EMS, Madrid, 1-5 Oct 2007

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Wind power predictability: comparative study of forecasts with MM5 and WRF for Portuguese transmission system operator

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Goal

- Wind Power Forecast for TSO (Transmission System Operator)
  - Dispatching decisions (hourly basis)
  - Load scheduling strategy (daily basis)

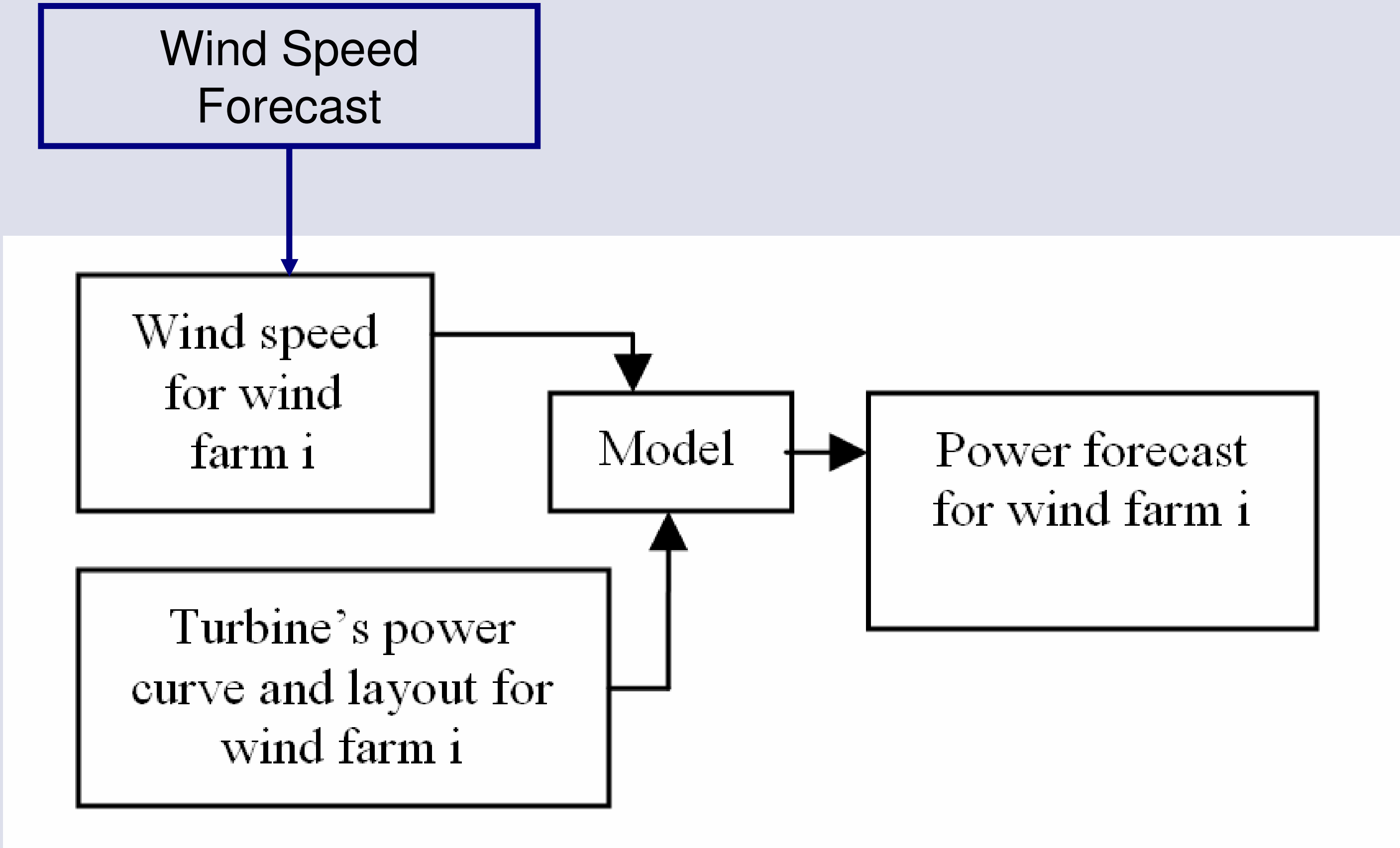
- Motivation
  - MM5 runs 4 times per day (00,06,12,18) with 72h lead time.
  - Best forecast?
  - Improvement of GFS 0.5º (40km) over 1º (80km)?
  - Improvement of WRF over MM5?

Presentation Outline

1. **Short Term Forecast (intra-daily)**
   - NWP + observations
   - NWP time lagged ensemble
2. **Medium Term Forecasts (daily)**
   - NWP time lagged ensemble
3. **Compare MM5 and WRF with GFS 1º and 0.5º resolution**

Observations from online wind parks and weather stations, for 1st semester 2007.

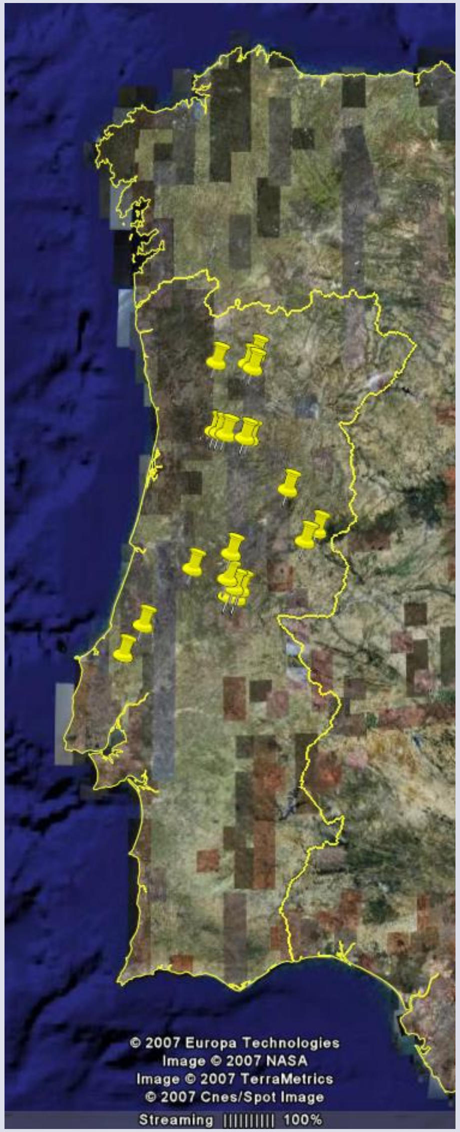
Transmission System Operator (TSO)



REN Power Forecast

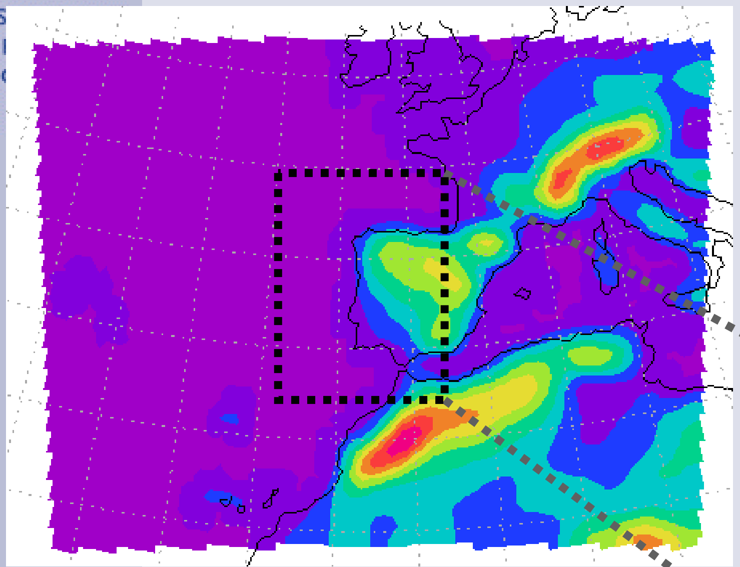
- Portugal:
  - 1 939 MW installed by July 2007 (147 parks).
  - 700 MW (13 parks) being telemeasured
  - 3 345 MW already licensed
- Persistence:
  - To improve short time scales
  - To correct initial numerical forecasts
- Plan Outages (wind farms, lines, …)

http://www.ren.pt/sections/exploracao/dpe/default.asp

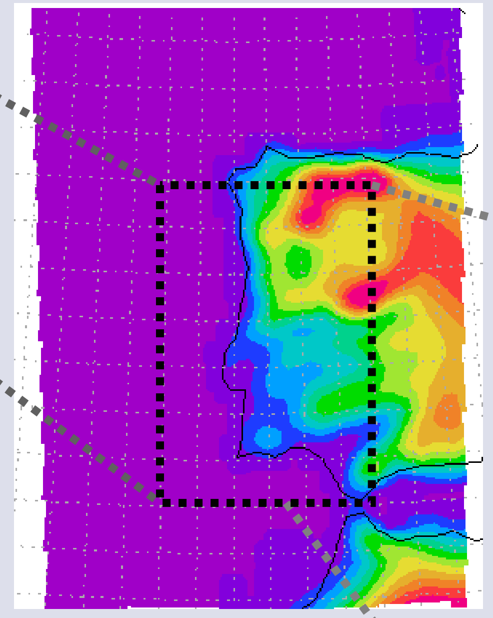


IST-MM5

http://meteo.ist.utl.pt
Operacional since 2000.
Online since 2001.

