Forest - added Turbulence: A parametric study on Turbulence intensity in and around forests

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Abstract. The scope of the investigation is to take on-site measured wind data from a number of sites inside and close to forests. From the collected on-site data the ambient turbulence intensity is calculated and analysed depending on the distance to the forest and height above the forest. From this forest turbulence intensity database it is possible to get an overview of the general behaviour of the turbulence above and downstream from the forest. The database currently consists of 65 measurements points from around the globe, and it will be continually updated as relevant sites are made available. Using the database a number of questions can be answered. How does the ambient turbulence intensity decay with height? What does the turbulence profile look like according to wind speed? Is it the general situation that high wind speeds are creating movement in the canopy tops, resulting in higher turbulence? From the forest turbulence database it can be seen that in general, the majority of the turbulence intensity created by the forest is visible within a radius of 5 times the forest height in vertical and 500 meters downstream from the forest edge in horizontal direction. Outside these boundaries the ambient turbulence intensity is rapidly approaching normal values.

Keywords: TI, Turbulence intensity, forest.

1. Introduction
The presence of a forest has some significant effects on the flow field:
- Reduced wind speeds
- Increased wind shear
- Increased turbulence intensity

This distorted flow field has some negative effects regarding loads and energy production for wind turbines downstream of a forest:
- Increased mechanical loads
- Increased uncertainty in resource assessments
- Increased uncertainty in turbine power curve

Very little information exists regarding measured flow disturbance induced by forests. Only some theoretic studies on single parameters can be found. We will here examine the changed turbulence levels above the forest and in the vicinity of a forest.
The results from the forest database are compared to results from a wind tunnel test conducted on the behalf of the Florida Building Commission [2].

We will present the following results from our analysis of the forest data:

- The variation of turbulence intensity with wind speed, comparing with the assumed behaviour as shown in the IEC standard [1]
- The variation of turbulence intensity with height, measured near the forest edge and 1000 m from a forest edge, compared to wind tunnel test results [2]
- The variation of turbulence intensity decrease with distance from the forest edge

All of the information mentioned above will be very useful when planning the wind farms in the proximity of forests.

2. Methodology

The forest turbulence database contains information from 65 measurements around the globe with different kinds of forests like pine, oak, olive trees etc. The tree height varies greatly from dense 20 m tall pine trees, to 6-8 m high olive plantations. The extent of the forest in front of the measurement masts varies from minimum 1000m to several kilometers of dense forest. Unfortunately no specific details are available for the individual sites about forest type, density and size. All results are averages of all the different types of forest in the database.

The measurement heights range from 30 meters to 100 meters agl. All measurements have been collected from cup anemometers and standard wind vanes. Unfortunately in general no detailed information is available about the instrumentation or regarding the mounting of these.

2.1. All sites in the database contain measurements with the following characteristics:

- Measurement mast within 2000 meters of forest edge
- Forest larger than 1000 x 1000 meters
- Minimum 1 year of data
- Minimum 30 meter above ground level on-site measurements

All sites are calculated and indexed the same way

- TI calculated using raw on-site measured data.
- Site specific ambient turbulence intensity above 10 m/s calculated and weighted average according to frequency.
- The turbulence intensity is calculated from 10-minute average mean wind speed readings and standard deviation on same. The TI readings are binned so that mean wind speed and standard deviation are obtained for every 1 m/s wind speed bin and 12 direction bins.
- Indexed with distance to forest edge in 12 sectors.
- Indexed according to measurement edge height.

2.2. TI as a function of wind speed

All results in this analysis are measurements on sites, where the measurement mast is within 200 m of a forest in the main wind direction. The results are presented as averages of all measurements included in the database.
Wind speeds below 5 m/s have not been used. The wind speed is indexed in 1 m/s bins with calculated mean TI. The standard error of the mean has been calculated to indicate the variation of the data (shown as deviation bars on the plots). The 40 m height measurements are used since this height has the largest amount of data. Results are based on 19 on-site measurements.

The results from all forest sites are compared to a “normal” TI curve [1] to visualise the difference in the TI distribution according to wind speed from flat, low roughness terrain.

2.3. TI as a function of height
All results in this analysis are from on-site measured data within 200 m and further away than 500 m from a forest edge. All results are averages of all data in the forest database.

The TI values are a frequency dependent overall 12 sectors mean. Only wind speeds higher than 10 m/s have been used. All measurements are downwind from forest edge. The mean distance of sites less than 200 m is 75 m from a forest edge. For sites further away than 500 m the average distance to the forest edge is 1000 m. The standard error of the mean has been used as deviation bars.

