HR Wallingford

Wave climate change and its impact on UK coastal management

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ABSTRACT

This research report considers long-term changes in wave conditions and sea levels around the UK coast, and how these changes may affect the planning, design and management of UK coastal defences. Some new numerical techniques were developed to enhance and to help interpret the measured and simulated data used in the study. The work included a literature and data review, and selective gathering and analysis of wind and wave data recorded near the UK coast. Predictions of future climate were obtained from a model developed by the UK Meteorological Office, and were used to predict the corresponding changes in wave conditions to be expected around the UK.

There have been significant increases in wave heights measured well offshore over the last twenty years or so. Sea levels are already rising slowly and the rate of rise is expected to increase. The modelling of future wave climate implies that small but significant changes in wave heights and directions can be expected in the future. The potential consequences for coastal management are severe and cannot be ignored.

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1. INTRODUCTION

1.1 General introduction

Climate change is a naturally occurring phenomenon, although the patterns of change are being altered and accelerated by man's activities. There is plenty of scientific evidence of very long-term changes in the Earth's climate, occurring over tens of thousands of years. There is also some shorter term weather and wave data collected over periods of about twenty years from which to make a more objective study of changes during recent times.

There is much public and scientific interest in climate change. There is speculation as to whether the increased amount of storm damage around the UK over the last few winters is part of a significant trend. As to the future, the speculation turns to the continuing and accelerating effects and consequences of "greenhouse" warming. The majority of the published research concentrates on "global" effects, as opposed to specific local or national problems. The majority view is that global warming and associated climate change are genuine effects, and that some of those effects are already beginning to show themselves. However, numerical models of global climate suggest that the changes would not be noticeable over periods as short as ten years without reliable instrumental measurements to detect them.

Climate change is not necessarily a bad thing for everyone: there will be some benefits as well as many disadvantages. However, any significant climate changes will lead to a review of civil engineering design and management criteria affected by those changes. For example, any expected changes in the pattern or volume of rainfall, the number of days of frost per year, wind speeds, wave heights, or sea levels would be of concern to civil engineers. The specific interest of the Ministry of Agriculture, Fisheries and Food (MAFF) in funding the present research is in the potential effects of changing wave conditions and sea level rise on UK coastal defences. This is an important subject since if one accepts some of the 'worst case' predictions for the future, large coastal areas of Britain could be subject to regular sea flooding unless defences are substantially improved.

There are many organisations world wide carrying out research on climate change, mostly based on existing climate records, but with a view to what will happen in the future. However, there are very few reliable and consistent climate records long enough to be certain that recent apparent changes are statistically significant, and not merely part of the natural variability of climate. There are a handful of organisations involved in numerical modelling of future climate, and rather more involved in interpreting the results for their own purposes.

Within the UK, HR has contacts with most of the public organisations involved in modelling, interpreting and planning for future climate change. These include MAFF and other Government Departments, the National Rivers Authority (NRA), coastal local authorities, the Institute of Oceanographic Sciences Deacon and Proudman Laboratories, the Meteorological Office, the Hadley Centre for Climate Studies, and the University of East Anglia Climatological Research Unit.

1.2 Scope of the study

The present research programme was included in HR's MAFF funded Flood Defence Research Commission specifically to look at changes in wave climate at the shoreline around the UK, and the consequences for coastal management. The research was to include a review of changes during recent years (say from 1960 onwards), and, by extrapolation and numerical modelling, to estimate changes over the next fifty years or so. The results were to be expressed in fairly general terms, rather than concentrating on specific problem sites.

The research was carried out over a period of two years from April 1989 to March 1991. An interim report (Ref 1) covered work done during the first year of the project. The present report marks the end of the MAFF funded research. However, research on climate change is continuing at HR under a commission awarded by NRA to examine site-specific coastal defence problems caused by climate change, and possible solutions to these problems.

Most of the original research work in the present study was devoted to studying changes in winds, and more particularly waves, in coastal areas around the UK. This involved analysis of existing wind and wave records, and simulation of long time series wave data from wind records, using numerical techniques developed at HR. It also involved taking simulated wind data from the Hadley Centre's gridded Global Climate Model of "present" and "future" world climate. Surface wind data from grid points over and around Britain was extracted, and used to simulate "present" and "future" wave climate data, again using methods developed at HR. No new work was done on sea level rise, but a detailed review of literature on the subject was carried out.

Roughly a quarter of the present research budget was spent on planning the work, reviewing the literature, gathering data and establishing contacts. Roughly half was spent on developing and validating numerical techniques, and on simulating and analysing time series wind and wave data. The remaining quarter was spent in interpreting the expected future changes in winds, waves and water levels, and their impact on UK coastal management, and reporting the results.

Chapter 2 is a selective literature review on climate change, particularly as it affects UK coasts, and a more detailed review of studies and conclusions about global sea level rise. Chapter 3 describes the numerical work done using existing wave and coastal wind data. Chapter 4 describes the numerical work done using simulations of future wind and wave conditions. Chapter 5 reviews the consequences for UK coastal management. Chapter 6 draws together the conclusions and makes recommendations for further research and future actions. The main results are presented in tables and figures at the end of the main text. Other results and data, of less immediate interest, and details of numerical techniques and models, are given in the appendices.

2. LITERATURE REVIEW

2.1 Introduction to the literature review

Climate change in its broadest sense includes historical trends, as well as changes in the recent past and expectations for the future. It also includes globally as well as nationally important changes, and all climatic parameters, and an assessment of their combined consequences. There are many papers on climate change amongst the more general technical journals, and some journals (including "Climatic Change" and "Global and Planetary Change"), conferences and books specialising in information on global climate change. Also, since the subject is one of general public interest, there are regular newspaper, radio and television reports on the subject. The literature review has included a watching brief on all of these potential sources of information. However, only the most extensive and the most relevant sources will be referenced directly in this report.

Many of the world's governments, meteorological agencies and other research associations have an interest in climate change and its consequences. Some of their research and conclusions were brought together recently in a book produced by the Inter-Governmental Panel on Climate Change (Ref 2: hereafter referred to as "the IPCC Assessment"). Within the UK, the major organisations researching or affected by climate change in coastal areas include: The Ministry of Agriculture, Fisheries and Food, the Departments of Energy and of the Environment, the National Rivers Authority, the Hadley Centre for Climate Studies, the Meteorological Office, the Natural Environment Research Council, the Institute of Oceanographic Sciences Deacon and Proudman Laboratories and the University of East Anglia's Climatological Research Unit. Other smaller research groups include universities, insurers, coastal local authorities, the Institute of Terrestrial Ecology, the Institute of Hydrology, British Maritime Technology and HR Wallingford. Many of the interested organisations in the UK have come together in the United Kingdom Climate Change Impacts Review Group.

The purpose of the present research project is to assess the effects of climate change upon design, maintenance and management of UK coastal defences. Sea level and wave climate are clearly the most relevant climatic parameters, although surface winds (and possibly surface pressures) are also of interest. Recorded climate changes around the UK, and expectations for the future are more relevant than global trends, although the latter are also of interest.

Section 2.2 is a general review of the literature on climate change and its consequences. Sections 2.3-2.5 concentrate on sea levels, wind climate and wave climate, respectively, especially changes recorded or expected around the UK.

2.2 Climate change in general

Climate change is a naturally occurring phenomenon. There is evidence of dramatic changes in climate and mean sea level, on an inter-glacial time scale of about one hundred thousand years. The Earth is presently in the warmer half of a glacial cycle, but temperatures have been both significantly higher and significantly lower than at present. During a complete glacial cycle, global mean surface temperatures vary by 5-7°C, although by rather more in the mid-latitudes of the Northern hemisphere. However, the majority of scientists believe that man's activities are having a measurable effect upon the Earth's climate via the "greenhouse effect", and that the changes are accelerating.

The IPCC Assessment (Ref 2) recently brought together the world's climate experts to assess the evidence of changes in the recent past, and the expected changes in the near future. This involved analysing meteorological records from around the world and predictions of future climate from Global Climate Models run at the UK Hadley Centre and in the USA.

Some of their main conclusions are quoted below:-

"Global-mean surface air temperature has increased by 0.3°C to 0.6°C over the last 100 years, with the five global-average warmest years being in the 1980's. Over the same period global sea level has increased by 10-20cm. These increases have not been smooth with time, nor uniform over the globe.

"The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability: alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more. There is no firm evidence that climate has become more variable over the last few decades.

"Although the overall temperature rise has been broadly similar in both hemispheres, it has not been steady, and differences in their rates of warming have sometimes persisted for decades. Much of the warming since 1900 has been concentrated in two periods, the first between about 1910 and 1940 and the other since 1975; the five warmest years on record have all been in the 1980's. The Northern Hemisphere cooled between the 1940's and early 1970's when Southern Hemisphere temperatures stayed nearly constant.

"Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFC's) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it.

"Atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide and the CFCs) adjust only slowly to changes in emissions. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present day rates, the greater reductions would have to be for concentrations to stabilise at a given level.

"Under the IPCC Business-as-Usual emissions scenario, a rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade); this is greater than that seen over the past 10,000 years. This will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century.

"Under the IPCC Business-as-Usual emissions scenario an average rate of global mean sea level rise of about 6cm per decade over the next century (with an uncertainty range of 3-10cm per decade), mainly due to thermal expansion of the oceans and the melting of some land ice. The predicted rise is about 20cm in global mean sea level by 2030, and 65cm by the end of the next century.

"Models predict that surface air will warm faster over land than over oceans, and a minimum of warming will occur around Antarctica and in the northern North Atlantic region.

"There are some continental-scale changes which are consistently predicted by the highest resolution models and for which we understand the physical reasons. The warming is predicted to be 50-100% greater than the global mean in high northern latitudes in winter, and substantially smaller than the global mean in regions of sea-ice in summer. Precipitation is predicted to increase on average in middle and high latitude continents in winter (by some 5-10% over 35-55°N).

"With the possible exception of an increase in the number of intense showers there is no clear evidence that the weather variability will change in the future."

Future climate models make no firm predictions about changes in winds and storms except to indicate that any such changes will be small. However, there is an inference that tropical storms will be slightly more intense whilst mid-latitude storms will be slightly less intense following global warming.

The UK will suffer from the future increases in temperature and sea levels predicted globally. More locally, it is predicted to have wetter winters and drier summers (with a reduced soil moisture content in the summer), following global warming. There is not likely to be any increase in storm frequency or intensity. An increase in mean wave heights around the UK has been observed over the last thirty years, although there is no evidence that this is linked to global warming.

There will be many UK consequences of these changes, for ecology, agriculture and water management. The water management aspects will include the following things. The increasing winter rainfall will increase drainage requirements. The decreasing summer rainfall may mean irrigation is necessary to maintain existing cropland. The changing pattern of rainfall will affect water collection, storage and supply. Increasing winter rainfall, sea levels and wave heights will cause a need for improved river and sea defences.

2.3 Global sea level rise

It is generally accepted that sea levels have risen slightly during this century, and that they will continue to rise, probably at an accelerated rate, during the next fifty years. Although such changes would not be apparent to a casual observer, they can be detected by fixed markers including tide gauges. The main adverse consequence of a sea level rise of half a metre or so would be more frequent and more severe flooding of low lying land near coasts and tidal rivers. There is some indication that sea level rise will vary slightly around the world. However, these regional variations will have little effect around the UK, and therefore all comments address the problems of "global" sea level rise.

An increase in ocean water volume will be caused by expansion as the temperature increases, at least at temperatures above 4°C. Some additional water necessary to cause sea level rise will be provided by melting glacial, Arctic and Antarctic ice. (It is true that melting of floating ice would cause no change in water level, but much of the ice, particularly in the Antarctic, is on land). Sea level rise may be demonstrated by tide gauge measurements, or may be inferred from measurements of the thickness of polar ice, or from measurements or climate modelling showing increasing temperature in the polar regions.

In Section 2.2 it was noted that global temperatures have been both higher and lower than at present over a timescale of thousands of years. More importantly, the last decade has been slightly, but significantly, warmer than any other this century. Whether or not this is part of the greenhouse effect, and it probably is, one is not surprised that a corresponding measurable decrease in volumes of polar ice and a consequent rise in mean sea levels have been detected. However, to put the expected changes into context, if all the ice in the world were to melt the oceans would rise by about 70m. Perhaps a more plausible long term "worst case" would be the melting of the entire West Antarctic Ice Sheet, which is grounded well below sea level, and which would raise global sea levels by about 5m.

Volumes of polar ice are difficult to measure. "Ice extent" can be monitored by satellite and by ships observations, but is subject to considerable variability. "Ice thickness" is a more definite sign of significant changes, but is difficult to measure. The IPCC Assessment reports that analysis of sea ice extent data since 1950 (before which records were unreliable) shows some decadal variation but no continuous trends. A change in the thickness of floating ice would not be particularly important in itself, but would suggest a corresponding change in land-supported ice. Sea ice thickness can only be measured by upward looking sonar from submarines. Some records show no significant change in thickness, but measurements over a large area north of Greenland show a 15% reduction in thickness from 1976 to 1987. Records at the British Antarctic base at Rothera show an increase in mean temperatures from 0.1°C between, 1977 and 1981 to 1.1°C between 1982 and 1986, with a corresponding marked reduction in ice cover in the vicinity of the base. A substantial, but not continuous, recession of mountain glaciers has taken place almost everywhere since the latter half of the nineteenth century. The rate of recession appears to have been greatest between about 1920 and 1960. The gradual reduction in ice volumes implied above provides a steady source of water for raising mean sea levels.

The most reliable evidence for sea level rise comes from direct measurements by tide gauges, but there are few records of any sort before the early 19th century. The longest continuous and consistent UK tide record (from Newlyn) covers the period from 1915 to date. Systematic collection and analysis of sea level data for the British Isles is now the responsibility of the Proudman Oceanographic Laboratory (POL). On a worldwide basis, POL are involved in the Global Sea Level Observing System (GLOSS) which will involve a global network of about

300 primary tide gauges. POL has installed GLOSS gauges at Lerwick, Stornoway and Newlyn in the UK, and Ascension, St. Helena, Tristan da Cunha, the Falklands, South Georgia and South Orkney.

POL's analysis indicates that mean sea levels were rising at a rate of about 1mm per year about one hundred years ago, rising to a rate of about 2mm per year at present, with a total rise of 150-200mm over the last century. Some details of their calculations are given below:

(i) UK 1916-82

Newlyn	1.8mm per year
Aberdeen	0.9mm per year
Sheerness	1.9mm per year
North Shields	2.6mm per year

(ii) elsewhere

Sydney (1896-1984)	0.5mm per year
Bombay (1879-1961)	1.0mm per year
San Francisco (1854-1981)	1.2mm per year
Brest (1807-1982)	1.0mm per year

The above conclusions are supported by the IPCC Assessment. Mean sea levels have been rising over the last one hundred years (at least). The present rate of increase is about 2mm per year and is probably accelerating. However, the rate of rise shows considerable variation from place to place (possibly due to variable land movements), and considerable variation with time, even on a decadal timescale. The main causes of sea level rise in the past have been: i) thermal expansion of the oceans, ii) melting of mountain glaciers and iii) melting of the Greenland Ice Sheet. From present data it is difficult to judge whether iv) the Antarctic Ice Sheet has contributed, either positively or negatively, to sea level rise. Reference 3 estimates the contributions to mean sea level rise since 1880, from the four factors above, to have been in the proportions 45%, 45%, 25% and -15%, although with considerable uncertainty. (The negative proportion indicates that snow has been accumulating in Antartica.)

There are several ways of predicting future sea level rise. The simplest is by extrapolation of recorded trends from the last century. Other ways include calculation of oceanic expansion based on expected temperature rises, calculation of ice masses which could melt and add to ocean volumes, and full-scale future climate modelling. The IPCC Assessment is the most recent extensive review of world wide research into future sea level rise. It used past measurements of mean sea levels and the knowledge gained from different Global Climate Models. It considered different scenarios, both with regard to rates of continued atmospheric pollution, and with regard to specific climatic responses, for example melting of the West Antarctic Ice Sheet. We can do no better than to quote some of its predictions with regard to future sea level rise, taken from Chapter 9 of Reference 2.

"For the IPCC Business-as-Usual scenario at year 2030, global-mean sea level is 8-29cm higher than today, with a best-estimate of 18cm. At the year 2070, the rise is 21-71cm, with a best-estimate of 44cm.

"Most of the contribution is estimated to derive from thermal expansion of the oceans and the increased melting of mountain glaciers and small ice caps.

"On the decadal time scale, the role of the polar ice sheets is expected to be minor, but they contribute substantially to the total uncertainty. Antarctica is expected to contribute negatively to sea level due to increased snow accumulation associated with warming. A rapid disintegration of the West Antarctic Ice Sheet due to global warming is unlikely within the next century.

"For the lower forcing scenarios (B, C and D), the sets of sea level rise projections are similar, at least until the mid-21st century. On average these projections are approximately one-third lower than those of the Business-as-Usual scenario.

"Even with substantial decreases in the emissions of the major greenhouse gases, future increases in temperature and, consequently, sea level are unavoidable - a sea level rise "commitment" - due to lags in the climate system.

"In general, this review concludes that a rise of more than 1 metre over the next century is unlikely. Even so, the rate of rise implied by the Business-as-Usual best-estimate is 3-6 times faster than that experienced over the last 100 years."

Reference 3 goes on to estimate the relative contributions of the four main factors to sea level rise over the next hundred years: thermal expansion (55%), glaciers (35%), Greenland ice (20%) and Antarctica (-10%), although there is considerable uncertainty.

These conclusions imply a continuous rise in mean sea levels of about 5-6mm per year for the next fifty years or so, and that this rise will occur almost regardless of any reduction in the rate of production of greenhouse gases. This prospect should be of major concern in many low-lying coastal areas subject to permanent or temporary inundation, and of some concern where cliff or beach erosion or salt intrusion occurs.

Many books and articles address the specific problems of sea level rise. A few of the most relevant are listed here. "Greenhouse Effect and Sea Level Rise" (Ref 4) and "The Effects of Ozone Modification and Climate Change" (Ref 5) are books based on US Environmental Protection Agency conference papers presented in 1983 and 1986, respectively: they address the economic, physical and coastal management problems of sea level rise in the US. "Climatic Change, Rising Sea Level and the British Coast" (Ref 6) is a report produced by the Institute of Terrestrial Ecology: it addresses the ecological and coastal problems of sea level rise in the UK. "The potential effects of climate change in the United Kingdom" is a broad review of climate change and its impact, produced by the United Kingdom Climate Change Impacts Review Group in 1991 (Ref 7). "Impact of sea level rise on society" is a broad review of the impacts of climate change and how to combat them, produced by a mainly Dutch review group in 1986 (Ref 8). A conference of River and Coastal Engineers at Loughborough in 1989 (Ref 9) brought together researchers, designers and statutory authorities to discuss the magnitude and impact of sea level rise in the UK. A policy study by de Ronde (Ref 10) reviewed the economic and physical consequences of sea level rise in the Netherlands, where low-lying coastal areas are particularly vulnerable to flooding.

Reference 7 works from the predictions and assumptions about future climate change given in the IPCC Assessment (Ref 2). It considers the potential impacts (especially as they affect the UK) of climate change in a wide variety of environmental and socio-economic areas. It includes a general appraisal of the type and value of land most vulnerable to future sea level rise.

Reference 10 estimates that the total cost of improving Dutch sea defences to meet the sea levels expected in one hundred years (ie + 60cm) would be 7½ billion US dollars. Reference 6 takes perhaps an unduly pessimistic view that sea levels will rise by 0.8-1.65m over the next one hundred years, and that the cost of upgrading UK coastal defences to meet this rise will be 5 billion pounds. Quoting from Reference 6:

"The coastline of Britain can be subdivided into two categories, the mainly low-lying soft coasts, often protected by a sea wall, and the harder, predominantly cliff, coasts. The cliff coasts associated with harder rocks in the north and west would be little affected even with a sea level rise of some magnitude, although there are sheltered inlets with salt marsh, shingle and sand dune communities. However, in the absence of artificial restraints, these isolated communities and ecosystems would probably adjust to rising sea levels by slowly migrating landwards.

"A rise in sea level would result in increased erosion, but such erosion can usually release enough sediments into circulation to allow the coast to reform more or less unchanged. The development of new marshes and mud flats is, however, a slow process, and it is possible that the rate of sea level rise might be too great for these natural processes of recovery to take place. In addition, these processes depend on there being no artificial barriers to limit the advance of the sea landwards.

"Along nearly all of the low-lying coasts of Britain this process is inhibited by the existence of sea walls that protect life and property against any intrusion of the sea. A rise in sea level would increase the rate of erosion of marshes seawards of the sea wall, and the sediment would generally be lost from the immediate system.

"Some parts of these low-lying coasts are fronted and protected by sand dunes or shingle banks. These areas would also be vulnerable to change as a result of a rise in sea level, especially where there is insufficient space for them to reform landwards.

"Sea level rise would also present a significant problem, however, in those areas with a cliff coast where the cliffs are composed of softer rocks. The present, not inconsiderable rates of erosion would be dramatically enhanced if erosion was allowed to proceed unchecked, then there would be a substantial enhancement of the supplies of sediment to salt marsh and sand dune areas further along the coast. Conversely, the prevention of erosion would cut off this supply of sand and sediment and could result in increased erosion elsewhere.

"In addition to the direct effect already mentioned, a rise in sea level would affect areas some distance inland. There is likely to be increased flooding in coastal areas by sea water or brackish water, and salt penetration of the groundwater would increase further inland.

"All parts of the British Isles would experience some effect from a change in sea level of the magnitude predicted. The largest changes would, however, be in the south and east, particularly from the Humber to Poole Harbour, and in other major estuaries such as the Severn, the Mersey, Morecambe Bay and the Solway Firth (Figure 1).

"In the past, small rises in sea level have been provided for, and factors of safety against storm surges have been increased mainly by raising the height of existing structures, although these actions have been supplemented by major projects, such as the Thames Barrier. The magnitude of the rises postulated, however, pose radically different problems. It appears that many existing sea walls lack the foundations to withstand raising them by the required amount. Even if such a measure were possible, it would cost between £2,500 and £3,000 per metre to raise the walls sufficiently to cope with a rise of 1.65m (A J Allison, pers. comm.). This estimate makes no allowance for secondary climatic effects, such as the deteriorating wave climate, which could make the situation worse.

"In addition to the costs of raising existing sea defences, there is also a problem of the various outfalls. The vast majority of gravity outfalls would become inoperable, and many pumping stations would have to be modified or replaced at an estimated cost of £2,000M."

In view of the heavy costs involved, Reference 6 goes on to suggest alternative sea defence strategies, and to review the ecological consequences of each:

(a) Present sea walls raised
(b) New sea walls constructed landwards of existing ones
(c) Storm surge barriers built across estuaries
(d) Impermeable barriers built across estuaries
(e) Abandonment of coast

A New Civil Engineer article (4 January 1990) also takes a rather pessimistic view of one metre of sea level rise over the next 50 to 100 years. It states that a one metre rise would affect only about 3% of the Earth's land, but a disastrous one third of all cropland. It also points out that some nations would lose land disproportionately: 16% of Bangladesh could be inundated, whilst some tropical island nations could disappear altogether. Reference 9 notes that whilst only 8% of Grade 1-3 agricultural land in England and Wales lies below 5mOD, a much larger 57% of Grade 1 agricultural land lies below 5mOD, the area most vulnerable to sea level rise.

Pugh (Ref 11) calculated a more modest rate of sea level rise, and considered how it might vary around the UK. These variations are due mainly to vertical land movement, but also to changes in ocean topography and adjustments in the shape of the ocean surface. For example, there is some evidence of a gradual uplift in the north of the UK, and of subsidence in the south-east, and it is of course the sea levels relative to local land levels which are of interest. Pugh (Ref 11) predicted the following increases in mean sea level for four UK tide gauge stations.

Location	Rise by 2027	Rise by 2087
Newlyn	0.14m	0.64m
Sheerness	0.15m	0.65m
North Shields	0.16m	0.72m
Aberdeen	0.10m	0.55m

Looking at these figures a different way, what is presently judged to be a 100 year water level at Newlyn would be reduced to a 5 year return period by 2027, and to 1 year by 2087. (These figures assume that extreme sea levels will increase by the same amount as mean sea levels.) Similarly the 100 year level at Sheerness, would be reduced to a 60 year return period by 2027 and to a 5 year return period by 2087. Note that if extreme water levels were expected to rise faster than mean water levels, perhaps due to changing weather patterns, then the rate of reduction in return period would be even higher.

Rates of change of high and extreme water levels are of more interest than the rates of change of mean sea level discussed above. However, changing high water levels are much harder to detect, explain or quantify, except insofar as they may change exactly in line with mean water levels. Reference 12 addresses the question of changing Mean Tidal Ranges (MTR) based on long-term tidal records around the UK. Some of its conclusions are given below. It shows that one cannot be too general in statements about past and future rates of mean sea level rise, or about the consequent effect on rates of increase of high and extreme water levels.

There is a natural tidal harmonic with a period of about 18.6 years, causing a variation in MTR of about ± 100mm from long-term mean values around the UK. The significance of this is that high water levels will be about 100mm higher at the peak of the 18.6 year cycle than at its trough. In the short term (periods of the order of 5 years), this variation may be more significant than globally increasing mean sea levels. However, the 18.6 year periodicity is well known and predictable in advance, and can therefore be incorporated into any extreme water level calculation.

There is also a continuous trend of change in MTR at all of the UK tide gauge stations examined in Reference 12, although the rates of change are several times smaller than the expected rates of change in mean sea level. As examples, the highest rates of increase and decrease in MTR reported are 1.3mm/year at Liverpool and -1.8mm/year at Holyhead. Assuming that these changes equally affect high and low water levels, then they would correspond to increasing high water levels of about 0.65mm/year at Liverpool and decreasing high water levels of 0.9mm/year at Holyhead (in addition to any contribution from increasing mean water levels).

Further results given in Reference 12 indicate the variation around the UK in rates of increase of mean sea level derived from tide gauge records over about the last century. These vary from -1.6mm/year (decreasing mean level) at Lerwick, through almost zero at Douglas, Belfast and Dublin, to 3.1mm/year at Holyhead and Southend and 5.6mm/year at Blyth.

2.4 Wind climate around the UK

Little has been written on changes in wind conditions in recent times around the UK, since few changes have occurred to arouse research interest. An exception to this statement is the fact that an unusual number of severe storms have affected Wales and Southern England in the last few years, beginning with the Great Storm of October 1987. No-one has yet proved that recent apparent increases in storminess are statistically significant or that the trend will continue into the future.

Unpublished work by Jenkinson (1977) of the Meteorological Office looked at wind data taken from charts representing conditions over the Atlantic, UK and North Sea, from 1881 to 1976. He found no significant changes in wind speeds. Similar unpublished work by Benwell (1967) and Hunt (1970) of the Meteorological Office drew the same conclusion about winds around the UK, specifically in relation to conditions likely to lead to surges.

Lamb and Weiss (1979, Ref 13) looked at historical wind records going back several hundred years and other historical evidence going back three thousand years. They detected a UK wind climate cycle with a repeat period of about two hundred years. Over the UK and the North Sea, the change consisted mainly of movement between northerly and westerly winds. At the time of writing, the proportion of northerly winds was increasing at the expense of westerlies, which would tend to increase average wave heights on the east coast of the UK. They forecast that this trend would continue for a further 70-100 years, presumably with a continued rise in mean wave heights on North Sea coasts of the UK.

A number of authors who have detected wave height trends around the UK (see Section 2.5) have reported no matching trend in wind speed over the last 30-40 years. However, Dr Davies of the School of Environmental Sciences at the University of East Anglia has detected a downward trend in average wind speeds during this century. His analysis shows that wind speeds in the North Atlantic and West coast of Britain were slightly higher during the 1930's and 1940's than during the 1960's and 1970's. This is also noted in the IPCC Assessment (Ref 2) in which a link is noted between temperatures and westerly winds in the North Atlantic, higher temperatures being associated with reduced westerly winds.

Section 7.9.2 of Reference 2 states: "The early twentieth century cooling of the Northern Hemisphere oceans was accompanied by a period of intensified westerlies in the extratropical Northern Hemisphere, especially in the Atlantic sector, that affected most of the year.... The global warming which took place in the 1920's and 1930's was largest in the extratropical North Atlantic and in the Arctic, and coincided with the latter part of the intense westerlies ... The inter-decadal variations of the pressure index are strikingly large, with weakest flow centred around the 1960's (less westerlies) and a return to stronger westerlies recently."

Expert opinion is that the recent (from October 1987 onwards) severe storms occurring in southern parts of the UK are probably not associated with the beginnings of the "greenhouse effect". Although the storms were bad, they were not as unusual as is generally thought, in the context of the whole of the

UK and surrounding waters. Severe storms are more frequent in the north of Scotland, where there are fewer people around to notice them, and who are in any case better prepared for them. Severe storms are likely to cause more damage in the populated areas of Wales and southern England, especially where people are living close to the sea. Climatic models of the effects of global warming do suggest that some changes in winds would occur. However, the models indicate that although tropical storms would tend to be more frequent and more intense over warmer oceans, that severe storms around the UK should tend to occur less often. To summarise, increased storminess around the UK is not an established trend, and there is no particular reason to assume that the unusually high frequency of severe storms in the last few years will continue in the future.

Models of future climate do not make any firm predictions about changes in wind patterns to be expected in the future, except to say that such changes will be small. The conclusions of the IPCC Assessment (Ref 2) are summarised in the following quote: "Tropical storms, such as typhoons and hurricanes, only develop at present over seas that are warmer than about 26°C. Although the area of sea having temperatures over this critical value will increase as the globe warms, the critical temperature itself may increase in a warmer world. Although the theoretical maximum intensity is expected to increase with temperature, climate models give no consistent indication as to whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades.

"Mid-latitude storms, such as those which track across the North Atlantic and North Pacific, are driven by the equator-to-pole temperature contrast. As this contrast will probably be weakened in a warmer world (at least in the Northern Hemisphere), it might be argued that mid-latitude storms will also weaken or change their tracks, and there is some indication of a general reduction in day-to-day variability in the mid-latitude storm tracks in winter in model simulations, though the pattern of changes varies from model to model. Present models do not resolve smaller scale disturbances, so it will not be possible to assess changes in storminess until results from higher resolution models become available in the next few years."

2.5 Wave climate around the UK

There are a number of types of data from which to draw conclusions about changes in wave severity in recent years. Visual observations (VOS data) of waves from moving ships and stationary Light Vessels have been collected in a consistent manner for over 40 years. Some wind records, from which inferences about waves can be drawn, go back further than that. Several meteorological agencies operate global and/or regional wave forecasting models, mainly for real-time use, and some have built up data archives extending over ten years or more. There are a handful of locations around the UK where instrumentally recorded wave data have been collected over a period of years. Finally, satellite remotely sensed wave data has been available since about 1985.

One should be wary of looking for gradual trends in data sets, in which the method of sensing or recording has altered substantially, possibly introducing a change of similar magnitude to the genuine climatic change that one is searching for. This is particularly true of real-time forecasting models, where quality of input and processing are frequently updated. However, the consistent conclusion drawn by several researchers from several sources of data is that wave heights well offshore from the UK have increased since about 1960. No satisfactory explanation has been given for these increases, although there are some ideas as to the cause, and so it is difficult to say whether these increases will continue into the future.

The best set of long term instrumentally recorded wave data around the UK was collected at Seven Stones Light Vessel from 1962 to 1986. Bacon and Carter (Ref 14) re-analysed the data, removing any spurious trends due to changes in instrumentation, and looked separately at "average" and "extreme" significant wave heights. The increases in <u>average</u> heights are quite noticeable, running at just over 1% (or about 2cm) rise per year. However, increases in predicted <u>extremes</u> are much smaller. A possible explanation, given by Hogben (Ref 15), is that wave activity in the Atlantic, which causes swell along the west coast of Britain, is increasing, leading to higher "background" wave heights along the coast. However, the most extreme wave heights and those causing damage to coastal defences, are usually associated with more locally occurring storms, and there is no clear evidence that these are increasing. This conclusion is consistent with additional information quoted in Reference 15, that no increases in wind speed were detected during the period of increasing wave heights.

The conclusion that wave activity around the UK is increasing is supported by other wave measurements in the area. A Dutch publication (Ref 16) shows the same trends over the period 1960-85, ie little change in wind speeds, but a steady increase in mean wave heights. However, it shows the highest waves of all occurring in the 1950's. Barratt and Hogben (Ref 17) have been looking at VOS wind and wave data (1950-85) from a few sea areas around the UK. Their conclusions are similar to those given above: mean wave heights have gradually increased by just over 1% per year, with no corresponding increase in wind speeds. A possible explanation given was that there had been changes to the size and paths of storms, thus altering the swell statistics but not affecting the statistics of extremes and winds. However, there is no specific meteorological evidence to support this theory.

The most comprehensive review of wave climate changes, as exhibited in wave data observed and measured around the UK, was carried out by Bacon and Carter (Ref 18), funded by the Department of Energy. They reference many papers and data sets covering the North Atlantic and North Sea from about 1952 onwards. The main data sets examined or reviewed comprise: Seven Stones Light Vessel measurements 1962-86, Ocean Weather Ship (OWS) Lima measurements 1975-88, and OWS India and OWS Juliett measurements 1962-73 in the Atlantic; Famita observations 1959-73 and Dowsing Light Vessel measurements 1970-85 in the North Sea, and; observed wave data from all OWS's 1952-65, and for a number of areas of VOS observations 1970-82. The main conclusions from Bacon and Carter (Ref 18) are reproduced in the following paragraph.

The evidence for wave climate change in the North

Atlantic is quite strong. One period of declining wave heights from 1960 to 1965 is apparent from OWS observations. The majority of the data sets, both measurements and observations, show steady and significant increases in mean wave heights in the North Atlantic, certainly since about 1965 and possibly since about 1950. The average rate of increase in mean wave heights in recent years has been about 2% per year. There is not enough data to be sure whether derived extreme wave heights are also increasing: they probably are increasing but not at so great rate as mean wave heights. In the North Sea, the available data suggest that mean wave heights increased from about 1960 to a peak around 1980, with a subsequent slight decline. However, recent winters not included in Bacon and Carter's detailed analysis (particularly 1988-89), have produced severe storms in the northern North Sea which may affect trends. Again, there is no clear evidence of changes in extreme wave heights.

Carter (Ref 19) has also been examining satellite remotely sensed wave data from late 1985 onwards. At present there is insufficient data to confirm wave height trends noted elsewhere. However, of the four winters 1985/86 to 1988/89, the highest average wave heights in the north-east Atlantic occurred in 1988/89 and the lowest in 1986/87. The inverse was observed in the north-east Pacific, with the highest average wave heights occurring in 1986/87 and the lowest in 1988/89.

Wave direction can be almost as important as wave height in some coastal engineering problems, for example in maintenance of mobile beaches. At present there is not enough quantity and quality of directional wave data for any trends in wave direction to have been noted. Also, distribution of storms could be important in situations where one would normally undertake some form of remedial work, immediately following storm damage to coastal defences. This remedial work may not be possible if storms arrive one after another in quick succession, rather than being spread more evenly throughout the year. Parts of the UK have suffered in this way, from successions of storms, during the last few winters, particularly 1989-90. However, there is not enough data to say that these apparent changes are statistically significant, and that they should be expected to continue in the future.

No-one has made any confident predictions of how wave conditions will vary in the future. The fact that mean wave heights have increased around the UK in recent years is no guarantee that they will continue to increase in the future, particularly as no satisfactory explanation is available to explain the phenomenon. Models of future climate have not addressed the problem of ocean waves: indeed waves are not even mentioned in the IPCC Assessment. The literature on climate changes suggests that the link between wind speeds and wave heights, at least in open oceans, is not as clear as one might expect. Therefore even if one could confidently predict future wind conditions, extrapolation to future wave conditions would be difficult.

If one assumes that recent increases in wave heights will continue in the future, the consequences for UK coastal defences are important, but probably not as important as an unchecked rise in sea level. Increases in wave heights offshore are likely to be moderated by the time the waves arrive at UK coasts. For one reason, the attenuation of wave heights due to coastal wave transformations will affect larger waves more than smaller ones. Also, the influence of locally generated waves, which will be dependent upon local winds, will become more important in nearshore areas. In any case, an increase in mean wave height, provided it affects all wave directions equally, and does not change the storm distribution, would have little effect on coastal defences other than to increase rates of erosion slightly. An increase in extreme wave heights would be far more important, rendering previous wave design criteria out of date on both hard and soft defences. However, there is no particular indication that derived extreme wave heights are likely to increase in the future.

2.6 Summary of trends relevant to UK coastal management

Mean sea level rise

The global average sea level rise has been about 150-200mm over the last one hundred years. This has been caused by thermal expansion of the oceans and melting of polar and glacial ice. The present rate of rise (from tide gauge data) is about 2mm per year and rising. Future climate modelling and other inferences conclude that sea levels will rise at about 5-6mm per year for the next fifty to one hundred years, and that this will occur even if "greenhouse" gas production is reduced. There is little evidence of regional variation in sea level rise, although land movements may cause apparent differences.

Wave climate around UK

Mean wave heights in the North Atlantic have increased by 1-2% per year since 1960, with no corresponding increase in wind speeds. Mean wave heights in the North Sea increased from 1960-1980. Derived extreme wave heights have not increased as rapidly as mean wave heights, and there is not yet enough data to say confidently that extremes are increasing. A possible explanation is that swell activity is increasing whilst storm wave generation by local winds is not. Nearshore waves would be rather less influenced by these unexplained increases since they are less exposed to swell.

There is no particular reason to expect that the increase in mean wave heights will continue in the future. Tentative conclusions from future climate models suggest that westerly storms reaching the UK would tend to be less frequent and less severe following global warming. The apparent increase in the number of severe storms in Wales and southern England in recent years has not been explained by "greenhouse effects" and has not been established as a clear statistical trend.

There is therefore no particular reason to think that the storms will continue at the same increased frequency in the future.

Consequences for UK coastal management

Only a few percent of UK land is at risk from climate change (See Figure 1). However, that land includes a high proportion of populated areas and high quality agricultural land. Those areas would be subject to more frequent and more severe inundation as sea levels rise. Coastal erosion would initially increase, and then settle into quite different patterns to what is seen today. Assuming that very little UK land would be abandoned to the sea, coastal and river defences would need to be enhanced. This would include sea walls, tidal river defences, and soft coastal defences (beaches, saltings etc). The additional cost of minimum improvements to UK sea defences (assuming that it is physically possible to do so) to guard against the effects of climate change over the next hundred years will be of the order of five billion pounds (at 1989 prices).

3. ANALYSIS OF PAST WIND AND WAVE DATA

3.1 Introduction

This chapter addresses the problem of measurable changes in wind and wave climate around the UK in recent times. The parameters of interest are wind speeds and directions, and wave heights and directions. Long continuous and consistent records would be best for this purpose, preferably with no change in instrumentation, logging method or location.

There are few continuous long spells of wave records around the UK or elsewhere, from which to determine long term variations in wave conditions. Bacon and Carter (Ref 18) have recently carried out an extensive review of all available wave data which might be used to detect long-term changes in wave heights in the North Atlantic and North Sea (see Section 2.5).

The few UK sources of long time series instrumentally recorded wave data do not include wave direction information, which would be important in assessment of beach response. Some numerical modelling of waves from long time series wind records would be of great benefit in analysing gradual changes in wave heights, directions, or frequency of storms. The wave hindcasting work carried out during the present research project was aimed at simulating several long time series of nearshore wave data for this purpose. These simulations were based on time series wind records, of 9 to 29 years duration, from several coastal weather stations around the UK.

Time series wind and wave data is expensive, and so no recorded data was purchased specifically for the present project. Instead, the data and most of the locations used, were chosen on an opportunistic basis, from past or present coastal studies. Details of the data locations are given later in this chapter.

3.2 Sources of data

Two types of measured data were used: wave heights recorded at three hourly intervals, and wind speeds and directions recorded at hourly intervals. The longest UK instrumentally measured wave record is from Seven Stones Light Vessel (1962-85). This data set was discussed in Chapter 2, but some results are reproduced here for comparison with other data sources. The other wave data set analysed in this study was recorded off Perranporth 1976-85. These are not the only long wave data sequences in existence around the UK, but they were the only readily available deep water sources covering a period of ten years or more.

HR holds time series wind data from many of the coastal anemographs deployed by the UK Meteorological Office. The longest such record, without change of site or instrument, and available in computer file format, is that measured at Rhoose (Cardiff Airport) from January 1960 onwards. Most of the other records are available from the 1970's onwards, and a full list of sources and dates used is given at the end of this section. These records are of high quality, and they are consistent and continuous.

The wind records were useful in themselves, in looking for long-term climatic changes. However, more importantly they were used as input to a wave hindcasting model, which converted wind speeds and directions to wave heights and directions (and periods) for a number of nearshore locations. More details of the model are given in the next section, but the locations used are shown in Figure 1a and are listed below.

Location	Source of wind data	Dates
Sunderland	South Shields	1976 - 88
Dowsing	Spurn Point	1978 - 86
Great Yarmouth	Gorleston	1973 - 90
Kentish Knock	Shoeburyness	1970 - 83
Littlehampton	Portland	1974 - 90
St Helier	Jersey Airport	1970 - 88
Barry	Rhoose	1960 - 88
North Wales	Squires Gate	1970 - 90

3.3 Simulation of additional time series wave data

It would be possible to study changes in wind climate (and by inference wave climate) simply by looking at changes in mean wind speed from year to year. However, this would neglect the importance of wind direction and of wind persistence in determining shoreline wave conditions. Instead the wind records were converted to equivalent sequential wave records using the Hydraulics Research HINDWAVE model, after which trends in wave height and direction could be examined. However, this approach can only detect changes in the "locally" (ie the area over which the wind conditions could be assumed to be reasonably homogeneous) generated waves. It does not address the problem of long-term changes in the intensity of distantly generated swell.

The HINDWAVE model (details in Appendix 1) is based on JONSWAP wave forecasting methods, taking as input the size and shape of the wave generation area and wind conditions defined in terms of speed, duration and direction. The size and shape of the surrounding area are specified in terms of radial fetch (open water) lengths, usually at 10° intervals around the wave prediction point. The wind conditions are derived by vector averaging of the hourly wind velocities leading up to the hour of interest. Wind speed "mark-up" factors (usually as a function of direction) are applied to the recorded values, to represent possible under exposure of the anemograph and the fact that wind speeds are generally higher over water than over land. HINDWAVE is not particularly sophisticated, but it is reliable and efficient enough to process the large quantities of data used in this study.

All of the site-specific HINDWAVE applications used in the present work had previously been calibrated (mainly by means of adjustments to the "mark-up" factors) and validated against measured wave data. They could therefore be re-used with confidence for the present purpose of analysing trends in wave height or wave direction. Note that even if a consistent error in the wave model were suspected, for example a 10% over prediction of wave height or a 10° shift in wave direction, this would not affect the trends which might be observed.

The simulated wave data produced by HINDWAVE could then be analysed in the same way as the recorded wave data, except that it contained additional wave direction information.

3.4 Analysis of wave height and direction changes

Any trend in nearshore wave heights would be of interest in coastal management, particularly if those trends were likely to continue in the future. The extreme wave heights to be expected are of greatest interest for design and maintenance of coastal structures. However, more commonly occurring wave heights and any trends in wave direction will be more important in aspects of coastal management involving sediment transport. These would include erosion and accretion of coasts, maintenance of sand and shingle beaches, and maintenance of dredged navigation channels.

Wave roses are a convenient way of expressing a distribution of wave height and direction, and wave roses representing the entire periods of simulated wave data are given in Figures 2-9. However, the size and resolution of wave roses makes it difficult to extract numerical detail, particularly on gradual trends. A more convenient way of analysing wave height trends is to look at the average significant wave height in each calendar year, or the wave height exceeded a certain percentage of the time in each year. This method can be applied equally well to both measured and simulated wave data, provided that several years of data are available.

Figures 10-19 show the significant wave heights exceeded 1% and 10% of the time and the mean values during each calendar year, for the simulated data sets listed earlier and for recorded wave data from Seven Stones and Perranporth. The various locations are shown in Figure 1a.

Simulated significant wave heights at Sunderland decreased slightly during the period examined, by of the order of 1-1½% per year. Conversely, those at Dowsing and Kentish Knock increased slightly, by of the order of 1½% per year (although up to about 2½% per year at the 1% exceedence level at Kentish Knock). There was very little upward or downward trend in results for Great Yarmouth, Littlehampton, St Helier, North Wales or Barry, although all but Barry showed a very slight upward trend (of the order of ⅓% per year) at the 1% exceedence level.

The corresponding changes in wind speeds, again at the average, 10% exceedance and 1% exceedance levels, are shown in Table 1. The table shows average values of the three wind speed parameters and their rate of change per year for each wind data set used in the HINDWAVE analysis. Not surprisingly (since the waves were derived from the winds), the wind speed and wave height trends are well correlated. For example, Sunderland was the only site at which wave heights reduced with time, and South Shields (the corresponding anemometer station) shows the greatest reduction in wind speeds. Similarly Dowsing and Kentish Knock showed the greatest increases in wave heights, whilst the corresponding Spurn Point and Shoeburyness anemometers showed the greatest increases in wind speeds.

The above conclusions are rather different to those expressed in Chapter 2, where no increase in wind speeds was found to correspond to observed increases in North Atlantic and North Sea wave heights. Local wave heights, predicted by HINDWAVE, closely follow changes in coastal wind speeds. Such changes are small, but wind speeds at Spurn Point and Shoeburyness have increased by of the order of 1% per year recently, whilst the highest winds at Squires Gate (Blackpool) have increased by of the order of ½% per year.

The plot of annually averaged significant wave heights at Seven Stones Light Vessel (values reproduced from Ref 14) shows an increase in wave heights from 1962 to 1985 of rather more than 1% per year. This supports one of the conclusions expressed in Chapter 2, that even if locally generated waves are not increasing on the west coast of the UK, that Atlantic swell is increasing. However, the upward trend in predicted extremes at Seven Stones (values reproduced from Ref 18) is rather less clear. The trend line drawn in Figure 18 implies that predicted extremes have increased by a little under 1% per year. However, this trend is heavily influenced by two unusually high values in 1983/4 and in 1986.

Figure 19 shows previously unpublished data recorded off Perranporth in Cornwall from 1976 to 1985. There is a significant increase in wave heights between 1976 to 1984, at the 1% level. However, the rate of increase is reduced by the wave heights for 1985, which are the lowest of all (at the 1% and 10% levels) during the ten year period. The trend lines shown in Figure 19 suggest a slight decrease in the commonly occurring wave conditions (10% > and mean values), but an apparent increase in the highest wave heights (represented by the 1% > trend line in Figure 19), from 1976 to 1985. It is interesting to note that this is the opposite conclusion to that to be drawn from the Seven Stones data, in which average wave heights were increasing more than extremes. However, there is insufficient length of data to be certain that the Perranporth trends are representative of long term conditions on Atlantic coasts.

The combined effect of any changes in wave height and direction upon mobile beaches remains difficult to assess. It would be helpful to convert the simulated wave data, for each year in turn, into potential for wave-induced littoral transport in the surf and inter-tidal zones. To do this, a standard wave steepness (relating wave period to wave height) was assumed, and a standard sediment transport formula (Appendix 2) was applied to convert the wave height and direction data into rates of drift on a number of typical straight beaches. A grain size typical of shingle beaches (use of a sand beach would simply multiply all results by a constant factor) and a number of beach orientations roughly parallel to the coast were tested at each location for which wave climates were derived. The model assumes parallel contours refraction between the wave prediction point and the wave breaker point.

The resulting rates of transport, both gross and nett, are listed in Tables 2-9 together with drift rate trends at each site tested. The mean inshore direction quoted is an average of the direction of each hourly wave condition, weighted according to its capacity for sediment transport. The "present" values of wave direction and drift are averaged over the whole period of simulated wave data at each of the sites considered. The "trends" are expressed as a base direction or rate of drift at the beginning of the period of hindcasting, and a rate of change of direction or drift per year. The drift values quoted are in arbitrary units since there are some calibration factors to be set before actual rates of drift can be calculated, and since only idealised beaches were tested. The results listed in Tables 2-9 are intended only for comparison purposes, for example east coast with south coast, one beach angle with another and trends from year to year. (The neglect of non-parallel refraction effects and the lack of calibration of the model means that the actual drift volumes predicted will not be reliable).

The physical significance of the small rates of change of wave direction and drift rate given in Tables 2-9 is not easy to see. However, Figure 20 is a plot of the same results (for a beach angle of 170° at Littlehampton, as an example) showing the year-to-year variation of mean wave direction and gross drift rate. This shows that a change in wave direction of the order of 6° appears to have occurred over 14 years, and that this has nearly doubled the rate of easterly drift on this typical south coast beach. This is not necessarily the true state of affairs at Littlehampton, or indeed at any south coast site, because of the sweeping simplifications involved in bringing the waves inshore. However, it does show the potential effect on south coast beaches of a barely noticeable change in mean wave direction. This small change in wave direction was derived from accurately measured wind data, and may therefore be a genuine climatic change. However, in order to be sure, one would need to do more detailed site-specific wave and littoral drift modelling.

If one were to accept the results listed in Tables 2-9 at face value, then the following conclusions could be drawn. Rates of easterly drift on the south coast (from Portland wind data) could have nearly doubled over the last fifteen years. Rates of drift (mostly southerly, but some northerly) on the Essex coast (from Shoeburyness wind data) appear to be small but to have increased slowly over the last fifteen years. Rates of southerly drift on the Suffolk and Norfolk coasts (from Gorleston wind data) could have reduced by 10-15% over the last twenty years. Rates of southerly drift on the North Norfolk, Lincolnshire and Humberside coasts (from Spurn Point wind data) could have increased by one third over the last thirteen years. Rates of southerly drift on the north-east coast of England (from South Shields wind data) are small but appear to have more than doubled in thirteen years. The easterly drift along the north Wales coast (from Squires Gate wind data) shows no change from year to year. Rates of drift at Barry are small (except for the south-south-west facing beach which shows a clear easterly drift) and there is no change from year to year. Rates of westerly drift at St Helier (from Jersey wind data) appear to be slowly increasing, going up by about 50% over twenty years. These conclusions may not be genuine (even the directions of drift may not be correct) but they do illustrate the potential of a small change in wave angle to influence a mobile beach.

3.5 Summary of trends

Wave recordings at Seven Stones, and elsewhere well offshore from the UK, show that mean wave heights have increased over the last thirty years, with no corresponding increases in wind speeds. The wave hindcasting done during this study implies that the same is not true of locally generated waves, in which small changes in wave height are closely matched by small changes in wind speeds. The HINDWAVE model takes account of wind speed, direction and persistence, and the inference is therefore that wind patterns and storm persistence have not changed much during the period of study.

Simulated significant wave heights at Sunderland decreased by of the order of 1½% per year. Conversely, those at Dowsing and Kentish Knock increased slightly, by of the order of 1½% per year. There was very little upward or downward trend in wave heights hindcasted for Great Yarmouth, Littlehampton, St Helier, North Wales or Barry. These trends are all matched by trends in the wind speeds from which they were derived. Previously unpublished measured wave data from Perranporth showed a slight increase in the highest wave heights and a slight decrease in the middle range wave heights during 1976-85.

The largest changes in wave heights noted above are of the same order as measured changes occurring at Seven Stones. The changes in simulated wave heights are probably genuine. The most significant trend is that heights at two of the East Anglian points (Dowsing and Kentish Knock) showed increases of about 12-20% over a ten year period. However, as there is little consistency between trends, and no meteorological explanation, there is no particular reason to think that the changes will continue to occur in the future.

Some additional tests involving changes in mean wave direction showed some very gradual changes in wave direction over periods of 10-30 years. Although the changes were small, and probably within the range of natural variability of climate, the potential effect on littoral drift was shown to be very significant. The actual rates of drift calculated are probably not accurate, but the importance of a very small change in (wind and) wave direction was demonstrated.

4. ANALYSIS OF FUTURE WIND AND WAVE DATA

4.1 Introduction

Previous chapters have looked at past trends in wind, wave and other climate data. However, past trends, particularly if they cannot be thoroughly explained and simulated, are not guaranteed to continue in the future.

Modelling present world climate requires sophisticated large scale models and dedicated staff and computers. Modelling future climate poses additional problems: firstly how is "future climate" to be defined; secondly, how is the model to be driven and validated without a regular input of recorded weather data. A small number of American organisations and the Hadley Centre for Climate Research at Bracknell have developed models of future global climate. None of these models addresses the problem of ocean waves directly, but they do consider surface winds and pressures which can be used as input to wave prediction models.

Surface wind and pressure data was obtained from the Bracknell climate model, both for "present" and for "future" conditions. The pressure data was examined for any obvious differences between present and future, since they might affect sea levels or storminess around the UK. The wind data was used as input to a wave hindcasting model, in order to assess any expected changes in wave height or wave direction to be expected in the future. (Wave direction would not be particularly important in the case of "hard" sea defences, but it is important in assessing the mobility of sand and shingle beaches).

The present analysis concentrated upon data from the two or three climate model points lying directly over the UK, and a further dozen points lying up to a few hundred kilometres offshore. However, a few additional more distant points were looked at in the North Atlantic.

4.2 The future Global Climate Model

The Hadley Centre for Climate Studies at Bracknell has a gridded Global Climate Model (GCM) calibrated against present climate conditions. Taking doubled carbon dioxide concentration as the definition of "future climate", the GCM has also been run for future conditions. It is not necessary for the present purposes to know details of how the GCM works. More details are given in the recently published "Climate Change: The IPCC Scientific Assessment" (Ref 2), which includes a comprehensive bibliography. Development and validation of the model have been subject to international scrutiny, and use techniques running close to the limits of present computer capacity. The GCM therefore provides the best source of data for going on to predict future changes in wave climate around the UK.

The GCM has eleven levels of vertical resolution, a 5° North-South spacing and a 7½° East-West grid spacing. (This means that the UK is represented by only two or three grid points in the model). The processes and parameters modelled are not particularly important for the present purposes, except that they include surface winds and pressures which have a direct input to wave generation and sea level variability.

HR purchased data from the GCM representing one year of "present" conditions and one year of "future" conditions, for each grid point covered by the model (ie global coverage). The four parameters involved are listed below:

(i) Mean sea level pressure over the day (mb)

(ii) Mean wind speed over the day (m/s)

(iii) East-west component of midnight wind velocity (m/s)

(iv) North-south component of midnight wind velocity (m/s).

Both the temporal and the spatial resolution of the model output is far too coarse for immediate use in local wave hindcasting. However, it should be adequate to describe the changes in surface winds and pressures expected to occur in the future.

The model grid points lying over and around the UK are shown in Figure 21.

4.3 Distribution of atmospheric pressure

Atmospheric pressure has a direct effect upon sea level. A lower than average pressure would tend to be associated with a higher than average water level, and vice versa. Most statements about sea level rise relate to global levels. If it could be shown that atmospheric pressures around the UK would be significantly different in the future, then expectations of sea level rise around the UK may be different to average global expectations.

"Present" and "future" atmospheric pressures from the GCM were analysed for the 16 grid points over and around the UK shown in Figure 21. The pressures were compared in terms of both their mean values and their distributions. There was no significant difference between present and future pressures. This line of study was therefore not taken any further.

4.4 Simulation of time series wind and wave data

The purpose of the present simulation exercise was to produce local wave climate data representative of future conditions, for comparison with existing conditions. The data available on future climate has been described earlier in this chapter. This section describes the methods designed to make fullest and most effective use of the available data.

Analysis of pressure data from the GCM showed no significant changes between present and future climate conditions. Atmospheric pressure is, in any case, very much of secondary importance to wind, in generation of ocean waves. The pressure data was therefore not used as input to any wave modelling.

Wind speed (ie without direction) is very much less useful for wave prediction purposes than wind velocity (ie with direction) data. Although the daily averaged wind speed data was useful for studying winds and storminess, it was not used in the wave prediction exercise, which was instead based upon the midnight wind velocity data.

Temporal and spatial resolution of the GCM data is low, but results for present and future conditions were derived in a consistent manner. Any noticeable differences between the two should therefore be significant, and a reliable guide to what would actually happen in changing to the doubled carbon dioxide situation. These changes could be expressed in terms of: (i) means and distributions of wind speeds, wind directions and storms, and (ii) the correlation between wind speeds or storms with wind direction or season. Storms are most easily assessed using time series data, whilst wind speeds and directions can conveniently be assessed using wind roses.

Time series plots of all the GCM mean wind speed data, for present and for future conditions, for the 16 grid points shown in Figure 21, are given in Appendix 3. A visual assessment of these plots reveals no consistent changes either in grouping of storms or in the distribution of storms throughout the year. The ratio of mean "future" wind speed to mean "present" wind speed is given in Table 10 for each of the 16 grid points. There is too little data to justify any more thorough statistical analysis of the storms. As there is no particular evidence of changes in storm grouping to be expected in the future, then such changes can reasonably be neglected in the simulation of future wave climate. Future mean wind speeds are predicted to be marginally higher than present values as seen in Table 10. (Nine of the 16 grid points show a small increase and seven a small decrease, but the average ratio of future to present wind speed in 1.022). However, the amount and importance of such changes are best quantified as described below.

All of the significant changes in winds to be expected in the future should be clear and quantifiable from an analysis of wind roses derived from the midnight wind vector data. Wind roses produced from the present and future GCM data for the 16 grid points lying over and around the UK are shown in Figures 22 and 23. (The individual wind roses are reproduced at a larger scale in Appendix 4, and wind roses for the 9 grid points closest to the UK are reproduced overlaid on a map of the UK in Figures 24 and 25).

Some changes are immediately obvious, particularly in regard to the distribution of wind directions. Beginning with conditions to the north and east of the UK: the future wind rose centred over northern Scotland shows rather more winds from the north-east and south-east, and rather less from the north-west and south-west, than at present. Similarly, the future wind rose centred over the northern North Sea shows rather more winds from the north to south-east sectors, at the expense of the south to north-west sectors, than at present. Similarly, the future wind rose centred over the southern North Sea shows a loss of wind data from the west and south-west as compared to present conditions. These observations suggest an increase in the proportion of winds, and therefore waves, coming towards the North Sea coasts of the UK in the future.

Now consider conditions to the south and west of the UK: the three most westerly wind roses in Figures 24 and 25 show no consistent changes. However, the future wind rose centred over north-west France shows rather more winds from the north and west, and rather less from the south and east, than at present. Also, the future wind rose centred over Wales shows rather more winds from the north-east, and rather less from west and south-east, than at present. These observations suggest a slight decrease in the proportion of winds, and therefore waves, coming towards the Atlantic and Channel coasts of the UK.

Detailed interpretation of the wind rose data is not necessary. Instead the method described below was developed which retains all of the information from the wind roses, whilst increasing the resolution of the wind data to the extent that it can be used for wave hindcasting.

A handful of sites shown in Figure 1a and listed in Section 3.2 were chosen around the UK for which long time series wind records were available for site-specific hindcasting of "present" wave climate. Some of those sites were also used in future wave climate analysis: they are listed in Table 11 together with a note of which GCM grid point best represents the wave generation area offshore from each site. It would be useful therefore, to have a means of simulating a "future" wind time series from data in the "wind rose" format available from the

GCM.

Differences between "future" and "present" wind roses for each of the necessary GCM points were broken down and defined as described in Appendix 5. However, simulating time series wind data is not a trivial matter, since it requires a knowledge of storm distribution and persistence, seasonality and typical rates of change of wind speeds and directions. The itemized changes were applied to the existing ("present") time series wind data in the way described in Appendix 5, to simulate an equivalent long "future" time series of wind data for each site. The method involved small changes to individual values in the existing time series, so that the new ("future") time series had the slightly modified distribution of wind speeds and directions appropriate to a different time period or location.

The new time series then retained the realistic storm distribution, seasonality and general variability of wind speed and direction of the original "present" time series. However, it incorporated the subtle changes in individual hourly wind velocities necessary to correspond to the desired distribution of wind speeds and directions associated with the "future" wind rose. This technique, known as the WINDSEQ model, made best use of all available measured wind data and future wind predictions. The resulting "present" and "future" wind roses for each site are reproduced in Appendix 4.

During development, the WINDSEQ model was validated against long time series wind records from Rhoose. One "future" (1970-9) period of wind data was synthesised from a "present" (1960-9) period of data using WINDSEQ. The resulting time series was compared with actual measured wind data for the same (1970-9) period. The satisfactory comparison achieved is described in Appendix 5.

The "present" and "future" wind time series derived for the future wave climate modelling points (see Table 11) were used as input to site-specific wave hindcasting models at each site of interest. In most cases these models had been validated against nearby recorded wave data during earlier repayment studies, and so they could be re-used with confidence. (Details of the HINDWAVE wave hindcasting model are given Section 3.3 and in Appendix 1). The result of this hindcasting exercise was time series wave data for "present" and for "future" conditions, at the sites listed in Table 11. Statistical analysis and interpretation of this data is described in the next section.

4.5 Analysis of wave height and direction changes

Any future changes in nearshore wave conditions would be important for coastal management. The extreme wave heights to be expected are of greatest interest for design and maintenance of coastal structures. However, more commonly occurring wave heights and any expected changes in wave direction will be more important in aspects of coastal management involving sediment transport.

The simulated "present" and "future" time series of wave conditions derived for UK sites listed in Table 11 are presented in wave rose format in Figures 26-35. Differences between present and future conditions can be seen, but are not quite as striking as the differences between the corresponding present and future wind roses presented earlier. The same information on present and future wave conditions is given in more numerical detail in the form of scatter diagrams of wave height against wave direction in Tables 12-21. These tables permit a detailed comparison of the distribution of wave height overall, and of the amount and distribution of data within each direction sector, for present and future conditions.

If we accept the wave climate results presented in Figures 26-35 and Tables 12-21 as they stand, then the following conclusions can be drawn. There will be a one third reduction in the proportion of waves from the westerly and southerly (135°-315°N) quadrants off Sunderland (48% reducing to 32%). There will be a corresponding increase in the proportion of waves from the northerly and easterly (315-135°N) quadrants. The larger waves will be affected slightly more than the smaller ones by the changes. There will be a one third reduction in the proportion of waves from the prevailing southerly (165-195°N) direction, and a one sixth reduction in waves from the south-west to north (195-15°N) sectors off Great Yarmouth. There will be large increases in the proportion of waves from the easterly (particularly 15-45°N and 105-135°N) directions, particularly amongst the largest wave heights. There will be a one eighth reduction in the proportion of waves from the prevailing west-south-west (225-285°N) sector off Littlehampton (41% reducing to 36%). There will be a corresponding 40% increase in the number of waves from the east-north-east (45-105°N) sector (18% increasing to 26%). The largest wave heights in the west-south-westerly sector will be reduced disproportionately. There will be a one seventh reduction in the proportion of waves from the prevailing westerly (255-285°N) direction off Barry (40% reducing to 34%). There will be a corresponding increase in the number of waves from the east and east-north-east (45-105°N) sectors. The largest waves will be disproportionately affected by the changes. There will be a one fifth reduction in the proportion of waves from the prevailing west-north-west (255-315°N) sector off North Wales (42% reducing to 34%). There will be a large increase in the number of waves from the north and north-east (315-75°N) directions (24% increasing to 37%). Again, the largest wave heights will be disproportionately affected by the changes.

These "predictions" of future wave climate change are very uncertain. They are, at best, only as good as the GCM predictions of changes in future wind conditions around the UK, which are themselves rather uncertain. Not surprisingly, the above conclusions about expected future changes in wave climate are consistent with conclusions expressed earlier about expected future changes in wind climate around the UK.

There is little point trying to quantify the changes any more precisely than given above, or to extrapolate to extremes. The reliability of the modelling techniques and assumptions would not justify any such numerical detail (although the necessary input data to such calculations could be extracted from Tables 12-21).

The combined effects of the expected changes in wave height and direction upon mobile beaches were assessed as described on Pages 40 and 41, using a simple sediment transport formulation for an idealised beach. The resulting rates of sediment transport, both gross and nett, are listed in Tables 2, 4, 6, 8 and 9 (ie the same tables as were used to demonstrate past trends). The values quoted are in arbitrary units since there are some calibration factors to be set before actual rates of drift can be calculated, and since only idealised beaches were tested. The results listed are intended only for comparison purposes, to show the potential for changes in the future and their variation from place to place. (The neglect of non-parallel refraction effects and the lack of calibration of the model means that the actual drift volumes, and even the main directions of drift predicted, will not be reliable). The mean wave directions given in Tables 2-9 are weighted averages of all the hourly inshore wave conditions predicted, where the weighting is dependent upon capacity for sediment transport.

The results show the potential effect on beaches of quite modest predicted changes in wind conditions to be expected in the future, and the consequent changes in mean inshore wave directions. However, even if one accepts the future wind predictions as accurate, more detailed site-specific wave and littoral drift modelling would be needed to check and quantify the predictions of beach response.

If one were to accept the results listed in Tables 2, 4, 6, 8 and 9 at face value, then the following conclusions could be drawn. "Future" rates of easterly drift near to Littlehampton would be reduced to two thirds of present levels. Rates of southerly drift at Yarmouth and at Sunderland would be about twice and about five times present levels, respectively. Rates of easterly drift on the North Wales coast would be slightly reduced, whilst rates of drift at Barry would remain small and be almost unchanged. All of these changes are associated with very small changes in mean inshore wave direction, of the order of one to four degrees, which would be imperceptible to a casual observer. Not surprisingly, these observations are consistent with those expressed earlier, following a comparison of "present" and "future" wind and wave roses. These conclusions may not be genuine (even the directions of drift may not be correct) but they do illustrate the potential of a small future change in wave direction (resulting from a small change in future wind conditions) to influence a mobile beach.