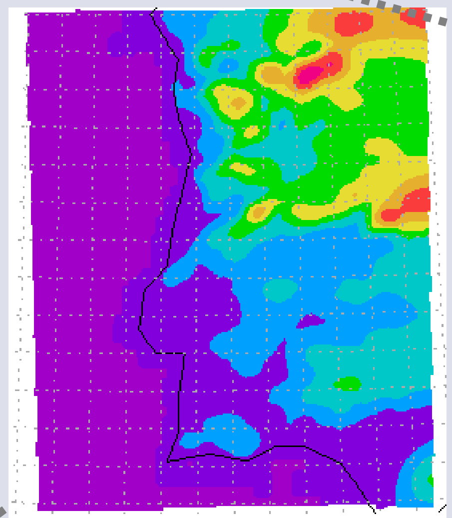


40x50
dx = 81 km



55x40
dx = 27 km

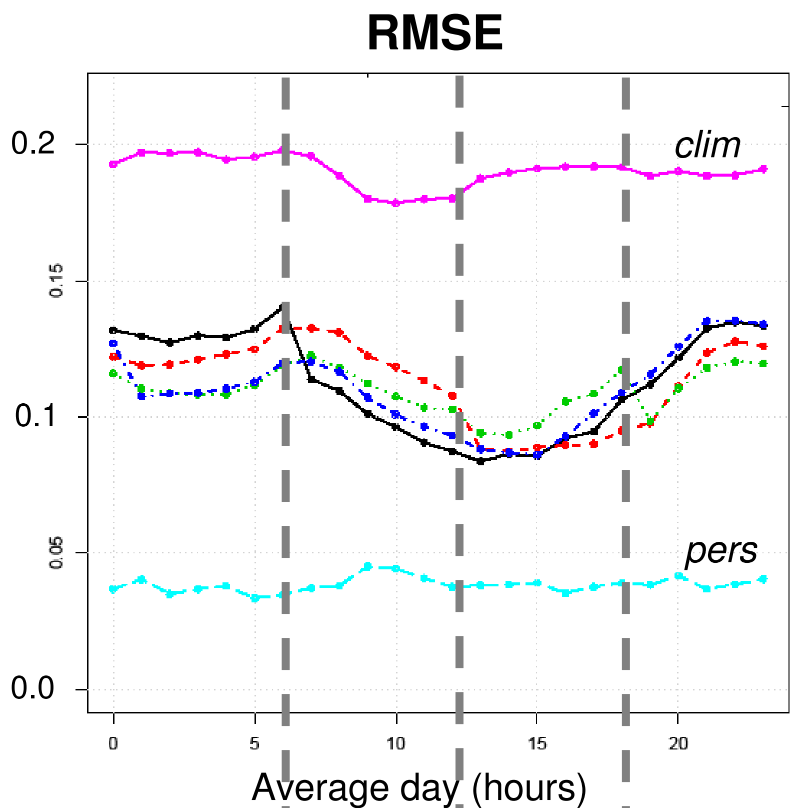
82x55
dx = 9 km

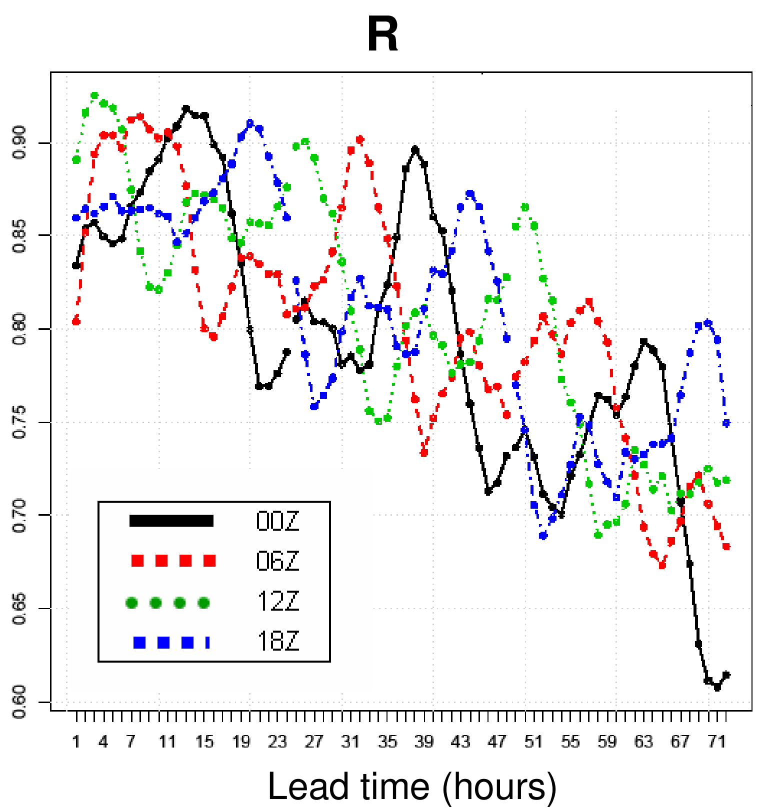


IST-MM5

- GFS initial and boundary conditions 1º resolution
- USGS topography
- 27 vertical levels
- Forecasts 72h, 4 times per day (00,06,12,18Z)

Compare MM5 (1º GFS) 4x day^{-1}





Smallest RMSE: ***18Z*** ***00Z*** ***06Z*** ***12Z***

6h 12h 18h

Within 24h, the best performance is achieved in **lead times from 6-12 h.**

RMSE increases with lead time, mainly due **phase errors** (↓ R)

Data set of ~700 MW for 1st semester 2007

Short Term Forecasts

- **S1** : Most recent available forecast (minimum lead time). Because each simulation takes about 5 hours to complete, we use lead times from 7 to 12 hours;

$$\hat{Y}_{t+i} = F_{t+i},$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Run	18Z						00Z						06Z						12Z					
HZ	7	8	9	10	11	12	7	8	9	10	11	12	7	8	9	10	11	12	7	8	9	10	11	12

- **S2** : Most recent available forecast combined with observations at t=0,6,12,18h, with linear weights.

$$\hat{Y}_{t+i} = (1 - \alpha_i)F_{t+i} + \alpha_i Y_{t+6},$$

$$t \in \{0, 6, 12, 18\}$$
$$i \in \{7, \ldots, 12\}$$
$$\alpha \in \{0.9, \ldots, 0.1\}$$

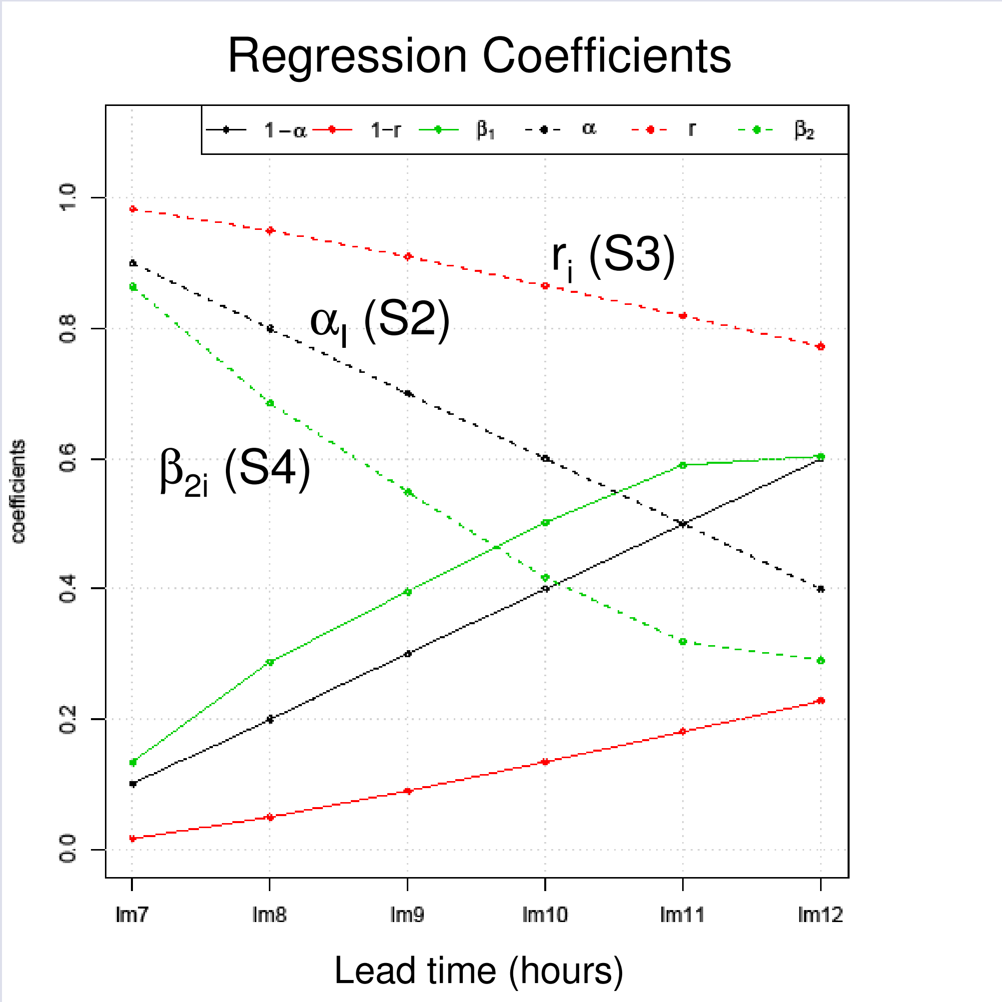
- **S3** : Most recent available forecast combined with observations at t=0,6,12,18h, with weights from autocorrelation function *r*.

$$\hat{Y}_{t+i} = (1 - r_{i-5})F_{t+i} + r_{i-5}Y_{t+6},$$

- **S4** : Most recent available forecast combined with observations at t=0,6,12,18h, with weights from LS regression

$$Y_{t+i} = \beta_{0,i} + \beta_{1,i}F_{t+i} + \beta_{2,i}Y_t$$

Short Term Forecasts



Coefficients in S2 (**black**) and S3 (**red**) forecast give more weight to the past observed values and less weight to NWP model than S4 weights (**green**).

