School of Engineering
Department of Civil Engineering

Assessment of the Most Adverse Wind Form-Factor for Single Storey Buildings

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This thesis is presented for the Degree of
Master of Philosophy (Engineering)
of
Curtin University of Technology

March 2013

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signed: .....

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Date: 10 March 2013

ACKNOWLEDGEMENTS

I would like to thank:

1. My supervisor, Professor Hamid Nikraz. FIE.Aust, CP.Eng, NPER, Head of Department, for his encouragement and unstinting dedication in helping me to complete my thesis to a high standard.

2. Toby Croasdale, for helping erect the twenty two flap anemometer poles.

3. My wife Karola, and sons Tegan and Alain for their encouragement.

ABSTRACT

A major consideration in the design of single storey buildings is the wind load imposed on the walls and roof of the structure. This wind load is mainly (by definition) the result of the wind velocity at the area of the building under consideration.

In Australia and New Zealand the Standard AS/NZS 1170.2:2011 is the main technical standard governing the assessment of wind loads on buildings, and hence a major influence on their design.

In AS/NZS 1170.2:2011 (p.14) there is an *implied assumption* that the wind, on the scale of buildings, has a straight or uniform front, where the velocity is identical from one end of the building to the other. And that if the wind is hitting the building at an angle, that the passage of the impacting wind front will be linear. In other words, that any gusts will be of the same magnitude as they pass various parts of the building.

Furthermore, on the same page (p.14), there is reference to a "3 second gust wind data", where the maximum wind velocity is maintained for 3 seconds on to the building.

This thesis shows that:

a) The wind does not impinge on to a building as a uniform, ruler-straight front, and

b) The wind does not maintain a maximum velocity for 3 seconds at any part of a building.

The thesis demonstrates that the wind has, at any interval of even a few seconds, a constantly fluctuating irregular front. Also, that the wind at a particular part of the building will vary in speed and direction from one fraction of a second to the next.

The implication for building design is that the structure cannot experience the full wind load even in the most adverse conditions. That only a part of the structure can suffer the maximum wind speed at a time, and even then for less than one second at a time.

Thus the total wind load that must be resisted by extended portions of a building is significantly less than assumed by AS/NZS 1170.2:2011.

The thesis proposes an equation that defines the "shape" of the wind front as a number which shall be called the "wind form factor". Although the behavior of air streams has been investigated in detail in respect of boundary layers and gradients varying with height, at levels of less than a metre, in micro seconds, and also at the very large scale of kilometres, and over hours, there is very little information as to the behavior of the wind at intermediate distances of a few metres and in time periods of seconds.

It is hoped that this thesis will go some way towards addressing the lack of data.

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1. Introduction and Literature Review

Most research regarding air flow has focused on the small and very large scale behaviour of air streams. On the small scale, of dimensions less than a metre in micro-seconds, using the principles of fluid mechanics, and on the very large scale, of dimensions of kilometres, over hours, investigating its meteorogical characteristics.

There has been very little work done in the intermediate range, of dimensions of about 1 to 100 metres. What work has been done has been mainly in the area of turbulence at airports, updrafts, downdrafts, vortices and such, that affect aircraft and may cause them to crash.

But a second area of interest has recently arisen; the effect of medium scale events on wind turbines. This is the research that is closest to this thesis. But even there, the focus is on differences of wind speed at various elevations above the ground, so that the difference in differential loads on the blades of the wind turbine can be assessed.

To the best of my knowledge there has not been a formal examination of the speed and direction of the wind on the scale of metres designed especially for its application to such things as single storey buildings.

Nothing appears to have been published in book or journal form. There is even very little on the internet on web pages that have the advantage of being current state of knowledge, but unfortunately are likely to be transient.

Several months of searching has failed to bring up anything that is a direct precursor to the present thesis. There are a few graphs showing the variation of wind speed over a short time period of only seconds (see windpower.org), but at only one station. And no connection was made as to the relevance of that data; it was only to indicate that the wind can vary at a wind generator turbine, leading to power output variations.

Extensive searching of Curtin University and University of Western Australia libraries turned up nothing.

Key words used in web searches, such as wind 'flutter', 'turbulence', 'variation', 'irregularity', 'profile', 'shear, and so forth, have produced results of thousands of pages (as would be expected), but have failed to elicit anything remotely relevant to this topic.

Infact, electrical engineering principles, such as 'form-factor', were easier to find. They were all similar, and excellent books are referenced in the bibliography. But other similar books may be used by the reader for the same background information.

From this paucity of material we can safely assume that the present research is novel and groundbreaking. It is at least a start in this area, and hopefully can be furthered in future by others.

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2. Research Hypothesis

The worst case wind force on to a building is when a high velocity wind is completely uniform, and steady over several seconds. Thus, when the wind reaches its highest velocities, the entire building is subjected to equally high structural loads, and little or no load-shedding to nearby less stressed areas is possible.

If, during a severe storm, there is a very local imposition of the highest wind velocity, but nearby the building has only low wind velocities inflicted on to it, and perhaps also hitting it from different directions, then the entire structure is not stressed to a maximum amount. There is load-shedding (for example; due to deflection in steel members tending to equalise moment and shear forces, or sideways normalization of the wind's pressure gradient along the face of the building).

The wind load design standard, AS/NZS 1170.2:2011 makes a worst case assumption that the wind will impact the whole building with the same speed from the same direction. That from ground level to the top of the building, with preset categories such as up to 3m, 5m, 10m, 15m and so forth, the velocity is adjusted by a factor referred to as $M_{(z,cat)}$ (p.19), the "terrain/height multiplier". This may or may not be so. It is the purpose of this thesis to examine its actuality.

The worst condition, the one which most closely approaches the assumption of the Standard (of linear, uniform wind speed) can only be found in areas where the wind has not been tampered with by obstructions which, by definition, would shield some parts, cause funneling of others, induce vortices, reflections and so on.

At reasonable cost the variations in the direction and speed of the wind, in short its velocity, need to be found at an optimal location.

The 'cleanest', or least turbulent wind, less than 5m above ground level; that which is in as pristine and uniform a condition as possible, can only be found along the coast.

Furthermore, the wind should have been blowing onshore from hundreds of kilometres of travel over open ocean, so that any irregularities can be reduced by lateral pressure equalization (at the scales that we are concerned with), which are able to proceed due to insignificant obstructions introducing further irregularities.

In Australia these ideal conditions for the most laminar and unchanging (in speed and direction) wind can most often be found on the West Coast, since the prevailing winds in the Southern Hemisphere run from West to East.

As we proceed inland, even beyond the first coastal sand dunes, the wind is affected more and more by obstructions such as buildings, bushes, trees, hills, and so forth. Each of these obstructions breaks up the wind into fractions with different directions and speeds. So, away from the seafront winds are never uniform, even if we have a steady wind front at the coast.

Hence the absolute necessity to do this research within metres of the waterfront. Geraldton is a prime location for this research, since for much of the year there is a steady strong onshore wind coming from across thousands of kilometres of the Indian and Arctic Oceans. This is as smooth, laminar and uniform as any wind can possibly be.

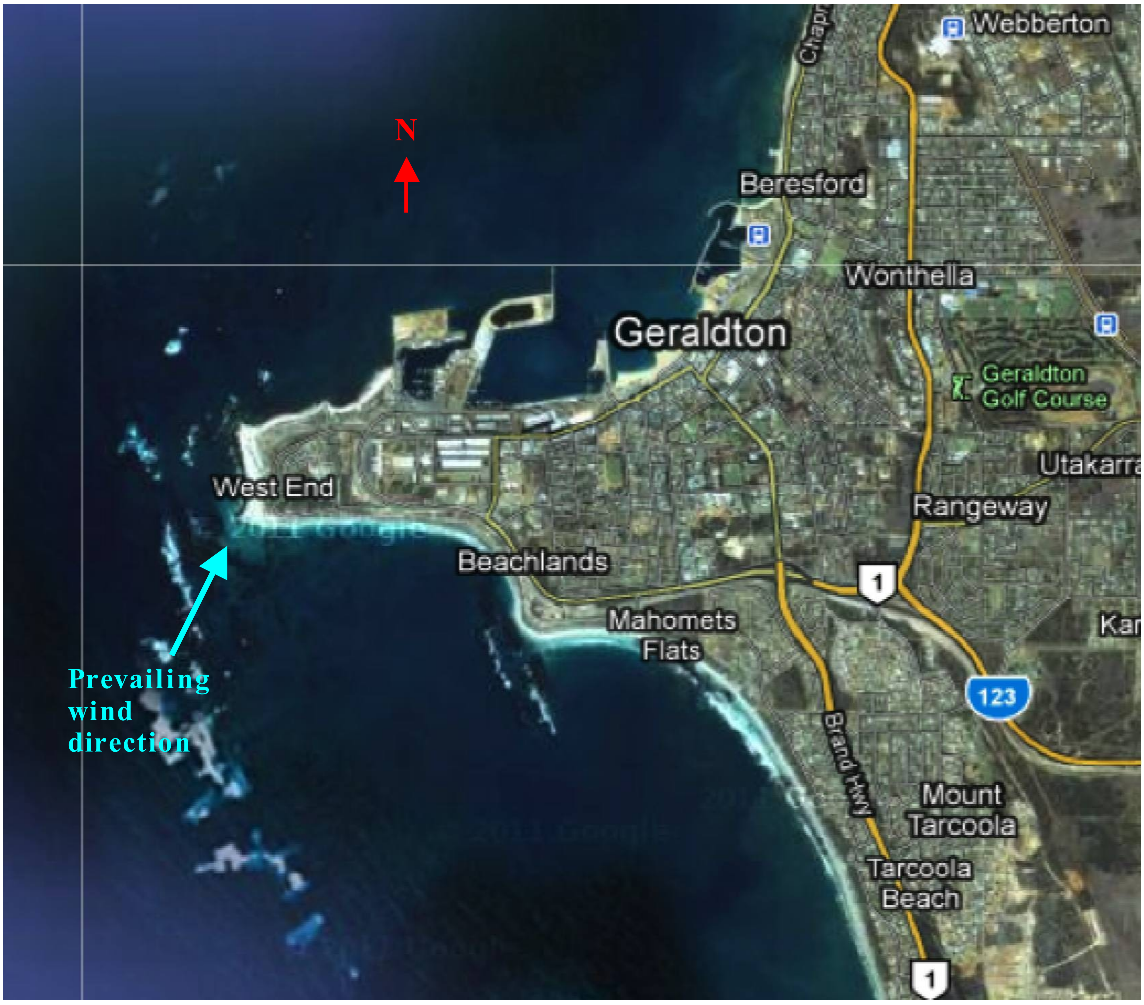

Fig. 1. Location of the tests; just below the 'e' of "West End" Ignore the white surf.

In figure 1, the surf at lower left is over reefs below sea level. In other words, the surf is no higher than the surrounding swell and does not affect wind laminar flow.

Geraldton is an ideal location for such winds coming in off the Indian Ocean. Even then, the experiment has to be carried out when the sea level isobaric pressure charts are favorable; that is, a 'low' is offshore south of Geraldton or an incoming 'high' is situated at the same latitude or a little further North

The next photograph in figure 2 shows the actual on-site view of the location. The beach is very flat. The tests were done within a few steps of the water's edge. The sand dunes are well downwind and to the East of the test location; the closest ones only about 3m high and almost 100m away.

Fig. 2. Location of the tests; in the distance on the far right. Note the clean ocean horizon

All wind measurements at the beach were done during steady meteorological conditions, when there were no cold or warm fronts or line squalls passing through or near the area. The nearest fronts were hundreds of kilometres away. So conditions were biased as much as possible in favour of several seconds of constant velocity.

2.1. Possible scenarios:

It may well be that at very high wind speeds (the conditions that concern us), the wind is indeed uniform, and maintains the same velocity over a long base line of several metres to 100 metres or more. That is the assumption of AS 1170-2: 2011, as well as previous editions going back more than 20 years. So the flaps, described in the next section, would all act identically as shown in figure 3:

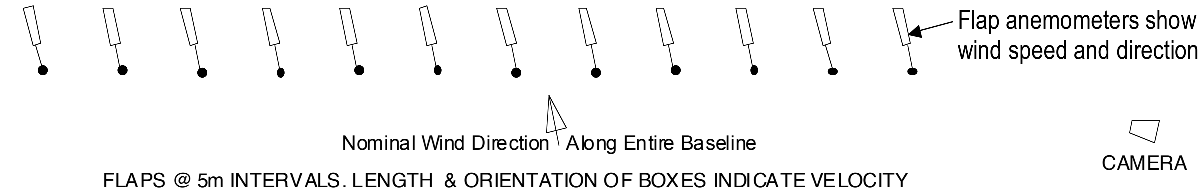

Fig.3 . Plan view. Uniform pattern as per AS1170-2 assumptions (not all flaps shown)

Or it may be that the wind, at moderate to high speeds, is entirely chaotic, irregular and turbulent. In which case we would expect the flaps to be "all over the place" as in the following illustration:

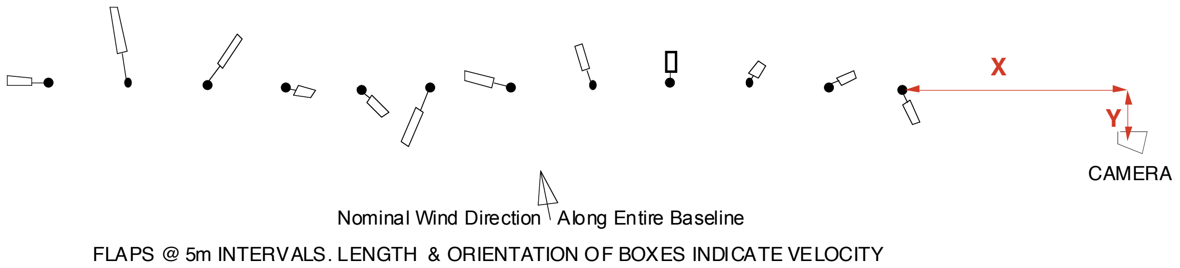

Fig.4 . Plan view pattern if there is extreme chaos and turbulence

The author's conjecture is that the wind *at the most ideal location* is neither uniform, nor chaotic, but somewhere in between. As in the following diagram:

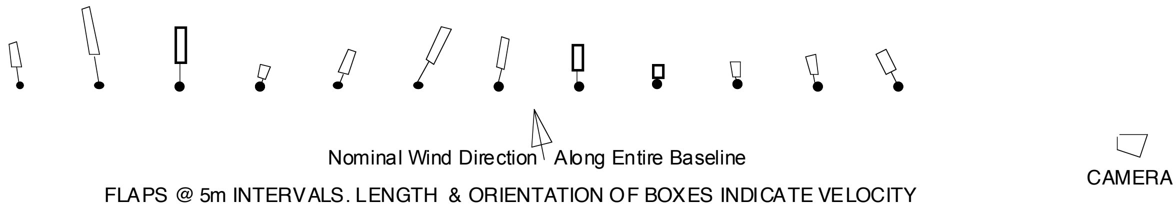

Fig.5 . Plan view of the expected pattern of the wind. There were 22 flaps at 5m intervals

It bears repeating; the experiment was done at an ideal place possible for a laminar, uniform, smooth wind form; an ocean facing beach with the wind not being interrupted for thousands of kilometres. **So, if the wind was not uniform at this location, under such conditions, it can not be so anywhere else, at any time**.

And we should also remember that the winds during the experiment were quite moderate, ranging at around 2.5m/s to 3m/s (about 10 km/hr) during the 22 flap experiment, to 7m/s to 11m/s (25 km/hr to 40 km/hr) for the spot reading experiment.

At higher speeds, the wind is even less regular, both spatially and temporally. It is more 'ragged', and its speed varies on the scale of metres and seconds to a greater extent and more rapidly. Though whether that variation is at the same ratio or percentage of the peak, or whether it is a fixed amount of X m/s, cannot be known unless many readings are done during a cyclone. That is outside the capability of a modest research program.

The above diagrams are general and not oriented geographically. But, in relation to the actual experiments, the flaps were set up in a line running North to South. So the line of flaps at the actual location had North to the left and South to the right.

With that orientation, the winds during the experiment were mainly from the SSW, or more from the bottom-right of the above diagrams.

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3. Methodology

My intention has been to measure, if possible, both the speed and direction of the wind along a straight line, representing the side of a straight, single storey building. To do this over a reasonable distance would become prohibitively expensive as an academic project. So a means had to be devised to do it quite cheaply.

There is a wide range of equipment available for measuring wind speed; e.g. propeller anemometers, vane anemometers, hot wire devices, laser and radar doppler speed sensors.

The proposed device is to use vane or flap anemometers set in a line over several metres. From here on I will call them *flap* anemometers, because that more clearly describes how they work: by the deflection of a flat sheet due to the force of the wind on to it. The force being proportional to the wind velocity.

