

Offshore Wind and Turbulence Characteristics – New Insights from the FINO1 Data

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Offshore wind and turbulence

- sea surface horizontally homogeneous, smoother than onshore

but

- roughness is wind speed dependent
- roughness elements are moving
- thermal conditions: annual instead of diurnal variation

thus:

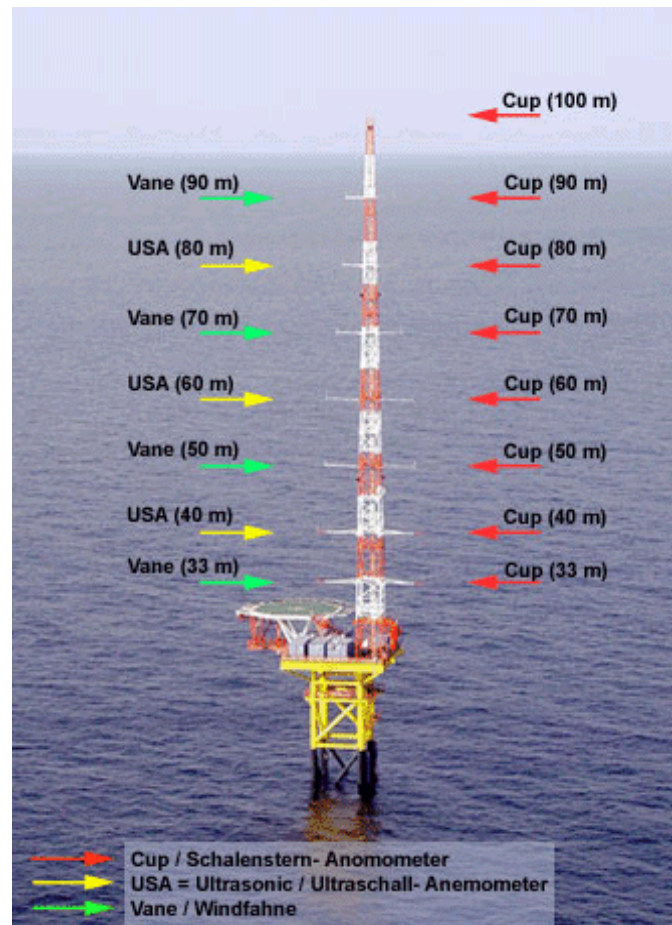
- different vertical structure of the boundary layer
- different wind conditions
- different turbulence conditions

- wave age is additional scaling parameter

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



data source:



Project OWID



Bundesministerium
für Umwelt, Naturschutz
und Reaktorsicherheit



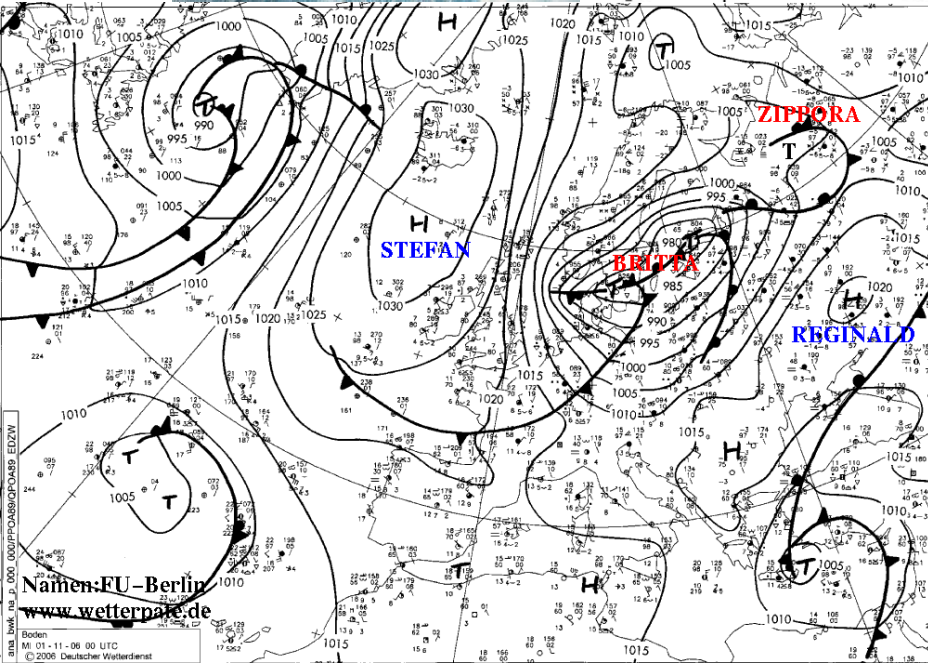
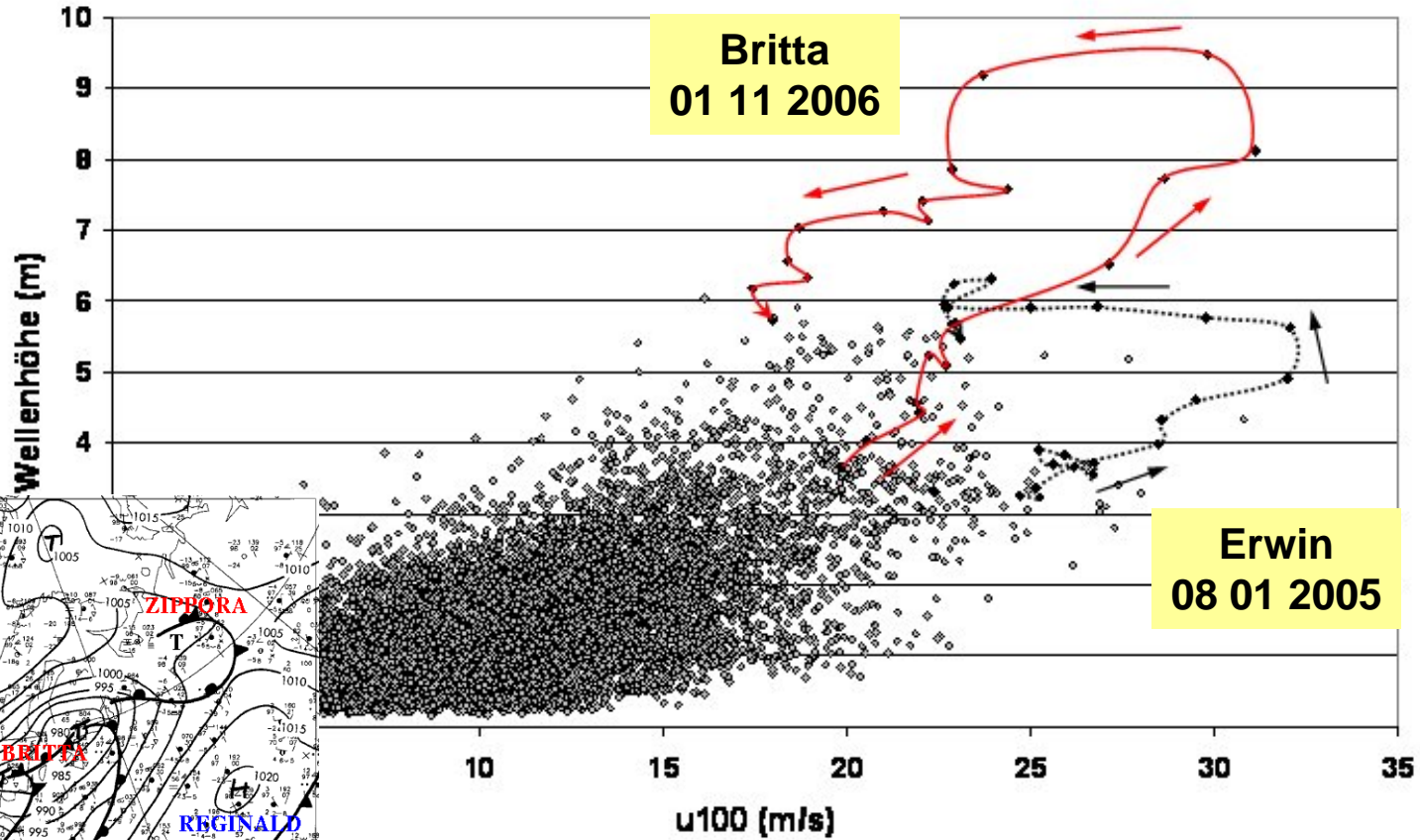
<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



**wave height,
vertical structure of the
marine boundary layer
and wave age**

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>

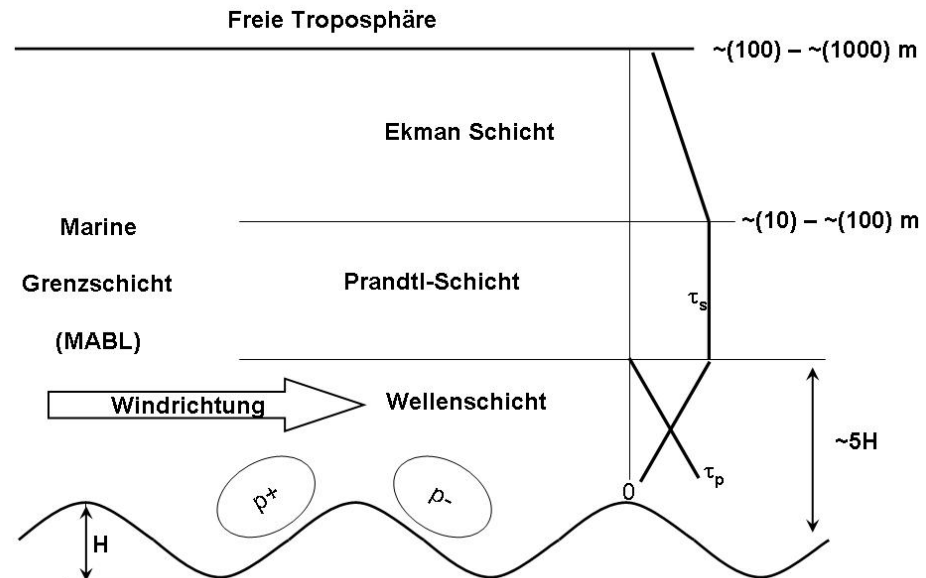
wave height as function of wind speed





wave and Prandtl layer height

wind speed	5 m/s	15 m/s	30 m/s
wave height	0,5 m	2 m	8 m
wave layer height	2,5 m	10 m	40 m
Prandtl layer height	10 m	40 m	100 m



