Ice ejection from rotating wind turbine blades

Ground impact probability distributions and danger level estimate

February 2014

Björn Montgomerie

Summary

The danger from ice being thrown is related to the size of the individual ice fragment and its velocity as it hits the ground. The ice fragments can be very small, causing mere annoyance or they can be big enough to be lethal. Between these extremes there is a scale of possible damage levels. It is important to have knowledge about the distance from the turbine where ice falls. Such information can be used for fencing in areas around the turbine or placing signs of warning, both of which are directed to the general public who might want to use the area for winter sports.

In this study the following areas of knowledge have been used.

Dynamics of bodies traveling throw the air
Statistical functions for distribution of ice thickness and throwing angle
Statistical information about the wind from measurements
Terrain characteristics

The results show that the heaviest pieces of ice, in the order of 10 kg, fall in the vicinity of the turbine, while very small fragments, in the order of 1 gram, will be blown as far as 600 m. The problem is complicated by the fact that very little is known about ice distributions around wind turbines. The methods used are therefore dependent on conjecture of several input parameters. These parameters can be modified and the computer programs that were used can be rerun in order to answer questions of type "what-if".

One section deals with the responsibility of the owner versus the public. An algorithm is proposed for the purpose to calculate the probability of a hit on an object of given size in the form of an area projection. For a human body this might be 0.5 m^2. The danger level results can be used for liability considerations as well as discussions with the insurance industry concerning premiums.

Contents

1. Introduction

Wind turbines like other structures, exposed to all weather conditions, will accumulate ice deposits under certain temperature conditions. The risk for ice formation is when the temperature is zero degrees or lower. When ice deposits melt the ice falls to the ground from any structure, whereas the ice may even be thrown from a turbine that operates. That situation may cause damage or injury. In order to analyze these consequences a model of ice ejection and analysis was created. The model was manifested as a set of computer programs jointly called KASTIS in this report. First (step 1) a mechanical dynamic program provides ice throw lengths, weight distributions and momentum distribution at ground impact. The output from this program is a large database in a typical run.

With initial values the trajectory from blade to ground is integrated using the resistive force from the relative wind and gravity as the driving forces. The output can typically contain about 60 million throws and the size of each output file then becomes four gigabytes. These perhaps surprisingly high numbers result from the technique to select a number of realizations from probability distributions of wind direction, wind speed, azimuthal throwing position and ice thickness. The ice, still on the blade, is primarily broken at preset radial positions according to the input. According to the model a break-up of the primary ice blocks, caused by the total pressure exposure at release from the blade, further increases the number of ice blocks thrown. All of these throws add up to the big output with one output line per throw.

Because of the considerable size of the output, from the first step, it was necessary to condense the material into statistical quantities, which were tabled in a program tool designed to read up the big output (step 2). Even the tabled statistical condensation would be far too tedious to the human mind to analyze, especially since the total process is required to be repeated for a large amount of mass class and momentum class cases. Therefore yet another program was created whose purpose it is to present the statistical data in a graphical form using color coding, which is better disposed for human interpretation (step 3).

The intent is that the resulting color charts be used as a foundation for the decision making concerning public access restrictions as well as risk assessment relating to humans and property.

2. Probabilities

Probability of several input variables is an input to the procedure of finding the ground hit probability. For this purpose the wind probability, for direction and velocity, is multiplied by the probabilities for azimuth angle and ice thickness. The resulting number is interpreted as the probability of an individual single throw valid for one piece of ice from *one blade* per throw situation. All pieces of ice leaving the blade will have different numbers assigned to their probability respectively.

The turbine site is divided into angular sectors with radially delimiting circles around the turbine according to Fig. 1. This figure will be made reference to using the term "dartboard". The area, bordered by spokes and circles, is referred to as a pane or a panel. A pane can be pointed to using the integer coordinate system (i, j). Since a pane has four corners a convention is necessary. The convention, used throughout the programs, is to use the highest spoke value and the highest circle value. One pane in Fig. 1 is shaded to illustrate the point. The red dot is placed in the "high" coordinate corner. The figure does not exactly agree with the dartboards used in the programs. There the number of circles, in the main study, was 11 rather than than 4 as Fig. 1 shows.

Each piece of ice will fall into one of the many panels of the dart board. When the whole series of throws has been completed ice will have fallen on most panes. Those that never caught any ice have an ice hit number equal to zero. The extent of the encircled area is set by program logics in step 2, which looks through the big file for the
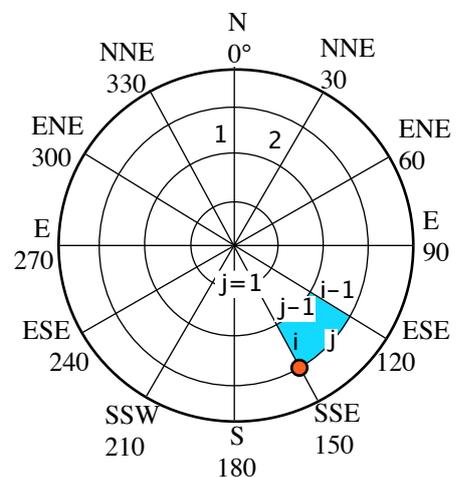

Figure 1

longest throw. The number of circles, however, is defined as an input.

Because the different ice fragments in the different panes represent a wide span of weight a classification is needed. E.g. when the individual ice fragment weights range from 0.8 grams to 12 kg a division into weight ranges is driven by the insight that the 1 gram pieces are innocuous and the weight in excess of say 1 kg is lethal. For purposes of injury risk and property damage the weight ranges, in the cases calculated, were by choice limited by the following limits 0.0008 0.001, 0.01, 0.1, 1.0, 10.0 and 12.0. As seen even decades was the basic principle, while the lowest and the highest values are exceptions. The weight range between two limits will be referred to as a class. In this particular context we have weight classes. Later momentum classes will be also considered. The first weight class is thus from 0.0008 to 0.001.

The division into classes can of course be divided into any other dividing scheme. The described choice was simply chosen as an example when the runs were carried out. A totally different approach would be to break the total mass range into say classes based on severity of a hit. These classes could be associated with guesstimated damage to say persons accordingly: Innocuous, hurting, hurting badly, injurious, lethal. Perhaps an institution such as European NCAP would place the limits between the classes differently. Perhaps the classification would be different when damage to property is considered instead of humans. At the present time this type of knowledge is not yet available to the author.

All individual ice fragment probability numbers, belonging in a weight range, are summed within every pane. The sum, as discussed in Appendix 5, is the number of ground hits of the class within the pane. A class number is assigned to the particular class. In the example six classes became the outcome. The first weight class is noted by the number 1. The other classes are noted by ascending integers. The procedure can be repeated to be valid for momentum at ground hit, rather than weight.

The set of data accumulated as described constitutes the output from the program system.

Program dartboardProb (of step 2), described in more detail below, generates the "probabilities" added within each class within each pane in a textual table format. The underlying technique is the addition of probability numbers and also these numbers divided by the pane area within which the probability numbers were collected. In summary there are two types of "probability" numbers (within each class). One is obtained as a simple sum of individual ice chunk probabilities within a class. It is referred to as type "P1". The other, which is divided by the connected pane area, is referred to as the "P2" type.

The purpose of the P1 type is to serve as a *number of ground hits*. This type is simple for the analyst to get a feel for and make use of for purposes of feasibility checking. The P2 type is used for multiplication by the projected hit area A of say a human. If the result is denoted by P we thus have: $P = P1*A/paneArea = P2*A$. The P2 values are thus more immediately connected to risk assessment for humans and any other object. The P2 values are generally one or two orders of magnitude smaller than the P1 values.

3. Programs

The set of tools used in this study consists of a number of interconnected programs and files. The word *program* in this context is used to mean *computer program*. In Fig. 2 rectangles with a fat blue frame signify program. Those with a thin black frame are files. The programs are presented below in the sequence as seen in the block chart.
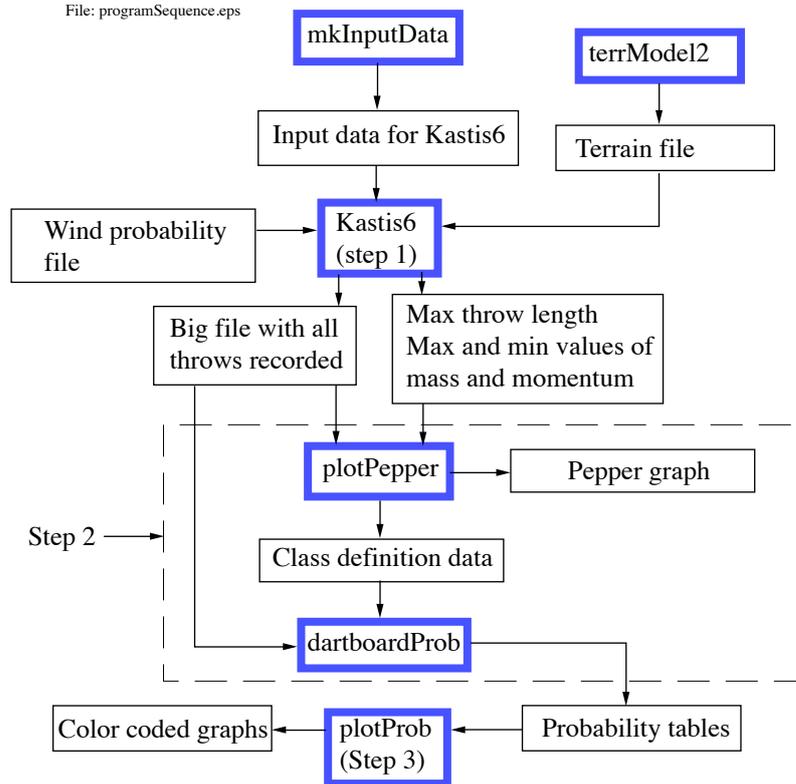
File: programSequence.eps

Figure 2

3.1 mkInputData

The "main" input to Kastis6 can be created with a specialized program/tool called "mkInputData". Its main purpose is to ascertain the quality of the resulting file. If edited from scratch some of the inputs might never be represented because of oblivion or neglect from the analyst of the ice throwing endeavor. Once one file has been created, using the tool, the simplest way to provide a new input to Kastis6 is to simply use a text editor program. The actual main input, for the main study, follows.

```
------------------------------------------------------------------------------
              Input data to program: KASTIS6
                   Sep 30, 2012 16:31
------------------------------------------------------------------------------
iceDist =  1        Ice thickness distribution type. 1 is Gauss, 2 is constant.
nIceThick =  9      Nr of ice thickness discretizations.
sigmaIceThick=0.01  One std deviation.Distr=one half Gauss (ave=0)
withinIce =T        Ice range rule.If true bars stay within 3sigma.
aIce      =0.0000   Low range end value for ice thickness if distr=constant.
bIce      =0.0000   High range end value for ice thickness if distr=constant.
clockDist =  2      Clock distribution type. 1 is Gauss, 2 is constant.
nClock    = 12      Nr of clock positions where ice is thrown from.
aveClock  = 7.000   Center of Gauss distr given as clock position.
sigmaClock= 2.0     Clock "time" width of one sigma.
withinClock =F      Clock range rule.If true bars stay within 3sigma else on limits.
aClock    =1.0000   Low range end value for clock position if distr=constant.
bClock    =12.000   High range end value for clock position if distr=constant.
iceLenRel = 0.10    Ice length rel chord length,valid for whole blade.
nB        =  3      Nr of blades.
nBE       = 51      Nr of blade elements where ice is thrown from.
Rtip   =  50.000    Rotor blade tip radius (m).
Rhub   =   2.000    Rotor blade hub radius (m).
G      =   9.810    Gravity acceleration (normally 9.81)
ROAIR  =   1.225    Air density (Standard sea level: 1.225)
CD0    =   1.000    Drag coefficient of an object with (relatively) sharp edges (=1.0)
H      =100.000     Tower height.
OMEGA  =   1.400    Rotor rotational speed (rad/s).
```

3

```
WG    = 0.000      Vertical wind positive up.For experimental purposes only.
DT    = 0.200      Simulation time step.
overHang= 5.000    Dist from tower center to hub
cutinWind = 3.000  Lowest wind for operation.
cutoutWind= 28.000 Highest wind for operation.
rf    =0.700       Factor on dynamic pressure when breaking ice.
sigmaUlt= 0.50E+06 Breaking tension for ice.
```

Further explanation of the main input is provided in Sect. 4. It can be noted that although the number of blades appears in the input. It is not used anywhere. It is, however, retained for future use.