The flap anemometers had to be simple enough to construct. There also had to be enough of them to make the results meaningful. It was decided that a series of 21 would be made, set at 5m intervals over a 100m line. (However, on the day of the experiment there was one spare anemometer, and so 22 flaps were erected over a 105m baseline.)

The flap anemometers also had to be rotatable, so that both the speed and direction of the wind could be assessed at the same time. So, as the wind veered a little this way or that, the flap would veer with it, just like farm windmills.

The flaps also had to be set at a height commensurate with single storey buildings. In the Wind Standard $M_{(z,cat)}$ has its lowest height interval finishing at 3m, and its next height bracket starting at 3m. So it was decided to mount the flaps at 3m high, as mounting them any higher was impractical due to cost and toppling forces on the temporary embedment.

A method to track the performance of all the flaps at the same time is by taking photographs and hopefully also videos. Though the resolution of videos is far less than with photographs.

The design of the flaps is on the next page (fig.6). They are made of A5 sized sheets of 200 gsm (gram per square metre) card. Trials were carried out with larger ones, but they were too greatly affected by even the lightest breezes. Anything smaller would be even more difficult to photograph. So the given size is a good compromise.

The flaps were mounted on 3m long 19mm x 19mm pine poles, dug into well compacted sand by about 250mm, which was enough to hold them. Since the 4mm diameter skewers used for the flap assembly were also about that length, the consistent 3m above ground level was approximately maintained, as can be seen in the photographs; figs. 6, 7, 8, 9, and 11.

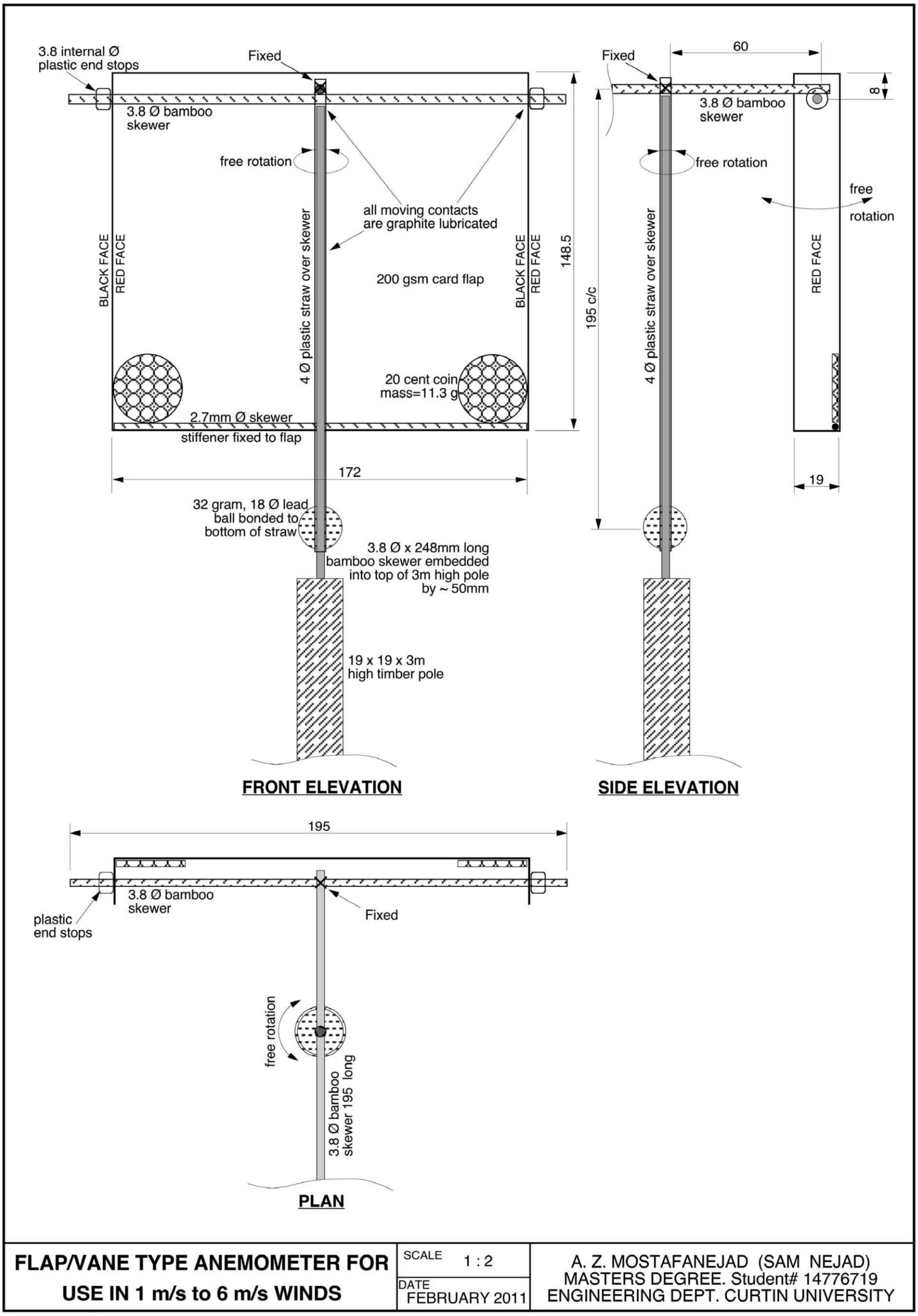

Fig. 6. The flap anemometer used in the experiment

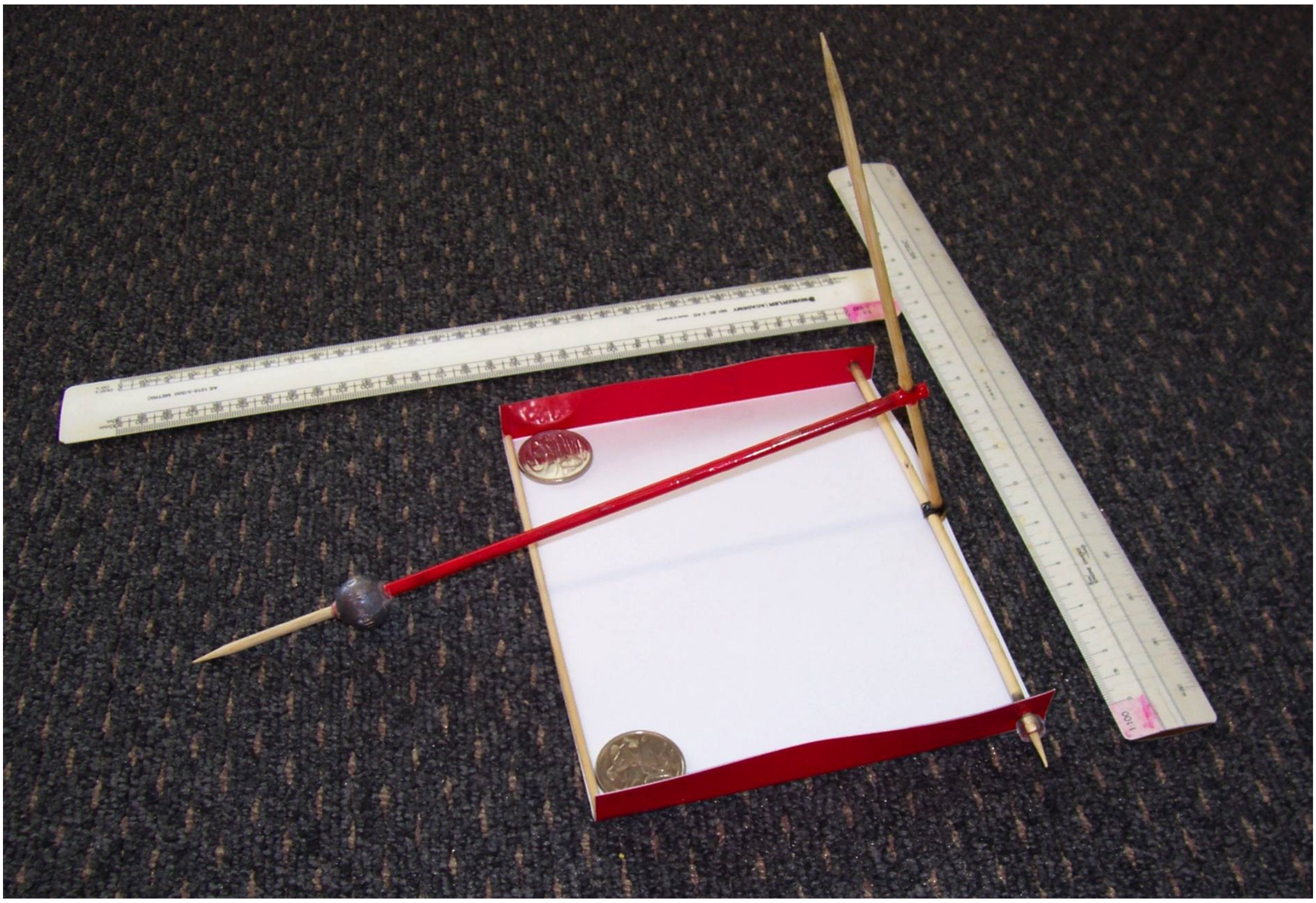

Fig. 7. The flap anemometer used in the experiment

3.1. Detection and Calibration:

The flaps are free to rotate to face the wind. Rotation sensitivity was determined to be typically about half a second, depending on the speed of the wind; the faster the wind, the more quickly they responded.

The flap moving surfaces were lightly coated with graphite powder dry lubricant to reduce any friction (which was already hardly noticeable), and allow rapid response.

The flaps also deflected upwards, further as the wind was stronger. Minimum to maximum inclination was determined by videoing and photographing a flap (their essential elements, such as surface area and response time were identical within less than 5%). The deflection was also very rapid, being always within half a second; faster for small wind variations than larger ones. But that is not to say that the flaps behaved well, or that there was always a one to one correspondence between wind speed and inclination. Their most consistent response was between 1m/s and 7m/s (4 to 20km/hr).

The flap inclination was calibrated with the HP816A digital propeller anemometer mounted just below and to the side of it as shown in the photograph (figures 8 and 15).

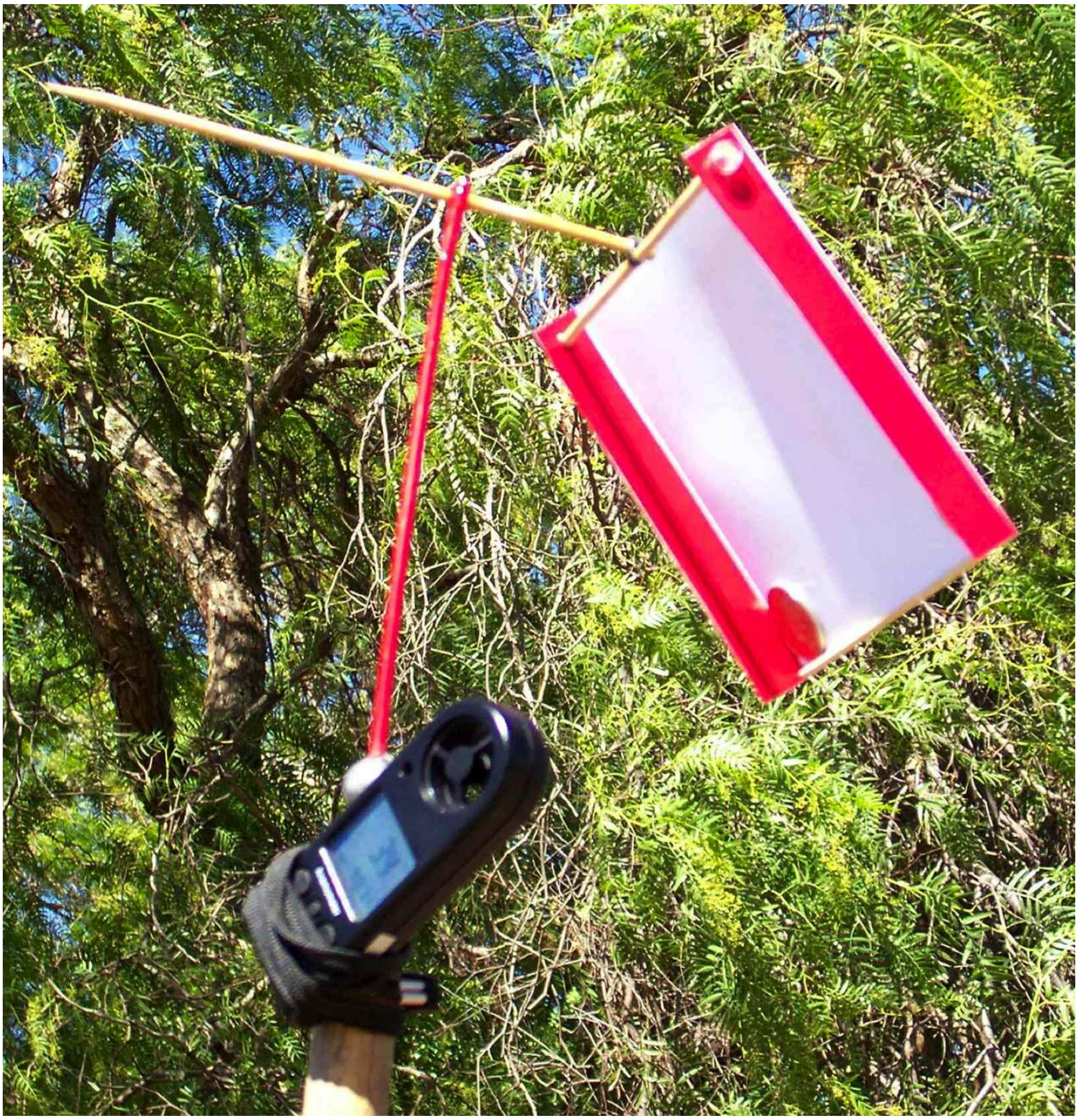

Fig. 8. Calibration of the flap with a digital anemometer. Readings were from a video.

The flaps had significant inertia due to weighing them down with the two 20 cent coins. But that was necessary otherwise they would flap about even in the lightest winds. And even though damping was naturally provided by the capture of a layer of air within the folds, the coins, which added 22.6 grams, imposed a slight pendulum action in light, variable winds.

A second source of inertia was the lead weight at the base of the straw (seen behind the digital anemometer). That was also necessary to stop the aerofoil action of an almost horizontal flap lifting the whole device off the vertical support (the bamboo skewer).

So the design was a compromise between being too light and over-sensitive, and being too heavy and unresponsive. In practice it operated reasonably well within the given range.

The wind values used were between 1m/s and 6m/s. Below 1m/s the flap was sluggish in response and slow to rotate on the horizontal axis. Above 6m/s the flap became unstable and generally fluttered and swung about due to aerodynamic effects. For those reasons, values less than 1m/s and more than 6m/s have been omitted.

Readings were made by looking from about 30 degrees to one side of the flap and anemometer, to allow the anemometer screen to be photographed. But the actual orientation of the anemometer relative to the camera was calculated for each photograph or video frame, since the height remains constant at 195mm (see figure 8 and 9), but the width of the flap, **A** , changes as the flap swings on the horizontal axis.

The real ratio of the (flap width)/(skewer height) was 172mm/195mm = 0.882
The value of 'A' is zero for the camera being edge-on to the flap ($\vartheta = 0$), and 172mm for the camera being face-on to the flap ($\vartheta = 0$). The orientation equation for a full scale image being:

Eqn 1: **Angle of orientation, $\vartheta = \sin^{-1} [(A/195) / 0.882]$**

But the image on the computer monitor is not full scale; it is reduced due to perspective and reduction to fit the screen. So the actual monitor image is measured with vernier calipers. (This was measured to the nearest 0.1mm on the computer monitor, which admittedly has greater errors the further away and blurred the object is). Let A_{act} be the actual measured value on the monitor. And H_{act} the actual skewer height. Then the equation becomes:

Eqn 2: **Angle of orientation, $\vartheta = \sin^{-1} [(A_{act} / H_{act}) / 0.882]$**

For example, for the photograph of figure 8, $\vartheta = 27.2^{o}$. That is, the flap is turned towards the camera 27.2^{o} from being edge-on.

The angle of elevation above the camera is very small, and so the perspective effect is minimal and can be dismissed. For example, if the elevation is even as great as 10 degrees above the camera, the (measured length)/(actual length) is still 98.5%, and taking the errors of measurement and the response delay and flutter into account, not diminishing from the accuracy, which is approximate at best.

