Simple rules-of-thumb for ice fall/throw safety distances

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Republic of Austria
Transport, Innovation
and Technology

IEA FORSCHUNGS KOOPERATION

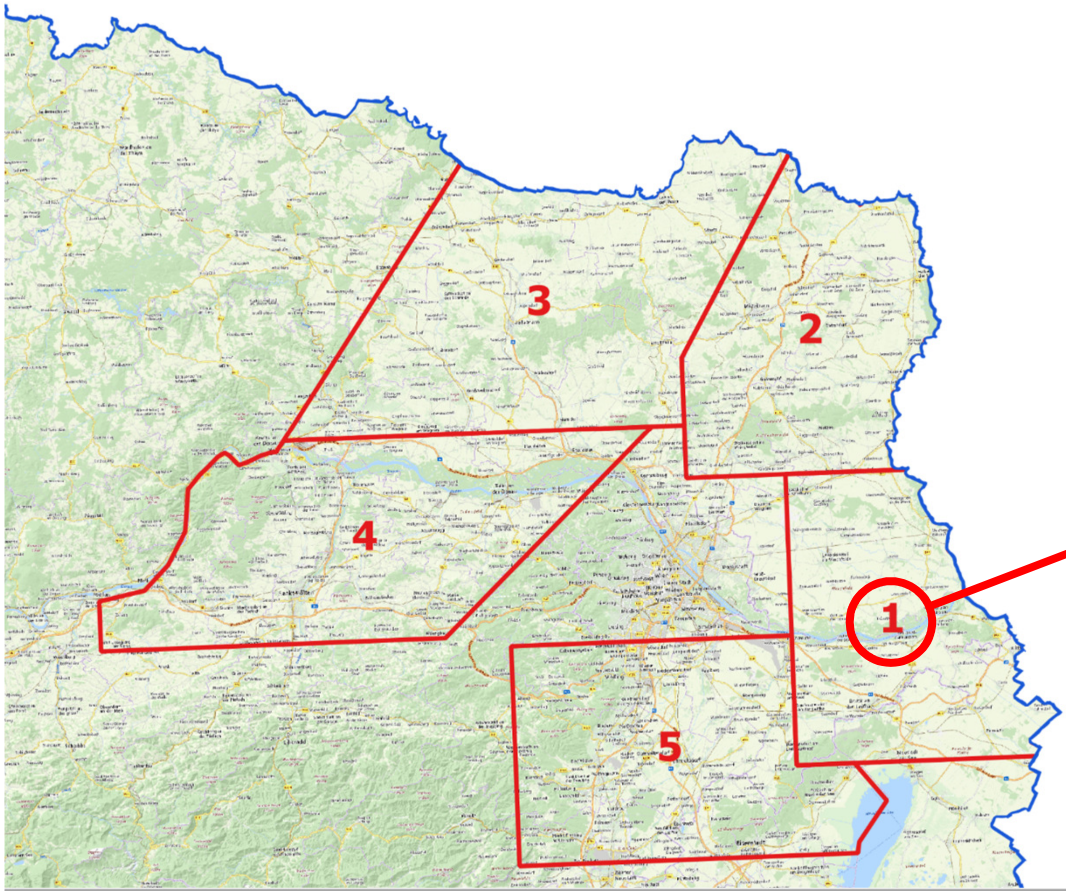
Scope

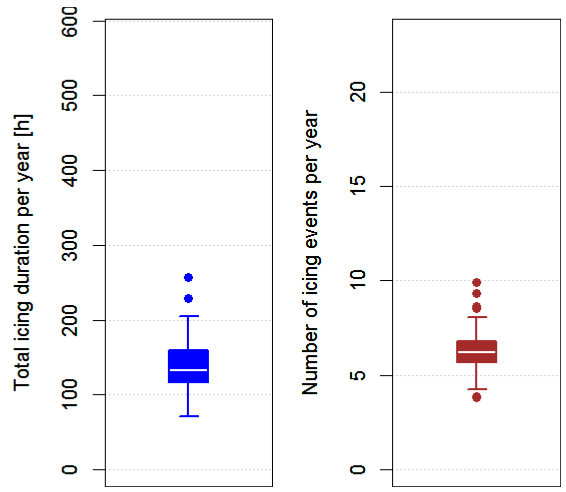
- This is a H&S presentation
- In Austria (as well as some countries) icing is first and foremost a H&S issue and icing losses are only of secondary importance
- Builds on a previous study in Austria
- And based on the conviction that, to be useful, any advise should be as simple as possible

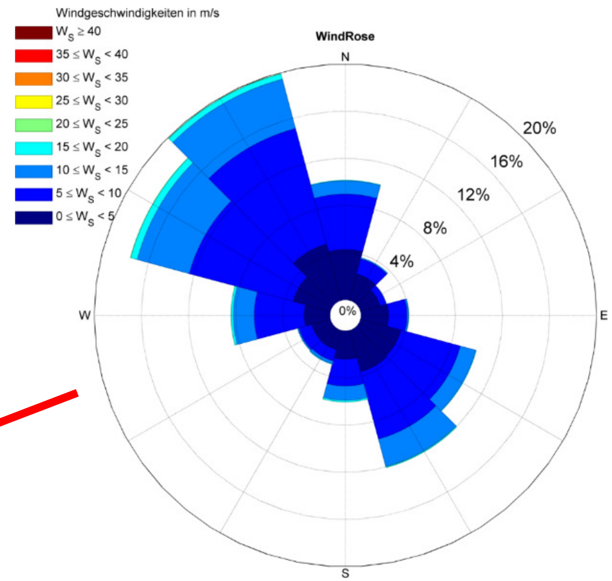
Austrian Project: R.Ice ‘Risk Analysis of Wind Turbine Icing’

- Part of this was presented on Winterwind 2019
- Looked at five more or less homogeneous regions in Eastern Austria
- Averaged wind- and icing-conditions

