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Estimating Optical Turbulence Using the PAMELA Model

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Abstract

We present an optical turbulence model that has evolved from the PAMELA model. After a preliminary report in SPIE 2003 it became apparent that more data was needed to refine this adaptive model. This led us to take twelve months of over-land data (~100 meters pathlength) at the Chesapeake Bay Detachment of the Naval Research Lab. We present data throughout the year with varying environments with comparison with the model prediction. Our recent modification includes segmenting the windspeed to 3 sections, morning, afternoon, and night for better fitting. This is an attempt to incorporate variable wind speed into the model which is known to contribute significantly to the turbulence in the atmosphere. In addition, we present preliminary results from the over-the-bay data (10 km pathlength).

1.0 Introduction

After the PAMELA report in August 2003 at the SPIE meeting [Oh et. al. Vol. 5160, 25-30 SPIE 2003], we have been collecting C_n^2 and weather data using a scintillometer at the Chesapeake Bay Detachment (CBD) of the Naval Research Laboratory. We acquired twelve months of continuous data to test the model behavior from hot to cold months with various changing weather inputs.

Since earlier report only yielded 1 week of data in June 2003, robustness of the model needed to be tested for all seasons. In addition to modification of the model, we investigate the effect of humidity on C_n^2. We also present a preliminary result from C_n^2 data taken across the Chesapeake Bay (10 miles) and its model fit.

2.0 Location and Data Logging:

The Chesapeake Bay Detachment of the Naval Research Laboratory is located right on the Chesapeake Bay, MD. The field where we collected C_n^2 data is on cliff side of the west Bay area. It is the longest stretch of bay in the United States. The transmitter is positioned just ~20 feet from the edge of the cliff where as the receiver is placed right outside the building 250. The direction of the bay is N-S and the tall tress are to the west and the whole field opens to the Bay area to the east. The site is mostly grassy area with an asphalt road. There is minimal human intervention hence the location is prime real estate for this type of work. The Optical Scientific, Inc LOA-004 scintillometer system consists of a transmitter and a receiver system positioned 110 meters pathlength in the grassy area. The scintillometer collected data every 10 seconds where as the weather station collected data every 5 minutes.

The weather station is positioned at the receiver side on a grassy area. Although the wind speed is higher at the transmitter side (near the cliff), due to logistical difficulties, the weather station remained at the receiver side. During month of December 2003, the weather station was moved to top of the building 250 roof after we found that shades from nearby tall trees were blocking the solar sensors prematurely. We did not notice significant changes in our weather data.

Although we planned on taking 12 months worth of good data, we encountered numerous difficulties during our 1-year campaign. Since the scintillometer needs routine checking and re-alignment, we find the scintillometer misaligned for months at a time during our absence. Often, strong wind caused the scintillometer to misalign and remained misaligned until we showed up to fix it. This actually was one of the biggest problems during data taking process. We would collect data for few months at a time. When analyzing the data, we find that about 80% of the data was misaligned data. However, we have vast

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amount of data at different seasons with different temperatures, humidity, wind speed, and solar insolation and were able to extract good set of data for 8/12 months. Here we present a good set of data with model from hot to cold months.

3.0 Model Inputs and Changes

Previously at the SPIE 2003 meeting, we presented a week worth of data and its comparison with the model. Since a week worth of data during a hot summer month is inadequate to prove ruggedness of our model, in this report we include a number of results from hot to cold months.

Each day has four separate plots. The first graph on upper left evaluates the measured solar insolation with the predicted solar insolation (the solid indicates the predicted solar insolation). The second graph on lower left illustrates the diurnal variation in temperature in F (solid line), humidity in % (dashed line). In the third graph on upper right the theoretical (modeled solar insolation) C_n^2 estimates are compared to the measured values for C_n^2. The final fourth graph on lower right is the wind speed with three separate sections as mentioned previously. The wind speed is broken into three averaged separate sections: 1) midnight to sunrise, 2) sunrise to sunset, 3) sunset to midnight. Separating into three different averaged wind speed values to the program is one of the most recent modifications to the model. The need for this "partition" of the wind speed was obvious, as during the day, solar insolation is the most dominant factor contributing to C_n^2 where as at night, wind speed is the most influential factor. Hence separating the wind speed to three parts allowed the model to reflect the real wind data. Based on parallel work by Oh Y. et. al [5550-36 SPIE2004], we have set the lower limit of wind speed to 1.5m/s. Also we have reduced the theoretical neutral events to reflect more real data. The real data shows neutral events indistinctly, not with dramatic effect as presented in the SPIE 2003 paper. A more thorough simulation and experimental data analysis on the model behavior can be found in Y. Oh et. al [5550-36 SPIE 2004].

