Deliverable 1.11

Database of existing wind parameter measurements for tall atmospheres across Europe

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EXECUTIVE SUMMARY

The **aim** of Deliverable D1.11 can be summarised as follows:

- Delivery of an overview about available data sets, including a description of the measurement sites, the data sources and access options
- Definition and delivery of exemplary characteristic data sets comprising selected processed data for a specific period that will be made available to interested partners. The data sets shall comprise rather standard conditions as well as conditions significantly deviating from these.

There are several **databases** which contain wind parameter measurements for various near- and offshore sites across Europe.

- FINO 123: wind and wave data of 3 research platforms in the North and Baltic Sea
- NORSEWInD: met mast and LiDAR data in the North and Baltic Sea
- MARNET: wind and wave data in the North and Baltic Sea
- eKlima: wind and wave data of met stations in the North and Norwegian Sea
- Irish Marine Weather Buoy Network: wind and wave data from buoys around Ireland

Selection of a data set:
For the exemplary characteristic data set measurements of FINO 3 have been analysed.
The main argument for selecting FINO3 has been the same measuring period of the available met mast and the LiDAR data. So, the LiDAR measurements can be evaluated up to a height of 100 m with reference to the data of the meteorological mast (in the following: met mast). This allows a reliable investigation of the wind conditions in tall atmospheres up to the maximum measuring height of the LiDAR system at 160 m. For the data of the met mast a mast correction can be applied.
Another argument for the dataset of FINO 3 is the availability of measurements of wave parameter since 2009.

Data analyses
After correction of the mast effect on the mast and LiDAR data, the available data have been investigated with the aim of detecting time periods with normal as well as extreme wind conditions. The high availability of the met mast data as well as the LiDAR data enabled reliable investigations of the wind conditions during 2011. The distribution of the wind speed, the stratification of the boundary layer as well as turbulence intensities have been analysed in detail. The LiDAR data have a high correlation of 0.9963 to the data measured with cup anemometers at the met mast.
Additionally a quick view into the available wave data has shown correlations between two wave parameter –significant wave height and peak period- and the wind speed.

In this report two **exemplary data sets representative for specific wind conditions** are analysed more detailed.

Exemplary wind condition 1: extreme turbulence intensity
The first represents a normal wind condition with wind speeds U from 8 - 12 m/s but with an extreme turbulence intensity $TI_{extreme}$ which is defined with values higher than four times the standard deviation σ.

$$8\,m/s < U < 12\,m/s$$

$$TI_{extreme} \geq TI_{mean} + 4\sigma_{TI}$$

<u>*Exemplary wind condition 2:*</u> extreme wind shear
The second exemplary wind condition is specified with wind speeds U from 8 - 12 m/s, turbulence intensities TI_{normal} lower than two times the standard deviation σ and an extreme wind shear.

$$8\,m/s < U < 12\,m/s$$

$$wind\ shear = U_{90m}/U_{50m}$$

$$TI_{normal} \leq TI_{mean} + 2\sigma_{TI}$$

$$wind\ shear_{extreme} \geq wind\ shear_{mean} + 4\sigma_{shear}$$

Based on the data analyses in this report each INNWIND.EU partner has the opportunity to get the data he or she needs regarding his or her requirements.

<u>*Access to the analysed data:*</u>
The required steps to obtain the analysed data are summarised as follows:

1. Due to the access conditions of the used databases time series of the analysed data cannot be circulated to INNWIND.EU partners. There is only a possibility if a partner has an access to the database by himself.
2. Request for an access for the FINO 3 data at BSH as described in 2.1.1.
3. Request for an access for the NORSEWInD database at Oldbaum Services as described in 2.1.2.
4. Due to the mast effect on the measured data of met mast and LiDAR system a data processing is required as described in chapter 4.
5. Selection of interesting wind conditions by results in chapter 5 and/or in section 6.1.

1 INTRODUCTION

Task 1.1 of the project INNWIND.EU deals with the external conditions and aims at providing the missing information on the external conditions at higher atmospheres which is needed for designing large offshore wind turbines. Table 1 includes the specific targets and participant actions of the SMART-Deliverable D1.11 with its title: Database of existing wind parameter measurements for tall atmospheres across Europe.

Table 1: SMART Deliverable D1.11.

Deliverable No: 1.11	**Title :** Database of existing wind parameter measurements for tall atmospheres across Europe
Month Due: 22	**Participants:** ForWind-OL, FhG (IWES), DTU, DHI, TUD, UStutt
Relevant Description: Gathering and compilation of existing offshore wind measurements performed at higher atmospheres using ground-based, floating or nacelle LIDARs and tall met masts, which are crucial to characterize the operating conditions of 10-20 MW offshore wind turbines.	
Specific targets: 1) A report giving an overview about available data sets, including a description of the measurement sites, the data sources and access options. 2) A supplement document (as annex to the report) on how to use data from different data sources and different measurement technologies. 3) Definition and delivery of exemplary characteristic datasets comprising selected processed data for a specific period (at least one year) that will be made available to interested partners. The data sets shall comprise rather standard conditions according to IEC 61400-3, as well as conditions significantly deviating from these (high temporal gradients in wind shear, wind speed, gusts and turbulence as well as very convective, unstable, neutral, stable and very stable stratification). The height range shall comprise the tip height of the InnWind.EU reference turbine (i.e. 250 m). This may require the spatial extrapolation of standard measurements (cup, sonic) with LIDAR results and model simulations. The location should be clearly offshore, preferably FINO3. It needs to be noted, that the delivery of the exemplary datasets strongly depends on the availability of appropriate data (see specific target 1).	
Measure of success: The description of the available data sets and the delivered exemplary data sets are accepted by partners in other WPs who will use them in the accompanying numerical modeling schemes and design processes.	
Participant Actions: **FhG:** Will provide detailed information on data sets and access options from EU FP7 NORSEWIND project incl. FINO1-3 data. Collect details about data from other partners, and include in documentation. Provide exemplary data sets on the basis of partners' requirements identified with a survey that is prepared for this purpose. Supplement guidelines for use of different data sources with particular focus on comparing turbulence and extreme values measured with LIDAR and conventional met. mast technology. **ForWind-OL:** Will provide detailed information on available data sets. **DTU:** Will provide detailed information on available data sets and contribute to the compilation of the example data sets. **DHI:** Will provide detailed information on available data sets. **TUD:** Will provide detailed information on available data sets. **UStutt:** Will provide detailed information on available data sets.	

The report is structured as follows:
This introduction is followed in section 2 by a documentation of available data sets and the selection of a data set for further analyses. The characteristics of the selected data set of FINO 3 are detailed in section 3. Section 4 and 5 are about the data processing and data analyses of wind and wave measurements at FINO 3. In section 6 an exemplary data set for two extreme wind conditions are described. This report is completed by the conclusions in section 7.

2 AVAILABLE DATA SETS

There are several databases which contain wind parameter measurements for various near- and offshore sites across Europe. Additional wave parameter measurements are relevant to investigate air-sea interaction and their parameterisation for coupled atmospheric and wave modelling.

2.1 Documentation of data sources and access options

To estimate wind conditions at large heights, the databases include wind measurements performed at higher atmospheres, i.e. wind measurements from tall meteorological masts or remote sensing instruments. The evaluation of turbulence and extreme wind conditions depends on different wind measurement techniques. It has to be meant that recorded values of a LiDAR are not directly comparable with the data from conventional mast measurements (Annex A). Different databases are presented in the following.

2.1.1 FINO 123

The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has supported three research platforms in the North Sea and Baltic Sea to obtain a better knowledge about the conditions at sea for wind energy purposes.
The FINO database includes the results of comprehensive meteorological and oceanographic measurements of the three research platforms and in the offshore test field in North and Baltic Seas.

The Fraunhofer IWES is involved in the BMU-project FINO-Wind (http://www.dwd.de/fino-wind) which deals with the standardisation and comparative analysis of meteorological FINO measurement data. The project started in March 2013 and will end at the end of 2015, coordinated by the German Weather Service (DWD, Deutscher Wetterdienst). The aim is to get a revised FINO database with consistent measurement data for a better comparability of the data of the three platforms. The wind climate of the North Sea and the Baltic Sea will be analysed in detail. Results from this project may be utilized as soon as they are available.

Details of the data source:

Table 2: Details of the data base FINO 123.

Name	Owner / Administrator	Country / Area	Description	Geographical position	Available period	Format
FINO 1	BSH, FuE Kiel	GER / North Sea	met mast	54° 01' N, 06° 35' E	since 01/2004	ASCII
FINO 2	BSH, GL GH	GER / Baltic Sea	met mast	55° 00' 25'' N, 13° 09' 15'' E	since 08/2007	ASCII
FINO 3	BSH, FuE Kiel	GER / North Sea	met mast	55° 11.7' N, 07° 9.5' E	since 09/2009	ASCII

Wind measurements:

Table 3: Details of wind measurements at FINO 123.

Name	Available data	Heights	Data resolution	Remarks
FINO 1	wind speed, wind direction	33, 40, 50, 60, 70, 80, 90, 100 m	10 min	mast correction necessary, shadowing effects by Alpha Ventus since 2009
FINO 2	wind speed, wind direction	31, 41, 51, 61, 71, 81, 91, 101 m	10 min	mast correction necessary
FINO 3	wind speed, wind direction	40, 50, 60, 70, 80, 90, 100 m	10 min	mast correction necessary

There are also several measurements of the sea state, like significant wave height, wave periods, current speed and direction in different depths etc., in the database.

Access conditions:
The FINO database is provided by the Federal Maritime and Hydrographic Agency (BSH, Bundesamt für Seeschifffahrt und Hydrographie) and is accessible from the following website: http://www.bsh.de/en/Marine_data/Projects/FINO/index.jsp

Responsible person at BSH: Olaf Outzen (olaf.outzen@bsh.de)

There are following restrictions for the use of FINO data:
- Use of the FINO data for research purposes is free of charge. The fee for commercial use is €1,500 per year.
- Publications should include a reference to FINO as data source.
- Original data and data series from which original data can be derived are not allowed to be passed on to any third parties.
- No guarantee is given as to the completeness and accuracy of the data.

Application for an access: via e-mail, after accepting the restrictions you get an account for the FINO database.

Higher temporal resolved data of wind measurements (raw data of the 10 min averages) are not included in the database. But there is a possibility to get those data on individual request from a project partner of the project FINO-Wind.

2.1.2 NORSEWInD

NORSEWInD (Northern Seas wind index database) has been an EU-project (2008-2012) to provide a dependable offshore wind atlas of the North, Irish and Baltic Seas, coordinated by Oldbaum Services.
The NORSEWInD database includes Wind Atlas Files as well as high resolved measurement data from met masts, satellites and LiDAR instruments in the North and Baltic Seas. The wind atlas not only is a map of wind resource but is also a data set that will provide added value to the wind industry. This includes annual long-term corrected mean wind speed, Weibull parameters (k & A), and directional distribution. During the project some 12 years of LiDAR data have been acquired, collated, quality controlled and analysed.

<u>*Details of the data source:*</u>
An overview over some of the met masts is shown in the following table.

Table 4: Details of data base NORSEWInD.

Name	Country / Area	Description	Geographical position (N)	Geographical position (E)	Available period
Greater Gabbard	GBR / North Sea	Met Mast	51.8727	1.91537	23.01.2006 - 12.07.2010
Gunfleet Sands	GBR / North Sea	Met Mast	51.7267	1.19667	24.01.2002 - 01.01.2006
Egmond aan Zee	NED / North Sea	Met Mast	52.6064	4.38964	01.07.2005 - 31.12.2008
Horns Rev	DEN / North Sea	Met Mast			01.01.2005 - 15.12.2009
Lillgrund	SWE / Baltic Sea	Met Mast	55.4998	12.7654	01.01.2009 - 31.12.2009
Horns Rev M2	DEN / North Sea	Met Mast	53.5191	7.78752	01.01.1999 - 31.12.2003
Hoevsoere	DEN / North Sea	Met Mast	56.4405	8.1508	27.02.2004 - 15.09.2010

For more details of the different measurement locations of the LiDAR systems and their measuring periods are described in Hasager et al. (2013).

<u>*Access conditions:*</u>
The NORSEWInD database is coordinated by Oldbaum Services. An access can be obtained via the contact option of this website:
http://www.norsewind.eu/

Responsible person at Oldbaum Services: Andy Oldroyd (andy@oldbaumservices.co.uk)

For the high resolved measurement data a formal declaration is needed:
- of the use and outcomes of the project and
- an undertaking that the data will remain the property of the owner

Application for an access: via e-mail, after sending the formal declaration you get an account for the NORSEWInD database, takes a while because of EU administration and acknowledgement/ legal agreement of the owners of the different data sets in the database.

2.1.3 MARNET
Effective marine monitoring can only be achieved through a combination of different monitoring methods including shipboard measurements, satellite observations, and quasi-continuous measurements at fixed monitoring stations. Each of the above observation methods has its particular advantages and disadvantages. Therefore, the Federal Maritime and Hydrographic Agency of Germany (BSH) is using all three methods in its monitoring activities.

The MARNET (Marine Environmental Monitoring Network) database presently contains eleven automated measuring stations in the North Sea and Baltic Sea and provides mainly data of the state of the sea.

Details of the data source:

Table 5: Details of the data base MARNET.

Name	Owner / Administrator	Country / Area	Description	Geographical position	Available period	Format
Deutsche Bucht	BSH	GER / North Sea	light vessel	54° 10' N, 07° 27' E	since 1989	ASCII
Ems	BSH	GER / North Sea	light vessel	54° 10' N, 06° 21' E	since 1989	ASCII
NSB II	BSH	GER / North Sea	buoy	55° 00' N, 06° 20' E	since 1991	ASCII
NSB III	BSH	GER / North Sea	buoy	54° 41' N, 06° 47' E	since 2003	ASCII
Elbe	BSH	GER / North Sea	light vessel	54° 10' N, 07° 27' E	1989 - 1999	ASCII
Helgoland	BSH	GER / North Sea	Waverider-buoy	54° 9,6' N, 07° 52' E		ASCII
Sylt (Westerland)	BSH, LKN-SH	GER / North Sea	Waverider-buoy	55° 00' N, 07° 53'E 54° 55' N, 08° 13,30' E	2002 - 2004 since 2005	ASCII
Arkona Becken	IOW, BSH	GER / Baltic Sea	buoy	54° 43' N, 13° 45' E 54° 53' N, 13° 52' E	2002 - 11/2004 since 11/2004	ASCII
Darßer Schwelle	IOW, BSH	GER / Baltic Sea	met mast	54° 42' N, 12° 42' E		ASCII
Fehmarn Belt	BSH	GER / Baltic Sea	buoy	54° 36' N, 11° 09' E	since 1976	ASCII
Kiel	BSH	GER / Baltic Sea	lighthouse	54° 30' N, 10° 16' E	since 1969	ASCII
Oder Bank	IOW, BSH	GER / Baltic Sea	buoy	54° 05' N, 14° 10' E	since 1996	ASCII

Wind and sea state measurements:
Wind measurements are available for a few of stations but only in low heights (10 m to 30 m). There are many measurements of the sea state, like significant wave height, wave periods, current speed and direction in different depths etc., in the database. The temporal resolution is about 20 min to 60 min.

