Assessing the Likelihood of Hail Impact Damage on Wind Turbine Blades

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Environmental Conditions

- Temperature
- Salinity in the air
- UV radiation from sunlight
- Lightning
- Airborne particles (Erosion)
  - Sand and other small particles
  - **Hailstones/Hailstorms**
  - Rain
- *An offshore environment requires additional consideration* – IEC 61400-1 international standard.

Impact of Erosion

- Increase in drag & decrease in lift production
  - Due to:
    - Degradation of aerofoil characteristics
    - Increased roughness
  - Results in a Decrease in annual energy production (AEP)
- Unbalanced Rotor
  - Waterlogged Blades
  - Vibrations
- Maintenance Concerns
  - Blade Repair
  - Full Replacement
  - Associated downtime
  - Offshore access

Table III. Effect of leading edge erosion on wind turbine blade performance as estimated by PROPID.

Condition	ΔC_d	ΔC_l	Avg wind speed m/s	AEP loss MWh/yr	AEP loss (%)
A1	+6%	−0.07	—	—	—
			7.05	383	−4.85
A2	+80%	−0.12	7.93	392	−4.10
			8.81	384	−3.49
A3	+150%	−0.15	—	—	—
B2	+150%	−0.16	—	—	—
			7.05	902	−11.42
B3	+200%	−0.14	7.93	930	−9.73
			8.81	917	−8.33
B4	+400%	−0.15	—	—	—
C3	+150%	−0.16	—	—	–
			7.05	1,858	−23.53
C4	+400%	−0.15	7.93	1,948	−20.38
			8.81	1,947	−17.68
C5	+500%	−0.17	—	—	—

"Effects of leading edge erosion on wind turbine blade performance" - Sareen *et al.* (2013)

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Methodology Outline

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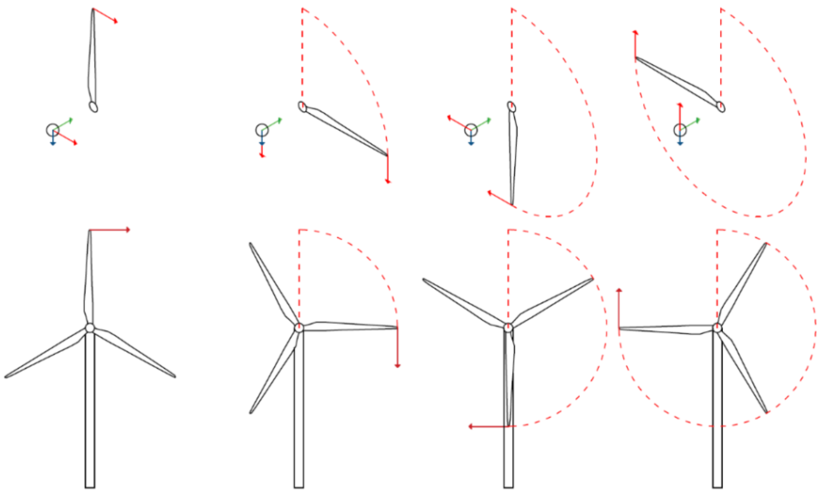
- Prior to testing and modelling hail erosion, important to understand practical scenarios and their likelihood.
  - **Impact Velocity** during hail events
    - Hailstone terminal velocity
    - Mean wind speed
    - Wind turbine rotational speed/tip speed
  - Other Hail Impact Considerations
    - Size distributions
    - Rates
    - Durations
    - Seasonality
    - Geographical Spread – Close to commercial wind farm sites



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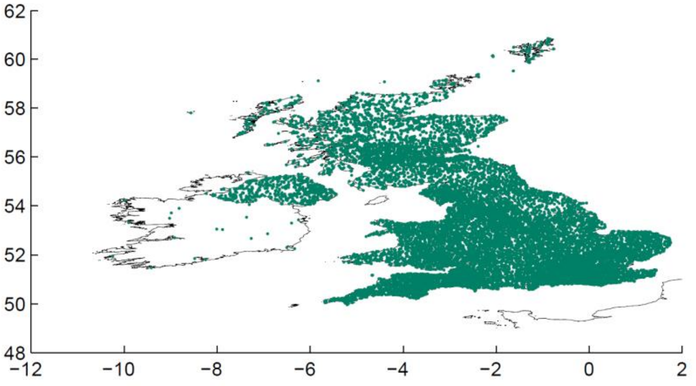
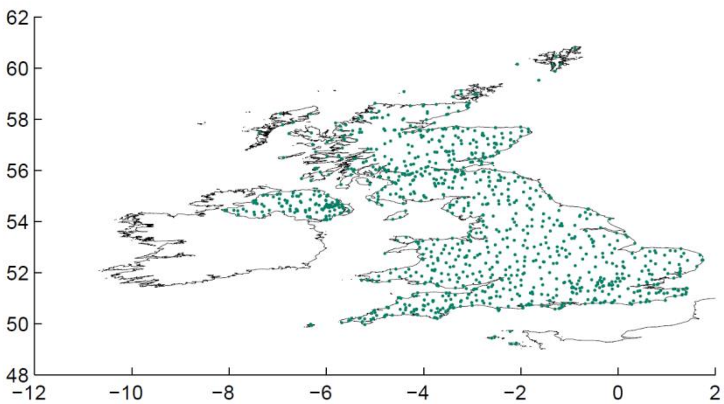
Meteorological Data

- Provided by the British Atmospheric Data Centre (BADC)
- MIDAS Land Stations [1875 (1949) – Present]
  - WMO hail codes (**daily**), wind speed
- CFARR (Chilbolton, England)
  - Campbell PWS100 Sensor [2011 – Present]
    - Distinguishes between graupel and "hail"
    - Particle information: counts, diameter, velocity
    - Time Resolution: **1 minute**
- NERC MST Radar Facility (Aberystwyth, Wales)
  - Vaisala Weather Transmitter WXT510 [2007 – Present*]
    - Distinguishes between rain and "hail"
    - Particle information: rate, accumulation
    - Time Resolution: **10 seconds**