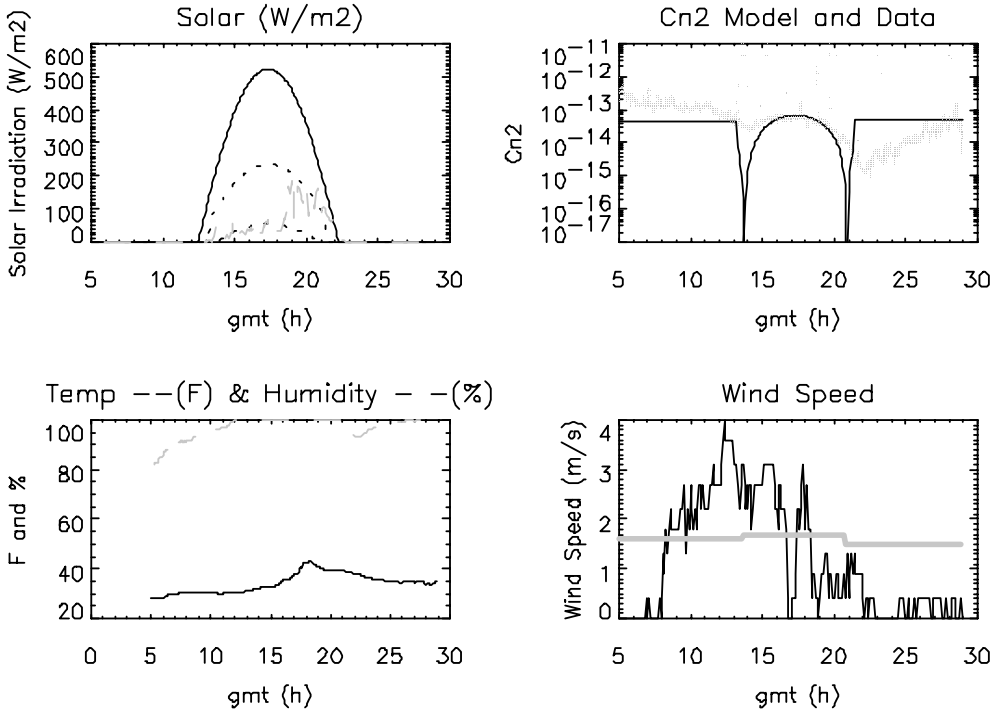
4.0 Model and C_n^2 data

The model behavior for cold month is shown in figure 1 for February 2004. The day is characterized by mostly cloudy sky with very humid conditions. Started to rain around 8:45am till ~1:15pm. The solar insolation was minimal (used 1/8) and wind was stronger in the morning. The temperature was cold (predicted to be snow but turned out to be rain). Our model predicts around 3x10E14 level of C_n^2 throughout the day except in the neutral events. As seen in the model with the data, the model reflects very well. Although the neutral events are indistinct, we can see where it happens. The model implies that C_n^2 during morning and night remains constant as we use constant factors mainly driven by the wind speed (note three different wind speed mentioned in the previous section). The real data does not remain constant but rather fluctuate throughout the night. We note that sometimes the model over/under predicts during night times. This is due to the fact that we are not accounting for the humidity as well as fluctuating windspeed.

Figure 2 shows about ½ clear day with clouds in and out all day. Wind speed was below the threshold at the receiving end hence lower limit of 1.5m/s was used for all three sections. Examine behavior of C_n^2 from 5h (gmt) to 12h (gmt). As one can see, most of the other variables remain constant including humidity, and temperature. When wind was calmer in the morning, C_n^2 varied drastically with large dynamic range, from 10E-12 to10E-15. Contrarily, when the wind picked up at nighttime, it seemed to contribute to better seeing condition. It is possible that the wind speed at the transmitter side varies greatly which we did not measure. However, a glimpse of humidity contribution to C_n^2 can also be seen here as relative humidity increases from 60% to 80% between 5h to 10h. Later in the section we investigate if such effect is present in other data as well. Overall, the model tracks fairly well.

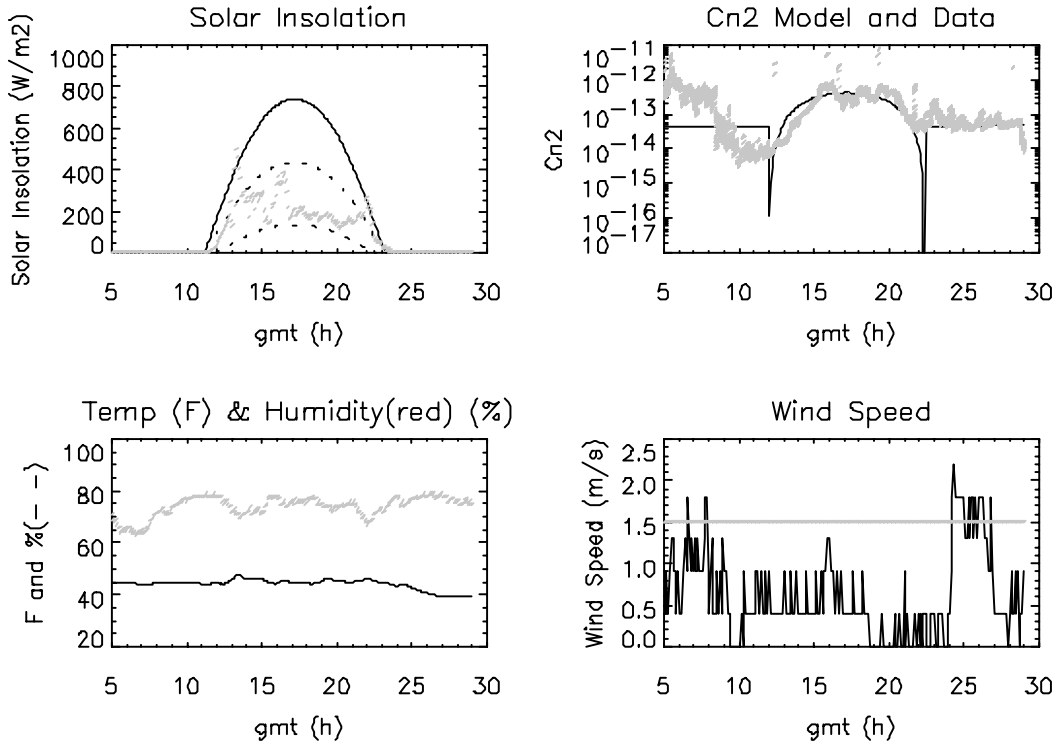
I. Cold Month - February 2, 2004

Figure 1.



