VALIDATION OF SHORT AND MEDIUM TERM OPERATIONAL SOLAR RADIATION FORECASTS IN THE US

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ABSTRACT

This paper presents an initial validation of a solar radiation service that provides historical, as well as up-to-the-moment solar resource data from satellites, short-term forecasts from cloud motion analysis, and medium term forecasts (up to seven days ahead) from numerical weather prediction models [1].

Forecasts are validated for several, climatically distinct regions of the US, investigating single-site performance against ground-truth measurements. We also present an initial analysis of regional performance using satellite-derived irradiances as a reference.

1. INTRODUCTION

There are two basic approaches to solar radiation forecasting.

One approach relies on numerical weather prediction (NWP) models which can be global, regional or local. As far as surface irradiance is concerned, these models are, in essence, *probabilistic* because they infer local cloud formation (and indirectly transmitted radiation) through numerical dynamic modeling of the atmosphere. NWP models cannot, at this stage of their development, predict the exact position of cloud fields affecting a given solar installation.

The other approach consists of projecting observed solar radiation conditions based on immediate measured history: The position and impact of future clouds is inferred from their motion determined from recent observations that can be either remote (from satellites) or from appropriate ground based instrumentation (e.g., [2]). This approach is initially *deterministic* because the initial position of clouds affecting a solar installation can be precisely known.

Past evidence has shown that the deterministic cloud-motion based models tend to provide better results that NWP models up to a forecast horizon of 4 hours, beyond which NWP models perform better [3].

2. SHORT AND LONG TERM FORECASTS

2.1 Medium Range Forecasts

Solar-irradiance forecasts are modeled from NDFD's gridded cloud amount data following the methodology previously described by the author and colleagues [4]. The NDFD cloud amount products [5] are the result of a multiphase forecasting process, involving (1) global NWP; (2) modification of the global forecasts by regional meteorological offices using a variety of tools including mesoscale models and human input; and (3) reassembling of the regional offices' products into a national grid. The NDFD data are produced on a 3-hourly basis for up to 3 days ahead and 6-hourly for days 4 to 7. Hourly data are extracted by time-interpolation of the cloud amount data. All forecasts analyzed in this paper originate at 11:00 GMT. The cloud-amount-to-irradiance procedure previously described [4] was adjusted empirically to better match the ensemble of observations at seven ground truth locations, particularly to account for a tendency towards cloud amount underprediction as the forecasts time horizon increases -- the initial procedure had been developed from 1-3 day forecasts only [4].

2.2 Short Range Forecasts

The short-term irradiance forecasts are produced using two consecutive satellite images from which pixel-specific cloud motion is inferred. Future images up to six hours ahead are derived from this localized motion. The methodology was patterned after Lorenz et al. [3], whereby pixel-specific motion vectors are determined by minimizing the cloud index RMSE of two consecutive areas surrounding each pixel displaced in the direction of the motion vector. Future images are subsequently smoothed by averaging each pixel with its immediate neighbor following the pragmatic approach described by Lorenz et al [3].

All medium-range and short-range forecasts are processed onto a grid matching our current satellite model resolution of 0.1 x 0.1 degrees.

1. FORECAST VALIDATION

Forecasts are validated both against single-point ground-truth stations, and extended local area footprint.

3.1 Single Point Ground-Truth Validation

Hourly forecasts are tested against irradiance data from each station of the SURFRAD network [6] including:

- Desert Rock, Nevada
- Fort peck, Montana
- Boulder, Colorado
- Sioux Falls, South Dakota
- Bondville, Illinois
- Goodwin Creek, Mississippi
- Penn State, Pennsylvania

These stations cover several distinct climatic environments ranging from arid (Desert Rock) to humid continental locations (Penn State) and from locations with a minor subtropical influence (Goodwin Creek) to the northern Great Plains (Fort Peck). Boulder is a challenging location for all types of radiation models, because of its high elevation and of its position at the Rocky Mountains' eastern edge, a turbulent junction between two weather regimes.

The present validation period spans August 23, 2008 to January 31, 2009.