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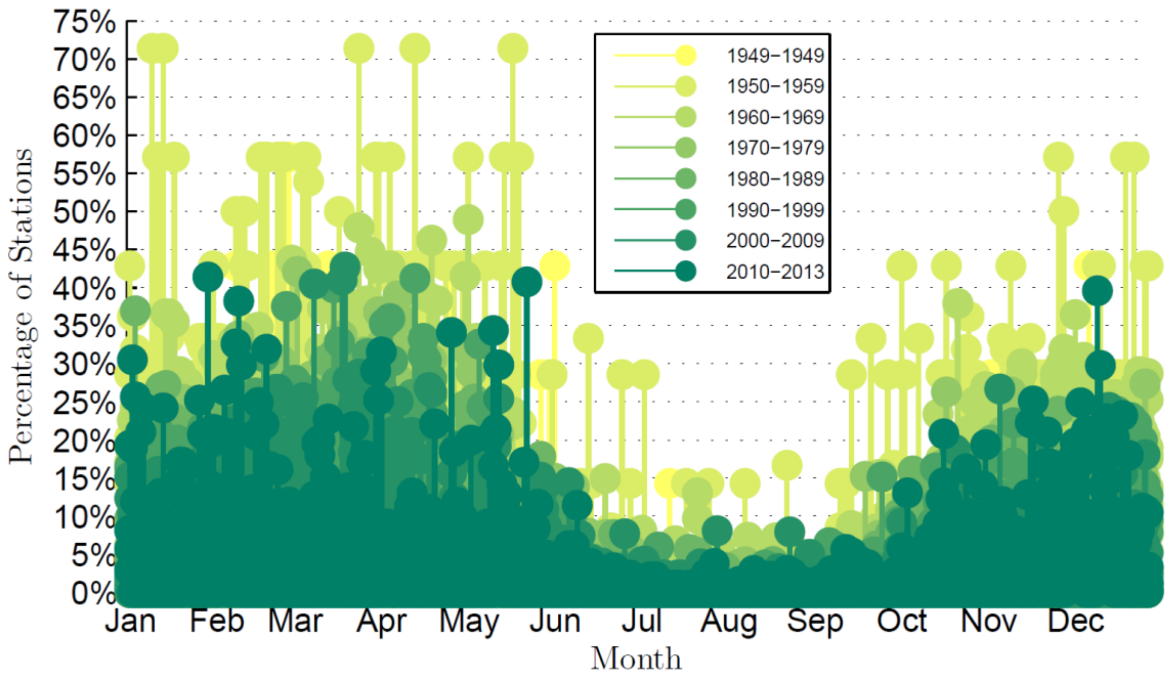
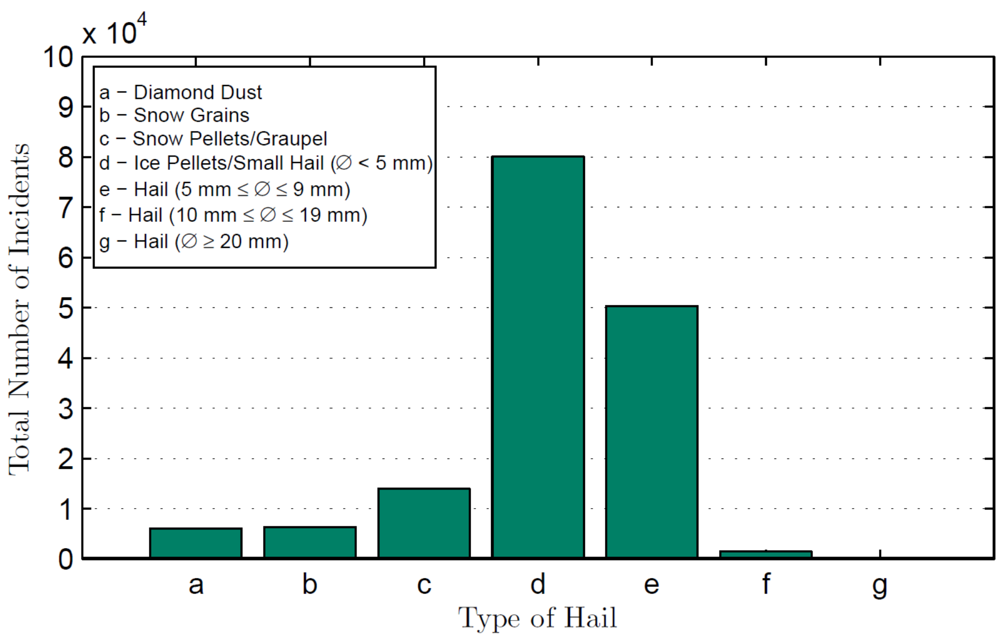
MIDAS - Seasonality

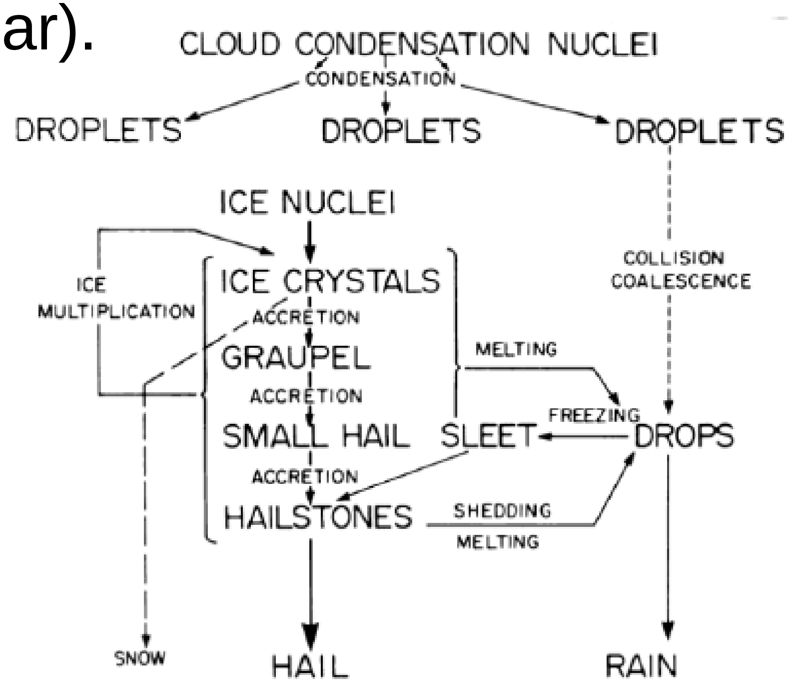
- Heavily Seasonal
  - Requirement for the temperature in the upper atmosphere is sufficiently cool to develop ice formation but warm enough on the surface in order to encourage thunderstorm development.
- NERC facility measurement period - between October and December



MIDAS - Distribution of Hail Types

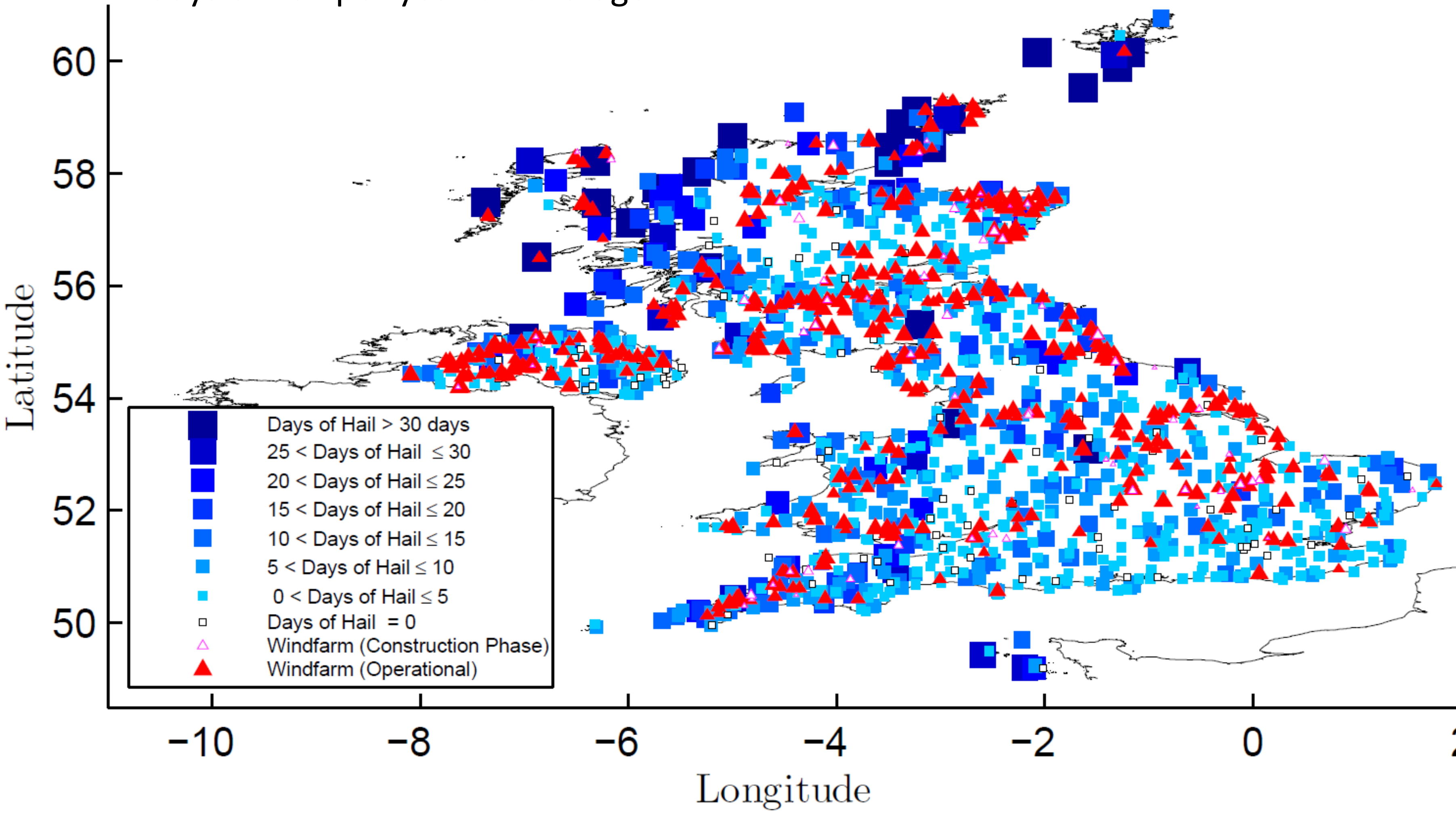
- Progressive states of hail
  - Spherically layered structure
- Larger hailstones are plausible in storms with:
  - large updraft speeds and wide updraft areas,
  - high liquid water content above the freezing level and
  - long lifetime (strong wind shear).