4.6 Changes at the North Atlantic points

It is quite likely that future changes in wind conditions would be different in the middle of the North Atlantic to those over and around the UK. A group of four GCM grid points (latitudes 52.5 and 57.5°N, longitudes 33.75 and 41.25°N) forming a square in the North Atlantic were chosen for further study.

The midnight wind vector data was extracted from the GCM "present" and "future" archives for the four grid points chosen. The time series wind data is reproduced in Appendix 3, but no consistent differences between present and future conditions are obvious from a simple visual inspection of the plots. The same data were used to create the eight wind roses presented in Figures 36 and 37, representing present and future conditions, respectively. There are some obvious differences between Figures 36 and 37, but no clear consistent trends. (The individual wind roses are reproduced at a larger scale in Appendix 4).

Table 22 shows some more numerical detail extracted from the wind roses, namely average speeds overall and by direction sector, percentage of records within each sector, and differences between present and future conditions. For the four locations, the predicted increases in annually averaged wind speeds as carbon dioxide levels double, are 18.6, 11.7, -7.2 and 0.0%. The westerly directions (south-west, west and north-west) are of most interest in the context of waves destined to reach UK coasts. Table 22 shows that two of the grid locations are predicted to have slightly more winds from the west in the future, one slightly less and one almost no change. The increases (or decreases) in wind speeds predicted for the future are almost the same for the westerly directions as overall, for each of the four grid points.

Results vary considerably between the four grid points and it is difficult to draw any firm conclusions. The small amount of data examined suggests that wind speeds could reduce by up to 10% or could increase by up to 20% in the North Atlantic of the future. A simple average of the four sets of results would lead one to expect about a 5% increase in wind speeds, including westerlies. Other things being equal, this would lead to roughly a 5% increase in Atlantic wave heights reaching the UK.

4.7 Summary of inferences from future wind and wave climate modelling

The Global Climate Model (GCM) data shows no change in the distribution of surface pressure around the UK to be expected in the future.

Models of future climate suggest that changes in wind conditions will be small. There are some slight inferences that the proportion of westerly winds around the UK and the number of mid-latitude storms may reduce following global warming. However, there are no firm indications as to whether the UK will be more or less stormy in the future. Analysis of "present" and "future" wind data for four GCM grid points in the North Atlantic showed slight increases in mean wind speeds and slight increases in the proportion of winds from the westerly directions. These conflicting conclusions suggest that future changes in North Atlantic winds will be small, and that their effects on UK coasts is uncertain.

Analysis of GCM wind predictions from grid points around the UK shows a slight increase in mean wind speeds to be expected in the future. A strong increase in easterly winds, at the expense of westerly winds, is predicted by the GCM for future conditions in the North Sea. This implies a significant increase in the proportion of waves coming directly towards the North Sea coasts of the UK in the future, although not necessarily any increase in extreme wave heights. The GCM grid point over north-west France predicts a future increase of northerly and westerly winds at the expense of southerly and easterly directions. The GCM grid point over Wales shows a future increase in north-easterly winds, at the expense of westerly and south-easterly directions. This implies a decrease in the proportion of waves coming directly towards the Atlantic coasts of the UK, although again not necessarily any reduction in extreme wave heights.

The above conclusions were supported by predictions of present and future wave conditions for locations off Sunderland, Great Yarmouth, Littlehampton, Barry and North Wales. Both Sunderland and Great Yarmouth show an increase in easterly waves, a reduction in westerly waves, and slight increases in the proportion of the highest wave heights. Littlehampton shows a slight shift from westerly to easterly waves, and a slight reduction in the proportion of the highest wave heights. Barry and North Wales show a shift of some of the prevailing westerly waves to northerly and easterly directions, but with little change in the proportion of the highest wave heights. These conclusions are very tentative, relying on the accuracy both of the GCM wind predictions and of the relatively simple wave hindcasting technique which was used.

The distributions of wave height and direction for present and future conditions were converted into potential rates of littoral drift. The simplifications involved render the detailed conclusions unreliable. However, it was demonstrated that the relatively small changes to be expected in future wave climate could have a dramatic effect on rates of littoral drift. Refined predictions of actual rates of drift and expected changes could be made, but would require site-specific wave transformation and beach modelling, and would still rely on the accuracy of the GCM wind predictions and the offshore wave model.

5. IMPACT ON UK COASTAL MANAGEMENT

5.1 Effects of climate change on UK coastal defences

Global warming will have a variety of effects on the coasts and seas around the UK. Some of these effects are widely accepted to be likely, but many are still the subject of uncertainty and debate. In order to emphasise how coastal defences may be threatened, a deliberately pessimistic view of what the future may hold is taken here. It should be remembered, however, that some coastal management problems may well be reduced rather than intensified.

Increased temperatures will produce faster rates of ice-melt (for example glaciers) and of thermal expansion of the upper layers of the ocean. As a consequence sea level will continue to rise, and probably accelerate from its present global-mean value of 1½-2mm/year. A future rate of 5mm/year is now widely used for coastal defence design in the UK. In addition to this 'eustatic' rise due to an increased volume of water in the seas, tectonic movements and settlement of sedimentary rocks, as in south-east England, may produce a downwards movement of the land mass. Both effects will produce a gradual reduction in the crest height of the existing man-made coastal defences relative to mean sea level. A long-term reduction in mean atmospheric pressure would add to this problem (although at present this is not expected to occur in the near future).

As well as any upward trend in mean sea level the tidal level variations may also increase. There is already evidence of (astronomic) tidal ranges increasing in some parts of the UK. In addition, more intense or more frequent depressions travelling over the north-west European continental shelf would produce larger or more frequent tidal surges. Design water levels for coastal defences may have to be revised upwards as the result of all these processes.

Changes in the global atmospheric circulation will bring about changes in wind fields, and hence in the generation of waves. Since waves are the major cause of damage to defences and scour of beaches, more intense wave energy is a clear cause of concern. Several different effects may occur, each of which may bring problems in their wake.

First, the largest wave heights may be increased. Since the design of many maritime or coastal structures depends on the height of the waves expected to occur, for example, once in 50 years, then an increase in the expected value of this statistic would necessitate at least a re-analysis of coastal defences. Structures such as breakwaters in deep water, protected by concrete armour blocks, may be particularly at risk.

At the coast however, these extreme waves have usually broken well offshore and although the 'set-up' they produce at the shoreline will be larger than previously anticipated, the effect on a seawall may not be much of a concern. The beach level in front of a wall is the most important factor in such cases.

Beaches respond to changing wave conditions by altering their shape, with winter storms typically drawing material seawards from the top of the beach and summer waves restoring it. It can take weeks or months for a sandy beach to recover from a single storm, particularly if dunes behind it have been eroded. If winter waves become more frequent (but not necessarily larger) then this annual cycle may be disrupted. This is more of a danger if vegetation is a factor in restoring upper beach levels (for example on saltmarshes or on dunes) when the rate at which the plants can grow is limited by climatic conditions. In passing, the vigour of such coastal vegetation may also be affected by changes in temperature, rainfall and the like.

A change in the frequency of occurrence of modest wave heights could also produce problems. For offshore structures, fatigue caused by persistent waves is a concern. The equivalent for a coast is the movement of sediment along a beach or the nearshore seabed. On many coasts it is the frequency and direction of waves with significant heights in the range of 0.5 to 1.5m which dominates alongshore sediment transport. Since many coastal erosion problems, along natural or artificially defended shorelines, are caused by alongshore drift (or more accurately variations in that drift from point to point) an increase in such moderate waves may be of greater concern than an increase in extreme events.

Finally, in the discussion of changes in the coastal wave regime, it is important to mention direction. As wind fields change, it is likely that their direction as well as their strength and frequency will alter. A minor change in mean nearshore wave direction will produce often major changes in the rate, and sometimes in the direction of the nett annual alongshore drift. Recently evidence has come to light of such changes occurring in the past.

Future changes may be more dramatic and worrying still.

Other climatic changes may also affect coasts. An increase in rainfall may increase sediment supply to a coast through greater river flows or faster erosion of 'soft' cliffs. Rainfall, as well as winds, may also affect aeolian transport of sand from the beach to dunes. The possible climatic impacts on coastal vegetation, such as marram grass which help stabilise dunes, have already been mentioned. Increased sunshine and temperatures could increase recreational use of beaches and this in turn would place extra pressure on dunes and other sensitive coastal areas. These however, are probably all minor concerns to a coastal manager compared to the effects on tidal levels and wave climate, and the resulting movement of beach sediment.

5.2 Future coastal defence management measures

Changes in climate have affected the development of coasts in the UK for time immemorial. Such changes have been gradual, however, and of modest magnitude. Maintaining defences against flooding or widescale erosion of land has therefore continued with little or no explicit account being taken of such changes. The main exception to this has been the inclusion of an allowance for a rise in sea level, based on historical trends in tide gauge data. This allowance has been a part of coastal defence design for at least 20 years.

Studies of global warming suggest that more rapid changes may soon start to be felt. Historic eustatic sea level rise is believed to have averaged 1-2mm/year; over the next 50 years or so this trend is predicted to increase to an average rate of about 5mm/year. Accompanying this predicted acceleration, changes in atmospheric circulation patterns may produce very different waves and tidal surges to those now experienced.

From the viewpoint of a coastal manager, the assessment of the effects of climate change on the existing defences and beaches is very speculative. It is only now becoming possible to differentiate between normal year-to-year variations in wave conditions and an underlying trend, eg a long-term change in wave heights, as demonstrated in this report. There is little indication whether such trends will continue in future years, or diminish, or even reverse.

Numerical hindcasting can also give information on variations in alongshore drift from year to year, and this can be substantiated to an extent by analysis of recorded beach changes. Again however, this does not necessarily give a prediction of future behaviour. Even for the most widely studied consequence of climatic change, the acceleration of sea level rise, there is little or no evidence in the UK that this process has started.

In view of all this, it does not seem likely, or even necessary, that immediate action to raise or strengthen defences will need to be taken. As data on tidal levels, winds and waves is gathered, then a review of design conditions should be undertaken periodically. Such assessments have recently been commissioned for the Anglian coast (Humber to Thames Estuary) by the National Rivers Authority, and for the north coast of Wales following the damage at Towyn, by the Welsh Office. Similar assessments are planned for the southern coast of England following the severe storms there in winter 1989/90. As new information is produced, then the likely performance of existing defences under severe conditions needs to be calculated.

For sea walls this will inevitably require knowledge of beach levels in front of the walls. For this, and other reasons, it is important that monitoring of beaches is carried out as the climate changes. As mentioned in the previous section, changes in the nett annual transport alongshore for a coast are likely to produce new beach erosion problems as well as changing existing ones. If the direction of drift reverses, it is even more likely that damage will occur. Many long groynes and harbour arms have been designed and built on the basis of nett drift from one direction, and will be less efficient, or even damaging, if that direction changes.

Management of beaches by re-cycling, bypassing or periodic nourishment may also have to be revised in the light of climate changes. If more frequent storms start to produce erosion of natural beaches, then monitoring will help determine whether active management is feasible, or whether more dramatic intervention is necessary. Similarly an intensification of drift may make re-cycling much more expensive. It would be appropriate to consider methods of reducing the drift rate, eg by groynes, in such circumstances.

Although this section has concentrated on possible adverse effects, it is quite possible that many existing problems may diminish or disappear in future years. Again monitoring will give invaluable guidance, and may show that the rate of expenditure on maintenance of beaches and coastal defences can be reduced in some areas. In summary a flexible approach to coastal management, served with up-to-date information on tides, wave conditions and beach levels, is necessary to optimise defences as the climate changes.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of relevant UK climatic changes - past and future

This section briefly recalls the measured and predicted climatic trends relevant to UK coastal management, identified in Chapters 2-4.

Global mean sea levels have risen by 150-200mm over the last 100 years, and are presently rising at a rate of about 2mm per year. The rate of rise is predicted to increase quickly to about 5mm per year and to continue at 5-6mm per year for the foreseeable future. Reference 2 predicts a global mean sea level rise of 180mm by 2030, 440mm by 2070 and 650mm by 2100. There will be some apparent regional variations, even around the UK, mainly due to expected land movements. Reference 11 predicts that apparent rises will be slightly less than average in Scotland, but slightly more than average in the south and east of England.

Mean wave heights in the North Atlantic have increased by 1-2% per year since 1960 with no corresponding increase in mean wind speeds. Mean wave heights in the North Sea increased between 1960 and 1980. Derived extreme wave heights have not increased as rapidly as mean wave heights. There has been an increase in the number of severe storms affecting Wales and southern England in the last few years, although this does not form part of a clear statistical trend. The various increases in wave activity have not been satisfactorily explained and there is therefore no reason to assume that they will continue in the future.

Small changes in locally generated waves from year-to-year, predicted by a wave hindcasting model, were closely matched by corresponding changes in the wind data from which the waves were derived. This implies that the general pattern of winds and storminess has not changed much over the last twenty years. Locally generated wave heights off Sunderland are predicted to have decreased during the period of study, whilst those at Dowsing and Kentish Knock have increased, and those on the south and west coasts of the UK have not changed. Again there is no explanation for these trends in recorded wind speeds and in predicted wave heights, and therefore no reason to assume that they will continue in the future.

Some additional tests involving changes in wave direction showed some very gradual changes in mean wave direction over periods of 10-30 years. The potential effect on littoral drift of the change in mean wave direction was shown to be very significant, although the drift rate changes cannot be quantified reliably.

Models of future climate suggest that changes in wind conditions will be small. Around the UK the proportion of westerly winds is predicted to reduce, and the proportion of easterly winds to increase, and mean wind speeds to increase slightly. There are some slight inferences that the proportion of westerly winds and the number of storms in the North Atlantic may reduce following global warming. A significant increase in the proportion of waves (and winds) coming directly towards the North Sea coasts of the UK is predicted for the future, although not necessarily any increase in extreme wave heights. Wave predictions off Sunderland and off Great Yarmouth showed an increase in the proportion of easterly waves, a reduction in the number of westerly waves, and slight increases in the proportion of the highest wave heights. A significant decrease in the proportion of waves (and winds) coming directly towards the Atlantic coasts of the UK is predicted for the future, although again not necessarily any decrease in extreme wave heights. Wave predictions off Barry and off North Wales showed a shift of some of the prevailing westerly waves to northerly and easterly directions, but with little change in the proportion of the highest wave heights. A small shift of waves from the prevailing westerly direction to the east is predicted for the future in the English Channel. Wave predictions off Littlehampton showed a slight shift from westerly to easterly waves, and a slight reduction in the proportion of the highest wave heights. These conclusions are very tentative, relying on the accuracy of the GCM wind predictions for individual grid points and of the fairly simple wave hindcasting model used.

The distributions of wave height and direction for present and future conditions were converted into potential rates of littoral drift. It was demonstrated that the relatively small changes to be expected in future wave climate could have a dramatic effect on rates of drift, although the changes in drift rates cannot be quantified reliably.

6.2 Impact on UK coastal defences and management

The impact of recent climatic changes on UK coastal defences has not been dramatic. However, the rate of change is expected to increase, and its effects cannot be ignored.

The most obvious effect of climate change will be that increasing mean sea levels will reduce the effective crest height of sea defences. Also changes in weather patterns may cause more frequent surges, and therefore greater potential for overtopping and other damage.

There is some evidence that wave heights have increased in recent years around the UK, although no particular reason to think that this trend will continue. Small increases in extreme wave heights will have a slight impact on breakwater design and assessment (although when coupled with sea level rise, the effects may be more significant). However, the impact on mobile beaches of the relatively small changes in wave heights and directions expected to occur in the future, could be more serious. Beaches and rates of littoral drift are sensitive to quite small changes in wave height, period or direction: hence the differences in beach profiles in winter and summer, before and after storms, and from year to year. It is impossible to make general statements about these changes, or even to say whether they will be damaging, beneficial or perhaps of no consequence. (It is hard enough to make predictions of future changes in the weather and wave conditions which cause these changes!). However, changes in patterns of sediment transport will occur and beach management organisations should be prepared to modify their management strategies when this happens.

6.3 Recommendations for further work and actions

1. Update the future wave prediction calculations from time to time as the theory and resolution of future climate modelling improves, eventually attempting future extremes predictions.

2. Refine the littoral drift calculations for a few particular locations of interest, using site-specific wave transformation and beach modelling, to quantify past drift trends and expected future changes in drift rates.

3. Begin a programme of government-funded long-term directional wave recording in coastal waters around England and Wales (more detailed proposals are given in Reference 20). This data could be used to monitor wave climate variability and long-term trends, and/or to validate numerical models of same.

4. Collate existing long-term information on rates of change of beach volumes, for example beach profile and beach re-nourishment data. Also, continue existing measurement programmes and begin new ones at a few potentially

vulnerable locations. Long-term variations in wave climate and sediment drift rates predicted by numerical models could be checked against field data to help establish whether or not the apparent changes in drift rate are genuine.

5. Coastal managers should be aware that climate and mean sea levels are slowly changing. They should be prepared to re-assess design conditions and safety of coastal defences from time to time.

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Tables

TABLE 1 Wind speed trends in the anemograph data used for wave hindcasting

Wind station	Dates	Average Speed (m/s)	Rate of change of average speed (m/s/year)	Wind speed exceeded 10% of the year (m/s)	Rate of change of 10% exceedence wind speed (m/s/year)	Wind speed exceeded 1% of the year (m/s)	Rate of change of 1% exceedence wind speed (m/s/year)	Site of wave prediction
South Shields	Jan 1976 -Dec 1988	5.13	-0.059	9.8	-0.006	15.1	0.010	Sunderland
Spurn Point	Jan 1978 -Dec 1986	6.39	0.038	10.6	0.077	14.9	0.056	Dowsing
Gorleston	July 1973 -June 1990	5.76	0.005	9.9	0.012	14.9	-0.002	Great Yarmouth
Shoeburyness	Jan 1970 -Dec 1983	5.03	0.041	8.3	0.098	12.1	0.086	Kentish Knock
Portland	Mar 1974 -Feb 1990	6.92	-0.030	12.0	0.000	18.1	0.006	Littlehampton
Jersey Airport	Jan 1970 -Dec 1988	5.89	-0.003	9.7	0.005	14.4	0.011	St Helier
Rhoose	Jan 1960 -Oct 1988	5.26	-0.013	9.3	-0.013	13.7	-0.020	Barry
Squires Gate	Mar 1970 -Feb 1990	5.74	-0.010	9.8	0.009	14.0	0.073	North Wales

Table 2 : Littoral drift trends - Sunderland 1976-88

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units) Southerly	Northerly	Nett(*)	Weighted mean annual wave direction (degrees N)
50	present	72420	49460	-22960	46.6
	double	139540	91030	-48510	46.9
70	present	68670	49420	-19250	66.8
	double	178860	81180	-97680	62.8
90	present	48590	36330	-12260	87.4
	double	153640	49560	104080	80.2

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1976

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
50	-1400 t - 13570	-0.40 t + 49.3
70	-1400 t - 9960	-0.20 t + 68.5
90	-780 t - 7210	0.11 t + 87.4

(*) negative figures indicate drift is southerly

Table 3 : Littoral drift trends - Dowsing 1978-86

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units) Southerly	Northerly	Nett(*)	Weighted mean annual wave direction (degrees N)
45	present	94520	25750	-68770	34.8
65	present	91750	23730	-68020	52.3
85	present	65530	21130	-44390	73.7

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1978

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
45	-790 t - 64770	-0.04 t + 35.1
65	-1600 t - 59890	-0.15 t + 53.5
85	-2165 t - 33390	-0.28 t + 76.3

(*) negative figures indicate drift is southerly

Table 4 : Littoral drift trends - Great Yarmouth 1973-90

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units)			Weighted mean annual wave direction (degrees N)
		Southerly	Northerly	Nett(*)	
70	present	72780	18340	-54430	58.0
	double	136890	52690	-84200	60.7
90	present	53730	19470	-34260	79.8
	double	118130	51930	-66200	80.8
110	present	34770	31450	-3320	108.9
	double	67250	44780	-22480	106.0

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1973

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
70	650 t - 60370	0.03 t + 57.7
90	230 t - 36310	0.08 t + 79.5
110	190 t - 5020	0.14 t + 108.7

(*) negative figures indicate drift is southerly

Table 5 : Littoral drift trends - Kentish Knock 1970-83

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units) Southerly	Northerly	Nett(*)	Weighted mean annual wave direction (degrees N)
110	present	26290	6750	-19540	95.8
130	present	14350	10970	-3380	126.5
150	present	4590	16760	12180	161.7

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1970

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
110	-1230 t -10200	-0.39 t + 99.6
130	-510 t + 470	-0.32 t + 129.5
150	290 t + 9980	0.05 t + 161.1

(*) negative figures indicate drift is southerly

Table 6 : Littoral drift trends - Littlehampton 1974-90

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units) Westerly	Easterly	Nett(*)	Weighted mean annual wave direction (degrees N)
150	present	13390	21030	7640	154.2
	double	18640	14210	-4430	147.1
170	present	13510	60900	47390	184.5
	double	12980	41660	28680	182.3
190	present	13850	91980	78120	206.2
	double	9550	64110	54570	206.3

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1974

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
150	460 t + 3780	0.39 t + 150.6
170	1720 t + 32840	0.43 t + 180.4
190	2260 t + 59010	0.26 t + 203.7

(*) negative figures indicate drift is westerly

Table 7 : Littoral drift trends - St Helier 1970-88

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units)			Weighted mean annual wave direction (degrees N)
		Westerly	Easterly	Nett(*)	
170	present	20010	4310	15700	182.6
190	present	47740	4480	43260	207.5
210	present	101960	6390	95570	230.1

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1970

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
170	270 t + 13030	0.25 t + 179.6
190	870 t + 34560	0.13 t + 206.1
210	1570 t + 79890	0.05 t + 229.6

(*) negative figures indicate drift is easterly

Table 8 : Littoral drift trends - Barry 1960-88

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units)			Weighted mean annual wave direction (degrees N)
		Westerly	Easterly	Nett(*)	
160	present	1410	1100	-310	157.3
	double	1310	880	-430	155.4
180	present	730	2080	1360	190.8
	double	480	1850	1370	193.8
200	present	670	23070	22400	225.0
	double	420	16980	16550	225.0

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1960

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
160	39 t - 900	0.33 t + 152.1
180	33 t + 870	0.11 t + 188.9
200	40 t + 21890	-0.03 t + 225.3

(*) negative figures indicate drift is westerly

Table 9 : Littoral drift trends - North Wales 1970-90

Beach normal (degrees N)	Carbon dioxide level	Annual drift (arbitrary units) Westerly	Easterly	Nett(*)	Weighted mean annual wave direction (degrees N)
325	present	6190	73540	-67350	310.6
	double	11750	57740	-45990	314.9
345	present	4340	75790	-71450	324.9
	double	8330	67300	-58960	329.2
5	present	3920	51660	-47740	342.9
	double	7320	54350	-47030	347.1

Trends obtained from linear regression of yearly values

(Present carbon dioxide levels)

't' is the time in years since 1970

Beach normal (degrees N)	Annual nett drift(*) (arbitrary units)	Weighted mean annual wave direction (degrees N)
325	-610 t - 61210	-0.17 t + 312.6
345	29 t - 71890	-0.11 t + 326.4
5	450 t - 52460	-0.05 t + 343.8

(*) negative figures indicate drift is easterly

TABLE 10 Increases in wind speeds expected in the future at the GCM grid points around the UK

The table below gives the ratio of future to present average wind speeds.

Latitude (North)	Longitude 18.75W	11.25W	3.75W	3.75E
62.5	1.093	0.978	0.971	1.051
57.5	1.146	1.061	0.988	1.052
52.5	1.071	1.033	0.961	1.044
47.5	1.009	0.925	0.973	0.991

Average ratio for the 16 points is 1.022

TABLE 11 Locations used for prediction of future wave climate

Location	Wind station	Nearest GCM point
Sunderland	South Shields	52.5N 3.75E
Great Yarmouth	Gorleston	52.5N 3.75E
Littlehampton	Portland	52.5N 3.75W
Barry	Rhoose	52.5N 3.75W
North Wales	Squires Gate	52.5N 3.75W

Table 12 "Present" wave height/direction scatter diagram for Sunderland

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.6	0.9621	1640	918	564	982	3780	3612	4563	1995	2783	2816	5704	1322
0.6	1.2	0.6553	4252	1370	534	803	5291	4204	3930	1013	1565	2611	8349	3071
1.2	1.8	0.2854	3400	948	456	686	2408	1232	311	68	126	177	993	1832
1.8	2.4	0.1590	2300	712	358	679	1409	315	2	0	0	0	0	816
2.4	3.0	0.0931	1563	560	457	887	759	20	0	0	0	0	0	283
3.0	3.6	0.0478	810	449	170	147	635	0	0	0	0	0	0	19
3.6	4.2	0.0255	469	237	305	283	167	0	0	0	0	0	0	0
4.2	4.8	0.0109	140	87	171	55	114	0	0	0	0	0	0	0
4.8	5.4	0.0052	39	88	97	7	76	0	0	0	0	0	0	0
5.4	6.0	0.0022	7	87	0	0	11	0	0	0	0	0	0	0
6.0	6.6	0.0011	0	23	46	2	20	0	0	0	0	0	0	0
6.6	7.2	0.0002	0	1	15	0	0	0	0	0	0	0	0	0
7.2	7.8	0.0001	0	5	0	0	0	0	0	0	0	0	0	0
Parts per thousand For each direction			152	57	33	47	152	98	92	32	47	58	156	76

Table 13 "Future" wave height/direction scatter diagram for Sunderland

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.6	0.9637	1252	1420	855	1556	3525	2086	2906	1691	2489	1773	4358	1843
0.6	1.2	0.7061	4720	2222	741	1735	5813	3778	3250	840	1015	945	3614	4346
1.2	1.8	0.3759	3467	1902	619	1241	3345	1033	90	27	38	35	242	2229
1.8	2.4	0.2333	2429	1641	457	1247	1906	158	1	0	0	0	0	838
2.4	3.0	0.1465	1476	1320	445	1210	984	8	0	0	0	0	0	245
3.0	3.6	0.0896	550	1115	209	419	679	0	0	0	0	0	0	24
3.6	4.2	0.0597	302	939	409	548	358	0	0	0	0	0	0	0
4.2	4.8	0.0341	161	621	259	253	161	0	0	0	0	0	0	0
4.8	5.4	0.0196	104	514	174	65	54	0	0	0	0	0	0	0
5.4	6.0	0.0104	9	383	32	0	7	0	0	0	0	0	0	0
6.0	6.6	0.0061	1	153	104	25	47	0	0	0	0	0	0	0
6.6	7.2	0.0029	0	27	38	11	27	0	0	0	0	0	0	0
7.2	7.8	0.0018	0	77	29	0	13	0	0	0	0	0	0	0
7.8	8.4	0.0006	0	50	12	0	0	0	0	0	0	0	0	0
Parts per thousand For each direction			150	129	45	86	176	73	65	27	37	29	85	99

Table 14 "Present" wave height/direction scatter diagram for Great Yarmouth

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.5	0.9571	1299	838	721	690	1048	1768	1682	2211	527	701	2475	2038
0.5	1.0	0.7971	2726	1886	803	772	1384	3586	7764	6050	440	866	3055	4355
1.0	1.5	0.4602	1705	1506	877	682	829	3346	7478	1965	68	163	773	2108
1.5	2.0	0.2452	2247	2029	636	619	624	1255	2196	232	3	9	95	1206
2.0	2.5	0.1337	1733	1651	565	427	283	587	1212	43	0	0	4	411
2.5	3.0	0.0645	695	1125	399	264	206	283	334	3	0	0	0	192
3.0	3.5	0.0295	128	202	227	134	150	148	156	1	0	0	0	36
3.5	4.0	0.0177	257	528	141	58	73	36	16	0	0	0	0	32
4.0	4.5	0.0063	95	165	44	15	21	3	0	0	0	0	0	15
4.5	5.0	0.0027	1	22	0	0	0	4	0	0	0	0	0	1
5.0	5.5	0.0024	38	70	32	0	0	3	0	0	0	0	0	1
5.5	6.0	0.0010	4	3	11	0	0	0	0	0	0	0	0	0
6.0	6.5	0.0008	7	36	0	0	0	0	0	0	0	0	0	5
6.5	7.0	0.0003	4	7	0	0	0	0	0	0	0	0	0	4
7.0	7.5	0.0002	3	0	0	0	0	0	0	0	0	0	0	9
7.5	8.0	0.0001	0	0	0	0	0	0	0	0	0	0	0	0
8.0	8.5	0.0001	6	0	0	0	0	0	0	0	0	0	0	0
Parts per thousand For each direction			114	105	47	38	48	115	218	110	11	18	67	109

Table 15 "Future" wave height/direction scatter diagram for Great Yarmouth

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.5	0.9593	1284	786	870	831	1254	789	760	1300	538	552	1909	2047
0.5	1.0	0.8301	2754	2400	1067	1021	2828	2268	5285	6152	683	429	2343	4009
1.0	1.5	0.5177	1406	2571	1020	811	2472	3532	5870	1558	40	55	454	1660
1.5	2.0	0.3032	1397	2761	799	695	1750	1993	1237	78	1	2	29	930
2.0	2.5	0.1865	923	2607	725	494	1225	1175	505	22	0	0	7	345
2.5	3.0	0.1062	372	2031	582	367	698	602	91	1	0	0	0	172
3.0	3.5	0.0570	60	399	321	249	343	304	28	1	0	0	0	38
3.5	4.0	0.0396	156	1152	173	113	250	164	2	0	0	0	0	36
4.0	4.5	0.0192	48	508	132	59	187	11	0	0	0	0	0	12
4.5	5.0	0.0096	28	106	9	43	101	3	0	0	0	0	0	1
5.0	5.5	0.0067	19	262	38	15	32	0	0	0	0	0	0	2
5.5	6.0	0.0030	0	21	32	5	22	0	0	0	0	0	0	0
6.0	6.5	0.0022	17	80	8	0	0	0	0	0	0	0	0	0
6.5	7.0	0.0012	5	66	0	0	0	0	0	0	0	0	0	0
7.0	7.5	0.0004	0	1	0	0	0	0	0	0	0	0	0	0
7.5	8.0	0.0004	1	21	0	0	0	0	0	0	0	0	0	0
8.0	8.5	0.0002	0	3	0	0	0	0	0	0	0	0	0	0
8.5	9.0	0.0002	0	15	0	0	0	0	0	0	0	0	0	0
9.0	9.5	0.0000	0	3	0	0	0	0	0	0	0	0	0	0
Parts per thousand For each direction			88	165	60	49	116	113	144	95	13	11	49	96

Table 16 "Present" wave height/direction scatter diagram for Littlehampton

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.4	0.9418	2004	1268	1873	2302	1200	693	661	810	1562	2637	2099	1877
0.4	0.8	0.7519	1002	1319	2967	3414	2000	1122	1013	1746	3387	4086	2185	862
0.8	1.2	0.5009	352	304	1295	2989	1306	780	893	1614	3726	3542	889	352
1.2	1.6	0.3205	31	60	316	1284	843	524	654	1321	3648	2094	339	92
1.6	2.0	0.2084	12	1	61	428	472	282	419	794	3319	1511	98	7
2.0	2.4	0.1344	0	0	18	269	247	232	421	719	2722	1061	9	0
2.4	2.8	0.0774	0	0	3	72	185	172	308	278	1238	706	3	0
2.8	3.2	0.0477	0	0	4	66	109	80	172	203	1427	416	0	0
3.2	3.6	0.0230	0	0	0	8	48	35	80	109	626	189	0	0
3.6	4.0	0.0120	0	0	0	0	16	11	78	56	226	133	0	0
4.0	4.4	0.0068	0	0	0	0	25	4	20	16	185	113	0	0
4.4	4.8	0.0032	0	0	0	0	4	3	2	6	159	47	0	0
4.8	5.2	0.0010	0	0	0	0	0	1	11	5	36	11	0	0
5.2	5.6	0.0003	0	0	0	0	0	0	0	1	6	1	0	0
5.6	6.0	0.0003	0	0	0	0	0	0	0	0	7	4	0	0
6.0	6.4	0.0001	0	0	0	0	0	0	0	0	12	1	0	0
6.4	6.8	0.0000	0	0	0	0	0	0	0	0	0	0	0	0
6.8	7.2	0.0000	0	0	0	0	0	0	0	0	0	1	0	0
Parts per thousand For each direction			36	31	69	115	69	42	50	82	237	176	60	34

Table 17 "Future" wave height/direction scatter diagram for Littlehampton

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15	15	45	75	105	135	165	195	225	255	285	315
			15	45	75	105	135	165	195	225	255	285	315	345
0.0	0.4	0.9367	2331	1477	2125	2777	822	582	608	887	1770	2259	1590	1736
0.4	0.8	0.7470	1386	1817	4633	4272	1166	933	1023	1866	3525	3291	1868	938
0.8	1.2	0.4798	738	340	1941	4143	792	626	858	1736	3716	2906	900	474
1.2	1.6	0.2881	65	23	352	2341	638	391	556	1177	3354	1885	405	228
1.6	2.0	0.1740	8	5	54	836	342	203	368	712	2788	1314	189	52
2.0	2.4	0.1052	0	0	19	539	200	169	330	484	2223	958	35	11
2.4	2.8	0.0556	0	0	5	199	158	77	193	198	842	608	7	0
2.8	3.2	0.0327	0	0	2	109	99	27	100	145	956	356	0	0
3.2	3.6	0.0147	0	0	0	41	61	7	66	59	323	197	0	0
3.6	4.0	0.0072	0	0	0	34	38	5	37	14	169	114	0	0
4.0	4.4	0.0031	0	0	0	8	17	1	6	4	98	48	0	0
4.4	4.8	0.0013	0	0	0	0	7	0	6	4	49	14	0	0
4.8	5.2	0.0005	0	0	0	0	5	0	0	1	17	8	0	0
5.2	5.6	0.0002	0	0	0	0	0	0	0	0	0	0	0	0
5.6	6.0	0.0002	0	0	0	0	0	0	0	0	10	2	0	0
6.0	6.4	0.0000	0	0	0	0	0	0	0	0	4	1	0	0
Parts per thousand For each direction			48	39	97	163	46	32	44	78	212	149	53	37

Table 18 "Present" wave height/direction scatter diagram for Barry

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.00	0.25	0.9397	719	1312	3280	2799	1645	1255	1122	1263	1205	3708	2640	632
0.25	0.50	0.7239	181	338	5621	4317	2291	1581	1322	1258	1960	8039	767	260
0.50	0.75	0.4445	5	15	3561	3440	1489	923	886	952	2173	6340	39	15
0.75	1.00	0.2462	0	4	1009	629	208	174	144	137	1222	5001	2	0
1.00	1.25	0.1609	0	0	305	252	36	11	6	43	734	4678	0	0
1.25	1.50	0.1002	0	0	33	28	9	2	0	2	200	3191	0	0
1.50	1.75	0.0656	0	0	0	4	1	1	0	0	73	2253	0	0
1.75	2.00	0.0422	0	0	0	1	0	0	0	0	35	1344	0	0
2.00	2.25	0.0284	0	0	0	0	0	0	0	0	15	1351	0	0
2.25	2.50	0.0148	0	0	0	0	0	0	0	0	2	447	0	0
2.50	2.75	0.0103	0	0	0	0	0	0	0	0	1	534	0	0
2.75	3.00	0.0049	0	0	0	0	0	0	0	0	1	168	0	0
3.00	3.25	0.0032	0	0	0	0	0	0	0	0	0	208	0	0
3.25	3.50	0.0012	0	0	0	0	0	0	0	0	0	46	0	0
3.50	3.75	0.0007	0	0	0	0	0	0	0	0	0	48	0	0
3.75	4.00	0.0002	0	0	0	0	0	0	0	0	0	5	0	0
4.00	4.25	0.0002	0	0	0	0	0	0	0	0	0	2	0	0
4.25	4.50	0.0001	0	0	0	0	0	0	0	0	0	7	0	0
4.50	4.75	0.0001	0	0	0	0	0	0	0	0	0	0	0	0
4.75	5.00	0.0001	0	0	0	0	0	0	0	0	0	7	0	0
Parts per thousand For each direction			10	18	147	122	60	42	37	39	81	398	37	10

Table 19 "Future" wave height/direction scatter diagram for Barry

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.00	0.25	0.9380	1010	1668	3581	3426	1419	1159	1188	1480	1484	3595	3376	908
0.25	0.50	0.6951	324	500	6646	4808	1472	1332	1079	1224	2208	6932	1157	423
0.50	0.75	0.4140	9	24	5071	3565	751	597	536	684	2219	5679	87	29
0.75	1.00	0.2215	0	0	1919	818	142	84	65	79	1150	4255	11	0
1.00	1.25	0.1363	0	0	646	280	52	0	1	15	597	4062	0	0
1.25	1.50	0.0797	0	0	83	67	15	0	0	0	165	2866	0	0
1.50	1.75	0.0477	0	0	3	5	4	0	0	0	67	1806	0	0
1.75	2.00	0.0289	0	0	0	2	1	0	0	0	33	1049	0	0
2.00	2.25	0.0181	0	0	0	1	0	0	0	0	15	959	0	0
2.25	2.50	0.0083	0	0	0	0	0	0	0	0	3	270	0	0
2.50	2.75	0.0056	0	0	0	0	0	0	0	0	0	347	0	0
2.75	3.00	0.0021	0	0	0	0	0	0	0	0	1	100	0	0
3.00	3.25	0.0011	0	0	0	0	0	0	0	0	0	67	0	0
3.25	3.50	0.0004	0	0	0	0	0	0	0	0	0	18	0	0
3.50	3.75	0.0002	0	0	0	0	0	0	0	0	0	20	0	0
3.75	4.00	0.0000	0	0	0	0	0	0	0	0	0	1	0	0
4.00	4.25	0.0000	0	0	0	0	0	0	0	0	0	0	0	0
4.25	4.50	0.0000	0	0	0	0	0	0	0	0	0	2	0	0
Parts per thousand For each direction			14	23	191	138	41	34	31	37	85	341	49	14

Table 20 "Present" wave height/direction scatter diagram for North Wales

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.4	0.9988	947	1253	2458	3652	2574	1301	788	1122	1169	1849	2350	1532
0.4	0.8	0.7888	1607	1525	2675	4073	4934	2838	1008	1429	2202	3896	4245	2428
0.8	1.2	0.4602	1219	664	1589	1293	1910	652	105	227	1596	6106	4421	1589
1.2	1.6	0.2465	452	354	505	293	178	19	2	43	367	3376	3531	1076
1.6	2.0	0.1446	241	180	128	74	2	0	0	5	55	2415	3177	766
2.0	2.4	0.0741	85	24	11	2	0	0	0	0	7	1240	1936	428
2.4	2.8	0.0368	23	7	1	0	0	0	0	0	0	399	1098	203
2.8	3.2	0.0195	6	0	0	0	0	0	0	0	0	289	784	124
3.2	3.6	0.0074	1	0	0	0	0	0	0	0	0	109	329	41
3.6	4.0	0.0027	0	0	0	0	0	0	0	0	0	28	111	16
4.0	4.4	0.0011	0	0	0	0	0	0	0	0	0	12	49	4
4.4	4.8	0.0004	0	0	0	0	0	0	0	0	0	13	22	3
4.8	5.2	0.0001	0	0	0	0	0	0	0	0	0	2	2	0
5.2	5.6	0.0000	0	0	0	0	0	0	0	0	0	2	0	0
Parts per thousand For each direction			46	40	74	94	96	48	19	28	54	198	221	82

Table 21 "Future" wave height/direction scatter diagram for North Wales

Data in parts per hundred thousand

Significant wave height in metres

H1	To H2	P(H>H1)	Wave angles in degrees North											
			-15 15	15 45	45 75	75 105	105 135	135 165	165 195	195 225	225 255	255 285	285 315	315 345
0.0	0.4	0.9986	1414	1800	3593	2971	2044	1054	639	1196	1270	1771	1906	1691
0.4	0.8	0.7851	2516	2532	3724	3577	4112	1581	612	1198	2326	4141	3020	2574
0.8	1.2	0.4660	1997	1398	2737	1755	1682	195	28	144	1281	5767	3179	2043
1.2	1.6	0.2440	752	702	1138	485	272	1	1	16	229	2980	2511	1750
1.6	2.0	0.1356	613	274	316	83	25	0	0	1	32	1972	2284	1250
2.0	2.4	0.0671	137	35	63	13	2	0	0	0	3	873	1410	748
2.4	2.8	0.0342	70	8	2	0	0	0	0	0	0	278	826	463
2.8	3.2	0.0178	26	0	0	0	0	0	0	0	0	131	548	255
3.2	3.6	0.0082	9	0	0	0	0	0	0	0	0	36	282	110
3.6	4.0	0.0038	3	0	0	0	0	0	0	0	0	6	157	31
4.0	4.4	0.0018	0	0	0	0	0	0	0	0	0	6	87	8
4.4	4.8	0.0008	0	0	0	0	0	0	0	0	0	3	50	4
4.8	5.2	0.0002	0	0	0	0	0	0	0	0	0	2	19	2
5.2	5.6	0.0000	0	0	0	0	0	0	0	0	0	0	1	0
Parts per thousand For each direction			75	68	116	89	81	28	13	26	51	180	163	109

TABLE 22 Comparison of "present" and "future" wind conditions for four GCM grid points in the North Atlantic

Grid point 57.5N 41.25W

Direction sector	Mean wind speed (m/s) present	Mean wind speed (m/s) future	Percentage increase in wind speed	Percentage in sector present	Percentage in sector future
N	5.6	6.0	8.0	10.0	10.6
NE	3.9	6.2	58.6	5.3	8.3
E	6.5	7.0	8.9	8.9	10.8
SE	5.0	6.7	33.9	5.6	4.4
S	5.6	6.4	13.9	8.9	6.4
SW	6.1	7.5	23.0	17.8	17.8
W	7.0	7.9	11.6	26.7	27.8
NW	5.8	7.6	30.4	16.9	13.9
All directions	6.1	7.2	18.6	100.0	100.0

Grid point 57.5N 33.75W

Direction sector	Mean wind speed (m/s) present	Mean wind speed (m/s) future	Percentage increase in wind speed	Percentage in sector present	Percentage in sector future
N	6.0	6.4	6.5	7.5	6.4
NE	6.8	6.2	-9.0	6.4	8.9
E	7.4	8.3	11.7	8.6	12.5
SE	5.3	7.7	45.5	5.0	4.7
S	4.7	5.4	15.0	4.2	6.1
SW	5.1	5.9	15.6	19.7	18.6
W	7.3	6.9	-4.7	25.8	21.7
NW	7.1	9.3	30.5	22.8	21.1
All directions	6.5	7.2	11.7	100.0	100.0

TABLE 22 (Cont'd) Comparison of "present" and "future" wind conditions for four GCM grid points in the North Atlantic

Grid point 52.5N 41.25W

Direction sector	Mean wind speed (m/s) present	future	Percentage increase in wind speed	Percentage in sector present	future
N	6.0	5.9	-0.9	8.1	6.7
NE	7.6	7.3	-4.5	12.5	10.3
E	7.9	8.3	5.8	20.3	15.6
SE	7.3	5.1	-30.0	8.9	8.6
S	4.0	4.4	10.1	6.9	10.0
SW	5.8	5.0	-14.1	10.6	13.9
W	6.6	6.4	-3.2	20.8	22.5
NW	6.8	6.6	-3.2	11.9	12.5
All directions	6.8	6.3	-7.2	100.0	100.0

Grid point 52.5N 33.75W

Direction sector	Mean wind speed (m/s) present	future	Percentage increase in wind speed	Percentage in sector present	future
N	6.4	8.1	24.9	12.2	5.8
NE	8.0	8.4	4.4	16.9	11.4
E	8.8	8.7	-0.9	17.2	14.4
SE	6.7	4.7	-30.0	4.4	8.3
S	3.0	4.2	40.4	2.5	4.4
SW	6.4	5.0	-21.4	9.4	6.1
W	7.3	7.4	0.7	20.0	25.3
NW	8.0	8.5	6.3	17.2	24.2
All directions	7.5	7.5	0.0	100.0	100.0

Figures

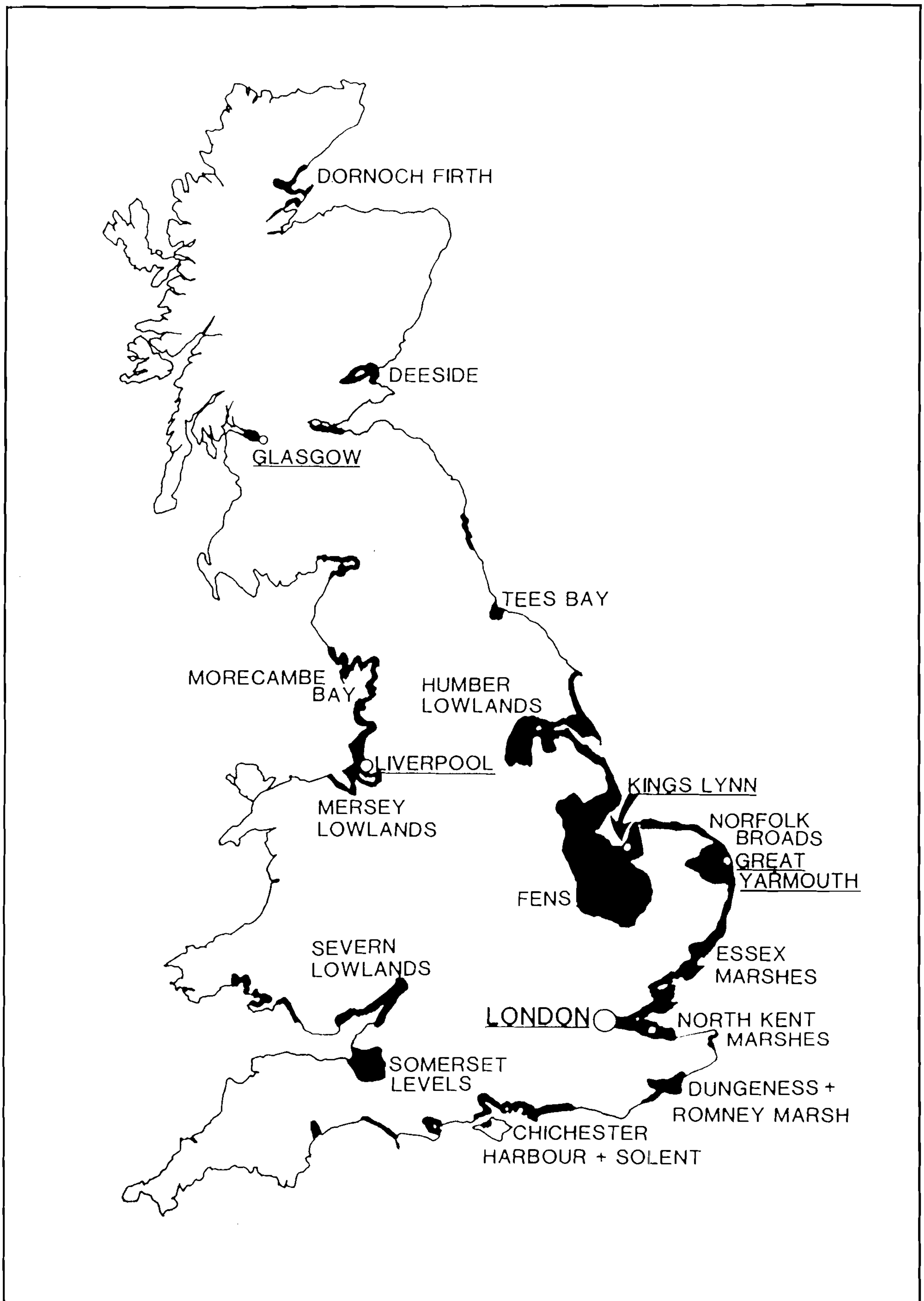


Fig 1 Areas of the UK most vulnerable to sea level rise (Reproduced from Ref 6).

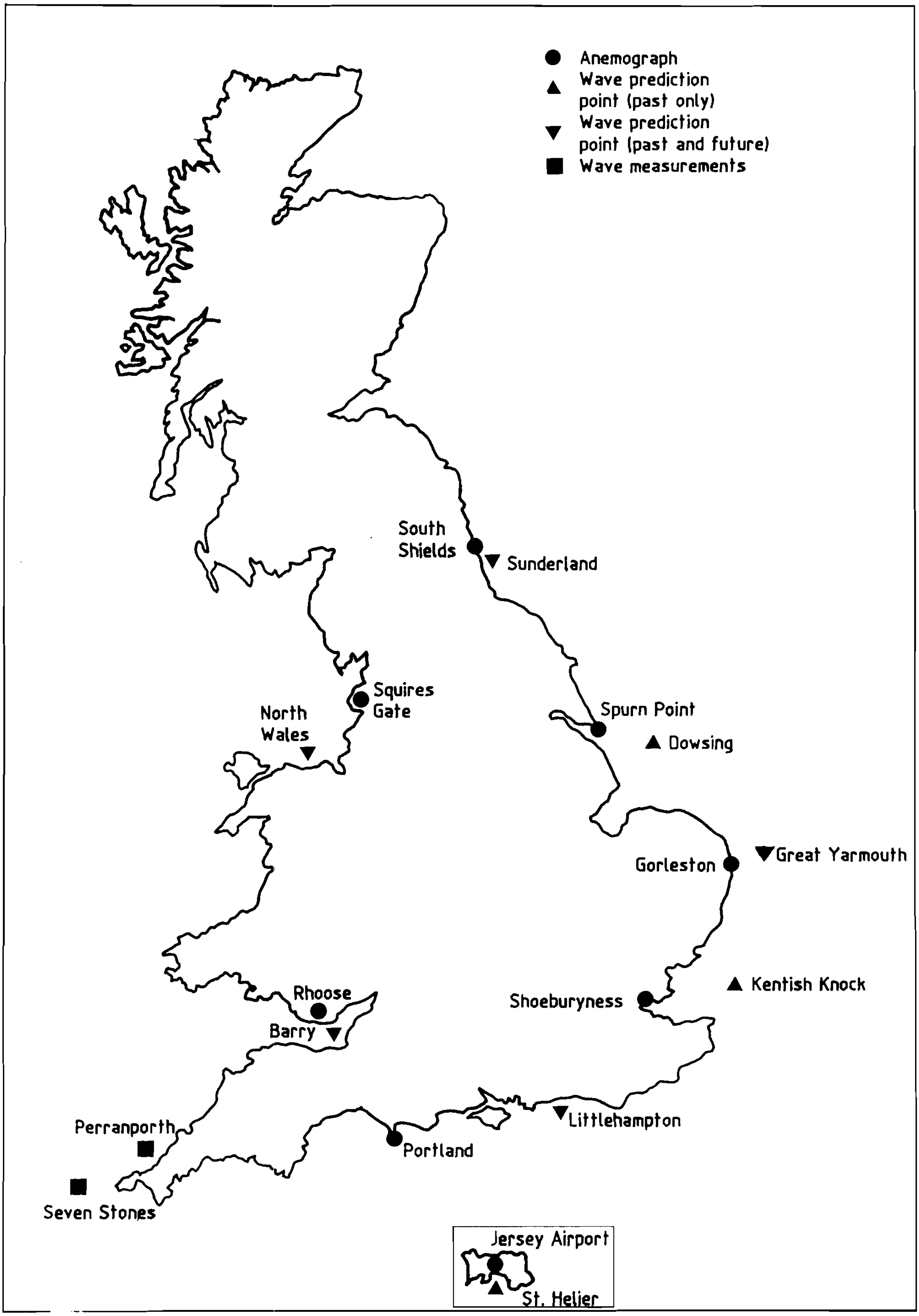


Fig 1a Location of anemographs and prediction points used in wave hindcasting.

