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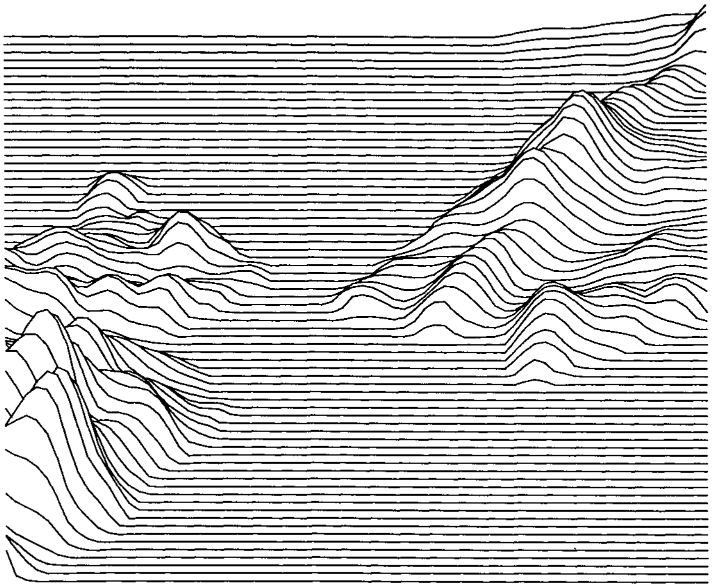
Steve Reid



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Cover: The orography which constrains wind flow in Cook Strait, looking from the south.

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Abstract

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Meteorological data from Cook Strait consists largely of weather reports from ships and station recordings from lighthouse stations around the coasts, many of which are on or close to steep hills. Pressure data have been found previously to offer advantages for calculating extreme winds over the sea and have been combined with new work on pressure-wind relationships in Cook Strait to determine speed values in extreme conditions at Wellington Airport and Kaukau. The data show that unlike conditions in the open seas where wind speed is approximately proportional to the pressure gradient, in Cook Strait wind speed has a markedly non-linear relationship with the pressure gradient. This has the effect that wind speeds tend to be high in Cook Strait under moderate pressure gradients, but with extreme gradients the wind speeds may be less than values on open coasts. Speed values at long return periods are in approximate agreement with values obtained from station data.

Introduction

Cook Strait is noted for its high frequency of strong winds. The highest wind speeds recorded by anemometers close to the Strait were from the south during the *Wahine* storm 10 April 1968. The wind speeds which may realistically be expected in future extreme storms in Cook Strait are important for the planning and operation of shipping services and for the design of structures on coastal sites and in Wellington. The wind speed and direction, combined with its fetch and duration, can be used to determine wave heights, which are also important information for the above applications. This report presents a method for combining wind and pressure data from meteorological stations to infer extreme winds in Cook Strait. Because of the importance of winds at long return periods for design and risk studies, the results have been compared with the data previously inferred from station data and published in New Zealand Standard 4203 (1992).

Wind and wave data

Basic information about winds and waves in Cook Strait can be obtained from analyses of routine weather reports from ships, and Reid & Collen (1981) have shown that wind directions are from the north or the south for much of the time in Cook Strait. Northerly winds occur more frequently, but are generally not associated with high waves in the Strait. High waves do affect the Strait when winds are from the south because of a relatively open exposure to the south so that high waves generated over the open sea enter the Strait without much reduction of amplitude from refraction and interaction with the bathymetry.

Ship's observations using the Beaufort scale are the largest data source of wind speeds over the sea in Cook Strait (about 97% of all values reported in the period 1970–74, but reducing to 60% reported in 1985–89), the remainder are observations using anemometers on the ships. The Beaufort scale relies on visual assessments of the sea state and data obtained using it can be quite accurate for estimating mean speeds. Weather reports from the regular ferry crossings show that the average wind speed in the area formed by the latitude lines at 41.0° and 41.5° S and the longitudes at 174.0° and 175.0° E, which is centred approximately on the narrows of the Strait, is 9.3 m/s. In the same-sized area at 1° of latitude to the north of the Strait the mean speed is 8.5 m/s, and at 1° of latitude to the south of the Strait the mean speed is 7.5 m/s.

Wind estimates from ships give an intermittent data stream that may exclude higher speeds occuring between reporting times and are thus unsuitable for obtaining information about extreme winds. Further, in extreme conditions many ships remain in port or take some action to avoid the areas of highest winds. Finally, the estimates themselves are likely to be less reliable in extreme conditions, partly because of the observers' unfamiliarity with the conditions and partly because a longer fetch is needed to establish an equilibrium between wind and waves so that the proximity of coasts may affect the state of the sea. Thus additional data are needed to determine the speeds of extreme winds in Cook Strait.

Wind data for the Cook Strait area are available from the land stations shown in Figure 1. These data have the advantage over ship reports of being obtained from instruments which can be kept in the same place on a stable structure for a prolonged period. However, sea cliffs can have major effects on the wind speeds, not only when the measurement site is on top of the cliff, but also when the cliff is alongside or even behind the instrument. Also, few of the stations in Figure 1 provide data which are available over a long time or do not have substantial gaps. Additionally, mean speed data, even when complete, consists of averages over 10 min at hourly intervals, so the sampling is over only part of the time.

Relationships between ship and coastal station wind speeds are summarised in Table 1. The comparison uses all available data in the period 1989–96, but is confined to wind directions between 150° and 220° at the land stations. The ratios of mean speeds show the degree of exposure of the land stations relative to the ship-reporting locations, the latter being mostly near the centre of Cook Strait. The correlation coefficient constitutes a summary parameter of the degree of scatter between the wind speeds. The mean direction difference is the systematic difference between the orientations of the winds at the two places. The standard deviation of the direction difference is an inverse measure of the degree of explained relationship between the wind directions. The values at Cape Campbell and The Brothers are particularly high showing that these stations, although physically within Cook Strait, do not appear to follow the conditions at ships in the Strait as well as Wellington Airport or Kaukau do. In fact, the last two stations seem, in all respects, to be the most useful places to measure winds speeds and directions that are representative of Cook Strait (they are representative in the sense that they give the most accurate estimates when adjusted by a constant).