3.2 terrModel2

Appearing on the right in Fig. 2 is the terrain file generating program "terrModel2". It is used together with a map of the site containing height curves, see Fig. 3. A radial beaming out from the turbine chosen provides a base for the heights given. This radial (even referred to as a *spoke*) has an angle to the north/south line measured like a wind direction. The spoke will cross over terrain height curves. The crossings, appearing in green in Fig. 3, are suitable bases for data points. The complete definition of a terrain point thus consists of spoke angle, radial measure and height.

A small error will be introduced because a wind turbine will rarely be placed exactly on a terrain height curve and the turbine height must therefore be conjectured. Terrain map height values are usually negative. Fig. 3 just illustrates the principle. The actual spoke layout is different in the study. The beginning of an example of a terrain file follows. Italicized text was added for explanation.To get a feel for distances the map height was measured to be approximately 2 km.

```
* File name at time of creation: terrain.txt

Direction:  18.0        <-- The spoke compass direction
 *----------------------
 *  Radius  Height
 *----------------------
  290.0          -10.0 <-- Meters and height rel. to the
  364.0          -20.0     tower foot height
  473.0          -30.0

Direction:  108.0
 *----------------------
 *  Radius  Height
 *----------------------
  120.0          -10.0
  244.0          -20.0
  309.0          -30.0
  436.0          -35.0
```
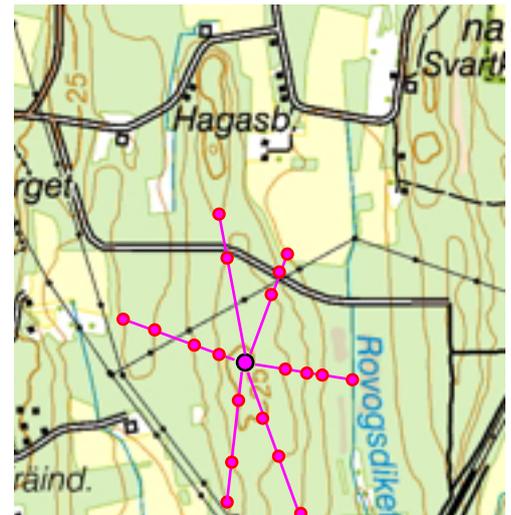

Figure 3

The reading mechanism ignores any line whose first character is an asterisk.

Winds at a site:
One of the three input files to Kastis6 contains the wind information. The following table, based on wind measurements, is a typical requirement. Together with the site terrain description it constitutes the site specific basis of the input set - for a complete study using KASTIS. Each column under the wind direction, in the table, represents the counts of occurrences of binned wind speeds. The wind speeds appear as integer numbers in the leftmost column headed "Bin Mean". If e.g. a wind speed average over 10 minutes is in the range 5.5 < = wind speed < 6.5 m/s then that average wind speed is recorded as 6 m/s. This rule is seen as the somewhat cryptic words "Start" and "End" in the table head.

The next column in the table contains the sum of the values on the right. Table line number 2 contains the average of the wind speeds in the column.

Bin	Start	End	Sum	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Mean				7.87	5.97	6.23	5.98	6.09	6.4	6.84	7.82	8.42	10	9.65	8.32	7.56
0		0.49	613	26	10	42	53	62	37	129	70	36	26	68	54
1	0.5	1.49	1153	94	46	93	79	127	80	137	108	50	68	123	148
2	1.5	2.49	2243	245	123	177	148	200	151	255	205	102	109	229	299
3	2.5	3.49	3638	389	252	263	240	305	246	355	309	179	213	417	470
4	3.5	4.49	5000	494	387	339	317	425	361	493	479	268	335	511	591
5	4.5	5.49	6304	617	524	400	359	499	427	700	654	337	405	668	714
6	5.5	6.49	6968	646	525	346	344	496	455	784	784	424	562	801	801
7	6.5	7.49	7071	499	450	305	366	440	451	775	847	570	633	870	865
8	7.5	8.49	6660	343	342	255	294	404	414	784	797	603	695	912	817
9	8.5	9.49	5846	270	257	196	211	306	364	718	759	626	682	779	678
10	9.5	10.5	4937	175	156	106	148	258	252	641	679	608	645	714	555
11	10.5	11.5	4040	105	92	89	91	187	177	504	596	587	591	586	435
12	11.5	12.5	3190	53	63	56	46	90	127	410	477	543	511	473	341
13	12.5	13.5	2400	36	26	36	30	59	65	294	360	478	456	338	222
14	13.5	14.5	1799	26	6	21	9	35	39	213	288	402	342	253	165
15	14.5	15.5	1301	11	1	9	6	18	30	104	221	313	297	188	103
16	15.5	16.5	920	5	1	6	1	7	6	100	141	243	189	139	82
17	16.5	17.5	589	0	1	3	2	3	11	41	87	149	155	91	46
18	17.5	18.5	396	3	0	1	2	1	2	25	41	116	119	60	26
19	18.5	19.5	261	2	0	2	0	1	0	17	26	69	79	39	26
20	19.5	20.5	169	2	0	1	0	0	0	11	19	59	46	21	10
21	20.5	21.5	87	2	0	0	0	0	0	5	4	19	30	16	11
22	21.5	22.5	52	2	0	0	0	0	0	0	3	15	22	8	2
23	22.5	23.5	21	0	0	1	0	0	0	0	3	4	7	3	3
24	23.5	24.5	12	0	0	0	0	0	0	0	0	2	3	5	2
25	24.5	25.5	9	1	0	0	0	0	0	1	0	1	3	3	0
26	25.5	26.5	6	0	0	0	0	0	0	0	0	1	2	1	2
27	26.5	27.5	1	0	0	0	0	0	0	0	0	0	0	0	1
28	27.5	28.5	2	0	0	0	0	0	0	0	0	0	1	1	0
29	28.5	29.5	0	0	0	0	0	0	0	0	0	0	0	0	0
30	29.5	30.5	0	0	0	0	0	0	0	0	0	0	0	0	0
31	30.5	31.5	0	0	0	0	0	0	0	0	0	0	0	0	0
32	31.5	32.5	0	0	0	0	0	0	0	0	0	0	0	0	0
33	32.5	33.5	0	0	0	0	0	0	0	0	0	0	0	0	0
34	33.5	34.5	0	0	0	0	0	0	0	0	0	0	0	0	0
35	34.5	35.5	0	0	0	0	0	0	0	0	0	0	0	0	0
36	35.5	36.5	0	0	0	0	0	0	0	0	0	0	0	0	0
37	36.5	37.5	0	0	0	0	0	0	0	0	0	0	0	0	0
38	37.5	38.5	0	0	0	0	0	0	0	0	0	0	0	0	0
39	38.5	39.5	0	0	0	0	0	0	0	0	0	0	0	0	0
40	39.5	40.5	0	0	0	0	0	0	0	0	0	0	0	0	0
41	40.5		0	0	0	0	0	0	0	0	0	0	0	0	0
SUM:			65688	4046	3262	2747	2746	3923	3695	7496	7957	6804	7226	8317	7469

The information consists of the number of periods the wind direction sector caught the wind. All wind sampling periods were of a certain sampling period usually of 10 min duration. The average wind, with its average direction, within a period, was put in its appropriate table bin by adding 1 to the number that was there prior to the addition.

Fig. 4 contains a graphic companion to the table, where the following idea is visualized. Each standard wind direction such as N, according to the table head, is a bin-notation for a measured 10 min average of the wind direction, which lies in the blue sector - likewise for NNE, ENE etc.
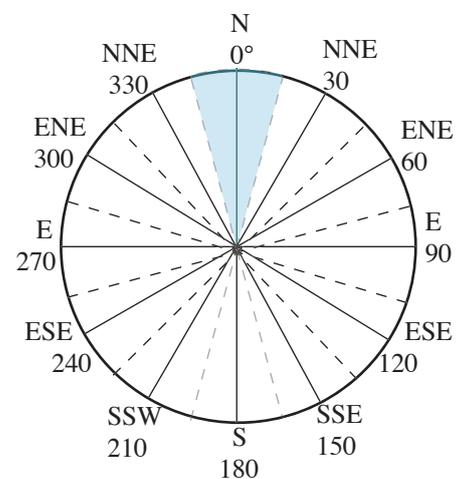
The *probability* of occurrence (not *frequency* of occurrence) is obtained when a bin number, in the table matrix, is divided by 65688. The latter number is the total number of wind catching periods, see the bottom line of the table. A new table can therefore be created in which all original numbers are replaced with the corresponding probability number. The converted table can be thought of as a *wind probability table*. It is not shown in this report. But, it is used as one of the input files to Kastis6.

Figure 4

3.3 Kastis6

3.3.1 *Throw angle*:

As a basis for the work finding the various probability numbers certain distributions of probability and ice accretion patterns must be established. One decision concerns the azimuth angle range within which ice will separate from a blade. This can be subdivided into two problems. The first is to make a statement as to where a typical (probable) azimuth separation angle is to be placed. Since gravity and centrifugal force cooperate at their maximum at 6 o'clock this angle must be a guiding basis. Because of an expected delay in the actual separation an incremental angle should be added. This will place the favored angle at say 7 o'clock. The program sports a Gaussian distribution around the favored angle, which allows possibilities to be explored. Both the favored angle, i.e. the average angle, and the standard deviation are inputs to Kastis6. There is also a constant distribution option available. It is only this constant distribution that was used in this study. Then no particular clock angle is favored. The choice of Gauss or flat is done in the main input file.

3.3.2 *Icing situations:*

Two situations can be discerned in which ice accretion occurs.

Case 1 - General ambient icing conditions:

In a situation when general icing conditions prevail and when the wind velocity is very low - too low for turbine operation. In this case the blades and other structures will collect ice for the same reasons of H_2O phase shift, thermodynamics and heat transfer.

Case 2 - Particular icing conditions on the blade:

One other possible situation is when the wind is up and there are near icing conditions, for fixed structures, but not quite icing. An operating turbine blade will then pick up ice on and near the leading edge at the bulgy side of the blades. The reason is an aerodynamically created low pressure region. The lower pressure is associated with a lower temperature, according to the general gas law and Bernoulli's law. The temperature, in this region of the blade, therefore will settle at a sub-freezing temperature giving rise to local ice accretion.