Table 6: Details of the available data of MARNET.

Name	Available data	Heights of wind meas.	Data resolution	Remarks
Deutsche Bucht	wind speed, wind direction	14 m	60 min	
Ems	wind speed, wind direction	14 m	60 min	
NSB II	wind speed, wind direction, Tm01, Tm02, Tp, Hs, Hmax, wave direction	10 m	60 min	
NSB III	wind speed, wind direction, current speed (-6m)	10 m	60 min	
Elbe	sea state		30 min	
Helgoland	Tm01, Tm02, Tp, Hs, Hmax, wave direction		25-30 min	
Sylt (Westerland)	Tm01, Tm02, Tp, Hs, Hmax, wave direction		60 min	relocation of the buoy in 2004/05 leads to significant differences concerning the sea state (within a time series)
Arkona Becken	wind speed, wind direction, Tm01, Tm02, Tp, Hs, Hmax, wave direction	10 m	20 min	relocation of the buoy in 11/2004 may lead to significant differences concerning the sea state
Darßer Schwelle	wind speed, wind direction	9 m	60 min	
Fehmarn Belt	wind speed, wind direction	4 m	60 min	
Kiel	wind speed, wind direction, current speed (-1m), Tm01, Tm02, Tp, Hs, Hmax, wave direction	31, 34 m	60 min	
Oder Bank	wind speed, wind direction	9 m	60 min	

Access conditions:
The MARNET database is also provided by the Federal Maritime and Hydrographic Agency (BSH) and is accessible from the following website:
http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/index.jsp

Responsible person at BSH: Susanne Tamm (susanne.tamm@bsh.de)

Application for an access: via e-mail, after accepting the restrictions (you get a form) you get the data (e-mail). The restrictions are the same as for the FINO database.

2.1.4 eKlima

eKlima is a web portal which gives free access to the climate database of the Norwegian Meteorological Institute, for all. The climate database contains data from all present and past weather stations of the Norwegian Meteorological Institute, as well as data from other institutions (owners) that are allowed distributed. From eKlima you can pick out simple lists or sophisticated analysis and you decide how the reports will look like.
There are wind and wave data for 11 different meteorological stations in the North and Norwegian Seas available.

Details of the data source:

Table 7: Details of the data base eKlima.

Name	Country / Area	Description	Geographical position (N)	Geographical position (E)	Available period
Ekofisk	NOR / North Sea	met station	56.5452	3.2148	since 04/1994
Sleipner A	NOR / North Sea	met station	58.3711	1.9091	since 10/1993
Heimdal	NOR / North Sea	met station	59.5742	2.2273	since 01/2003
Troll A	NOR / North Sea	met station	60.6435	3.7193	since 01/1998
Gullfaks C	NOR / North Sea	met station	61.2042	2.2687	since 11/1989
Statfjord A	NOR / North Sea	met station	61.2553	1.8522	since 01/1978
Ormen Lange	NOR / Norwegian Sea	met station	63.564	5.2351	since 09/2007
Draugen	NOR / Norwegian Sea	met station	64.352	7.7792	since 10/1993
Heidrun	NOR / Norwegian Sea	met station	65.3229	7.3156	since 11/1995
Norne	NOR / Norwegian Sea	met station	66.0256	8.085	since 03/1998
Mike	NOR / Norwegian Sea	met station	66.00	2.00	since 01/1949

Access conditions:
The eKlima database is provided by the Norwegian Meteorological Institute and is accessible from the following website:
http://www.eklima.no

Application for an access: after registration at the webpage you get a password for Login via e-mail.

2.1.5 Irish Marine Weather Buoy Network

The Irish Marine Weather Buoy Network is a joint project designed to improve weather forecasts and safety at sea around Ireland. The buoy network provides data for weather forecasts, shipping bulletins, gale and swell warnings as well as data for general public information and research. The project is the result of successful collaboration between the Marine Institute, Met Eireann, The UK Met Office and the Irish Department of Transport.

There are wind and wave data of six different buoys in the seas around Ireland available.

Details of the data source:

Table 8: Details of the data base Irish Marine Weather Buoy Network.

Name	Country / Area	Description	Geographical position (lat)	Geographical position (lon)	Available period
M1	IRL	buoy	53.1266	-11.2	since 02/2002
M2	IRL / Irish Sea	buoy	53.48	-5.43	since 02/2002
M3	IRL / Celtic Sea	buoy	51.217	-10.55	since 02/2002
M4	IRL	buoy	55	-10	since 02/2002
M5	IRL / Celtic Sea	buoy	51.69	-6.7	since 02/2002
M6	IRL	buoy	53.07	-15.88	since 02/2002

Wind and sea state measurements:
Wind speed and direction measurements are available from the different buoys (ca. in 2 m height). There are also measurements of the sea state, like significant wave height, wave periods and wave direction in the database. The temporal resolution is about 10 min for the wind measurements and about 17.5 min for the sea state parameter.

Access conditions
The database is provided by the Marine Institute of Ireland and is accessible from the following website:
http://www.marine.ie/home/publicationsdata/data/buoys

Application for an access: open.

2.2 Selection of a data set

In the section before available data sets are described. All available measurement locations are summarised in the following figure. The locations of buoy measurements (black/white points) and met masts (red and yellow markers) in the North and Baltic Sea are shown. The yellow markers signalise met masts where the access to the data depends on industrial owners. Measurement locations of a LiDAR system during the NORSEWInD project can be found in Figure 2.

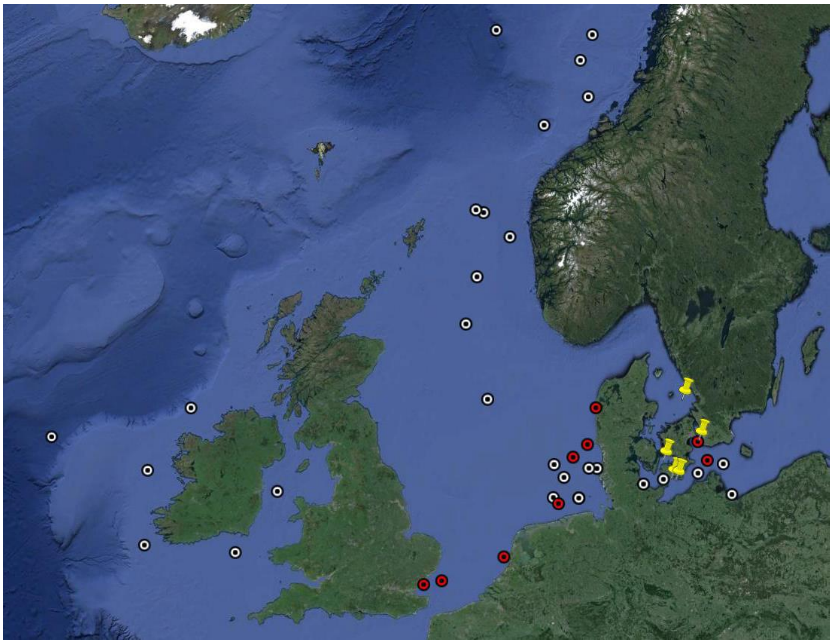


Figure 1: Map of all measurement locations in the North and Baltic Seas, available in databases.

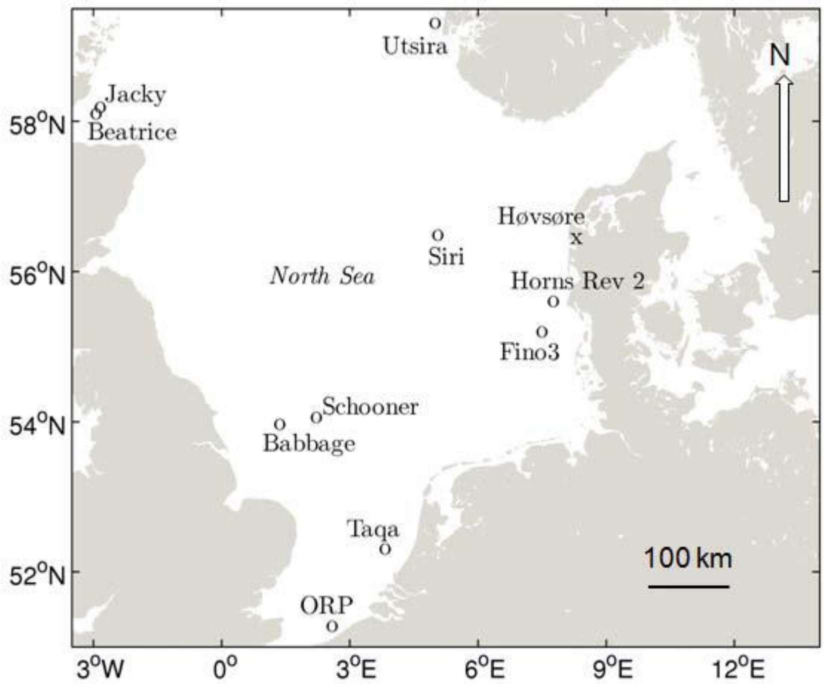


Figure 2: Map of measurement locations of the LiDAR systems during the project NORSEWInD (Hasager et al., 2013).

The exemplary data set should provide data from a met mast and data of a LiDAR system to characterize the wind conditions in tall atmospheres (Target 3 of Deliverable D1.11, Table 1). Following these requirements only two measurements locations can be found: *Horns Rev 2* and *FINO 3* (Figure 3). Table 9 gives an overview of the available data of the two selected datasets.

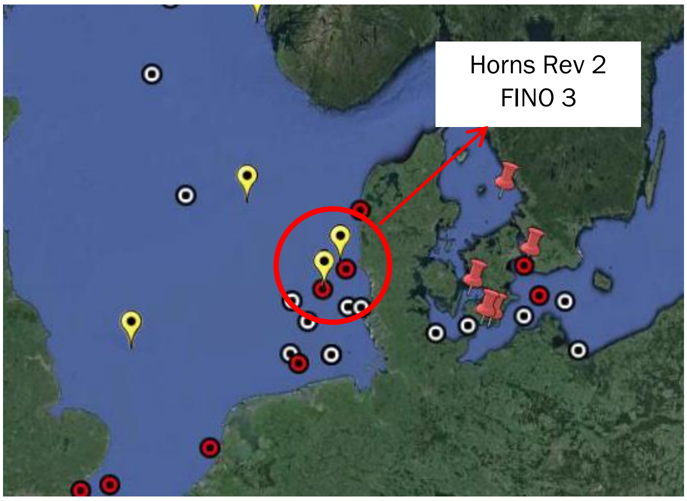


Figure 3: Map with measurement locations of met mast and LiDAR system.

Table 9: Overview of the data sets Horns Rev 2 and FINO 3.

	Horns Rev 2	FINO 3
source	NORSEWInD database	BSH database
met mast		
max. meas. height	60 m	100 m
meas. period	1999 - 2003	since 2009
LiDAR system		
max. meas. height	286 m	160 m
meas. period	07/2009 – 09/2011	04/2011 - 10/2011

For the exemplary characteristic data set measurements of FINO 3 will be analysed.
The main argument for this selection is the same measuring period of the met mast data and the LiDAR data. So the LiDAR measurements can be evaluated up to a height of 100 m with reference to the data of the met mast. This allows a reliable investigation of the wind conditions in tall atmospheres up to the maximum measuring height of the LiDAR system at 160 m. For the data of the met mast a mast correction can be applied.
Another aspect for the dataset of FINO 3 is the availability of measurements of wave parameter since 2009, e.g. the sea level, significant wave height, peak frequency, mean period, ocean current speed and direction as well as the wave direction.

3 CHARACTERISTICS OF FINO 3

The FINO 3 research platform in the North Sea is placed 80 km (45 sea miles) off Sylt (Germany). Its coordinates are 55° 11.7' N and 07° 9.5' E (Figure 4). The platform was constructed and set up at the end of June 2009. More information can be found in 2.1 and here: www.fino3.de.

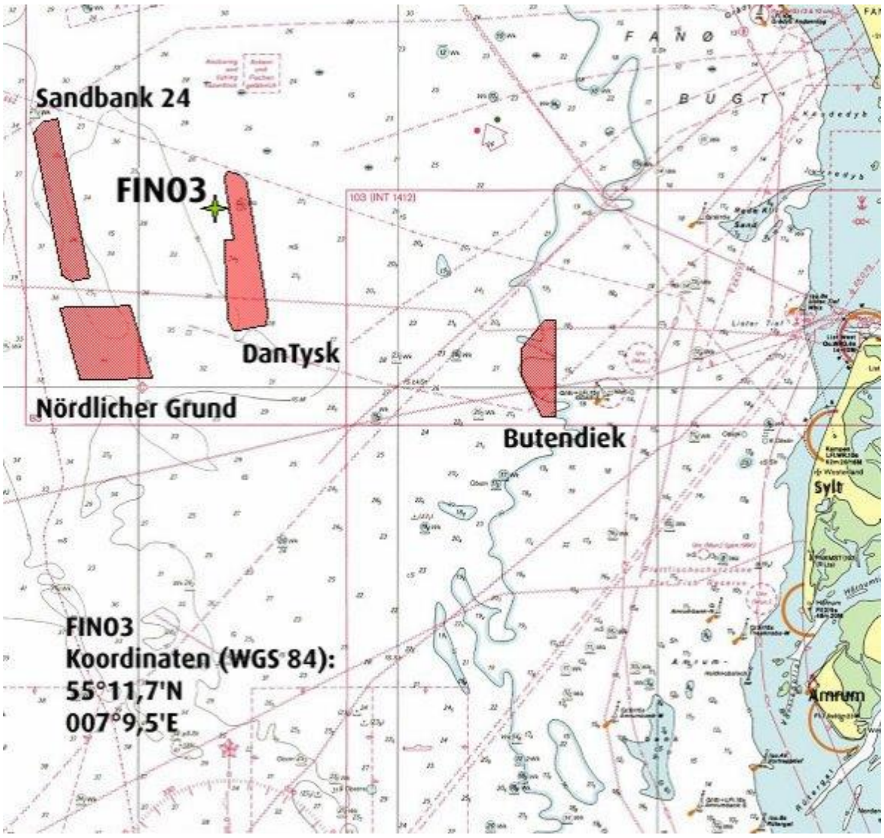


Figure 4: Map with the location of the met mast FINO 3.