Pressure gradients and surface winds

A previous determination of extreme wind speeds on the New Zealand coast (Reid 1981) used analyses of maximum pressure differences between coastal stations. The differences could be used to obtain the onshore wind speed by means of the geostrophic relation. In this way, problems in obtaining suitable coastal wind measurements and difficulties in maintaining wind observations in extreme conditions could be overcome through the use of pressure data. The winds which were determined were directed onshore and were regarded as applicable to points between the pressure-measuring stations. The pressure difference between Wellington and Christchurch was compared with winds at Kaikoura: high pressure gradient occurrences did not bear a strong relationship to the associated wind speeds at Kaikoura. A surprising finding of the 1981 study, based on 17-year periods up to 1978, was that intense onshore pressure gradients were less frequent on this section of coast than on to the northern and southern extremities of the country. The *Wahine* storm produced very large gradients but there were few other occurrences above the threshold used.

Over open seas winds tend to be parallel to the isobars (lines of constant pressure), but the flow into Cook Strait is mainly across the isobars. This is because the speed and direction of the wind have to change considerably near Cook Strait because of obstructing mountain ranges. The required accelerations are obtained from the flow down the pressure gradient. In Cook Strait, using the onshore pressure gradient is unlikely to give correct predictions of wind speeds because accelerations of the flow produce conditions which are far from geostrophic. However, if the equations which include acceleration can be applied, the method of using the pressure differences may be appropriate.

Reid (1996) showed that the major contributions to the pressure gradients in Cook Strait were generally from the differences between stations in the north-south direction or across the ranges. The east-west pressure differences had a smaller influence on the size of the gradients, but had a strong effect on the directions of the gradients. In the narrows of the Strait, analysis of the cross-wind balance of forces showed that there was a strong predominance in the combined Coriolis and pressure gradient forcing acting towards the South Island in both northerlies and southerlies. This seemed to correspond to a curvature of the flow around the northeast corner of the South Island. Pressure gradients between Cape Campbell and Wellington were unusual in that there was little consistency in their directions, possibly because they have a role in reorienting wind directions through Cook Strait. An important feature of the balance of forces in the along-wind direction was that the same pressure gradient was associated with a higher wind speed in southerlies than in northerlies, suggesting lower accelerations with the southerly, i.e., the speed has reached its maximum before it enters the Strait.

To determine where the most important accelerations occur, pressure differences between pairs of stations were tested as predictors of the Wellington Airport and Kaukau wind speeds in southerly directions using the pressure pairs between stations near the strait. These were supplemented with the differences Christchurch-Wellington and Kaikoura-Wellington. The quality of the predictor was simply determined from the square of the correlation coefficient. The data are given in Table 2. Of the station pairs identified by Reid (1996) as having a characteristic delta pattern in the variation of the pressure difference with wind speed, Paraparaumu-Wellington and Paraparaumu-Ngawihi were poor predictors (explaining less than 25% of the variance) but Kaikoura-Cape Campbell was a good predictor (explaining almost 60% of the variance).

The statistical link between the Kaikoura-Cape Campbell pressure difference and Wellington winds is not likely to be spurious because physical arguments suggest that the Kaikoura coast between Cape Campbell and Kaikoura is the key area in which southerlies are accelerated. In the Southern Hemisphere, pressure decreases towards a gap only along ranges on the left side of the gap (relative to the direction the wind is going). On the right side of the gap, the large-scale pressure distribution is unlikely to lead to acceleration towards the gap. Moreover, the size of the Kaikoura mountain range is a dominating feature of the orography and blocking of the southeast onshore wind flows will extend through a considerable depth of the atmosphere. The unusual behaviour of the pressure gradient between Cape Campbell and Wellington (mentioned above) and the lower correlation given by the Kaikoura-Wellington pressure difference compared with the Kaikoura-Cape Campbell difference (Table 2) both support the idea of reorientation rather than acceleration being the dominant process to the north of Cape Campbell. Increasing pressure along streamlines towards the mountains, required to brake airflows, will modify the large scale pressure field so that acceleration is towards the northeast. Therefore, because of the very constrained range of wind directions in Wellington, significant redirection must take place.

The relationships between winds and pressures are governed by the equations of motion. For practical purposes, attention is focused here on those determining horizontal wind motion in orthogonal directions and may be written:

$$Du/Dt - fv + 1/r \; \partial p/\partial x = 1/r \; \partial \tau_x/\partial z \qquad (1)$$

$$Dv/Dt + fu + 1/r \; \partial p/\partial y = 1/r \; \partial \tau_y/\partial z \qquad (2)$$

where the term beginning D represents a derivative following an air parcel:

$$D u/D t = \partial u/\partial t + u\, \partial u/\partial x + v\, \partial u/\partial y + w\, \partial u/\partial z \qquad (3)$$

u and v are orthogonal components of the wind velocity in the x and y directions, f is the Coriolis parameter, r is the air density, p is the pressure, x and y are the horizontal orthogonal axes, and τ_x and τ_y are the components of the frictional stress in the x and y directions, respectively.

Taking the x-direction to be the mean wind direction then v is small, and, provided that u varies as rapidly in the x-direction as in the y-direction, $u\, \partial u/\partial x >> v\, \partial u/\partial y$. Within the surface layer in the absence of wind turning with height, friction acts opposite to the direction of the wind (Haltiner & Martin 1957) so that $\tau_y \cong 0$. Also, assuming that the vertical air motions may be neglected ($w = 0$) and the flow is steady ($\partial u/\partial t = 0$), then Equations 1 and 2 become

$$u\, (\partial u/\partial x) + 1/r\ \ \partial p/\partial x = 1/r\, \partial \tau_x/\partial z \qquad (4)$$

$$u\, (\partial v/\partial x) + f u + 1/r\ \ \partial p/\partial y = 0 \qquad (5)$$

The excluded terms may certainly be large and may dominate in particular cases, such as when there are strong temporal changes or large vertical motions. The orography and large scale wind field near Cook Strait involve large wind direction changes in the entrance and exit regions of the Strait for much of the time, requiring inclusion of the first term of Equation 5.