Validation metrics: For this initial investigation, we focus our analysis on overall mean bias and root mean square errors (MBEs and RMSEs).

Results: Table 1 and 2 report respectively the MBE and RMSE of all forecasts at all sites. Forecasts include 1-6 hours predictions from cloud motion and same-day to 7-day NDFD forecasts. Forecast models are compared to measured persistence. 1 to 6 hour persistences are obtained by extrapolating measured irradiances using a constant GHI/GHI_{clear} ratio. Future day persitences are obtained by extrapolating the previous day's mean GHI/GHI_{clear} ratio. All forecasts are benchmarked against the same experimental values – note that because of the six-hour forecast, the experimental "common validation denominator" is limited to points six hours after sunrise.

Figure 1 summarizes the results of Table 2 in a unique plot showing the mean RMSE trends for all sites. Also included in the figure, but not reported in the tables is a forecast based on persistence of observed satellite measurements.

Figure 2 reports a sample of measured vs. model scatter plots at four of the seven sites. This sample includes the satellite model reference, the 2-hour cloud-motion forecast and the 2-day NWP forecast.

Discussion: The NDFD-NWP results are consistent with initial evaluations. This is significant, because this is the first time such a test includes winter months which are typically more difficult to predict. The tendency to over predict as the forecast horizon increases was reduced by adjusting the cloud-cover to irradiance model, but could not be entirely eliminated. This tendency is caused by a reduction of the cloud amount dynamic range towards the middle as long term forecasts become more imprecise and a middle ground prediction is the safest choice.

Cloud-motion forecasts are more accurate than NWP up to 4-5 hours ahead with a performance gain approaching nearly 40% for the 2-hour forecast. These forecasts also perform better than on-site measurement extrapolation with performance gain peaking at hour 4. Interestingly, the cloud motion forecasts performs better than the satellite model (from which they are derived!) at hour one, and nearly as accurately at hour 2. A possible explanation for this is that motion vector forecasts tend to smooth projected images (via convergence and divergence of motion vectors). A corollary of this is that attempting to achieve better short term accuracy of satellite models by increasing ground resolution might be illusory given the satellite navigation and parallax uncertainties.

1.2 Extended-area validations

For these validations, we consider 2^o x 2^odegree regions (~ 15,000 sq. km) surrounding each ground-truth station. Because we do not dispose of gridded instrumentation spanning the considered areas, we rely on satellite-derived irradiances data as a performance benchmark.

Validation metric: We focus here on the ability of the forecast models to reproduce the mean microclimatic features of the solar resource for any selected period. This capability can be assessed visually by comparing mapped averages and can be summarized quantitatively by measuring the mean square root difference of the mean irradiance over all pixels in the selected 2° x 2°degree regions.

TABLE 1

Mean Bias Error for all Sites, Forecast Models and Measured Persistence (W/m^2)

MBE	Desert Rock		Fort Peck		Boulder		Sioux Falls		Bondville		Gdwn Creek		Penn State	
Mean Obeserved GHI	399		232		282		262		259		298		238	
Satellite Model error	(1)		11		17		16		10		3		17	
Forecast/ persistence	**Frcst**	**Persis**	**Frcst**	**Persis**	**Frcst**	**Persis**	**Frcst**	**Persis**	**Frcst**	**Persis**	**Frcst**	**Persis**	**Frcst**	**Persist**
1-hour ahead	0	11	1	8	18	17	12	9	2	7	(3)	10	5	2
2-hours ahead	(0)	17	(0)	11	25	31	7	14	0	12	(5)	12	0	3
3-hours ahead	(0)	20	(3)	12	29	38	2	16	(3)	17	(8)	12	(3)	3
4-hours ahead	3	19	(6)	8	27	39	(2)	13	(2)	19	(9)	8	(0)	(0)
5-hours ahead	2	7	(6)	2	23	35	(4)	5	(2)	15	(6)	(2)	1	(10)
6-hours ahead	(13)	(18)	(7)	(9)	6	22	(14)	(10)	(3)	6	(12)	(19)	(6)	(23)
1-Day (Same day)	13		32		20		5		(5)		(25)		(17)	
2-Day (Next Day)	12	(1)	29	(4)	25	2	4	(4)	(2)	(4)	(22)	(3)	(9)	2
3-Day	9	(1)	24	(2)	28	1	(5)	(2)	(4)	(1)	(18)	(6)	(13)	4
4-Day	13	(0)	32	(1)	33	4	(3)	(1)	9	(0)	(26)	(10)	(5)	5
5-Day	14	0	34	0	35	4	9	1	15	(1)	(29)	(8)	(9)	7
6-Day	14	0	37	2	44	6	28	3	20	1	(22)	(6)	(9)	8
7-Day	16	1	37	7	42	4	41	7	30	6	(15)	(8)	(18)	10