Figure 5 shows the design of FINO 3 on the left and details of the measurement heights on the right.
FINO 3 has a triangular structure with three booms at each measurement height. At the heights 50 m, 70 m and 90 m three cup anemometers are installed which are needed for the used mast correction method (see chapter 4.1). During the measurement campaign of NORSEWInD the LiDAR system ZephIR ZP152 was also installed at the platform. The LiDAR system measured the wind speed and direction in 50 m, 70 m and 90 m height and additionally in 100 m, 130 m and 160 m height.

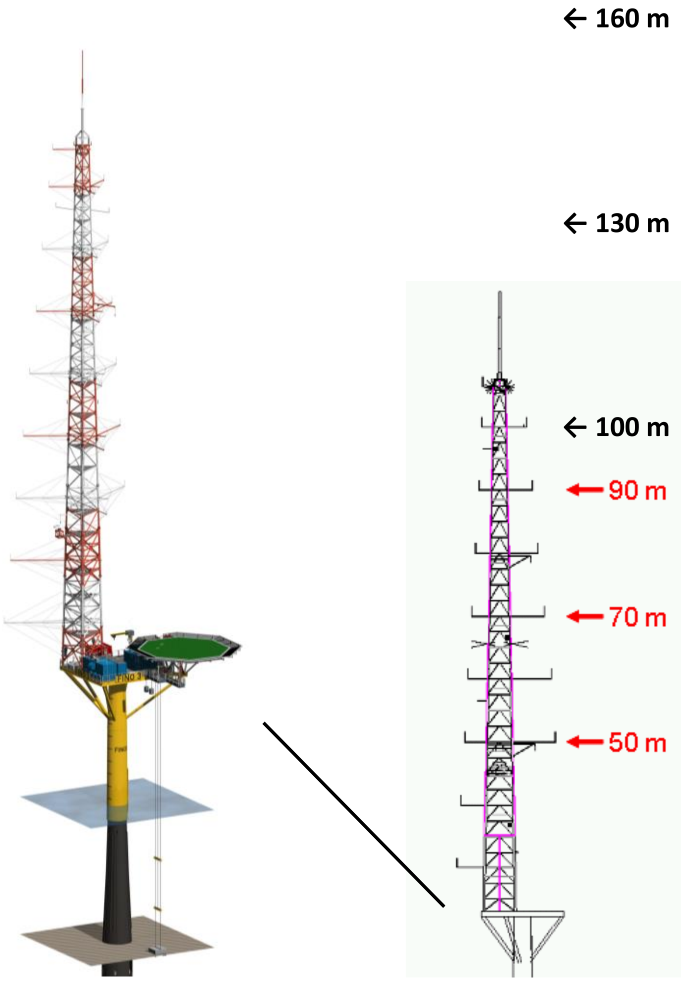


Figure 5: Design (left) and height details (right) of the cup anemometer (red) and the LiDAR (red + black) measurements at FINO 3.

The databases include data which were mainly quality checked regarding spikes. For data measured at the met mast a correction of mast effects on the data is necessary. Another aspect concerning the data quality is the availability of the measurements which can vary significantly each year.
The mast as well as the LiDAR data are available as 10-min-mean values for the wind speed and the wind direction.

For an evaluation of turbulence and extreme wind conditions based on the two datasets the different wind measurement techniques have to be considered. It has to be taken into account that recorded values of a LiDAR are not directly comparable with the data from conventional mast measurements. Some notes about this issue can be found in Annex A.

4 DATA PROCESSING

Before analysing the data of the met mast and the LiDAR system a correction of the mast shadow effects is necessary. The used methods for both mast and LiDAR data are shown in the following.

4.1 Mast correction method for the mast data

The here shown mast correction method was developed by GL GH (Kindler, 2011) and uses the data of three cup anemometers at one measurement height of FINO 3.

The cup anemometers are installed at each end of a boom, sprouting from each vertex of the triangular mast and run as an extension of the mast edge. The boom directions are 225° (A), 345° (B) and 105° (C). The mast structure influences the flow in the field of the cup anemometers which lead to a distortion of the undisturbed flow and results in erroneous wind speed measurements. In Figure 6 the influence of the mast effect on the wind speed measurements on the booms A, B and C in dependence on the wind direction can be seen. On the ordinate the ratio of disturbed to undisturbed wind speed measurement is shown. There is a maximum error of about 40% to 45 % for all booms.

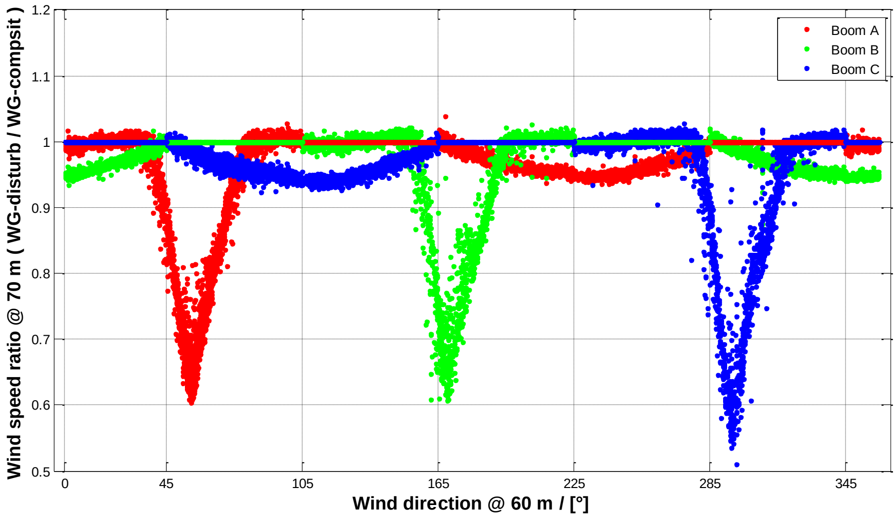


Figure 6: Mast effect on the anemometer measurements at 70 m height at FINO 3 (source: GL GH).

Based on these results, undisturbed flow directions can be determined for the booms A, B and C (Figure 7). The undisturbed wind sector has a width of 2 × 60° for each boom respectively.

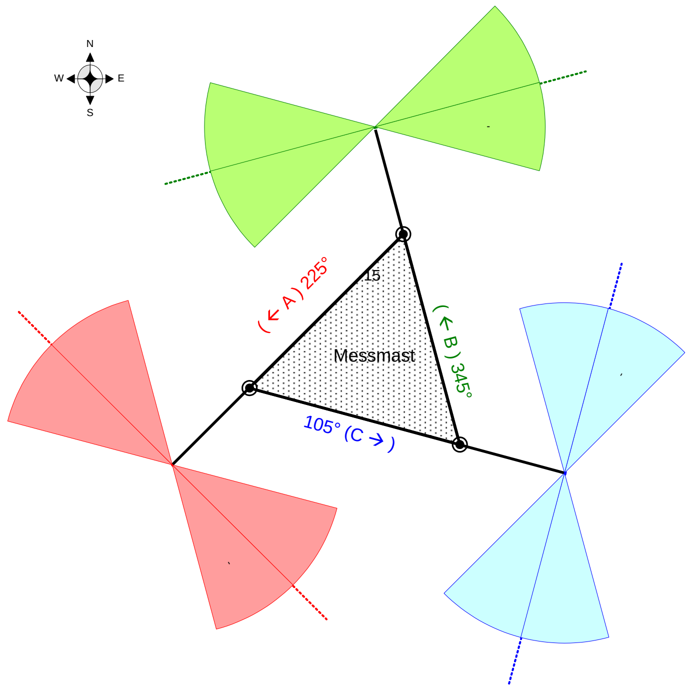


Figure 7: Illustration of undisturbed wind sectors, 2 x 60° for each of the booms A, B and C (source: GL GH).

It has to be mentioned that this correction method is not perfect because the data in the so called undisturbed wind directions are still slightly affected by the mast structure. This results in uncertainties in the data. Hopefully a better method will be developed during the German project FINO-Wind (further information in 2.1).

4.2 Mast correction for the LiDAR data

There are mast effects nearly for all wind directions for the wind data at the met mast. For the LiDAR system it is only expected a decrease in wind speed in the direct mast shadow of the met mast.

Figure 8 shows the difference in wind speed in 50 m and 70 m height between the LiDAR data and corrected mast data plotted over the measured wind direction in 100 m height at the mast. A decrease in wind speed can be observed for wind directions from 35° to 80° which is corrected by blanking the LiDAR data in this region demonstrated in Figure 9.

The plot also shows the systematic error in the mast correction method for the mast data (steps in the wind speed data at a certain wind direction, e.g. at 225°).

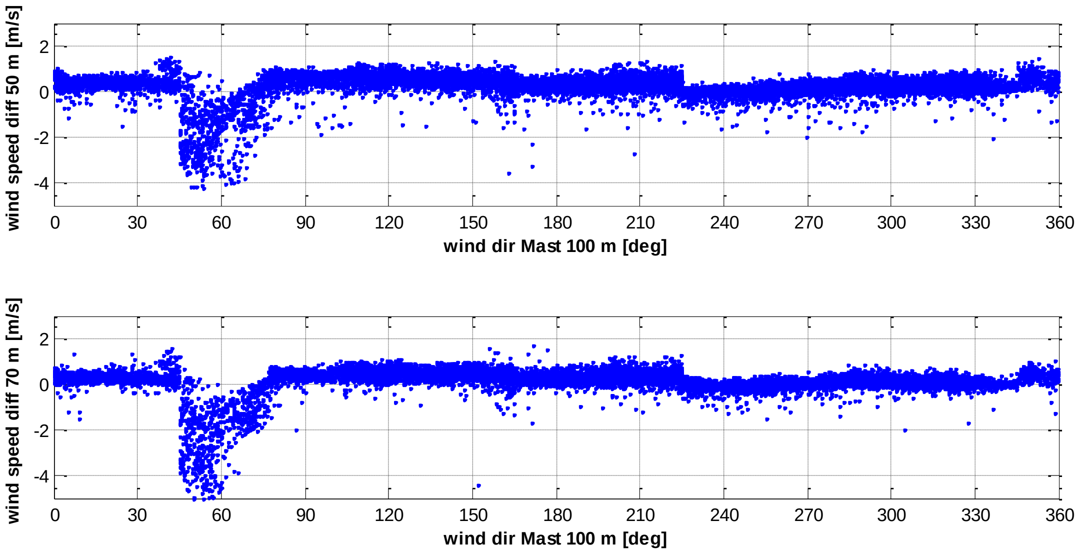


Figure 8: Mast effect of the met mast on the LiDAR measurements in 50 m (top) and 70 m (bottom) height at FINO 3.

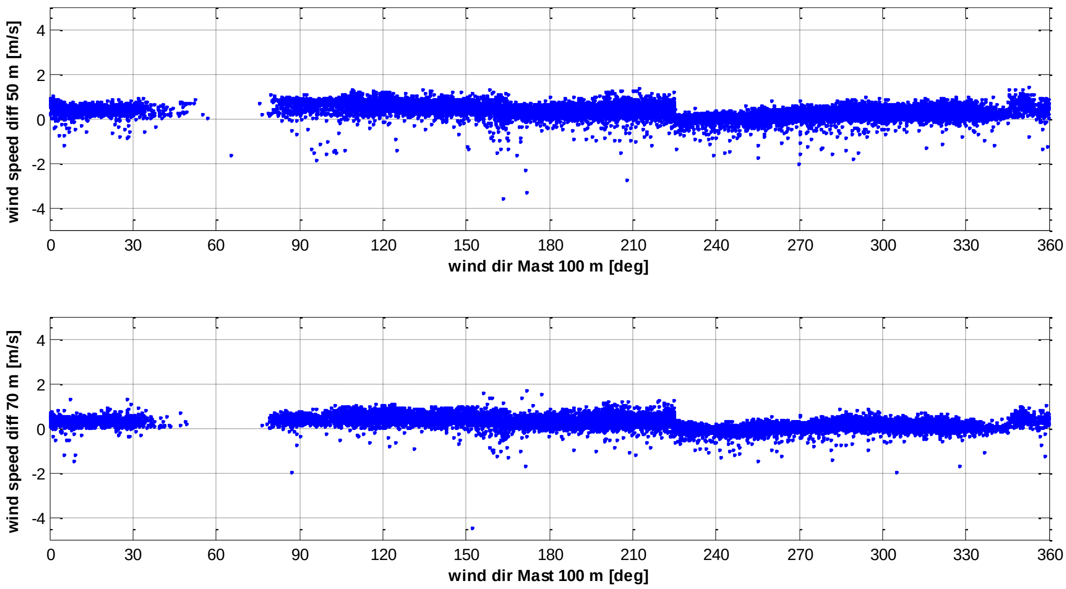


Figure 9: Corrected LiDAR measurements in 50 m (top) and 70 m (bottom) height at FINO 3 by blanking of the data in the mast shadow.

5 DATA ANALYSES

Target 3 of the Deliverable D1.11 (Table 1) aims at the following:
"Definition and delivery of exemplary characteristic datasets comprising selected processed data for a specific period (at least one year) that will be made available to interested partners. The data sets shall comprise rather standard conditions according to IEC 61400-3, as well as conditions significantly deviating from these (high temporal gradients in wind shear, wind speed, gusts and turbulence as well as very convective, unstable, neutral, stable and very stable stratification)."

This chapter presents investigations of the available data of the met mast FINO 3 and the LiDAR system to detect time periods with normal as well as extreme wind conditions. Additionally a quick view inside available wave data will show some correlation between two wave parameter – significant wave height and peak period- and the wind speed.

5.1 Wind data of the met mast

First, the data of the met mast FINO 3 will be analysed for the whole year of 2011.