The effect of the rotation of the earth appears in Equation 5 as the quantity f, the Coriolis parameter. The equation shows that in the direction perpendicular to the wind, the y-component of the pressure gradient force is balanced by the term fu. If the terms in the left hand side of Equation 5 are much larger than those in Equation 4, then Equation 5 becomes a definition of the geostrophic wind, i.e., the isobars are parallel to the x axis, $\partial p/\partial x = 0$ and the pressure gradient is in the y direction.

Equation 4 shows that air within a pressure field experiences an acceleration in the opposite direction to the x component of the pressure gradient and is opposed by a friction force. The left hand side of Equation 4 shows that pressure falls as the wind speed rises (the Bernoulli effect). The southerly speed increase along the Kaikoura coast, Δu, produced by a pressure drop (Δp) can be simulated using an integrated (with respect to x) version of Equation 4. This integrated version has the form:

$$u\, \Delta u + 1/r\, \Delta p = 1/r \int (\partial \tau_x/\partial z)\, dx \qquad (6)$$

Equation 6 is difficult to evaluate with much precision because the length of streamline over which the acceleration takes place is not known, although it is limited by the physical extent of the mountain range. The friction term is especially difficult to determine because it almost certainly has some dependence on u, which also varies along the streamline. Nevertheless, in an accelerating flow, friction cannot be dominant and the other terms must determine the nature of the relationship. Assuming the initial speed to be zero and friction negligible, Equation 6 becomes just the Bernoulli relation and takes the form

$$u^2 = - 2/r\ \ \Delta p \qquad (7)$$

but a more general quadratic expression, which enables the best possible fit to the data to be obtained, is

$$\Delta p = k_1 u^2 + k_2 u + k_3 \qquad (8)$$

and is used below for extrapolation.

In Figure 2, pressure difference data between the station pairs Kaikoura-Wellington and Christchurch-Wellington, which include the most important area of coast, have been used as predictors and plotted against the simultaneous wind speeds at Kaukau and Wellington Airport for southerly winds.

Unfortunately, data from Cape Campbell are not as complete as those from Kaikoura, Wellington, and Christchurch and have not been used. The pressure difference can be negative or positive, but for southerly wind directions is mostly positive. The data consist not only of values from the 1 year period (1 April 1993–31 March 1994) used by Reid (1996), but have been supplemented with data to better define the high wind speed end of the relationship. Data from the years 1980–86 have been used to define the variation at about 20 m/s and data from the period 1970–86 (1965–80 at Wellington Airport) have been used to improve the definition at 25–30 m/s. Whereas the low speed data are consistent with a linear relation between the speed and the pressure difference, there is considerable curvature suggested by the high speed data and the data have been found to be well fitted by quadratic functions of the form of Equation 8. The parameters for the curves of best fit in Figure 2 are given in Table 3. The percentage variance described by the curves is high.

The curves of best fit in Figure 2 appear to have a considerable range of shapes. However, they are also for a range of pressure differences, and to compare them, the curves defined by the parameters in Table 3 have all been plotted for a range of pressure differences in Figure 3. The curves for the Kaikoura-Wellington pressure difference are shown in the upper part of Figure 3 and for Christchurch-Wellington in the lower part. The former is given between 0 and 15 hPa and the latter, where higher pressure differences are present, is given for 0–20 hPa. Most of the data in Figure 2 are within these ranges. For comparison, Equation 7 (the Bernoulli relation) has also been plotted in Figure 3 using the wind speed obtained directly from the relation and the values obtained if allowance is made for a reduction of speed in the boundary layer to 10 m above the surface due to frictional drag. The frictional drag effect is evaluated using the approach of Reid (1981). A further comparison is included by plotting in Figure 3 the geostrophic wind based on the pressure difference between the appropriate stations both obtained directly and for the frictional drag case.

The curves in Figure 3 show that those following the observations are roughly between the graphs based on Equation 7 with and without frictional drag. The theoretical ones are mostly more curved than those based on the observations, probably because there are insufficient observed data to obtain the true curvature in the quadratic fits. In the low speed ranges, where most of the data lie, the graphs based on Equation 7 are clearly better models for the observations than those based on the geostrophic relation. The wind speeds are generally much higher than expected, based on the geostrophic relation. However, when the pressure difference is very high, the speeds based on the quadratic model converge with those based on the geostrophic model. At very high pressure differences, beyond those yet observed, the geostrophic speeds could become higher than the quadratic model speeds. For this reason, channelled winds in Cook Strait may not constitute as great a hazard at very long return periods as the intense winds on other sections of coast.

Extreme winds

Extreme value analyses made here have been based on the work of Gumbel (1958). The method depends on the largest events in the series being measured to a reasonable accuracy. An intermittent series of observations, or one in which the magnitude of the maxima is doubtful, is clearly not suitable. The longest available complete data series are the pressures at Christchurch and Wellington. The annual maximum pressure differences between Christchurch and Wellington have been used to determine the extremes. The data are plotted as ranked values against the reduced variate y, where

$$y = -ln(-ln(1-1/T)) \qquad (9)$$

T is the return period of the speed value and is determined from Gringorten (1963)

$$T = (N+0.12)/(i-0.44) \qquad (10)$$

where N is the number of years of data and i is the rank of the speed value. The return periods of 5, 20, 50, and 350 years correspond approximately to reduced variates of 1.5, 3.0, 3.9, and 5.9, respectively. The plotted data and a best fit line are shown in Figure 4.

The pressure differences between Christchurch and Wellington have been evaluated from Figure 4 at return periods of 5, 20, 50, and 350 years. These are return periods used in engineering design for a variety of structures and have corresponding pressure difference values which are equalled or exceeded at average intervals of the return period. These values are given in the third column of Table 4. The pressure differences between Kaikoura and Wellington are closely related to the Christchurch to Wellington values as shown by the regression line in Figure 5. The Kaikoura to Wellington differences are in the fourth column of Table 4. The pressure difference data have been substituted in the equations using the coefficients in Table 3 to obtain speeds. Only the equations for which the amount of variance explained is the greatest have been used, so for the solutions in Table 4, the Kaukau winds have used the relation with the Kaikoura-Wellington pressure difference and the Wellington Airport wind is based on the relation with the Christchurch-Wellington pressure difference.