<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



wave age

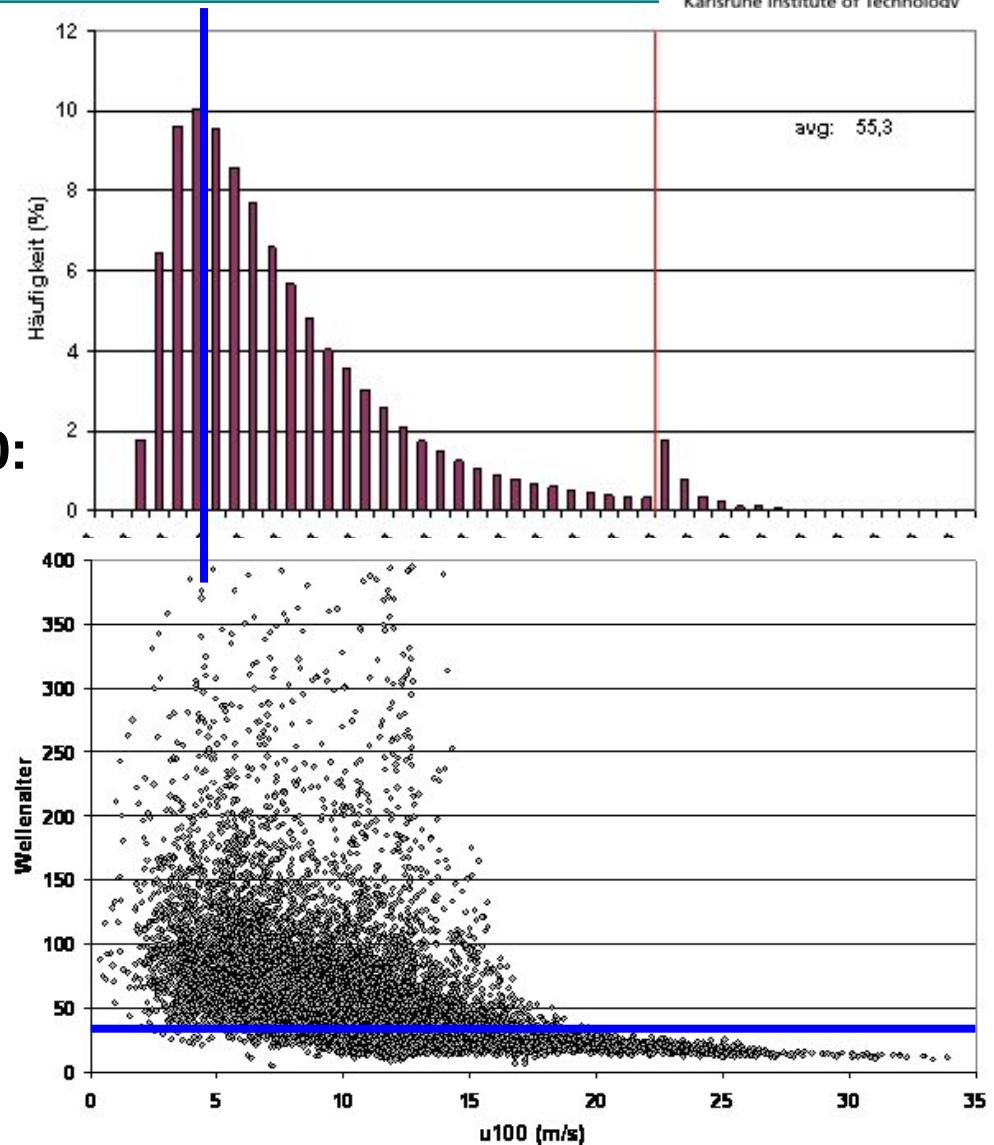
u_*/c_{ph}

smaller than ~30:

