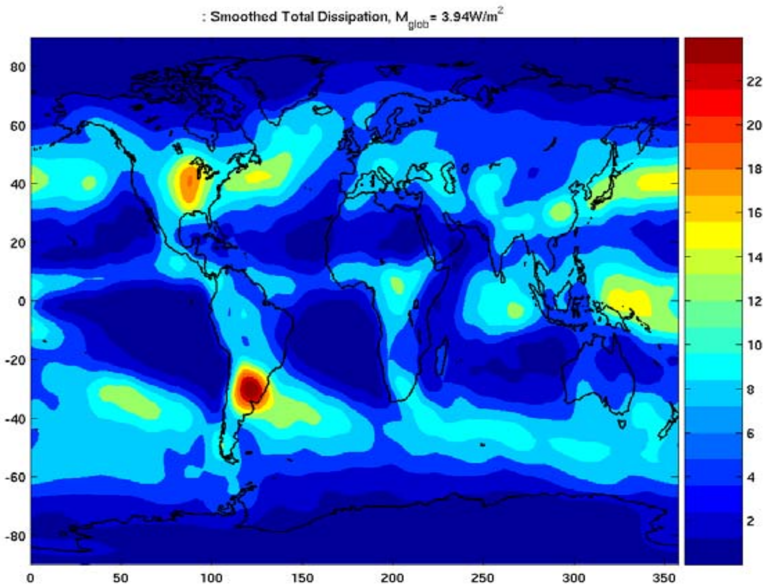




2.4. SPectral stochastic Backscatter Scheme (SPBS)

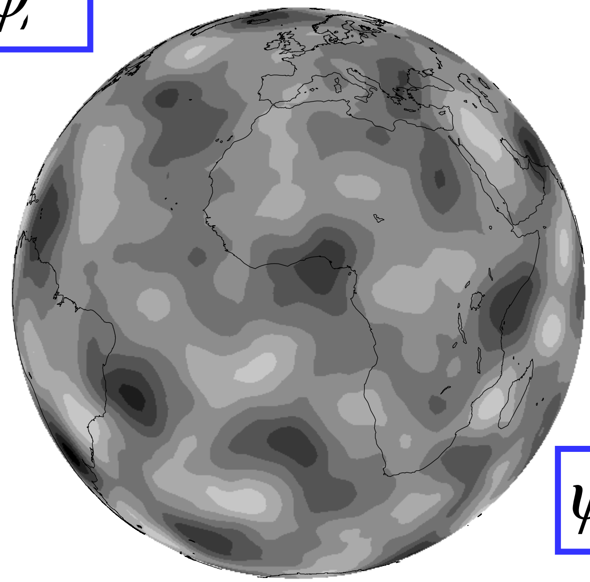
Rationale: A fraction of the dissipated energy is scattered upscale and acts as stream-function forcing for the resolved-scale flow ([1]):

$$\Delta \psi^* \propto \sqrt{D}\,\psi'$$



D

Total Dissipation rate from numerical dissipation, convection, gravity/ mountainwave drag



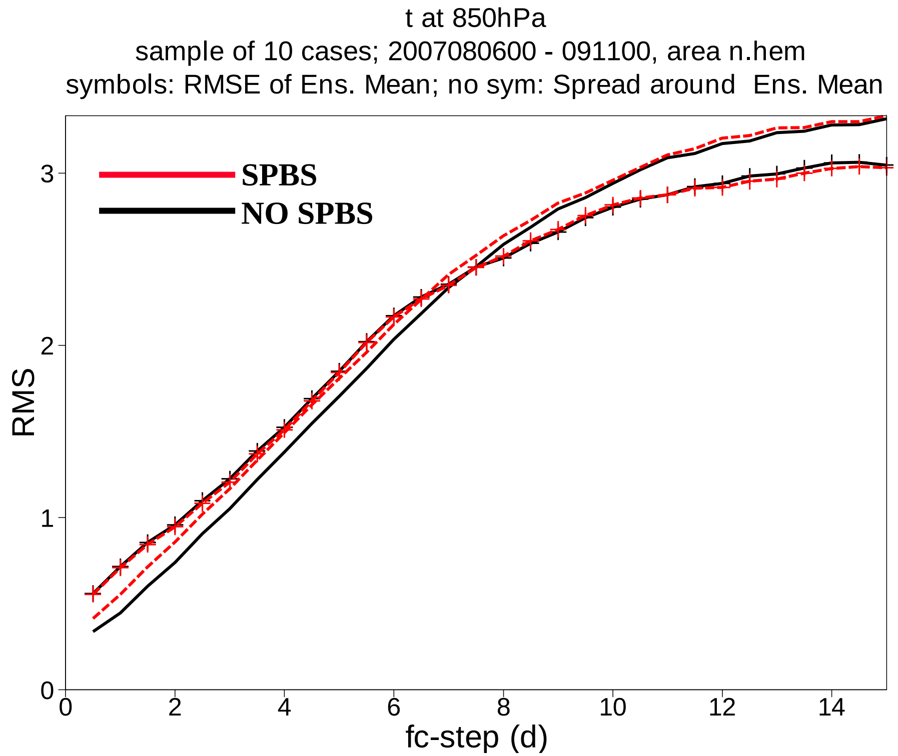
ψ'

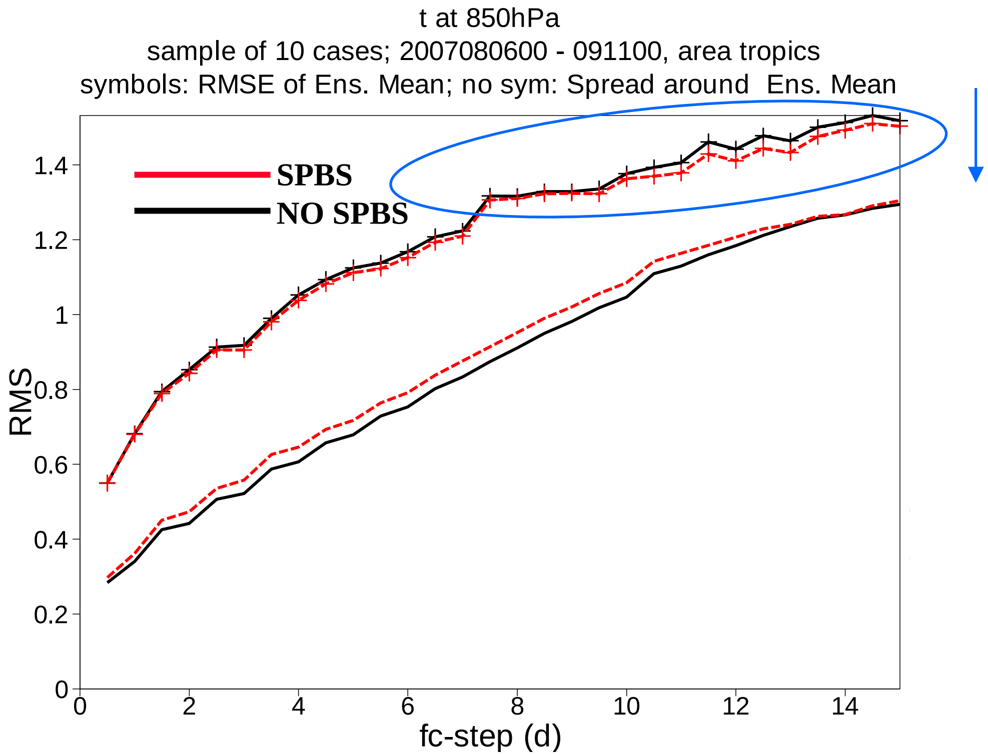
Autoregressive process for each wavenumber in spectral space: temporal and spatial correlations

2.4 SPBS: recent results with T_L399L62 model

Preliminary results ([1]) with a TL399L62 resolution (10 cases, 51-member ensembles) indicate that SPBS is generating some extra spread, which has a positive impact on the ensemble spread/skill relationship.

Results also suggest that SPBS has neutral to positive impact on the skill of probabilistic predictions of U850 and T850, but a neutral impact for Z500. Work is in progress to run more cases, spanning also other seasons.





Outline

1. Status of the ECMWF ensemble prediction system

    1.1 The operational VAriable Resolution Ensemble Prediction System (VAREPS)

    1.2 Performance of VAREPS in 2007

    1.3 Comparison of global ensemble systems using the TIGGE data-base

2. Developments

    2.1 VAREPS extension from 15 to 32 days

    2.2 Use of re-forecasts for calibration

    2.3 Simulation of initial uncertainties using a combination of ensemble data-assimilation methods and singular vectors

    2.4 Simulation of model uncertainties using a stochastic back-scatter scheme

3. Conclusions

3. Conclusions

❖ Status of the ECMWF ensemble:

- The implementation of model cycle 32r3 (6 Nov ’07) with the adjustment of the initial perturbation amplitudes, has lead to a better tuned spread.
- The skill of ECMWF ensemble predictions continues to improve.
- Comparison of ensemble forecasts in the TIGGE data-base indicates that the ECMWF ensemble system is outperforming the other global systems.

❖ Developments:

- Simulation of initial uncertainties: work is progressing to test using an ensemble of analyses (EDA) together with SVs in the ensemble system. Results indicate that EDA-only perturbations are suboptimal, and it is best to combine EDA and SVs.
- Simulation of model uncertainties: work is in progress to test a new stochastic spectral back-scatter scheme (SPBS): its implementation should further improve the matching between ensemble spread and forecast error.
- System configuration: by mid 2008, the 15d VAREPS and the coupled monthly ensemble systems will be unified in the 32d VAREPS.
- Calibration: by mid 2008, the implementation of the re-forecast suite will provide users with all information required to calibrate ensemble forecasts.

Acknowledgements

The success of the ECMWF ensemble system is the result of the enthusiastic and hard work of many ECMWF staff, consultants and visitors who had continuously improved the ECMWF model, analysis, diagnostic and technical systems. Collaborations with ECMWF Member States and other national and international institutions have also provided valuable insights and guidelines. The work of everyone is recognized and acknowledged.

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… other material

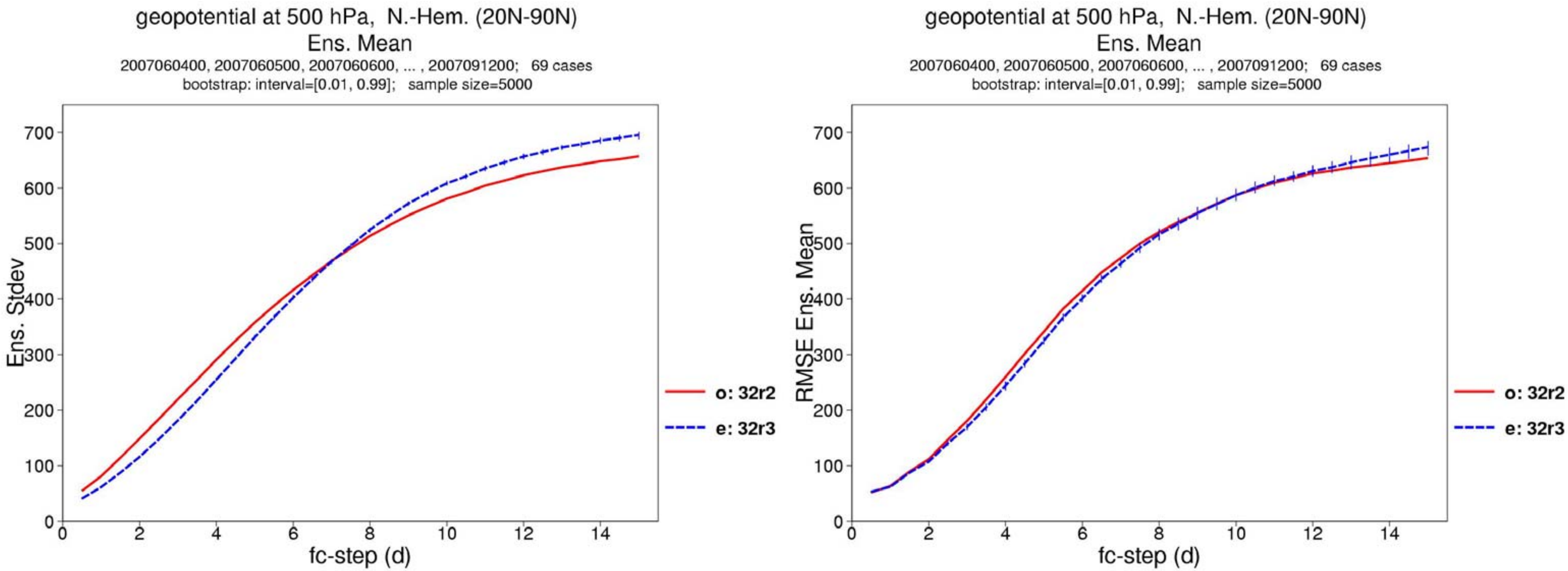
1.1 Since May '94 the EPS configuration changed 15 times

Between Dec 1992 and Sep 2006 the ECMWF system changed several times: ~50 model cycles (which included changes in the model and DA system) were implemented, and the EPS configuration was modified 15 times.