Discussion

The wind speeds in Table 4 may be compared with design code values given by NZS 4203 (1992) (henceforth called the code). The latter apply to all places in an area but the code is specific enough that the value for Wellington Airport may be compared directly with the code value multiplied by a channelling factor which applies at Wellington Aiport. The 1-hour mean speed given by the code at a return period of 350 years (the ultimate limit state) for the south direction is 36 m/s. At a return period of 20 years (the serviceability limit state) the value is 29 m/s. The comparable values from Table 4 are 43 m/s and 35 m/s, respectively. The code therefore seems to seriously underestimate the true values.

There are a several possible explanations for the discrepancy between the code and the value derived here. It is possible that the method used produces values which are too high, particularly at the higher speeds where the extrapolation may be incorrect. However, the discrepancy is as large at the 20-year return period as at the 350-year one, so this explanation is probably incorrect. Another possibility is that the observed winds, which are 10-minute averages, may be much greater than the code values because the latter are 1-hour averages. However, these differences are small. The most likely explanation is that the code incorrectly assumes that the 1-hour mean is 0.60 of the 3-second gust speed. In fact, the observed mean to gust speed at Wellington Airport is 0.68 (*see* Figure 6) and this explains most of the discrepancy. If the code values of mean speed are recalculated with the factor 0.68 instead of 0.60, they become 41 m/s at the 350-year return period and 33 m/s at the 20-year return period — reasonably close to the values in Table 4.

At Kaukau (445 m a.s.l.), the relationship to the code values is less well defined. On top of a hill and 122 m above ground level the wind speed can be expected to be considerably higher than at Wellington Airport, but the observed speeds are only about 20% higher. However, the channeling factor applied at Wellington Airport to account for the funneling effect by local hills is not used at Kaukau because it is on top of a hill and not subject to these effects. Between the Kaukau anemometer site and 10 m above ground on a flat, open site in the Wellington area, for the southerly direction the code gives a mean speed increase of about 80%. The mean speed formed by dividing the Kaukau speed by 1.8 gives a value for a flat, open site of 27 m/s at a return period of 350 years (the ultimate limit state) for the south direction. At a return period of 20 years (the serviceability limit state) the value is 23 m/s. The comparable values from the code are 29 m/s and 23 m/s respectively (using the mean to gust factor of 0.68), a good agreement.

Conclusions

Wellington Airport and Kaukau are the best wind monitoring stations for representing southerly wind speeds and directions in Cook Strait. For pressure differences between pairs of stations, up to about 60% of the southerly speed variance at the wind monitoring stations can be explained by pressure difference variations. The pressure difference between Kaikoura and Cape Campbell is the best statistical predictor of the winds, supporting physical arguments which point to the importance of the blocking of onshore flows by the high Kaikoura Ranges on Cook Strait winds. The relevant equations of motion for channeled winds indicate that the pressure difference should depend on the square of the wind speed. The observations are consistent with such a relation and help to explain the unusual wind climate of Wellington, where high winds occur frequently. Mean wind speeds at a return period of 350 years, which are important for engineering design, are found to be 49 m/s at Kaukau and 43 m/s at Wellington Airport. Speeds over the sea in Cook Strait at the same return period are likely to be between these values.

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***Table 1*: Relationships between wind speeds and directions reported by ships in Cook Strait and shore stations in southerly directions. The direction difference is (shore station direction - ship direction). Data period is August 1989 to January 1996**

Wind station used for correlation with ships	Mean speed ratio: station wind /ship wind	Correlation coefficient	Direction difference: mean (q) (degrees)	Direction difference: standard deviation (degrees)	Number of observations used
Wellington Airport (WN)	0.89	0.70	0	70	893
Kaukau (KK)	1.42	0.64	-1	62	668
Cape Campbell (CC)	0.89	0.50	-4	90	346
The Brothers (BR)	1.58	0.61	11	95	506
Paraparaumu (PP)	0.50	0.60	-9	65	326
Ngawihi (NG)	0.68	0.49	1	74	224

***Table 2*: Percentage of the speed variance at Wellington Airport and Kaukau explained by the pressure difference between pairs of stations in southerly (150°– 220°) winds. Station codes as in Table 1 plus BM (Blenheim), KI (Kaikoura), and CH (Christchurch). The data period is April 1993 to March 1994**

	Pressure stations							
	WN	WN	NG	NG	CC	CC	WN	WN
	PP	BR	BM	PP	KI	WN	KI	CH
WN	12	28	2	4	56	31	41	48
KK	23	40	1	12	61	29	44	44

***Table 3*: Coefficients of the best fit curves and their percentage of variance explained in Figure 2 between wind speeds and pressure differences**

Pressure difference	Wind speed station	Coefficient of u^2 (k_1)	Coefficient of u (k_2)	Constant term in relation (k_3)	% of variance described
P(KI)-P(WN)	KK	0.0083	-0.05	0.31	72
	WN	0.0013	0.26	-0.90	72
P(CH)-P(WN)	KK	0.0035	0.19	-0.64	65
	WN	0.0086	0.23	-1.17	76

***Table 4*: Pressure differences at selected return periods and the corresponding speeds at Wellington Airport and Kaukau using best-fit curves**

Return period (years)	Reduced variate	Pressure difference (hPa)		Wind speed (m/s)	
		P(CH)-P(WN)	P(KI)-P(WN)	Kaukau	Wellington Airport
5	1.50	14.0	10.3	38	31
20	2.97	17.6	13.0	42	35
50	3.90	19.8	14.7	45	38
350	5.86	24.4	18.1	49	43

