GBT Memo #304

An Evaluation of the Weather Forecasts Used in the GBO DSS

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Abstract

An analysis of forecast values used in scheduling observations on the GBT is performed. A full comparison of raw forecast values from the sites of Lewisburg (WV), Elkins (WV) and Hot Springs (VA) to on-site measured observations is performed for wind speed and opacity. It is found that the 'tipper' used for local measurements of opacity is not adequate to provide useful observations and thus forecast data must be used without direct confirmation of local opacity measurements.

The comparison of wind speed forecasts to on-site measurements indicates that the forecasts from the Elkins site are, overall, detrimental to the overall 'skill' of the average forecast. While the forecast data assimilated to the Dynamic Scheduling System (DSS) are currently 'corrected', with corrections dependent upon time-of-day, this is based upon an approach of assimilating average forecast values from all three sites. Further work, including the analysis of multiple years worth of data and determination of seasonal variations is suggested.

Multiple other suggestions for improvements to the DSS from a weather analysis point of view are proposed, including an examination of point forecasts for wind speed, the use of ensemble forecasts in order to provide 'confidence' estimates in given forecasts, a deeper analysis of atmospheric opacity forecasts using archived sky temperature measurements and the extraction/use of atmospheric profile forecasts at the GBO site, rather than the three locations currently used.

1 Introduction

The Dynamic Scheduling System (DSS) used when timetabling observations using the Robert C. Byrd Green Bank Telescope (GBT)[1] primarily uses forecast opacity determinations, or analogs thereof, and wind speed predictions in order to determine which projects are most suited to the expected weather conditions at the Green Bank Observatory (GBO) site. The comparison of predicted to actual values is not routinely carried out and so this memo represents an effort to establish the forecast 'skill' and to determine if there exist any previously unknown issues with the forecast data. Also, to determine if there are any potential improvements that can be made to the current system related to the forecast data.

[1]The Green Bank Observatory is a facility of the National Science Foundation under cooperative agreement by Associated Universities, Inc.

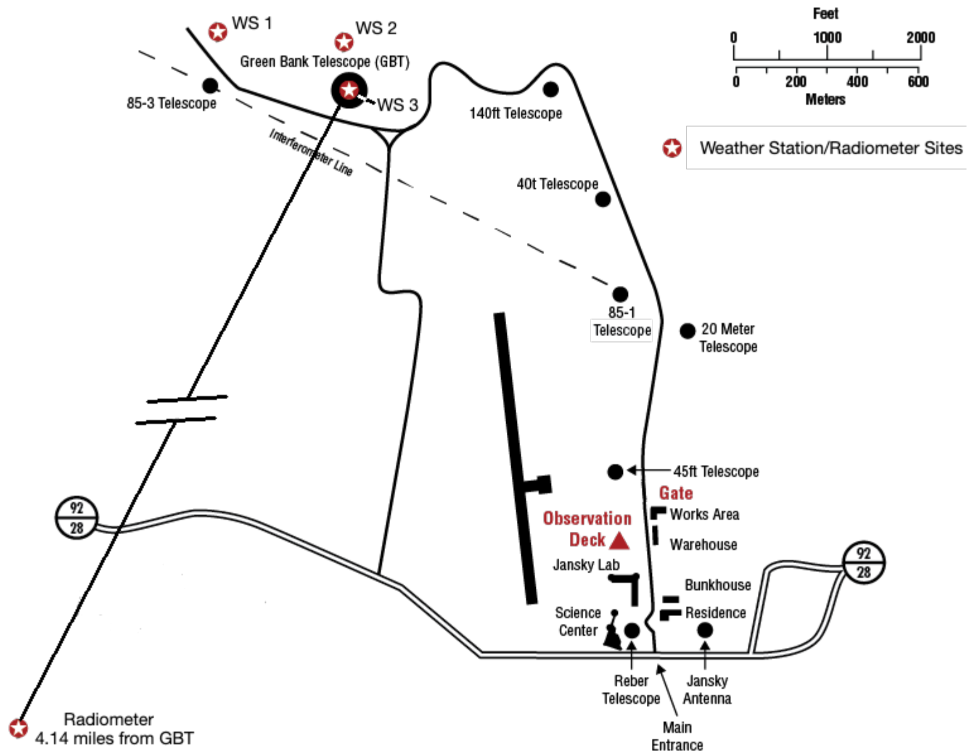

Figure 1: Location of on-site weather stations and off-site radiometer.

2 Site Measurements

The GBO has three weather stations on site, the locations of which are shown in Fig.1. Station 1 is located across the road from the interferometer control building and is mounted at a height of 20 m. Station 2 is located in the field near the GBT and is mounted at a height of 35 m. Station 3 is mounted on the RFI antenna gimbal at the tip of the GBT feedarm. It is on a pole such that it is unshielded and, due to the nature of its location, has a variable height dependent upon the activity of the GBT, with a peak of ∼148 m.

Weather station 1 provides measurements of wind speed, wind direction, atmospheric pressure, humidity and temperature. In addition, station 1 incorporates a lightning detector. Weather station 2 also provides measurements of wind speed, wind direction, atmospheric pressure, humidity and temperature. In addition, it provides dew point, wind chill, partial pressure of water calculations based on its own measurements of humidity, pressure, temperature and wind velocity. Station 3 provides wind speed and wind direction measurements.

In addition to the three weather stations on site, there is a radiometer (tipper) located approximately 4.14 miles south-south-west of the GBT. This radiometer makes measurements of the sky opacity at integer GHz frequencies between 22 and 30 GHz on an hourly basis.

3 Forecasts and Observations

The forecast data used to predict the GBO site weather conditions for DSS purposes are provided by the National Weather Service (NWS). While the NWS provides many different products, extracted from several different forecast models, the DSS primarily relies upon the North American Mesoscale Model (NAM). The NAM comprises 3.5 day forecasts at 12 km horizontal resolution covering the continental United States. It is run four times daily at 00z, 06z, 12z and 18z with one hour temporal resolution.