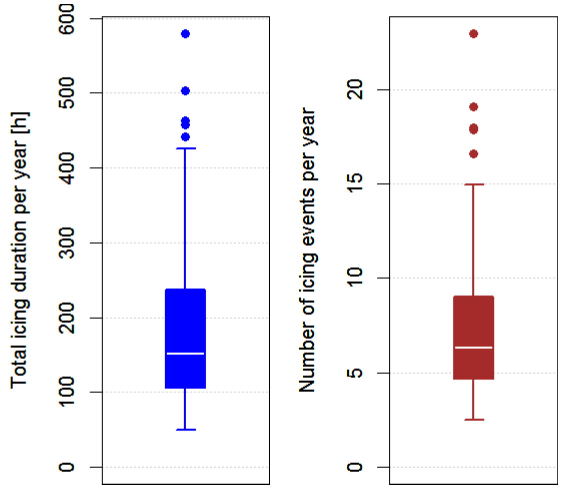
Region-wise wind- and icing conditions…

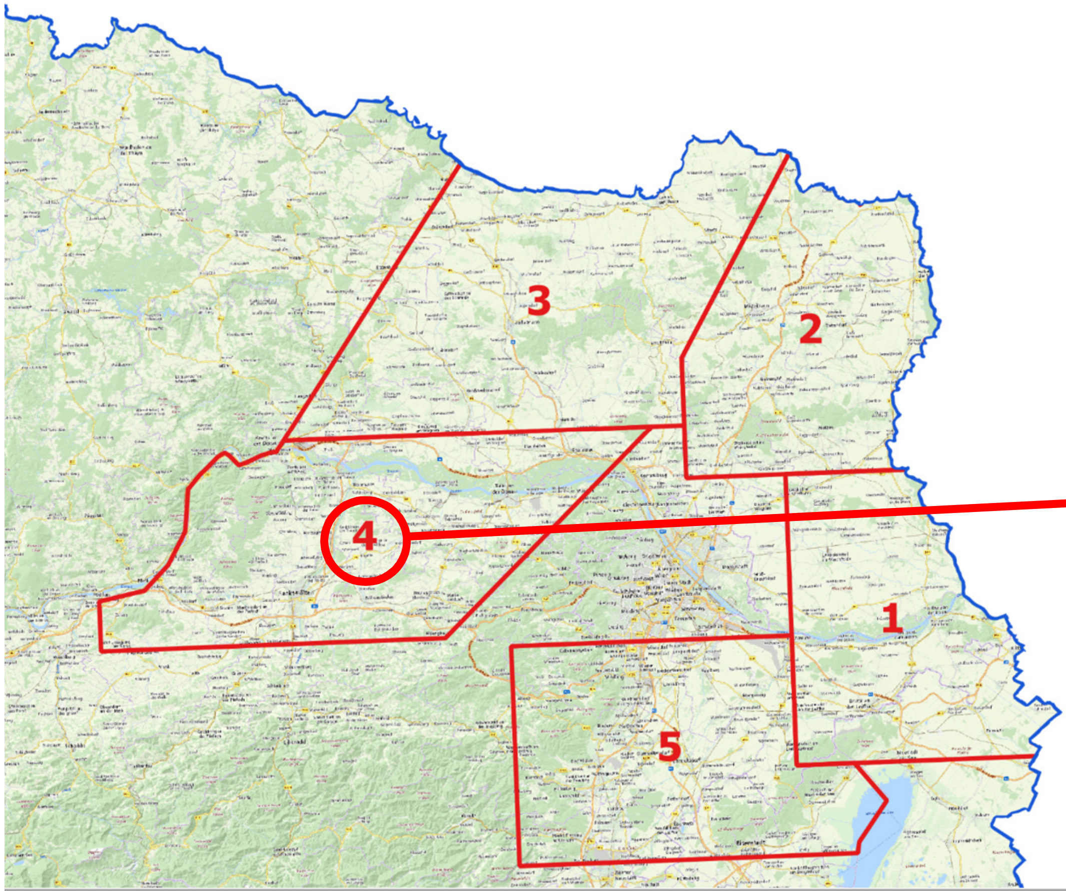


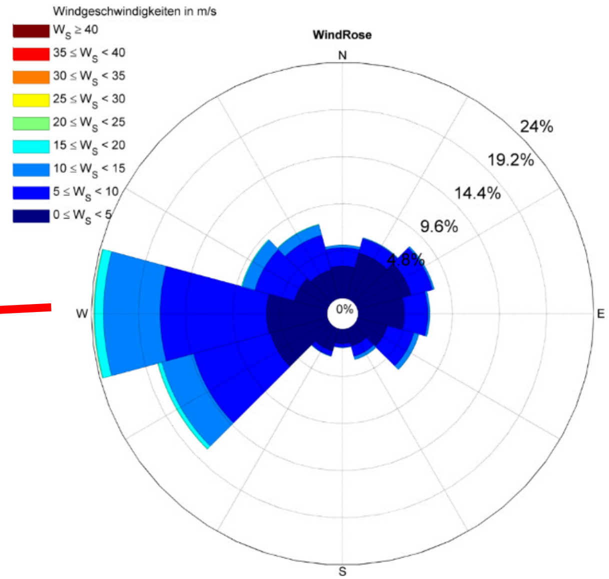




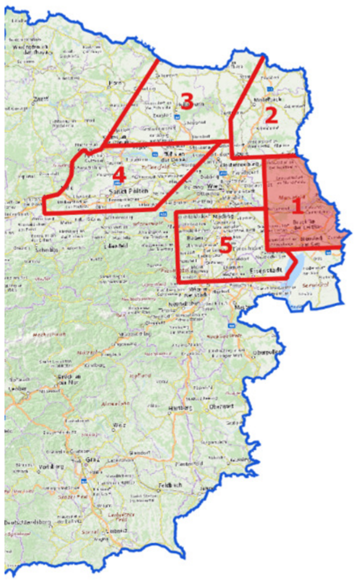
Region-wise wind- and icing conditions…

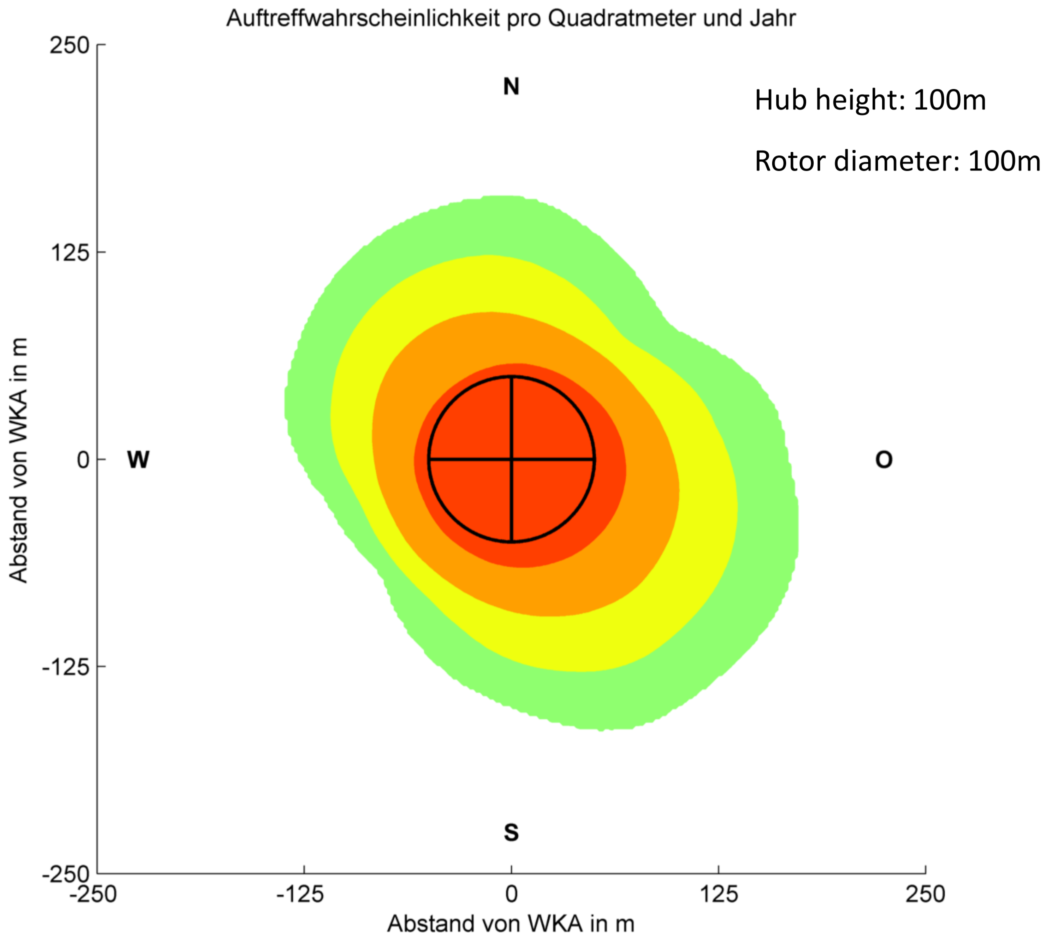




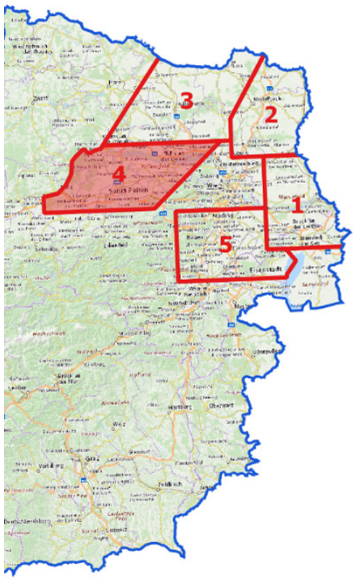


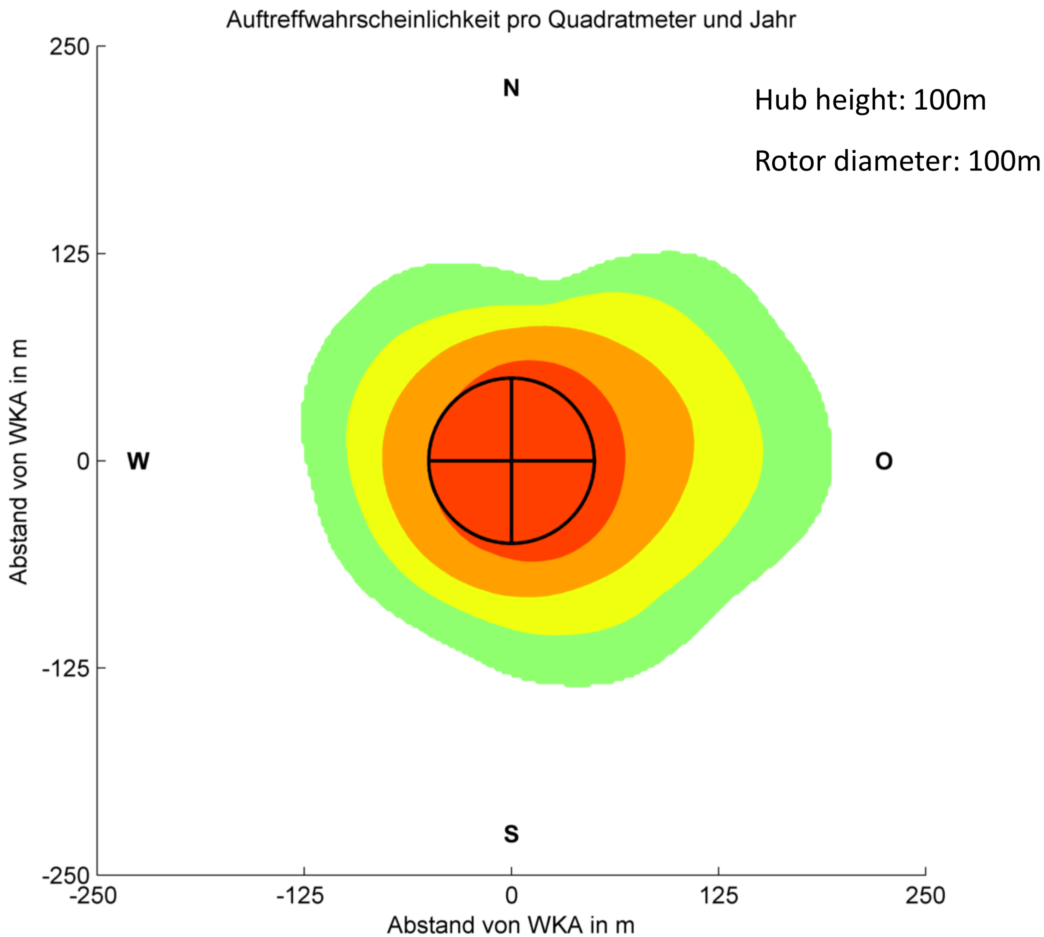
… lead to region-wise impact distributions





… lead to region-wise impact distributions





Limits and stand-off radii

Considering two limits for the yearly impact probability:

- **10^{-3} m^{-2} year^{-1}** for non-critical infrastructure and usage scenarios (also used for ice fall warning signs/warning lights), e.g.:
  - Unspecified activities up to, on average, 0,5h per day (indiv.)
  - Pedestrian, jogger, biker, on average, once per day (indiv.)
  - Vehicles dirt/forest road, twice per day (indiv.), 200 per day (coll.)
  - Hiking/biking path, 500 per day (coll.)

- **10^{-5} m^{-2} year^{-1}** corresponds to a LIRA (localized individual risk) < 10^{-6}
  - Ice fall risk is no concern
  - Fine to have public roads, railways, leisure areas, settlements, etc.

Based on accepted risk levels of 10^{-6} year^{-1} individual and 10^{-4} year^{-1} collective (IEA Task 19 recommendations)

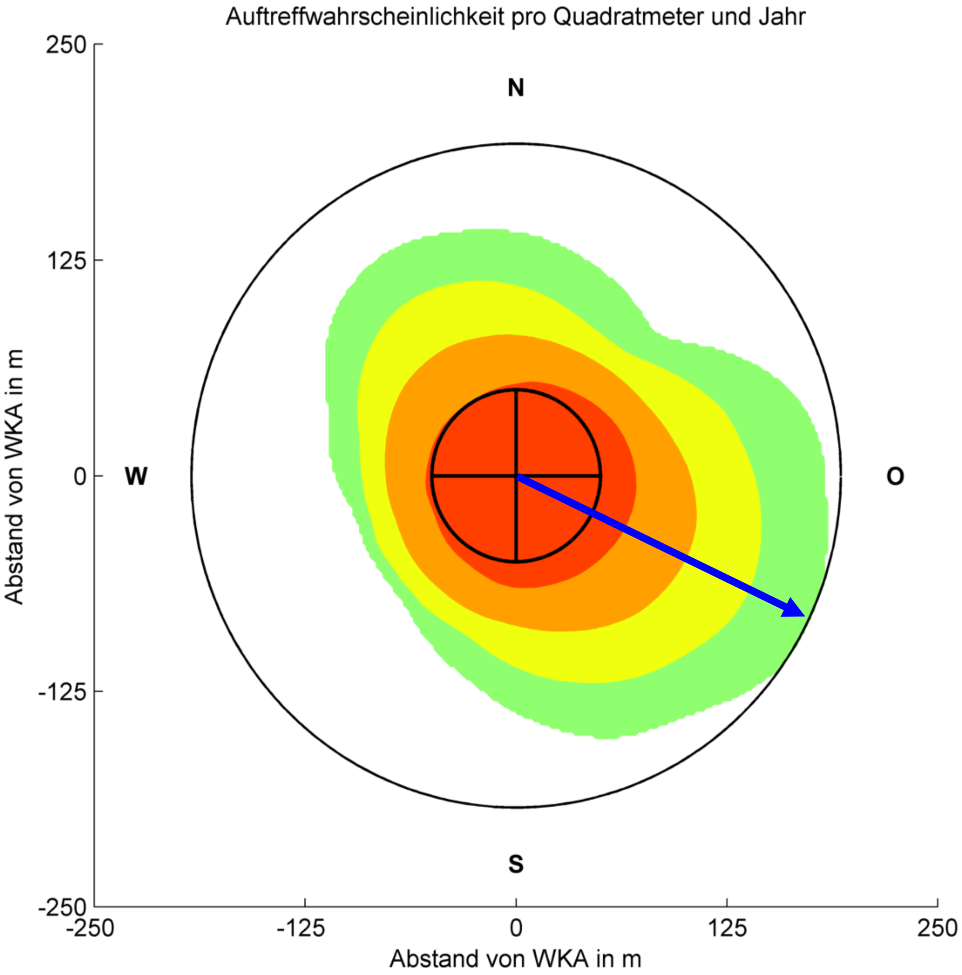
Either extreme assumptions or with a safety factor of 10 or greater

Everything on average during icing season

To simplify matters:
only considering the maximum over all directions

- It turns out (as we will see later) that the blade tip height is the relevant reference
- Leads to standoff radii in units of the blade tip height:

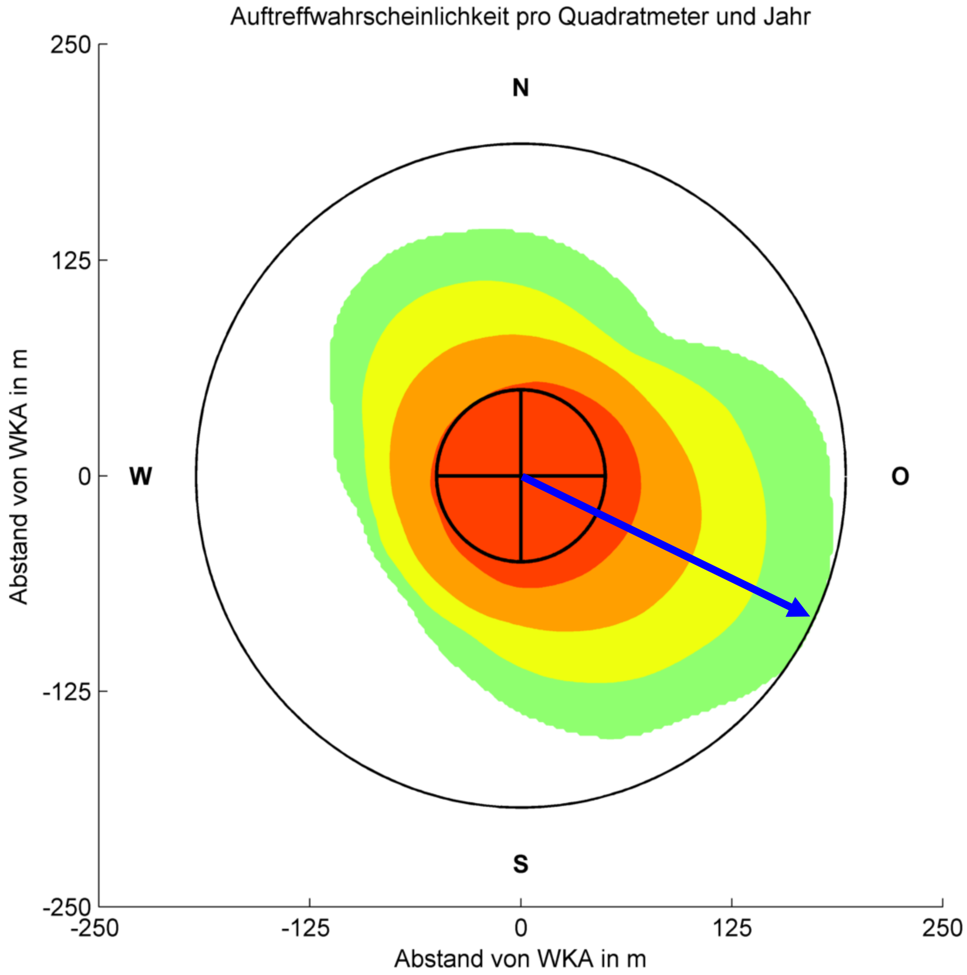
Level # $yr^{-1}m^{-2}$	10^{-3}	10^{-5}
Region 1	0,74	1,27
Region 2	0,74	1,28
Region 3	0,69	1,18
Region 4	0,78	1,36
Region 5	0,78	1,34



To simplify matters:
only considering the maximum over all directions

- For ice fall (WT Stopped)
  The maximum distance is determined by the wind direction with the highest wind speed and the frequency of occurrence in that bin.