In the case of mist and sub freezing temperature in the ambient air the turbine blades will also collect ice, but with a different physical mechanism. Whichever situation prevails the leading edge of the blades can then display the different shapes of ice known from aviation literature. The physics, in the described wind turbine situation, is then identical to that of the wing of a flying airplane exposed to the same atmospheric conditions.

Discussion of the cases:

In case 1 the ice, under zero wind or very low wind conditions, will be formed depending on the wind direction and possibly also on the height above ground. If the temperature increases, without any significant increase in wind velocity, the ice will fall down and hit ground below the rotor in a predictable way. The situation might be that mist, drifting at low height above the ground, will dominantly be conducive to ice accretion on the upper blade(s). As the wind picks up an "intelligent" control system, after initial starting, will soon discover a one-per-revolution imbalance. This should lead to an expeditious halt, whereupon a renewed attempt might or might not be successful depending on the presence of ice, which might have fallen off the blades essentially without rotation. In the case of an interrupted start it seems likely that the rotation will be interrupted long before operational RPM has been reached. The ice, if it does fall off, will essentially fall in the predictable vicinity below the rotor. Falling ice trajectory is treated below.

In case 2 the gradual ice accretion does not necessarily lead to a noticeable unbalance immediately. Therefore the situation will pass unnoticed by the control system, while the ice is building up. Following an increase in the ambient temperature ice may be thrown and this happens at operational RPM. This case is the more troublesome one since ice can be thrown a long way from the turbine if it is compact. The general public might be unaware of the phenomenon and therefore be potentially exposed to an unacceptable risk of injury. This case therefore represents the more serious situation, which merits a deeper analysis. This is therefore the topic of this report, while general ice accretion is not treated.

In both cases (1 and 2) ice can be blown by the wind while the turbine is parked. A wind velocity of 9 m/s will cause a trajectory, for the falling ice, which approximately has an angle to the ground of about 70°. At 15 m/s this angle becomes 56° from a numerical example investigated. The trajectory is not a straight line and the compactness and absolute weight of an ice block all contribute to the trajectory shape. The numbers given are therefore approximate. But, they are good for drawing the conclusion that ice from a parked turbine is capable of traveling a long distance before hitting ground. This is a situation which was not covered numerically in the computer runs reported here. But, the train of steps of calculation would be similar to those presented here. One additional concern would consist in the expected deviation in wind direction and nacelle direction, because all control systems may not turn the nacelle into the wind while being parked.

3.3.3 *Ice forms*:

In reality the flying ice will take an infinite amount of shapes. There is, however, a common feature of all these shapes benevolent to analysis. They have mostly sharp edges. This allows the application of beneficial "sharp edges aerodynamics". A blade of a wind turbine is the very opposite. Its shape allows the lifting force to be in the order of 100 times larger than the drag force. In this case lift is the power generating component of the total aerodynamic force on the blade. The characteristic of the lift is that it is perpendicular to the relative oncoming wind. In the case of a blade failure the lift component might extend the "flight" of a blade thrown. The blade lift is partly caused by the smooth leading edge. Without it the lift would be poor and on a par with the drag force. The latter always works in the direction of the local relative wind (relative to the "flying" object).

When the ice leaves the blade it will therefore essentially only be affected by gravity and drag. Disregarding lift in a model of a simulation method, for the throw dynamic equations during flight, simplifies the problem considerably. It means that the only aerodynamic force acting (drag) is in the direction opposite to the relative wind. The moderate lift force, acting perpendicularly to the relative wind in the real throw, is assumed to give a stochastic deviation, such that on the average the ground hit distribution will not seriously deviate from that of a large amount of tested real cases (which still does not exist). If also lift were to be included in the model the associated dynamics would e.g. require a model for rotation of the ice block. This poses a considerable complication of the dynamics equations with only a very doubtful improvement of accuracy in the predicted ground hit position distribution. The lack of improvement, if lift were to be included, can be assigned to the lack of knowledge of lift and moment characteristics.

The ice forms can therefore be stylized to look like square edged blocks like a board or a brick, see App. 1. The relation between the sides of the block is important. If the shape is close to a cube its gravity load will be much more dominant than the air load. This leads to a trajectory, which is more close to ditto in vacuum. Vice versa the thin ice sheet will travel on a trajectory, whose shape is more like that of a falling autumn leaf, which essentially drifts with the absolute wind. Because of these differences in trajectories a variation of the block shape is necessary in the simulations of the throws in order to mimic reality.

Calling the length of the sides of the ice block *a*, *b* and *c*, where *c* is the thickness, the effective variable, determining the form of the trajectory, is the mass of the block divided by its average area (*Aa*). The average area is obtained as the normal projection of the block integrated over all space angles. This is because the block is assumed to tumble through all angles during its journey from blade to ground. It is then assumed that it has time to expose itself to all relative wind directions. The integral, resulting from this model assumption, has an analytic solution leading to a very simple expression for the average area (*Aa*) exposed to the relative wind during the trajectory.

$$Aa = (ab + ac + bc)/2$$

The details of the derivation appear in App. 1.

Ice mass formula:
The ice mass (*m*) depends on absolute size accordingly:

$$m = a \cdot b \cdot c \cdot \rho_{ice}$$

7

The density of ice is approximately: $\varrho_{ice} = 900$ [kg/m^3].

The selection of size of c is complicated by the large variability of the parameters affecting ice accretion. One dominating parameter is the size of the turbine. For lack of a simple theory the selection of ice thickness is left to the user of the software. By giving a value to the one sigma deviation the maximum ice thickness will result from the selection of number of discretizations from the ice thickness distribution. This is further discussed in Sect. 4.1.

The outer part of the blade travels faster than the inner part. Therefore, on the average, the ice accretion tendency is greater toward the tip, while the surface to stick on is smaller. Thus, there seems to be two counteracting effects pointing in the direction that the ice absolute thickness maybe is about constant along the blade. There is more theoretical support for such an assumption. This has to do with the dynamics of the mist droplets hitting the blade leading edge. There seems to be an effect reminding of the Reynolds number effect because small droplets will "notice" the oncoming blade earlier where it is thick. Therefore they have more time to be driven *along* the "stream lines" rather than hitting the blade surface head on.

The hypothesis of the ice thickness being constant with radius was adopted in the icing model, thereby shortcutting the very complex background for the ice accretion.

All of the described areas are implemented in Kastis6. It outputs a formidable file (the present one of 4 GB) containing many characteristics of every throw. There is also a mechanism that gathers maximum throw length and the maximum and minimum values of mass and momentum at the ground hit points. These extreme values are outputted in a "diagnostics" file.

The main output consists of one line per throw. The following is a list of the contents of such a line, where the first word preceding the explanation is the Fortran name of the variable.

3.3.4 *Kastis6 output*:

```
lineCount     Counter of the throws (... not lines; there are a few leading lines before
the results).
xHit          X coordinate of the ground hit (X points east)
yHit          Y coordinate of the ground hit (Y points north)
zHit          Height above tower foot (frequently negative).
mass          Mass of ice block.
v             Velocity of ice block at ground impact.
hitAngleDeg   Hit angle relative to the vertical.
Whub          Wind speed at hub height (input from the wind probability file WPF).
FIDEG         Azimuthal angle at which the ice was thrown.
GAMDEG         Wind direction (input from the WPF).
prob          Probability from: WPF, distributions of ice thickness and azimuth angle
rPos          Radial position when the ice left the blade.
Arf           Aerodynamic reference area
thick         Ice thickness (called c in the derivation of the reference area)
```

3.4 PlotPepper：

The output files from Kastis6 are next fed into a program called "plotPepper". It outputs a proposed classification of mass and momentum, based on the maximum and minimum information in the diagnostic file from Kastis6. Both of mass and momentum contain values from very small to quite big. To put these on an understandable scale it turned out necessary to use the 10logarithm of the mass and momentum values as explained in Sect. 2. The classification can be modified by the user on line, in response to a dialog, if necessary. The major part of the classes file appears next:

```
 *     Output from program plotPepper
 *     *****************************
 *     May 1, 2012 11:50:23

File: classesA4.txt

Number of blades =   3
   *** Mass classes ***
  ------------------------
  Number    Class limits
  ------------------------
      1          0.00080
      2          0.00100
      3          0.01000
      4          0.10000
      5          1.00000
      6         10.00000
      7         11.16000


   *** Momentum classes ***
  ------------------------
  Number    Class limits
  ------------------------
      1          0.00470
      2          0.01000
      3          0.10000
      4          1.00000
      5         10.00000
      6        100.00000
      7        372.67999
  ------------------------
```

Again the number of blades appears without a purpose. This is just one of many features of a program that is academic and under development. I.e. it is far from commercial standard. This is in fact so also for the other programs in the program chain. It also means that the technique to run the programs requires the knowledge and vigilance of the creator to produce the correct results.

plotPepper also outputs plots showing the ground hits for all throws within a class. The output emerges as ground pepper strewn over the dartboard while plotPepper works its way through the big file from Kastis6. Typically five to six minutes are needed to complete the plotting. This is, however, of no consequence for the probability/number-of-ground-hits issue. The plotting is designed to enlighten the analyst as to what sort of pattern the pepper portrays. From these charts it appeared that 30° sectors must be used as dictated by the wind table set of directions and seen in Fig. 1.

3.5 dartboardProb:

The big file from Kastis6 and the classes file from plotPepper are used as input to program "dartboardProb". dartboardProb generates a text file containing the probabilities for all dartboard panes for both of the classes for mass and momentum. The first half is valid for mass, while the second is the corresponding momentum information. A small excerpt from the beginning an output file (of about 32 pages) from dartboardProb follows:

```
 * Created: May 7, 2012 16:26:16
 * This is a probability file from program dartboardProb.
 * File name at time of creation = paneProbA4.txt


 * Catch area definition:
    Max radius = 611.0
    Number of spokes = 12
    Number of circles = 13


 * Probabilities of mass:
   ********************

    Mass class = 1
    Interval = 0.8000E-03 0.1000E-02
 *---------------------------------------------------------
 *   Spoke     Circle     Probability  Probability/paneArea
 * ---------------------------------------------------------
      1          1         0.24220E+00    0.41881E-03
      1          2         0.12731E+01    0.73379E-03
      1          3         0.14234E+01    0.49226E-03
      1          4         0.10257E+01    0.25338E-03
      1          5         0.60779E+00    0.11677E-03
      1          6         0.41100E+00    0.64608E-04
      1          7         0.20218E+00    0.26893E-04
      1          8         0.82677E-01    0.95308E-05
      1          9         0.30914E-01    0.31444E-05
      1         10         0.80616E-02    0.73367E-06
      1         11         0.13615E-02    0.11210E-06
      1         12         0.29416E-03    0.22115E-07
      1         13         0.00000E+00    0.00000E+00

      2          1         0.21278E+00    0.36794E-03
      2          2         0.13266E+01    0.76464E-03
      2          3         0.13691E+01    0.47347E-03
      2          4         0.10142E+01    0.25052E-03
      2          5         0.65763E+00    0.12635E-03
      2          6         0.48806E+00    0.76721E-04
      2          7         0.28054E+00    0.37316E-04
      2          8         0.13718E+00    0.15814E-04
      2          9         0.64989E-01    0.66104E-05
      2         10         0.20486E-01    0.18644E-05
```

The third column is still headlined "Probability". But, it might as well be called "Number of ground hits". It seemed, however, convenient to use the shorter word Probability. The two columns for probabilities are also referred to as probability of type P1 and probability of type P2. Even though the word probability is used throughout this report the true technical meaning is number of ground hits.