3.1 Datasets

Data collected by the three on-site weather stations are routinely archived within the GBO system. In addition, weather forecast data and measurements from the radiometer are archived through the CLEO weather forecast system produced by R.Maddalena and now maintained by GBO. These archives permitted the production of datasets for forecast wind speeds and atmospheric opacities for each of the three local sites (Elkins, Lewisburg and Hot Springs) which are used to evaluate expected weather conditions at the GBO site. In addition, archived data for each of the three on-site weather stations and the radiometer were retrieved to create a self-consistent set of measured wind speeds and opacities covering the year 2020.

3.2 Data Cleaning and Manipulation

The on-site weather stations record data approximately every second, in order to compare these data to the forecasts, which have a cadence of one hour, hourly median values were calculated over a range of 30 minutes before, to 30 minutes after the hour. This is the same method used for wind speed data in the DSS database. The radiometer data archive consists of hourly measurements, where available.

Each of the datasets were examined for spurious or missing values. Notably, weather station 2 data were suspect, due to malfunctioning sensors, from approximately September 2018 until June 2020 (J.Ray, *priv comm*). From inspection it appeared that the data for station 2 became reliable again on July 8th at 19:45 UTC. In addition, there were two periods in 2020 for which the station 3 data were unreliable (i.e. wind speeds consistently measuring as 0.00 m/s). These periods (April 9th, 08:00 UT - May 27th, 14:00 UT & July 10th, 23:00 UT - September 23rd, 15:00 UT) were excised from the data set.

Due to the way that the radiometer calculates zenith opacity (chiefly by taking the ratio of sky measurements at two different elevations), environmental factors such as uneven cloud cover can lead to poor values. Some accounting for poor values was performed through removing any values greater than the maximum forecast value across all three forecast locations for the whole of the year 2020. After removing these excessive values, it was seen that there were 810 values remaining for 2020 at 29 GHz, with 565, 423 and 169 values at 22, 23 and 24 GHz, respectively. All other frequencies retained less than 50 values for the year. Consequently, my analysis used 22, 23, 24 and 29 GHz as comparison points and disregarded other frequencies.

4 Analysis

In order to determine how effectively the DSS is scheduling the telescope, in terms of how accurately the NAM forecast is predicting actual conditions at the GBO site, I here present an analysis of the forecasts compared to measured wind speeds and opacities for all available data from the year 2020.

4.1 Opacities

A comparison of forecast atmospheric opacities to those measured by the radiometer shows many inconsistencies in the observed data. As a preliminary example, I will use the 29 GHz data as this frequency has the most measurements over the period in question.

Some data cleaning has been performed on the observed opacity measurements. Primarily, a nominal maximum opacity value was determined at each frequency by simply taking the maximum forecast value across the entire year, across all sites. While it is possible that some small number of true measurements may exceed this value, this was assumed to be minimal in impact. It is also evident that the observed opacities contain many non-physical (i.e., large) values and some estimate of an upper cut-off threshold is necessary. Having determined this upper threshold, any observed values exceeding it were discounted.

The left figure of Fig.2 shows the distribution of forecast values for zenith opacity at 29 GHz over the whole of 2020, for each station and the average of those three stations. The right figure shows the distribution of measured values at the same frequency over the same period. These plots are shown less to demonstrate any features of the distributions of sky opacity for the individual sites but rather to show that the forecasts for each site (and the average) follow a similar distribution peaking at low values and falling away with a similar tail that is suggestive of a log-normal distribution. This is perhaps what we would expect, given that precipitable water vapor measurements from radiosondes and GPS exhibit a log-normal distribution (Foster et al., 2006). The stark contrast of forecast and observed values here is interpreted as reflecting the poor standard of observed data taken from the radiometer.

As mentioned, the collected observed opacities contained many non-physical values. At least some portion of these have been attributed by the author and colleagues (i.e. R.Maddalena, *priv comm*) to the fact that the measured opacities are derived from a ratio of sky temperatures taken at two different elevations/zenith angles. In the case that sky measurements at these two elevations are taken under differing fundamental conditions, such as clear sky at one elevation and cloud at the other on 'patchy' days, or even with birds perching on the antenna, as has been observed, then the ratio of these values may result in non-physical measurements. Separate from the values which are clearly non-physical, it is not clear what impact such effects may have upon the measurements which are otherwise within physical ranges. In addition, it is not possible, at least in retrospect, to account for these effects in the observed data. We must thus reject all observed opacity data taken from the tipper.

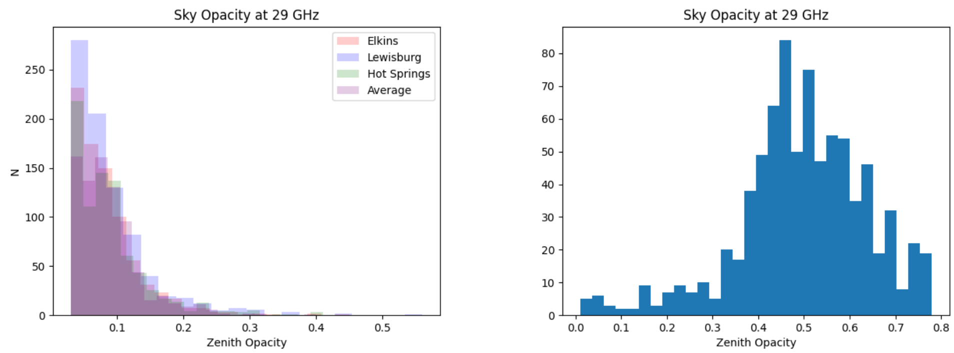

Figure 2: (left) Distribution of forecast opacity values at 29 GHz for the Elkins, Lewisburg and Hot Springs sites, as well as the average of those sites. (right) Distribution of observed opacity values at 29 GHz, as measured by the Green Bank site radiometer 'tipper'.