MIDAS - Geographical Spread

- Majority of stations subject to 0 < hail days ≤ 5 per year on average
- Approximately 2.26% of all MIDAS stations receive more than 30 days of hail per year on average.



MIDAS - Coastal Considerations

- Lack of dedicated offshore measurement stations.
- Mean number of hail days per year for these coastal stations is ~10.5 compared with ~6.5 for those more inland

THE FREQUENCY, SIZE, AND DISTRIBUTION OF HAIL AT SEA.

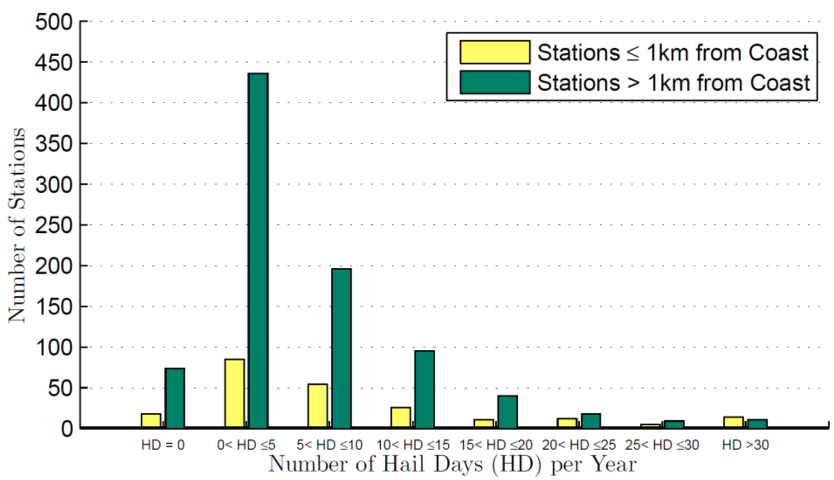
By HENRY HARRIES, F.R.Met.Soc.
Mem. German Met. Soc.

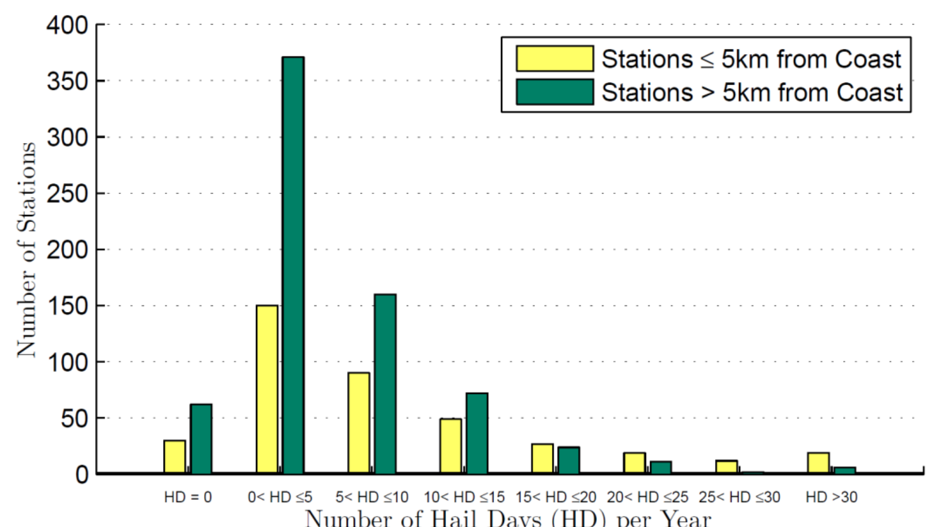
[Received May 7th.—Read June 19th, 1895.]

When reading the Hon. Rollo Russell's comparatively recent work *On Hail*, it occurred to me that the author, in the absence of either positive or negative information, had fallen into an error in his treatment of one branch of the subject, namely, that of the occurrence of hailstorms out on the ocean. Having had much to do with maritime weather records, I felt sure that a general examination of some of them would reveal facts at variance with the conclusions arrived at in the book referred to.

The references to falls of hail are confined almost wholly to those observed on land, the numerous authorities quoted evidently contenting themselves with land records, and Mr. Russell has thus been unwittingly led to suppose that hail is essentially a land phenomenon.

On pages 57 and 58 there is an extract from the *Philosophical Magazine* giving a brief account of "a shower of ice in irregular pieces" which lasted three minutes, at a distance of about 800 miles south of the Cape of Good Hope. Page 94 contains a reference to showers of hail "in the Atlantic"





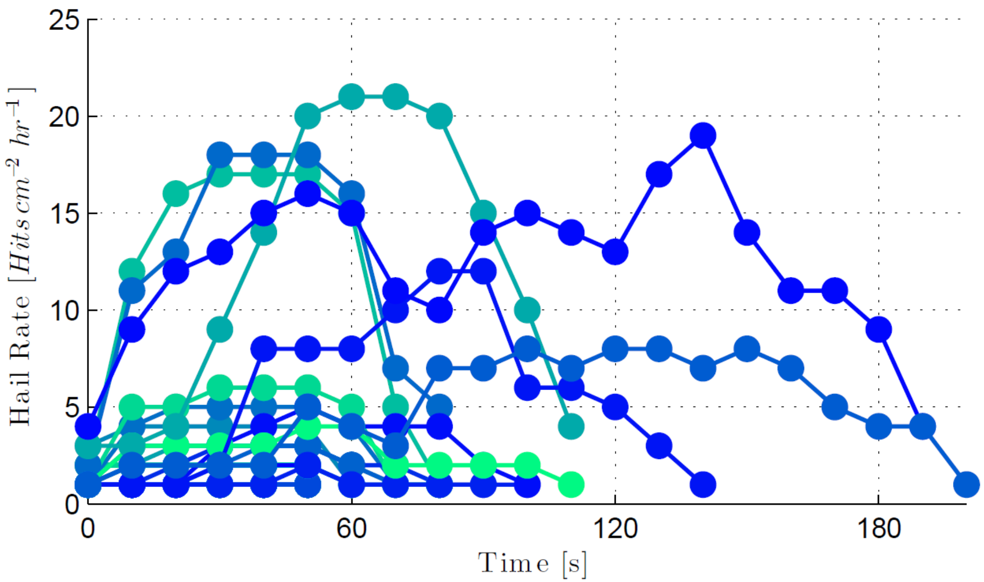
CFARR & NERC - Hail Durations and Rates

Table I. Duration of hailstorms at CFARR and NERC observatory stations.

