QUANTIFYING TROPICAL CYCLONE TRACK FORECAST UNCERTAINTY AND IMPROVING EXTENDED-RANGE TROPICAL CYCLONE TRACK FORECASTS USING AN ENSEMBLE OF DYNAMICAL MODELS

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1. INTRODUCTION

Consensus tropical cyclone (TC) track forecast aids formed using TC track forecasts from regional and global numerical weather prediction models have become increasingly important in recent years as guidance to TC forecasters at both the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (Goerss et al. 2004). Forecasters at NHC routinely utilize consensus forecast aids (e.g., GUNA) formed using the interpolated TC track forecasts from the GFDL model (GFDI; Kurihara et al. 1993, 1995, 1998) and the Global Forecast System (AVNI; Lord 1993) run at NCEP, the Navy Operational Global Atmospheric Prediction System (NGPI; Hogan and Rosmond 1991, Goerss and Jeffries 1994), and the UK Meteorological Office global model (UKMI; Cullen 1993, Heming et al. 1995). In this study a second consensus aid (CONU) is formed using the interpolated TC track forecasts from the GFDL model (GFNI; Rennick 1999) run at FNMOC along with those from the aforementioned models. The TC track forecast performance of CONU is compared with that of GUNA.

The primary purpose of this study is to determine to what extent the TC track forecast error of the consensus models, GUNA and CONU, can be predicted prior to the time when official forecasts must be issued. Predictors of consensus forecast error must be quantities that are available prior to the time when official forecasts must be issued. Consensus model spread is defined to be the average distance of the member forecasts from the consensus forecast. Forecast displacement is defined to be the difference between the initial and forecast latitudes (or longitudes). The possible predictors examined in this study are consensus model spread; initial and forecast TC intensity; initial TC location and forecast displacement of TC location (latitude and longitude); TC speed of motion; and the number of members available to the consensus model (for CONU).

2. CONSENSUS MODEL TRACK FORECAST PERFORMANCE

The interpolated versions of the aforementioned five high-quality TC track forecast models available to the forecasters at NHC were used in this study. GUNA is a consensus model routinely used by the forecasters at NHC which is computed when the track forecasts from all four models (GFDI, AVNI, NGPI, and UKMI) are available. CONU is a consensus model computed when track forecasts from at least two of the five models (GFDI, AVNI, NGPI, UKMI, and GFNI) are available. The TC track forecast performance for the consensus models and individual models was determined for the 2001-2003 Atlantic hurricane seasons. A homogeneous comparison of the TC track forecast errors for GUNA and the individual models it is computed from is shown in Fig. 1. The TC track forecast errors for the individual models ranged from 68-81 nm at 24 h,122-145 nm at 48 h, 186-216 nm at 72 h, 241-306 nm at 96 h, and 312-385 nm at 120 h. The respective errors for GUNA were 61 nm, 112 nm, 165 nm, 214 nm, and 271 nm.

One difference between GUNA and CONU is the addition of the GFNI to the pool of models used to form the consensus. For a homogeneous sample, the respective TC track forecast errors for GFDI and GFNI were 69 and 74 nm at 24 h, 131 and 138 nm at 48 h, and 212 and 210 nm at 72 h.

Based on this comparison and the one shown in Fig.1, we conclude that the forecast performance of GFNI is comparable to that for GFDI and the other individual models used to form GUNA. While guidance from GFNI was only available out to 72 h for the 2001-2003 seasons, it will be available out to 120 h for the 2004 season.

A homogeneous comparison of the TC track forecast errors for GUNA, CONU, and NHC Official for the three seasons is shown in Fig. 2. The CONU forecast errors were slightly smaller than those for GUNA out to 72 h, and the errors for both consensus models were slightly smaller than the official errors. Since the GFNI forecasts were only made to 72 h, the CONU and GUNA forecast errors are identical at 96 h and 120 h. The official errors were the same as those for the consensus models at 96 h and slightly smaller than those for the consensus models at 120 h.

The major difference between GUNA and CONU is that the forecasts from all four models must be present before the former can be computed while the latter can be computed when forecasts from at least two of five models are available. A homogeneous comparison of the TC track forecast errors for CONU and NHC Official for the three seasons is shown in Fig. 3. Just as we saw in Fig. 2, the CONU forecast errors were slightly smaller than the official errors out to 72 h and were slightly greater than the official errors at 96 h and 120 h. For all forecast lengths, the number of forecasts in the homogeneous comparison shown in Fig 3 is larger than that for the homogeneous comparison shown in Fig. 2. This increase is due to the number of CONU forecasts that can be determined when all of the four models required for GUNA are not available but at least two of the five CONU models are. It should be noted that the CONU and NHC Official forecast errors in Fig. 3 are larger than those shown in Fig. 2. This increase in forecast error is primarily due to two things: (1) the error for 2-model and 3-model consensus forecasts is larger than the error for 4-model and 5-model consensus forecasts; and (2) the forecast errors for the individual NWP models decrease as TC intensity increases and one is much more likely to only have a 2-model or 3-model consensus for tropical depressions and weak tropical storms.

Finally, we define the consensus forecast availability to be the percent of the time that consensus forecasts were available to the forecaster when he/she was required to make a TC forecast. While the TC track forecast errors for CONU were found to be comparable to those for GUNA, the forecast availability for CONU was found to be superior to that for GUNA. As shown in Fig. 4, the respective forecast availability for GUNA and CONU was 72% and 91% at 24 h, 68% and 91% at 48 h, 65% and 90% at 72 h, 53% and 86% at 96 h, and 50% and 85% at 120 h. This dramatic increase in forecast availability may well be the attribute of CONU that will be most valuable to the forecaster.

3. ESTIMATION OF CONSENSUS MODEL TRACK FORECAST ERROR

The correlations between consensus model TC track forecast error and each of the aforementioned predictors were determined for the Atlantic and eastern North Pacific basins for 2001-2003. Using stepwise linear regression and the pool of predictors, regression models were found for each forecast length to predict the TC track forecast error of the consensus models. In the following sub-sections the results for the different consensus models and basins are described.

a. CONU for the Atlantic basin

For CONU in the Atlantic basin, the consensus model spread was found to be directly related to consensus model TC track forecast error for all forecast lengths. This relationship is illustrated in the scatter plots displayed in Figs. 5-9, where we see that, in general, larger (smaller) CONU forecast track error is associated with larger (smaller) model spread. The strongest relationship was found for the 96-h and 120-h CONU forecasts (Figs. 8 and 9) for which the correlations between spread and forecast error were 0.63 and 0.59, respectively. The correlations for the shorter forecast lengths ranged from 0.28 to 0.39 (Figs. 5-7). As shown in the scatter plots displayed in Figs. 10-14, initial and forecast TC intensity were found to be consistently but, in general, less strongly related to track error with correlations ranging from 0.30 to 0.40. TC intensity and CONU forecast track error were found to be inversely related with larger (smaller) track error associated with weaker (stronger) tropical cyclones. Note here, as shown in Figs. 10 and 11, that initial TC intensity is recorded in 5-kt increments while the values for forecast TC intensity are not constrained in any way. Other predictors were found to be reasonably well correlated with forecast error at certain forecast lengths. Scatter plots for some of the more highly correlated predictors for CONU 120-h forecast track error are displayed in Figs. 15-17. The inverse relationship (correlation of 0.52) between longitude displacement and track error is illustrated in Fig. 15 where we see that larger (smaller) track error is associated with larger eastward (westward) forecast displacements. In Fig. 16, we see that CONU 120-h forecast track error is directly related to initial TC latitude with a correlation of 0.43. Similar to what we saw in Fig. 14, the inverse relationship between track error and forecast TC intensity is illustrated in Fig. 17.

Using stepwise linear regression and the pool of predictors from the Atlantic basin for 2001-2003, regression models were found for each forecast length to predict the CONU TC track forecast error. To avoid over fitting the dependent data set, we required that a predictor explain at least 3% of the variance before allowing it to be used by the final regression equation. The regression equations and scatter plots displaying the relationship between CONU track forecast error and predicted error are shown in Figs.18-22. The model spread (SPR) was found to be the leading predictor at 96 h and 120 h and the second leading predictor at 24 h, 48 h and 72 h. Initial TC intensity (INTI) was found to be the leading predictor at 24 h and the third leading predictor at 120 h. Forecast TC intensity (INTF) was found to be the leading predictor at 48 h and 72 h and the second leading predictor at 96 h. Initial TC latitude (LATI) was found to be the second leading predictor at 120 h. Using these linear regression models, the percent variance of CONU TC track forecast error that could be explained for the 2001-2003 Atlantic seasons ranged from just over 15% at 48 h to nearly 50% at 120 h.

For the 2001-2003 Atlantic hurricane seasons, circular areas with static radii based on NHC's official forecast error for the last ten years of 81 nm at 24 h, 150 nm at 48 h, 225 nm at 72 h, 282 at 96 h, and 374 nm at 120 h drawn around the official forecasts contained the verifying TC position 67-71% of the time. For the same period, radii were computed by adding a constant varying with forecast length to the predicted TC forecast error derived using the linear regression models. The constants chosen were 15 nm at 24 h, 30 nm at 48 h, 45 nm at 72 h, 60 nm at 96 h, and 75 nm at 120 h. These predicted radii, which varied from 25-140 nm at 24 h, 40-250 nm at 48 h, 60-550 nm at 72 h, 75-1000 nm at 96 h, and 100-1200 nm at 120 h, were used to draw circular areas around each of the CONU forecast positions. These areas were found to contain the verifying TC position 72-74% of the time. These radii are represented in Figs. 18-21 by the dashed lines. The points below the lines represent the cases where the CONU forecast error is less than the predicted radius and the verifying TC position would be contained within the circular area surrounding the CONU forecast position. The points above the lines represent the cases where the CONU forecast error is greater than the predicted radius and the verifying TC position would be located outside the circular area surrounding the CONU forecast position. We illustrate the application of these predicted circular areas for two specific cases in Figs. 23 and 24. In Fig. 23, the 120-h CONU forecast for Hurricane Isabel made at 00Z September 13, 2003 is shown along with the predicted circular area. For this case, the verifying position of Isabel (indicated by the large blue dot) falls just within the boundary of this unusually small area (radius of approximately 100 nm), which is consistent with the small spread of the 120-h model forecasts for AVNI, GFDI, NGPI, and UKMI. On the other hand, in Fig. 24, the predicted circular area surrounding the 120-h CONU forecast for Hurricane Kate made at 00Z September 30, 2003 is quite large (radius of approximately 800 nm), which is consistent with the large spread of the 120-h model forecasts. This large spread is primarily due to the UKMI forecast, which is over 1000 nm east southeast of the CONU forecast position and even farther from the forecast positions of the other models. While the verifying position of Kate is contained within the circular area, it is approximate 600 nm from the CONU forecast position. Thus, based on the size of these circular areas, a forecaster can determine the confidence that can be placed upon the CONU forecasts and use that information in the process of producing the official forecast.

b. GUNA for the Atlantic basin

The relationship between consensus model spread and GUNA TC track forecast error in the Atlantic basin is quite similar to that for CONU. For all forecast lengths we see in the scatter plots displayed in Figs. 25-29 that larger (smaller) GUNA forecast track error is associated with larger (smaller) model spread. The strongest relationship was found for the 72-h, 96-h, and 120-h GUNA forecasts (Figs. 27-29) for which the correlations between spread and forecast error were 0.51, 0.68, and 0.57, respectively. The correlations for the 24-h and 48-h GUNA forecasts (Figs. 25 and 26) were 0.33 and 0.37, respectively. The inverse relationship between TC intensity and GUNA forecast error is illustrated in Figs. 30-32. The correlations between GUNA track forecast error and initial TC intensity for 24 h, 48 h, and 72 h were 0.32, 0.32, and 0.35, respectively. As we saw for CONU (Fig. 15), the inverse relationship (correlation of 0.51) between the 120-h GUNA track forecast error and longitude displacement is shown in Fig.33.

Following the same procedures outlined in the previous sub-section for CONU, regression models were found for each forecast length to predict the GUNA TC track forecast error. The regression equations and scatter plots displaying the relationship between GUNA track forecast error and predicted error are shown in Figs. 34-38. For GUNA, the model spread (SPR) was found to be the leading predictor for all forecast lengths and the only predictor at 96 h. Initial TC intensity (INTI) was found to be the second leading predictor at 24 h, 48 h, and 72 h while longitude displacement (LOND) was found to be the second leading predictor at 120 h. Using these linear regression models, the percent variance of GUNA TC track forecast error that could be explained for the 2001-2003 Atlantic seasons ranged from nearly 20% at 24 h to just over 45% at 96 h.

Just as was done for CONU, predicted radii were computed to be used to form circular areas around the GUNA forecast positions. For GUNA, these predicted radii varied from 25-145 nm at 24 h, 50-300 nm at 48 h, 60-500 nm at 72 h, 100-800 nm at 96 h, and 120-900 nm at 120 h. The points below the dashed lines in Figs. 34-38 represent the cases where the GUNA forecast error is less than the predicted radius and the verifying TC position would be contained within the circular area surrounding the GUNA forecast position. These areas were found to contain the verifying TC position 73-77% of the time.

c. CONU for the eastern North Pacific basin

The relationship between consensus model spread and forecast error for CONU in the eastern North Pacific basin was found to be weaker than the relationship found for the Atlantic basin. This is illustrated in the scatter plots displayed in Figs. 39-43 where we see that the strongest relationship was found for the 120-h CONU forecasts (Fig. 43) for which the correlation between spread and forecast error was 0.48. In Fig. 9, we see that the correlation for the Atlantic basin was 0.59. The largest difference between the two basins was at 96 h where the correlation for the eastern North Pacific basin was 0.23 (Fig. 42) while that for the Atlantic basin was 0.63 (Fig. 8). The correlations for the shorter forecast lengths ranged from 0.22 to 0.33 (Fig. 39-41). Unlike the Atlantic basin, the number of models available to CONU was found to be an important predictor. As shown in the scatter plots displayed in Fig. 44-48, the number of models was found to be consistently but less strongly related to forecast error than spread with correlations ranging from 0.20 to 0.26. As expected, the number of models available to CONU was inversely related to forecast error with larger (smaller) track error associated with fewer (more) available models. The inverse relationship between forecast TC intensity and CONU track forecast error for 96 h and 120 h is illustrated in Figs. 49 and 50, where the respective correlations were 0.17 and 0.25. While the correlation between initial TC latitude and the 120-h CONU forecast error was weak (Fig. 51), this predictor was chosen for the regression model.

Following the procedures previously outlined, regression models were found for each forecast length to predict the CONU TC track forecast error. The regression equations and scatter plots displaying the relationship between CONU track forecast error and predicted error are shown in Figs. 52-56. The model spread (SPR) was found to be the leading predictor for all forecast lengths. The number of models available to CONU (NUM) was found to be the second leading predictor for all forecast lengths except 120 h where it was found to be the third leading predictor. Forecast TC intensity (INTF) was found to be the second leading predictor at 120 h and the third leading predictor at 96 h. Finally, initial TC latitude (LATI) was found to be the fourth leading predictor at 120 h. Using these linear regression models, the percent variance of CONU TC track forecast error that could be explained for the 2001-2003 eastern North Pacific seasons ranged from 8% at 48 h to 35% at 120 h. For the Atlantic basin, where there was a stronger relationship between spread and forecast error, the percent variance explained was just over 15% at 48 h and nearly 50% at 120 h.

For the 2001-2003 eastern North Pacific hurricane seasons, circular areas with static radii based on NHC's official forecast error for the last ten years of 72 nm at 24 h, 131 nm at 48 h, and 185 nm at 72 h drawn around the official forecasts contained the verifying TC position 61-65% of the time. Areas with static radii based on the official forecast error for 2001-2002 of 196 nm at 96 h and 223 nm at 120 h contained the verifying TC position only 42-44% of the time. Clearly, to be consistent with the Atlantic basin, these radii, which are used to generate the Potential Day 1-5 Track Area graphic, should be adjusted. As described previously for the Atlantic basin, predicted radii were computed to be used to form circular areas around the CONU forecast positions. For CONU, these predicted radii varied from 50-220 nm at 24 h, 100-320 nm at 48 h, 140-440 nm at 72 h, 150-450 nm at 96 h, and 150-600 nm at 120 h. The points below the dashed lines in Figs. 52-56 represent the cases where the CONU forecast error is less than the predicted radius and the verifying TC position would be contained within the circular area surrounding the CONU forecast position. These areas were found to contain the verifying TC position 71-75% of the time.

d. GUNA for the eastern North Pacific basin

As we saw for CONU, the relationship between consensus model spread and forecast error for GUNA in the eastern North Pacific was not as strong as that found for the Atlantic. From the scatter plots displayed in Figs. 57-61, we see that the correlations between spread and forecast error was 0.24, 0.28, 0.41, 0.44, and 0.53 at 24 h, 48 h, 72 h, 96 h, and 120 h, respectively. The respective correlations for GUNA for the Atlantic (Figs. 25-29) were 0.33, 0.37, 0.51, 0.68, and 0.57. The inverse relationship between initial and forecast TC intensity and GUNA forecast error is illustrated in Figs. 62-65 where we see that the correlations range from 0.17 to 0.32. The inverse relationship (correlation of 0.22) between the 72-h GUNA track forecast error and latitude displacement is shown in Fig. 66.

Following the procedures outlined previously, regression models were found for each forecast length to predict the GUNA TC track forecast error. The regression equations and scatter plots displaying the relationship between GUNA track forecast error and predicted error are shown in Figs. 67-71. For GUNA, the model spread (SPR) was found to be the leading predictor for all forecast lengths and the only predictor at 120 h. Initial TC intensity (INTI) was found to be the second leading predictor at 24 h and 48 h. Forecast TC intensity (INTF) was found to be the second leading predictor at 96 h and the third leading predictor at 72 h while latitude displacement (LATD) was found to be the second leading predictor at 72 h. Using these linear regression models, the percent variance of GUNA TC track forecast error that could be explained for the 2001-2003 eastern North Pacific seasons ranged from nearly 10% at 24 h to nearly 30% at 120 h.

Just as was done for CONU, predicted radii were computed to be used to form circular areas around the GUNA forecast positions. For GUNA, these predicted radii varied from 40-180 nm at 24 h, 80-210 nm at 48 h, 100-380 nm at 72 h, 140-340 nm at 96 h, and 210-540 nm at 120 h. The points below the dashed lines in Figs. 67-71 represent the cases where the GUNA forecast error is less than the predicted radius and the verifying TC position would be contained within the circular area surrounding the GUNA forecast position. These areas were found to contain the verifying TC position 71-79% of the time.

e. Independent data testing

Finally, we outline the results of the independent data testing that was performed for CONU for the Atlantic basin. For each forecast length, regression equations were computed using stepwise linear regression and the pool of predictors from the Atlantic basin for 2001-2002. Using these equations derived from the previous two seasons, predicted TC forecast errors were then computed for the 2003 Atlantic season. Scatter plots displaying the relationship between CONU track forecast error and the independent predicted error are shown in Figs. 72-76. While the values of the various regression coefficients vary, we found that the predictors chosen to be used at each forecast length were the same as those chosen when the 2001-2003 Atlantic seasons were used as the dependent data set. Using these linear regression models, the percent variance of the CONU track forecast error that could be explained for the 2003 Atlantic season ranged from 23% at 24 h to 46% at 96 h, quite similar to what we found from the dependent testing outlined in Section 3a. Just as was done previously, predicted radii were computed to be used to form circular areas around the CONU forecast positions. For this independent sample, these predicted radii varied from 25-150 nm at 24 h, 30-340 nm at 48 h, 45-550 nm at 72 h, 60-650 nm at 96 h, and 75-850 nm at 120 h. The points below the dashed lines in Figs. 72-76 represent the cases where the CONU forecast error is less than the predicted radius and the verifying TC position would be contained within the circular area surrounding the CONU forecast position. These areas were found to contain the verifying TC position 68-83% of the time and, except for 120 h, the percentages were actually higher than those found for the dependent sample (Figs. 18-22). In all areas of comparison we see that the results found from independent testing compare quite favorably with those found from dependent testing. Although not shown in this report, we found the same thing when we conducted independent testing for GUNA in the Atlantic basin and for both consensus models in the eastern North Pacific basin. We conclude from our independent testing that the regression equations derived from previous seasons appear to be quite stable and can be effectively applied to the next season.

4. SUMMARY AND CONCLUSIONS

In this study, we first examined the TC track forecast performance of two consensus models, GUNA and CONU, for the 2001-2003 Atlantic hurricane seasons. GUNA is a consensus model computed when the track forecasts from GFDI, AVNI, NGPI, and UKMI are available. CONU is a less restrictive consensus model computed when the track forecasts from at least two models from a pool of five models (the aforementioned four models and GFNI) are available. In a homogeneous comparison for the 2001-2003 Atlantic seasons we found that the CONU forecast errors were slightly smaller than those for GUNA out to 72 h. This slight improvement was due to the addition of GFNI to the pool of models available to CONU. While the TC track forecast errors for CONU were found to be comparable to those for GUNA, the forecast availability for CONU was found to be superior to that for GUNA. The forecast availability for CONU ranged from 91% at 24 h and 48 h to 85% at 120h, while that for GUNA ranged from only 72% at 24 h to only 50% at 120 h.

The primary purpose of this study was to determine to what extent the TC track forecast error of the consensus models, GUNA and CONU, can be predicted prior to the time when official forecasts must be issued. The possible predictors examined in this study were consensus model spread; initial and forecast TC intensity; initial TC location and forecast displacement of TC location (latitude and longitude); TC speed of motion; and the number of members available to the consensus model (for CONU).

After examination of both consensus models for both the Atlantic and eastern North Pacific basins, it was found that consensus model spread was the most important predictor followed by TC intensity (either initial or forecast). For certain combinations of forecast length, consensus model, and basin, some of the other predictors proved important as well. Consensus model spread was found to be directly related to consensus model TC track forecast error while intensity was found to be inversely related.

Using stepwise linear regression and the pool of predictors for the 2001-2003 seasons, regression models were found to predict consensus model TC track forecast error for each combination of forecast length, consensus model, and basin. For both CONU and GUNA and for both basins, it was found that the regression models explained more of the track forecast error variance for the longer forecast lengths (96 h and 120 h) than they did for the shorter forecast lengths (24 h and 72 h). For both consensus models, the regression models consistently explained more of the track forecast error variance for the Atlantic basin (15-20% for the shorter forecast lengths and 45-50% for the longer forecast lengths) than for the eastern North Pacific basin (about 10% for the shorter forecast lengths and 30-35% for the longer forecast lengths).

Predicted radii were derived by adding a constant, which varied with respect to forecast length, to the track forecast error predicted by the regression models. These radii were used to draw circular areas around each of the consensus model forecast positions for each combination of forecast length, consensus model, and basin. The additive constants were chosen so that for both consensus models and both basins, the verifying TC position was contained within the circular area surrounding the consensus model forecast position 71-79% of the time for the 2001-2003 seasons. For both models in the Atlantic basin, these predicted radii varied from 25-145 nm at 24 h, 40-300 nm at 48 h, 60-550 nm at 72 h, 75-1000 nm at 96 h, and 100-1200 nm at 120 h. For both models in the eastern North Pacific basin, these radii varied from 40-220 nm at 24 h, 80-320 nm at 48 h, 100-440 nm at 72 h, 140-450 nm at 96 h, and 150-600 nm at 120 h. Based on the size of these radii, a forecaster can determine how much (or little) confidence can be ascribed to the consensus model forecast position.

Finally, independent data testing was performed for both consensus models for both basins. The 2001-2002 seasons were used as the dependent data set and regression models were derived. These regression models were then applied to the 2003 seasons. In all areas of comparison (percent variance of consensus model track forecast error explained, range of the predicted radii, and percent of verifying TC positions contained within the circular areas), we found that the results from the independent testing compared quite favorably with those found from dependent testing. Thus, we concluded that we should be able to effectively utilize the regression models determined from the 2001-2003 seasons to produce guidance to be used during the 2004 season.

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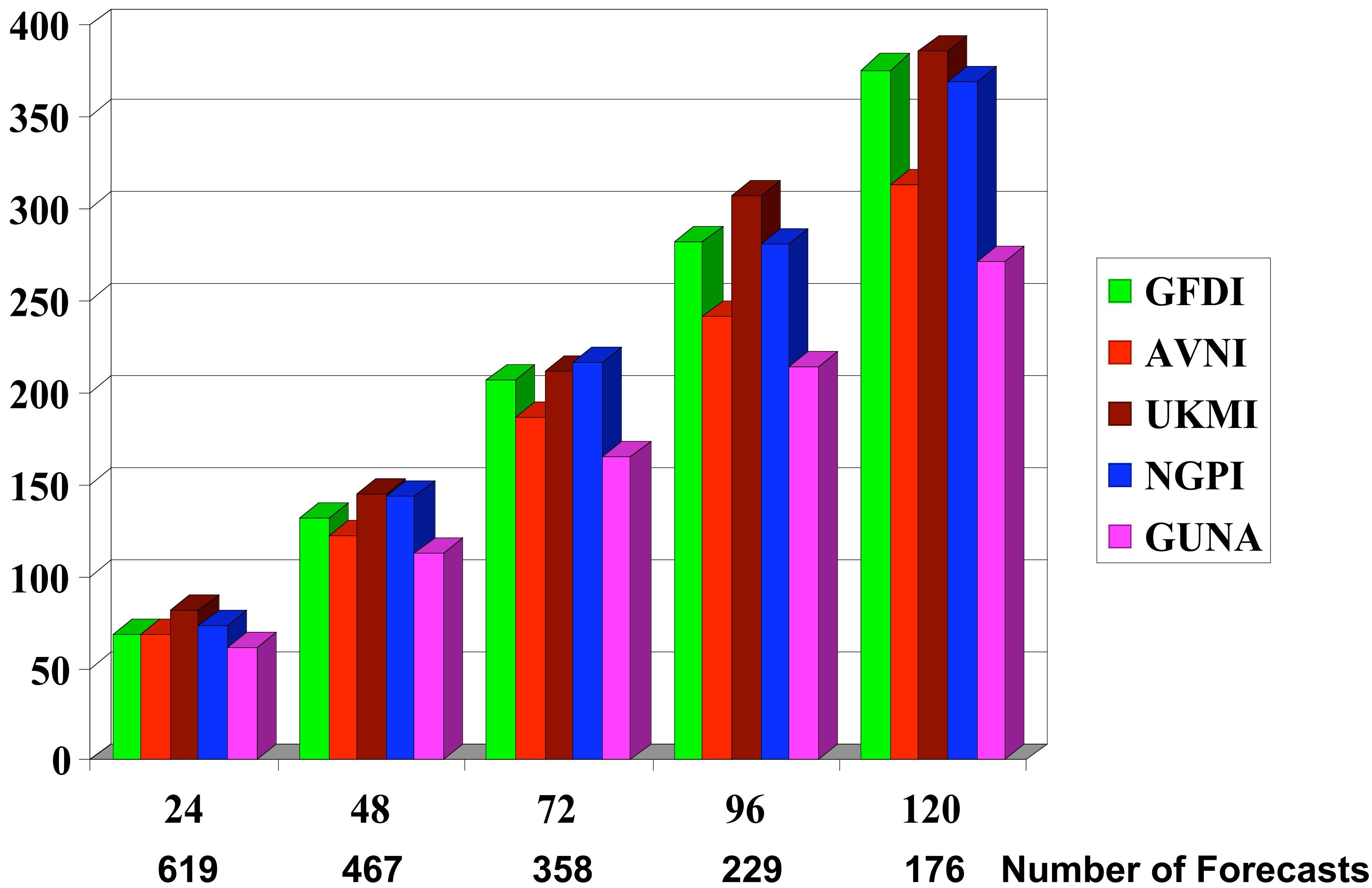

Fig. 1. Homogeneous comparison of TC track forecast error (nm) for the 2001-2003 Atlantic hurricane seasons

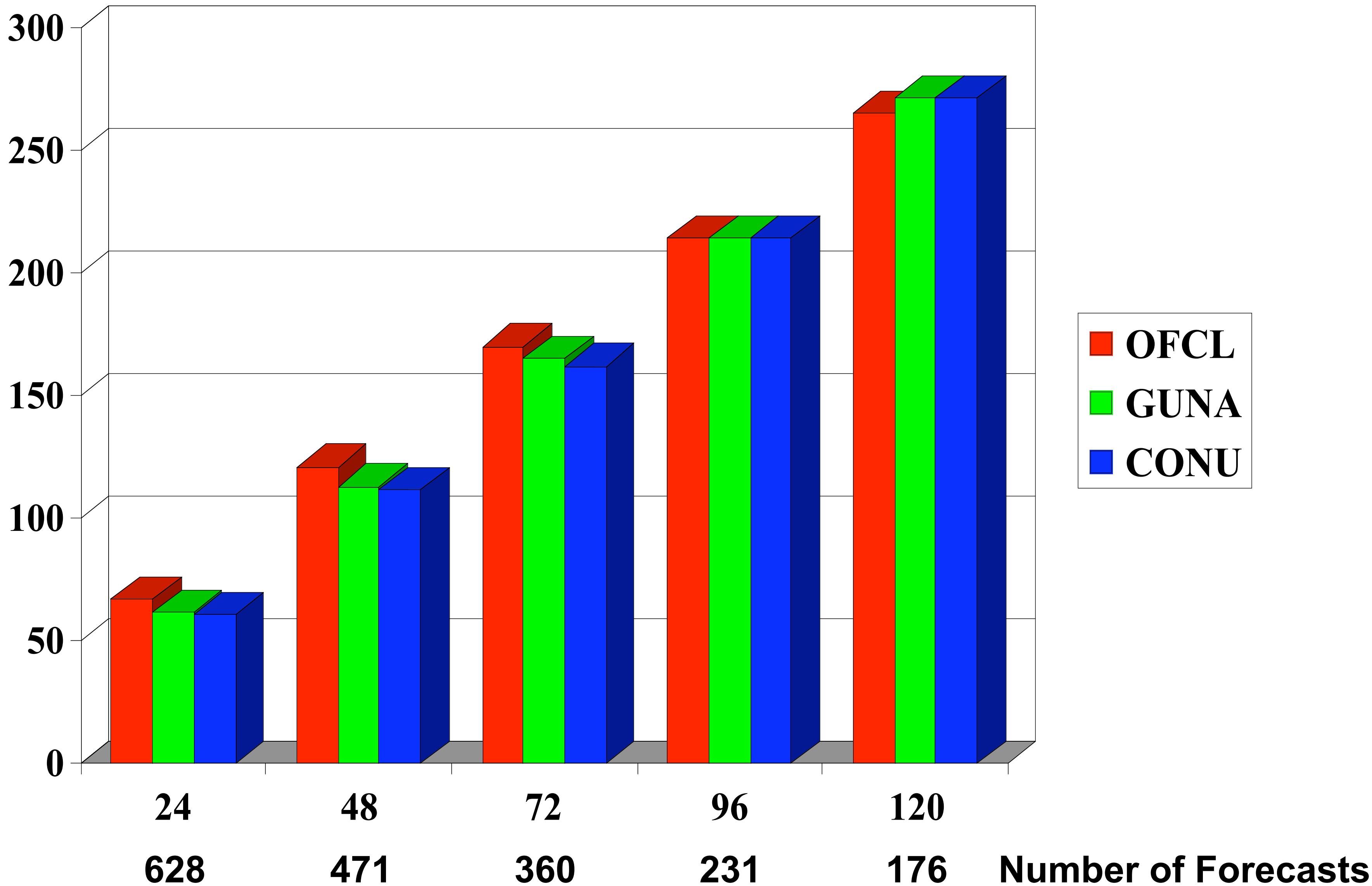

Fig. 2. Homogeneous comparison of TC track forecast error (nm) for the 2001-2003 Atlantic hurricane seasons

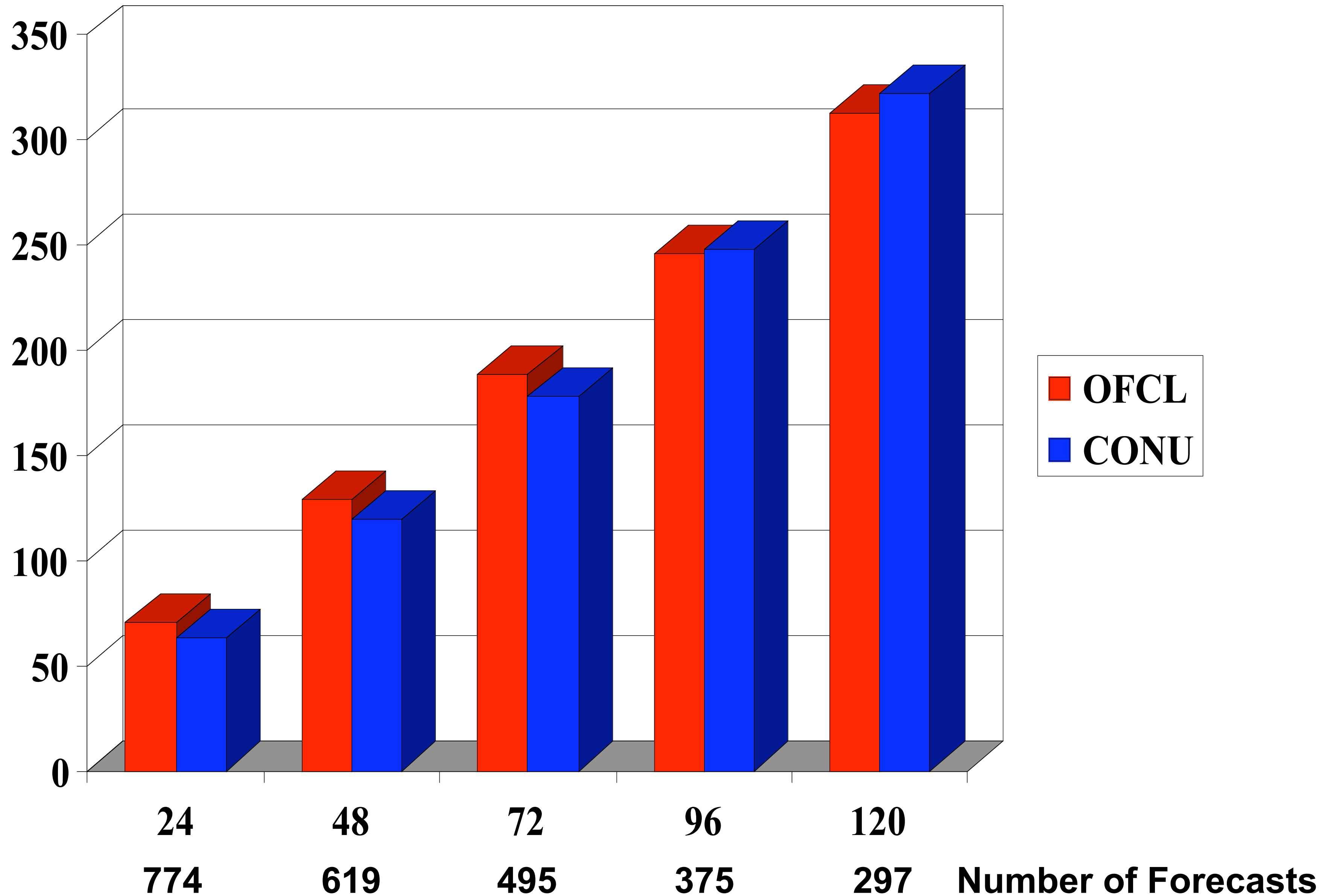

Fig. 3. Homogeneous comparison of TC track forecast error (nm) for the 2001-2003 Atlantic hurricane seasons

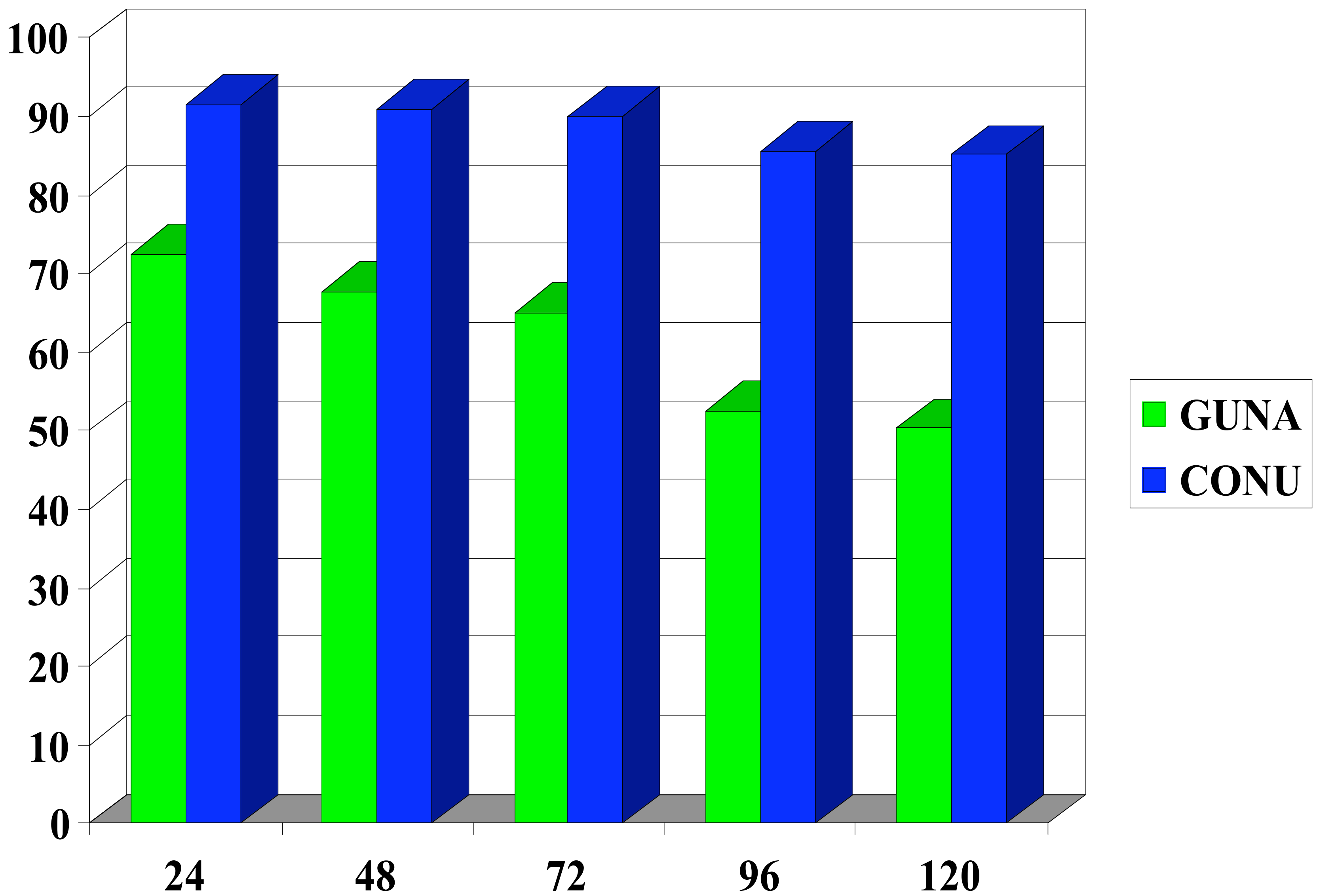

Fig. 4. Consensus model forecast availabilty (percent) for the 2001-2003 Atlantic hurricane seasons