- For ice throw (WT operating)
  Things are not quite as straightforward and require a short discussion…



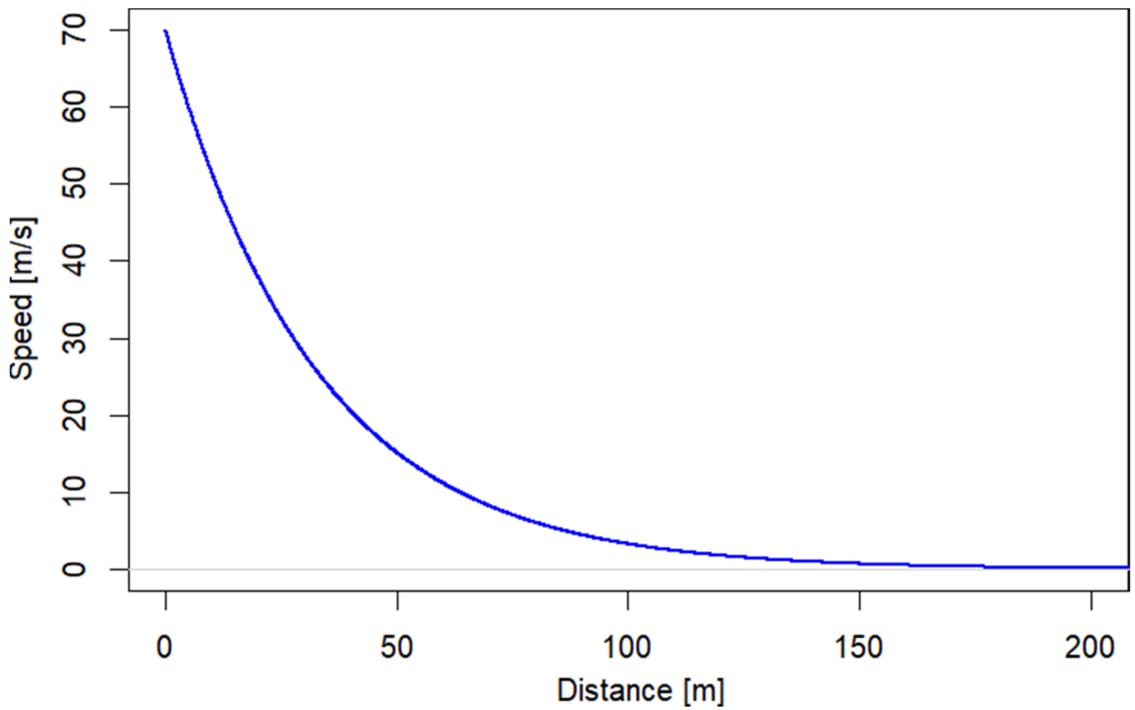
Stopping length and turbine size

Equation of motion for an ice piece in one DOF:

$$\frac{1}{2}\rho u^2 \, c_D \, {}^{A}\!/_{m} = -a = -\frac{\partial u}{\partial t}$$

Has the solution

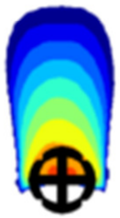
$$u = u_0 \cdot e^{-\frac{x}{l_{\text{stop}}}}$$ with stopping length $$\frac{1}{l_{\text{stop}}} = \frac{1}{2}\rho \, c_D \, {}^{A}\!/_{m}$$



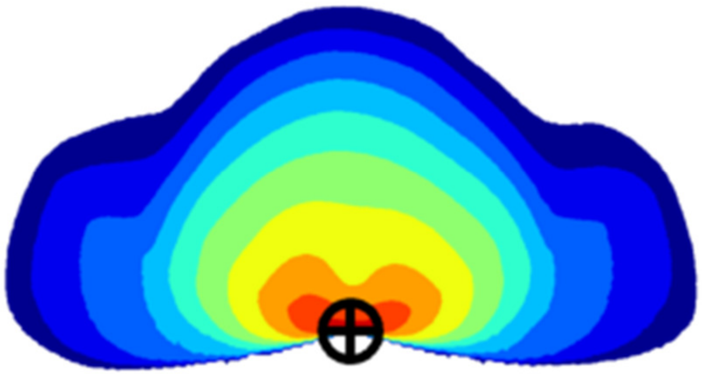
u_0 = 70 m/s
ρ = 1,225 kg/m³
c_D = 1
${}^{A}\!/_{m}$ = 0,05 m²/kg
$\boldsymbol{l_{\text{stop}}}$ **≈ 33m**

Regardless of turbine size!!

For small WT, the maximum ice fall distance is determined from ice throw from the rotating rotor in the rotor plane.
=> Much larger ice fall distribution for ice-throw than for ice-fall



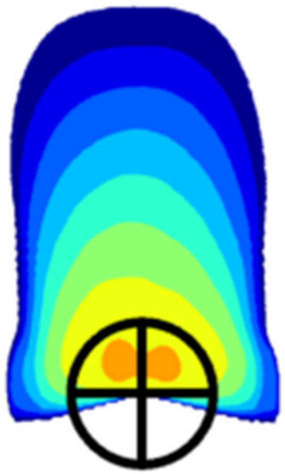
Iced WT stopped / ice-fall



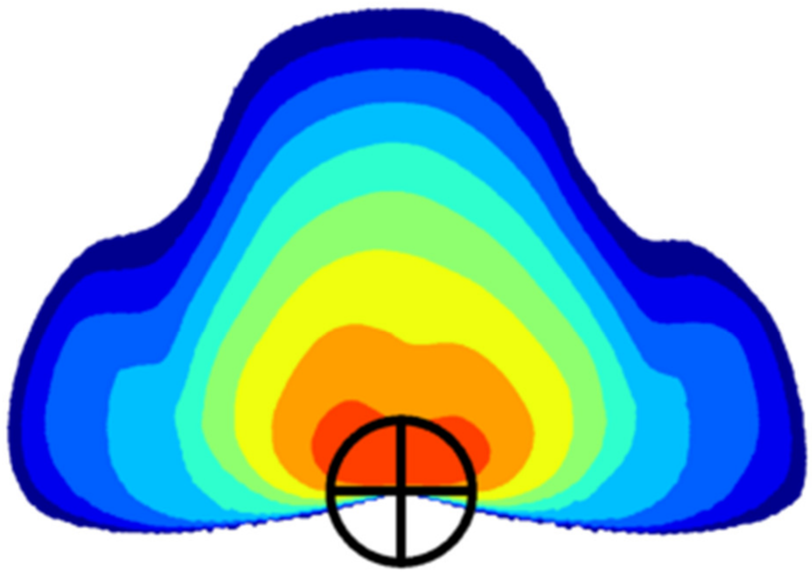
Iced WT operating / ice-throw

Dia: 40m HH: 40m TH: 60m
V_{avg}: 10 m/s

For medium sized WT, transportation of the ice pieces with the wind becomes more important also for the ice-throw case



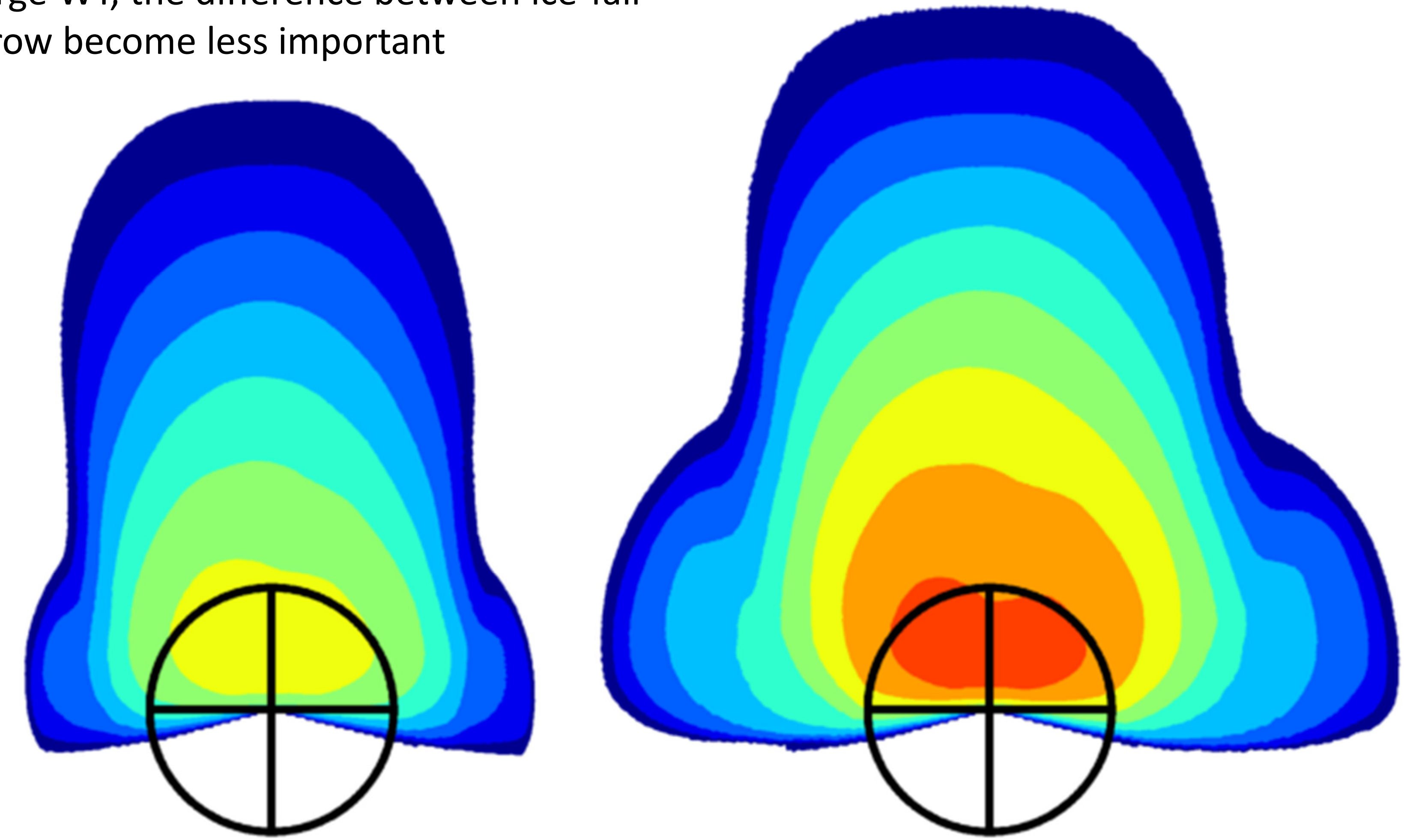
Iced WT stopped / ice-fall



Iced WT operating / ice-throw

Dia: 100m HH: 100m TH: 150m
V_{avg}: 10 m/s

For very large WT, the difference between ice-fall and ice-throw become less important