3.6 plotProb:
The probability text file, as described in the previous subsection, contains the important result of this study. Since lengthy tables of numbers are difficult to use for an impression of overview, and therefore interpretation, the plotProb program was created to make these things easier. There is, however, a difficulty arising from this decision. It has to do with shades of color.

The basic idea is to assign a light color to a low probability. Increasing probability numbers should then give the impression of higher probabilities. After experimentation it was discovered that a maximum of seven shades of the same color can be used. Trying eight shades made interpretation difficult, because some shades appeared too similar. This was emphasized when such a color scheme was printed. Printer outputs are generally not sufficiently faithful to the colors of the computer screen.

Since it would have been attractive to be able to represent the probabilities in perhaps eight shades an additional color other than blue was tested in the same scale. The result, however, appeared to be slightly confusing and the idea was therefore abandoned.

It should be noted that four categories of classes exist. The two classes of mass and momentum respectively have, under their definitions, two classes of probabilities to be coined *sub-probabilities*. The sub-probabilities, P1 and P2, are distributed on a scale just like the distributions of mass and momentum. That is the reason for grouping even the probabilities into sub-probability classes. The numbers seen above, in the text file, are thus never directly seen in the color coded charts directly. Instead probability of both types P1 and P2 are fitted into their appropriate class. Then the class* is color coded and applied to each dartboard pane. This is the background for the dartboards seen in the results section of this report.

4. Algorithms
4.1 Model ideas
Fundamentals:
The following statements are fundamental in this study.
The probability of ice on the "full" aerodynamic length of the blades = 100%.
The probability of a throw from a given blade station (throw station) is 100%.

Number of blades:
The blades are considered identical concerning the build-up of ice. Each blade thus contributes identically to the ice deposits on the ground, because all throws are deterministic. This allows the analysis to be limited to one blade and the probability results are simply multiplied by the number of blades, see Appendix 5. The actual multiplication is not carried out in the KASTIS6 (Step 1) program. This should be done after all calculations have been carried out by the KASTIS family of programs.

Geometric issues about ice:
A discrete number of radial stations (*nBE*) were used for the release of the ice blocks. The ice block was sometimes subdivided into smaller fragments because of the impulsive onslaught of the wind relative to the ice at the moment of release. Before release the ice is of course stabilized by the blade surface, while at the time of release different parts of the ice block will experience different dynamic pressures. The difference in dynamic pressure, resulting in a force distribution and a bending moment distribution, is modeled in a simplified way to accomplish the cracking of the original ice released, see Appendix 4. Cracking of course causes the geometry to change and the calculation method takes this into account partly by assigning the notation *a* to the longest side of the fragment and *b* to the shorter. The thickness (*c*) remains the thickness.

The part of the blade between radial stations is referred to as "blade elements". The length of each blade element will thus determine the initial radial length (*a*) of the corresponding original ice block. This length is also equal to the maximum ice block length, maximum with respect to the cracking in the air, which will create smaller length ice shards.

The release point radius of the ice is placed at the radial mid-point between stations. There are thus *nBE* blade elements and as many ice release points. The root part, being excluded as an ice ejector, is thus determined by the first blade station.

One input quantity sets the fraction of chord length where ice exists. This results in a number for the measure *b*, the breadth of the ice sheet - depicted in Appendix 1. This measure is not treated as a stochastic variable. Only the thickness is.

There is an inherent difficulty in obtaining a known accuracy in this method for the ice geometry. The only way to approach a solution is to study actual events where ice was or is being thrown. The events should preferably be taken up by a video camera and the frames studied one by one where the events of interest occurred. Conclusions from such studies will suggest the numerical settings of both input and model parameter values. At the time of writing this text there are no such data available.

Gauss distribution of the ice thickness:
The absolute ice thickness probability is assumed to be Gauss distributed and must be defined in input. The input quantities are the size of the standard deviation, of the ice thickness (c), and number of realizations of the thickness. The input value of the maximum ice thickness, in the distribution, is modeled to coincide with 3σ. Only the right half of the Gauss bell curve is used because the other half is negative. The chord is preferably obtained from the relevant blade or possibly estimated from similar blade geometries. In the study presented here a photograph of a Siemens blade was used as a basis for obtaining the approximate chord-vs-radius typical data and the chords were normalized using the tip radius, see App. 3. The author makes no claim to accuracy in the resulting geometry of the blade, which is only "sketchy". But, considering other approximations in the model this should cause no disturbing error of the final results - because in truth there is no way to check any accurate behavior of any general ice geometry.

The blade azimuth angle at ice release can be Gauss distributed or have a constant distribution as chosen in the input.

The combination of wind speed and wind direction, from meteorologists, is available and assumed valid for winter conditions.

A Gauss distributed quantity is modeled to be divided into discrete probabilities inside of *three* standard deviations (3σ). By input choice this may also be, but was not in this study, the model rule for the distribution of throw position azimuth angles. The sum of the discrete probabilities is forced to be exactly equal to 1.0. This is accomplished by modifying the flank probabilities a little to include the minute amount of remaining probability outside of the three σ.

The present implementation, in the ice thickness area, is to use a Gauss distribution, whose average value is zero. Only the possible positive side is used. Since only one half of the bell curve is used its ordinate values are multiplied by 2 in order to make the area under the curve equal to 1.0, see Fig. 5.

The Gauss curve can be approximated by a series of vertical bars of equal width. The width, of each bar, is used from the left limit to the right limit to integrate under the curve. The result is the probability, that the ice thickness will be in the interval from the left to the right limit of the bar. The approximation can also be seen as a *discretization* of the curve. In the model the corresponding discrete representative thickness values were chosen to be the mid-points of the individual intervals, which are pointed at by the triangles under the ordinate.
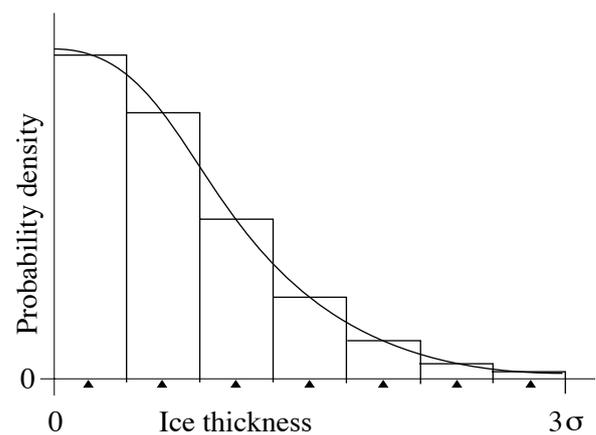

Figure 5

Fig. 5 displays an example with 7 discrete ice thicknesses and correspondingly 7 probability numbers. It can be deduced, from a mere glance at the figure, that if the number of bars is increased it has the consequence that the first bar (corresponding to the lowest ice thickness) becomes narrower, causing the leftmost triangle to move left. Therefore the lowest ice thickness will be lowered. Analogously the highest ice thickness increases when the number of bars is increased. Yet, as pointed out above, the sum of the discrete probability values is exactly 1.0. One consequence of the method is that ice thicknesses are not known beforehand.

The reason for choosing the normal curve in this manner was because it is simple to treat and because there was no guidance to the author to a better theory. The corresponding code was implemented in Kastis6.

Material characteristics of ice:

*Since the plots only show classes, not exact individual numbers, the source of the probability plots must be consulted for more exact knowledge.

The material characteristics of ice having a temperature near 0°C are available in the literature. The ultimate stress in tension varies around 1 MPa, the lowest value of course being 0 and colder ice having values of several MPa. The input includes an ultimate stress variable. Then bending moments can be crudely estimated during the release phase where breakup of the ice occurs. The break-up model is described in Appendix 4.

The ideal would be actual statistics from a site where comprehensive ice throwing has occurred on soft and deep snow, followed by an educated gathering, measuring and sorting of the pieces found. Sources of this type of information, although very valuable, are also very sparse not to say non-existent.

4.2 Wind:

During the throw the natural wind (V) varies as a function of the height above the ground. For a flat and horizontal ground various formulae, originally extracted from measurement and analyzed to fit in a mathematical form, exist to describe the variation with height. A simple and practical application, of the various expressions seen in the literature, is the following.

$$V(x) = V_H \left(\frac{x}{x_{Hub}} \right)^{1/7}$$

where x is the height above ground and V_H is the wind velocity at hub height. In order to adapt to real circumstances the exponent should be changed to reflect the atmospheric stability. The 1/7 used here is valid for neutral stability. The formula was implemented in this study with the added feature that wind velocity below the tower foot was set equal to zero. However, since very small and light ice fragments were shown to travel a long way at 28 m/s of wind speed, in excess of 600 m, it might be attractive to use a more refined wind model for future studies of the same nature. For this purpose the following expression can be used.

$$V(x) = V_{hh} \ln \left(\frac{x - h_0 + z_0}{z_0} \right)$$

Here x is the height above a flat and horizontal ground. V_{hh} is a reference wind which causes the hub height wind velocity $V(x_{hub})$ to be the one selected for each wind case. It is calculated from inverting the expression such that

$$V_{hh} = V(x_{hub}) / \ln \left(\frac{x_{hub} - h_0 + z_0}{z_0} \right)$$

h_0 is the height of the "zero plane" relative to that of the tower foot. Instead of tower foot height, as a base for the formula zero height, a horizontal plane above the tower foot height is sometimes considered to be the zero plane from which the height should be counted. Application of this idea is suited when e.g. a forested landscape constitutes the basis for the wind variation with height. Then an approximate 2/3 up the average tree height is being suggested as the zero plane height. Values of z_0 can be obtained from Appendix 2.

Undulating ground is considered in this study. Therefore an approximate extension, to heights *below* the ground at the tower foot, can be made. There are two different cases that come to mind when this problem is pondered. One is to consider only the height above ground regardless of the variable height of the ground. This would require a recalculation of V_{hh} at every time step of the simulation. This ascertains that the wind has some finite value even when the ice block is lower than the tower foot (or if applicable the zero plane).

The other case to consider is the wind velocity = 0 when the ice block is below the level of the tower foundation, as is the case in the present study, although with the exponential formula.

4.3 Aerodynamics

The aerodynamic force, acting against the relative wind, is obtained from the following expression.

$$D = \frac{1}{2}\rho W^2 Aa \cdot C_D$$

where the air density ρ[kg/m³] is variable with the meteorological pressure, temperature and altitude above sea level. Normally an industry standard atmosphere is used in contexts like this. For a standard atmosphere only altitude is necessary to extract ρ from a standard (std) atmosphere table. At sea level std $\rho = 1.225$ [kg/m³]. This number was used in this study. W[m/s] is the momentary relative wind velocity vector at an arbitrary time step in the integration of the journey. Aa is the reference area derived in App. 1. For the drag coefficient C_D a standard value equal to 1.0 was used.