Station	Resolution	Number of 'Hail Days' per year	Continuous duration Mean (min)	Continuous duration Maximum (min)	Non-continuous duration Mean (h)	Non-continuous duration Maximum (h)
CFARR (hail)	1 min	11.66	1.79	10	3.49	13.23
CFARR (graupel)		4.46	2.2	10	3.82	6.55
NERC MST	10 s	12	1.19	3.33	3.07	17.19

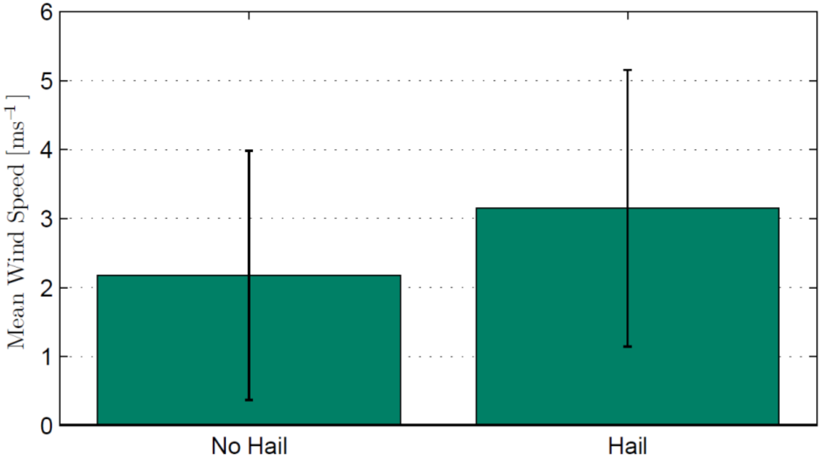
- Different types of hail are not mutually exclusive, with incidents of graupel and hail occurring during the same intervals at the CFARR observatory

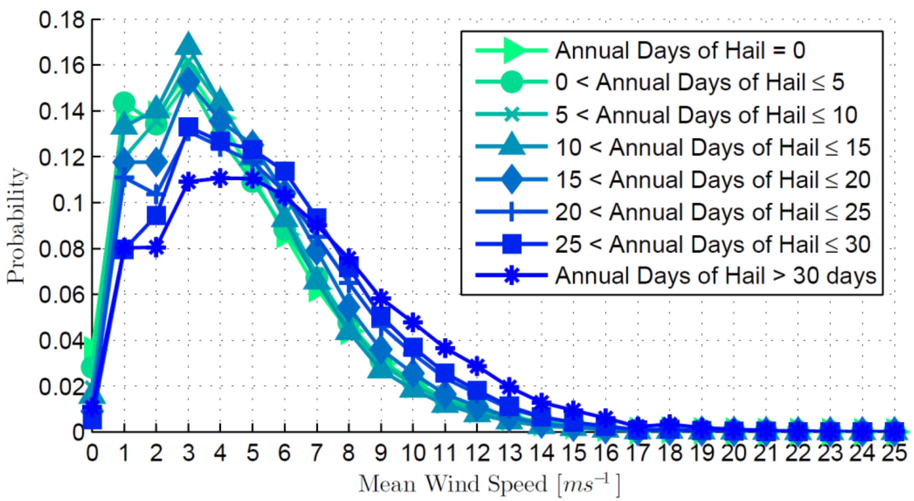
- The mean rate of hail measured at NERC facility ranges from 1 to 21 hits $cm^{-2}hour^{-1}$. The start and end hail rates do not exceed more than 4 hits $cm^{-2}hour^{-1}$, with 1 hits $cm^{-2}hour^{-1}$ the most common.

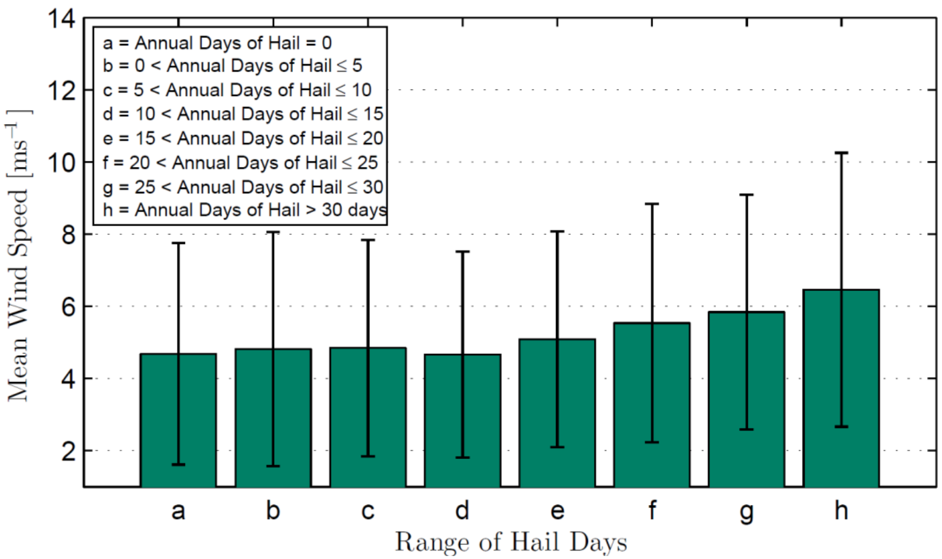


MIDAS/NERC - Wind Speed During Hail Events

- Wind profiles extracted from those MIDAS stations that experience on average "x" annual days of hail.
- As well as directly influencing the rotational speed, the wind speed will also inform the pitching of the blades – impact angle.
- Greater resolution from NERC facility.