	Date	Description	Singular Vectors's characteristics						Forecast characteristics					
			HRES	VRES	OTI	Target area	EVO SVs	sampl	HRES	VRES	Tend	#	Mod Unc	Coupling
EPS / VAREPS	Dec 1992	Oper Impl	T21	L19	36h	globe	NO	simm	T63	L19	10d	33	NO	NO
	Feb 1993	SV LPO	"	"	"	NHx	"	"	"	"	"	"	"	"
	Aug 1994	SV OTI	"	"	48h	"	"	"	"	"	"	"	"	"
	Mar 1995	SV hor resol	T42	"	"	"	"	"	"	"	"	"	"	"
	Mar 1996	NH+SH SV	"	"	"	(NH+SH)x	"	"	"	"	"	"	"	"
	Dec 1996	resol/mem	"	L31	"	"	"	"	TL159	L31	"	51	"	"
	Mar 1998	EVO SV	"	"	"	"	YES	"	"	"	"	"	"	"
	Oct 1998	Stoch Ph	"	"	"	"	"	"	"	"	"	"	YES	"
	Oct 1999	ver resol	"	L40	"	"	"	"	"	L40	"	"	"	"
	Nov 2000	FC hor resol	"	"	"	"	"	"	TL255	"	"	"	"	"
	Jan 2002	TC SVs	"	"	"	(NH+SH)x+TC	"	"	"	"	"	"	"	"
	Sep 2004	sampling	"	L40	"	"	"	Gauss	"	"		"	"	"
	Jun 2005	rev sampl	"	"	"	"	"	"	"	"		"	"	"
	Feb 2006	resolution	"	L62	"	"	"	"	TL399	L62	10d	"	"	"
	Sep 2006	VAREPS	T42	L62	48h	(NH+SH)x+TC	YES	Gauss	TL399(0-10)+TL255(10-15)	L62	15d	51	YES	NO
MONTHLY	Mar 2002	Oper Impl	T42	L40	48h	(NH+SH)x+TC	YES	simm	TL159	L40	32d	51	YES	YES
	Sep 2004	sampling	"	"	"	"	"	Gauss	"	"	"	"	"	"
	Feb 2006	resolution	"	L62	48h	(NH+SH)x+TC	YES	Gauss	TL159	L62	32d	51	YES	YES
32d VAREPS / MONTHLY	2007/08	32d-VAREPS	T42	L62	48h	(NH+SH)x+TC	YES	Gauss	TL399(0-10)+TL255(10-32)	L62	32d	51	YES	YES from d10

1.2 JA07: ECMWF o- & e-suites – Z500 NH

The spread reduction in the early fc-range is due to the 30% reduction of the initial perturbations' amplitude. Due to the increased model activity, the ensemble spread of the e-suite reaches the level of the o-suite at ~fc-day 7, and remains higher thereafter (left panel). The error of the ensemble-mean is significantly smaller in the e-suite between fc-day 3 and 7 (right panel).



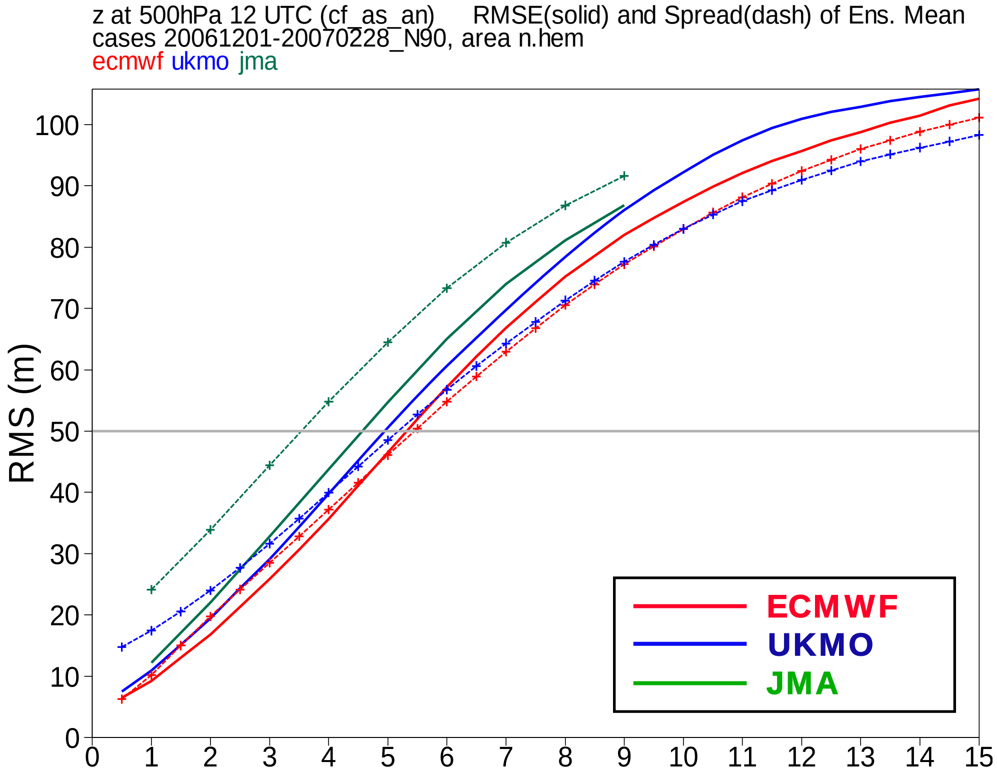
1.3 Characteristics of the TIGGE ensembles compared

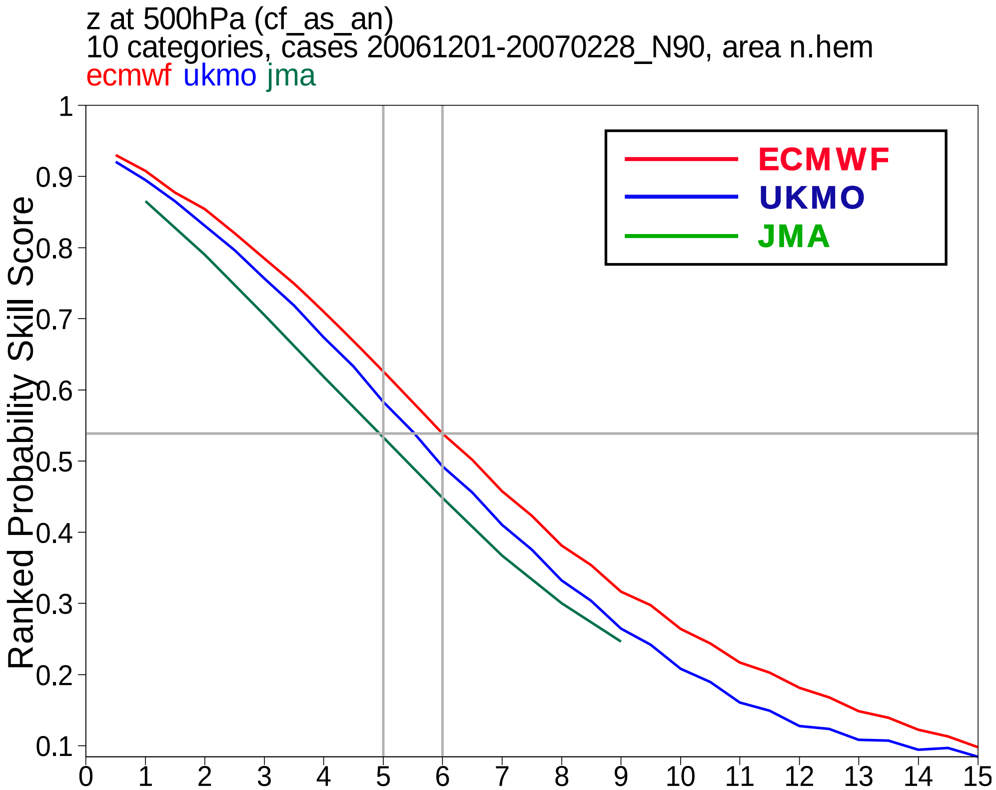
- The performance of the following ensemble systems have been compared during periods for which data were available in the TIGGE archive.
- Note that ensembles differ, especially in resolution and size.
- Each ensemble has been verified against its own analysis.

	BMRC	CMA	ECMWF	JMA	KMA	MSC	NCEP	UKMO
Model error	NO	NO	YES	NO	NO	YES	NO	YES
Init perturb	SVi	BVs/SVs	SVi+e	BVs	BVs	Sys-Sim	ET-BVs	ETKF
Perturb area	NH+SH	NH+TR	Globe	NH+TR	NH	NH	Globe	Globe
HRES fcs	TL119	T213	TL399(d0-10) TL255(d10-15)	T106	T213	TL149	T126	N144 (~80km)
# vert-lev	19	31	62	40	40	28	28	38
fc length (d)	10	10	15	9	10	16	16	15
# pert mem	32	14	50	50	16	20	20	23
# runs (d)	2 (00/12)	2 (00/12)	2 (00/12)	1 (12)	2(00/12)	2(00/12)	4 (00/06/ 12/18)	2 (00/12)
# mem (d)	66	30	102	51	34	42	84	48