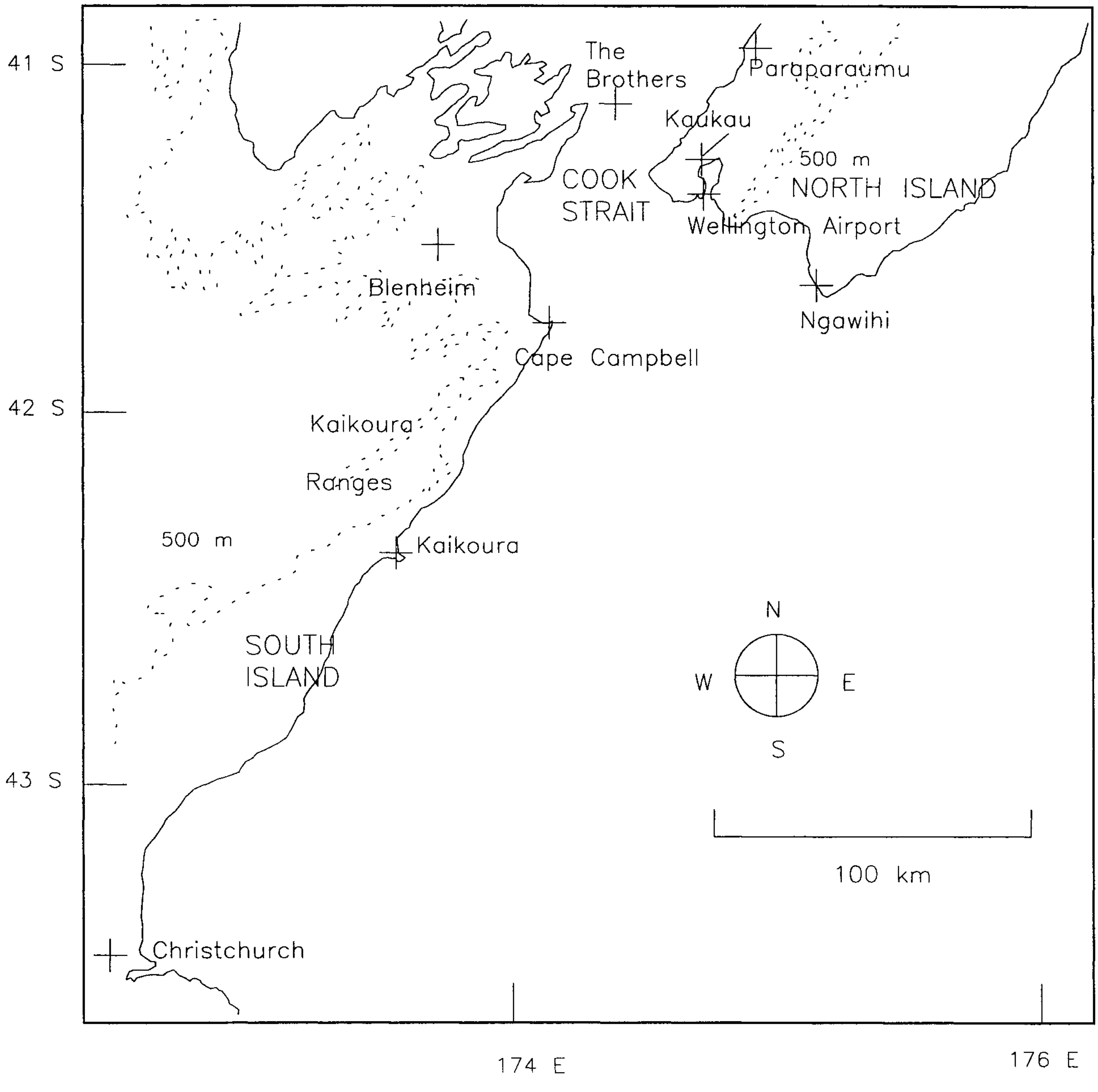


***Figure 1*: Positions of the meteorological stations in and around Cook Strait.**

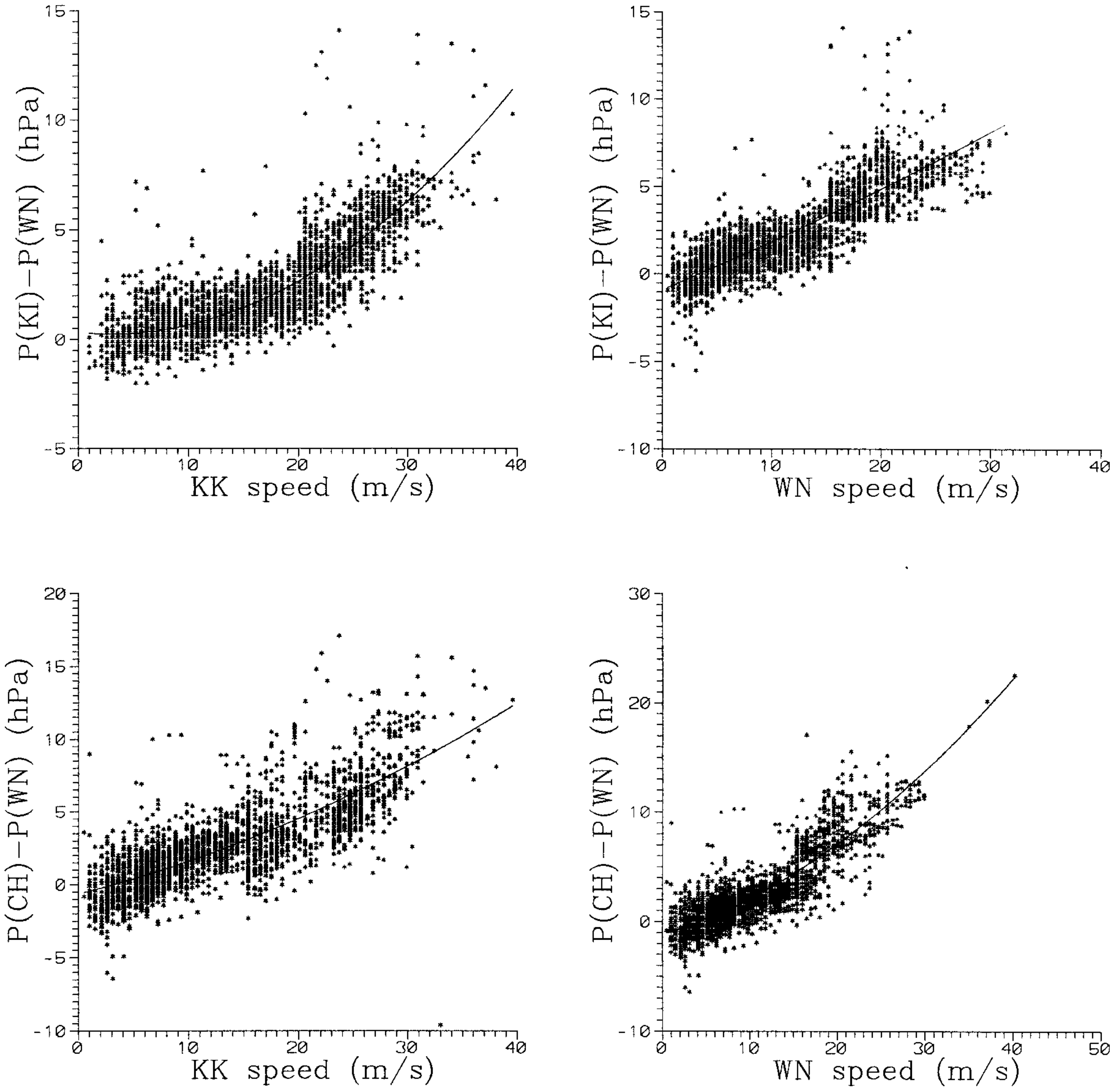
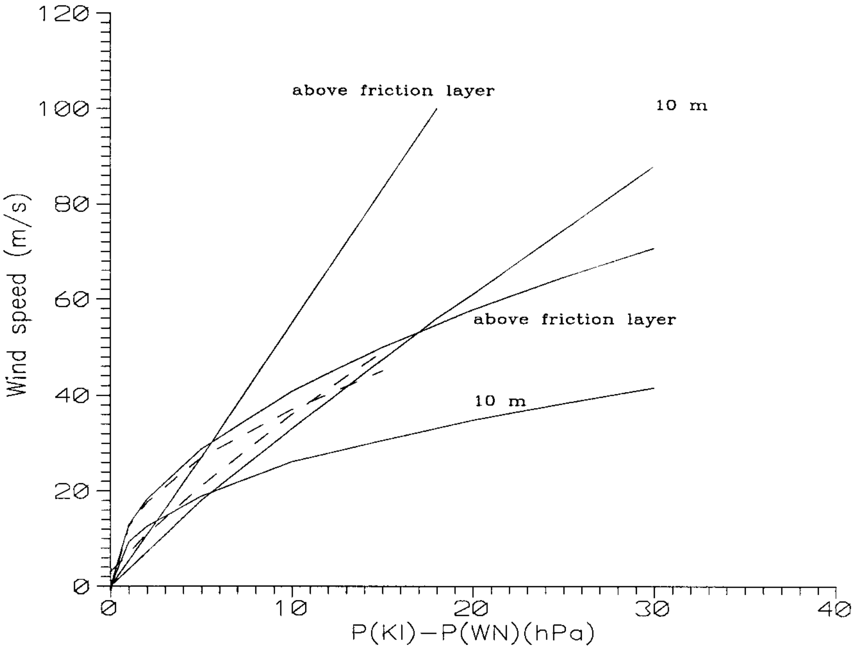


***Figure 2*: Scatter plots of pressure differences between Kaikoura (KI) and Wellington (WN) versus Kaukau (KK) speed (*upper left*) and Wellington Airport speed (*upper right*) for southerly winds. The lower panels are similar, but use Christchurch (CH) as the first pressure-measuring station. Second