4.4 Dynamics:

The characteristics of the ice is determined from the input values leading to the radial extent of the primary "mother" ice block. The following break-up into smaller fragments will lead to the final shape used for assessment of weight, aerodynamic reference area and the trajectory.

The ice block, ready to be thrown, is modeled to leave the blade at an initial velocity equal to the velocity of the radial mid-point of the blade element from where the block separates. Its subsequent absolute velocity is governed by the vectors of gravity force and resistive drag leading to a curvilinear trajectory, which is integrated per time step. The integration, over a single time step, is carried out twice (from acceleration to velocity to position) using a Runge-Kutta 4th order method. Monitoring both height of the block (hb) and height of the undulating ground (hg) makes it possible to calculate the difference $dh = hb - hg$. When dh is found to be negative the corresponding throw dynamic calculation is interrupted. Then the ground hit coordinates are found by linear interpolation using the situations in the two last time steps. The ground hit is represented by one text line, in the output file, including the quantities described under the Kastis6 section above. There is one line per ice fragment thrown.

6. Turbine owner risk assessment

A slightly different type of dartboards, where the class probabilities is divided by the pane area, has also been generated. The quotient was given the notation "P2". The danger for an object on the ground, which/who is present in the pane, when ice is being shed, is now easy to calculate. Assuming that the hit area of the object is A_{Obj} m² gives

$$P_0 = P2 \cdot A_{Obj} \quad \left(= \frac{P1}{A_{Pane}} \cdot A_{Obj} \right) \tag{1}$$

where P_0 is the probability of a hit provided there is *one* object in the pane area.
This is also the appropriate place to mention that the final probability, for the object, also depends on the frequency of sensitive objects being present in a pane. This is the responsibility of the turbine owner and the activity needed is as follows:

Table of site specific variables:
1. Define an area C around the turbine, which is a circle having a radius R equal to twice the tower height
2. Define the fraction of the year (days/365) when icing conditions can occur (k)
3. Find out how frequently (times/month) parties of people, animals, or vehicles, pass through C during the icing period (f)
4. Find out how large the average party size is (can be a number with decimals trailing the period) (N_{Ave})
5. Find out how long time (hours/visit) these parties tend to be present in C (T_{pres})
6. Calculate (find) the area of the pane (A_{Pane})
7. Number of ice throw events/year $N_{Event} = 3$
8. Number of years of the period of interest $N_{Years} = 1$

The probability of an object being present in the pane area when the ice falls is P_{Pres}. This is equivalent with the number of objects (mathematically smeared to be) permanently present in the pane area during the icing

season - a number considerably less than 1 if people or vehicles are under consideration. (The duality between probability and "number of" reappears.) P_{Pres} is calculated from:

$$P_{Pres} = k \cdot 12 \cdot f \cdot N_{Ave} \cdot \frac{T_{Pres}}{365 \cdot 24} \cdot \frac{A_{Pane}}{\pi R^2} \tag{2}$$

The probability per year and per ice throw event is called P.

$$P = P_0 \cdot P_{Pres} \tag{3}$$

This is the probability/year/(throw event) that an object is hit by an individual ice block of the class. It is emphasized that if there are more than or less than one throw event per year, or a certain period of time in excess of one year is considered, the value must be multiplied by number of events/year (N_{Event}) and (N_{Years}).

There is also a possibility to decrease the risk by establishing safety measures near and on the site. These could be information boards informing the public what upwind and downwind means and that the downwind side is the dangerous one. Also general icing information, at weather conditions described, as well as the danger of falling ice from a parked turbine could be part of the information. Signs of warnings spread out in the terrain and fences reduce the risk even more. The reduction can be expressed as a factor (f_{Safety}). It can be noted that the safety factor is = 1.0, i.e. there is no risk reduction when animals are the objects of an analysis.

The encompassing formula including all ingredients is:

$$P_{Pane} = P2 \cdot A_{Obj} \cdot k \cdot 12 \cdot f \cdot N_{Ave} \cdot \frac{T_{Pres}}{365 \cdot 24} \cdot \frac{A_{Pane}}{\pi R^2} \cdot N_{Event} \cdot N_{Years} \cdot f_{Safety} \tag{4}$$

This expression is used to calculate the risk of hit in *one* pane area. The only numerical change between panes is in $P2$, T_{pres}, A_{Pane} and f_{Safety}. A practical application is therefore to separate $P2$, T_{pres} and f_{Safety} from the rest of the formula. The rest is denoted B. An algorithm for producing a basis for cost and business agreements could be designed as follows:

Start of algorithm:

1. Preparation
    Settle for a KASTIS output based on the $P2$ concept
    Settle for a class
    Settle for the site specific input variable values
    Prepare a list of values of T_{pres}
    Prepare a list of values of f_{Safety}

    Calculate B from:
$$B = A_{Obj} \cdot k \cdot 12 \cdot f \cdot N_{Ave} \cdot \frac{1}{365 \cdot 24} \cdot \frac{1}{\pi R^2} \cdot N_{Event} \cdot N_{Years} = \tag{5}$$
$$4.3604E - 04 \cdot A_{Obj} \cdot k \cdot f \cdot N_{Ave} \cdot N_{Event} \cdot N_{Years} / R^2$$

2. Next pane
    Get the appropriate $P2$ value
    Get T_{pres} from the list
    Get f_{Safety} from the list
    Calculate P_{Pane} from: $P_{Pane} = B \cdot P2 \cdot T_{Pres} \cdot A_{Pane} \cdot f_{Safety}$ (6)

    Save P_{Pane} suitably connected to the appropriate pane coordinate system (i, j), see Fig. 1.
    If (there are panes left for analysis) then
        go to 2
    else
        goto 3

end if
3. Next class
        if (all classes have been used in the analysis) then
                END/STOP
        else
                Sum up the Ppane values to be the probability to hit a person of this class.
                Choose a new class
                go to 2
        end if
End of algorithm

Numerical example. Object is human:
From figure 9 we have:
Mass class 5: 1kg < mass < 10kg Probably lethal.
Probability class 3: 10^{-6} < P2 < 10^{-4} To be conservative P2 = 10^{-4} is chosen.
Pane position W - WSW, 6th pane from the center
A_{Pane}= 6000 m^2
A_{Obj} = human hit area 0.5 m^2
P_0 = P2*A_{Obj} = 10^{-4} * 0.5 = 0.5E-04
k = 0.42 (= 5 months)
f = 6
N_{Ave} = 2.5
T_{Pres} = 0.33 h
R = 180 m
N_{Event} = 3 Ice events per season (per year)
f_{Safety} = 0.6

The result for this one pane is: 1.51E-8

7. Future development of KASTIS
Many ideas for improving the KASTIS code package has been pondered by the author. Some of the more important ones are described here.

The group of programs of KASTIS should be fused into one program. There are some gains in calculation speed to be expected when this is completed. Besides it will be easier for the user to maneuver between the different parts.

The number of blade elements could be subject for application of a probability distribution. The present equidistance feature of the blade elements, as of the present model, could be changed to reflect some future findings that e.g. the primary ice blocks near the root tend to be longer than those of the tip region. Presently, however, there is no knowledge of any such indicators.

The ice thickness, presently assumed constant with the radial coordinate, should be thinner toward the tip. Photographs indicate this fact.

The output from KASTIS6 includes, on the output line, *mass* and *momentum*. Both refer to the ground collision velocity. Future development of the KASTIS system will also include the *energy* of the ice clumps at the ground hit event. A similar set of dartboards, valid for energy, will then result.

The risk assessment, according to the section on this theme, should be coded for ease of handling.

8. Main results
The ground has variable height according to an example of a terrain map appearing in Fig. 3. When the final analysis results from using the terrain map and flat ground were compared the difference was found to be

small. The difference in the surrounding terrain patterns were, however, quite different. This indicates that the terrain has a relatively minor influence on the outcome of the ice landing positions. This is explained by the fact that the wind velocity, below the tower foot height was set equal to zero by the algorithm. Thus the wind does not drive the ice below this level causing the horizontal component of the velocity to approach zero.

Appearing in the following figures are both of mass and momentum (2 of) with probability type 1 and probability type 2 (2 of) giving rise to four diagram types. Then there are 6 classes in each of the four combinations giving rise to 6*4 = 24 diagrams.

The reader is made aware of the fact that the color plots are simplified representations of the probability text files generated by the dartboardProb program. This file, the source of the plots, contains more detail. The probability files were found to be too big to be included in this report. The two cases presented, having one probability file each, would have required about 64 pages for this purpose.

The analysis results proper are preceded by example results from the plotPepper program. Since the method to produce these diagrams was intended only as an intermediate step in the creation of the total method only a few are shown in this context. They have no bearing on the final results.

Fig. 6 shows the ultimate influence from the wind because the ice fragments are of small size, as seen in the mass class definition. The small fragments are not noticeably affected by the ejection velocity. They rather attain the natural wind velocity almost immediately after release. As a result they leave their 3D ejection point and drift with the wind in a straight line in this top view. In reality the drifting is affected by natural turbulence and a minor variable lifting force, which would smoothen the sharp outlines of the different spoke patterns. But, the largest smoothening effect, in the natural case, would come from the continuous character of the direction of the nacelle.

The paneling, chosen for the catch area definition, represents 12 wind directions. These were used for the throwing procedure. It is seen how the ice landing positions occur on and around the radials giving the visual impression that there is no ice falling between these artifactual spokes. But, this is expected behavior simply because an infinite number of wind directions were not available from the wind data file.
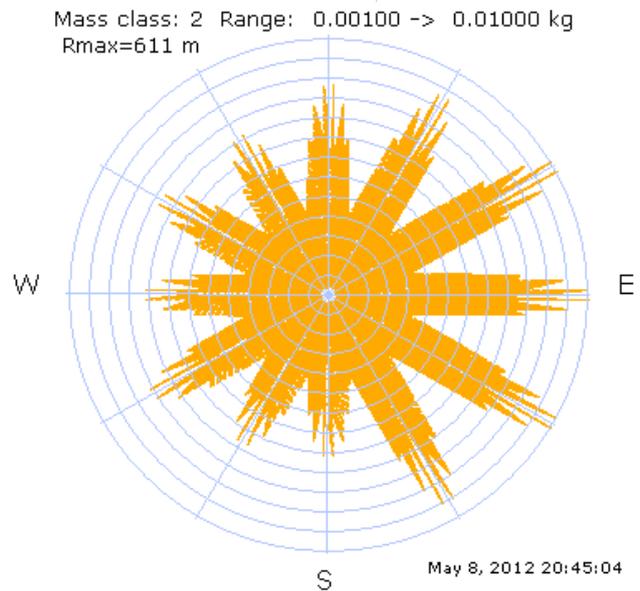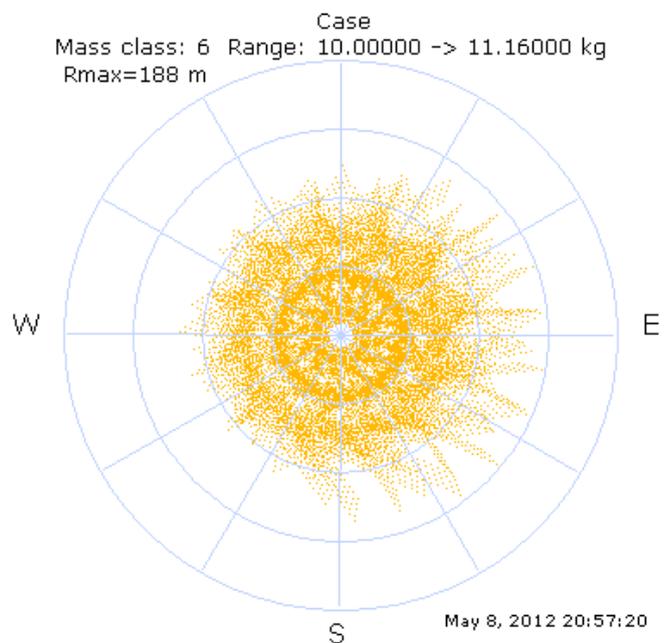

Figure 6

Figure 7

17

Fig. 7 is a zoomed-in picture of the heaviest mass class. In relation to Fig. 6 it is demonstrated how the heaviest pieces of ice are collected around the turbine. The remotest positions are at about 140 m from the tower.