1.3 D06-JF07 (90c): EC/UK/JMA – Z500 NH

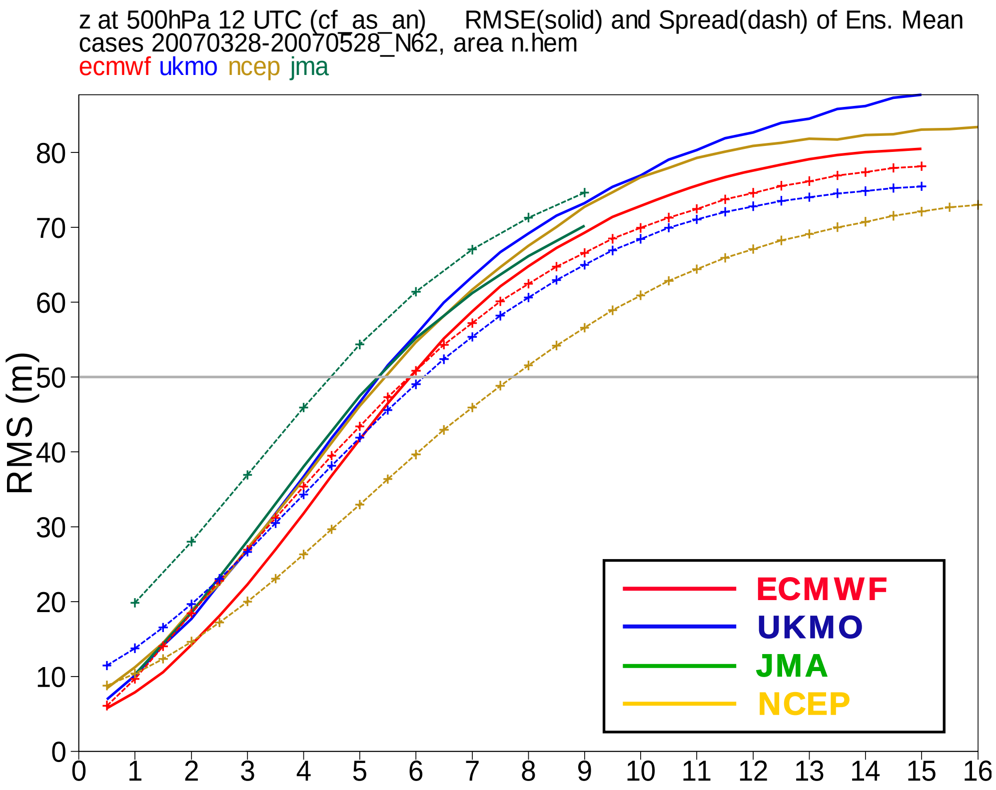
- spread (left, dashed): EC best match of std & rmse(EM); JMA too large; UK too large (small) in short (medium) range.
- rmse(EM) (left, solid): EC has lowest rmse for whole forecast range.
- RPSS (right): EC has best skill (at t+5d, ~0.5d gain in predictability).

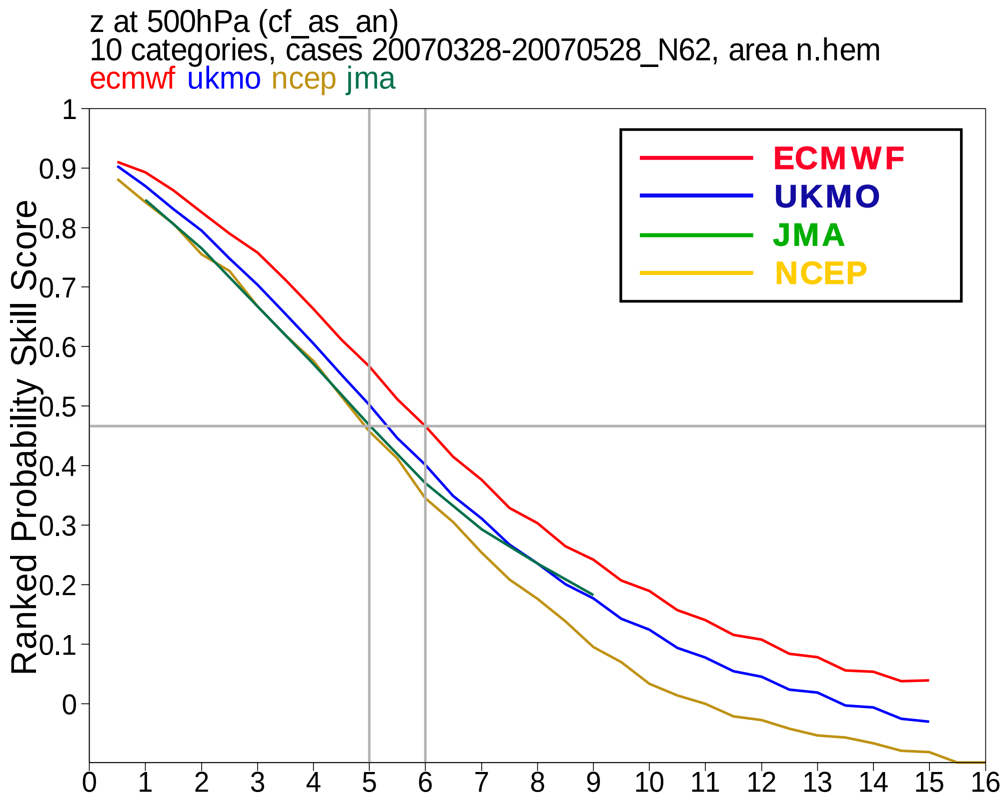




1.3 AM07 (62c): EC/UK/NCEP/JMA - Z500 NH

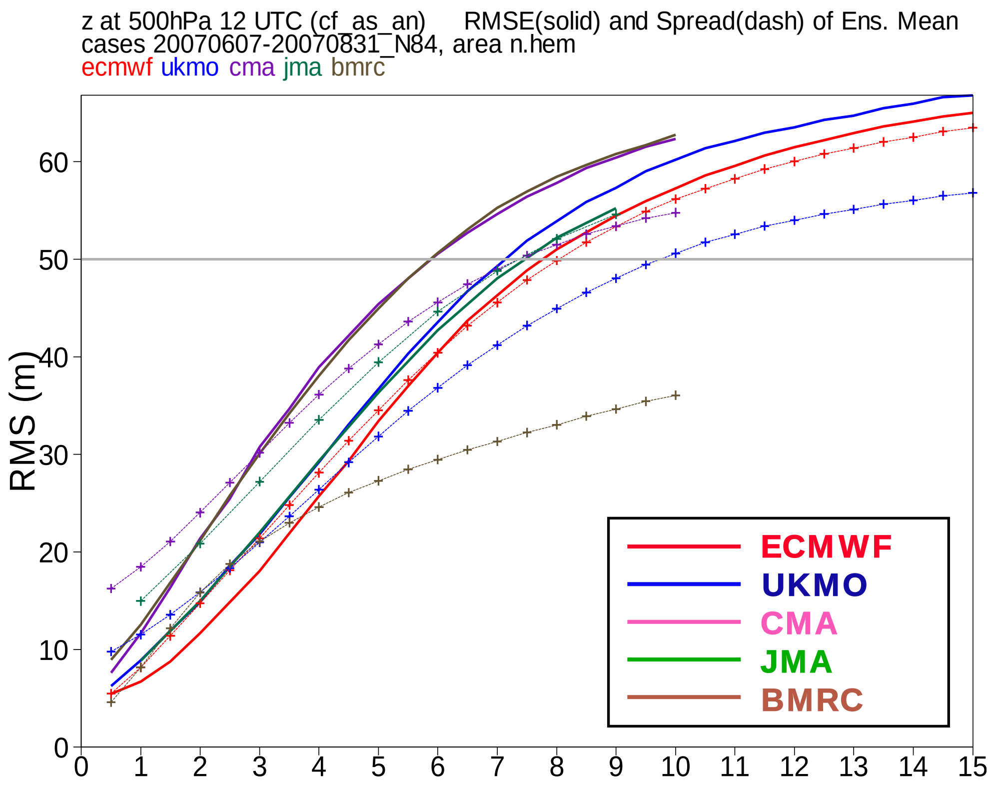
- spread (left, dashed): EC best match of std & rmse(EM); UK similar to EC after day 2; JMA too large, NCEP too small.
- rmse(EM) (left, solid): EC has lowest rmse for whole forecast range.
- RPSS (right): EC has best skill (at t+5d, ~0.75d gain in predictability).

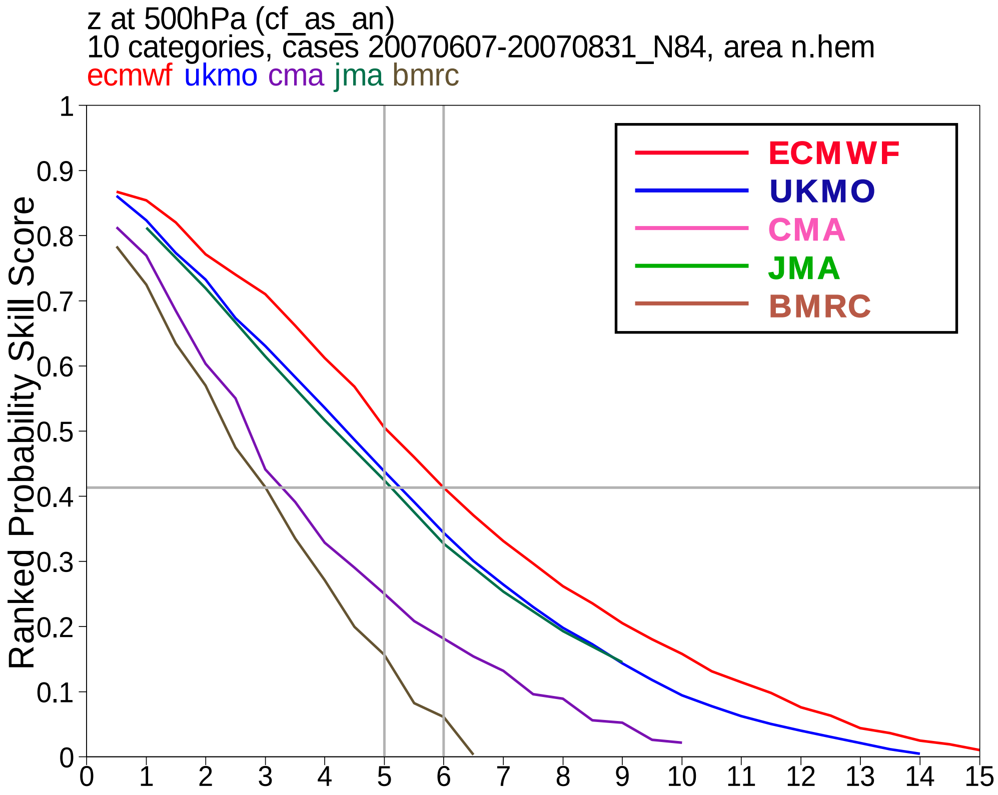




1.3 JJA07 (84c): EC/UK/CMA/JMA/BMRC – Z500 NH

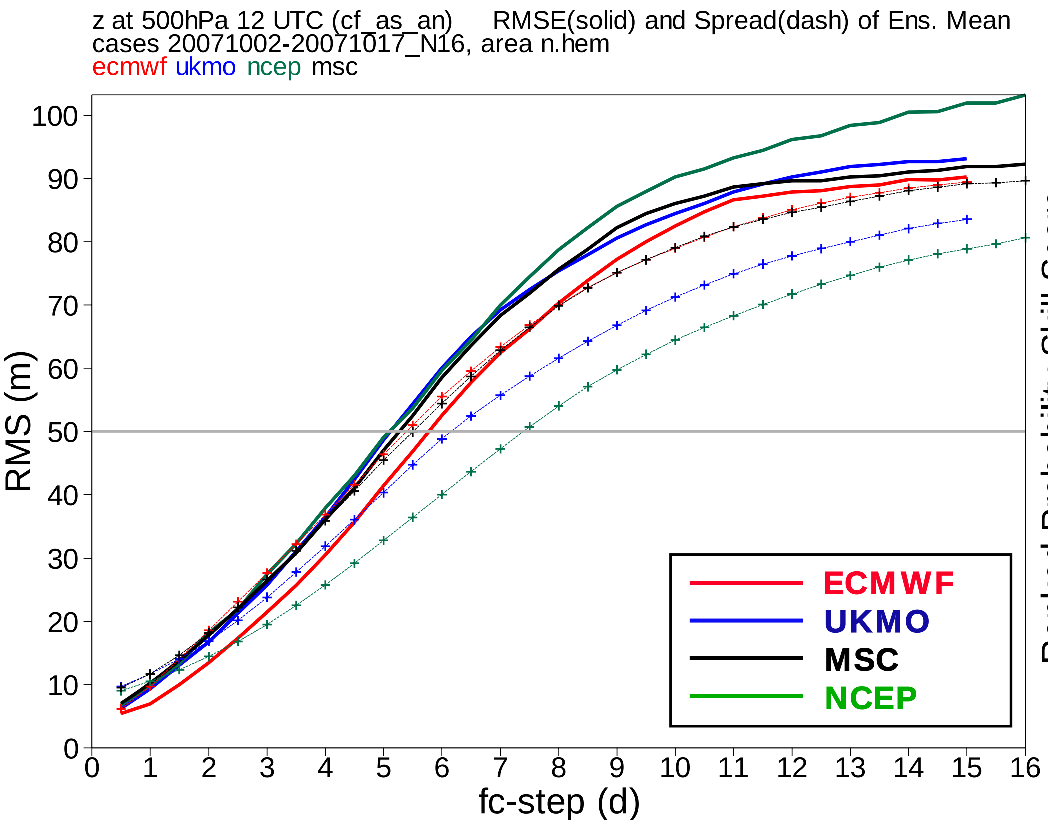
- spread (left, dashed): EC best match of std & rmse(EM); CMA/JMA too large; UK too small in medium range; BMRC too small.
- rmse(EM) (left, solid): EC has lowest rmse for whole forecast range.
- RPSS (right): EC has best value (at t+5d, ~0.9d gain in predictability).