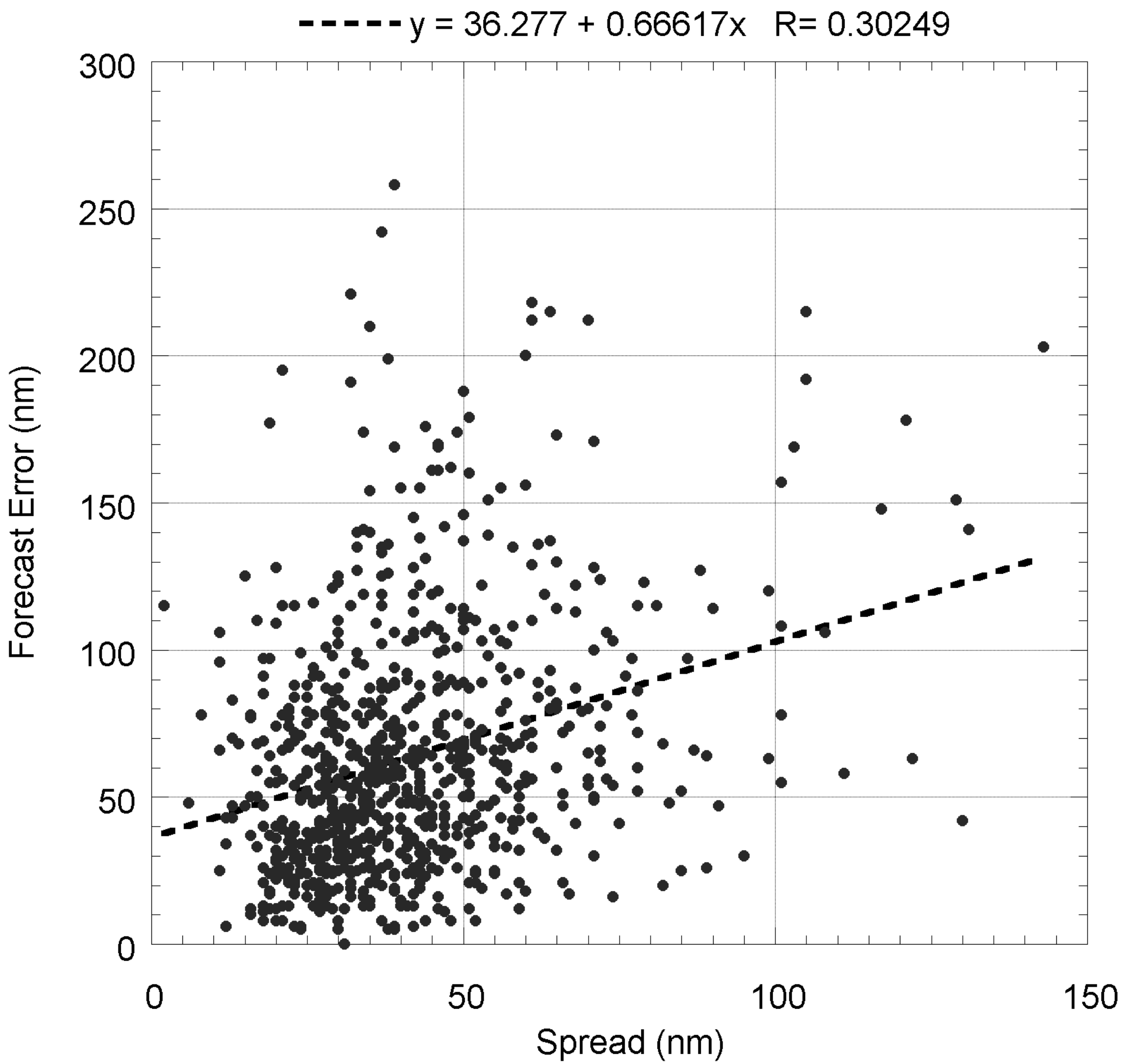

Fig. 5. CONU 24-h track forecast error vs. spread for 2001-2003 Atlantic

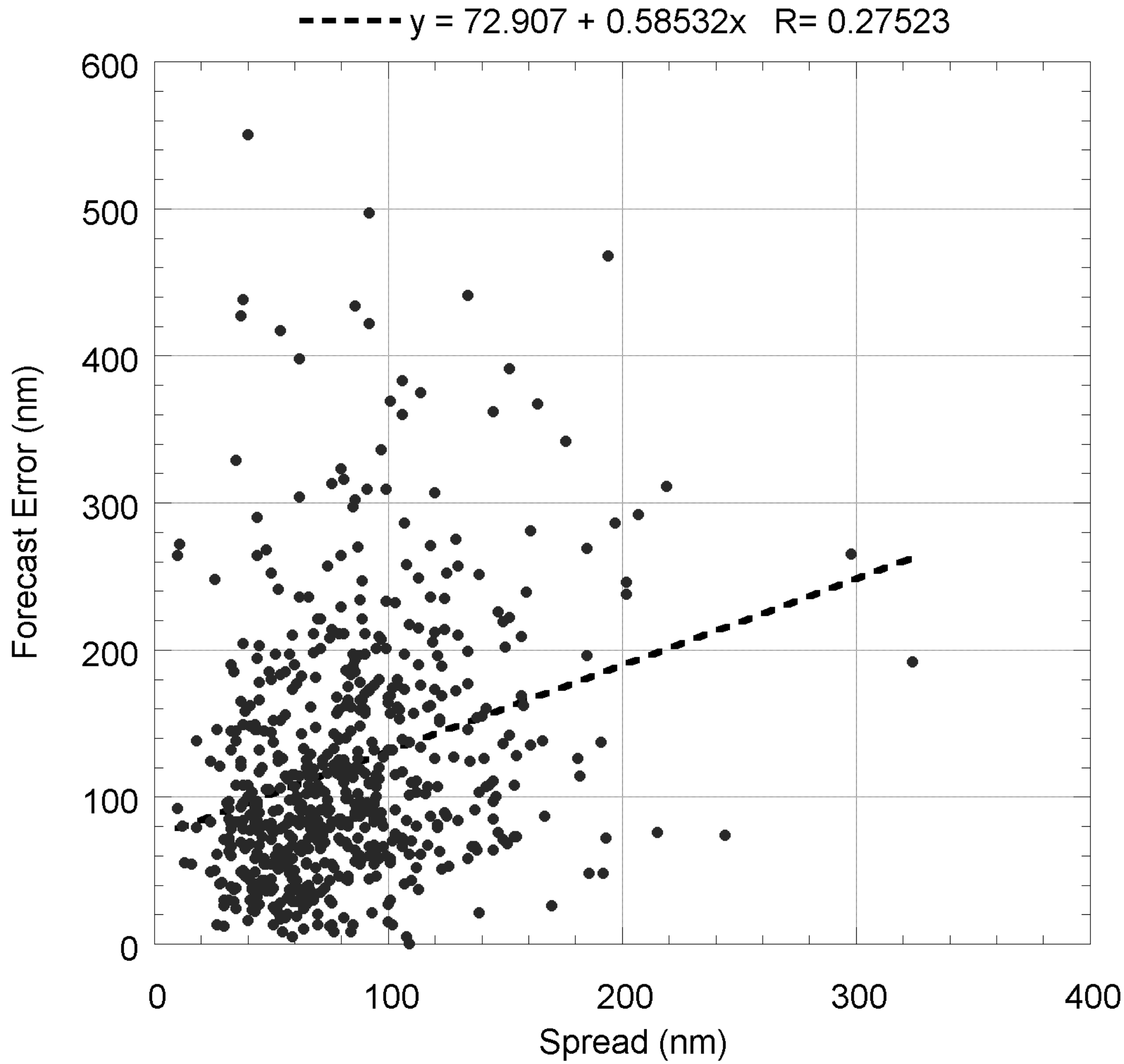

Fig. 6. CONU 48-h track forecast error vs. spread for 2001-2003 Atlantic

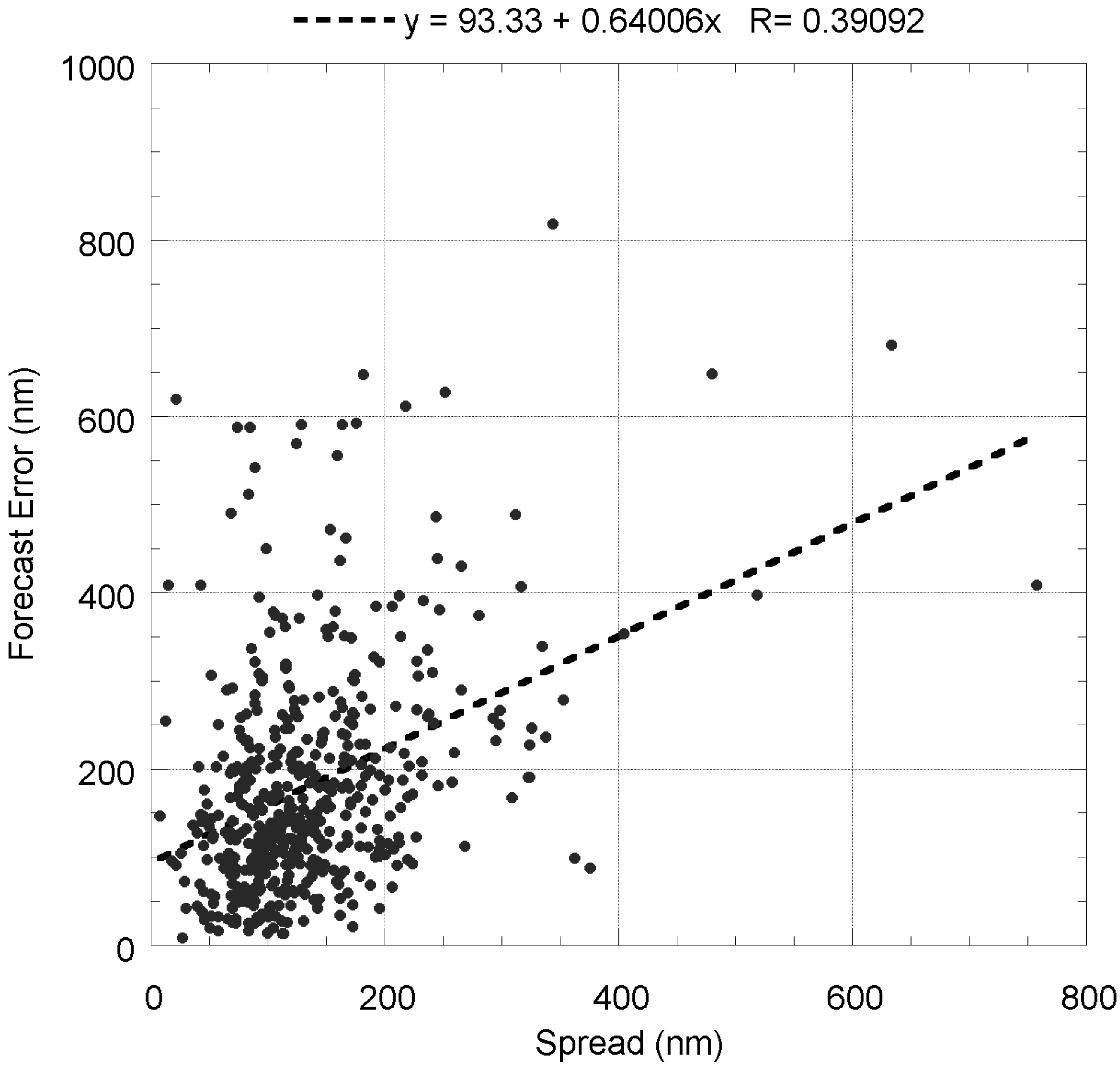

Fig. 7. CONU 72-h track forecast error vs. spread for 2001-2003 Atlantic

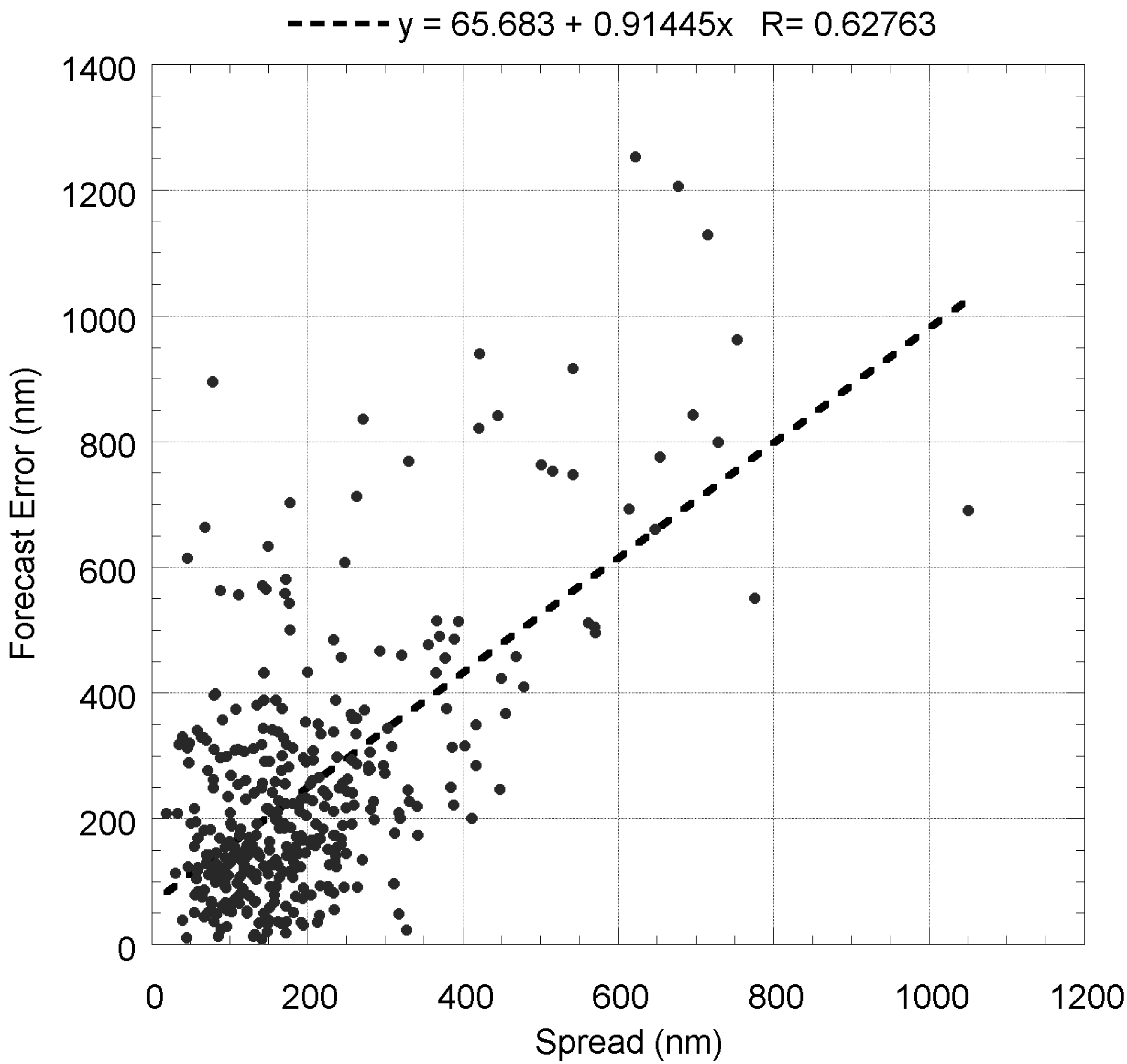

Fig. 8. CONU 96-h track forecast error vs. spread for 2001-2003 Atlantic

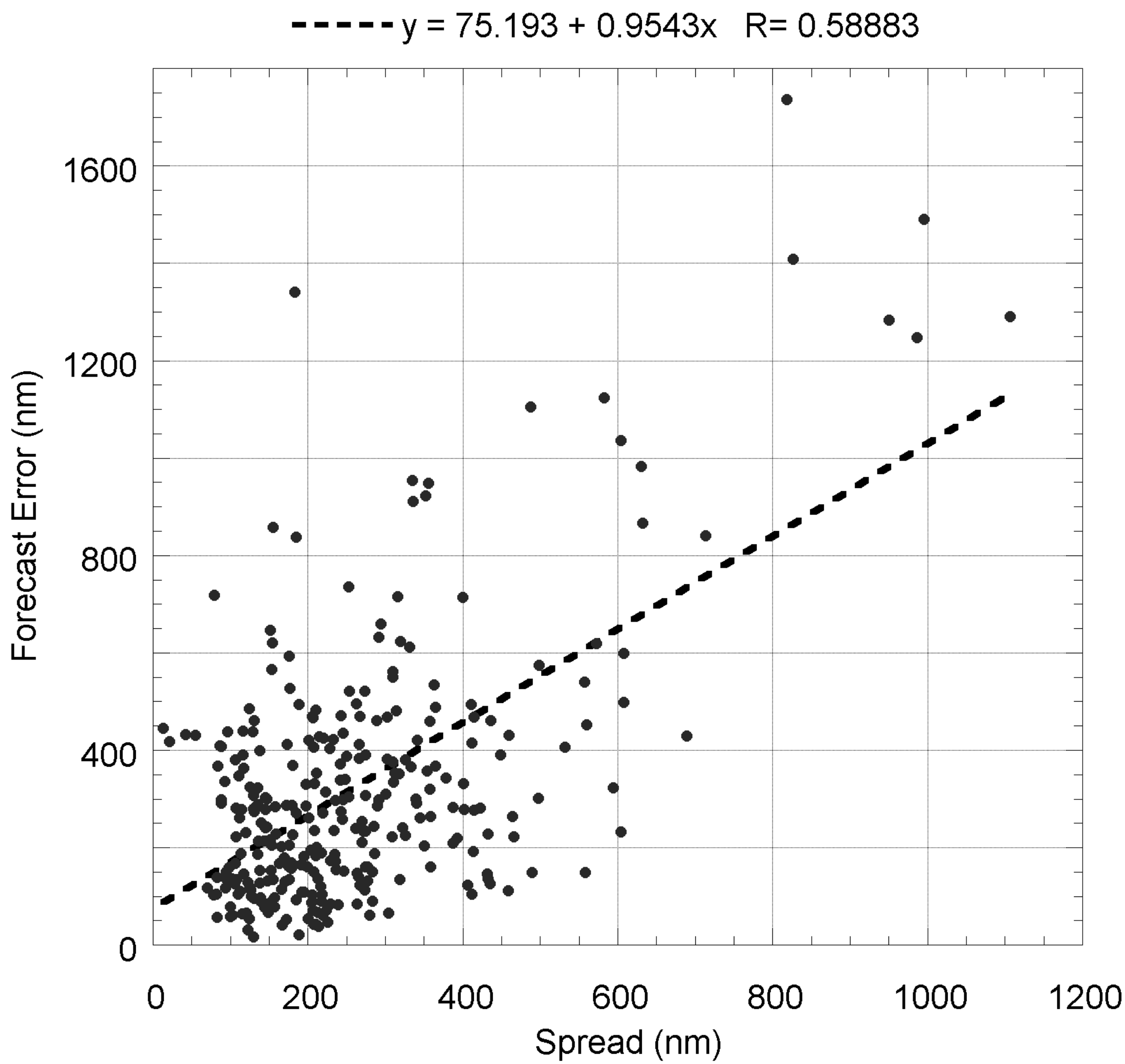

Fig. 9. CONU 120-h track forecast error vs. spread for 2001-2003 Atlantic

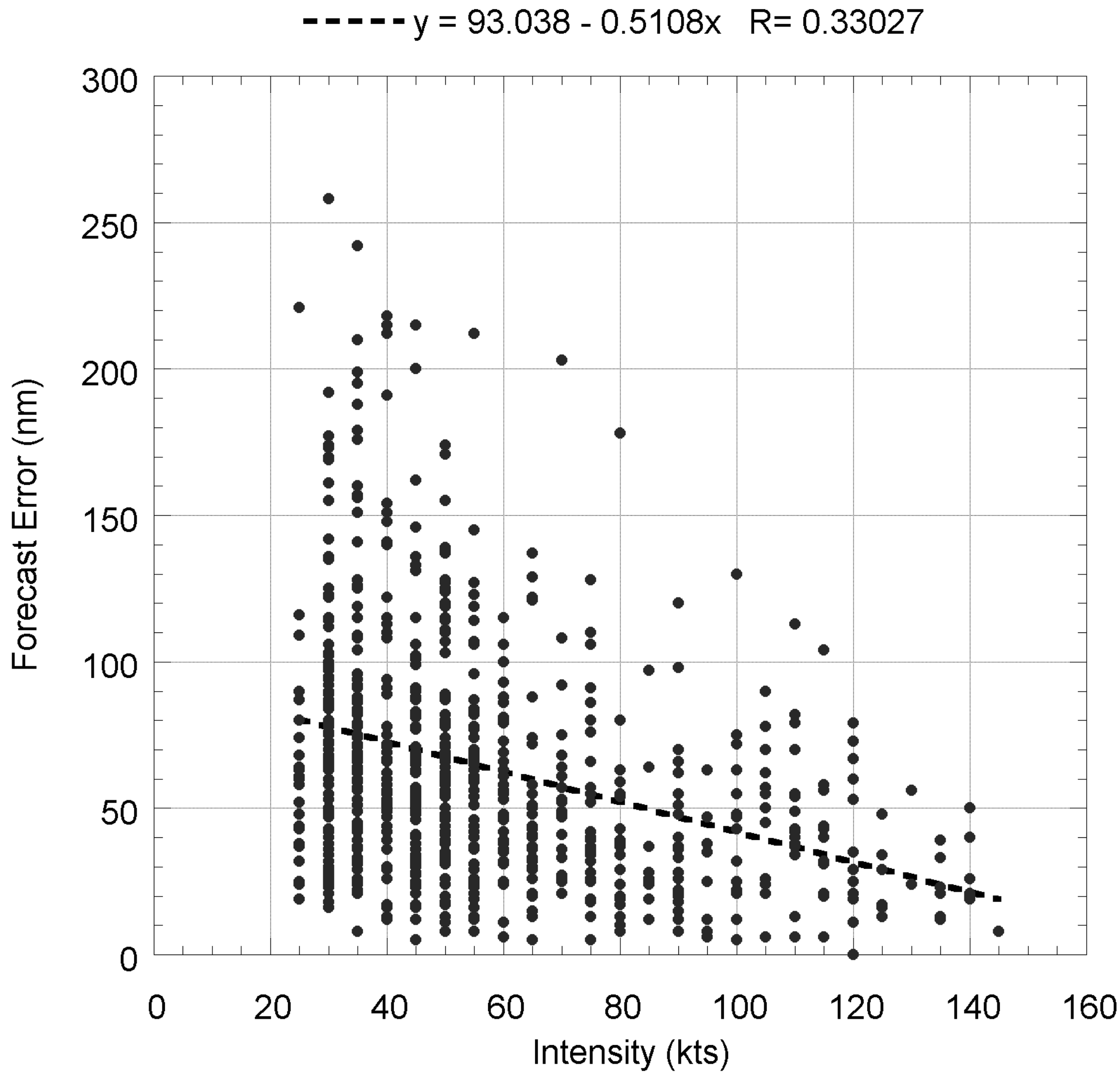

Fig. 10. CONU 24-h track forecast error vs. initial TC intensity for 2001-2003 Atlantic

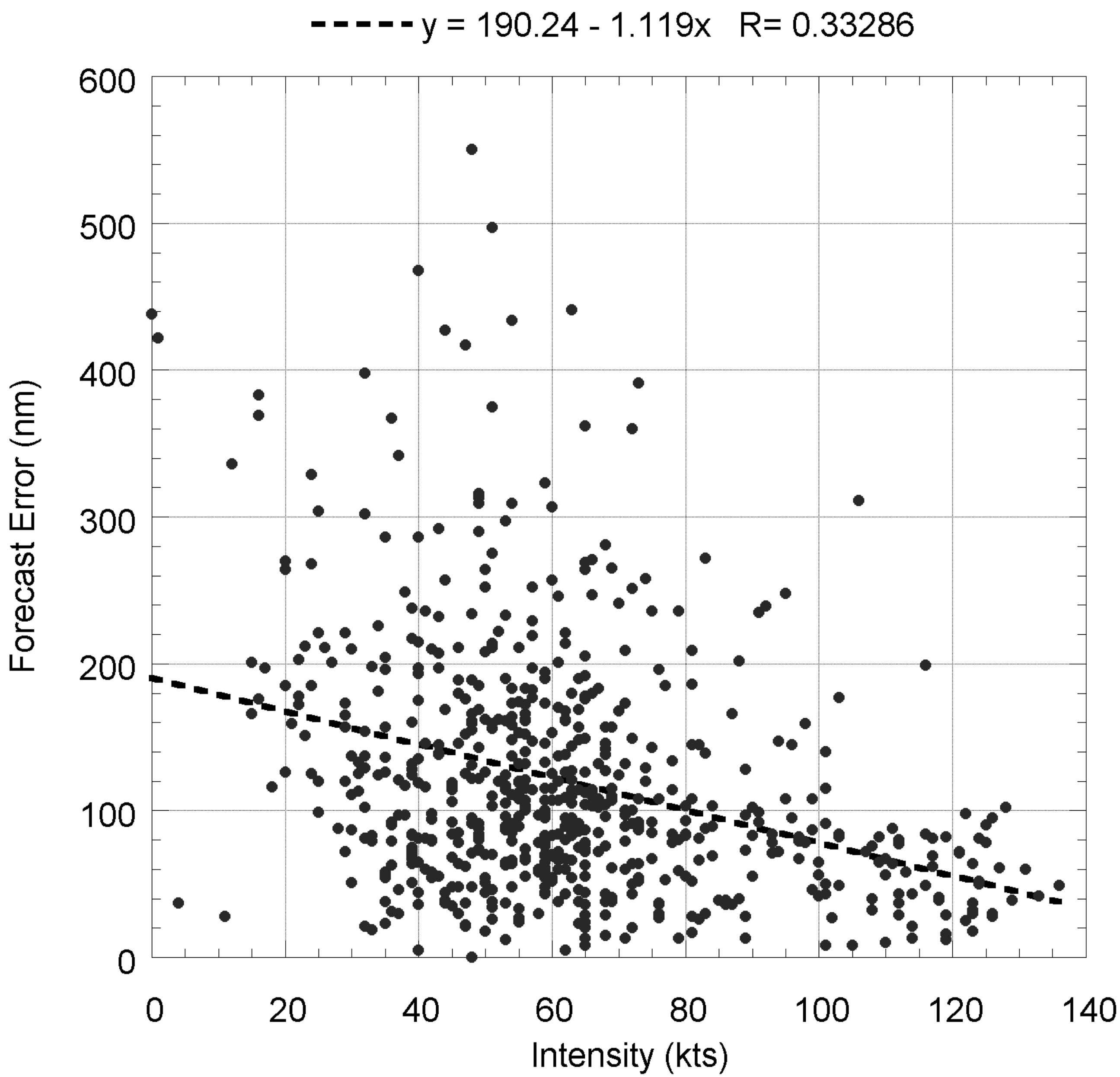

Fig. 11. CONU 48-h track forecast error vs. forecast TC intensity for 2001-2003 Atlantic

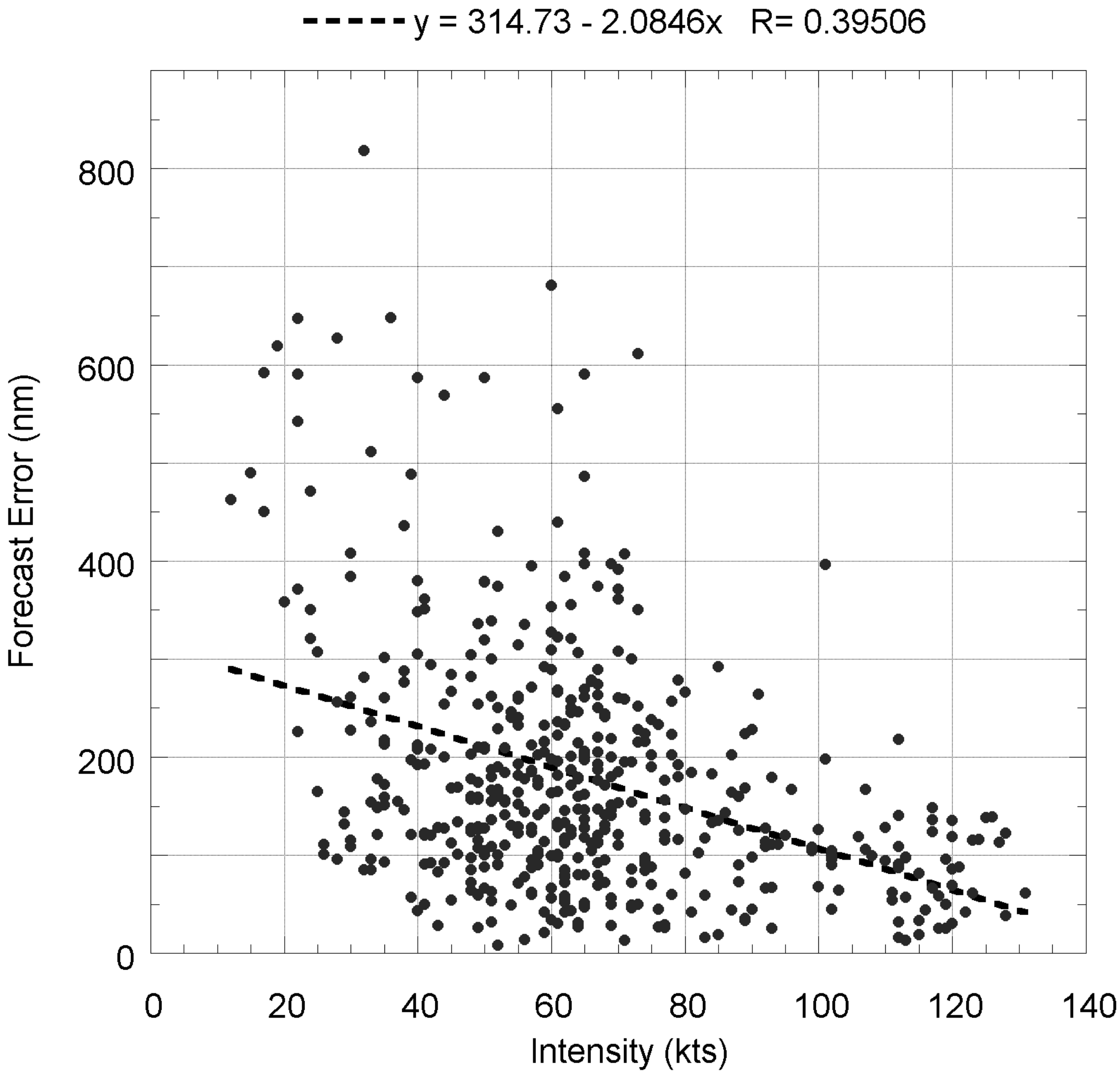

Fig. 12. CONU 72-h track forecast error vs. forecast TC intensity for 2001-2003 Atlantic

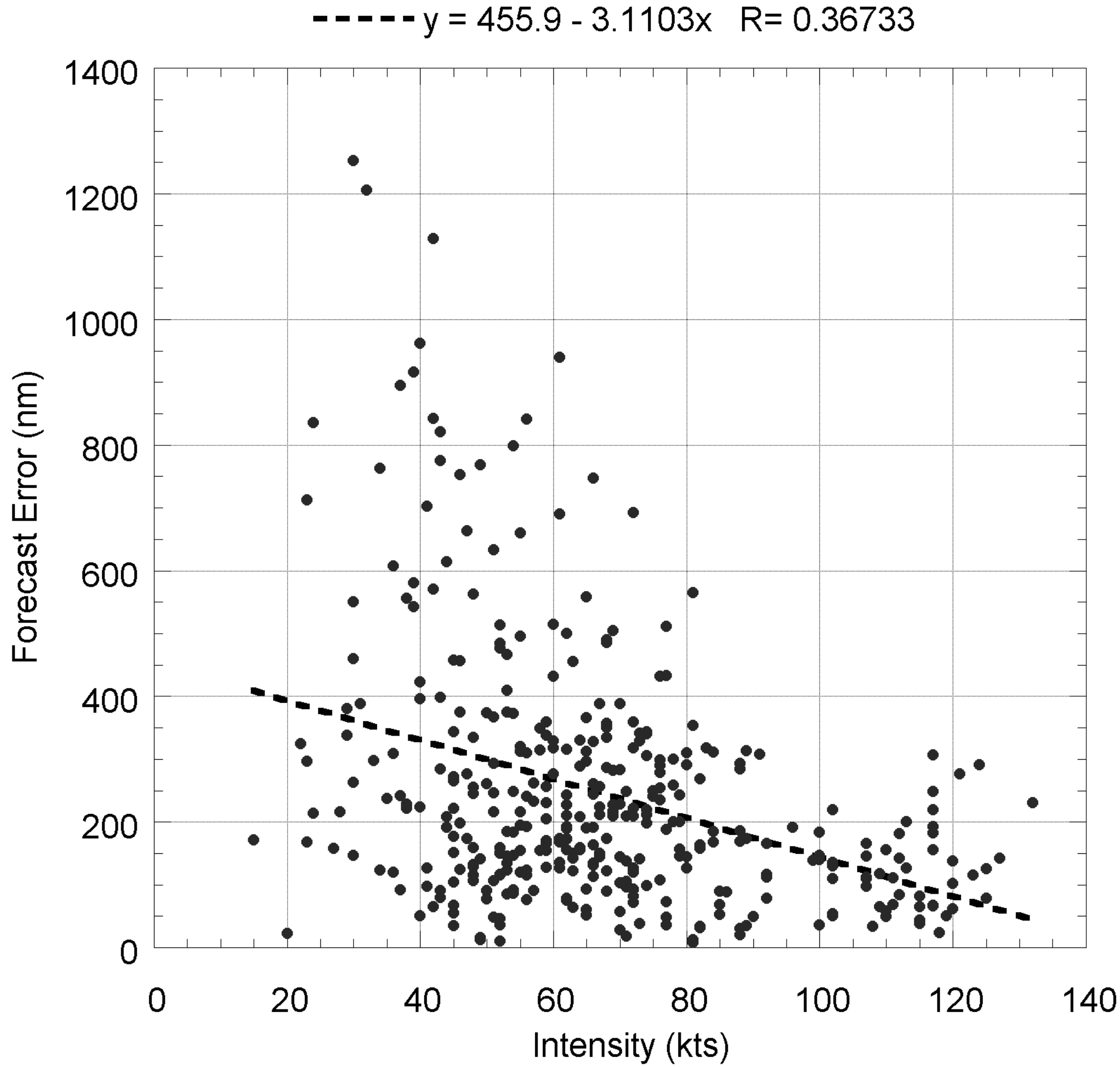

Fig. 13. CONU 96-h track forecast error vs. forecast TC intensity for 2001-2003 Atlantic

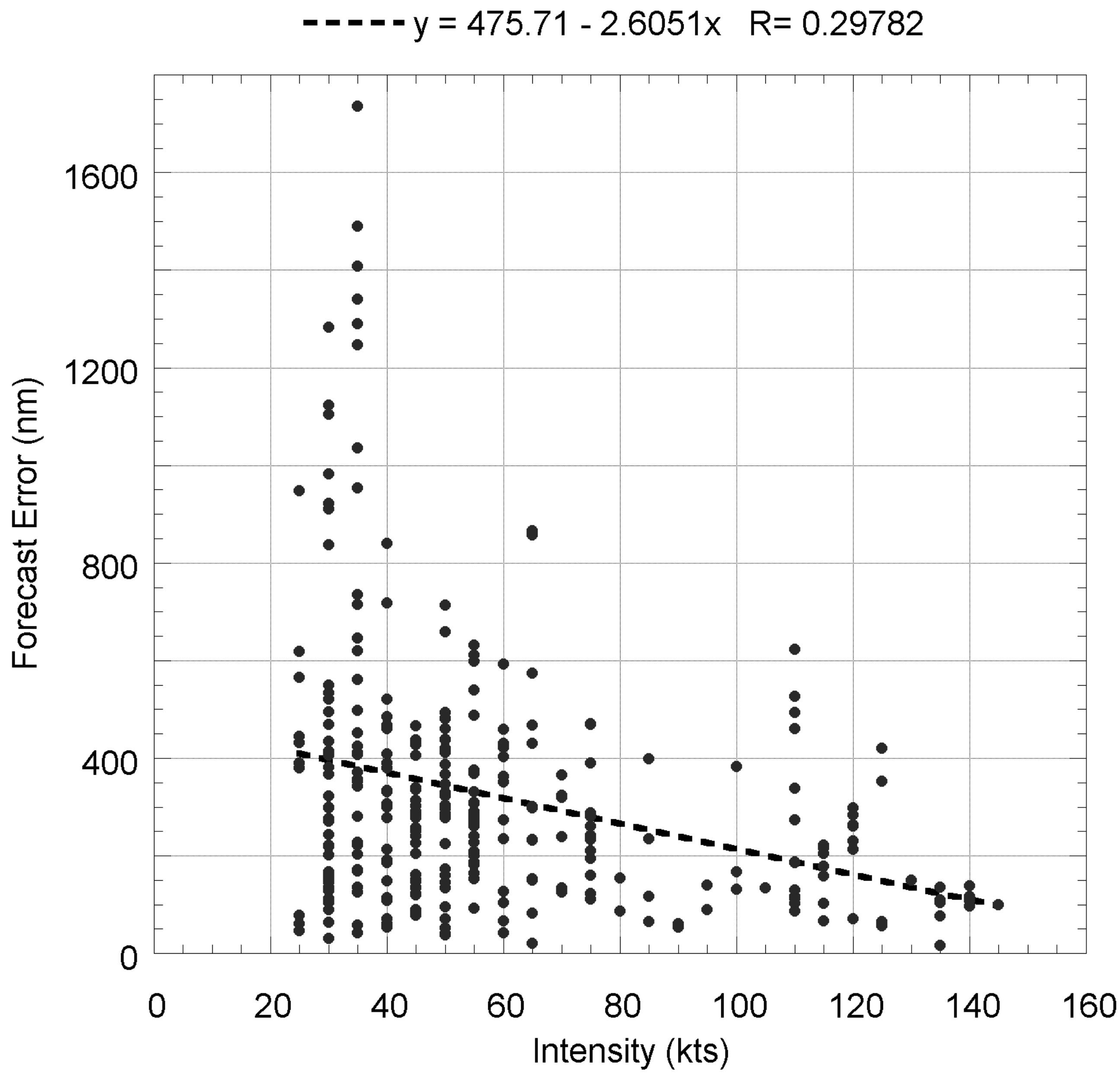

Fig. 14. CONU 120-h track forecast error vs. initial TC intensity for 2001-2003 Atlantic