5.1.1 Availability and distribution of wind speed

Figure 10 shows the availability of wind speed measurements of the cup anemometers in 50 m and 90 m height for each month of 2011. The availability looks very similar for the different heights. In January 2011 the availability is only about 66 % and in July about 82 %. But during the other months wind data is in 90 % to 100 % of the time available.

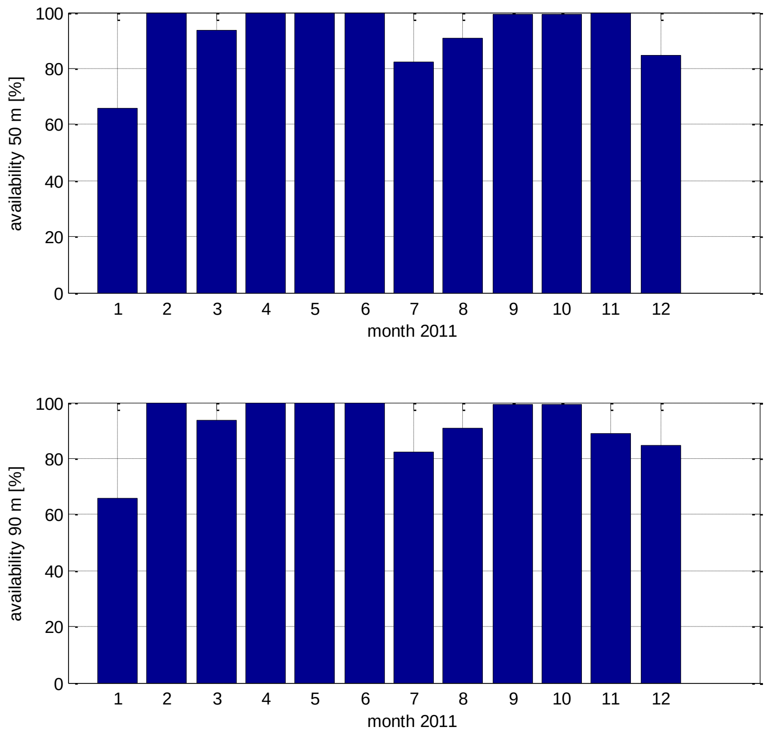


Figure 10: Availability of the wind speed data at FINO 3 in 50 m (top) and 90 m (bottom) height for each month of 2011.

The plotted time series of the year 2011 demonstrate that the availability of 82 % in July is due to a small gap in the data acquisition for all heights (Figure 11). In the middle of the figure the standard deviation of the wind speed in 50 m, 70 m and 90 m height is plotted which shows higher values for the winter months as expected due to higher wind speeds and turbulences. At the bottom of this figure the wind direction measured in 100 m height can be seen. Its availability corresponds to the availability of the wind speed.
In summary, the data set of FINO 3 has a high availability in the year of 2011 which allows further investigations.

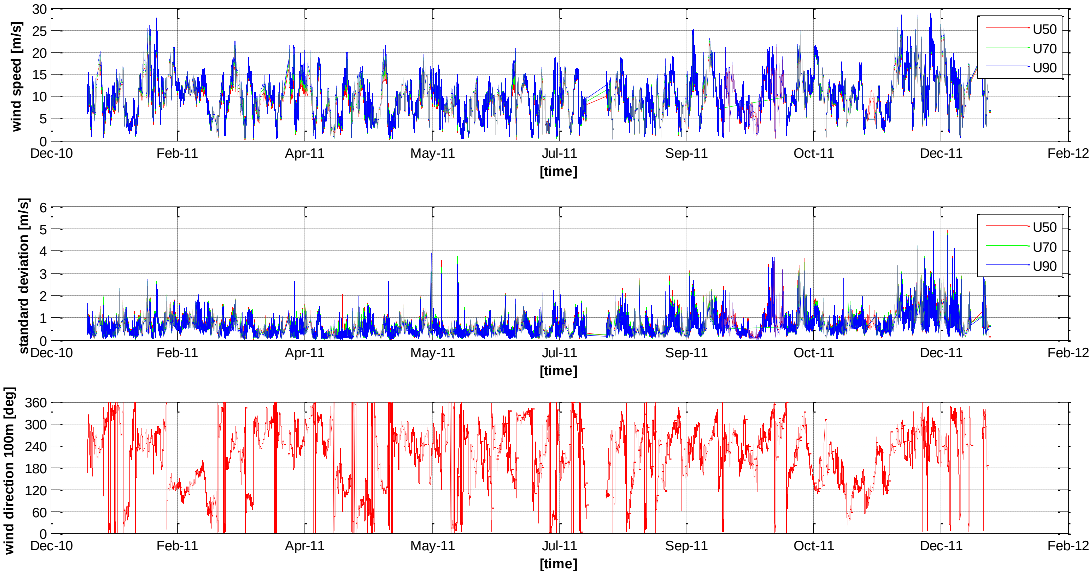


Figure 11: Time series of the wind speed (top), standard deviation of the wind speed (middle) in 50 m, 70 m and 90 m height and wind direction (bottom) in 100 m height at FINO 3 during year 2011.

The next diagram in Figure 12 presents the frequency distribution of the wind speed in 90 m height for the whole year of 2011. The Probability Density Function (PDF) of the wind speed is plotted in red while the blue curve represents the Rayleigh distribution fitted to the data (referred to IEC 61400-1).

A more detailed view regarding the PDF of the wind speed can be seen in Figure 13. Here the PDFs of the wind speed in 90 m height are plotted for each month of 2011 (thin lines) in addition with the PDF (thick black line) of the whole year. A high variability in the shape of the PDFs in dependence to the month (annual variability) can be observed. The peak of the most frequent wind speed for the winter months is located at about 11 m/s and in the summer months at about 8 - 9 m/s.

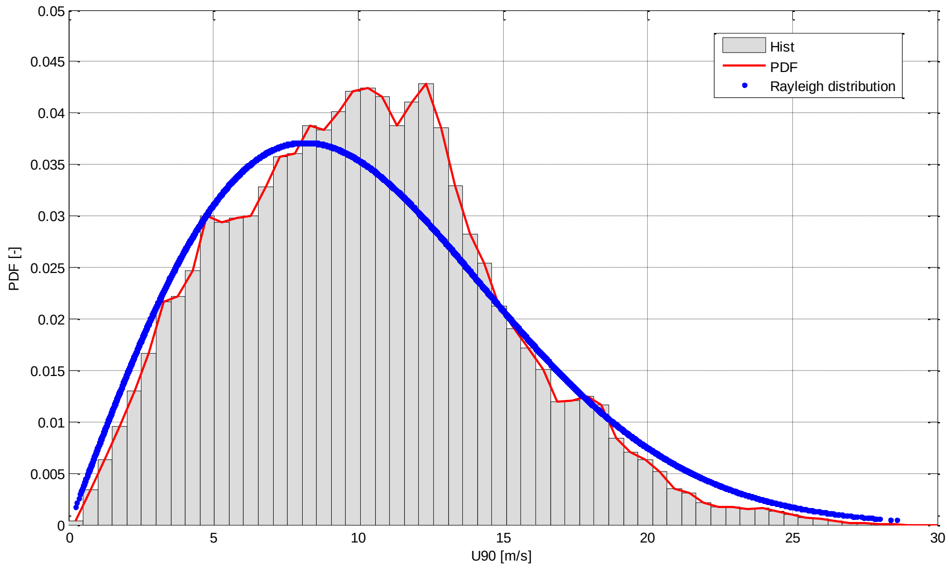


Figure 12: Frequency distribution, PDF and Rayleigh distribution of the wind speed at FINO 3 in 90 m height for year 2011.

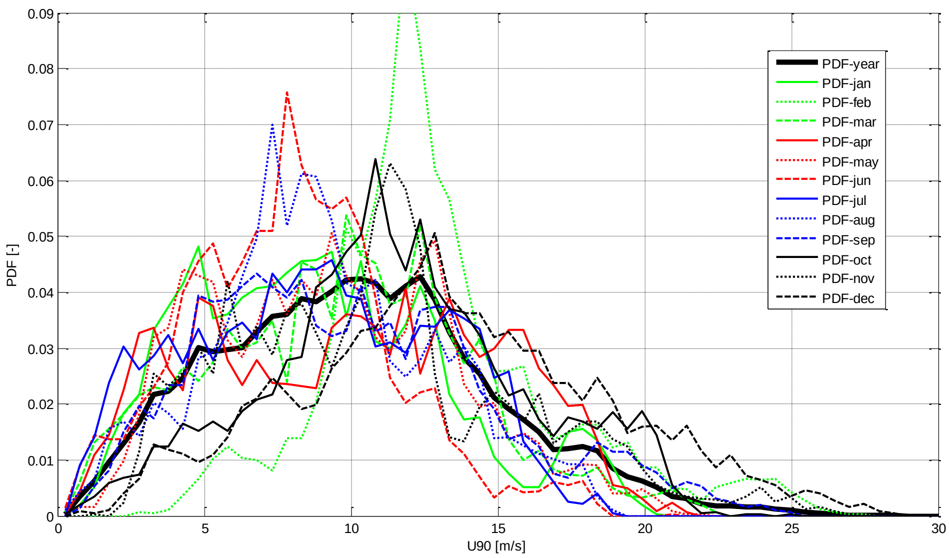


Figure 13: PDFs of the wind speed at FINO 3 in 90 m height for each month (thin lines) and for the whole year (thick line) of 2011.

5.1.2 Stability

In this section, the data of FINO 3 will be analysed regarding the atmospheric stratification during year 2011. Table 10 shows the definition of the five stability classes used here.

Table 10: Definition of stability classes.

stratification	stability parameter		
very stable	0.2	< z/L <	+ ∞
stable	0.04	< z/L <	0.2
neutral	-0.04	< z/L <	0.04
unstable	-0.2	< z/L <	-0.04
very unstable	- ∞	< z/L <	-0.2

The Monin-Obukhov-Length L is calculated with the Gradient-Richardson-Number. Figure 14 shows the distribution of the stability parameter z/L plotted against the ratio of the wind speed in 50 m and 90 m height (U90/U50). The black vertical lines represent the different stability classes whereas the colours indicate the magnitude of the wind speed in 90 m height.
It has to be mentioned that the results are depending sensitively on the used measurement height of the wind speeds. A stable stratified atmosphere corresponds usually with low heights of the Prandtl-layer which means that at a height from 50 m to 90 m no significant shear is measurable. Reliable wind and temperature measurements with a high availability in lower heights are not available for the analysed year 2011.

To obtain information about the time periods with a certain stability class, the stability parameter is plotted as a time series (Figure 15). From January to March the atmospheric stratification is very stable whereas in the summer and fall months more very unstable stratification can be observed which is marked with horizontal black lines. The dependence of the stability on the wind speed in 90 m height is again demonstrated by different colouring.

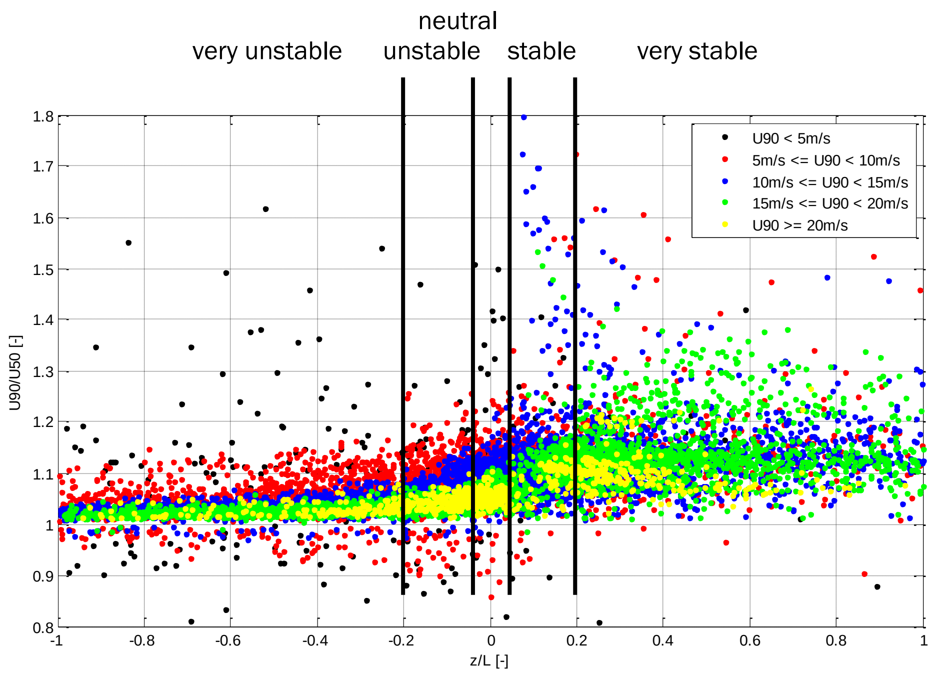


Figure 14: Stability parameter z/L at FINO 3 for 2011 depending on different wind shears U90/U50.

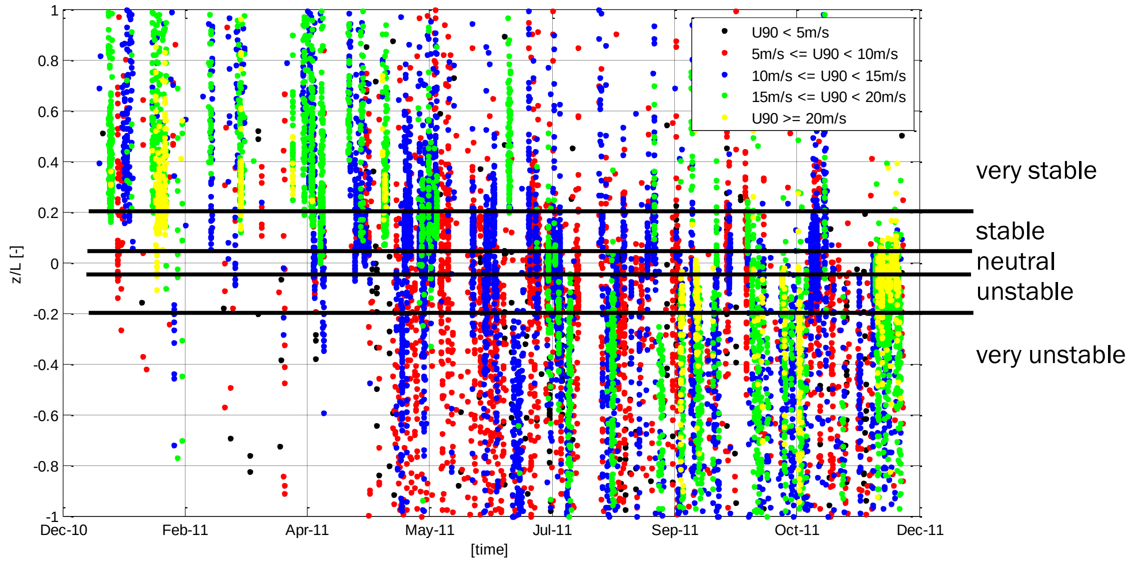


Figure 15: Stability parameter z/L at FINO 3 depending on the time of the year 2011.