TABLE 2

Root Mean Square Error for all Sites, Forecast Models and Measured Persistence (W/m^2)

RMSE	Desert Rock		Fort Peck		Boulder		Sioux Falls		Bondville		Gdwn Creek		Penn State	
Mean Obeserved GHI	399		232		282		262		259		298		238	
Satellite Model error	60		75		83		59		66		63		63	
Forecast/ persistence	**Fcst**	**Prst**	**Fcst**	**Prst**	**Fcst**	**Prst**	**Fcst**	**Prst**	**Fcst**	**Prst**	**Fcst**	**Prst**	**Fcst**	**Prst**
1-hour ahead	53	56	64	59	91	102	51	53	60	56	53	58	59	65
2-hours ahead	58	65	70	72	97	128	59	70	69	80	64	79	67	87
3-hours ahead	64	74	84	87	113	144	70	87	83	100	77	91	73	92
4-hours ahead	68	77	87	96	123	153	82	100	90	113	88	105	79	102
5-hours ahead	79	89	91	105	131	157	89	110	96	114	95	113	88	109
6-hours ahead	105	108	108	118	159	157	110	124	124	119	133	125	100	119
1-Day (Same day)	75		98		136		80		95		114		103	
2-Day (Next Day)	80	100	100	153	131	163	89	142	105	165	127	156	99	141
3-Day	83	119	91	178	134	179	102	159	110	198	120	189	108	169
4-Day	87	128	95	178	144	185	105	160	120	195	123	194	118	161
5-Day	85	128	104	178	151	192	116	159	125	197	134	198	122	168
6-Day	95	130	112	177	145	189	123	146	133	208	142	209	130	177
7-Day	97	130	118	169	146	182	132	150	140	188	144	211	137	175

As an example of visual check we selected the Boulder area because it represents the strongest local microclimatic effect due to its location at the foothills of the Colorado Mountains. In Fig. 3, we mapped the mean irradiance for the month of October as reported by the satellite model (top left) the 2-hour cloud motion forecasts (top right) the two-day NWP forecast (bottom left) and the seven-day NWP forecast (bottom right). The considered monthly averages are based on the same number of hours for all the models analyzed here, which are largely afternoon points.

While the cloud-motion forecast conserves the main micro-climatic features observed after the fact from satellite (albeit with significant smoothing of features), the NWP model is not able to recreate the observed microclimatic effect. The NWP model tends to promote cloud formation (hence lower mean irradiance) above the highest Rocky Mountains peaks at the west of the city. Observations show that for the considered month of October, clouds tended to be more prevalent in the wake of the mountains immediately at the East of the City for the considered hours (largely PM) common to all models. Also apparent in Figure 3 is the tendency of the NWP model to overpredict radiation as the forecast horizon increases to seven days.

For the quantitative assessment we present (Figure 4) the RMSE of mean monthly forecasts in October with respects to satellite means over all grid points' at all sites. This is compared to the range of monthly means within each region. Cloud-motion based forecasts errors represent ~ 10% of this range of values. While seven-day forecast errors are considerably larger, they nevertheless represent only a fraction of the observed range of mean values overall.