The actual (reduced) tilt of the flap is measured with a protractor directly off the computer monitor:

Eqn 3: **Deflection from Vertical, φ = measured angle** x **cos ϑ**

During the calibration photography the flap veered a little on the horizontal axis, which was accounted for by the above equation. The anemometer remained fixed, but the effect on it was a function of the cosine of the change in wind direction. Even if the wind veered by as much as 10 degrees, the change in effective wind velocity was only cos 10^{o} , which is 98.5% of the actual wind velocity. Enough readings were made for 50 reliable ones to be extracted from still photographs as well as the better frames of a video, for a fair approximation of the angle of the flap relative to the wind speed.

This 'brute force' method of numerous data points reduces the random effects of flap inertia and flutter, which were significant due to the unsteadiness of the wind, *even at the beach after hundreds of kilometres of unimpeded travel*.

The least 'noisy' performance of the flap anemometer was between 2m/s and 5m/s. Although, as already mentioned, values from 1m/s to 6m/s were good enough for use.

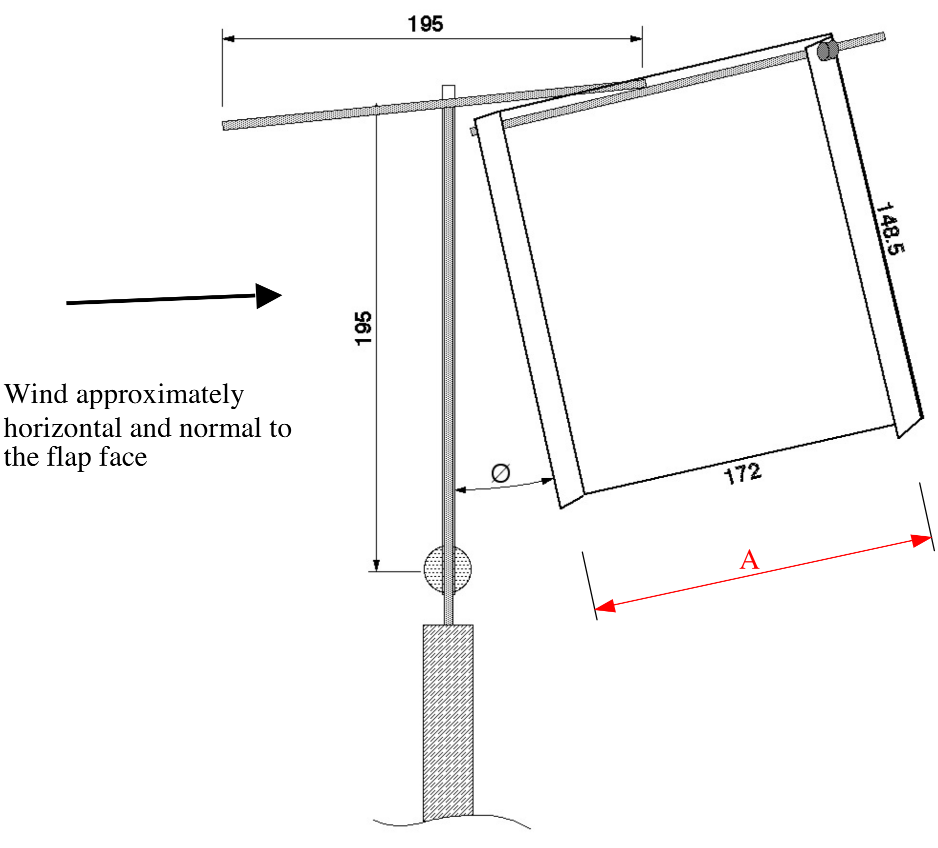

Fig. 9. Illustration of flap for calibration angle calculation

The data points were then entered into Microsoft Excel. A scatter graph was made, and a best-fit regression applied (Chart 1).

Curiously the regression that fitted the points best was a straight line, and not a logarithmic curve as I had expected. This is probably due to the wind force at higher speeds being negated by the smaller area of flap presented to the wind. But in any event the equation is accurate enough for the purpose of this experiment and the limitations of the equipment.

The correlation coefficient, R was 0.82, and the coefficient of determination; R^2 was 0.6724 for a straight line best fit, while only 0.3702 for a logarithmic line. The data points, as can be seen, scatter quite well around the regression line. There are 50 data points, but not all can be seen because several overlap. The high R value proves the reliability of the flap anemometer concept and the calibration method. The tabular form is in Chart 2.

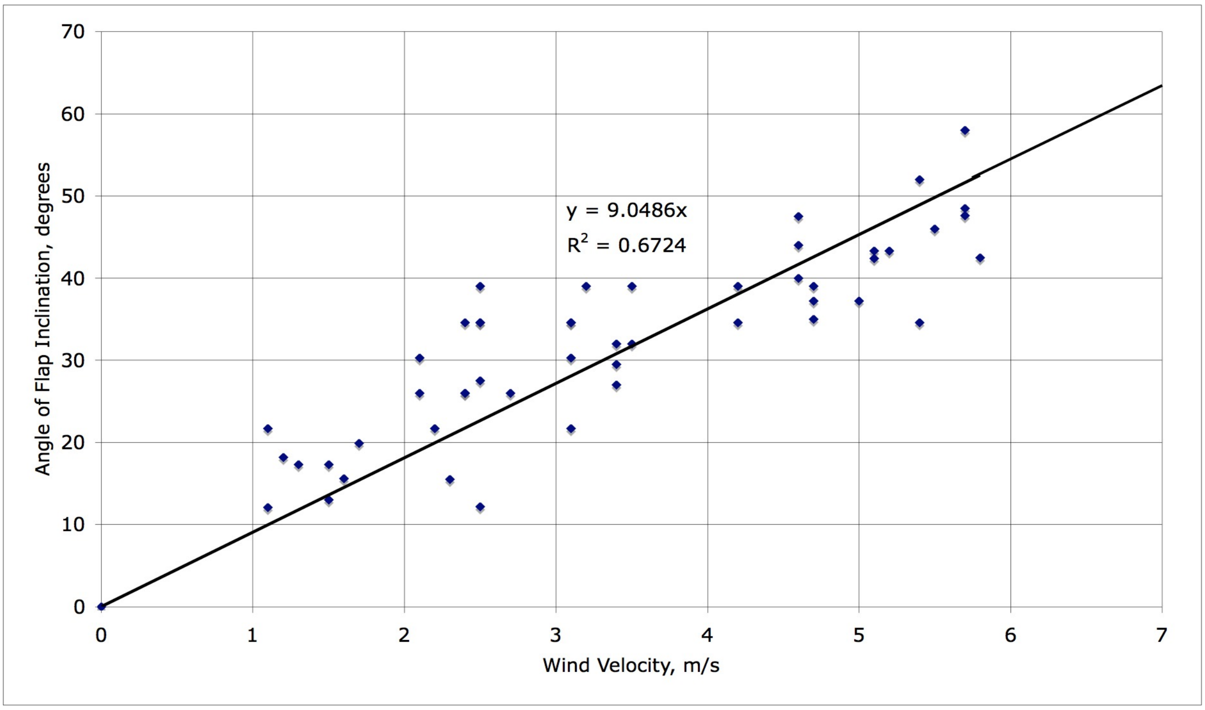

Chart. 1. Sample points and regression line for flap angle for wind velocities of up to 6 m/s

Wind Velocity m/s	Flap Angle to Vertical. Degrees
0	0
1	9
2	18
3	27
4	36
5	45
6	54
7	63

Chart 2. The derived angle of the flaps for wind velocities of 0 m/s to 7 m/s

The HP816A anemometer that was used is a very sensitive device. It converts the wind speed to a digital readout via a frictionless electronic detector. It takes a spot reading every half second which is recorded on the camera for later attention. So the above values are accurate within the practical considerations of this experiment. Any extra accuracy, using far more expensive instruments would only by superfluous to the practical calculations that can already be done.

4. Implementation

Two types of experiment were carried out:

1) The setting up of a line of 22 flap anemometers near the water's edge, at the lighthouse beach, West End, Geraldton, on Friday 25 February 2011 about 2 PM. When the wind was south-south-westerly, and coming in over hundreds of kilometres off the Indian ocean (figs 16 to 23). The flaps were set up at 5m centres in a North-South line, spanning 105m in all.

2) Wind speed readings were also taken at the same location, from the beginning of April 2011 whenever the wind was coming in over hundreds of kilometres over the Indian Ocean. Those readings were done only with the HP816 digital anemometer, for high accuracy wind speed fluctuation readings at 0.5 second intervals.

The wind speed data was collected for continuous periods of about 1 minute (about 120 spot values), when the wind was at its highest speed.

Efforts were made to go to the beach during the highest wind speeds (normally around noon), since the point of the experiments has been to place some limits on what the maximum wind load on a single storey building is, and by definition, that happens at the higher wind velocities. It also happens that as a fluid, such as air, moves at higher speeds, it becomes more turbulent due to shear at boundary layers. That principle is well documented for pipes and channels. Our subject is wind in the open, but the general principle should apply, though its boundaries are not known for this situation.

The camera was set up North of the line of flap anemometers, as well as South of the line. The distances were as in figure 4;. When the camera was North of the line, **X = 30m to its N, and Y = 12m to its W**. When the camera was South of the line **X = 30m to its S, and Y = 10m to its W**. The slight difference had to do with the minimal distance to the water!

The closest sand dunes, just 4m high at most, were almost 100m away and downwind of the experiment. So they could not have influenced the results.

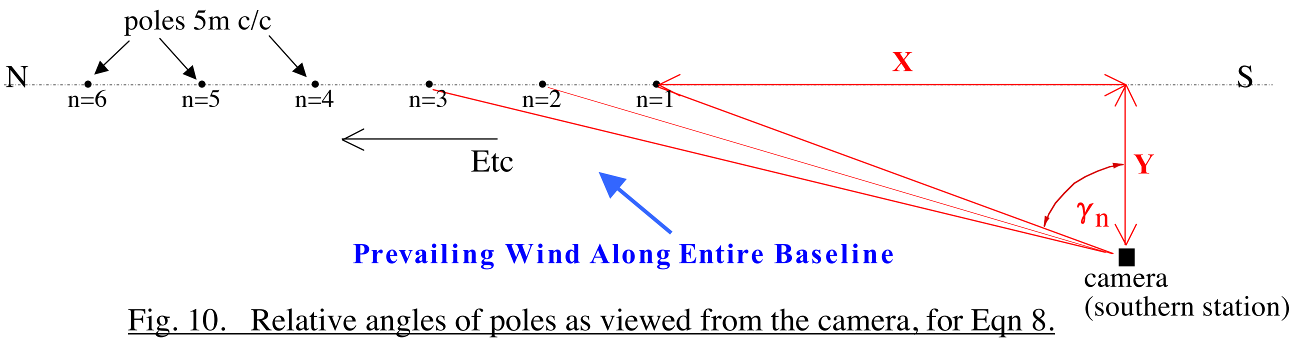

Fig. 10. Relative angles of poles as viewed from the camera, for Eqn 8.

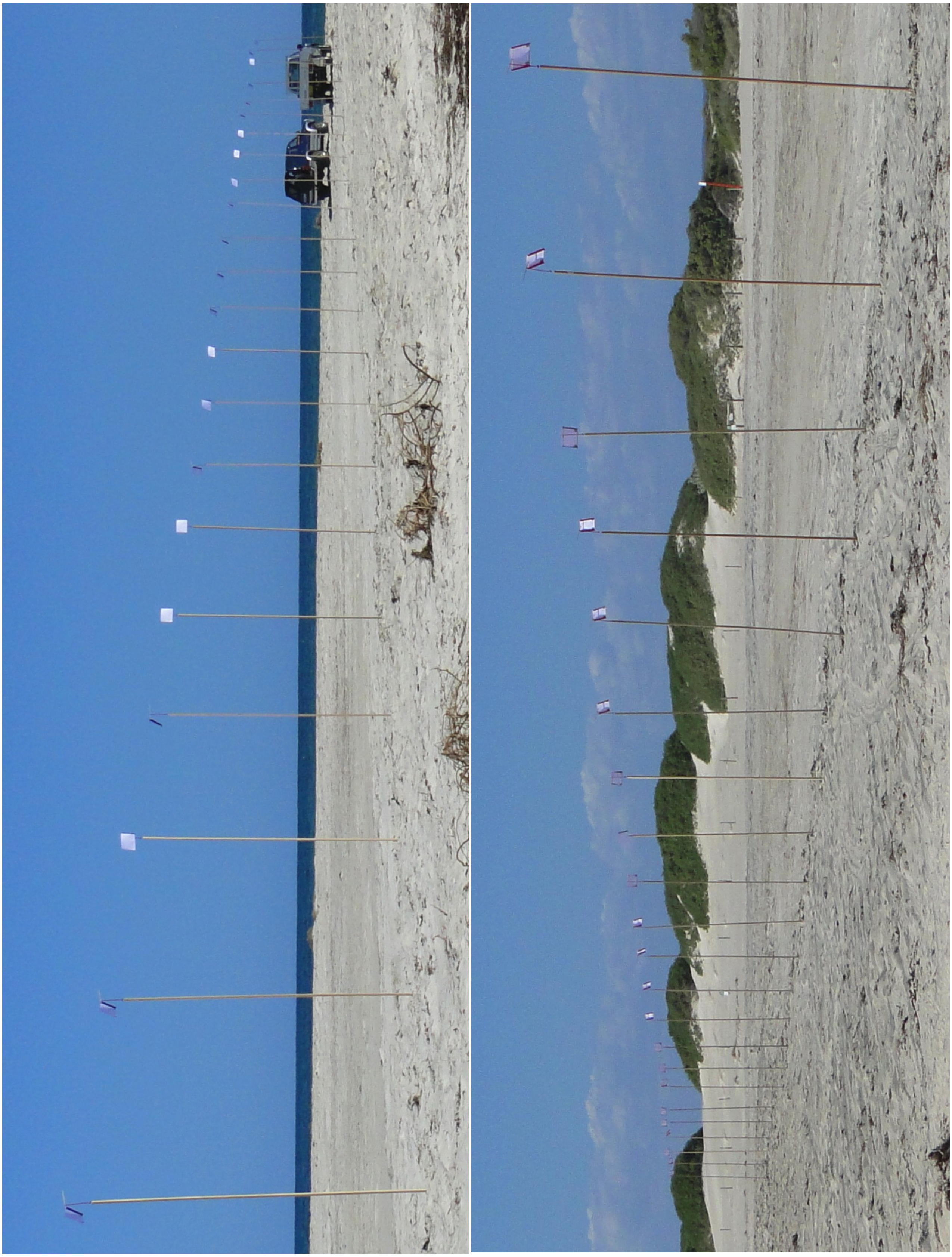

Fig. 11. On the left we see the flaps from the northern station. On the right from the southern. The cars in the left photo are several metres to the East and downwind of the far flaps. Note that at most only two flaps are oriented in about the same way; just 5m apart. Unfortunately videos did not have adequate resolution, but the photos (52 of them) came out quite well, and were zoomed in on the computer for detection and measurement.

5. Results and Analysis

The following enlarged frames show the degree of definition. On the computer screen the resolution is better than in print, because the screen is larger (56 cm) and has more pixels per mm, so the measurements were clearer than what appears here. They could also be enhanced locally. So the photographs are only the best printable version.

Fig. 12. The furthest flaps; #18 to #22. Note the dimension extents (illustrative only)

Fig. 13. The middle flaps; #10 to #14. The skewers can now be clearly seen

Fig. 14. The closest flaps; #1 to #5. The vertical skewer is measured and scaled for all poles

The height of the skewer is constant at 195mm. As the post and flap are further away, the photographic image is smaller. The first pole and flap is used as the datum against which the others are measured at the same magnification on the monitor.

So even when the skewer is well nigh invisible, calibration can be done well enough using the scale off the photograph.

For the reduction of the calibration images the following equations are used:

Let X = closest skewer distance in the N-S component.

Then, from the Southern camera post, distance = $(30^2 + 10^2)^{0.5}$

So the closest pole is 31.6m away. The accuracy of placement was about 5cm.

Applying that equation in a general format, using the notation X and Y of figs 4 and 11:

Eqn 4: **Distance to any flap = $(Y^2 + (X + 5(n-1)^2)^{0.5}$**

Where n is the pole number from closest (#1) to farthest (#22)

Then, the relative heights of the vertical skewers must be:

Eqn 5: **Let F = Fraction of height of vertical skewer n =** $$\mathbf{\frac{(Y^2 + X^2)^{0.5}}{(Y^2 + (X + 5(n-1))^2)^{0.5}}}$$

So, for example, the seventh skewer is

$$(10^2 + 30^2)^{0.5} / (10^2 + (30 + 5(7-1))^2)^{0.5}$$
$$= 31.623 / (100 + (30 + 30)^2)^{0.5} = 0.5198$$

So, if a highly zoomed in photograph show the nearest vertical skewer as 50mm high on the computer monitor, then the 7th skewer would be 0.5198 x 50mm = 26mm high, and the 22nd skewer would be 0.2336 x 50mm = 11.7mm high. (Checked and confirmed).