4.2 Wind Speeds

Wind speed data were compared between the three on-site weather stations. Figure 5 (left) shows a histogram of the hourly median wind speeds measured at each station over the period of analysis. It should be noted that the plotted values are all exclusive of the periods detailed in Section 3.2, i.e., even though station 1 may have valid data for the period Jan 1st, 2020 - July 8th, 2020, those data have been excluded from this plot in order to make any comparisons between the different stations self-consistent. It may be noted that there are some discrepancies between the different stations in that station 3 has fewer measurements below 1.5 m/s than either station 1 or 2. Station 3 then also has a greater preponderance of values above 1.5 km/s than either of stations 1 or 2. The likely cause of these differences is the location of station 3 on the GBT feedarm at a height peaking at 148m. Some smaller discrepancies in the wind speeds as measured by stations 1 and 2 can be seen if Fig.5. These are somewhat minor on the scale of the general range of wind speeds measured from these stations (max wind speeds over the relevant period are 8.3 m/s and 6.2 m/s for stations 1 and 2, respectively). As such they can likely be attributed to variations in the 'shielding' of station 2 by the local orography and/or the telescope structure in comparison to station 1.

Having established the level of self-consistency between the three local weather stations, in terms of wind speed, it can now be justified to use stations 1 and 3 as the main representatives of on-site observed wind speed. The main reason for doing so being the larger number of data points available, in comparison to station 2.

4.3 Comparison of Forecast to Observed Values

In order to determine the 'best' available predictive data when forecasting GBO site conditions, several analyses were performed. Measures of forecast 'skill' were made for the NAM forecasts at 6, 12, 24, 36 and 84 hour lead times. In addition to the 'surface wind speed' (generally considered to be 10m above the ground), these analyses were also performed for forecasts of wind speed at heights of 35m, 75m and 150m.

As previously mentioned, forecasts for the GBO site weather conditions are taken from

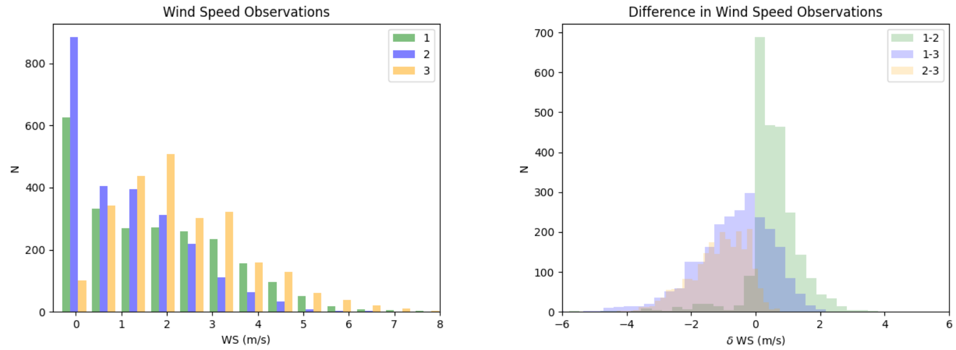

Figure 3: (left) Histogram of the wind speed values measured at each of the GBO weather station locations. (right) Histogram of the difference between each pair of the GBO weather stations.

predicted values for the locations of Hot Springs, Va, Lewisburg, WV, Elkins, WV, as well as the averaged values of all three sites. It is worthwhile here to consider these sites locations (i.e. direction and distance) in relation to the GBT. The site of the Hot Springs forecast center is at 55.2 km from the GBT in a southerly direction, Lewisburg is 81.9 km to the south-west and Elkins is 50.8 km to the north of the GBT. Perhaps more relevant to these sites' importance in terms of relevance to local conditions than their distance, is their direction. Prevailing winds at the latitude of the GBT are south-westerly - that is, coming from the south-west towards the north-east. Therefore, weather conditions at the GBT are also, in general, coming from the west and south. It may therefore be expected that the locations of Hot Springs and Lewisburg may be of more relevance when predicting GBO site conditions than Elkins is. Adding a further level of complexity to this discussion, it should be noted that the GBO is located in a mountainous region, with a great deal of variability in its orography on scales ranging from ∼1 km to ∼100 km. Figure 4 shows the topographical profiles along direct lines towards each of the three forecast sites. It may be seen from these profiles that there is considerable potential for differences between the weather conditions at the GBT site and those at the forecast sites to arise.

Forecast 'skill' is commonly any statistical evaluation of the accuracy of forecasts (see the glossary of the American Meteorological Society - https://glossary.ametsoc.org/wiki/Skill). For the purposes of this study, measurements were made of the forecast bias (forecast value - observed value, F-O), the mean absolute error (MAE $= \frac{\sum_{i=1}^{n}|F_i - O_i|}{n}$), the root-mean-square error (RMSE $= \sqrt{\frac{\sum_{i=1}^{n}(F_i - O_i)^2}{n}}$) and the Pearson correlation coefficient ($R_{FO} = \frac{C_{FO}}{\sigma_F . \sigma_O}$, where C_{FO} is the covariance between F and O and σ_F and σ_O are the respective standard deviations of F and O). The Pearson correlation coefficient measures the degree of linear correlation between two variables, with an absolute value of 1 indicating a perfect linear correlation between the two measurements (the sign of the coefficient indicates whether the correlation is positive or negative). Values of R_{FO} which may be considered to indicate 'strong', 'moderate' or 'weak' correlations are situational (see e.g. Lord et al. 2021). However, representative values for forecast data in specific instances might be expected to remain above 0.6 for forecast leads of up to 4 days (see Fortin et al. 2015).