S2 $\hat{Y}_{t+i} = (1-\alpha_i)F_{t+i} + \alpha_i Y_{t+6},$

S3 $\hat{Y}_{t+i} = (1-r_{i-5})F_{t+i} + r_{i-5} Y_{t+6},$

S4 $Y_{t+i} = \beta_{0,i} + \beta_{1,i}F_{t+i} + \beta_{2,i}Y_t$

Data set of ~700 MW for 1st trimester 2007

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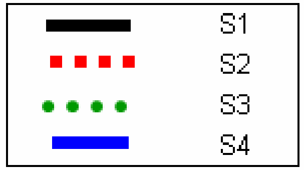
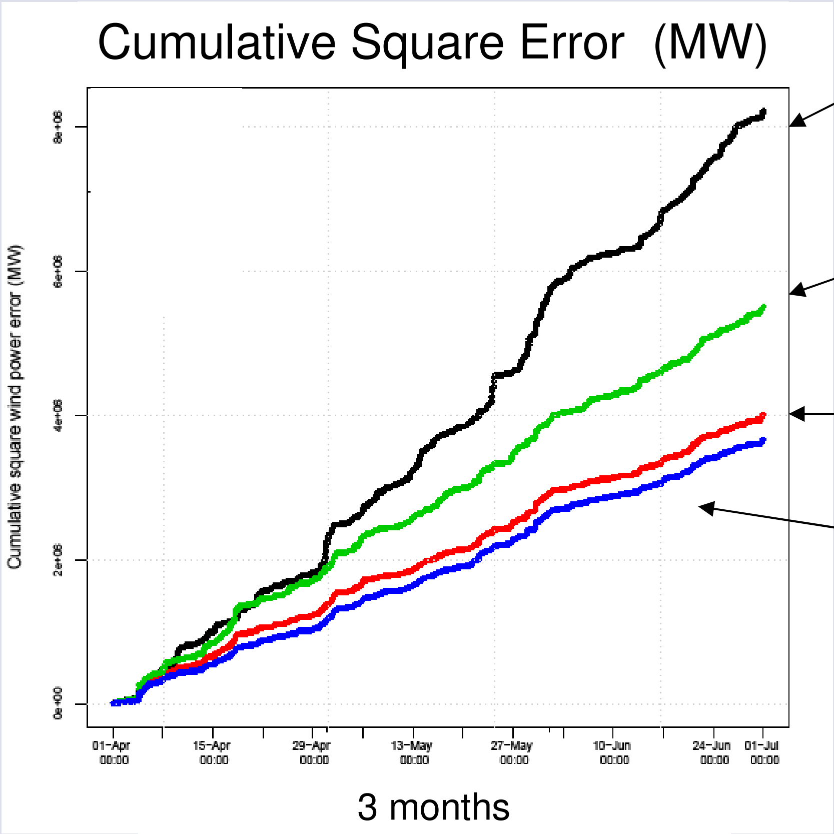
Short Term Forecasts





S1 (only NWP forecast)

S3 (weights from ACF)

S2 (linear weights)

S4 (LS regression weigths)

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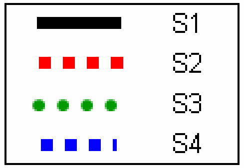
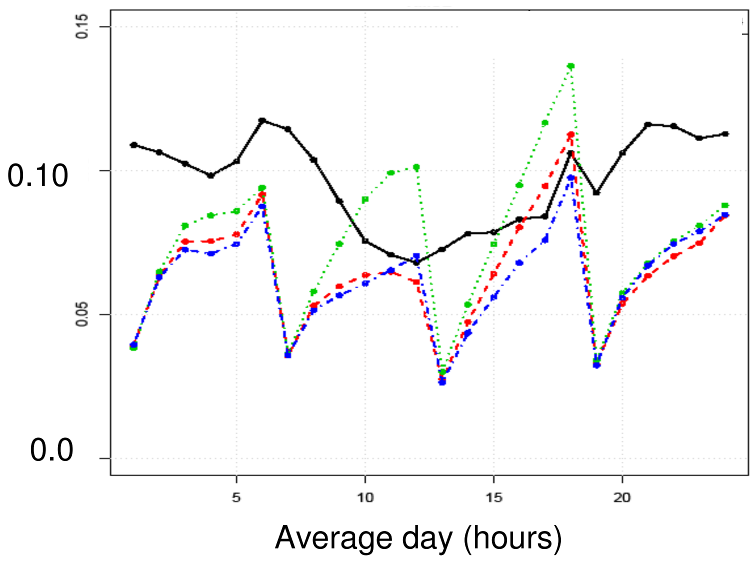
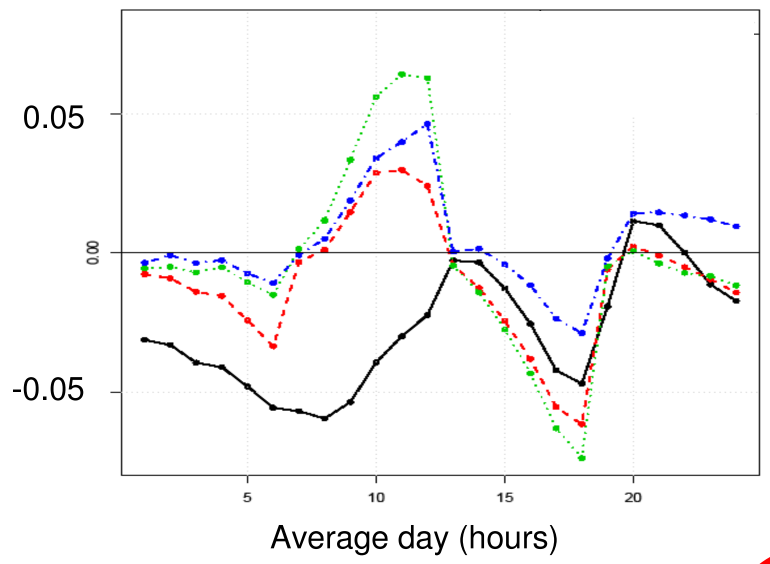
Short Term Forecasts



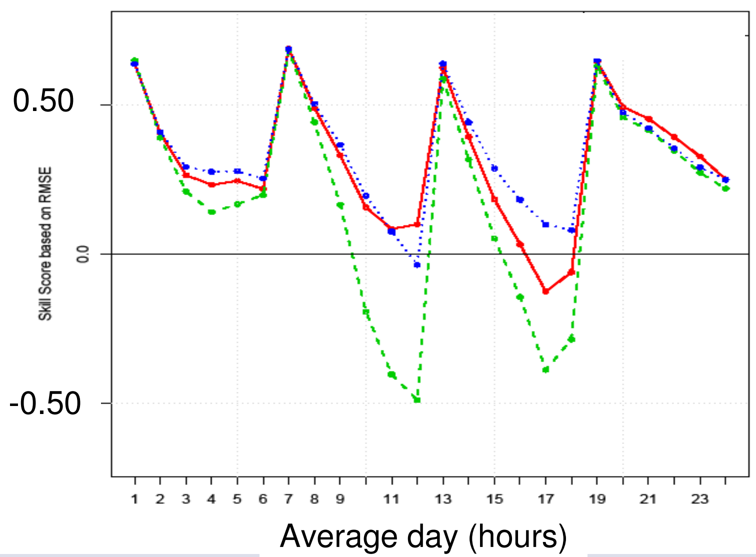
RMSE



BIAS



Skill Score



	S1	S2	S3	S4
RMSE	9.8%	6.8%	8.0%	6.5%
SS	-	30%	18%	33%

Data set of ~700 MW for 2nd trimester 2007

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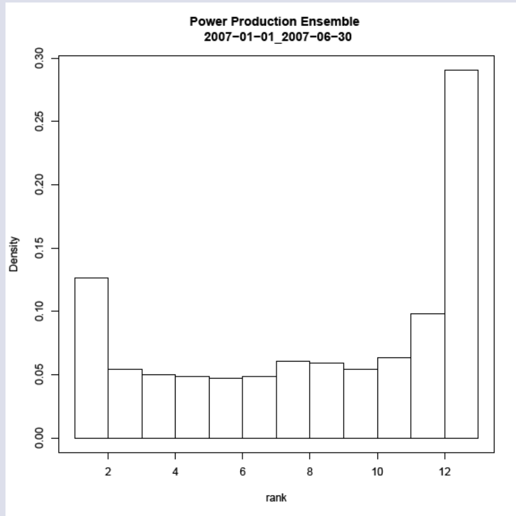
Time Lagged Ensemble

- There are 11 available forecasts for each hours and each site.
- **Can we improve the most recent forecast (S1)?**
  - Mean Ensemble (equal weights)
  - Stepwise Multilinear Regression (step.reg)
  - Principal Components Regression (PCR)
  - Partial Least Squares Regressiom (PLSR)