The difference in throwing patterns, between the two pictures, is also to be referred to the ice breaking mechanism, where the dynamic pressure is the driving force. Since the dynamic pressure depends on the radial position ice release velocity squared, its influence is greatest at the tip of the blade. Thus, the further tipward the smaller the fragments. As a consequence the heavier ice blocks released from the vicinity of the root have a low initial velocity, because of the small radius, causing short throw lengths.

The characterization of the difference of the ice throwing patterns is very sensitive to the assumed value of the ultimate tension of the ice. In an otherwise equal study an increase of ultimate tension will give rise to longer throws of the heavier ice blocks. Another consequence would be that the total number of throws would be reduced, since the fragmentation would be less pronounced.

Two examples out of the many cases calculated follow. The mass classification was chosen for presentation. All plots in figure 8 and 9 represent one given input set. Figure 8 shows the same set for probability type 1. It is provided for reference only.
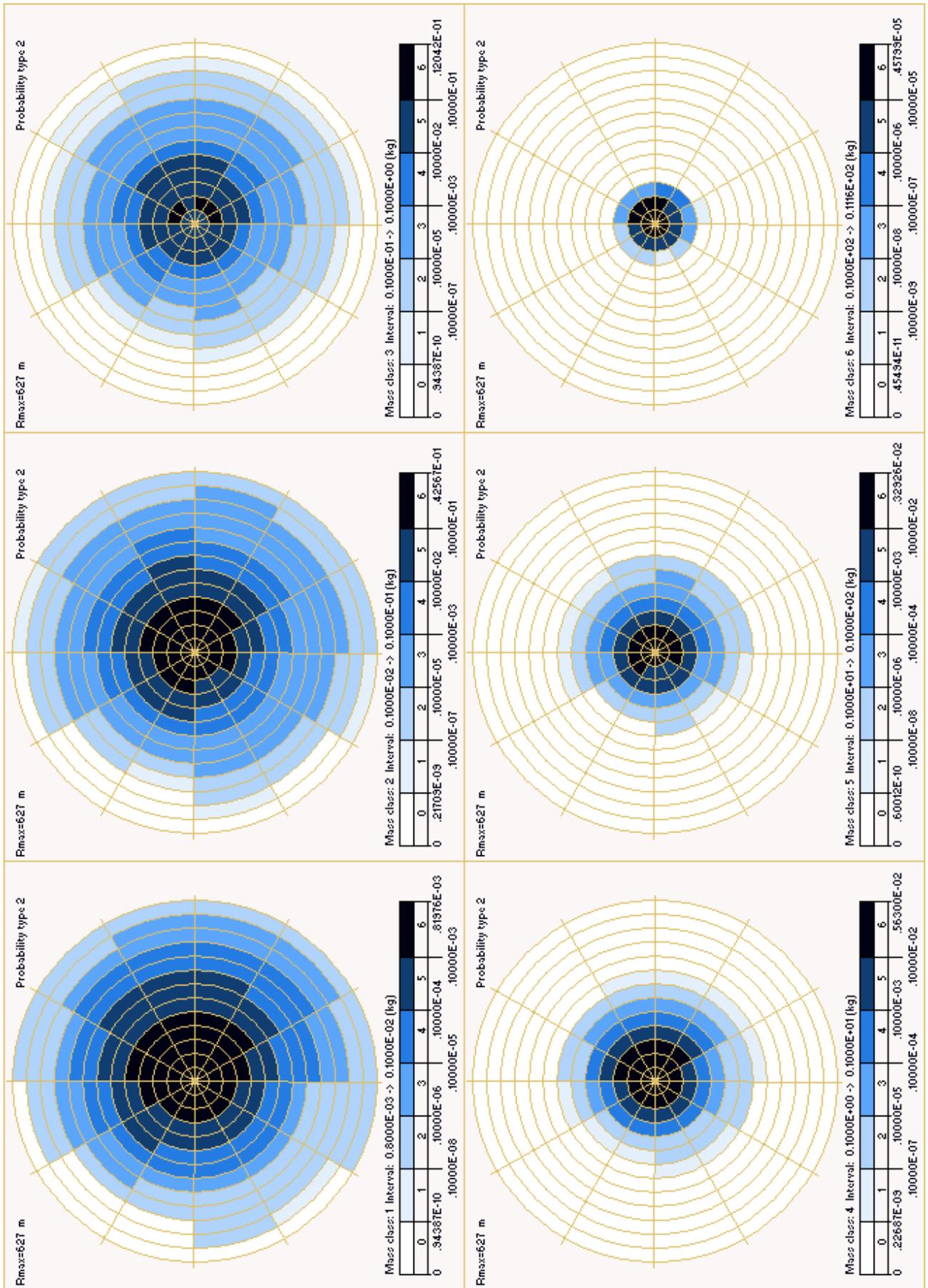
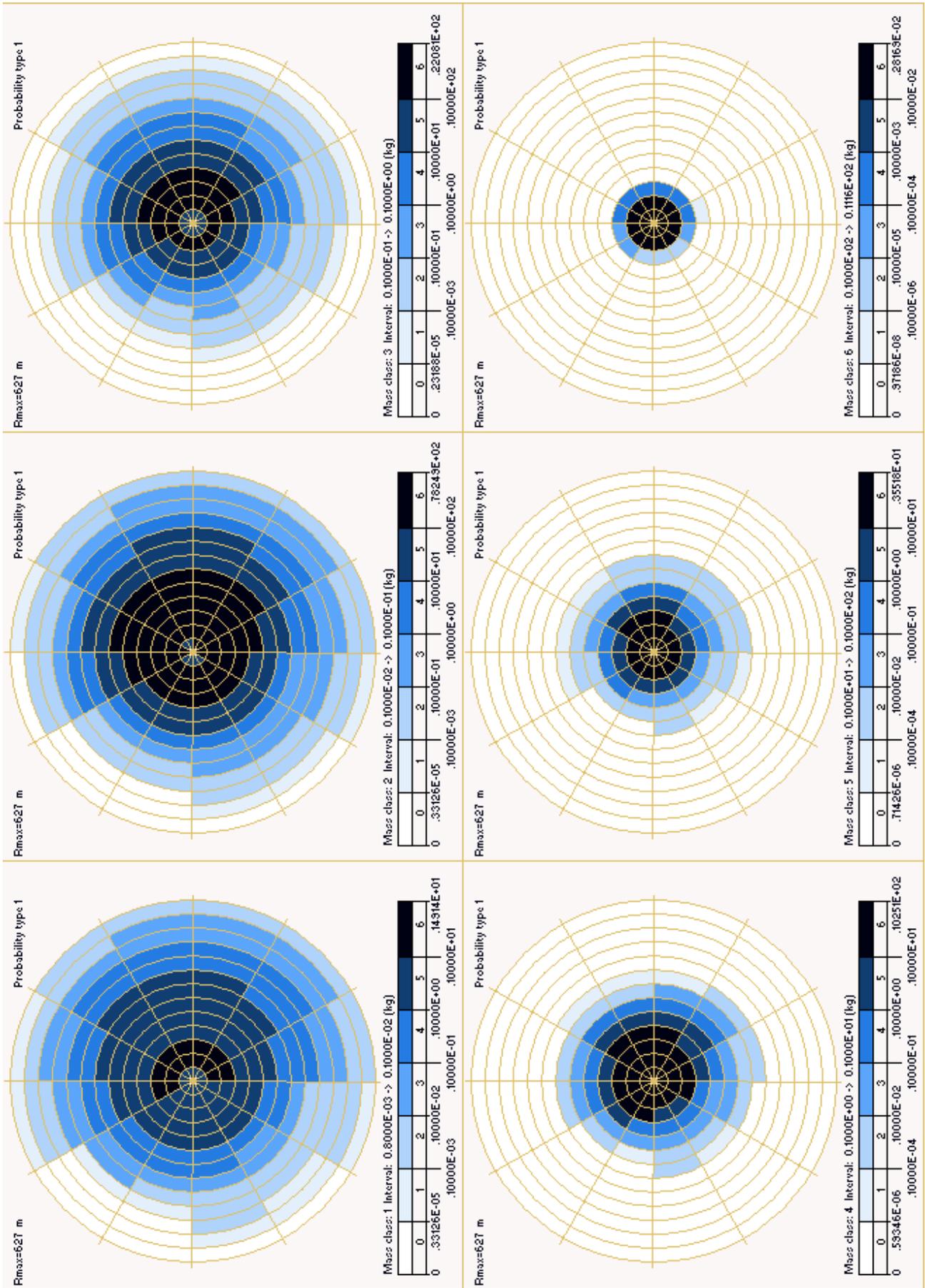Figure 8 - Probability type 1 - Mass classes

Figure 9 - Probability type 2 - Mass classes

20

Appendices

Appendix 1 - Derivation of effective aerodynamic reference area

The aerodynamic assumption is that an object with sharp corners has a drag area, which is the projection on a plane, whose normal is parallel to the relative wind. The relative wind is the wind that the object "feels" in its exposure to the air during travel. That wind is composed of the free stream wind vector, at the position of the object, minus its traveling velocity vector. The negative of the velocity vector is needed as realized from say a bike ride, when the biker moves forward but the wind is in the face of the biker. Thus the bike rider's velocity must be negated to represent the aerodynamically effective wind.