Results are based on measurements from 24 on-site met-masts.

2.4. TI as a function of distance to a forest edge
All results in this analysis are from data measured on-site where a forest is present. Note that sectors from which there is no forest present are also logged as 2000 m.

The TI is indexed in twelve 30 degree sectors with 100 m distance bins to a forest edge. The results are an average of all on-site measurements from each 100 m distance bins. The presented results are based on 400 individual on-site measurements. All results are measurements downwind at varying distances from a forest.

3. Results
Using the database a number of questions can be answered.

3.1. How does the ambient turbulence intensity decay with height?
The forest turbulence database contains data from different sorts of forests with varying tree heights. No detailed information regarding the individual forests heights from the sites were available. From site pictures the estimated average tree height is 12 m.

In Figure 1 the curve denoted “Average TI% 500 to 2000 m from forest” shows an average of all on-site measurements in the database, where the distance in main wind direction is greater than 500 m and up to 2000 m.

From Figure 1 it can be seen that the forest added turbulence above the forest is consistently high up to a height of about 5 times the average tree height. For greater heights the TI decreases drastically.
Wind tunnel tests [2] show similar results with a drastically reduced forest added turbulence, at around 5 times the tree height (tree height in wind tunnel test is 10 m), where the turbulence intensity levels approach the same order of magnitude of TI had the forest not been there.

Note that a direct comparison is not possible due to the forest database consisting of wind speeds above 10 m/s in contrast to the wind tunnel test containing full scale wind profile.

However both results show that above 5 times the forest height the forest added TI are heavily reduced and approaching expected normal values for TI.

3.2. What does the turbulence profile look like as a function of wind speed? Is it the general situation that high wind speeds are creating movement in the canopy tops, resulting in higher turbulence?
Figure 3: TI 40m agl. Versus wind speed

Figure 3 illustrates the average turbulence as a function of wind speed, based on 19 measurements at 40 m agl.

Figure 3 shows a constant high TI as the wind speed increases. Note that above 20 m/s the forest turbulence database lacks sufficient measurements. When comparing the results from the forest database to a standardized TI distribution according to IEC [1] it is shown that the ambient TI alone is quite high and in some cases exceeds the IEC design limits for a class A turbine. [2]

The purpose of Figure 3: TI 40m agl. Versus wind speed, is to illustrate that in general a forest turbulence profile, does not follow the normal trends for reduced turbulence at higher wind speeds.

3.3. How does the ambient turbulence intensity decay, at different height as a function of distance to the forest edge?

Figure 4: TI at different measurement heights agl downstream from a forest edge
Figure 4 is illustrating the decaying turbulence intensity levels when moving away from the forest edge. It can be seen that for an average wind turbine where hub height normally exceeds 60 m, the variation of TI is large in the first 500 m from the forest edge. Further away than 500 m from the forest the added TI is quite low. Within the first 500 m there is a risk for exceeding the IEC design limit [2] due to the added turbulence.

Also important to note is that the forest database is an average of many sites with a big variance of forest types and tree heights. This means that the results shown in Figure 4 should only be taken as an indication of the turbulence level. It is extremely important to obtain highly detailed site specific information regarding the wind climate whenever a forest is close to a wind farm.

4. Conclusions
We have shown that the ambient turbulence intensity in general is very high within the first 500 m of the forest edge and up to 5 times the tree height. If WTGs are planned within this radius of a forest, it is imperative to have very high quality on-site measurements and preferably using several measurements.

It is shown that in general the TI induced by the forest at higher wind speeds is much greater than the normal values. In fact the ambient TI at a height of 2-3 times the forest height can exceed the IEC design requirements [2] and continue to do so several hundred meters from the forest edge.

The results of the forest turbulence database can with “great caution” be used to estimate the TI values at hub height. If you only have measurements at lower heights, it is suggested to compare the measured TI values to calculated ones obtained by software programs such as WAsP Engineering or more advanced CFD programs. A relationship between calculated and measured TI, at different heights can be established and in turn used to predict the turbulence intensity at hub height.

5. Future work
The database will continue to grow as more sites are made available. When sufficient data is included in the database, the analysis will be divided in different kinds of forest, terrain etc. In the future measured turbulence in forests will be compared with calculated TI based on the WAsP Engineering and other software.

References
[1] Wind turbines – Part 1: Design requirements. IEC 61400-1 (ed. 3), 2005-08
[2] Assessment of windborne debris Criteria for the Florida panhandle, February 2006, ARA progress report, Applied Research Associates, Inc.