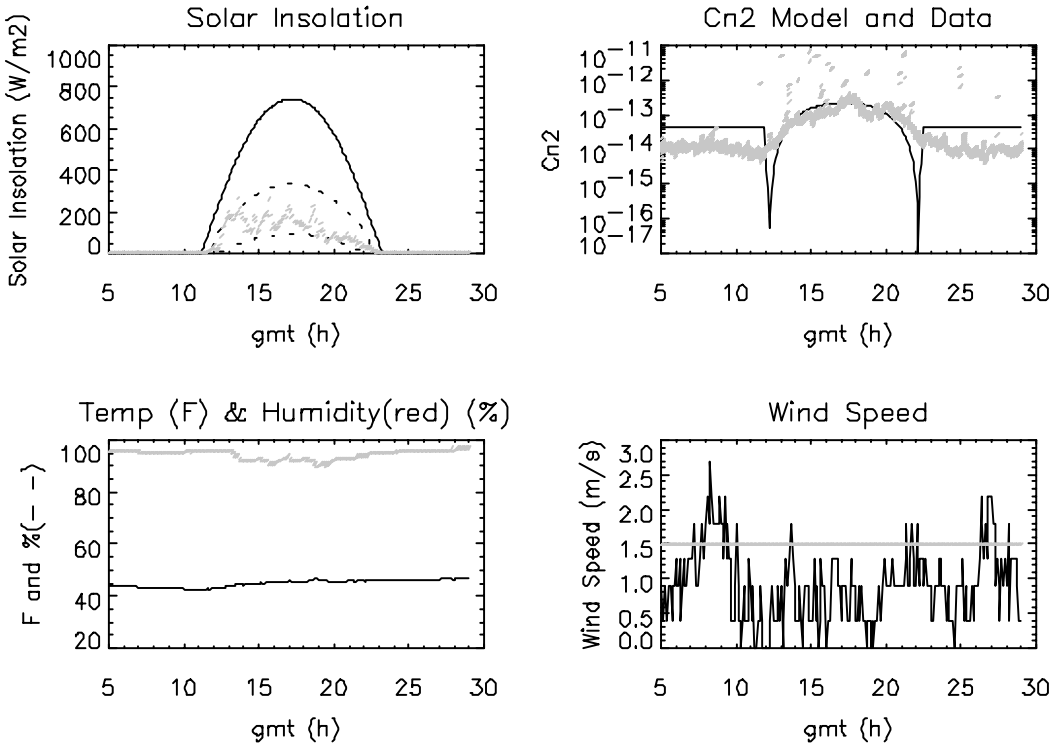
II. Spring – March 28, 2004

Figure 2.



III. Spring - March 30, 2004

Figure 3.



IV Hot Month - June 2, 2004

Figure 4.

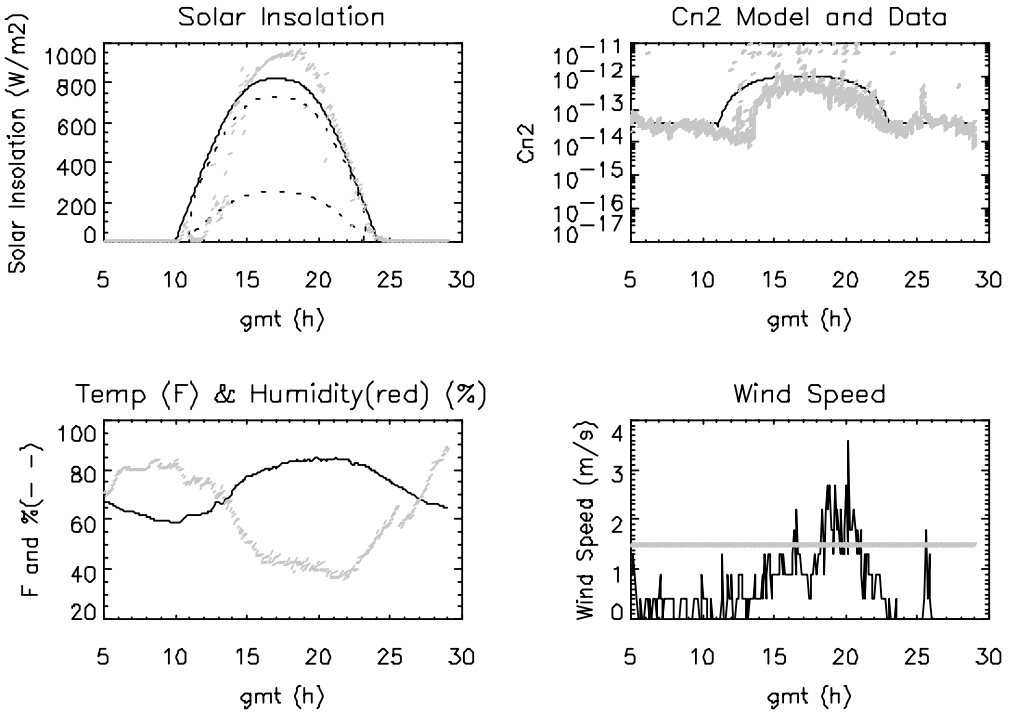


Figure 3 shows that throughout the day, it was mostly cloudy with on and off rain. The humidity is close to 100% with nominal temperature. The wind speed was below the lower limit hence 1.5m/s is used. The model predicts fairly well even in this type of conditions. During the day, the model is a very good predictor. At morning and night times, the model over predicts. Since wind speed is the constant input in our model, the model does not explain the varying C_n^2 during those times. However, holding wind speed constant we note that significant amount of relative humidity seemed to have caused the turbulence to calm down hence lowering C_n^2 values below the predicted model. We see this effect often throughout the year, although not as dominant in colder months but strongly reflected in the hotter months.