5. CONCLUSIONS

The numerical weather prediction-based irradiance forecast analyzed here lead to results which are consistent with our previous limited evaluations. The present validations include a more diverse set of climatic environments and include winter months when model performance is known to be poorer then in summer. Satellite-derived cloud motion-based forecast lead to a significant improvement over NWP forecasts up to 4-5 hours ahead. One and two-hour forecasts are on par or slightly better than the satellite model from which they are derived. The probable reason is that the cloud motion methodology results in a smoothing of the predicted images which tends to mitigate satellite's navigation and parallax uncertainties. A corollary of this maybe that the short term accuracy of satellite models may not be improved significantly by increased image resolution – this comment applies only to short term of course and does not apply to long term averages and the delineation of solar microclimates, where high resolution would be beneficial.

6. ACKNOWLEDGEMENT

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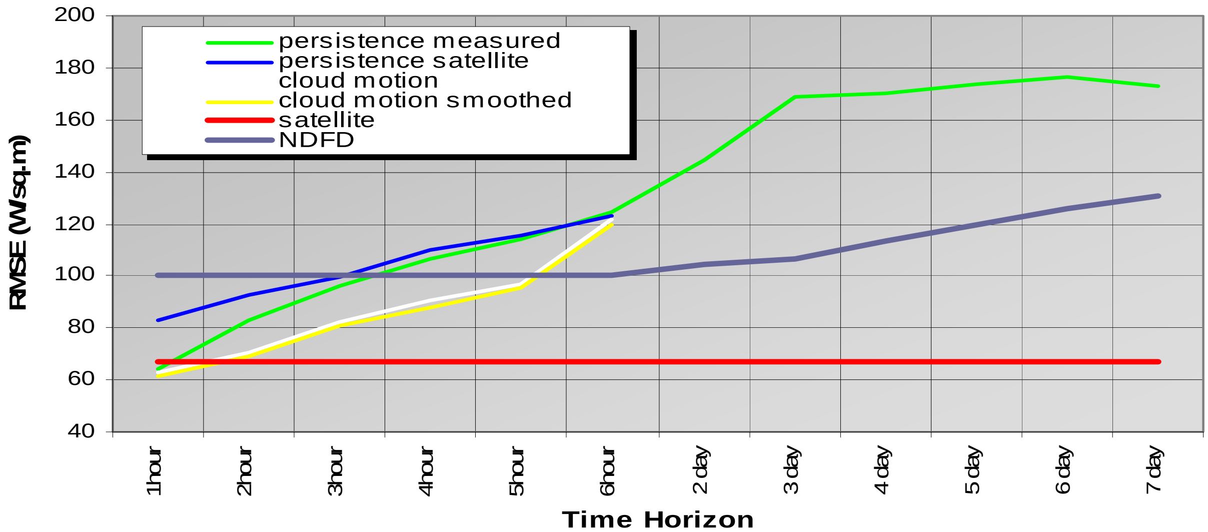

Figure 1: All site composite of RMSEs for all forecast and persistence models compared to the RMSE achieved by the reference satellite model