The calculation of the Monin-Obukhov-Length depends strongly on the temperature measurements. Figure 16 shows temperature measurements in 29 m, 55 m and 95 m height at the met mast as well as the sea surface temperature during year 2011. The wind and temperature gradient between 50 m and 90 m height has been analysed before. For height 30 m no wind speed with a mast correction is available. So, the gradient between 95 m and the water level will be analysed additionally. An investigation of the stratification is only possible for a few months due to the low availability of sea surface temperature measurements. The stability parameter z/L is plotted against the ratio of the wind speed at sea surface and 90 m height (U90/Useasurface) in Figure 17.

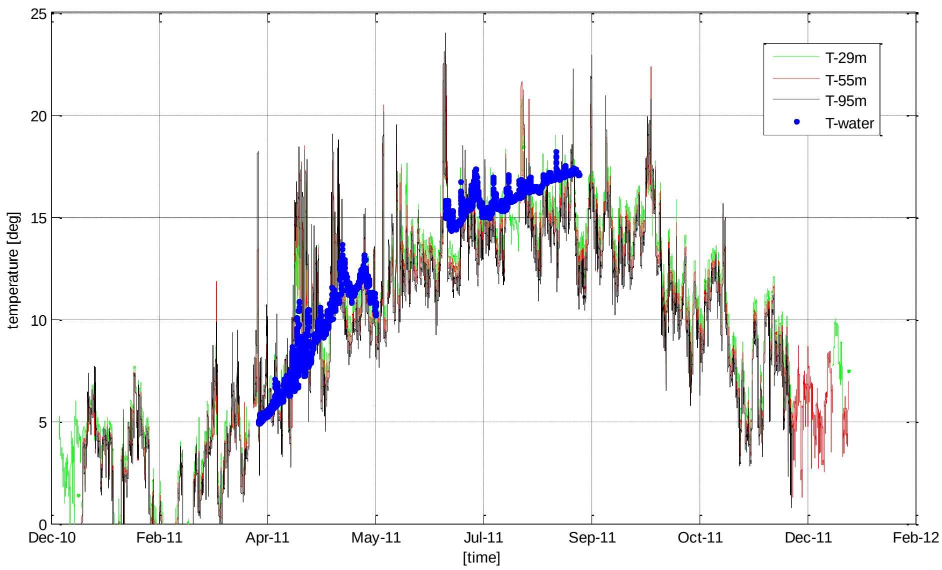


Figure 16: Temperature T in 29 m, 55 m and 95 m height at the met mast as well as the sea surface temperature at FINO 3 during year 2011.

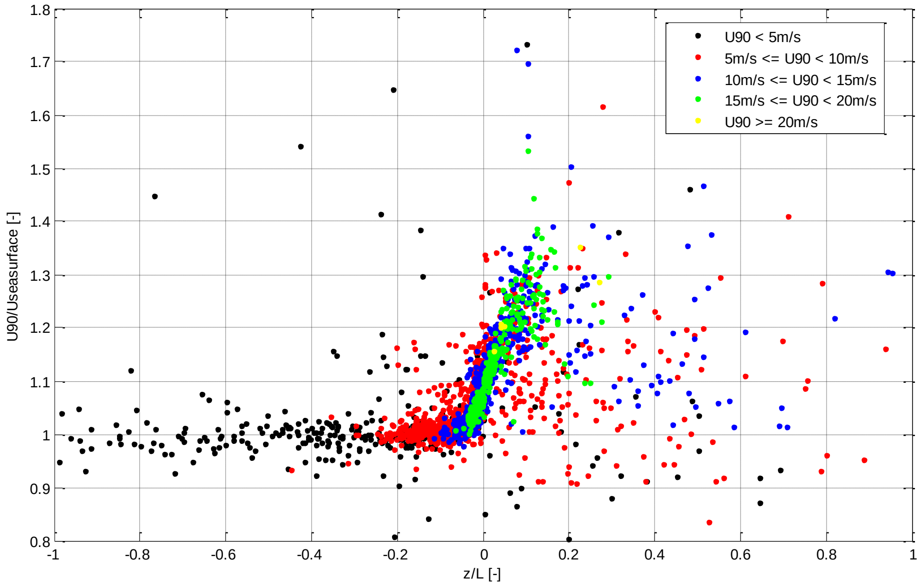


Figure 17: Stability parameter z/L at FINO 3 for 2011 depending on different wind shears U90/Useasurface.

It can be seen that in comparison to Figure 14 more stable conditions are observed. This can be caused by the investigated time periods in the spring and summer as well as by the better detection of stable stratification due to the higher gradient in measuring height.

5.1.3 Turbulence Intensity

The turbulence intensities of the mast measurements in 2011 are investigated in this section. The turbulence intensity TI is calculated as follows:

$$TI = \frac{\sigma}{V_{hub}}$$

V_{hub} represents the measured wind speed in 90 m height at the met mast of FINO 3 and σ its standard deviation.

First, the turbulence intensity is analysed in correlation to other wind parameter regarding the stratification of the atmosphere. A high wind shear is connected with a stable stratification corresponding to Figure 14 which suggests low turbulence in comparison to an unstable well mixed boundary layer.
The correlation between turbulence intensity in 90 m height and wind shear U90/U50 is shown in Figure 18. It can be observed that high values for the wind shear correspond to low turbulences. In Figure 19 the turbulence intensity in 90 m height is plotted over the stability parameter z/L. For the stable stratification z/L>0 slightly lower turbulence intensities are calculated. The highest turbulence intensities can be expected for unstable wind conditions as mentioned before.

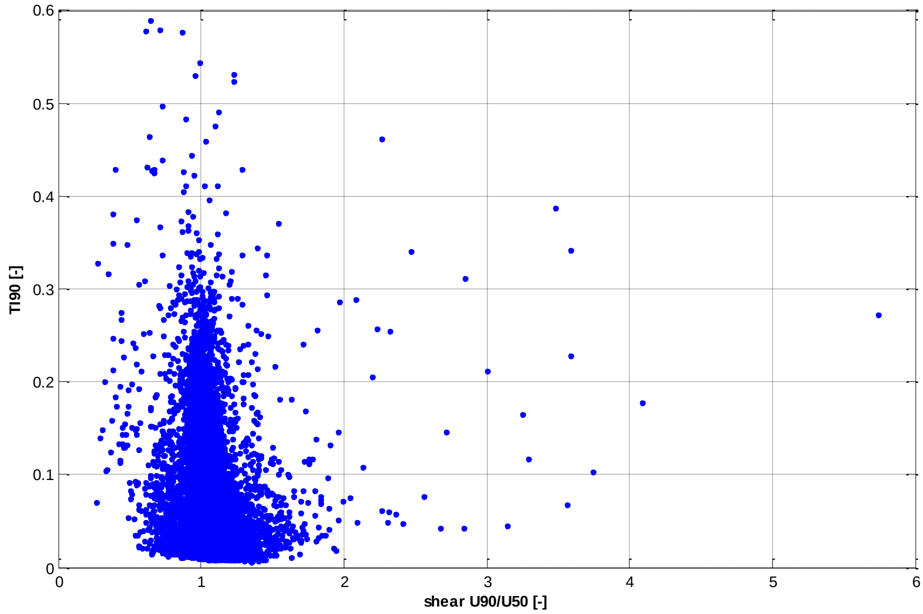


Figure 18: Correlation between turbulence intensity TI in 90 m height and wind shear U90/U50 at FINO 3 during year 2011.

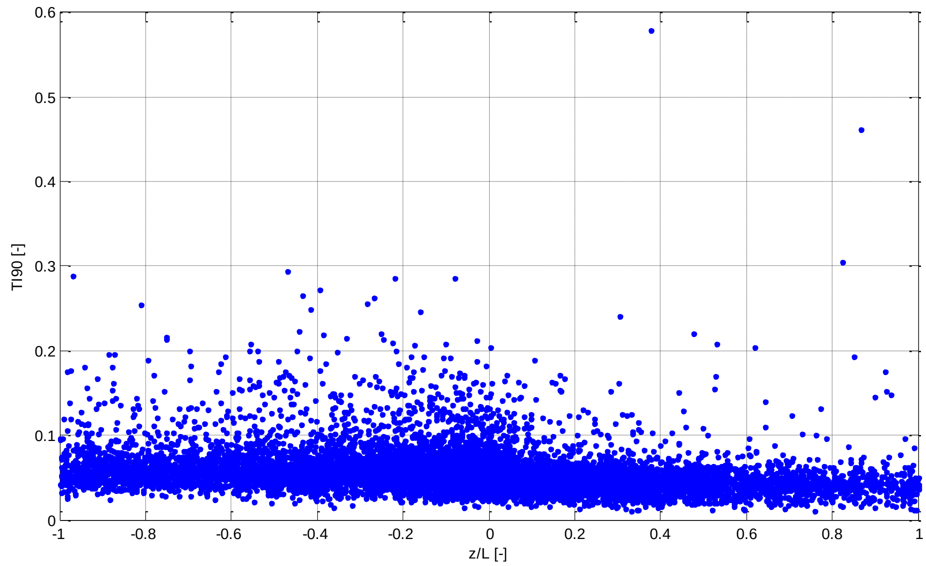


Figure 19: Correlation between turbulence intensity TI in 90 m height and stability parameter z/L at FINO 3 during year 2011.

In the international standard IEC 61400-1 (Ed.3) a Normal Turbulence Model (NTM) can be found where the standard deviation is defined as

$$\sigma = I_{ref}\ (0.75 * V_{hub} + 5.6)$$

including different turbulence characteristics for onshore conditions as follows:

A: $I_{ref} = 0.16$
B: $I_{ref} = 0.14$
C: $I_{ref} = 0.12$

In Figure 20 the turbulence intensity TI of the measured wind speed in 90 m height is plotted in dependence on the wind speed in 90 m height. Additionally, theoretical values of turbulence intensities calculated with the Normal Turbulence Model for different turbulence characteristics at onshore sites are shown. Most of the time, the turbulence intensities at FINO 3 are located beneath the theoretical lines. Lower turbulence intensities are measured caused by lower roughness lengths at offshore sites than at onshore sites. Plotted as time series (Figure 21) time periods with high turbulence intensities can be analysed.

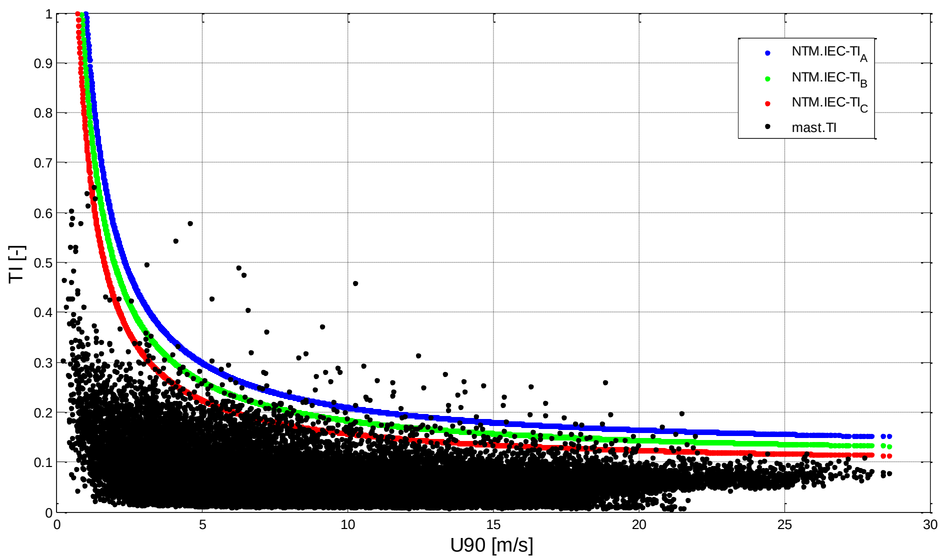


Figure 20: Turbulence intensity TI of the wind speed at FINO 3 in 90 m height and the theoretical values of the Normal Turbulence Model (IEC 61400-1 Ed.3).

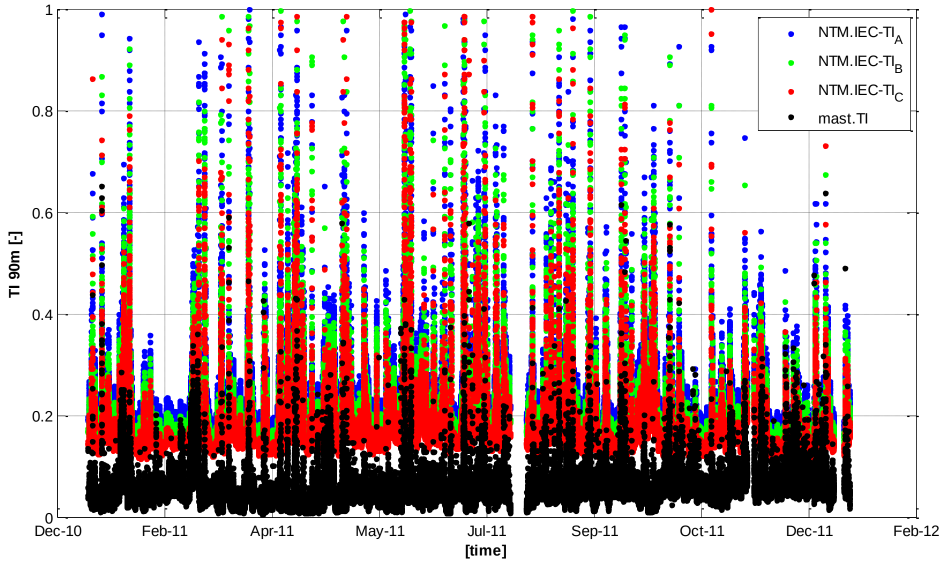


Figure 21: Turbulence intensity of the wind speed at FINO 3 in 90 m height and the theoretical values of the Normal Turbulence Model (IEC 61400-1 Ed.3) depending on the time of the year 2011.