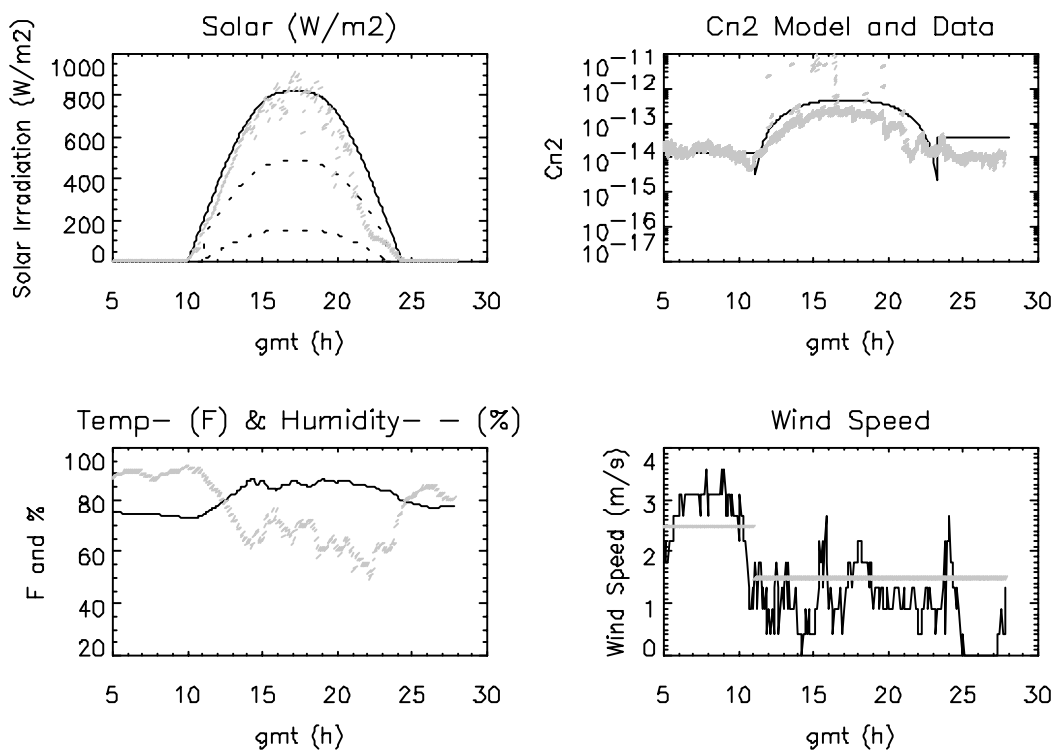
June 2nd, 2004 started with some clouds in the morning but became clear throughout the day as shown in figure 4. The attenuation in solar insolation in the morning is due to cloud cover with intermittency. The model does good job at predicting C_n^2 as partial blocking of the sun in the morning is reflected strongly in the data. The wind was minimal throughout the day hence the 1.5 m/s default was used. The humidity is relatively higher in the night time. We have reduced the neutral events so that it matches the data better. Apparently, the model fits well for nighttime and daytime. Seems that about 80% relative humidity is optimally tuned for the model.

Figure 5 is a corrected results from 2003 SPIE report with modification applied as mentioned in the previous sections. The model does an excellent job at predicting C_n^2 given the input parameters.

As temperature cools and enters the fall season, we see a drop in the amount of solar insolation as well as shorten solar duration as seen in figure 6. The humidity is nominal throughout the day with higher wind during the morning compared to minimal wind at afternoon and night. Although the overall shape of C_n^2 data is strikingly similar, the model over estimates the day time C_n^2 by ½ order of magnitude. Although no obvious effect can be related to such an effect, perhaps a local effect such as higher wind speed at the transmitter side can cause such an effect.

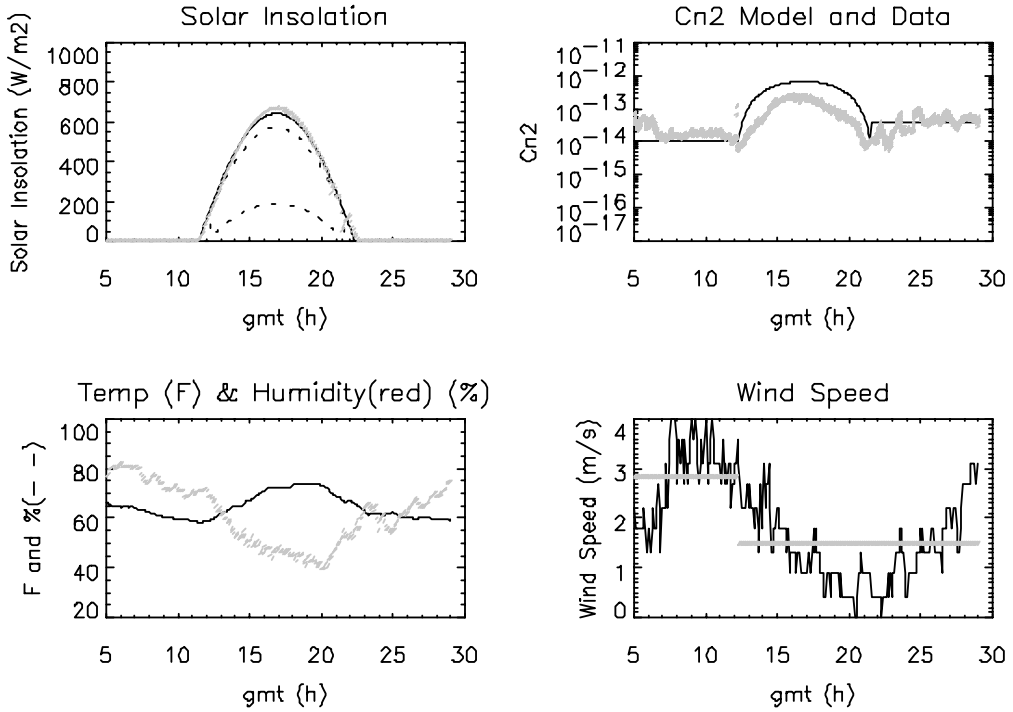
V Hottest Month – June 30, 2003 (corrected from 2003)