We notice from figure 9 that no matter what the rotation of the flap, within the accuracy limits of this experiment, its height is only determined by its elevation, (inclination to the horizontal plane). So a simple measurement of its height on the screen, reduced by the applicable reduction ratio will give us that angle of elevation:

The deflection from the vertical of the flap is thus simply a case of the measured flap height relative to the fractional height of a vertical flap calculated by the above equation.
For the above example of a measured 1st skewer of 50mm, we have height of first flap (limply hanging) should be (148.5/195) x 50mm = 38.1mm . So the 22nd flap, if hanging vertically would be 0.2336 x 38.1mm high = 8.9mm. But its deflection from the vertical is:

Eqn 6: **Deflection from Vertical, $\varphi = \cos^{-1}$ [measured flap height / (38.1 x F)]**

Eqn 7: Again for this example we have; **Vertical deflection** $\varphi = \cos^{-1}[8.7 / 8.9] = 12^{o}$

As already stated, the further away the flap, the greater the possibility of error, but great care was taken to get as good an approximation as possible.

Finally, if we want its rotation about the vertical axis, in relation to the North-South base line, that is also a matter of scaling, and taking into account the angle of view of the camera, which is skewed to the baseline.

Let γ be the angle from the camera to any specific flap. Let D be the perceived width. Let **D'** be the perceived width **if** face on.

The perceived width of the flap is also reduced by the same ratio. In the above example, the nearest one face on would be (172/195) x 50mm = 44.1mm on the screen. So the 22nd flap should be 0.2336 x 44.1mm wide face on = 10.3mm . If it is less, then it has rotated.

Eqn 8: $$\gamma_n = \tan^{-1}\{[X + 5(n-1)]/Y\}$$

Eqn 9: $$\text{Rotation to N-S line} = (90 - \gamma_n) + \cos^{-1}(D / D')$$

It measured 4.9mm on the screen which corresponds *from the point of view of the camera* to a rotation about the vertical of about 62 degrees away from being face on. Its rotation relative to the base line (N-S) was:

Eqn 10: $$\text{Rotation away from N-S line} = (90 - \tan^{-1}\{[X + 5(n-1)]/Y\}) + \cos^{-1}(D / D')$$

Eqn 11: $$\text{Rotation away from N-S line} = (90 - \tan^{-1}\{[30 + 5(22-1)]/10\}) + \cos^{-1}(6.5 / 10.3) = 55^{o}$$

And by inspection of the photograph, that rotation was clockwise looking down on top of the pole. In other words, the wind at that instant for that flap, was about West-South-West.

So, if the first vertical 195mm skewer is (say) 200 pixels high, and another one further away is 100 pixels high, it follows that all other dimensions of the further flap anemometer are reduced by the same scale.

The reduced and projected flap angle vs. wind velocity data is in the table of Chart 2.

Any bending of the 3.8mm vertical round bamboo skewer is irrelevant, since both the horizontal and vertical rotation of the flap are around fulcrums which are both independent of the position of the mounting structure.

On the face of a flat sided building there will be some normalization of the wind pressure due to air pressure transfer from a high wind velocity area to a low wind velocity area. But this pressure transfer happens at a speed similar to the speed of sound in air, which is about 345m/s.

So over (say) a 10m distance the pressure transfer happens in just 0.03 seconds. The skin friction of the building will be irrelevant in this process, since that retardation is only significant at the boundary layer within millimetres of the surface.

The results show that the assumption of Figure 5, moderate variability of the wind, is the reality.

Is it possible that on a different day the wind would be perfectly uniform and constant on the several metre and many second scale? No. Because as already stated, these measurements were taken on days during which the wind was coming towards the station over more several hundred kilometres of ocean. That is the most favourable condition for perfectly uniform wind flow. And if on such days the wind was still variable in speed and direction, then it would be at least that variable on any other day, *since there is no mechanism which would produce a smooth wind flow over rougher terrain*.

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6. Wind 'Form Factor'

In electrical engineering there is a concept called 'form factor' generally used to describe the effective uniformity of the potential across a circuit. Form factor is a dimensionless number that describes how variable the voltage is about the mean (Reference. See, for example, J. O. Bird. (2003). *Electrical circuit theory and technology*).

Eqn 12: **The voltage form factor =** $\dfrac{\textbf{Peak Voltage}}{\textbf{Average Voltage}}$

This is a useful concept that will now be applied to the wind. As equipment becomes available for more easily detecting and recording the speed of the wind over distance and over time, we can more accurately work out the actual forces that the wind will impart on to the side and roof of a building over any given distance and time.

The wind form factor (FF) has 6 portions which can be used individually or together.

Along any given datum it is comprised of the (peak value) / (average value) for:

Items **1)** Differences in speed at *any* point of baseline at the same instant as other points.

2) Variations in speed at *one* point at equal intervals, such as 0.5 seconds.

3) Differences in speed with *altitude* at a base, such as ground level, 1m, 2m, etc.

4) Differences in direction at *all* points along the base line at one instant in time.

5) Variations in direction at a *specific* point over time at given time intervals.

6) Differences in direction with *altitude* at a given location at one instant in time.

Notice that items 1, 2, and 3 concern the speed of the wind, and when combined represent the plane face of a hypothetical building. Items 4, 5, and 6 concern the direction of the wind, and their combination represents the plane face of the hypothetical building.

The six items are the elements that determine the force on the face, or parts of the face, of a building. The most important ones being items 2, 4 and 5.

Notice that items 4 and 5 are interchangeable in an open or unchanneled system. In other words, the swing in the direction of the wind moves along the face of the building (or baseline) very rapidly, at about the speed of the wind itself. If this was not so, we would have persistent areas of differential pressure.

All six items can be combined into one multivariate calculation of combined form factor. But each can also be analyzed individually as we will do for items 1, 2, and 4.

The linear form factor (FF) of item 1 is:

Eqn 13: **The horizontal spatial** $\mathbf{FF_{\delta x, x}} = \dfrac{\textbf{Peak Speed}}{\textbf{Average Speed}}$ (spatial data)

Where δx is the sampling station separation, here 5m. And X is the total sample distance, here 105m. Note that the speed has already been normalized for a specific direction. Here the component used is the perpendicular to the baseline. But there is no theoretical reason why the component vector would not be in some other direction, chosen presumably due to the direction of the face of the building.

The variation in speed FF at a given point in a given direction of item 2 is:

Eqn 14: **The temporal** $\mathbf{FF_{\delta t, t}} = \dfrac{\textbf{Peak Speed}}{\textbf{Average Speed}}$ (temporal data)

Where δt is the time interval used, here 0.5s , and t is the total time over which it is averaged. Here the component used is the actual direction of the wind. But there is no theoretical reason why a component vector would not be used in some other direction.

The linear altitude, or vertical FF of item 3 is:

Eqn 15: **The vertical spatial** $\mathbf{FF_{\delta h, h}} = \dfrac{\textbf{Peak Speed}}{\textbf{Average Speed}}$

Where δh is the sampling stations' vertical separation, here 0m. We did not do this selection in this experiment since we had a flap at every pole at 3m high.

The vertical form factor would possibly be used for a high rise building, or to work out the typical uniformity of winds vs. altitude at an airport. Again, there is no theoretical reason why the component vector would not be in some other direction.

The direction FF of item 4 is relative to the perpendicular of the base line or vertical plane or face under consideration. It always resolves to one equation whether it is a line or plane being analyzed, because the direction is at an angle to the perpendicular, whatever the rotation, about the sampling point:

Eqn 16: **The impinging direction $FF_{\delta\varepsilon xh,\,\varepsilon xh}$ = $\frac{\text{Peak Rotation}}{\text{Average Rotation}}$**

Where $\delta\varepsilon$ is the sampling station separation, here 5m. Here only the angle with respect to the 105m base line ($FF_{\delta\varepsilon x,\,\varepsilon x}$) was found from observation (of a photograph).

The direction FF of item 5 is relative to the perpendicular of the base line or vertical plane or face under consideration, at a given location but at intervals, such as 0.5 seconds.

Eqn 17: **The impinging direction $FF_{\delta\varepsilon t,\,\varepsilon t}$ = $\frac{\text{Peak impinging angle}}{\text{Average impinging angle}}$**

Where $\delta\varepsilon_t$ is the time interval. This was not done in this experiment due to lack of rapid rotation of the flap anemometers. In any event, a wide variation was not observed. The biggest variation over time and distance was in the wind speed.

Finally, variations in direction with altitude at one location at a given instant give:

Eqn 18: **The impinging direction $FF_{\delta\varepsilon h,\,\varepsilon\eta}$ = $\frac{\text{Peak impinging angle}}{\text{Average impinging angle}}$**

Where $\delta\varepsilon_h$ is the altitude. This was not done in this experiment due to lack resources.

Any of the above can be combined to produce a form factor over both distance and time. For example, all the above can be used:

Eqn 19: **Combined 6 stage FF = $FF_{\delta x} \times FF_{\delta\tau} \times FF_{\delta\eta} \times FF_{\delta\varepsilon\xi\eta} \times FF_{\delta\varepsilon\tau} \times FF_{\delta\varepsilon\eta}$**

However, it must be remembered that some factors may be inter-dependent, and using the product of such factors would give an unjustifiably too low a result.

Factor multiplication is used since, assuming there is no canceling mechanism, the reductions are cumulative. For example, If one form factor, such as direction, is 2 and another, such as speed, is 1, then it follows that the second form factor does nor alter the results (since it asserts that the variable is constant). Then the product of the two factors is 2 x 1 = 2. Thus it remains that only the first form factor has an effect on the final results.

However, as mentioned above and shown below in chapter 8, lacking further information it may be prudent to use only one of possibly conflicting form factors, such as variation in direction along a baseline versus variation is speed along the baseline, since the direction and speed may be co-dependent.

The form factor should always be defined as being spatial, temporal, angular or whatever combination of the above types (and possibly other types as well).

It can be seen that if the peak and average are the same, then FF = 1. But as they are increasingly different, then the form factor also increases to greater than 1.

If, for example, FF = 3 , and the average wind speed is 10m/s. Then we can see that the peak speed must be 30m/s. However the form factor does not tell us if the peak speed was for a fraction of a second or several seconds. Taken over a 1 minute interval, so long as the wind went in the same general direction, it could operate at most for 20 seconds, since:

FF = (30 m/s) / [(30 m/s x 20s + 0m/s x 20s + 0m/s x 20s) / 60s] = 30/10 = 3.

But that is impossible; that the wind is perfectly still for 40 seconds, then blows at 30m/s . A perfect square wave(s) in a 60 second interval for a natural event.

We see then that the form factor may be supplemented with reference to both the maximum (peak) *and* the minimum (trough) wind speed over the given interval.

I mention this only for academic reasons, since it is not useful in calculating the force of the wind on to a surface, but only for refining the shape of the wind front.

The method can be called **the second order form factor, or $_2$FF** . All the above insignia apply to $_2$FF except the subscript 2 placed before FF, to denote that the difference between the maximum and minimum is used in the calculation.

For example:

Eqn 20: **The horizontal spatial $_2FF_{\delta x, x}$ = $\dfrac{\text{(Peak Speed - Trough Speed)}}{\text{Average Speed}}$**

The use of $_2$FF does not make the normal first order FF redundant, because the $_2$FF can not, by itself show what the maximum and minimum values were.
In the above example, if the minimum wind speed was 5m/s for 20 seconds, then:

$_2$FF = (30 m/s - 5m/s) / [(30 m/s x 20s + 5m/s x 20s + 0m/s x 20s) / 60s] = 25/11.7 = 2.14

Notice that if the peak and trough are identical to the average, we will get $_2$FF = 0.

Further layers of analysis can be drawn in. Such as, how long each gust and lull lasted. So you could derive a 3rd order value that can be called ${}_3FF$.

But rather than introduce extra and possibly needless complications, it is enough to point out that ***as the time period increases, the classical form factor will tend to greater than 1, and ${}_2FF$ will tend to 2. <u>Thus short intervals have a distinct advantage for practical use</u>.***

As mentioned, It is better to quote the classical form factor, since wind force calculations may be done from it (see below, Chapter 7, subsection 7.4, and 8), and simply comment that **the maximum wind gust <u>in the best possible situation</u> does not last longer than about 1.5 seconds**. Especially as the wind gets stronger and fluctuates more rapidly and wildly.

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7. Analysis Using Wind Form Factor

7.1. The results of this experiment are of course for one specific point on Earth's surface at one tiny period of time. There are over 63 million half second readings of wind characteristics at any one location during one year. And if the readings are taken at, say, 5m centres; there are over 20 000 000 000 000 or 20 x 10^{12} of those 5m x 5m cells. So we have a combined number of sample points of about 1.23 x 10^{21} ! (Not including altitude).

But that does not mean that we can never come to some conclusions because there may be, at some point in time, somewhere, a remarkable fleeting exception. And that, at that exact place at that time there may be a building that may be damaged by that event.

We are dealing with possibilities less than the likelihood of an asteroid strike, and we never design for asteroid strikes. For one thing, it is impractical, unaffordable, and ends up probably costing more lives in the long run since we are distracted from more urgent and immediate concerns, and instead waste time and money on unlikely events.

So we can come to some conclusions based on limited data (no matter how much data we obtain). The conclusions being that the wind is not uniform, even for a few metres, and even for a few seconds, and even at the most ideal place (at the coast), at the most ideal time (unimpeded flow without weather fronts).

We cannot use physics equations such as the Raleigh equations for turbulence or Reynolds numbers, because we are not dealing with an enclosed system, such as a pipe. Nor are we even dealing with something such as a channel. The system is completely open and affected by too many things beyond present analytical capacity.

The wind direction and speed of the Bureau of Meteorology can be found in the appendix. The raw data for this research was extracted from videos during seconds of fairly clear reading, and is available as an electronic file. But its essential features are in the Excel spreadsheet transcripts of the graphed sections Chart 8 of the appendix.

7.2 The 22 Station Flap Readings:

The first data examination is of the 22 station flap anemometer readings. A sample analysis has been done based on photographs, such as those shown above, but in higher definition on the computer monitor where high levels of zooming in on details could be done.
The weather chart for the time that the readings were made is shown in the appendix.

The following, Chart 3, is a sample of flap rotation, at one instant, along the 21 pole baseline:

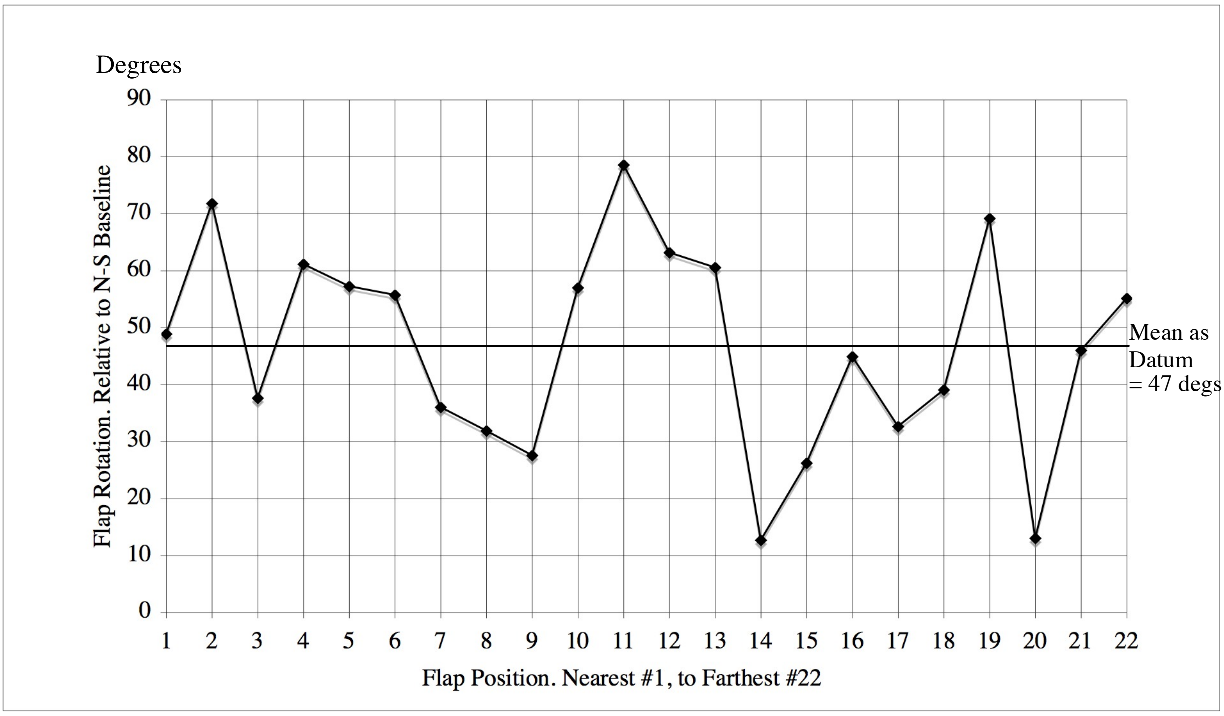


Chart 3. Rotation of flap indicating direction at each of 22 stations at 5 m c/c

The above rotations are at a single point in time. The mean direction of the wind is at almost 47 degrees West of South, or 227 degree to true North (clockwise). That mean will be used as the datum from which a maximum average deviation can be derived. That is the average above the mean or datum value or that below it; which ever is the greater.