**wind driven,
known PBL
theories valid**

larger than ~30

wave driven





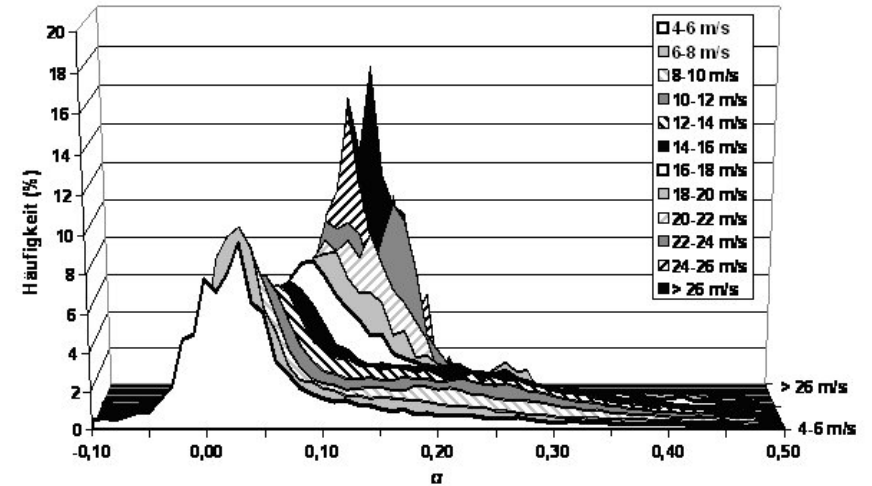
wind profiles and turbulence

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>

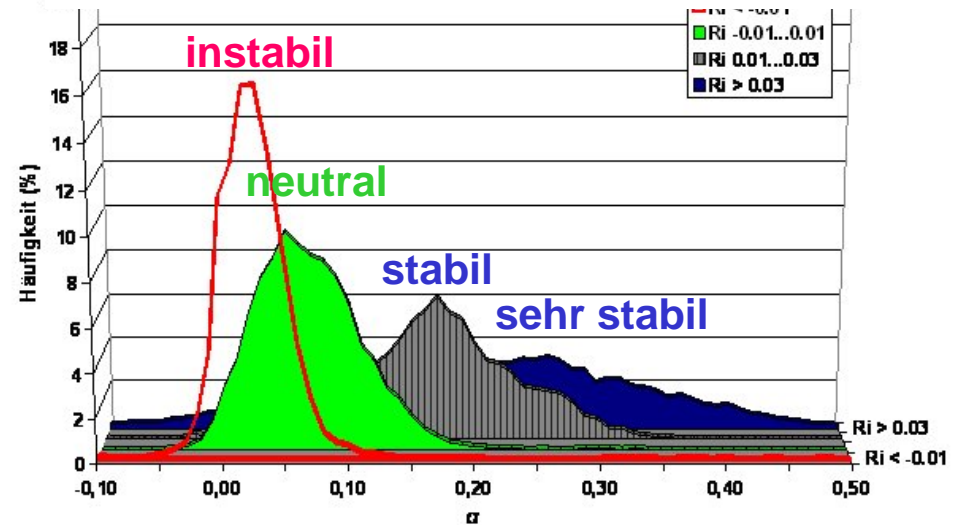


exponent of power law

as function of
wind speed



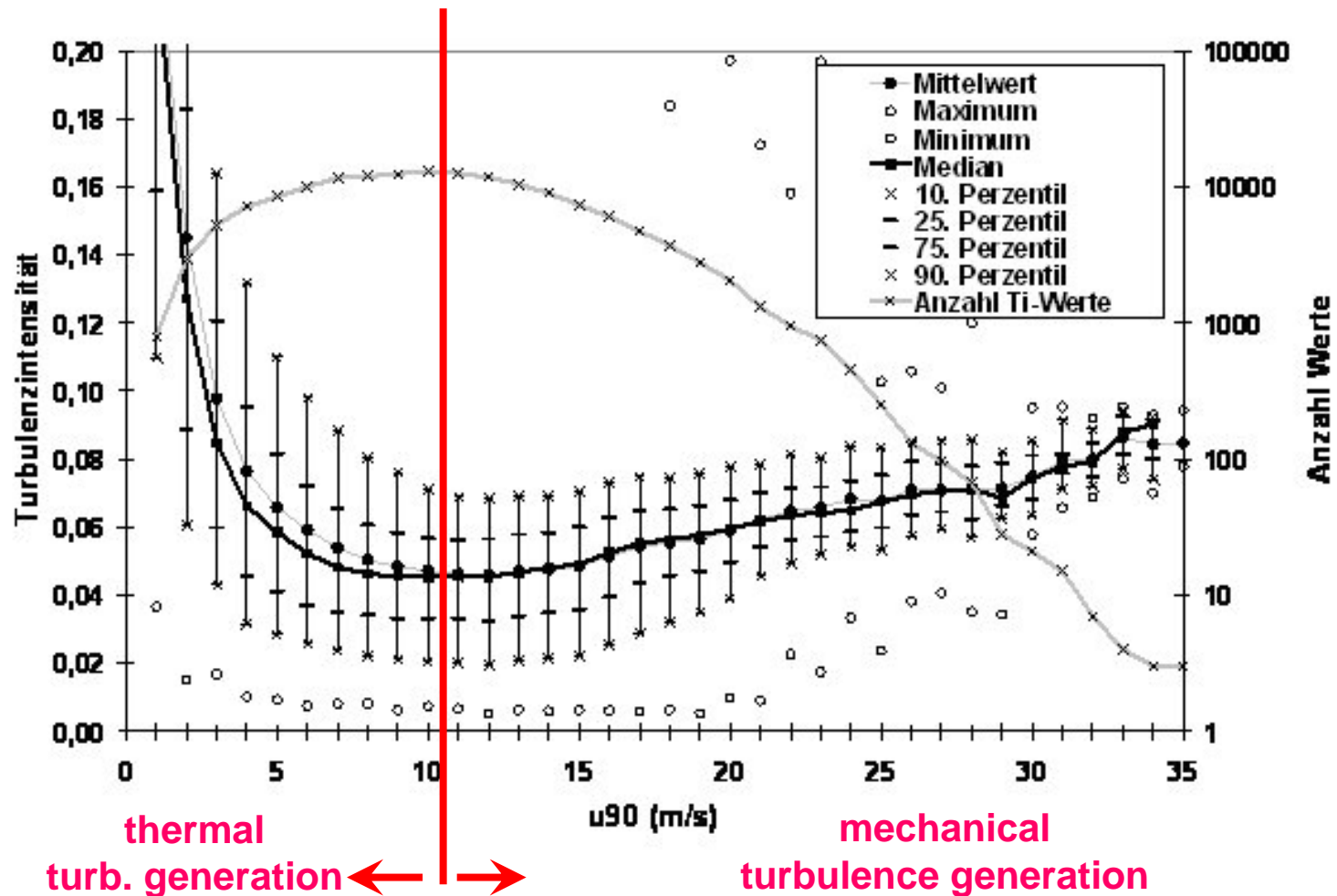
as function of
thermal stratification



<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



turbulence intensity as function of wind speed



<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



Comparison with the assumptions made in IEC 61400-1 and 61400-3

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>

Normal wind profile model (NWP)

The IEC 61400-3 gives 0.14 for the power-law exponent

Evaluation for $z_{\text{ref}} = 40 \text{ m}$, $z = 90 \text{ m}$

Wind speed (m/s)	Mean	Standard deviation	Number
4-6	0,048	0,144	18178
6-8	0,068	0,114	23318
8-10	0,094	0,109	25236
10-12	0,116	0,109	24599
12-14	0,129	0,104	19863
14-16	0,137	0,101	13645
16-18	0,138	0,092	8540
18-20	0,142	0,084	4874
20-22	0,131	0,056	2270
22-24	0,133	0,039	1210
24-26	0,130	0,034	384
>26	0,130	0,025	247

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Normal wind profile model (NWP)

The IEC 61400-3 gives 0.14 for the power-law exponent

Evaluation for $z_{\text{ref}} = 40 \text{ m}$, $z = 90 \text{ m}$

Bulk-Richardson-Number Ri_B	Mean	Standard deviation	Number
< -0,01	0,023	0,036	9450
-0,01...0,01	0,063	0,048	11939
0,01...0,03	0,149	0,065	10626
> 0,03	0,190	0,185	11361

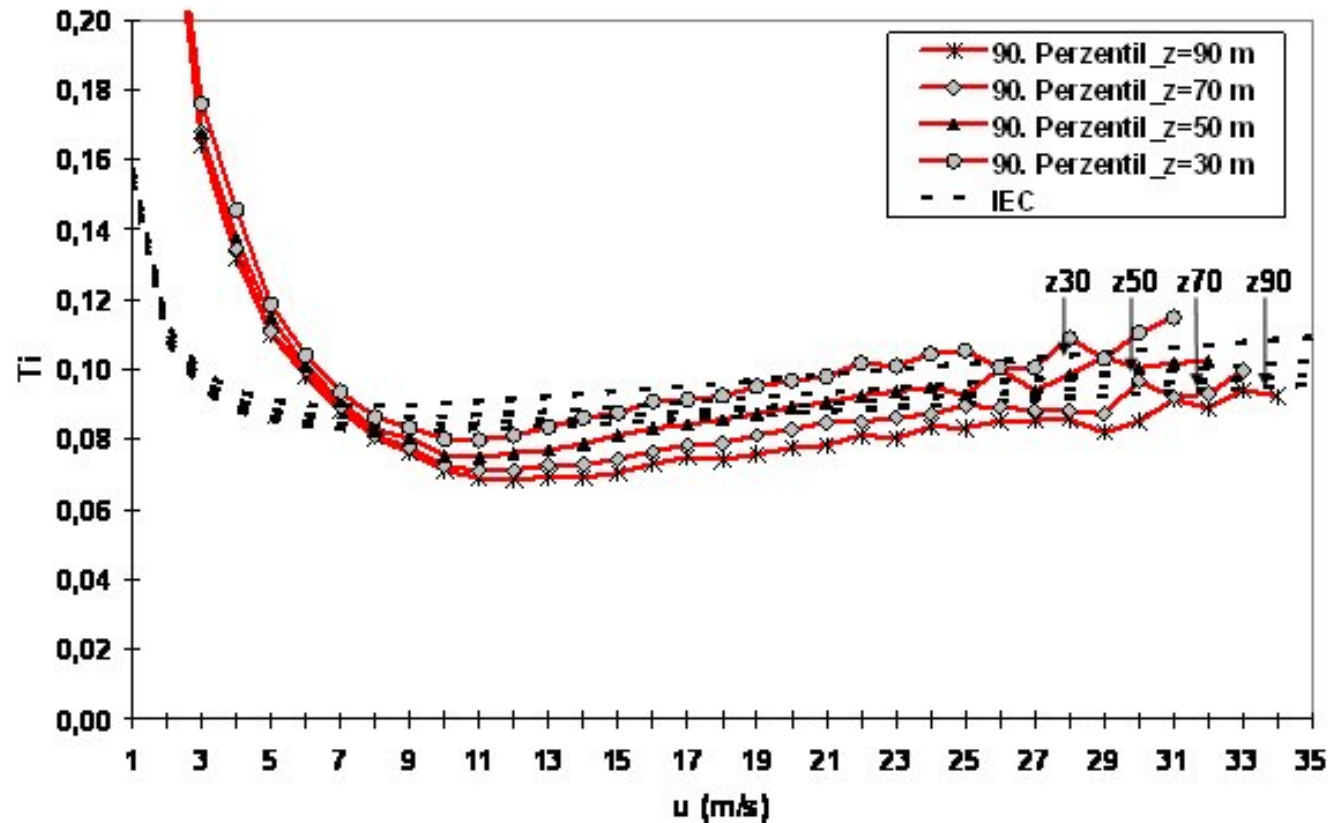
IEC 61400-3 does not seem to be sufficiently conservative in all cases.

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



Normal turbulence model (NTM)

Comparison: observed and assumed by IEC-Norm
90-Percentiles of turbulence intensity



<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



Normal turbulence model (NTM)

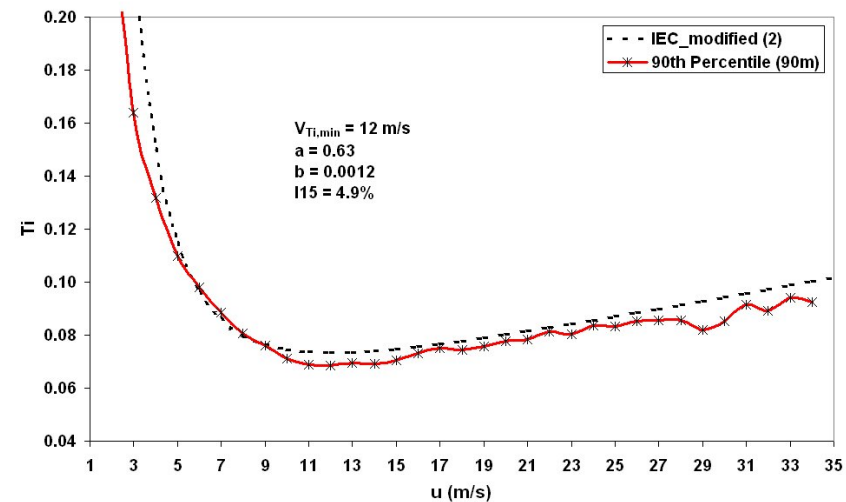
IEC 61400-3 (Eq. 27) says:

$$\sigma_{u,s} = \frac{V_{hub}}{\ln(z_{hub} / z_0)} + 1,28(1,44m / s)I_{15}$$

alternative proposal:

$$\sigma_{u,s} = a \frac{V_{hub}}{\ln(z_{hub} / z_0)} + \frac{2V_{Ti,min}}{V_{hub}} (1,44m / s)I_{15} + bV_{hub}$$