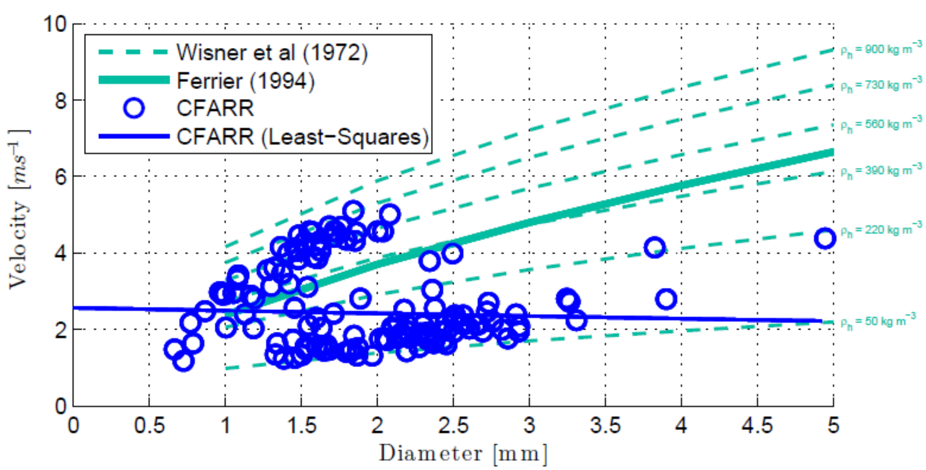


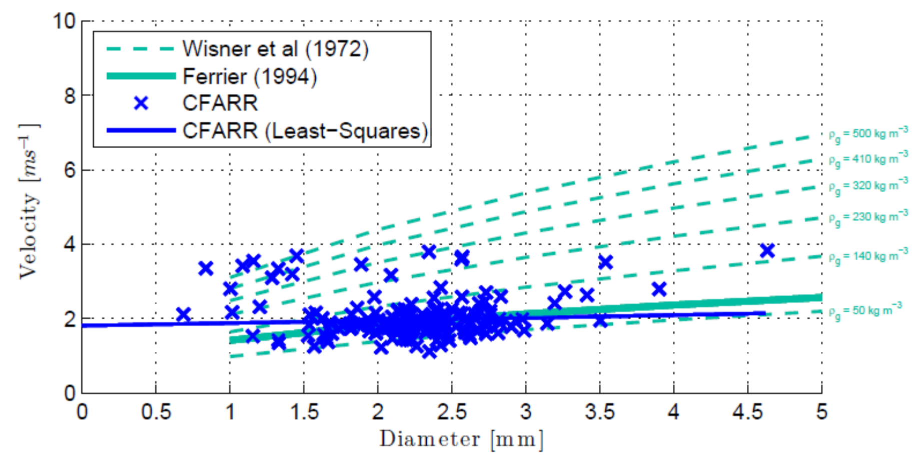


CFARR – Hail Terminal Velocity

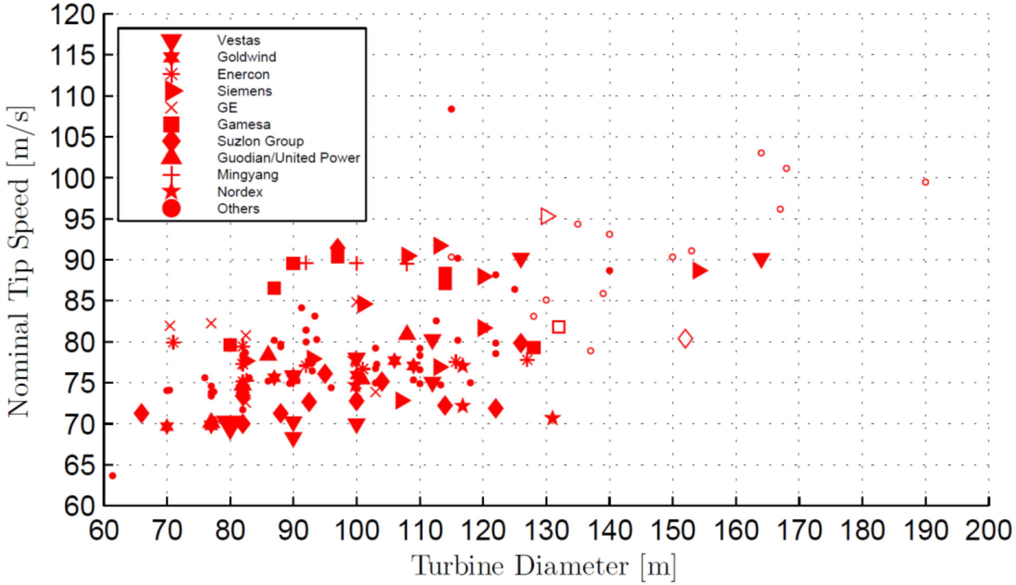
- Overestimation by both relations for both forms of hail.
- Higher diameter samples required.

Author	Graupel ($500\,\mathrm{kg\,m^{-3}}$)	Hail ($900\,\mathrm{kg\,m^{-3}}$)			
	5 mm	5 mm	10 mm	15 mm	20 mm
Wisner *et al.*	6.9429	9.3148	13.1732	16.1338	18.6297
Ferrier	2.5692	6.6464	10.3459	13.4024	16.1044