The average above = 14.8 degs. The average below = 15.3. the average of the two is 15 degrees rounded to the nearest degree. (More decimal places were used in the calculations). Now, the greatest deviation from the 15 degree average above and below the 'mean datum' is the 13 degrees of poles #14 and #20.

Eqn 21: Hence, the form factor $\mathbf{FF_\delta} = \dfrac{\textbf{Peak impinging angle about the datum}}{\textbf{Average impinging angle about the datum}}$

In this example, the form factor $FF_\delta = \dfrac{\text{Mod}(47 - 13)}{15} = \mathbf{2.27}$ over a 105m baseline.

For a 10m distance, the form factor is about 2 (depending on which 10m we use).

This form factor taken at different times or different locations can be used to compare the directional steadiness of the wind over metre scales, from one time or location to the next.

It is likely that *in open terrain* but near obstructions the form factor will be greater than by the coast. But in a forced situation such as down an alley, the wind is funneled along a predetermined course, and so the form factor will be less.

In the above example there is a variation of +34 degrees to -25 degrees (252^{o} to 205^{o}) at the particular instant of observation. A part of which may be due to the time it takes a gust to travel that distance.

But the two stations of maximum divergence (#11 and #14) are only 15 metres apart, so at the typical speed of 3m/s at that time that is only a 5 second travel time. Three things may cause this:

1) Wind flaps that were stuck. (Dry graphite lubrication was used to minimize this).
2) Slow eddies and vortices in the wind.
3) Stream patterns in the wind that persist for longer than the wind velocity.

Item 1 is unlikely since the flap connections were all freely rotating and they were checked intermittently as the experiment progressed. Furthermore the wind was quite moderate and the flap assemblies were not under great stress.

It is likely that items 2 and 3 are the cause; the wind acting similar to meanders in the flow of a slow moving river. The preferred streaming of different parts of the wind front would persist for several seconds at a time and gradually dissipate and reform further to one side or the other, or even above or below the point of observation.

We must remember that although this set of experiments was done in 2 dimensions (the baseline together with the lateral wind velocity), we are actually dealing with a 3 dimensional fluid; the wind is also transferring its velocity and pressure gradient in altitude. So it is not constrained to a vertically closed system.

7.3 A sample of wind speed, at a given instant, along the baseline:

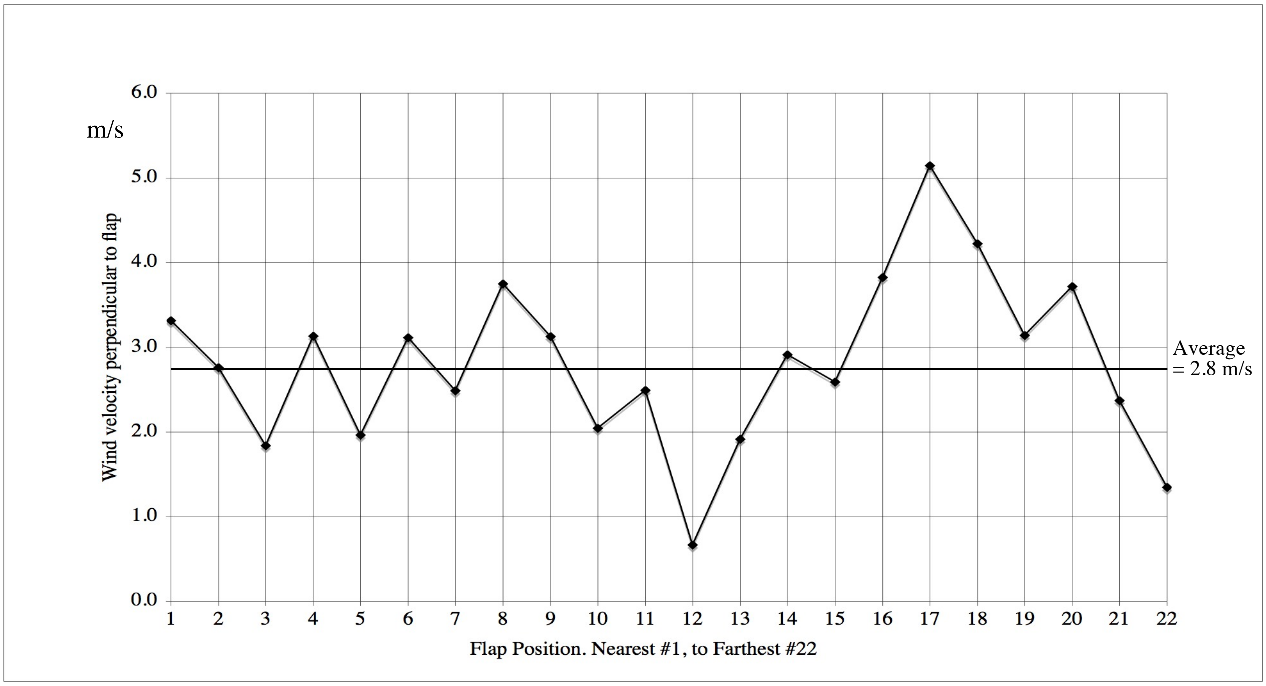


Chart 4. Wind velocity perpendicular to 22 flaps at the same time (5 m c/c)

The wind speed form factor of chart 4 agrees quite well with the wind direction of chart 3. Over a 105m baseline or a 10m one we get a form factor of about 1.82.

It was observed that the wind flows in preferred streams for several seconds at a time. But these streams (by definition) are not at the same speed, as can be seen in the velocity graph taken at the same locations at the same instant.

It can not be assumed that if a stream persists for several seconds that its velocity must also remain identical. Its velocity can fluctuate, as would the velocities of adjacent streams. And they will mingle, lose their boundaries and reform (but evidently as a different stream). In short we have a fairly disorganized system which does not obey simple expectations.
In the above graph the form factors are as defined in equations:

Eqn 22: $$\textbf{The instantaneous } \mathbf{FF_v} = \frac{\textbf{Peak Speed}}{\textbf{Average Speed}}$$

$$\text{The instantaneous } FF_v = \frac{5.1}{2.8} = \mathbf{1.82}$$

Eqn 23: $$\textbf{The instantaneous } \mathbf{{}_2FF_v} = \frac{\textbf{(Peak Speed - Trough Speed)}}{\textbf{Average Speed}}$$

$$\text{The instantaneous } {}_2FF_v = \frac{(5.1 - 0.7)}{2.8} = 1.6$$

The close correspondence between the two form factors shows that the minimum velocity is close to zero. In other words, that there is a large variation in wind speed.

Note that the wind speed is over 4m/s difference from position #12 to position #17, a distance of just 25m. And over 80% of the peak wind speed measured along that baseline.

If that baseline is the face of a 25m long building in an open area it would be absurd to claim that because the wind speed is about 5.1m/s second at one end, it must similarly be at about 5m/s at the other end. Observation shows us that in this case it was just 0.7m/s at the other end.

The difference in wind loading due to that difference in velocity is directly proportional to V^2 , and so of the order of $5.1^2 / 0.7^2$. A 53 fold difference!

We thus see that it is highly unlikely that during a severe storm the wind speed, and hence the force, impinging on to the face or roof of even a modest single storey building is going to be uniformly extreme, *even for a second or so during an extended period.*

7.4 Readings taken at one spot over a period of time:

Finally we come to the time series wind velocity readings taken at one spot by the seashore during 'steady' winds which had traveled hundreds of kilometres over the ocean, and were not associated with a cold or warm front. In other words 'uniform winds', or rather, as we have seen, as laminar and uniform as can be expected...which is not very uniform at all.

Here the readings use only the digital anemometer that samples every 0.5 seconds. In total 39 samples, of aggregate duration 80 minutes 56 seconds were taken over several days. The best two, i.e, highest wind speed over one minute (continuous) portions are shown in Chart 5 and Chart 6, and their spread sheet attached at the end of the appendix. But the other samples had similar rapid variation in wind speed, which indicated similarly significant form factors.

Again, the isobaric and wind maps at the time of the experiments are in the appendix; Chart 7 and Fig.17 to 24, showing the path the wind took before reaching the measuring point.

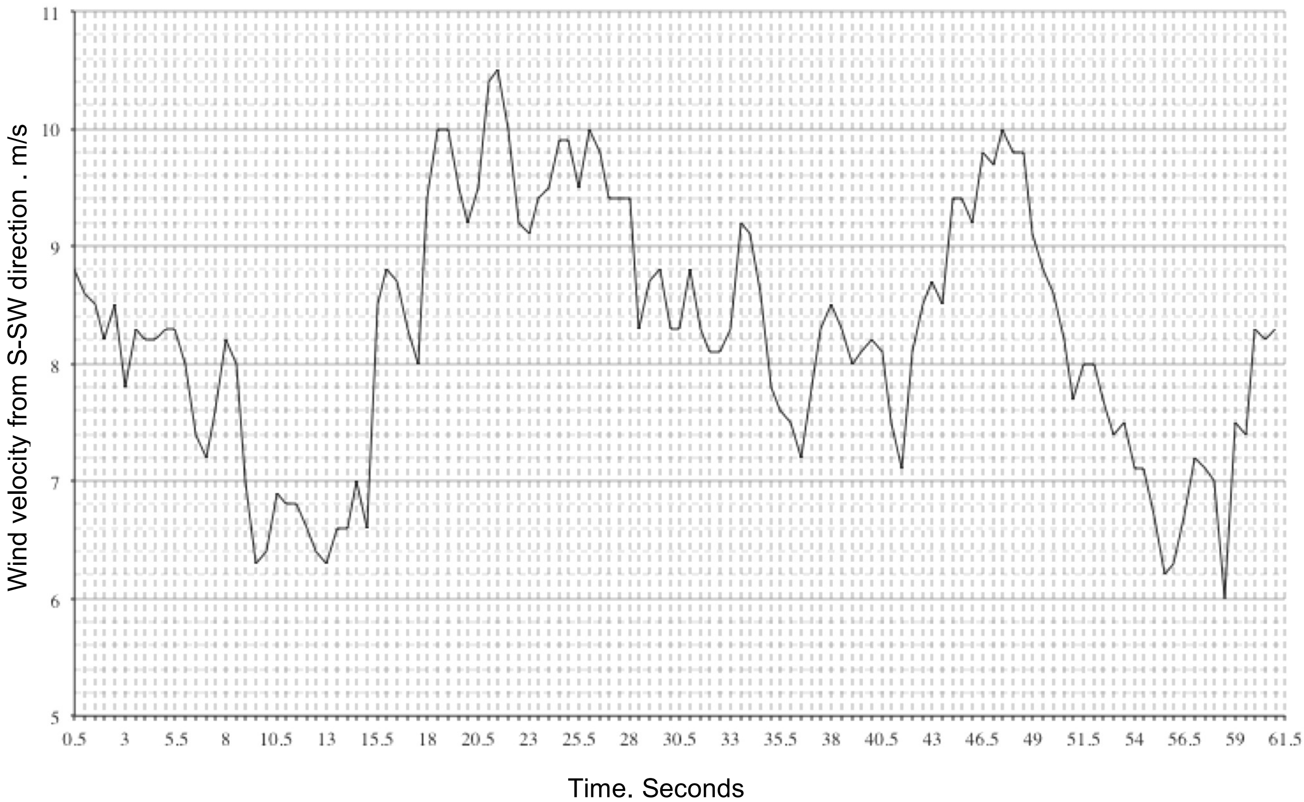


Chart 5. Wind velocity at one station over 60 seconds (13 April 2011)

The above graph (Chart 5) shows wind speeds for 120 samples at 0.5 second intervals, over a 60 second span (first entry at 0.5 seconds). The average is 8.247 m/s. The peak is 10.5 m/s.

So the 1 minute Form Factor = $FF_v = \frac{10.5}{8.247} = 1.273$

But this is not really useful. Suppose, for example, that we took readings for a whole day, and that during that time the speed varied from zero to 70 m/s (as it would from the eye of a cyclone to its maximum vortex speed), that is of no use for calculating the structural forces on the building.

The useful portion of such a graph is the variations near the peak, in other words the form factor over a 1 to 2 second interval, the duration which can accommodate load shedding.
For the above graph that interval is from 20.5s to 22.5s, which corresponds to a mean of 9.92m/s, with a peak of 10.5m/s. The FF is thus 1.06, or virtually 1.

We thus have a maximum wind load **at one point in space** that is about equivalent to that produced by the peak wind speed, but that is disregarding the variation of wind direction.

In the next graph, Chart 6, we have a form factor of 1.01 (close to 1), for a 1.5 second period (from 31.5s to 33s into the readings and peak of 11.5m/s) and mean 9.62m/s.

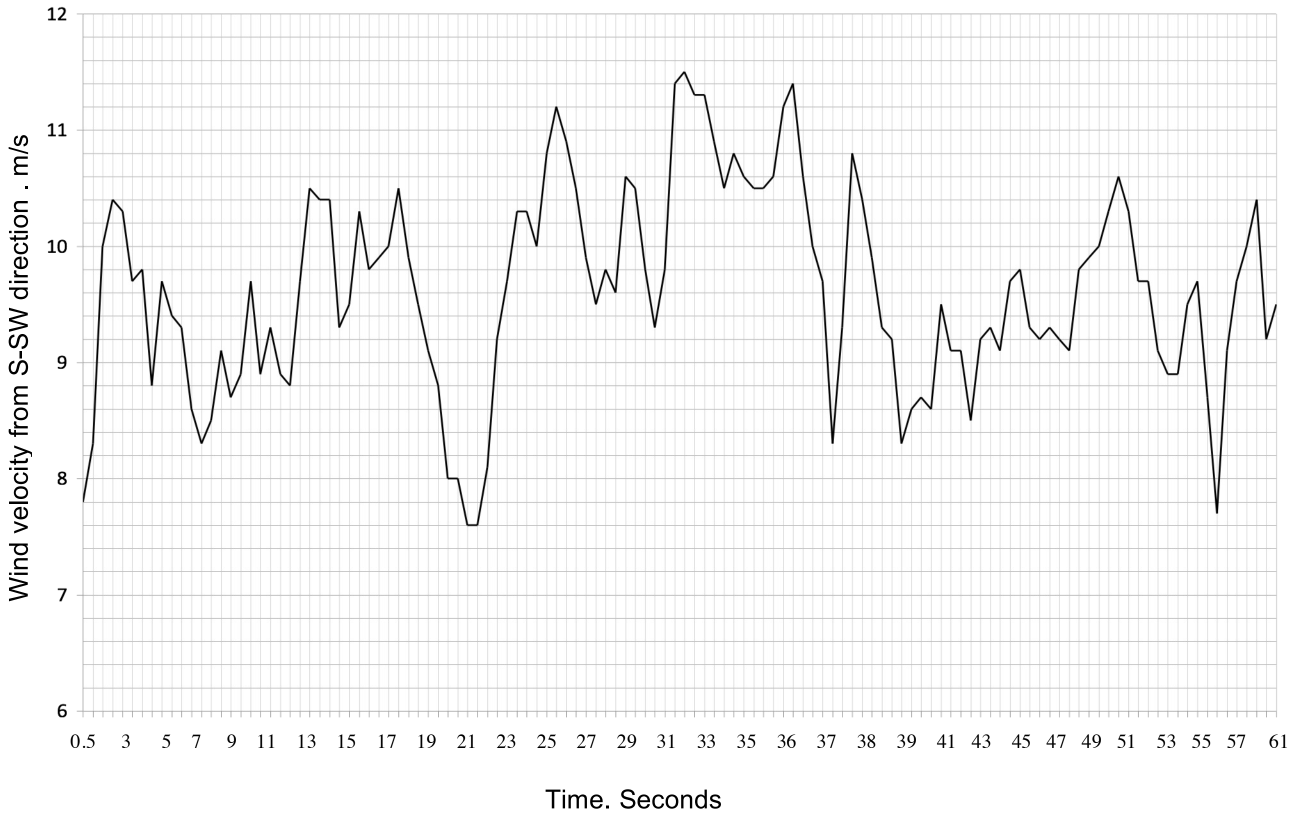


Chart 6. Wind velocity at one station over 61 seconds (18 April 2011)

In summary of this chapter, it is clear that form factor calculations can be made either on a peak vs average wind speed (FF), or on a peak vs. trough wind speed ($_2$FF). And that various components can be brought into play, such as speed, direction, and duration.