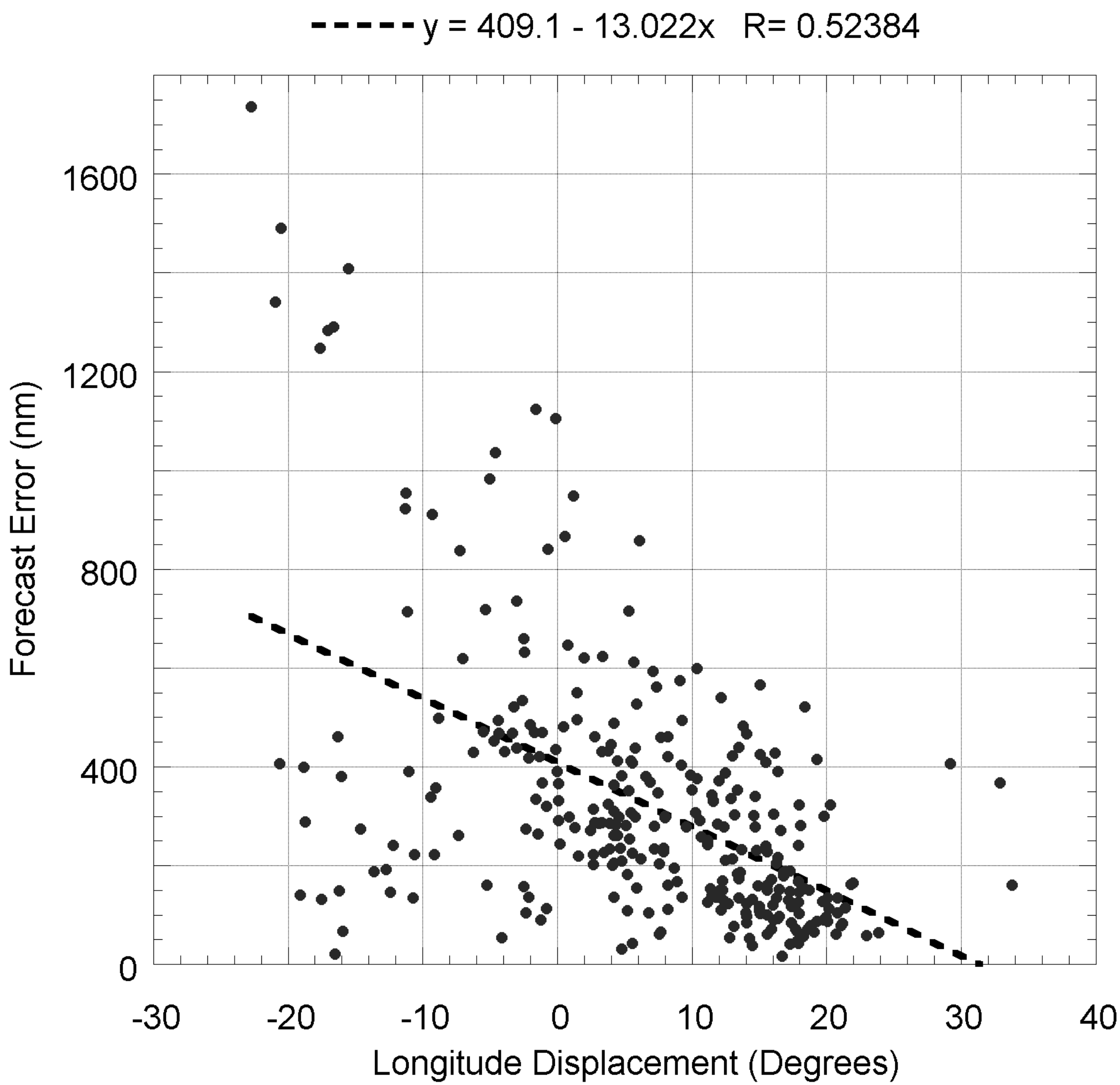

Fig. 15. CONU 120-h track forecast error vs. longitude displacement for 2001-2003 Atlantic

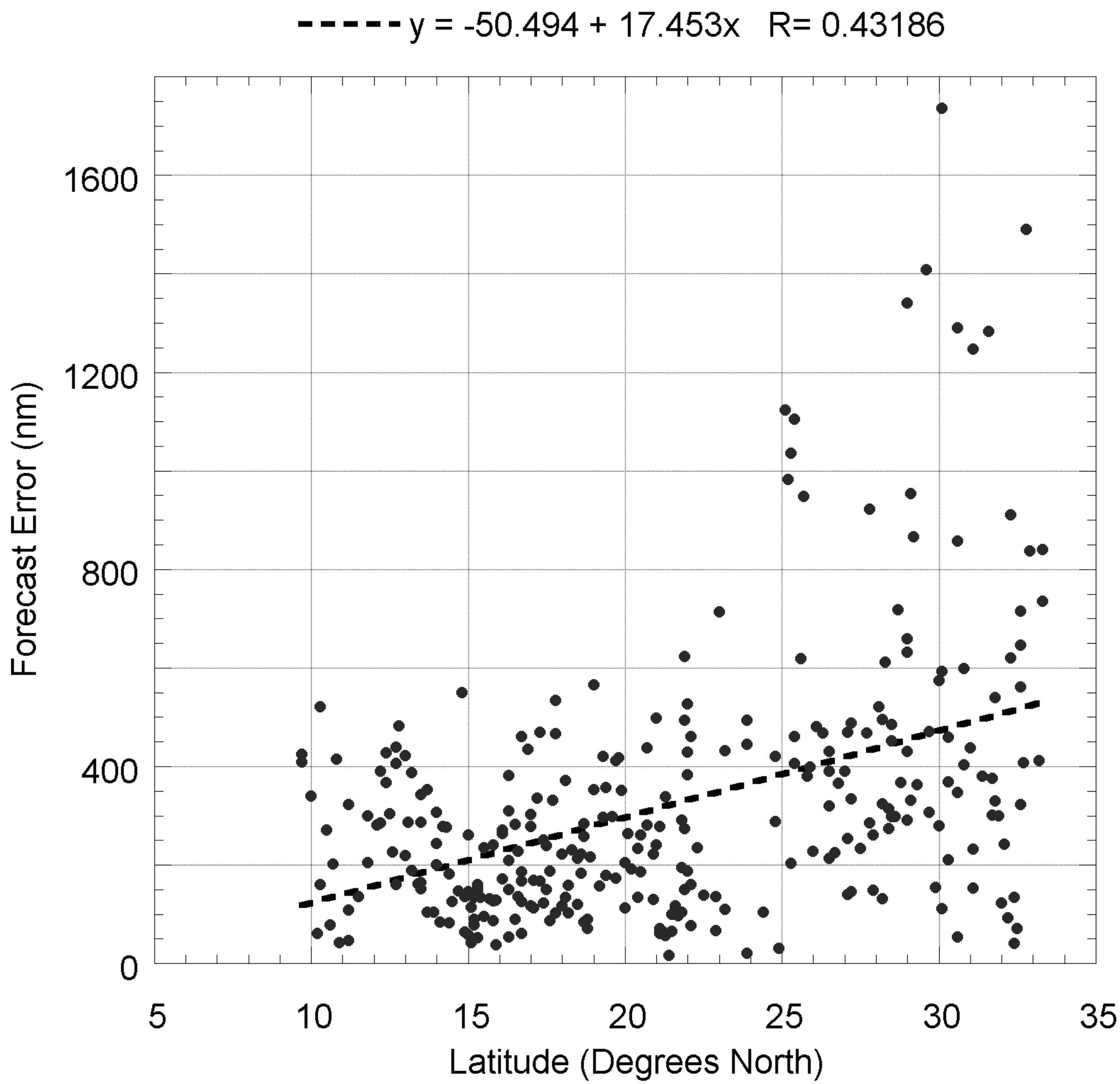

Fig. 16. CONU 120-h track forecast error vs. initial TC latitude for 2001-2003 Atlantic

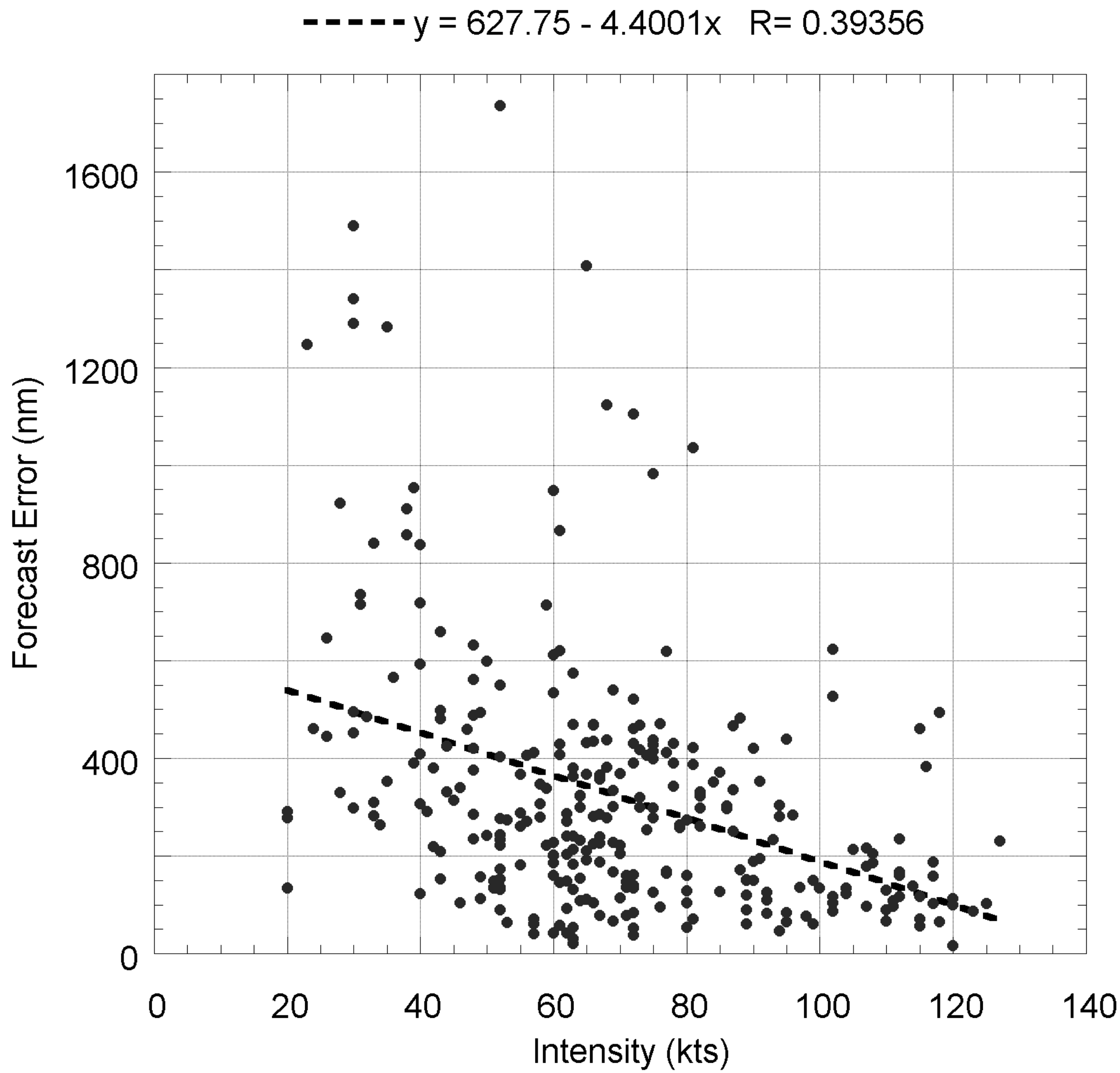

Fig. 17. CONU 120-h track forecast error vs. forecast TC intensity for 2001-2003 Atlantic

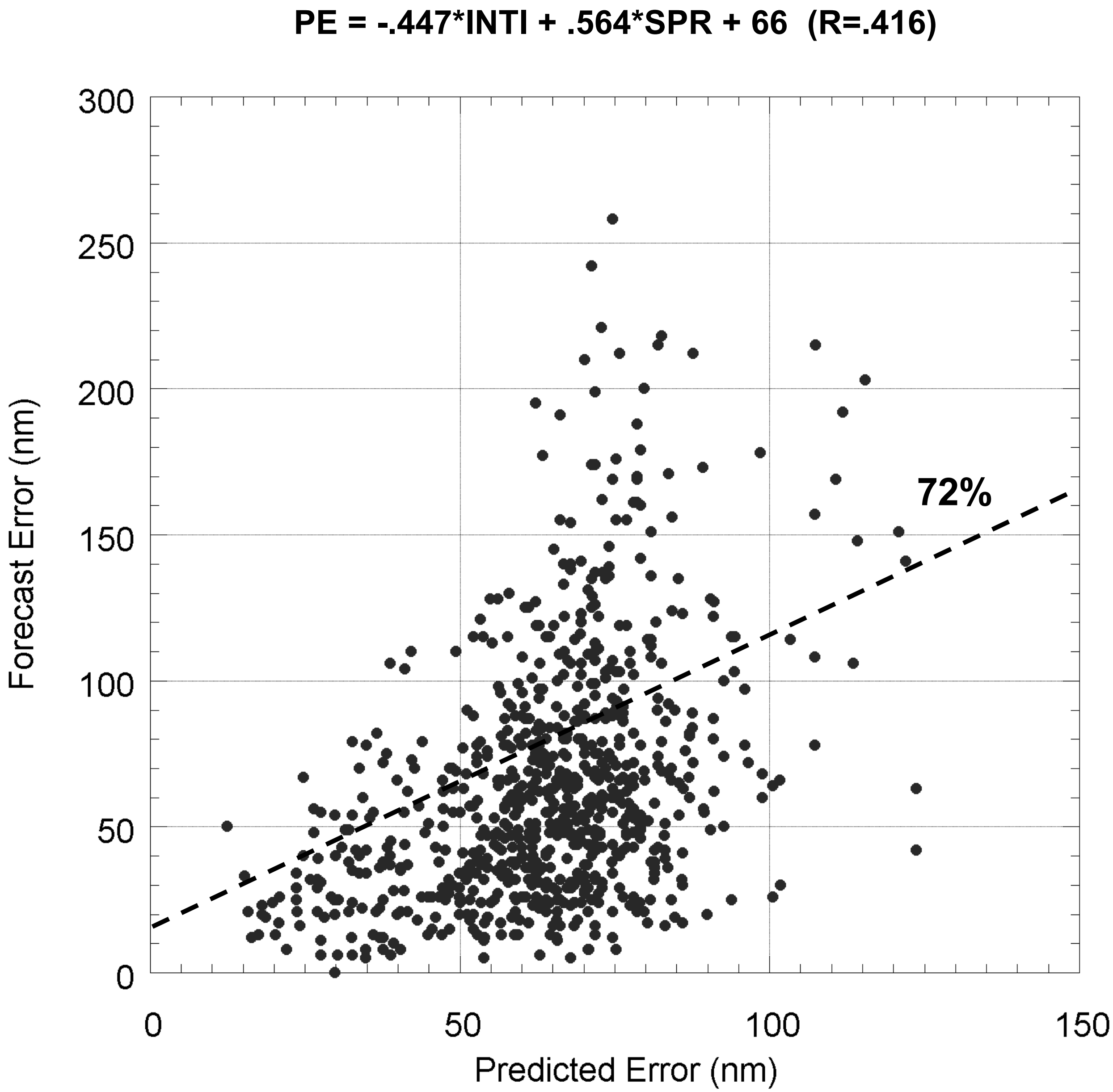

Fig. 18. CONU 24-h track forecast error vs. predicted error for 2001-2003 Atlantic

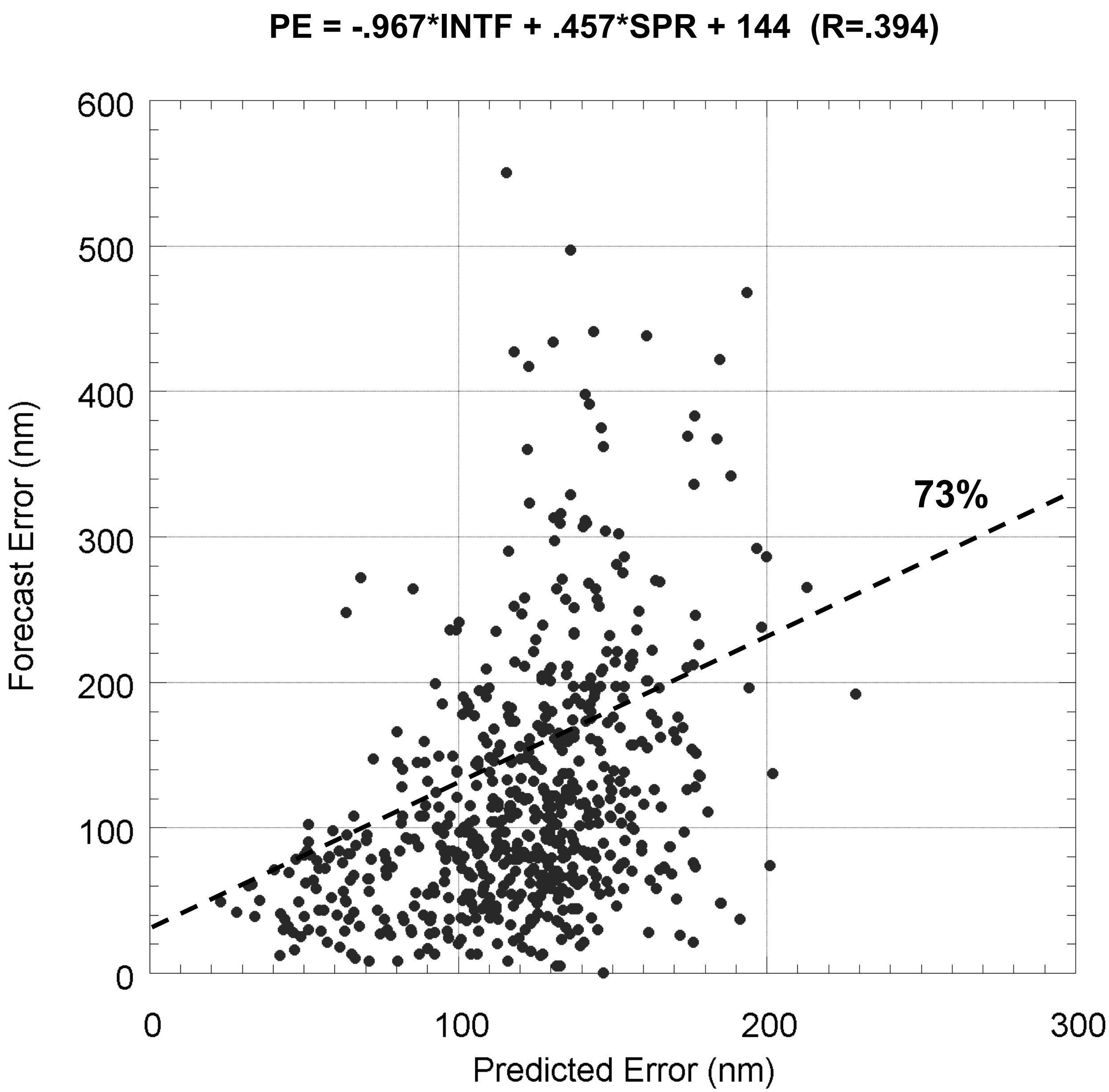

Fig. 19. CONU 48-h track forecast error vs. predicted error for 2001-2003 Atlantic

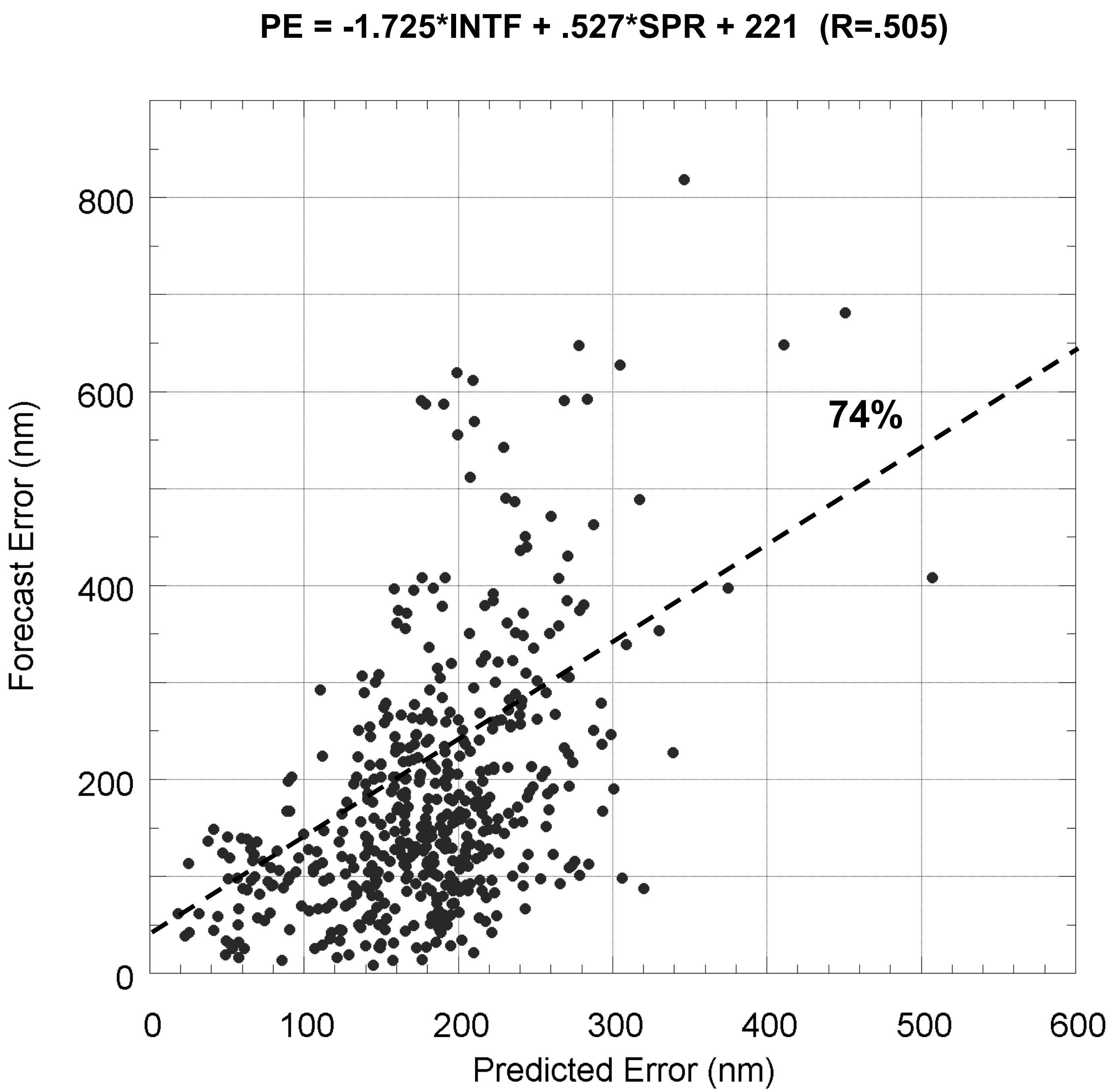

Fig. 20. CONU 72-h track forecast error vs. predicted error for 2001-2003 Atlantic

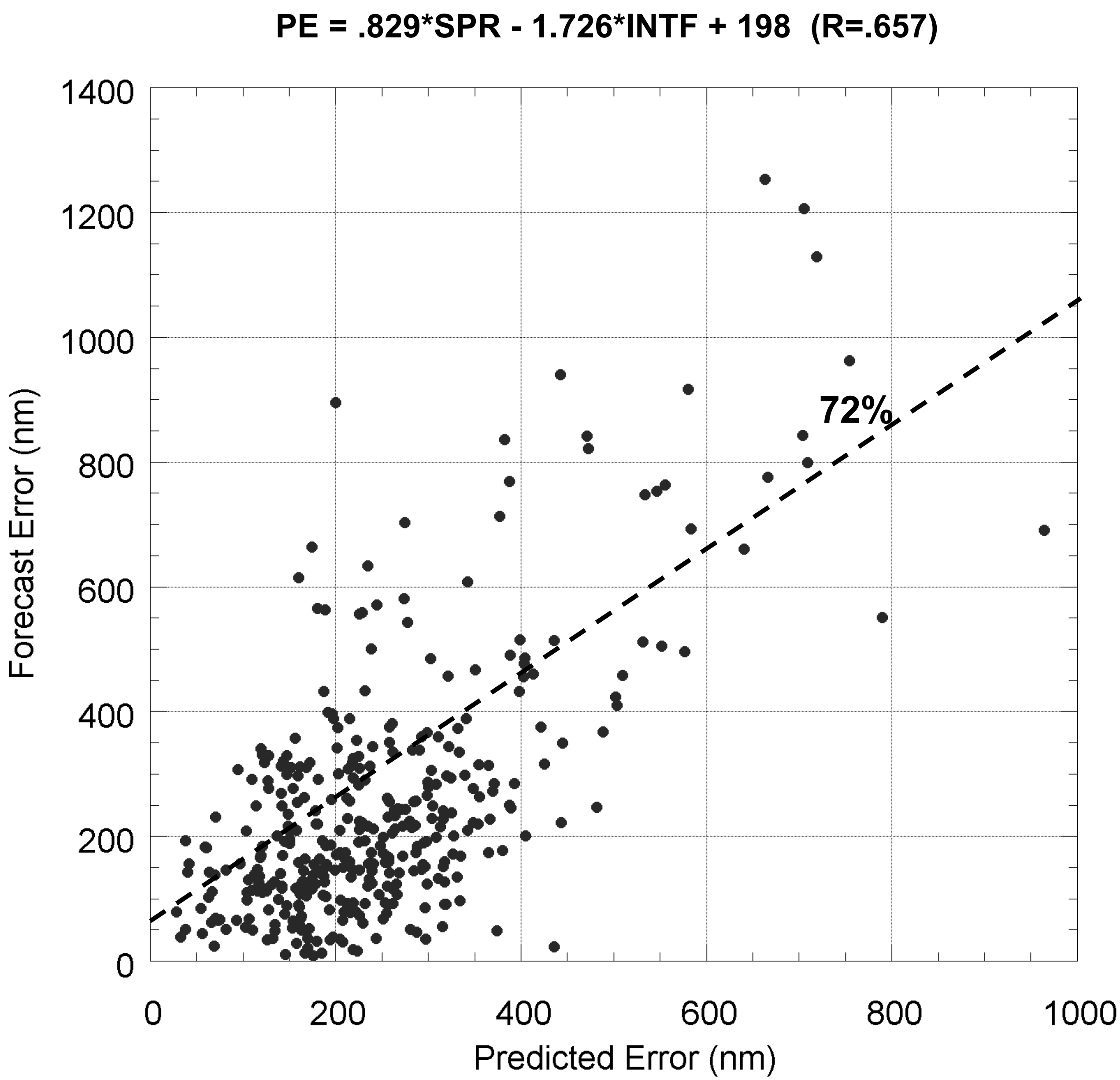

Fig. 21. CONU 96-h track forecast error vs. predicted error for 2001-2003 Atlantic

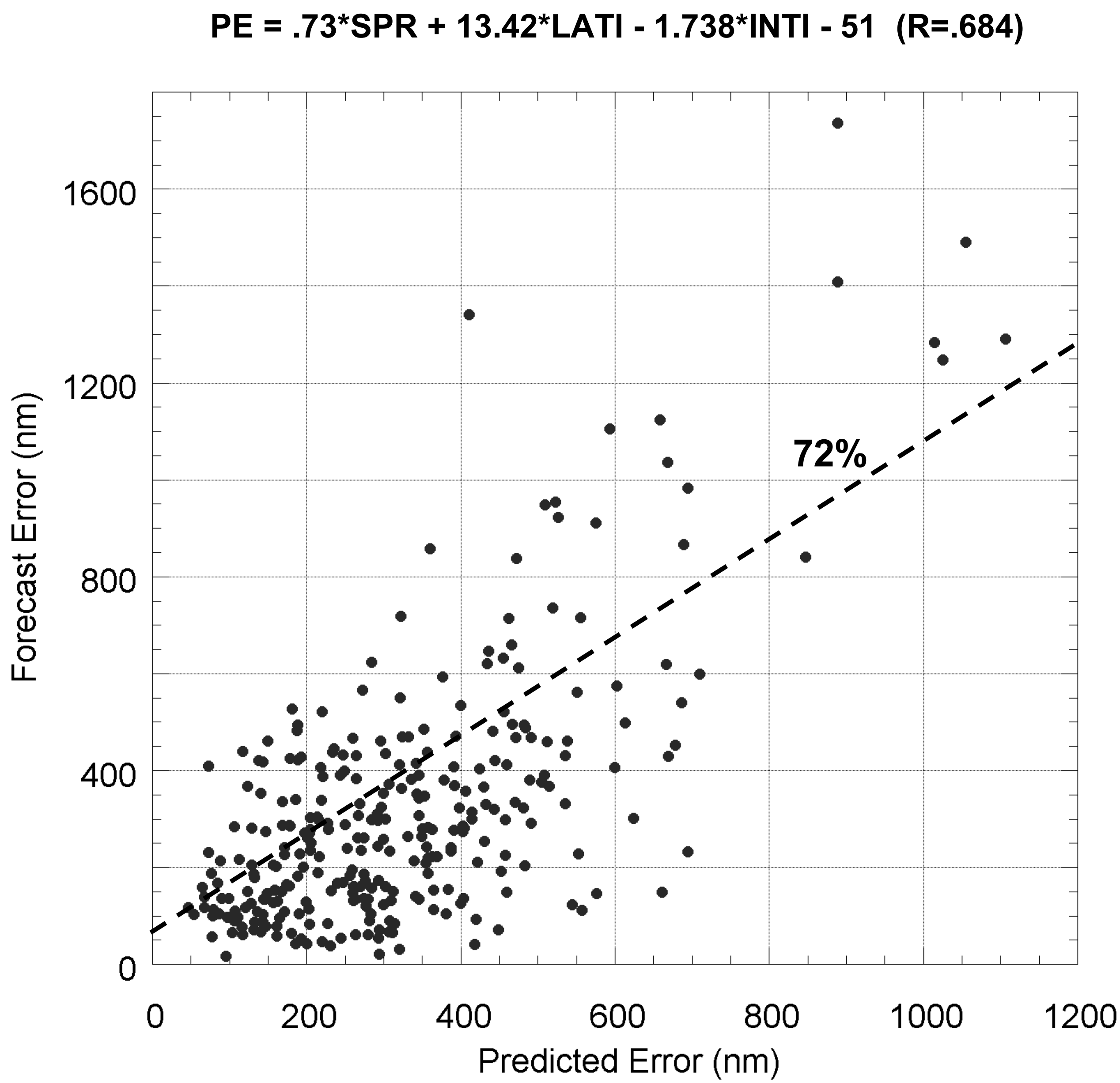

Fig. 22. CONU 120-h track forecast error vs. predicted error for 2001-2003 Atlantic

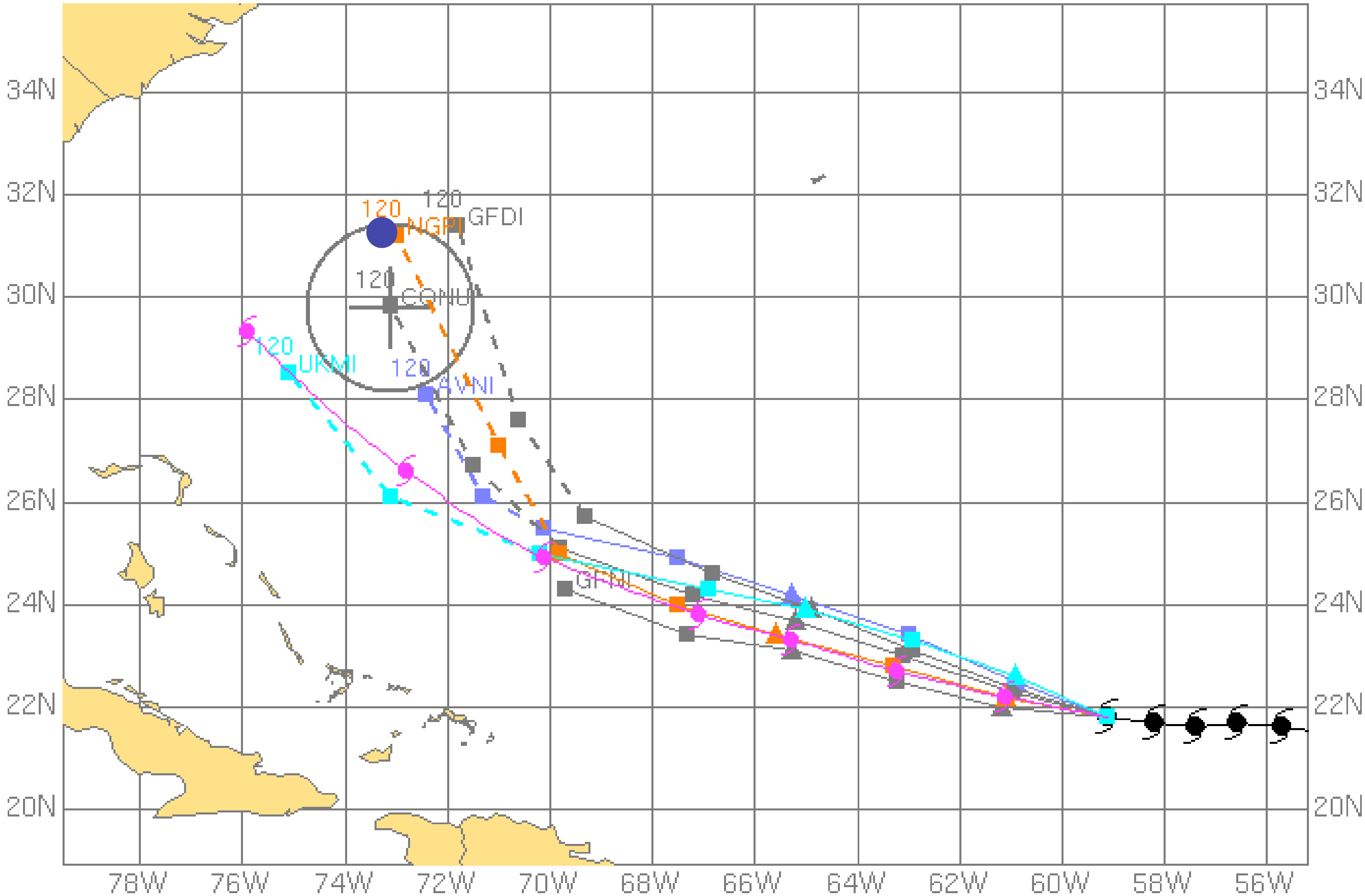

Fig. 23. Predicted 72% confidence radius surrounding the 120-h CONU forecast for Hurricane Isabel, 00Z September 13, 2003.

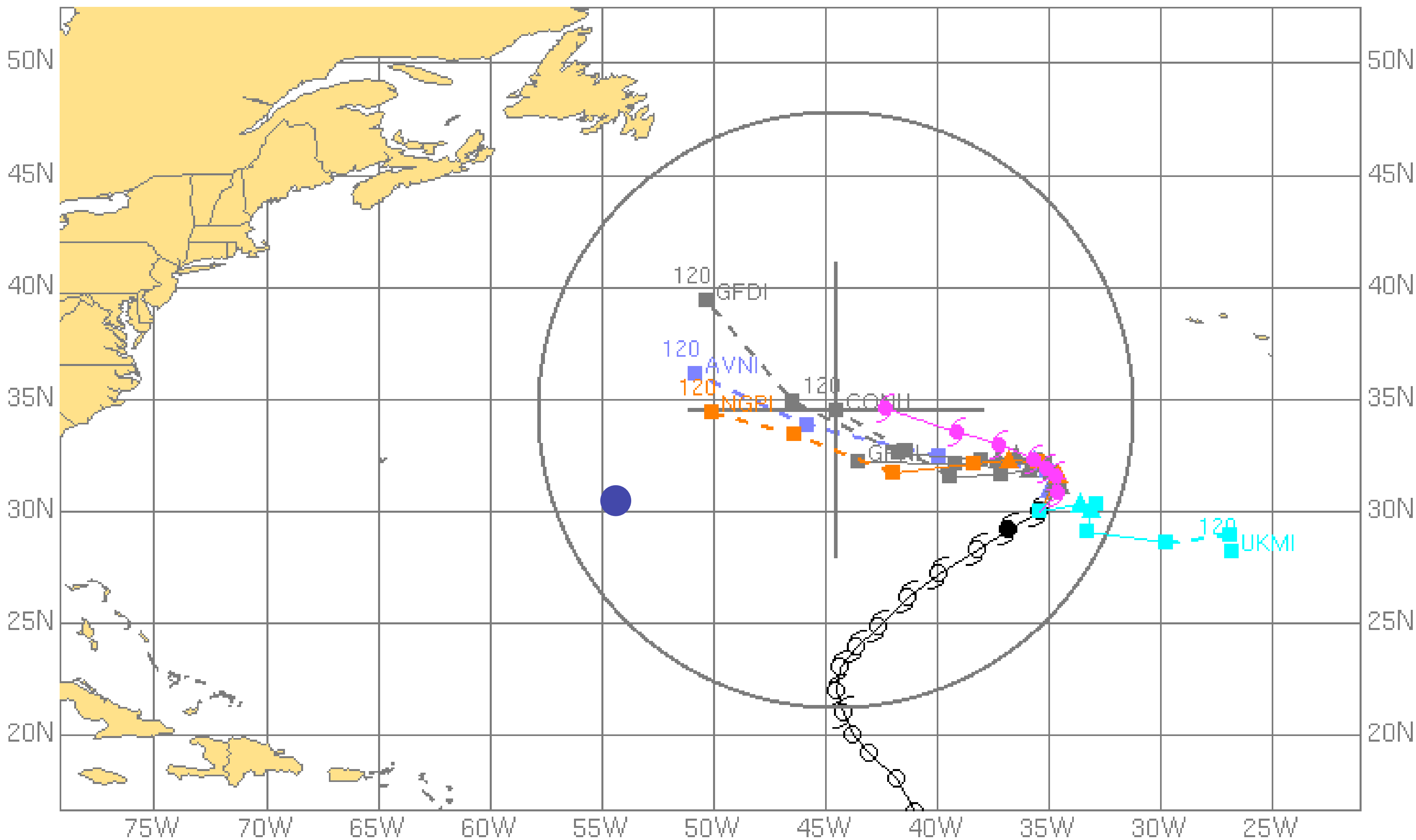

Fig. 24. Predicted 72% confidence radius surrounding the 120-h CONU forecast for Hurricane Kate, 00Z September 30, 2003.