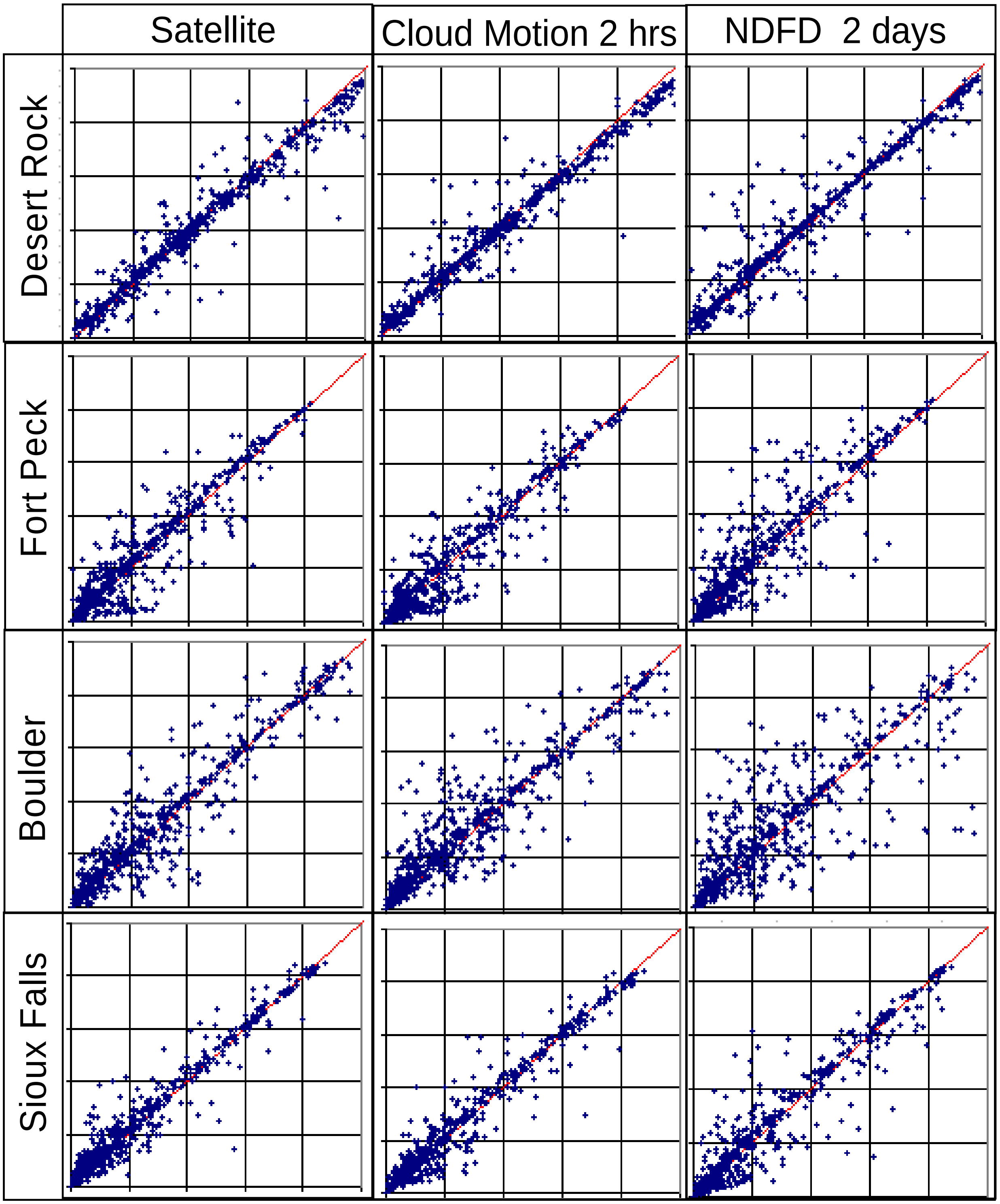

Figure 2: Sample modeled vs measured scatter plots for four locations, including the satellite reference model, the 2-hour cloud motion forecast and the 2-day NWP-NDFD forecast