Figure 5.



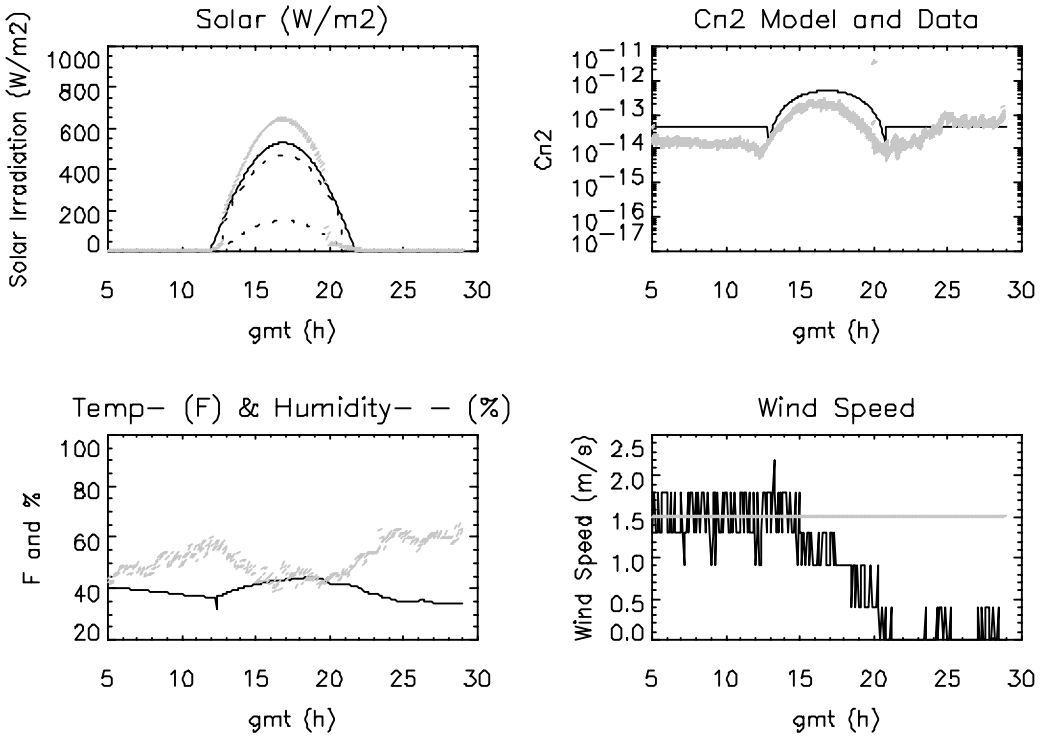
VI Fall – October 13, 2004

Figure 6.



VII – Cold Month - November 9, 2003

Figure 7.



First, solar insolation in figure 7 shows that the surrounding trees prematurely blocked the solar radiation. Hence one can see the premature cutoff in solar insolation at around 20h (gmt). The day was clear with no clouds. The wind was stronger in the morning but calm in the afternoon and at night. Wind was higher before the sunset than after sunset but C_n^2 level is less before sunrise than sunset. One obvious effect can be seen here. When wind was minimal (20h to 29h), C_n^2 increased and oscillated. This was strikingly similar to the report by Doss-Hammel et. al. [SPIE 5550-35] where he reported similar effect for wind speeds below about 2m/s. We also see the same effect although not as drastic in the humid environment.