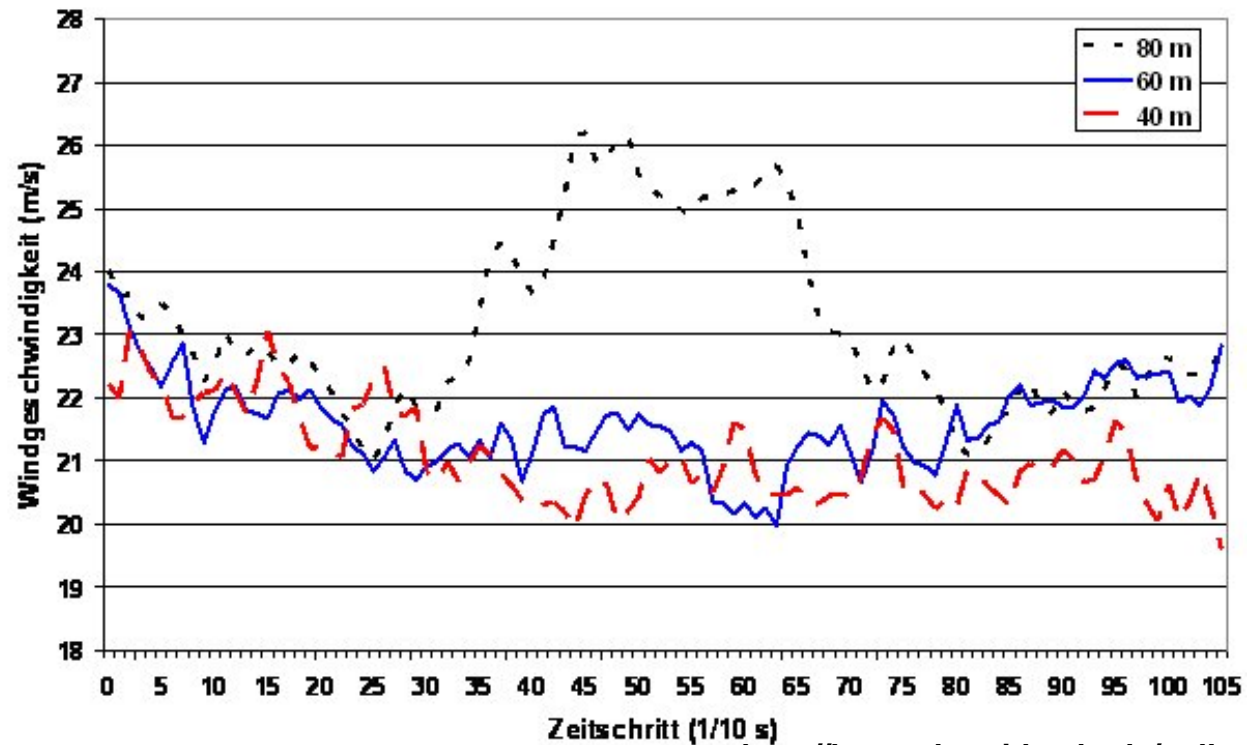
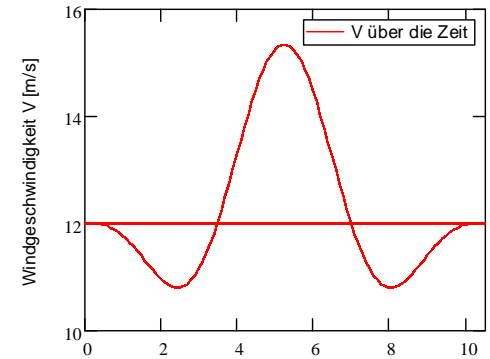
with $a = 0.63$, $b = 0.0012$, $I_{15} = 4.9\%$, $V_{Ti,min} = 12 \text{ m/s}$ for $z_{hub} = 90 \text{ m}$





Extreme operating gust (EOG)

simultaneous observation in three
heights (10,5 s), correlation > 0,85

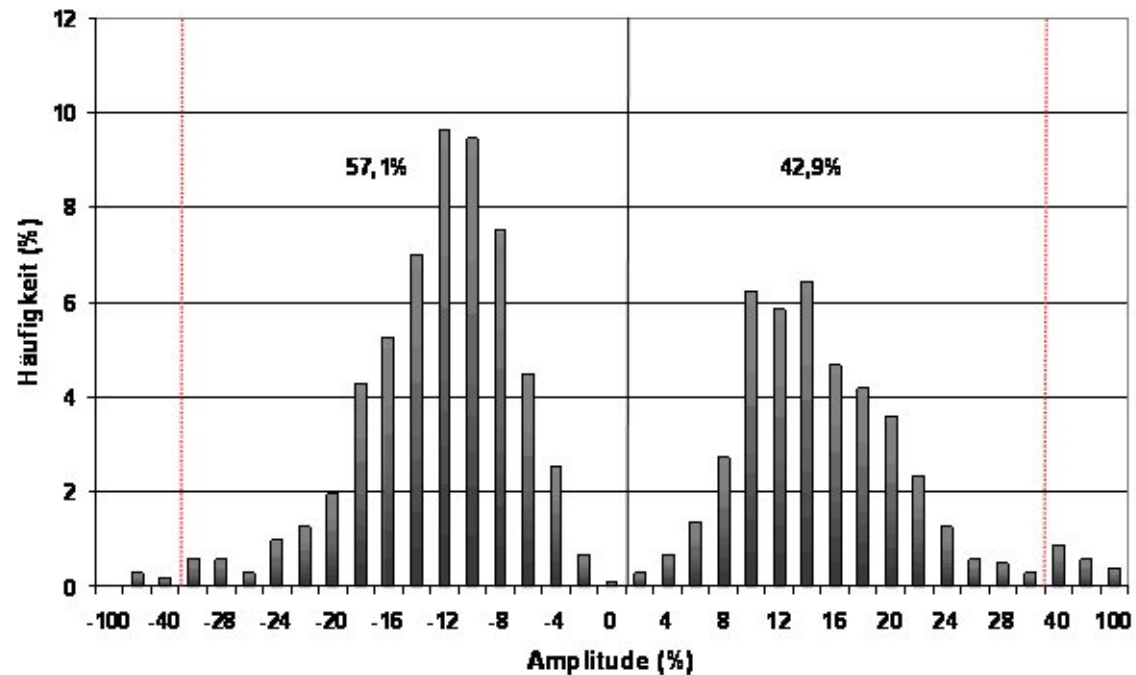


<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



Extreme operating gust (EOG)

frequency distribution of EOG (10,5 s) in 80m height
(e.g. 440 cases in 2005)



<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>

more negative as positive „Mexican hats“



Summary comparison to IEC 61400

NWP: exponent 0.14 is not always conservative

NTM: Eq. (27) for σ_u in IEC 61400-3 should be reformulated

EWM: Class II seems to be sufficient

**EOG: - more negative than positive „hats“
- EOG with 8 s length 1.6 times more frequent than those with 10.5 s length**

<http://kups.ub.uni-koeln.de/volltexte/2008/2524/>



Some final thoughts on offshore windparks with a simple analytical model

momentum balance of a windpark in a turbulent flow (EF93-model)

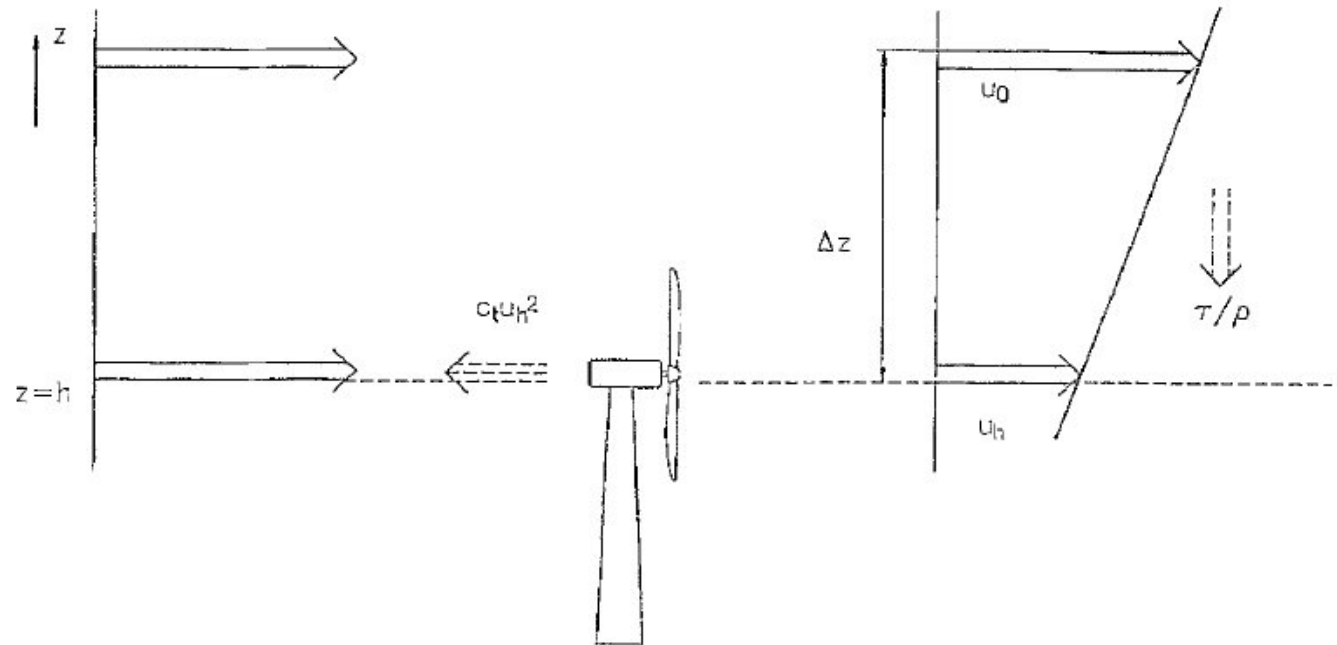
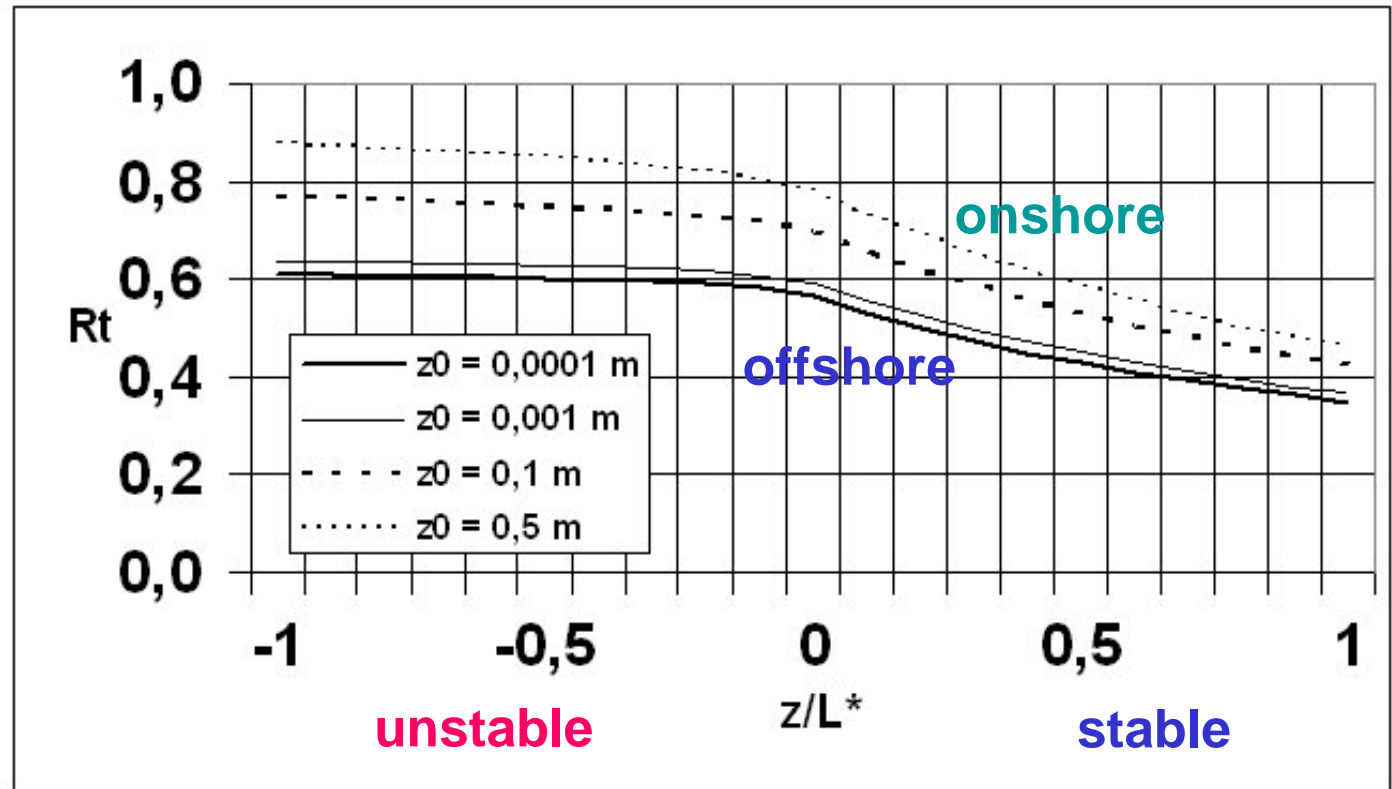