8. An Example Calculation Showing Real World Effects

In the above example, we have seen that using just the wind speed at only one station, the form factor is irrelevant, since it is close to 1. But in terms of load distribution in a steel building, the directional or wind difference (Charts 3 and 4) over a distance of 10m or more, the form factor is close to 2.

Since the wind load is directly proportional to the square of the velocity, the effective wind load is **lower** than the peak wind load by the square of the form factor.

When we go back to charts 3 and 4, we had a form factor of about 1.82. Combined with the spot velocity of charts 5 and 6, where, being cautious, the form factor was about 1:

Eqn 24: **Total or velocity Form Factor = $FF_v \times FF_d$**

Combined 2 stage FF = 1 x 1.82 = 1.82

That is, the wind load is 1.82^2 or 3.31 times less than an unfactored wind load using only the maximum gust speed. This is a significant amount in terms of saving materials.

In the above calculation only the baseline directional or its commensurate baseline speed form factor was used, not the combination, since I have assumed that as one increases, there is the potential for the other to decrease. However with sensitive and sophisticated equipment it may be possible to use both readings, since the reduction of speed may be due to pressure relief in altitude, not in baseline distance.

As mentioned, the above reduction is more relevant to steel buildings, since each component is fixed to nearby sections, and the assembly has some degree of load transfer. With masonry elements, such as tiled roofs, the individual tiles can not transfer load to other nearby elements, so the form factor reduction is not so applicable, except over shorter distances.

Eqn 25:

$$\textbf{\textit{Effective} wind load} = \frac{\textbf{Wind pressure from peak wind speed}}{\textbf{Total Form Factor}^2}$$

Using the above charts we can calculate the raw wind pressure (before shape of building, etc are factored in).

Equation 2.4(1) of AS1170-2 designates the wind pressure as:

$$p = (0.5\ \rho_{\text{air}})\ [V_{\text{des},\theta}]^2\ C_{\text{fig}}\ C_{\text{dyn}}$$

Where p is pressure in Pascals or N/m^2. ρ is air density, proposed as 1.2 kg/m^3. $V_{des,\vartheta}$ is the velocity at the incipient angle. C_{fig} (aerodynamic shape factor) is derived from Section 5.2 of AS/NZS 1170.2:2011, varies for each part of the building, and is generally less than 1, but is simplified here to 1. C_{dyn} (dynamic response factor) is assumed as 1 by AS/NZS 1170.2:2011, barring further information.

So, for the peak wind speed of Chart 5, our basic wind pressure is:

p = 0.5 x 1.2 x 11.5^2 = 79.4 N/m^2 = 0.08 kPa. (The raw, unfactored value)

But our combined form factor here is 1.82 , so the wind pressure drops down to:

p = 0.5 x 1.2 x (11.5 / 1.82)^2 = 23.96 N/m^2 = 0.024 kPa.

When simplified, we get [0.5 x 1.2 x 11.5^2] / 1.82^2 which resolves to:

$$\textit{Effective}\text{ wind load} = \frac{\text{Wind pressure from peak wind speed}}{\text{Total Form Factor}^2} = \frac{0.08}{1.82^2}\text{ kPa} = 0.024\text{ kPa}$$

Which is a third of the original raw value. In real situations this scenario does not normally arise, since AS1170-2 recommends 30m/s as a minimum value for open-air situations. So, using 30m/s we get 0.5 x 1.2 x 30^2 = 0.54 kPa as the raw wind pressure, and 0.54/1.82^2 = 0.16 kPa as the adjusted value.

If a similar form function is found at some cyclonic location, for example Wind Region D, Terrain Category 2 with no shielding, we have 88 m/s gust velocities, supposedly for 3 seconds without fluctuation, as per AS1170-2, and most unlikely since, as already explained, the wind becomes more 'ragged' as the velocity increases. Using the same formula, the raw pressure is 4.65 kPa, and the adjusted value is 1.4 kPa.

Now, I must stress that these are the values to use for ultimate capacity design loads. The engineer may wish to use more conservative (closer to 1) form factors for serviceability calculations, since those deflections are dependent on the client's taste and perceptions.

9. Conclusion and Future Work

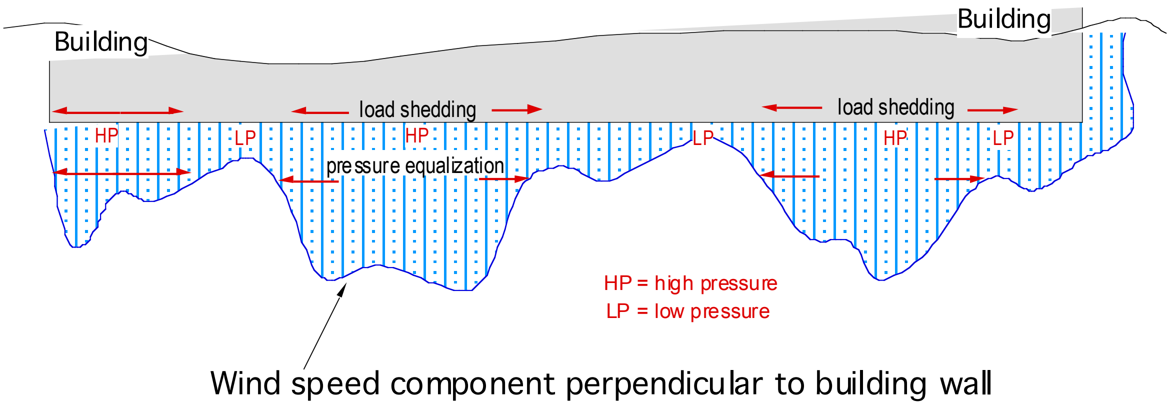
It has been shown that far from being a uniform entity in a real world ideal setting, even on a scale of only a few metres, the wind varies significantly:

1) In time frames of a second or less.

2) In both direction and speed.

3) Over distances of as little as 5 to 10m, in the 3 components of direction, duration and speed.

The wind flutters along a building, in waves of significant variation; causing continuous changes in the imposed load both in time and space. High wind velocity produces localised high pressure on the wall. This tends to even out with areas of lower wind speed, and hence lower pressure nearby. As shown in Fig 15, we thus have an extended wall with a significantly reduced overall pressure bearing onto it, in line with the Form Factors described above.



<u>Fig 15. The tendency for wind pressure equalization and stress load shedding</u>

This has the effect of greatly reducing the effective wind load experienced by extended areas of the structure. Hence, in reality the wind load over an extended surface is decidedly less than what the engineering codes imply. Hence, there is no such thing as a uniform mass of air hitting a building of any appreciable length, say, longer than 10m, from exactly the same direction, at exactly the same speed, and at exactly the same instant.

So far as non--brittle structures, such as steel buildings are concerned, the effective wind load is far less than that due to a hypothetical maximum uniform velocity of 3 seconds (stipulated in AS/NZS 1170.2:2011) hitting the entire building as one uniform mass.

In testing laboratories scaled buildings can be made to fail structurally when subjected to wind tunnel streams which are uniform, and at very small scales. But in the real world setting the wind is not uniform, and so, for the purpose of wind load modeling, real buildings can not be treated as simply scaled up versions of models. The maximum loads on full sized structures do not happen at the same instant, as they do on models, and so, within reason, high stresses are normalized by transfer to adjacent areas which have plenty of reserve capacity.

This thesis indicates that the worst real life outcomes are not nearly as bad as conventionally assumed (such as a 3 second maximum gust acting on the entire building at the same time).

In addition to the material in the body of the thesis, its propositions are supported anecdotally by the fewness of failures of buildings which have experienced the full design wind load. This is usually excused (using a curious reversed type of logic) by saying that the fact that a building did not fail must have been *because* it did *not* experience the full wind speed. But the findings of this thesis suggest that it is actually impossible for the full wind load, to impact an extended surface, as proposed and defined in AS/NZS 1170.2:2011. The implication is that wind load design standards, such as AS 1170 part 2, are well over specified, and thus wasteful of materials.

It is thus proposed that, as a way forward, buildings which are more than 10m long would benefit by applying the Wind Form Factors as described in the body of this thesis.

As mentioned previously, no prior work could be found in this area. There is therefore more that can be done beyond this thesis.

This work has essentially dealt with a single, linear dimension, along one datum line. It can be expanded to 2 dimensions; along a plane, where the wind properties would be examined over a vertical plane, corresponding to a tall building, rising above the 105m baseline, at the fixed 3m height, researched here. It can even be extended to three dimensions, for example over a 100 metres before reaching the 105m baseline used here. In other words the three dimensional vector can be sensed for given time periods of seconds, minutes or even hours.

If a 5m x 5m x 5m grid of stations were used in a 100m x 100m x 100m cube sampling space, for 1 hour, at 0.5 second intervals, we would have 57.6 million samples, each identified by direction and speed . Depending on the velocity and time accuracy required, we would need perhaps 50 GB of raw storage.

But that only needs to be done a few times, in a severe storm such as a cyclone. And the reduced information is far smaller, since all we need to know is what were the worst outcomes during the peak of the storm.

Having said that, the linear velocity assessments that have been done in this thesis are the most relevant for ordinary buildings, and they can be repeated in a cyclone using suitable electronic equipment, say, a line of digital anemometers with computer links.

The 2 and 3 dimensional research would be more of academic interest or applicable to such things as aeronautics, rather than the flat, solid faces of buildings., since as soon as the wind gust reaches the building, the 2 and 3 dimensional vectors would be badly compromised, by lateral pressure equalization, which further reduces the local maximum pressure. So the depth and volume velocities would no longer be accurate, and would moderate the maximum values, so they are mainly of interest as physics projects.

In any case, to do 2 or 3 dimensional research in this area we would need expensive and sophisticated equipment. Laser and microwave rapid scanning doppler radar comes to mind. We are then talking of hundred of thousands of dollars.

Mounting individual anemometers on lattice frames, and having them linked, and working in 200 km/hour (and faster) winds is not a practical proposition.

If nothing else, the equipment needs to be compact enough and elegant enough that when a cyclone is approaching a particular coastline, a van with the devices can race to the location, have the machinery up within an hour or two, and await the results. So a scanning doppler transmitter and receiver appears to be a necessity.

In future years, as more sophisticated and portable equipment becomes readily available at affordable prices, determining the characteristics of the wind at any location will become a practical option, and using the form factor to reduce the wind pressures used in calculations should become a routine and dependable procedure.

10. References

As already mentioned, due to the novelty of this topic there are no references that deal directly with similar material. There are only works of peripheral interest, for example shear and turbulence as it affects airplanes and wind generators, velocity gradients on high buildings, and general works of electrical engineering. Here is a list of what the reader may find useful. I have tried to keep to printed material:

Bakshi, V.U., & Bakshi, U.A. (2008). *Basics Of Electrical Engineering*. Maharashtra, India: Technical Publications.

Bird, J. O. (2003). *Electrical circuit theory and technology*. Oxford, UK. Routledge.

Burton, T. (2001). *Wind energy handbook*. New Jersey, USA: John Wiley and Sons.

Granger, R. A. (1985). *Fluid mechanics*. New York: Courier Dover Publications.

Holmes, J. D. (2001). *Wind loading of structures*. London: Taylor and Francis.

Lesieur, M. (2008). *Turbulence in fluids*. New York: Springer.

Manneville, P. (2009). *Instabilities, Chaos and Turbulence*. London: World Scientific.

NIST. (1986 to 2011). *Extreme Wind Speeds: Publications*. Reston, USA. Journal of Structural Engineering., American Society of Civil Engineers.

Riera, J. D., & Davenport, A. G. (1998). *Wind effects on buildings and structures*. London: Taylor and Francis.

Standards Australia/Standards New Zealand Committee BD-006/ (2011). AS/NZS 1170.2:2011 *Structural Design Actions. Part 2: Wind Actions*. Sydney: SAI Global and Standards Australia.

Internet Sites:

http://www.wind-power-program.com/intermittency.htm

http://www.wind-power-program.com/wind_statistics.htm

http://wiki.windpower.org/index.php/Turbulence

http://wiki.windpower.org/images/8/8d/Variabtu.gif

http://wiki.windpower.org/index.php/Main_Page

Appendix

The HP816A anemometer is a very sensitive device. It converts the wind speed to a digital readout via a frictionless electronic detector. It takes a spot reading every half second which was recorded on the camera for later attention.

<u>Model: HP816A</u>

Function:

1) Wind speed and temperature measurement
2) Wind chill indication.
3) ºC/ºF unit select
4) Different wind speed measurement unit
5) Measure wind speed in: Current / Average / Max
6) Low battery warning
7) LCD back-light
8) Auto/Manual off

Specification

	Wind speed range		
Unit	Range	Resolution	Threshold
M/s	0~30	0.1	0.1
Ft/min	0~5860	19	39
Knots	0~55	0.2	0.1
Km/hr	0~90	0.3	0.3
Mph	0~65	0.2	0.2

	Temperature range		
Unit	Range	Resolution	Accuracy
ºC	-10ºC~45ºC	0.2	±2ºC
ºF	14ºF~113ºF	0.36	±3.6ºF

Packing:

Weight : 53g(with battery)

Unit Size :11.4 x 4 x 1.8 cm

Power : CR2032 3.0V x 1

100 pcs / ctn

Ctn size: 43x64x35 cm

Gw/Nw: 10 / 9 Kgs

<u>Fig. 16. The HP 816A digital anemometer used in thesis</u>

Two digital cameras were used: A Sony DSC HX1 of maximum 9 Mpx , and a Kodak C330 of 4 Mpx. Both had basic video abilities.

The relevant electronic files of the photographs used here are embedded in the Microsoft Word document of this thesis. Further files that were used in data reduction are available on request.

Geraldton, Western Australia
February 2011 Daily Weather Observations

Observations from Geraldton Airport.

Date	Day	Temps		Rain	Evap	Sun	Max wind gust			9 am						3 pm					
		Min	Max				Dir	Spd	Time	Temp	RH	Cld	Dir	Spd	MSLP	Temp	RH	Cld	Dir	Spd	MSLP
		°C	°C	mm	mm	hours		km/h	local	°C	%	8^{th}		km/h	hPa	°C	%	8^{th}		km/h	hPa
1	Tu	18.5	31.9	0	7.4		S	50	14:05	28.0	45	1	SE	20	1009.2	28.1	50	1	S	39	1006.6
2	We	19.3	31.8	0	9.0		S	50	14:28	26.8	61	1	SSE	33	1006.9	30.1	44	1	S	35	1005.6
3	Th	22.6	29.9	0	9.8		NW	39	14:06	27.0	68	2	W	11	1006.6	29.3	61	2	WNW	22	1006.9
4	Fr	21.6	29.6	0	7.2		S	39	17:19	25.2	73	7	WSW	13	1010.0	27.4	64	5	SW	24	1009.1
5	Sa	21.5	35.0	0	7.8		S	57	13:58	26.8	38	0	SE	31	1012.0	32.4	37	1	S	41	1008.2
6	Su	23.6	36.8	0	14.6		E	57	07:26	28.4	26	3	E	39	1011.0	33.2	22	7	NE	26	1009.5
7	Mo	23.6	38.9	0	11.0		ENE	50	08:10	31.2	16	7	NE	33	1010.2	37.2	14	6	SSW	33	1007.0
8	Tu	24.5	37.8	0	13.8		SSW	52	16:00	32.7	27	1	NE	20	1006.8	35.3	22	1	SSW	35	1003.9
9	We	19.7	35.8	0	11.0		S	54	14:52	29.9	44	0	SSE	13	1006.7	31.8	47	1	S	41	1005.8
10	Th	21.6	43.6	0	9.8		SSE	57	16:25	35.7	33	1	ESE	28	1006.7	35.7	38	6	S	43	1004.2
11	Fr	26.6	36.0	0	11.4					32.4	58	7	NE	15	1010.2	33.6	48	7	SSW	26	1008.5
12	Sa	26.2	35.1	0	7.8		E	61	10:13	27.0	53	7	ENE	33	1012.5	33.8	36	4	E	31	1009.8
13	Su	23.7	37.7	0	11.8		ENE	52	08:02	28.4	44	2	NE	33	1012.3	37.1	22	1	SSE	20	1008.0
14	Mo	23.7	39.5	0	10.8		NE	46	08:52	33.2	38	1	NE	30	1008.8	37.5	29	2	SSW	33	1005.9
15	Tu	24.1	35.9	0	11.4		SW	39	15:02	32.3	45	1	N	17	1008.3	34.4	39	2	SW	28	1005.1
16	We	23.7	38.3	0	9.2		SSE	69	18:26	32.2	51	1	SSW	9	1006.8	36.1	34	2	SSW	28	
17	Th	23.6	36.7	9.4	11.4		S	54	16:56	29.0	65	3	E	24	1005.4	33.4	51	4	SSW	31	1001.0
18	Fr	24.1	34.8	0	9.4		SW	41	14:01	29.3	55	1	ENE	22	1004.7	33.3	42	1	SSW	30	1002.2
19	Sa	24.1	31.3	8.0	9.6		WNW	39	05:22	24.7	95	7	ESE	7	1006.7	29.2	61	8	E	28	1005.6
20	Su	22.5	32.8	31.6	4.6		ENE	61	23:49	27.0	70	7	E	22	1009.4	32.2	57	7	E	24	1007.4
21	Mo	25.1	36.3	6.6	6.2		NE	61	00:35	29.8	46	6	E	22	1009.0	35.5	38	2	NE	20	1006.2
22	Tu	24.0	37.4	0	10.2		ENE	48	08:04	28.7	49	1	NE	26	1006.0	37.0	33	7	E	20	1001.8
23	We	24.1	36.7	0	10.0		ENE	44	07:37	29.8	52	3	ENE	28	1004.4	33.8	46	7	S	24	1001.6
24	Th	26.7	37.3	0	7.8		NE	35	11:48	33.0	42	1	N	13	1005.2	35.0	39	6	S	24	1002.3
25	Fr	23.7	33.7	0	7.8		WSW	35	13:30	30.0	66	0	WSW	9	1006.2	32.8	50	1	WSW	22	1004.6
26	Sa	25.1	35.8	0	6.8		S	41	16:37	32.4	53	1	NNE	15	1007.6	33.7	50	1	SSW	30	1005.0
27	Su	24.1	40.4	0	9.4		S	37	17:46	34.2	39	2	E	15	1006.5	36.4	43	5	SSW	24	1003.8
28	Mo	25.4	37.2	0	9.0		S	41	18:04	32.8	50	1	ESE	7	1006.5	35.3	38	1	SSW	28	1003.8