5.0 Humidity Effect

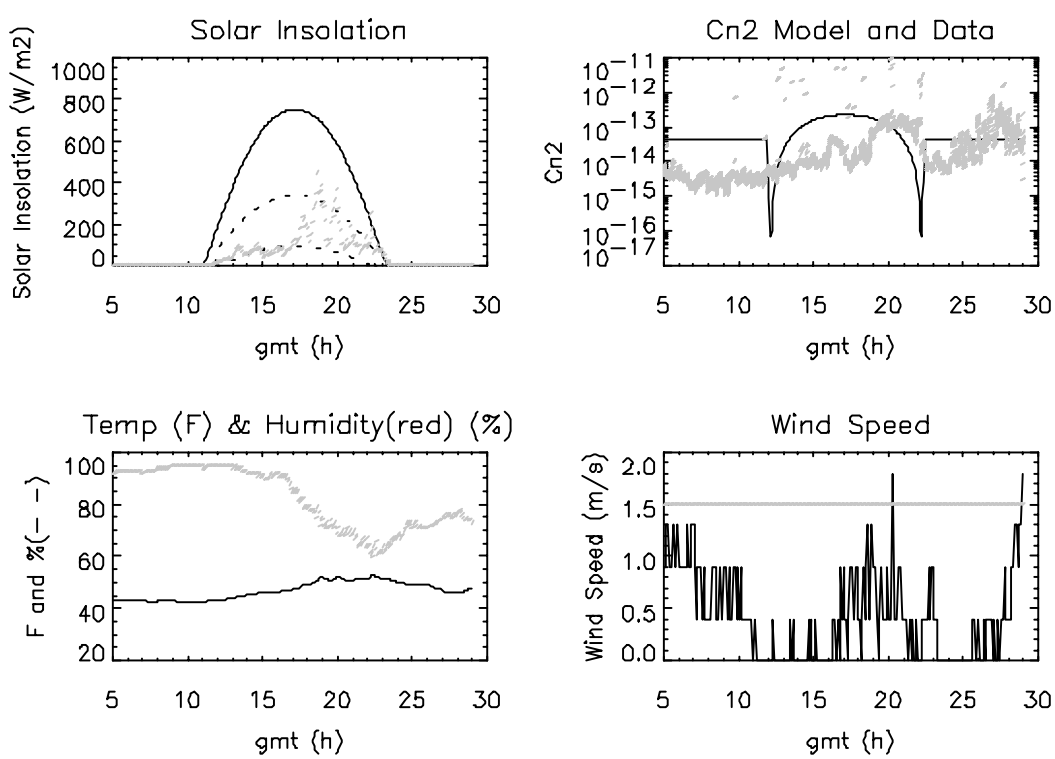
The following five results are presented in order to distinguish the effect of the humidity to C_n^2. We concluded that the best way to really understand humidity is to look at as many examples as possible. Here we present four over-the-land data and one over-the-water data to show the effect of humidity.

The effect of the humidity is fairly obvious as the reader is encouraged to compare the night time data only. Since during the day, the solar insolation dominates, the humidity effect is less obvious. Hence concentrating on comparing two sections "a" and "b" where "a" is between midnight to sunrise and "b" is sunset to midnight, the effect is counter-intuitive but very evident.

As shown in figure 8, for April 2, 2004, higher humidity during "a" compared to lower humidity at "b" causes C_n^2 to behave the opposite; C_n^2 is lower at "a" than "b". With other parameters being held constant and wind speed being minimal, the only varying parameter was the humidity. The immediate correlations with windspeed is not so evident in this data. However, since windspeed and humidity were not separate parameters in this data, concluding humidity- C_n^2 inverse relationship is premature. More data needs to be examined.

Humidity I - April 2, 2004

Figure 8.



Humidity II – February 27, 2004

Figure 9.

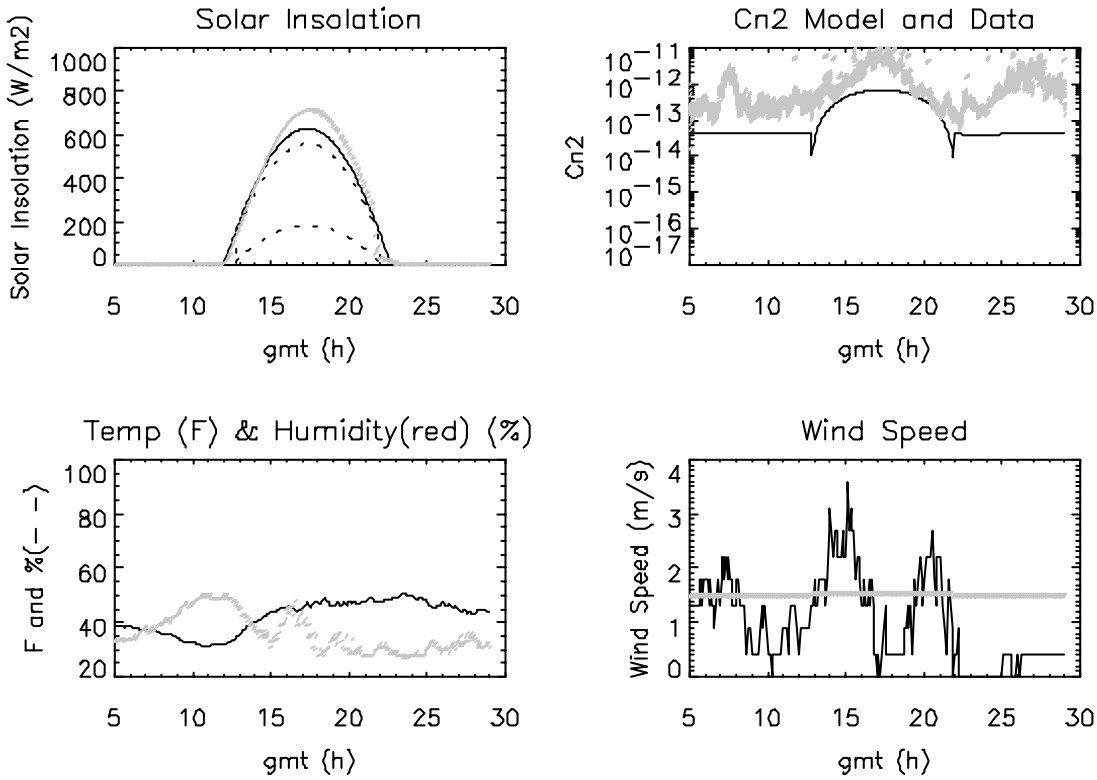


Figure 9 supports the previous Humidity- C_n^2 inverse relationship. As shown low humidity throughout the day triggers a higher C_n^2. The model clearly under predicts the data since humidity is not an input to the model. The humidity being as low as it is, it is a great puzzling effect to see this type of relationship.