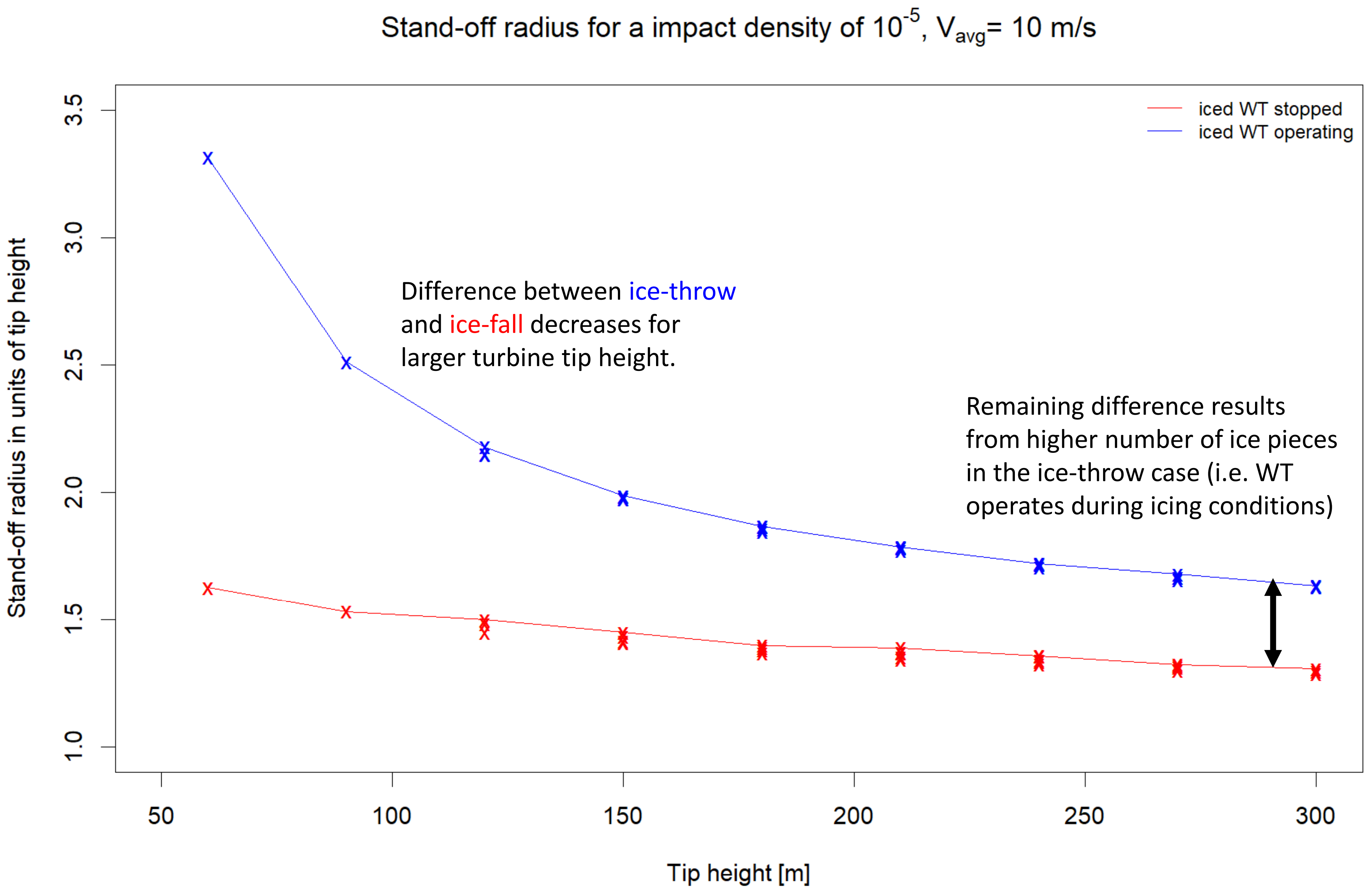


Iced WT stopped / ice-fall

Iced WT operating / ice-throw

Dia: 200m HH: 200m TH: 300m

V_{avg}: 10 m/s

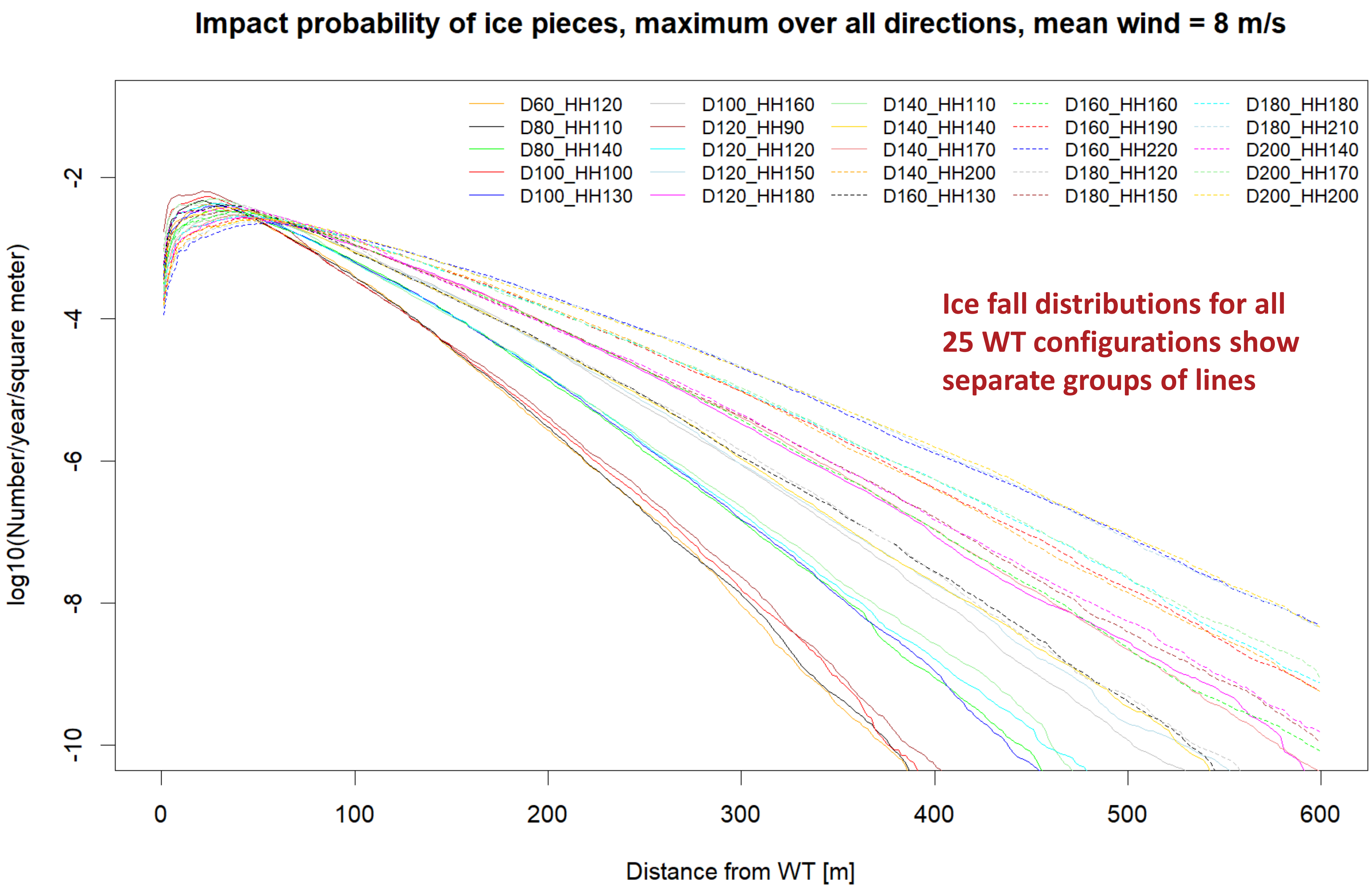

Stand-off radius for a impact density of 10^-5, V_avg= 10 m/s
iced WT stopped
iced WT operating
Difference between ice-throw and ice-fall decreases for larger turbine tip height.
Remaining difference results from higher number of ice pieces in the ice-throw case (i.e. WT operates during icing conditions)
Stand-off radius in units of tip height
Tip height [m]
1.0
1.5
2.0
2.5
3.0
3.5
50
100
150
200
250
300

Procedure in this study

- Take reference to the average wind speed in the „worst bin“: from 7 m/s to 15 m/s
- Wind turbines from 150m to 300m tip height in 25 different configurations
- For IEA icing classes 1 to 5
- Considering ice throw and ice fall

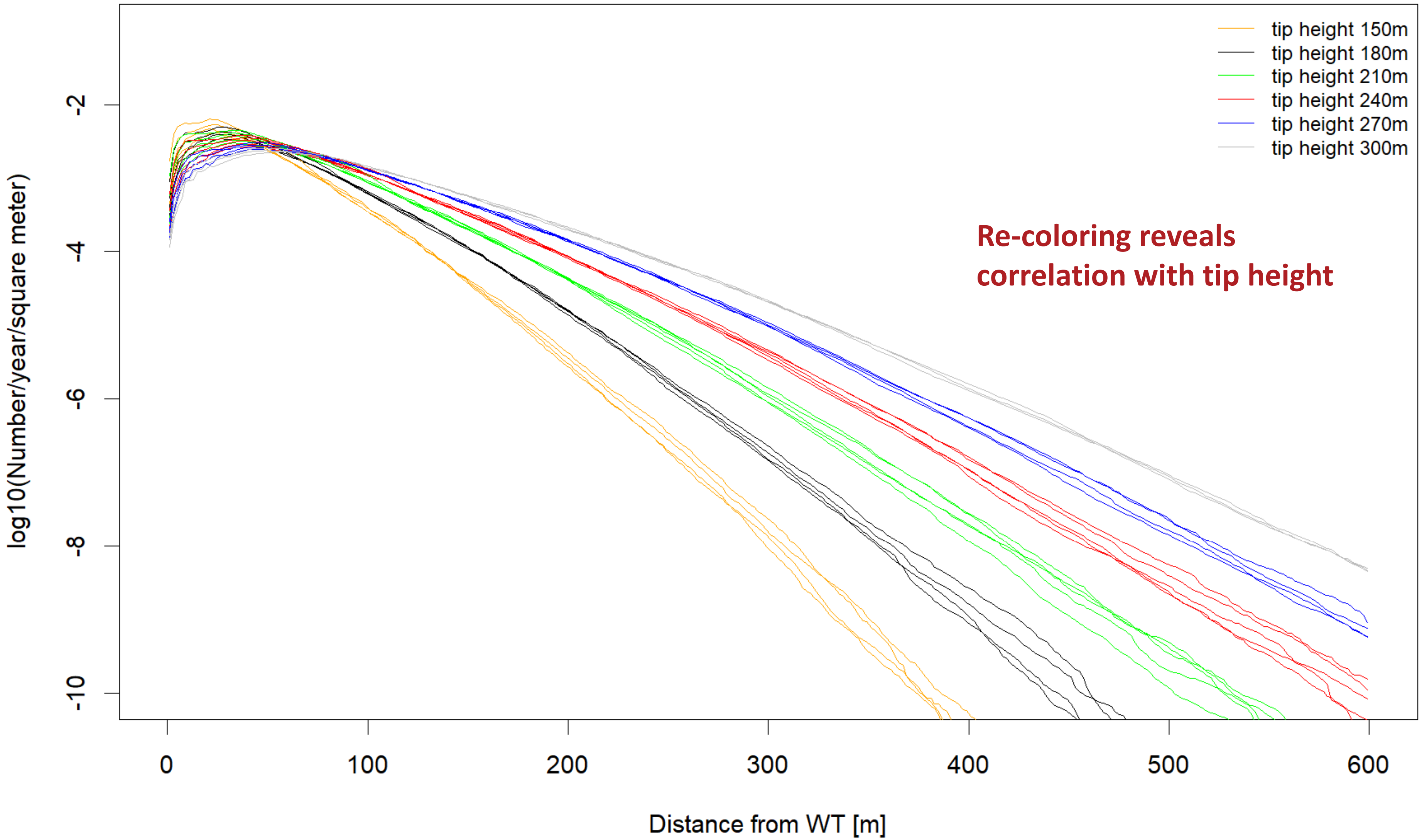
Technicalities & Assumptions

- WT operation: cut-in 3 m/s, rated 12 m/s, cut-out 25 m/s
- Spectrum of ice pieces in A/m, according to Task 19 ice fall recommendations
- Ice pieces above 100g are considered potentially lethal
- Number of ice pieces according to Task 19 ice fall recommendations and scaled with turbine size
- Factor 10 more ice pieces for WT operation during icing conditions as compared to stopped WT
- Wind speed defined at hub height, Rayleigh distribution, wind sheer with α=2
- Binning in 12 wind directions