degree polynomial curves of best fit are drawn through the points. Data period, 1965–94.**



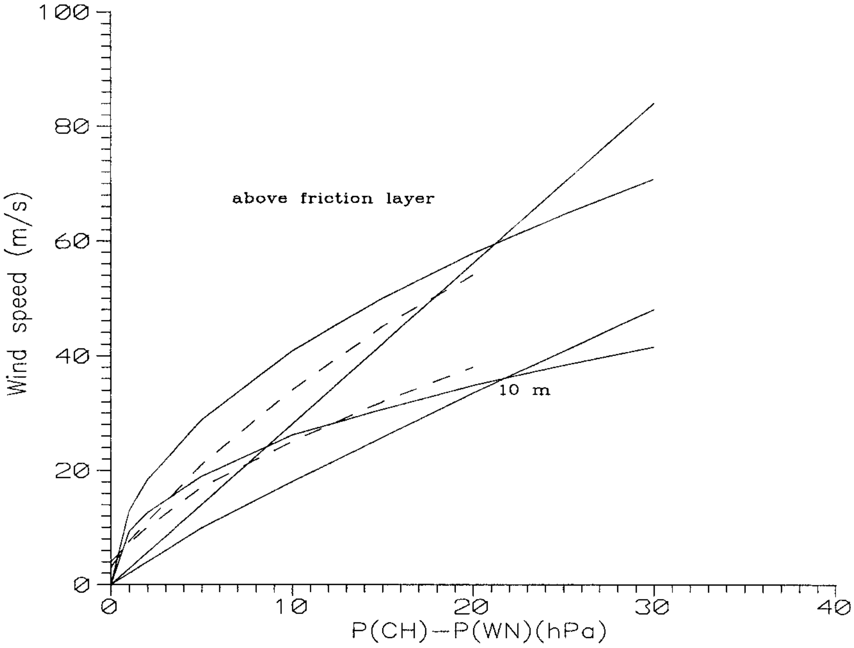


***Figure 3*: Redrawn curves of best fit from Figure 2 (dashed curves) for southerly winds: (*upper*) Kaikoura-Wellington pressure difference; (*lower*) Christchurch-Wellington pressure difference. The solid lines represent winds in geostrophic conditions above the friction layer and at 10 m above the sea and the solid curves represent conditions determined by Equation 7.**