Chart 7. Geraldton wind and temperature conditions for all of February 2011

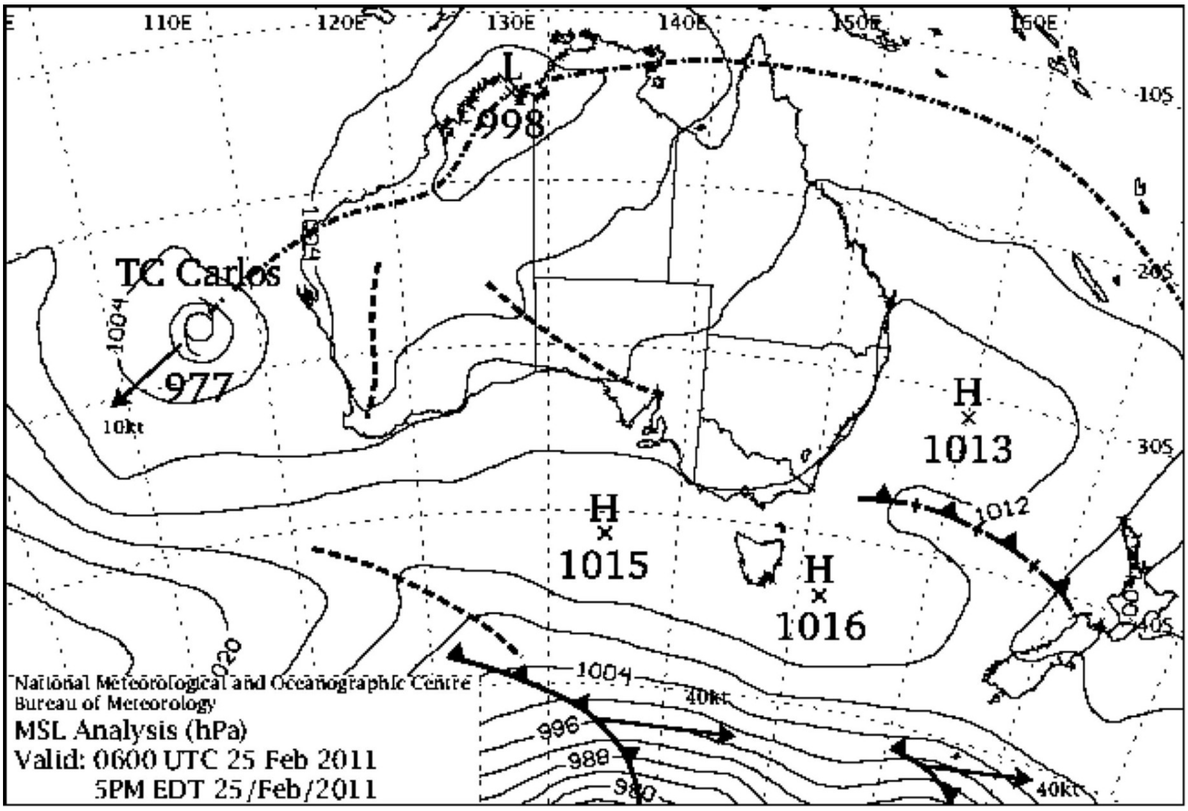


Fig. 17. Australia ground isobars 0600 UTC, 25 February 2011

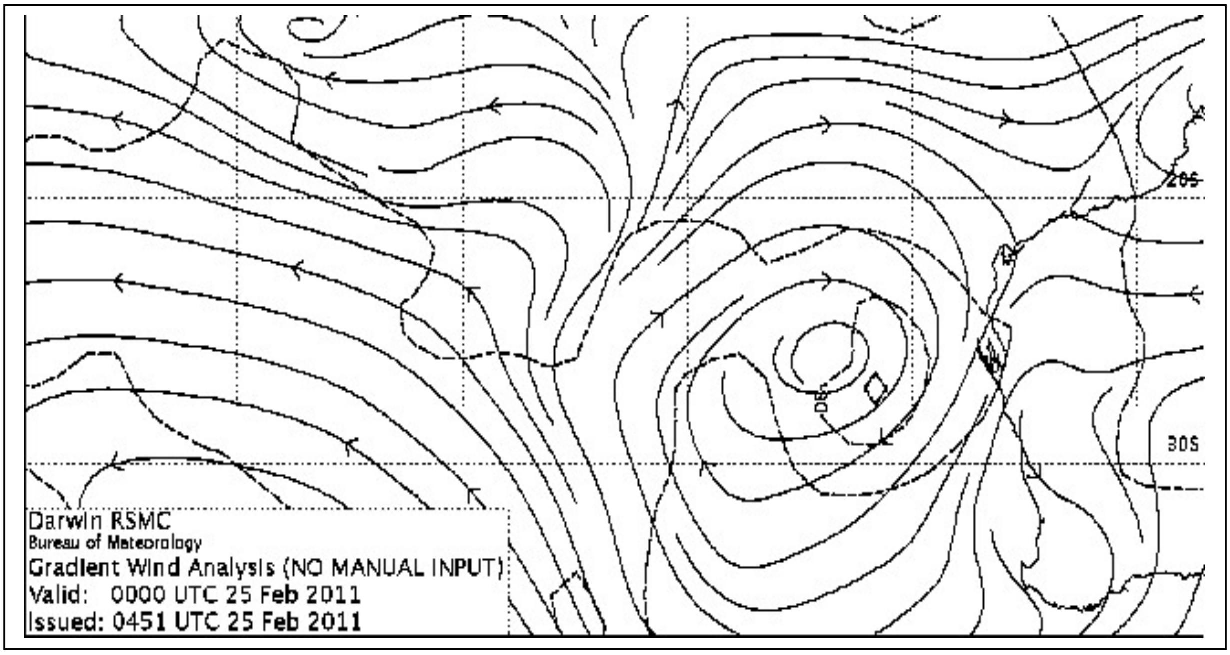


Fig. 18. Western Australia ground isobars 0000 UTC, 25 February 2011

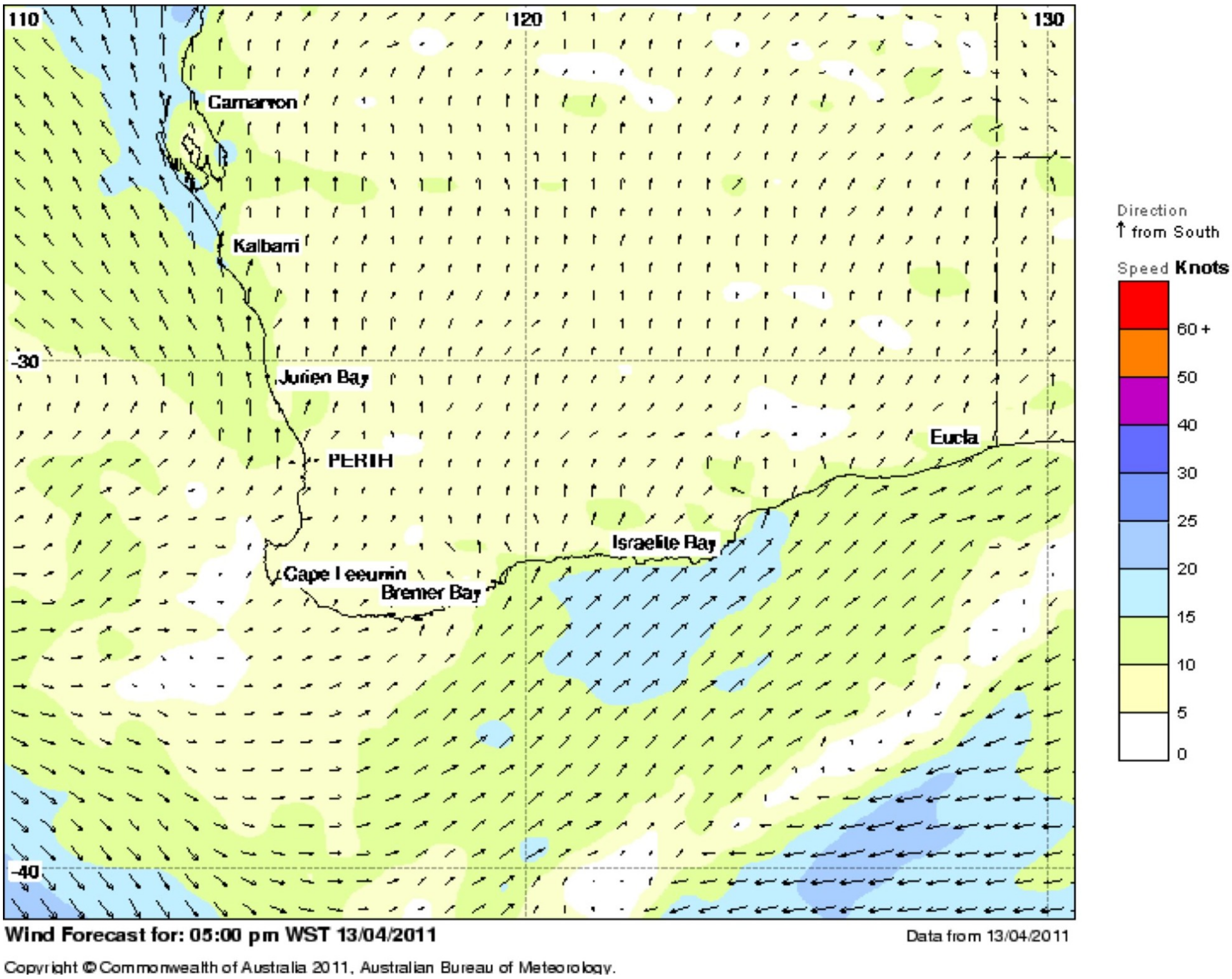


Fig. 19. Western Australia wind ground directions 1700 WST, 13 April 2011

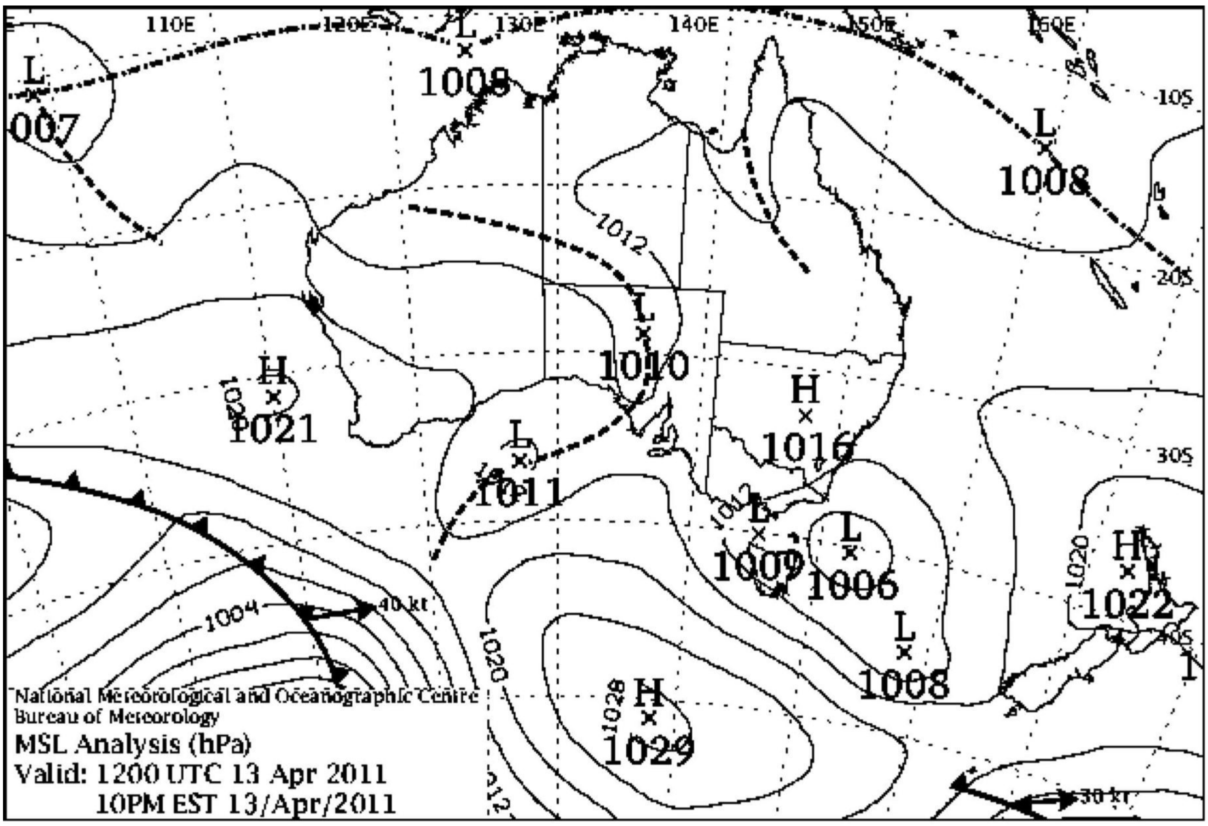


Fig. 20. Australia ground isobars 0000 UTC, 13 April 2011

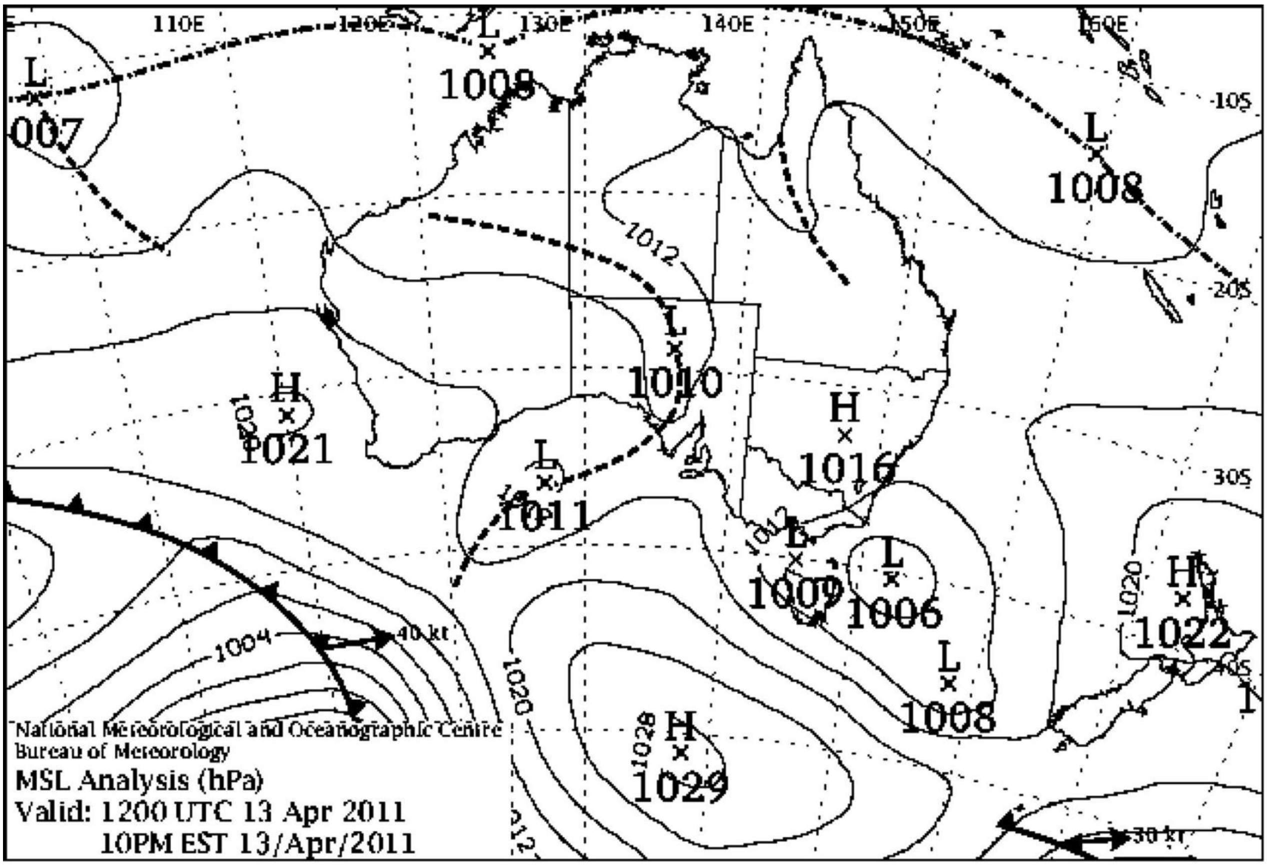


Fig. 21. Australia wind ground isobars 1200 UTC, 13 April 2011

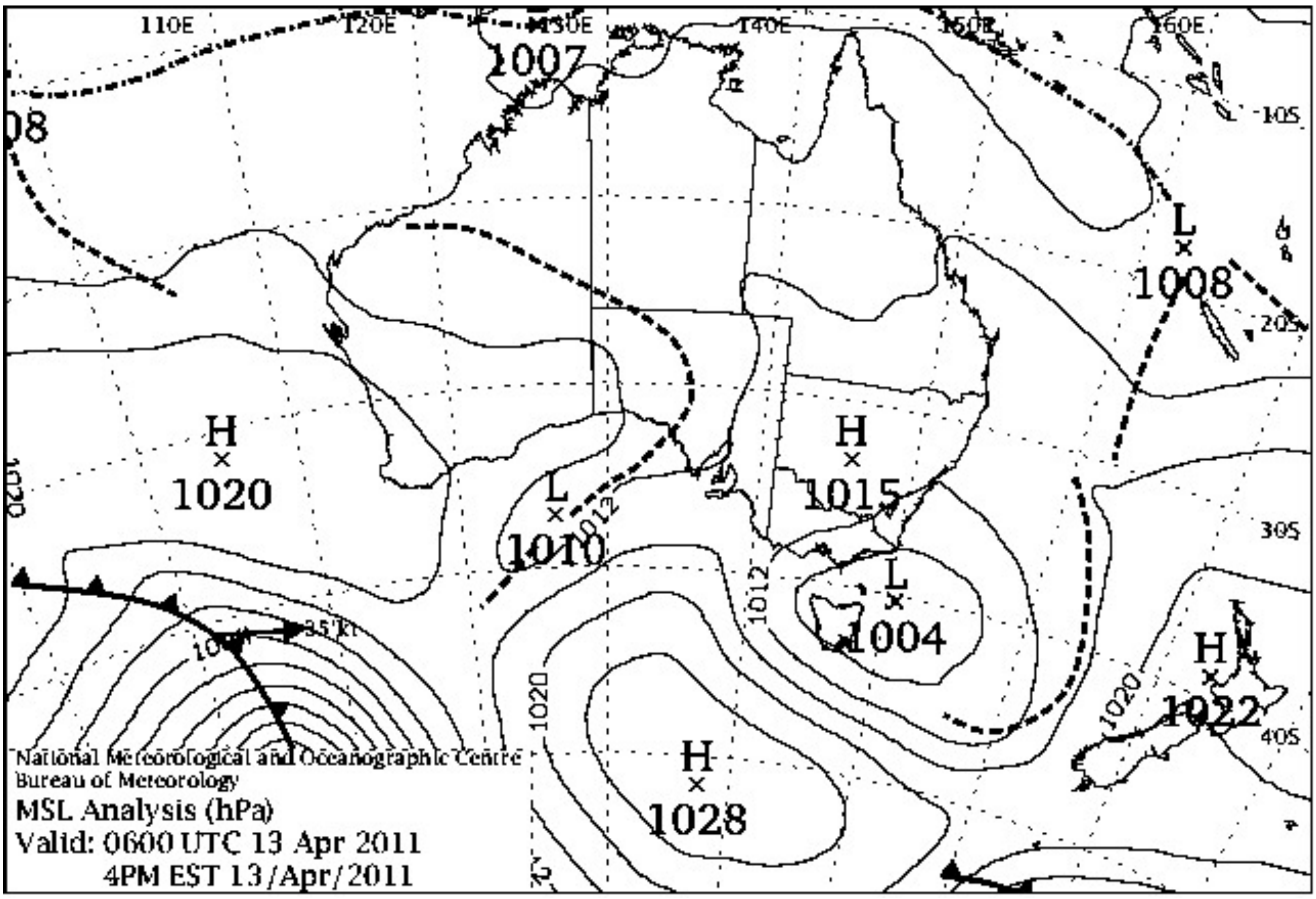


Fig. 22. Australia wind ground isobars 0600 UTC, 13 April 2011

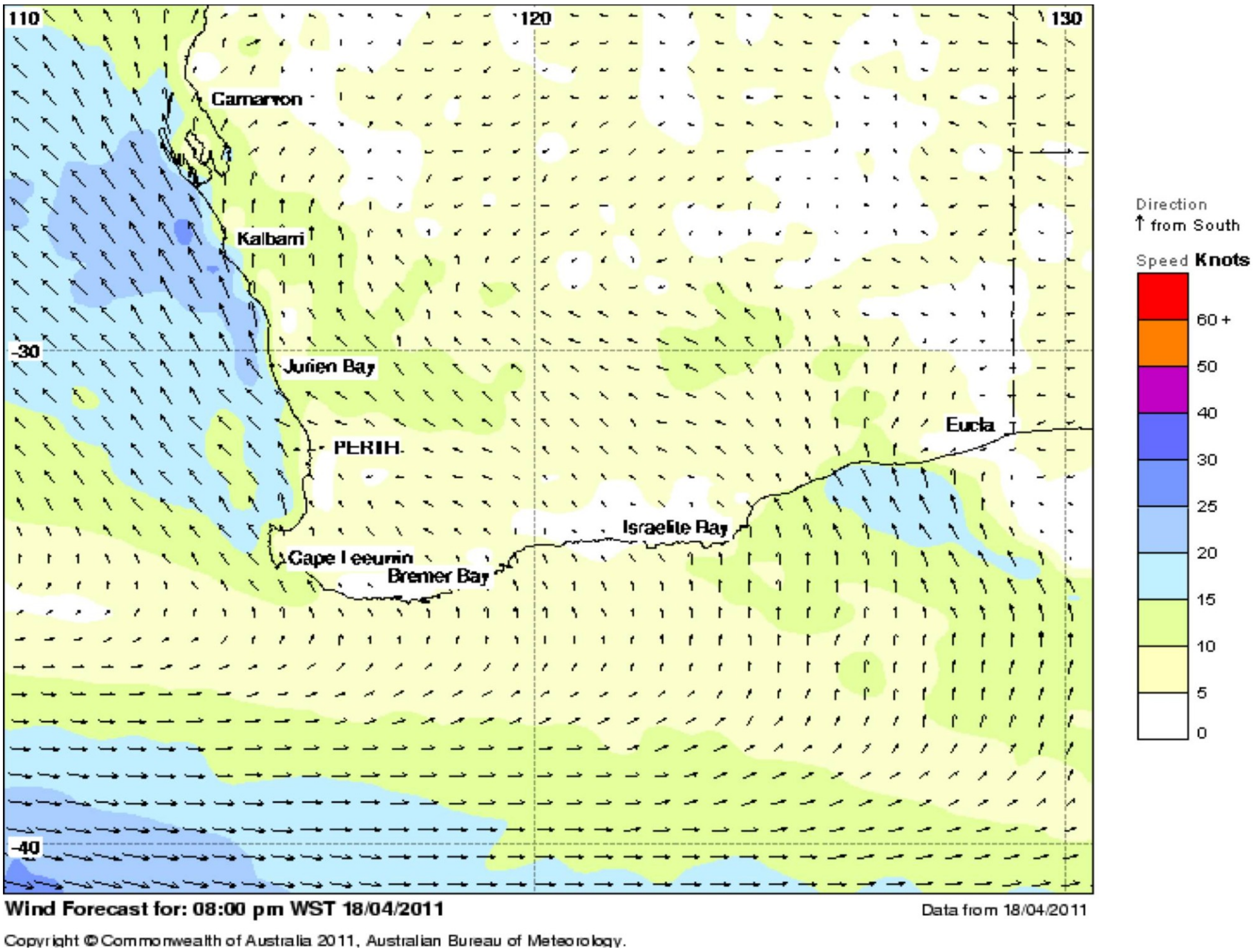


Fig. 23. Western Australia wind ground directions 2000 WST, 18 April 2011

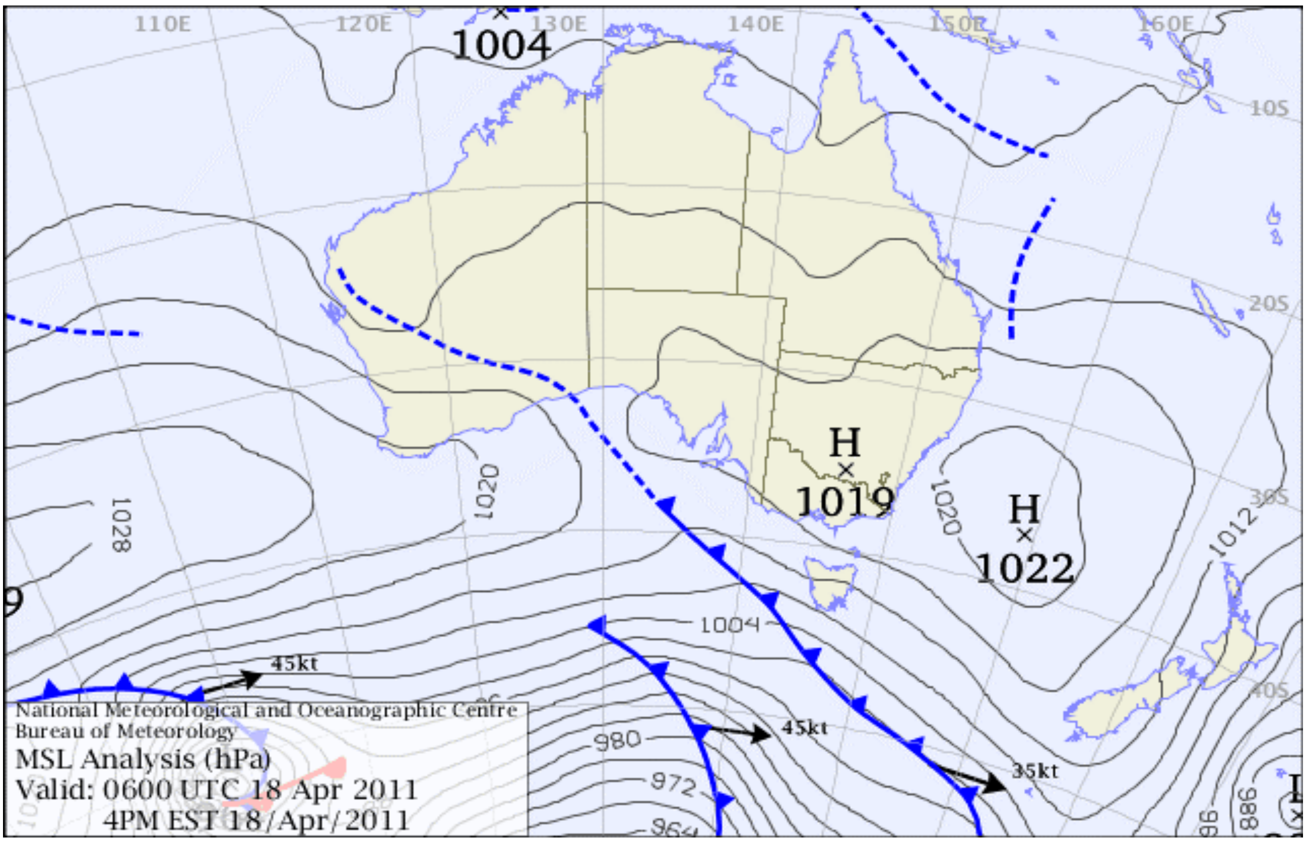


Fig. 24. Australia wind ground isobars 0600 UTC, 18 April 2011

Duration into sample. Secs	13 April 2011 Video 100_4224 **CHART 5** Wind Speed m/s	18 April 2011 Video 100_4246 **CHART 6** Wind Speed m/s	Duration into sample. Secs Continued	Video 100_4224 **CHART 5** Continued Wind Speed m/s	Video 100_4246 **CHART 6** Continued Wind Speed m/s
0.5	8.8	7.8	30.5	8.3	11.4
1	8.6	8.3	31	8.8	11.5
1.5	8.5	10	31.5	8.3	11.3
2	8.2	10.4	32	8.1	11.3
2.5	8.5	10.3	32.5	8.1	10.9
3	7.8	9.7	33	8.3	10.5
3.5	8.3	9.8	33.5	9.2	10.8
4	8.2	8.8	34	9.1	10.6