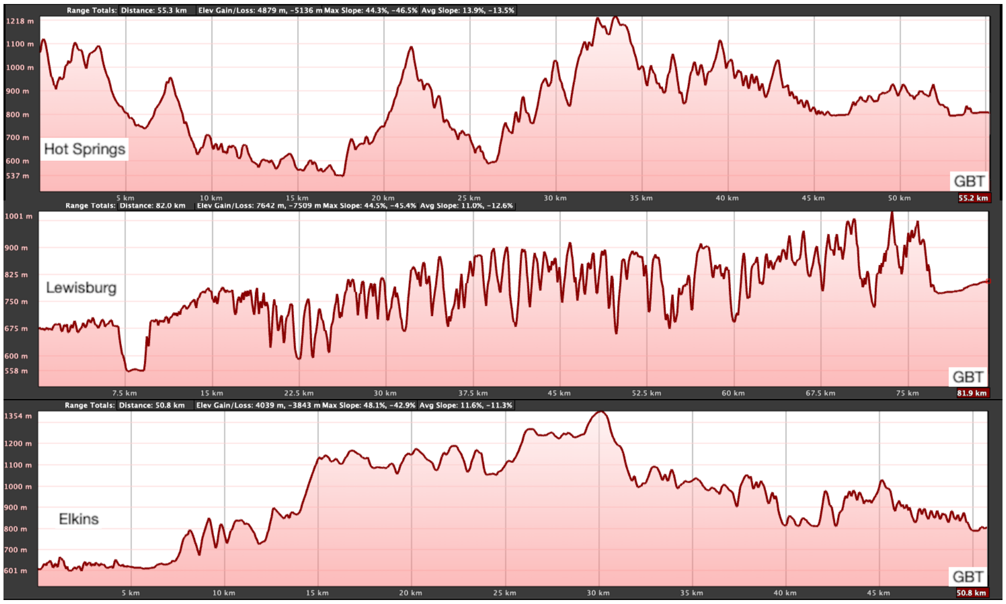

Figure 4: Topographical profiles of the orography in a direct line to each of the forecast sites, Hot Springs, VA (Top), Lewisburg, WV (Middle) and Elkins, WV (Bottom).

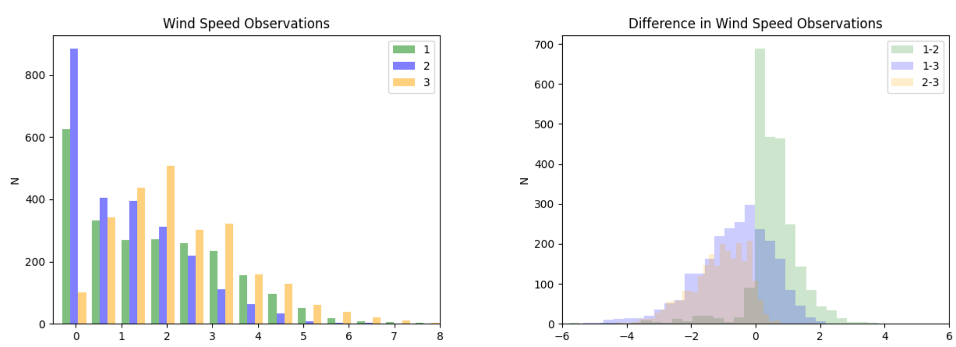

Figure 5: (left) Histogram of the wind speed values measured at each of the GBO weather station locations. (right) Histogram of the difference between each pair of the GBO weather stations.

5 Results

Full results for each station/forecast lead time/location/height are available in the appendix. Here I shall summarize the key conclusions drawn from these data.

5.1 Individual Weather Station Analysis

Almost without exception, all measures of forecast skill deteriorate (Bias, MAE and RMSE increase, while R values decrease) when our measured weather station wind speed values are compared to forecasts above surface level. That is, surface level forecast wind speeds are most accurate when compared to any of our weather stations. There are several possible explanations for this observation, most likely among them is the fact that local orography will have particularly important effects upon our measured wind speed values (see §4.3).

It is perhaps unsurprising that wind measurements from weather stations 1 and 2 relate most closely to forecasts at 'surface' level, as station 1 is nearest to this nominal 'surface' height and station 2, while actually at 35 m, might also reasonably be expected to related closely to this surface value. Given the uncertainties in our data, in addition to issues such as the distance and geographical difference between the GBT and the forecast sites, the correlation between wind forecasts at surface level being stronger than at higher levels for stations 1 and 2 does not seem inconsistent. In fact, given the rather low values of R for any of the station/forecast site combinations, it is suggested that the forecast values of wind speed are only marginally correlated to on-site measurements at best.

At this point, it should be considered that different physics are at play in the atmosphere (and the forecast model) depending on the height of the atmosphere under examination. The 'surface boundary layer' is a layer of air, tens of meters thick in magnitude. Within this layer mechanical (shear) generation of turbulence exceeds buoyant generation or consumption and the wind speed profile, as a function of height above the ground, is insensitive to frictional effects. However, above this layer, friction effects decrease with height and wind speed forecasts must be considered as a function of elevation. I suggest that the surface level forecasts correlate most closely with all three of the GBO weather stations because the forecast model at this elevation is disregarding height effects on the vertical wind profile. Incorporating these effects may well improve the correlation between forecasts and observed measurements. However, that would require forecasts specifically generated for the GBO site, incorporating, for example, improved modelling of the local topography.

As noted, wind speed measurements from stations 1 and 2 show the highest degree of correlation to forecasts when those forecasts are evaluated at surface level. Further to this, it may be noted that the level of agreement between forecast and observation deteriorates proportionately with increasing height (see Table A). In addition, when comparing station 3 observations to forecasts, this relationship becomes much weaker. That is, while wind speed observations from station 3 are still most highly correlated with forecasts at surface level, this correlation is a) worse than either station 1 or 2 on average and b) not seen to deteriorate as rapidly when forecasts at higher heights are considered. There are several possible explanations for this observation, most likely is that the variable height of this wind station introduces a large degree of scatter to our comparisons with forecasts.