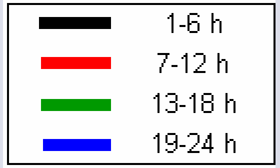


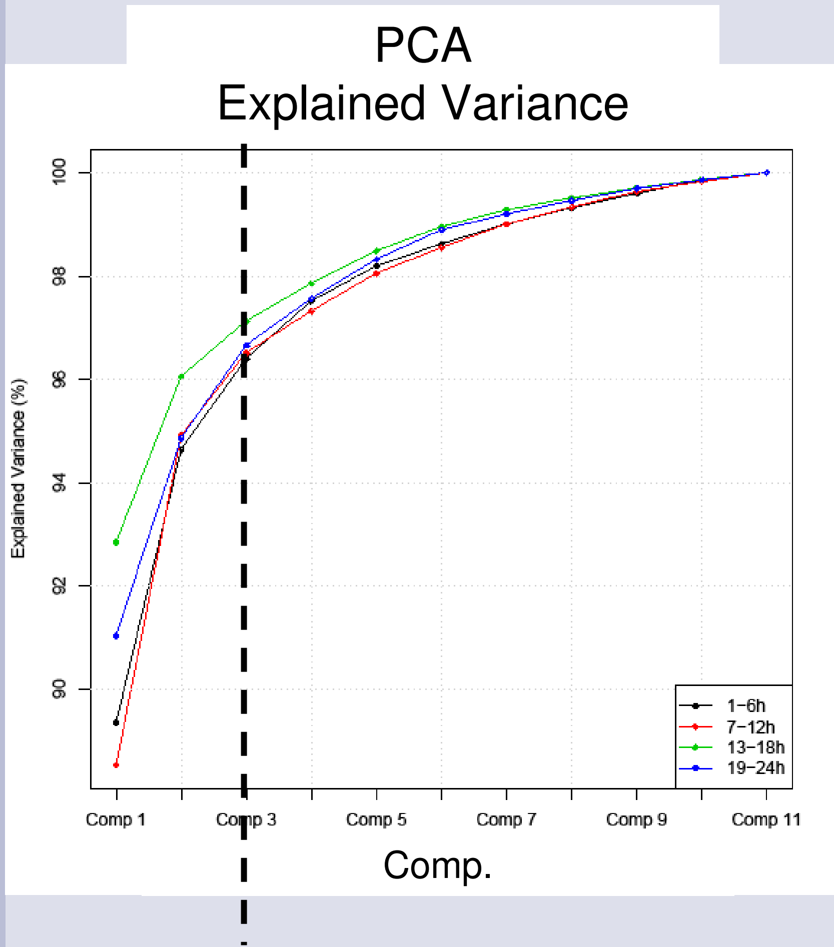
Members are not dispersive and tend to underestimate observations

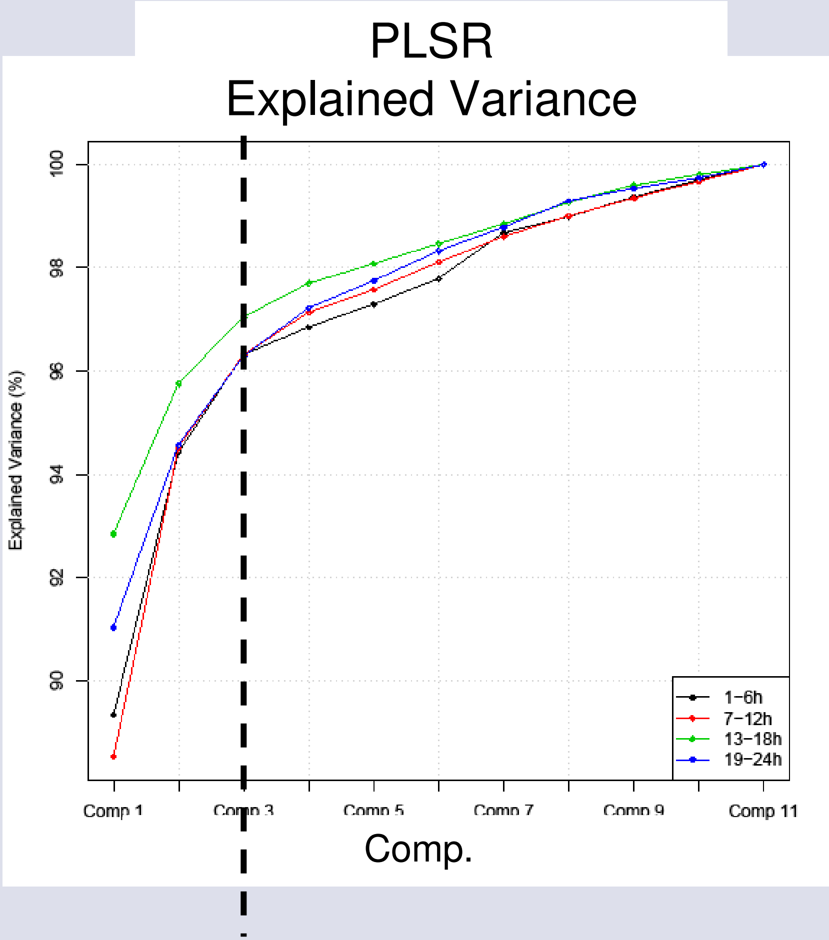
Day 0 – available forecasts

Day 0 Ensemble 00 (11 members)						Ensemble 06 (11 members)						Ensemble 12 (11 members)						Ensemble 18 (11 members)					
1	2	3	4	5	**6**	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
06d2 67	06d2 68	06d2 69	06d2 70	06d2 71	**06d2 72**																		
12d2 61	12d2 62	12d2 63	12d2 64	12d2 65	**12d2 66**	12d2 67	12d2 68	12d2 69	12d2 70	12d2 71	12d2 72												
18d2 55	18d2 56	18d2 57	18d2 58	18d2 59	**18d2 60**	18d2 61	18d2 62	18d2 63	18d2 64	18d2 65	18d2 66	18d2 67	18d2 68	18d2 69	18d2 70	18d2 71	18d2 72						
00d2 49	00d2 50	00d2 51	00d2 52	00d2 53	**00d2 54**	00d2 55	00d2 56	00d2 57	00d2 58	00d2 59	00d2 60	00d2 61	00d2 62	00d2 63	00d2 64	00d2 65	00d2 66	00d2 67	00d2 68	00d2 69	00d2 70	00d2 71	00d2 72
06d1 43	06d1 44	06d1 45	06d1 46	06d1 47	**06d1 48**	06d2 49	06d2 50	06d2 51	06d2 52	06d2 53	06d2 54	06d2 55	06d2 56	06d2 57	06d2 58	06d2 59	06d2 60	06d2 61	06d2 62	06d2 63	06d2 64	06d2 65	06d2 66
12d1 37	12d1 38	12d1 39	12d1 40	12d1 41	**12d1 42**	12d1 43	12d1 44	12d1 45	12d1 46	12d1 47	12d1 48	12d2 49	12d2 50	12d2 51	12d2 52	12d2 53	12d2 54	12d2 55	12d2 56	12d2 57	12d2 58	12d2 59	12d2 60
18d1 31	18d1 32	18d1 33	18d1 34	18d1 35	**18d1 36**	18d1 37	18d1 38	18d1 39	18d1 40	18d1 41	18d1 42	18d1 43	18d1 44	18d1 45	18d1 46	18d1 47	18d1 48	18d2 49	18d2 50	18d2 51	18d2 52	18d2 53	18d2 54
00d1 25	00d1 26	00d1 27	00d1 28	00d1 29	**00d1 30**	00d1 31	00d1 32	00d1 33	00d1 34	00d1 35	00d1 36	00d1 37	00d1 38	00d1 39	00d1 40	00d1 41	00d1 42	00d1 43	00d1 44	00d1 45	00d1 46	00d1 47	00d1 48
06d0 19	06d0 20	06d0 21	06d0 22	06d0 23	**06d0 24**	06d1 25	06d1 26	06d1 27	06d1 28	06d1 29	06d1 30	06d1 31	06d1 32	06d1 33	06d1 34	06d1 35	06d1 36	06d1 37	06d1 38	06d1 39	06d1 40	06d1 41	06d1 42
12d0 13	12d0 14	12d0 15	12d0 16	12d0 17	**12d0 18**	12d0 19	12d0 20	12d0 21	12d0 22	12d0 23	12d0 24	12d1 25	12d1 26	12d1 27	12d1 28	12d1 29	12d1 30	12d1 31	12d1 32	12d1 33	12d1 34	12d1 35	12d1 36
18d0 7	18d0 8	18d0 9	18d0 10	18d0 11	**18d0 12**	18d0 13	18d0 14	18d0 15	18d0 16	18d0 17	18d0 18	18d0 19	18d0 20	18d0 21	18d0 22	18d0 23	18d0 24	18d1 25	18d1 26	18d1 27	18d1 28	18d1 29	18d1 30
~~00d0 1~~	~~00d0 2~~	~~00d0 3~~	~~00d0 4~~	~~00d0 5~~	**~~00d0 6~~**	00d0 7	00d0 8	00d0 9	00d0 10	00d0 11	00d0 12	00d0 13	00d0 14	00d0 15	00d0 16	00d0 17	00d0 18	00d0 19	00d0 20	00d0 21	00d0 22	00d0 23	00d0 24
						~~06d0 1~~	~~06d0 2~~	~~06d0 3~~	~~06d0 4~~	~~06d0 5~~	~~06d0 6~~	06d0 7	06d0 8	06d0 9	06d0 10	06d0 11	06d0 12	06d0 13	06d0 14	06d0 15	06d0 16	06d0 17	06d0 18
												~~12d0 1~~	~~12d0 2~~	~~12d0 3~~	~~12d0 4~~	~~12d0 5~~	~~12d0 6~~	12d0 7	12d0 8	12d0 9	12d0 10	12d0 11	12d0 12
																		~~18d0 1~~	~~18d0 2~~	~~18d0 3~~	~~18d0 4~~	~~18d0 5~~	~~18d0 6~~