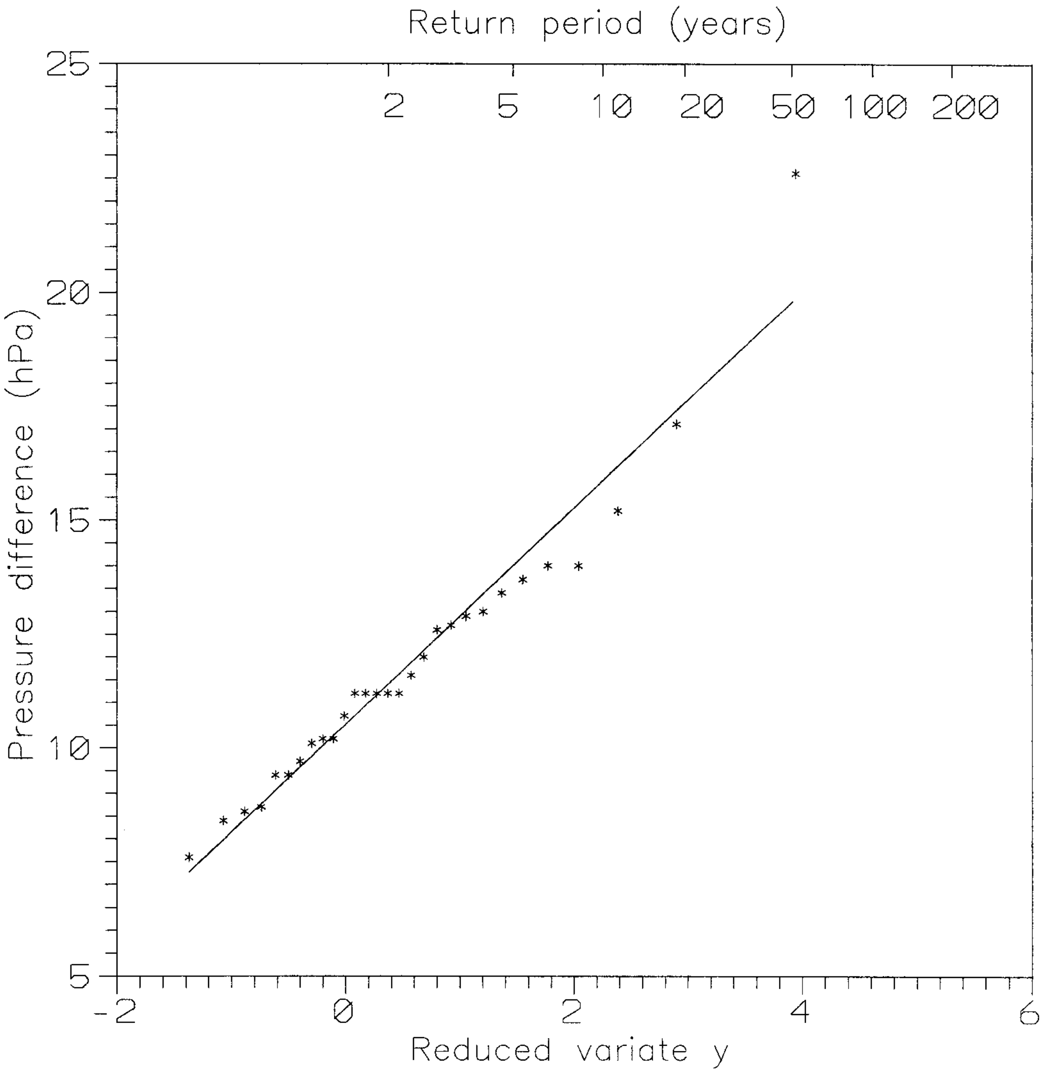


***Figure 4*: Extreme value plot of annual maximum pressure difference between Christchurch and Wellington. The data have been placed in order of magnitude and plotted against the reduced variate y (*see* text). Data period, 1960–94.**