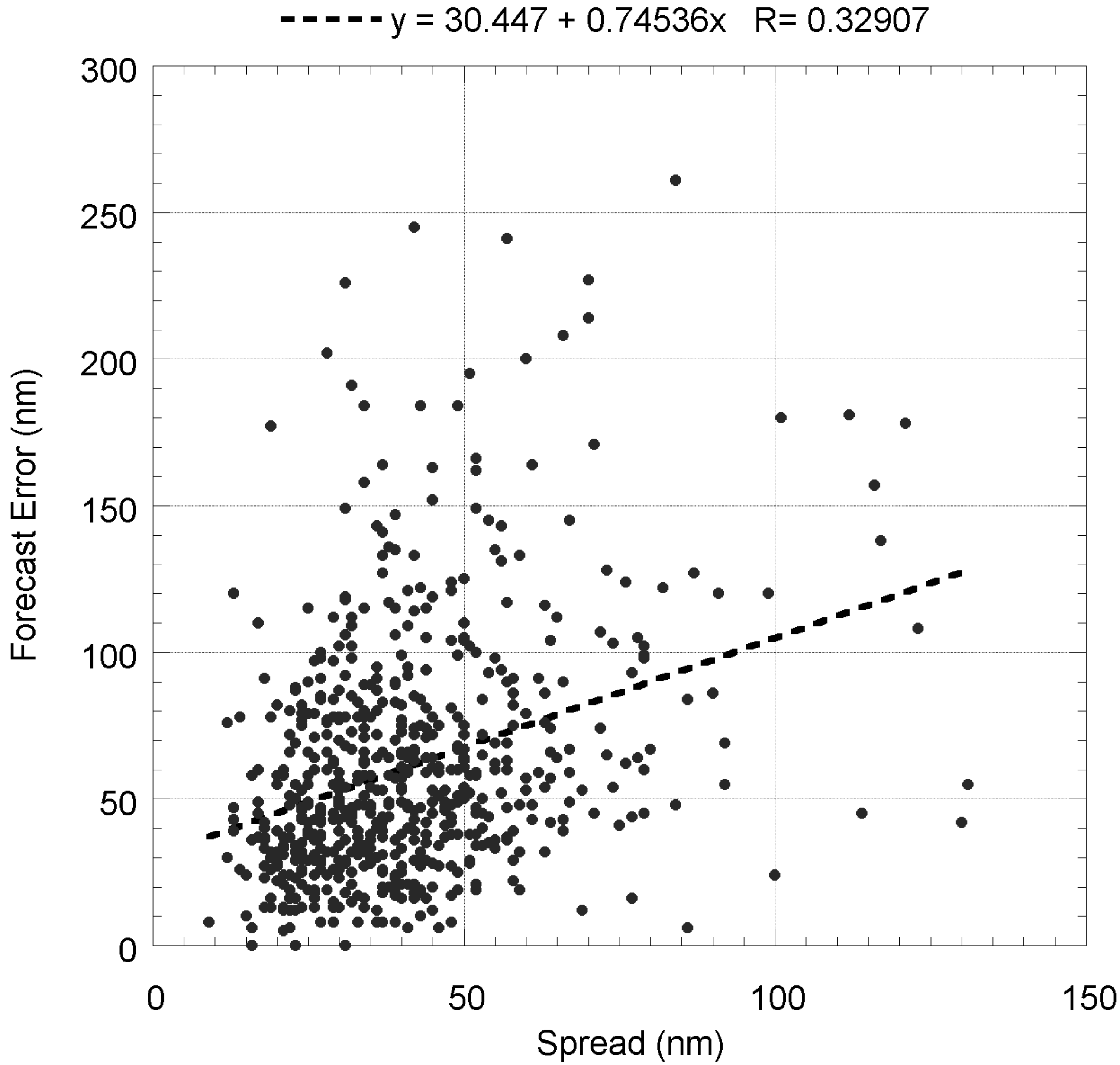

Fig. 25. GUNA 24-h track forecast error vs. spread for 2001-2003 Atlantic

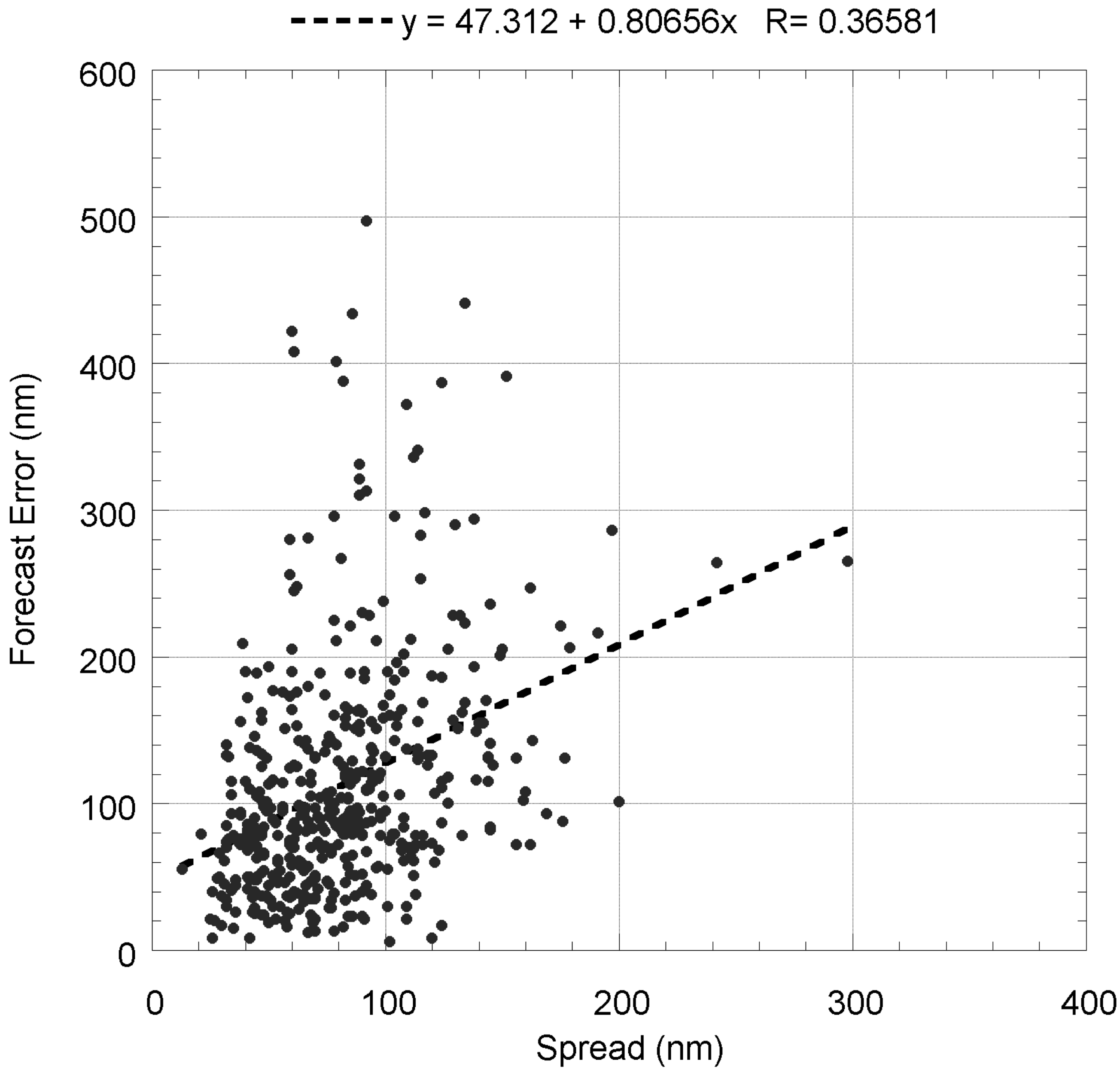

Fig. 26. GUNA 48-h track forecast error vs. spread for 2001-2003 Atlantic

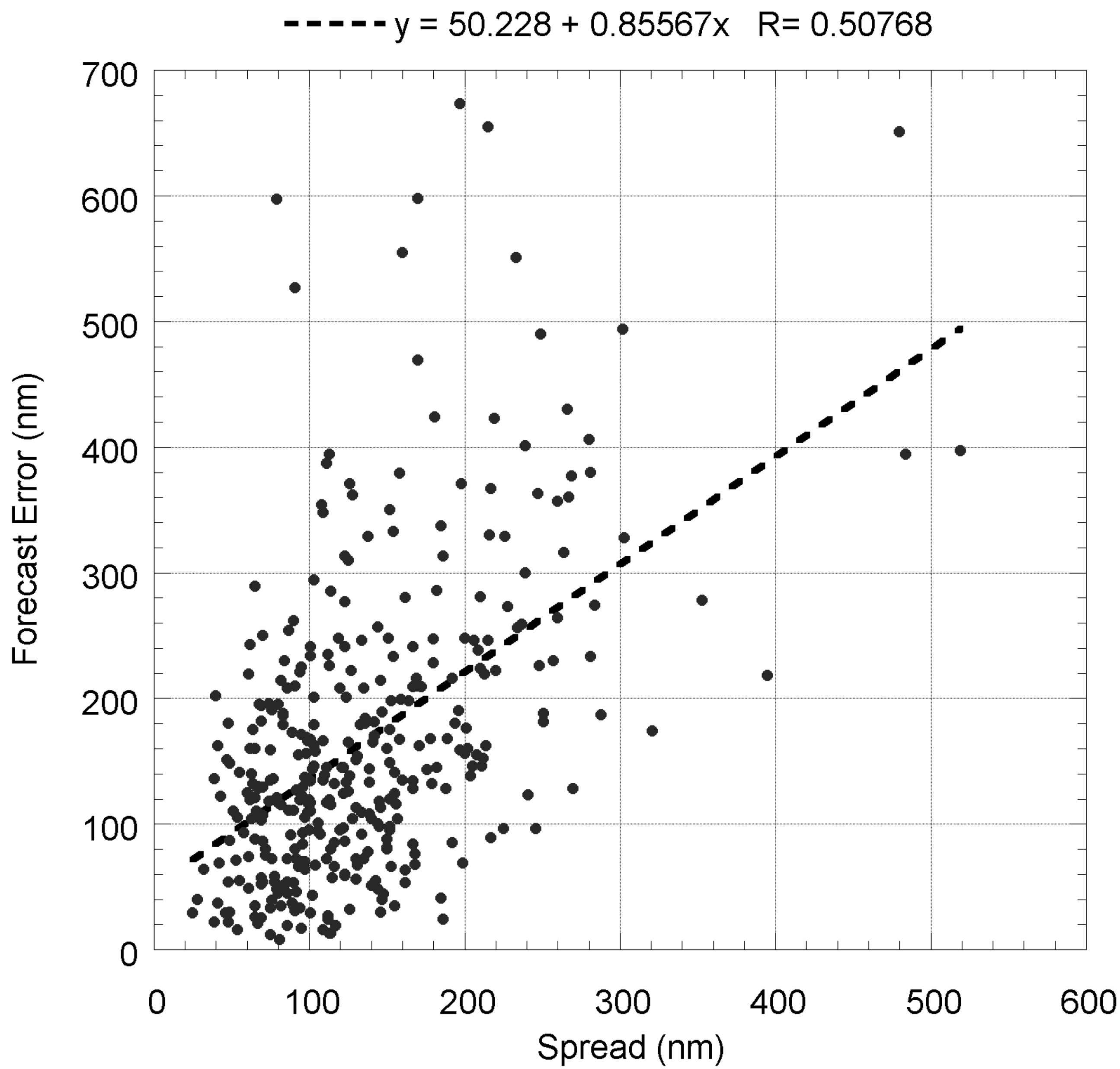

Fig. 27. GUNA 72-h track forecast error vs. spread for 2001-2003 Atlantic

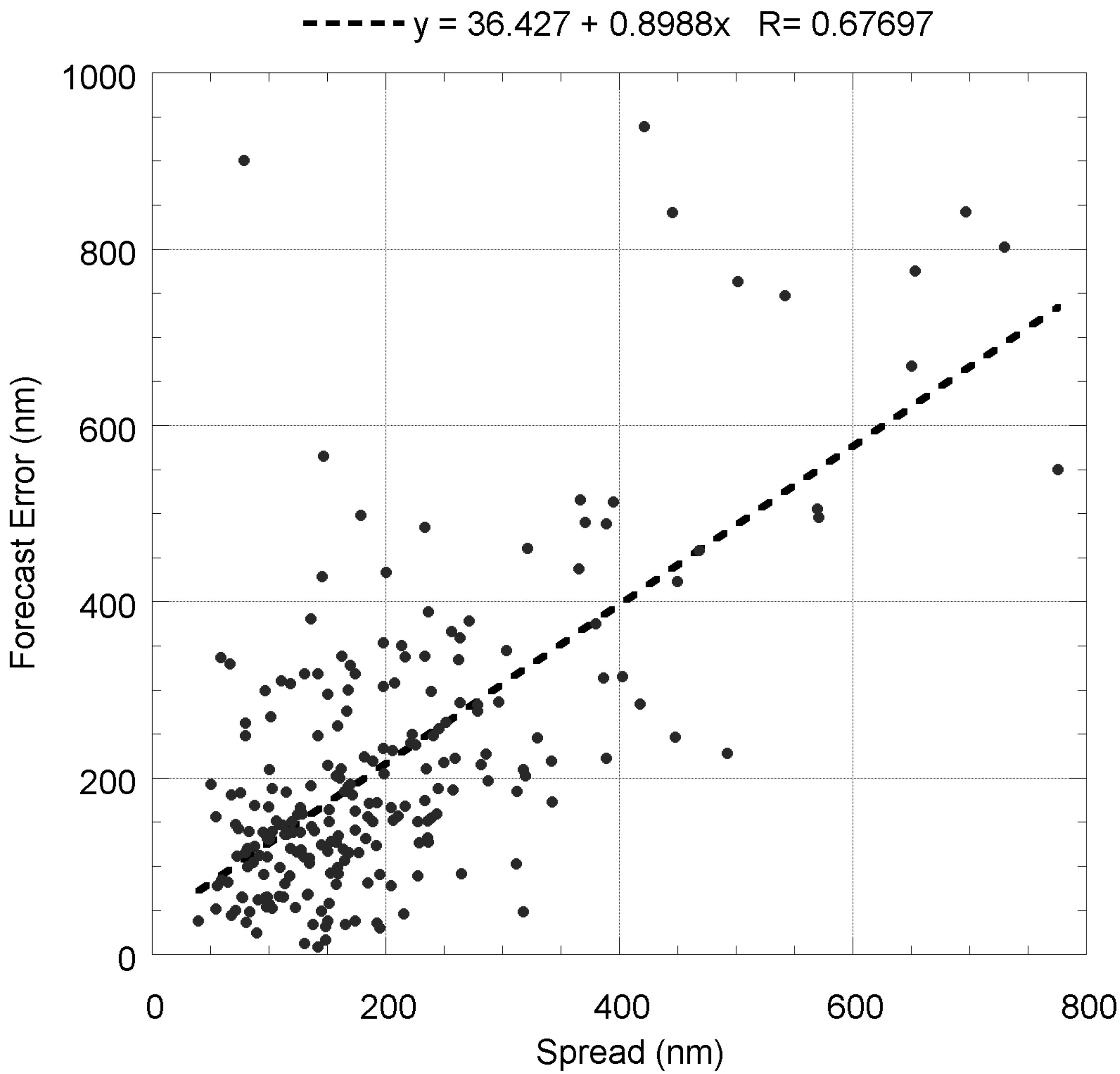

Fig. 28. GUNA 96-h track forecast error vs. spread for 2001-2003 Atlantic

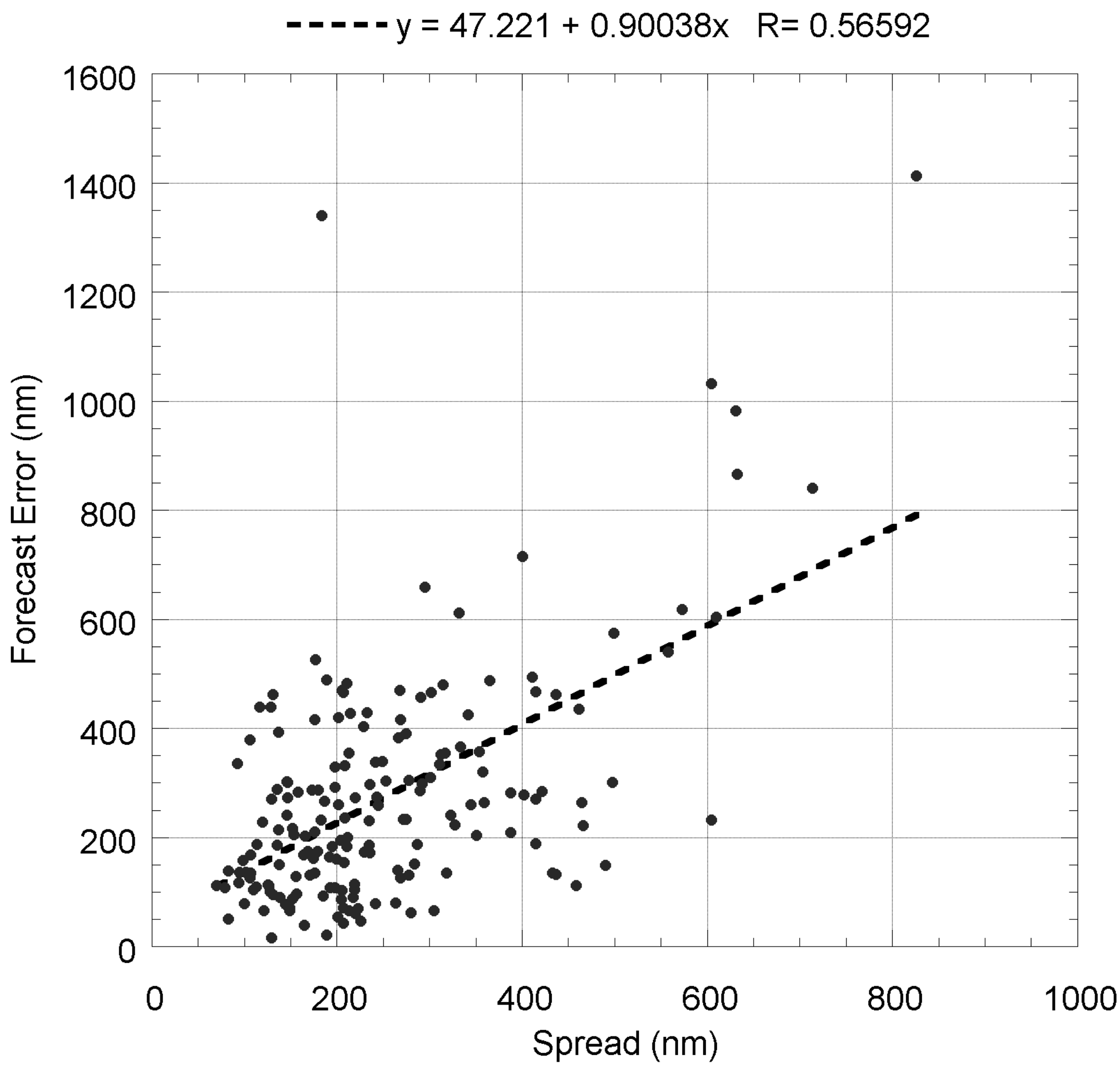

Fig. 29. GUNA 120-h track forecast error vs. spread for 2001-2003 Atlantic

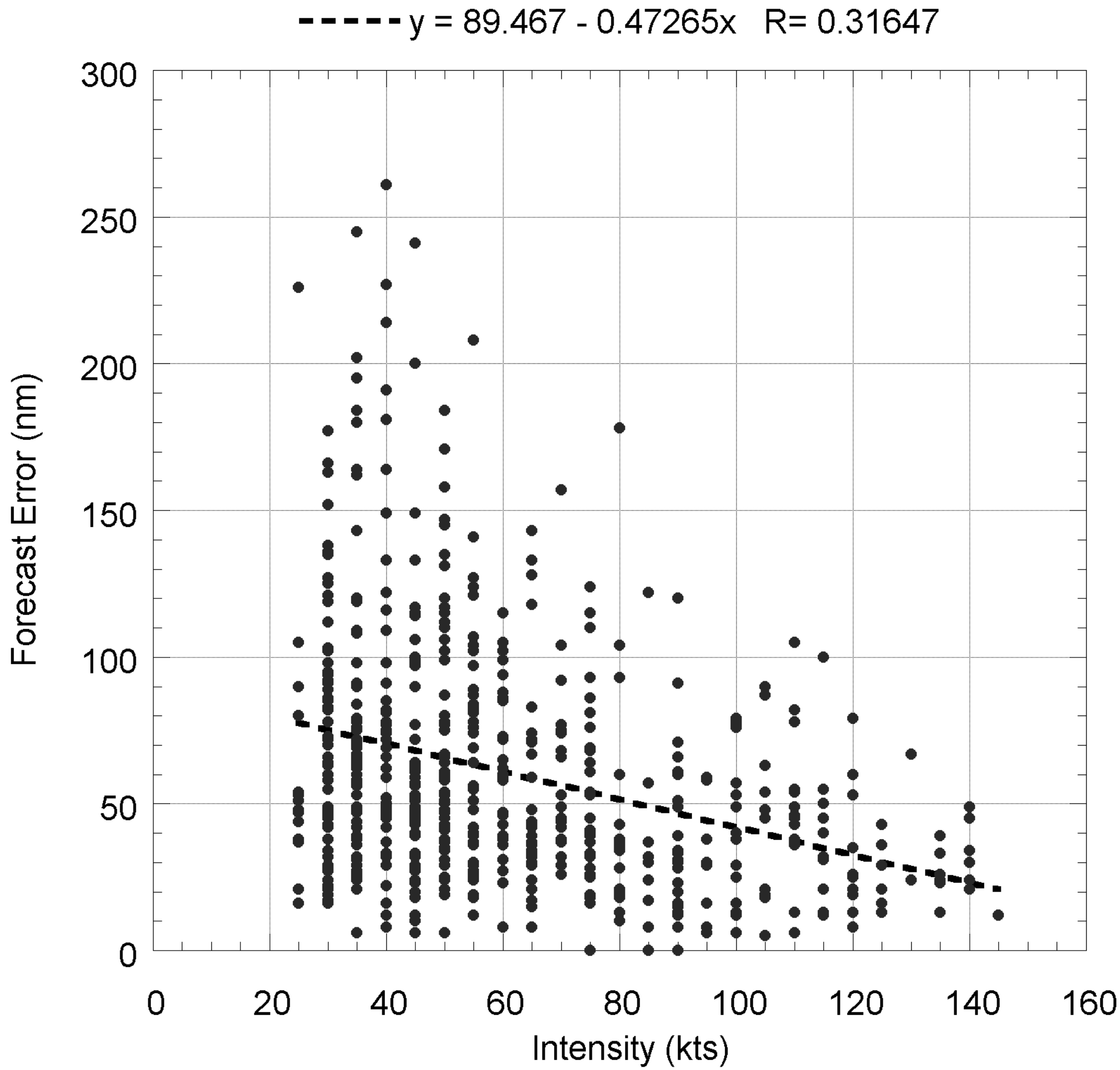

Fig. 30. GUNA 24-h track forecast error vs. initial TC intensity for 2001-2003 Atlantic

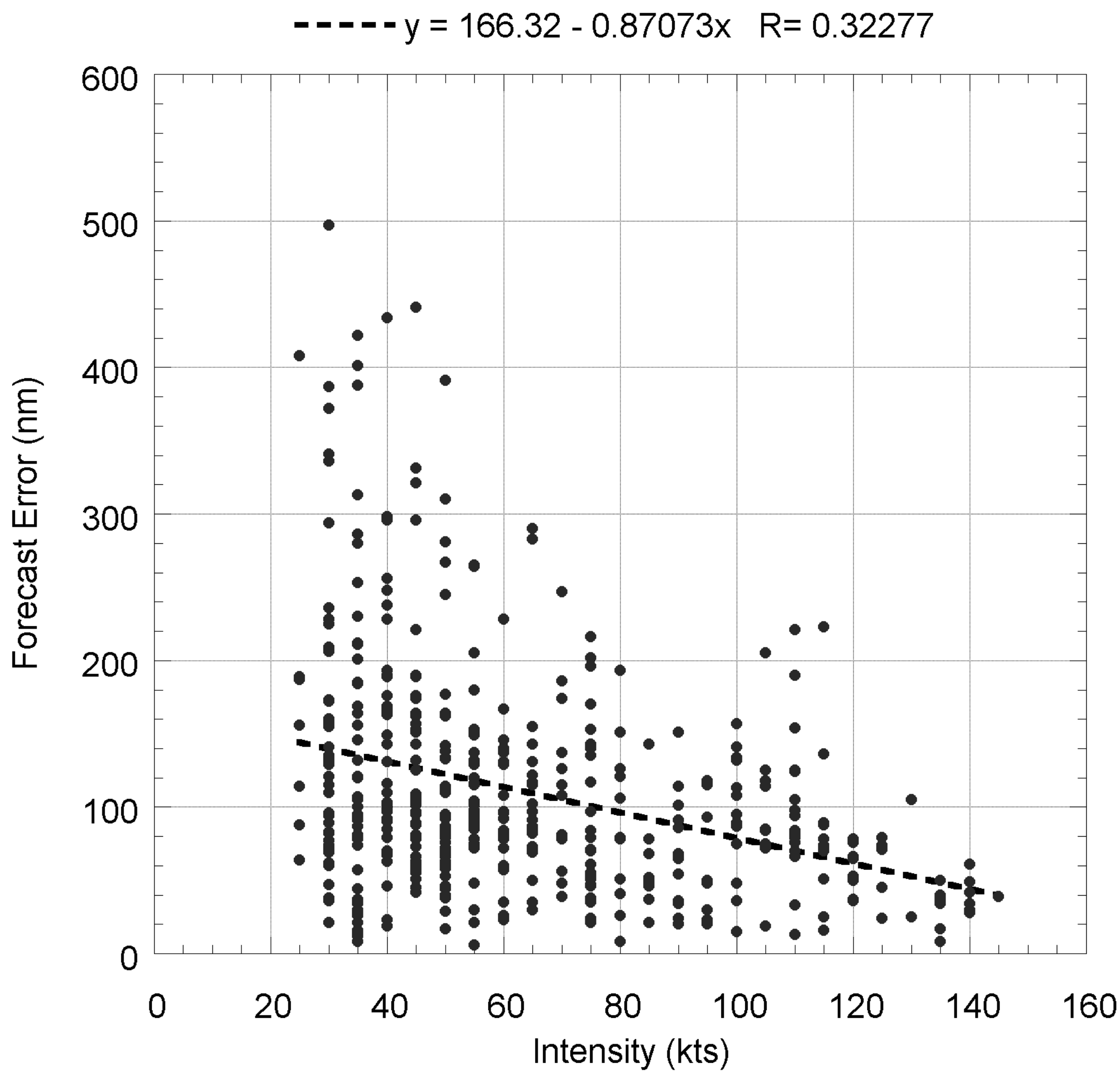

Fig. 31. GUNA 48-h track forecast error vs. initial TC intensity for 2001-2003 Atlantic

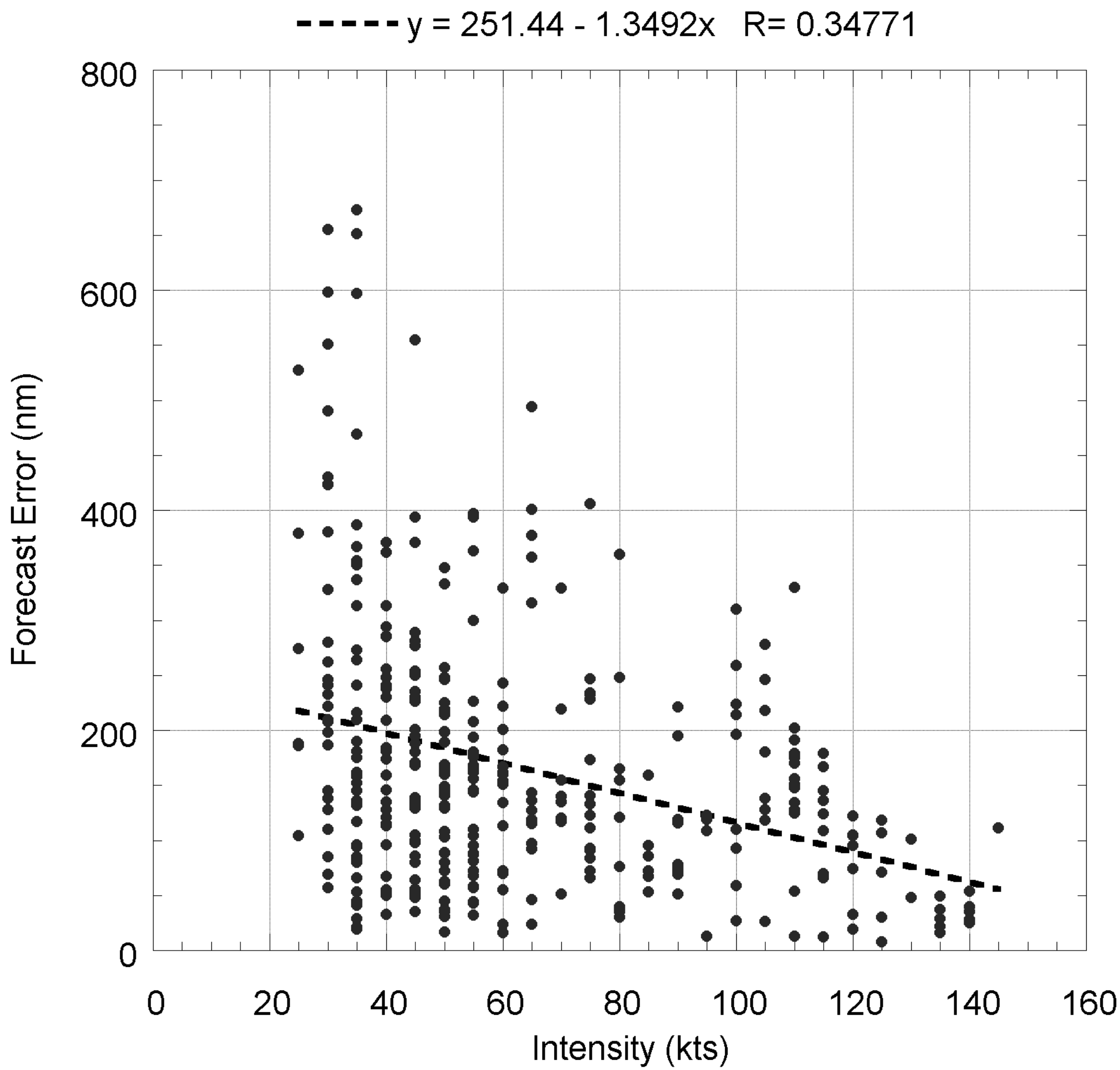

Fig. 32. GUNA 72-h track forecast error vs. initial TC intensity for 2001-2003 Atlantic

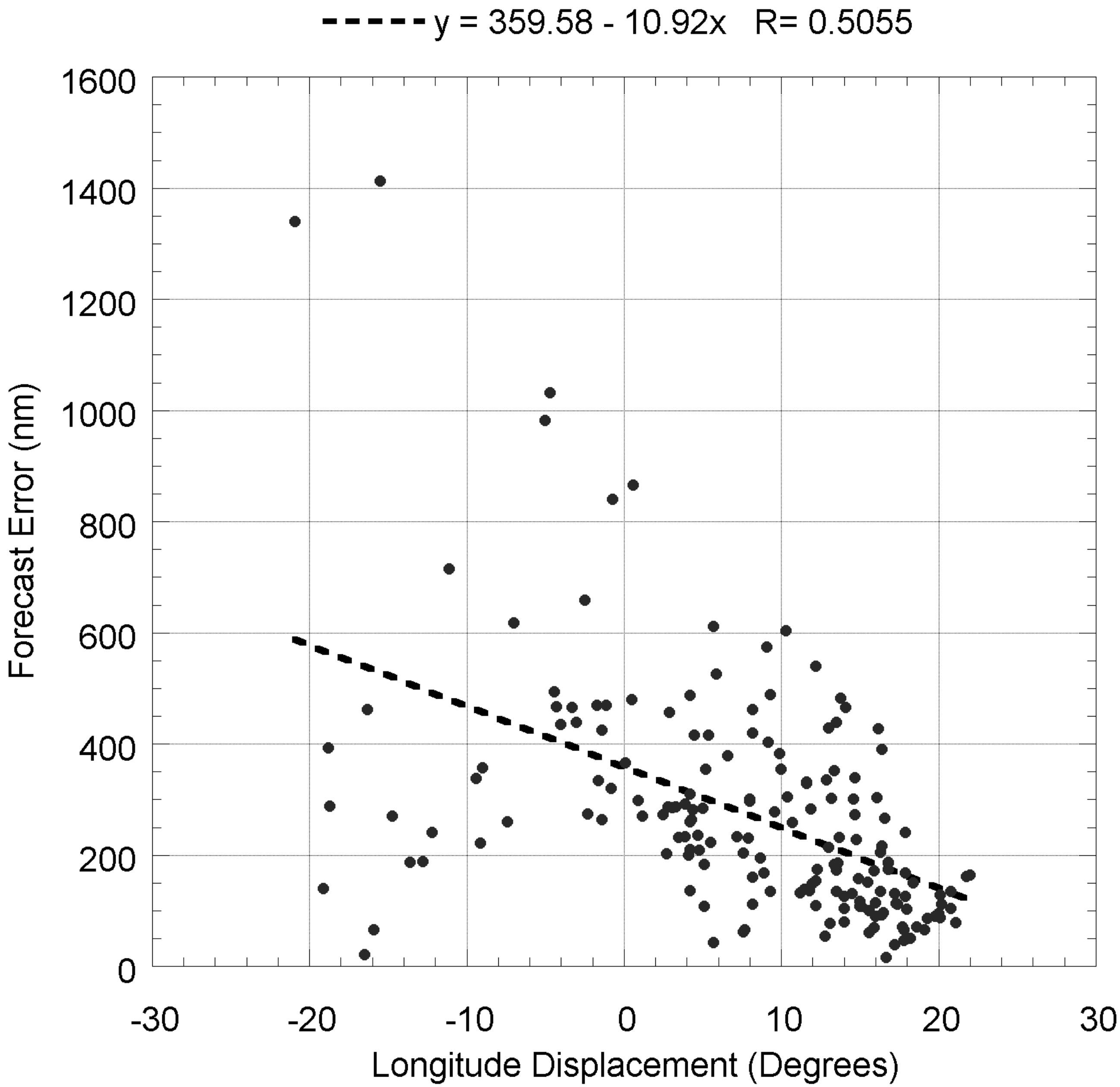

Fig. 33. GUNA 120-h track forecast error vs. longitude displacement for 2001-2003 Atlantic

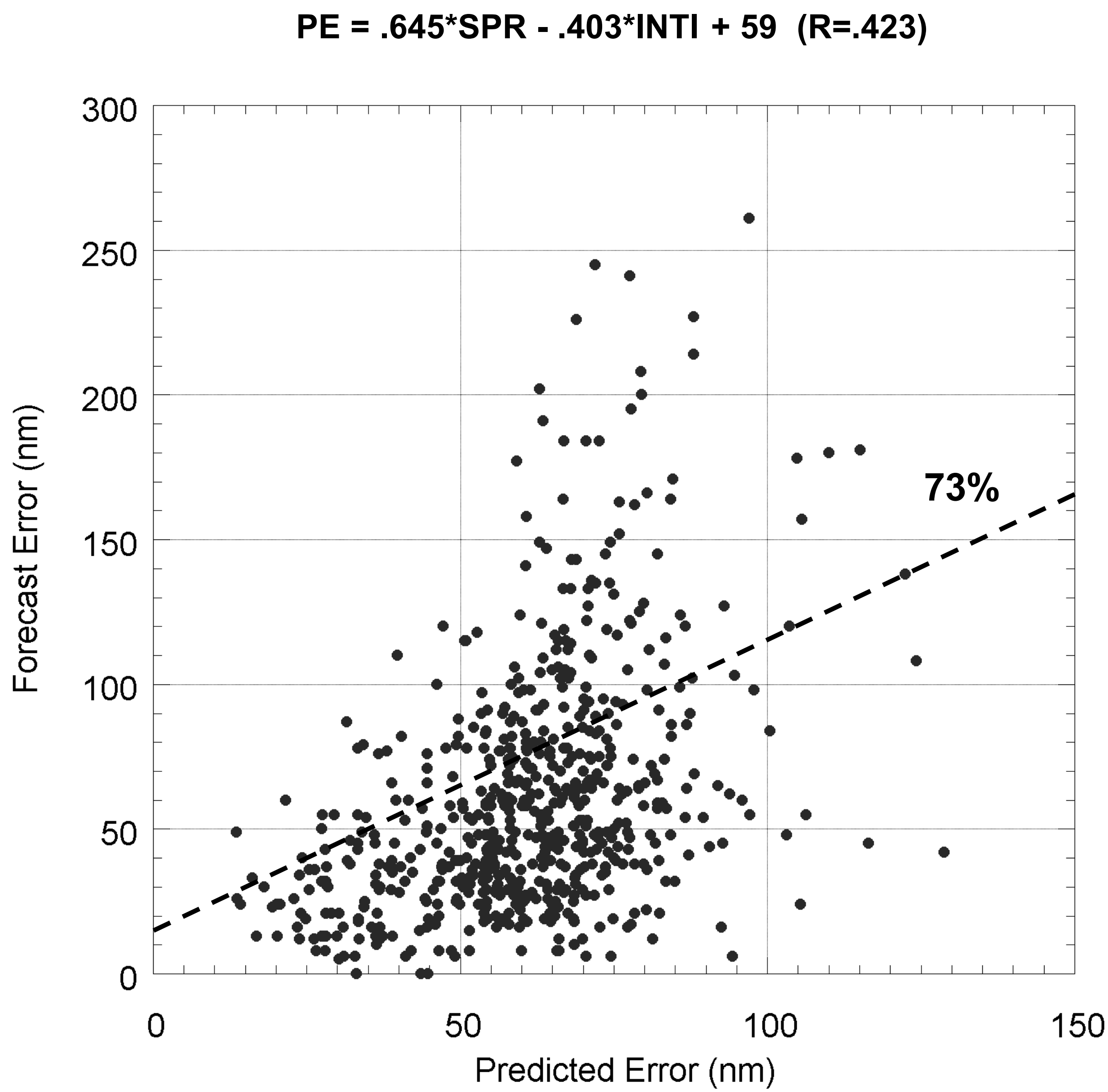

Fig. 34. GUNA 24-h track forecast error vs. predicted error for 2001-2003 Atlantic

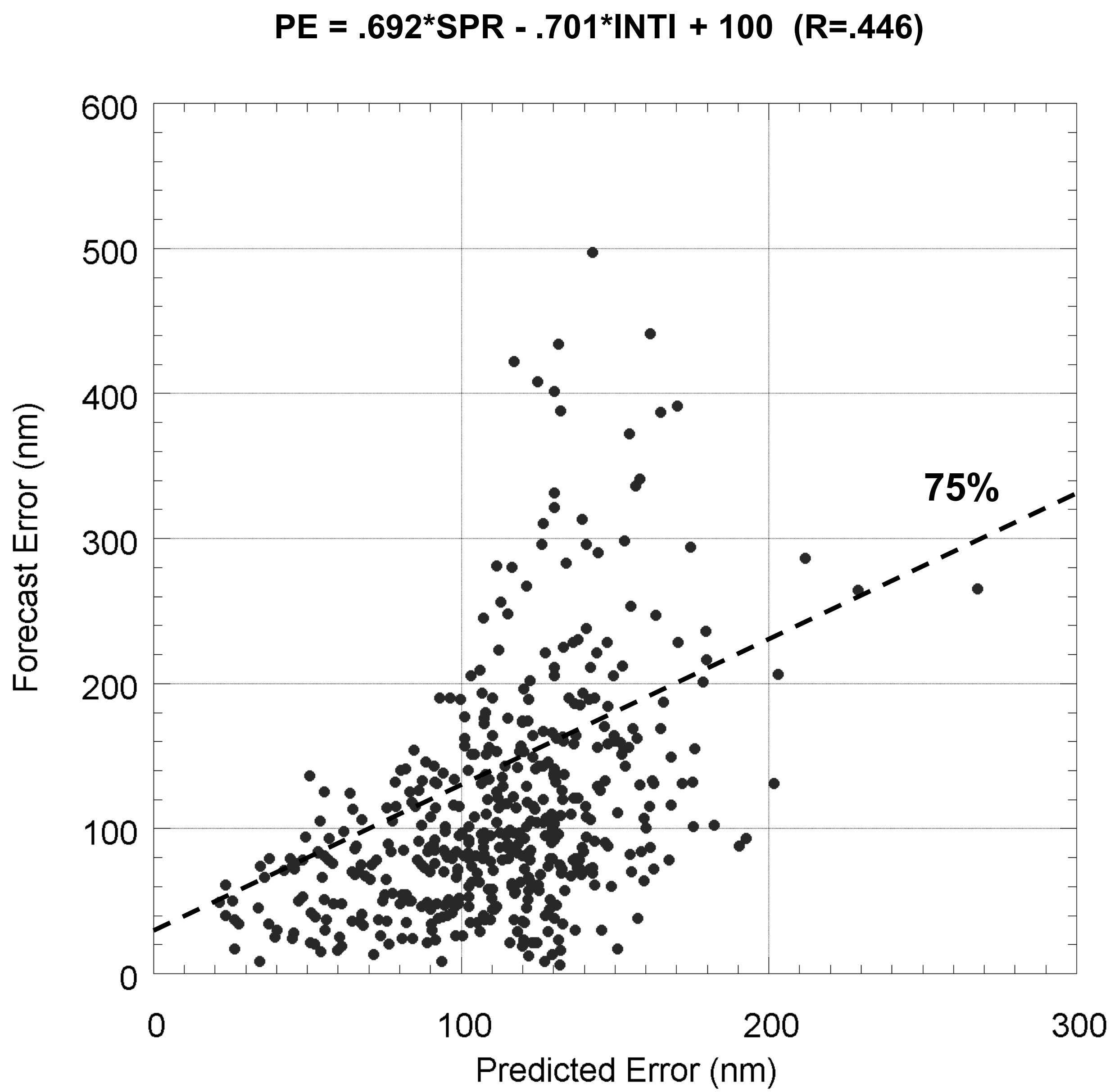

Fig. 35. GUNA 48-h track forecast error vs. predicted error for 2001-2003 Atlantic