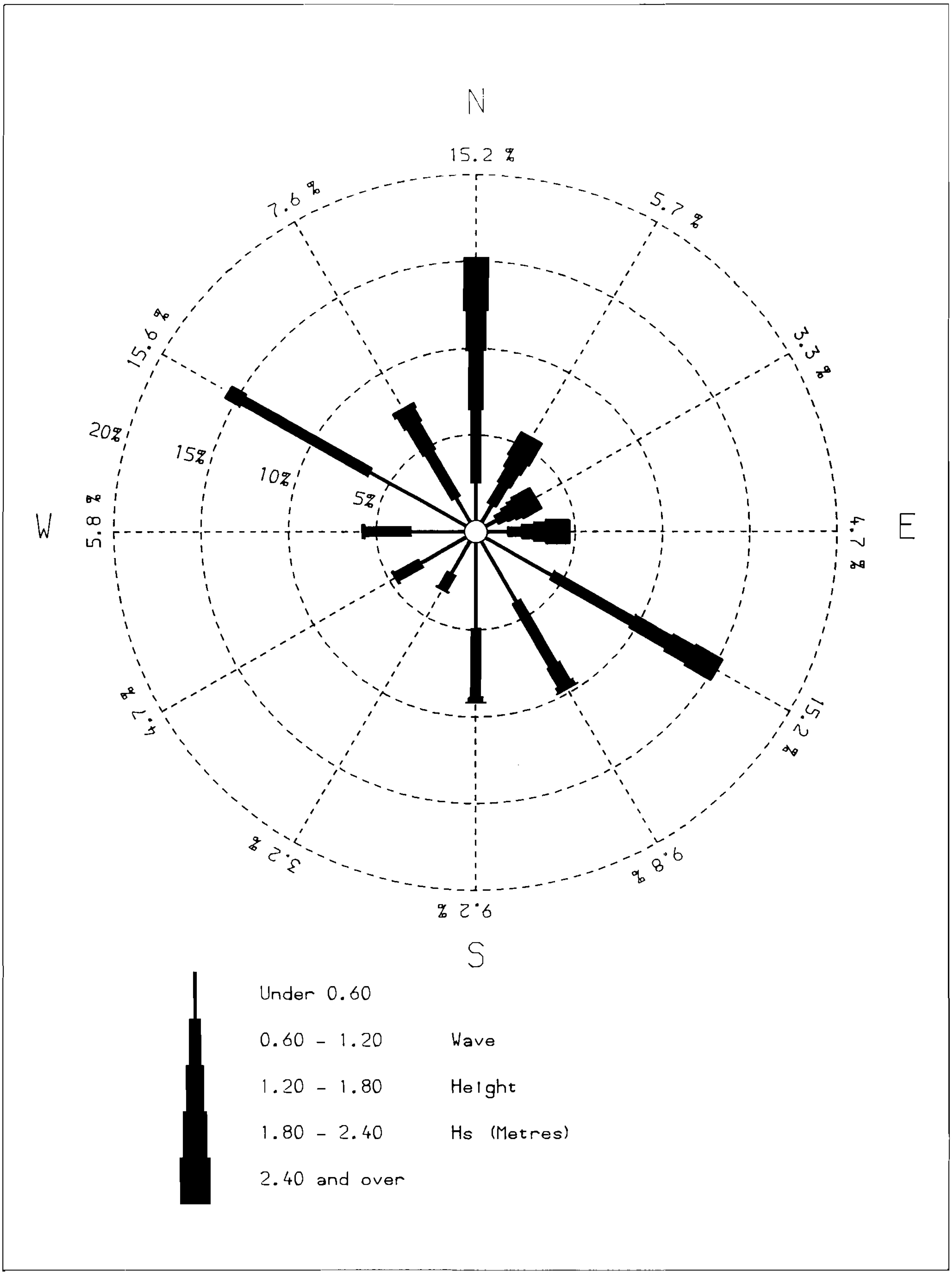


Fig 2 Wave rose for Sunderland 1976-88

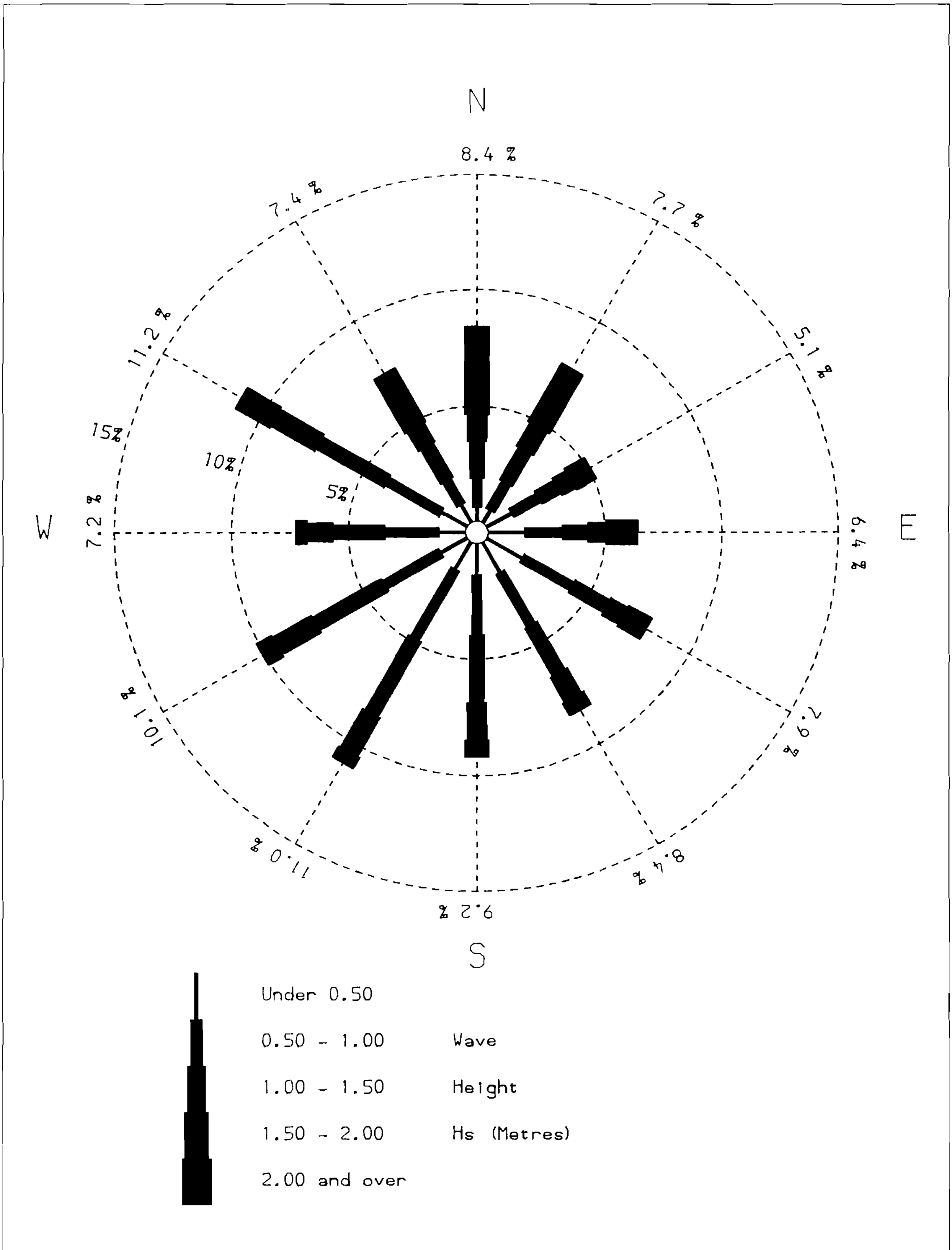


Fig 3 Wave rose for Dowsing 1978-86

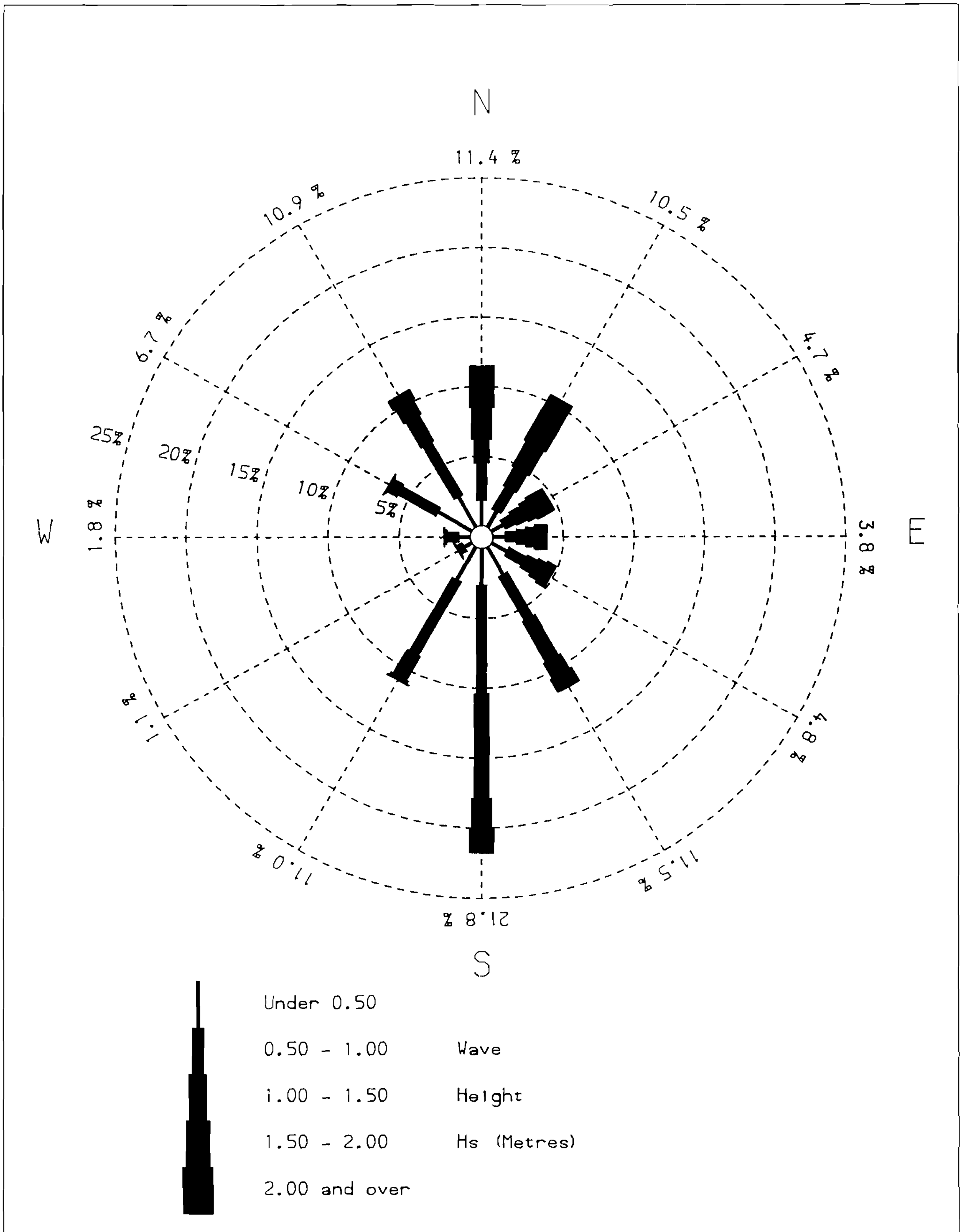


Fig 4 Wave rose for Great Yarmouth 1973-90

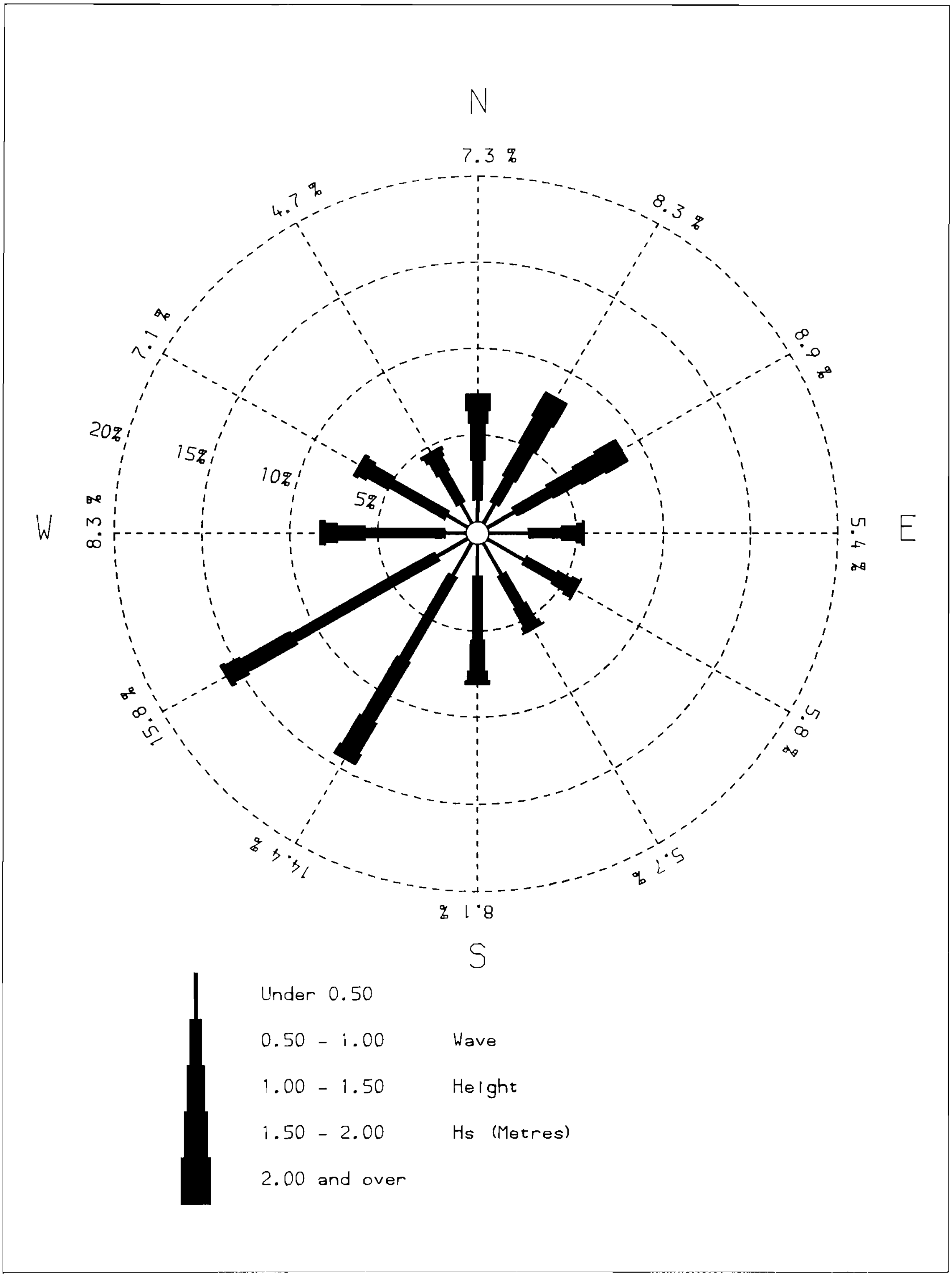


Fig 5 Wave rose for Kentish Knock 1970-83

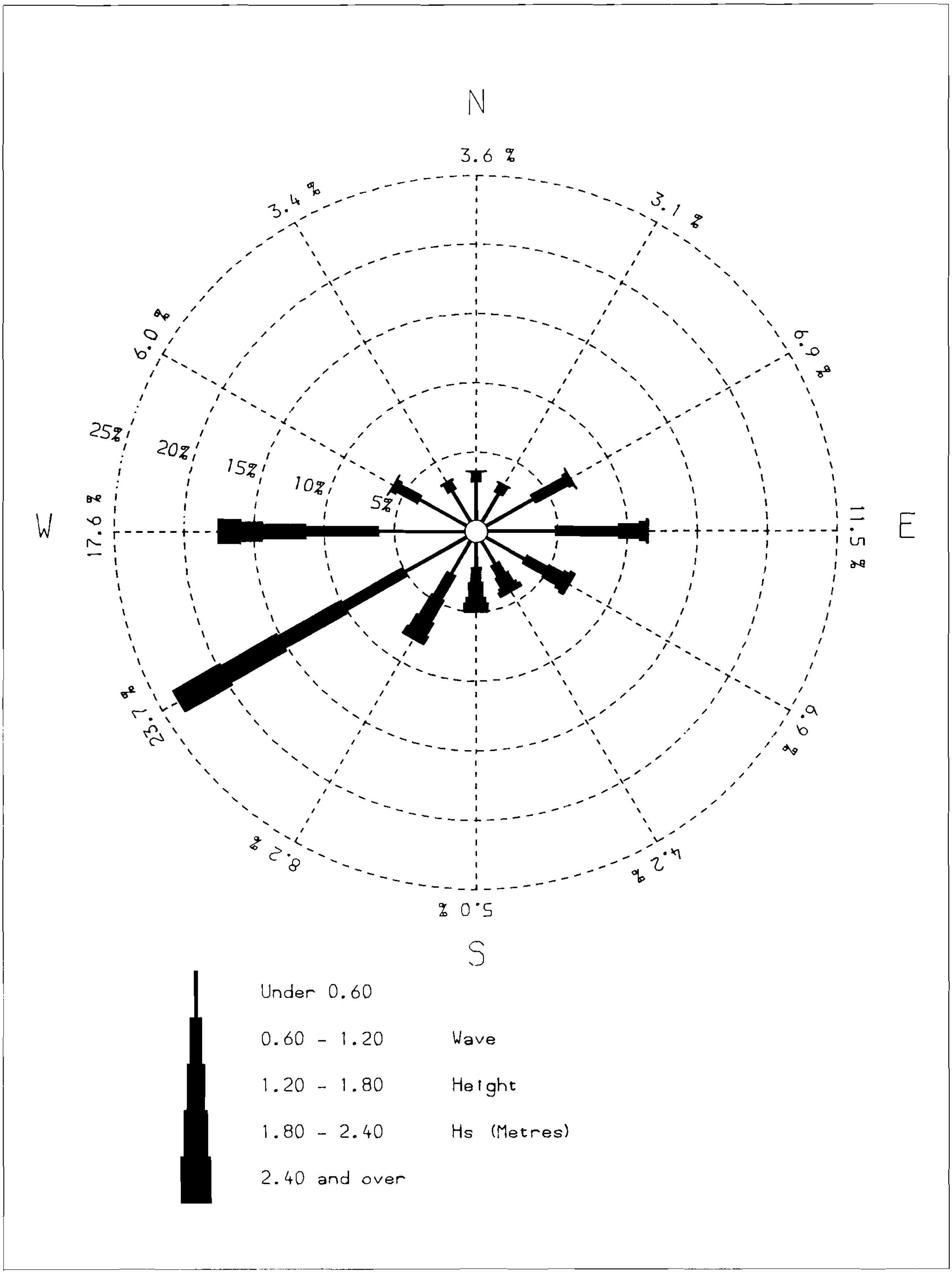


Fig 6 Wave rose for Littlehampton - 1974-90

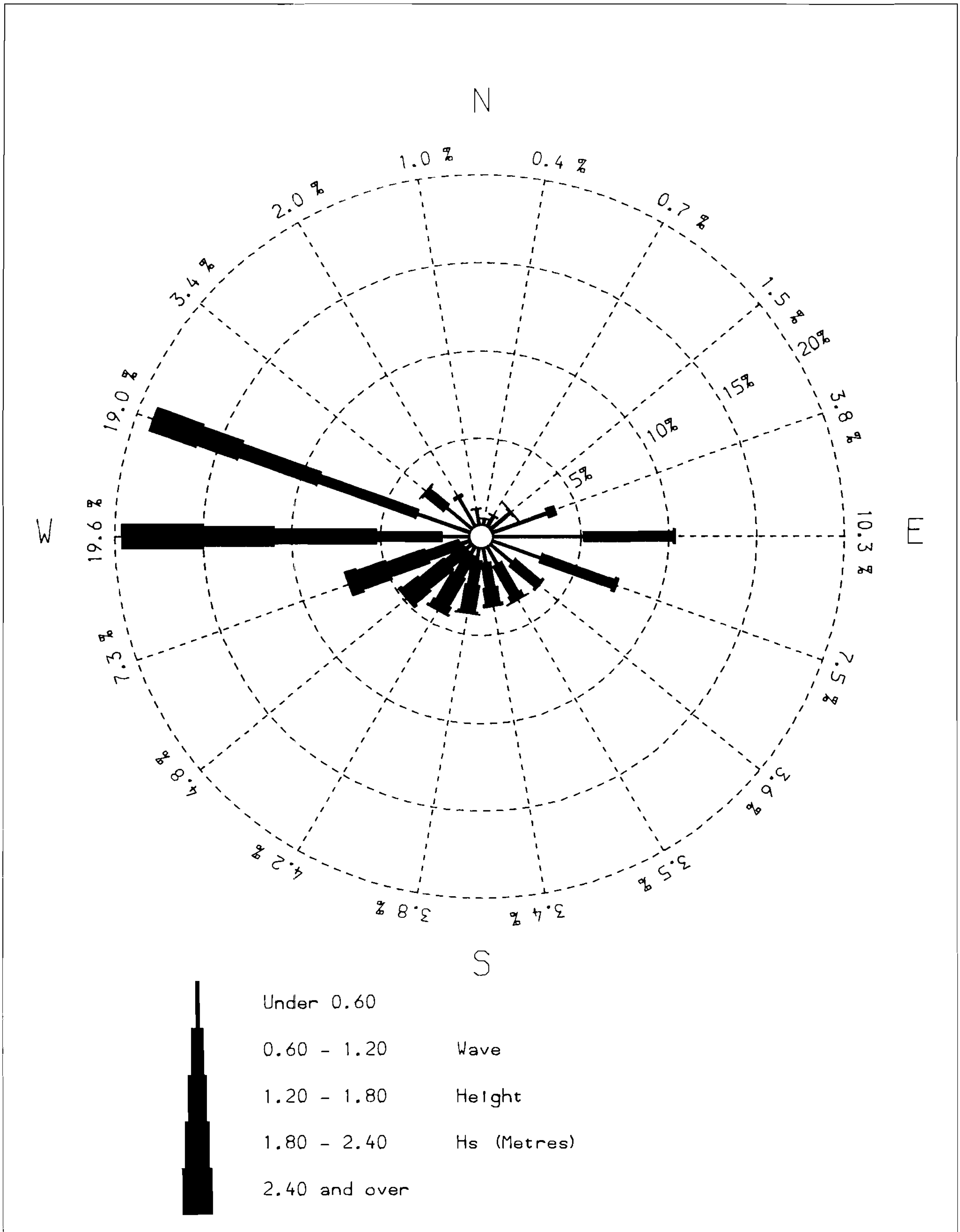


Fig 7 Wave rose for St Helier 1970-88

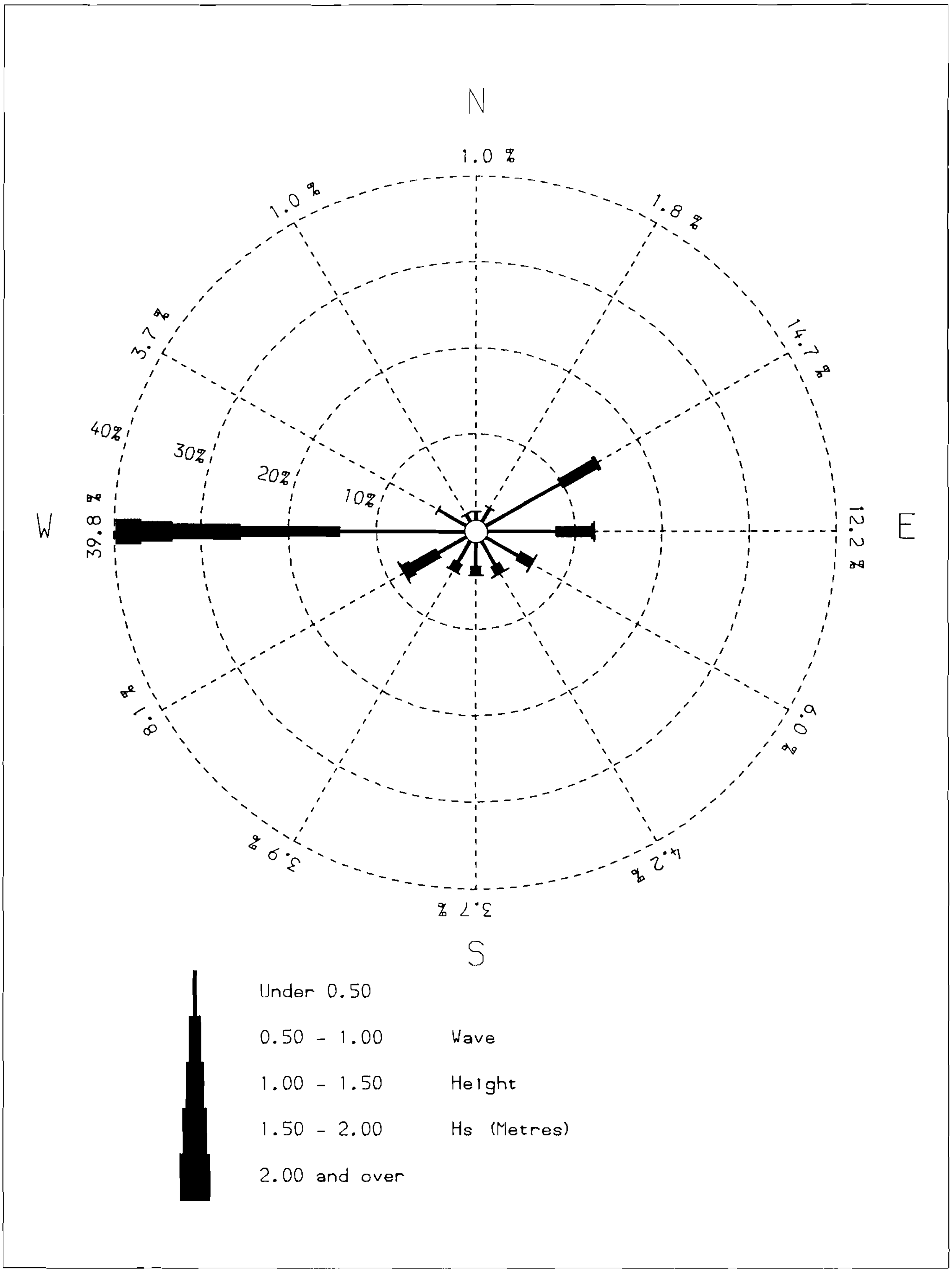


Fig 8 Wave rose for Barry 1960-88

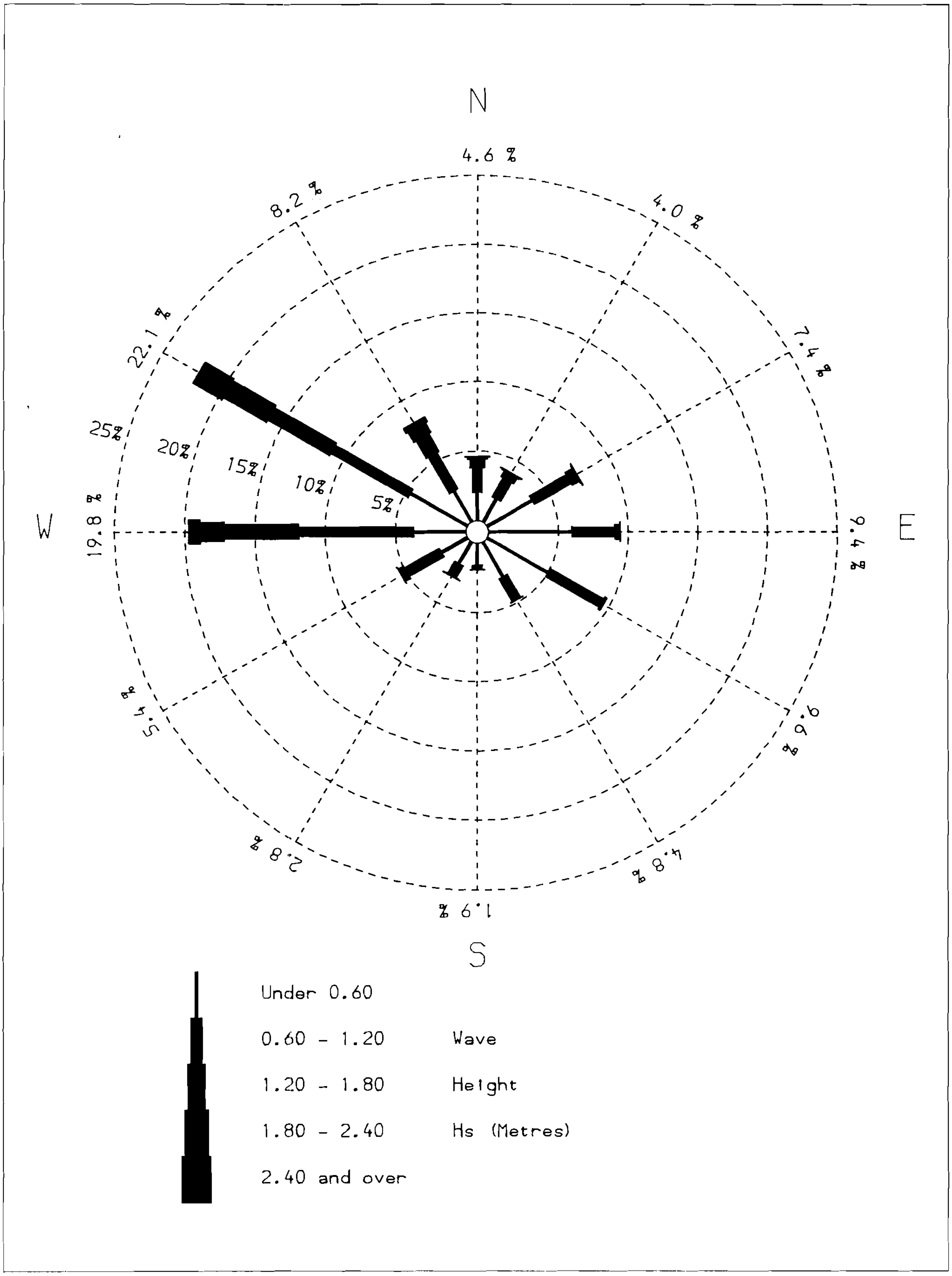


Fig 9 Wave rose for North Wales 1970-90

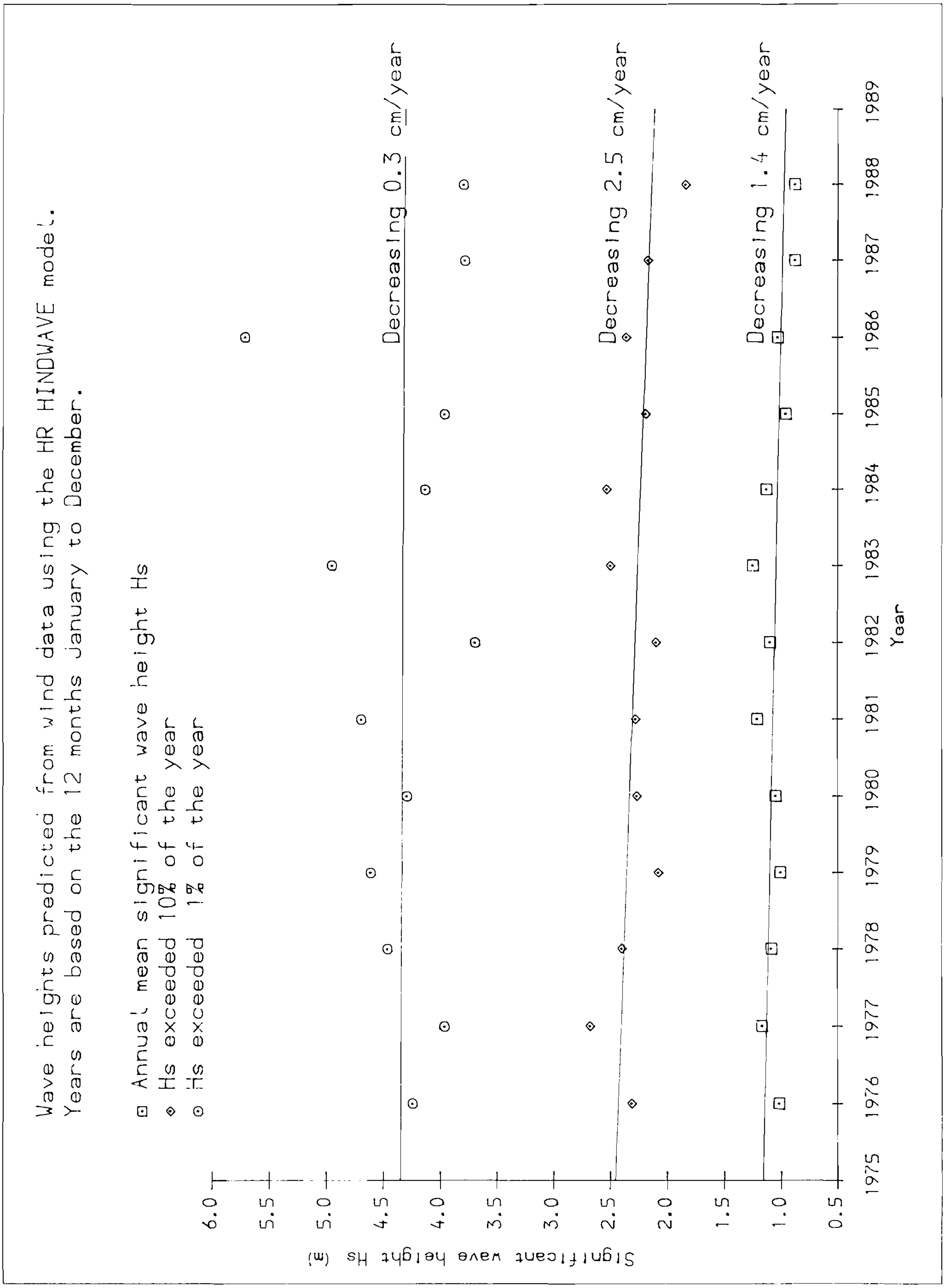


Fig 10 Variation in annually averaged Hs - Sunderland 1976-88

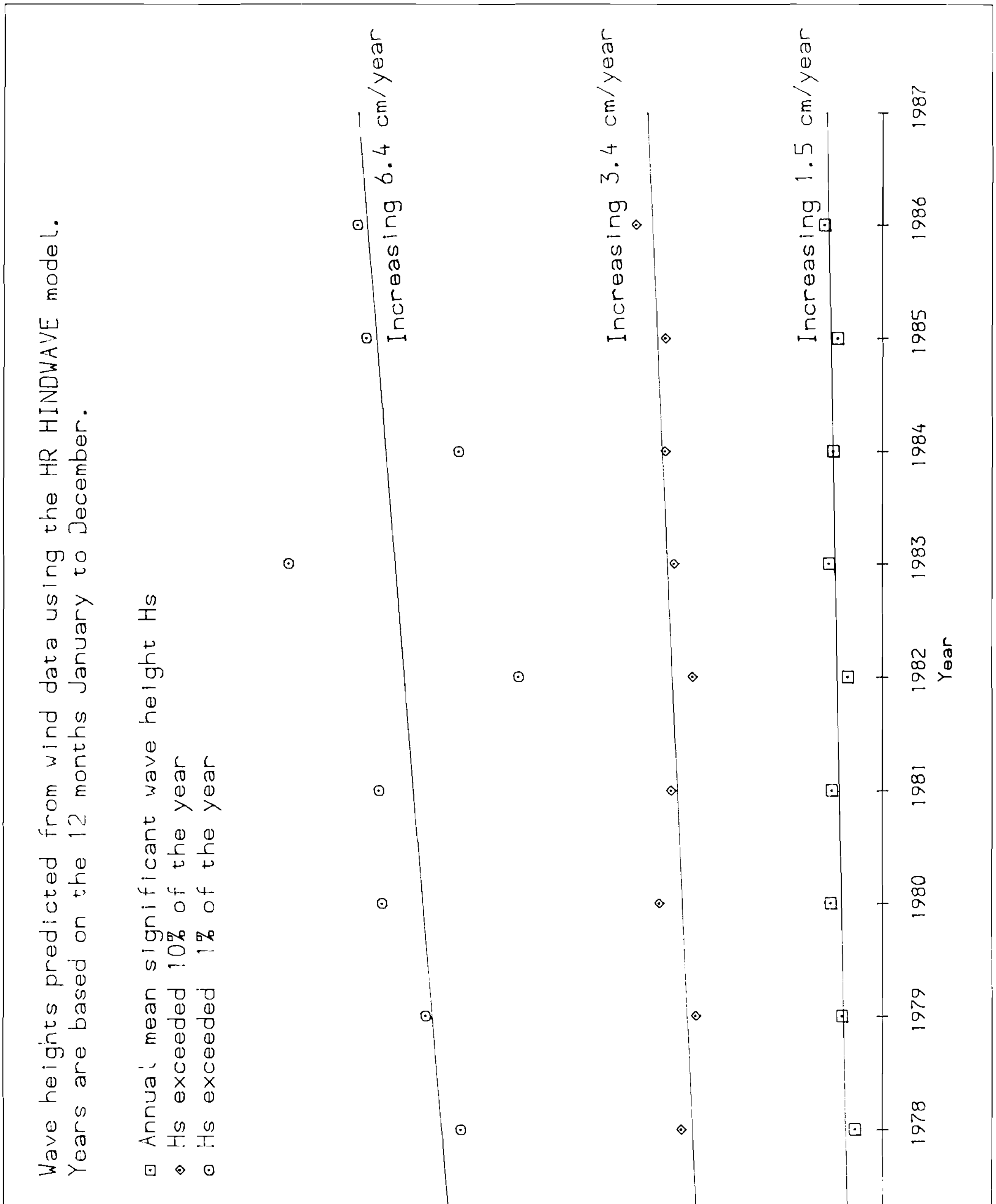


Fig 11 Variation in annually averaged Hs - Dowsing 1978-86

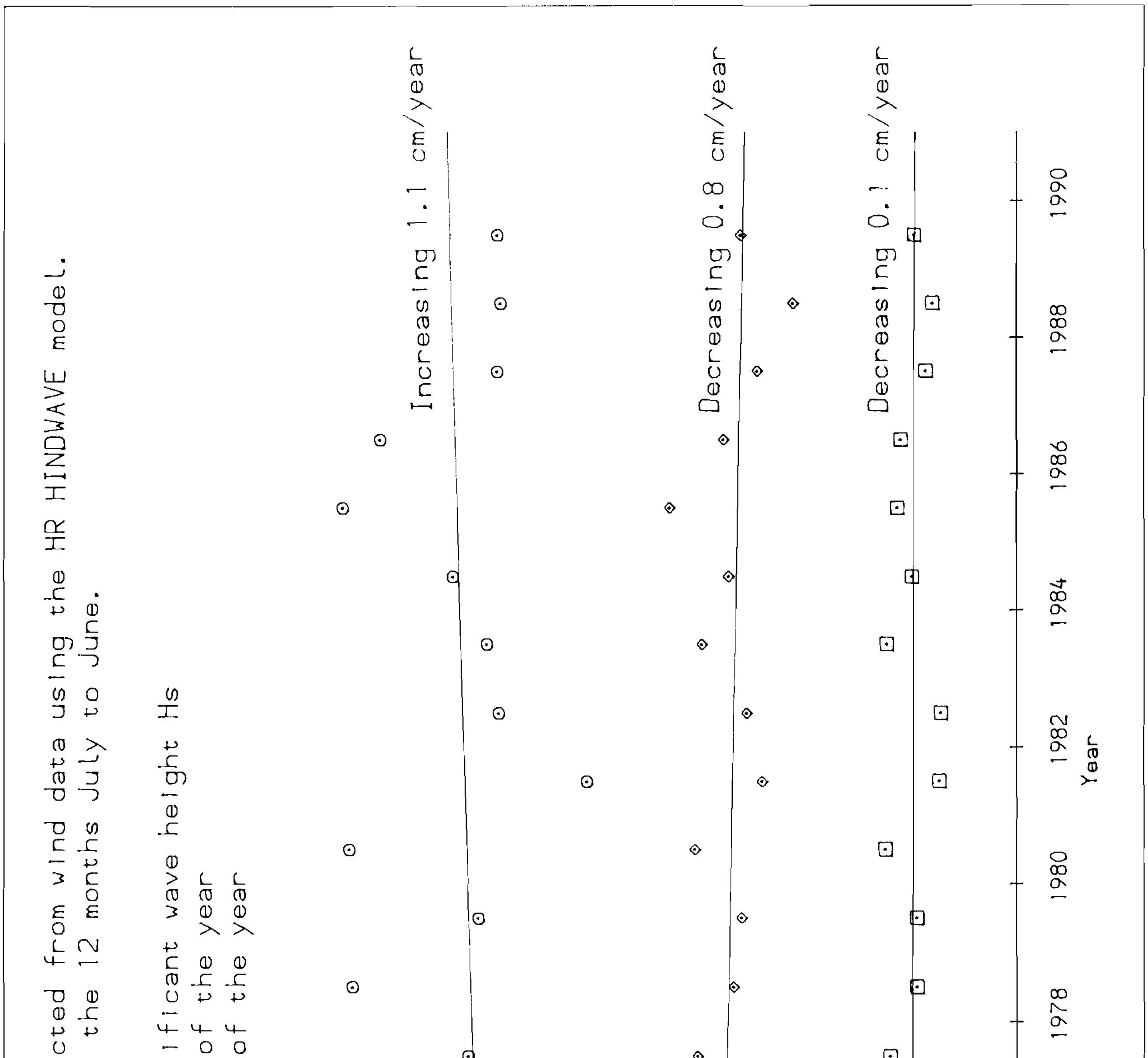


Fig 12 Variation in annually averaged Hs - Great Yarmouth 1973-90

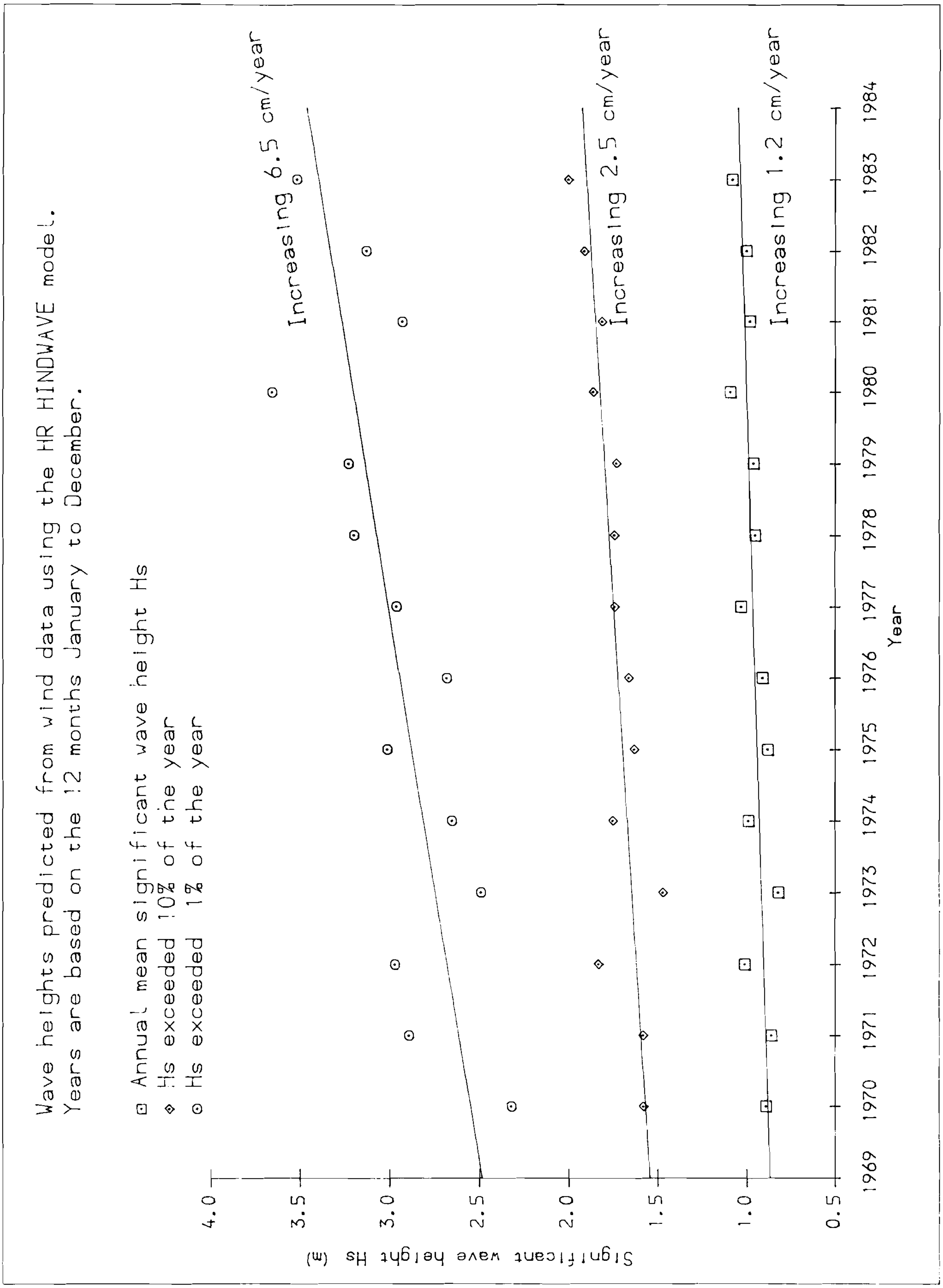


Fig 13 Variation in annually averaged Hs - Kentish Knock 1970-83

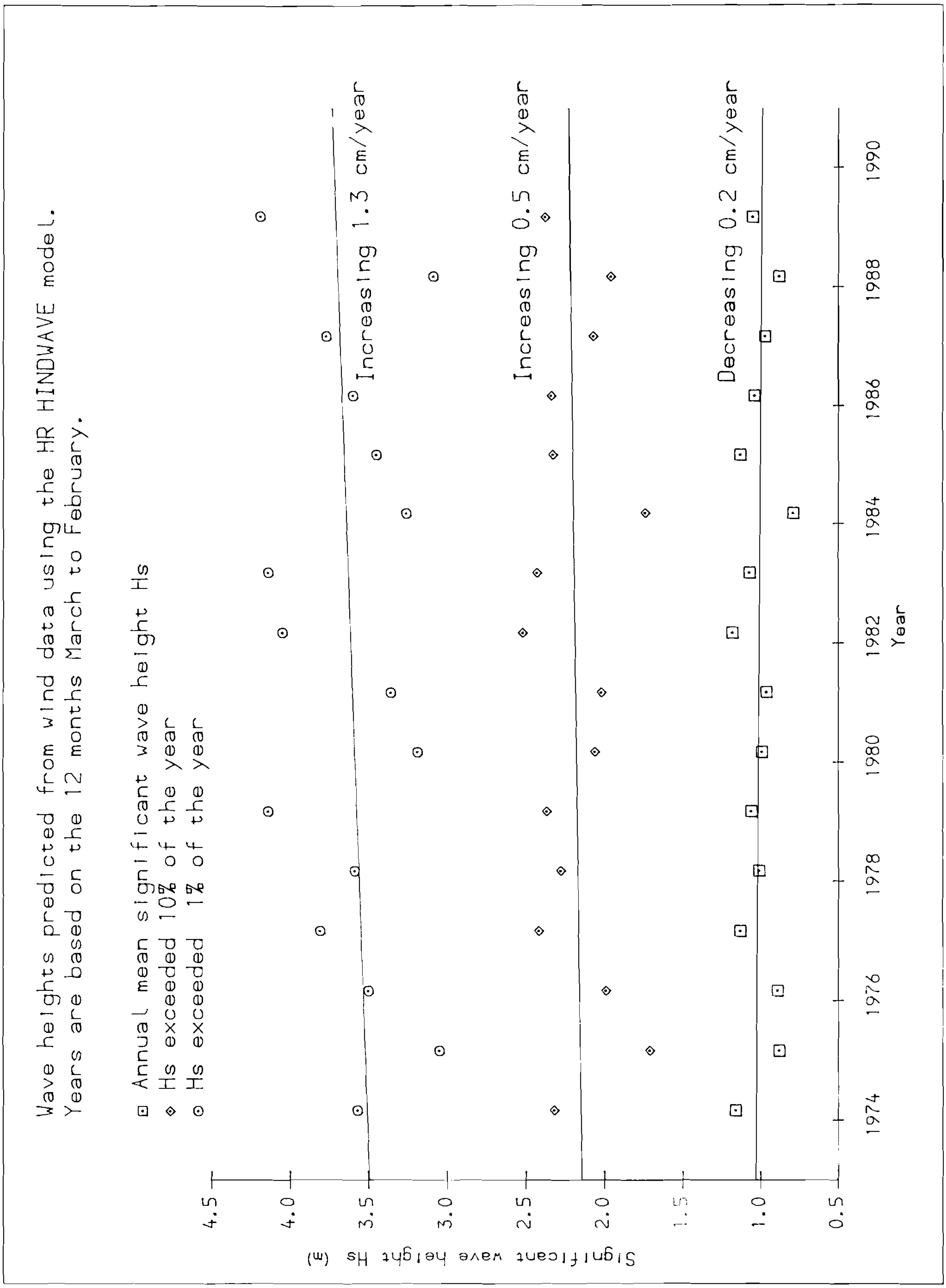


Fig 14 Variation in annually averaged Hs - Littlehampton 1974-90

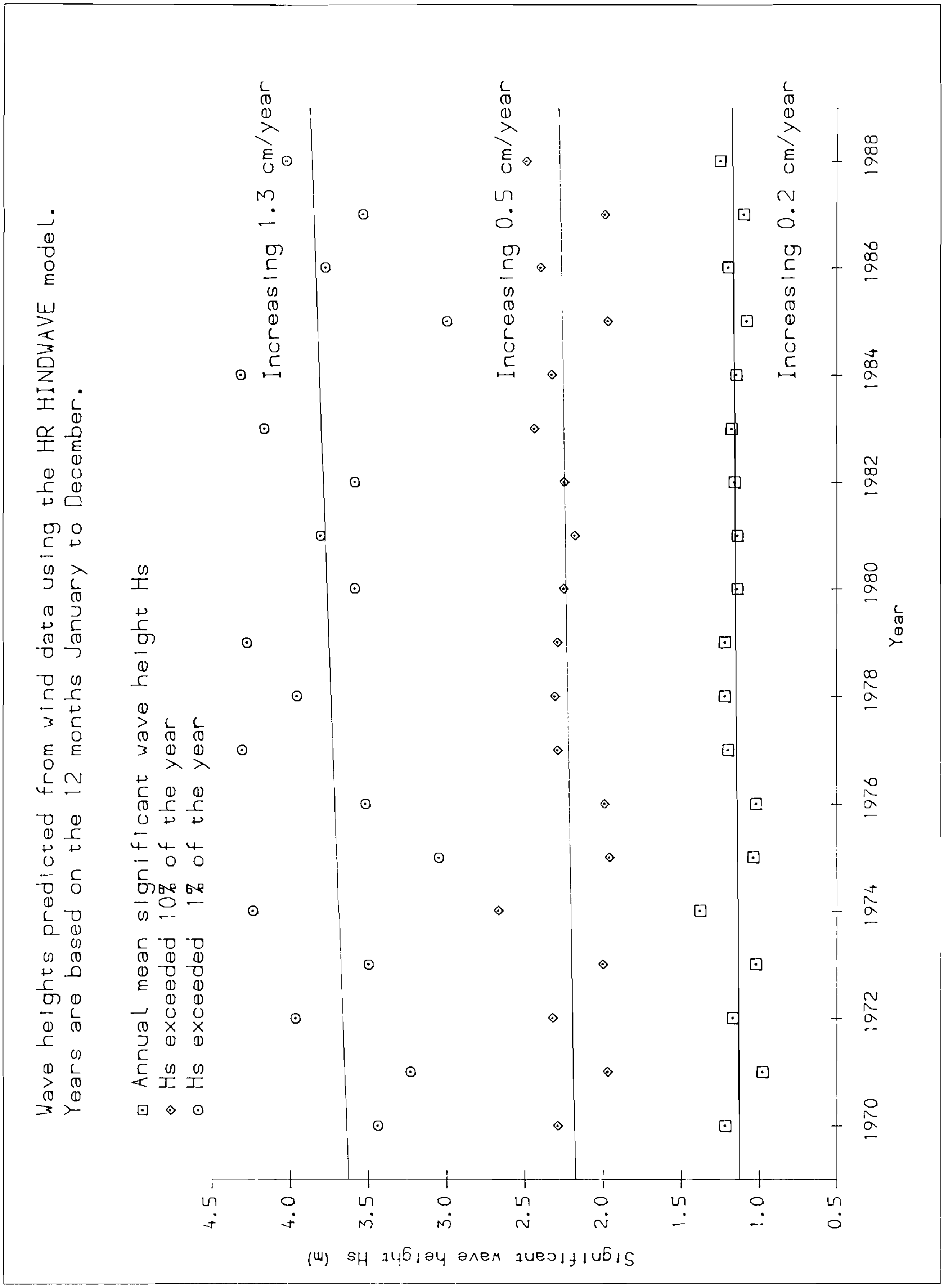


Fig 15 Variation in annually averaged Hs - St Helier 1970-88

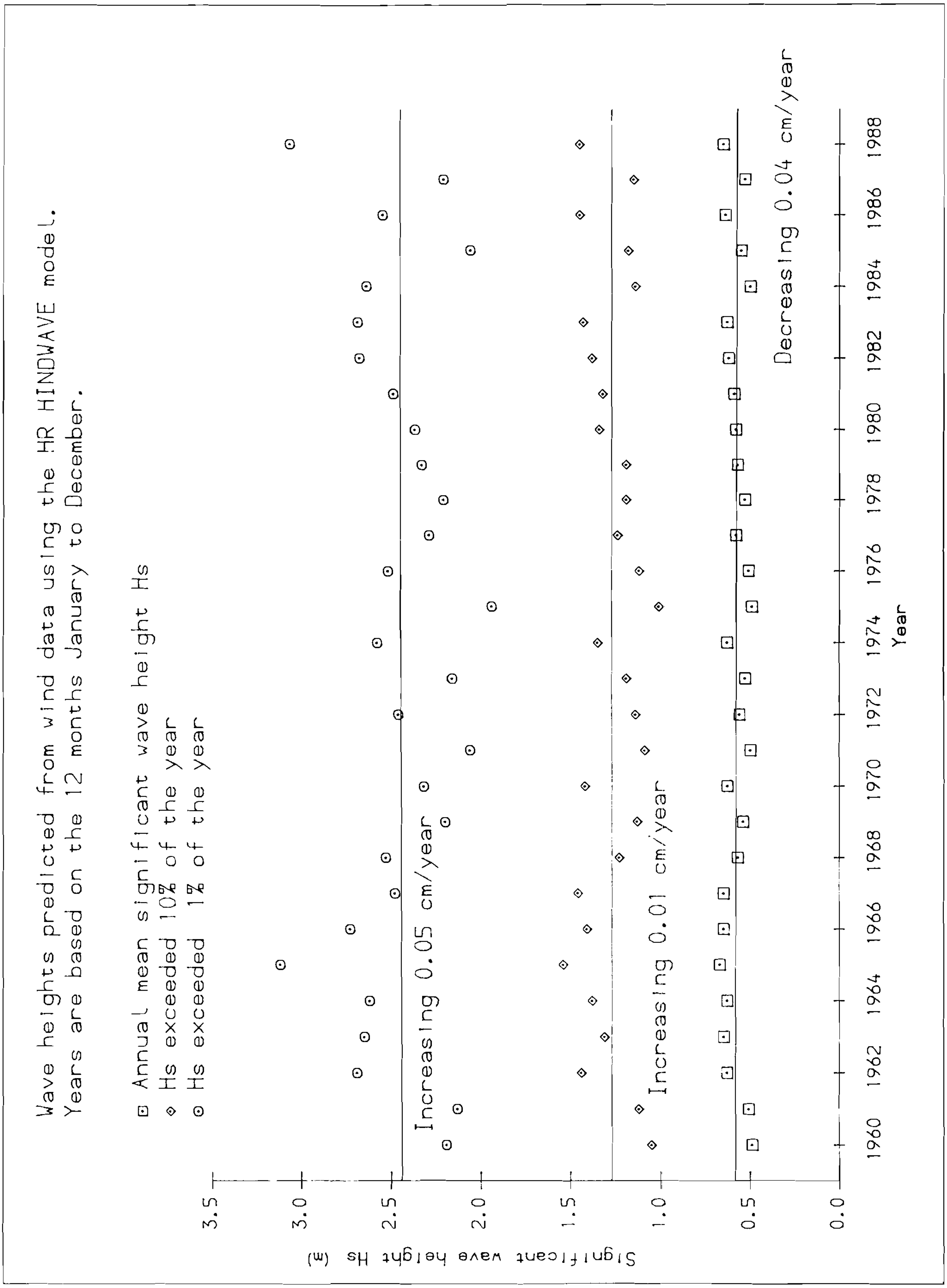


Fig 16 Variation in annually averaged Hs - Barry 1960-88

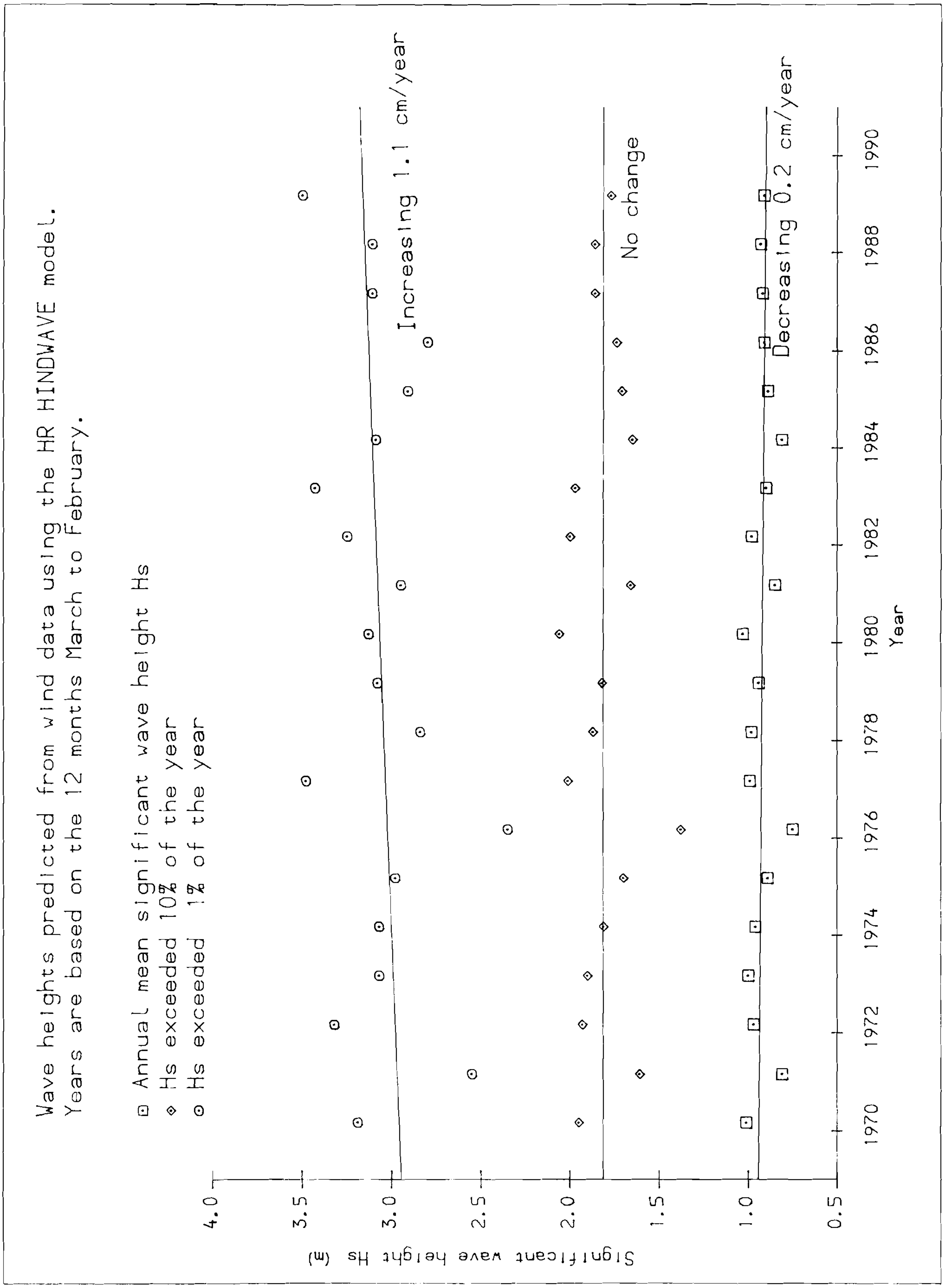


Fig 17 Variation in annually averaged Hs - North Wales 1970-90

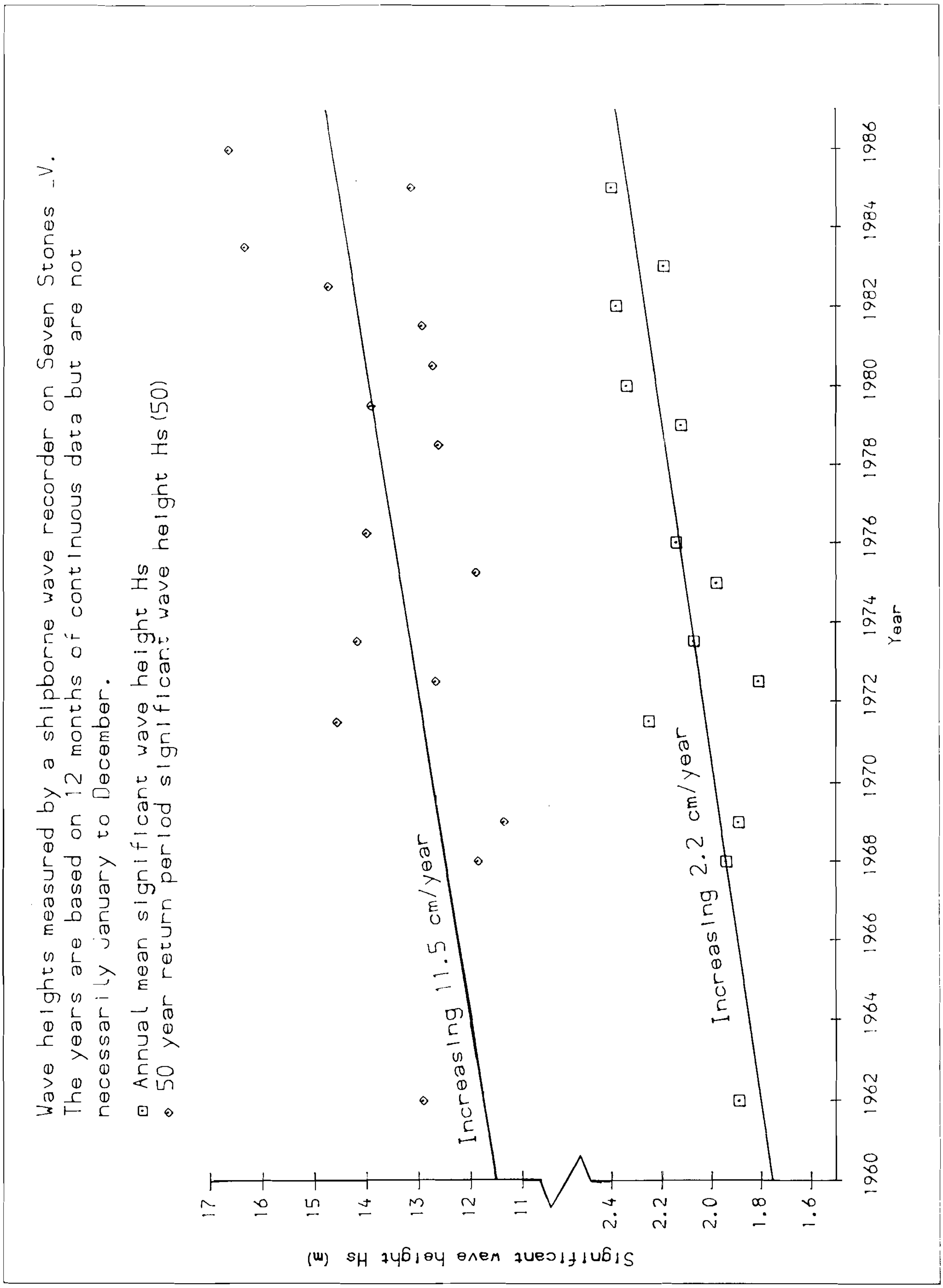


Fig 18 Variation in annually averaged Hs - Seven Stones 1962-86

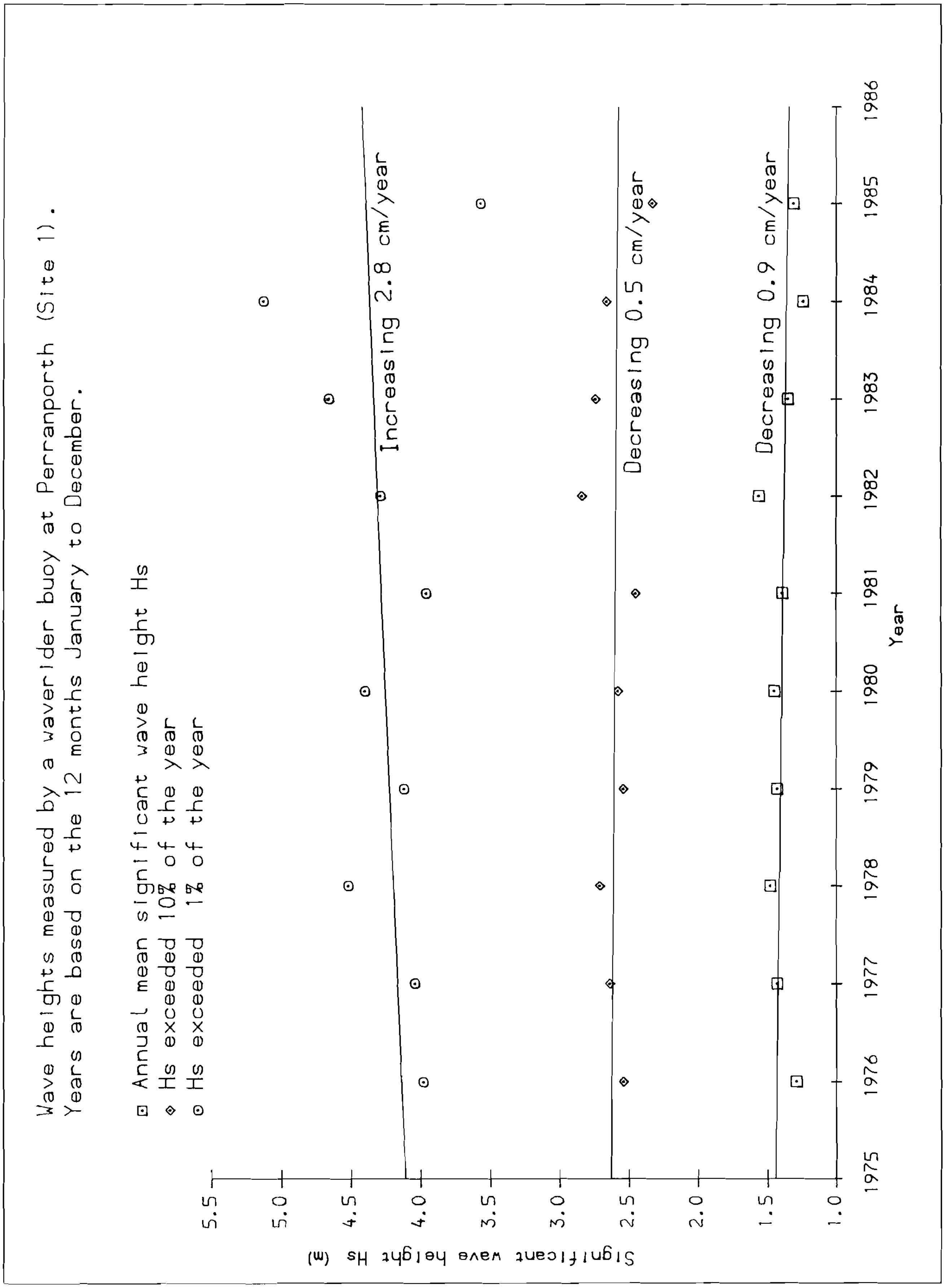
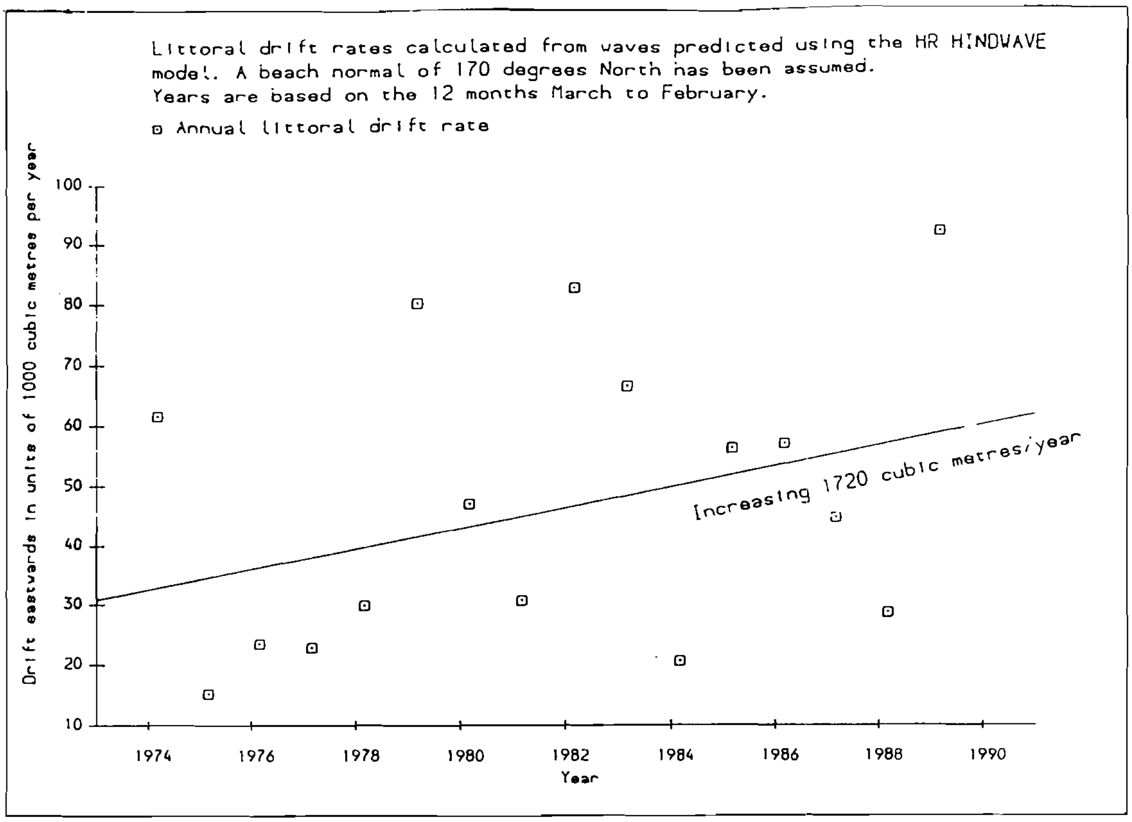


Fig 19 Variation in annually averaged Hs - Perranporth 1976-85



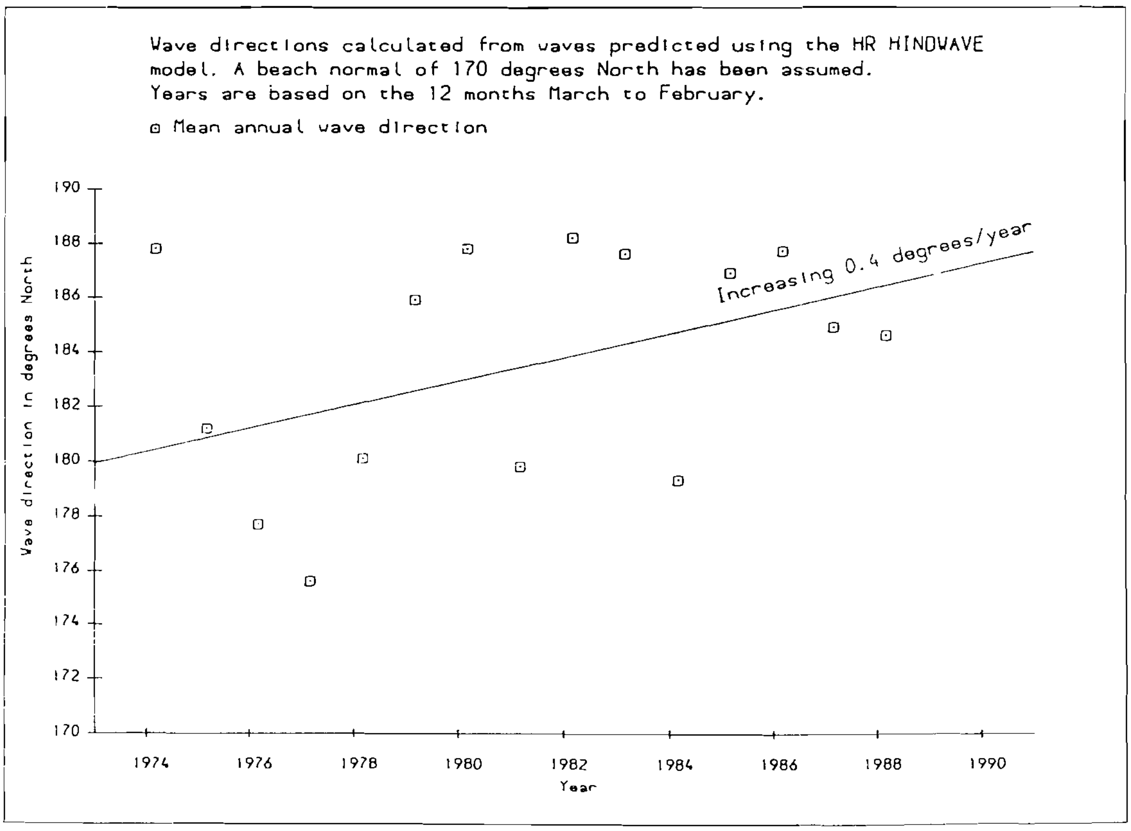


Fig 20 Potential variation in annually averaged littoral drift Littlehampton 1974-90

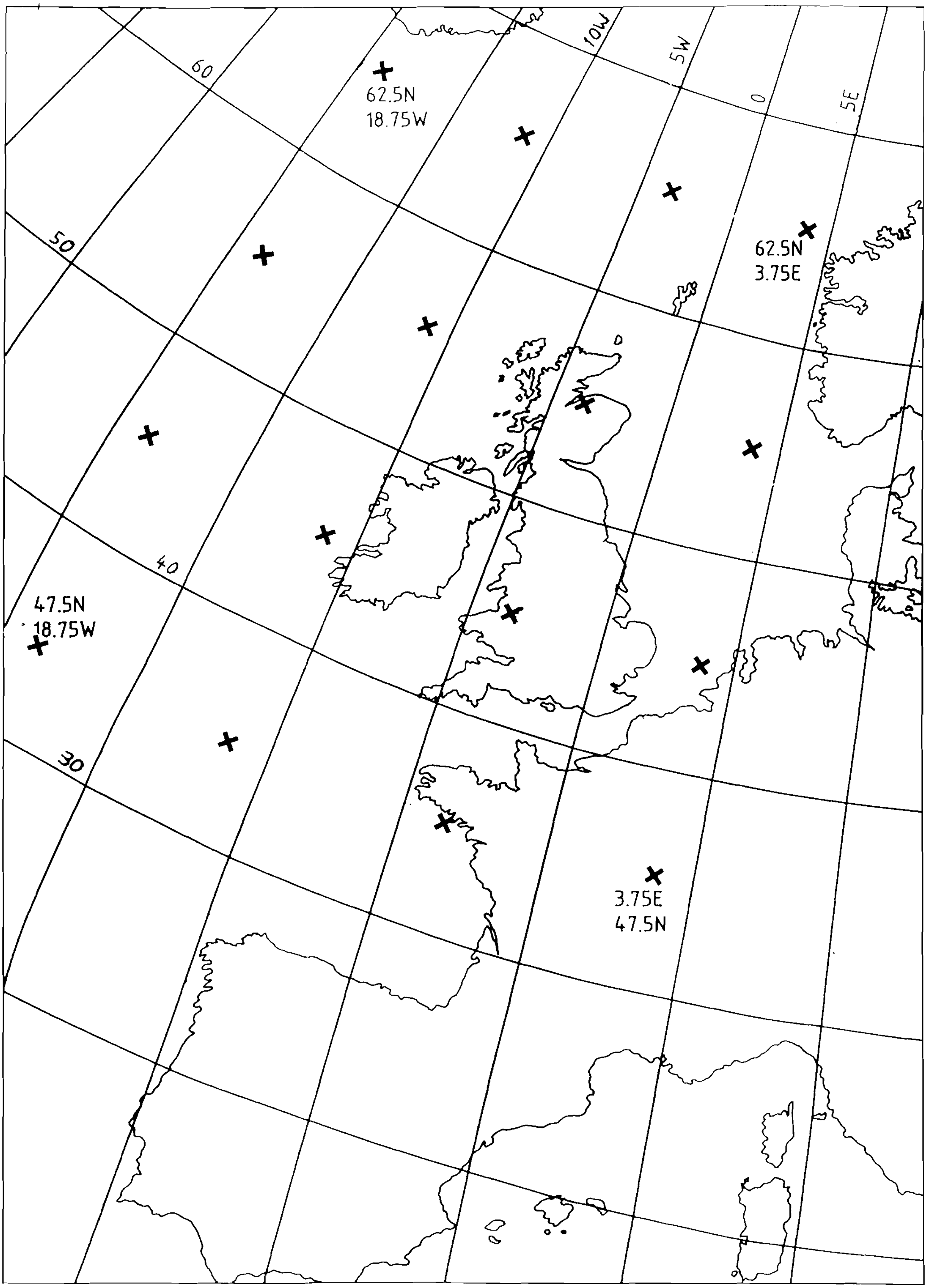


Fig 21 Distribution of Global Climate Model grid points around the UK.