It is hypothesized that the ice chunk tumbles such that it it has time to expose all sides of itself to the relative wind. On the average, therefore, it will expose its average projected area to the wind. The resistive force *drag* of the air is directed as the relative wind and any *lift* force is directed perpendicularly. But, for the same reason as for the exposure of the area, the lift will, on the average, be pointing in all directions while traveling toward the ground. Therefore it is concluded that the net of the lift, as an average during the throw, can be ignored as a model assumption. This leads to the important consequential assumption that lift can be ignored altogether. The force acting on the ice object is therefore driven by gravity and drag only.
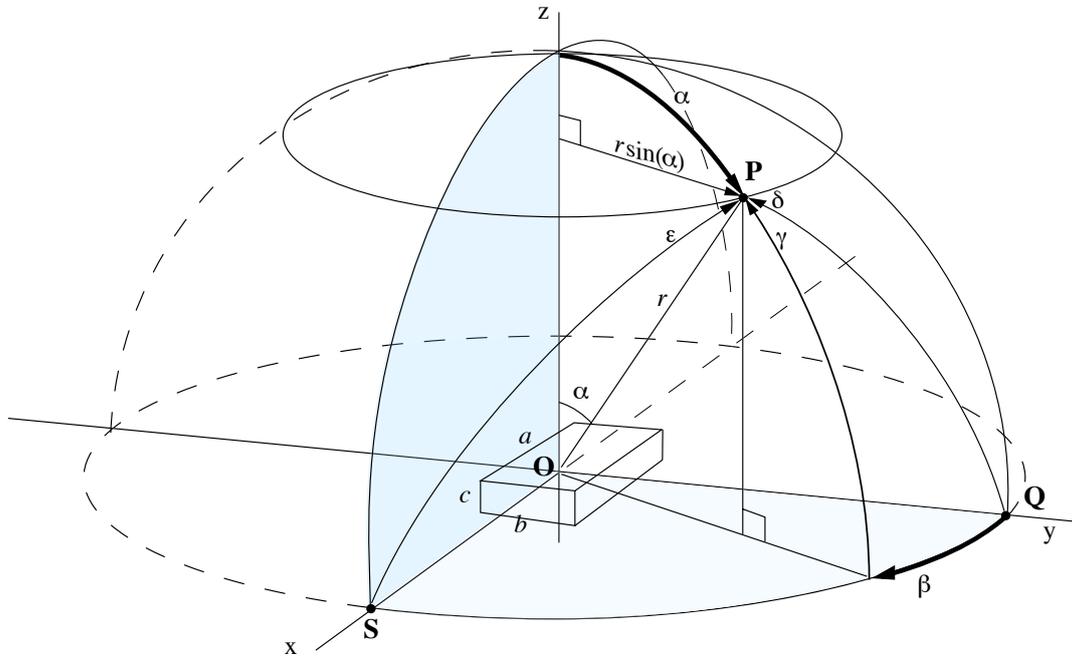
The figure shows a view of the model ice block being seen from a very remote point **P**. The projection of the block, on a plane tangent to a sphere in **P**, is the aerodynamically active area according to the model. The stylized ice block is modeled to have its coordinate axes parallel to its sides. The upper surface *ab* is seen from **P** as A_{ab} as follows.

$$A_{ab} = a \cdot b \cos \alpha \qquad (1)$$

The angle α is the angular deviation from the normal. The other side projections are obtained analogously.

$$A_{ac} = a \cdot b \cos \delta \qquad (2)$$

and $\quad A_{bc} = a \cdot b \cos \varepsilon \qquad (3)$

The basic coordinates are α and β, therefore δ and ε must be substituted. But, first **P**, **Q** and **S** must be expressed as vectors.

$$P = \left\{ \begin{array}{c} r\cos\gamma\sin\beta \\ r\cos\gamma\cos\beta \\ r\cos\alpha \end{array} \right\} = \left\{ \begin{array}{c} r\sin\alpha\sin\beta \\ r\sin\alpha\cos\beta \\ r\cos\alpha \end{array} \right\} \quad (4)$$

$$Q = (0, r, 0) \quad (5)$$

$$S = (r, 0, 0) \quad (6)$$

$$\cos\delta = \frac{P \cdot Q}{|P \cdot Q|} = \cos\gamma\cos\beta = \sin\alpha\cos\beta \quad (7)$$

$$\cos\varepsilon = \frac{P \cdot S}{|P \cdot S|} = \cos\gamma\cos\beta = \sin\alpha\sin\beta \quad (8)$$

The average ice block area A_{ref} is obtained from the idea that an infinitesimal spherical area at P functions as a weight coefficient when the block is viewed from P. The complete integral, according to this view, must then be divided by the whole area of the sphere. However, because of the polar symmetry of the problem, only 1/8 of the sphere need be used for the integration, because the same part integration repeats eight times if the whole area is used for integration. The surface area of the sphere is $4\pi r^2$. One eighth of this is $\frac{1}{2}\pi r^2$.

The average area is therefore

$$A_{ref} = \frac{1}{\frac{1}{2}\pi r^2} \int_{\alpha=0}^{90°} \int_{\beta=0}^{90°} (A_{ab} + A_{ac} + A_{bc})(r \cdot d\alpha)(r\sin\alpha d\beta) \quad (9)$$

which, after integration and insertion of the limits yields the following simple expression.

$$A_{ref} = \frac{1}{2}(ab + ac + bc) \quad (10)$$

Appendix 2

ROUGHNESS CLASSES AND ROUGHNESS LENGTHS, EU

The roughness classes are defined in the European Wind Atlas on the basis of the roughness length in meters z_0, which is the height above ground level where the wind speed is theoretically zero, according to:

$$z_0 \leq 0.03, \; class = 1.699823015 + \frac{\ln z_0}{\ln 150}$$

$$z_0 > 0.03, \; class = 3.912489289 + \frac{\ln z_0}{\ln 3.33333}$$

Roughness Class	Roughness Length, z_0 [m]	Energy Index [percent]	Landscape
0	0.0002	100	Water surface.
0.5	0.0024	73	Completely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 1250 meters.
2	0.1	39	Agricultural land with some houses and 8 meter tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 meters tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	18	Larger cities with tall buildings.
4	1.6	13	Very large cities with tall buildings and skyscrapers.

Appendix 3 - Obtaining chord as a basis for ice mass calculation

A simple assumed geometry is defined to be valid for all blades. Its length is 1. The measures must therefore be scaled by the tip radius.

The coordinates are:

----

x	chord/(tip radius)
0.025	0.06
0.1	0.06
0.2	0.093
0.28	0.093
1	0.02

----

chord
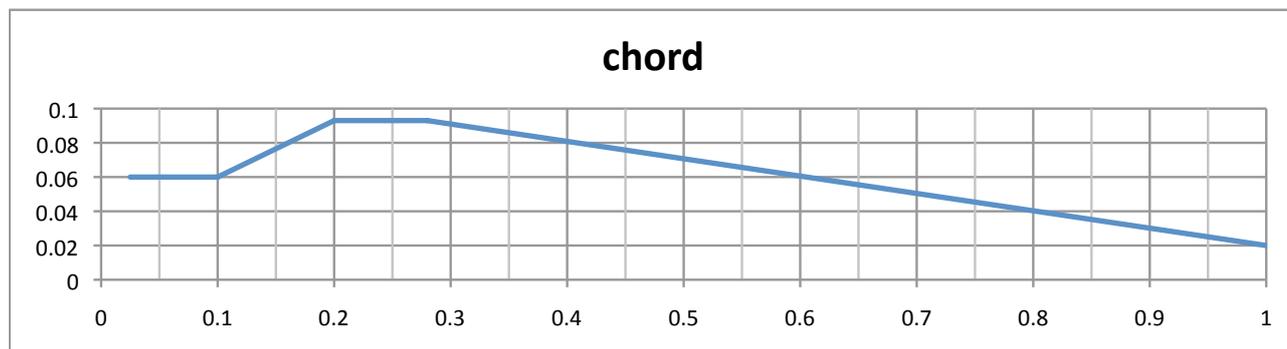
Note: The x and y axes are not equally scaled.

Appendix 4 - Ice fragmentation in the air

As soon as the ice leaves its position on the blade it is exposed to a distribution of variable dynamic pressure, which acts to accelerate the ice and also to cause a bending moment. The infinite variability at this event cannot be replicated. Instead a rudimentary simplification will have to be relied upon in order to create an algorithm. The following ideas are the foundation for this algorithm.

The simplified shape of an ice sheet is seen in Fig. 1. It is assumed that only one end of the sheet is affected by the dynamic pressure at release from the blade. The ultimate tension σ_u of the ice will be used to determine the breaking position, provided the ice breaks at all.
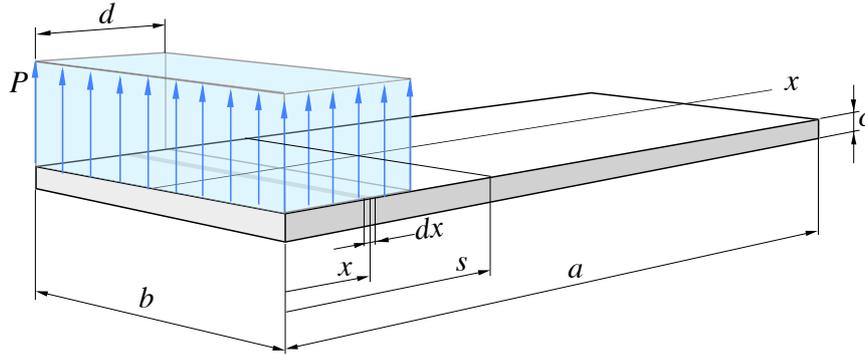
The *structural* bending moment is assumed to be symmetrical such that the tension, on the lower side of the plate, is the negative of the compression on the upper side. In a view of a piece of the *ac* side the tension distribution varies as illustrated in Fig. 2. In reality the ice ultimate compression has a higher numerical value than that of the tension value. This fact is not used in favor of a simpler analysis.
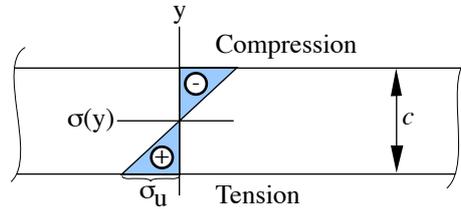
The ultimate *structural* bending moment is obtained from the following expression.

$$M_u^s = 2 \int_0^{c/2} \sigma y \cdot b \cdot dy \qquad (1)$$

Using $\quad \sigma(y) = \sigma_u \dfrac{y}{c/2} \qquad (2)$

where σ_u = ultimate tension. We obtain

$$M_u^s = \frac{4b}{c}\sigma_u \int_0^{c/2} y^2 \, dy = \frac{4b\sigma_u}{3c}\left(\frac{c}{2}\right)^3 = \frac{1}{6}bc^2\sigma_u \qquad (3)$$

The *external* moment, caused by the wind load, is calculated from the assumption that the right end, of the ice sheet according to Fig. 1, is firmly attached to an imaginary wall. This condition will be relaxed below, but it is used initially for the sake of derivation of the equations.

The external bending moment, from the wind loading, is obtained from the following expression.

$$dM = (s - x)df \qquad (4)$$

s is the x coordinate where the bending moment is evaluated. Using the aerodynamic pressure P we have

$$df = Pbdx \qquad (5)$$

Hence

$$M = \int dM = \int_0^d pb(s - x)dx = pb\left(sd - \frac{1}{2}d^2\right) \qquad (6)$$

Setting the two moments equal and extracting the point of moment evaluation (s) yields

$$s_u = \frac{c^2\sigma_u}{rf \cdot 6Pd} + \frac{1}{2}d \qquad (7)$$

where rf is a model reduction factor, selectable in the main input to Kastis6. It operates on the aerodynamic bending moment to account for the fact that the right end of the ice sheet is not fixed to a wall. Instead the mass moment of inertia, of the ice sheet, provides a resistive dynamic moment, which gives a lower bending load than that initially used. It is obvious that this model can be considerably improved upon.