Components Regression



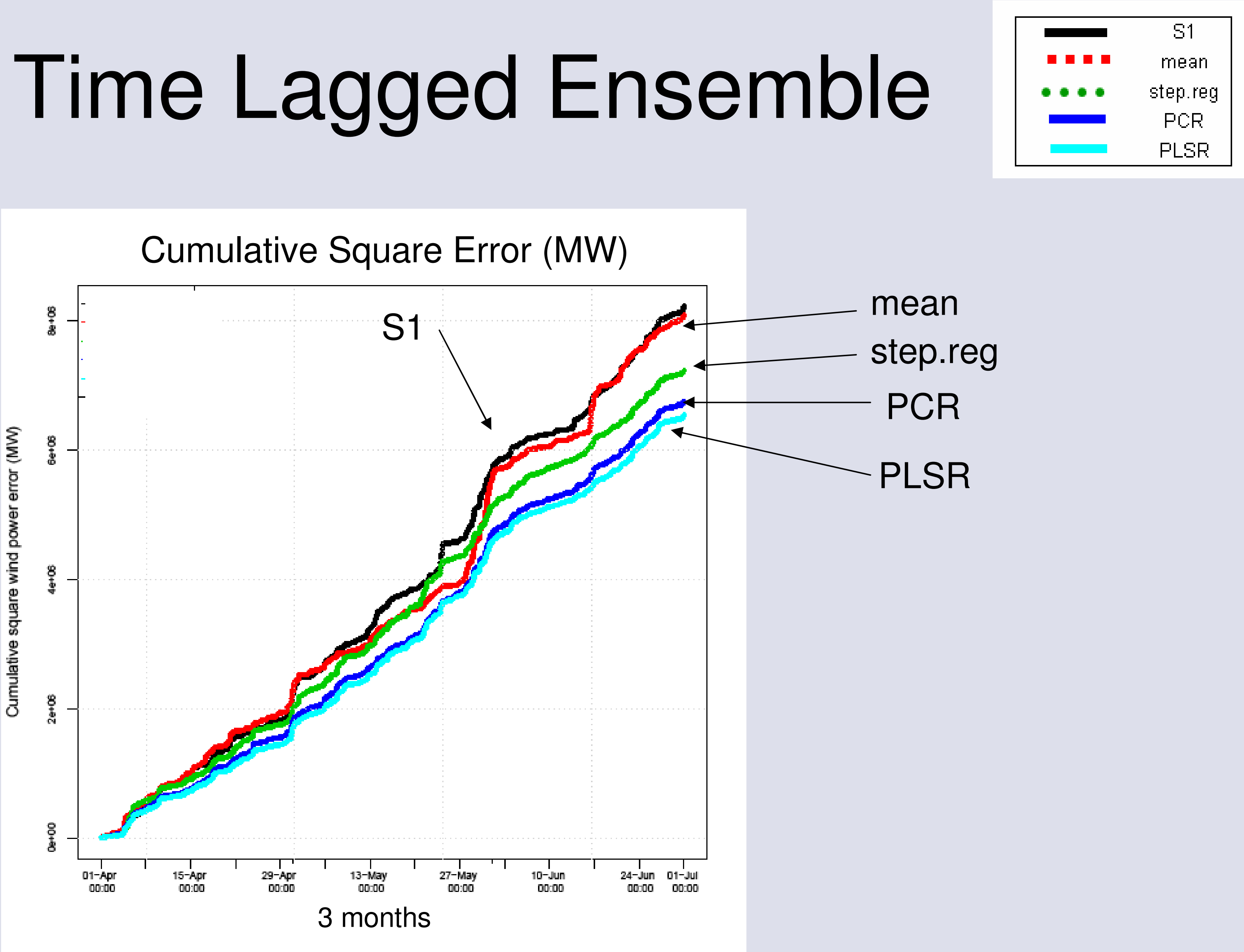




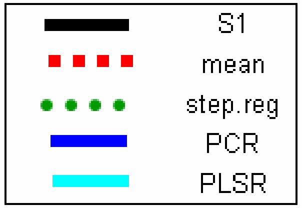
3 components explain > 96% of variance

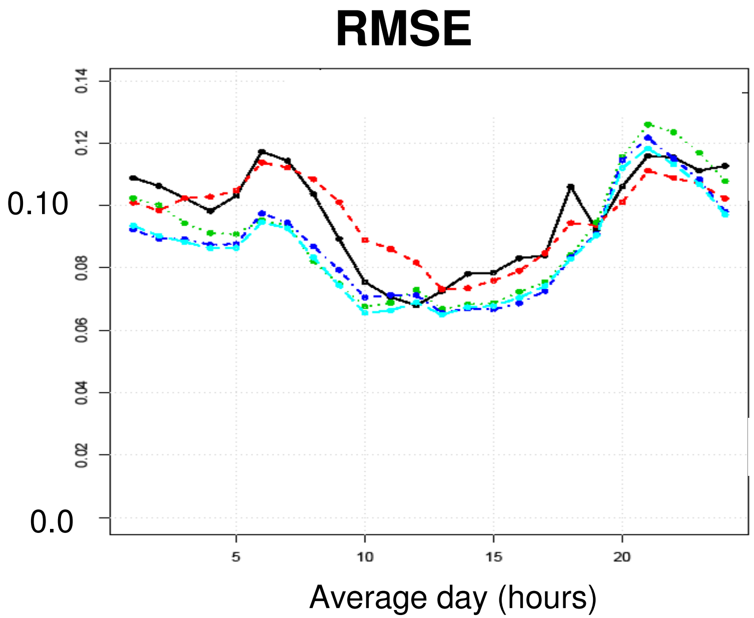
Data set of ~700 MW for 1st trimester 2007

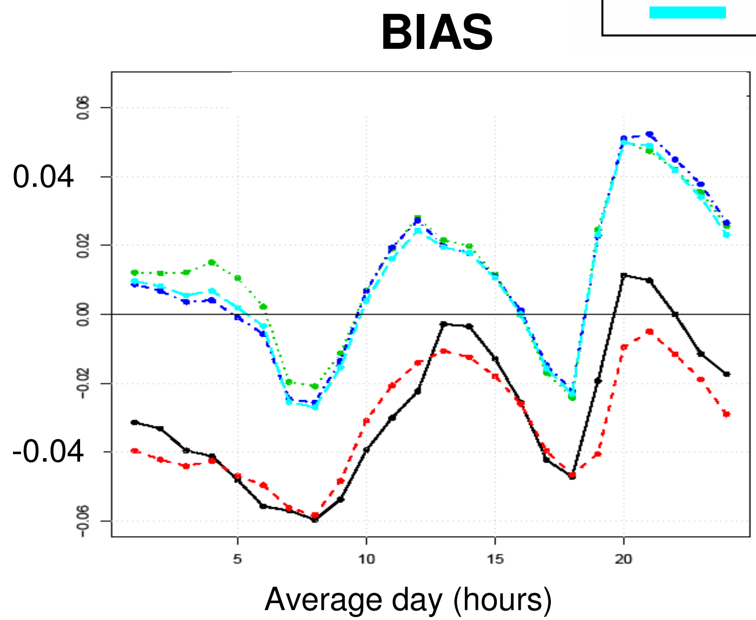
Time Lagged Ensemble

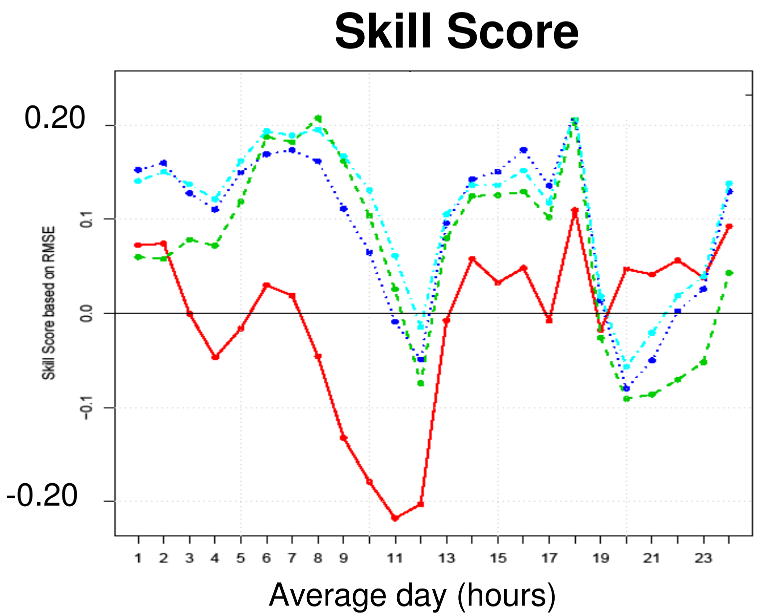


Time Lagged Ensemble









	RMSE	SS
S1	9.8%	-
mean	9.7%	1%
step.reg	9.2%	6%
PCR	8.9%	9%
PLSR	8.7%	11%

Data set of ~700 MW for 2nd trimester 2007

Medium Range Forecasts

- Forecasts for the next 2 days
- Need to be ready at 6 a.m. (day 0)