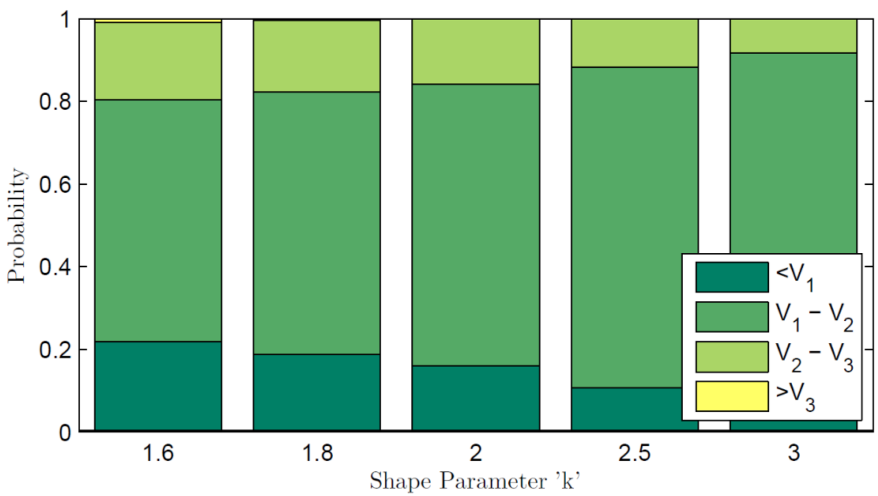


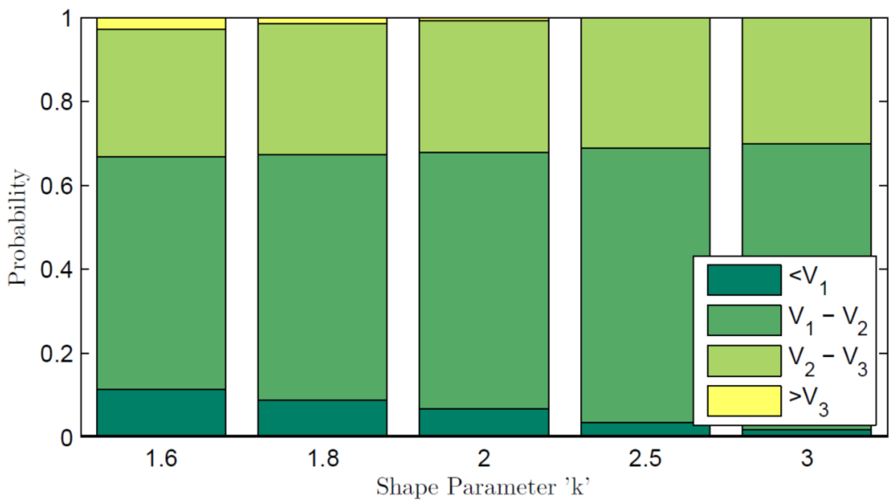


Impact Velocity Components

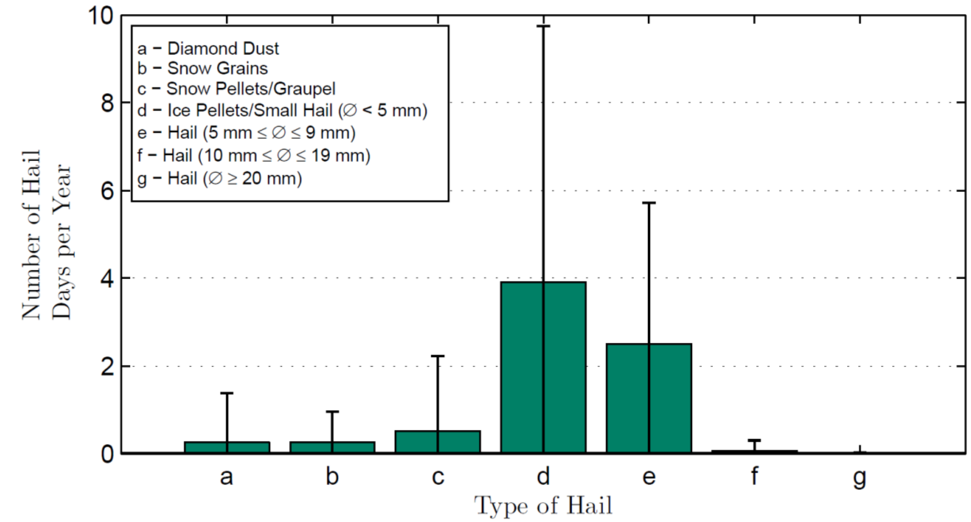


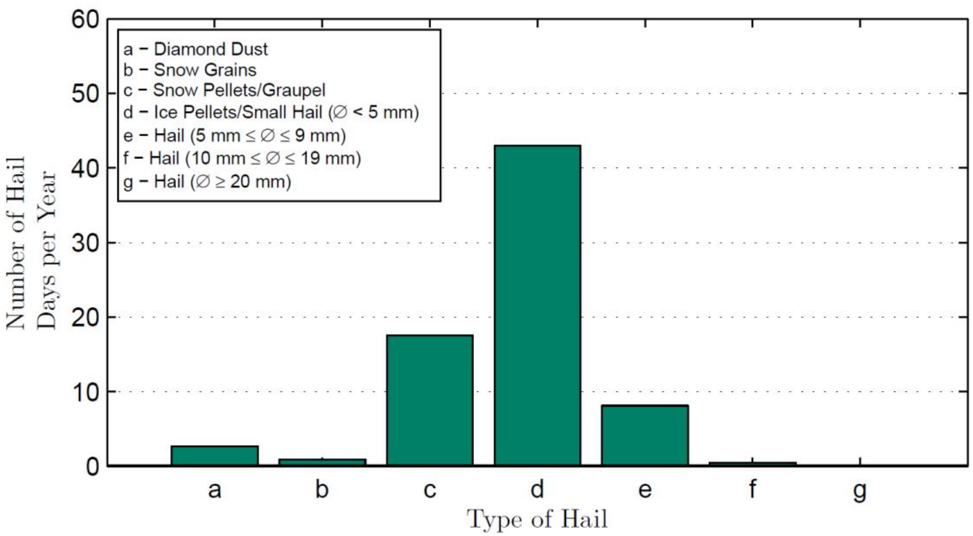
- Based on BTM Consult 2013 Market Share (over 1 MW)
- Empty markers represent turbines in "prototype stage" (July 2014)

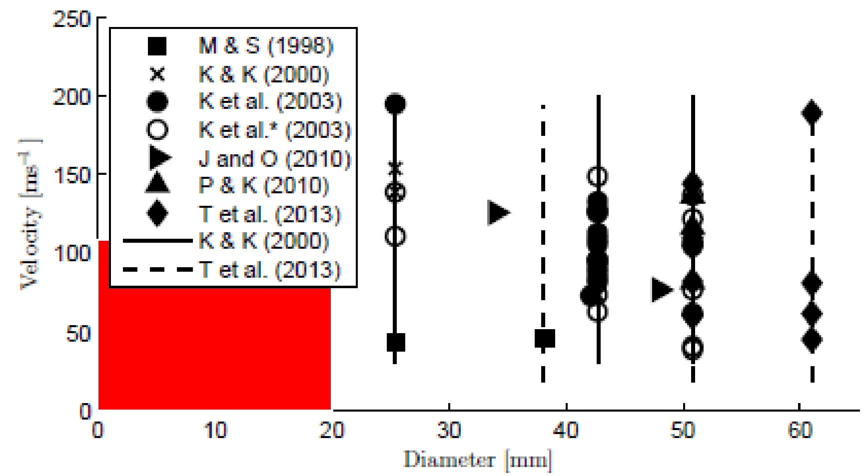




Impact Profiles







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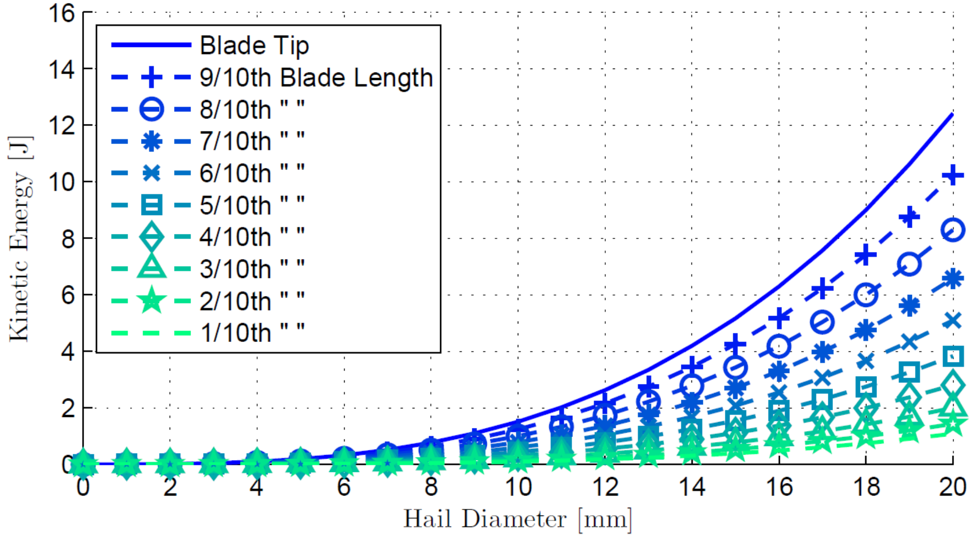
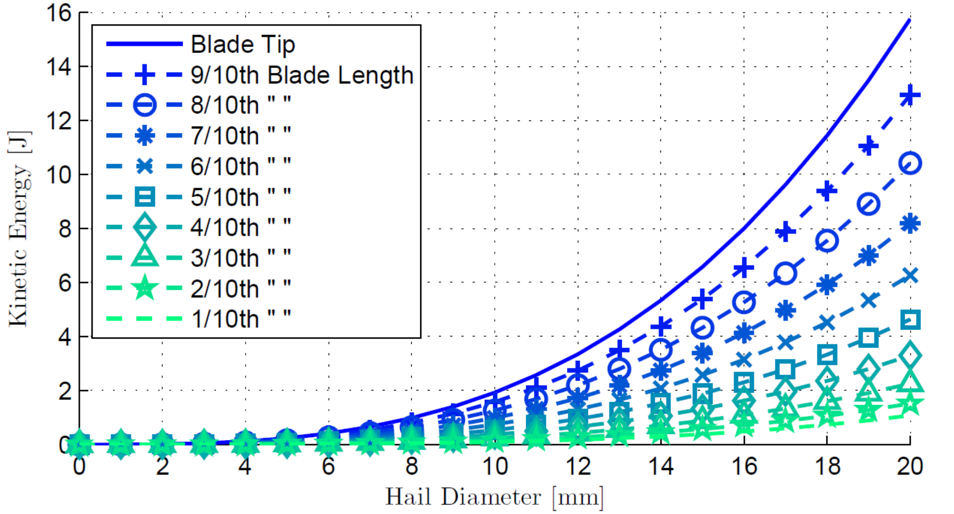
Impact Energy

- Aggregation of the *annual* separate contributions for a weather station with hail incidence for two different turbines.
  - T_1=1/2 mv^2 for the different hail sizes of hail along discrete locations along the blade. One impact per hail event.
- Cumulative failure for threshold energy of 72–140 J for CFRP (Appleby Thomas *et al.)*
- Higher thresholds for glancing impact
- Gap in the literature for GFRP





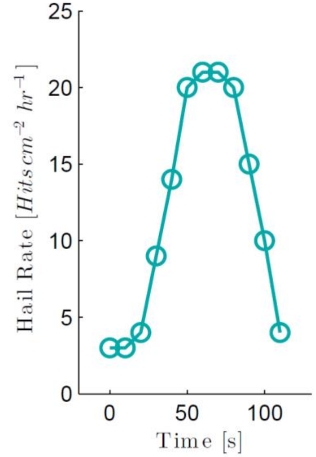
	Category				Total
	c	d	e	f	
2.3 MW Class IIa Onshore Turbine					
Mean Profile	0.0272 J	0.3721 J	1.9236 J	0.6307 J	2.9537 J
Extreme Profile	0.9302 J	4.0811 J	6.2477 J	4.5734 J	15.8325 J
6 MW Class Ia Offshore Turbine					
Mean Profile	0.0348 J	0.4767 J	2.4581 J	0.8013 J	3.7709 J
Extreme Profile	1.1915 J	5.2275 J	7.9836 J	5.8104 J	20.2130 J