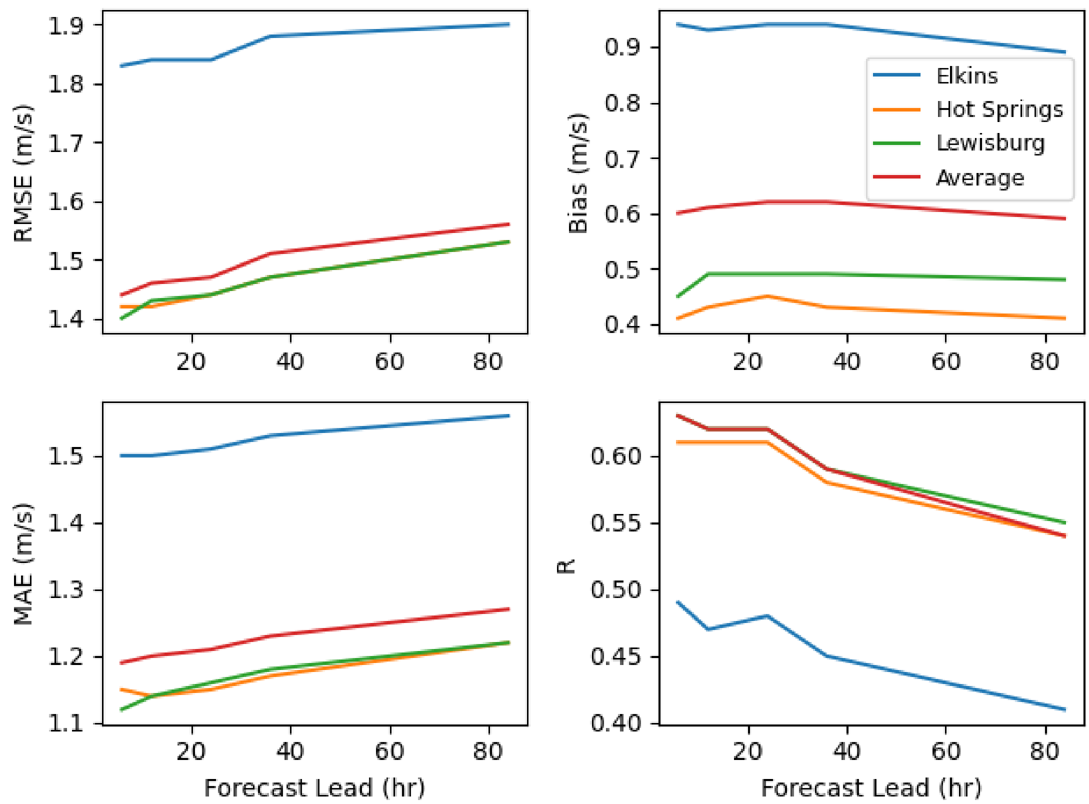

Figure 6: The statistical properties of the comparison between on-site observations taken from weather station 1 and the various forecast sites. (Top left) the root-mean-square error, (top right) the bias (forecast-observation), (bottom left) the median absolute error and (bottom right) the Pearson R coefficient between forecast and observed data, respectively. For all plots the data from Elkins forecasts are plotted in blue, Hot Springs forecasts are plotted in orange, Lewisburg forecasts are plotted in green and the three-site average forecast is plotted in red.

5.2 Forecast Location Sites

It can be readily seen from Tables A through A that all measures of forecast skill are worse (Bias, MAE and RMSE are higher, while R values are lower) when using Elkins as the forecast location, rather than Hot Springs or Lewisburg. In fact, the degree to which forecasts for the location of Elkins disagree with the on-site measurements means that the averaging of all three sites (as is done for the DSS evaluation) is making for poorer forecasts than if this site were disregarded altogether. This is true for all on-site stations, at all forecast lengths.

As an illustration of the degree to which Elkins forecasts disagree with the other locations, Fig.6 shows plots of the main statistical relationships for comparisons of forecast values, for each of the three forecast locations, with observations from weather station 1 (station 1 was used as this has slightly 'better' results, in comparison to stations 2 and 3. As might be expected, values of root-mean-square error (Fig.6 - top left) and median absolute error (Fig.6 - bottom left) increase with increasing forecast lead for all forecast locations. Similarly, Pearson 'R' correlation coefficients (Fig.6 - bottom right) decline with increasing forecast lead in general. The bias measurement (Fig.6 - top right) is slightly less straightforward to interpret, with two of the three forecast sites showing a decrease in bias with increasing forecast lead. The third site, Lewisburg, WV shows an essentially flat relationship. It should be noted here that 'bias', as used here, is an averaged quantity over multiple data points. What may be interpreted as a decrease in bias, may equally be due to an increase in bias in the opposite direction.

For all of the plots in Fig.6, it is quite obvious that forecasts from the Lewisburg and Hot Springs sites are in better agreement with each other than with forecasts from the Elkins site. Furthermore, it can be seen that forecasts from the Elkins location are significantly 'worse' than for the other two sites. Indeed, it is evident that the Elkins forecasts are having a deleterious effect on the overall average forecast skill in all cases. As a further demonstration of this, Fig.7 shows the bias plot of Elkins compared to an average of the other two sites with shaded areas indicating zones within one standard error of the mean. It should be noted that the use of the standard error of the mean rather than a standard deviation here is mainly for illustrative purposes. The spread of bias values in the presented sample is large ($\sigma \sim$1.36 m/s for the two-site average) but the number of measurements is also large, therefore the standard error of the mean may be assumed to better reflect the likelihood that any given set of measurements will tend to the mean, as plotted here.

It is immediately obvious from Fig.7 that forecasts from the Elkins location are significantly and consistently less predictive of actual site conditions than the Lewisburg and Hot Springs sites. Not only is Elkins a worse predictor of the on-site conditions than either of the other two sites, the separation between the predictions of the Elkins site and the other two is very large. At the 24 hour forecast point, the mean bias measurement for the Elkins site is 0.94 m/s. For the average of the Hot Springs and Lewisburg sites, the mean bias is 0.47 m/s. The standard error of the mean in the Elkins measurements at the 24 hour forecast point is 0.04 m/s. Thus, the results from the Elkins site are nearly a factor of 12 times the standard error away from the average of the other two sites. A further demonstration of the adverse contribution of the Elkins forecast to the overall analysis is that the three-site average bias at a 24 hour forecast lead is 0.62 m/s. The standard error of the mean for the two-site average measurement at 24 hours is 0.025 m/s. Thus, including Elkins in a forecast average worsens the site prediction by a factor of six times the standard error of the mean.