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Day 1 – available forecasts

Day 1																							
Ensemble 00 (8 members)						Ensemble 06 (7 members)						Ensemble 12 (6 members)						Ensemble 18 (5 members)					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
06d2 67	06d2 68	06d2 69	06d2 70	06d2 71	06d2 72																		
12d2 61	12d2 62	12d2 63	12d2 64	12d2 65	12d2 66	12d2 67	12d2 68	12d2 69	12d2 70	12d2 71	12d2 72												
18d2 55	18d2 56	18d2 57	18d2 58	18d2 59	18d2 60	18d2 61	18d2 62	18d2 63	18d2 64	18d2 65	18d2 66	18d2 67	18d2 68	18d2 69	18d2 70	18d2 71	18d2 72						
00d2 49	00d2 50	00d2 51	00d2 52	00d2 53	00d2 54	00d2 55	00d2 56	00d2 57	00d2 58	00d2 59	00d2 60	00d2 61	00d2 62	00d2 63	00d2 64	00d2 65	00d2 66	00d2 67	00d2 68	00d2 69	00d2 70	00d2 71	00d2 72
06d1 43	06d1 44	06d1 45	06d1 46	06d1 47	06d1 48	06d2 49	06d2 50	06d2 51	06d2 52	06d2 53	06d2 54	06d2 55	06d2 56	06d2 57	06d2 58	06d2 59	06d2 60	06d2 61	06d2 62	06d2 63	06d2 64	06d2 65	06d2 66
12d1 37	12d1 38	12d1 39	12d1 40	12d1 41	12d1 42	12d1 43	12d1 44	12d1 45	12d1 46	12d1 47	12d1 48	12d2 49	12d2 50	12d2 51	12d2 52	12d2 53	12d2 54	12d2 55	12d2 56	12d2 57	12d2 58	12d2 59	12d2 60
18d1 31	18d1 32	18d1 33	18d1 34	18d1 35	18d1 36	18d1 37	18d1 38	18d1 39	18d1 40	18d1 41	18d1 42	18d1 43	18d1 44	18d1 45	18d1 46	18d1 47	18d1 48	18d2 49	18d2 50	18d2 51	18d2 52	18d2 53	18d2 54
00d1 25	00d1 26	00d1 27	00d1 28	00d1 29	00d1 30	00d1 31	00d1 32	00d1 33	00d1 34	00d1 35	00d1 36	00d1 37	00d1 38	00d1 39	00d1 40	00d1 41	00d1 42	00d1 43	00d1 44	00d1 45	00d1 46	00d1 47	00d1 48

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Day 2 – available forecasts

Day 2 Ensemble 00 (4 members)						Ensemble 06 (3 members)						Ensemble 12 (2 members)						Ensemble 18 (1 members)					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
06d2 67	06d2 68	06d2 69	06d2 70	06d2 71	06d2 72																		
12d2 61	12d2 62	12d2 63	12d2 64	12d2 65	12d2 66	12d2 67	12d2 68	12d2 69	12d2 70	12d2 71	12d2 72												
18d2 55	18d2 56	18d2 57	18d2 58	18d2 59	18d2 60	18d2 61	18d2 62	18d2 63	18d2 64	18d2 65	18d2 66	18d2 67	18d2 68	18d2 69	18d2 70	18d2 71	18d2 72						
00d2 49	00d2 50	00d2 51	00d2 52	00d2 53	00d2 54	00d2 55	00d2 56	00d2 57	00d2 58	00d2 59	00d2 60	00d2 61	00d2 62	00d2 63	00d2 64	00d2 65	00d2 66	00d2 67	00d2 68	00d2 69	00d2 70	00d2 71	00d2 72

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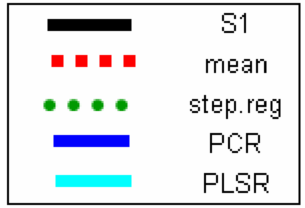
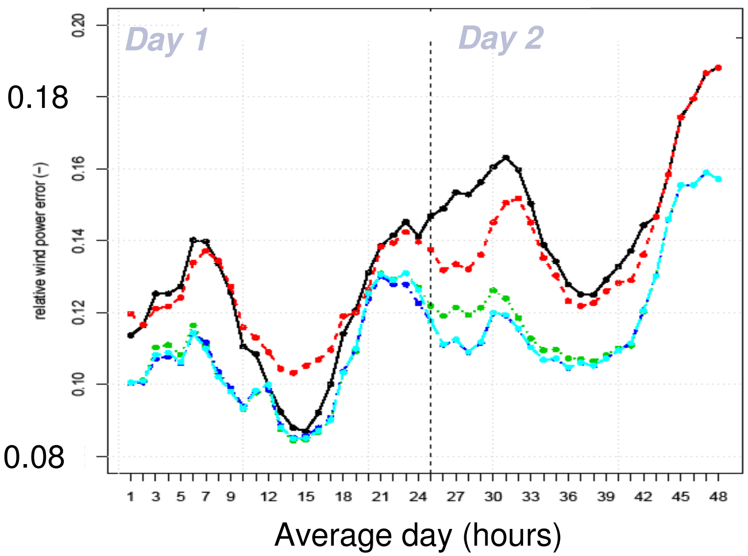
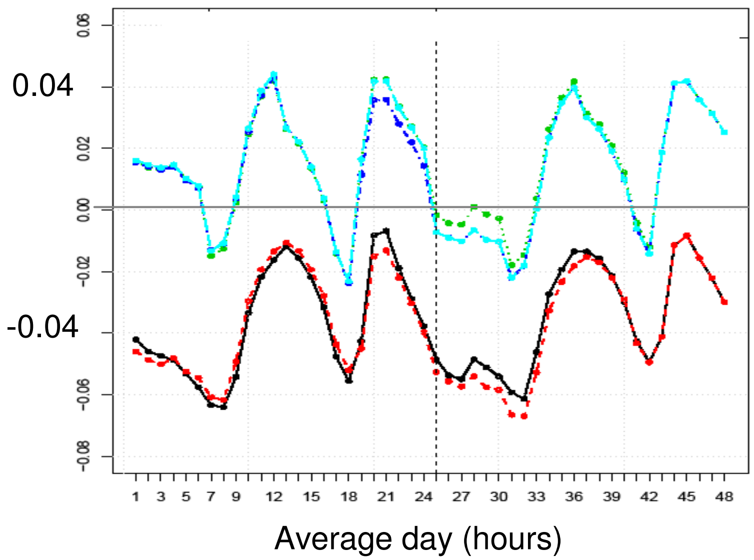
Medium Range Forecasts



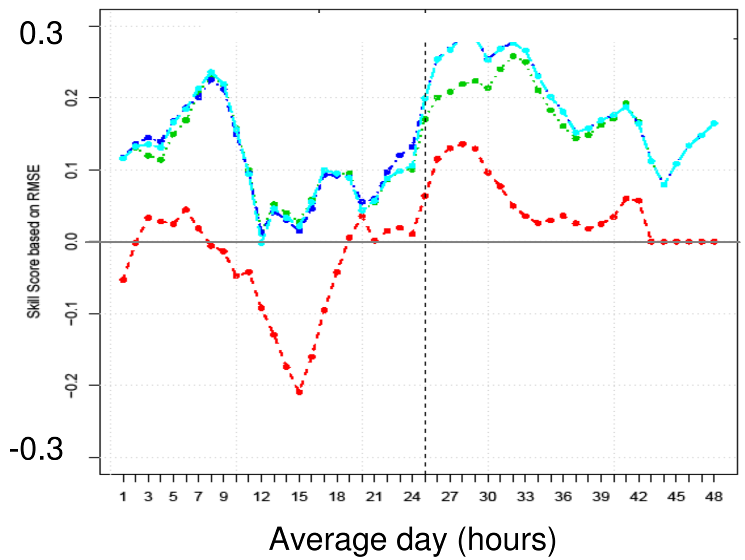
RMSE



BIAS



Skill Score



M1 = 00Z with HZ = 25 - 72 h

Day 1	M1	mean	step.reg	pcr3	plsr3
RMSE	12.0%	12.3%	10.7%	10.6%	10.6%
SS	-	-2%	11%	12%	12%

Day 2	M1	mean	step.reg	pcr1	plsr1
RMSE	15.2%	14.5%	12.5%	12.3%	12.3%
SS	-	5%	18%	19%	19%