Fig. 1. Basic momentum budget for an ensemble of wind turbines in a turbulent flow. The momentum loss due to the turbines is compensated by downward turbulent momentum flux.

Emeis, S., Frandsen, S., 1993: Reduction of Horizontal Wind Speed in a Boundary Layer with Obstacles. Bound.-Lay. Meteorol., 64, 297-305.



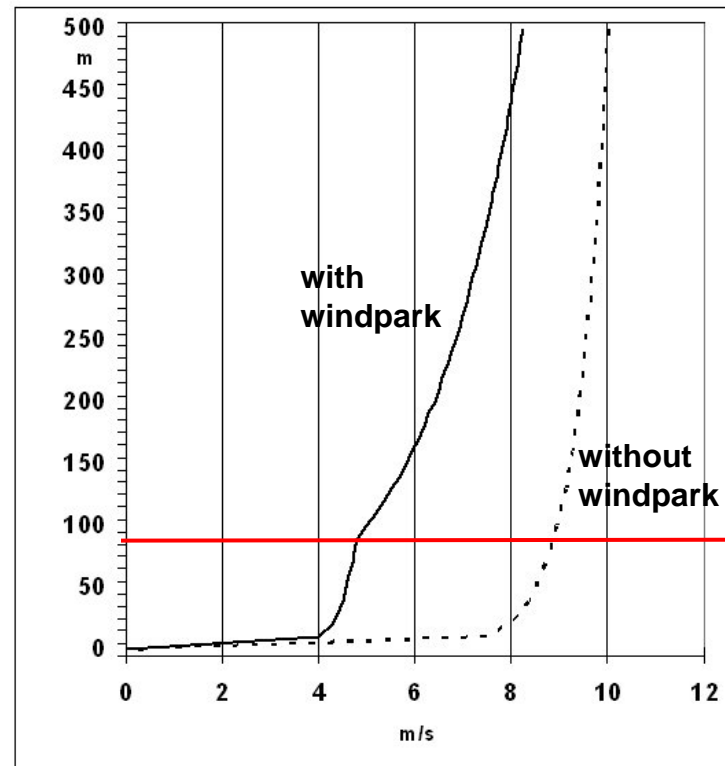
momentum balance of a windpark in a turbulent flow : reduction of wind speed in hub height (enhanced EF93-Model)



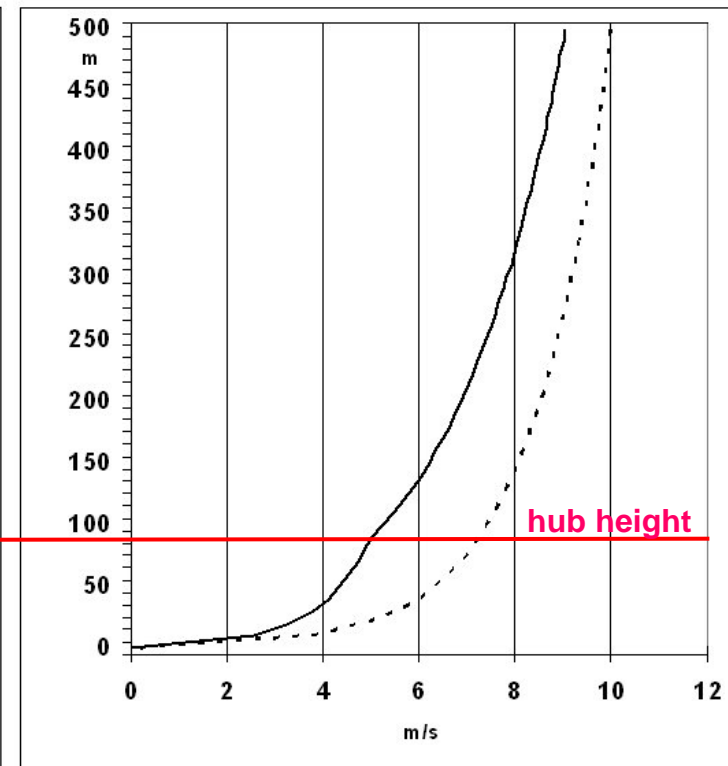
the rougher the surface → the more effective the windpark



momentum balance of a windpark in a turbulent flow : vertical wind profile neutral stratification (enhanced EF93-model)



smooth ($z_0 = 0.0001$ m)

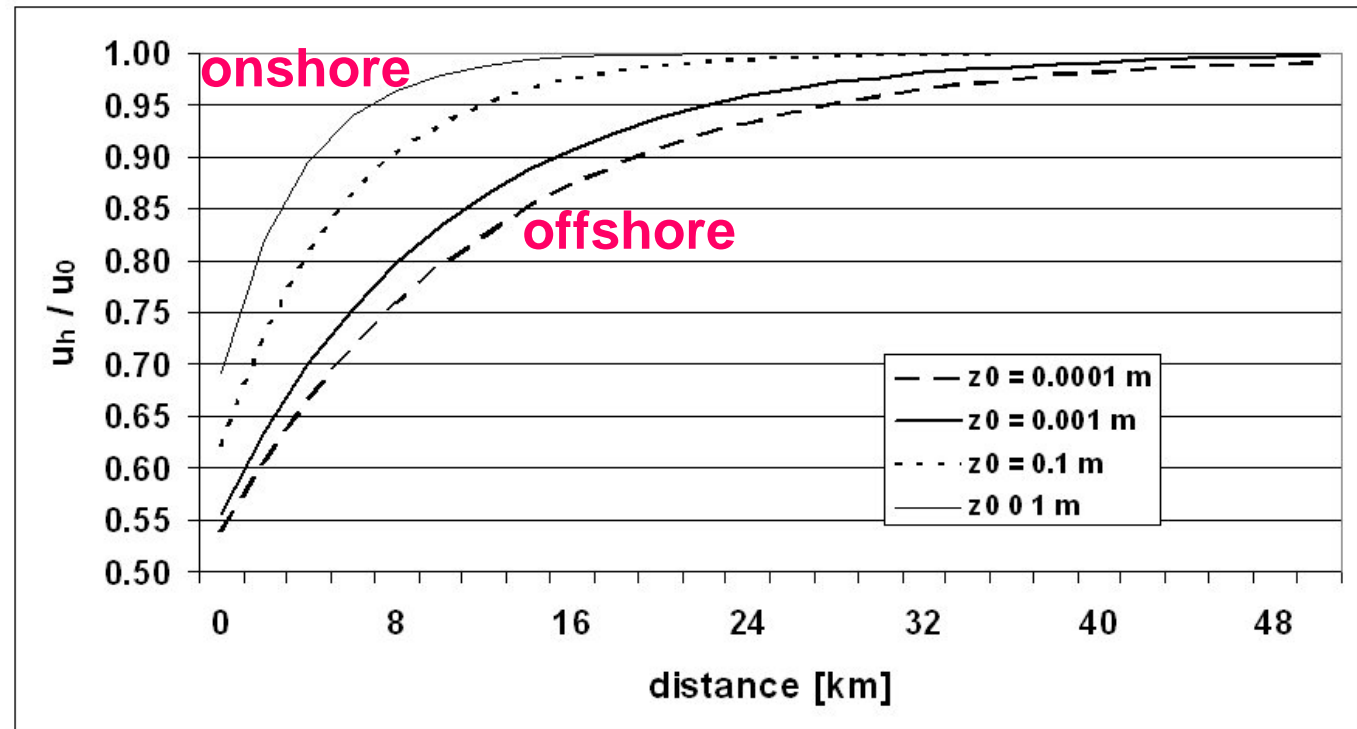


$u = 10$ m/s

rough ($z_0 = 1$ m)



momentum balance of a windpark in a turbulent flow : length of wake of a wind park (enhanced EF93-model)



neutral stratification, $u_0 = 10$ m/s



Summary and outlook



difference offshore - onshore

different surface (smoother, moving)