The Extreme Turbulence Model (ETM) is defined in the guideline IEC 61400-1 (Ed.3) with a standard deviation of

$$\sigma = 2 * I_{ref}\left(0.072\left(\frac{V_{avg}}{2}+3\right)\left(\frac{V_{hub}}{2}-4\right)+10\right)$$

According to the procedure with the Normal Turbulence Model, following results can be obtained for the extreme turbulence intensity (Figure 22).

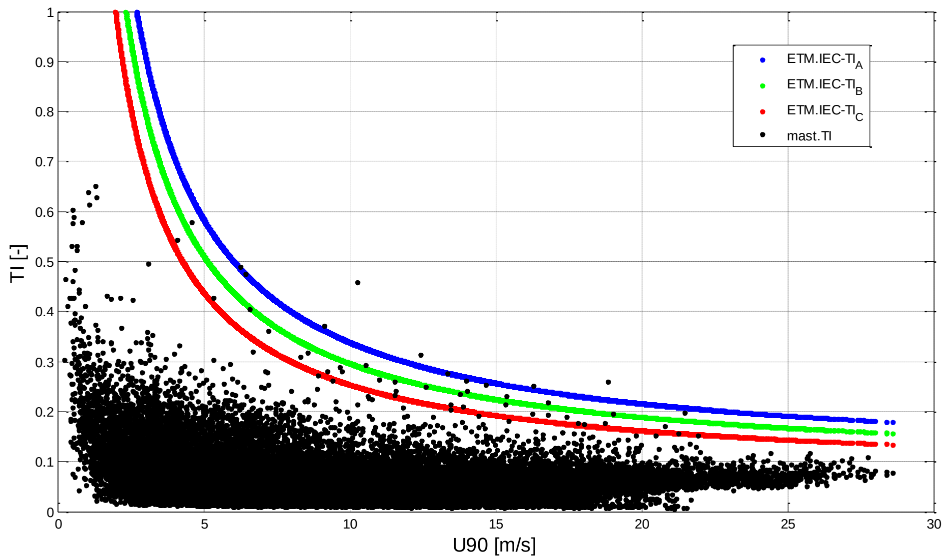


Figure 22: Turbulence intensity TI of the wind speed at FINO 3 in 90 m height and the theoretical values of the Extreme Turbulence Model (IEC 61400-1 Ed.3).

5.2 Wind data of the LiDAR system

During six months of 2011 a ZephIR LiDAR system was placed next to the met mast at FINO 3. The measuring period started on 11 April 2011 at 16:00 UTC and ended on 12 October 2011 at 9:50 UTC. The availability and correlation with the mast data during this time period will be analysed in the following section.

5.2.1 Availability

The LiDAR system was measuring in seven different heights as shown in Table 11.

Table 11: Measurement levels and heights of the LiDAR system at FINO 3.

height level	height [m]
1	51
2	64
3	71
4	91
5	101
6	130
7	160

The availability for each measuring height is plotted in Figure 23. For the height levels 1-3 and 4-5 a data availability of 90 % to 100 % is reached. Level 4 features only 33 % and level 7 67 %. If the time series of level 4 and 5 are plotted together with level 1 (Figure 24), it demonstrates that in the middle of June the measuring height of the LiDAR system was changed from 91 m in the first time period to 160 m to the end in October.

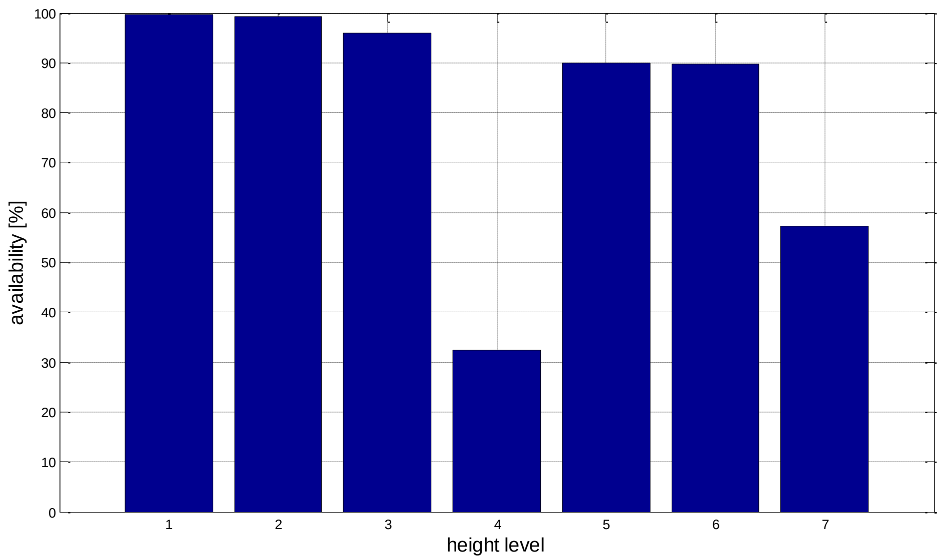


Figure 23: Availability of the LiDAR data at different height levels installed at FINO 3 from April to October of 2011.

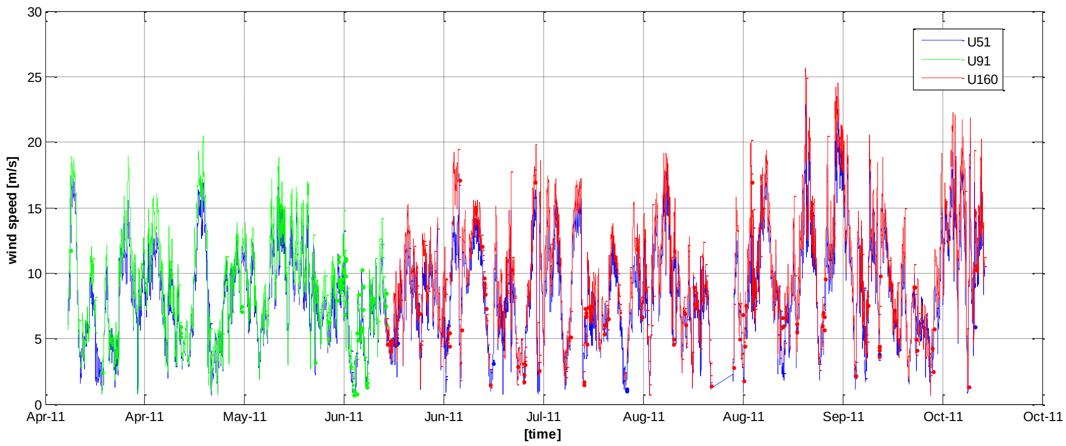


Figure 24: Time series of the LiDAR data in 51 m, 71 m and 91 m height at FINO 3.

5.2.2 Correlation of mast and LiDAR data

In this section the LiDAR data will be compared with the mast data to obtain information about the accuracy of the LiDAR measurements. For a first impression the data are plotted together as time series in 50 m, 70 m and 90 m height. A good similarity is observed.

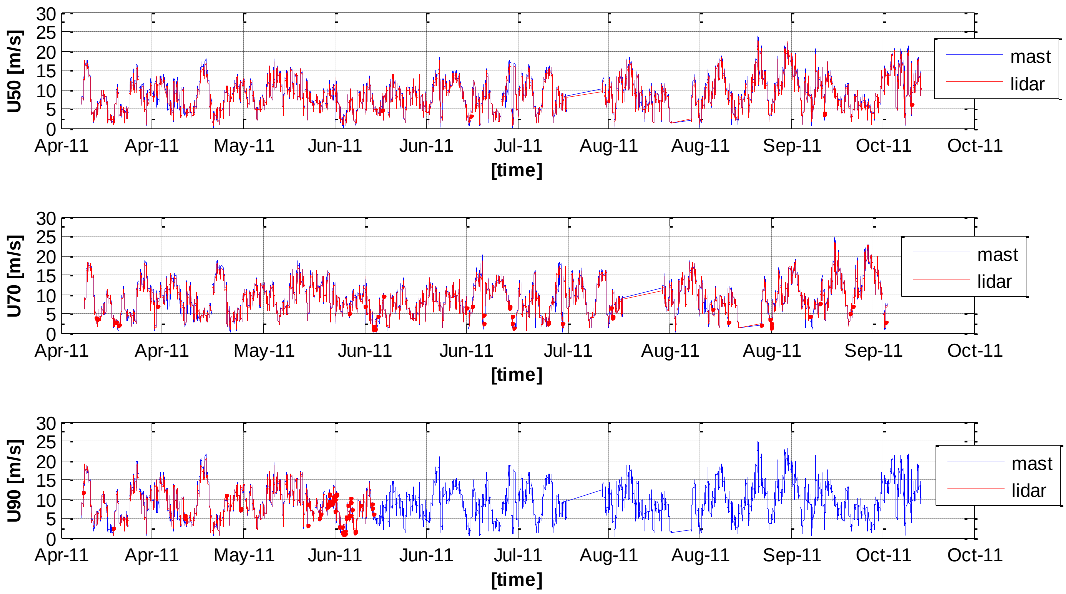
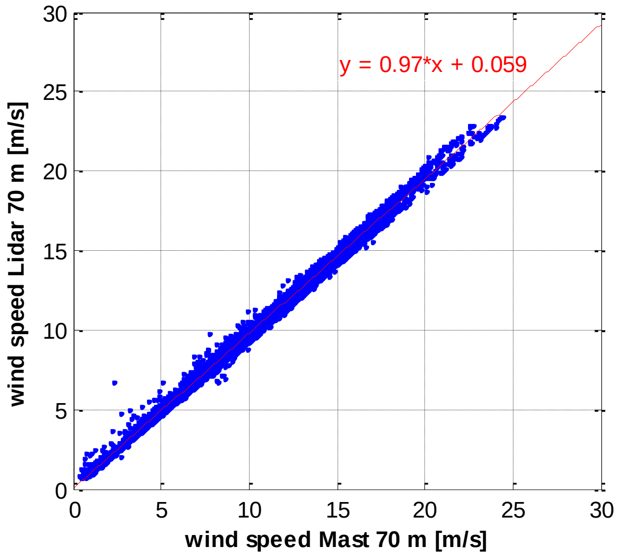


Figure 25: Comparison of the time series of the LiDAR data with mast data in 50 m (top), 70 m (middle) and 90 m (bottom) height at FINO 3.

The correlation between LiDAR and mast data is shown in the following. Figure 26 pictures a scatterplot of the data in 70 m height. Similar to the other heights (not shown here), the correlation coefficient in this height is 0.9963 whereas the gradient of the regression line is low. This means that at the met mat slightly higher wind speed are measured than with the LiDAR system.



Number of data: 18 932

Correlation coefficient: R^2 = 0.9963

Figure 26: Correlation of the wind speed of the met mast and of the LiDAR at 70 m height at FINO 3.

5.3 Correlation of wind and wave parameter

The FINO 123-database of BSH (see 2.1) includes:

- mean sea level
- significant wave height - measured by buoy and AWAC (30-min-mean values)
- peak period - measured by buoy and AWAC (30-min-mean values)
- wave direction - measured by AWAC (1-hour-mean values)
- ocean current speed in 2-22 m depth (10-min-mean values)
- ocean current direction in 2-22 m depth (10-min-mean values)

In this section some correlations will be shown to get a first impression of the wind and wave interaction. A deeper investigation of these phenomena are analysed in the Deliverable D1.13. In this report the correlation between the parameters wind speed, significant wave height and the peak period will be described. The measured wave data of the buoy is analysed in the following.

For year 2011 the data of the significant wave height as well as the peak period have an availability of 94 % respectively. The time series of both parameters are plotted in Figure 27. A gap in the data of three weeks in June can be observed.

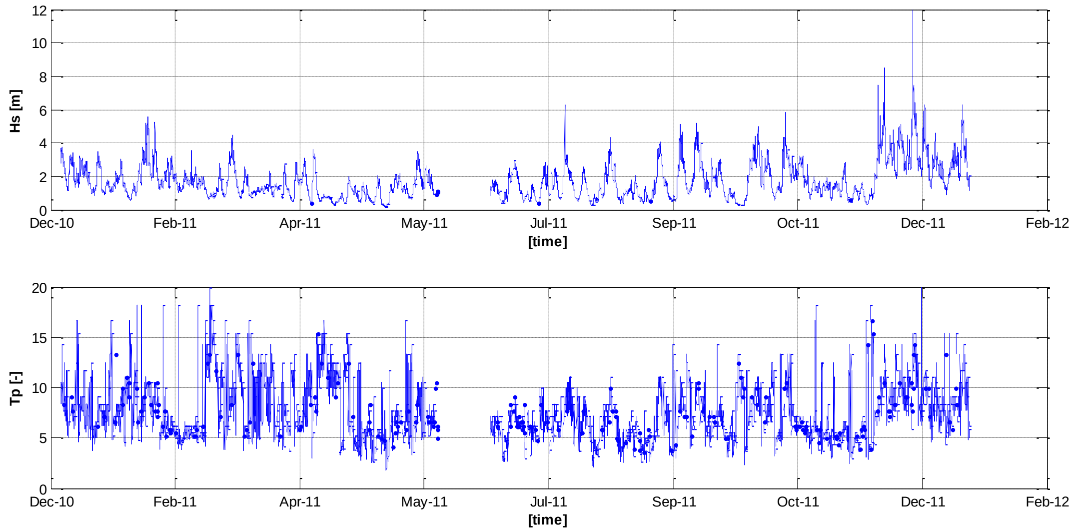


Figure 27: Time series of the significant wave height Hs (top) and the peak wave period Tp (bottom) measured by the buoy at FINO 3 during year 2011.

The following graphics show the correlations between wind and wave parameter for year 2011. The dependence of the significant wave height to the wind speed in 90 m height at the met mast is plotted in Figure 28 while the correlation between peak wave period and wind speed is shown in Figure 29. Additionally, a scatterplot of the significant wave height and the peak period is drawn in Figure 30.