Data set of ~700 MW for 2nd trimester 2007

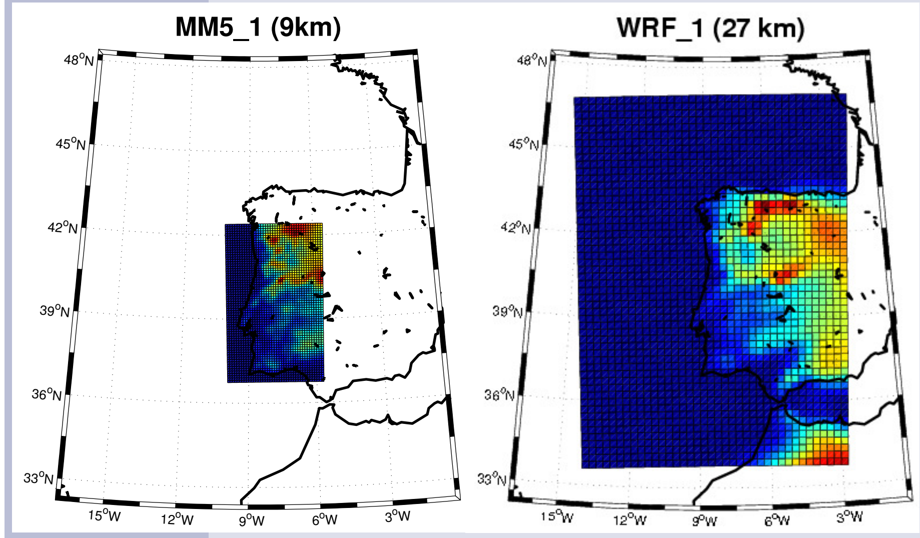
Compare GFS Resolution

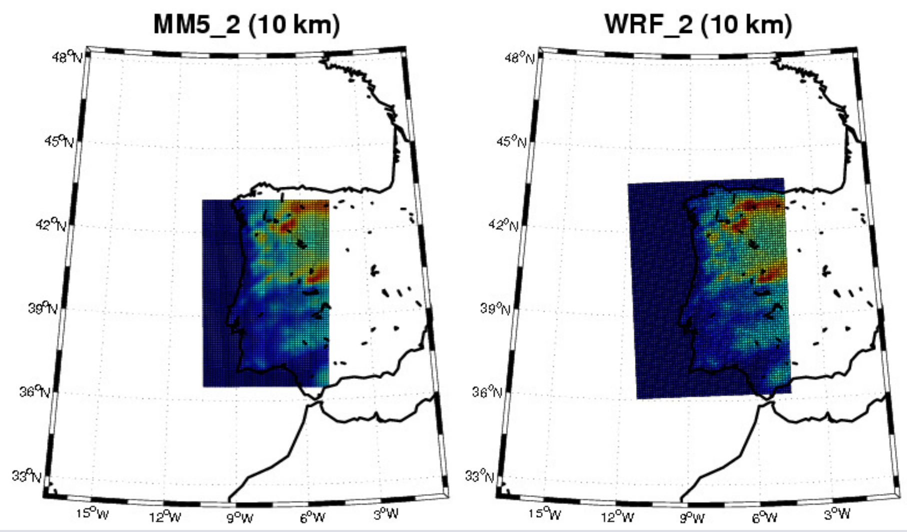
- Compare 00Z simulations
- 6 < HZ <= 30 hours (1st 6-hours are not forecast)
- BC updated in 3h intervals

- $MM5_1$ & WRF_1 (GFS 1º resolution)
- $MM5_2$ & WFR_2 (GFS 0.5º resolution)

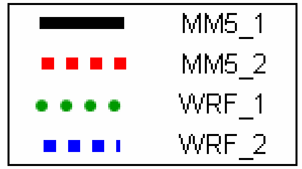
GFS Resolution – Domains

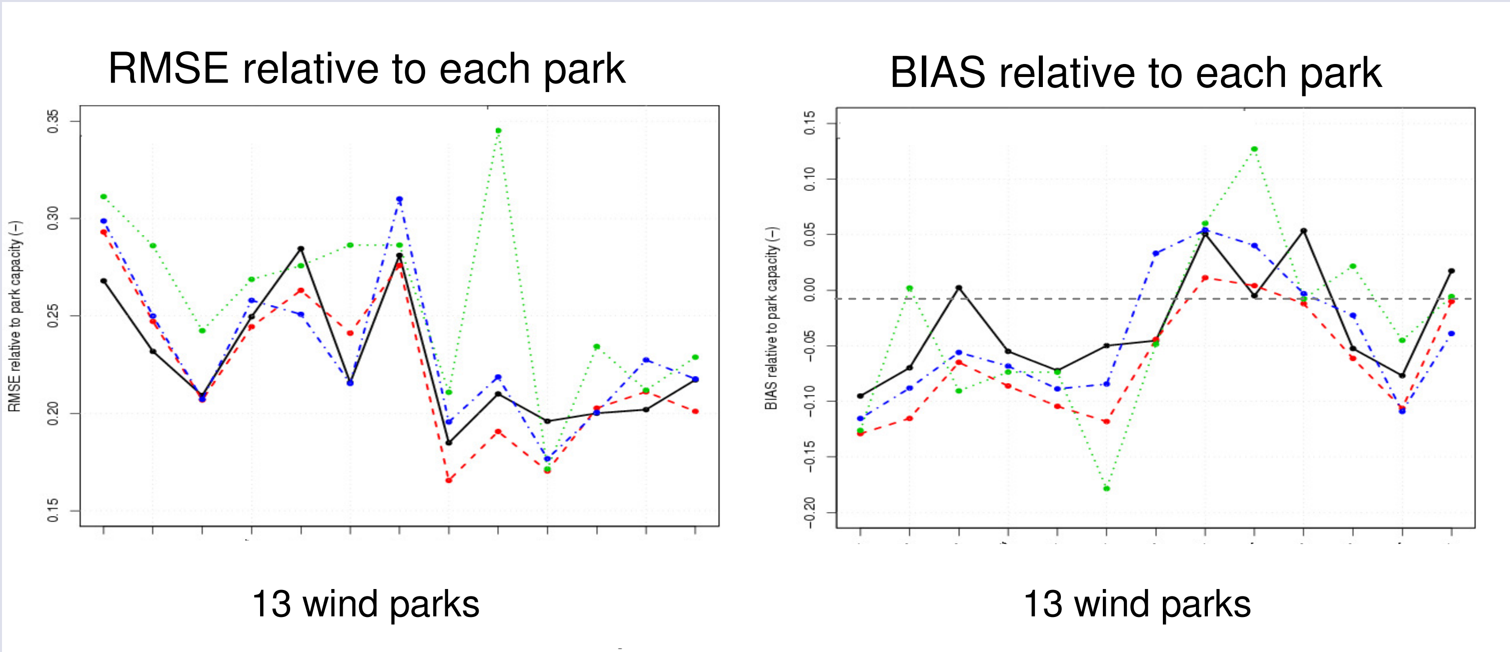
	D1	D2	D3
MM5_1	81 km (31x31)	27 km (43x31)	9 km (70x43)
WRF_1	81 km (50x40)	27 km (55x40)	-
MM5_2	-	27 km (55x40)	9 km (82x25)
WRF_2	-	30 km (81x81)	10 km (85x61)





GFS Resolution – Parks





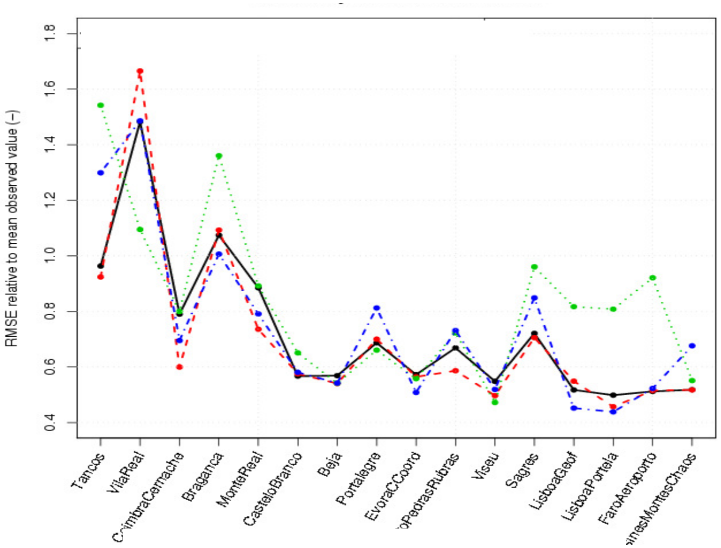
Parks are ordered by power capacity

	RMSE (-)	SS
MM5_1	2.41%	-
MM5_2	2.38%	2%
WRF_1	2.65%	-10%
WRF_2	2.49%	-3%

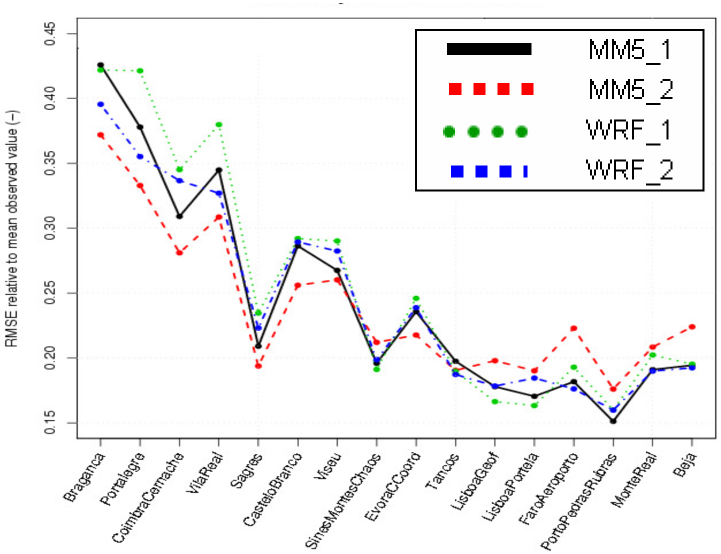
Data set of ~700 MW for 1st trimester 2007

GFS Resolution – Stations (**RMSE**)