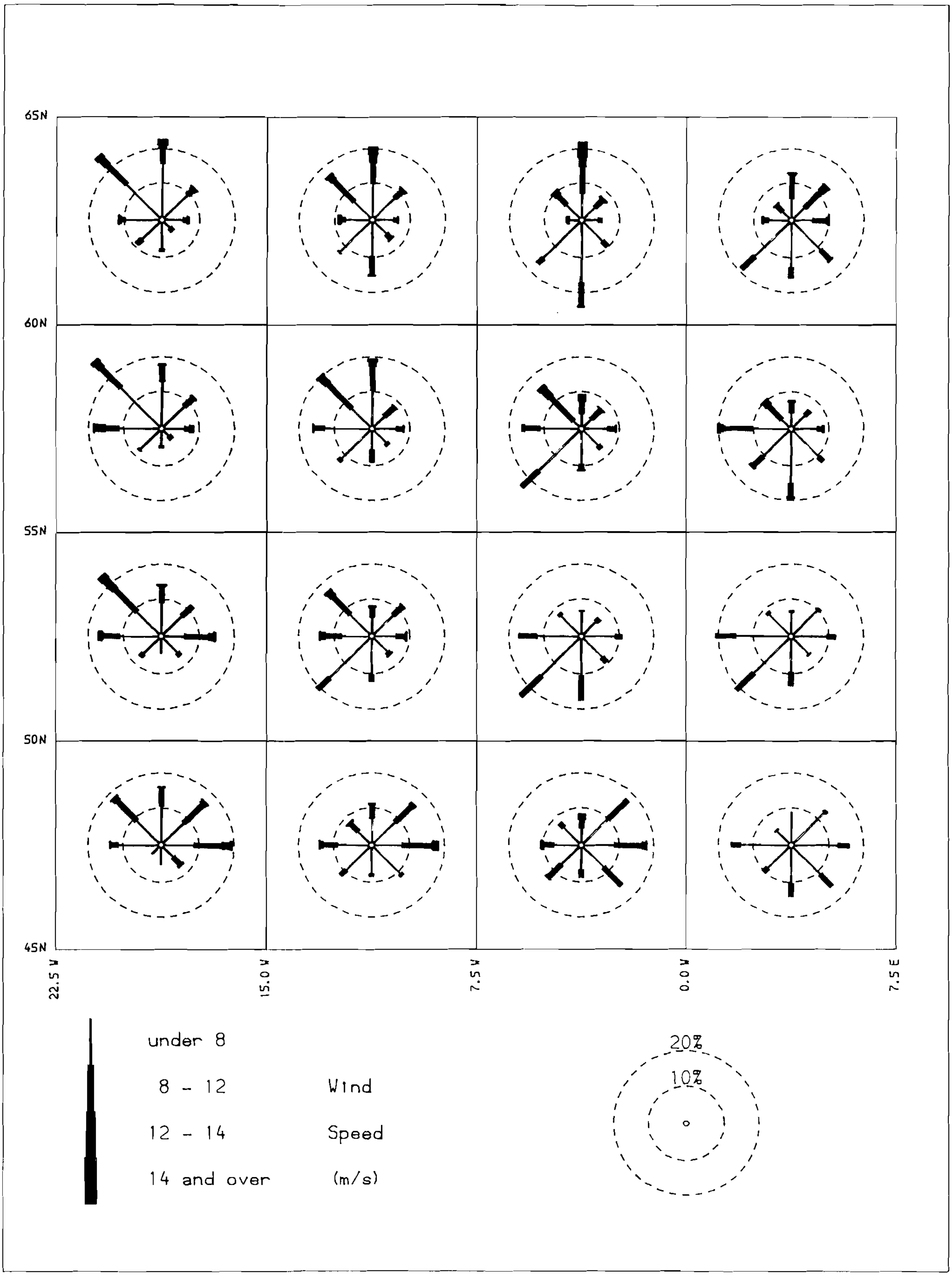


Fig 22 'Present' wind roses for the GCM grid points around the UK

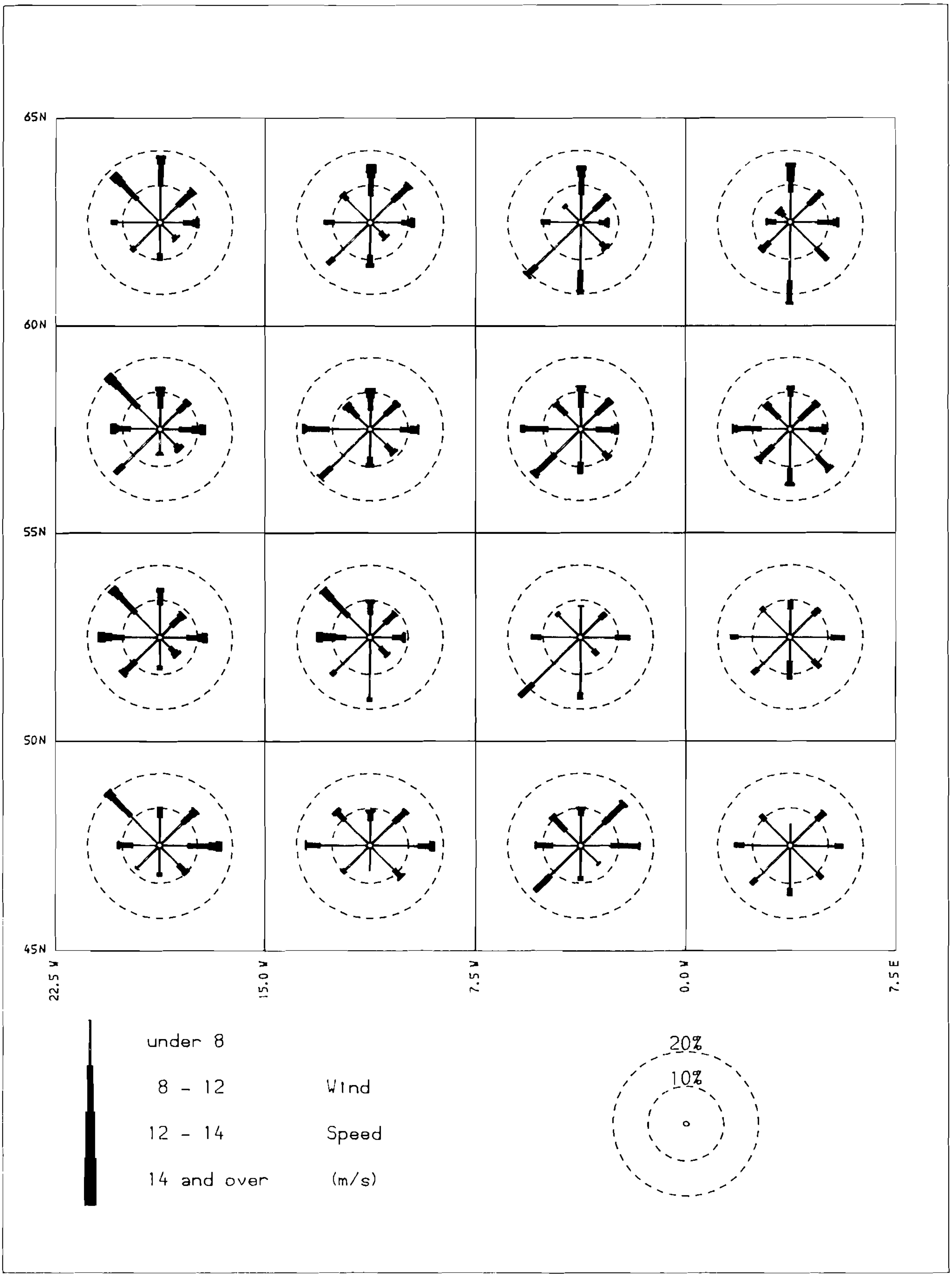


Fig 23 'Future' wind roses for the GCM grid points around the UK

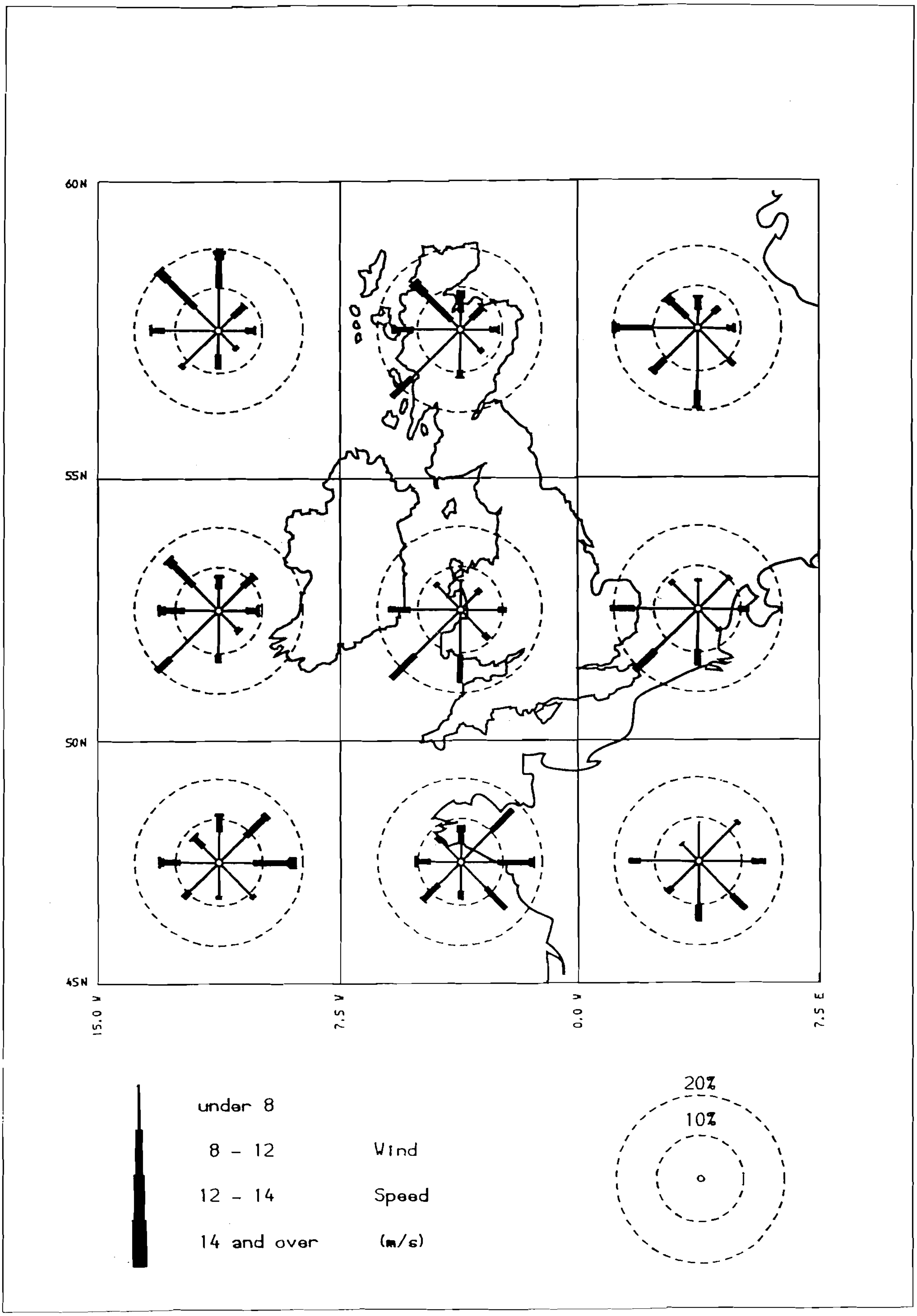


Fig 24 'Present' wind roses for the GCM grid points closest to the UK

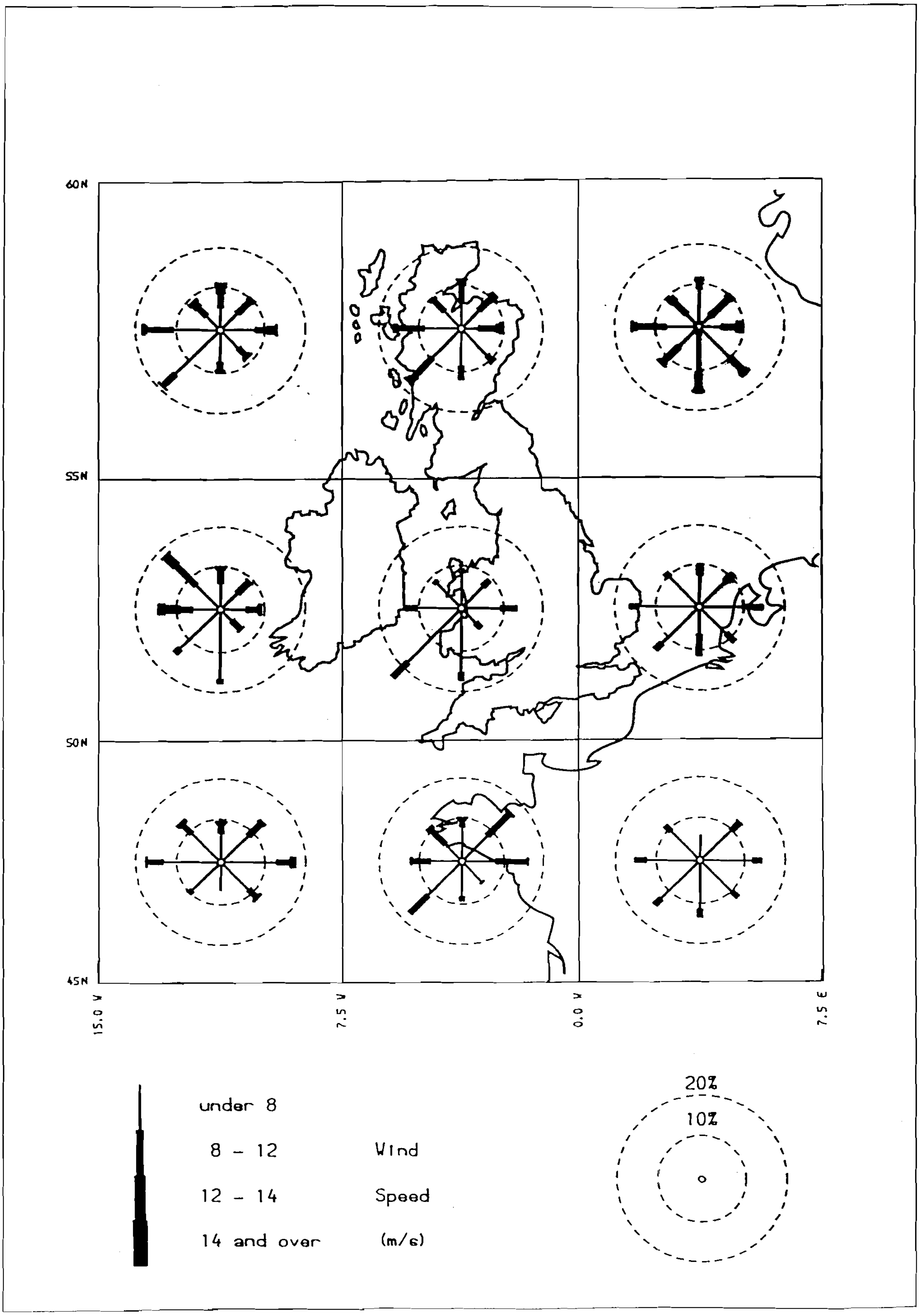


Fig 25 'Future' wind roses for the GCM grid points closest to the UK

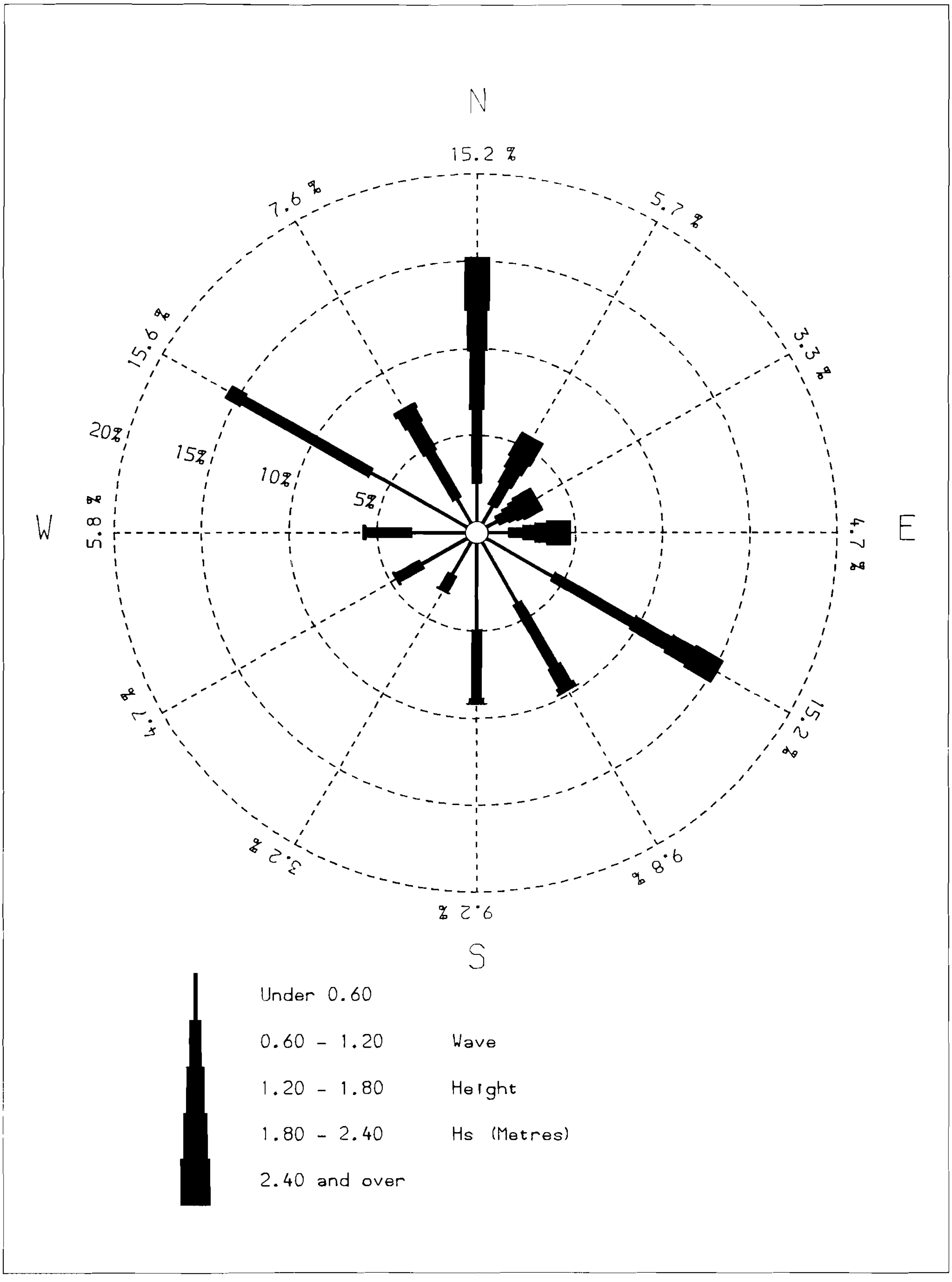


Fig 26 "Present" wave rose for Sunderland

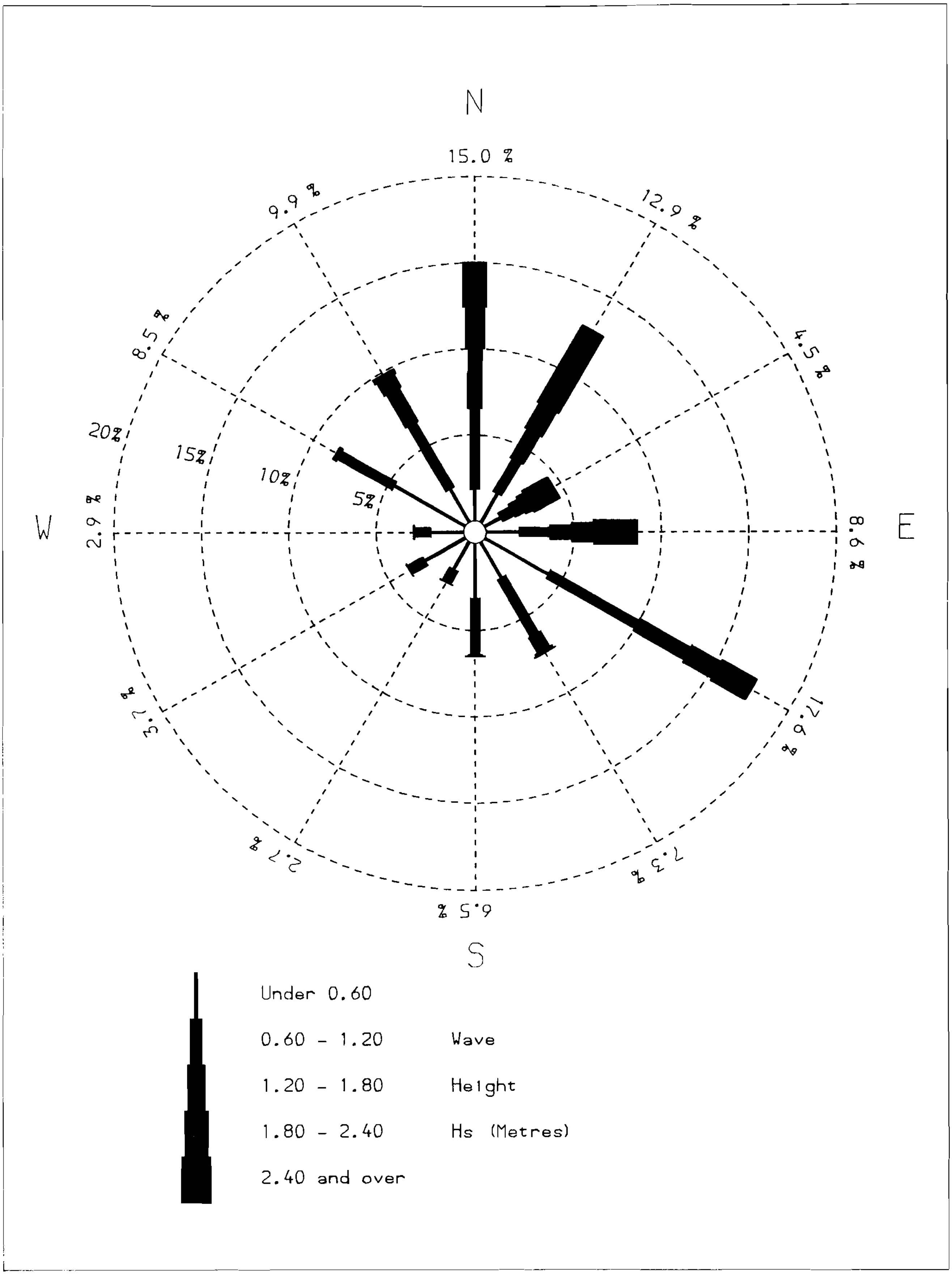


Fig 27 "Future" wave rose for Sunderland

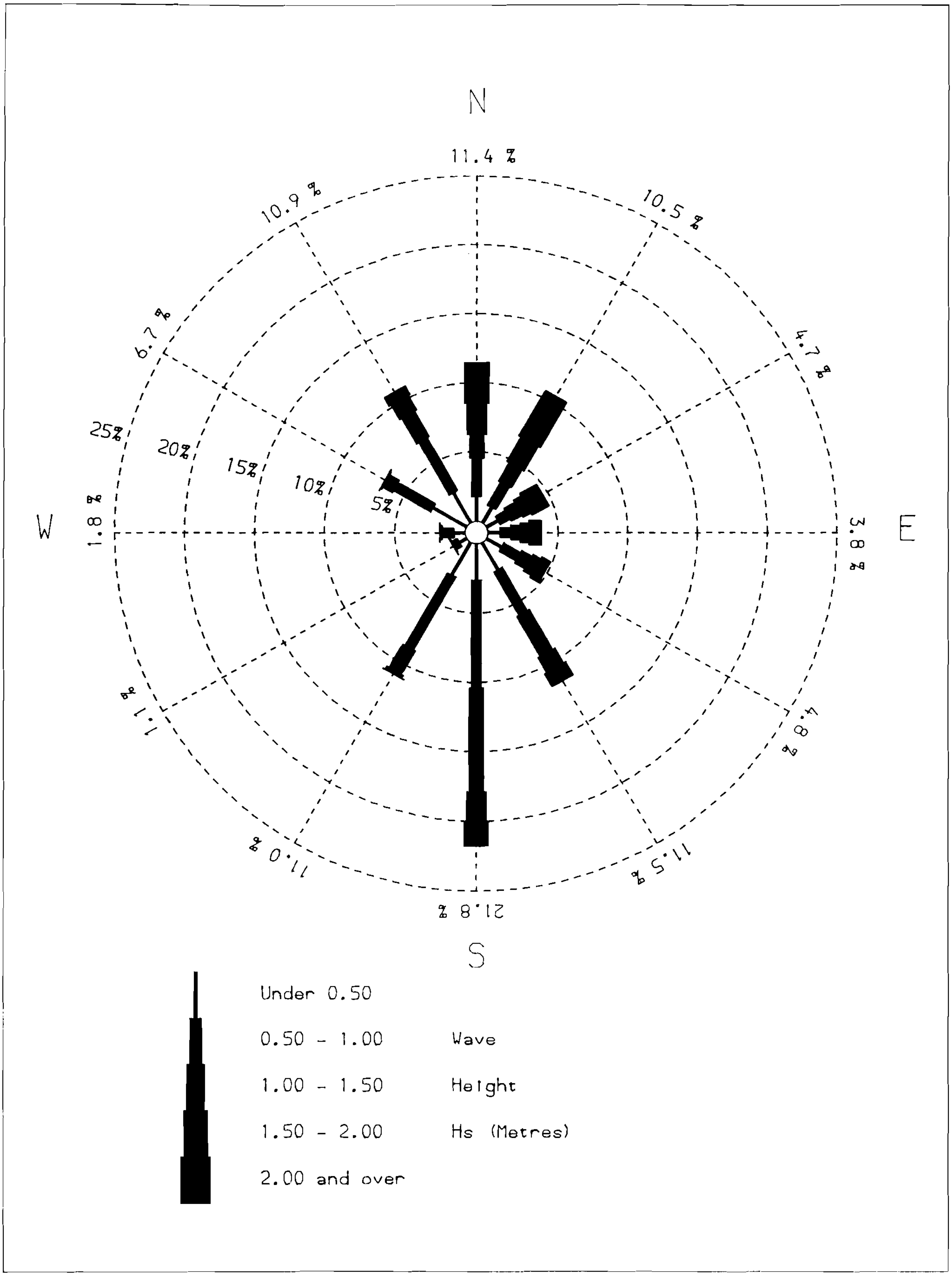


Fig 28 "Present" wave rose for Great Yarmouth

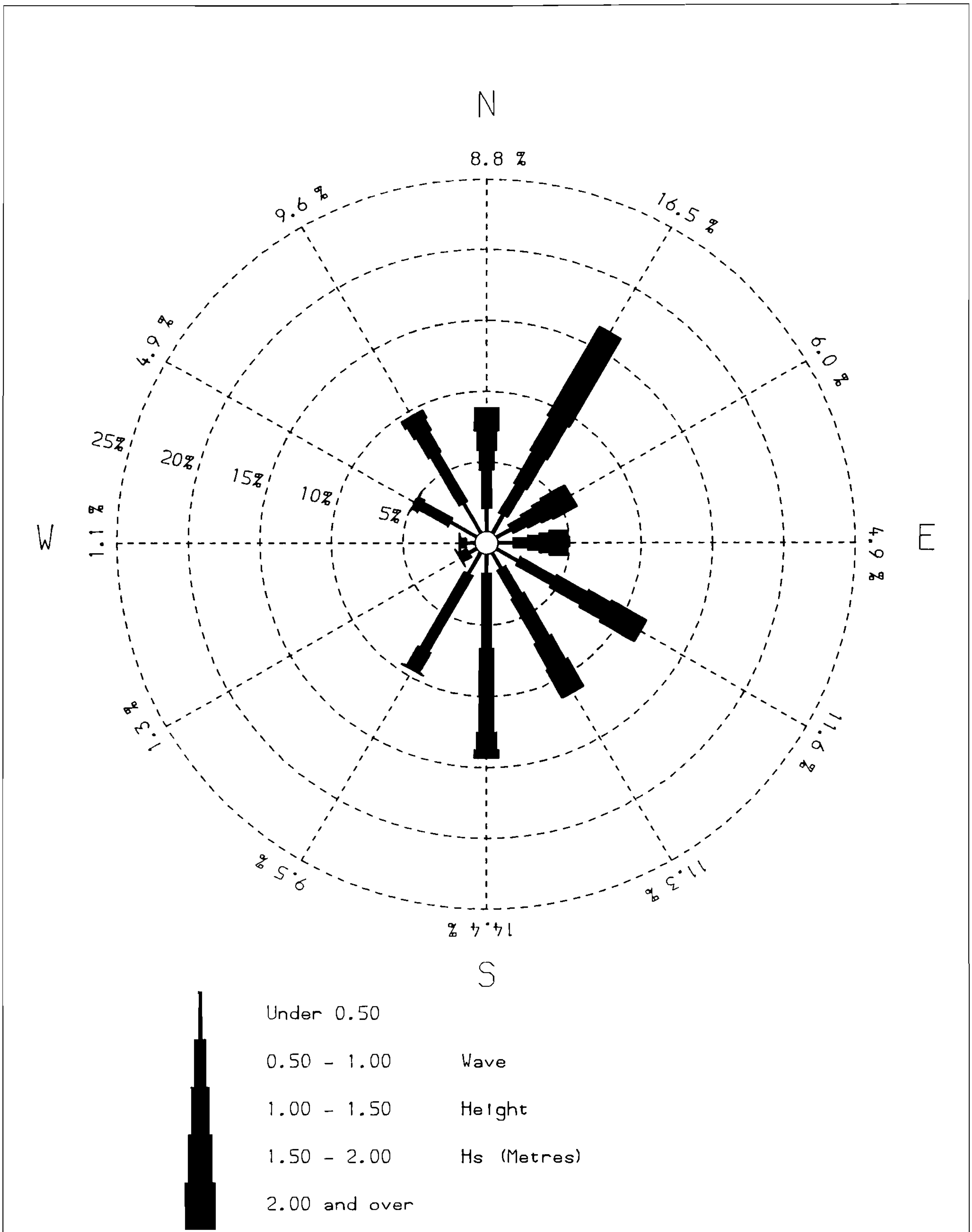


Fig 29 "Future" wave rose for Great Yarmouth

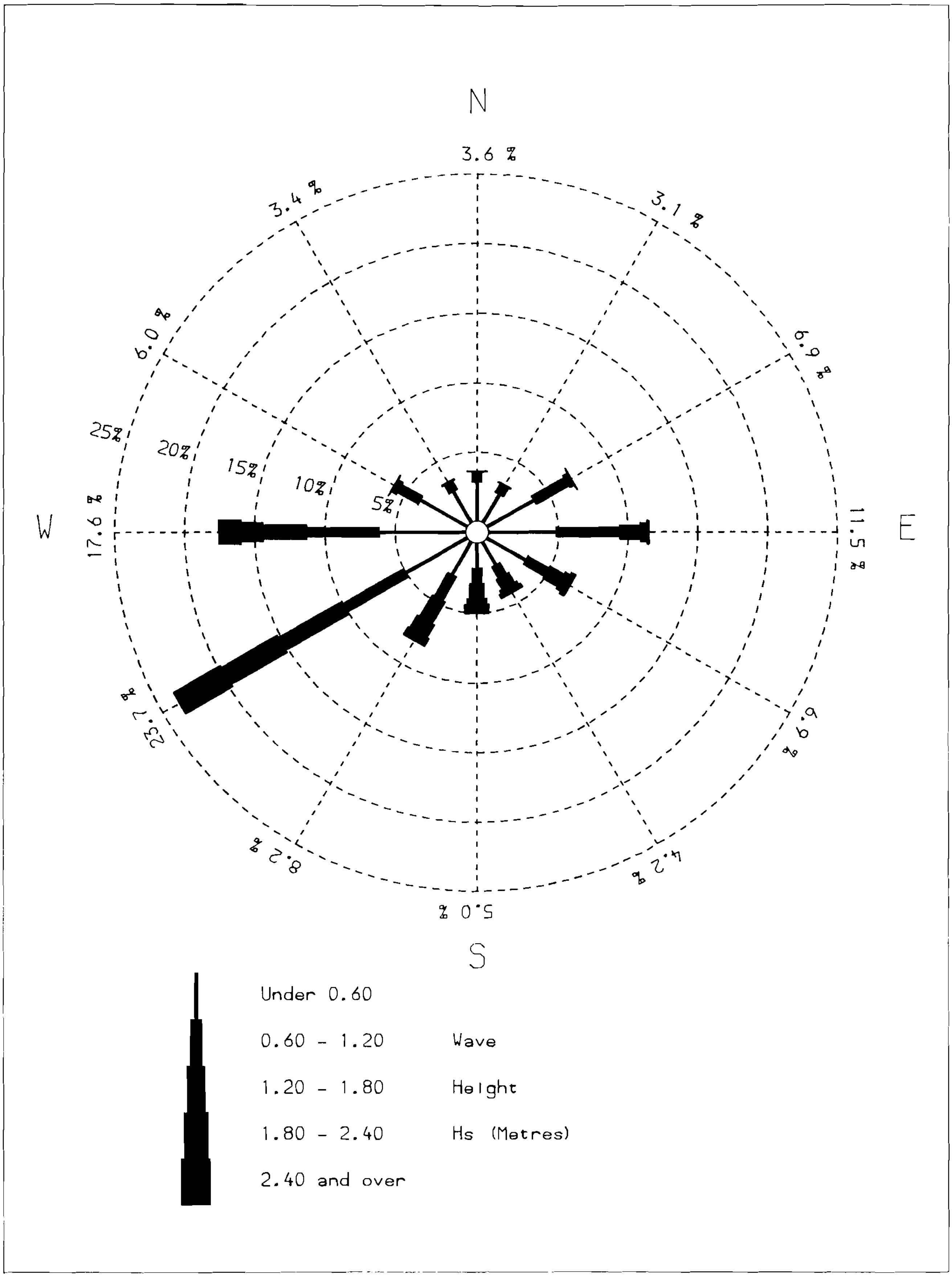


Fig 30 "Present" wave rose for Littlehampton

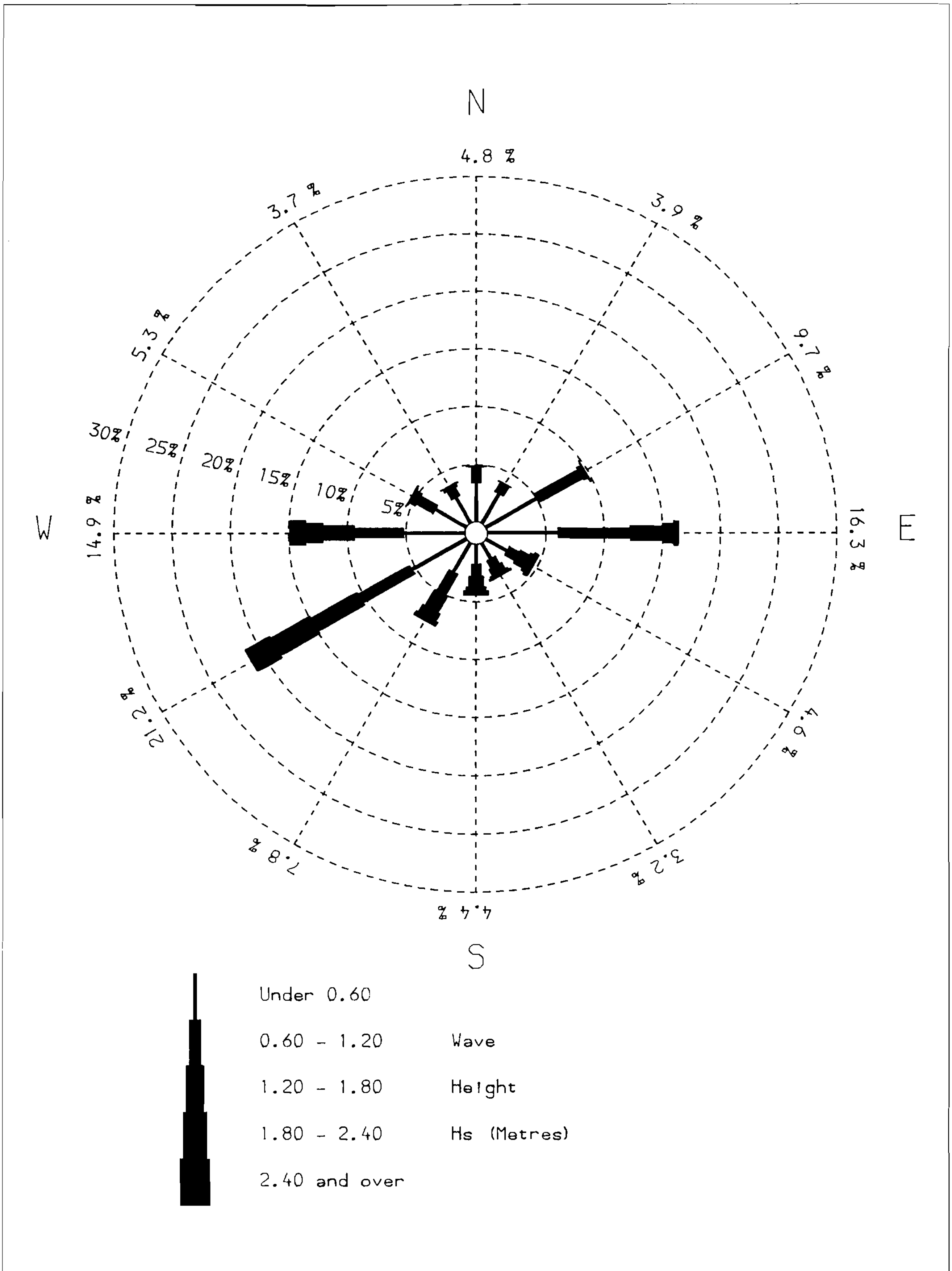


Fig 31 "Future" wave rose for Littlehampton

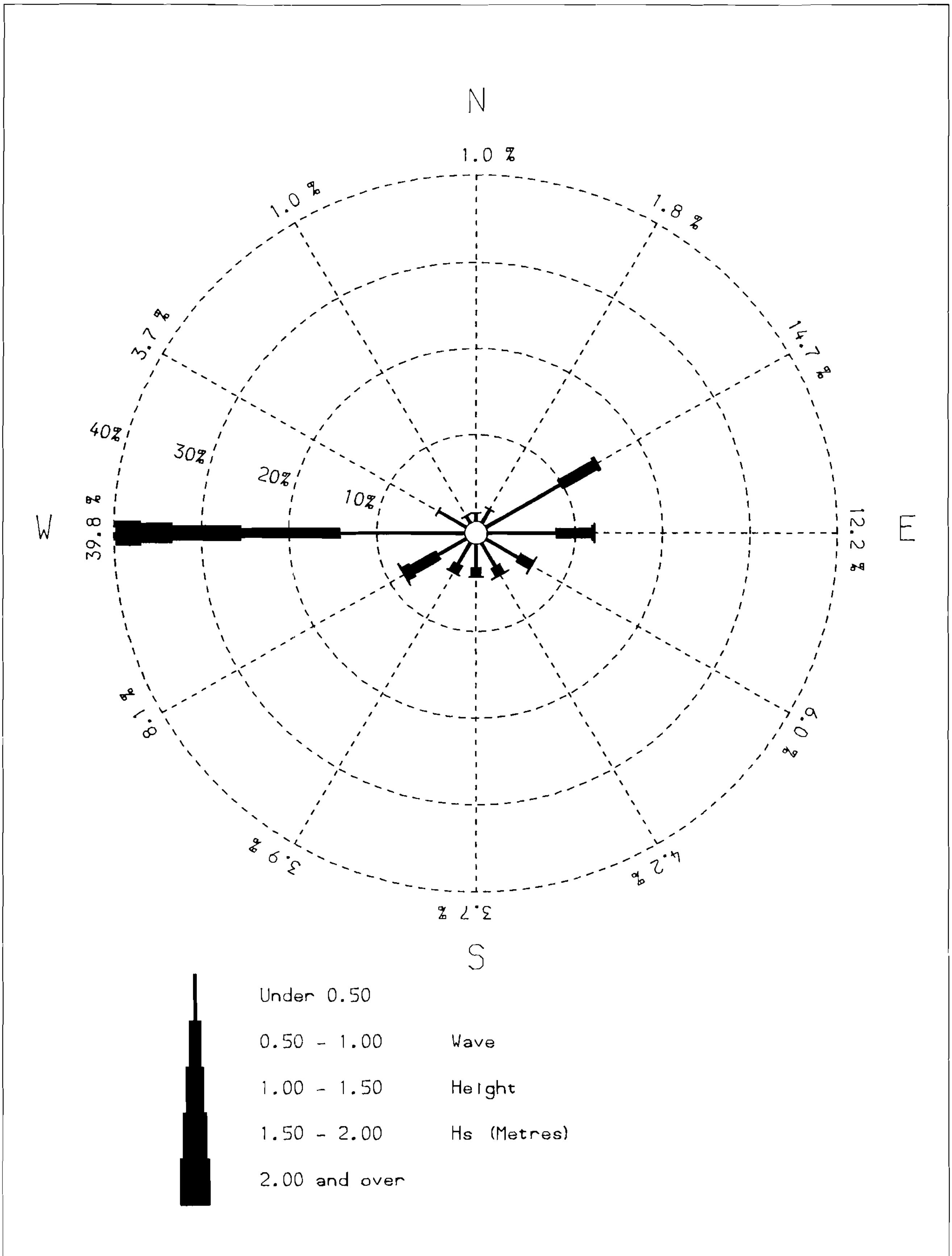


Fig 32 "Present" wave rose for Barry

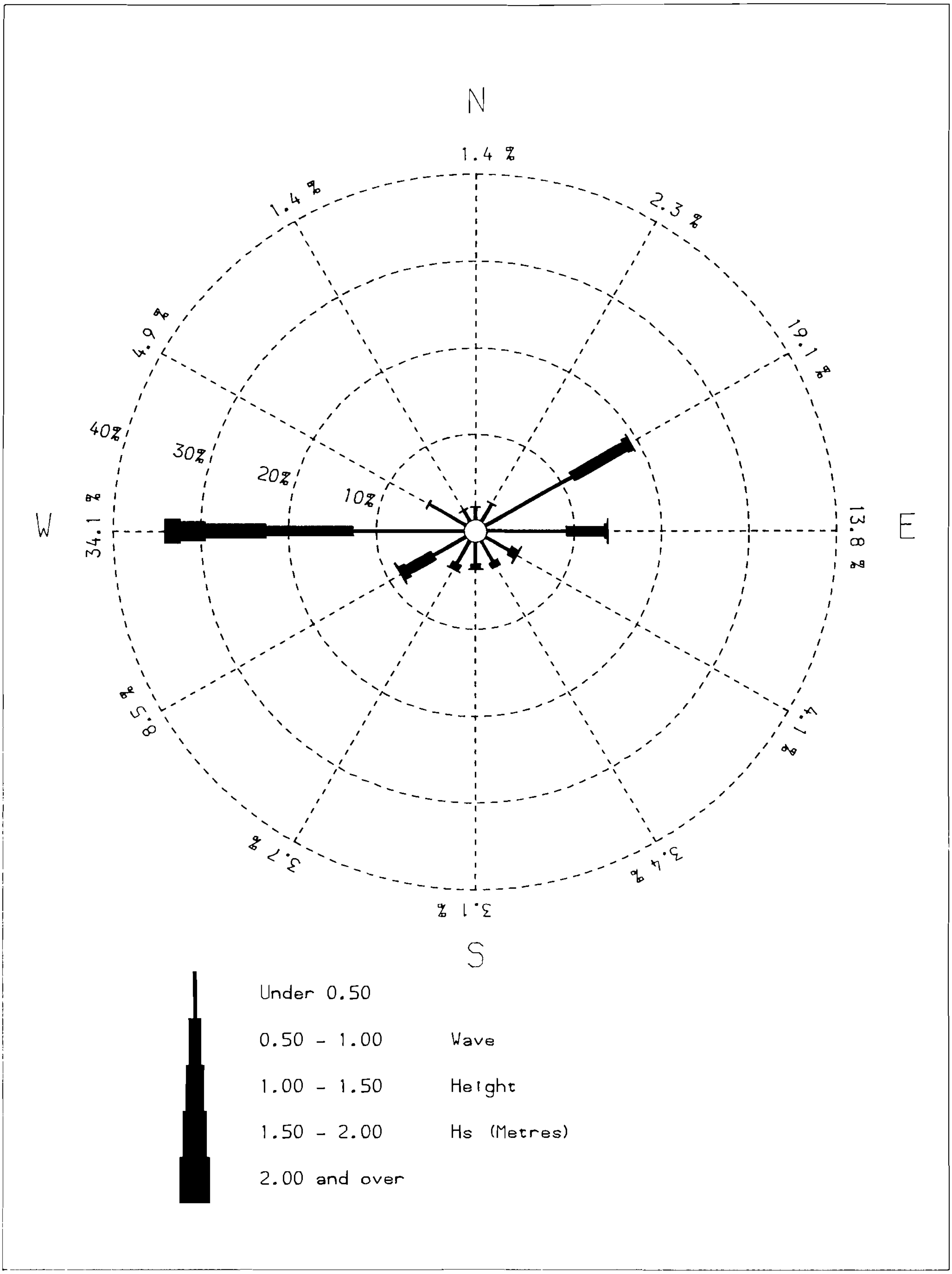


Fig 33 "Future" wave rose for Barry

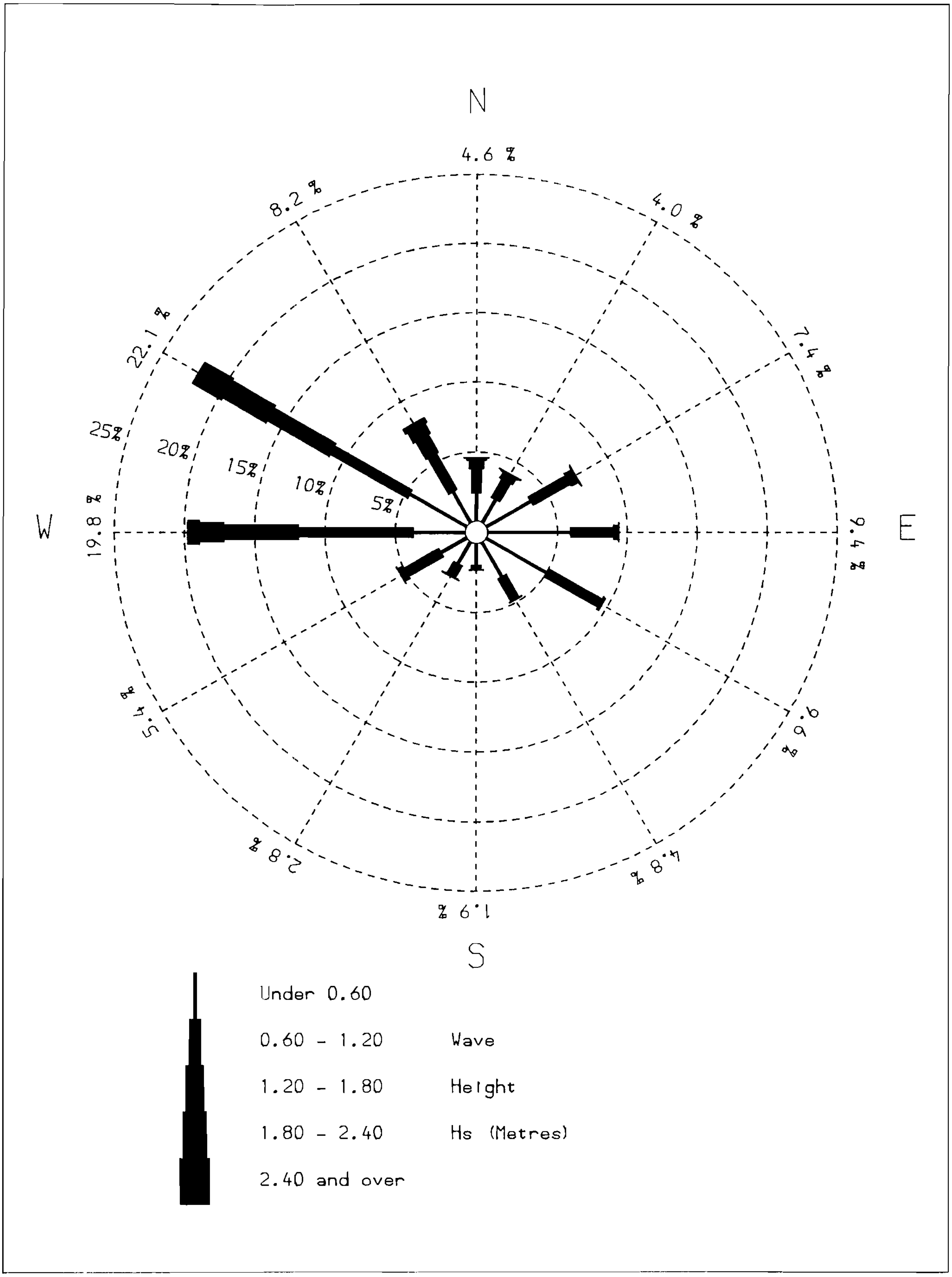


Fig 34 "Present" wave rose for North Wales

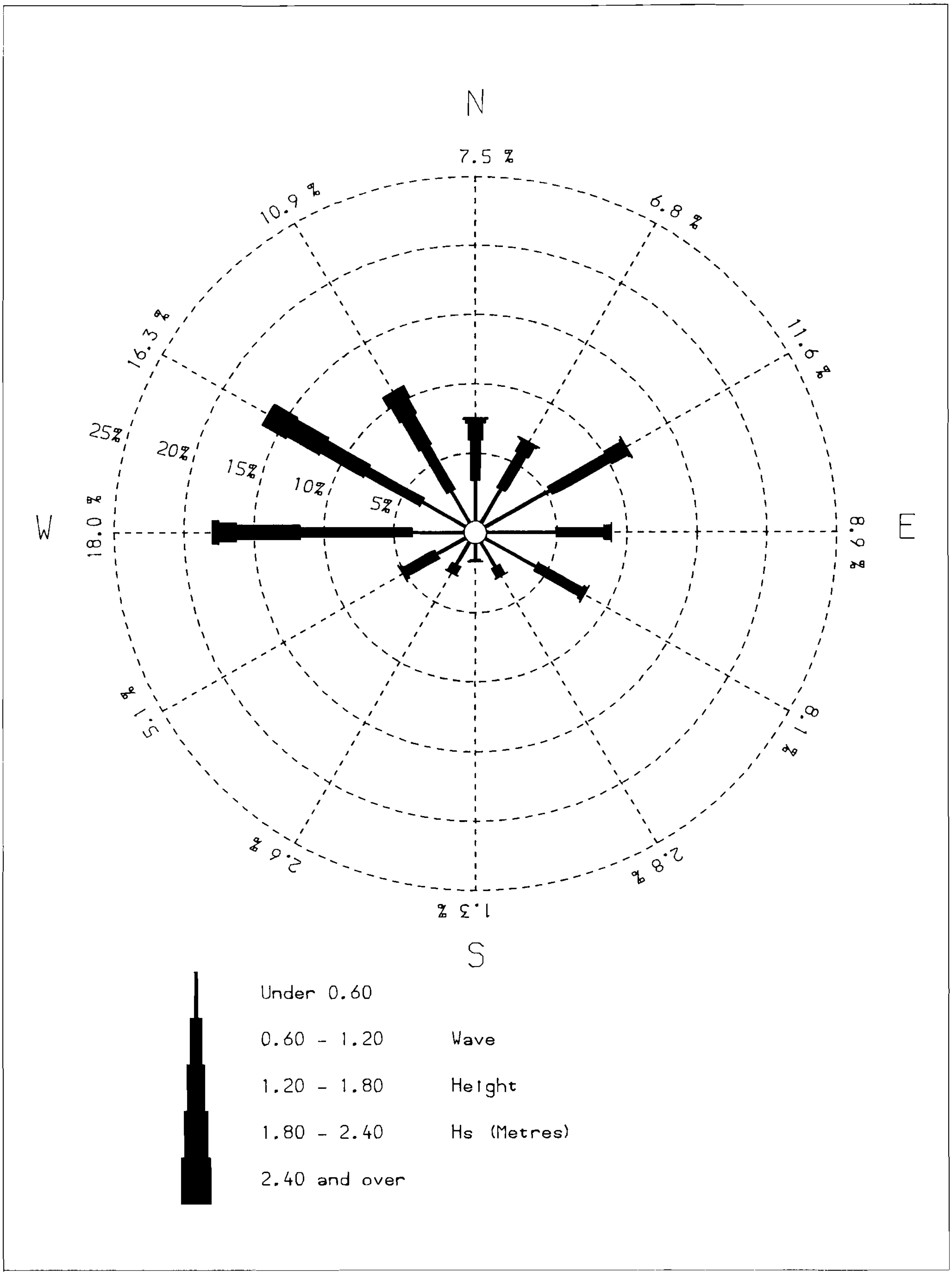


Fig 35 "Future" wave rose for North Wales

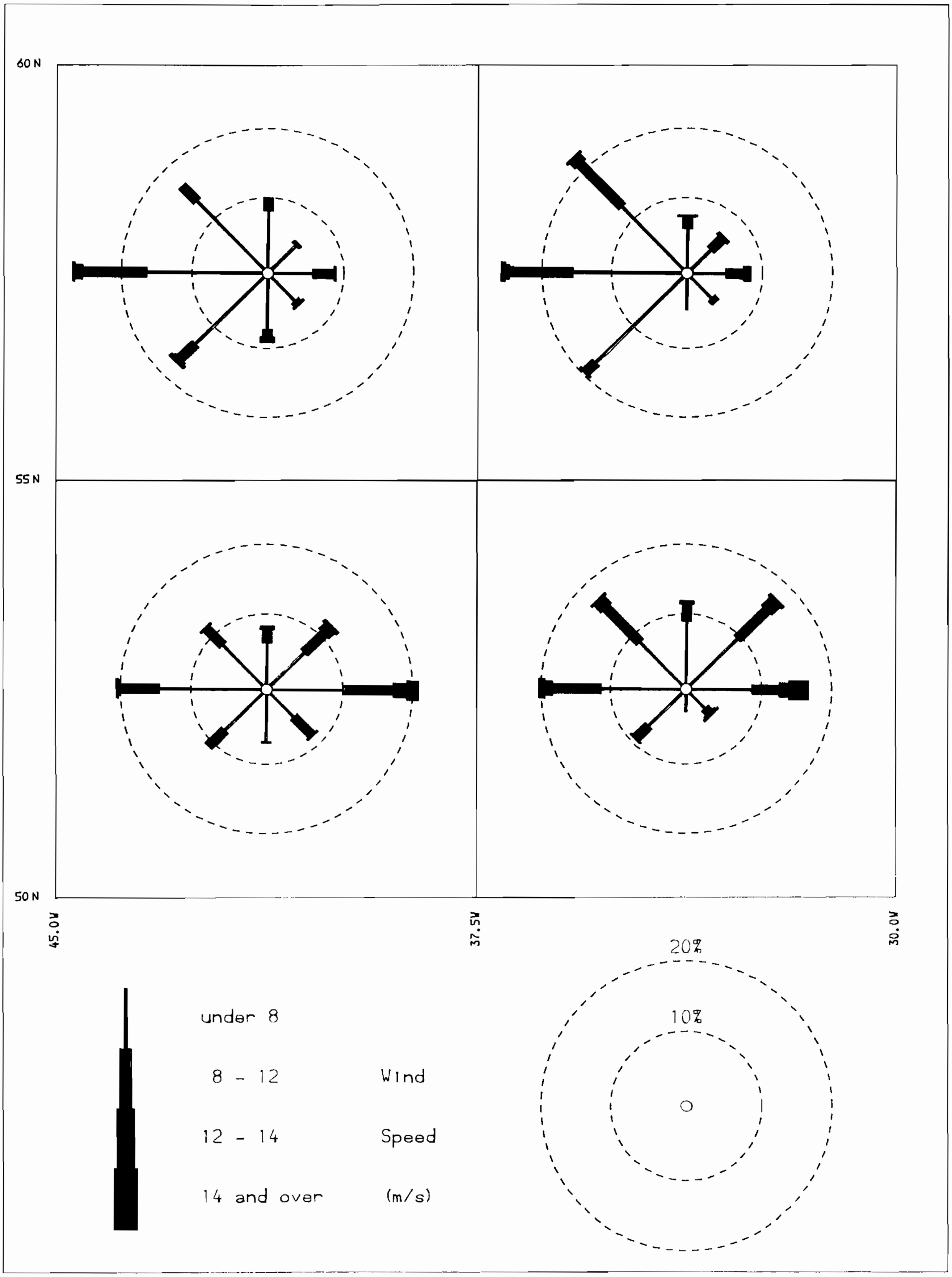


Fig 36 'Present' wind roses for four GCM grid points in the North Atlantic

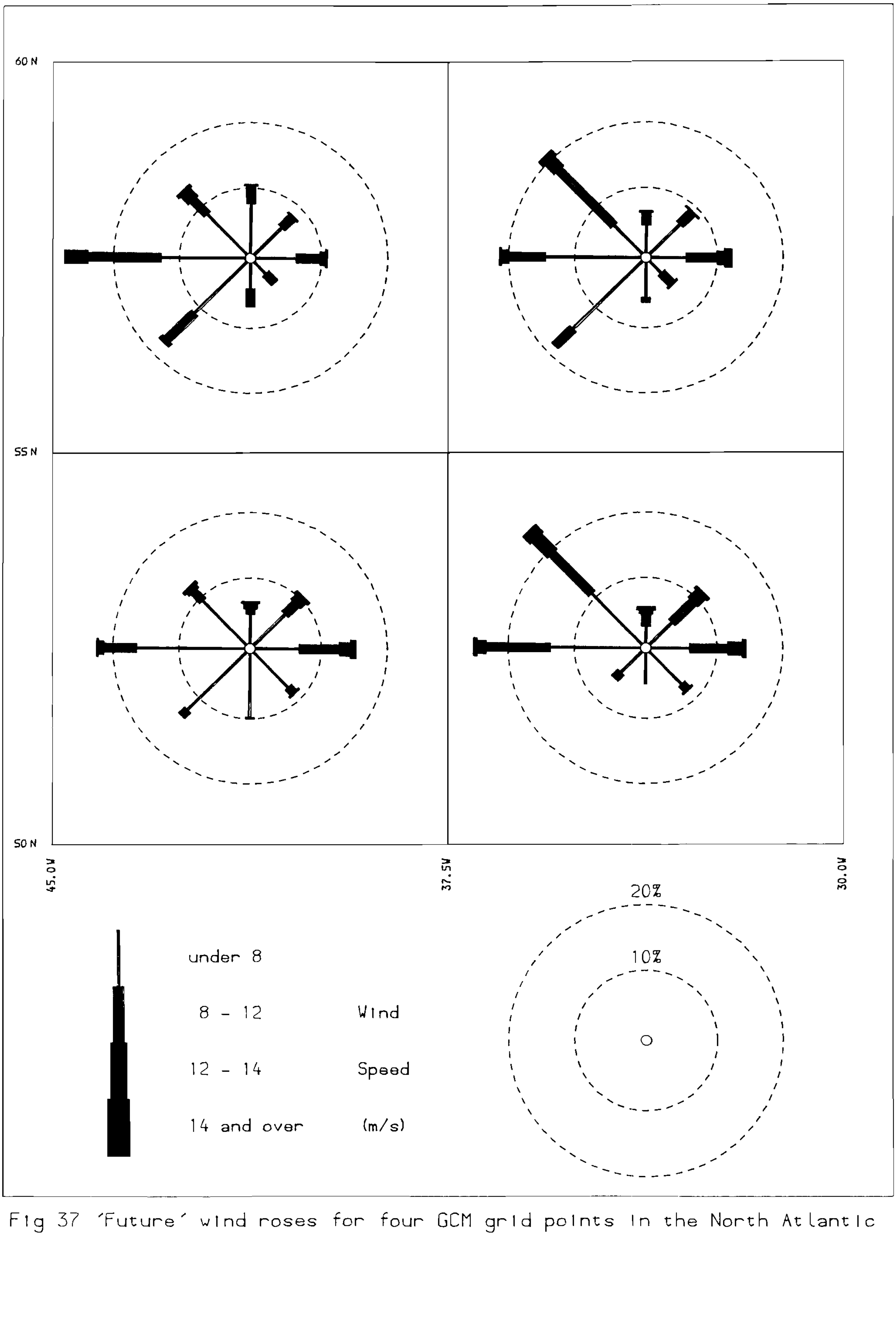


Fig 37 'Future' wind roses for four GCM grid points in the North Atlantic

Appendices

APPENDIX 1

The HINDWAVE wave hindcasting model

Simulation of time series wave
data from time series wind data

APPENDIX 1

The HINDWAVE Wave Hindcasting Model

The HINDWAVE Model

The HINDWAVE model (Ref 1) has been developed at HR, for prediction of wave climate at coastal locations, based on wind records for the area. It has been used successfully on many projects at various sites around the British coast.

The computations are split into two main parts. The first stage consists of production of a menu (or list) of about one thousand possible wave conditions from a similar number of specific wind conditions. Fetch or open water rays are measured at 10° intervals around the wave prediction point for use as input to the first element of HINDWAVE, ie the JONSEY wave generation sub-model described later in this Appendix. The second part consists of analysis of wind records. For each hour in the sequence, the wind/wave condition most closely corresponding to actual wind activity at that time is chosen from the menu. The analysis works with measured wind data collected at hourly intervals over a period of several years. The wave conditions at any time are estimated with regard to wind speeds during the preceding day or so.

It is first necessary to define a few standard terms used in wave prediction and analysis. Significant wave height (H_s) is a parameter in common use among coastal engineers as a means of expressing wave severity. It equates to the average height of the highest one third of the waves in a sequence. Wave period (T_z), or peak period (T_p) at which the wave energy spectrum is densest. Direction can be expressed as either wind direction (θ), or the mean wave direction (θ_w) averaged over all frequency and direction components.

The JONSEY program is used to assign a particular H_s, T_p and θ_w to each member of a particular set of wind conditions. The set comprises all possible combinations of sufficient values of speed, direction and duration to cover the range of values expected at that location. The predicted heights, periods and directions are stored for use as a look-up table. The technique described here is to break down the measured wind data into discrete categories, and then to select the corresponding H_s, T_p and θ_w from the table.

If the wind speed remains steady over a long period, a twenty-four hour or even longer generation time is likely to be appropriate for exposed sites. However, if the wind speed or direction is rapidly varying, a shorter duration will be used as input to the wave prediction equations. The method of selecting the duration, wind speed and wind direction for each hour, is explained below.

Hourly wind speeds and directions are obtained from the Meteorological Office in the form of a computer data file. For each hour in turn, the method determines, for the chosen group of durations, the dominant set of wind conditions at the prediction location, with reference to the H_s table. This is achieved by vectorially averaging the wind velocities over the various chosen durations leading up to that time in order to obtain an average speed and direction for each. The largest value is then selected from the corresponding set of H_s levels. This figure is retained together with the appropriate wave period and wave direction, in order to build up a probability distribution for each month.

A further option is automatic extrapolation to extreme wave heights, for different direction sectors, based on the overall predicted distribution of H_s. This is done by fitting a three-parameter Weibull distribution to the data in each direction sector in turn, after which the results are tabulated for various return periods.

The JONSWAP/ SEYMOUR wave prediction model

It is observed that wind-generated waves show some directional spreading about their mean direction of propagation. Wind travelling over a water surface transmits energy to the water in directions on either side of its own direction, which may fluctuate during the period of wave generation.

To incorporate this effect in the model, components of the total wave directional spectrum are calculated for various directions either side of the mean, and then a weighted average is taken using a standard spreading function. The significant wave height, period and direction are then calculated at the target point, by numerical integration of the spectrum.

The component directions (i = 1 to n) are spaced at regular intervals ($\Delta\theta$) in the range ±90° from the mean (θ_o). For each one (θ_i), the mean JONSWAP equation (Ref 2), representing a growing wind sea, is used to define the spectrum (E_i), given as a function of frequency (f):

$$E_i(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\{-1.25 (f/f_m)^{-4}\} \gamma^{\eta} \quad (1)$$

where:

$\alpha = 0.032 (f_m U/g)^{2/3}$

$\gamma = 3.3$

$$\eta = \exp\left\{\frac{-(f - f_m)^2}{2 f_m^2 \sigma^2}\right\}$$

$\sigma = 0.07$ for $f \le f_m$

0.09 for $f \ge f_m$

f_m = the peak frequency (Hz)

$= 2.84 g^{0.7} F^{-0.3} U^{-0.4}$

U = the windspeed (ms^{-1})

F = the fetch (m)

(fetch-limited conditions)

$= 0.008515 t^{1.298} g^{0.298} U^{0.702}$

(duration-limited)

g = the acceleration due to gravity (ms^{-2})

t = the duration (s)

The summation of the component spectra is then performed using the Seymour equation (Ref 3), which includes the cosine-squared directional spreading function for a directional wave spectrum ($E(f,\theta)$). It is applied in the range ±90° from the principle wind direction. If the fetches are measured at say 10° intervals ($\Delta\theta$), then the effective wave spectrum (E) for a particular direction (θ_o) is calculated as the weighted average for seventeen component spectra

$$(E_i(\theta_i), \theta_i = -80°, -70°, ..., 80° \text{ for } I = 1, 17)$$

as indicated in equation (2).

$$E = (2\Delta\theta/\pi) \sum_{i=1}^{17} E_i \cos^2(\theta_i - \theta_o) \qquad (2)$$

Although it is not part of the original theory, experience at HR indicates that cosine-sixth is sometimes a better spreading function to use. This is particularly true when the wave generation area is unusually narrow or the peak period is unusually long. In order to use this modification, the cosine term in equation (2) is raised to the power six rather than two, and the coefficient $2/\pi$ is increased to $3.2/\pi$.