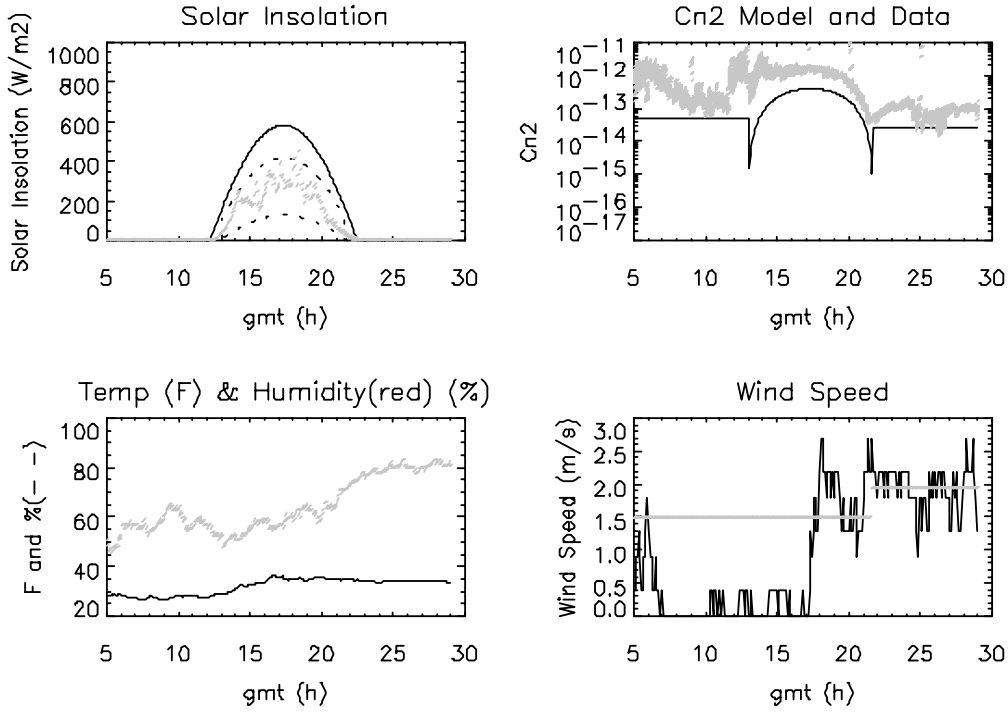
Figure 10 is a prime example of coupled windspeed and humidity. The presence of low wind speed and low humidity at "a" causes C_n^2 to oscillate more and increase where as higher wind speed and high humidity at "b" causes C_n^2 to decrease and calm down. This is the most puzzling effect as two variables are counter intuitively affecting C_n^2.

Similar effects are evident in figure 11 where wind was constant throughout the day. Humidity is high throughout the day. If we consider this day as total separation of windspeed and humidity, the effect is strikingly obvious as higher humidity causes C_n^2 to decrease. The model undoubtedly over predicts C_n^2 as expected.

We present the following results shown in figure 12 obtained from a separate passive scintillometer developed by Moore et al. [SPIE 5160-53]. Following the relationship with humidity and windspeed, C_n^2 data acquired for the across the bay shows very flat graph compared to data obtained for the over the land. The "hump" in the middle is minimized as the big bay water works as a heat sink for the solar radiation received. The weather data shown is data collected at the receiver side therefore it does not show correct air temperature and winspeed throughout the pathlength of the bay. But one can guess that temperature is lower and humidity and winspeed is higher throughout the 10 mile pathlength. Given that assumption, we do expect C_n^2 to decrease as expected. The data shows that such is true. Although only one result is presented here, most of the data taken over 12 months show more or less the same trait. This is a prime example of the humidity and windspeed contribution to C_n^2.

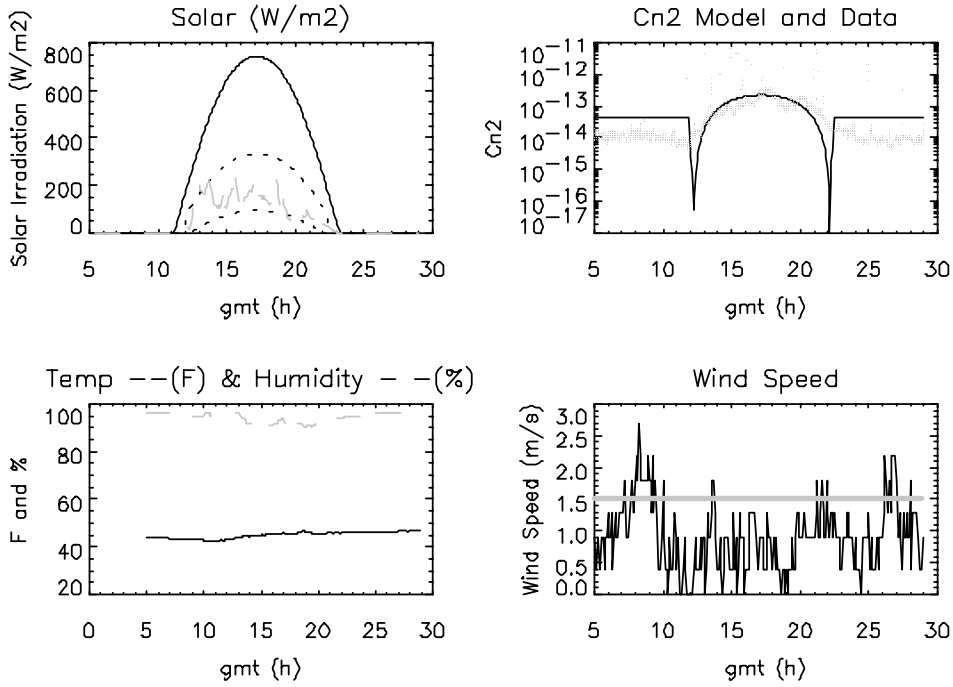
Humidity III – February 16, 2004

Figure 10.