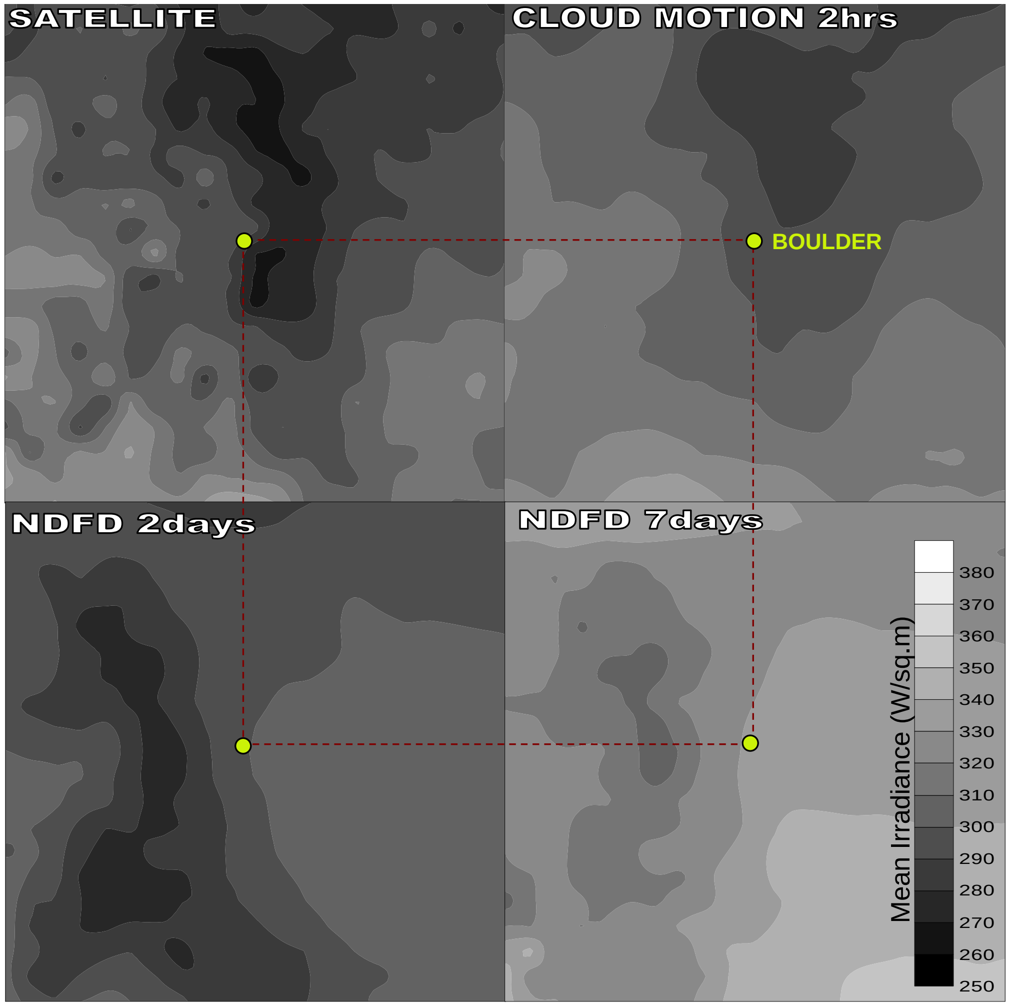

Figure 3: Comparing Mean irradiance in a $2^o x 2^o$ latitude-longitude region around Boulder Colorado as derived from the satellite model, the cloud motion based model (2-hour forecast) the next-day (2-day) NWP forecast and the 7-day forecast

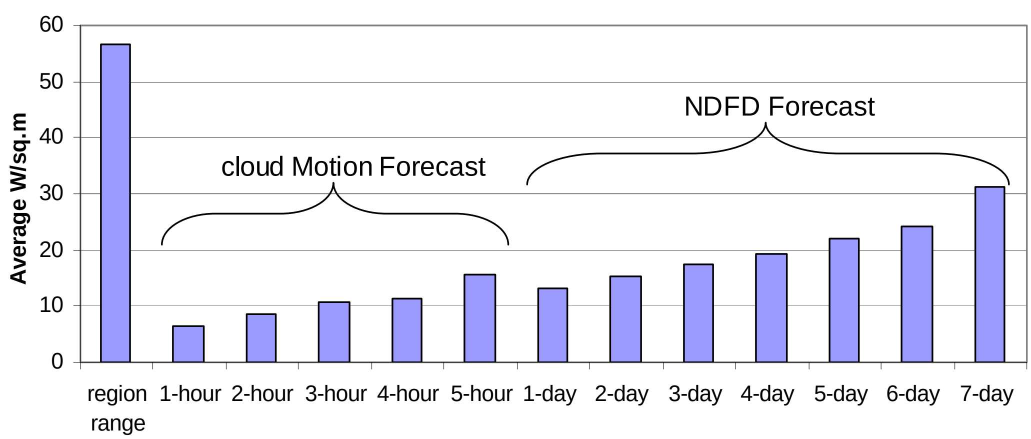

Figure 4: Comparing the average range of mean monthly values in the 7 $2^o x 2^o$ regions to the RMS error of the mean monthly forecasts over all regions and all region grid points.