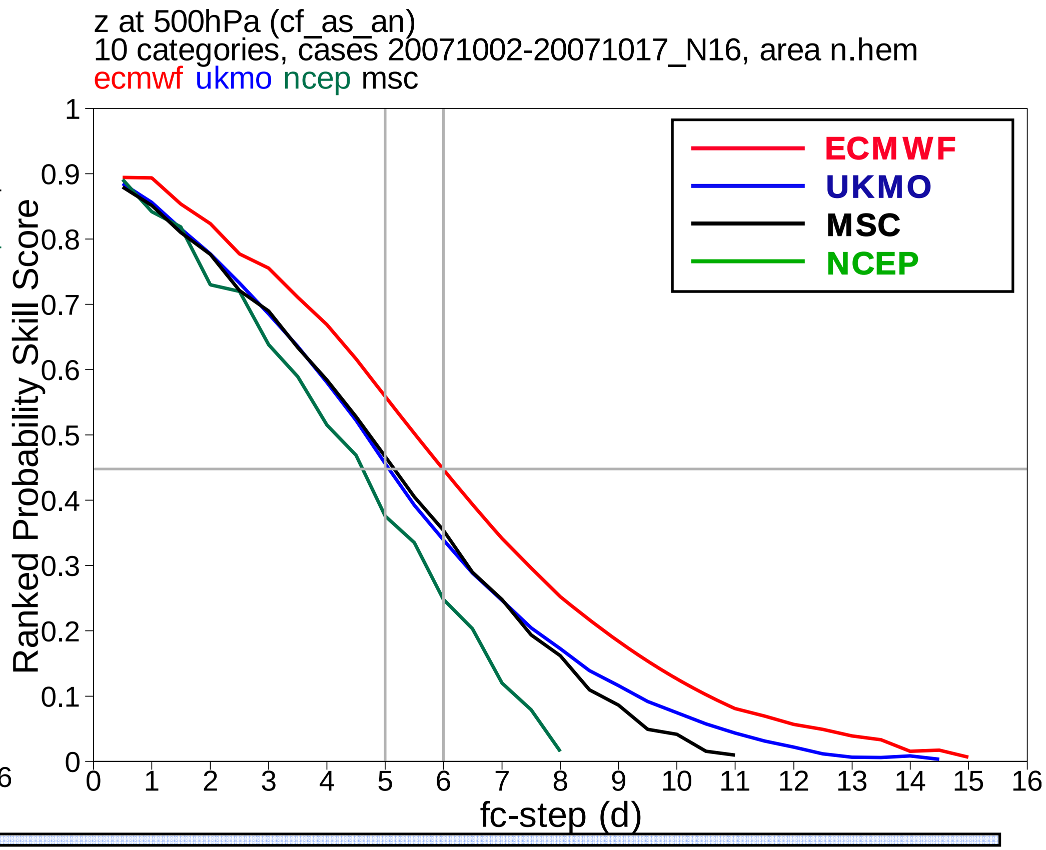




1.3 O07 (16c): EC/MSC/NCEP/UK – Z500 NH

- spread (left, dashed): EC & MSC best match of std & rmse(EM); UK too small in medium range; NCEP too small.
- rmse(EM) (left, solid): EC has lowest rmse for whole forecast range.
- RPSS (right): EC has best value (at t+5d, ~0.9d gain in predictability).

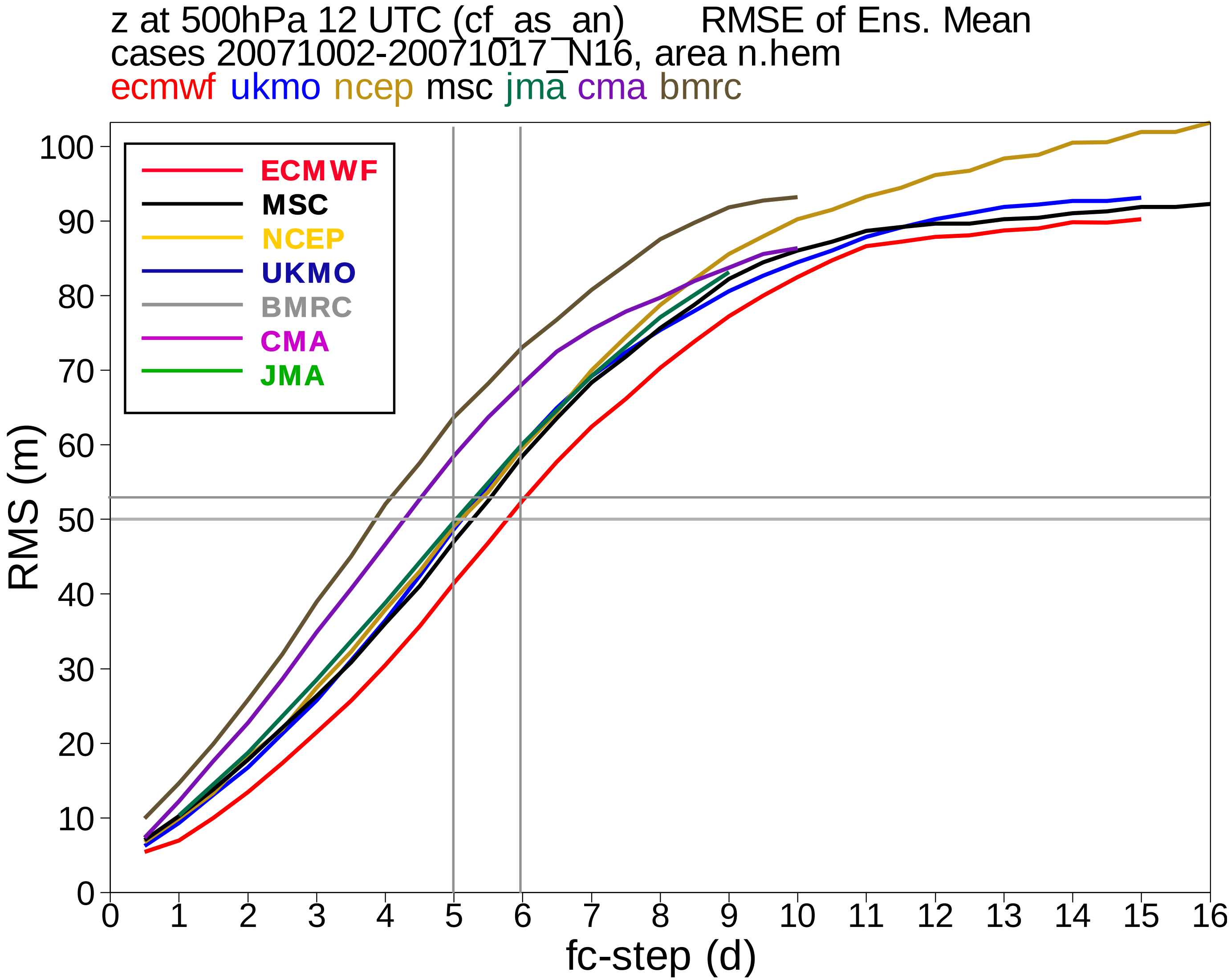




1.3 O07 (16c): EC/MSC/NCEP/UK/BMRC/CMA/JMA EM

Most recent TIGGE results: this figure shows the O07 average RMSE of the ensemble-mean fc for Z500 over NH. The EC ensemble-mean outperforms the group of 2nd best ensembles (MSC, UKMO and JMA for this period) for the whole fc range, with ~0.6d gain in predictability at t+5d.

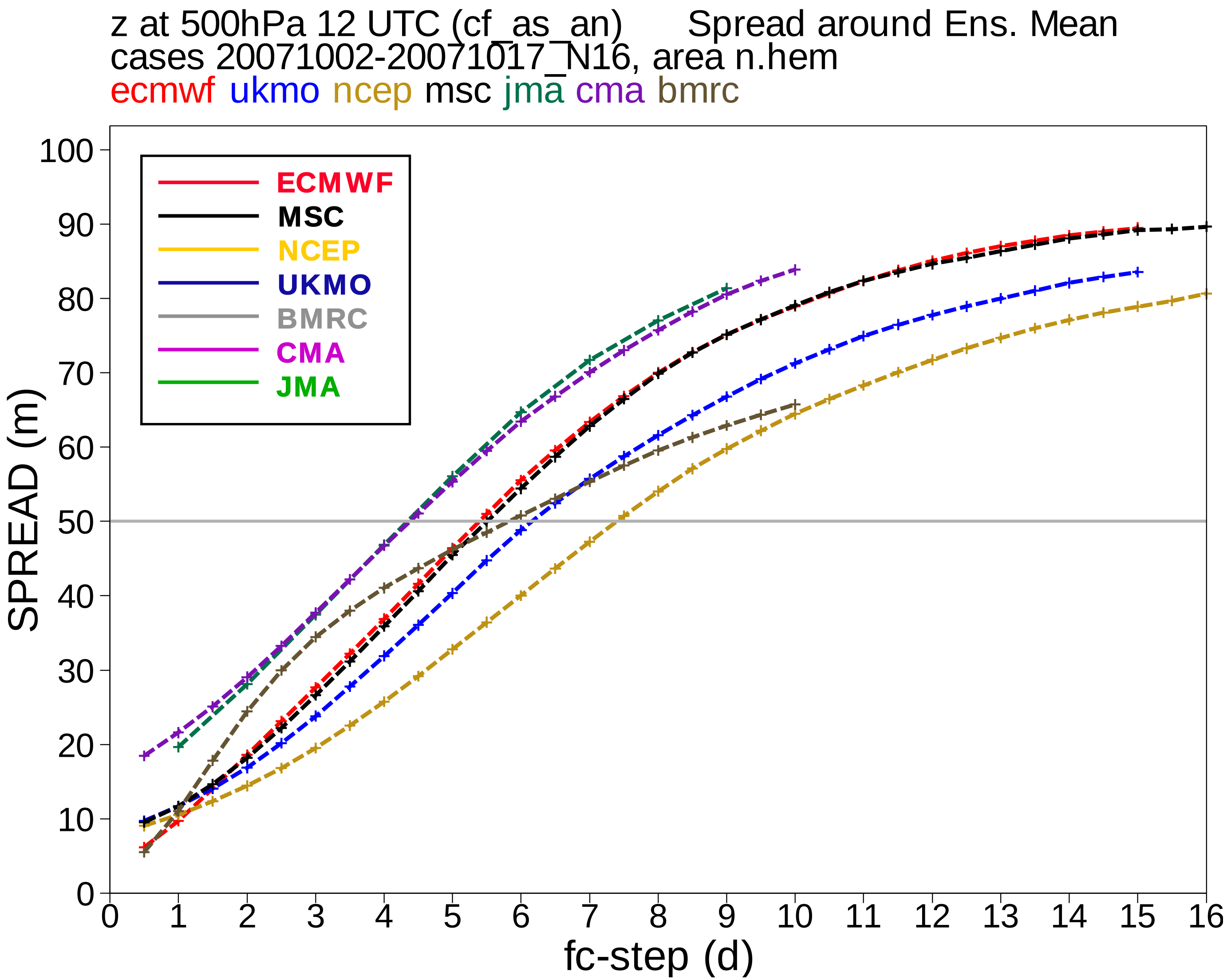
This indicates that the differences in skill of the ensemble probabilistic forecasts is not only due to model/analysis, but also to the ensemble design (e.g. use of SVs).