The significant wave height (H_s) is the average height of the largest one third of the waves. The mean zero-upcrossing period (T_z) is the period measure most frequently used in engineering, this being the average time between successive upcrossings of the mean level by the water surface. The mean wave direction (θ_w) is taken as the average of the spectral components over all frequencies and directions. They are all approximated by numerical integration of equation (2).

$$H_s = 4m_0^{1/2} \tag{3}$$

$$T_z = (m_0/m_2)^{1/2} \tag{4}$$

$$\theta_w = \theta_0 + \frac{\int\int E(f,\theta)\ (\theta - \theta_0) df d\theta}{\int\int E(f,\theta) df d\theta} \tag{5}$$

where $m_n = \int E(f)\ f^n df$

In order to use this method, fetch lengths must be known over a range of at least 180° around a point. It is convenient to use discrete frequencies in equations (1) and (2) which should also be specified.

For each application of the method, a duration and a fetch are given, although only one or other of these will produce the limiting condition used in equation (1). A complete directional spectrum is calculated, from which is obtained the one-dimensional spectrum as well as H_s, T_z and θ_w.

The directional spread of the predicted wave spectrum will generally be frequency dependent. The cosine-squared function is applied to component spectra, which are generated over different fetch lengths, and which will consequently have different total energies and different peak frequencies. This has the following realistic effect upon the calculated directional spread of energy. If the wind direction corresponds to one of the long fetch directions, then the spreading of energy at the peak will be lower than average, whilst more spreading will be observed at the highest frequencies. If the wind is blowing along one of the shorter fetches, then the spread will tend to be more even across different frequencies, and in an extreme case, may produce greater than average spreading at lower frequencies.

References

1. Hawkes P J. A wave hindcasting model. Conference on modelling the offshore environment, Society for Underwater Technology, April 1987.

2. Hasselmann K et al. Measurements of wind wave growth, swell and decay during the Joint North Sea Wave Project (JONSWAP). Deutsches Hydrographisches Institute, Hamburg, 1973.

3. Seymour R J. Estimating wave generation on restricted fetches. Proc ASCE, Vol 103, No WW2, May 1977.

APPENDIX 2

The BEACHPLAN model :

The relationship between waves and littoral drift

APPENDIX 2

The beach plan shape mathematical model

In this Appendix a general description of the beach mathematical model is given. Further details on the derivation of the equations presented here, and the numerical scheme used for their solution can be found in Ref 1.

The model is essentially a finite difference solution of the following equation which expresses the continuity of the volume of sediment moving along the shoreline:

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} = 0 \qquad (1)$$

where:

Q is the volume rate of alongshore sediment transport,
x is the distance along the shore,
A is the beach cross-sectional area, and
t is time

The basic equation can be modified to:

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} + q = 0 \qquad (1A)$$

where q is used to express the volume of material brought onshore by wave action, added to the beach by artificial nourishment or removed from the beach by mining. By denoting the co-ordinate perpendicular to the beach by y, the beach cross-sectional area, A, can then be expressed by the product of y and a depth D. If D is assumed not to vary with time, then equation (1A) can be written:

$$\frac{\delta Q}{\delta x} + D \frac{\delta y}{\delta t} + q = 0 \tag{2}$$

Starting from some initial position, y = y (x), the model evaluates successive beach positions at time intervals δt, at points along the shore separated by δx. So for each ordinate x_i (separated from its neighbour x_{i+1} by δx) we have y_i (0), y_i (δt), y_i ($2\delta t$) and so on. The model used is of a type known as 'one-line', that is to say that the beach position is given by the location of a single contour which represents, say, the high water line. An important factor in the accuracy of the model is the representation of the alongshore rate of sediment transport, Q, which is dominated by the breaking waves. For waves of small unevenness in height along a beach with nearly straight contours, Q can be well approximated by:

$$Q = K_1(\gamma_s)^{-1}E_b(nC)_b(\sin 2\alpha_b - K_2 \frac{\delta H_b}{\delta x}\cot \beta \cos \alpha_b) \tag{3}$$

where

K_1, K_2 are non-dimensional coefficients

E is the wave energy density = $0.125\rho\, gH^2$

H is the wave height

g is the acceleration due to gravity

ρ is the water density

γ_s is the submerged weight of beach material in place

nC is the group velocity of the waves

α is the angle between their crests and the local depth contours

$\tan\beta$ is the mean slope of the beach face, and where

b used as a subscript denotes breaking wave conditions.

The first term in equation (3) is the well known CERC (Scripps) formula and describes the alongshore sediment transport due to obliquely breaking waves. The second term takes into account the transport created by any alongshore variation in breaking wave height, which becomes important for beaches in the lee of headlands or breakwaters where diffraction effects are significant.

Some of these quantities (ρ, g, $\tan\beta$ and γ_s) can be found, or accurately estimated, whilst others have to be deduced from site data. For example, the coefficient K_1 was found to be about 0.38 on the sandy Californian coast of the United States. In tests carried out at HR during the proving stages of the model K_1 = 0.35 gave the best results and this is the value that we apply for estimating the littoral transport of sand (Ref 2). However, from our experience we have found that at a site where beach material is a mixture of sand and shingle, the rate of transport can be ten times less than that of sand (Ref 3). Studies using aluminium tracer pebbles carried out by Southampton University have shown that shingle transport alone may, in fact, be eighteen times less than that of sand. Hence a value of K_1 = 0.02 is used for estimating littoral transport of shingle.

Very little practical work has been carried out into the assessment of K_2. Purely theoretical calculations (Ref 1) can produce a value of 3.2, but some recent work by Kraus & Harikai (Ref 3) has suggested a low figure may be more correct, in the range from 0.8 to 1.2. For the sand beaches a value of K_2 = 1.1 is normally used.

The height, period and direction of the breaking waves, however, are more difficult to prescribe. Although it is occasionally possible to represent the mean annual wave activity at a site by a single breaking wave condition, typically several such conditions are required. Often it is necessary to supplement such wave data, either with results from the analysis of previous beach plan shape changes in the study area, or by using offshore wave conditions and predicting the resulting conditions at wave breaking by means of wave refraction analysis.

Having specified the data for the model, the sequence of operations is as follows:

1. For the first breaking wave condition, the alongshore rate of sediment transport is calculated at regular spacings along the shoreline using equation (3) above.

2. The difference in neighbouring rates of transport is then used to calculate the erosion or accretion of the beach, during a time interval δt, in the intervening sections, giving a new beach plan shape.

3. A check is made that the model has not become 'unstable', a common problem in the numerical solution of differential equations. (If the model has become unstable it automatically reduces the time-step δt that it is using, and step 2 is re-worked).

4. Having accepted the new beach plan shape steps 2 and 3 are repeated until the required

duration of the first wave condition has been reached. The whole procedure is then repeated for the remaining wave conditions. The model prints out the beach plan shape at intervals of one or two years and can be run for as many years as required. However, if the beach shape is changing rapidly it is sometimes necessary to pause and re-compute the wave refraction patterns and hence the incident wave conditions every few years.

For any particular study, it is necessary not only to prescribe the incident wave conditions, beach slope and composition but also any 'boundary' conditions. Some examples are:

1. **Free boundary** - Often, at one end of the stretch of the coast being considered lies a long straight beach where sediment is free to move along the shore without hindrance. The beach at this model boundary must therefore be allowed to accrete or erode as it wishes, and sediment allowed to cross the boundary in either direction.

2. **Fixed boundary** - Any point along a beach can be fixed, i.e. not allowed to accrete or erode. This may be the case at a rock outcrop, for example, and such a condition can be applied at a boundary of the model or inside the area being studied.

3. **Specific transport boundary** - In this case the rate at which sediment crosses a section of the model can be specified. The most usual application is the special case where the rate is set to zero. This condition can therefore be used to describe the result of building a groyne or harbour arm. As in the previous

example, this condition can be used either at a boundary or inside the model.

4. **Inerodible boundary** - This condition can be used to describe a seawall, allowing accretion of the beach in front of some specified limit but not allowing it to erode landward of that limit. Again this condition may be used at any point along the beach, not just at its ends.

References

1. OZASA H and BRAMPTON A H. Models for predicting the shoreline evolution of beaches backed by seawalls. HR Ltd, Report IT 191, 1979.

2. PRICE W A, TOMLINSON K W and WILLIS D H. Predicting changes in the plan shape of beaches. Proceedings 13th Coastal Engineering Conference, Vancouver, 1972.

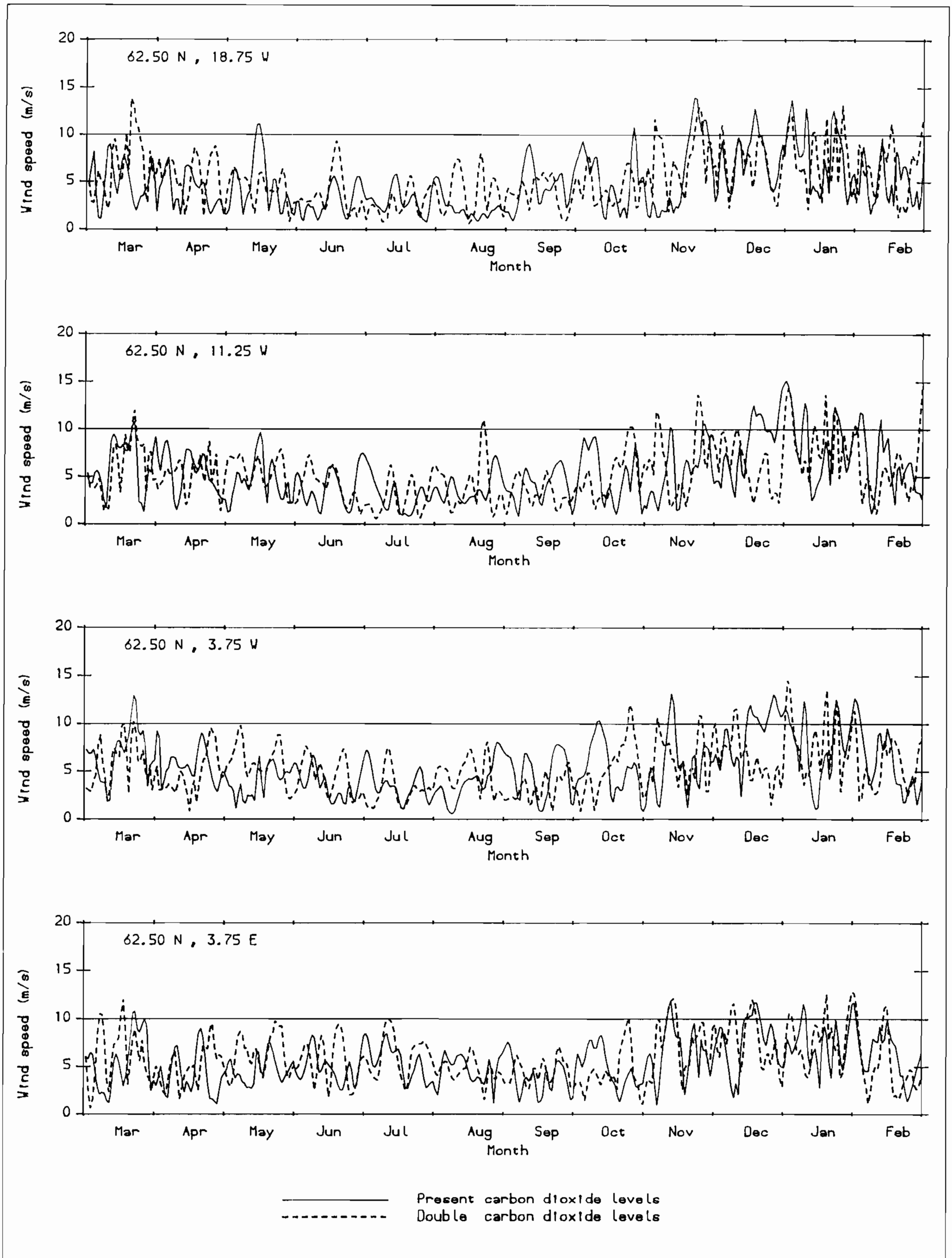
3. KRAUS N C and HARIKAI S. Numerical model of the shoreline change at Oarai Beach, Coastal Engineering, No 1, 1983.

APPENDIX 3

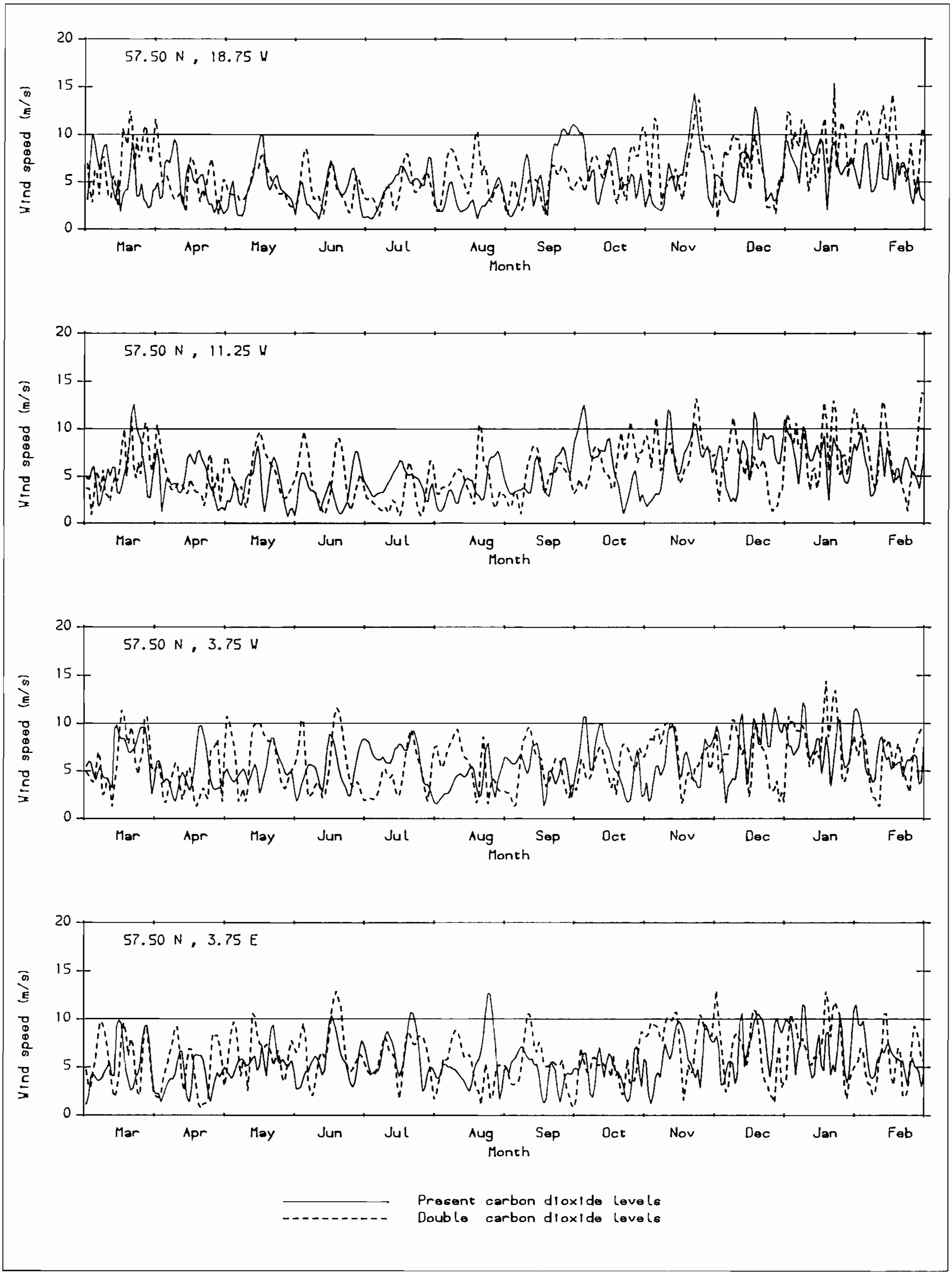
Time series wind data for present and future conditions from the Meteorological Office Global Climate Model

Data is reproduced for a model run of one year's duration for 16 grid points over or around the UK and for 4 grid points in the North Atlantic.

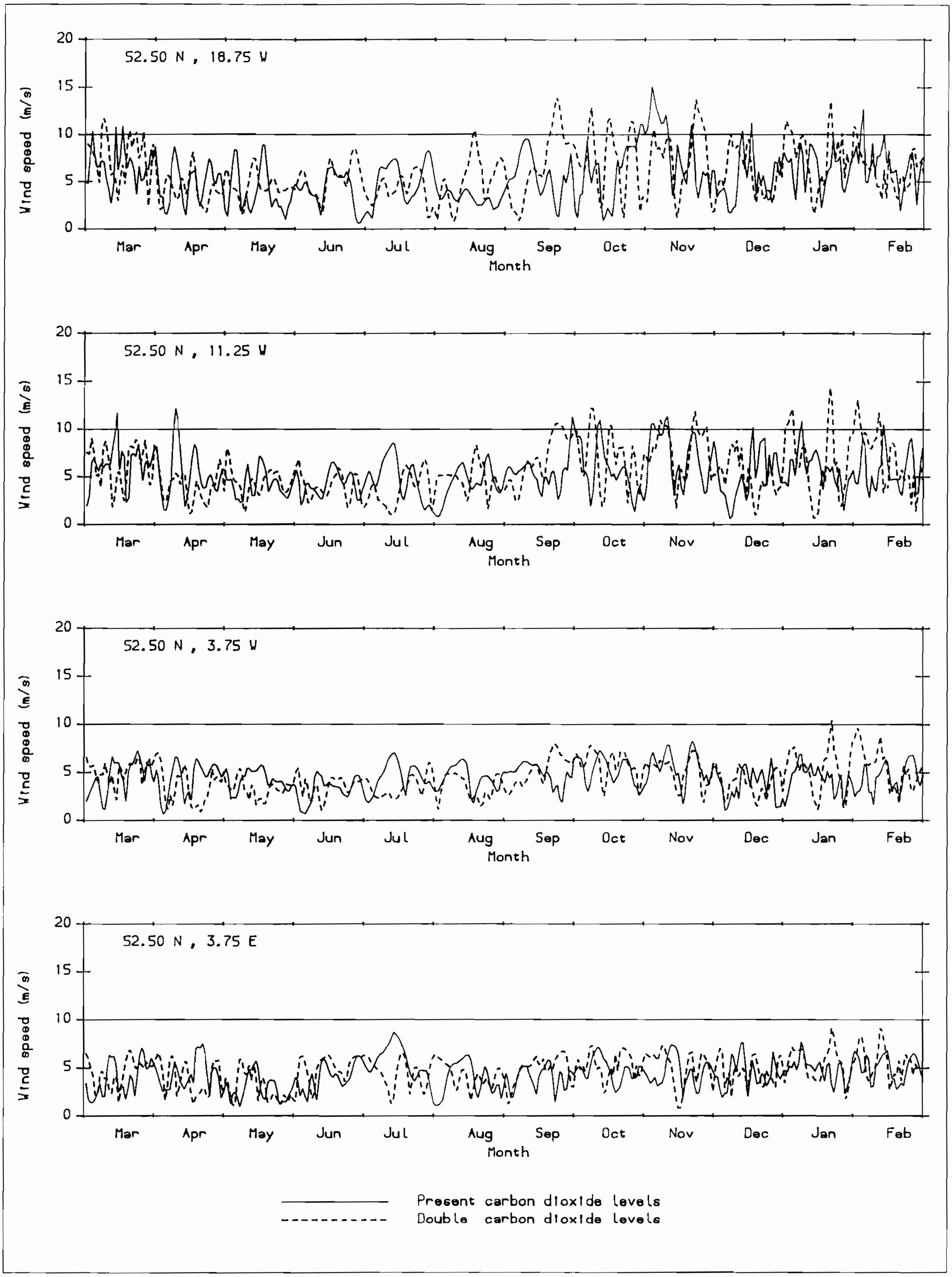
The first four pages show overlaid time series plots of daily averaged wind speed, both for present and doubled CO_2 conditions, for the 16 UK points. The next eight pages show overlaid time series plots of wind speed and direction based on the midnight wind vector data, for present and doubled CO_2 conditions, for the 16 UK points. The last two pages show overlaid time series plots of wind speed and direction based on the midnight wind vector data, for present and doubled CO_2 conditions, for the 4 North Atlantic Points.



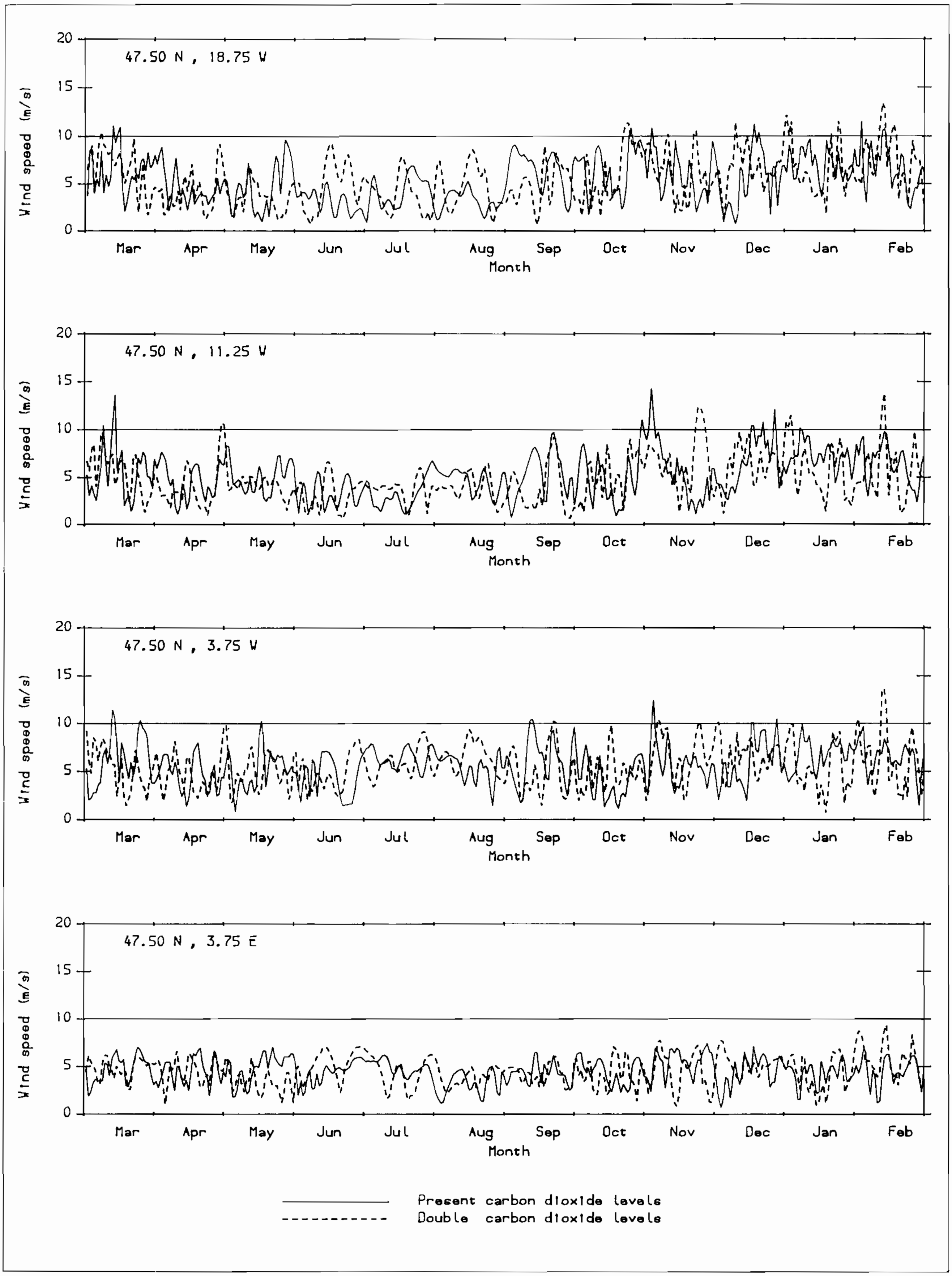
Present and future daily averaged wind speeds - 62.5 N



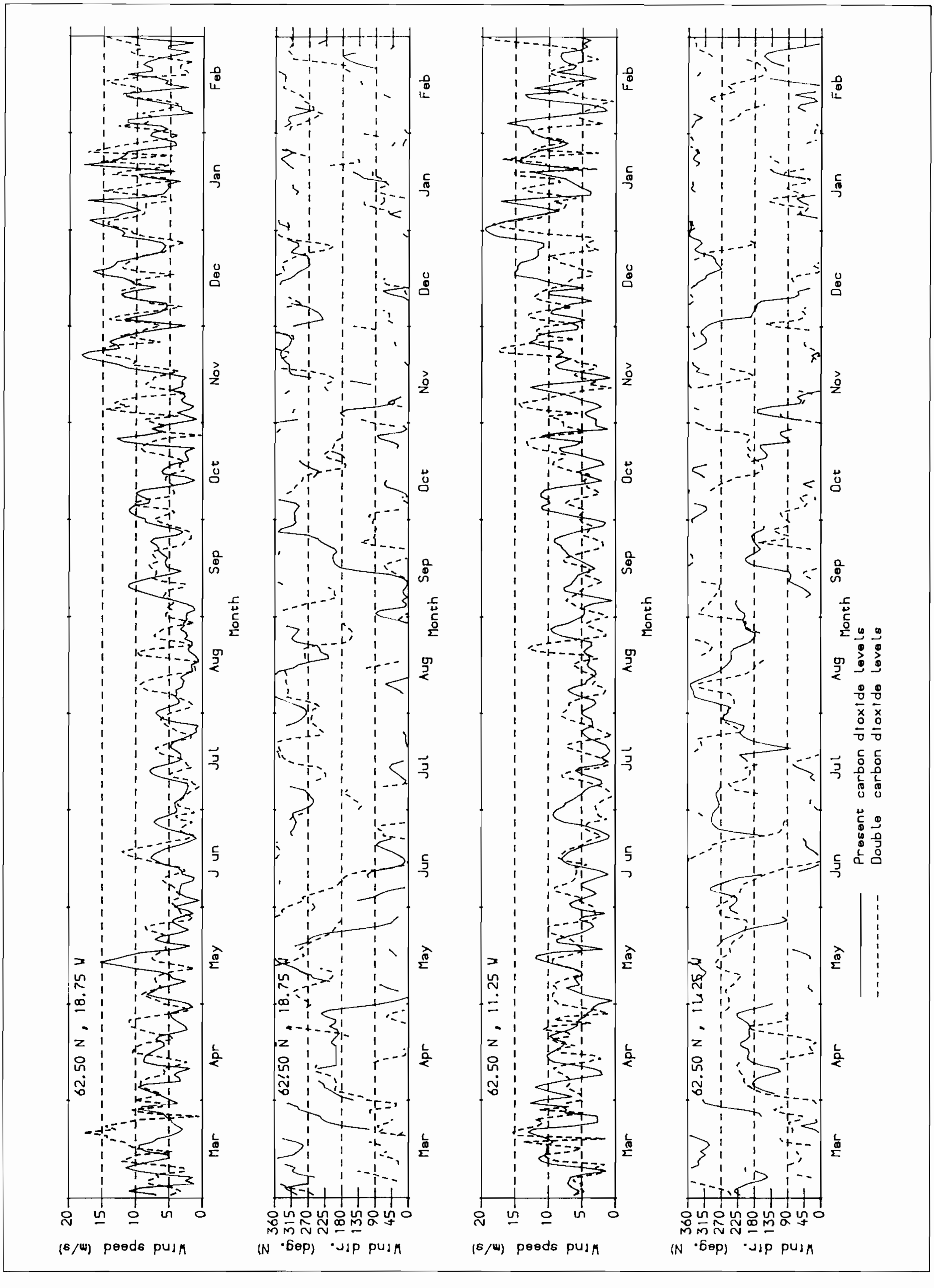
Present and future daily averaged wind speeds - 57.5 N



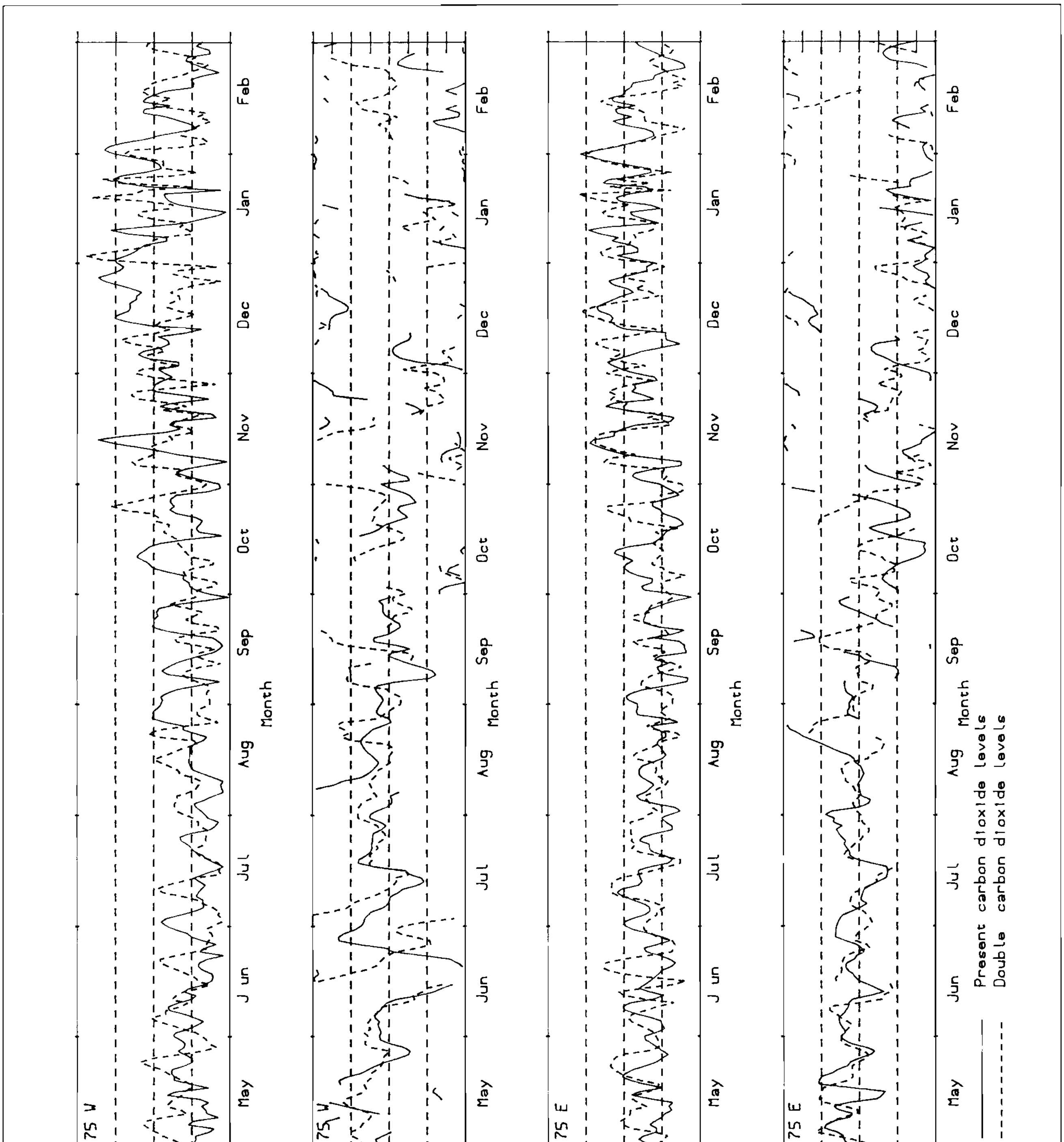
Present and future daily averaged wind speeds - 52.5 N



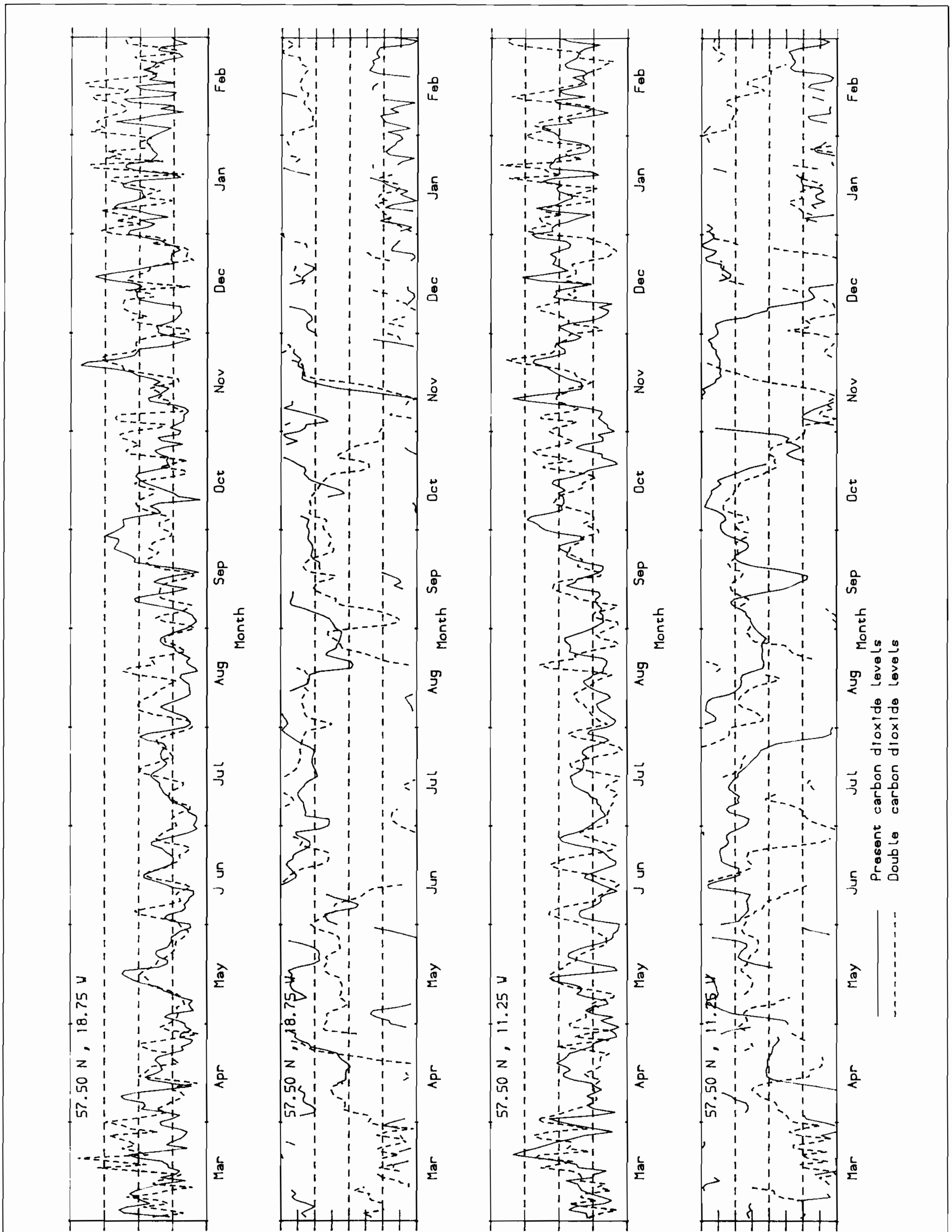
Present and future daily averaged wind speeds - 47.5 N



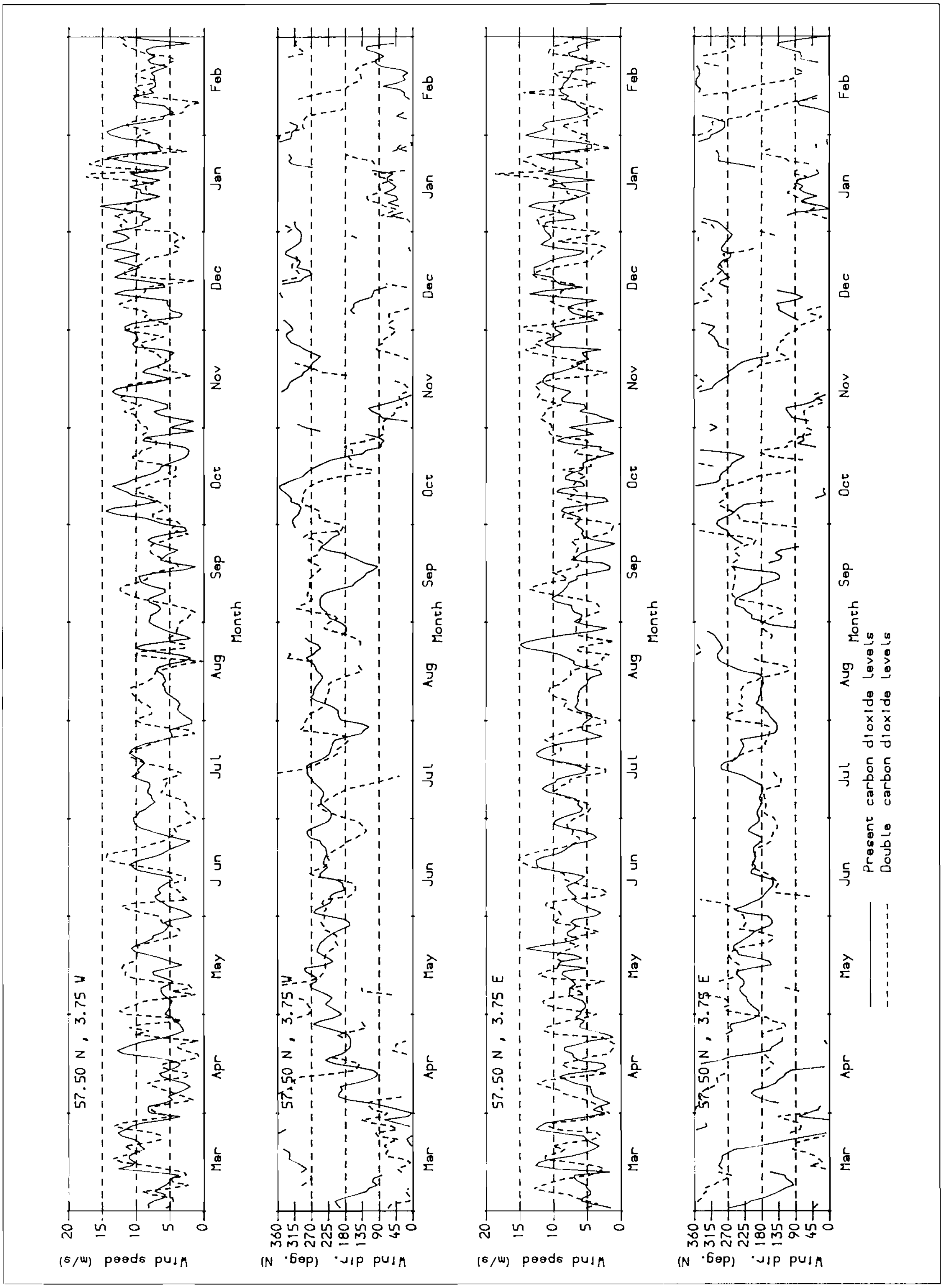
Present and future wind conditions - 62.5 N , 18.75 & 11.25 W



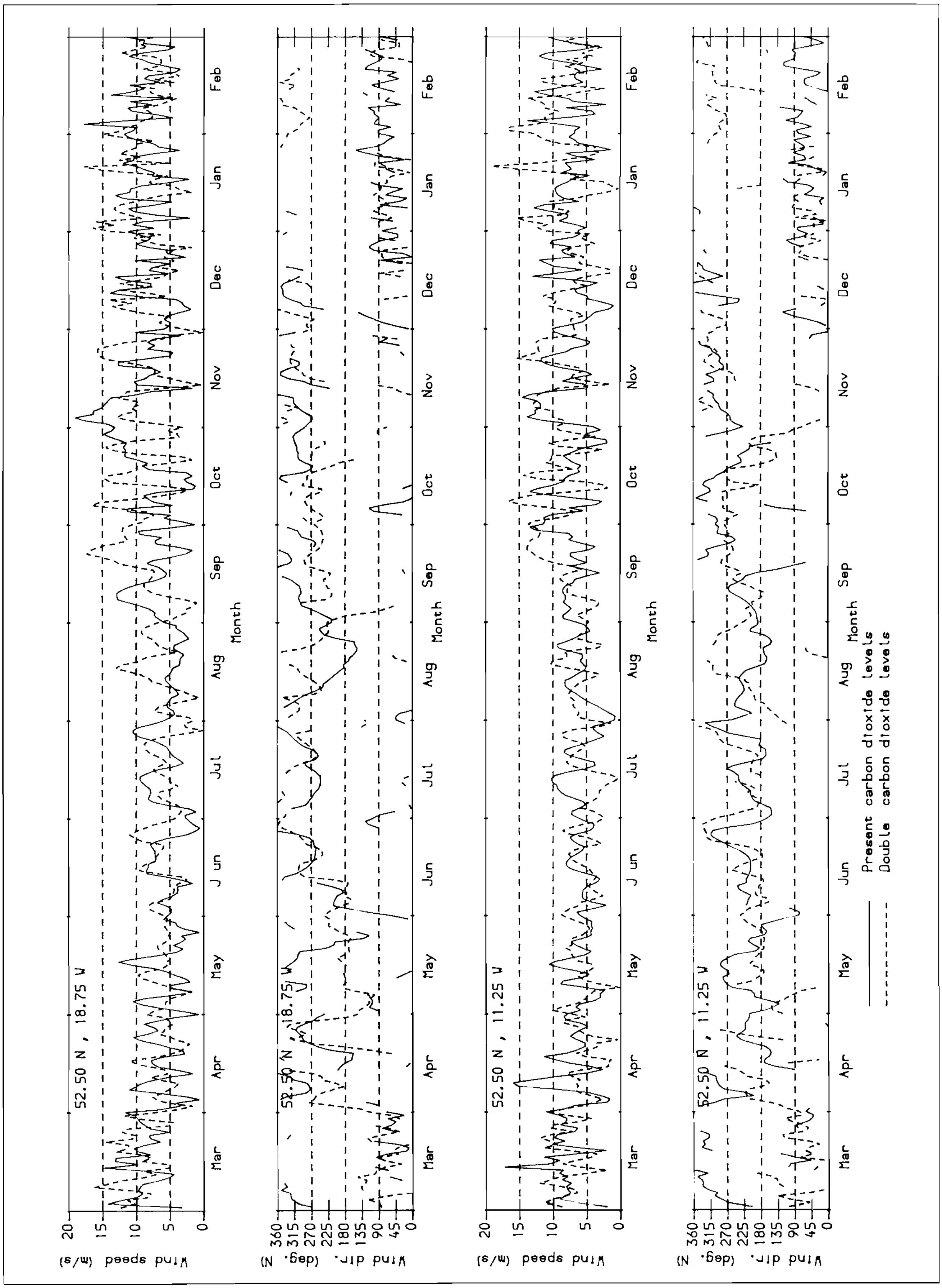
Present and future wind conditions - 62.5 N , 3.75 W & 3.75 E



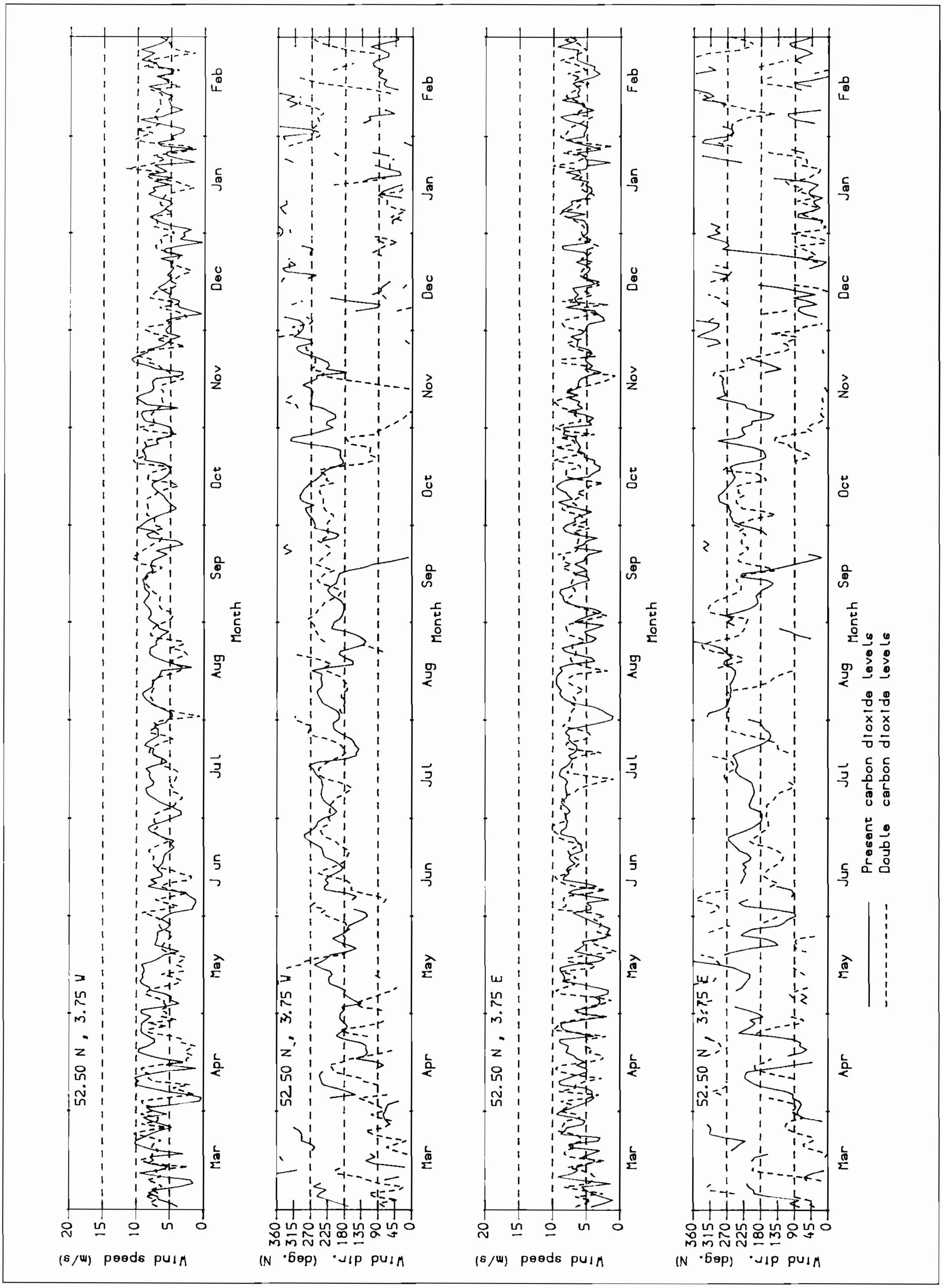
Present and future wind conditions - 57.5 N , 18.75 & 11.25 W



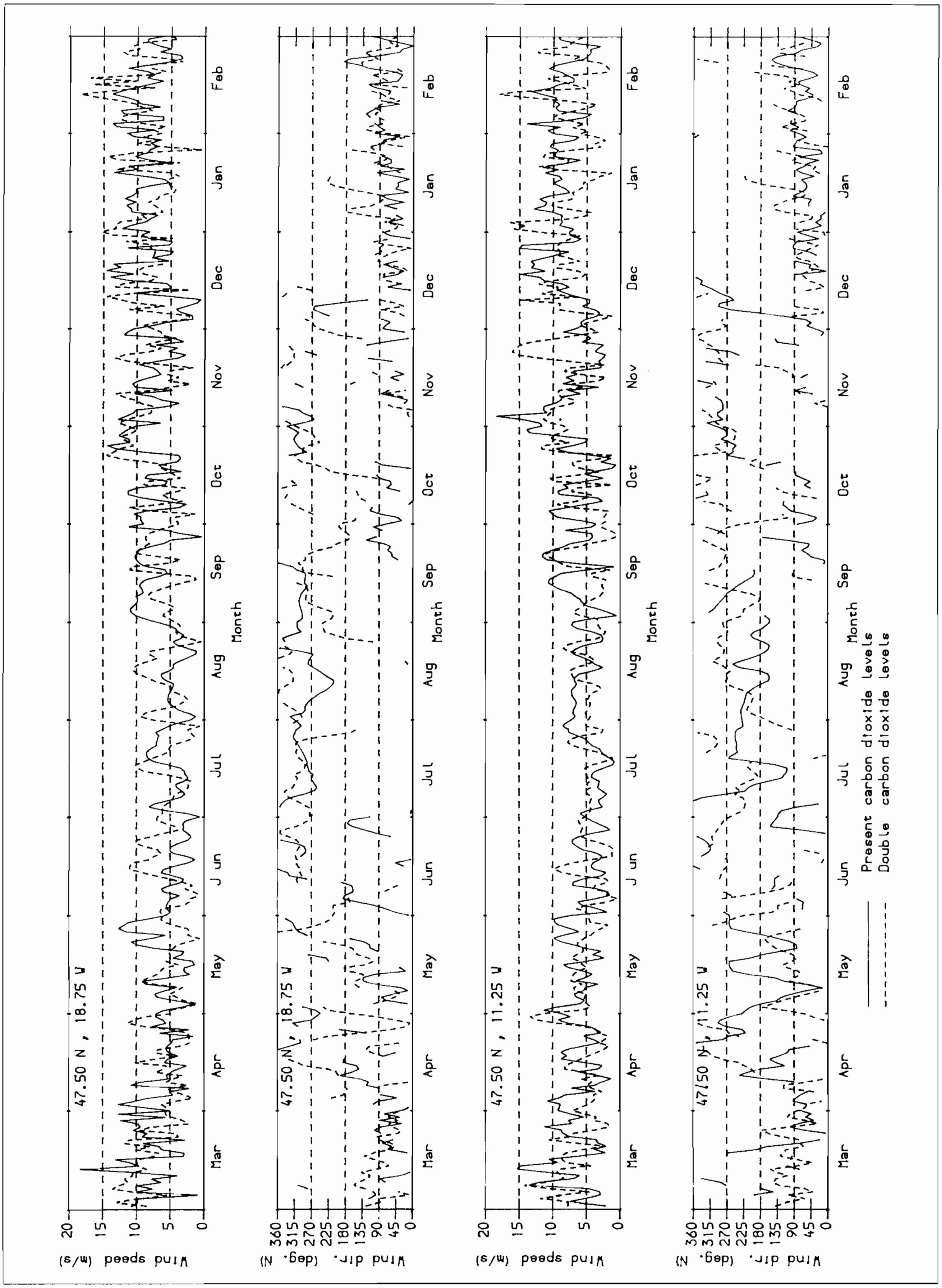
Present and future wind conditions - 57.5 N , 3.75 W & 3.75 E



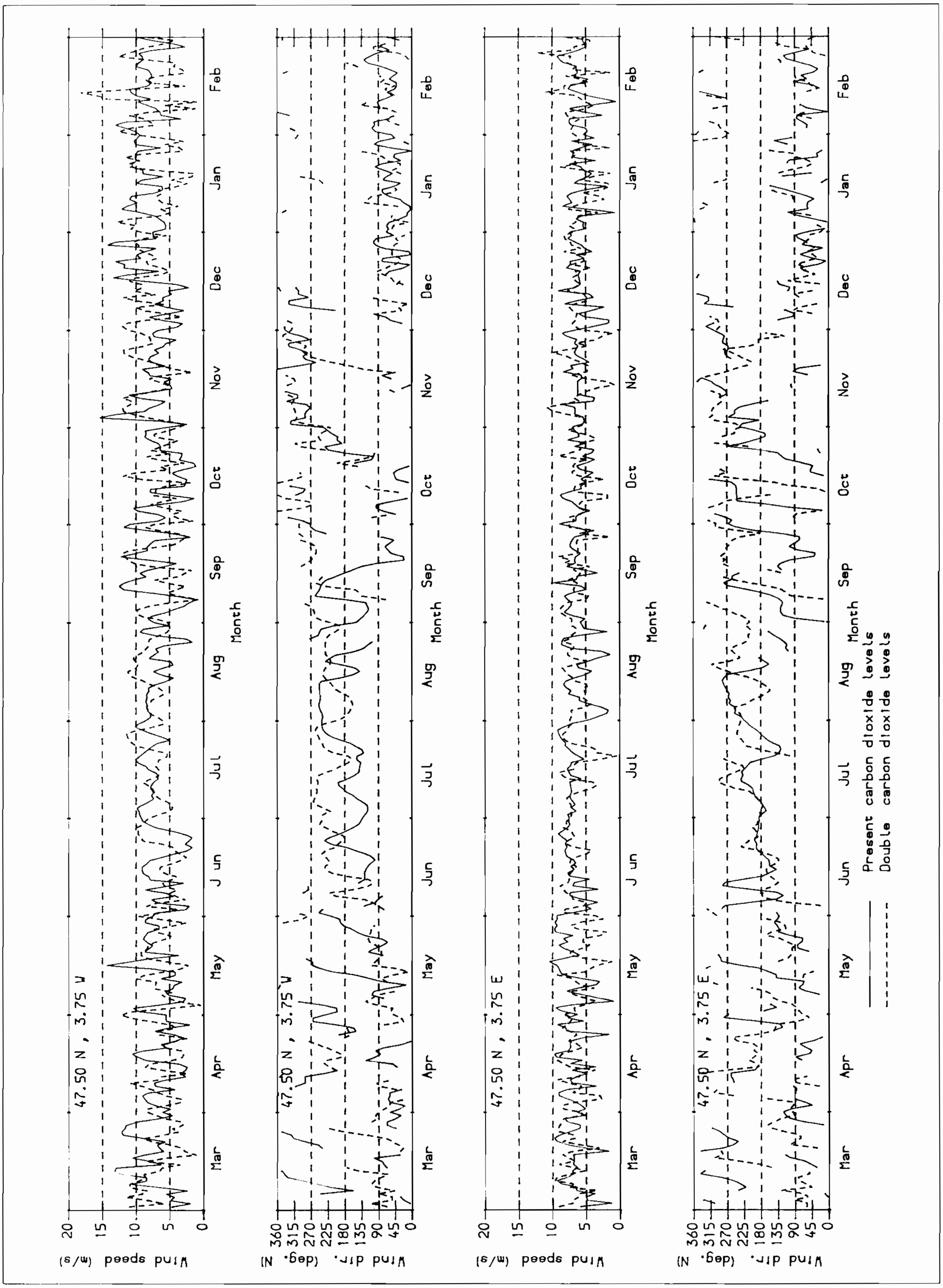
Present and future wind conditions - 52.5 N , 18.75 & 11.25 W



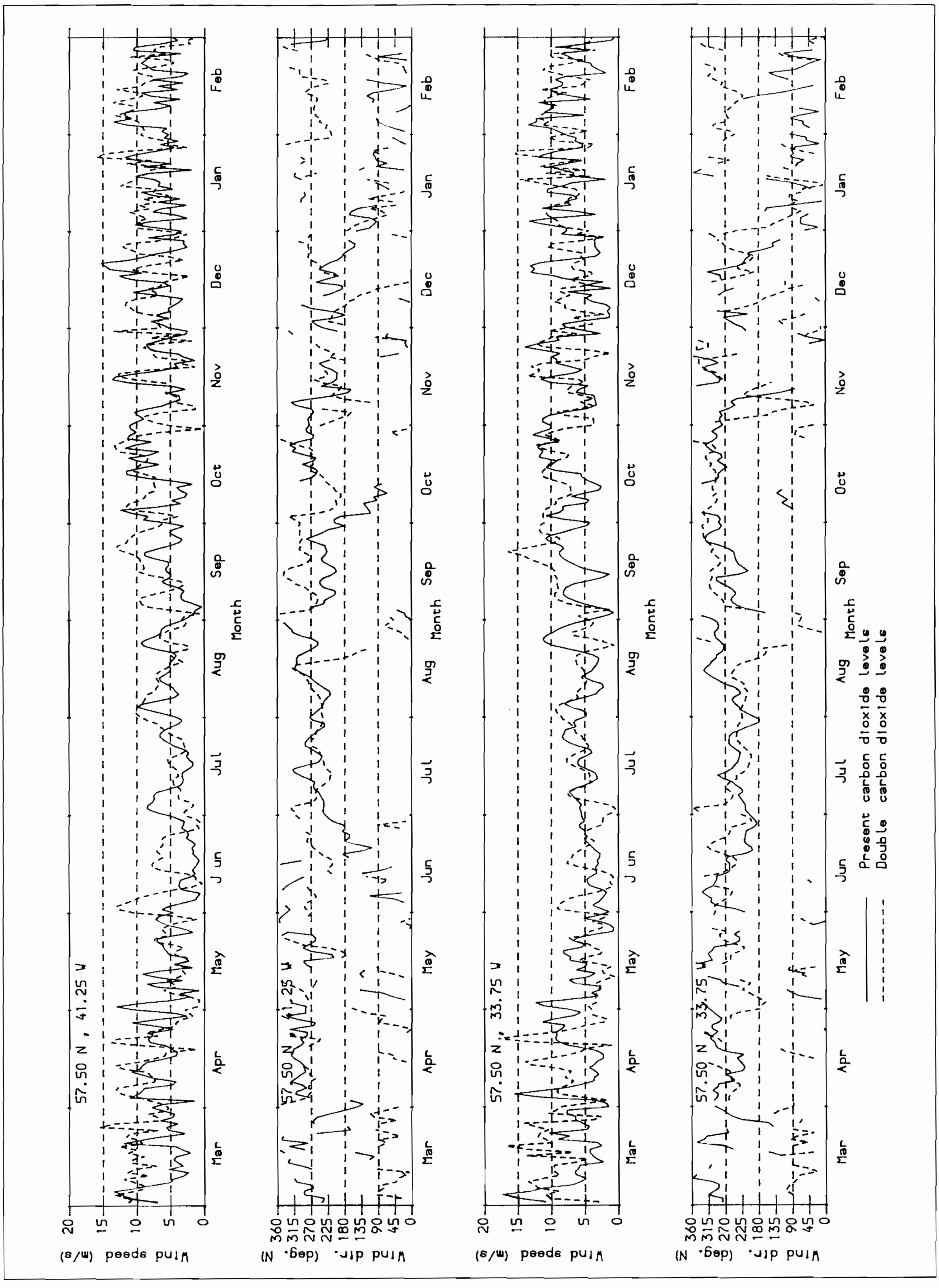
Present and future wind conditions - 52.5 N , 3.75 W & 3.75 E



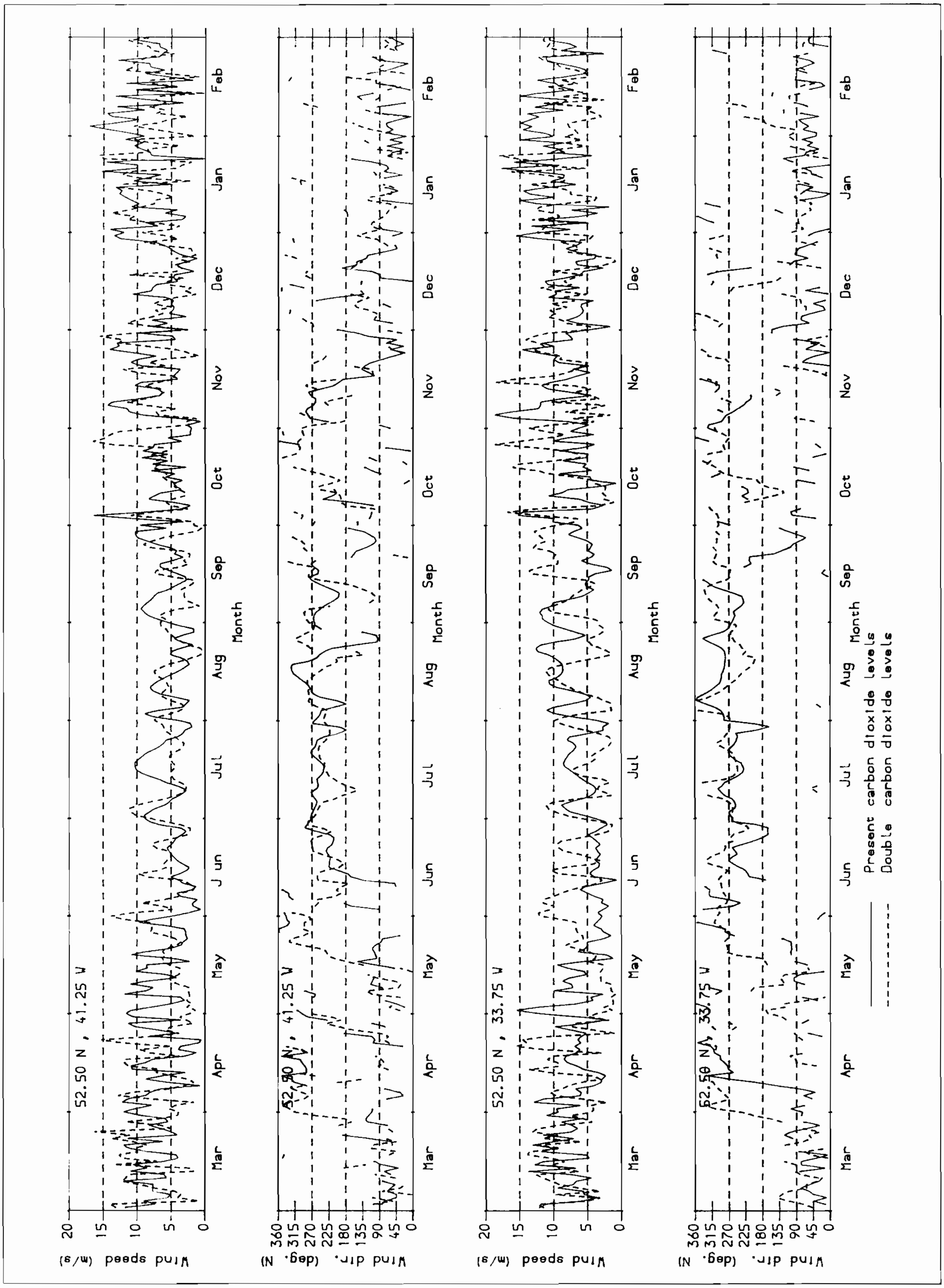
Present and future wind conditions - 47.5 N , 18.75 & 11.25 W