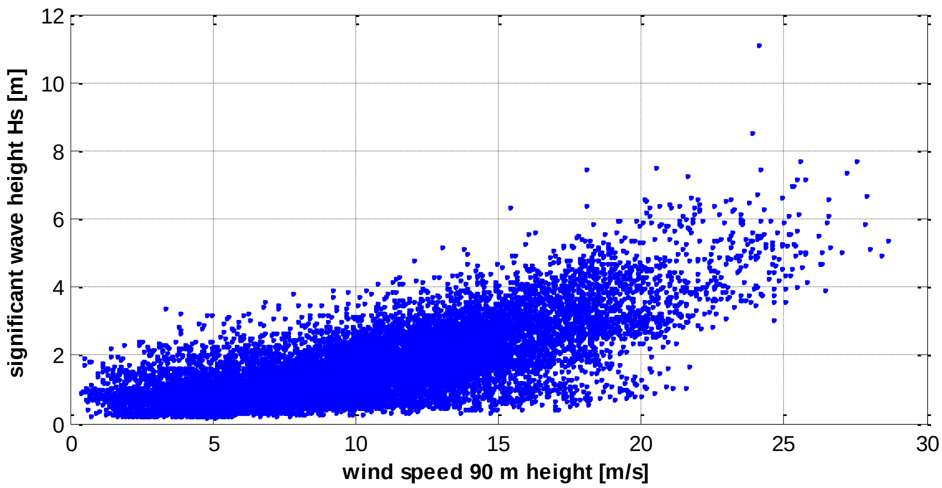


Figure 28: Correlation between significant wave height Hs and wind speed in 90 m height measured by the buoy at FINO 3 during year 2011.

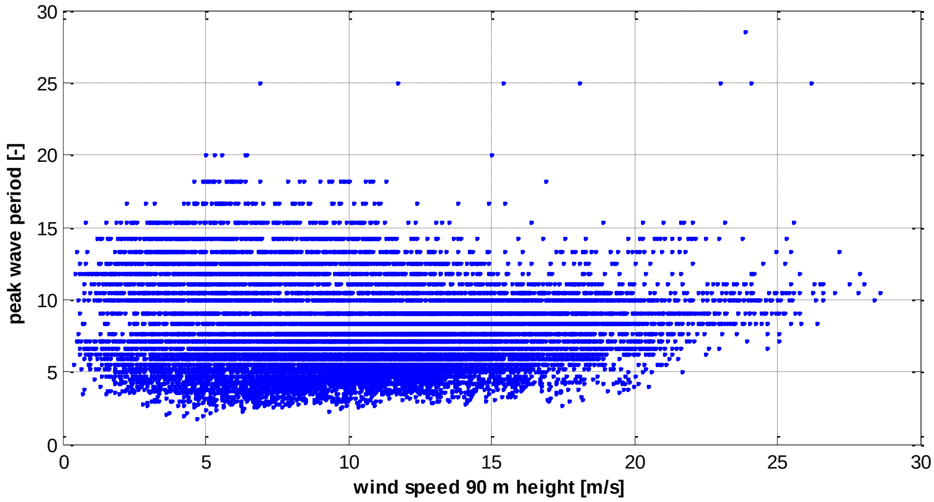


Figure 29: Correlation between peak wave period Tp and wind speed in 90 m height measured by the buoy at FINO 3 during year 2011.

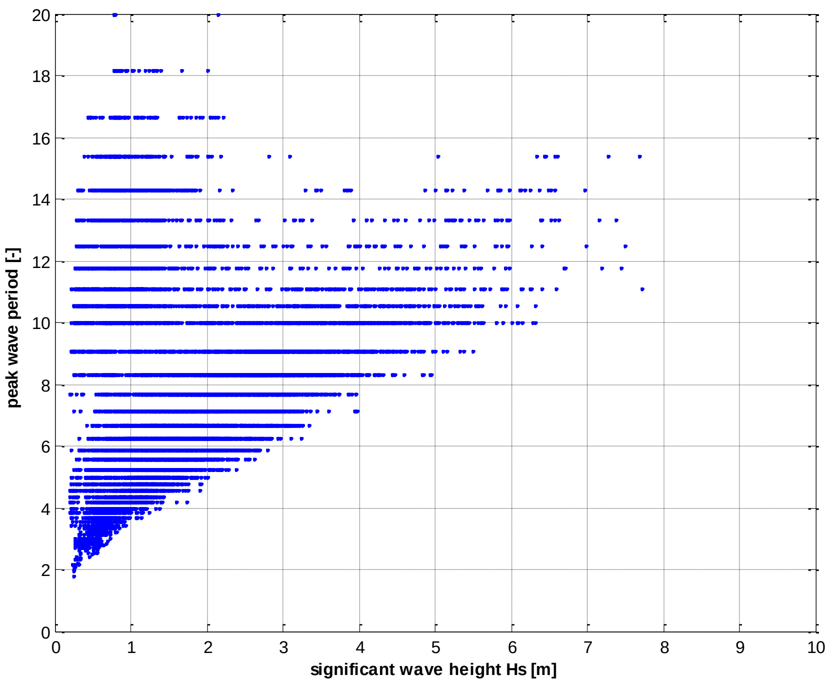


Figure 30: Correlation between significant wave height and peak wave period measured by the buoy at FINO 3 during year 2011.

6 EXEMPLARY CHARACTERISTIC DATA SET

The data of year 2011 at FINO 3 are analysed regarding to normal as well as extreme wind conditions. This chapter presents two exemplary characteristic data sets representative for specific wind conditions and demonstrates how the analysed data can be obtained.

6.1 Normal and extreme wind conditions

The selection of normal and extreme wind conditions depends on the individual requirements. The results in the section before can be helpful to detect interesting time periods. If the wind speed in high altitudes is interesting, the summer months have to be chosen because of the availability of LiDAR measurements. If extreme wind conditions are interesting then the winter period should be analysed. The wind measurements at the met mast have a high availability but it has to be checked if the here analysed year 2011 is a representative year regarding extreme wind conditions. There is also the possibility to classify normal and extreme wind conditions in correlation to wave parameter.

In this report two exemplary wind conditions are analysed.
The first represents a normal wind condition with wind speeds from 8 - 12 m/s but with a high turbulence intensity which is defined with values higher than four times the standard deviation. The second exemplary wind condition is specified with wind speeds from 8 - 12 m/s, turbulence intensities lower than two times the standard deviation and an extreme wind shear.

Exemplary wind condition 1: extreme turbulence intensity

$$8\,m/s < U < 12\,m/s$$

$$TI_{extreme} \geq TI_{mean} + 4\sigma_{TI} = 0.22$$

Figure 31 shows the frequency distribution and the time series of the turbulence intensity during year 2011. The red lines indicate the threshold value $TI_{extreme}$. The time series show that this threshold is exceeded during the whole year. No seasonal dependence can be observed. Most of the extreme turbulence intensities occur during wind conditions with wind speeds up to 6 m/s (Figure 32). The red box marks the received situations of the exemplary wind condition 1 during year 2011 at FINO 3. The number of observations is 23.

This is a list of dates where the exemplary wind condition 1 can be found in the database:

13-Jan-2011 04:00:00	17-Jan-2011 16:10:00	17-Jan-2011 23:00:00
13-Jan-2011 04:40:00	17-Jan-2011 16:20:00	26-Jan-2011 02:50:00
17-Jan-2011 14:20:00	17-Jan-2011 16:30:00	26-Jan-2011 19:50:00
17-Jan-2011 15:00:00	17-Jan-2011 17:00:00	26-Jan-2011 23:00:00
17-Jan-2011 15:20:00	17-Jan-2011 17:20:00	26-Jan-2011 23:10:00
17-Jan-2011 15:30:00	17-Jan-2011 17:30:00	26-Jan-2011 23:30:00
17-Jan-2011 15:50:00	17-Jan-2011 17:40:00	27-Jan-2011 01:00:00
17-Jan-2011 16:00:00	17-Jan-2011 18:00:00	

All found wind conditions are measured in January 2011 in the afternoon and at night characterized by very stable stratification of the boundary layer (see Figure 15).

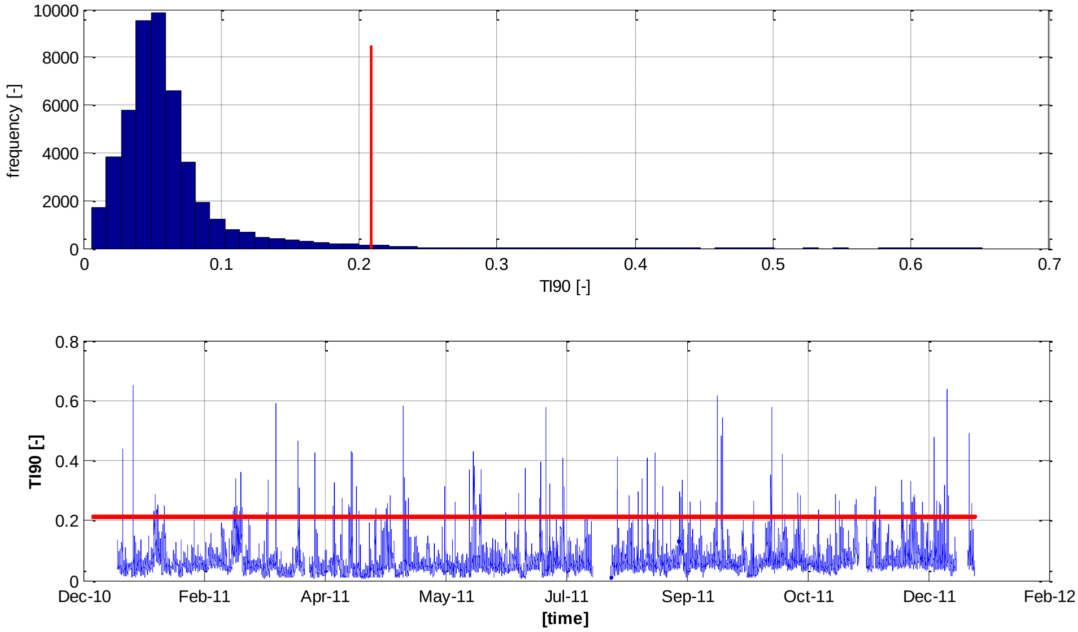


Figure 31: Frequency distribution and time series of the turbulence intensity TI at FINO 3 during year 2011, value of four times σ of TI marked with red line.

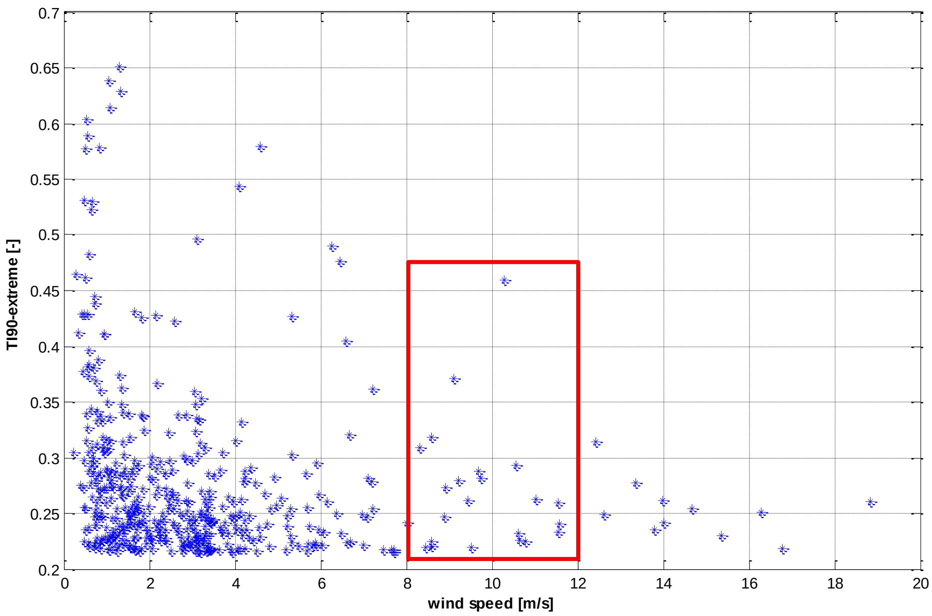


Figure 32: Extreme turbulence intensities in dependence to the wind speed at FINO 3, exemplary wind condition 1 marked with red box.

Exemplary wind condition 2: extreme wind shear

$8\,m/s < U < 12\,m/s$

$wind\ shear = U_{90m}/U_{50m}$

$TI_{normal} \leq TI_{mean} + 2\sigma_{TI} = 0.14$

$wind\ shear_{extreme} \geq wind\ shear_{mean} + 4\sigma_{shear} = 1.47$

For this exemplary wind condition the wind shear is analysed additionally. The wind shear is calculated by the quotient of the wind speed in 90 m and 50 m height. The threshold to extreme wind shear conditions is 1.47. Their correlation can be seen in Figure 33 where the function of the linear regression is calculated as follows:

$y_{mast} = 1.1\mathrm{x} - 0.038$

Investigating the wind shear in higher altitudes follwing results are obtained by analysing the wind shear between 50 m and 160 m height of the LiDAR system. The threshold to extreme wind shear conditions arises up to 1.81 which is caused by the higher wind speeds in 160 m height. The function for the linear regression is represented by this equation:

$y_{lidar} = 1.1\mathrm{x} + 0.16$

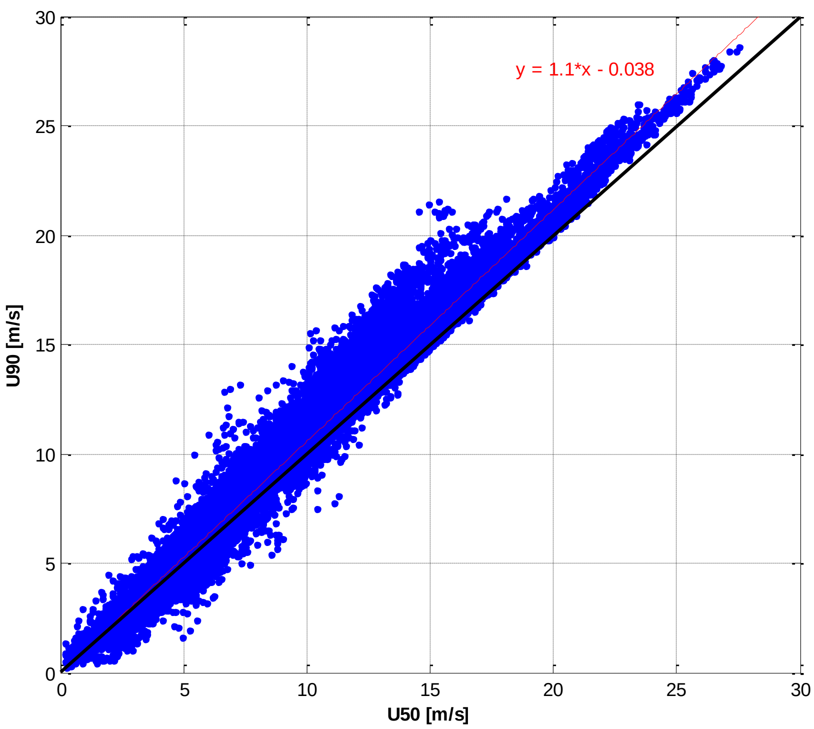


Figure 33: Scatterplot of the wind speeds in 50 m and 90 m height measured at the met mast on FINO3 during year 2011.