1.3 O07 (16c): EC/MSC/NCEP/UK/BMRC/CMA/JMA STD

Most recent TIGGE results: this figure shows the O07 average STD for Z500 over NH.

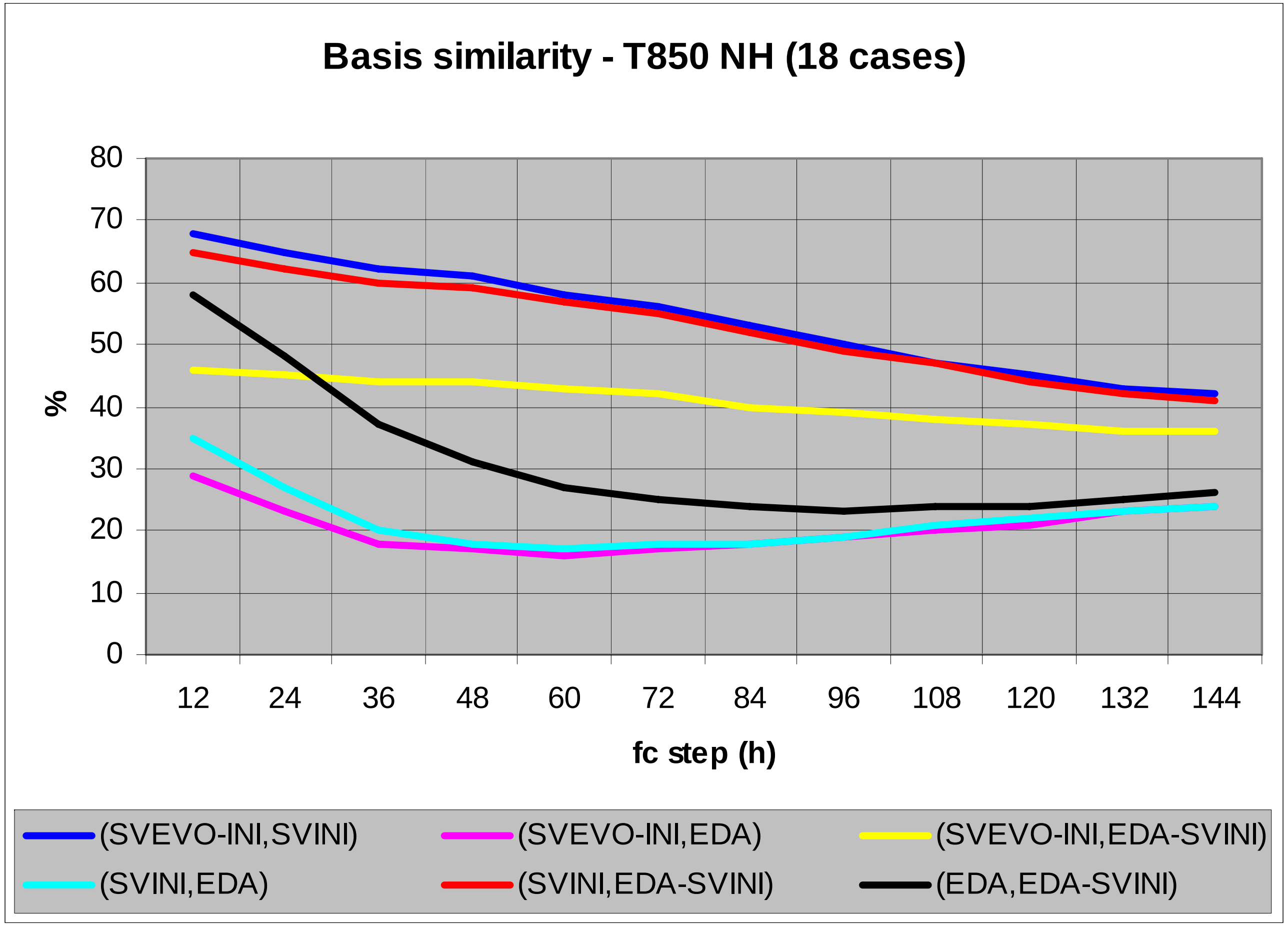
The EC and MSC ensembles have very similar STD. UKMO and NCEP has a smaller STD, while CMA and JMA have a larger STD.



2.3 Similarity between ortho-normal basis – T850 NH

Over NH, the highest degree of similarity is shown between the SVINI and the SVEVO-INI (blue line), and the SVINI and the EDA-SVINI ensembles (red line). The lowest degree is shown between the EDA and the SVEVO-INI (magenta line), and the EDA and the SVINI ensembles (cyan line).

These results confirm the different nature of the SV- and EDA- perturbations. They also suggest that over the extra-tropics the SVINI perturbations dominate the ensemble spread.

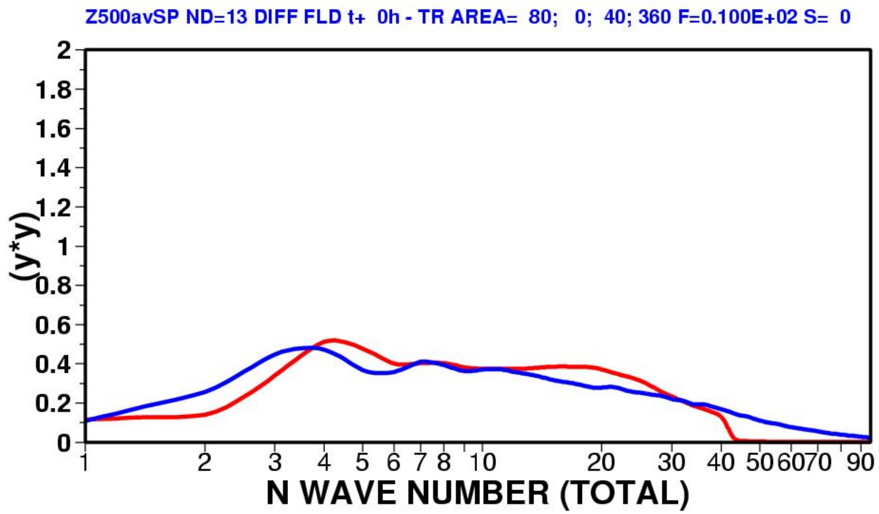


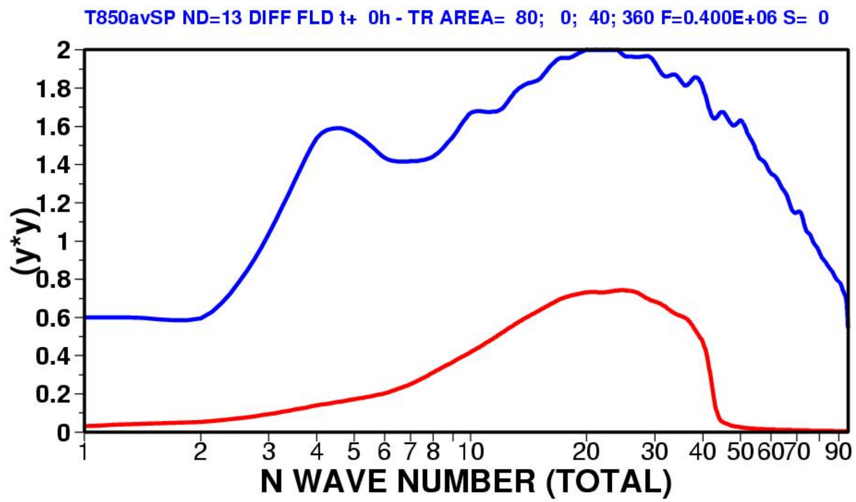
2.3 Spectra of EDA & SVINI ensembles – NH t0

The top figure shows the squared amplitude of the SVINI (red) and EDA (blue) perturbations in terms of Z500 over NH. The bottom panel shows the same but for T850. Results have been averaged over 13 cases.

At initial time, the SVINI perturbations are confined to T42 by construction.

The EDA(3,1,HR) perturbations are larger in terms of T850.



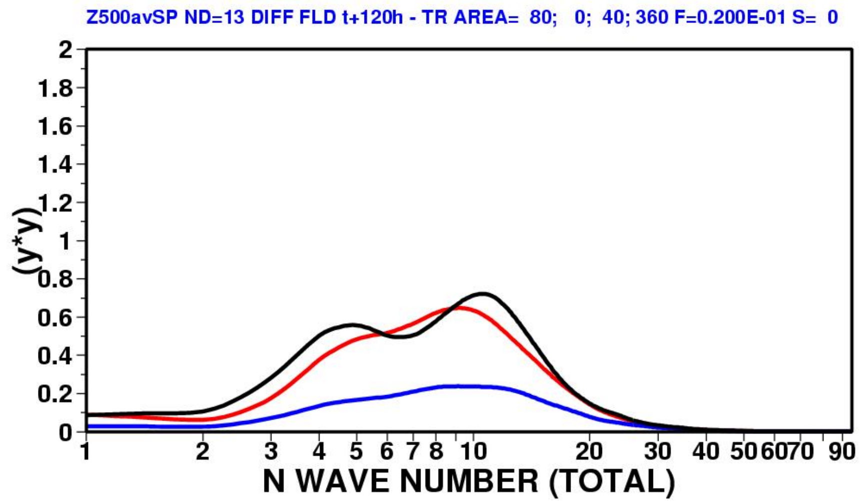


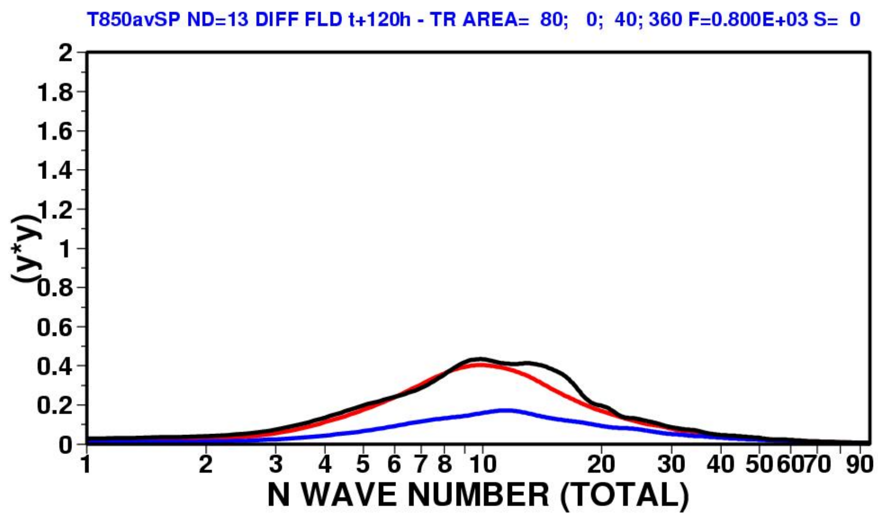
2.3 Spectra of EDA & SVINI ensembles – NH +120h

The top figure shows the squared amplitude of the SVINI (red) and EDA (blue) perturbations in terms of Z500 over NH, and of the error of the t+120h control forecast (black). The bottom panel shows the same but for T850. Results have been averaged over 13 cases.