Present and future wind conditions - 47.5 N , 3.75 W & 3.75 E



Present and future wind conditions - Mid Atlantic - 57.5 N

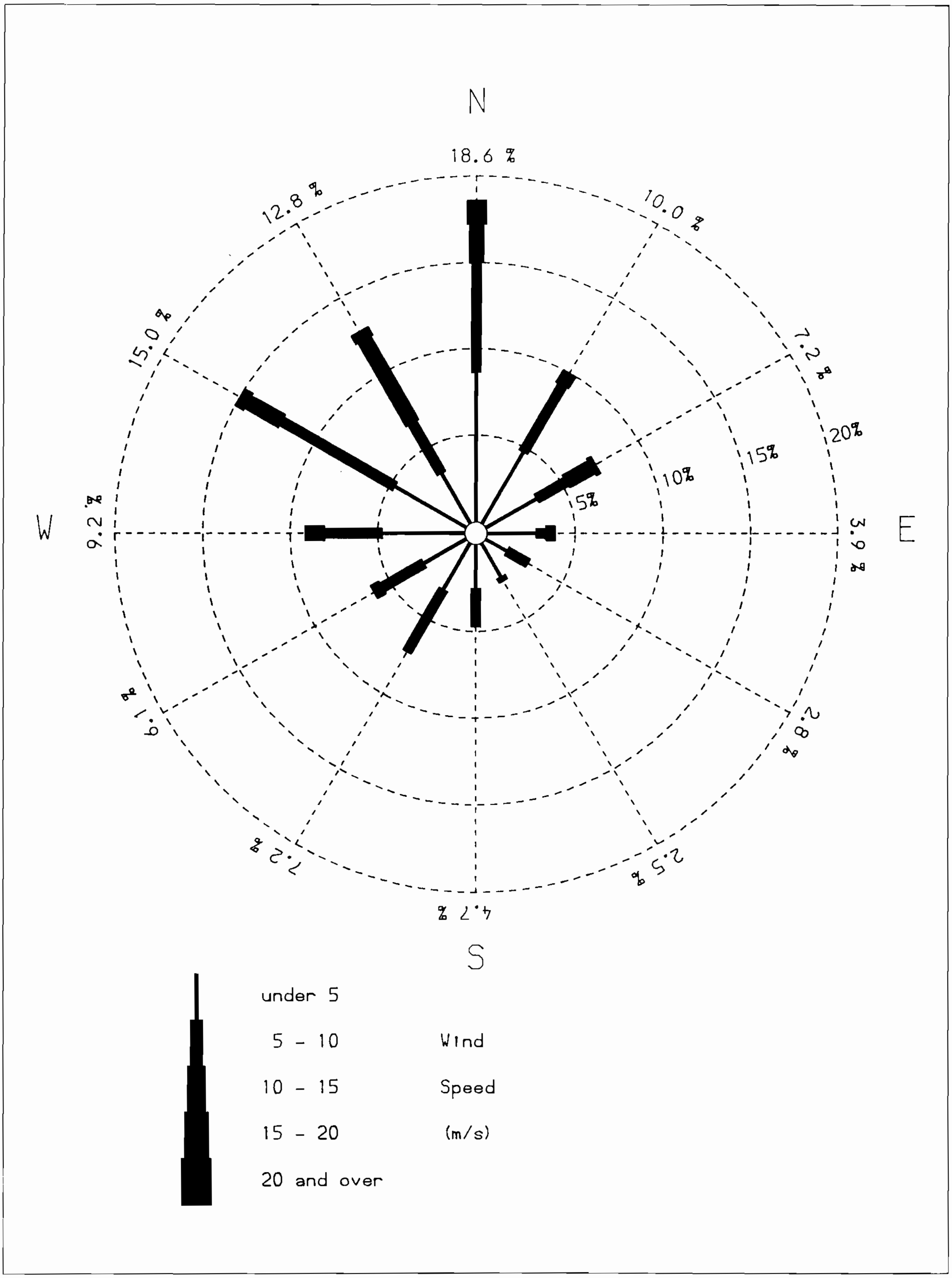


Present and future wind conditions - Mid Atlantic - 52.5 N

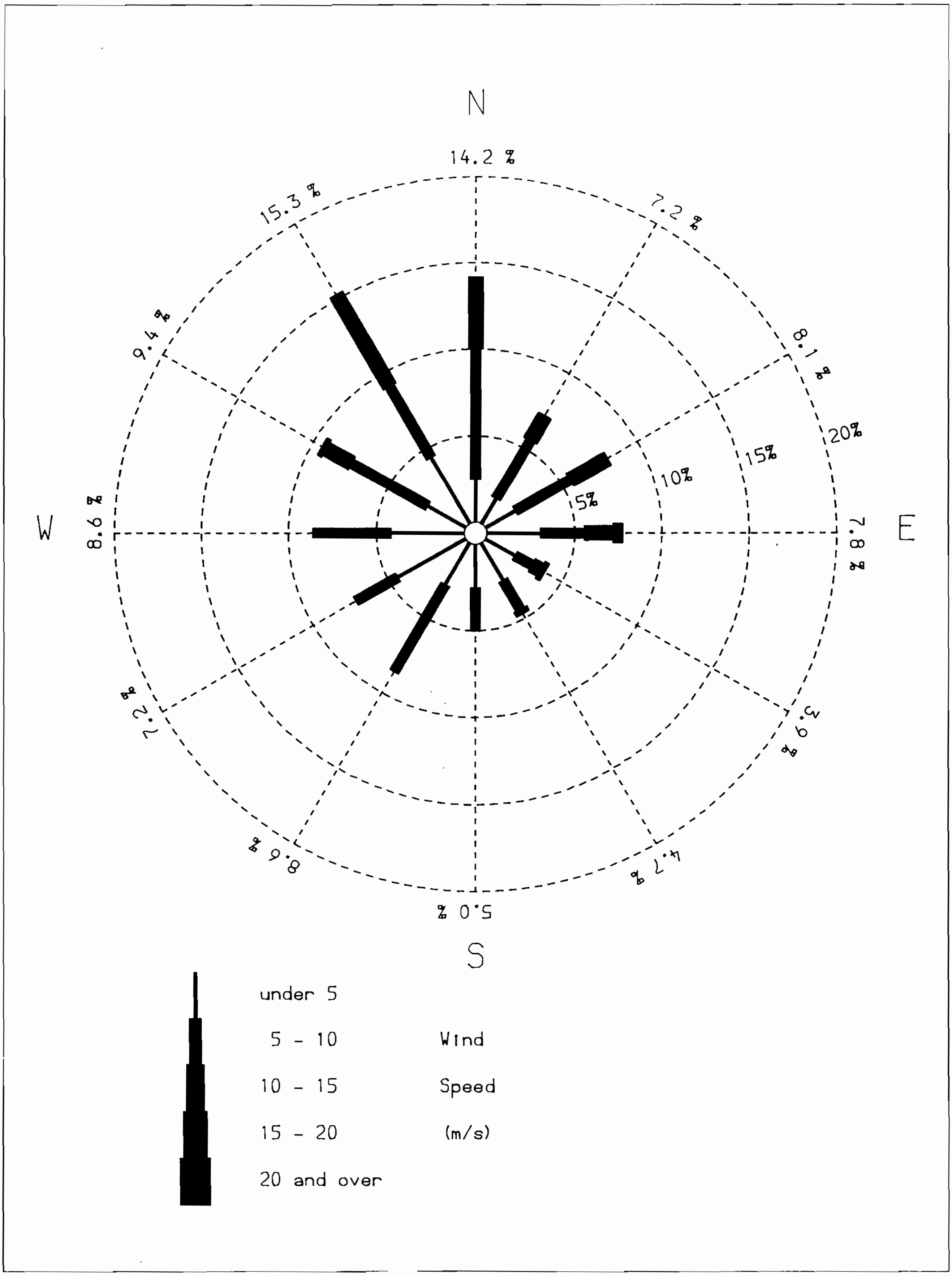
APPENDIX 4

Wind roses for GCM grid points around the UK, for HINDWAVE points and for the North Atlantic points, for "present" and "future" conditions

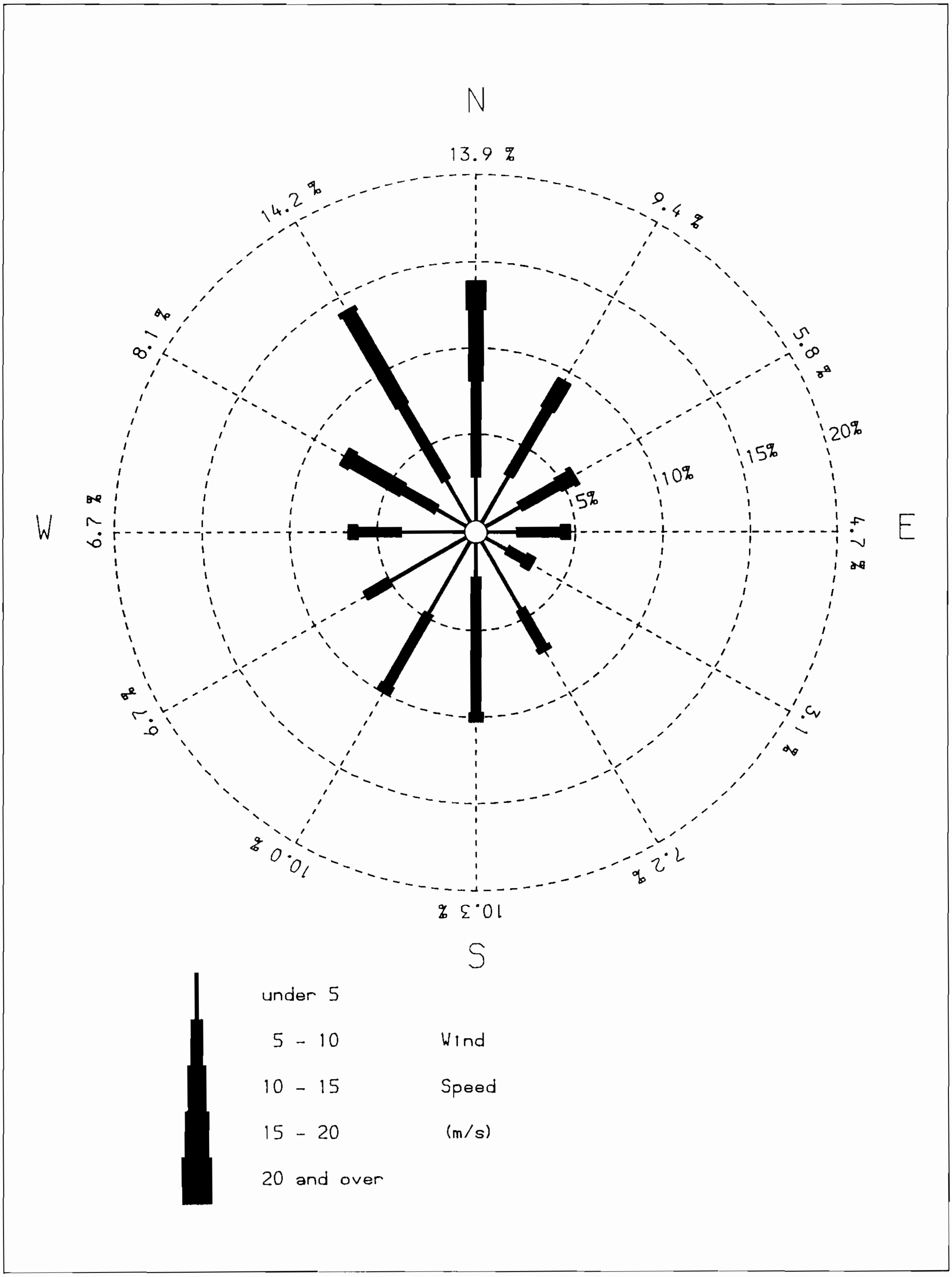
The first 16 pairs of wind roses show the distribution of wind speed and direction, derived from the midnight wind vector data, for present and for doubled CO_2 conditions, for the 16 UK points. (This is the same information shown in Figures 22-25). The next 4 pairs show similar data for the four North Atlantic points. The last 5 pairs show wind roses from sequential wind data used in "present" and "future" HINDWAVE runs (see Table 11). The "present" HINDWAVE wind roses are based on recorded long time series wind data, whilst the "future" roses are derived from the WINDSEQ procedure applied to the "present" roses.



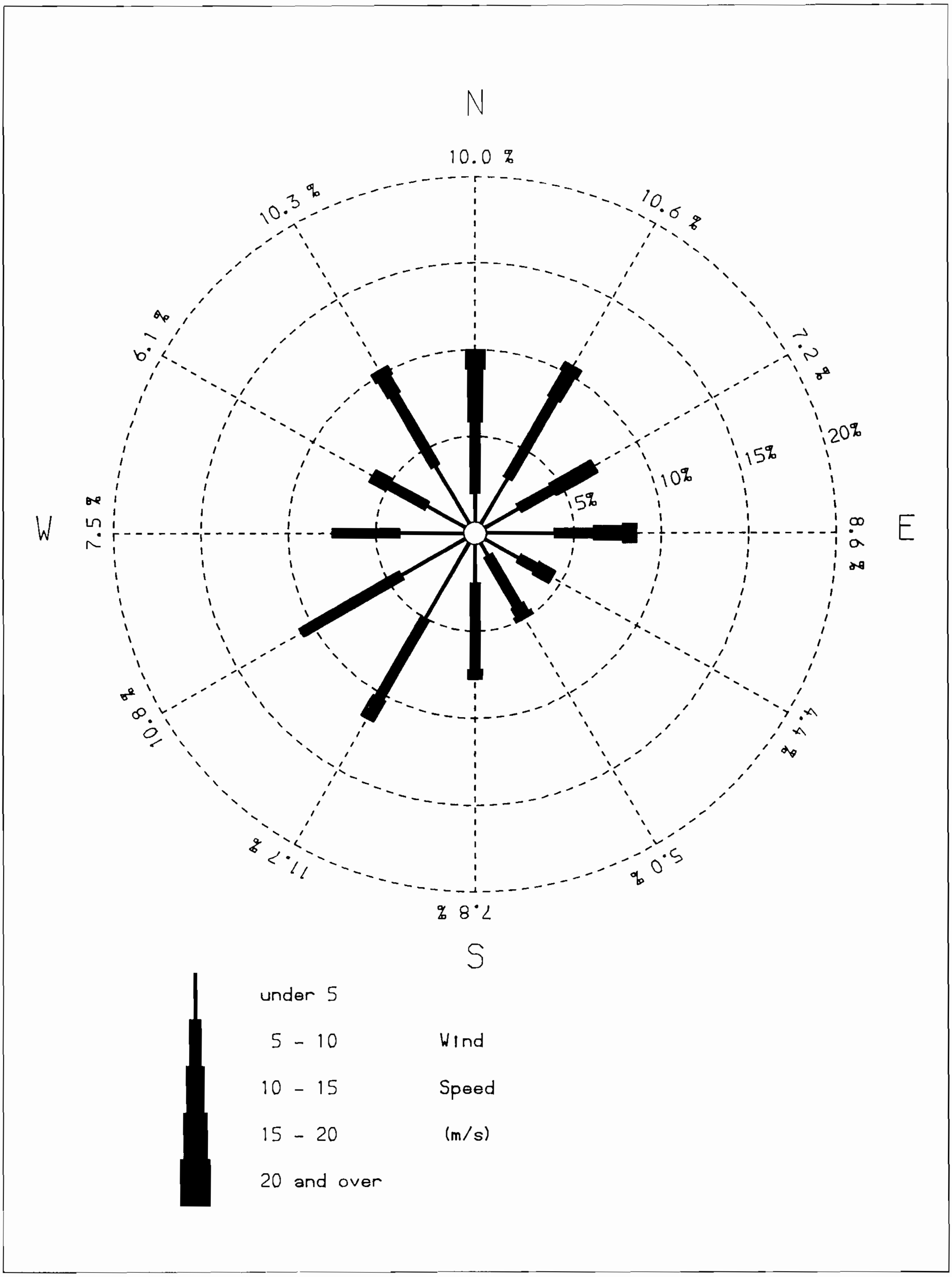
Wind rose for 62.5 N 18.75W 1*co2



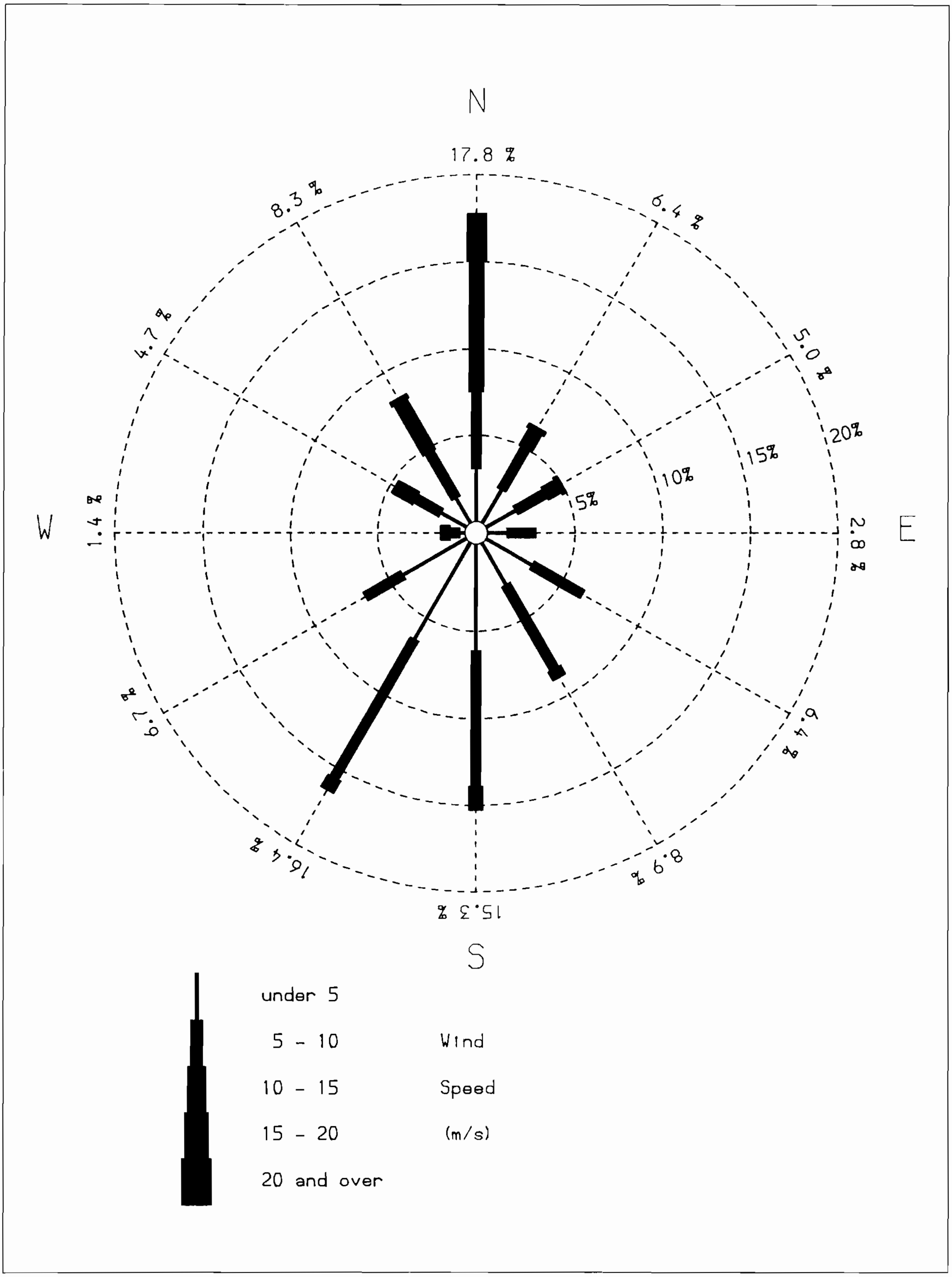
Wind rose for 62.5 N 18.75W 2*co2



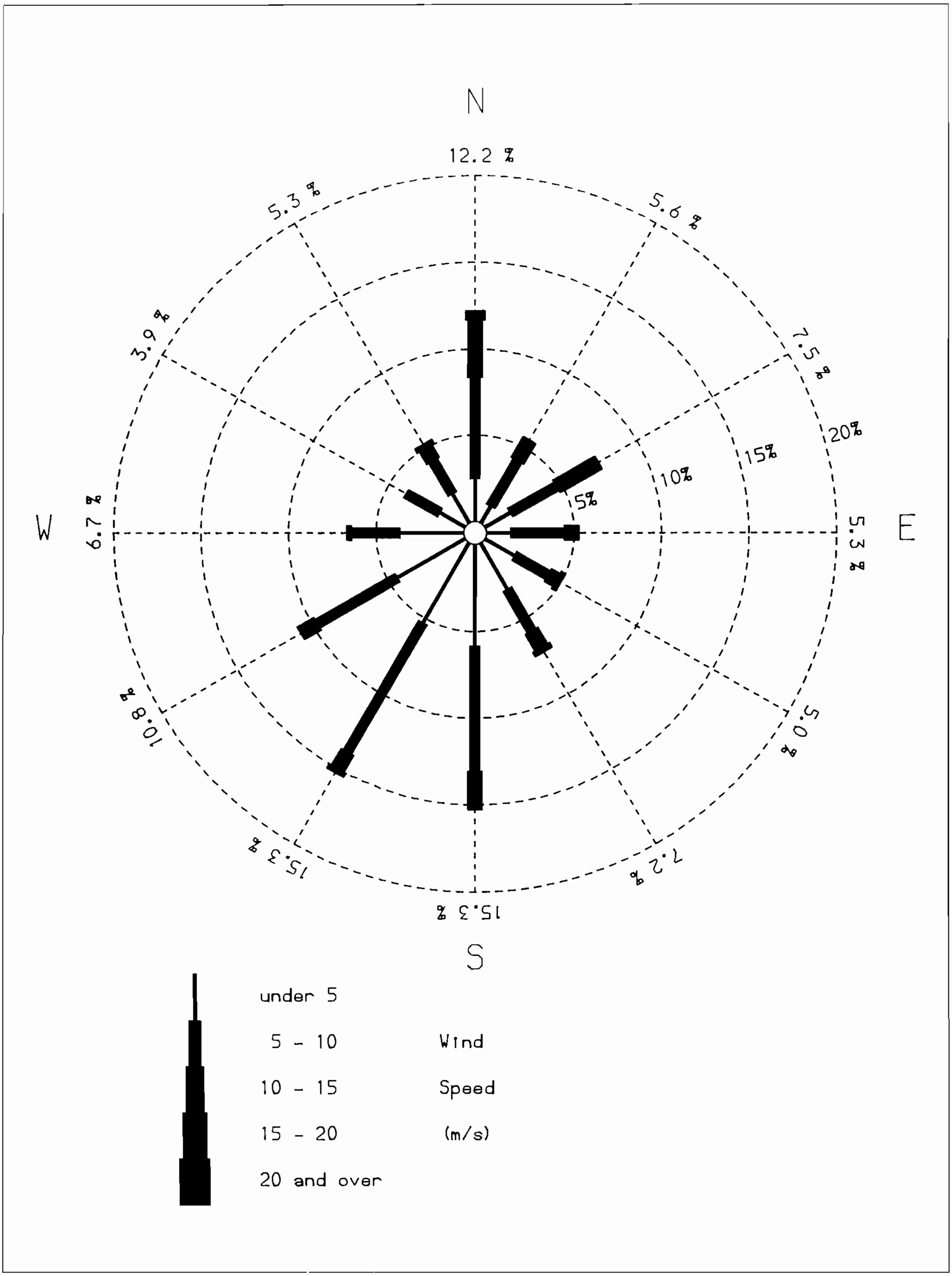
Wind rose for 62.5 N 11.25W 1*co2



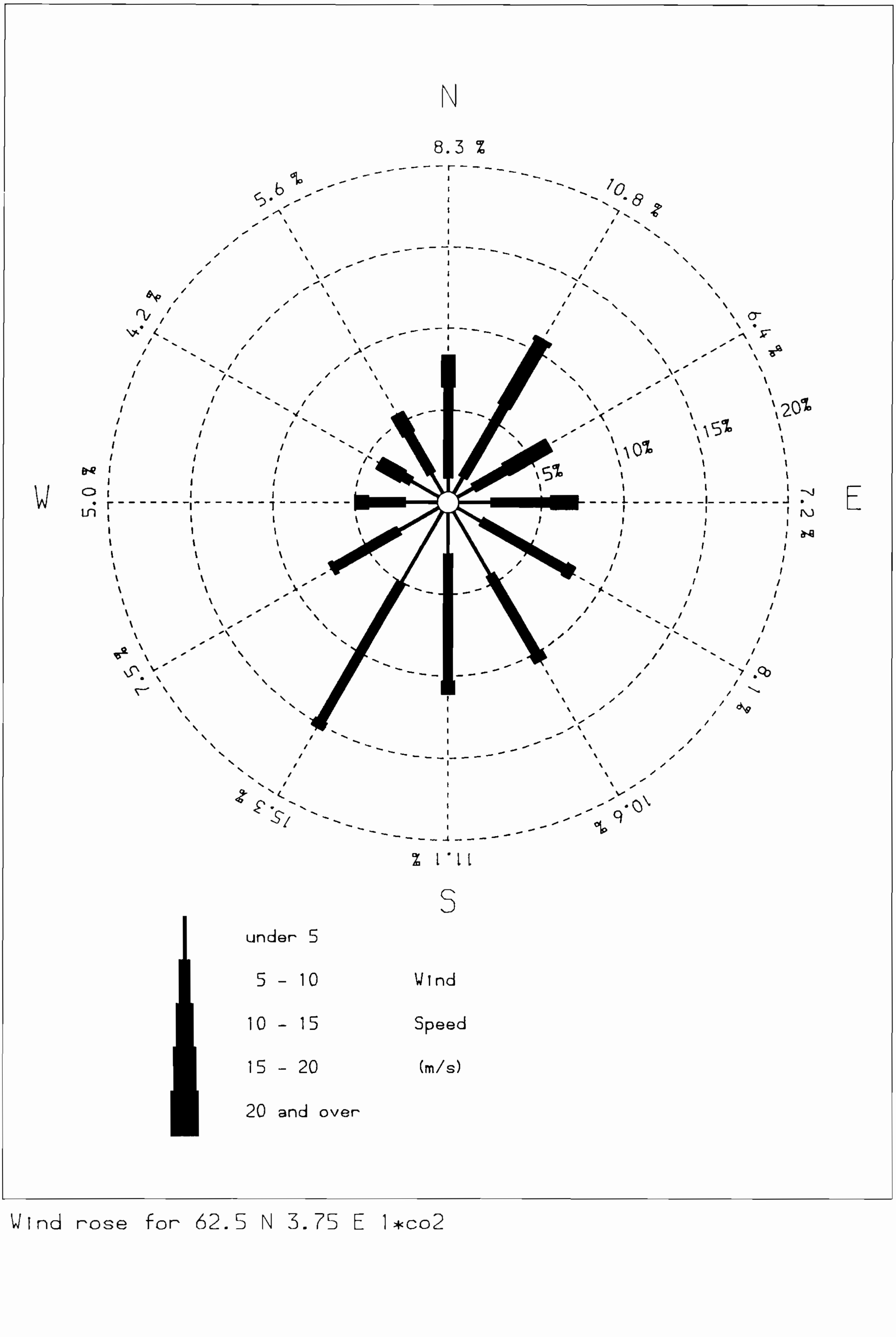
Wind rose for 62.5 N 11.25W 2*co2



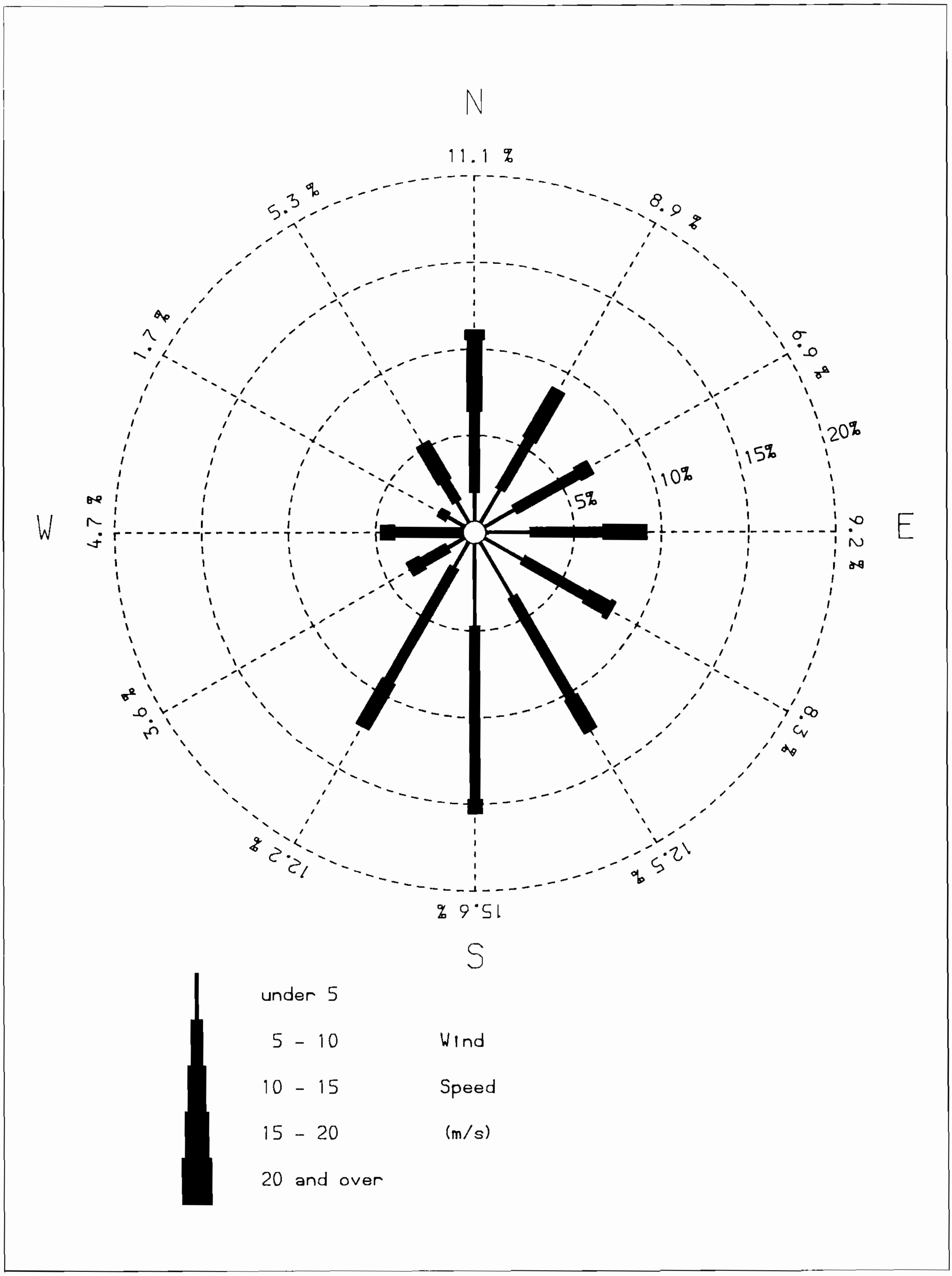
Wind rose for 62.5 N 3.75W 1*co2



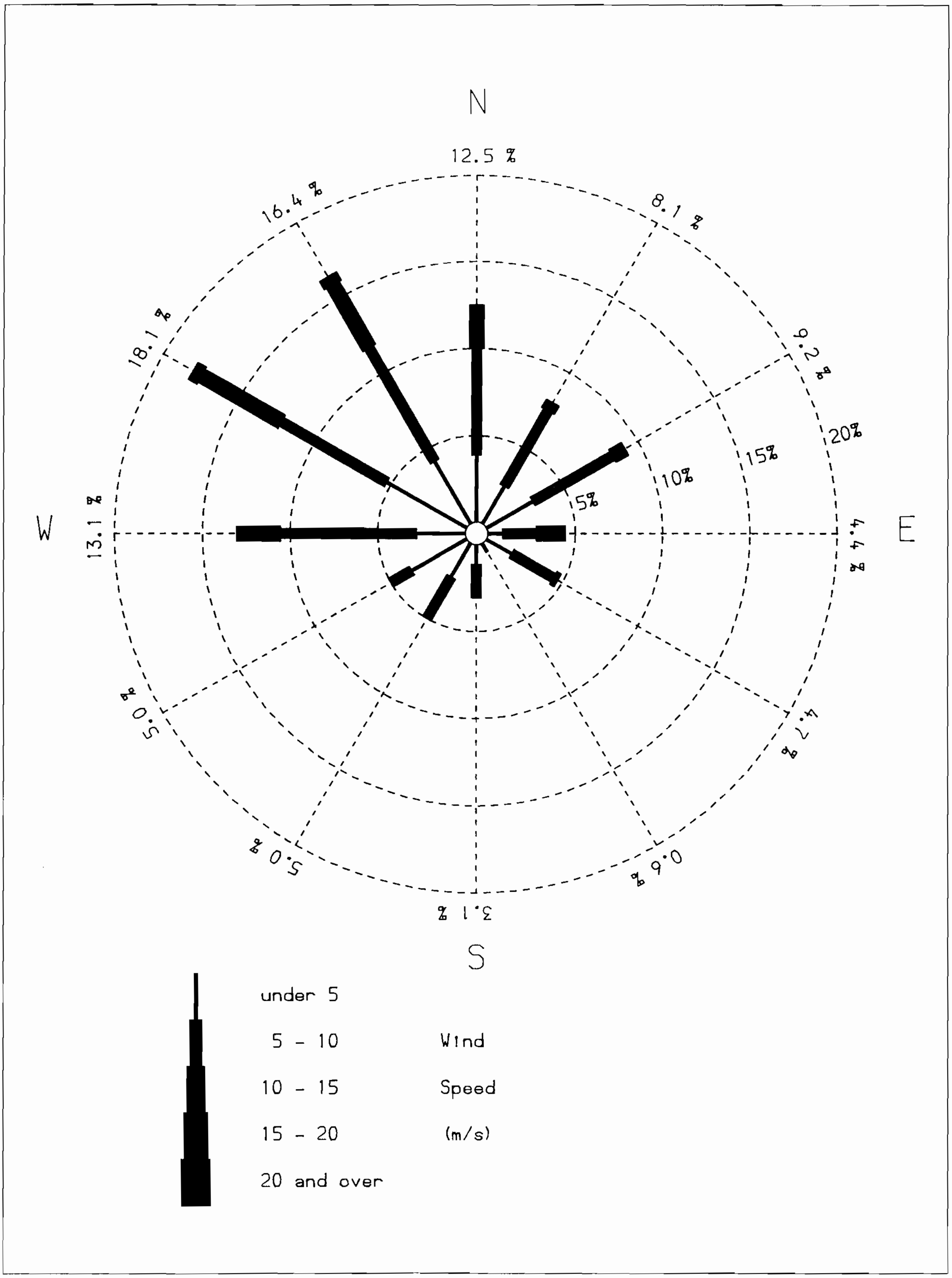
Wind rose for 62.5 N 3.75W 2*co2



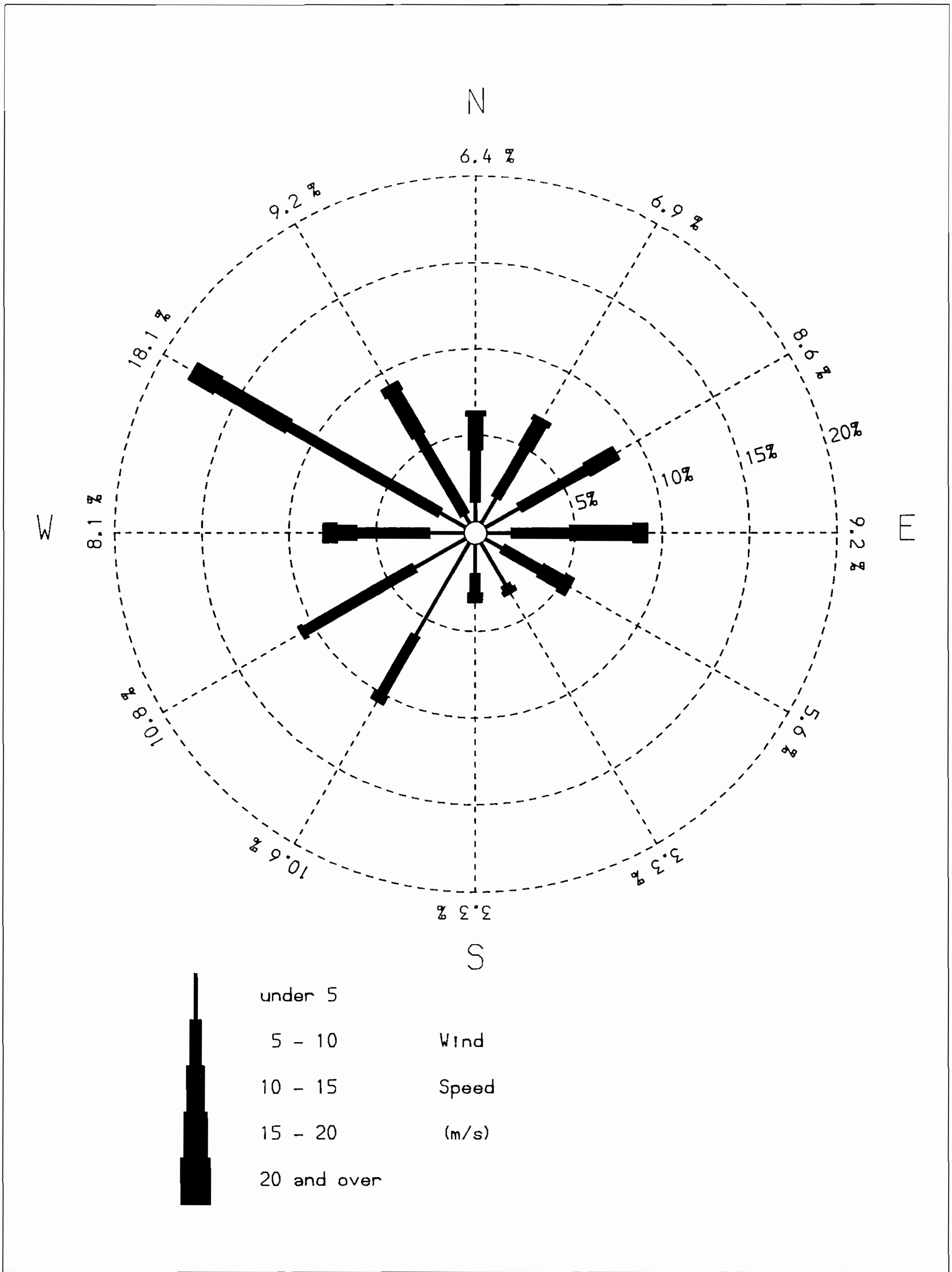
Wind rose for 62.5 N 3.75 E 1*co2



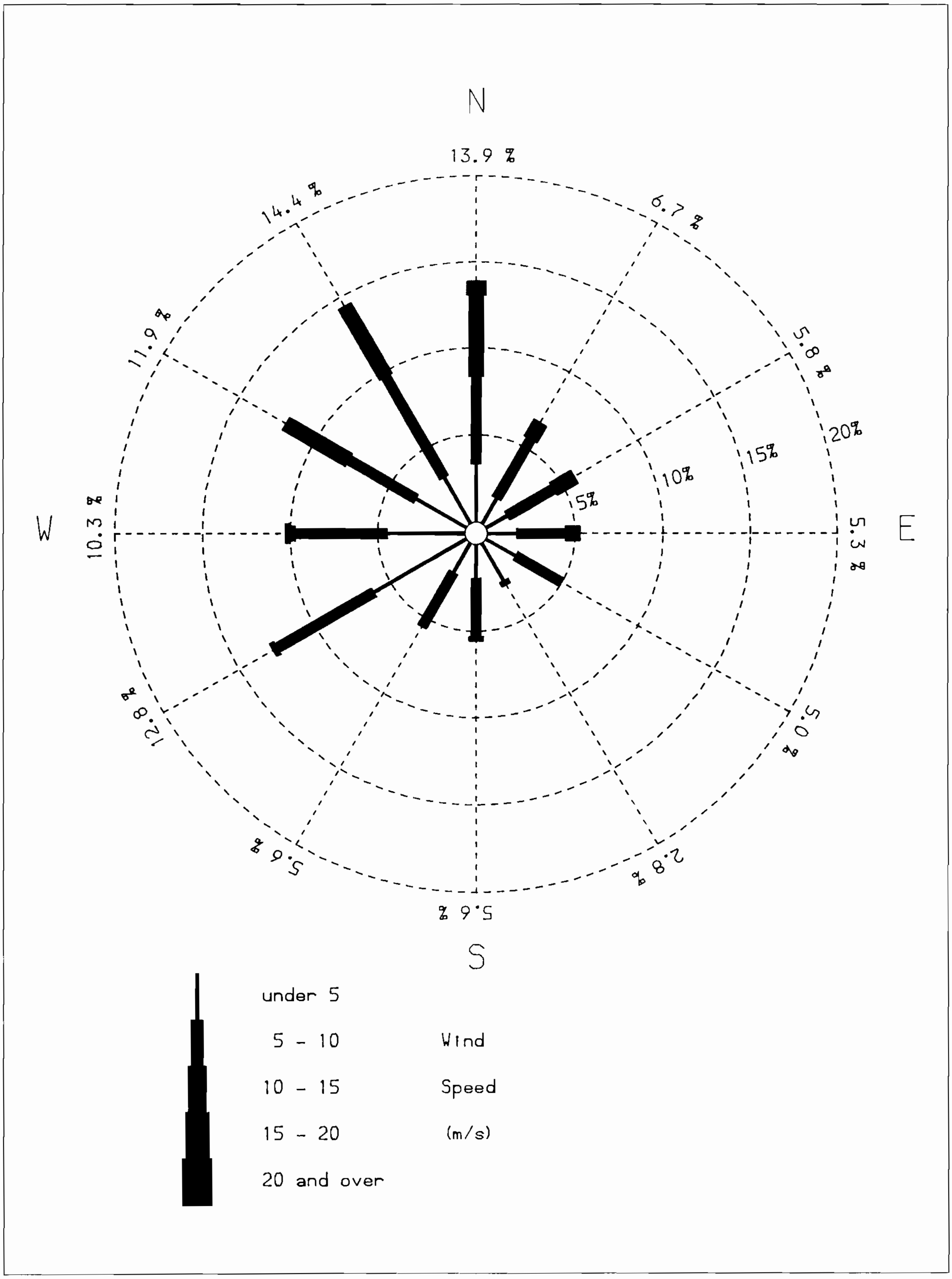
Wind rose for 62.5 N 3.75 E 2*co2



Wind rose for 57.5 N **18.75W** 1*co2



Wind rose for 57.5 N 18.75W 2*co2



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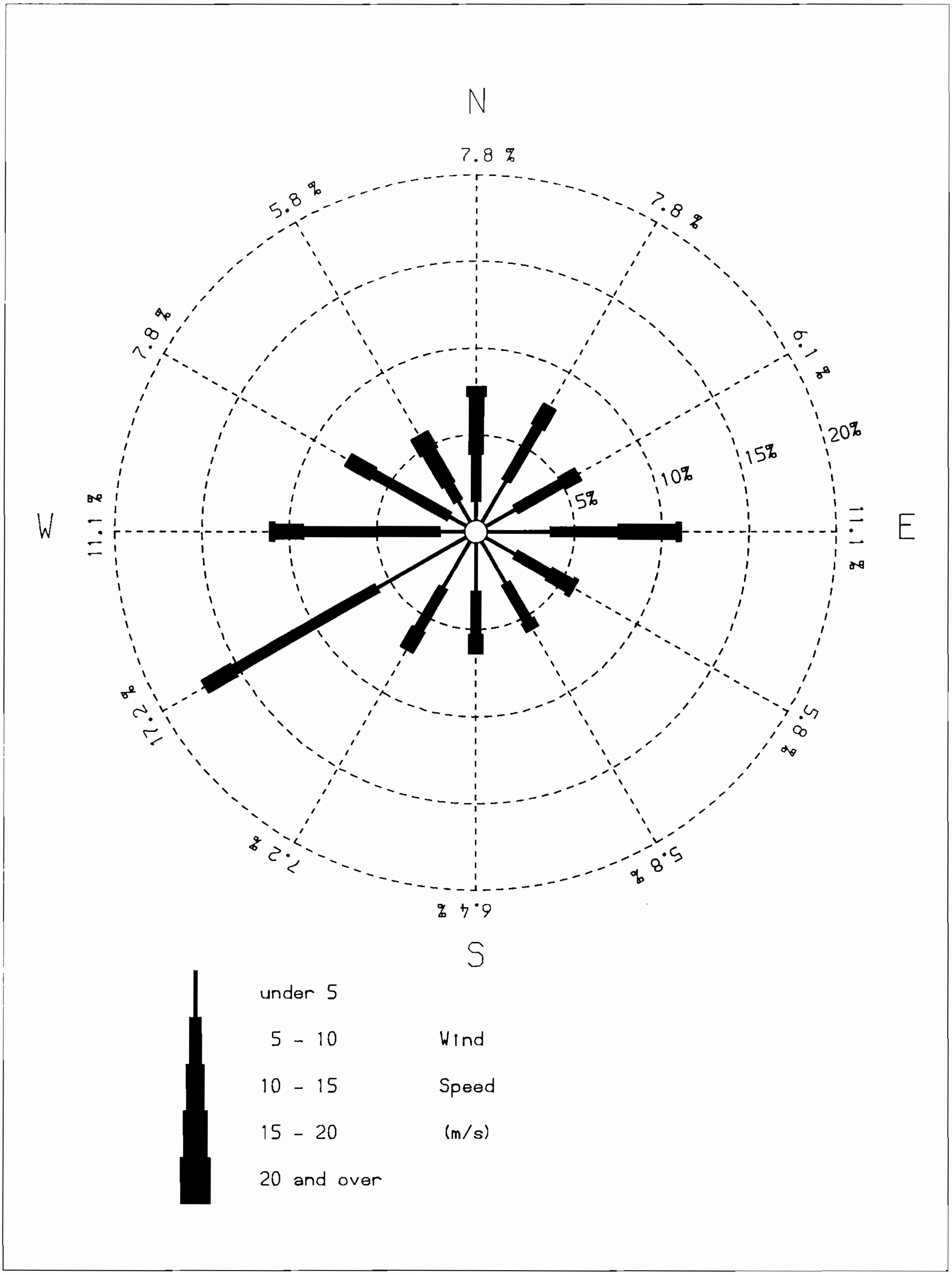

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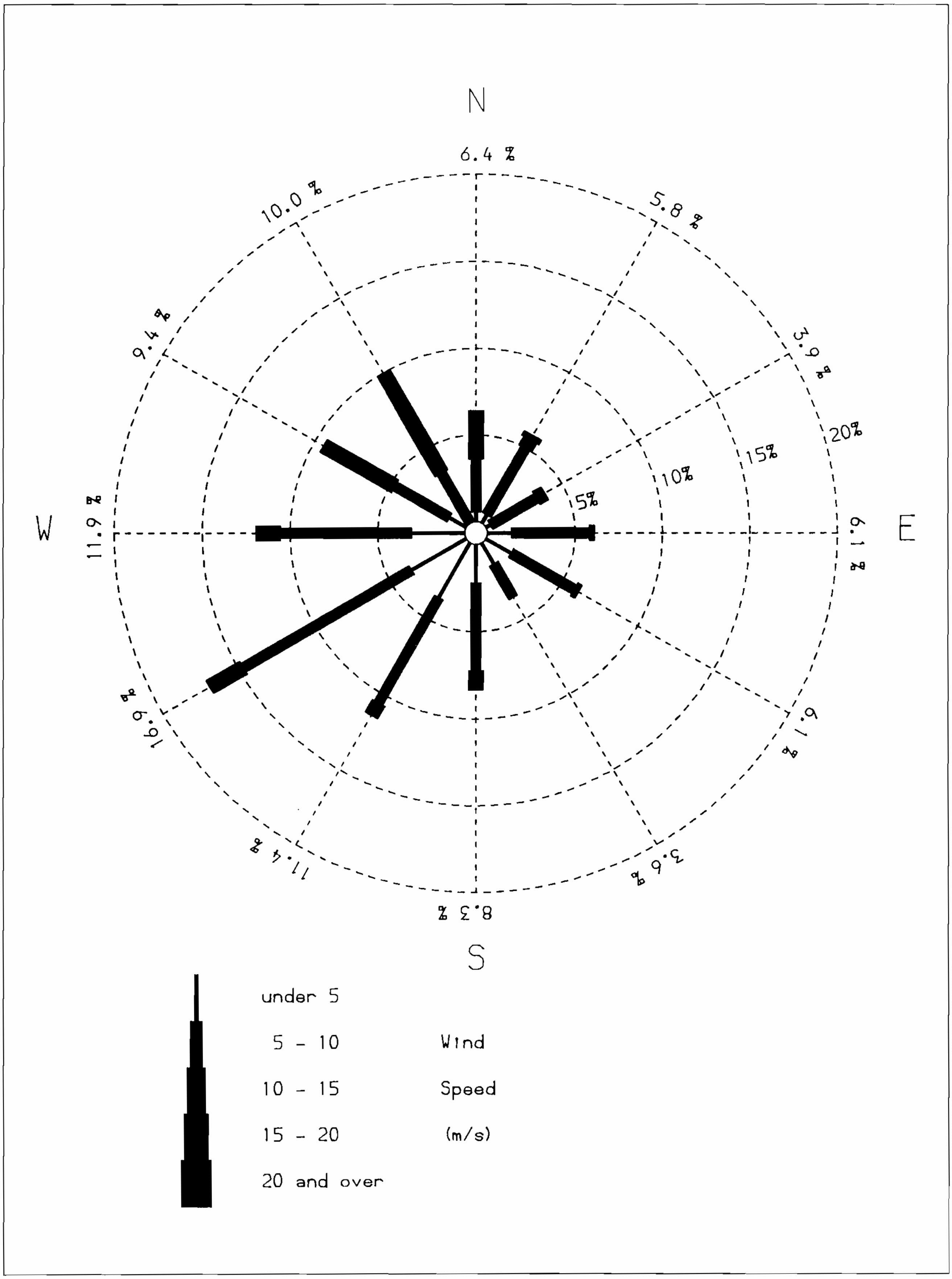

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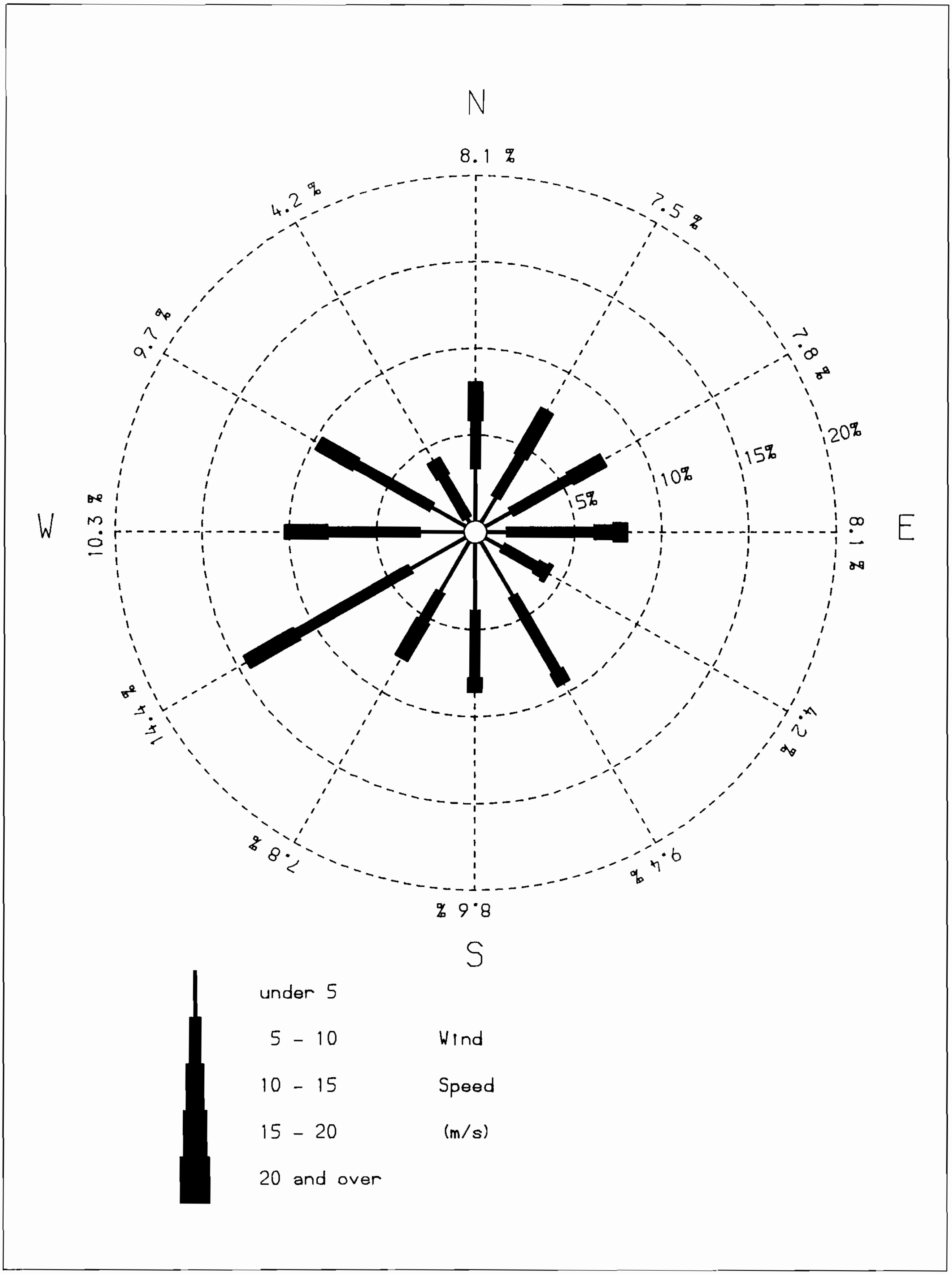

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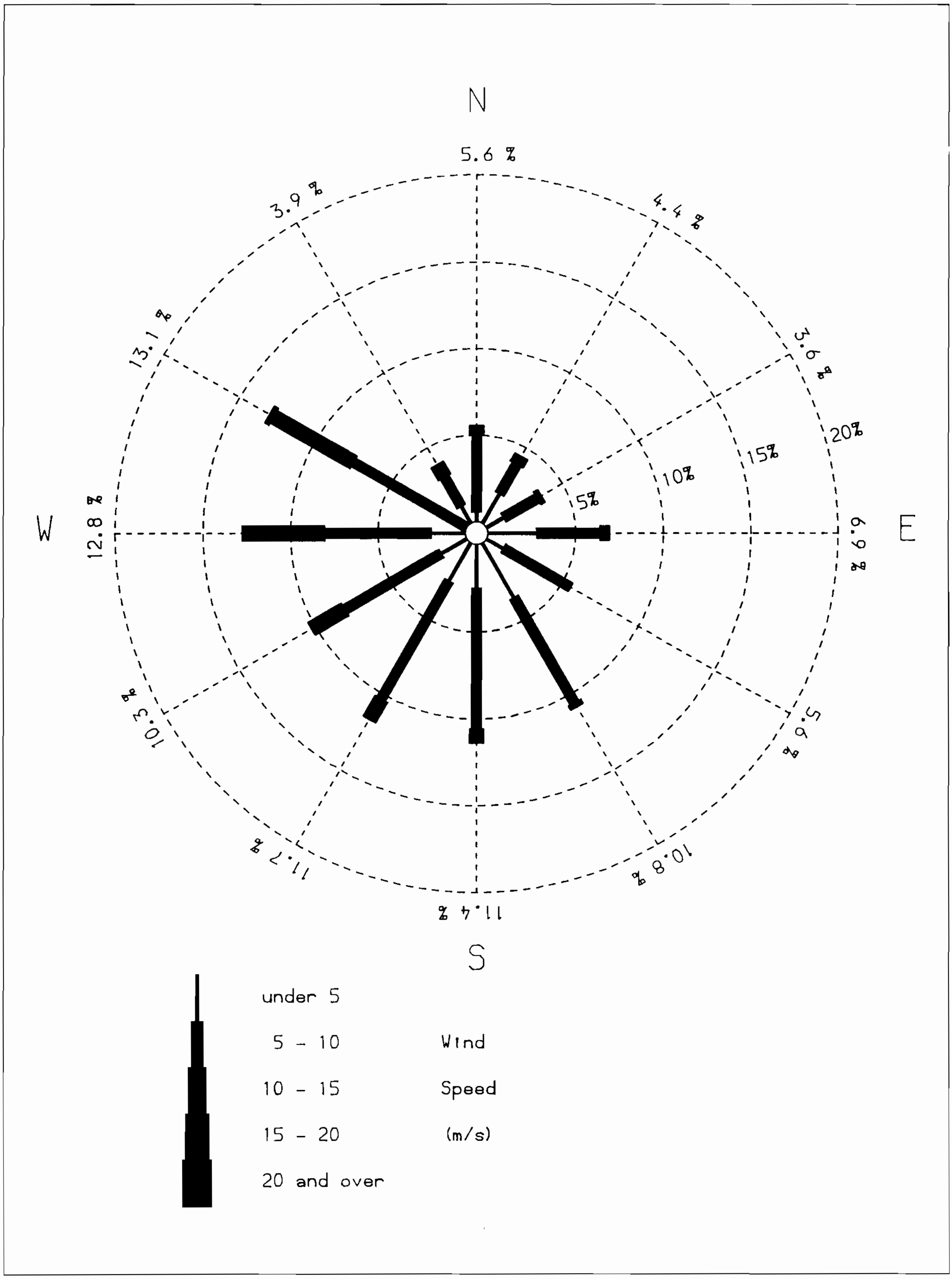

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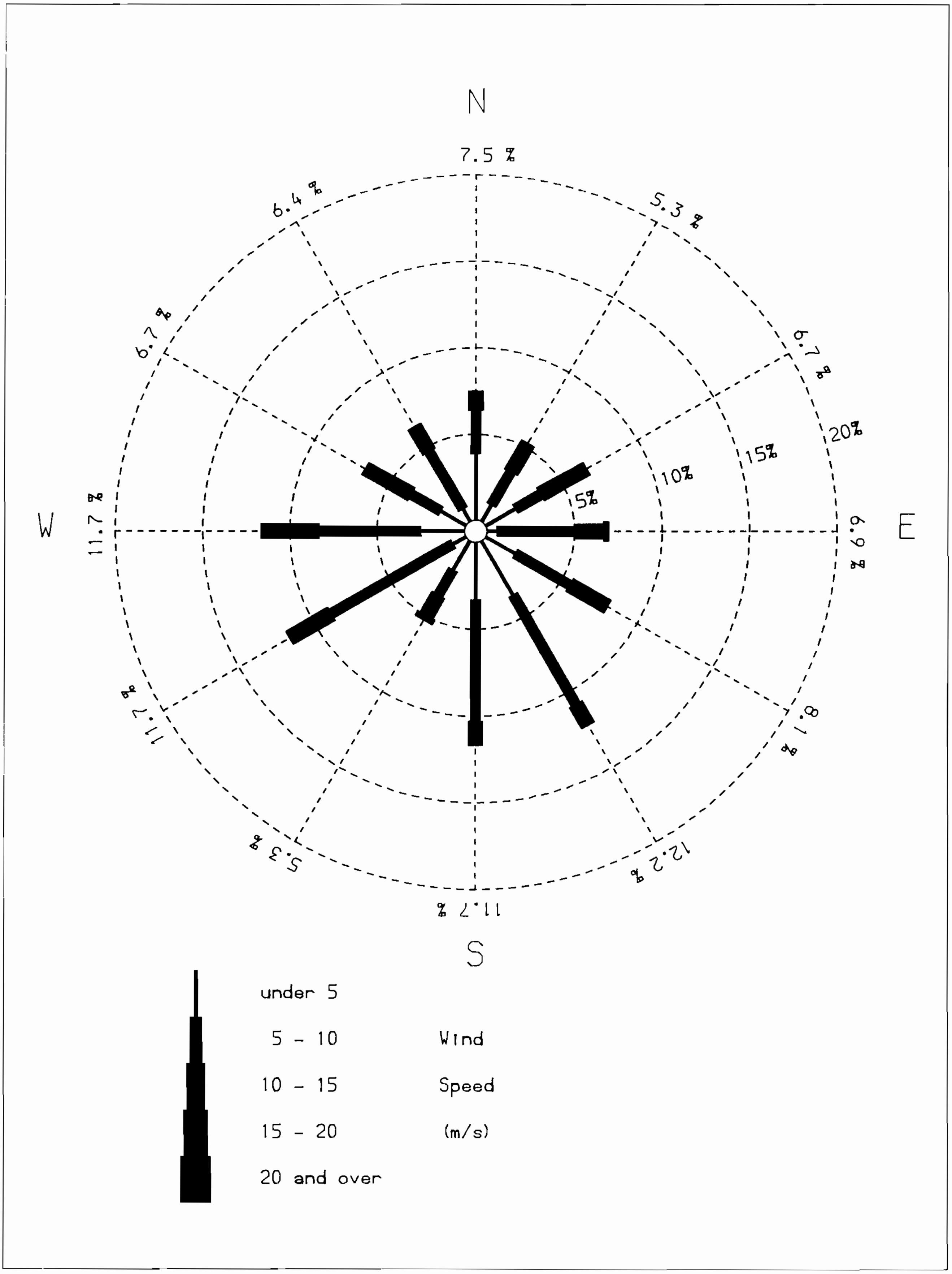

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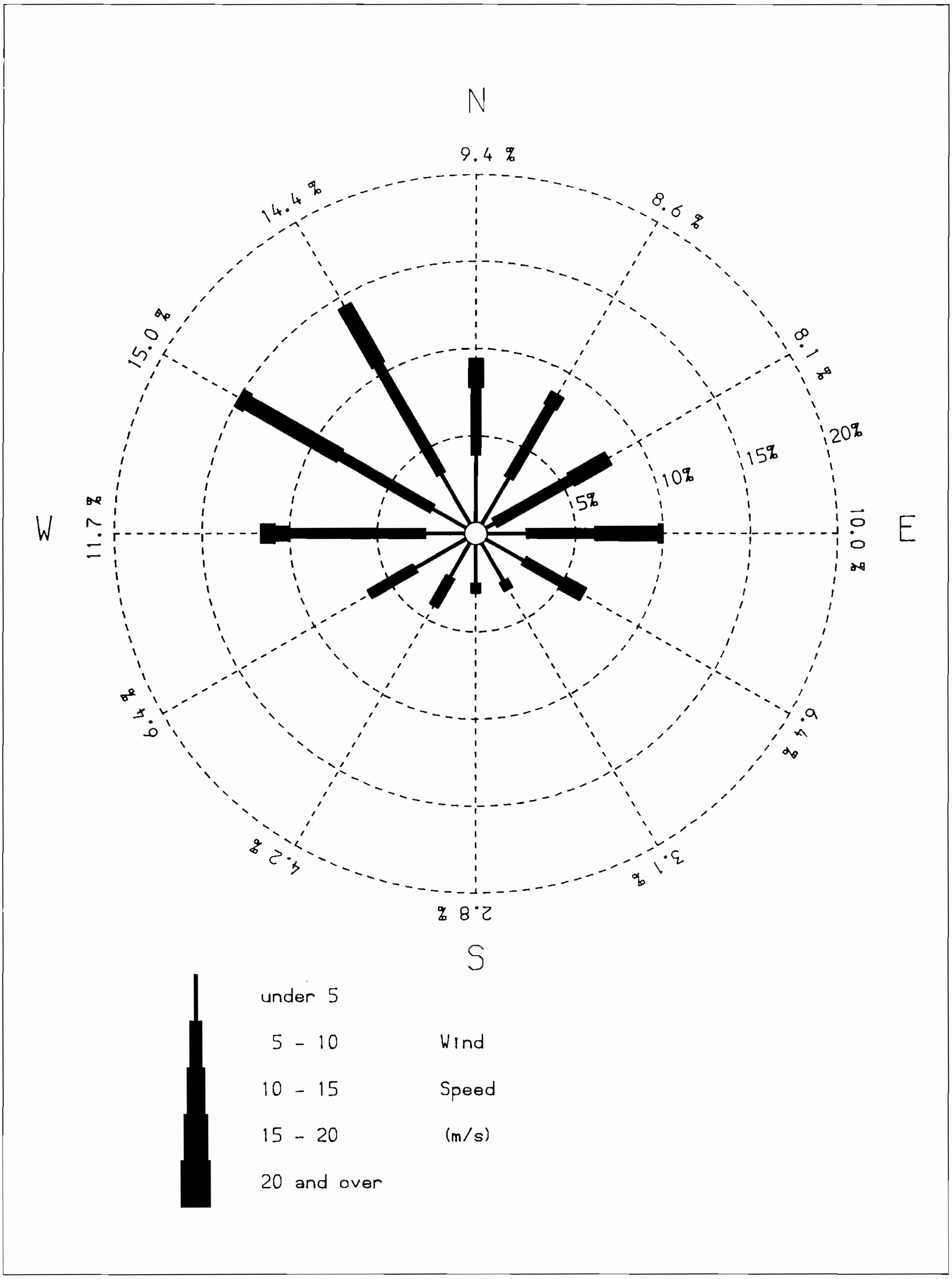

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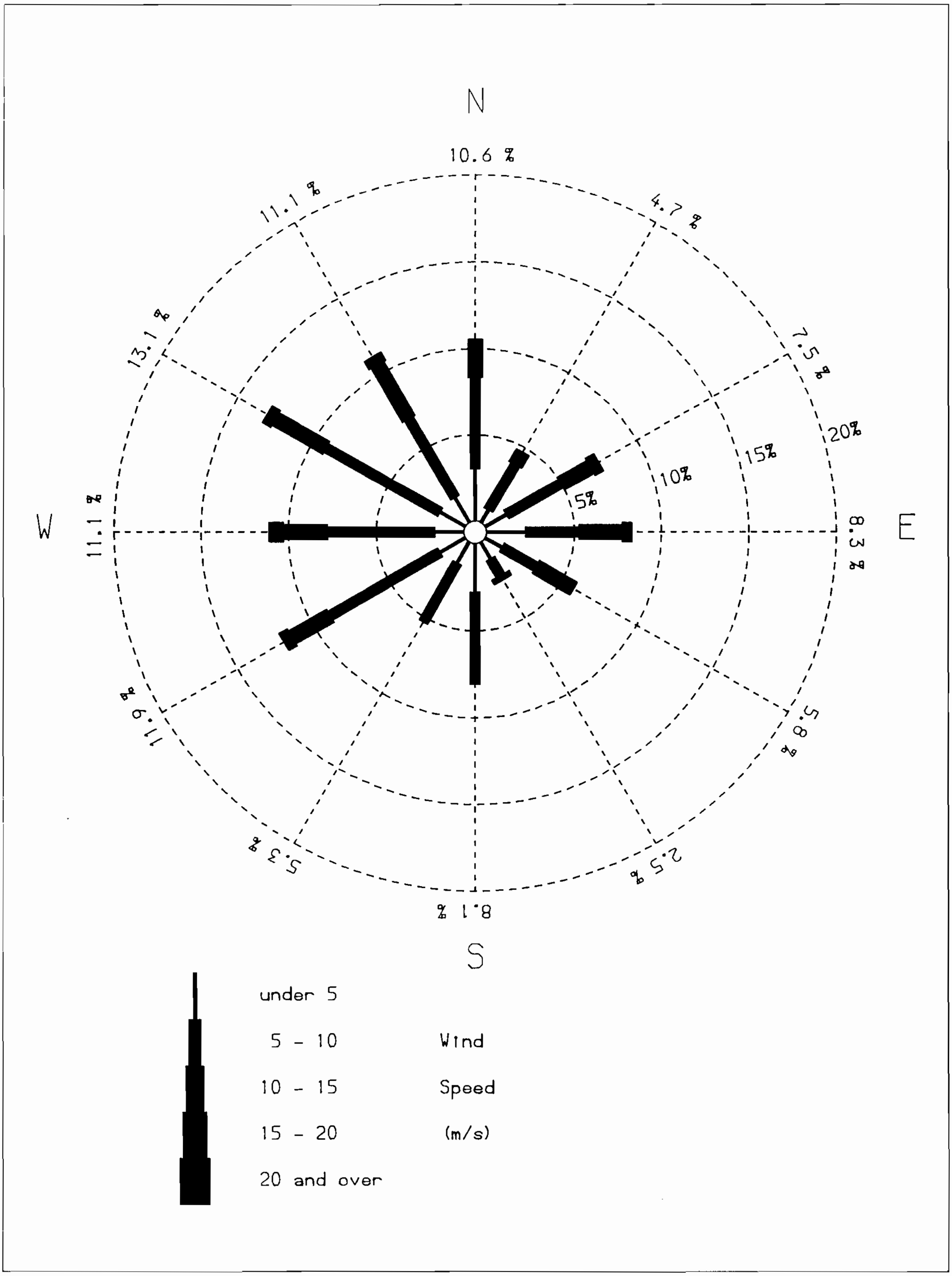