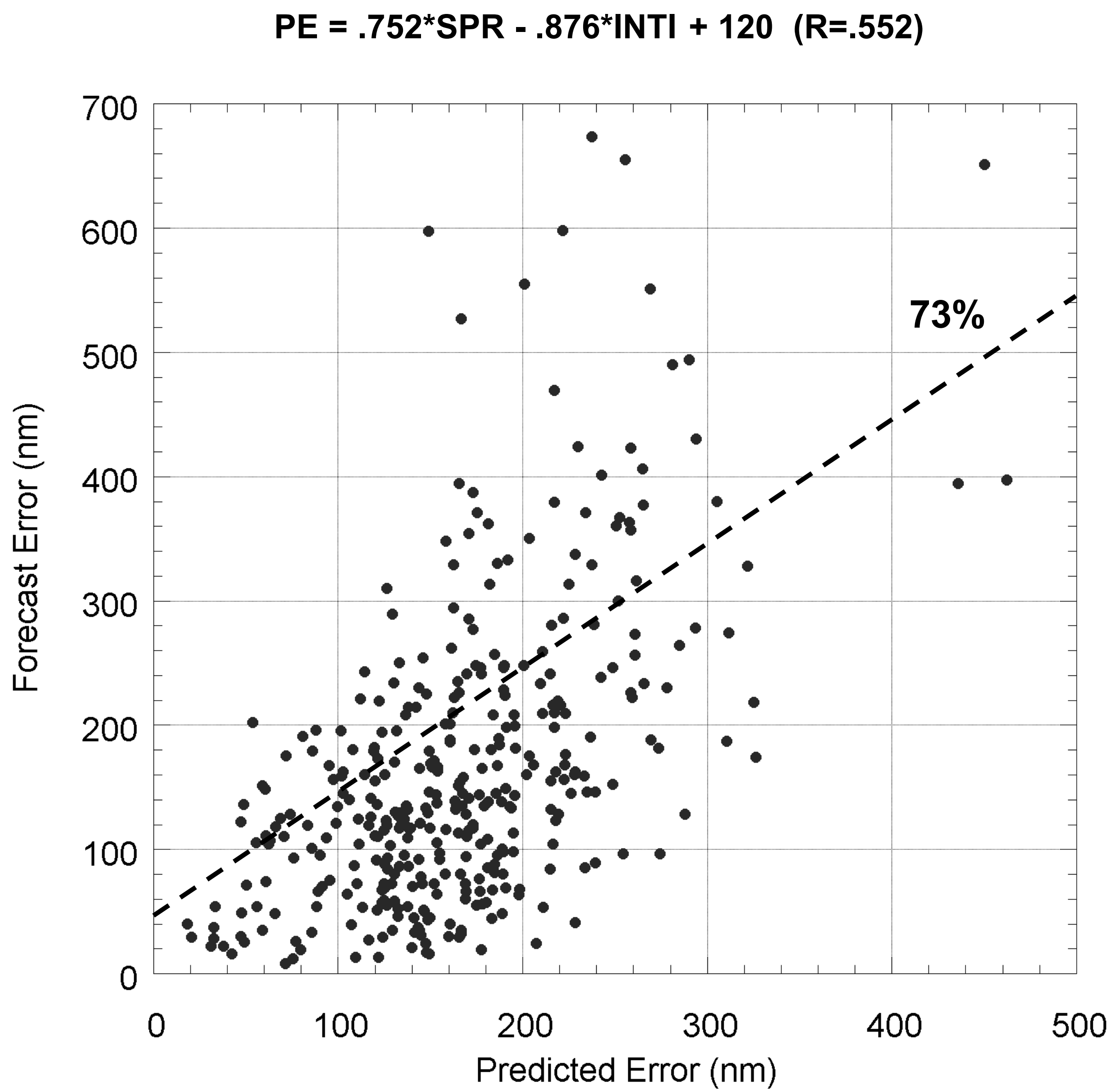

Fig. 36. GUNA 72-h track forecast error vs. predicted error for 2001-2003 Atlantic

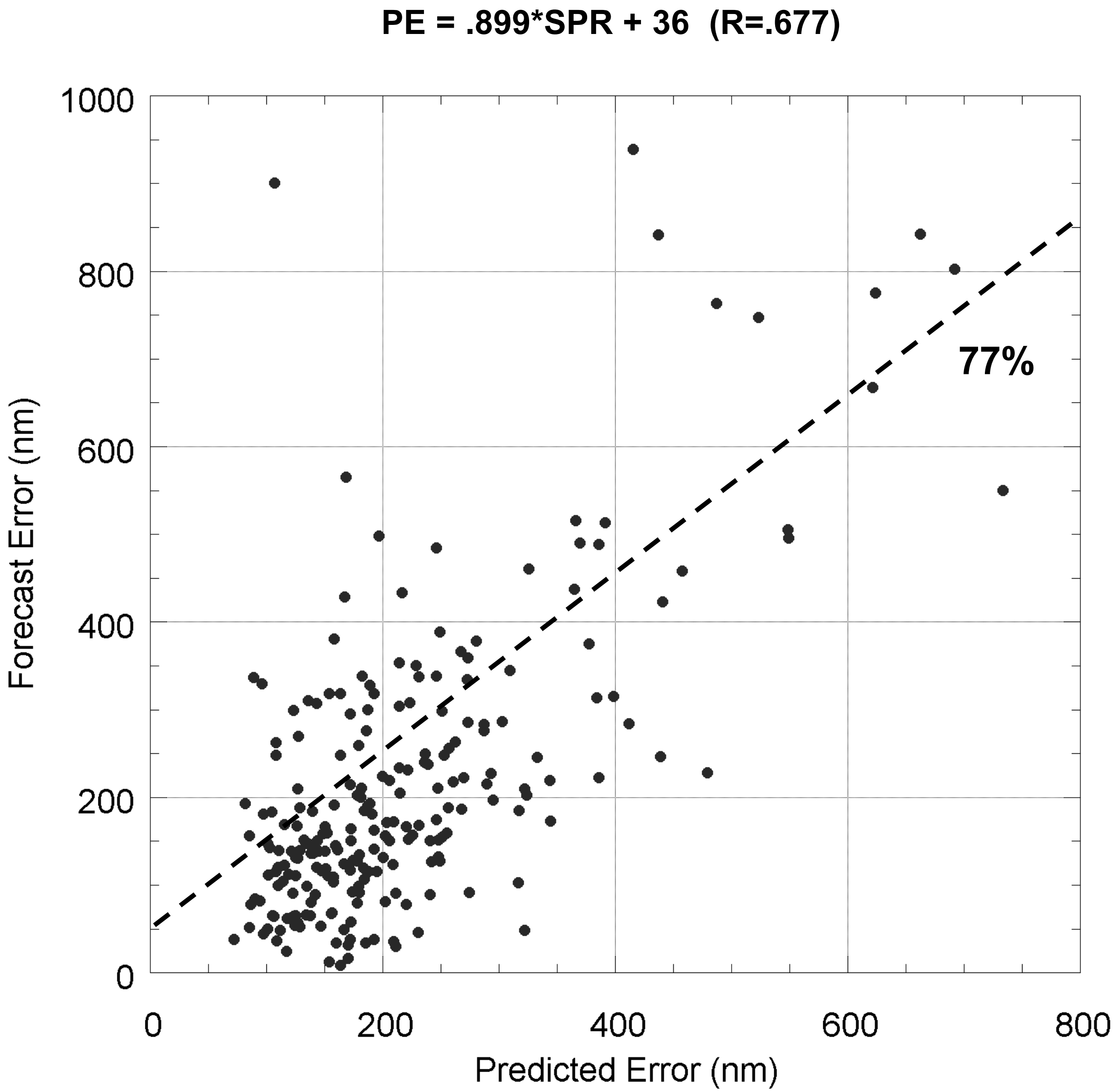

Fig. 37. GUNA 96-h track forecast error vs. predicted error for 2001-2003 Atlantic

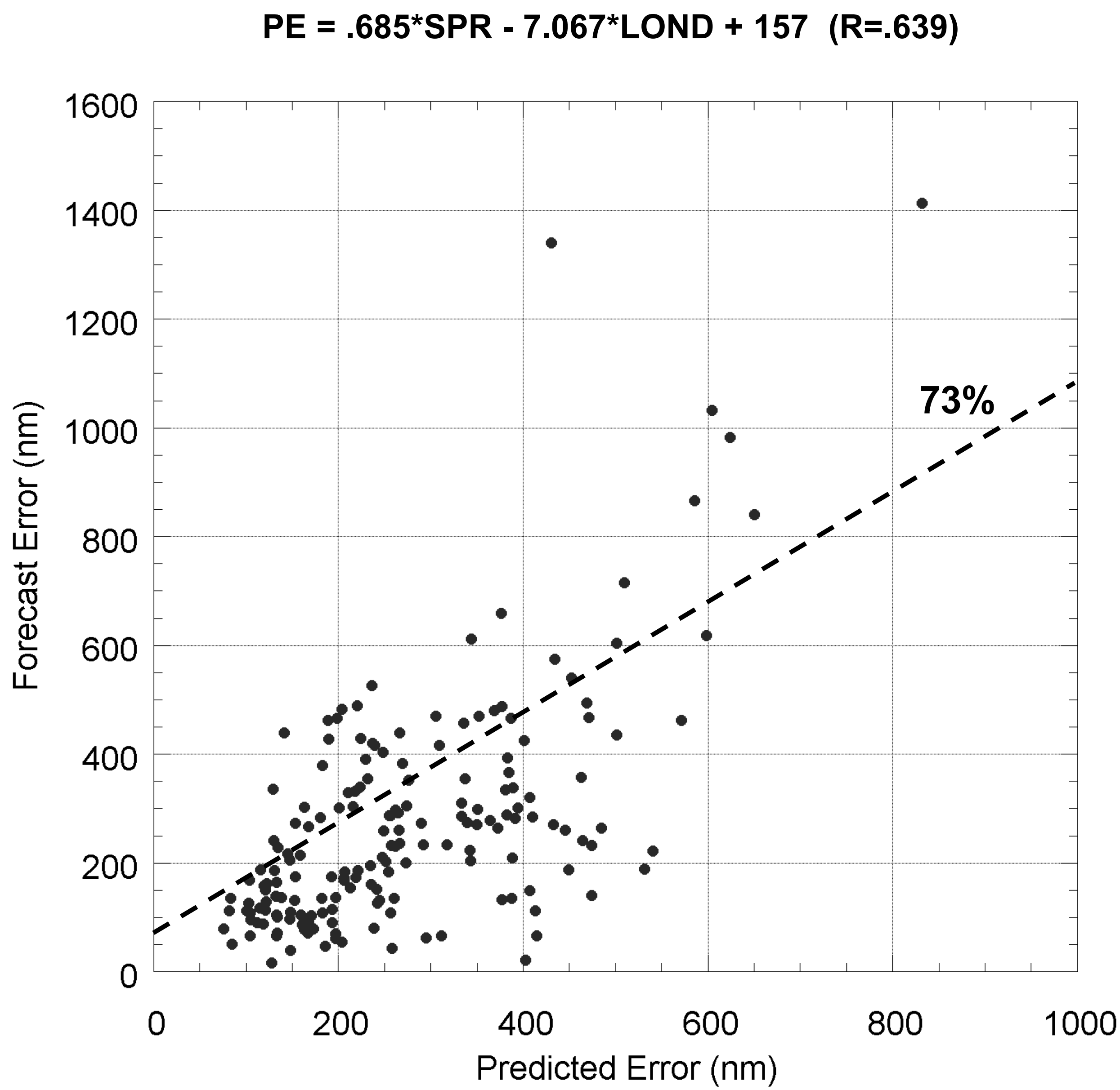

Fig. 38. GUNA 120-h track forecast error vs. predicted error for 2001-2003 Atlantic

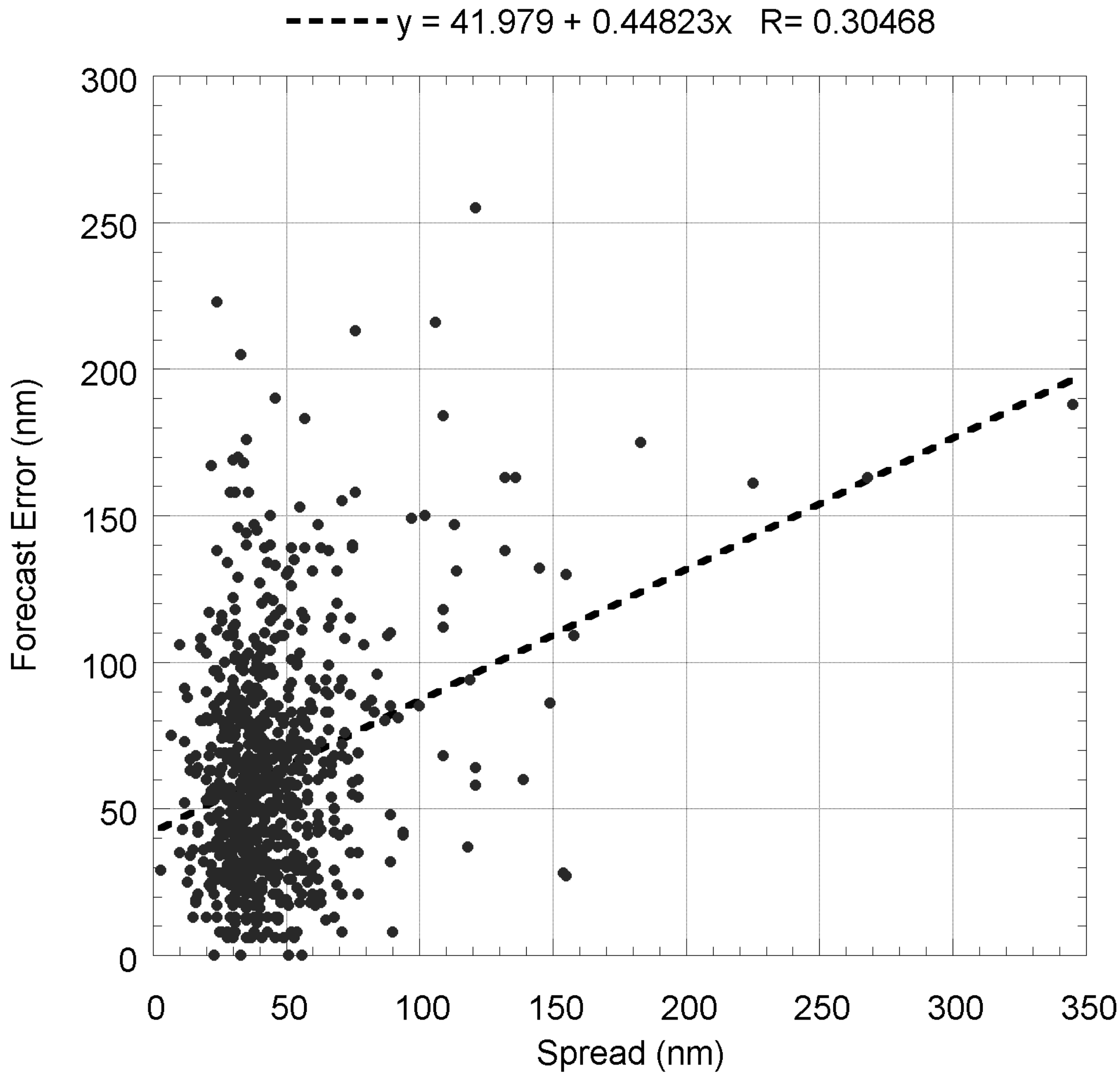

Fig. 39. CONU 24-h track forecast error vs. spread for 2001-2003 eastern North Pacific

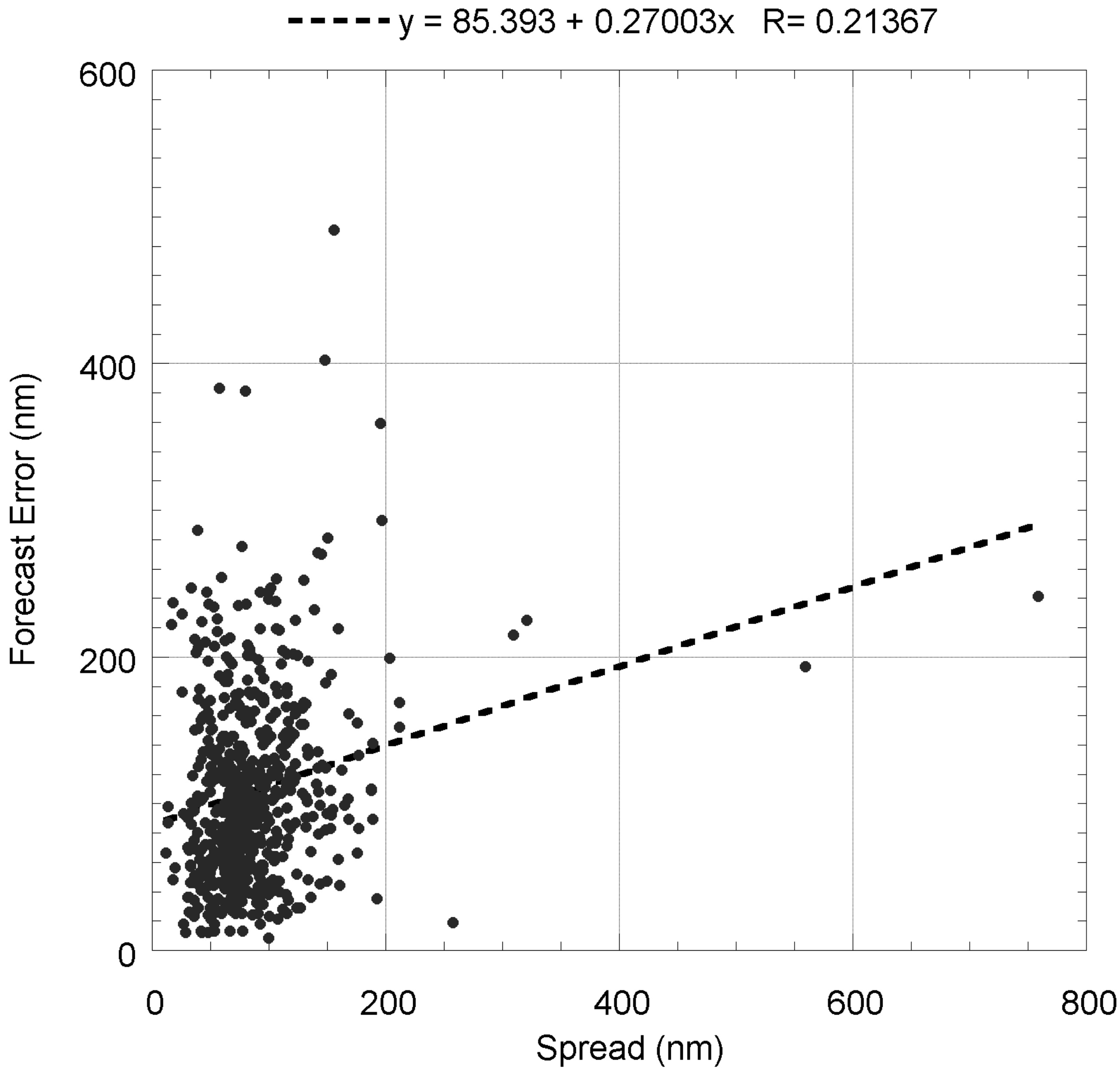

Fig. 40. CONU 48-h track forecast error vs. spread for 2001-2003 eastern North Pacific

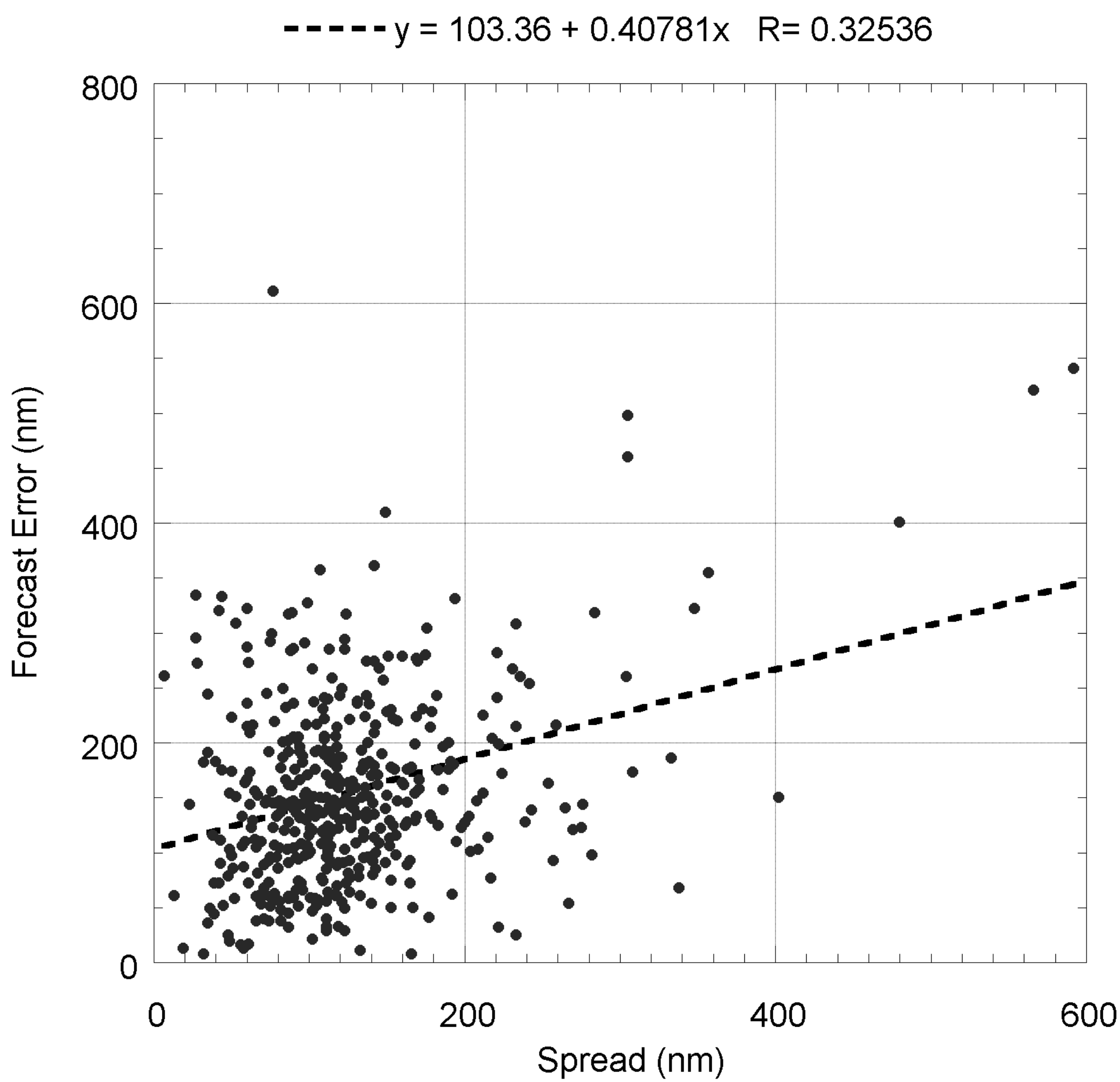

Fig. 41. CONU 72-h track forecast error vs. spread for 2001-2003 eastern North Pacific

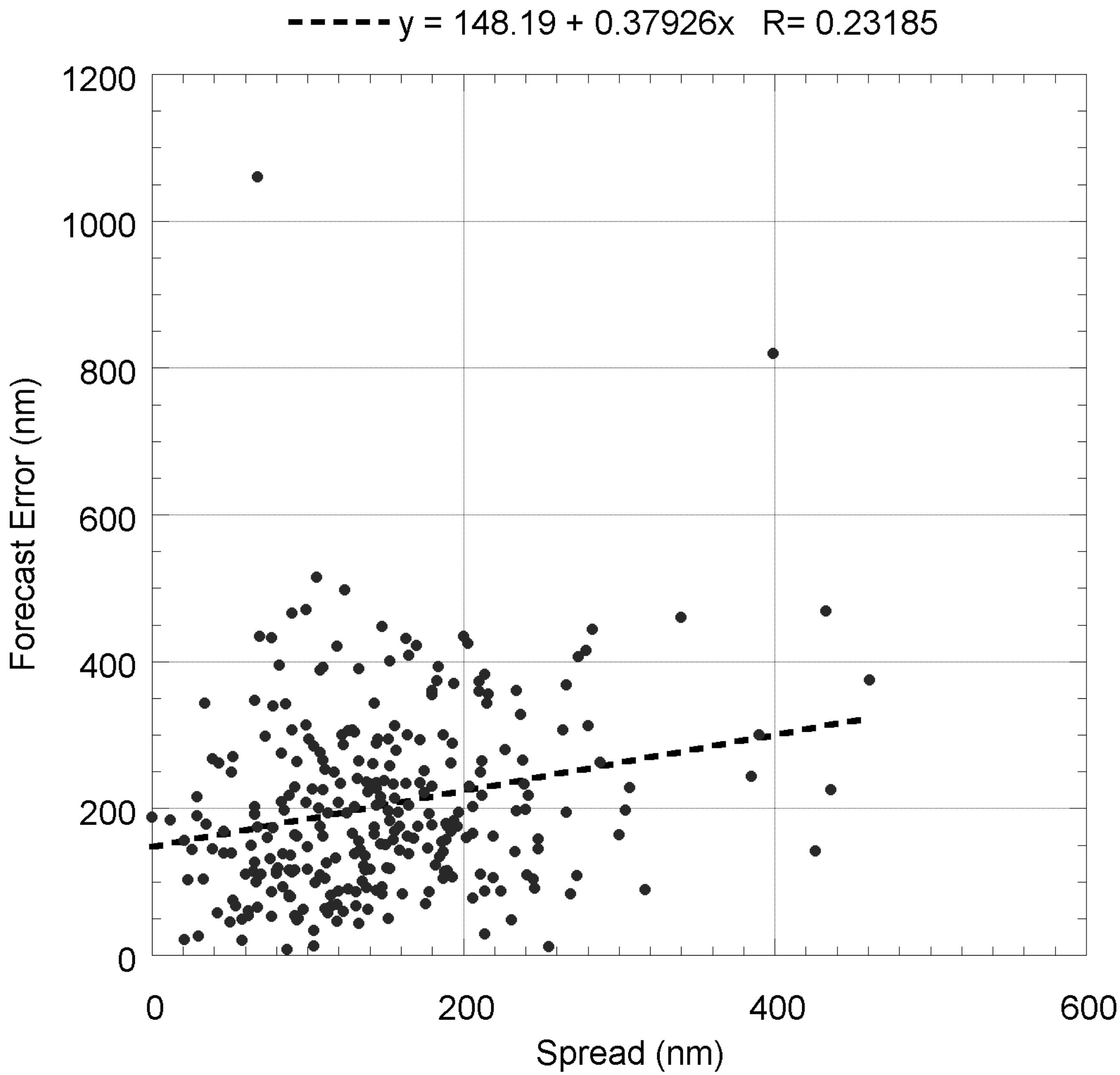

Fig. 42. CONU 96-h track forecast error vs. spread for 2001-2003 eastern North Pacific

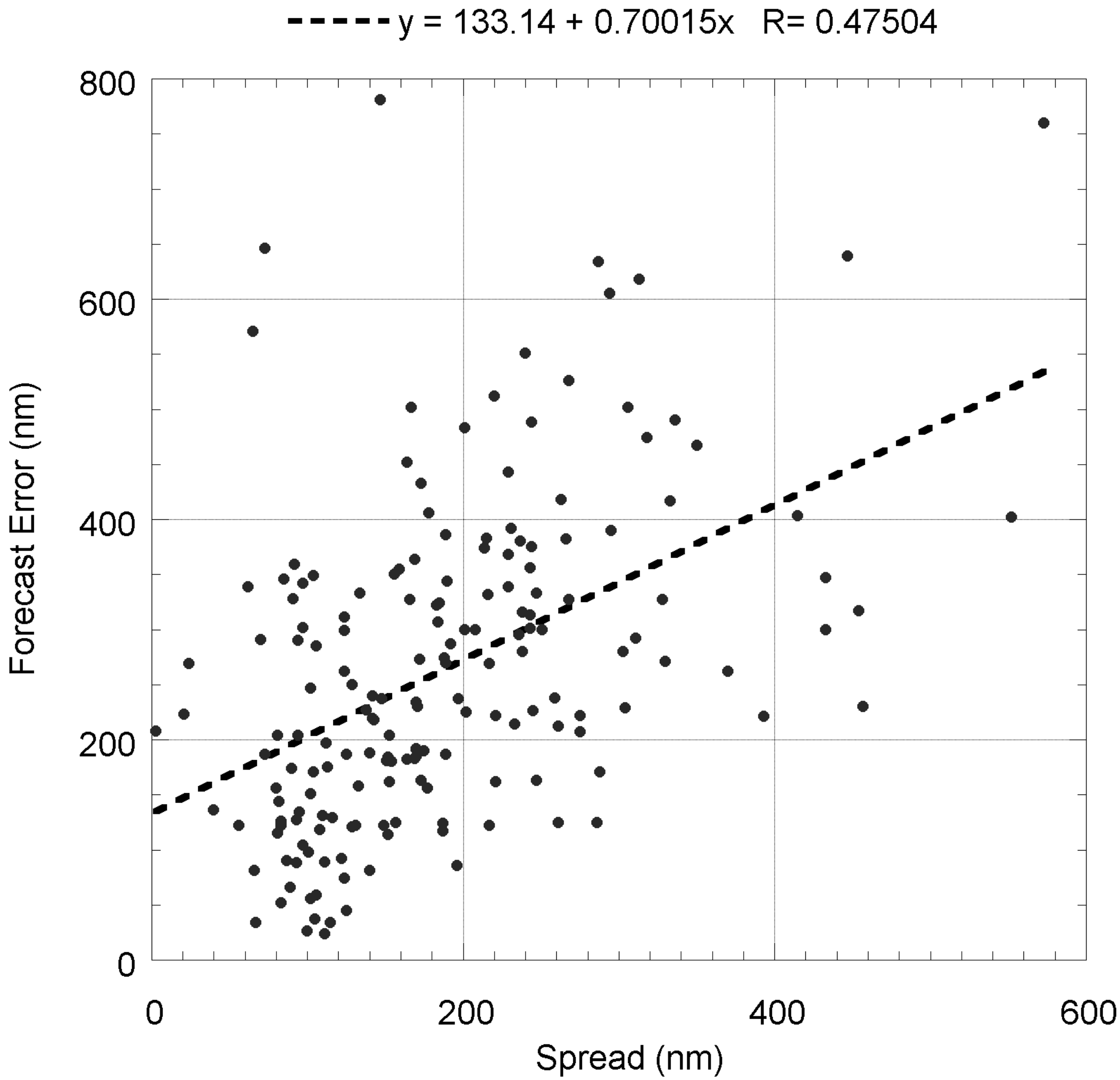

Fig. 43. CONU 120-h track forecast error vs. spread for 2001-2003 eastern North Pacific

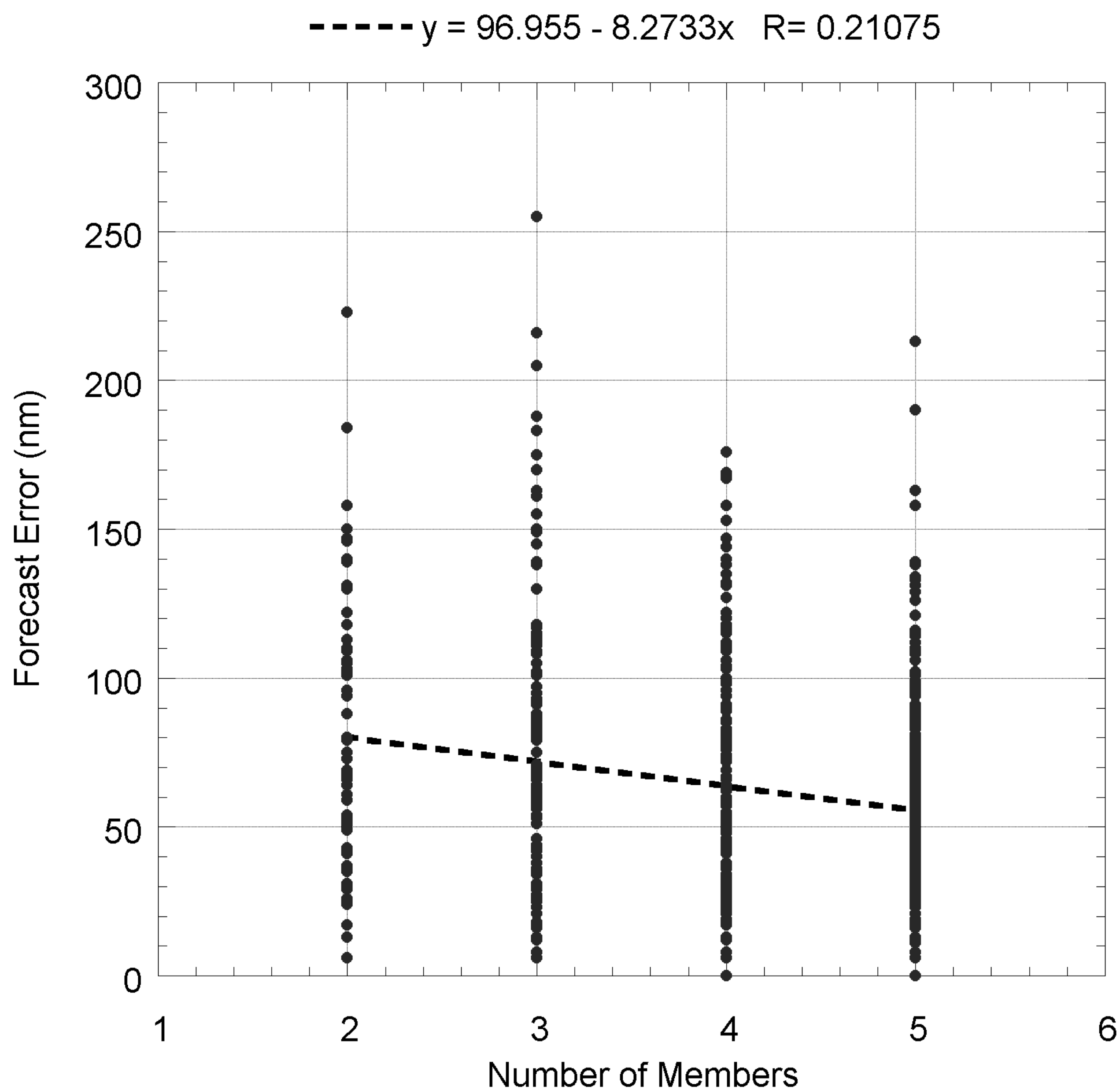

Fig. 44. CONU 24-h track forecast error vs. number of members for 2001-2003 eastern North Pacific

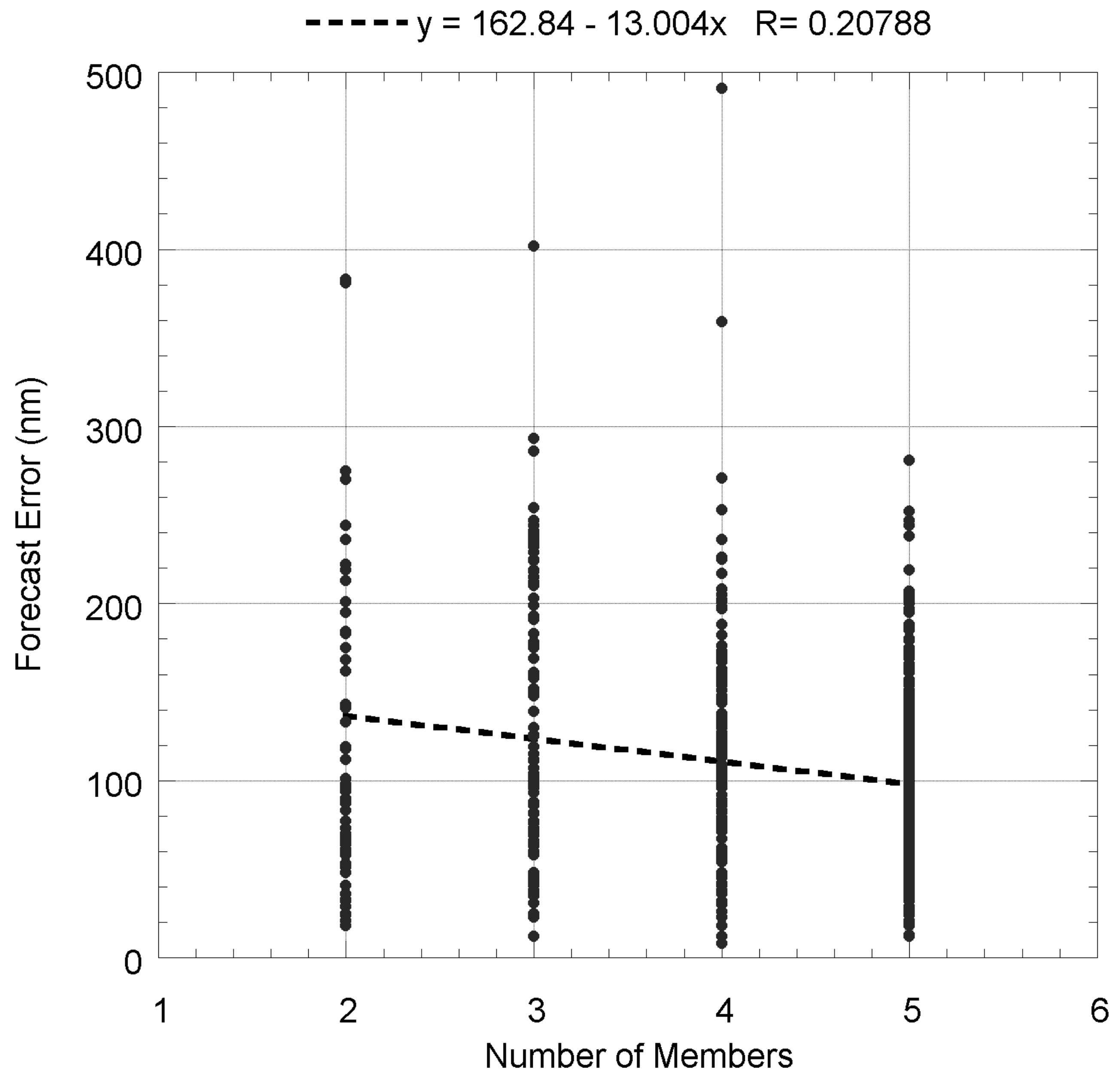

Fig. 45. CONU 48-h track forecast error vs. number of members for 2001-2003 eastern North Pacific