At t+120h, the difference in spread between the SVINI and the EDA is even more evident.

On average, the spectra of the SVINI ensemble spread is very close to the spectra of the control error.



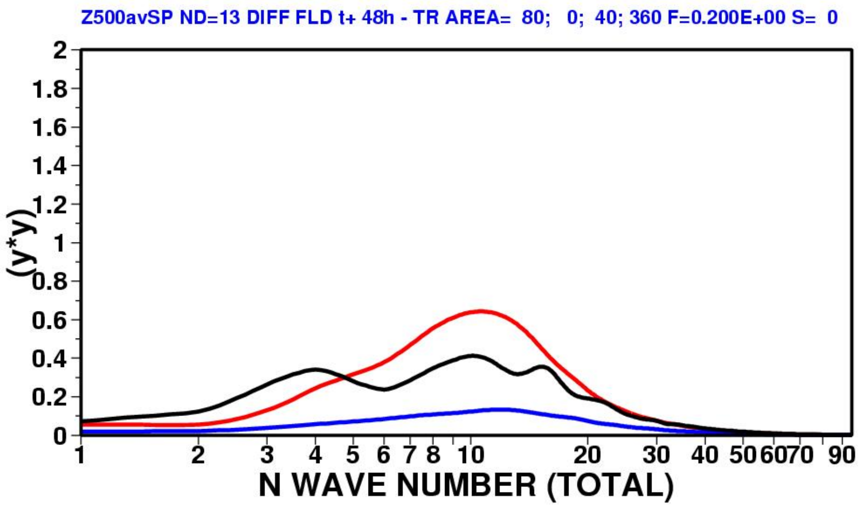


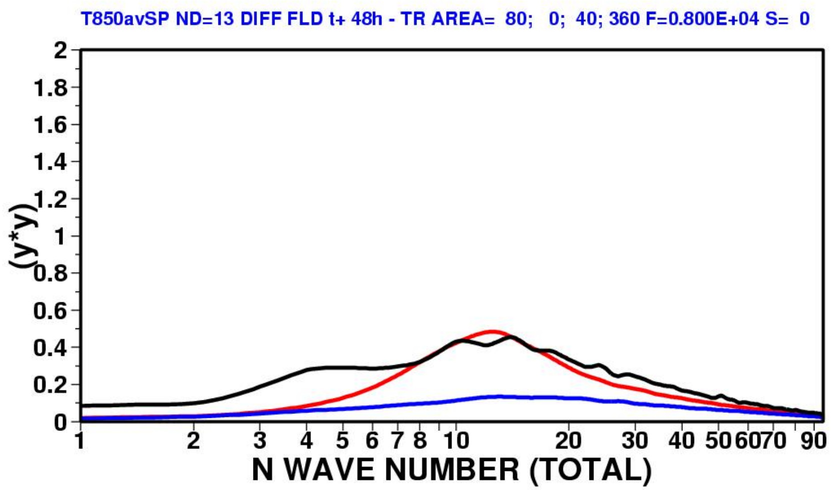
2.3 Spectra of EDA & SVINI ensembles – NH +48h

The top figure shows the squared amplitude of the SVINI (red) and EDA (blue) perturbations in terms of Z500 over NH, and of the error of the t+24h control forecast (black). The bottom panel shows the same but for T850. Results have been averaged over 13 cases.

At t+24h, the SVINI perturbations have a larger amplitude than the EDA perturbations, especially in the wave-numbers where the SVs total energy peaks at optimisation time.

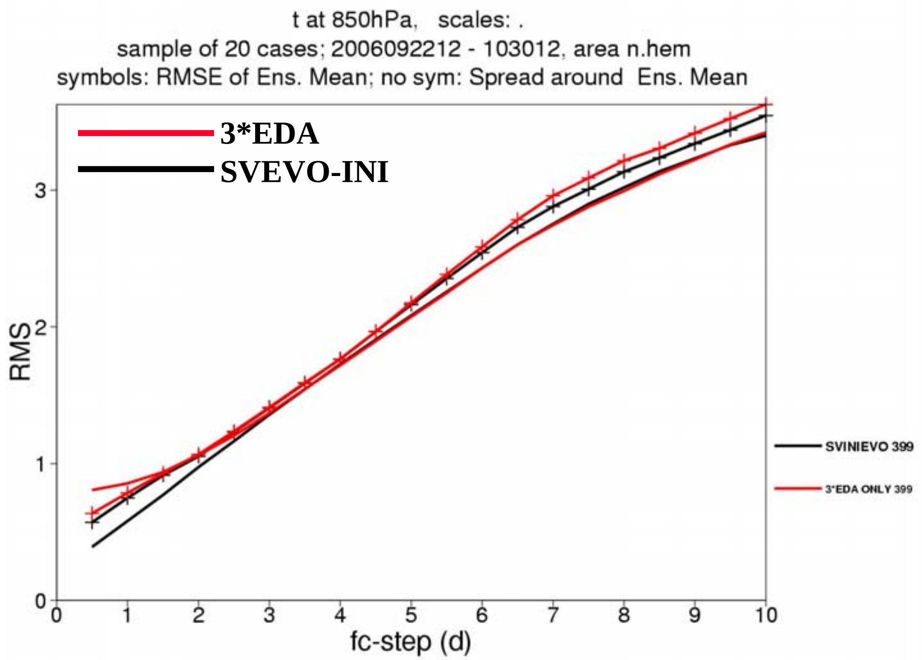
On average, the spectra of the SVINI ensemble spread is closer to the spectra of the control error.

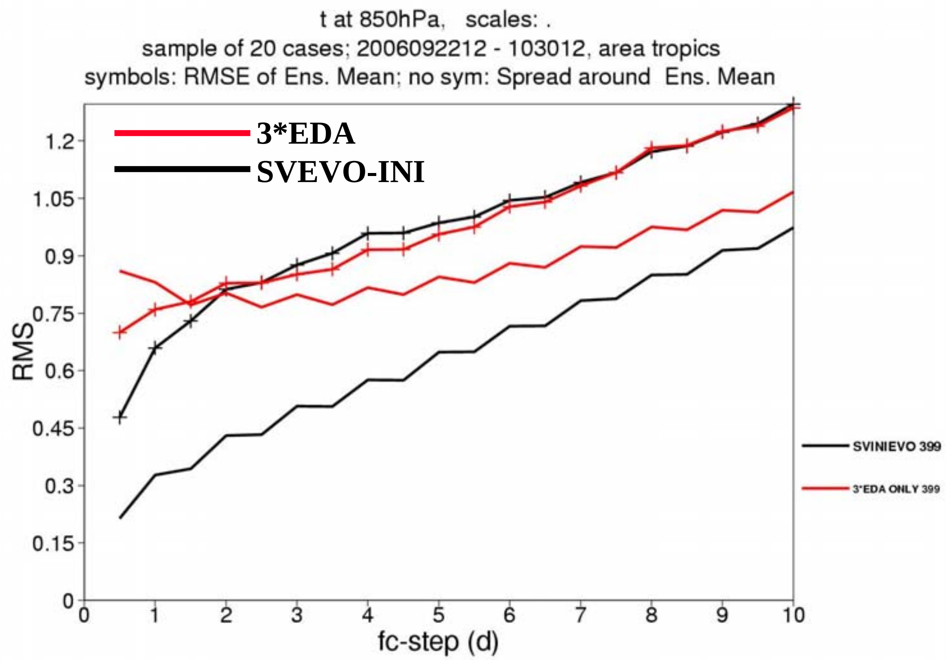




2.3 std/EM of 3*EDA and SVEVO-INI EPS

In the EDA-only ensemble, a better match between the ensemble std and the EM-error can be achieved by inflating the initial distance between the perturbed analyses by a factor of 3. Such an inflation leads to a similar spread to the SVEVO-INI ensemble over the NH after forecast day 4 (left). Over the NH, the SVEVO-INI EM has a smaller error after forecast day 5, while over the tropics the SVEVO-INI EM has a smaller error up to forecast day 2, while between forecast day 3 and 7 the 3*EDA EM has a smaller error.

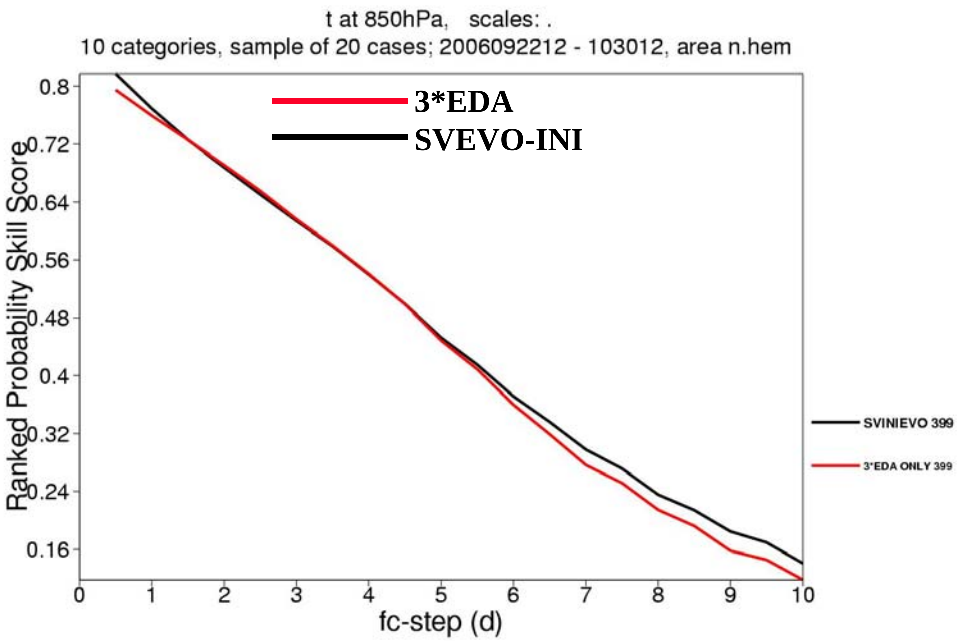


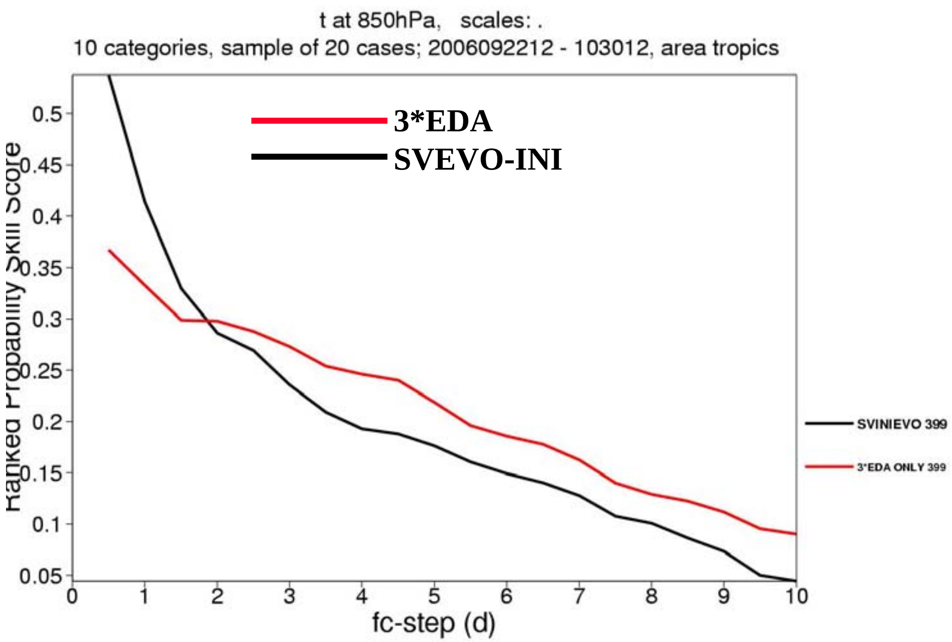


2.3 RPSS of 3*EDA and SVEVO-INI EPS

Over the NH (left), the SVEVO-INI ensemble has a better RPSS up to forecast day 2 and after forecast day 5, while over the tropics it has a better RPSS only up to day 2 (right panel).