6 Summary

Comparing local forecasts of wind speed to on-site observations indicate that these forecasts are not particularly well correlated with conditions at the GBO site. In particular, the locations of the three 'local' sites from which the GBO system currently draws forecast data are sufficiently distant that it is suspected that orography effects, in addition to prevailing wind direction, etc, mean that these forecasts are only marginally correlated with on-site conditions, at best. This is particularly true for the Elkins site, which has been shown to consistently and significantly worsen forecast accuracy across all metrics of 'skill'.

An important caveat to the analysis presented in this memo is that 'raw' wind speed forecast values (as presented here) are not what is used in the current actual implementation

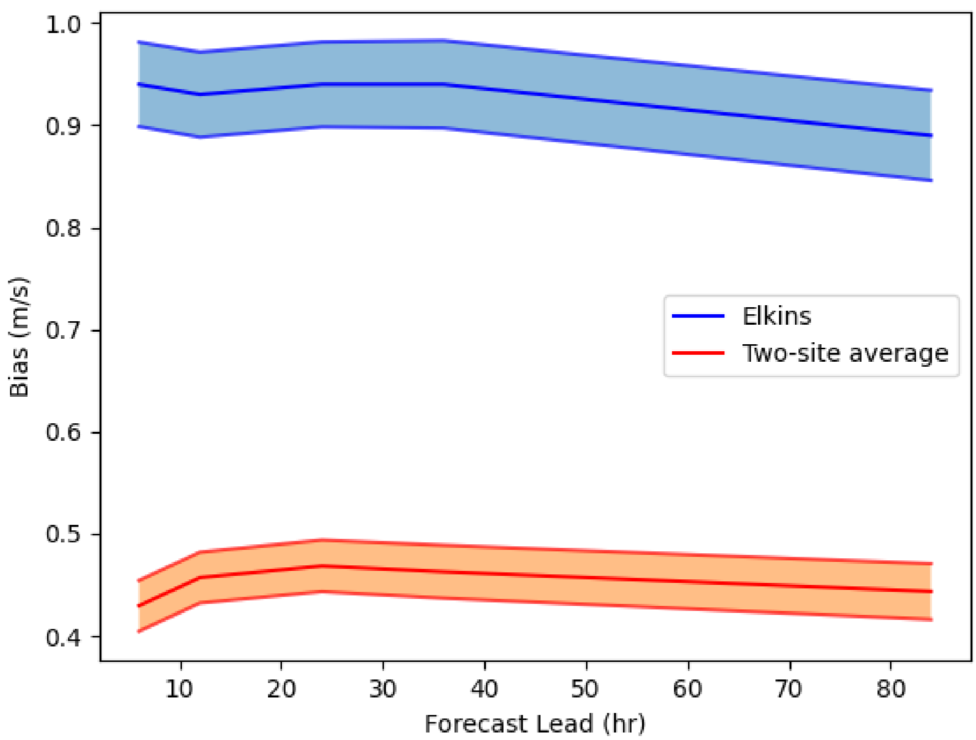

Figure 7: The bias (forecast-observation) measurements for the Elkins forecast location (blue) and for the three-site average (red/orange).

of the DSS. As described in Balser (2010), forecast wind speed values are 'corrected' via a polynomial function, dependent upon the relevant time of day[2]. Notably, these corrections are applied to the forecast measurements averaged over the three sites of Elkins, Lewisburg and Hot Springs. As the analysis presented here is largely directed toward a comparison of the forecasts arising from each of the three sites, it was not felt that incorporating these corrections for the average was particularly of use. Further, while this would have a clear impact on the magnitude of the difference between forecast and observed values, this would not impact the degree of correlation. Thus, this approach was not pursued for the purposes of this study.

As mentioned above, previous studies have separated wind speed forecasts (and their comparisons to on-site measurements) into 'day' and 'night' samples, which exhibit different characteristics. Extending the presented analysis to incorporate these sub-samples, in addition to a seasonal/monthly analysis, is a worthwhile goal, currently beyond the scope of this report. Further to this, there are archival values of both forecasts and observed values going back to the inception of the DSS (and farther). It would be of interest to also compare year-to-year skill statistics, particularly when assessing the direct relation of forecast data to on-site weather conditions.

It has been noted that the opacity measurements made with the local 'tipper' are unsuitable for comparison with forecasts and are of little to no use in general. Recommendations for alternative ways to assess local atmospheric opacity are made in the next section.

7 Recommendations

There are several actions which could be taken with minimal effort on short timescales which are likely to significantly improve the utility of monitoring weather forecasts at the GBO site. These are listed below in reverse order of estimated effort.

1. Elkins should be removed from the average forecast used in the DSS procedure. This would be an easy alteration to the current system and would yield immediate improvements in the quality of the DSS forecast.

2. Point forecasts should be examined, in the same way as presented in this report, to see if significant improvements can be attained by using such data. Wind forecasts for the exact site of the GBT are available and are, in fact, already monitored and archived. However, these have not been assessed to determine what level of forecast skill is reached by these forecasts in comparison to the actual system in use.

3. The GBO currently uses the NAM forecasts to evaluate forecast weather conditions. The NWS also provides results from the Global Forecasting System (GFS), which is an ensemble modelling and data assimilation scheme. While this model is run at an 18 km grid resolution (compared to the NAM 12 km resolution), the GFS provides estimates of uncertainties in predicted values. This would allow for a DSS incorporation of 'confidence' in forecast data.

[2]'daytime' hours, in this context, are considered to begin two hours after sunrise and end three hours after sunset

4. An analysis similar to that performed here for wind speed should also be carried out for atmospheric opacity. As demonstrated in this report, measurements from the GBO 'tipper' are unusable for this purpose. It is suggested that sky temperature measurements may be derived from archival measurements of Tsys. This method has been used with some success in the past (Maddalena, R., 2010), although without extending the analysis to examining the forecast skill relevant to different forecast sites, as presented for wind speed data here.