4.5	8.2	9.7	34.5	8.6	10.5
5	8.3	9.4	35	7.8	10.5
5.5	8.3	9.3	35.5	7.6	10.6
6	8.0	8.6	36	7.5	11.2
6.5	7.4	8.3	36.5	7.2	11.4
7	7.2	8.5	37	7.8	10.6
7.5	7.6	9.1	37.5	8.3	10
8	8.2	8.7	38	8.5	9.7
8.5	8.0	8.9	38.5	8.3	8.3
9	7.0	9.7	39	8.0	9.3
9.5	6.3	8.9	39.5	8.1	10.8
10	6.4	9.3	40	8.2	10.4
10.5	6.9	8.9	40.5	8.1	9.9
11	6.8	8.8	41	7.5	9.3
11.5	6.8	9.7	41.5	7.1	9.2
12	6.6	10.5	42	8.1	8.3
12.5	6.4	10.4	42.5	8.5	8.6
13	6.3	10.4	43	8.7	8.7
13.5	6.6	9.3	43.5	8.5	8.6
14	6.6	9.5	44	9.4	9.5
14.5	7.0	10.3	44.5	9.4	9.1
15	6.6	9.8	46	9.2	9.1
15.5	8.5	9.9	46.5	9.8	8.5
16	8.8	10	47	9.7	9.2
16.5	8.7	10.5	47.5	10	9.3
17	8.3	9.9	48	9.8	9.1
17.5	8.0	9.5	48.5	9.8	9.7
18	9.4	9.1	49	9.1	9.8
18.5	10	8.8	49.5	8.8	9.3
19	10	8	50	8.6	9.2
19.5	9.5	8	50.5	8.2	9.3
20	9.2	7.6	51	7.7	9.2
20.5	9.5	7.6	51.5	8.0	9.1
21	10.4	8.1	52	8.0	9.8
21.5	10.5	9.2	52.5	7.7	9.9
22	10	9.7	53	7.4	10
22.5	9.2	10.3	53.5	7.5	10.3
23	9.1	10.3	54	7.1	10.6
23.5	9.4	10	54.5	7.1	10.3
24	9.5	10.8	55	6.7	9.7
24.5	9.9	11.2	55.5	6.2	9.7
25	9.9	10.9	56	6.3	9.1
25.5	9.5	10.5	56.5	6.7	8.9
26	10	9.9	57	7.2	8.9
26.5	9.8	9.5	57.5	7.1	9.5
27	9.4	9.8	58	7.0	9.7
27.5	9.4	9.6	58.5	6.0	8.7
28	9.4	10.6	59	7.5	7.7
28.5	8.3	10.5	59.5	7.4	9.1
29	8.7	9.8	60	8.3	9.7
29.5	8.8	9.3	60.5	8.2	10
30	8.3	9.8	61	8.3	10.4
			61.5		9.2
			62		9.5
				Σ = 989.6	**Σ = 1174.1**
				Mean= 8.247	**Mean= 9.624**

Chart 8. The data series for the highest windspeed extracts for Charts 5 and 6.