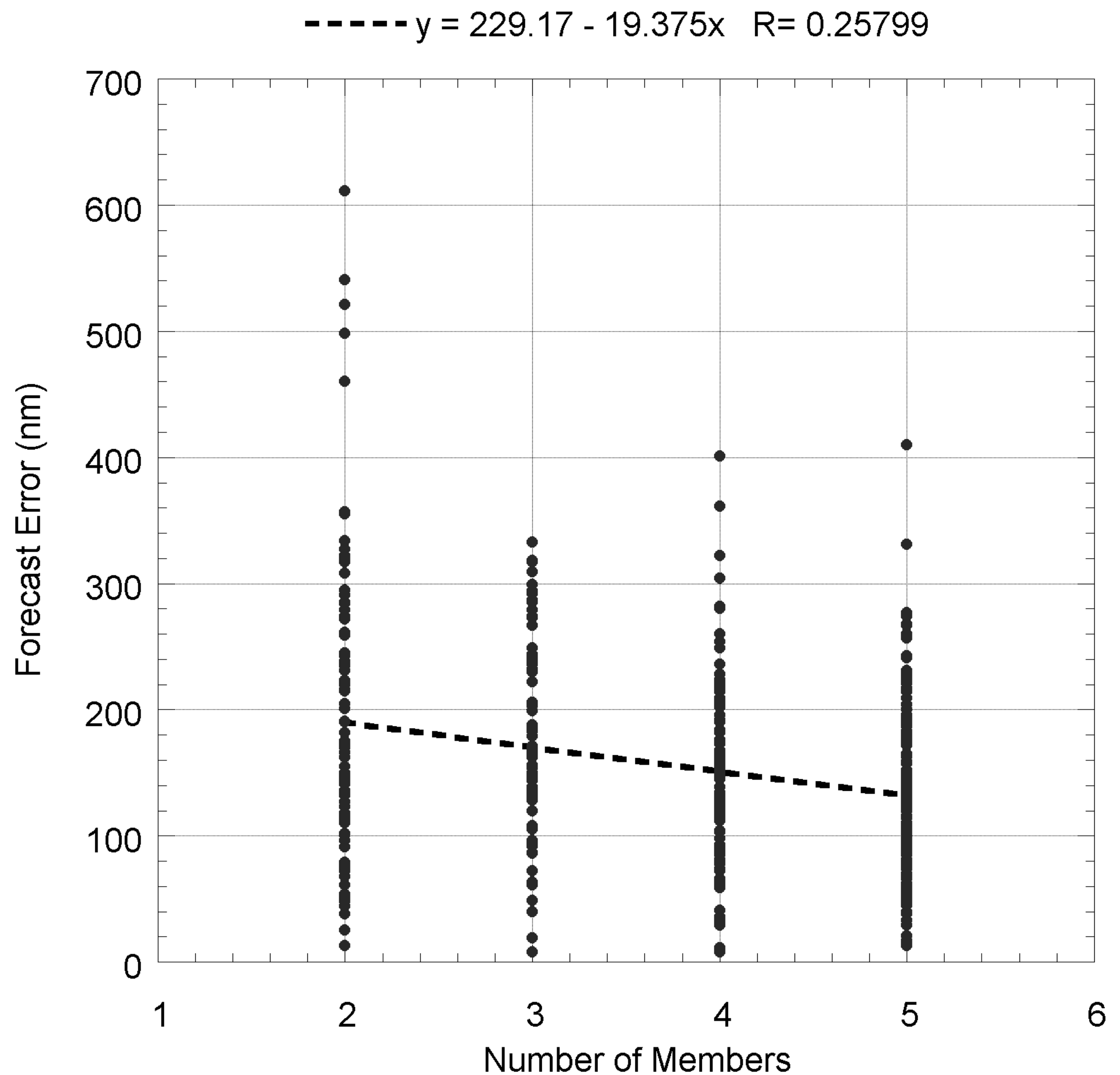

Fig. 46. CONU 72-h track forecast error vs. number of members for 2001-2003 eastern North Pacific

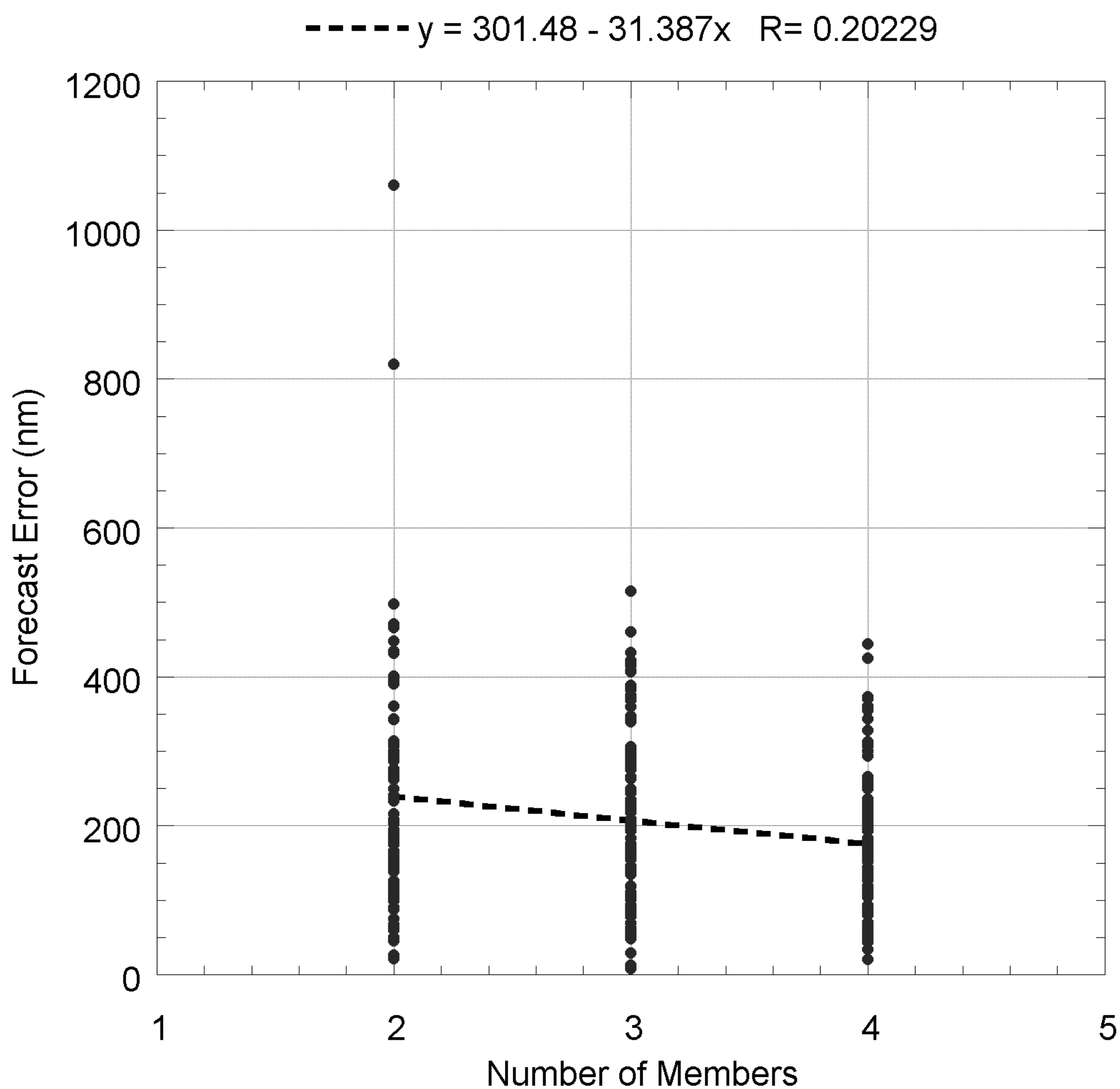

Fig. 47. CONU 96-h track forecast error vs. number of members for 2001-2003 eastern North Pacific

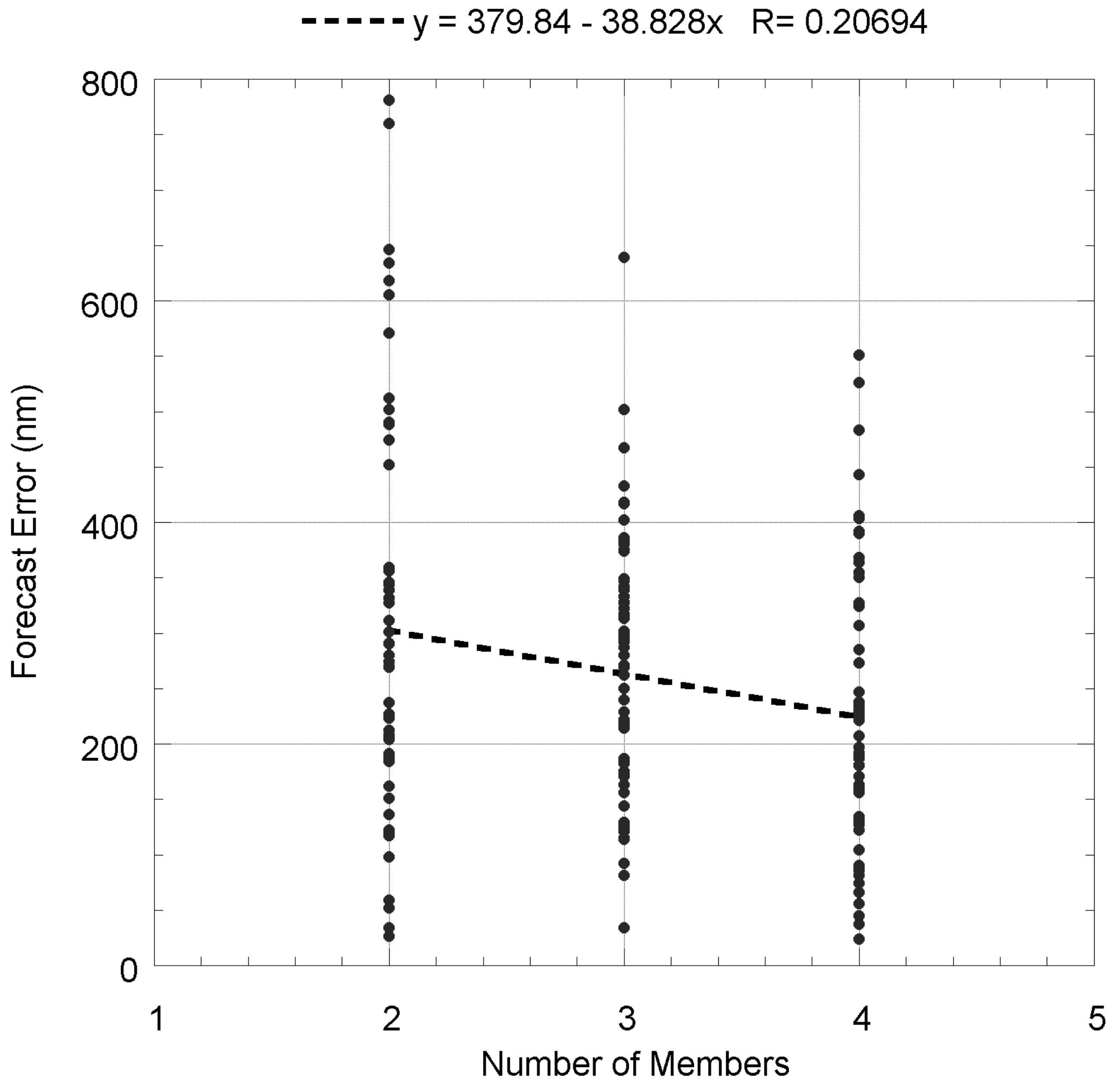

Fig. 48. CONU 120-h track forecast error vs. number of members for 2001-2003 eastern North Pacific

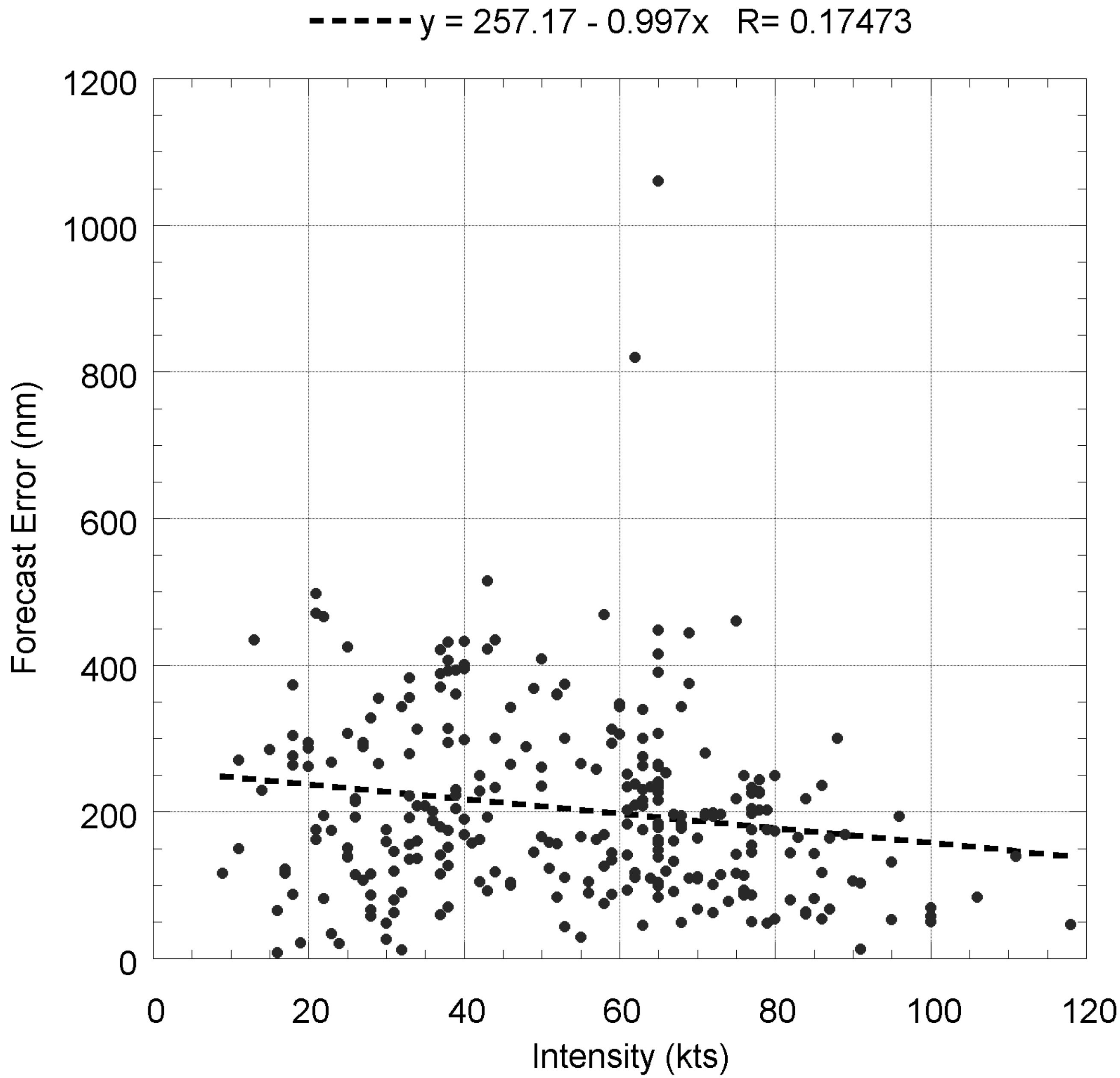

Fig. 49. CONU 96-h track forecast error vs. forecast TC intensity for 2001-2003 eastern North Pacific

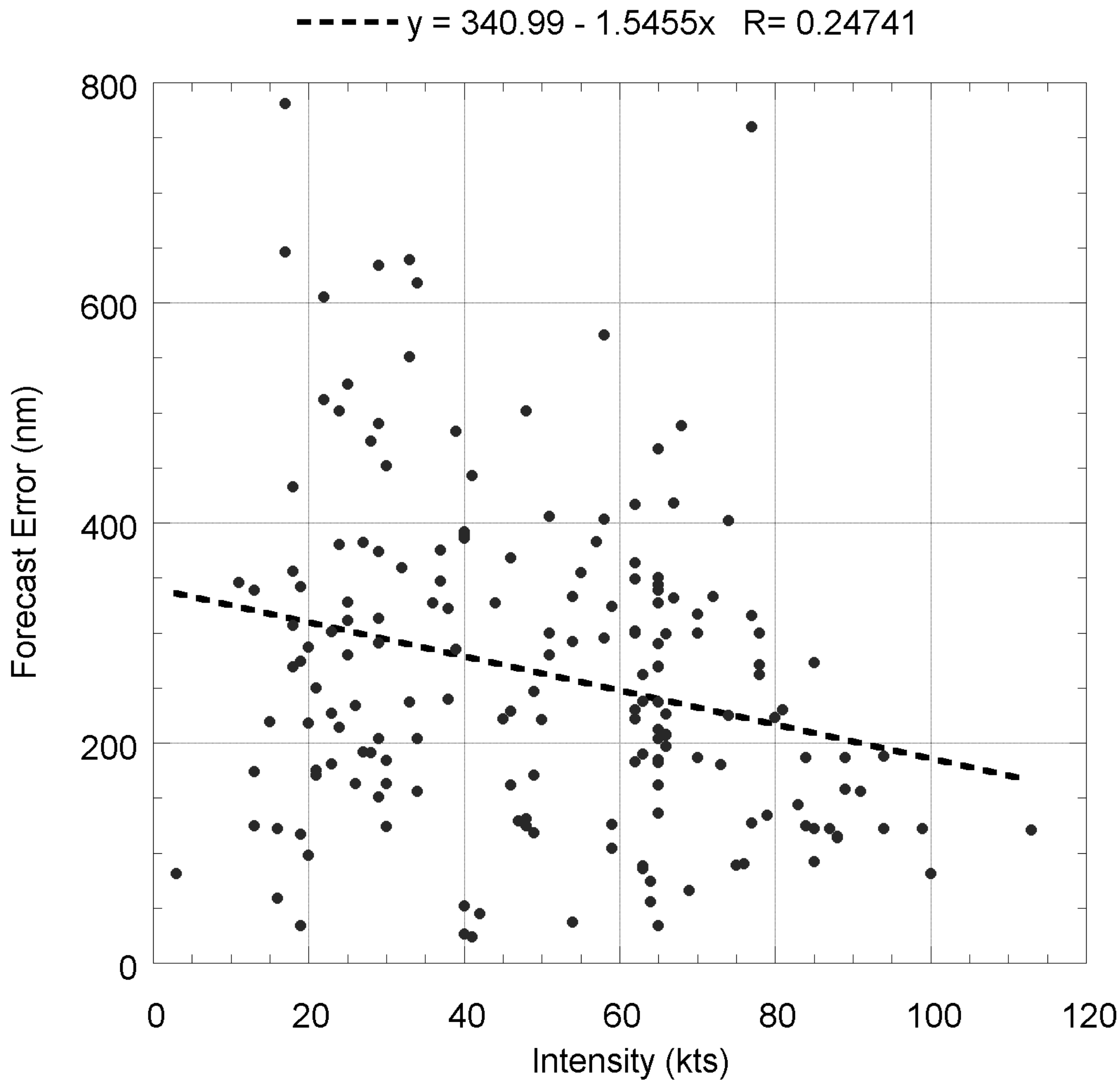

Fig. 50. CONU 120-h track forecast error vs. forecast TC intensity for 2001-2003 eastern North Pacific

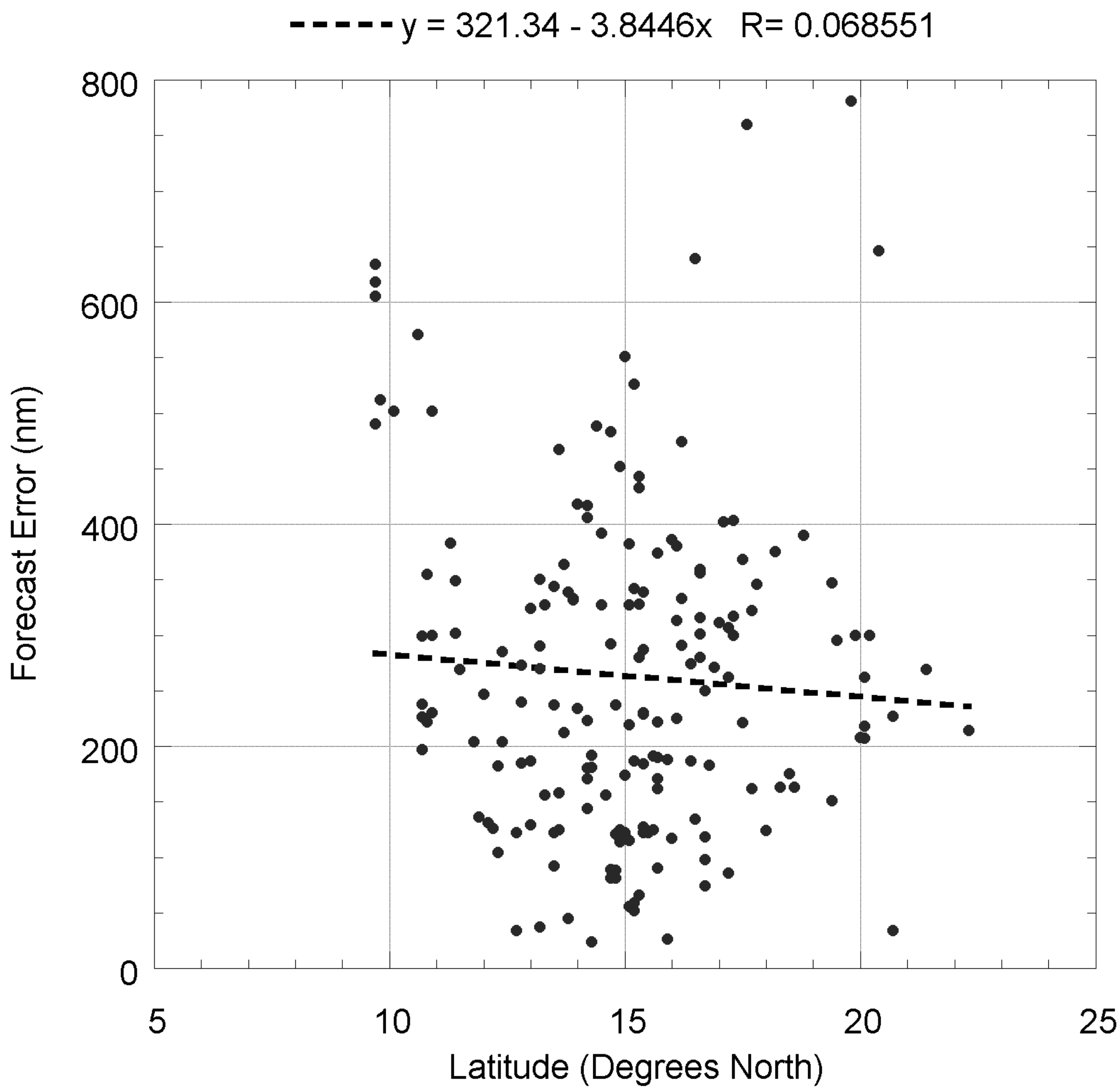

Fig. 51. CONU 120-h track forecast error vs. initial latitude for 2001-2003 eastern North Pacific