5. Further to item 4, it should be noted that it is no longer necessary to evaluate atmospheric profiles at specific sites. Previously, and at the time of constructing the current GBO forecasting system and the DSS, it was necessary to evaluate the atmospheric conditions (i.e. opacity) at nearby sites, rather than at the actual location of the GBT. This was due to the availability of 'Binary Universal Form for the Representation of meteorological data' (BUFR) profiles, in particular, the fact that these were available only for specific locations within the US. It is now possible to retrieve BUFR forecast data for any given location via an extraction and decoding of data from the 'General Regularly distributed Information in Binary form' (GRIB) files provided by the National Oceanic and Atmospheric Administration. This would require some amount of resources devoted to data retrieval and extraction, with subsequent data quality testing and then a further analysis similar to that presented in this document to demonstrate the improvement (or otherwise) to forecast skill.

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A Appendix

Table 1: Forecast skill statistics for Weather Station 1, relevant to each of the three local forecast sites.

Elkins					Hot Springs				Lewisburg			
6 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.94	1.50	1.83	0.49	0.41	1.15	1.42	0.61	0.45	1.12	1.40	0.63
35m	2.53	2.74	3.31	0.40	1.79	2.13	2.56	0.50	1.88	2.15	2.60	0.53
75m	3.48	3.63	4.34	0.34	2.70	2.94	3.49	0.43	2.87	3.07	3.60	0.44
150m	4.83	4.94	5.90	0.26	4.08	4.25	4.99	0.32	4.33	4.47	5.19	0.31
12 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.93	1.50	1.84	0.47	0.43	1.14	1.42	0.61	0.49	1.14	1.43	0.62
35m	2.48	2.72	3.27	0.40	1.80	2.13	2.56	0.51	1.90	2.17	2.60	0.53
75m	3.43	3.59	4.28	0.34	2.71	2.94	3.48	0.44	2.87	3.06	3.59	0.44
150m	4.78	4.91	5.82	0.26	4.04	4.20	4.92	0.35	4.28	4.42	5.13	0.33
24 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.94	1.51	1.84	0.48	0.45	1.15	1.44	0.61	0.49	1.16	1.44	0.62
35m	2.51	2.73	3.29	0.40	1.83	2.16	2.61	0.51	1.91	2.19	2.63	0.53
75m	3.47	3.64	4.32	0.34	2.71	2.96	3.51	0.45	2.84	3.04	3.58	0.46
150m	4.83	4.97	5.88	0.27	3.98	4.17	4.91	0.37	4.22	4.36	5.08	0.36
36 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.94	1.53	1.88	0.45	0.43	1.17	1.47	0.58	0.49	1.18	1.47	0.59
35m	2.49	2.73	3.31	0.36	1.80	2.16	2.61	0.48	1.91	2.21	2.65	0.50
75m	3.45	3.63	4.32	0.31	2.67	2.93	3.48	0.42	2.85	3.07	3.60	0.42
150m	4.79	4.93	5.87	0.24	3.96	4.15	4.88	0.34	4.22	4.37	5.08	0.32
84 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.89	1.56	1.90	0.41	0.41	1.22	1.53	0.54	0.48	1.22	1.53	0.55
35m	2.44	2.76	3.31	0.32	1.76	2.15	2.63	0.44	1.90	2.21	2.68	0.45
75m	3.41	3.64	4.33	0.26	2.62	2.90	3.49	0.38	2.82	3.05	3.61	0.38
150m	4.77	4.94	5.88	0.19	3.90	4.11	4.86	0.30	4.19	4.36	5.07	0.28

Table 2: Forecast skill statistics for Weather Station 2, relevant to each of the three local forecast sites.

	Elkins				Hot Springs				Lewisburg			
6 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	1.50	1.62	1.93	0.48	0.96	1.18	1.42	0.57	0.97	1.16	1.43	0.60
35m	2.99	3.06	3.53	0.37	2.23	2.33	2.74	0.43	2.29	2.38	2.79	0.47
75m	3.88	3.93	4.55	0.30	3.08	3.16	3.68	0.34	3.25	3.31	3.82	0.36
150m	5.09	5.13	6.01	0.23	4.36	4.42	5.13	0.24	4.60	4.65	5.35	0.23
12 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	1.50	1.62	1.93	0.48	0.98	1.17	1.43	0.58	1.04	1.20	1.46	0.61
35m	2.97	3.04	3.48	0.38	2.27	2.36	2.76	0.45	2.37	2.43	2.83	0.49
75m	3.83	3.88	4.47	0.33	3.13	3.18	3.68	0.36	3.29	3.34	3.84	0.38
150m	5.06	5.10	5.95	0.25	4.34	4.38	5.07	0.27	4.59	4.63	5.29	0.26
24 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	1.48	1.61	1.92	0.48	0.96	1.18	1.43	0.57	0.99	1.19	1.44	0.59
35m	2.96	3.02	3.48	0.37	2.23	2.34	2.75	0.43	2.31	2.40	2.79	0.46
75m	3.85	3.90	4.49	0.30	3.03	3.12	3.62	0.36	3.19	3.25	3.75	0.36
150m	5.08	5.12	5.98	0.24	4.17	4.23	4.93	0.28	4.42	4.47	5.15	0.27
36 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	1.47	1.61	1.92	0.45	0.94	1.18	1.43	0.55	1.00	1.20	1.45	0.57
35m	2.92	3.00	3.45	0.35	2.23	2.34	2.74	0.40	2.33	2.42	2.80	0.43
75m	3.80	3.87	4.45	0.28	3.03	3.12	3.62	0.34	3.21	3.27	3.75	0.34
150m	5.01	5.06	5.90	0.22	4.19	4.25	4.93	0.27	4.46	4.50	5.16	0.25
84 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	1.42	1.59	1.91	0.39	0.90	1.18	1.44	0.48	0.99	1.22	1.48	0.51
35m	2.86	2.96	3.43	0.27	2.13	2.27	2.70	0.34	2.29	2.40	2.80	0.37
75m	3.77	3.85	4.45	0.20	2.93	3.03	3.55	0.26	3.16	3.24	3.74	0.27
150m	5.00	5.06	5.91	0.14	4.06	4.14	4.83	0.19	4.39	4.45	5.11	0.19

Table 3: Forecast skill statistics for Weather Station 3, relevant to each of the three local forecast sites.