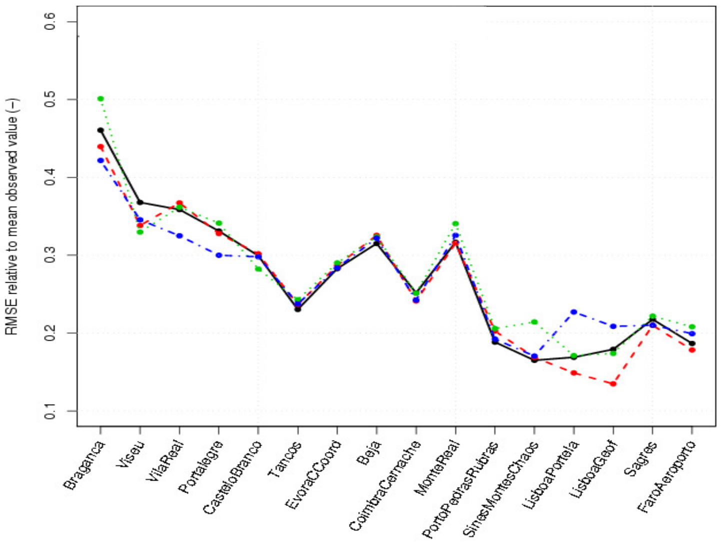
Wind speed at 10m



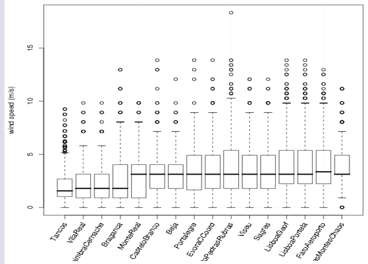
RH at 2m



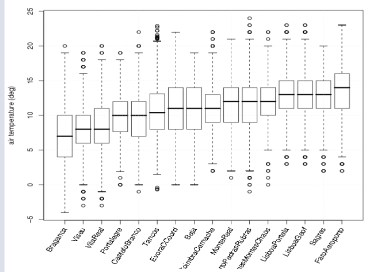
Air temperature at 2m



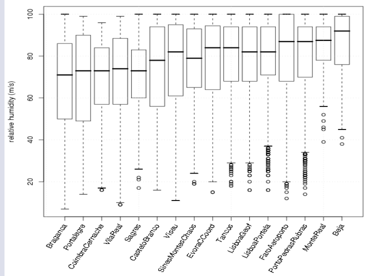
Wind speed at 10m



Air temperature 2m



Rel Hum. at 2m



Stations are ordered by mean observed value

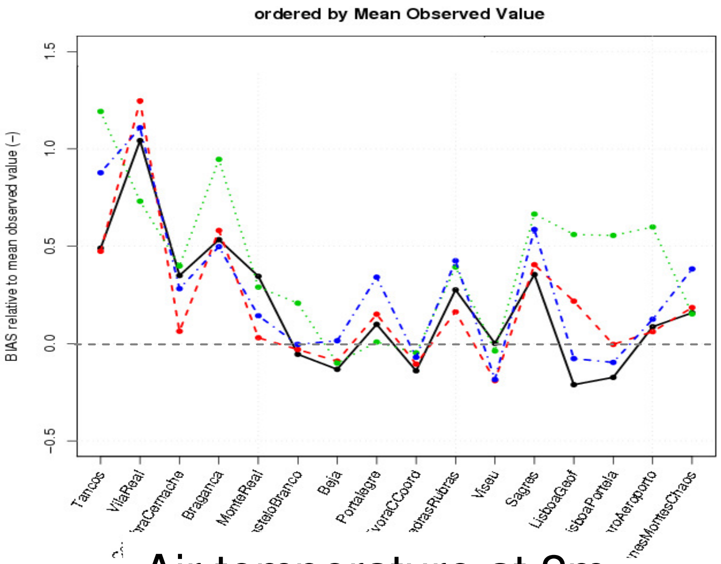
RMSE	MM5_1	MM5_2	WRF_1	WRF_2
WS (m/s)	2.22	2.15	2.60	2.28
T (deg)	2.78	2.71	2.88	2.81
HR (%)	18.27	18.07	19.05	18.28

SS	MM5_1	MM5_2	WRF_1	WRF_2
WS (m/s)	-	3%	-17%	-3%
T (deg)	-	2%	-4%	-1%
HR (%)	-	1%	-4%	0%

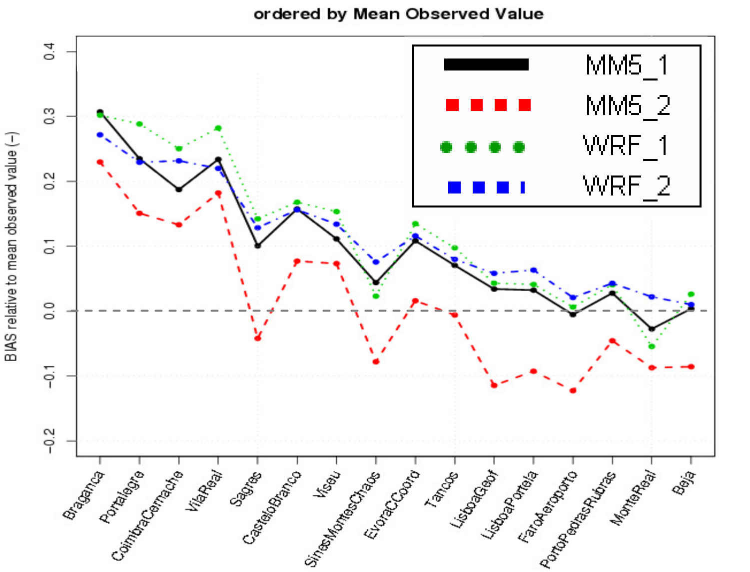
Data set from Wunderground for 1st trimester 2007

GFS Resolution – Stations (**BIAS**)

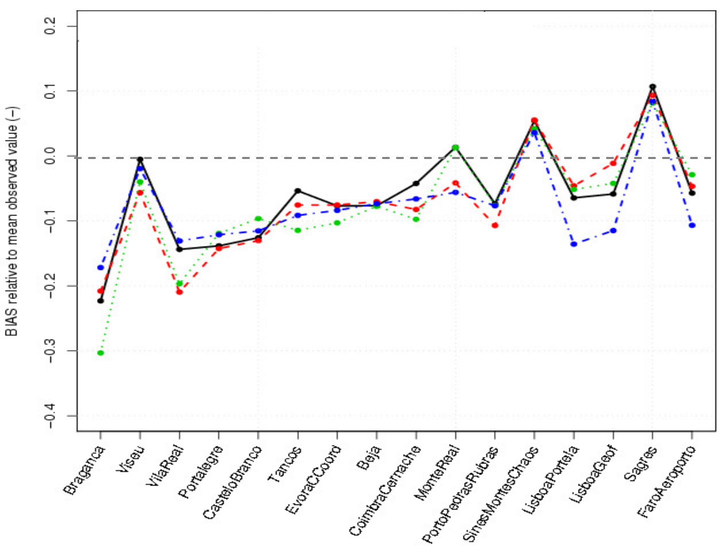
Wind speed at 10m



RH at 2m



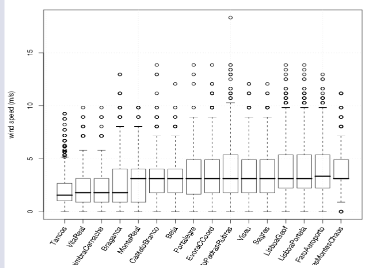
Air temperature at 2m



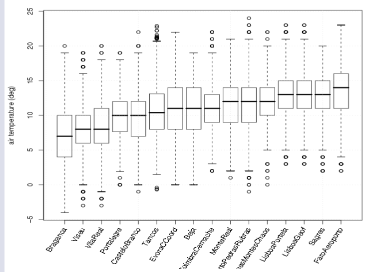
Stations are ordered by mean observed value

- MM5_2 does not underestimate RH as much as the other models
- Higher amplitude errors for high mean temperature sites, which are in this case the farthest away from the Sea.

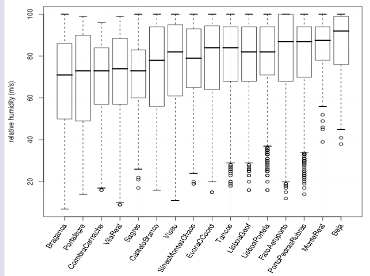
Wind speed at 10m



Air temperature 2m



Rel Hum. at 2m



Data set from Wunderground for 1st trimester 2007

Conclusions

	RMSE ref	RMSE best	SS
Short Term with data	10%	7%	33%
Short Term witout data	10%	9%	11%
Medium Term Day 1	12%	11%	12%
Medium Term Day 2	15%	12%	19%

- Persistence is good to forecast wind power up to 6h (33%), but can go against diurnal cycle if not updated regularly.

- When there is no online data, improved forecast can be obtained with regressions from the time lagged ensemble (11%, 12% and 19% for days 0,1,2), but these regressions do not improve phase errors.

- The current configuration (MM5 with 1º GFS resolution) is:
  – Less skilled than MM5 0.5º GFS (~2%)
  – More skilled than WRF 0.5º GFS (~2%).

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Thank you!

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Error Decomposition

$$rmse^2 = bias^2 + sde^2 = bias^2 + sdbias^2 + disp^2$$

$\varepsilon = x_{prd} - x_{obs}$	Error
$rmse = \sqrt{\overline{\varepsilon^2}}$	Root Mean Square Error
$bias = \overline{\varepsilon}$	Bias
$sde = \sigma(\varepsilon)$	Standard Deviation of Error
$sdbias = \sigma(x_{prd}) - \sigma(x_{obs})$	Variability Error
$disp = \sqrt{2\sigma(x_{prd})\sigma(x_{obs})(1-r)}$	Dispersion (phase error)

Lange M. (2005). *On the Uncertainty of Wind Power Predictions — Analysis of the Forecast Accuracy and Statistical Distribution of Errors*. Journal of Solar Energy Engineering. Vol. 127:177-184.