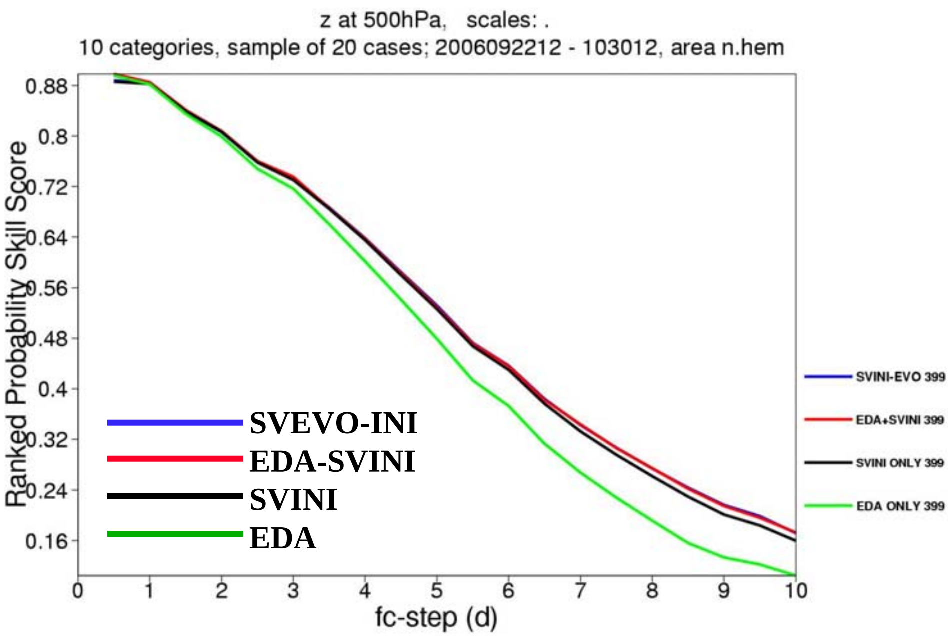
In the short forecast range, the 3*EDA ensemble is penalized by having a too large ensemble spread. Over the tropics, the SVEVO-INI ensemble suffers from the fact that tropical initial uncertainties are not properly sampled by the tropical SVs, which are restricted to only few target regions.

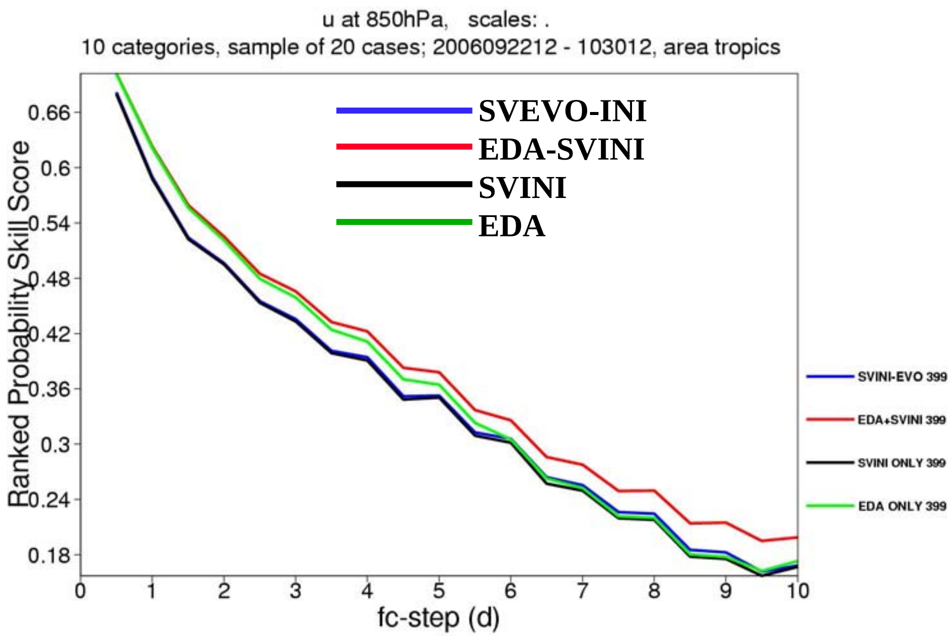




2.3 RPSS of EDA, SVINI, EDA-SVINI & SVEVO-INI EPS

The benefits of combining EDA- and SVINI-based perturbations can be detected also if other variables are considered. Over the NH (left), the EDA-SVINI ensemble has the highest RPSS for the probabilistic prediction of Z500. Over the tropics (right), the EDA-SVINI ensemble has the highest RPSS for the probabilistic prediction of U850.

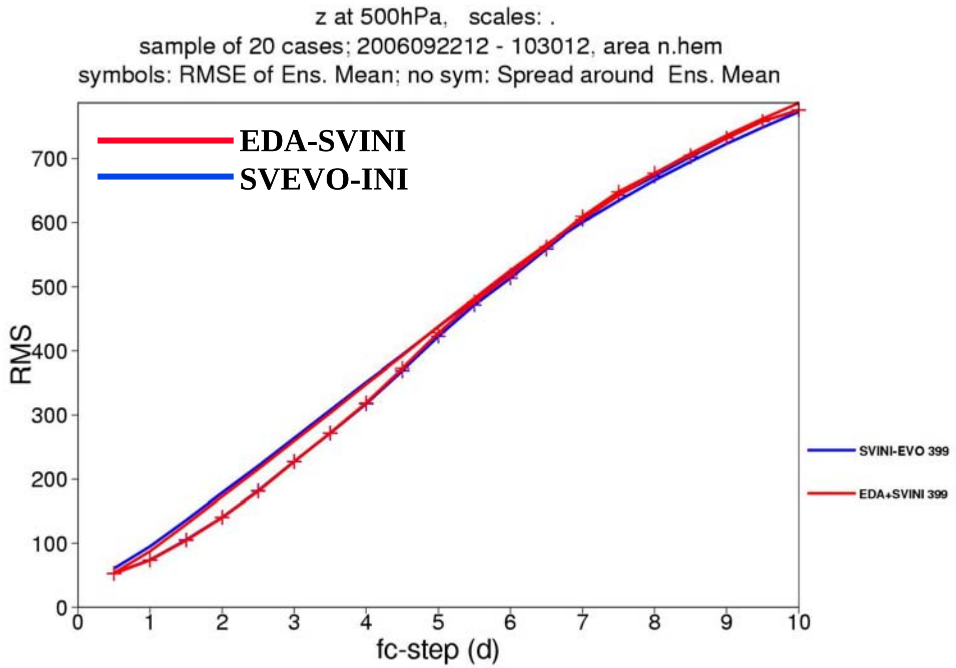


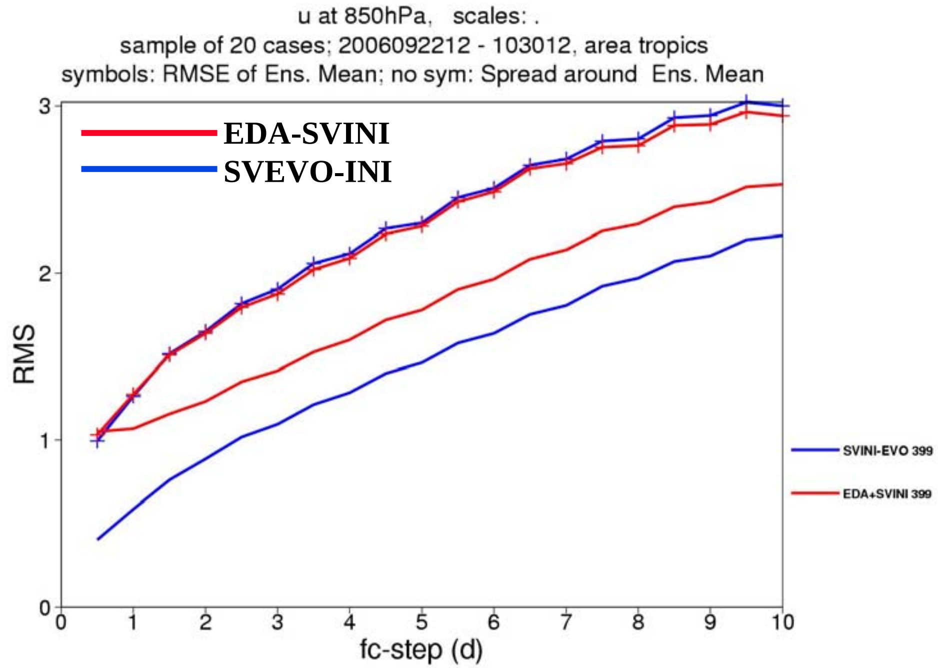


2.3 std/EM of EDA-SVINI and SVEVO-INI EPS

Over the NH (left), the two ensembles have similar spread (in terms of Z500 std), and similar ensemble-mean error.

Over the Tropics (right), EDA-SVINI EPS has a larger spread (in terms of U850), closer to the error of the ensemble-mean, and a smaller ensemble-mean error.