	Elkins				Hot Springs				Lewisburg			
6 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.84	1.68	2.13	0.47	0.31	1.63	2.09	0.39	0.35	1.58	2.04	0.43
35m	2.42	2.74	3.34	0.44	1.69	2.30	2.88	0.37	1.78	2.28	2.87	0.42
75m	3.38	3.56	4.28	0.42	2.60	2.95	3.64	0.36	2.77	3.03	3.70	0.40
150m	4.72	4.84	5.74	0.39	3.96	4.12	4.95	0.37	4.22	4.33	5.11	0.39
12 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.83	1.69	2.13	0.47	0.33	1.61	2.07	0.40	0.39	1.59	2.03	0.44
35m	2.38	2.71	3.30	0.44	1.70	2.28	2.87	0.39	1.80	2.29	2.87	0.43
75m	3.32	3.52	4.21	0.42	2.60	2.95	3.62	0.38	2.76	3.02	3.68	0.41
150m	4.67	4.79	5.66	0.40	3.92	4.08	4.88	0.38	4.17	4.28	5.05	0.40
24 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.84	1.72	2.17	0.45	0.35	1.62	2.10	0.40	0.39	1.61	2.07	0.42
35m	2.41	2.75	3.35	0.43	1.73	2.33	2.92	0.38	1.81	2.34	2.92	0.41
75m	3.36	3.57	4.28	0.41	2.61	2.97	3.66	0.37	2.74	3.03	3.72	0.39
150m	4.72	4.86	5.74	0.38	3.88	4.05	4.89	0.38	4.11	4.24	5.05	0.38
36 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.84	1.72	2.17	0.44	0.34	1.64	2.12	0.38	0.40	1.62	2.08	0.41
35m	2.39	2.74	3.34	0.42	1.71	2.35	2.92	0.35	1.82	2.35	2.92	0.39
75m	3.35	3.56	4.26	0.40	2.57	2.98	3.64	0.35	2.75	3.05	3.72	0.37
150m	4.69	4.82	5.71	0.38	3.86	4.05	4.87	0.36	4.11	4.24	5.05	0.37
84 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.81	1.78	2.23	0.39	0.32	1.68	2.15	0.35	0.39	1.66	2.13	0.38
35m	2.36	2.79	3.38	0.37	1.67	2.36	2.94	0.33	1.81	2.39	2.96	0.36
75m	3.32	3.61	4.30	0.35	2.53	2.96	3.66	0.32	2.73	3.07	3.74	0.34
150m	4.68	4.86	5.75	0.33	3.81	4.01	4.85	0.34	4.09	4.25	5.04	0.34

Table 4: Forecast skill statistics for the individual Weather Stations, relevant to the averaged forecasts of the three local forecast sites.

	WS1				WS2				WS3			
6 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.60	1.19	1.44	0.63	1.14	1.28	1.50	0.61	0.50	1.57	2.00	0.47
35m	2.07	2.29	2.69	0.52	2.51	2.56	2.90	0.47	1.96	2.33	2.89	0.45
75m	3.02	3.17	3.69	0.43	3.40	3.45	3.90	0.36	2.91	3.10	3.74	0.43
150m	4.41	4.53	5.26	0.32	4.68	4.72	5.40	0.25	4.30	4.39	5.15	0.41
12 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.61	1.20	1.46	0.62	1.17	1.29	1.51	0.62	0.51	1.57	1.99	0.48
35m	2.06	2.30	2.69	0.52	2.54	2.58	2.92	0.49	1.96	2.33	2.89	0.46
75m	3.00	3.16	3.67	0.44	3.42	3.45	3.89	0.39	2.90	3.09	3.72	0.44
150m	4.36	4.48	5.19	0.33	4.67	4.68	5.34	0.28	4.25	4.35	5.09	0.42
24 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.62	1.21	1.47	0.62	1.14	1.28	1.51	0.60	0.53	1.59	2.03	0.46
35m	2.08	2.32	2.72	0.52	2.50	2.55	2.90	0.46	1.98	2.37	2.94	0.44
75m	3.01	3.17	3.69	0.45	3.36	3.40	3.85	0.37	2.90	3.11	3.76	0.42
150m	4.34	4.46	5.18	0.35	4.56	4.59	5.25	0.28	4.24	4.33	5.11	0.41
36 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.62	1.23	1.51	0.59	1.13	1.29	1.51	0.58	0.52	1.60	2.04	0.45
35m	2.07	2.32	2.73	0.49	2.49	2.56	2.89	0.44	1.97	2.39	2.94	0.43
75m	2.99	3.17	3.68	0.41	3.35	3.39	3.84	0.35	2.89	3.12	3.75	0.41
150m	4.32	4.45	5.17	0.32	4.55	4.58	5.23	0.26	4.22	4.32	5.09	0.39
84 hour Forecast												
Height	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R	Bias	MAE	RMSE	R
Surface	0.59	1.27	1.56	0.54	1.10	1.29	1.52	0.51	0.51	1.66	2.09	0.41
35m	2.03	2.32	2.75	0.44	2.43	2.51	2.86	0.37	1.95	2.42	2.97	0.39
75m	2.95	3.16	3.70	0.37	3.28	3.35	3.80	0.27	2.86	3.13	3.78	0.37
150m	4.29	4.44	5.17	0.27	4.48	4.54	5.18	0.19	4.19	4.33	5.11	0.36