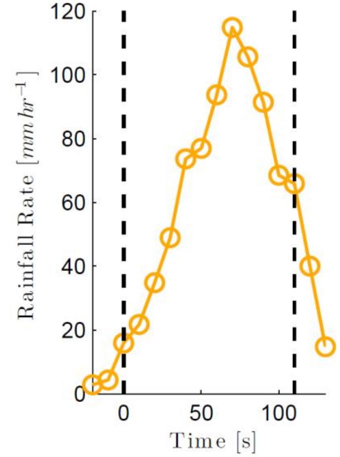
Meteorological Conclusions

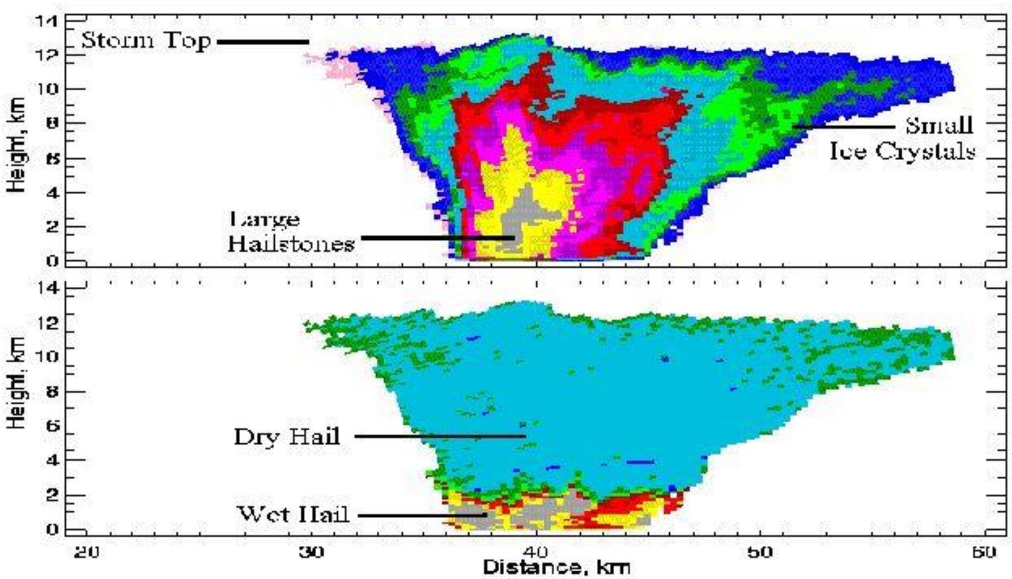
- Ice pellets/small hail (diameter < 5 mm) is the most frequent category of hail.
- Incidents involving diameters of hailstones greater than 20 mm are very rare events, with only 102 incidents recorded over the entire 65 year period.
- The majority of stations experience fewer than 5 days of hail a year (prevalence a lot less than rain).
- Two example experimental profiles developed
- Even for an extreme case study, signs of damage would not be expected until many years of operation.

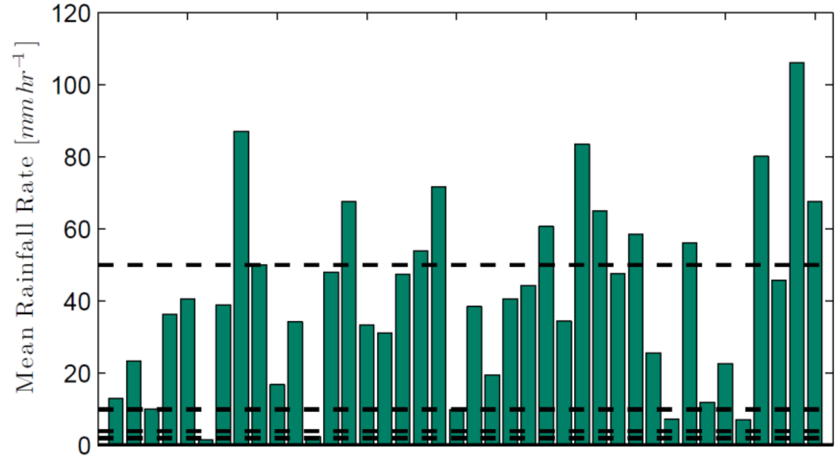
Hailstorms – not just hailstones

- 0 to 2 mmh^{-1} - slight
- 2 to 10 mmh^{-1} - moderate
- 10 to 50 mmh^{-1} - heavy
- > 50 mmh^{-1} - violent



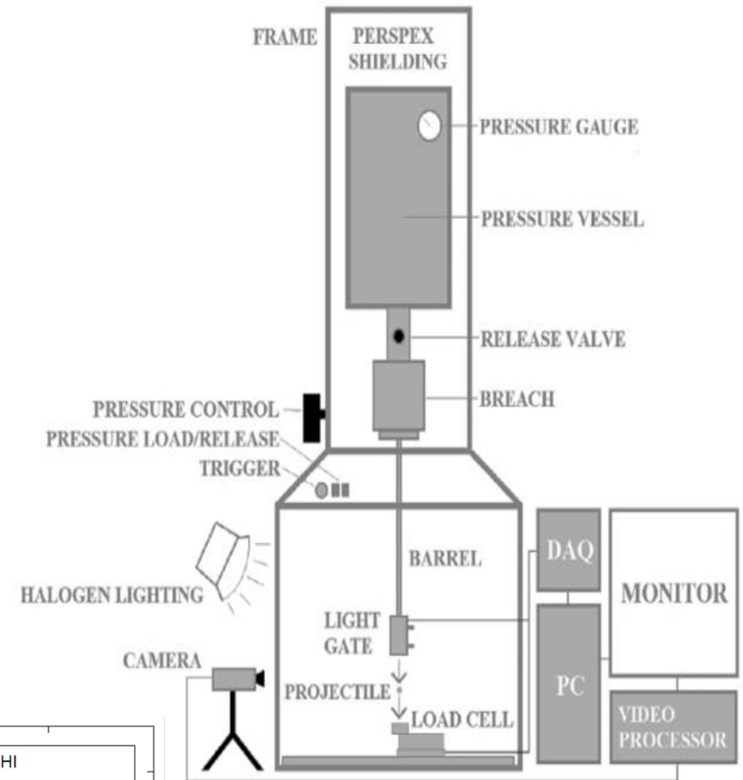


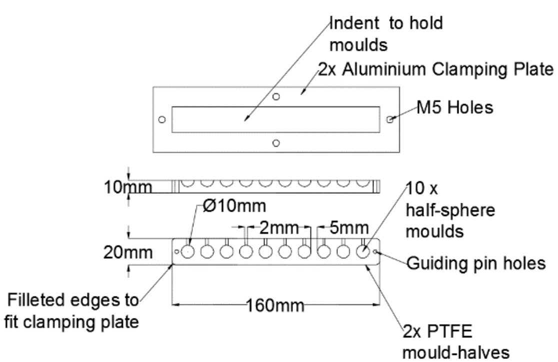


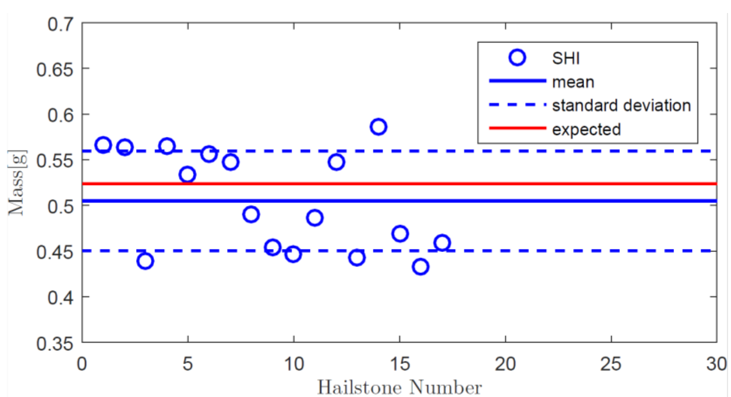


Hailstone Rig

- Modifications
  - 5mm, 15mm, 20mm barrels (& SHI moulds)
  - Dynamic force transducer
  - Secure composite clamping arrangement
- Capable of >100 m/s speeds
- Variables
  - SHI Diameter (Originally exclusively 10mm)
  - Velocity
  - Number of Impacts
    - Cumulative annual assessment
- Importance of consistency of projectiles
  - Temperature