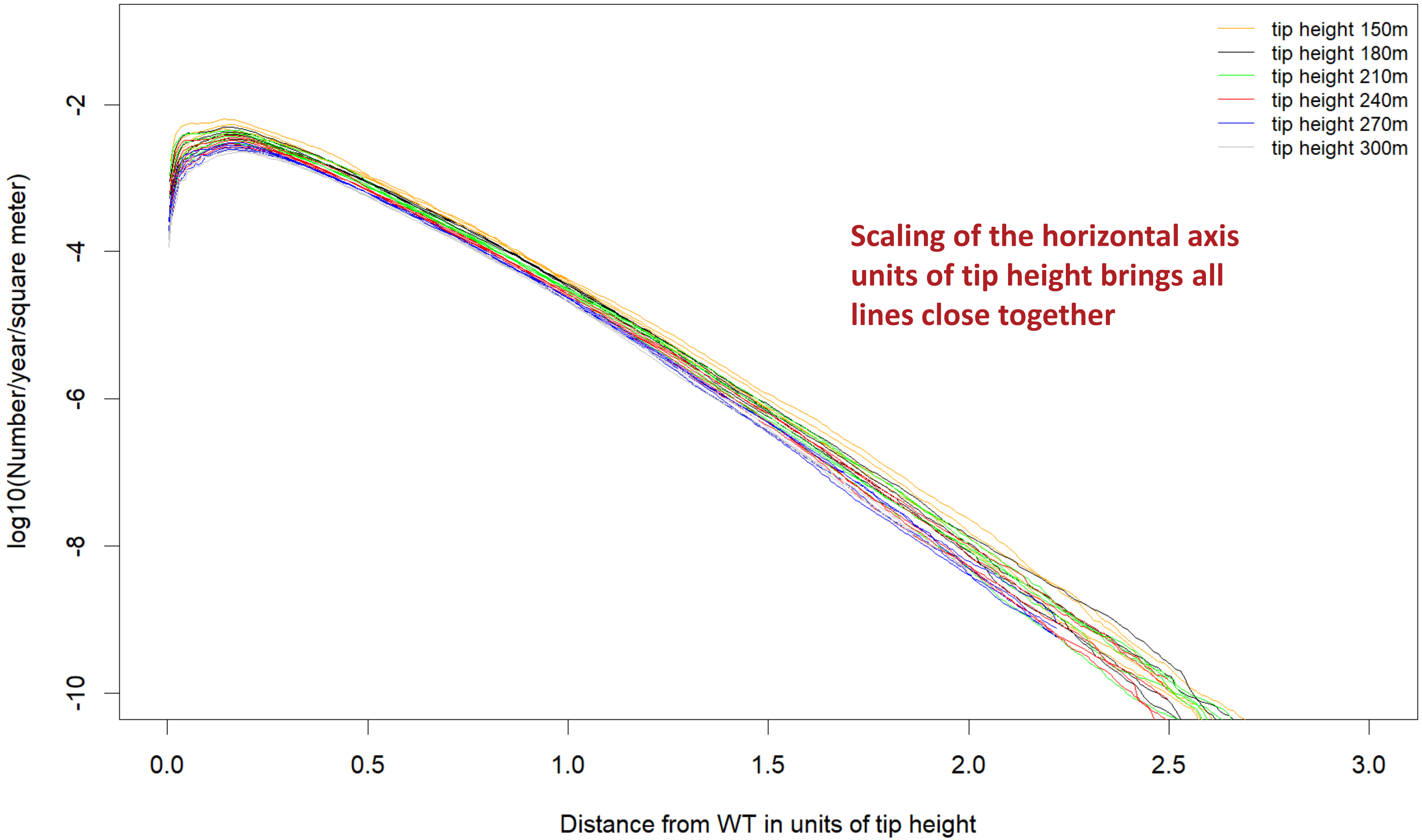
Impact probability of ice pieces, maximum over all directions, mean wind = 8 m/s
log10(Number/year/square meter)
-2
-4
-6
-8
-10
0
100
200
300
400
500
600
Distance from WT [m]
D60_HH120
D80_HH110
D80_HH140
D100_HH100
D100_HH130
D100_HH160
D120_HH90
D120_HH120
D120_HH150
D120_HH180
D140_HH110
D140_HH140
D140_HH170
D140_HH200
D160_HH130
D160_HH160
D160_HH190
D160_HH220
D180_HH120
D180_HH150
D180_HH180
D180_HH210
D200_HH140
D200_HH170
D200_HH200
Ice fall distributions for all 25 WT configurations show separate groups of lines

Impact probability of ice pieces, maximum over all directions, mean wind = 8 m/s



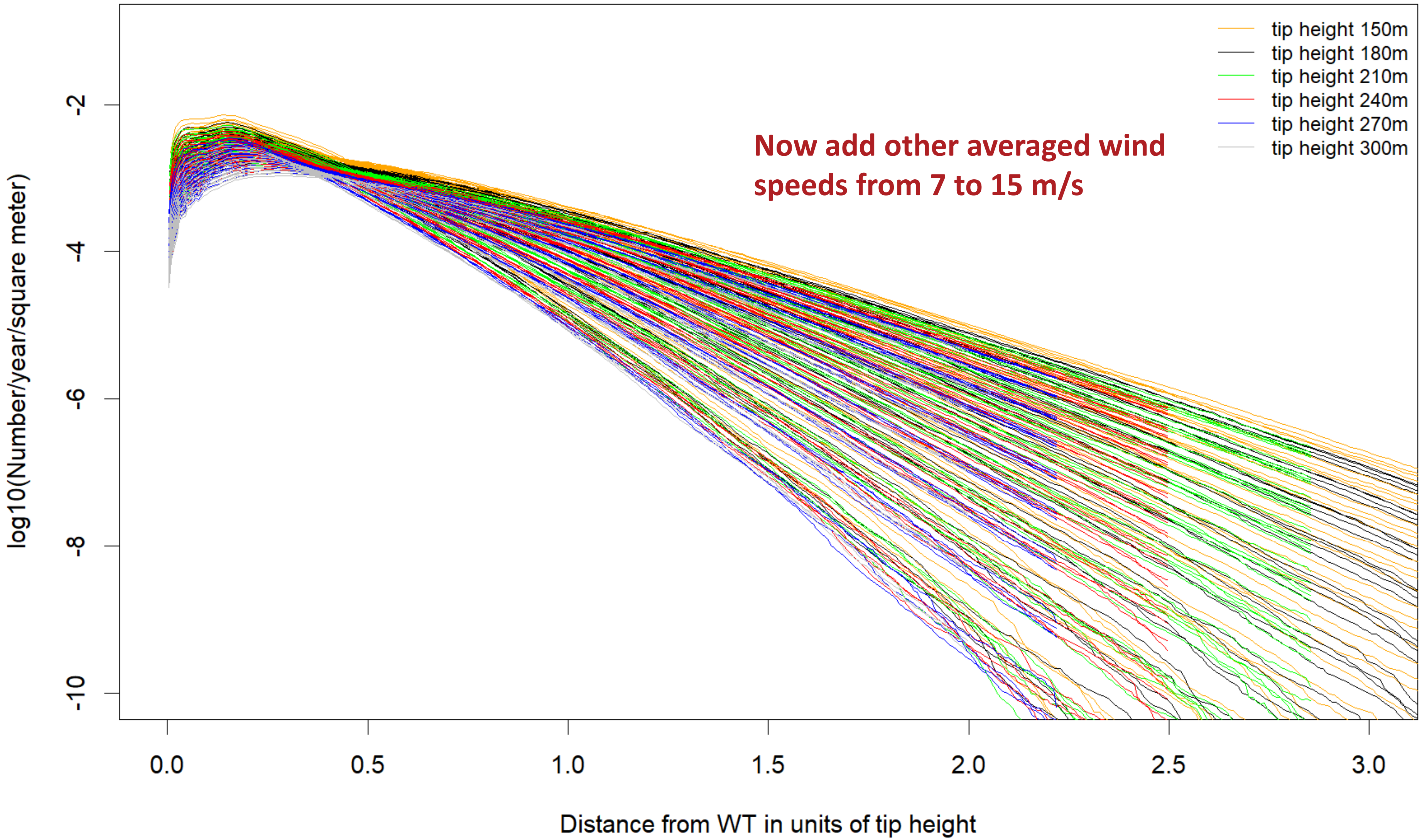
Re-coloring reveals correlation with tip height