The following figure was used in support of the development of this simple model.
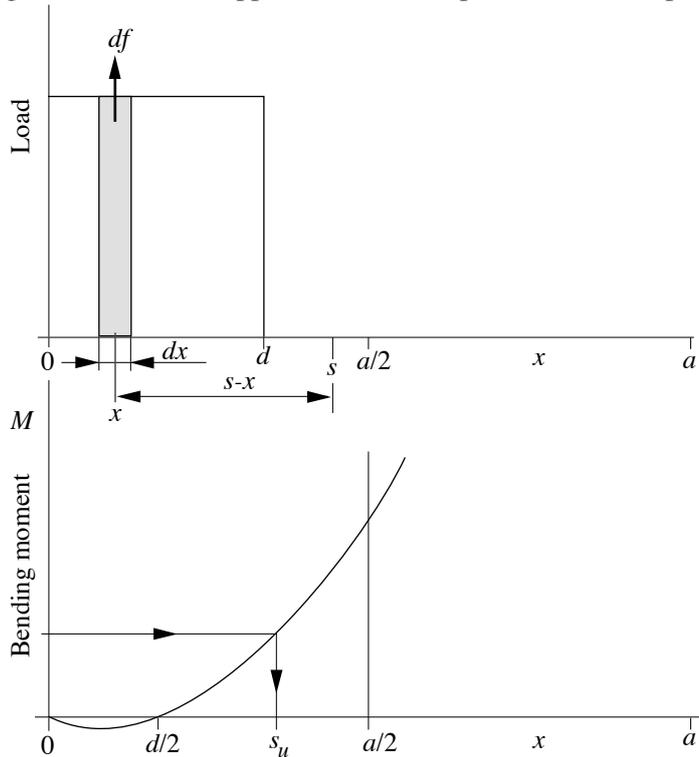
Eq. (7) has a graphic interpretation following the arrows from the bending moment axis to the solution of s_u. It is seen that the absolute of the moment, between 0 and $d/2$ will always be a small number. Moreover a bending moment solution greater than $a/2$ is meaningless because the same solution is obtained if the left part of the ice sheet is fixed to a wall. These observations together indicate that a solution, according to Eq. (7), is accepted only if s_u is in the interval accordingly: $d/2 < s_u < a/2$. Else there is no break.

Before the breaking analysis is started the sides of the fragment are reorganized such that the longest side is called a and the shorter side is called b, wile the c measure for thickness is left unperturbed. This reorganization corresponds to the view that the crack will always occur perpendicular to the longer side a.

The described procedure is repeated for the two fragments resulting from a break and the same rules are applied to the next generation fragments. In each such analysis the fragment under scrutiny can break or not break. Those that cannot break are saved temporarily in one storage location A, which can be thought of as a stack. Those that do break are stored as two fragments in another stack B. Then the fragment on top of the B stack is picked up and analyzed using the break conditions etc. Eventually the B storage will be empty. Then all fragments in A are thrown, one by one, using the standard throwing mechanism.

Appendix 5 - Relationship between probability and "number of ..."

There is a duality between probability of the existence of a particular piece of ice and the number of manifestations of this particular piece of ice. Ideas fundamental to the theory pertaining to the statistical part of the KASTIS program family is developed here.

A thought experiment based on a simplified model is used explain the idea. It consists of an imaginary one-bladed wind turbine which is exposed to westerly winds only. It has one single radial position, e.g. the tip, as its throwing position. There is only one piece of ice at that position. There is only one throw event. The blade can only throw one lump of ice from either position of 6 or 12 o'clock and both of those positions are equally likely. Three basic conclusions about this situation can be made accordingly:

1. The general ground must be hit once
2. The north half must be hit 0.5 times, where 0.5 is the probability P1.
3. The south half must be hit 0.5 times, where 0.5 is the probability P1.

The east-west going dividing line between north and south runs through the turbine footing.

A three-bladed turbine, under the same simplified assumptions valid per blade, would therefore yield the probability P2 of hitting the north or south halves according to P2 = 3*P1 = 3*0.5 = 1.5 times each. From this simple extension of the model it is seen that the number arrived at, at the ground, should no longer be interpreted to be a probability. It has to be seen as a number of ground impacts.

The model investigated has similarities with the reality of a wind turbine. A wind turbine can throw ice many times, whereas the simple model did this only once. The similarity in this respect arises from a small shift of view. Let us relax the only-once prescription. In stead of stating that the model only eject ice once we can think of the situation as something occurring *per* throw occasion. This expansion of the model does not change the three conclusions above, provided we accept them to be true per throw event.

In conclusion it appears that *n* blades and *m* occasions would give rise to 0.5*n*m number of ground hits on either side - north and south. Furthermore, extending our model, it seems that the ice can be associated with a *probability of its existence* to be = 0.5. What if its value were to be P1= 0.3324 or P1 = 0.001234 or ... any number less than 1.0. What circumstances could provide such a twist to our model? A feasible reason could be that the forces of gravity and centrifugal effect coincide and reinforce each other at 6 o'clock, whereas at 12 o'clock they counteract each other. The probability of ice release at 6 o'clock could then be say 0.6 and 0.4 likewise for 12 o'clock. This would give the three-bladed "probability" P2 = 3*0.6 = 1.8 for 6 o'clock and P2 = 3*0.4 = 1.2 for the 12 o'clock release position.

The learning form the latter thought experiment is that whatever the source of inherent probability P, that probability can be modeled as a number-of-occurrence figure. Looking at the more realistic operating wind turbine, its ice accretion and release thereof has the following background and characteristics.

Wind distribution:
There is a variable probability of the combination of wind direction and velocity. The wind table in the main text can be converted from frequency of occurrence to probability by dividing all numbers in the table by the total sum of occurrences. Let us call the resulting variable probability, in the bins of the table, Pw.

Azimuth distribution:
Another probability affecting the ice is where in its circular travel on the blade it is released. Its radial position on the blade is given in the input. But, the angular position (the azimuth angle) of the blade at release, is not given a priori. The probability of any azimuth angle is distributed. In the main text it is explained that two choices are available. Either a Gauss curve, centered on a given angle is chosen or a flat distribution can be applied. Flat means that any angle is equally likely. Regardless of choice of distribution let us call the probability, of release of the ice in an angular range, Pa.

Ice thickness distribution:
The ice can assume different forms. But, all forms are modeled as a square angled block. Thus there is length, breadth and thickness to characterize the form of the initially ejected ice block. Length and breadth are specified in the input. But, the thickness is modeled to be distributed in a form based on the normal distribution. The particular ice block can thus assume any thickness within the scope of the chosen distribution definition. The corresponding probability will be called Pi.

Probability synthesis:
The probability (P) of an ice block having the attributes described above is calculated from P = Pw*Pa*Pi. The resulting value is an instantiation of an infinite amount of possibilities. Infinite amounts are not treated. In stead a number of instantiations, based on discretizations, of the probability distributions are applied.

Pw: The wind discretization is already inherent in the wind table. In the study winds between 4 m/s and 28 m/s were used as input. This gives rise to nw = (12 wind directions)*(28-4+1 wind speeds) = 300. It is assumed that a turbine is always facing the wind as in a normal operation state.

Pa: The azimuth angles can, for comfort of mind, be expressed in clock hours. Reasoning on assumed flat distribution every clock hour is equally likely. Choosing 12 clock angles, to be the discretization rule, it is immediately realized that every choice has a probability Pa = 1/12. Choosing the Gauss option gives 12 clock angles different probabilities, i.e. Pa is different between clock angles. na = 12.

Pi: The ice thickness distribution has only Gauss distribution available. 7 or 9 discretizations were used in the runs based on a consideration of balance between accuracy (many discretizations) and speed of calculations. Let us ay that ni = 9

The total number of instantiations of all these combinations is = nw*na*ni = 300*12*9 = 32400

There are between 50 and 200, say 100 ice fragments thrown from several radial positions amounting to 3240000 individual ice clumps and flakes.

Method synthesis:
As for the simplified one-bladed turbine discussed above every ice fragment carries its own probability number. Also as in the simple case each ice clump's probability number in the active case can be taken to be the number of clumps of this particular type - a number much less than 1.0.

The simple turbine example included a dividing line from west to east thereby creating two sections. In the active case the ground around the turbine is more finely divided into sections or panes as seen in the adjacent figure. The following text will refer to such a pane. Therefore the pane has been magnified on the right in order to illustrate certain principles.
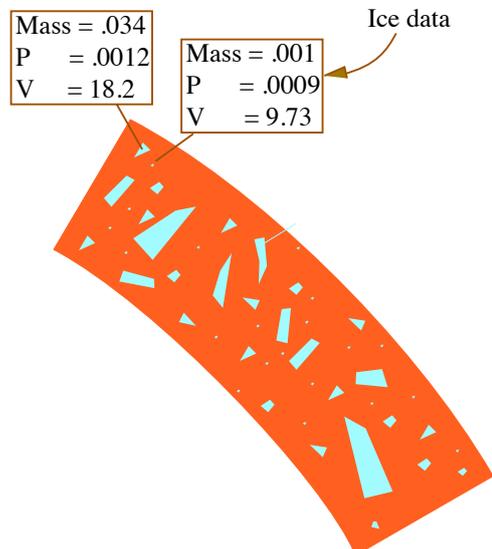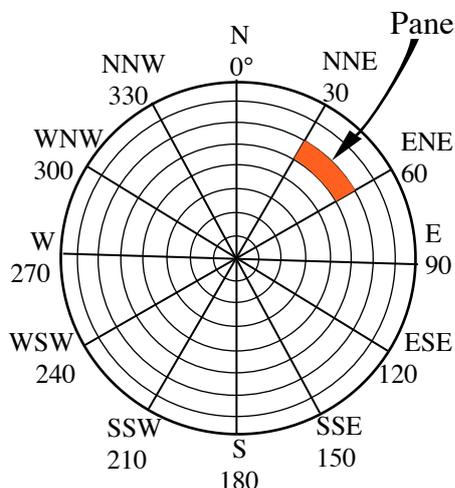
The figure on the right is thus a pane littered with pieces of ice. Each piece has a set of numbers associated with it. The numbers of importance, in this context, are seen in the example "Ice data" boxes. Because of the large variation of mass, from 0.8 g to 11 kg, the masses are organized into *classes* of mass in order to reflect different levels of danger.

When classes of mass (or momentum when the velocity (V) is also used) are created the probabilities of all ice clumps, within the class, are summed to become the local probability of its class. The sum thereby also becomes the number of ground hits of the class. The output blue "dartboards" in the main text portray this probability in the panes in shades of blue. This probability number is denoted "$P1$" in the main text. Each dartboard represents one mass/momentum class. For damage assessment the momentum dartboards are the more important ones for damage analysis.

References

1. Daniel Gustafsson
Vattenfall Vindkraft AB, SE-162 87 Stockholm, Jämtlandsgatan 99, Sweden
Email of October 2011:
Excel file - Frequency of occurrence as a function of binned wind directions and wind speeds.
(Used in the development of the KASTIS program set as an example of the file type)

2. Is på vindkraftverk - Detektering, utbredning, personskaderiskminimering och produktionsbortfall
Elforsk rapport 09:06
Rolf Westerlund, HoloOptics Februari 2009

3. Svenska erfarenheter av vindkraft i kallt klimat – nedisning, iskast och avisning
Elforsk rapport 04:13
Göran Ronsten, FOI Maj 2004

4. Fallstudie av iskast på Stor-Rotliden
Bengt Göransson
Vattenfall Power Consultant AB
2011-05-31