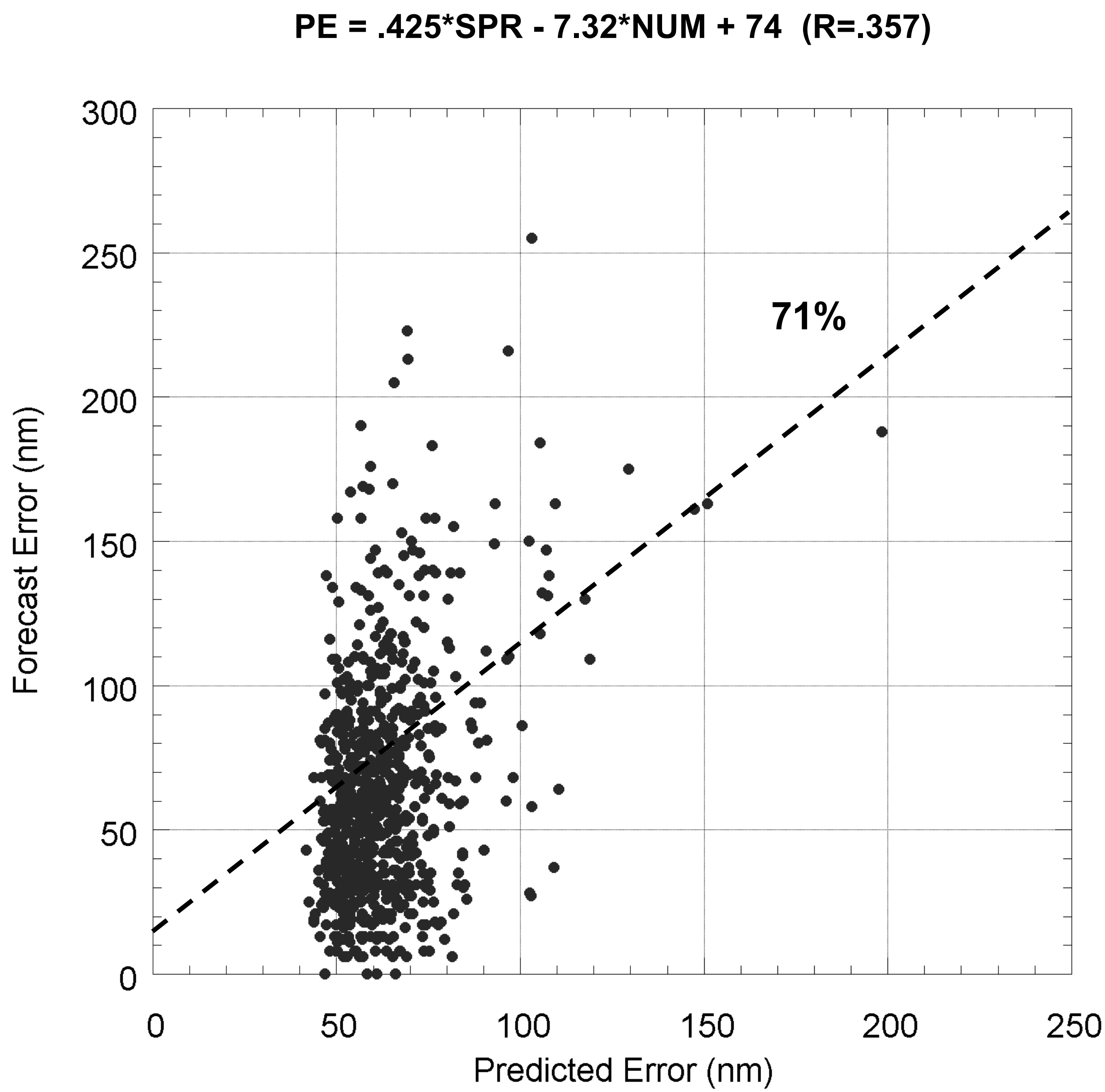

Fig. 52. CONU 24-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

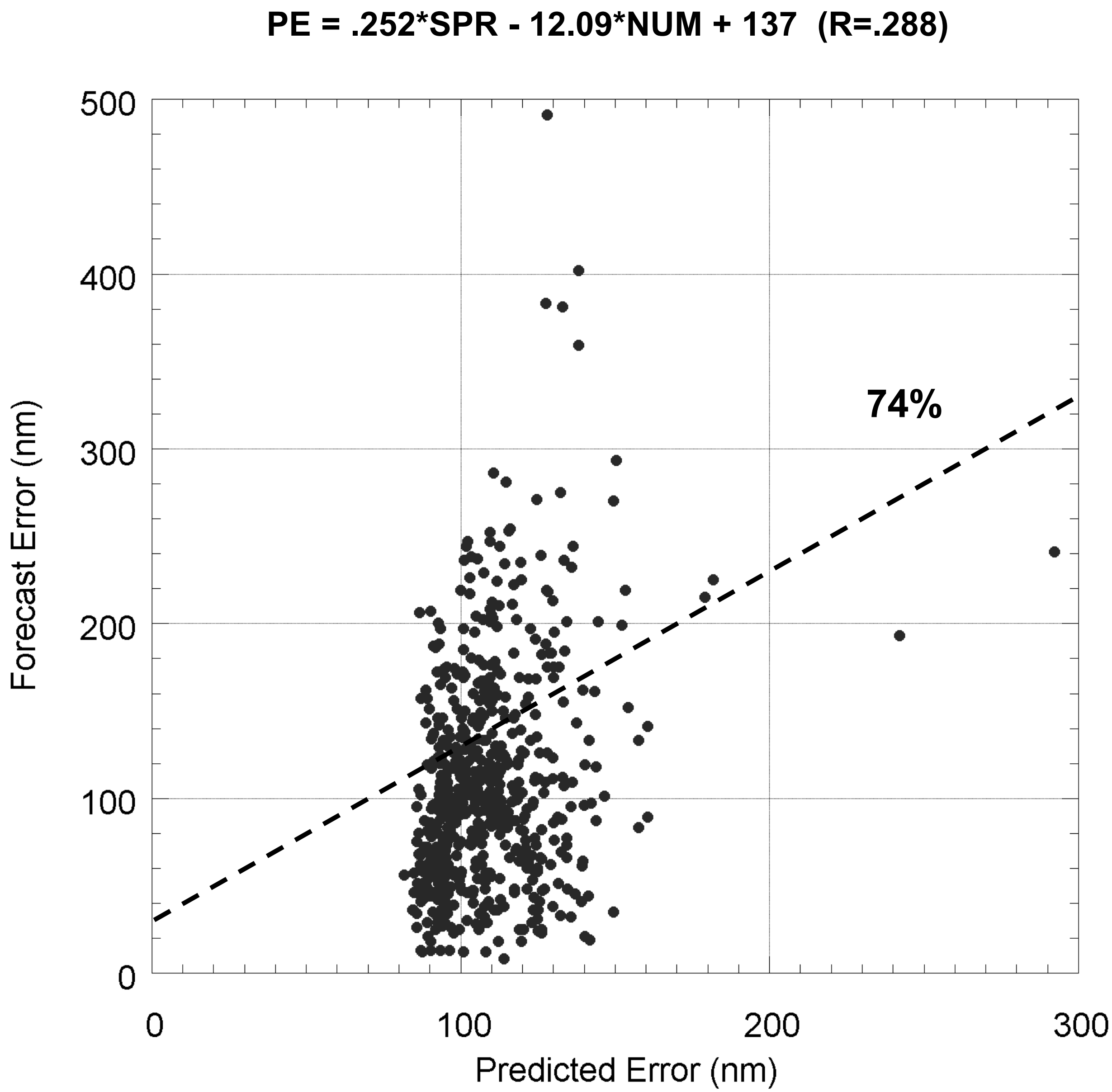

Fig. 53. CONU 48-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

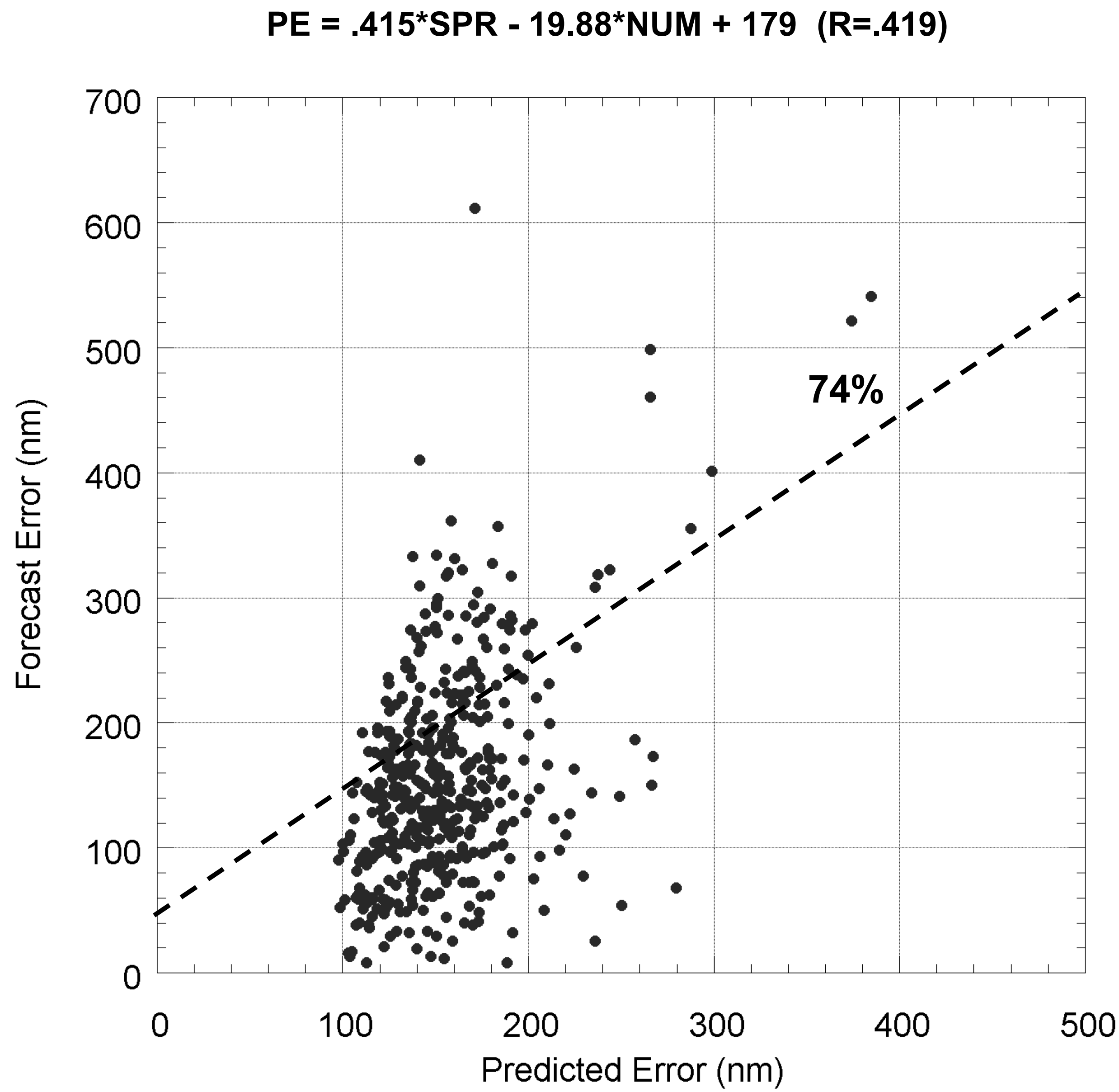

Fig. 54. CONU 72-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

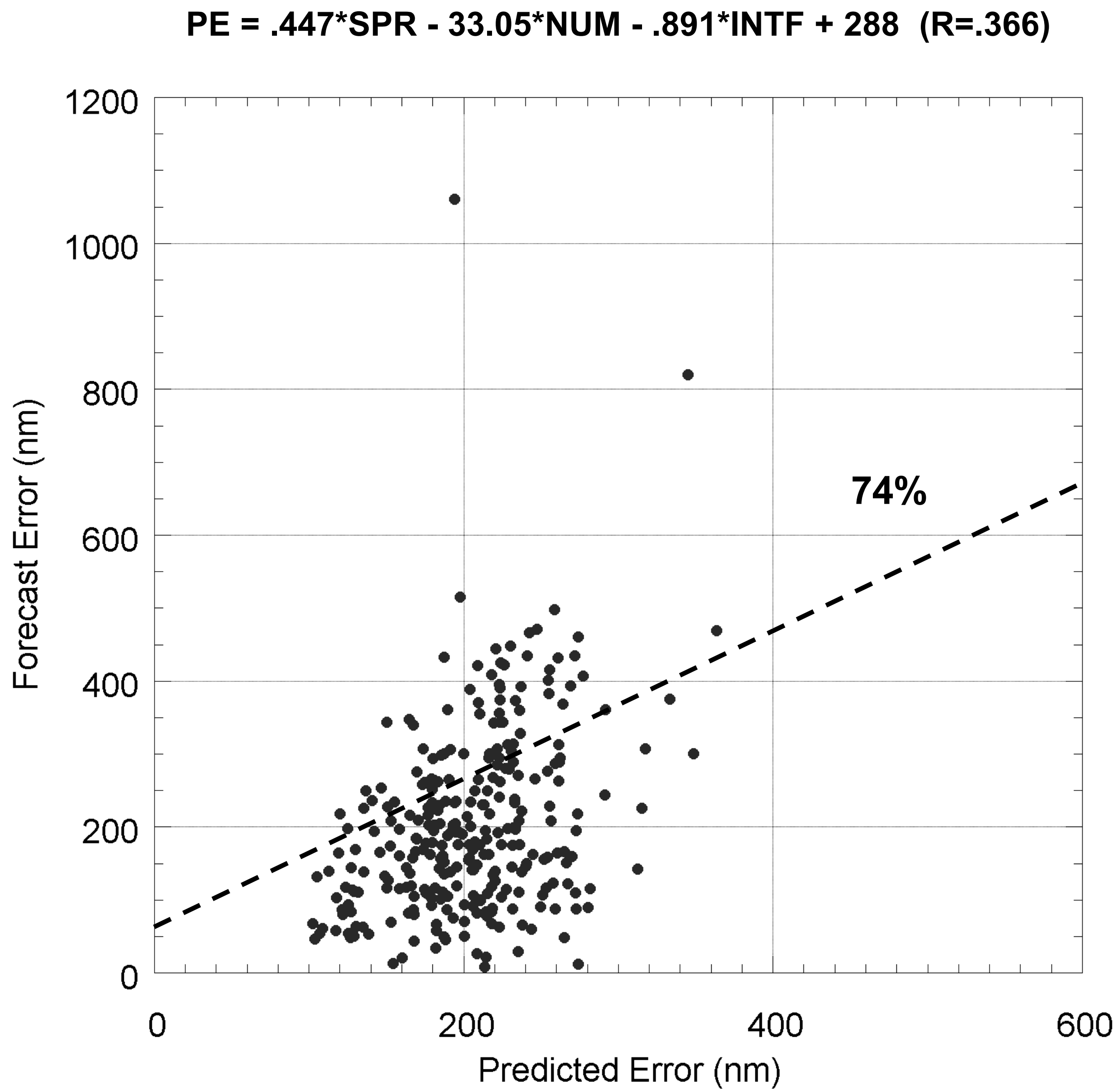

Fig. 55. CONU 96-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

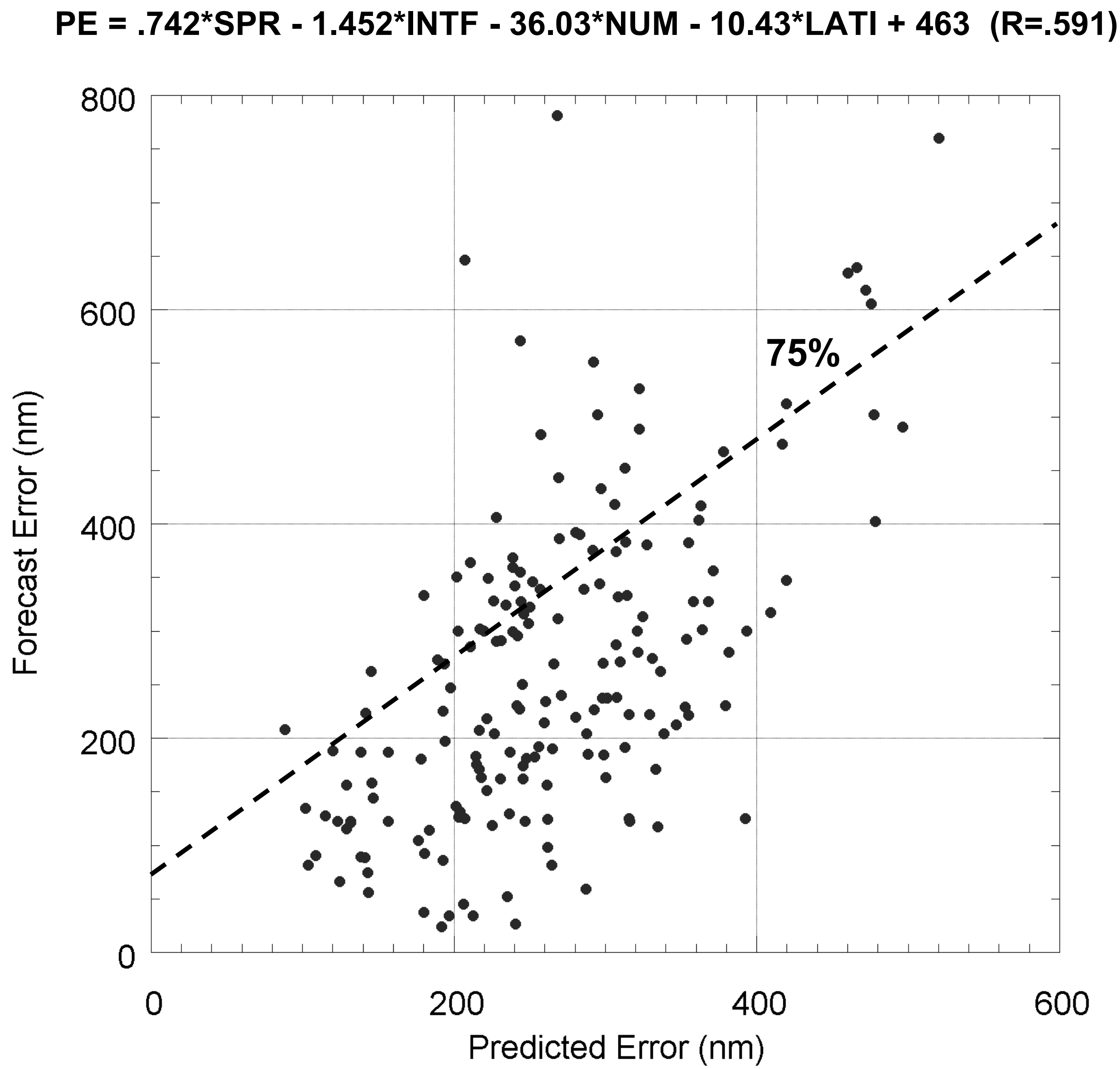

Fig. 56. CONU 120-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

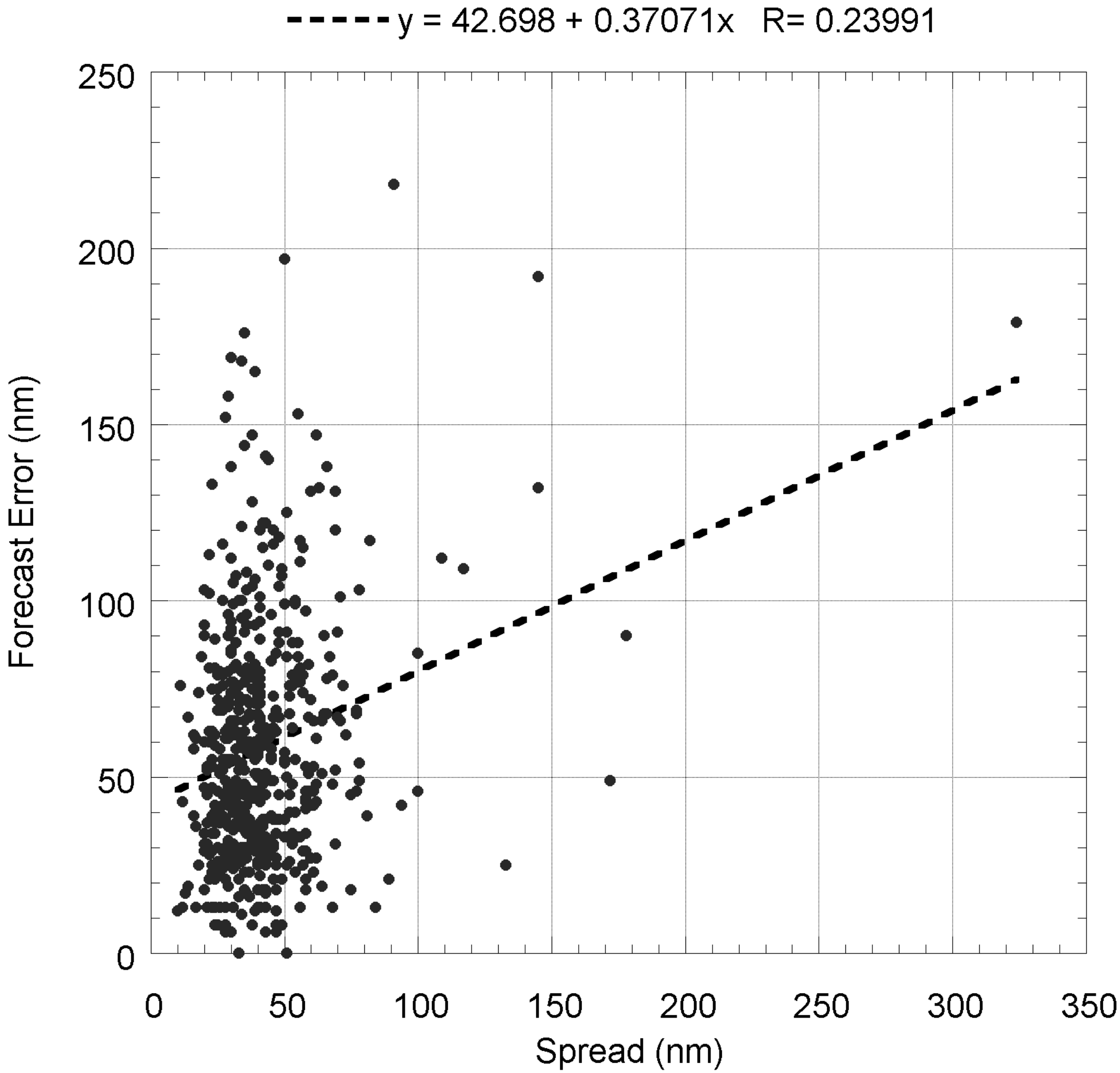

Fig. 57. GUNA 24-h track forecast error vs. spread for 2001-2003 eastern North Pacific

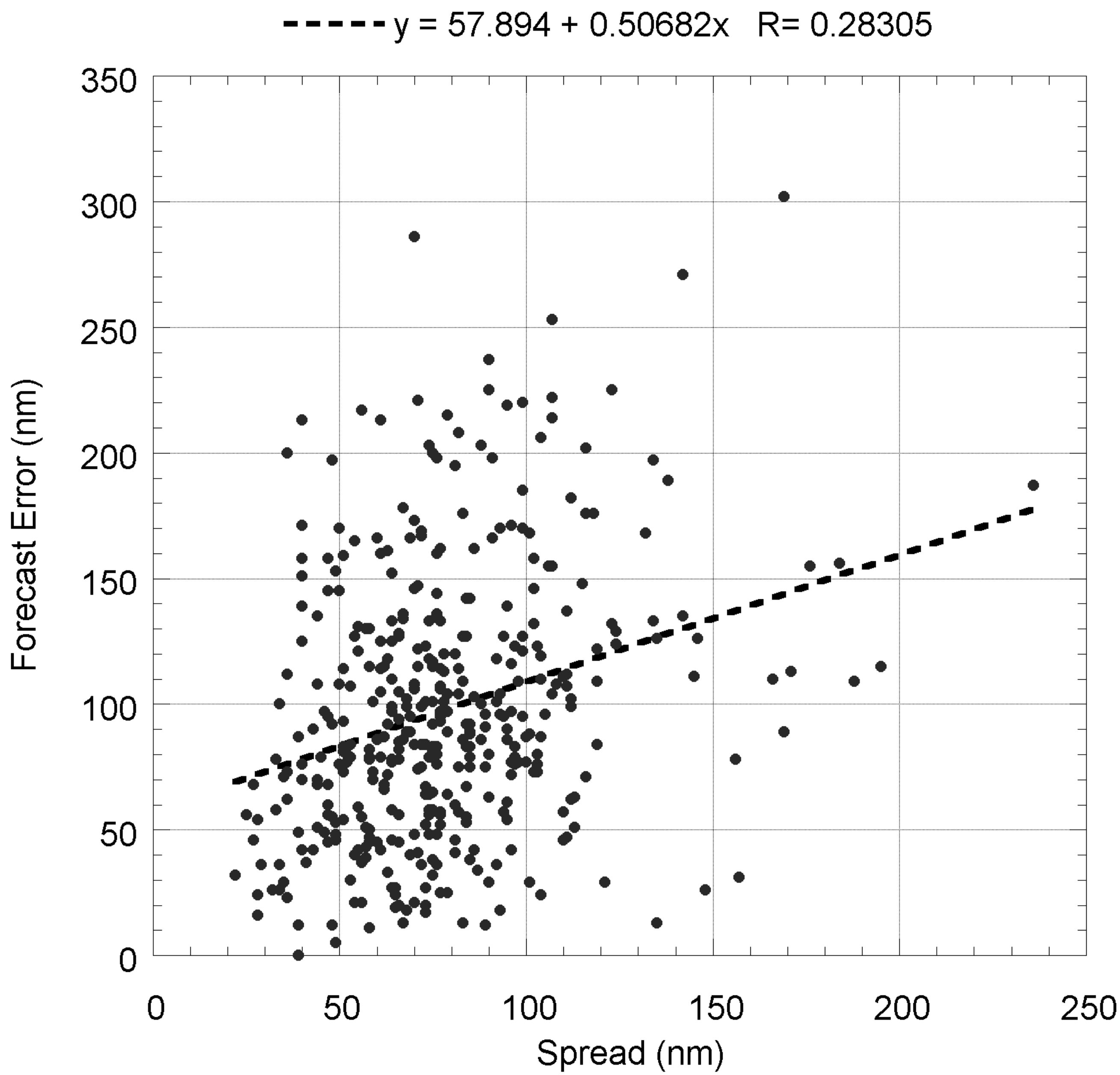

Fig. 58. GUNA 48-h track forecast error vs. spread for 2001-2003 eastern North Pacific

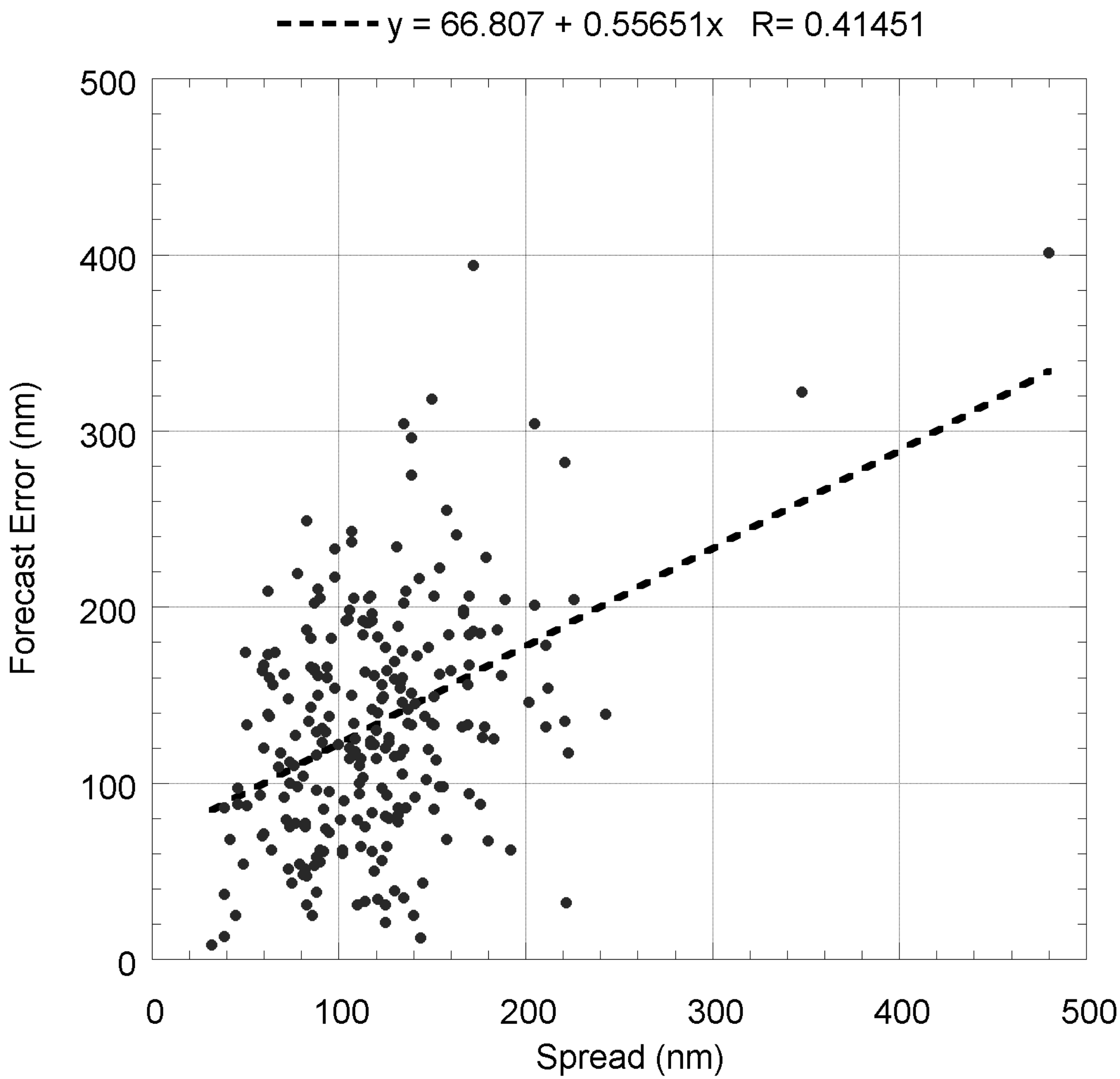

Fig. 59. GUNA 72-h track forecast error vs. spread for 2001-2003 eastern North Pacific

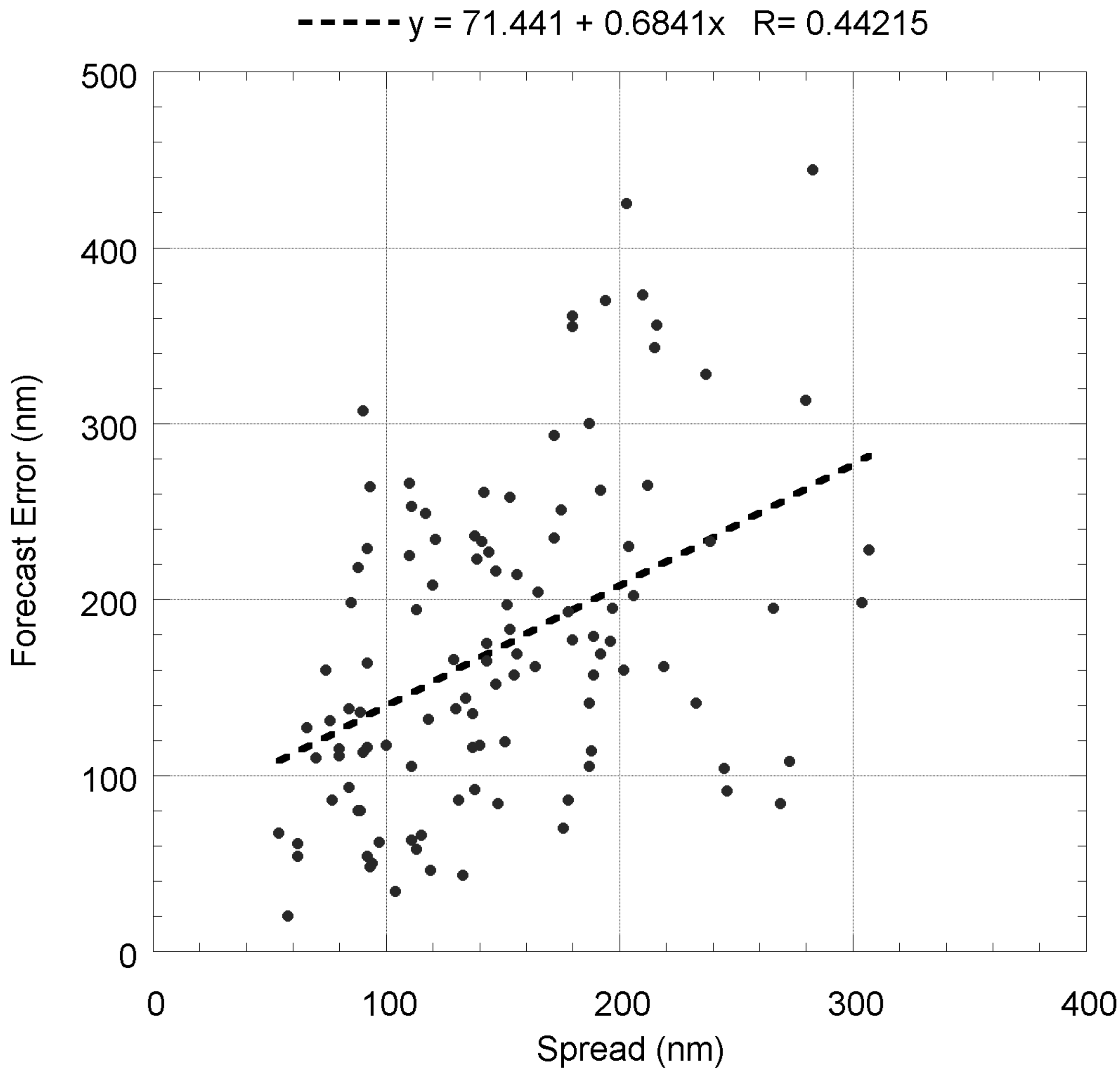

Fig. 60. GUNA 96-h track forecast error vs. spread for 2001-2003 eastern North Pacific

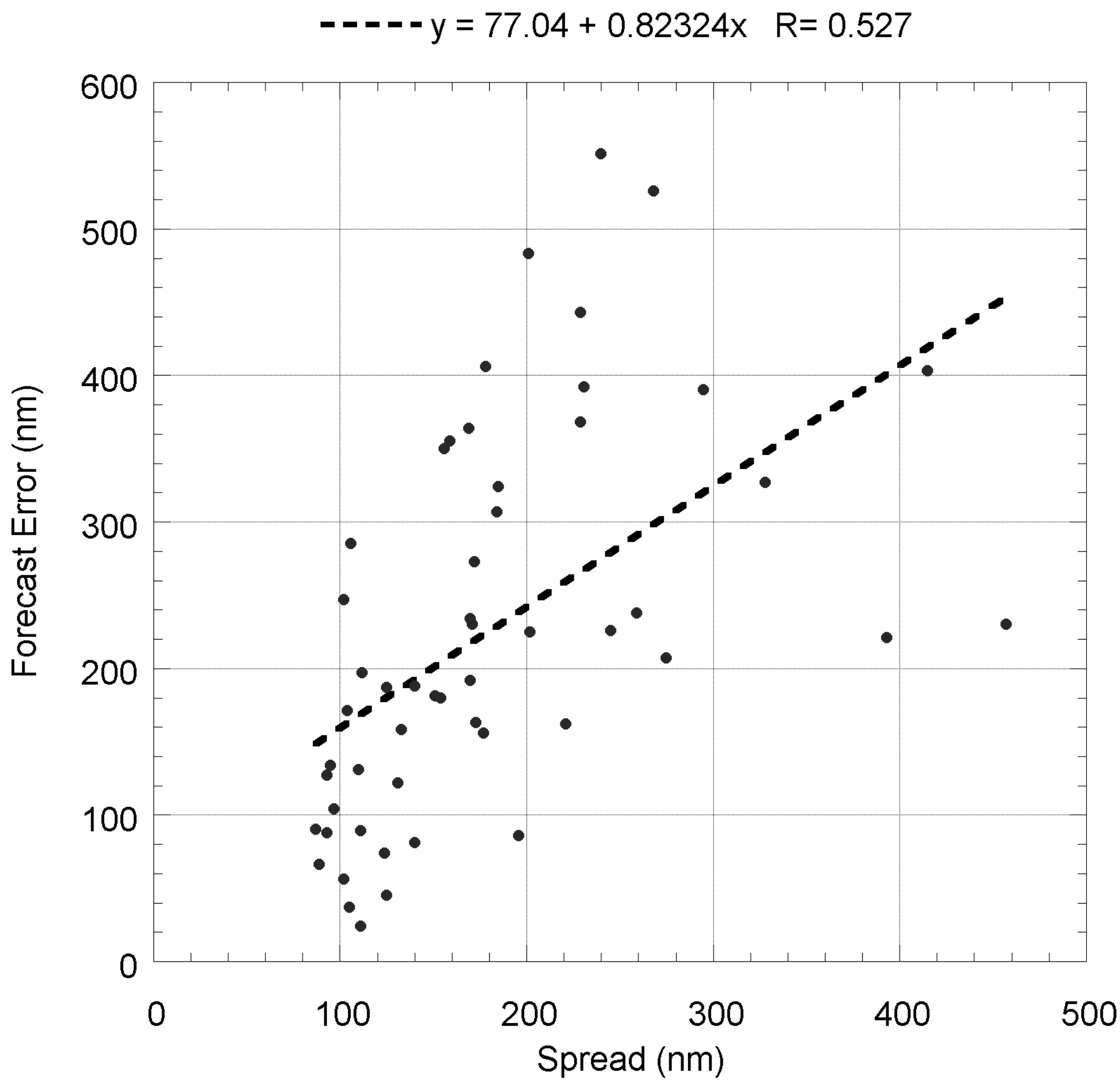

Fig. 61. GUNA 120-h track forecast error vs. spread for 2001-2003 eastern North Pacific

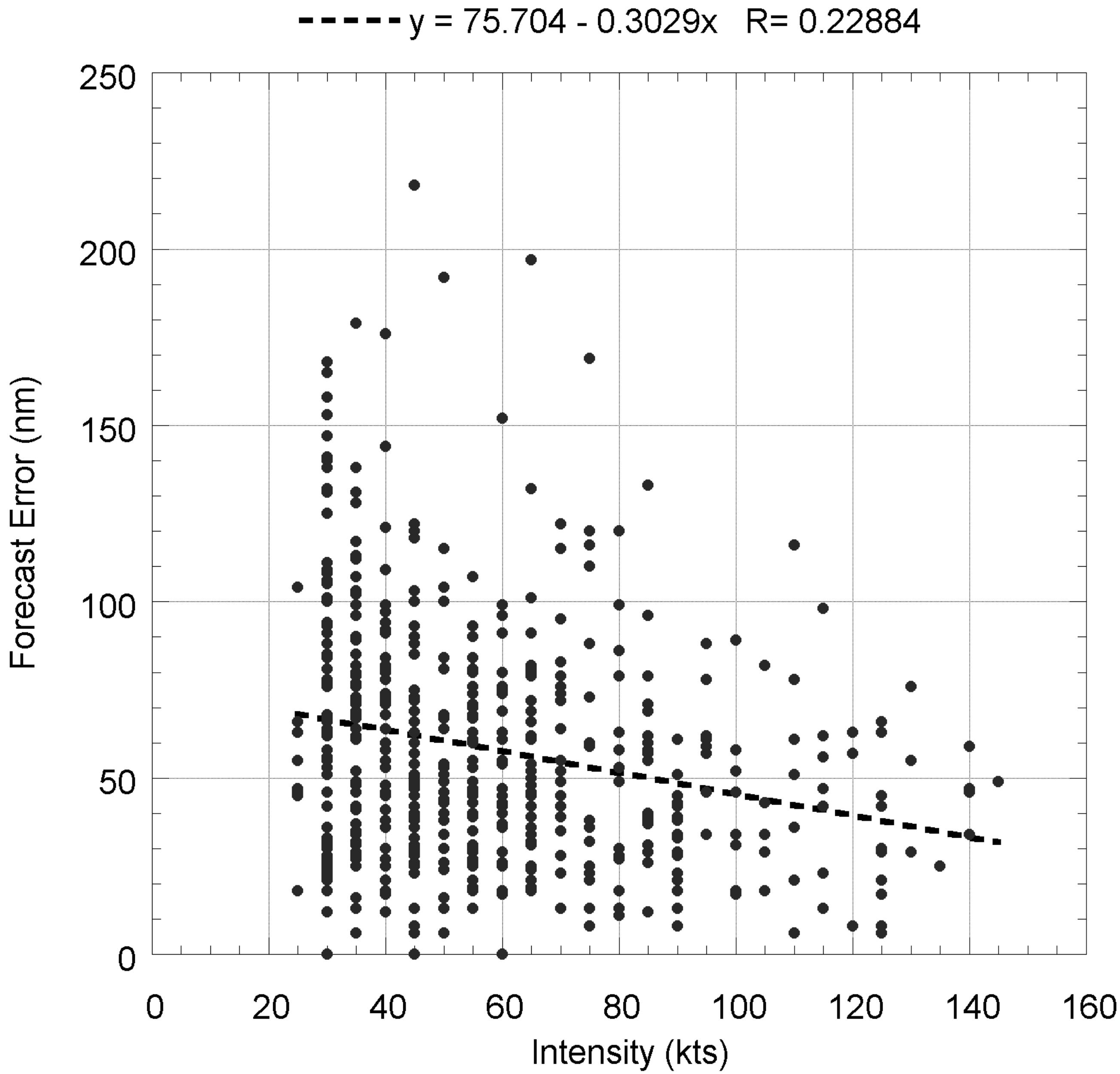

Fig. 62. GUNA 24-h track forecast error vs. initial TC intensity for 2001-2003 eastern North Pacific

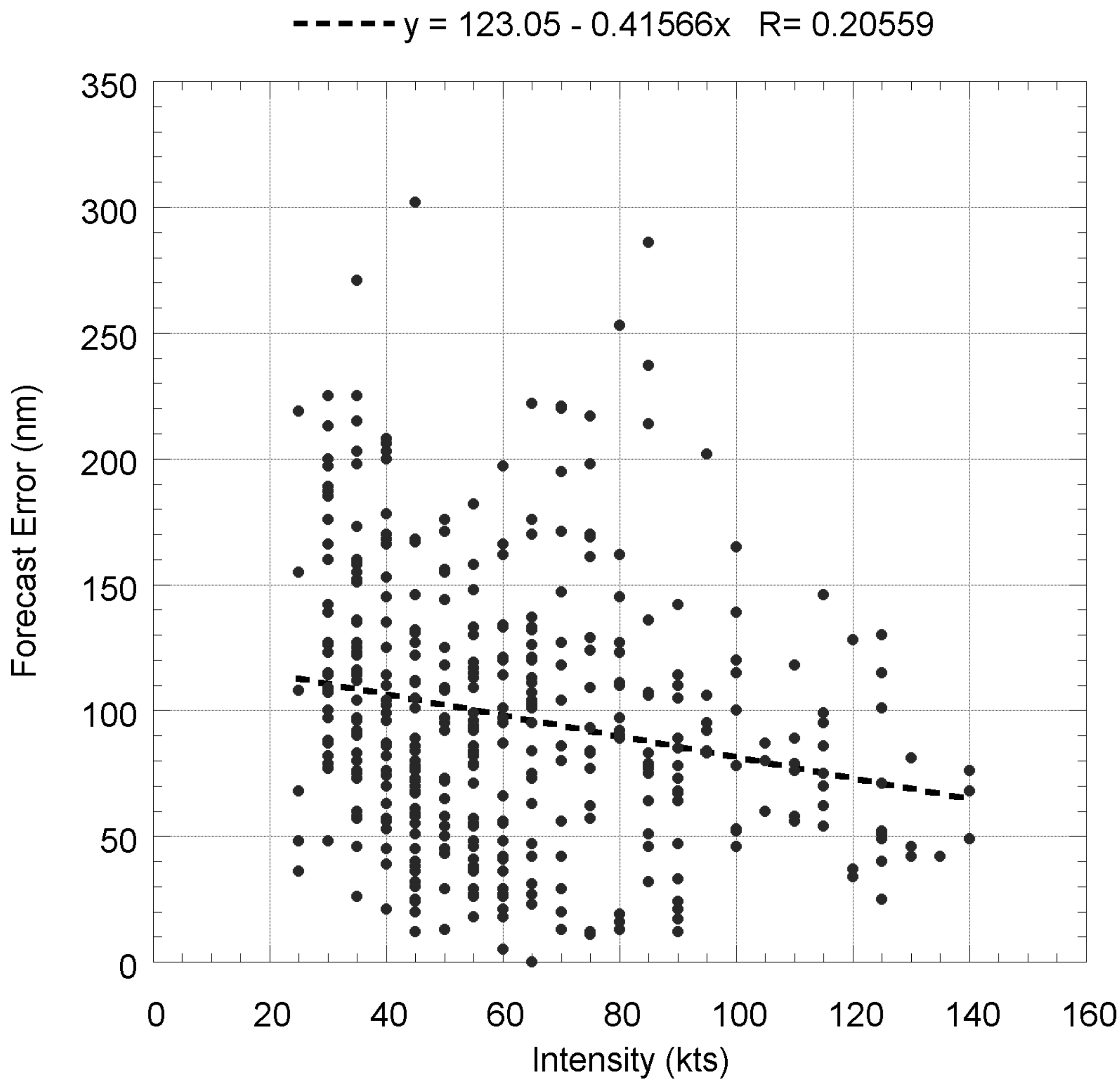

Fig. 63. GUNA 48-h track forecast error vs. initial TC intensity for 2001-2003 eastern North Pacific

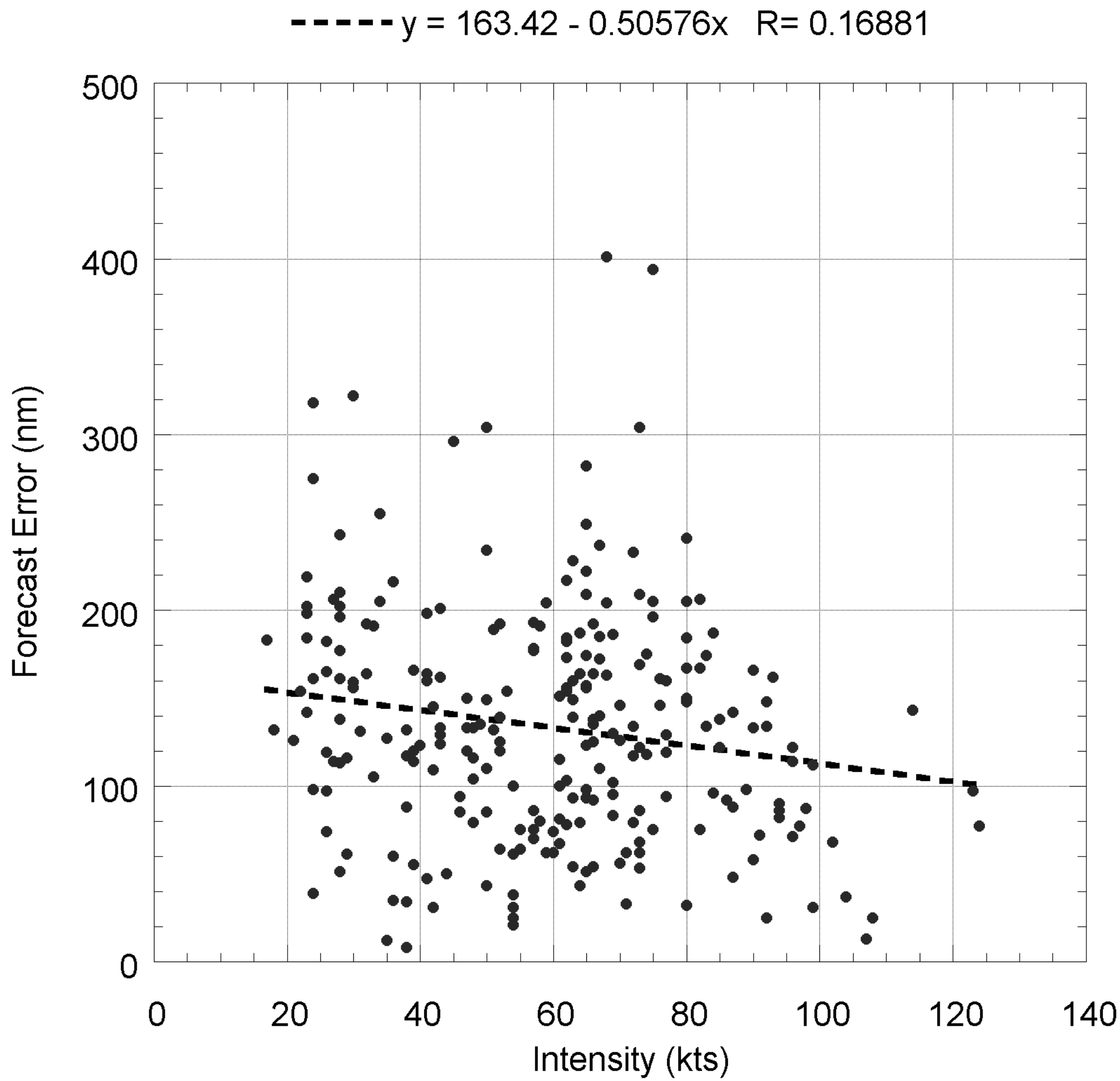

Fig. 64. GUNA 72-h track forecast error vs. forecast TC intensity for 2001-2003 eastern North Pacific

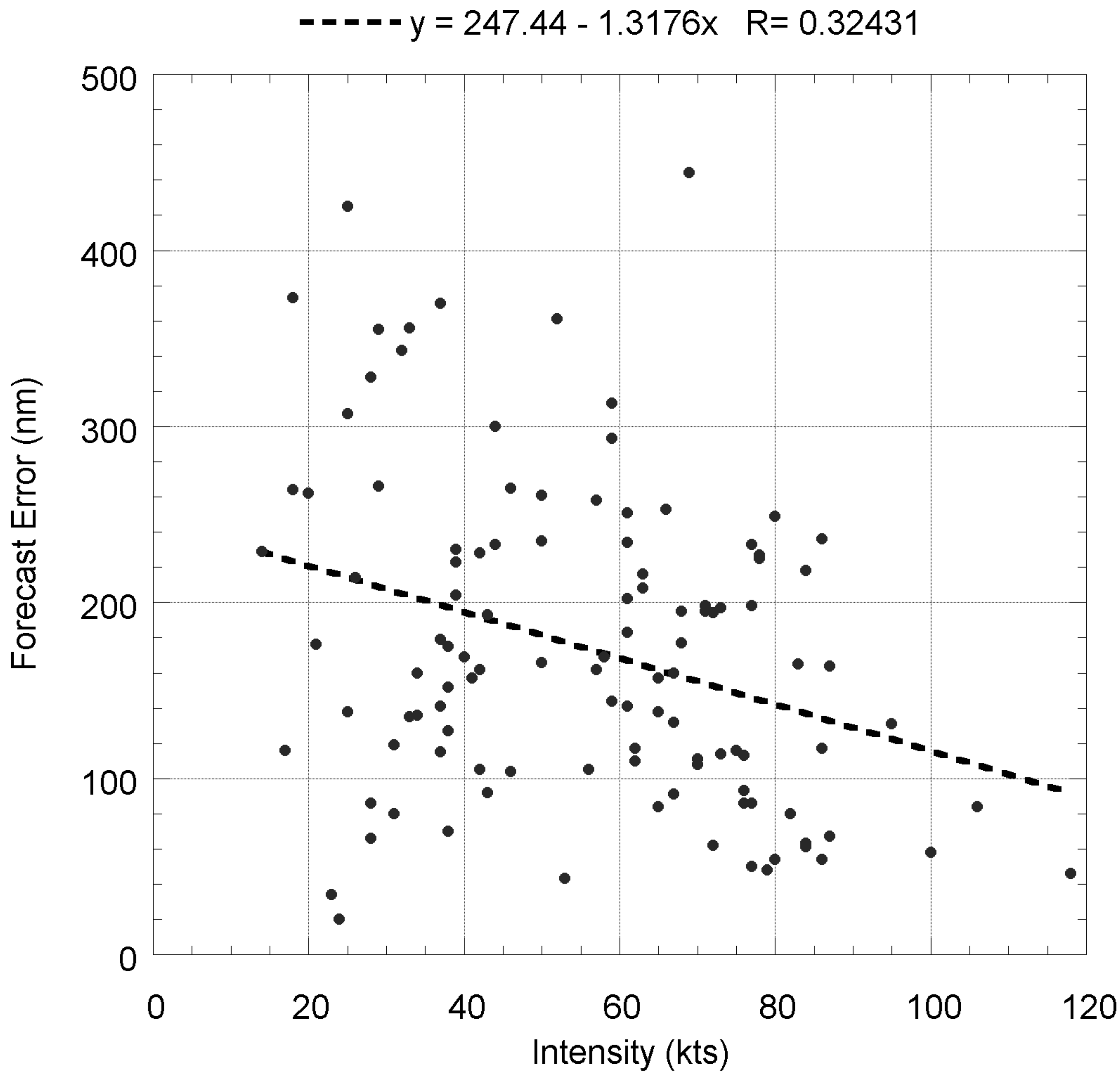

Fig. 65. GUNA 96-h track forecast error vs. forecast TC intensity for 2001-2003 eastern North Pacific

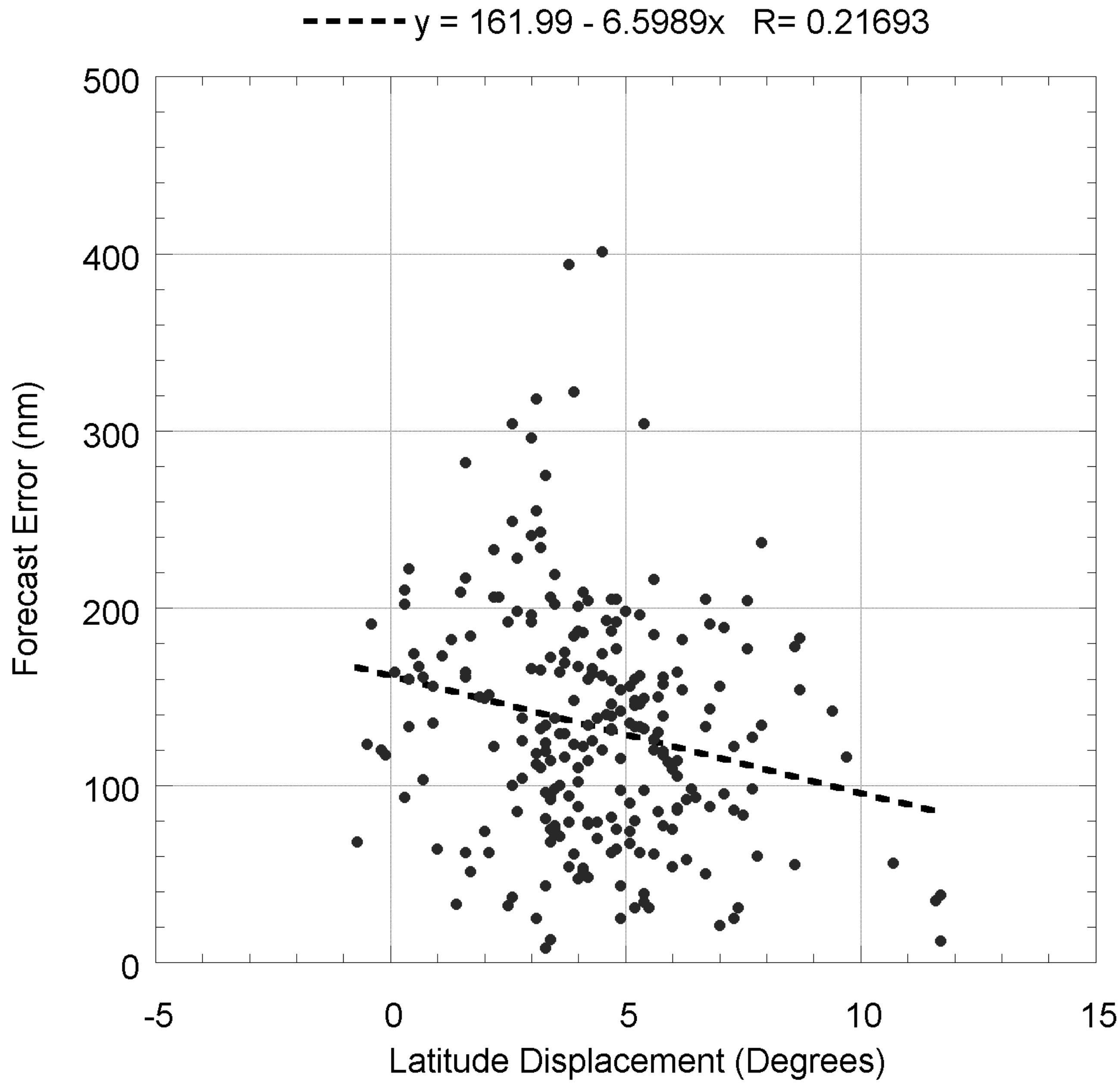

Fig. 66. GUNA 72-h track forecast error vs. latitude displacement for 2001-2003 eastern North Pacific