Impact probability of ice pieces, maximum over all directions, mean wind = 8 m/s

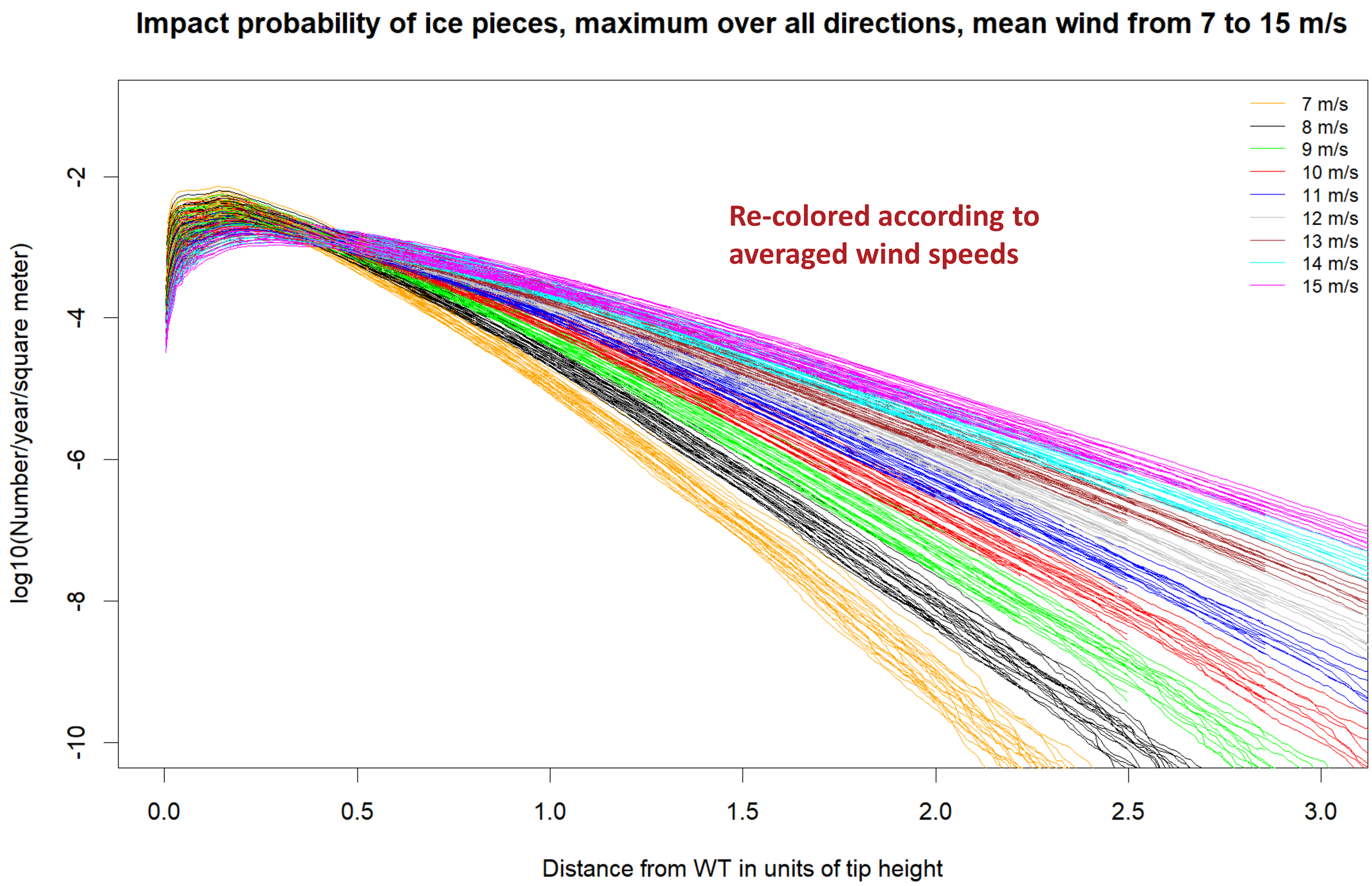


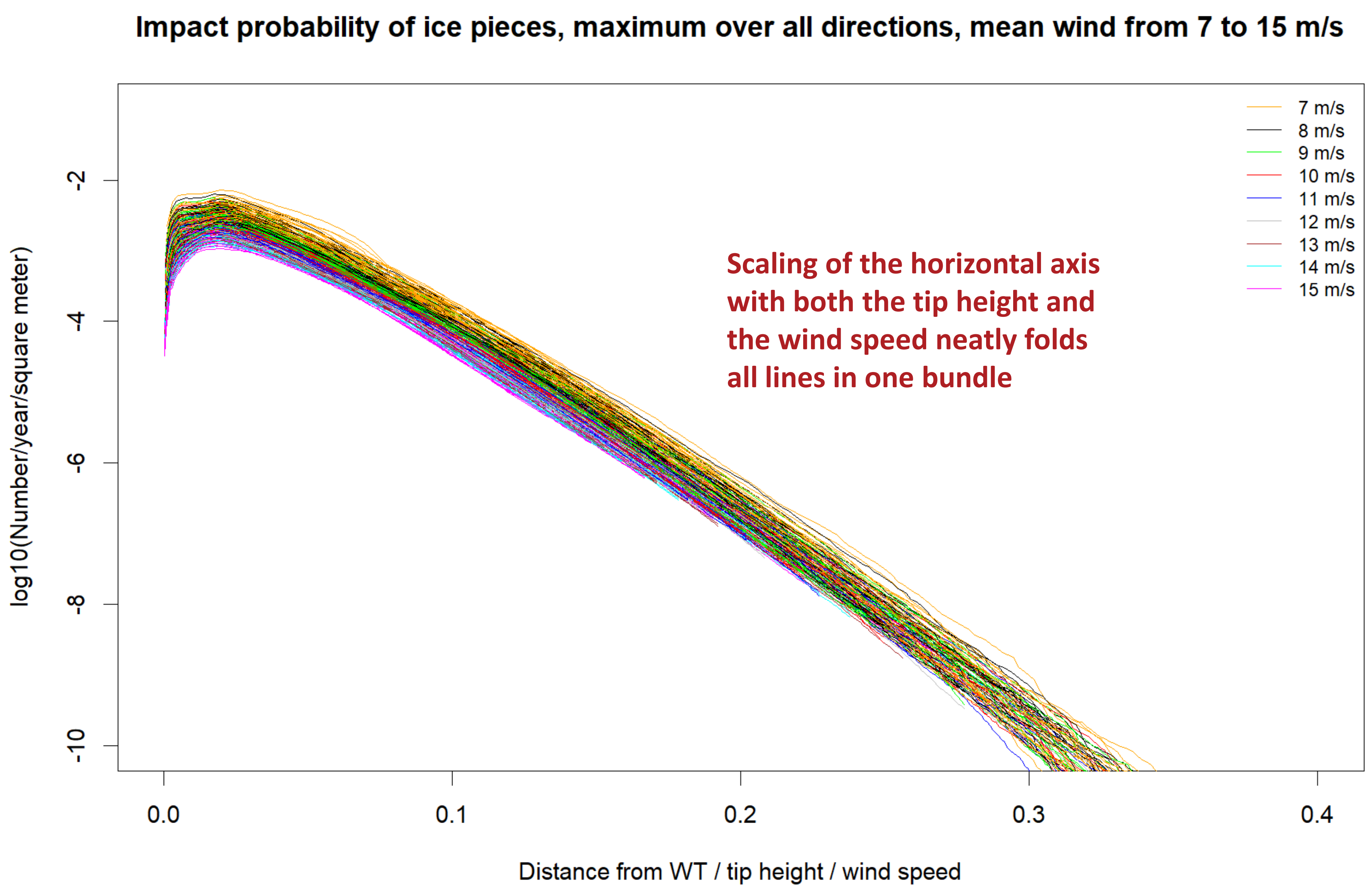
Scaling of the horizontal axis units of tip height brings all lines close together

Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s

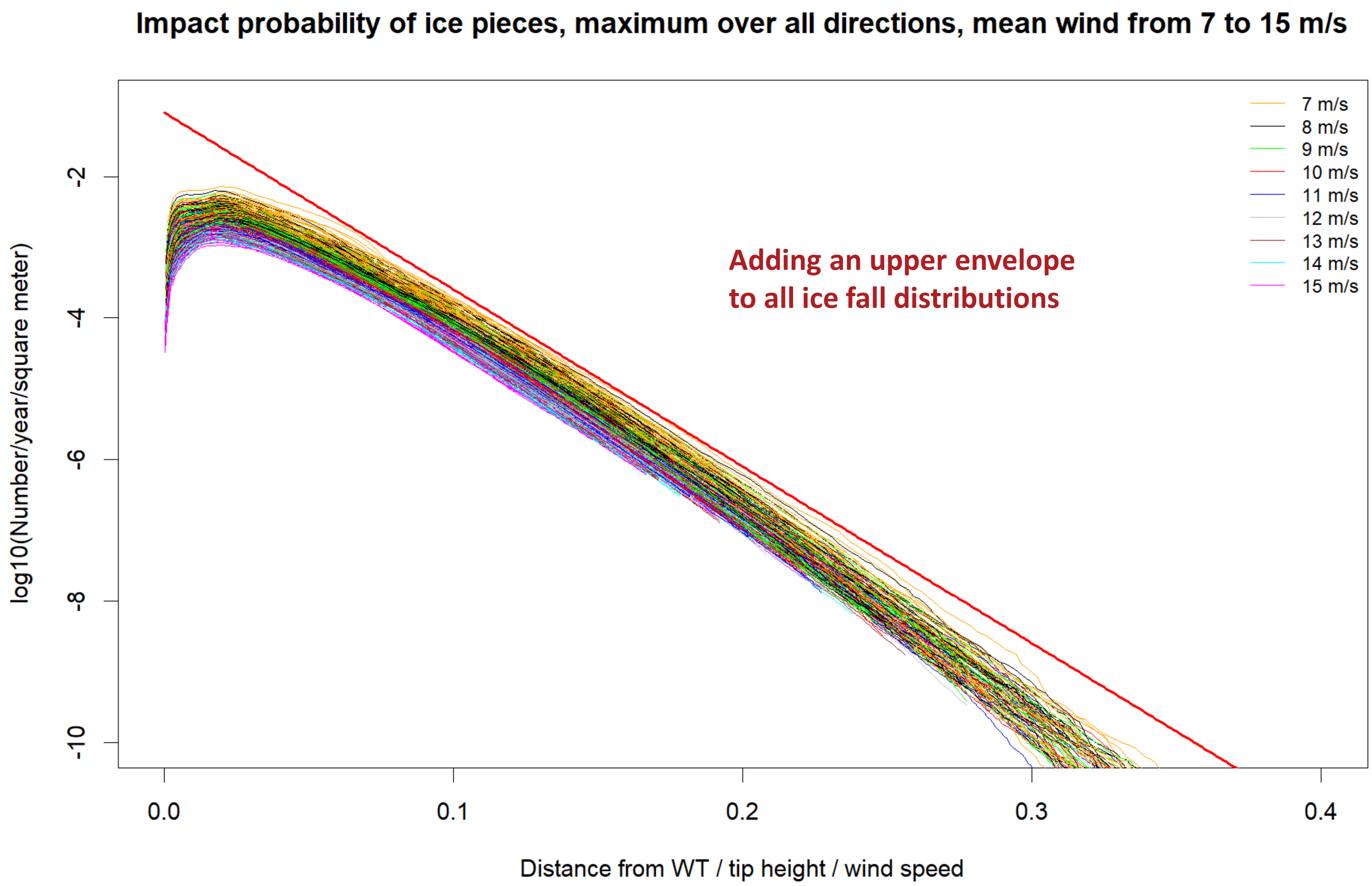


Now add other averaged wind speeds from 7 to 15 m/s

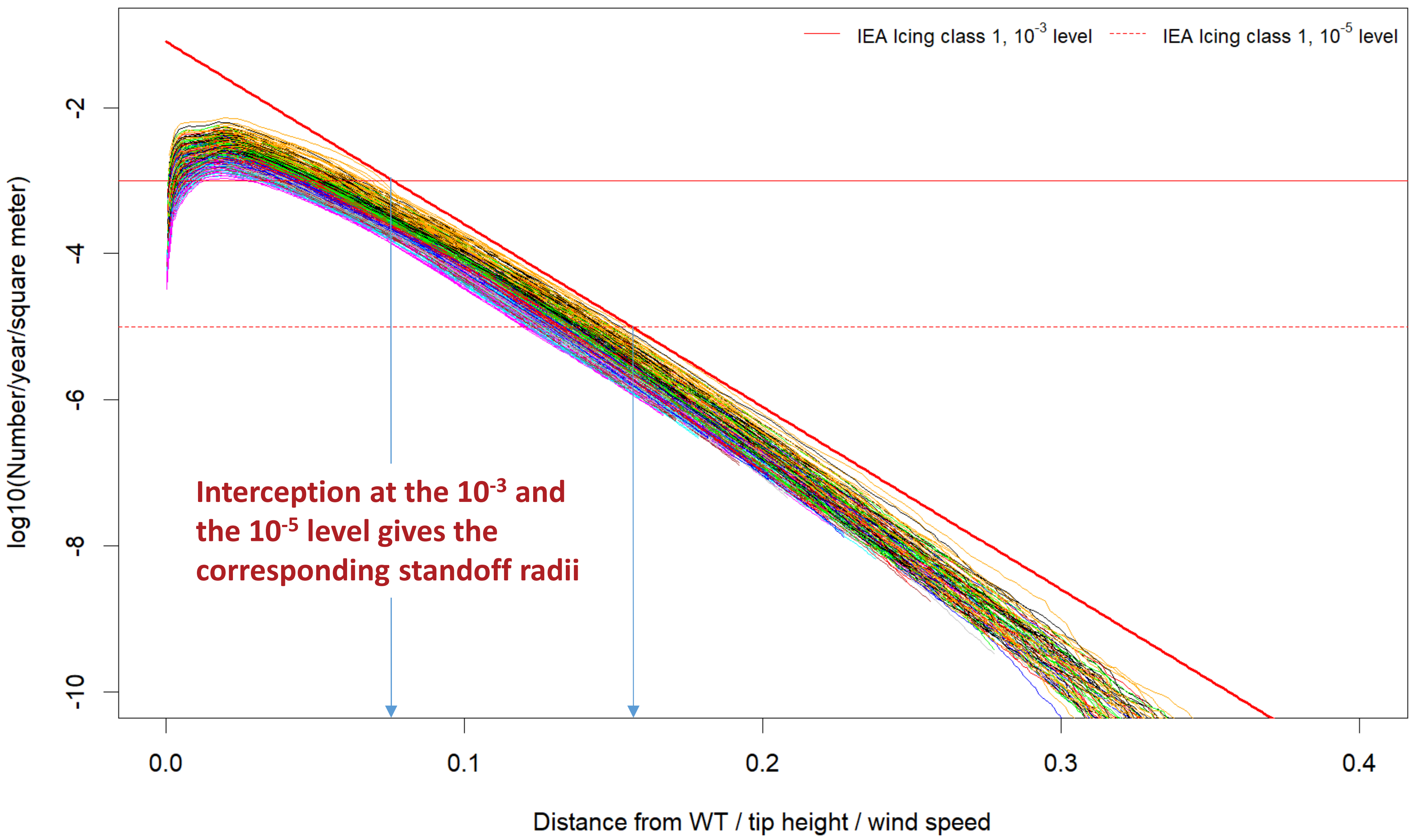

Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s
Re-colored according to averaged wind speeds
7 m/s
8 m/s
9 m/s
10 m/s
11 m/s
12 m/s
13 m/s
14 m/s
15 m/s
log10(Number/year/square meter)
-2
-4
-6
-8
-10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Distance from WT in units of tip height

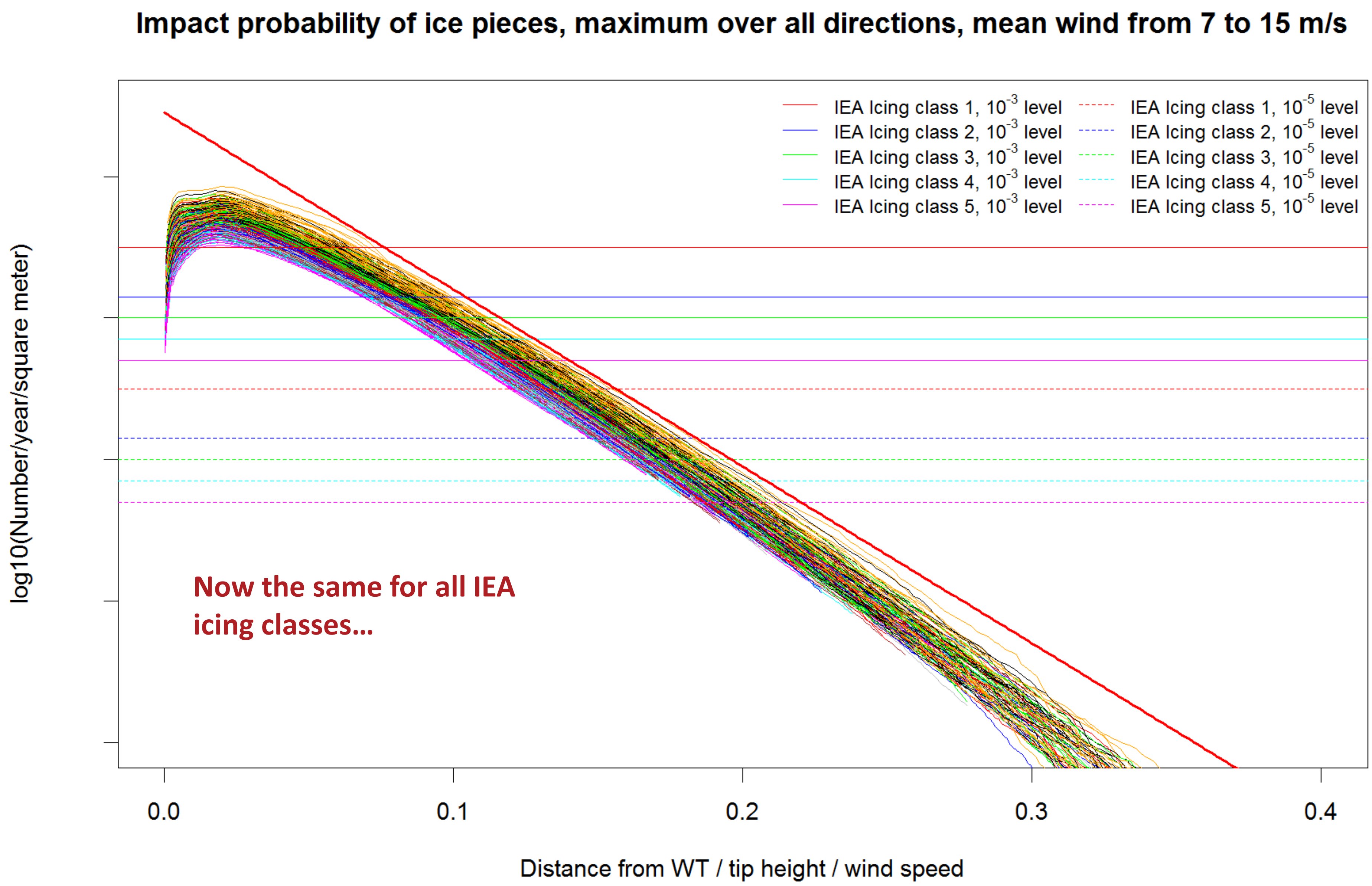


Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s
7 m/s
8 m/s
9 m/s
10 m/s
11 m/s
12 m/s
13 m/s
14 m/s
15 m/s
Scaling of the horizontal axis with both the tip height and the wind speed neatly folds all lines in one bundle
-2
-4
-6
-8
-10
log10(Number/year/square meter)
0.0
0.1
0.2
0.3
0.4
Distance from WT / tip height / wind speed


Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s
log10(Number/year/square meter)
-2
-4
-6
-8
-10
0.0
0.1
0.2
0.3
0.4
Distance from WT / tip height / wind speed
7 m/s
8 m/s
9 m/s
10 m/s
11 m/s
12 m/s
13 m/s
14 m/s
15 m/s
Adding an upper envelope
to all ice fall distributions

Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s





Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s
IEA Icing class 1, 10^{-3} level
IEA Icing class 2, 10^{-3} level
IEA Icing class 3, 10^{-3} level
IEA Icing class 4, 10^{-3} level
IEA Icing class 5, 10^{-3} level
IEA Icing class 1, 10^{-5} level
IEA Icing class 2, 10^{-5} level
IEA Icing class 3, 10^{-5} level
IEA Icing class 4, 10^{-5} level
IEA Icing class 5, 10^{-5} level
log10(Number/year/square meter)
0.0
0.1
0.2
0.3
0.4
Distance from WT / tip height / wind speed
Now the same for all IEA icing classes…

Formulae for stand-off radii: iced WT stopped

- **10^{-3} m^{-2} year^{-1}** for non-critical infrastructure and usage scenarios (also used for ice fall warning signs/warning lights)

$$\frac{R_{\mathrm{min}}}{\mathrm{TH}} = V_{\mathrm{avg}} \frac{3 + \log(a) + \log(b) - 1.1}{25}$$

10^{-5} m^{-2} year^{-1} corresponds to a LIRA (localized individual risk) < 10^{-6} ,i.e. ice fall risk is no concern

$$\frac{R_{\mathrm{min}}}{\mathrm{TH}} = V_{\mathrm{avg}} \frac{5 + \log(a) + \log(b) - 1.1}{25}$$

$$a = \begin{cases} 1 & \text{for IEA icing class 1} \\ 5 & \text{for IEA icing class 2} \\ 10 & \text{for IEA icing class 3} \\ 20 & \text{for IEA icing class 4} \\ 40 & \text{for IEA icing class 5} \end{cases}$$

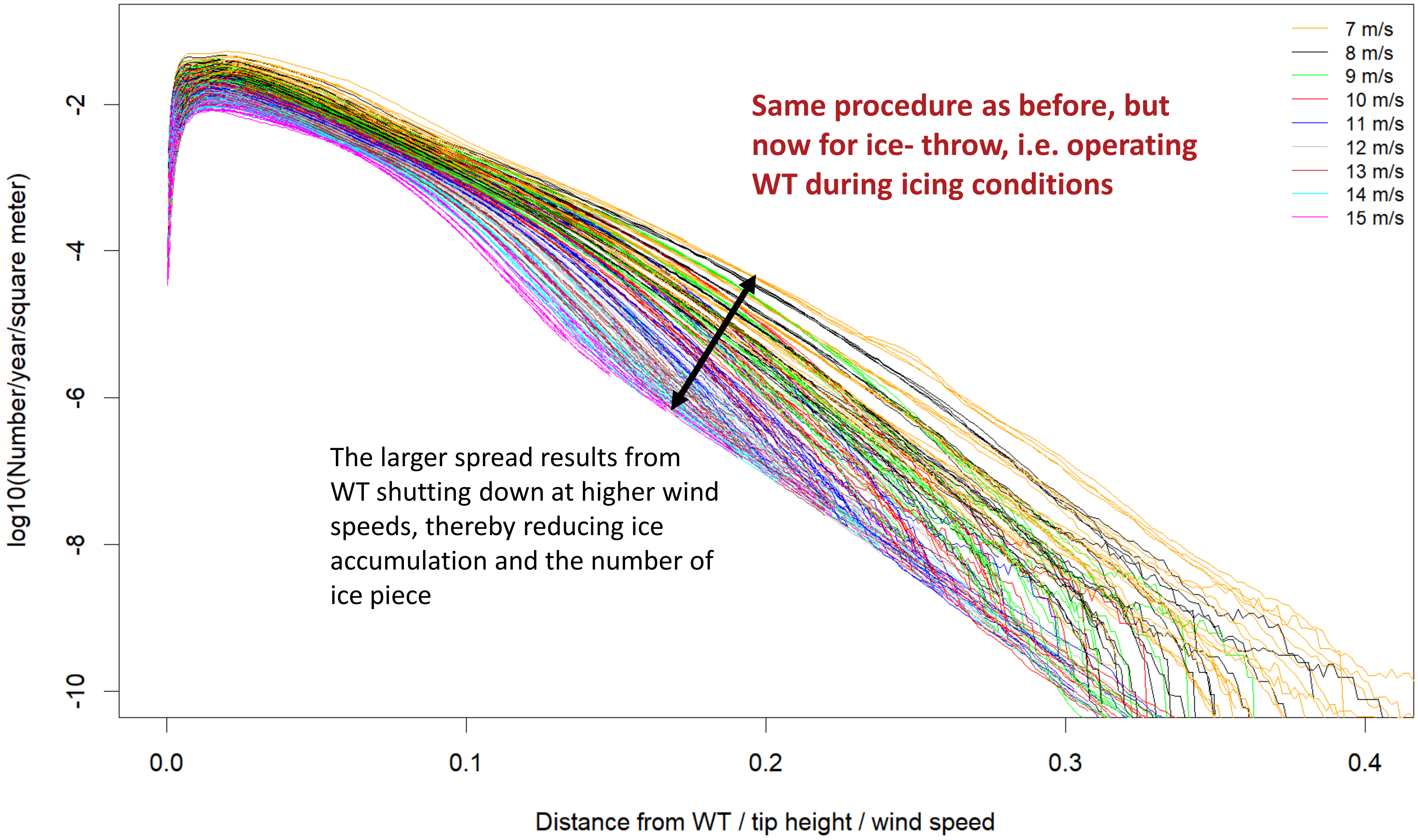
$b = \max(1, P_{\mathrm{bin}} \cdot 12)$

TH ... tip height

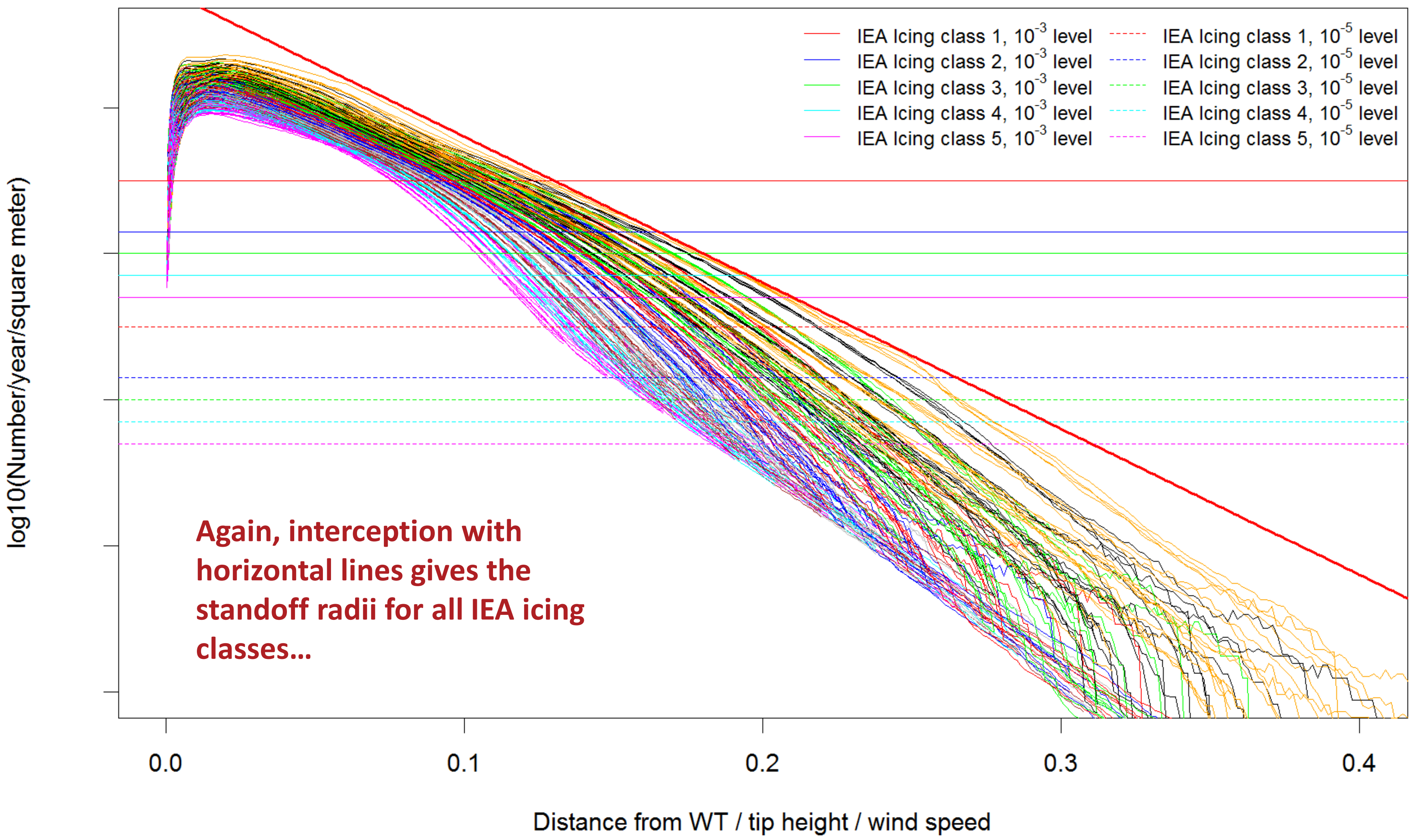
V_{avg} ... average wind speed in "worst bin" [m/s]

P_{bin} ... frequency of occurence for "worst bin" [1]

Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s



Impact probability of ice pieces, maximum over all directions, mean wind from 7 to 15 m/s



Formulae for stand-off radii: iced WT in operation

- **10^{-3} m^{-2} year^{-1}** for non-critical infrastructure and usage scenarios (also used for ice fall warning signs/warning lights)

$$\frac{R_{\min}}{\mathrm{TH}} = V_{\mathrm{avg}} \frac{3 + \log(a) + \log(b) - 0.4}{20}$$

10^{-5} m^{-2} year^{-1} corresponds to a LIRA (localized individual risk) < 10^{-6} ,i.e. ice fall risk is no concern

$$\frac{R_{\min}}{\mathrm{TH}} = V_{\mathrm{avg}} \frac{5 + \log(a) + \log(b) - 0.4}{20}$$

$$a = \begin{cases} 1 & \text{for IEA icing class 1} \\ 5 & \text{for IEA icing class 2} \\ 10 & \text{for IEA icing class 3} \\ 20 & \text{for IEA icing class 4} \\ 40 & \text{for IEA icing class 5} \end{cases}$$

$b = \max(1, P_{\mathrm{bin}} \cdot 12)$

TH ... tip height

V_{avg} ... average wind speed in "worst bin" [m/s]