WEC operate mainly in Ekman layer not in Prandtl layer (except for very high wind speeds)

different boundary layer structure („young“ waves only in 30% of cases)

assumptions of IEC 61400 not always conservative

**less turbulence leads to a lesser effectivity of windparks
(→ larger distance between WECs necessary)**

<http://kups.uni-koeln.de/volltexte/2008/2524/>

consequences for offshore wind energy generation

adaptation of models

larger distances of WECs in windparks

larger distances between windparks

a lot of open tasks for further research, eg. in RAVE



Thank you for your attention



End



Wellenhöhe als Funktion der Windgeschwindigkeit

bisher an FINO1
beobachtet

Schätzung 50-Jahreswert

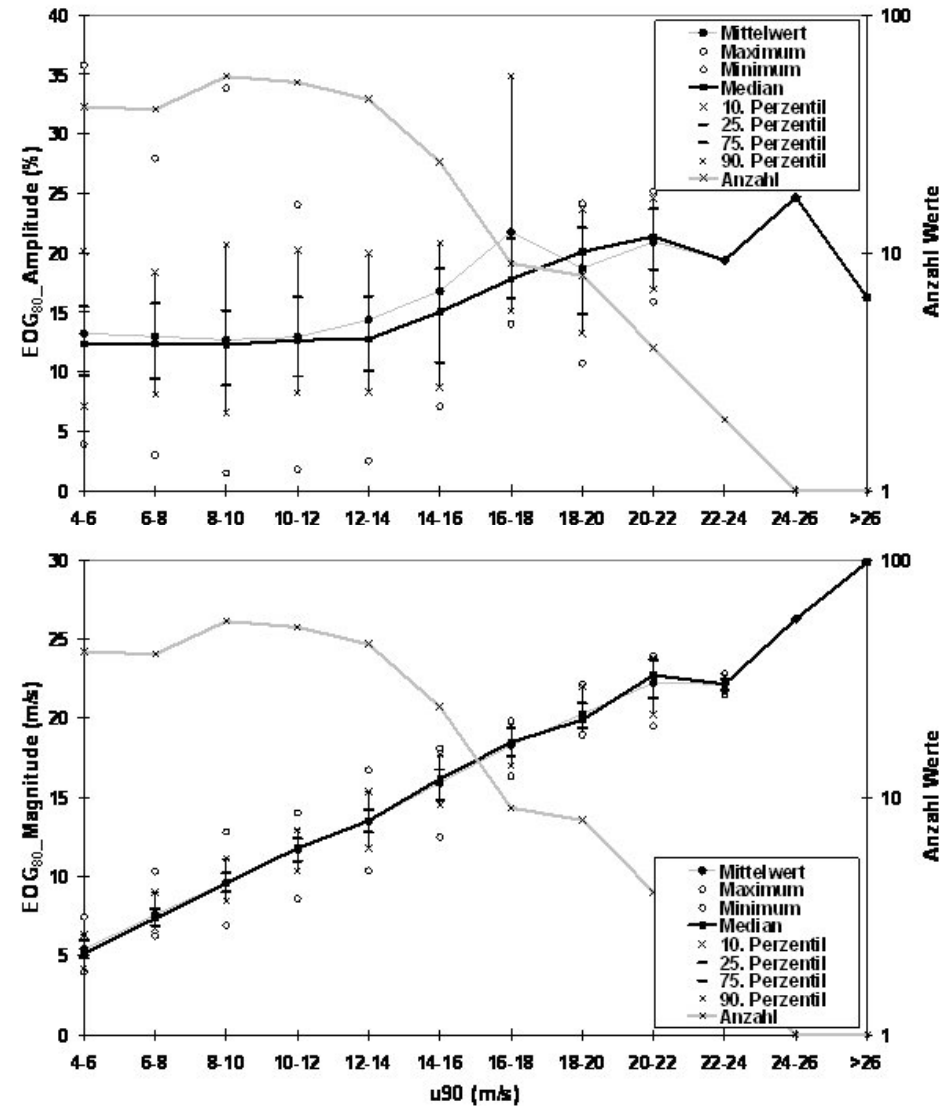
Sektor / Windgeschwindigkeit	25 m/s	30 m/s	35 m/s	40 m/s	Erklärte Varianz [R ²] in %
nördlich (290 - 40°)	6,7	9,2	12,1	15,5	69,5
östlich (40 - 120°), instabil	5,2	7,0	9,2	11,8	75,2
südlich (120 - 210°), instabil	4,2	6,0	8,1	10,6	61,3
südlich (120 - 210°), stabil	3,4	4,8	6,5	8,5	53,0
westlich	4,1	5,3	6,6	8,1	56,6
östlich (40 - 120°), stabil	1,6	1,6	1,7	1,6	29,9