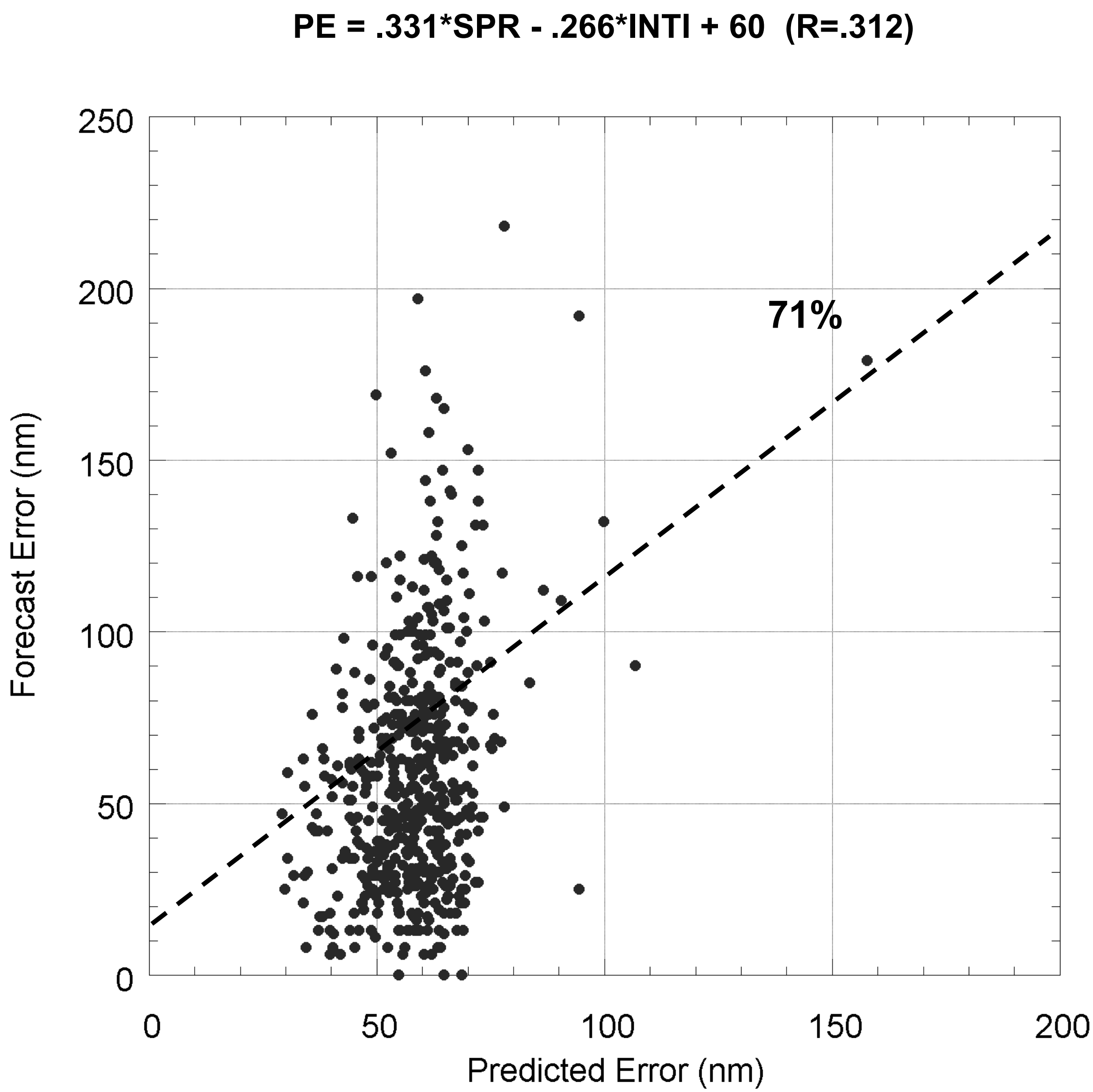

Fig. 67. GUNA 24-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

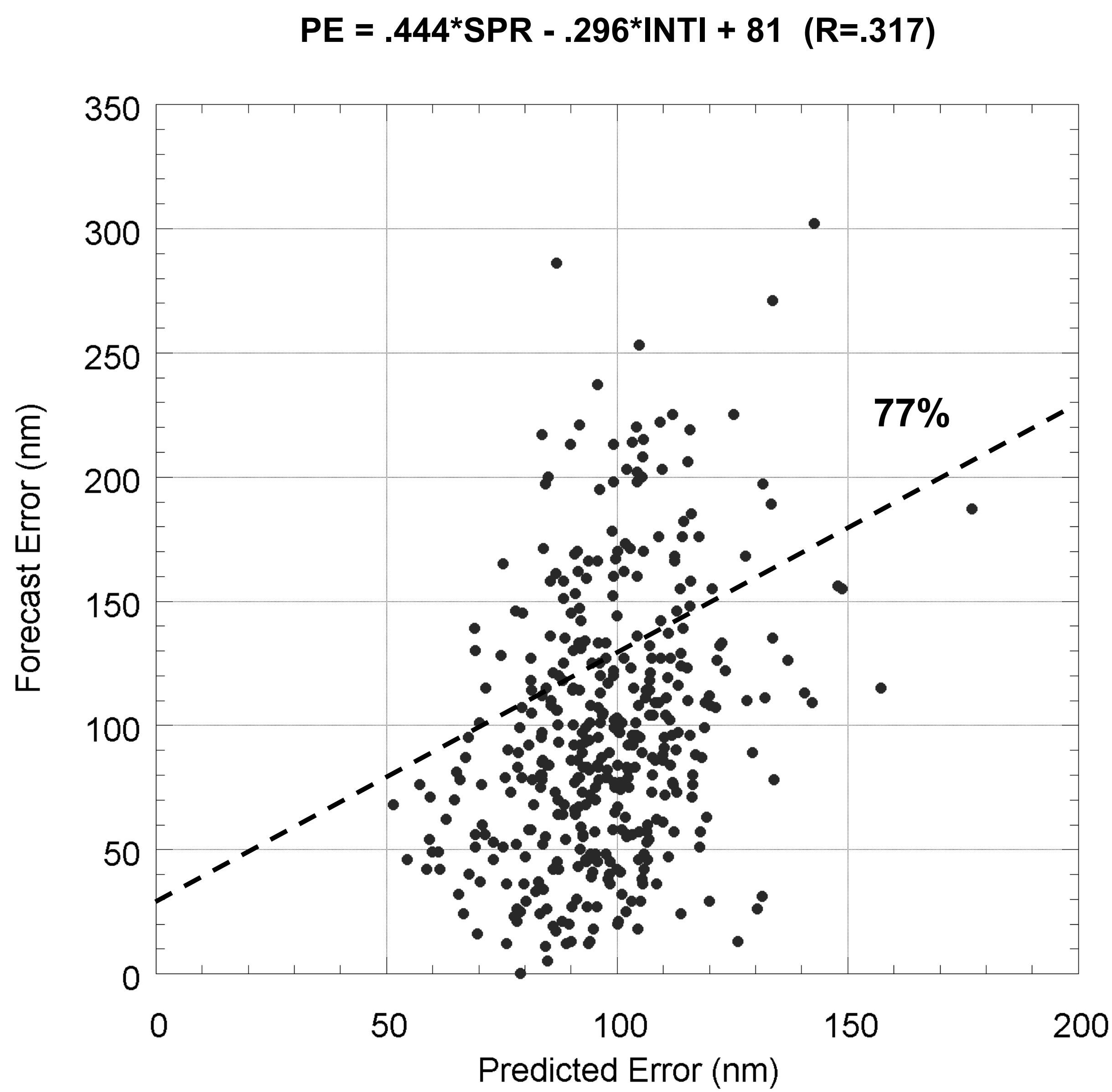

Fig. 68. GUNA 48-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

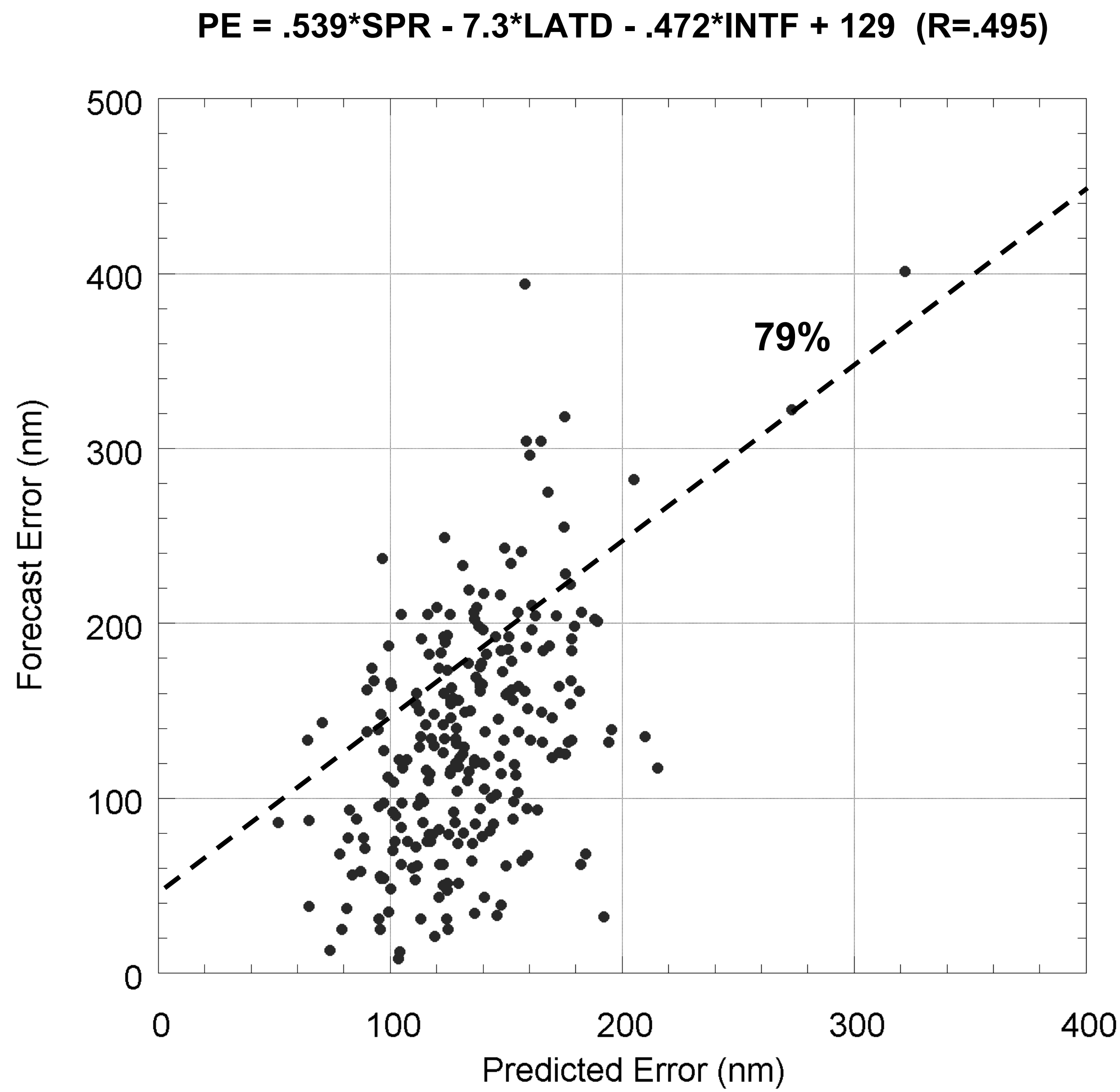

Fig. 69. GUNA 72-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

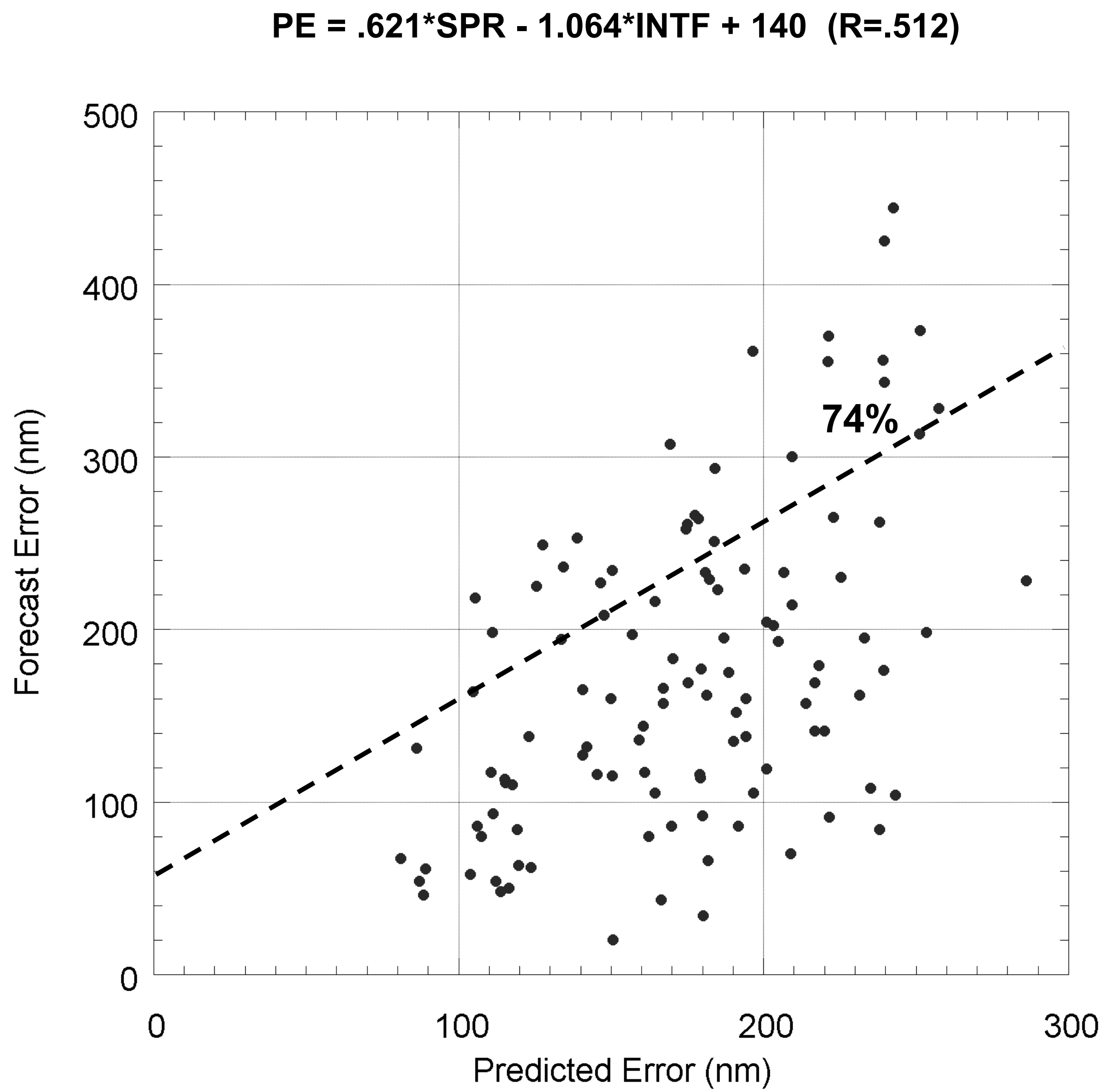

Fig. 70. GUNA 96-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

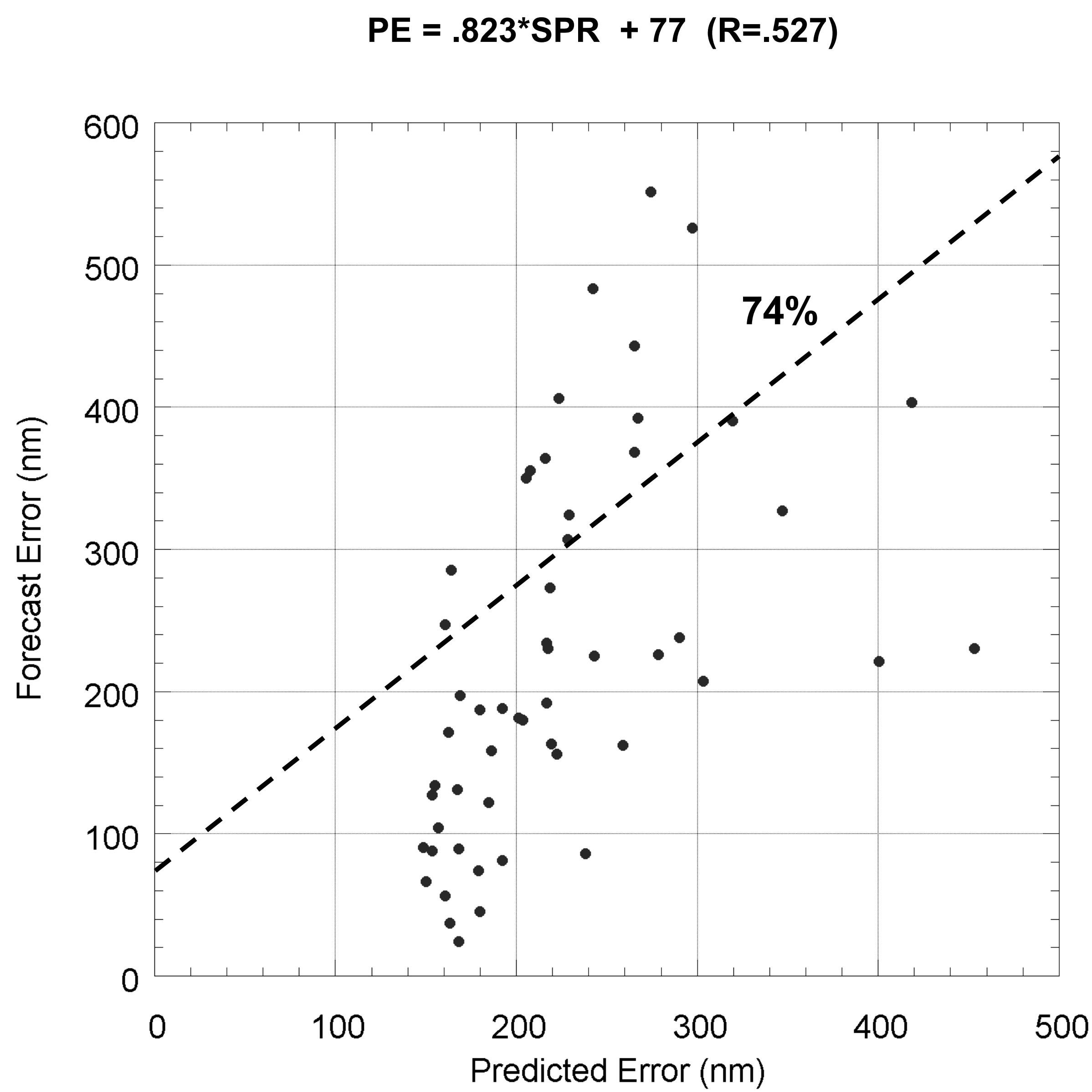

Fig. 71. GUNA 120-h track forecast error vs. predicted error for 2001-2003 eastern North Pacific

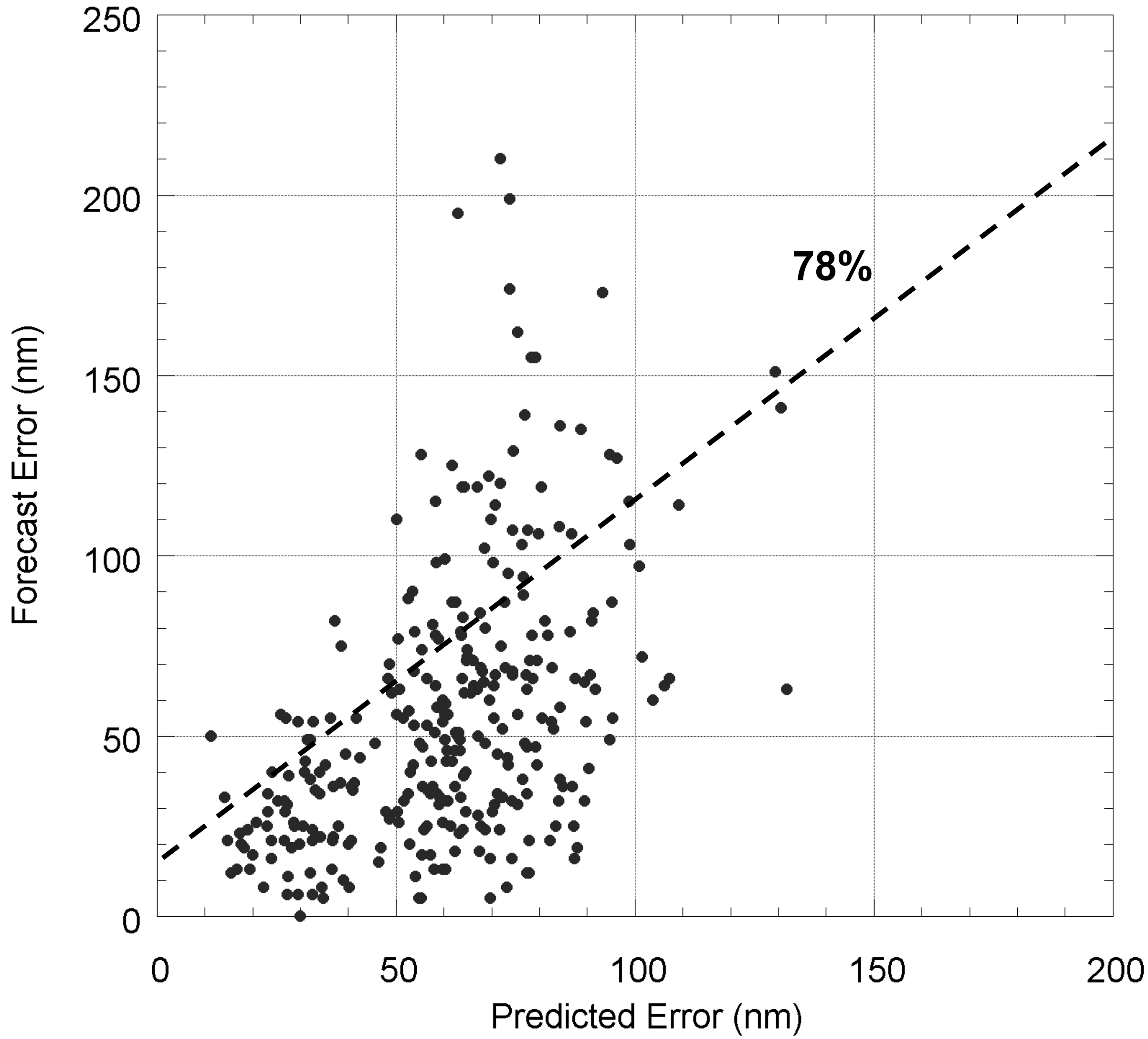

Fig. 72. CONU 24-h track forecast error vs. predicted error for 2003 Atlantic (Independent Testing)

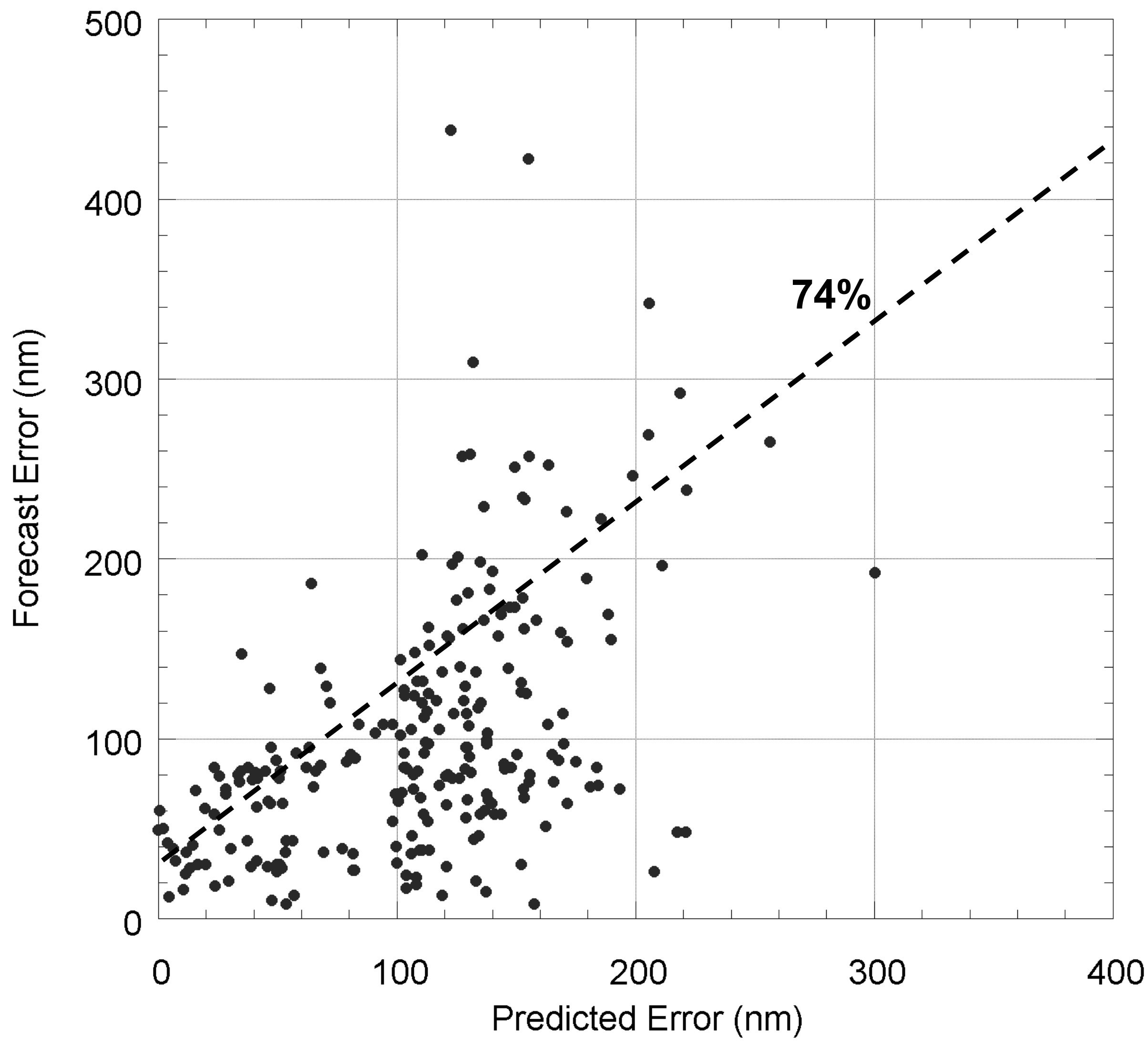

Fig. 73. CONU 48-h track forecast error vs. predicted error for 2003 Atlantic (Independent Testing)

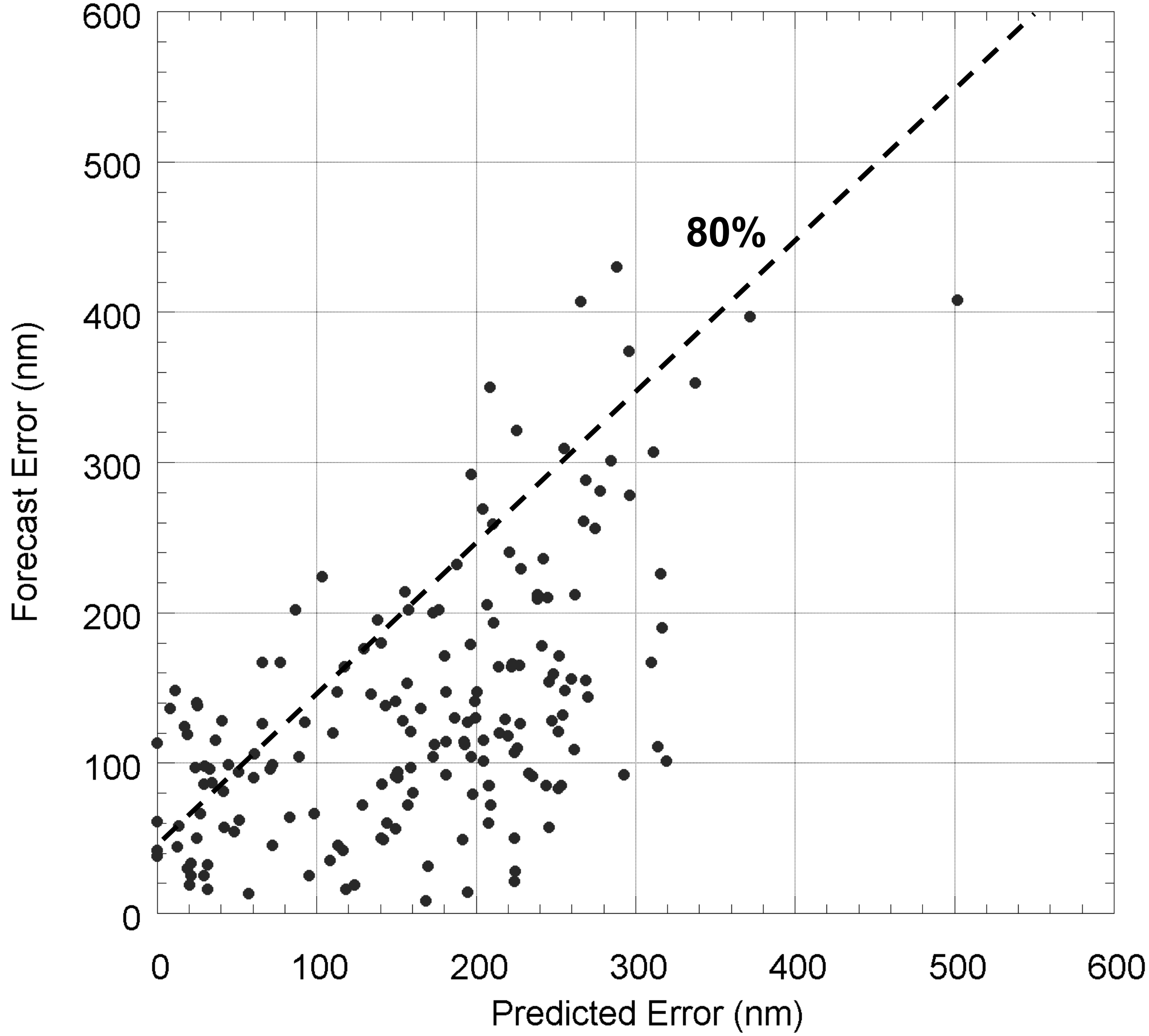

Fig. 74. CONU 72-h track forecast error vs. predicted error for 2003 Atlantic (Independent Testing)

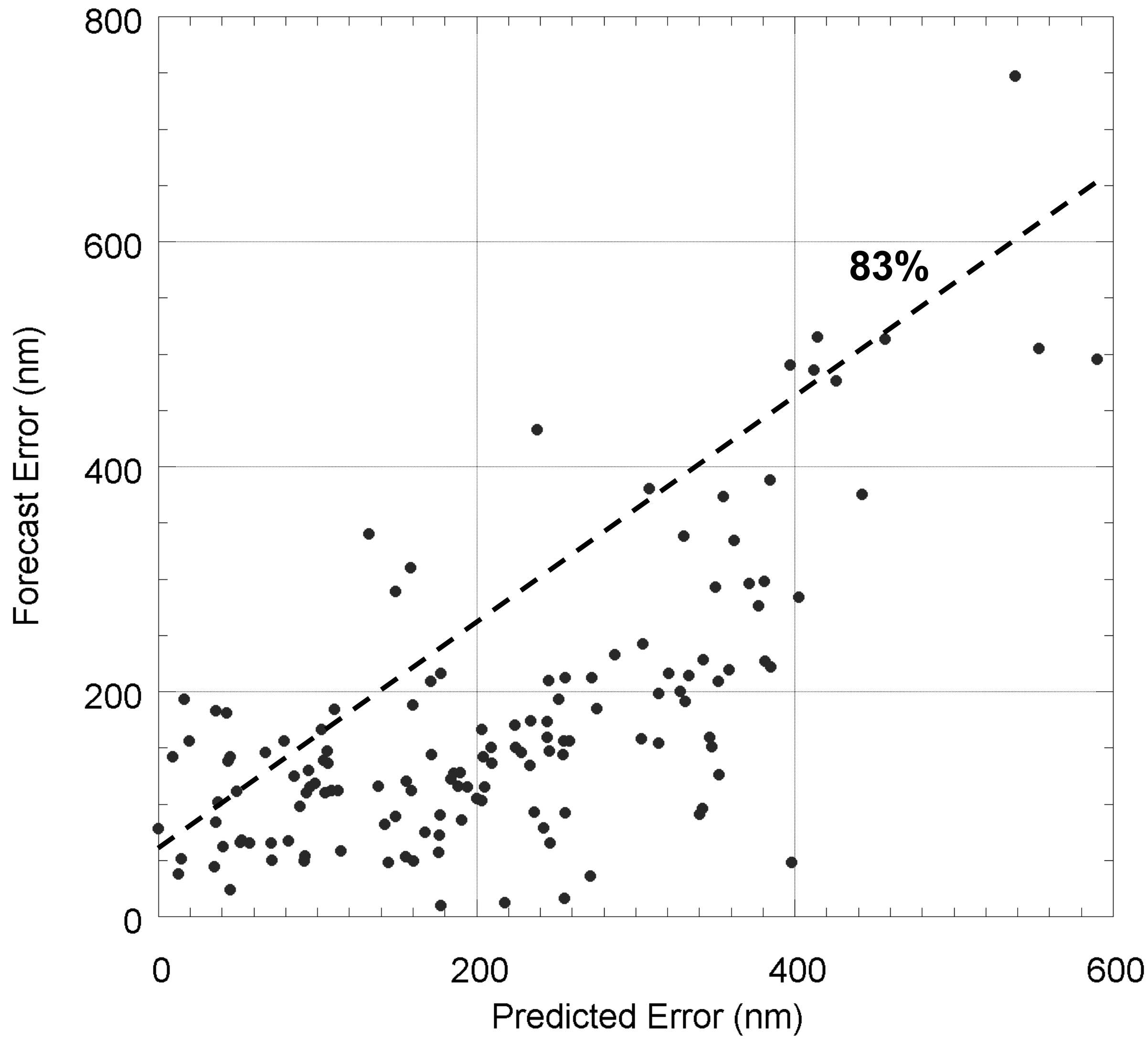

Fig. 75. CONU 96-h track forecast error vs. predicted error for 2003 Atlantic (Independent Testing)

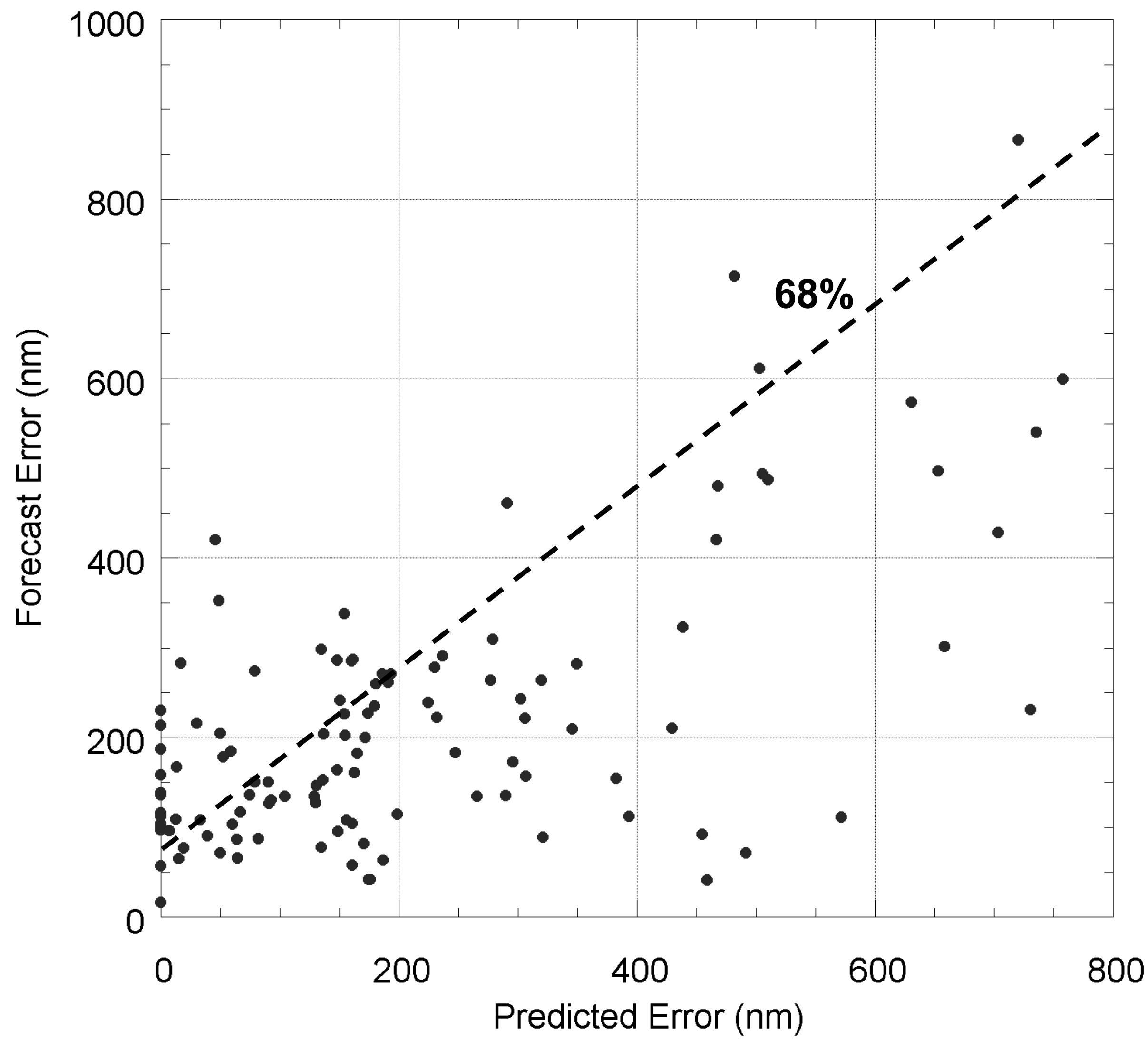

Fig. 76. CONU 120-h track forecast error vs. predicted error for 2003 Atlantic (Independent Testing)