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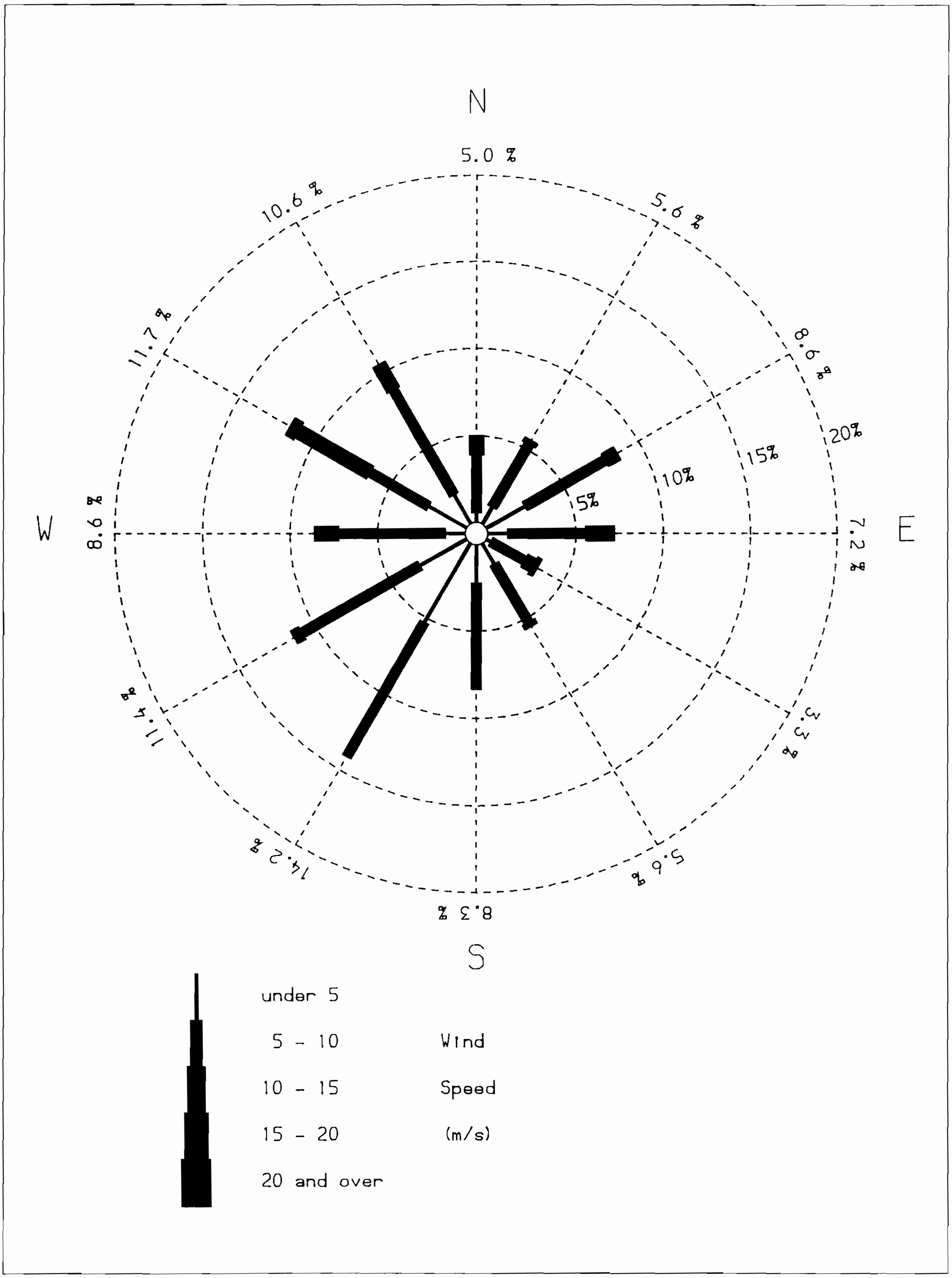

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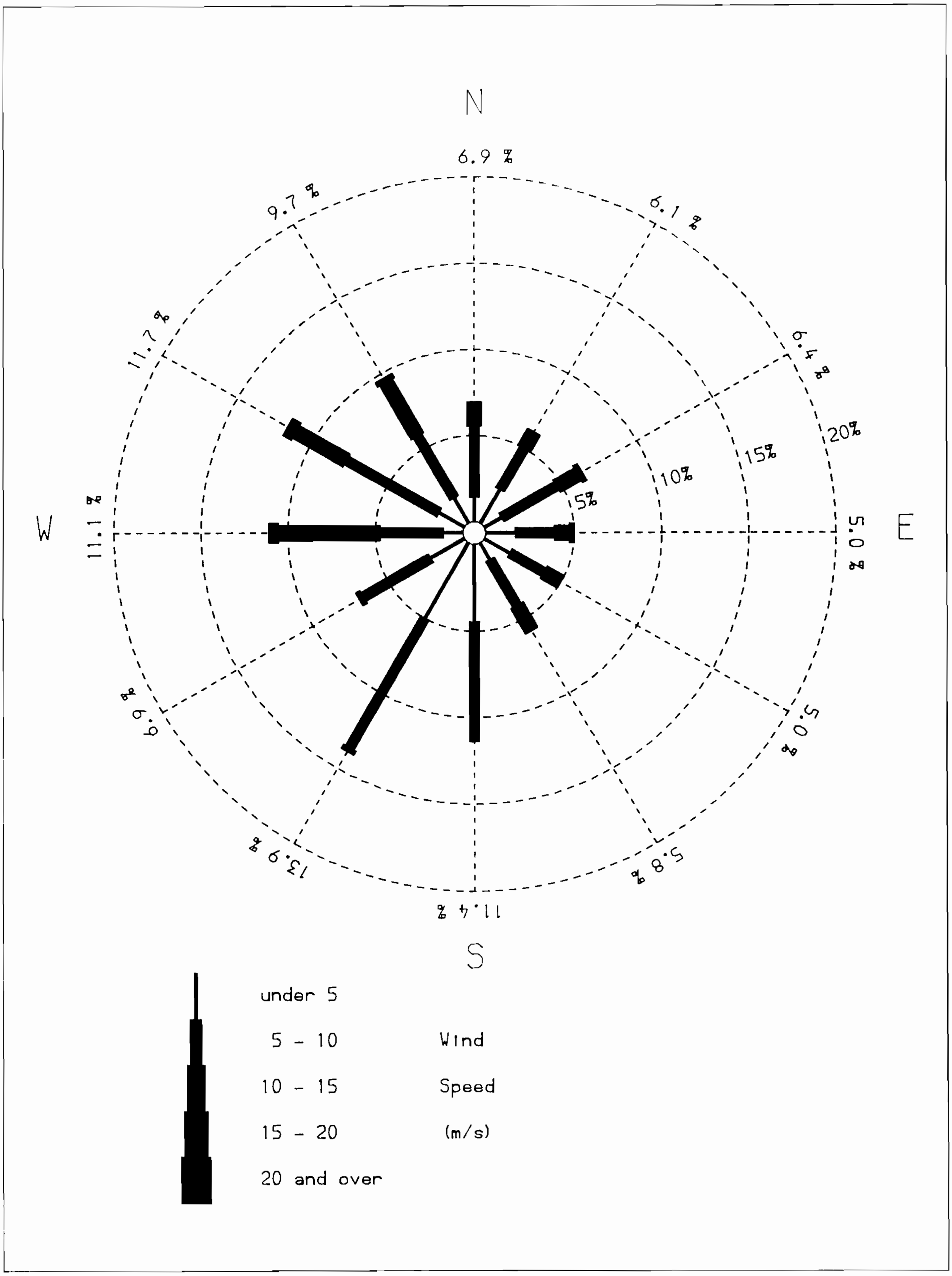

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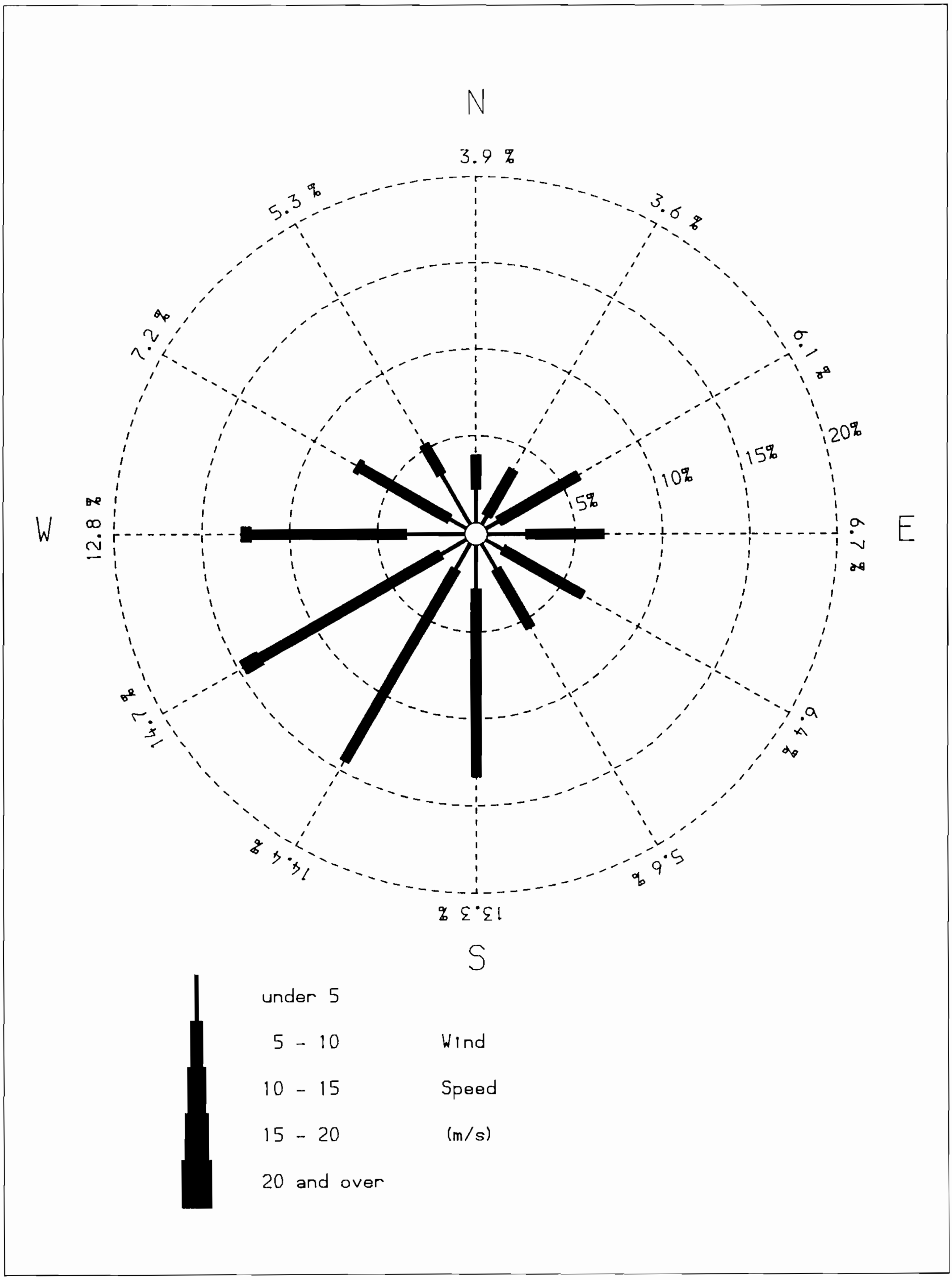

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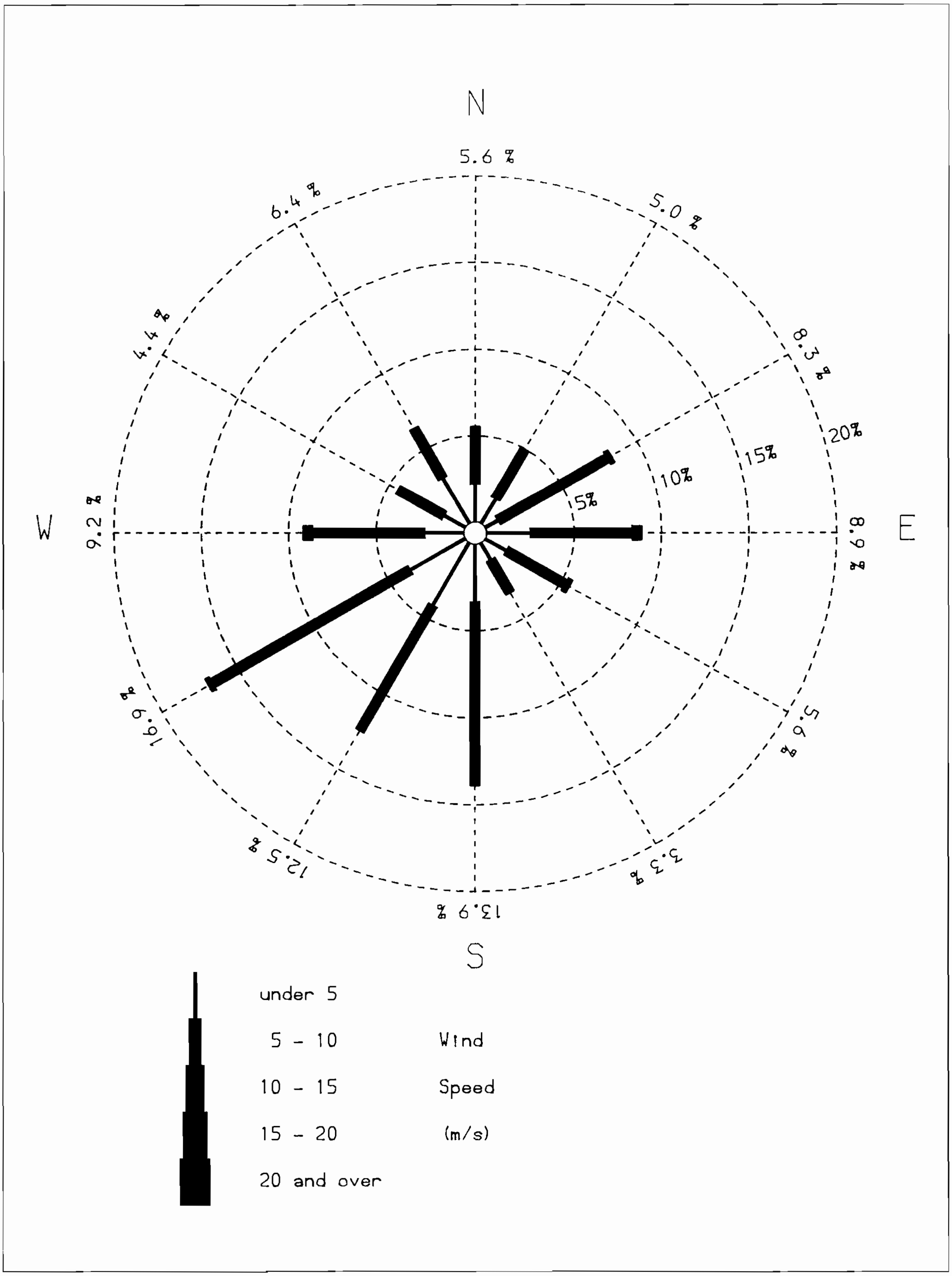

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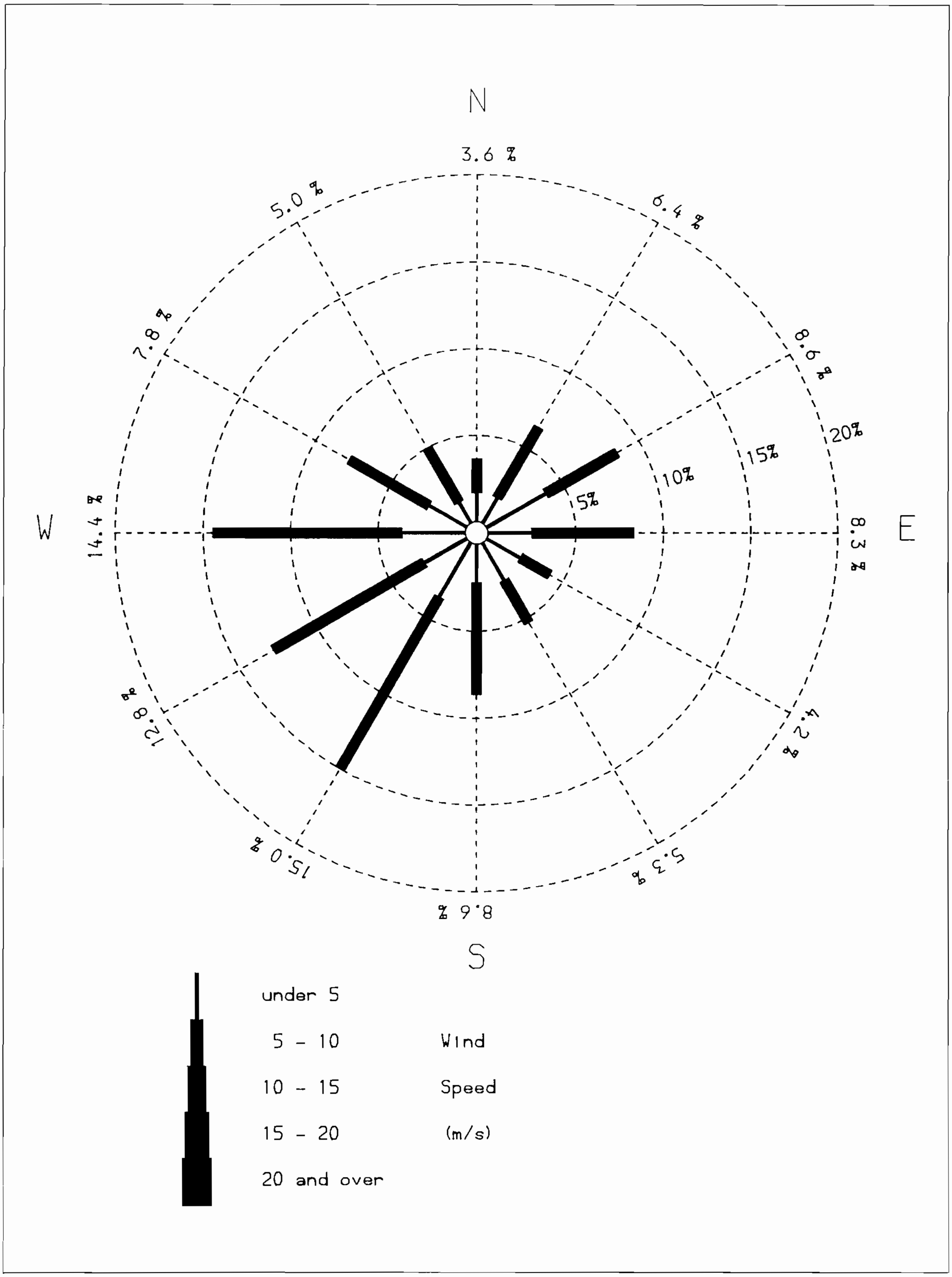

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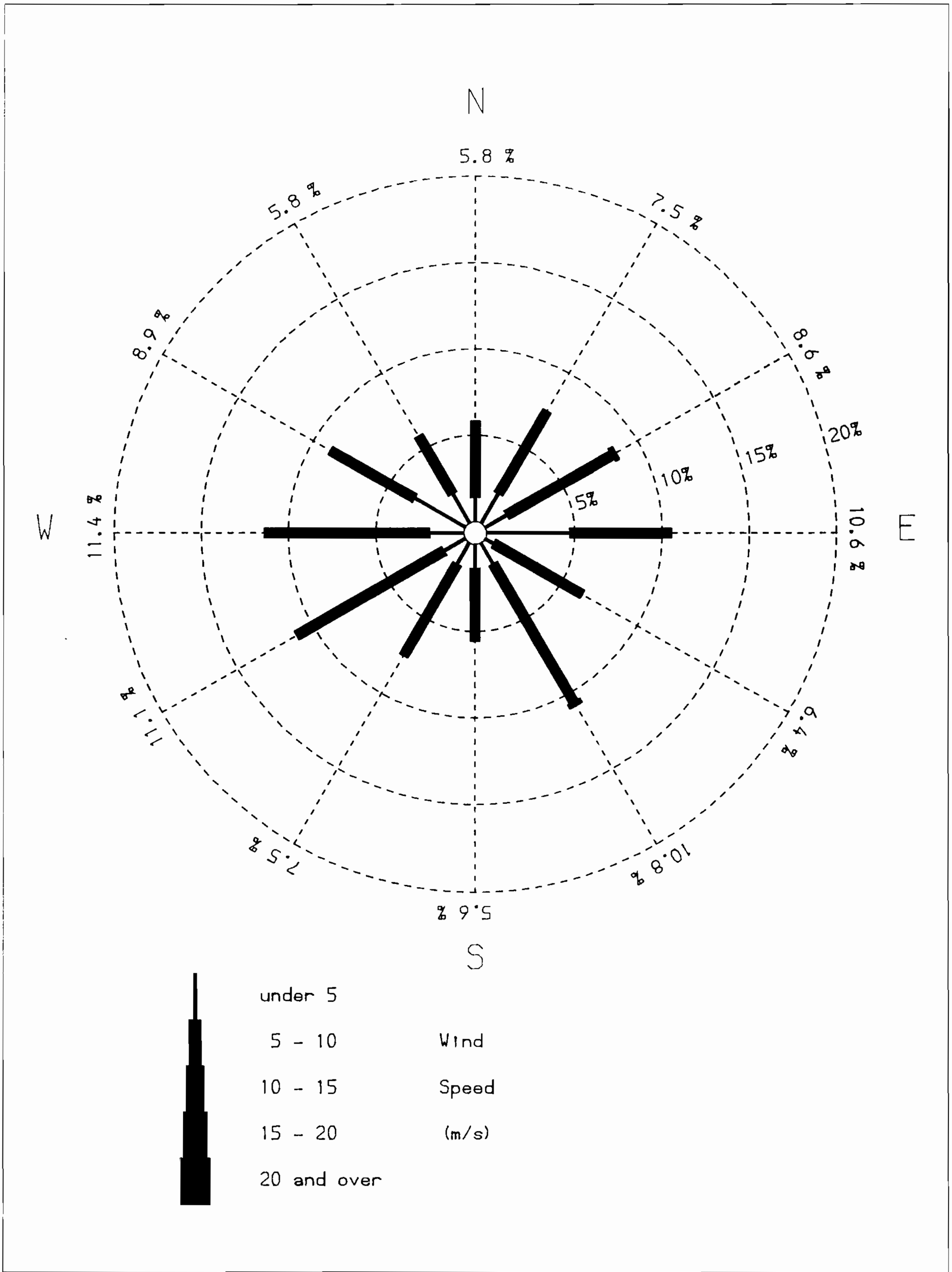

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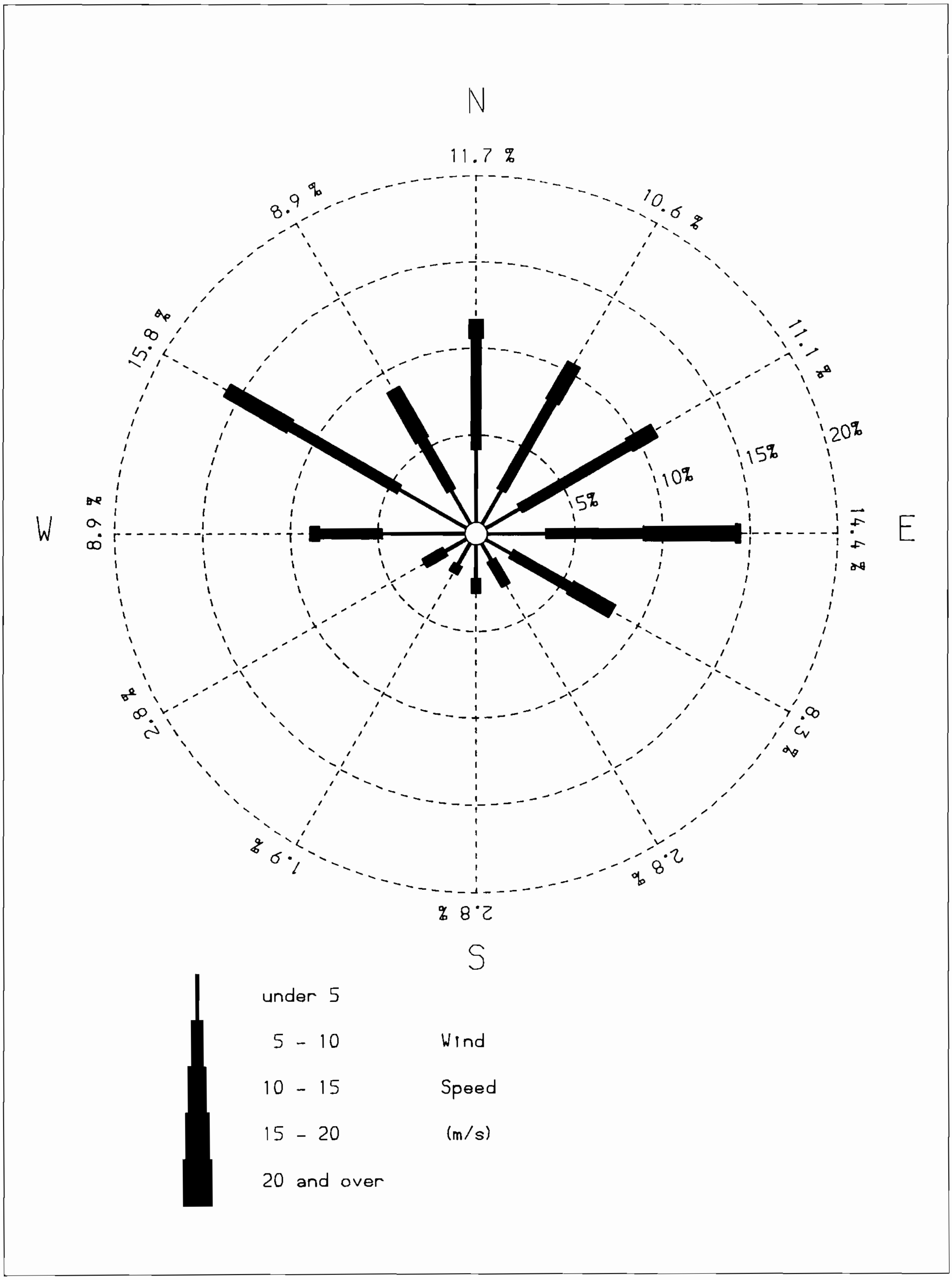

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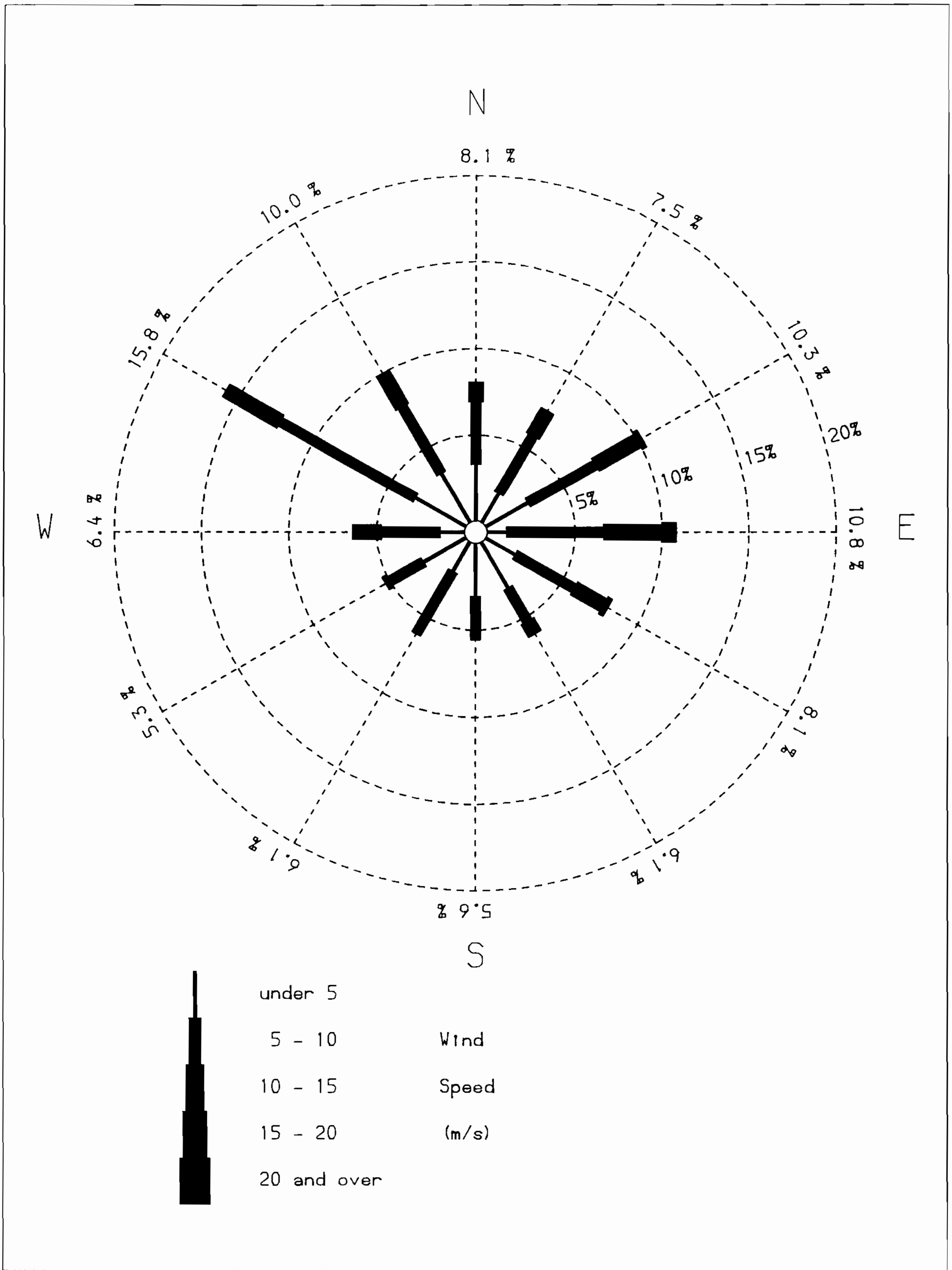

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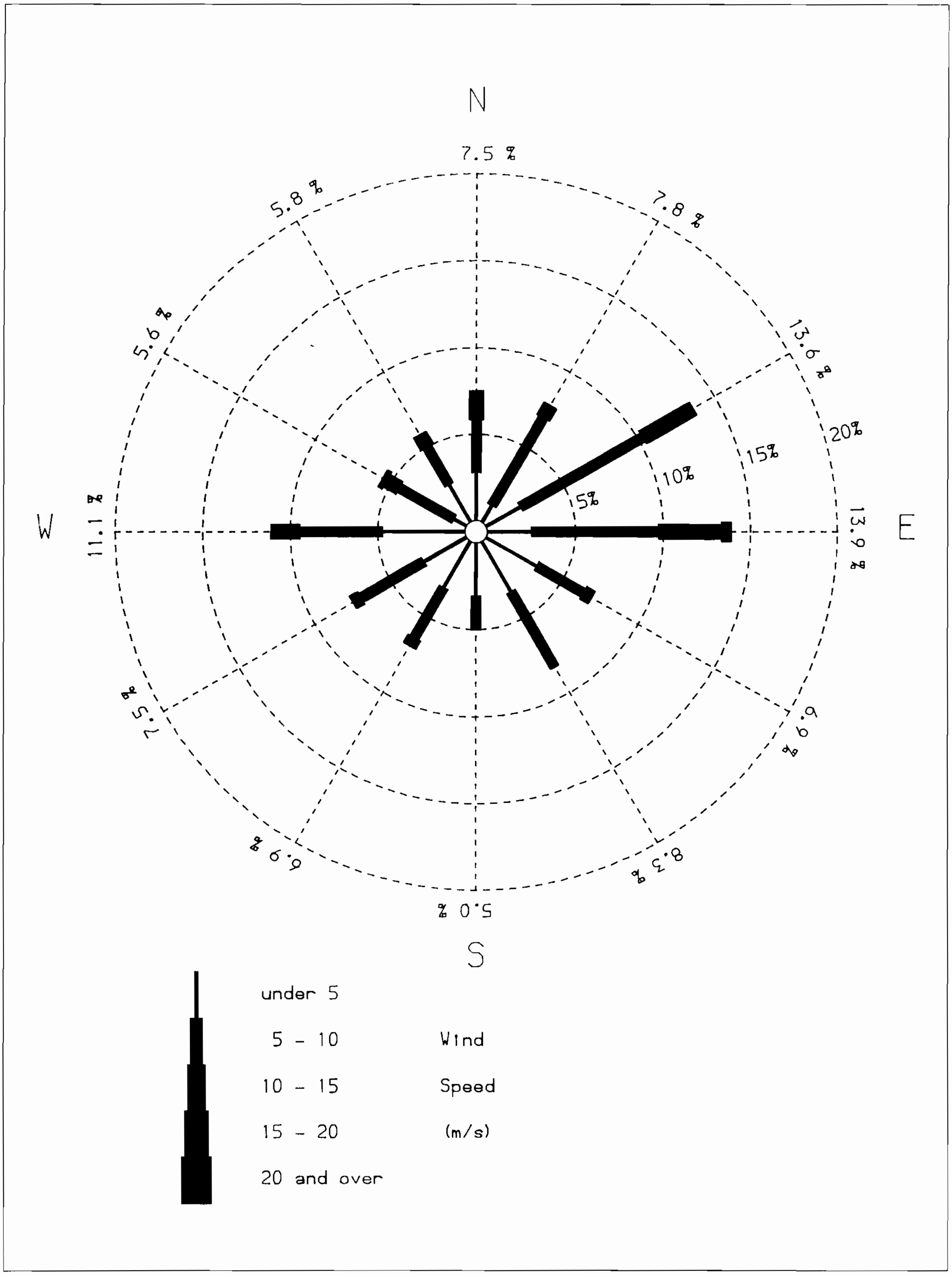

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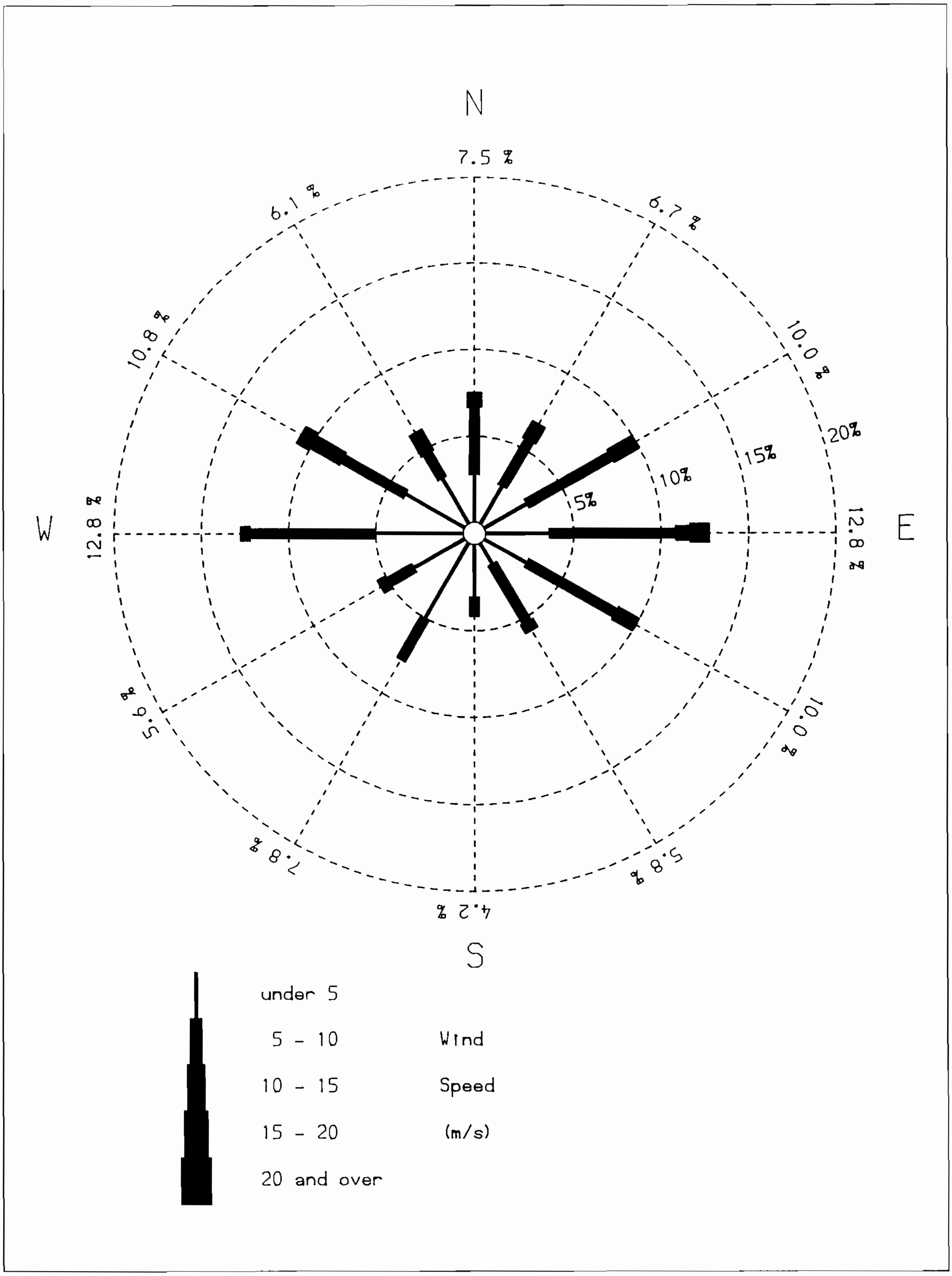

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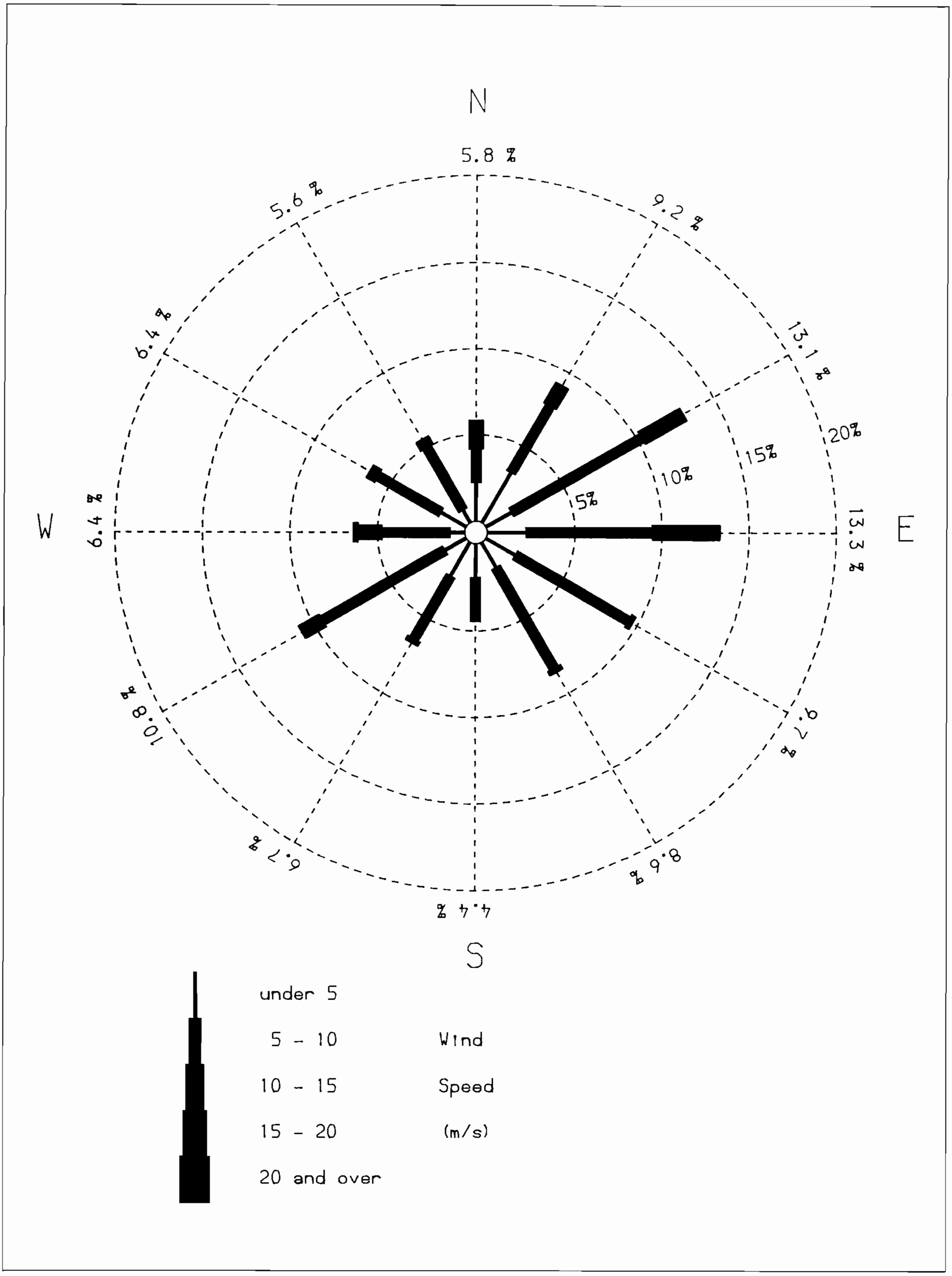

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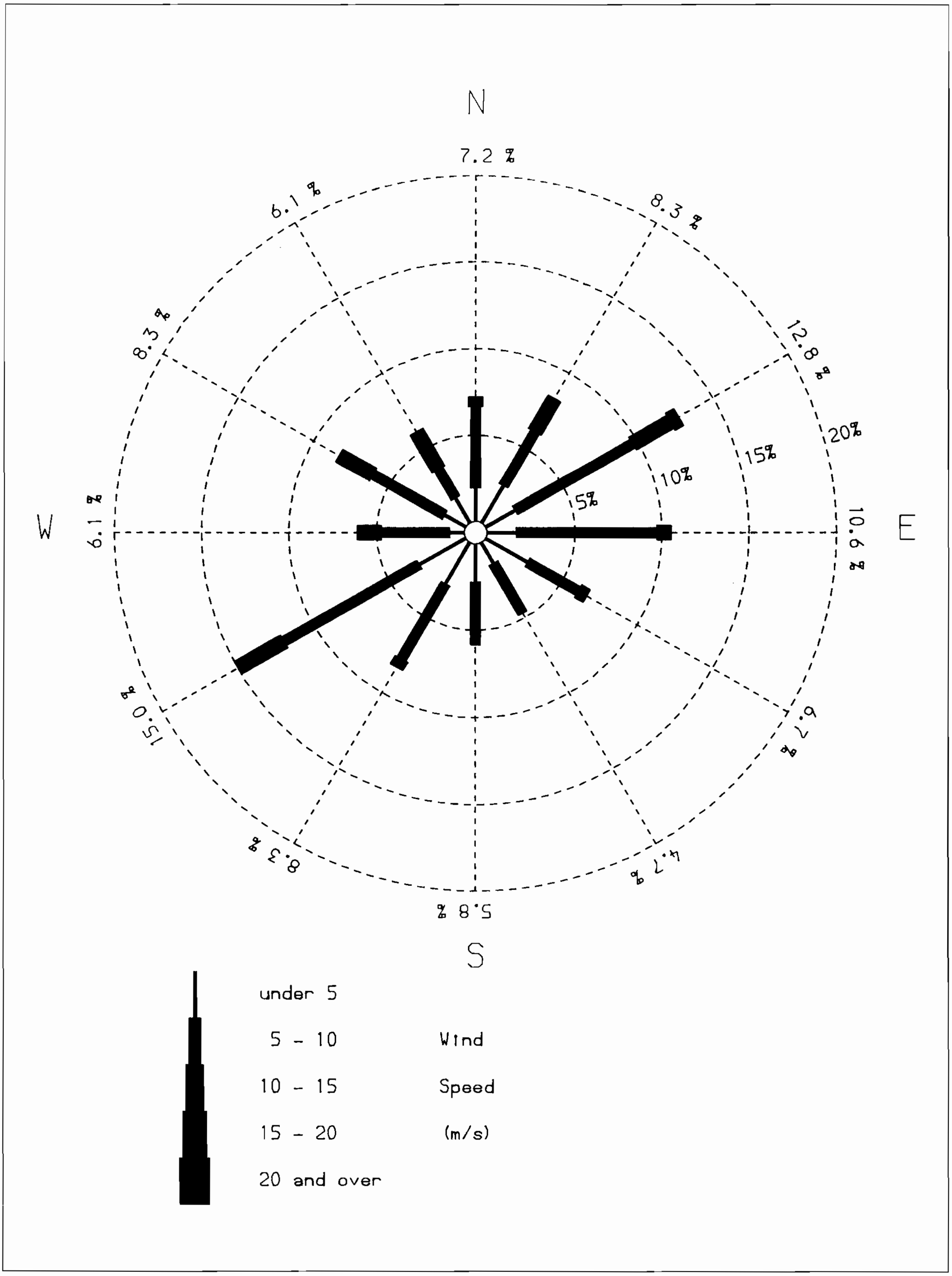

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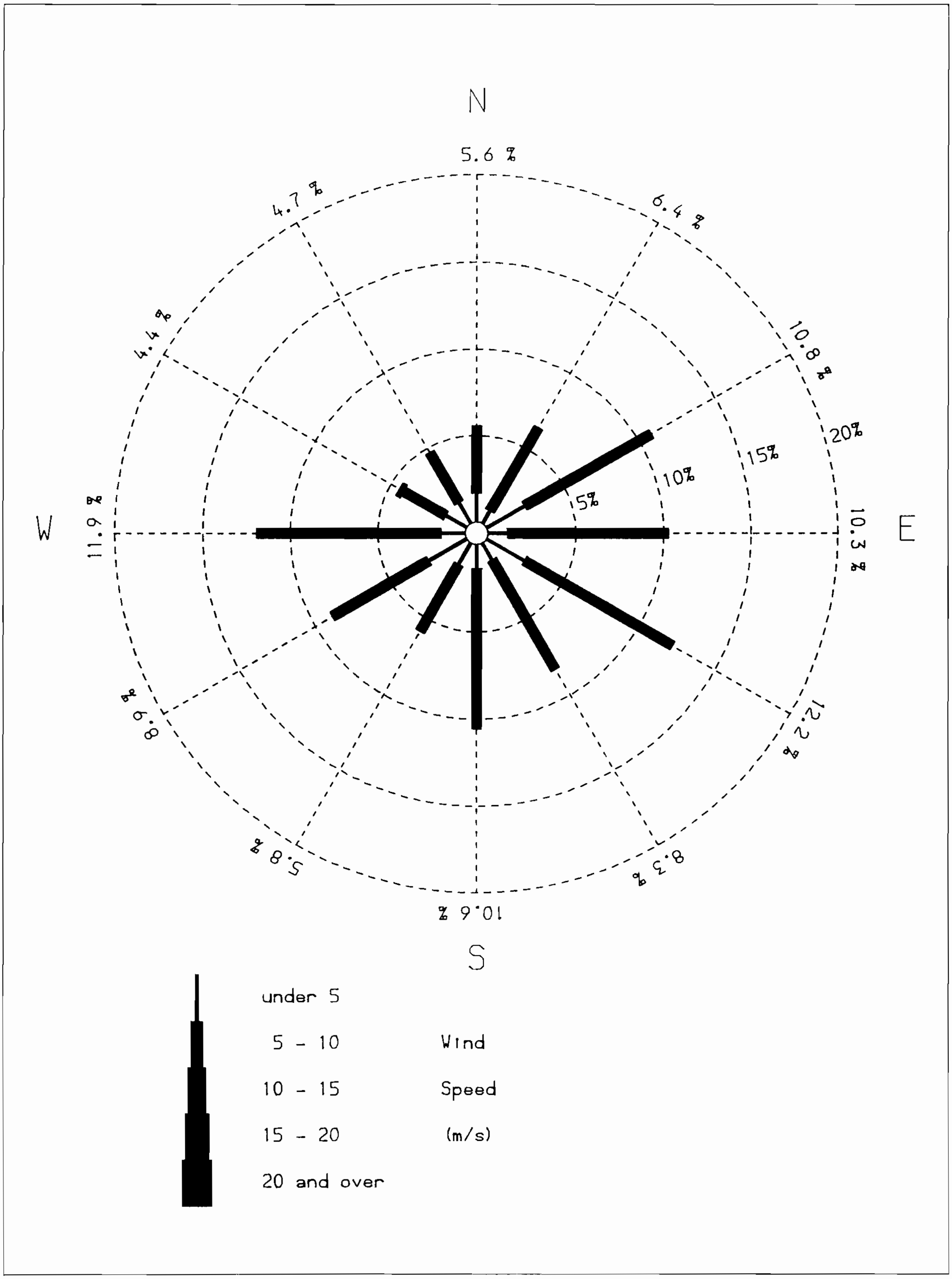

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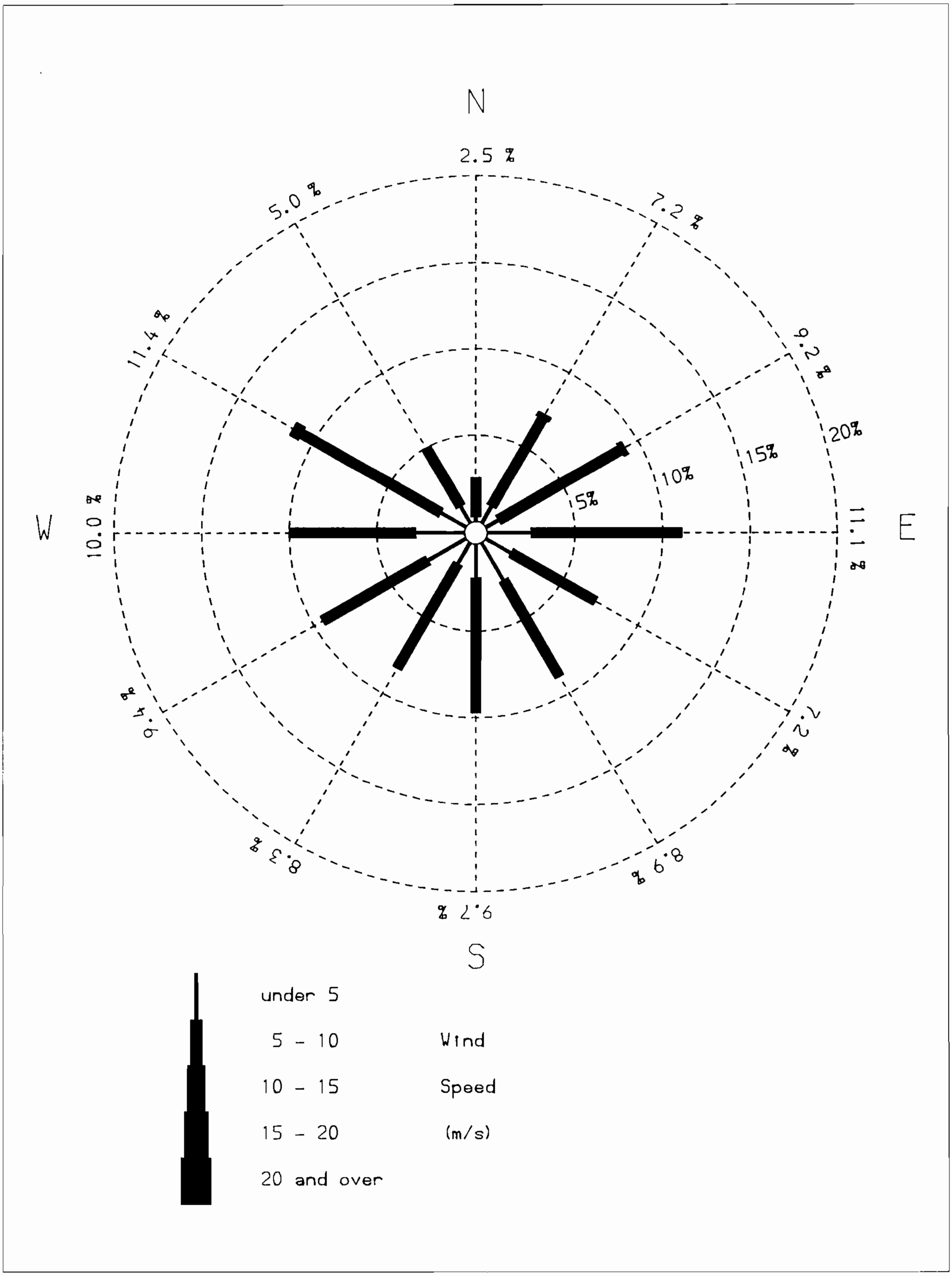

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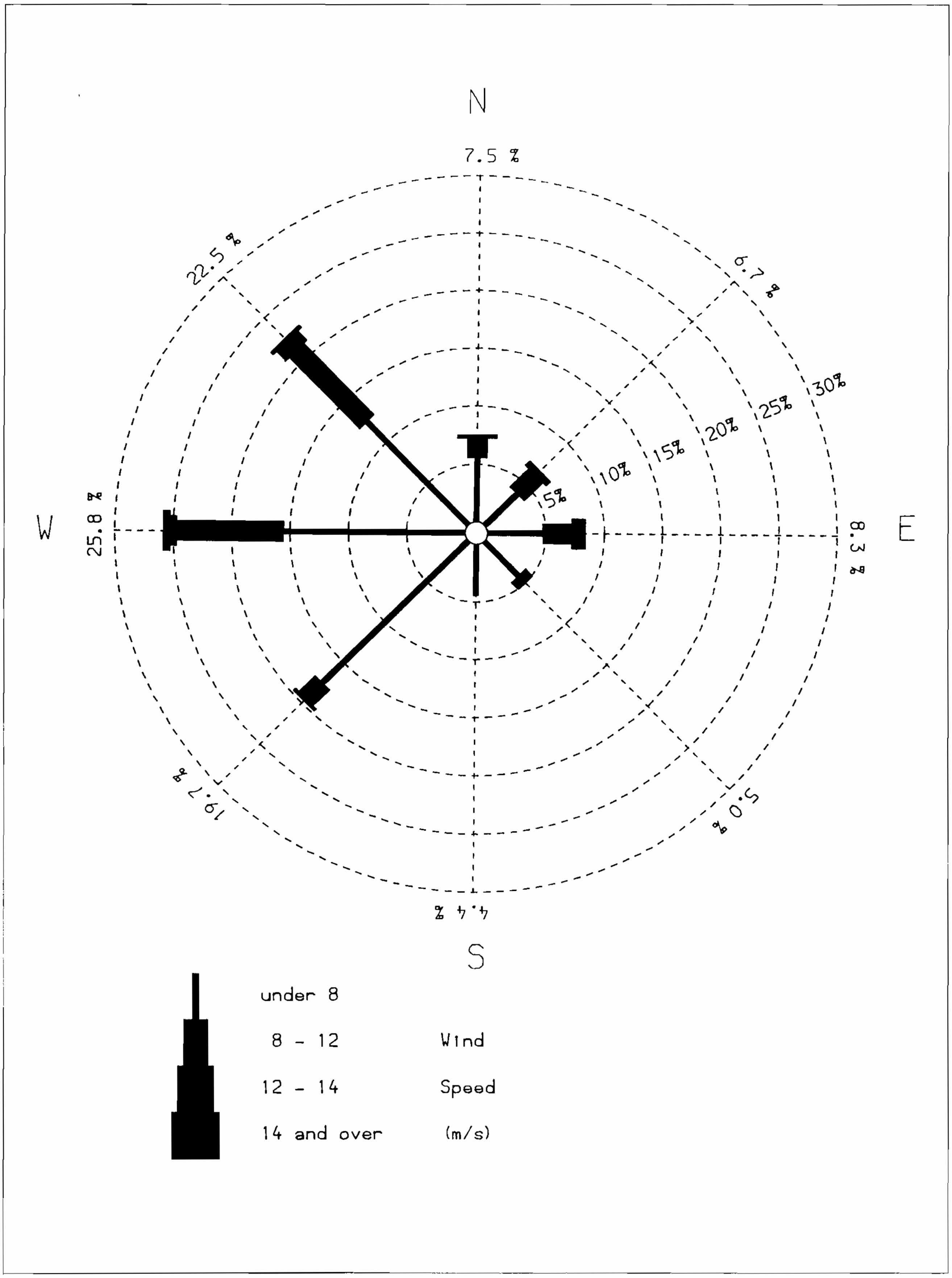
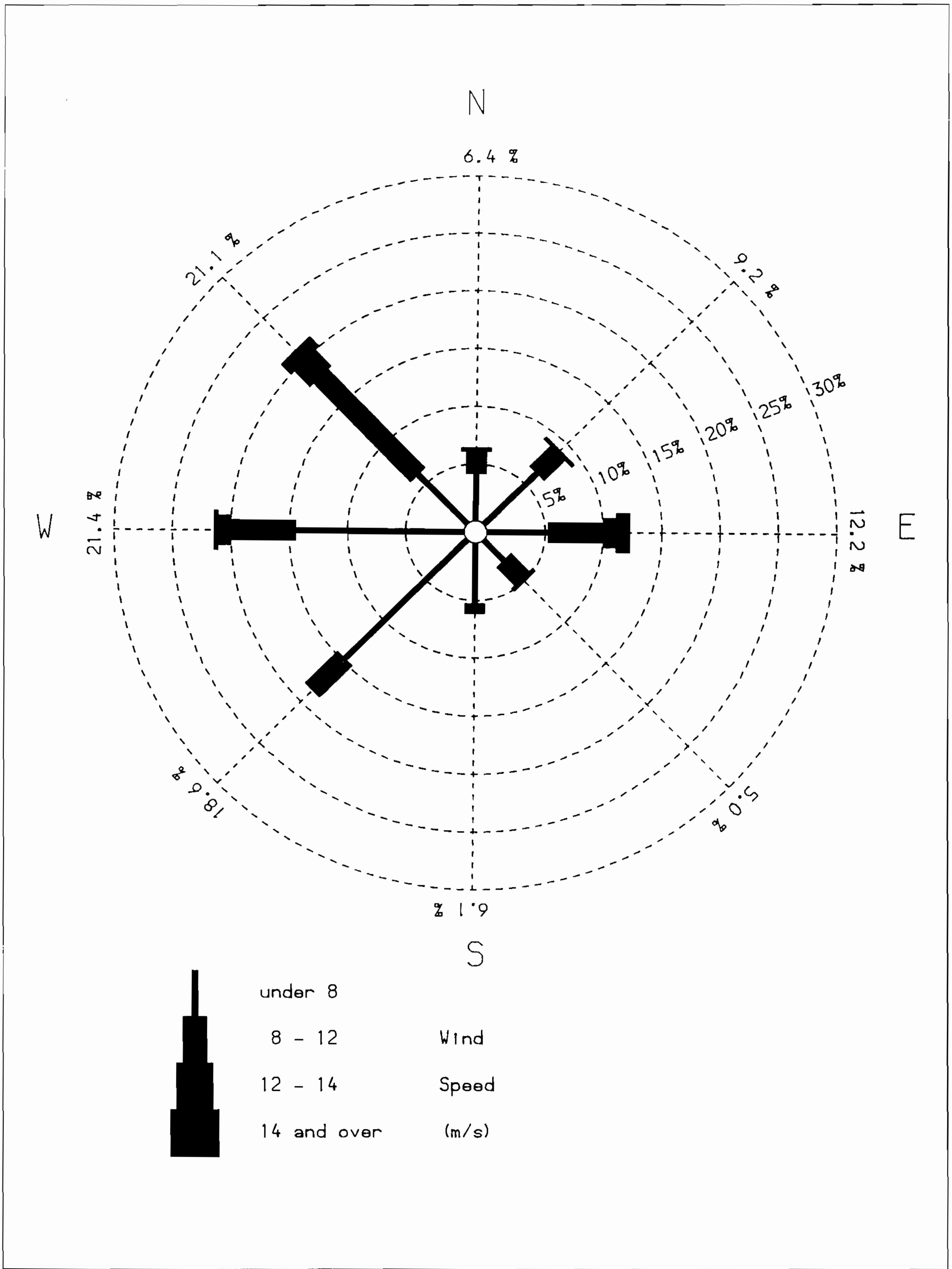