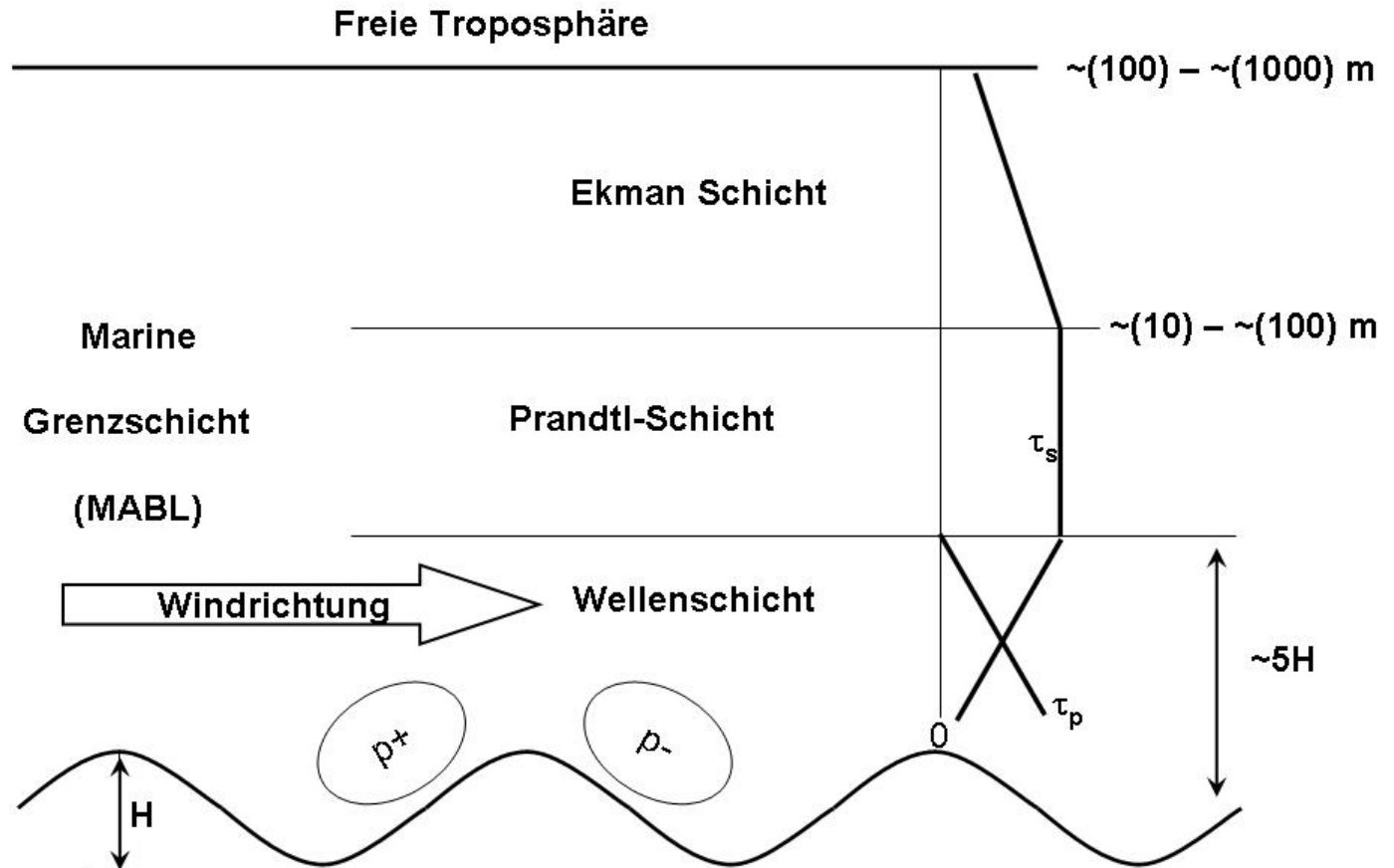
**Extreme
operating
gust (EOG)**

**Amplitude
(Diff. Min-Max)**

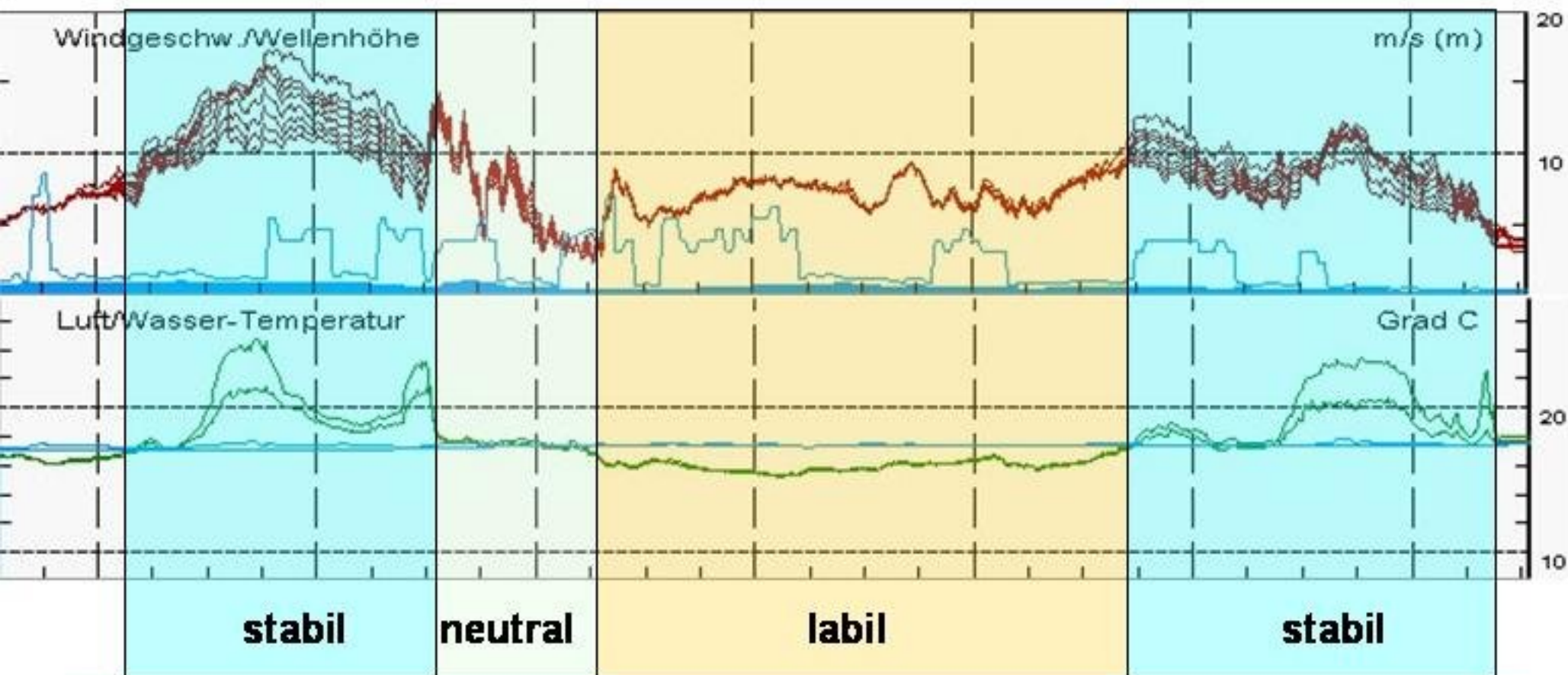
**Magnitude
(Max)**



Vertikalaufbau der marinen Grenzschicht

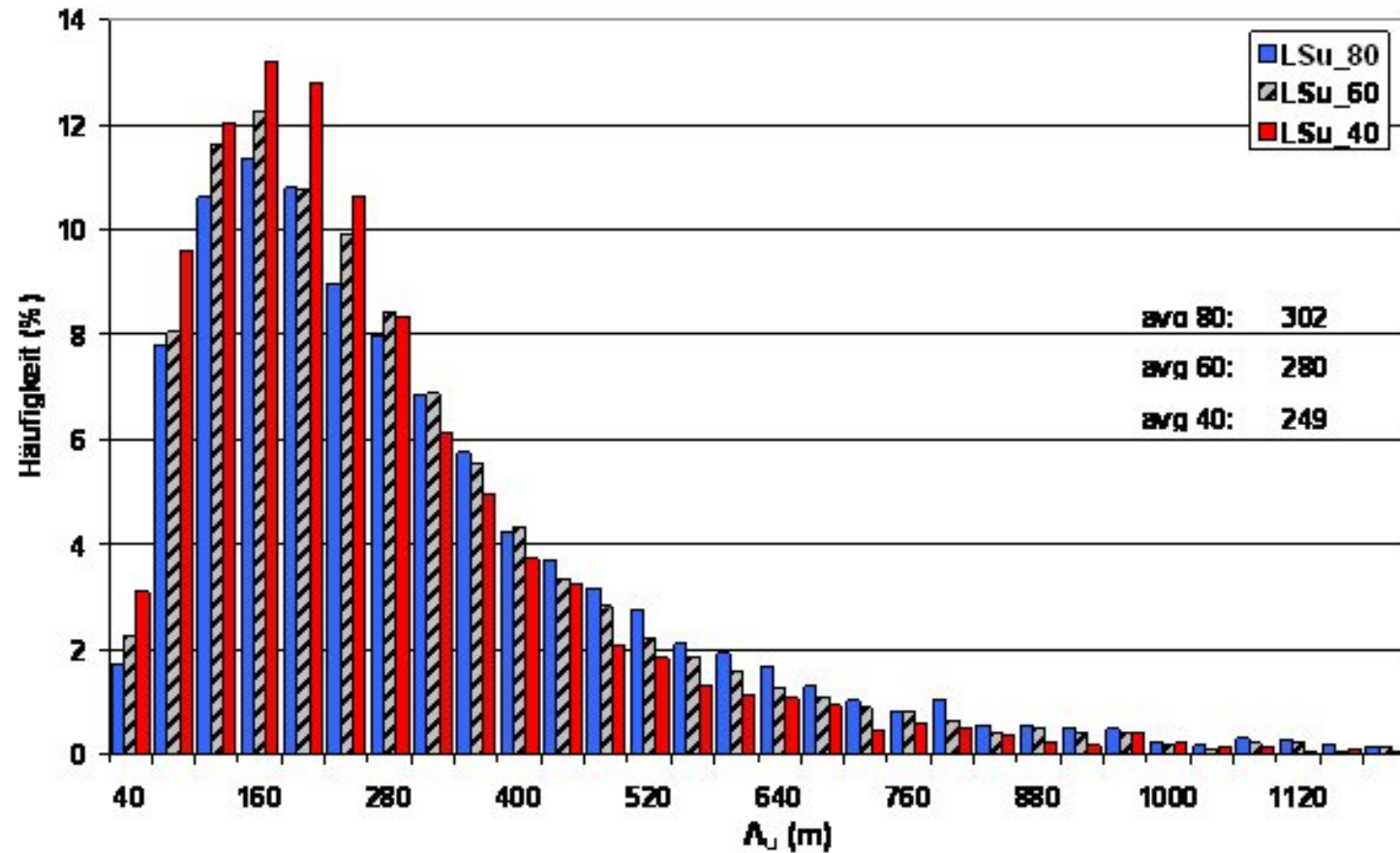


**Zeitreihen von der FINO1-Plattform:
Windgeschwindigkeit und Luft/Wasser-Temperatur
Woche bis zum 6. September 2005 11:46 Uhr**