P_{bin} ... frequency of occurence for "worst bin" [1]

Radius for $10^{-3}\ yr^{-1}m^{-2}$ – iced WT stopped / ice-fall

Mean wind	IEA Icing class 1	2	3	4	5
7 m/s	0,53	0,73	0,81	0,90	0,98
8 m/s	0,61	0,83	0,93	1,02	1,12
9 m/s	0,68	0,94	1,04	1,15	1,26
10 m/s	0,76	1,04	1,16	1,28	1,40
11 m/s	0,84	1,14	1,28	1,41	1,54
12 m/s	0,91	1,25	1,39	1,54	1,68
13 m/s	0,99	1,35	1,51	1,66	1,82
14 m/s	1,06	1,46	1,62	1,79	1,96
15 m/s	1,14	1,56	1,74	1,92	2,10

Radius for $10^{-5}\ yr^{-1}m^{-2}$ – iced WT stopped / ice-fall

Mean wind	IEA Icing class 1	2	3	4	5
7 m/s	1,09	1,29	1,37	1,46	1,54
8 m/s	1,25	1,47	1,57	1,66	1,76
9 m/s	1,40	1,66	1,76	1,87	1,98
10 m/s	1,56	1,84	1,96	2,08	2,20
11 m/s	1,72	2,02	2,16	2,29	2,42
12 m/s	1,87	2,21	2,35	2,50	2,64
13 m/s	2,03	2,39	2,55	2,70	2,86
14 m/s	2,18	2,58	2,74	2,91	3,08
15 m/s	2,34	2,76	2,94	3,12	3,30

Radius for $10^{-3}\ yr^{-1}m^{-2}$ – iced WT operating / ice-throw

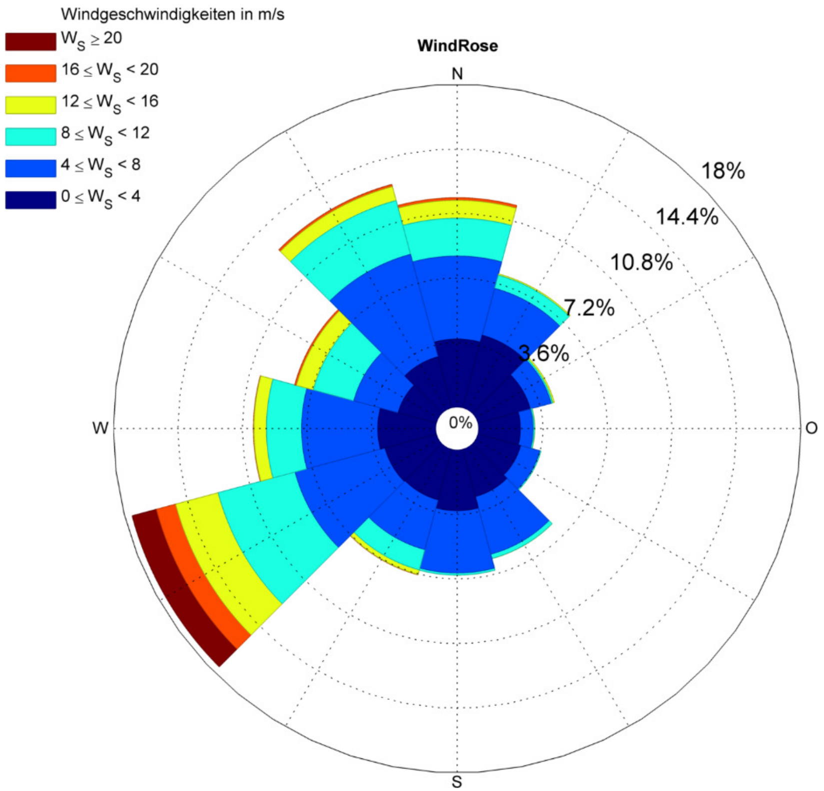
Mean wind	IEA Icing class 1	2	3	4	5
7 m/s	0,91	1,15	1,26	1,37	1,47
8 m/s	1,04	1,32	1,44	1,56	1,68
9 m/s	1,17	1,48	1,62	1,76	1,89
10 m/s	1,30	1,65	1,80	1,95	2,10
11 m/s	1,43	1,81	1,98	2,15	2,31
12 m/s	1,56	1,98	2,16	2,34	2,52
13 m/s	1,69	2,14	2,34	2,54	2,73
14 m/s	1,82	2,31	2,52	2,73	2,94
15 m/s	1,95	2,47	2,70	2,93	3,15

Radius for $10^{-5}\ yr^{-1}m^{-2}$ – iced WT operating / ice-throw

Mean wind	IEA Icing class 1	2	3	4	5
7 m/s	1,61	1,85	1,96	2,07	2,17
8 m/s	1,84	2,12	2,24	2,36	2,48
9 m/s	2,07	2,38	2,52	2,66	2,79
10 m/s	2,30	2,65	2,80	2,95	3,10
11 m/s	2,53	2,91	3,08	3,25	3,41
12 m/s	2,76	3,18	3,36	3,54	3,72
13 m/s	2,99	3,44	3,64	3,84	4,03
14 m/s	3,22	3,71	3,92	4,13	4,34
15 m/s	3,45	3,97	4,20	4,43	4,65

Computed for a frequency of occurrence of $^1/_{12}$ in wind direction bin with the highest wind speed, i.e. $P_{\mathrm{bin}} = {^1/_{12}}$.

An example…



Iced WT stopped / ice-fall

Radius for 10^{-3}: $1.13 \cdot TH$

Radius for 10^{-5}: $1.90 \cdot TH$

Iced WT operating / ice-throw

Radius for 10^{-3}: $1.75 \cdot TH$

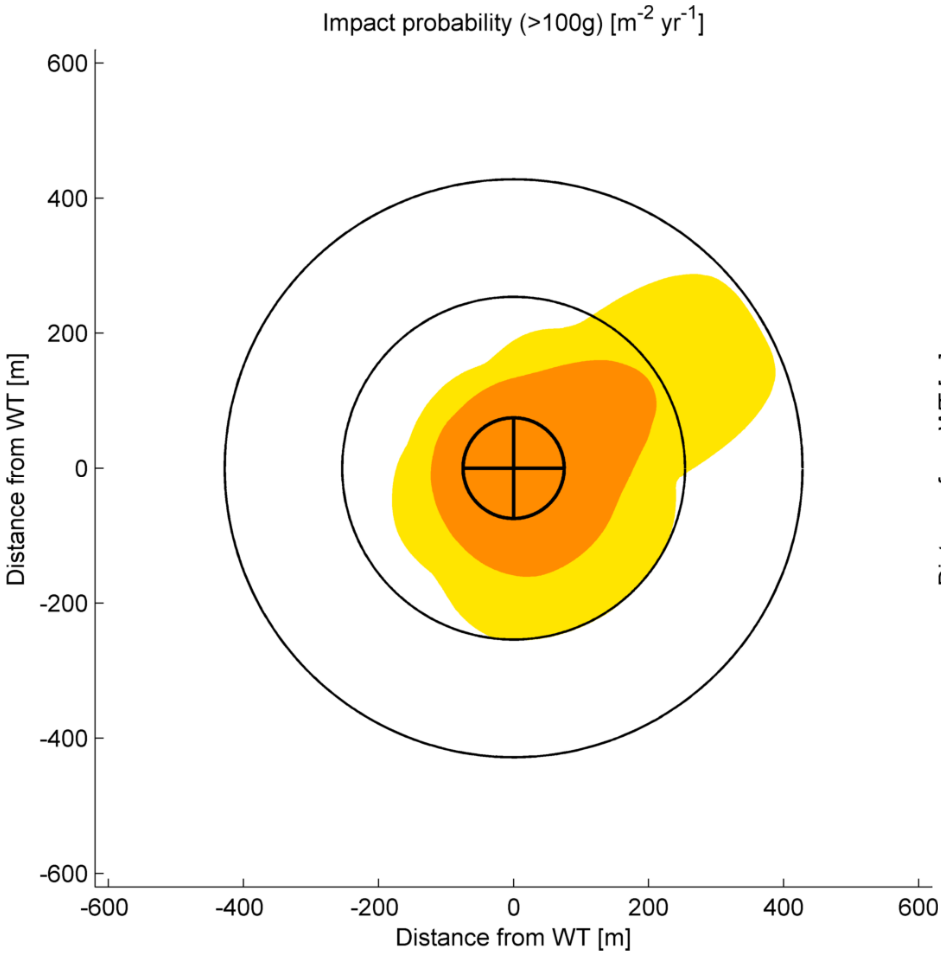
Radius for 10^{-5}: $2.72 \cdot TH$

+ IEA Icing class 2

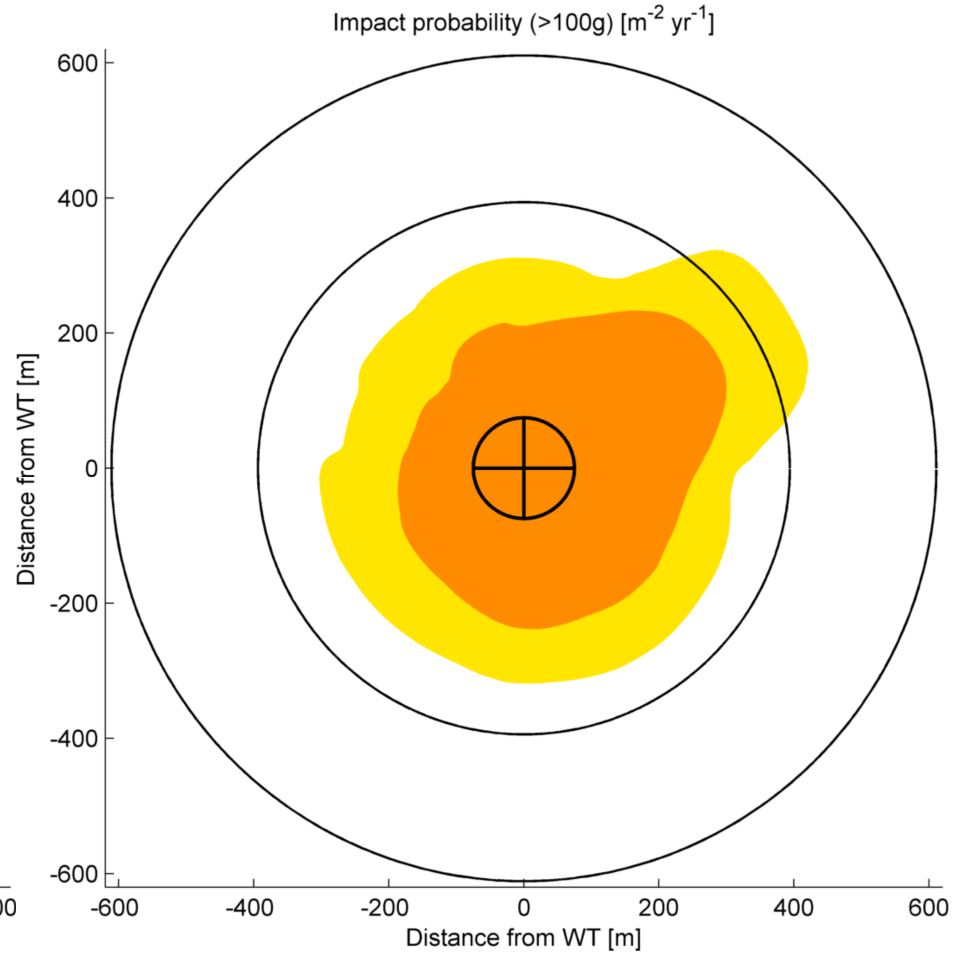
Wind sector [°]	0	30	60	90	120	150	180	210	240	270	300	330
Fraction [1]	0.12	0.08	0.04	0.03	0.04	0.06	0.07	0.07	0.18	0.10	0.08	0.13
Mean wind [m/s]	6.28	4.41	3.59	3.29	3.46	4.48	4.16	5.42	9.66	6.10	7.21	6.68

An example…

Iced WT stopped / ice-fall



Iced WT operating / ice-throw



Figures for a WT with Dia 150m and HH 150m (TH 225m)

Disclaimer

- Is a rough and simple estimate
- No allowance of: wind directions, actual icing conditions, air density, actual WT operation, non-Rayleigh distribution, de-icing or anti-icing
- Ignores actual presence & frequentation of people
- Uncertainties in the ice-fall computations (A/m, ice shape, c_D, number and distribution of ice pieces)
- Nevertheless – useful conservative estimate:
  - Threat from falling ice pieces is largely overestimated (every ice piece above 100g causes a casualty)
  - Most wind directions are better than the “worst” direction
  - Most wind turbines are better than the “worst” turbine
  - Based on conservative usage scenarios

Thank you!