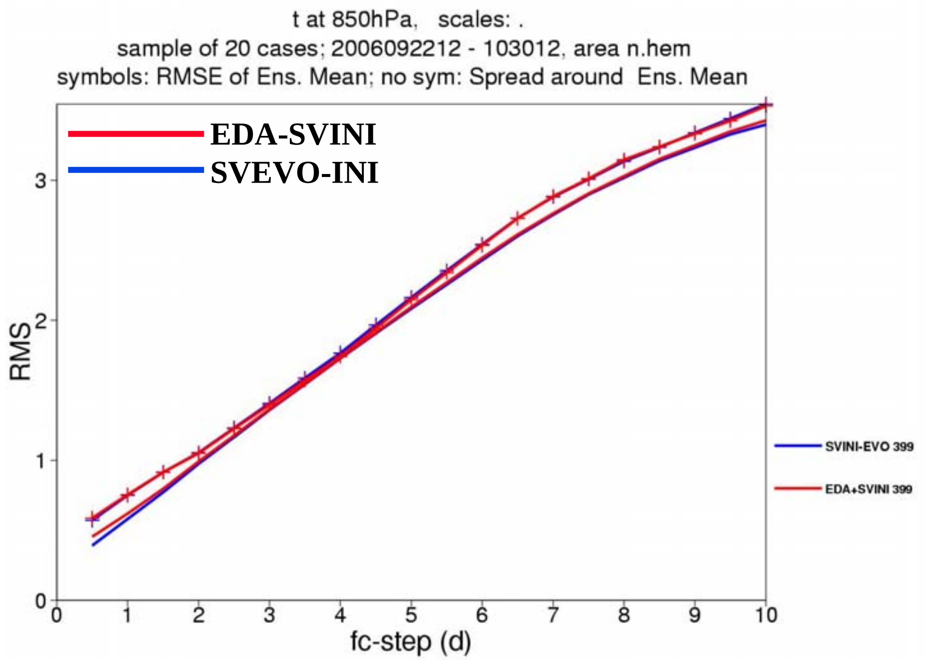


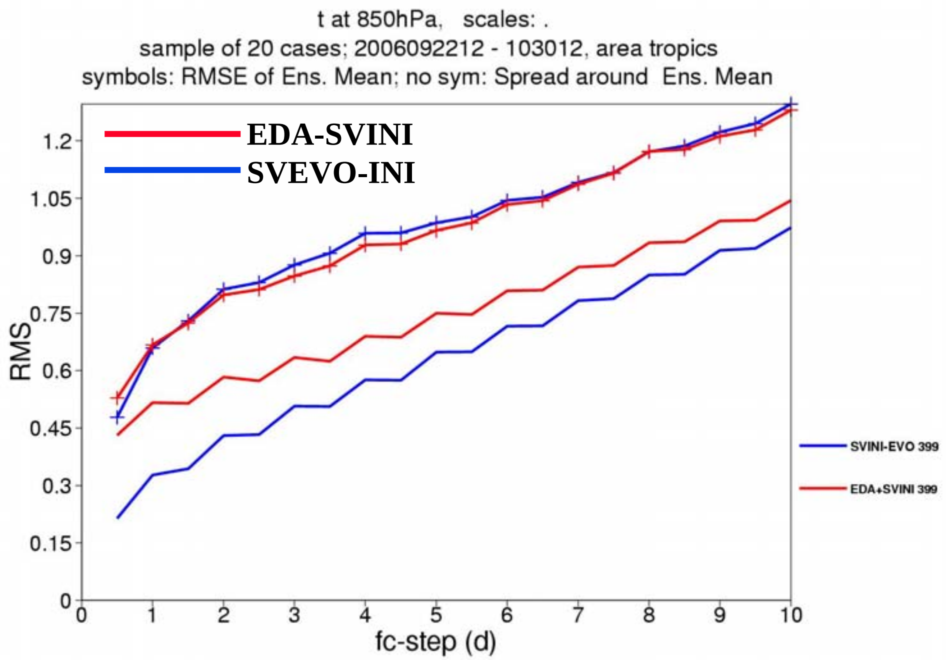


2.3 std/EM of EDA-SVINI and SVEVO-INI EPS

Over the NH (left), the two ensembles have similar spread (in terms of T850 std), and similar ensemble-mean error.

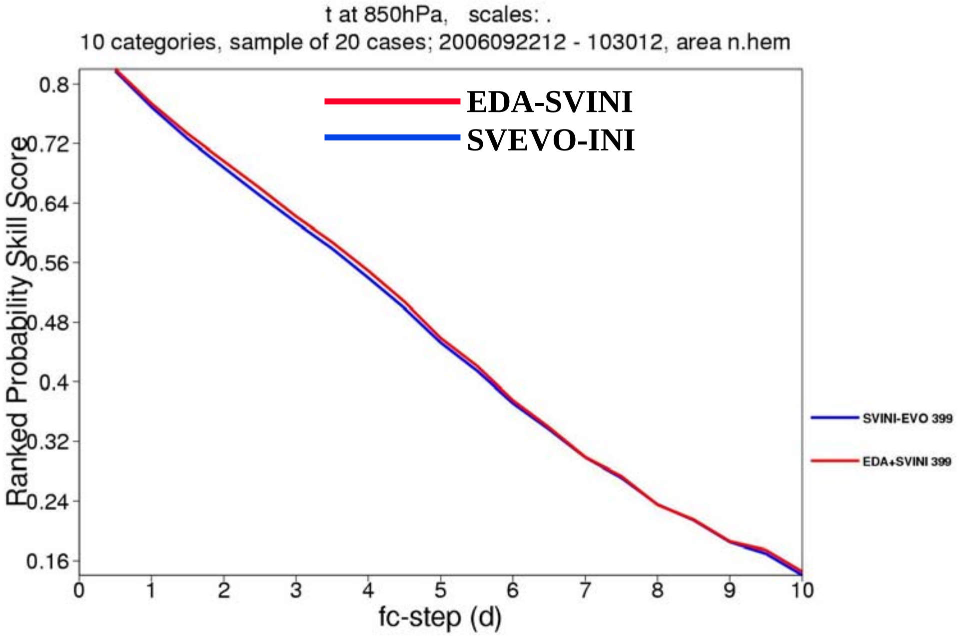
Over the Tropics (right), EDA-SVINI EPS has a larger spread (in terms of T850), closer to the error of the ensemble-mean, and a slightly smaller ensemble-mean error.

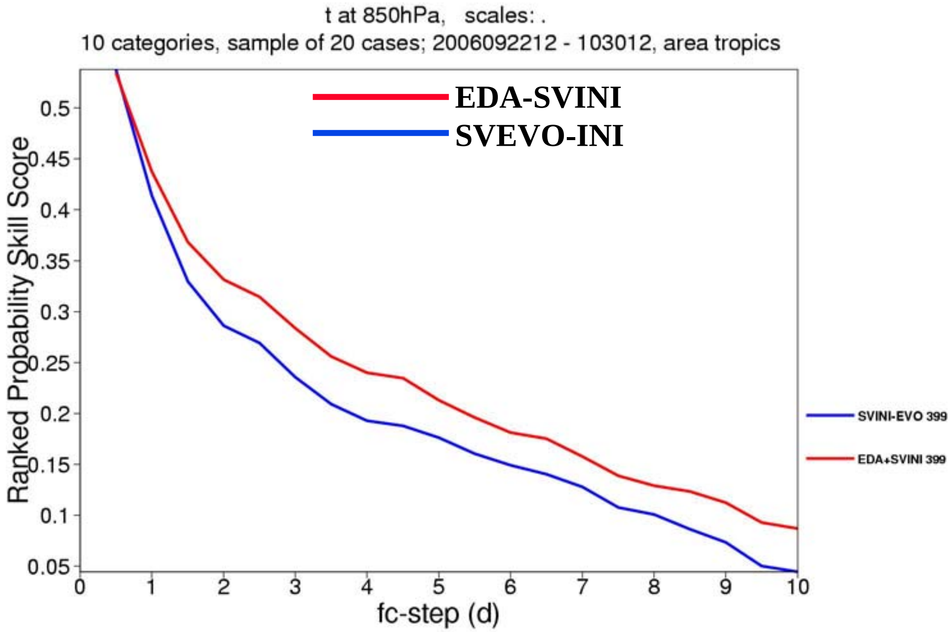




2.3 RPSS of EDA-SVINI and SVINI-EVO EPS

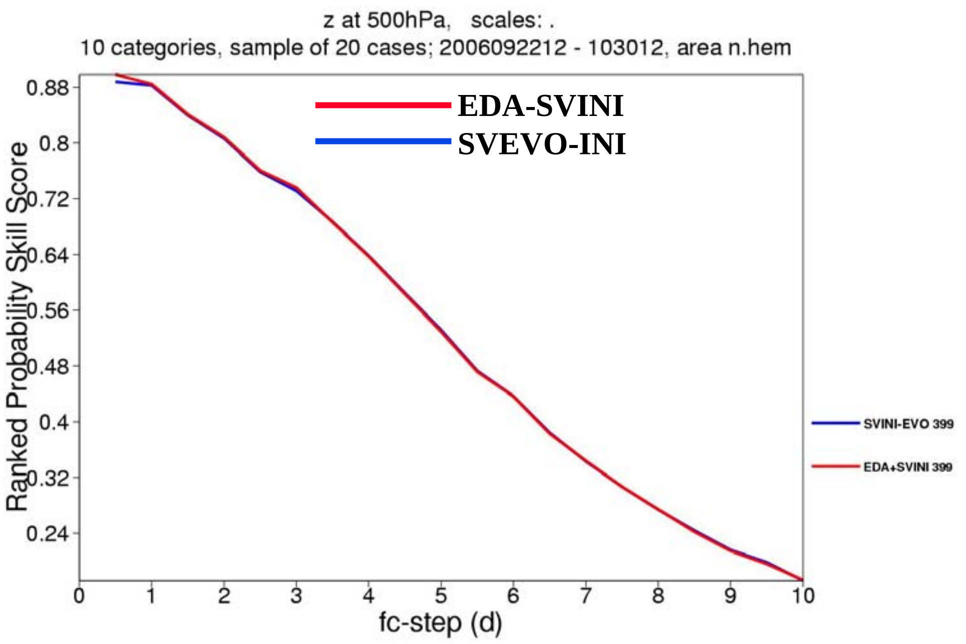
Over the NH (left), the EDA-SVINI ensemble has a higher RPSS for T850 probabilistic predictions. The difference is larger over the Tropics (right panel).

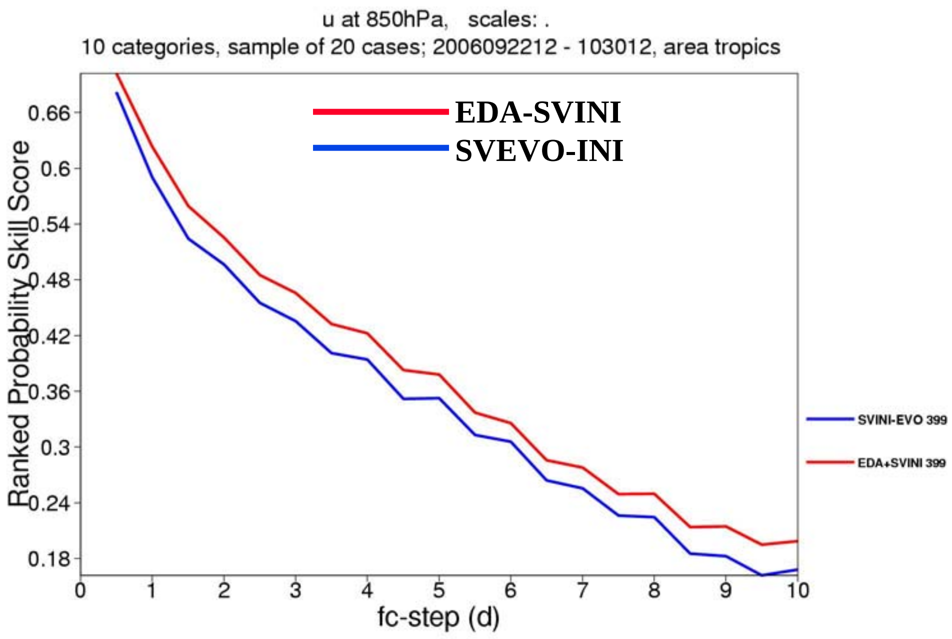




2.3 RPSS of EDA-SVINI and SVEVO-INI EPS

Over the NH (left), the EDA-SVINI ensemble has a higher RPSS for Z500 probabilistic predictions. The difference is larger over the Tropics for the probabilistic prediction of U850 (right panel).





2.4 Characteristics of the SPBS scheme

The SPectral stochastic kinetic-energy Backscatter Scheme (SPBS) has been designed to inject energy in regions of large dissipation, which are the regions of large model errors.

The key characteristics of SPBS are:

- *Stochastic:* autoregressive process for each spherical harmonic coefficient of stream-function forcing
- Spatial and temporal correlations
- Complete control over *scale-dependence*
- Prescribed slope of forcing kinetic energy spectrum
- Total injected kinetic energy is known
- *Flow-dependent* (weighting with dissipation rates)
- *Spectral*: consistent with spectral dynamical core
- *Isotropic* pattern on sphere
- Option to force divergence, temperature and pressure increments in balance with stream-function forcing

2.4 SPBS: recent results with T_L399L62 model

Rank Probability histograms for the extratropics and percentage of outliers in the Tropics are improved.