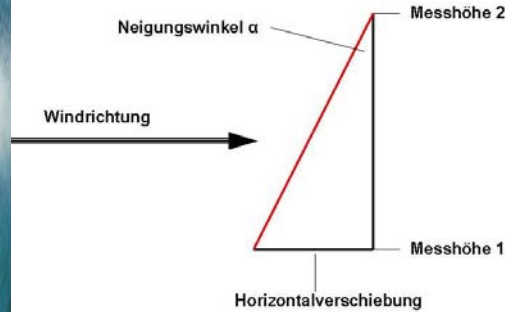
Längenskalen der Turbulenzelemente



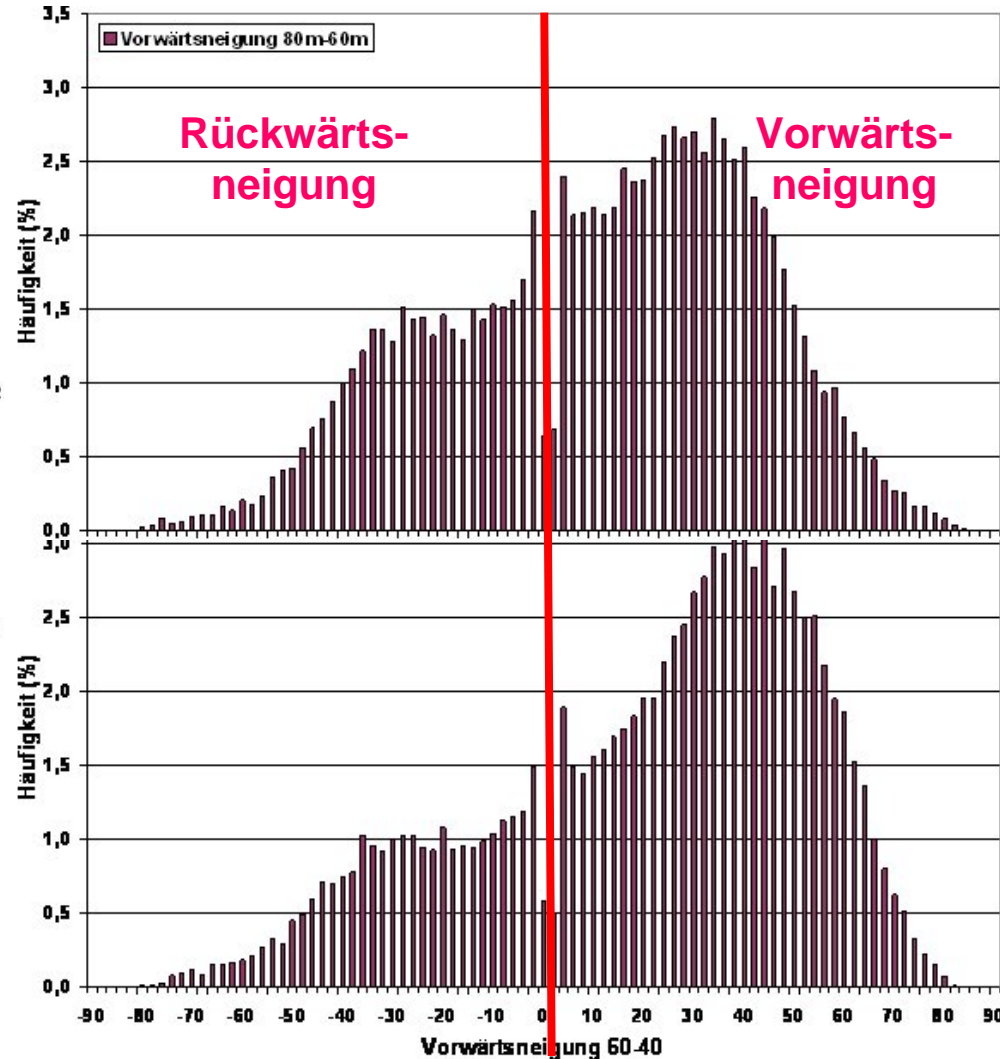
Vorwärtsneigung der Turbulenzelemente



60 bis 80 m



40 bis 60 m





Extreme operating gust (EOG)

Häufigkeit in Abhängigkeit von der Länge
(relativ zur Häufigkeit für 10,5 s Länge)

8 s	10,5 s	14 s
1,60	1,00	0,63

kürzere EOGs sind häufiger als die 10,5 s-EOGs der Norm



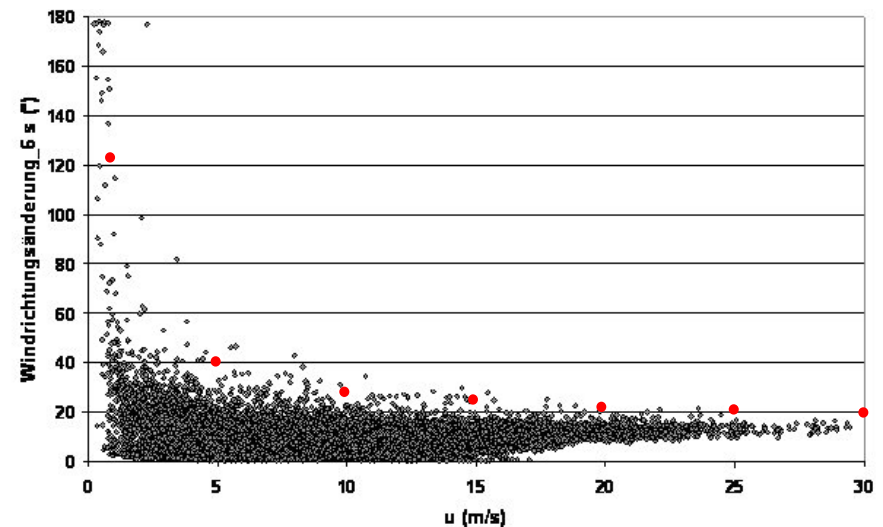
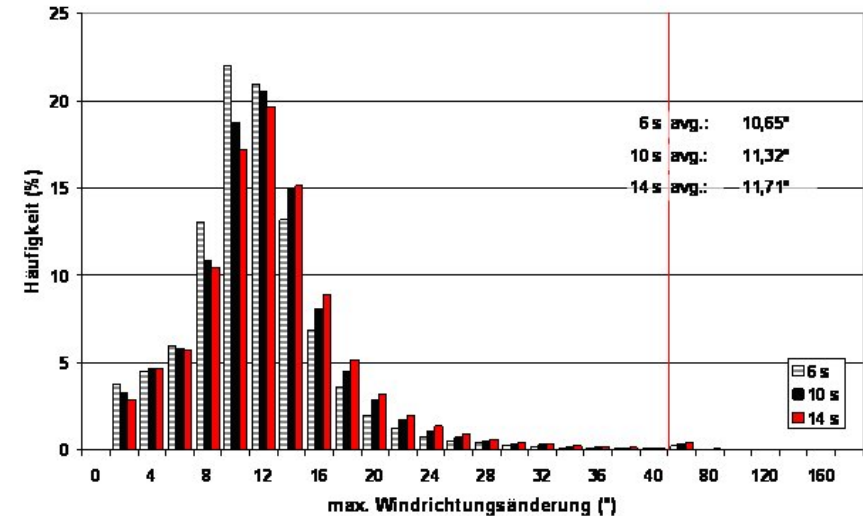
Extreme direction change (EDC)

Häufigkeits-
verteilung für
6, 10 und 14 s

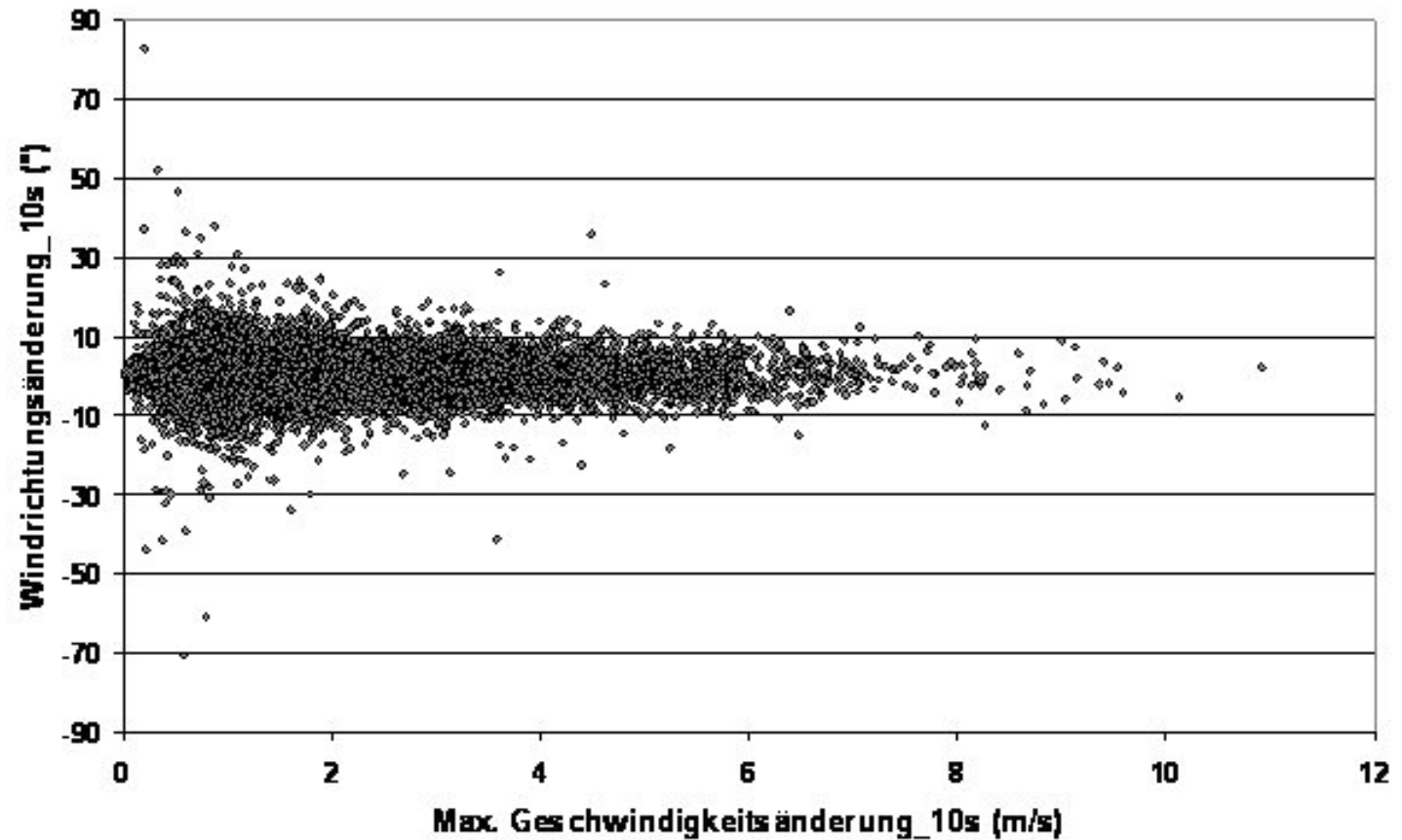
als Funktion der
Windgeschw.

Vergleich mit
61400-1, Gl. 20:

$D = 120 \text{ m}$
 $\Lambda = 42 \text{ m}$



Extreme coherent gust with direction change (ECD)





Extreme wind speed model (EWM)

Der Hellmann-Exponent für die Extremwinde:

für das 10 min-Mittel scheint 0,11 richtig

für die 3 s-Böe scheint 0,11 etwas zu hoch

Der 50-Jahreswert für die Turbulenzintensität:

0,11 erscheint ausreichend konservativ

(die Extrapolation der Daten ergibt ca. 0,10)

Extreme wind speed model (EWM)

Vertikale Profile der 50jährigen Extreme



10 min-
Mittel

3 s-Böe

(mit 0,983 aus
den 1 s-Daten
errechnet)