In Figure 34 the frequency distribution and time series of the wind shear U90/U50 at the met mast is plotted where the red lines signalise the threshold for an extreme wind shear. Most of the extreme values for the wind shear occur during the spring in months March and April.

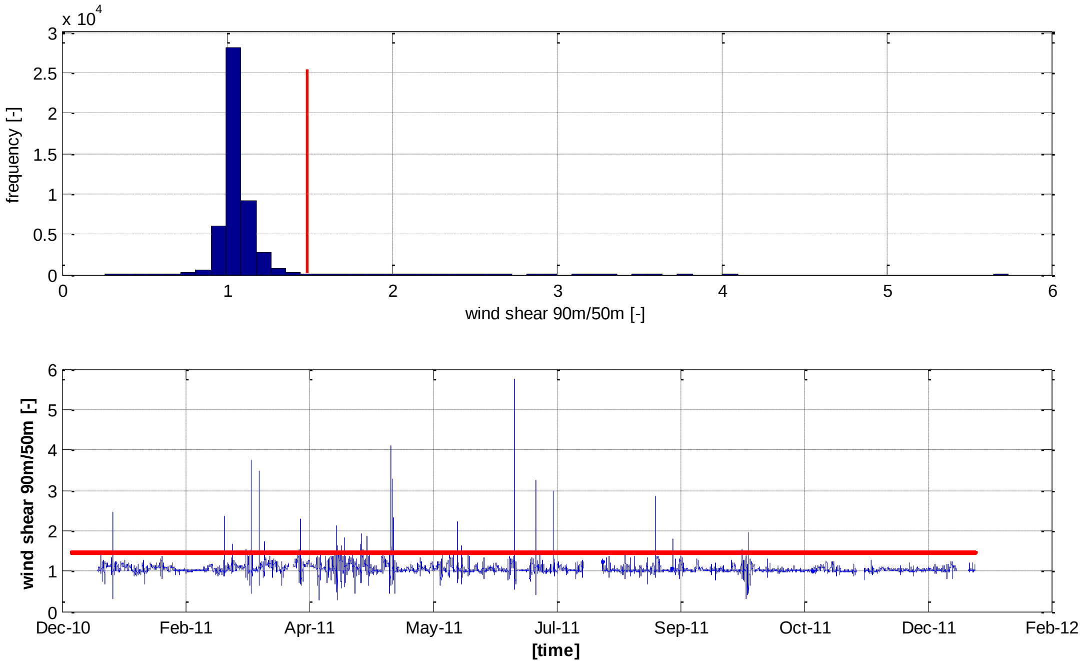


Figure 34: Frequency distribution and time series of the wind shear U90/U50 at FINO 3 during year 2011, value of four times σ of shear marked with red line.

Figure 35 shows the extreme wind shear which have a normal turbulence intensities in correlation with the wind speed. The highest values for the wind shear are observed at low wind speeds up to 3 m/s. For the normal wind speeds from 8 – 12 m/s wind shears of 1.5 to 2 can be found. The number of observations is 35.

This is a list of dates where the exemplary wind condition 2 can be found at FINO 3:

17-Jan-2011 17:10:00
03-Mar-2011 18:50:00
03-Mar-2011 19:00:00
03-Mar-2011 19:10:00
06-Mar-2011 20:30:00
06-Mar-2011 20:40:00
06-Mar-2011 20:50:00
06-Mar-2011 21:00:00
06-Mar-2011 21:10:00
06-Mar-2011 21:20:00
06-Mar-2011 21:30:00
12-Mar-2011 17:20:00
12-Mar-2011 17:30:00
12-Mar-2011 17:40:00
14-Mar-2011 08:20:00
14-Mar-2011 08:40:00
14-Mar-2011 08:50:00
14-Mar-2011 09:00:00
14-Mar-2011 09:10:00
14-Mar-2011 09:20:00
14-Mar-2011 09:40:00
14-Mar-2011 09:50:00
14-Mar-2011 10:00:00
14-Mar-2011 17:10:00
14-Mar-2011 17:20:00
14-Mar-2011 17:30:00
14-Mar-2011 18:00:00
20-Mar-2011 00:10:00
20-Mar-2011 00:20:00
20-Mar-2011 03:10:00
20-Mar-2011 03:20:00
20-Mar-2011 03:30:00
03-Apr-2011 01:50:00
03-Apr-2011 02:00:00
03-Apr-2011 11:20:00

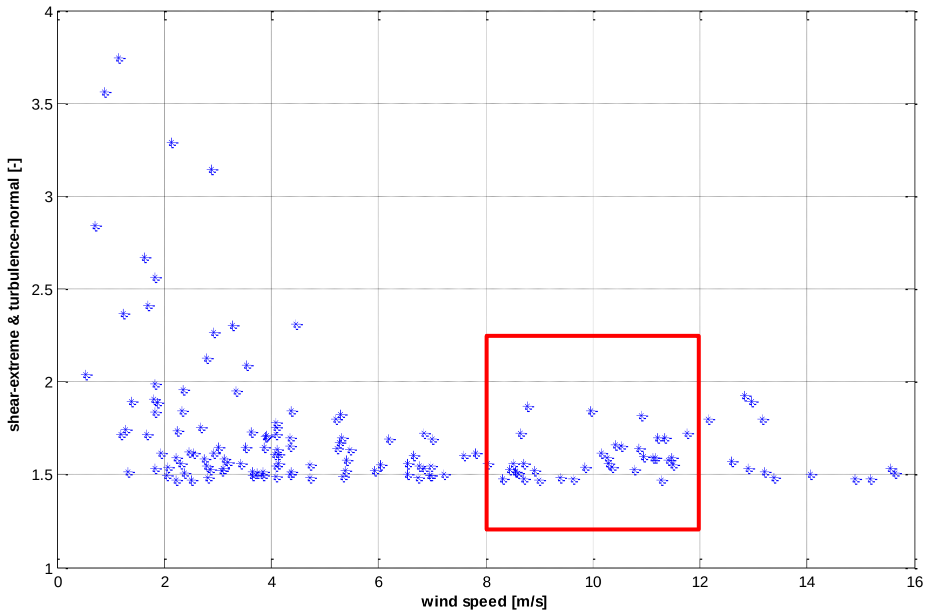


Figure 35: Extreme wind shear (selected for normal TI) in dependence to the wind speed at FINO 3, exemplary wind condition 2 marked with red box.

6.2 Access to the analysed data

The required steps to obtain the analysed data are summarised as follows:

1. Due to the access conditions of the used databases time series of the analysed data cannot be circulated to INNWIND.EU partners. There is only a possibility if a partner has an access to the database by himself.
2. Request for an access for the FINO 3 data at BSH as described in section 2.1.1.
3. Request for an access for the NORSEWInD database at Oldbaum Services as described in section 2.1.2.
4. Due to the mast effect on the measured data of met mast and LiDAR system a data processing is required as described in chapter 4.
5. Selection of interesting wind conditions by results in chapter 5 and/or in section 6.1.

7 CONCLUSIONS

This report describes the results of Deliverable D1.11 “Database of existing wind parameter measurements for tall atmospheres across Europe”.

The collection and documentation of relevant data sets provides information about wind measurements from tall meteorological masts or remote sensing instruments for various near- and offshore sites across Europe. Five different databases are presented including details about data sources and access options: FINO 123, NORSEWInD, MARNET, eKlima and Irish Marine Weather Buoy Network.
For further analyses the data set of FINO 3 has been selected. It includes wind measurements from a met mast as well as from a LiDAR system during the summer months of 2011. Additionally measurements of several wave parameters are available. Due to the influence of the mast structure on the flow the wind data has been corrected to this effect.
The wind data of FINO 3 has been analysed more detailed to obtain information about normal and extreme wind conditions. The high availability of the met mast data as well as the LiDAR data enabled reliable investigations of the wind conditions during 2011. The distribution of the wind speed, the stratification of the boundary layer as well as turbulence intensities have been analysed in detail. The LiDAR data has a high correlation of 0.9963 to the data measured with cup anemometers at the met mast. The correlation between wind speed and significant wave height and peak wave period respectively is shown in scatterplots to get a first look inside air-sea interactions.
These results were used to prepare a data set with two exemplary wind conditions which were defined together with the partners in WP1. A description how to get the access to the analysed data was given.
Based on the data analyses in this report each INNWIND.EU partner has the opportunity to get the data he or she needs regarding his or her requirements.

REFERENCES

BSH: Website of data base "FINO 123", http://www.bsh.de/en/Marine_data/Projects/FINO/index.jsp.

BSH: Website of data base "MARNET", http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/index.jsp

Hasager, C.B., Stein, D., Courtney, M., Peña, A., Mikkelsen, T., Stickland, M., Oldroyd, A. (2013): Hub height ocean winds over the North Sea observed by the NORSEWInD LiDAR array: measuring techniques, quality control and data management. *Remote Sens.*, 5(9), 4280-4303; http://www.mdpi.com/2072-4292/5/9/4280.

IEC 61400-1 Ed. 3.0 (2005): Wind turbines – Part 1: Design requirements.

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Kindler, D. (2011): 20 months of wind data from FINO3 meteorological mast. *FINO Conference, 11.05.2011, Hamburg*.

Marine Institute of Ireland: Website of data base "Irish Marine Weather Buoy Network", http://www.marine.ie/home/publicationsdata/data/buoys

Norwegian Meteorological Institute: Website of data base "eKlima", http://www.eklima.no.

Oldbaum Services: Website of data base "NORSEWInD", http://www.norsewind.eu/.

ANNEX A: USE OF DIFFERENT DATA SOURCES AND MEASUREMENT TECHNOLOGIES

Different measurement principles for LiDAR and mast data

A specific issue in the study documented in this report and an argument for the selection of the dataset – as described in 2.2 – has been the combination of measurement data from two different sources to a more comprehensive data set. The wind data from the FINO 3 met mast, recorded by cup anemometers at different height levels basically, have been complemented by data measured with a LiDAR device that was positioned next to the mast on the same platform for a limited period of the considered time span. The LiDAR data have the advantage that they cover greater heights and thereby allow the user to study larger wind profiles when combining the mast and LiDAR to one data set.
One the other hand, the combination of data from two different sources is not trivial, and before using the data for further studies the different measurement principles and their impact on the derived quantities should be considered in more detail.
The LiDAR data, available as part of the combined FINO 3 data set, were measured with a Lesophere Windcube v1 instrument that applies a so-called VAD (Velocity Azimuth Display) scanning technique.[1] As a consequence, the LiDAR measurement corresponds to a volume measurement – with a measurement volume of a non-negligible dimension – whereas the cup anemometer measurements are considered as point measurements.

Comparison of 10-min-mean wind speeds

For the comparison of 10-min-mean values of LiDAR and mast wind speed data the two different measurement principles seem to have no significant impact.[2] A corresponding verification test, based on an XY-correlation plot for the two data sets (i.e. LiDAR versus mast data) and a linear regression analysis applied to these data, was supposed in different guidelines to trace back the LiDAR measurements to a suitable reference, which is for most wind-energy related free-field wind measurements the cup anemometer, and to define the respective measurement uncertainty.[3] The pre-analysis in 5.2 was performed following this concept of a LiDAR-mast verification test – the results confirmed that a concurrent use of LiDAR and mast 10-min-mean wind speeds is justified and possible with consideration of a reasonable uncertainty.

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[1] Cf. J.-P. Cariou, M. Boquet: LEOSPHERE Pulsed LiDAR Principles – Contribution to UpWind WP6 on Remote Sensing Devices. (http://www.upwind.eu/Publications/~/media/UpWind/Documents/Publications/6%20-%20Remote%20Sensing/D611.ashx)

[2] See e.g.:
J. Gottschall, M. S. Courtney, R. Wagner, H. E. Jørgensen, and I. Antoniou (2012): LiDAR profilers in the context of wind energy – a verification procedure for traceable measurements. Wind Energy, Vol. 15, pp. 147-159.

[3] See e.g.:
IEA Wind Recommended Practice 15 (2013): Ground-based vertically-profiling remote sensing for wind resource assessment. (http://www.ieawind.org/index_page_postings/RP/RP%2015_RemoteSensing_1stEd_8March2013.pdf)
CDV IEC 61400-12-1 Wind Turbines – Part 12-1 (2013): Power performance measurements of electricity producing wind turbines / Annex L.

Comparison of TI (Turbulence Intensity) values

The concurrent use of TI values derived from LiDAR and cup anemometer data is less straightforward. Due to the large measurement volume TI values from LiDAR measurements are typically attenuated when compared to their counterparts from point measurements.[4] Since the degree of the attenuation is not only dependent on the used type of LiDAR device but also on the atmospheric conditions the measurement site and at the particular time of the measurement, a simple correction and calibration of the LiDAR values with respect to those of the in-situ instrument used as a reference is not applicable. It is rather a point of discussion and investigation if alternative LiDAR scanning approaches can produce turbulence quantities from LiDAR measurements that are better comparable to those from point measurements.[5]

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[4] A. Sathe, J. Mann, J. Gottschall, M.S. Courtney (2011): Can Wind LiDARs Measure Turbulence? J. Atmos. Oceanic Technol., Vol. 28, pp. 853-868 (doi: http://dx.doi.org/10.1175/JTECH-D-10-05004.1)

[5] See e.g.:
A. Sathe, J. Mann (2013): A review of turbulence measurements using ground-based wind LiDARs. Atmospheric Measurement Techniques, Vol. 6, pp. 3147–3167.