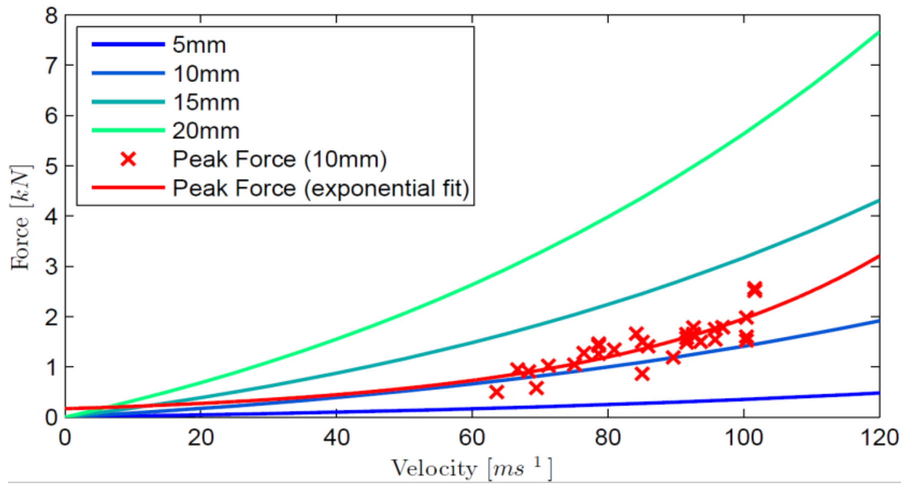


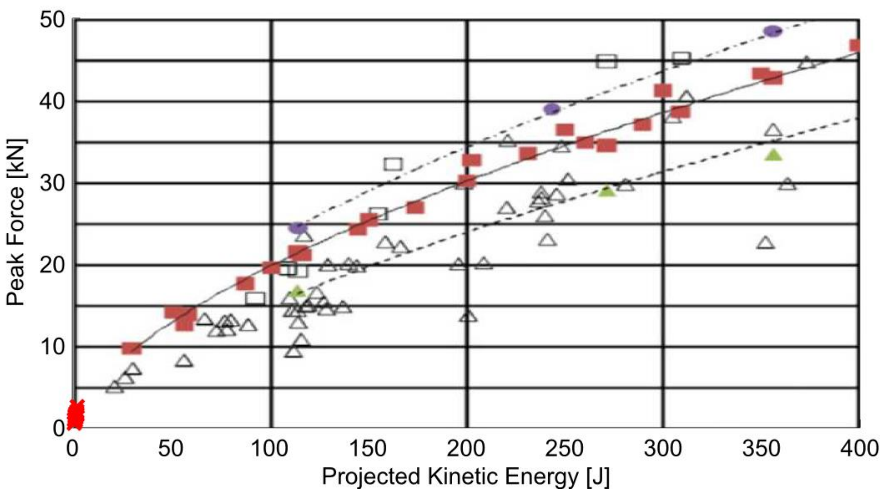


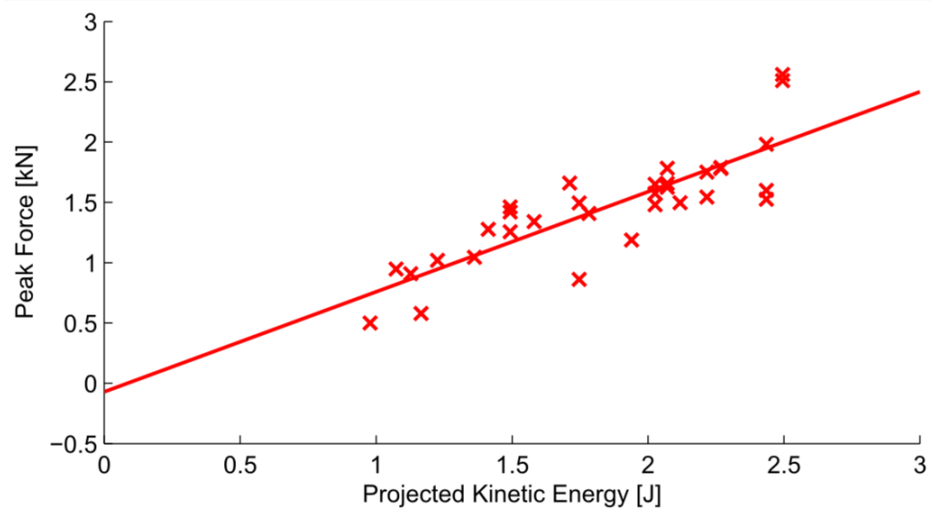


Initial Calibration/Comparisons

- Peak Force vs. Velocity
  – Roisman and Tropea [2015]
  – $F \approx \frac{4\pi}{3} R_0^2 U_0 \rho^{\frac{1}{2}} Y^{1/2}$
- Peak Force vs. Kinetic Energy
  – Tipmmann *et al.* [2013]







Ongoing Work

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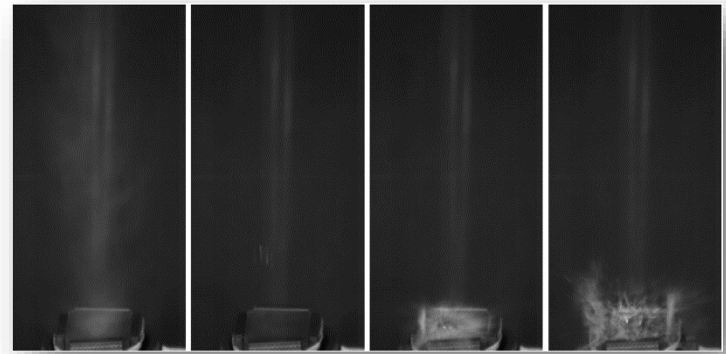
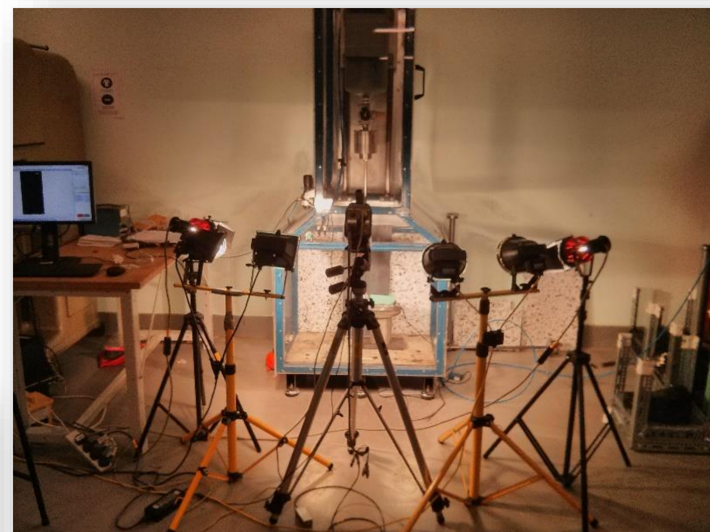
- Series of Experimental tests
  - Diameter vs. velocity vs. impacts
  - Glass epoxy manufactured in-house
- Potential variables
  - Impact angle
  - Hail composition (salt)
  - Composite thickness
  - Hail/Rain Interaction
- Composite inspection
  - Visual/ High Speed Camera
  - Mass loss
  - SEM (Scanning electron microscope)
  - Composite Properties after impact
- Numerical Comparison
  - LS DYNA





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