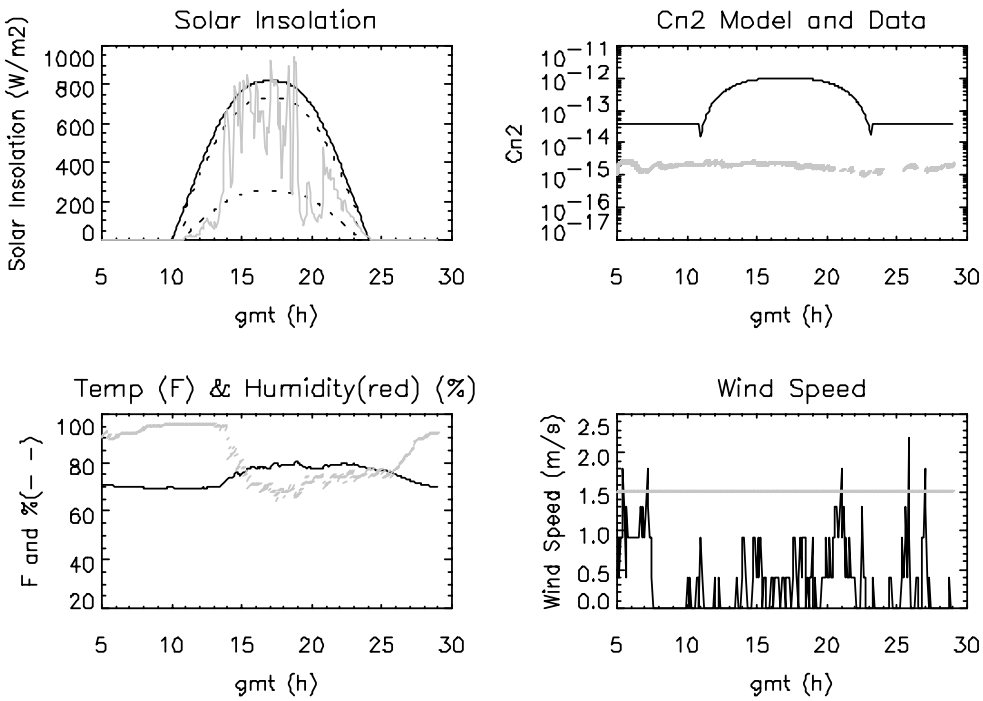
Humidity IV – March 30, 2004

Figure 11.



Humidity V - Over the Chesapeake Bay C_n^2

Figure 12 (Across the Chesapeake Bay - 10 miles)



7.0 Conclusion

The results from 2003-2004 C_n^2 data collected at CBD offers preliminary insight into several areas. First the model behaves fairly well throughout the year from hot to cold months. Although some over/under prediction is seen, the lack of humidity input to the model is identified. The coupled humidity-windpeed effect is of great interest and the relationship is shown well in this report. We identified that humidity and C_n^2 is inversely proportional. The model has some weakness to the windspeed [Y. Oh et al. SPIE 5550-36], forcing us to use a lower limit in order for the model to behave well with decreasing windspeed. Future theoretical and experimental study is needed to confine this elusive variable. As most similarity based theory and model suggest no such thing as "zero" wind speed exist. We know that significantly low wind speed (0-3m/s) is a problem to the theory and the model. This area of unstable regime should be explored experimentally and theoretically so that this model as well as other models can improve its effectiveness in modeling C_n^2 at low wind speeds.

As far as model's capability to estimate the over the water data, the model does not perform well. Several modifications can be made to work well for marine environment. One of the first modifications is the reduction of solar radiation input into the model. We know that land absorbs and re-emits the heat from the sun. When there is water, this effect is minimal as the water acts as a heat sink. Hence the re-radiation factor in the model can be adjusted to match the effect of water heat sink. Second, correct surface roughness length for the water needs to be experimentally obtained. The PAMELA model does not contain a correct surface roughness value for water. It is a crucial parameter which can only be obtained experimentally. Third, a true surface temperature of water and windpseed and humidity of the bay area needs to be measured or extrapolated. With such inputs, the modification to the model is forseen.

The model to include humidity as one of the input is the most obvious step to improve the model. Some difficulties arise from incorporating the humidity into the model. First , there is very little work done in trying to understand humidity contribution to C_n^2. The relationship must be obtained experimentally and an in-dept theoretical work must support the relationship. Second, separating windspeed and humidity

outside environment is almost impossible as two are intertwined and varying constantly. Hence an experiment must be performed in a controlled environment where the two variables are separable and controllable. Third, humidity factor at a different environment is needed to support the claim. Would humidity at a more dry environment cause the same effect? Such questions can be answered with more involved experiment at different locations

The model is an evolving coupled equations with room for improvement. Based on results from CBD, given the input parameters, we can predict and/or explain the behavior of C_n^2. Various work done by Doss-Hammel et. al. [5550-35] and Y. Oh et. al.[5550-36] also support strengths and weaknesses of the model to windspeed. The robustness of the model to various terrain and weather types is self evident. However, with some modifications, this simplified similarity based model can be utilized with greater accuracy.

6.0 Future Work

We plan on performing some computer analysis on the data collected and find a relationship between humidity and C_n^2. Another anticipated experiment is a controlled experiment where we run scintillometer inside the building in a long corridor where we hold all parameters constant except the wind speed and humidity. Hence controlling windspeed and humidity separately will allow us to ascertain the relationship distinctly.

7.0 References

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