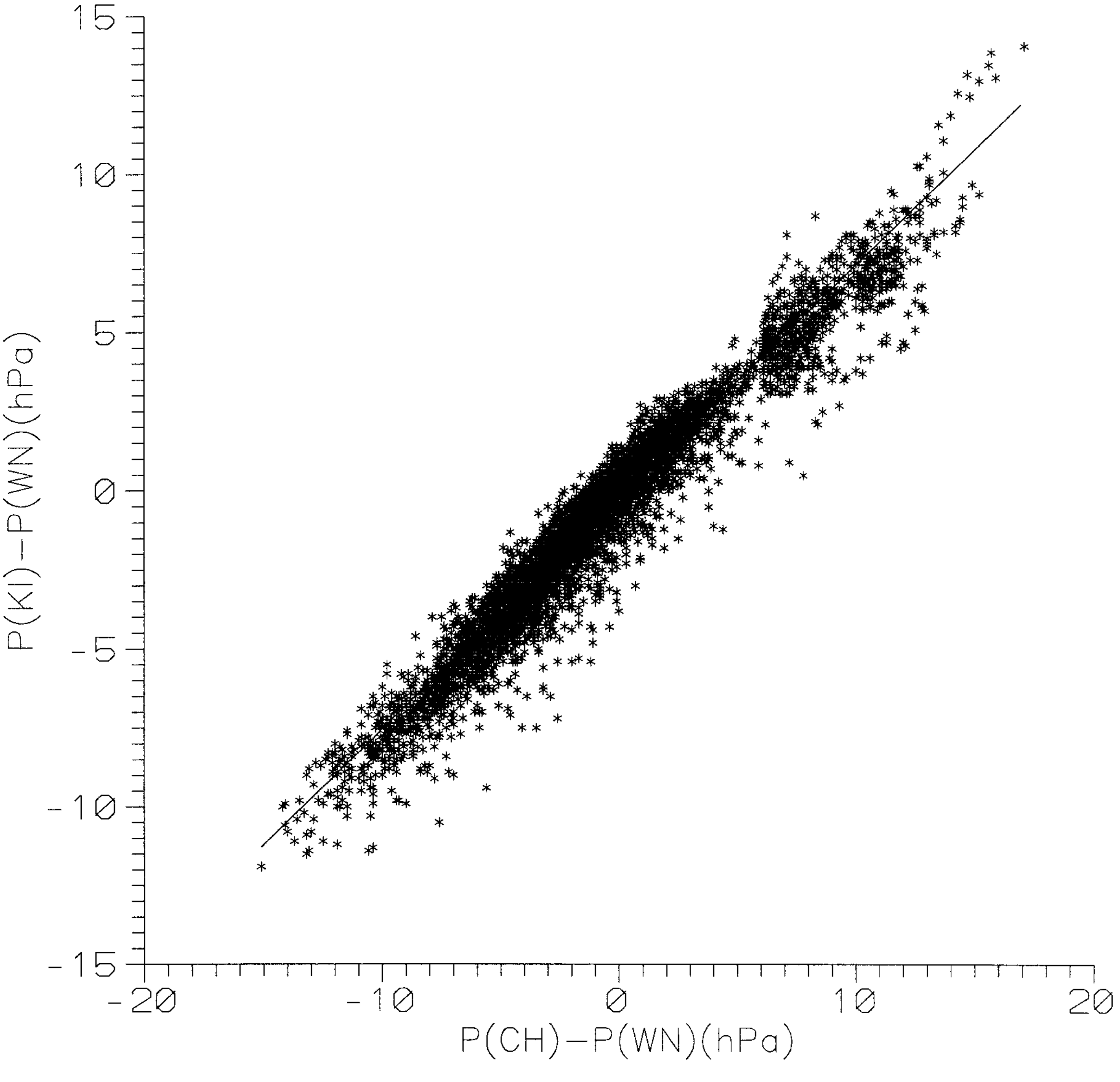


***Figure 5*: Scatter plot of Christchurch-Wellington pressure difference versus the Kaikoura-Wellington difference for southerly winds. The relation has been represented by a line. Data period, 1970–94.**

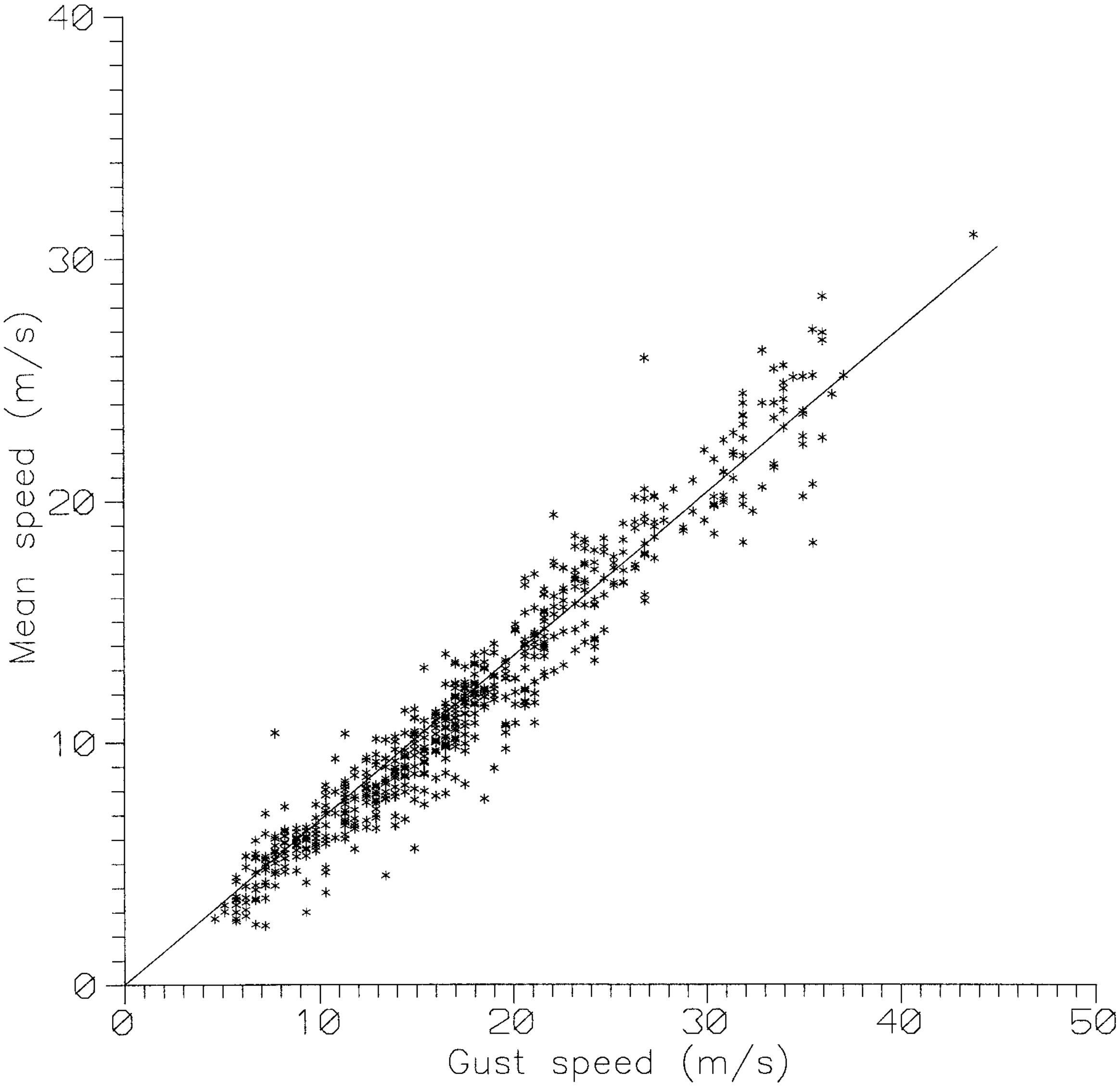


***Figure 6*: Scatter plot of the daily maximum mean speed at Wellington Airport versus the daily maximum gust, 1972–85. The fitted line has a slope of 0.68.**