Wind rose for 57.5 N 41.25 W . Present co2 levels



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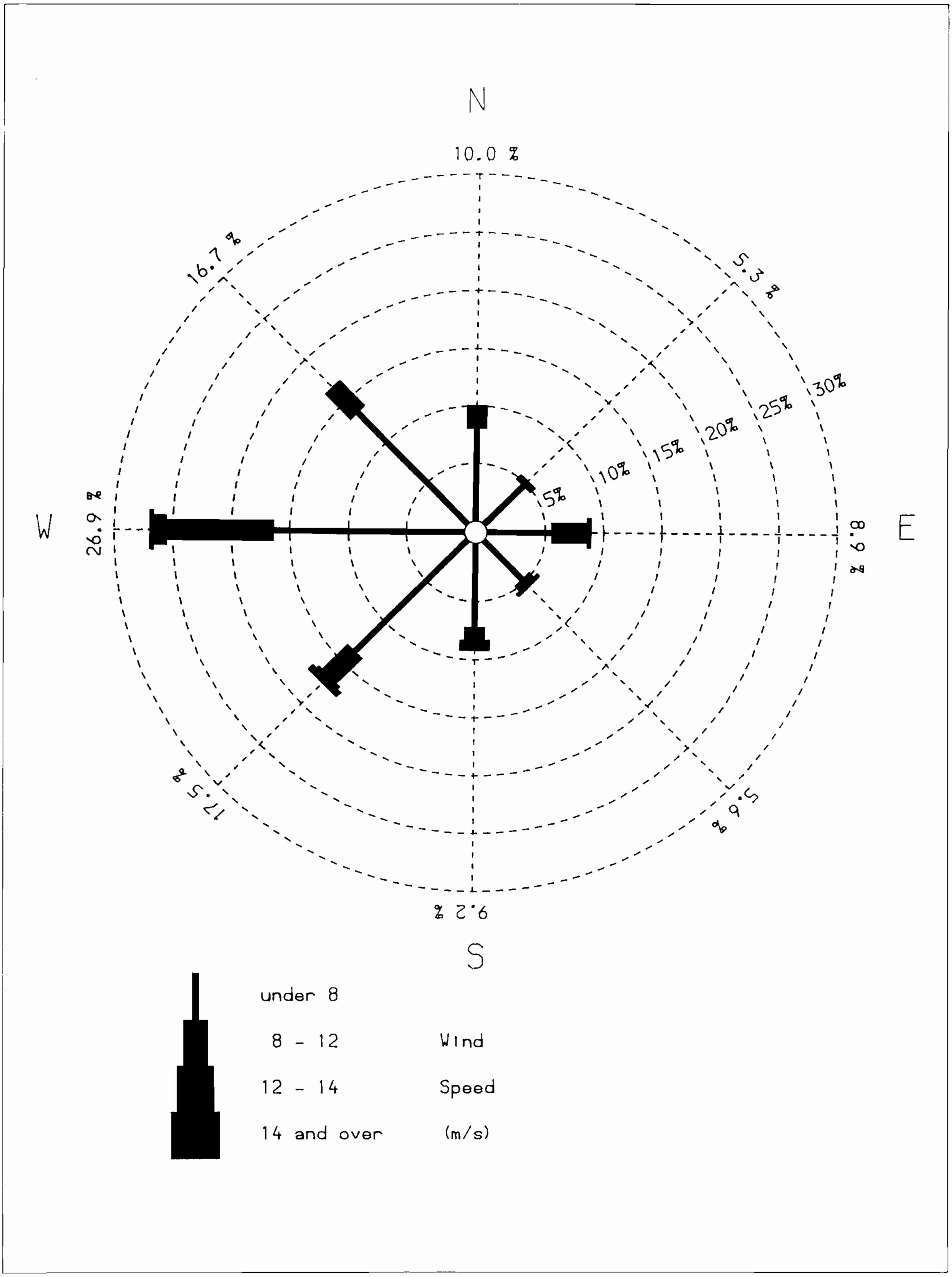
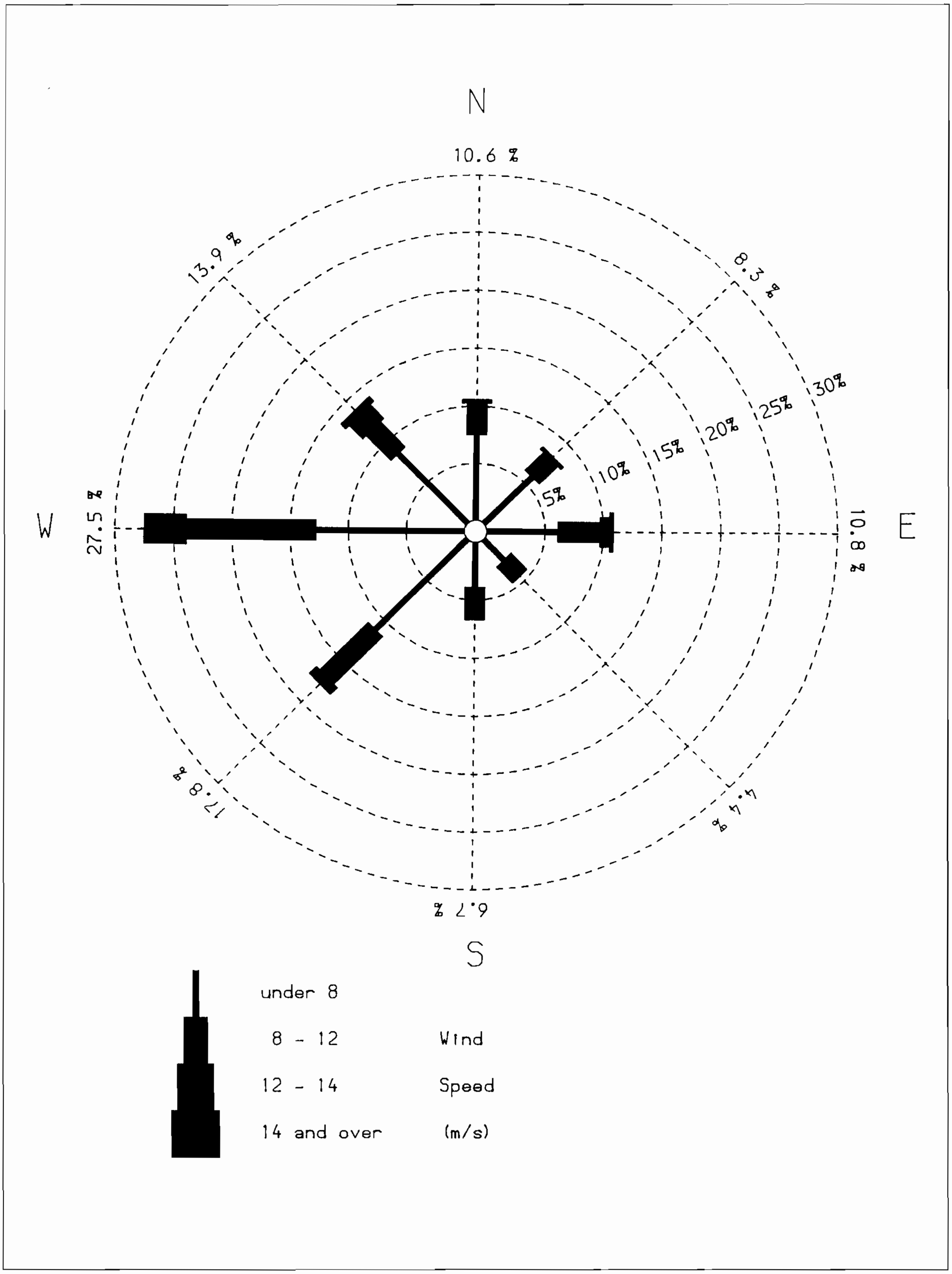


Wind rose for 57.5 N 33.75 W . Present co2 levels



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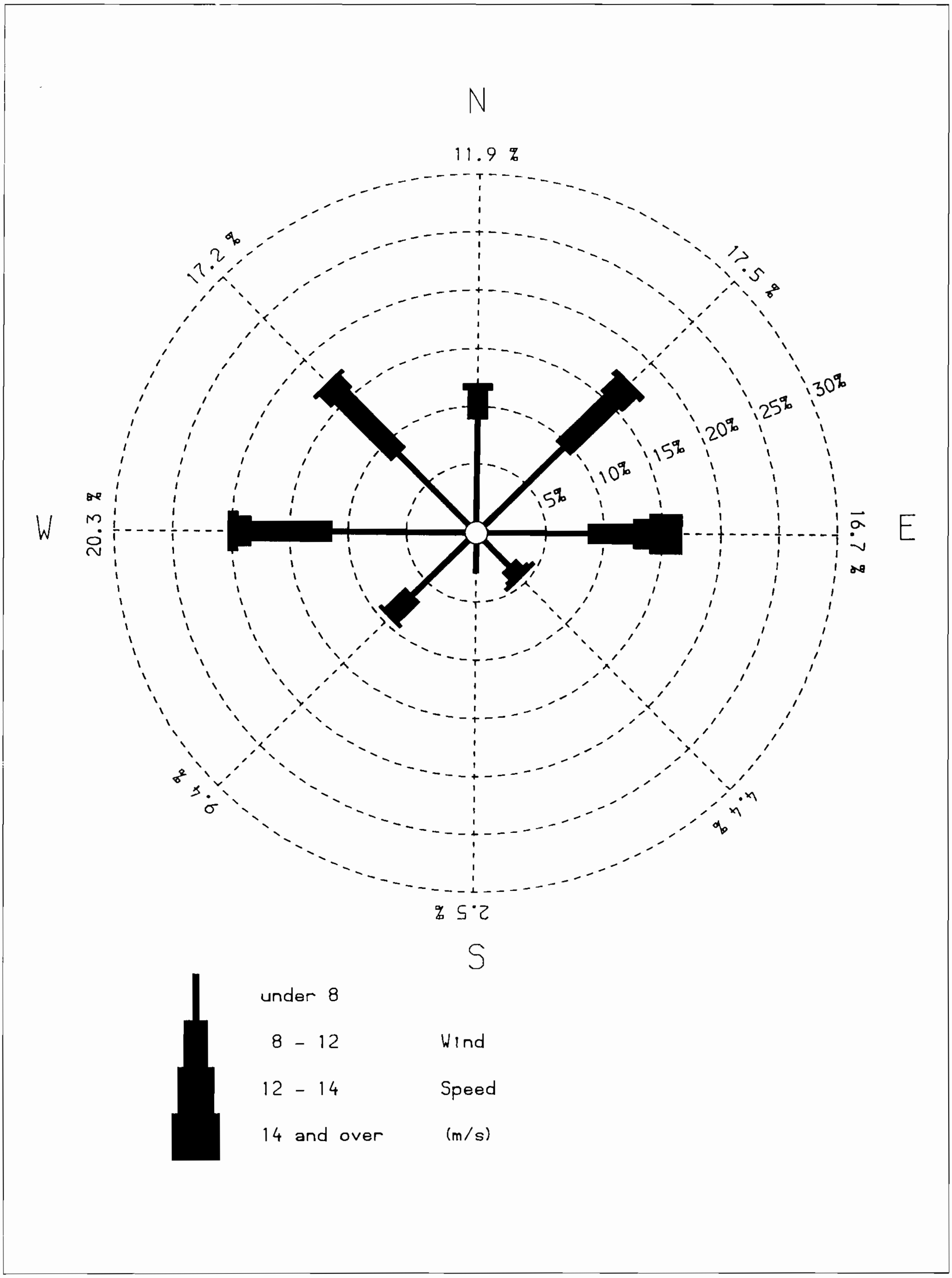

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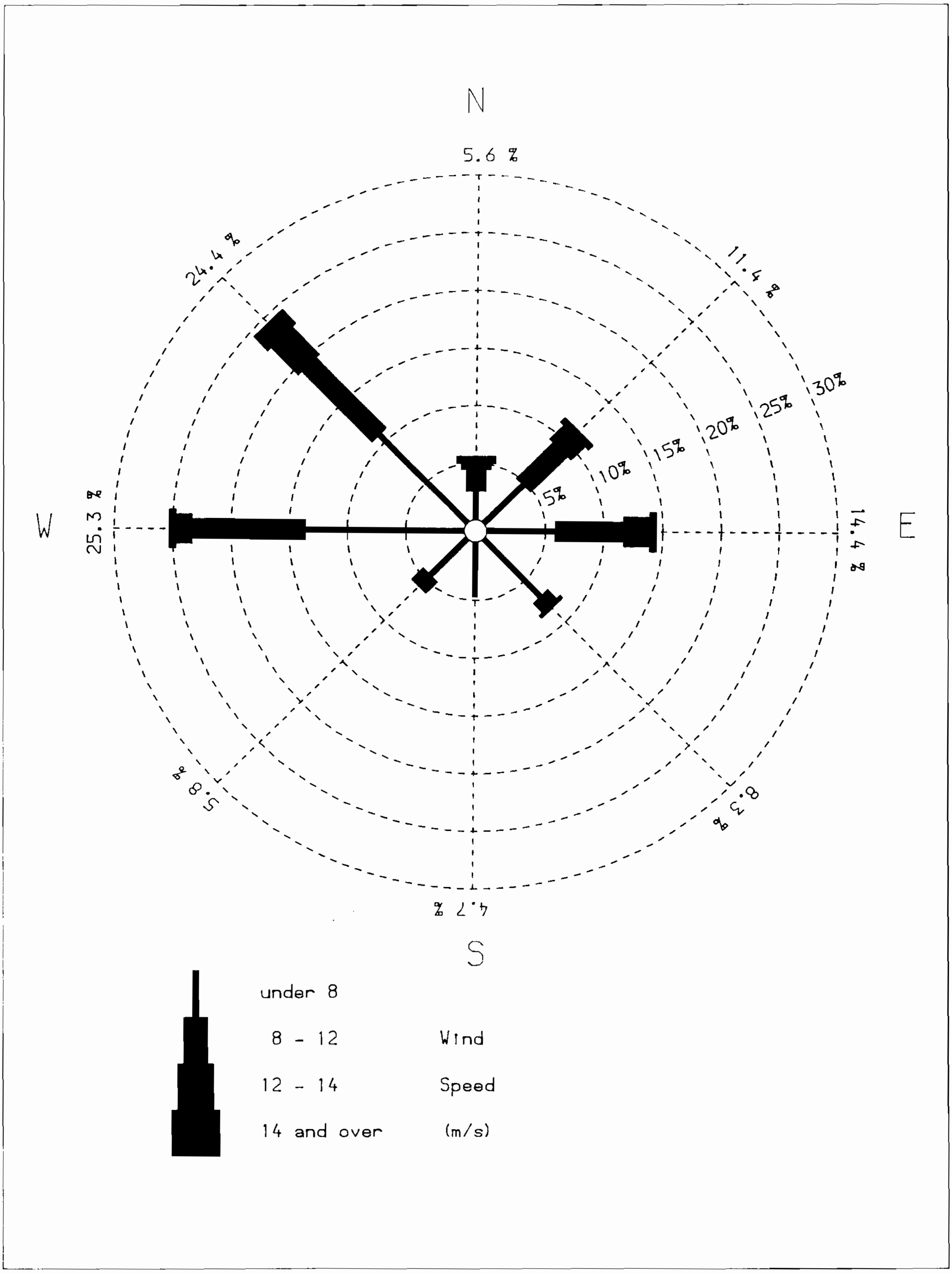

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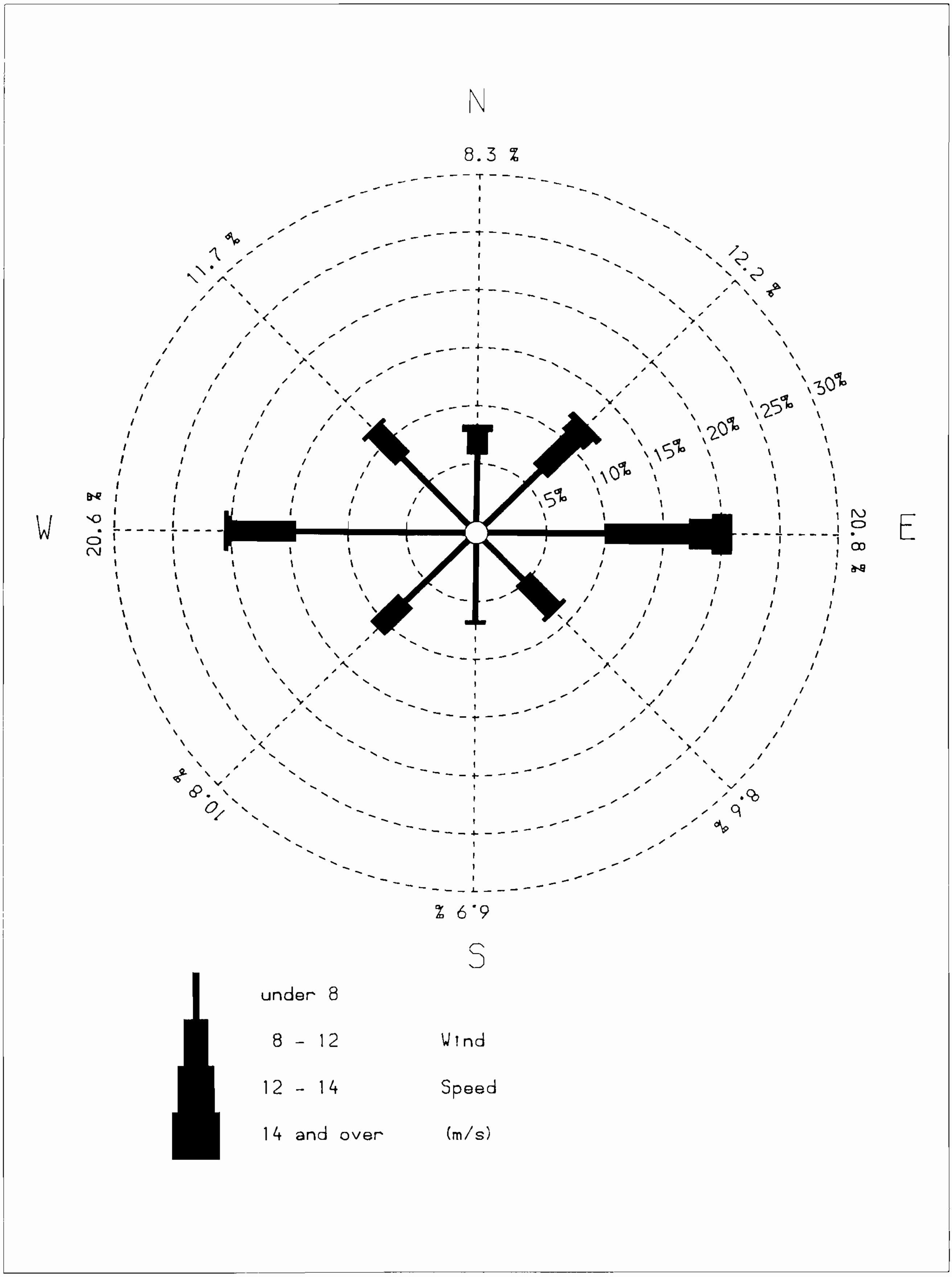

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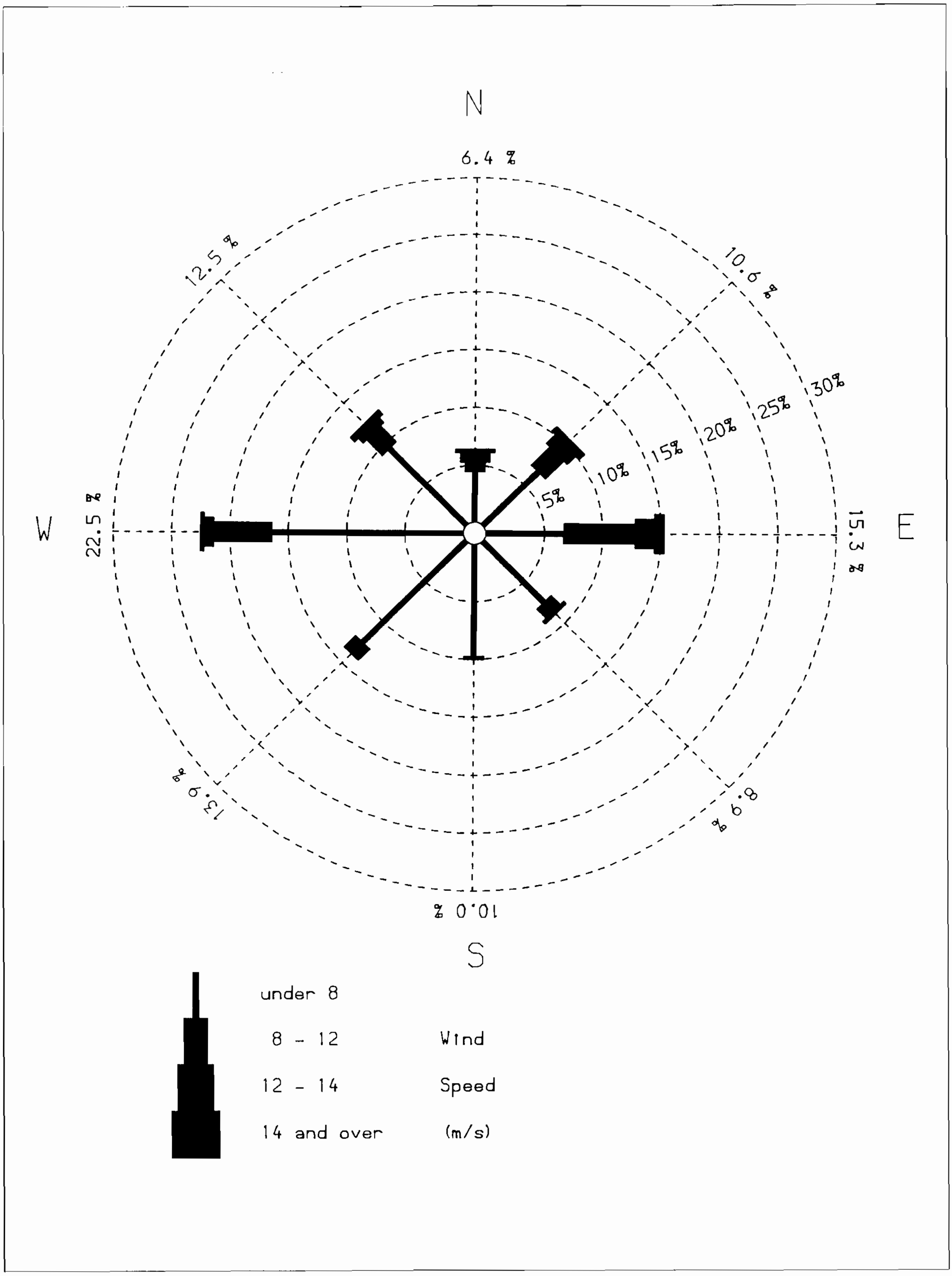

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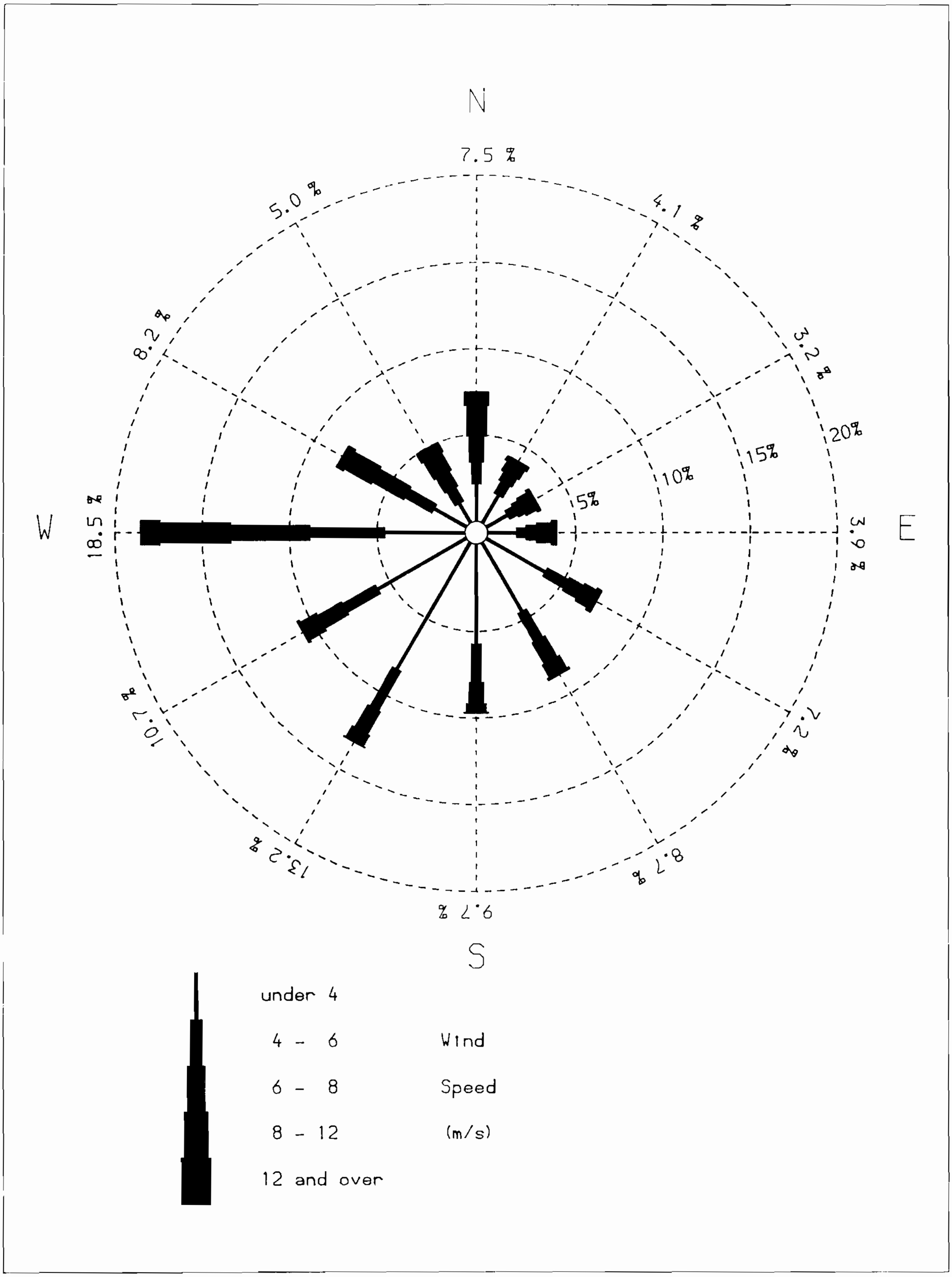
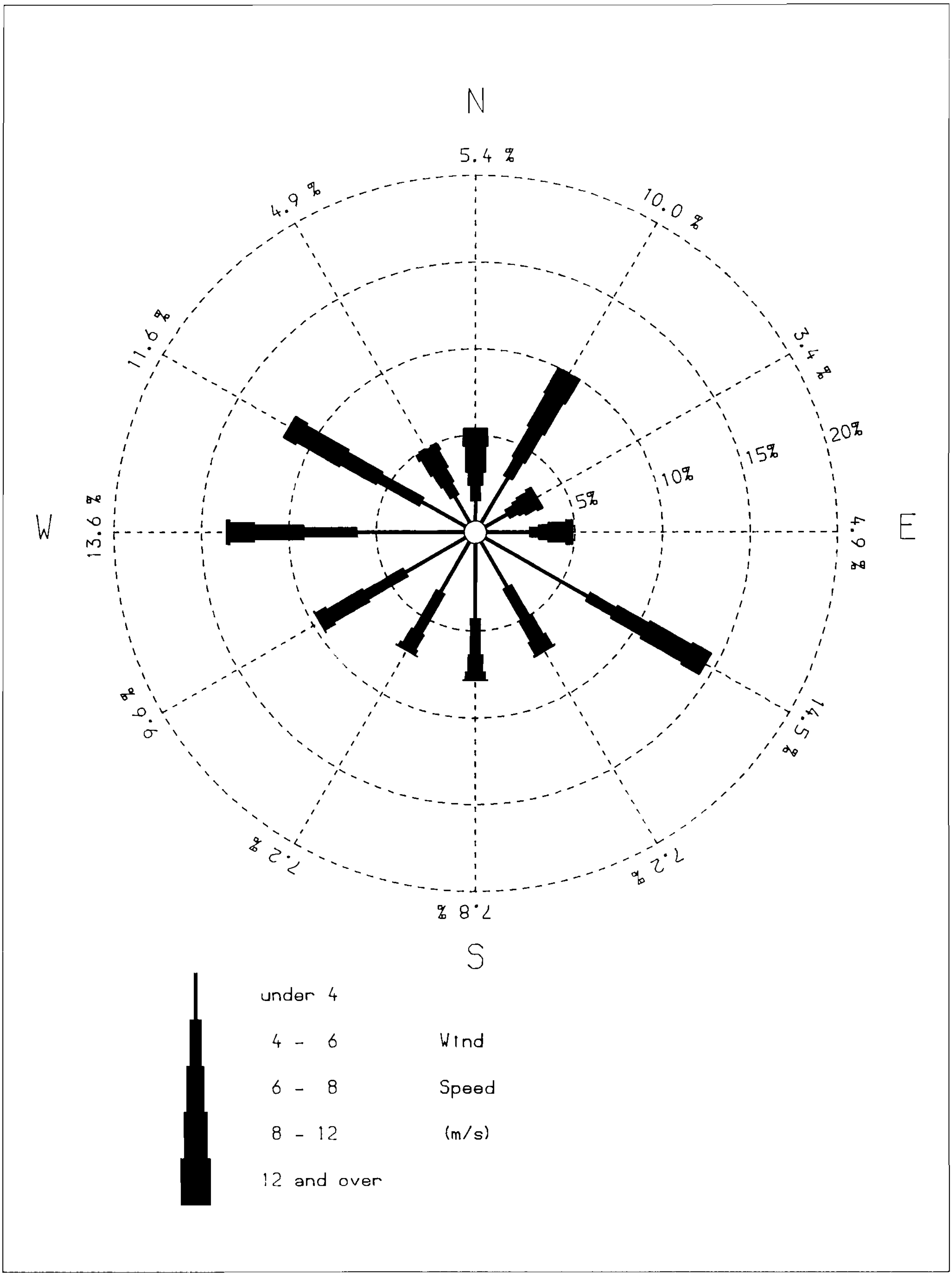
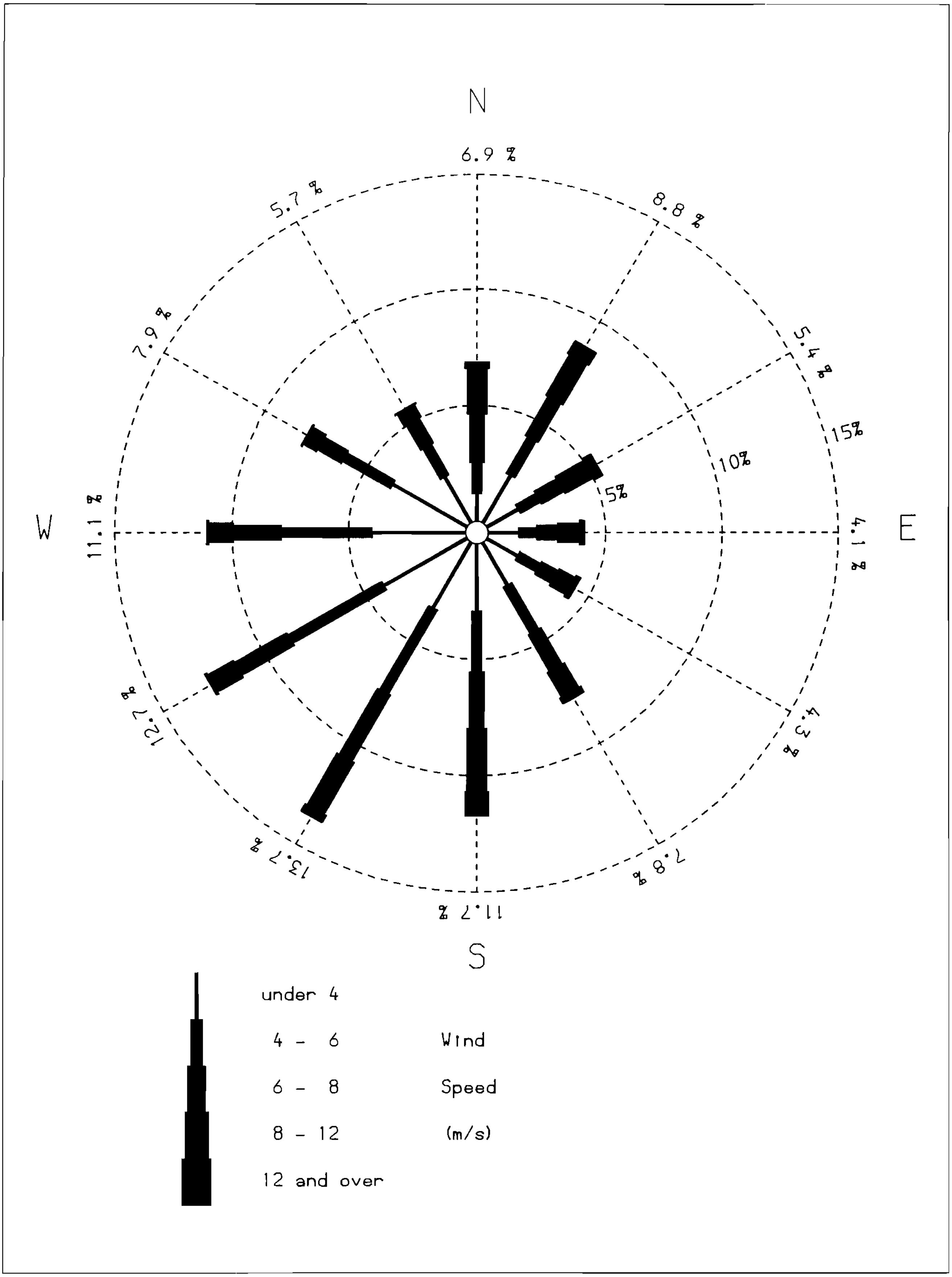


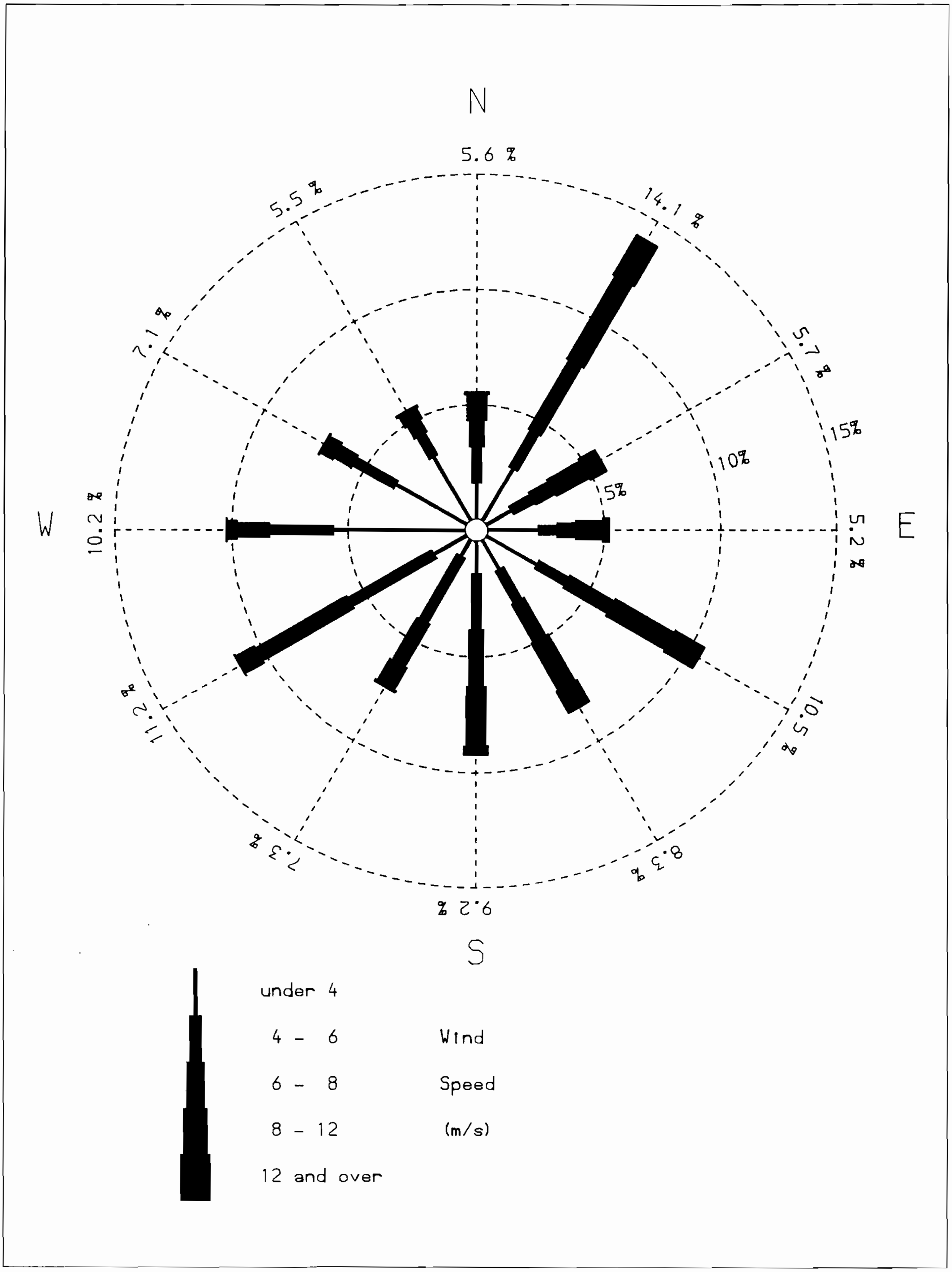
Wind rose for South Shields - Present CO2 levels



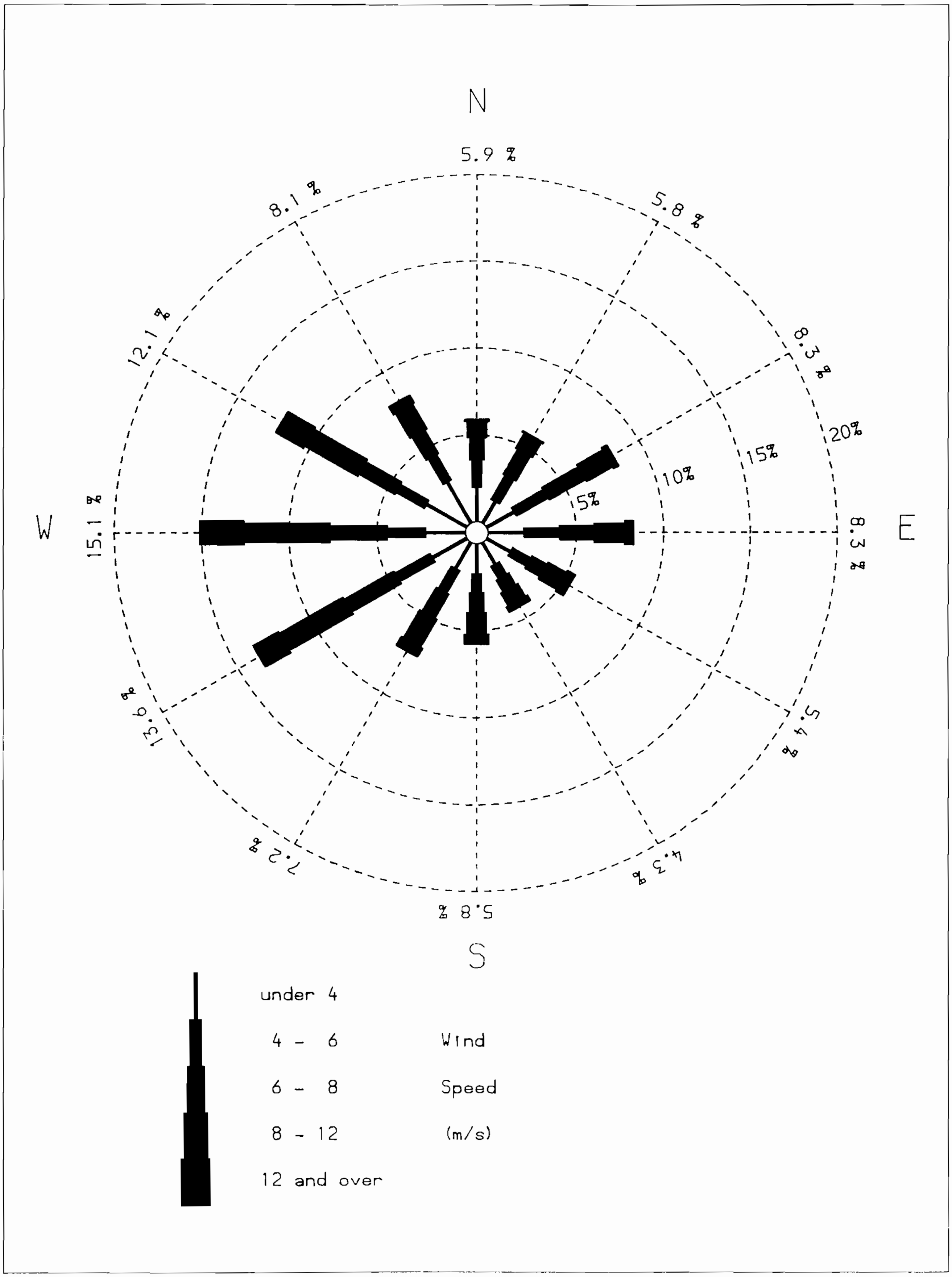
Wind rose for South Shields - Double CO2 levels



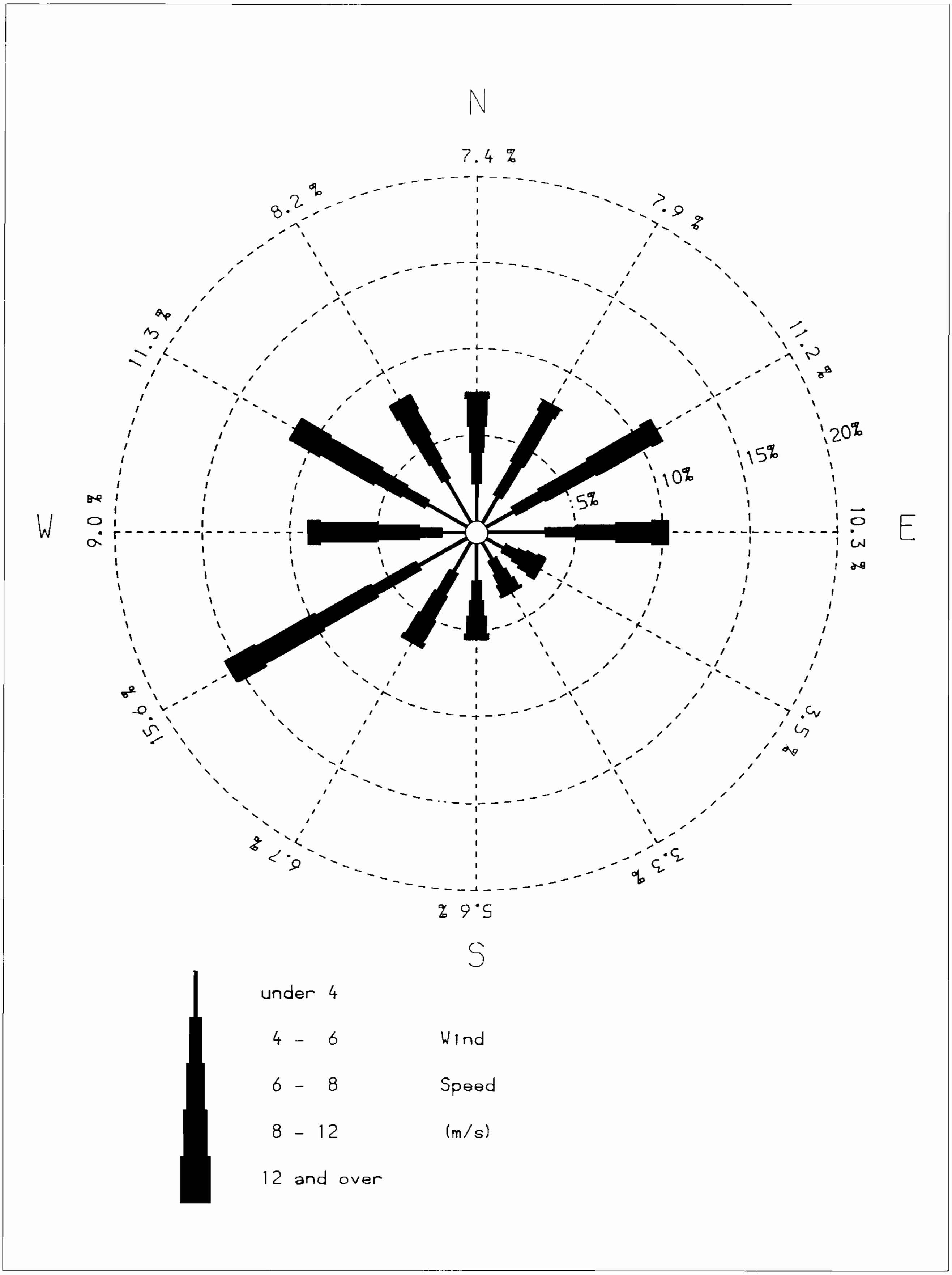
Wind rose for Gorleston - Present CO2 levels



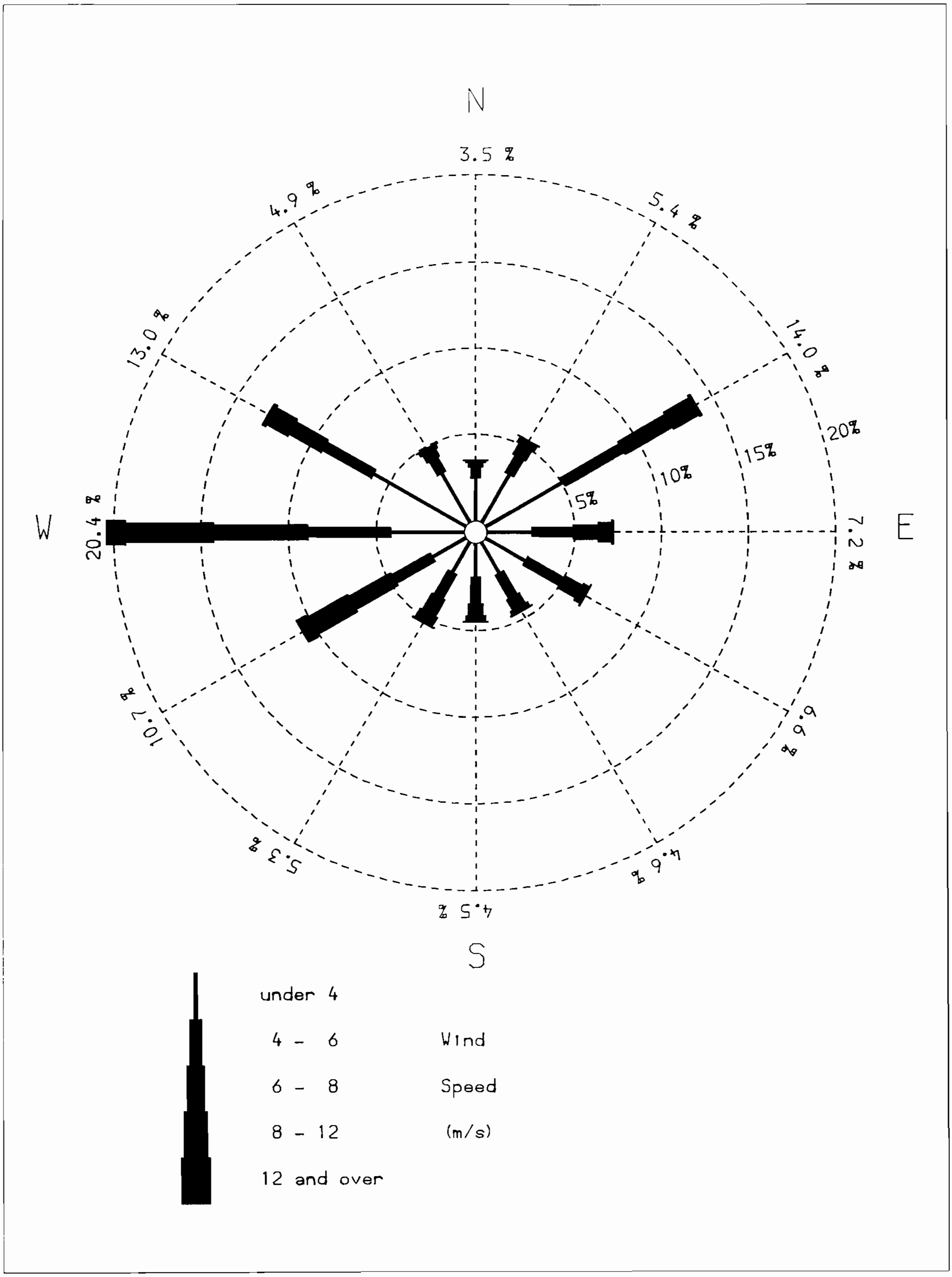
Wind rose for Gorleston - Double CO2 levels



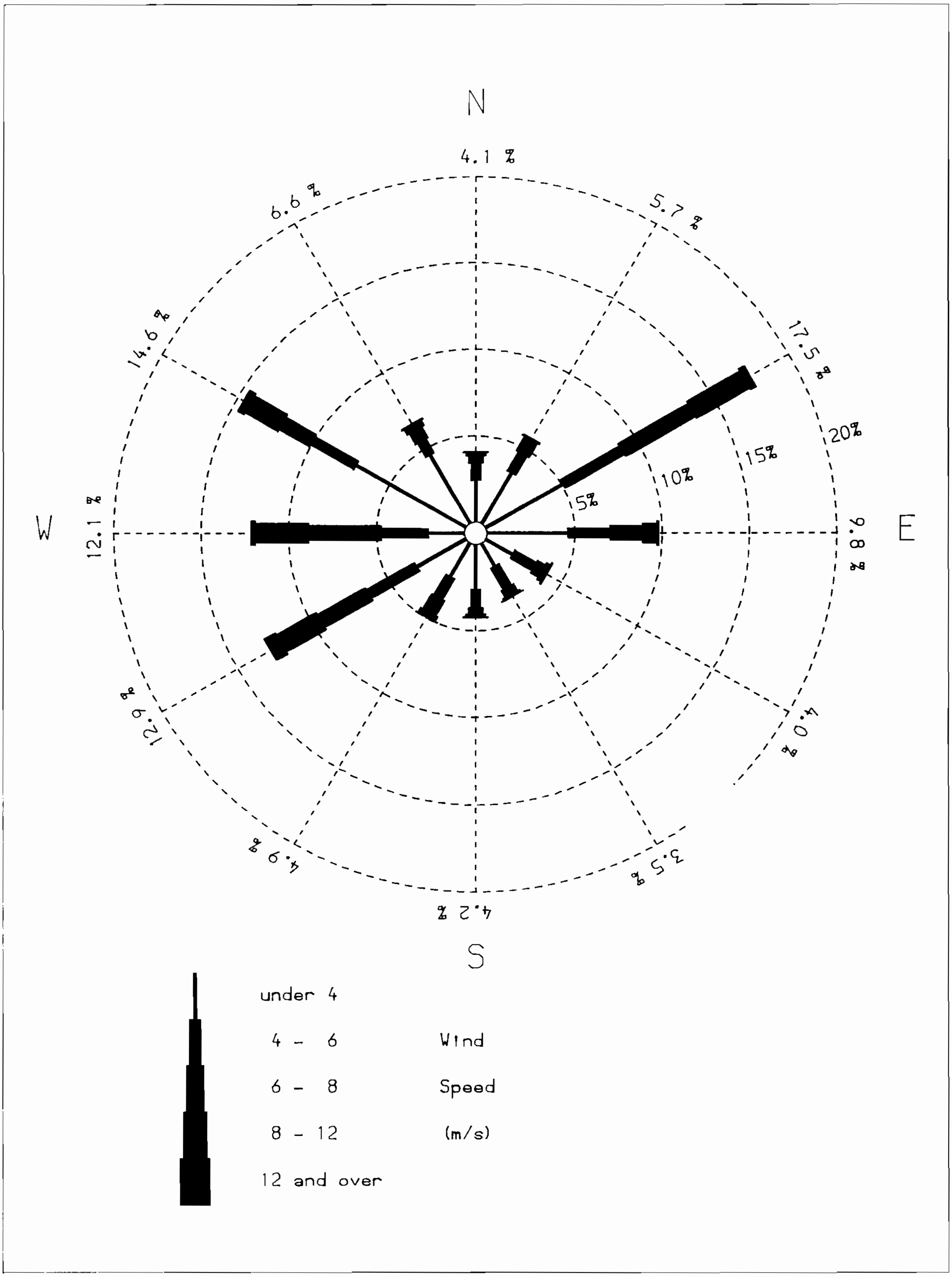
Wind rose for Portland - Present CO2 levels



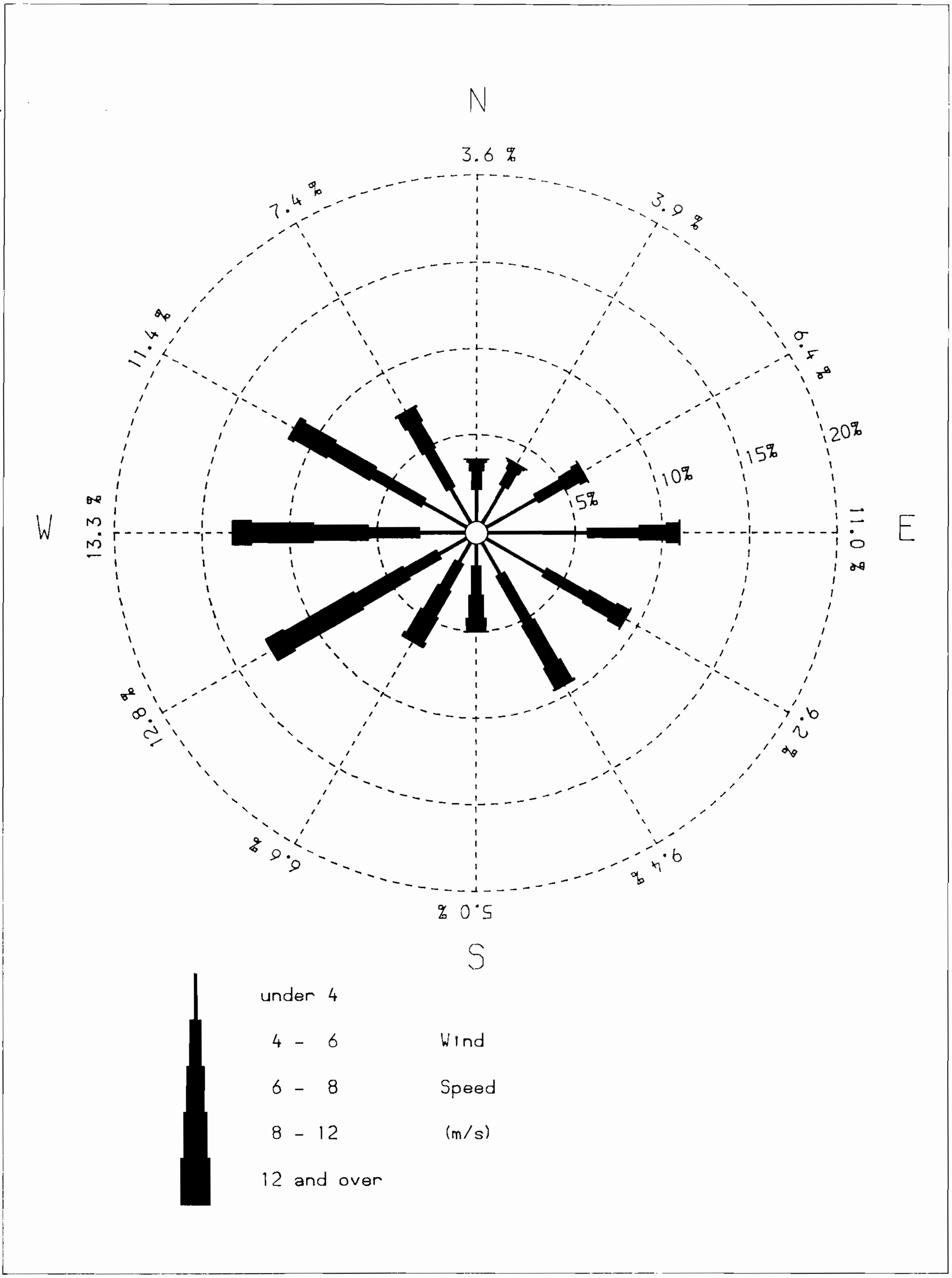
Wind rose for Portland - Double CO2 levels



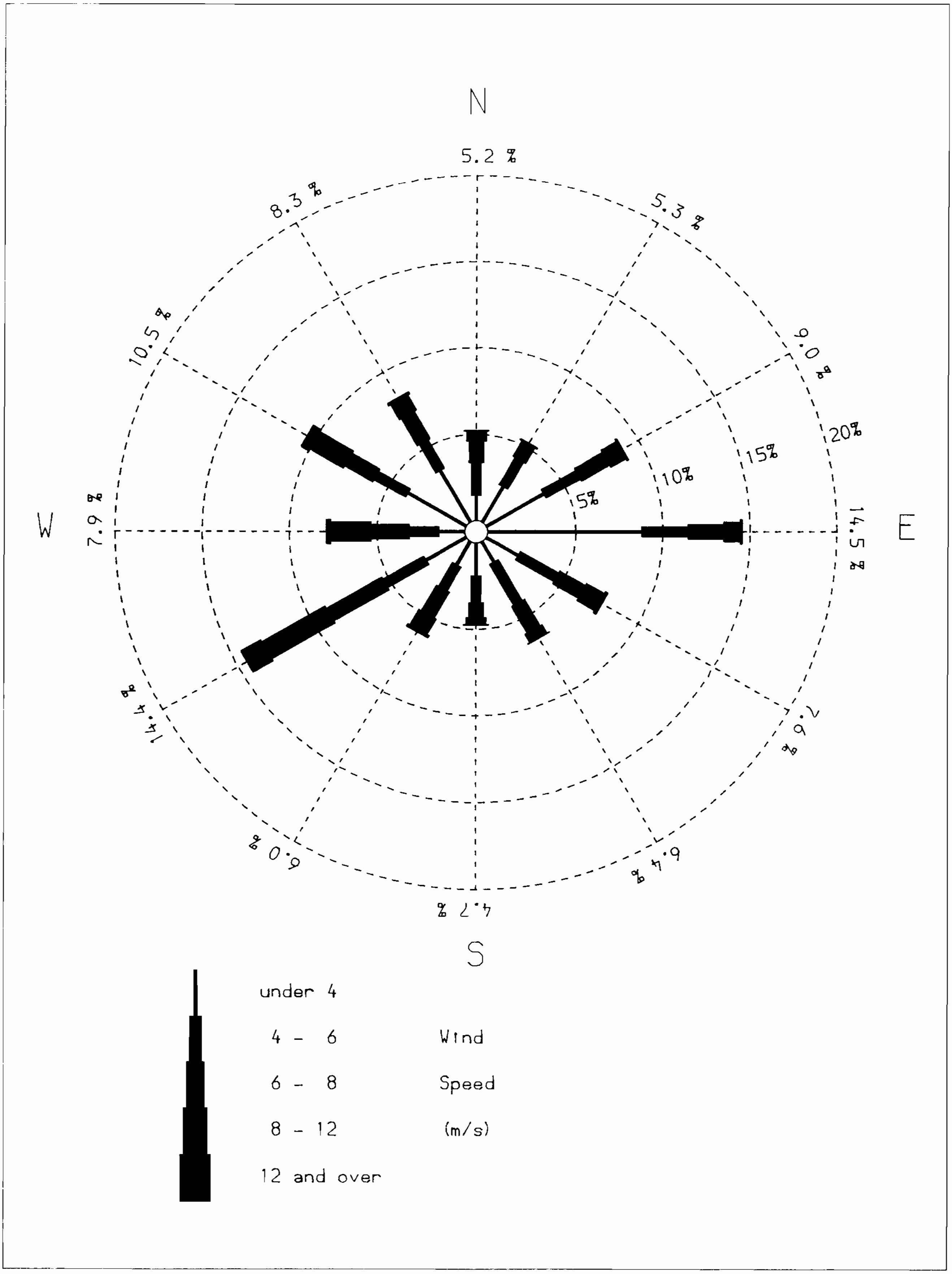
Wind rose for Rhoose - Present CO2 levels



Wind rose for Rhoose - Double CO2 levels



Wind rose for Squiresgate - Present CO2 levels



Wind rose for Squiresgate - Double CO2 levels

APPENDIX 5

The WINDSEQ Model :

Simulation of time series wind data from wind rose information

APPENDIX 5

The WINDSEQ model

1. Introduction

Wind records have been kept in the UK for over one hundred years. These records are adequate for determining when the worst storms occurred and how severe they were, and whether certain individual years were more or less stormy than average. However, the slight lack of consistency between some of the recording techniques, particularly amongst the older wind records, limits any detailed comparison. For example, locations and types of instrumentation change from time to time, and most older records involved a subjective assessment of chart rolls or gauges by an experienced operator. Much of this data has been summarised in the form of wind roses or wind frequency tables, which can be used to compare winds at different locations or over different periods of time.

The many anemograph stations in the UK provide consistent and reliable wind records in computer format from January 1970 onwards, with a very small number of stations going back before that date. Very few other or earlier UK sequential wind records are available in computer file format.

Sequential wind data is necessary for the site-specific wave hindcasting often undertaken during HR's many coastal engineering studies. It would be useful therefore to have a means of simulating a wind time series from data in wind rose format. (It is assumed that the cost involved in acquiring, keying in and checking the original hand- or type-written data would be prohibitive). However, simulating time series wind data is not a trivial matter, since it requires a knowledge of storm distribution and persistence, seasonality and typical rates of change of wind speeds and directions. The method developed involves small changes to individual values in an existing time series, so that the revised sequence has the slightly modified distribution of wind speeds and directions appropriate to a different time period or location. The new series then has a realistic storm distribution, seasonality, and dependence between successive hourly values. It also has the desired distribution of wind speeds and directions associated with the time or location for which only wind rose data was available.

2. The numerical method

The method requires at least one year of time series wind speed and direction data in computer file format, and wind rose or wind frequency data for a different time period or for a different nearby location. It is a simple matter to derive an "original" wind rose from the time series data for comparison with the "target" wind rose for the desired time period or location. The two wind roses should be based on a number of complete years of data, to avoid distortions due to seasonal effects. The problem is then to define the differences between the two wind roses in such a way that those differences can be converted to computer program code for application to the "original" time series. The actual procedure used is iterative, (or in other words it involves a certain amount of trial and error), and derivation of the "differences" is done manually.

The following are examples of the ways in which the differences between the wind roses can be defined:

(i) 20% of the winds in sector 255-285°N in the "original" wind rose move to sector 285-315°N in the "target" wind rose

(ii) The average speed of winds in the 15-45°N sector is 12% higher in the "target" wind rose than in the "original"

(iii) The average speed of winds above 8m/s in the 75-105°N sector is 15% lower in the "target" wind rose than in the "original".

Items (ii) and (iii) would be quite straightforward to implement since they apply to all records within clearly defined classes. However, Item (i) would require a random number approach, as only a proportion (20%) of records within a class would be affected by the change.

The original wind data is recorded to the nearest ten degrees. In order to maintain a smooth distribution of wind directions it is desirable to shift recorded wind directions by only ten or twenty degrees and to shift some further wind data into the gap thus created. For example, to fulfil Item (i) above, move 60% of winds recorded at 280°N (approximately equal to 20% of records in sector 255-285°N) to a new direction of 290°N. (To affect only a percentage of the data, those records that drew a random number in the range 0.0 - 0.6 would be moved whilst those that drew a random number in the range 0.6 - 1.0 would not be moved). Meanwhile, in order to smooth the movement, 40% of records originally at directions 270 and 290°N would move to 280 and 300°N, respectively. Similarly, 20% of records originally at directions 260 and 300°N would move to 270 and 310°N, respectively. The same principle is observed even where the main change of direction is larger. For example the movement of 20% of records from sector 225 - 255°N to non-adjacent sector 285 - 315°N would still be implemented by a series of ten degree movements smoothed out within the affected sectors. When more than about one third of the data within a thirty degree sector is to be moved, it would be necessary to shift some of the records by more than ten degrees.

The measured wind speeds are recorded to the nearest knot. However, because of the use of a general wind speed-up function in HINDWAVE, the wind speeds used in wave hindcasting are real numbers. The additional wind speed factors necessary to convert from the "original" to the "target" wind rose are therefore applied to all of the affected wind records, the results being stored as real values of wind speeds in knots. This may have the consequence of introducing a discontinuity in the distribution of wind speed. For example, if winds up to 10m/s were unchanged but winds of 10m/s or more were increased by 10%, there would no longer be any wind speeds in the range 10-11m/s. However, a slight discontinuity in wind speed is not as important as a slight discontinuity in wind direction, and no attempt is made to smooth the wind speed distribution when this occurs.

The initial definitions of the differences between the "original" and "target" wind roses are derived manually from a visual inspection of the two wind roses (and of the numerical values used to plot them). The WINDSEQ procedure is then applied to the "original" time series, and the resulting first attempt at a "target" wind data sequence is examined in wind rose format. Some further small adjustments will be necessary in order to refine the agreement between the simulated and required "target" wind roses. These adjustments are superimposed on the initial definitions of the differences and WINDSEQ is re-run. Adjustments and re-runs are repeated iteratively until a good simulation of the "target" wind velocity sequence and wind rose is achieved. During this iteration procedure, the principle of minimum alterations to individual wind records is maintained.

Once the differences between the "original" and the "target" wind roses have been defined as described above, they are applied to the "original" time series data in order to simulate the "target" time series to be used in wave hindcasting. Each record in turn is scanned to see whether or not its wind speed and/or direction falls within one or two of the difference definition categories. If it does, any necessary random number tests are carried out and any necessary adjustments are applied. The direction changes are carried out first, and then the speed changes are carried out (using the revised wind directions if appropriate). For example, to implement Items (i) to (iii) above:

a) 20% (random number 0.0-0.2) of records with an original direction of 260°N would move to 270°N
b) 40% of original 270°N would move to 280°N
c) 60% of original 280°N would move to 290°N
d) 40% of original 290°N would move to 300°N
e) 20% of original 300°N would move to 310°N
f) Records with revised directions of 20, 30 or 40°N would have their speeds increased by 12%
g) Records with revised directions of 80, 90 or 100°N and original speeds above 8m/s would have their speeds reduced by 15%

Each of these points would be addressed by a single FORTRAN IF Statement (if necessary incorporating a random number test). Each line of code would be tested in turn to see whether or not it was applicable.

3. Example of use and validation

The longest period of sequential wind data in computer format from a single site is that recorded at Rhoose (Cardiff Airport). This data was used to develop and validate the WINDSEQ model. Two periods of data were chosen: 1960-69 to act as the "original" distribution and 1970-79 to act as the "target" distribution. Wind roses for the two periods are shown at the end of this section and differences between the two were itemised as described in Section 2 of this appendix. This involved a manual examination of the two wind roses and a certain amount of trial and error until the "target" wind rose was satisfactorily simulated.

The WINDSEQ procedure was then applied to the "original" time series, using the itemised differences listed below. This created a time series with length and persistence characteristics of the "original" series, but with the modified wind speed and direction distribution of the "target" wind rose.

The first step in the procedure was to determine how the wind directions would need to be altered to obtain the "target" directional distribution from the "original" directional distribution. The direction changes were chosen so that the number of direction changes was minimised. The direction changes are listed below.

"original" sector	"target" sector	percentage in original sector moved to target sector
345-15	15-45	39.9
15-45	45-75	13.4
75-105	45-75	26.5
105-135	75-105	2.6
105-135	135-165	1.8
135-165	165-195	0.7
195-225	225-255	12.4
255-285	225-255	7.9
285-315	255-295	18.7
315-345	285-315	15.8
315-345	345-15	17.4

The wind directions were recorded to the nearest ten degrees, so a random number process had to be used to decide which winds were moved from one sector to the next. Where possible wind directions were not altered by more than ten degrees. It was necessary to move 8.8% of the winds in the "original" 345-15°N sector by twenty degrees into the 15-45°N sector. Some of the winds were moved ten degrees within sectors as described in Section 2.

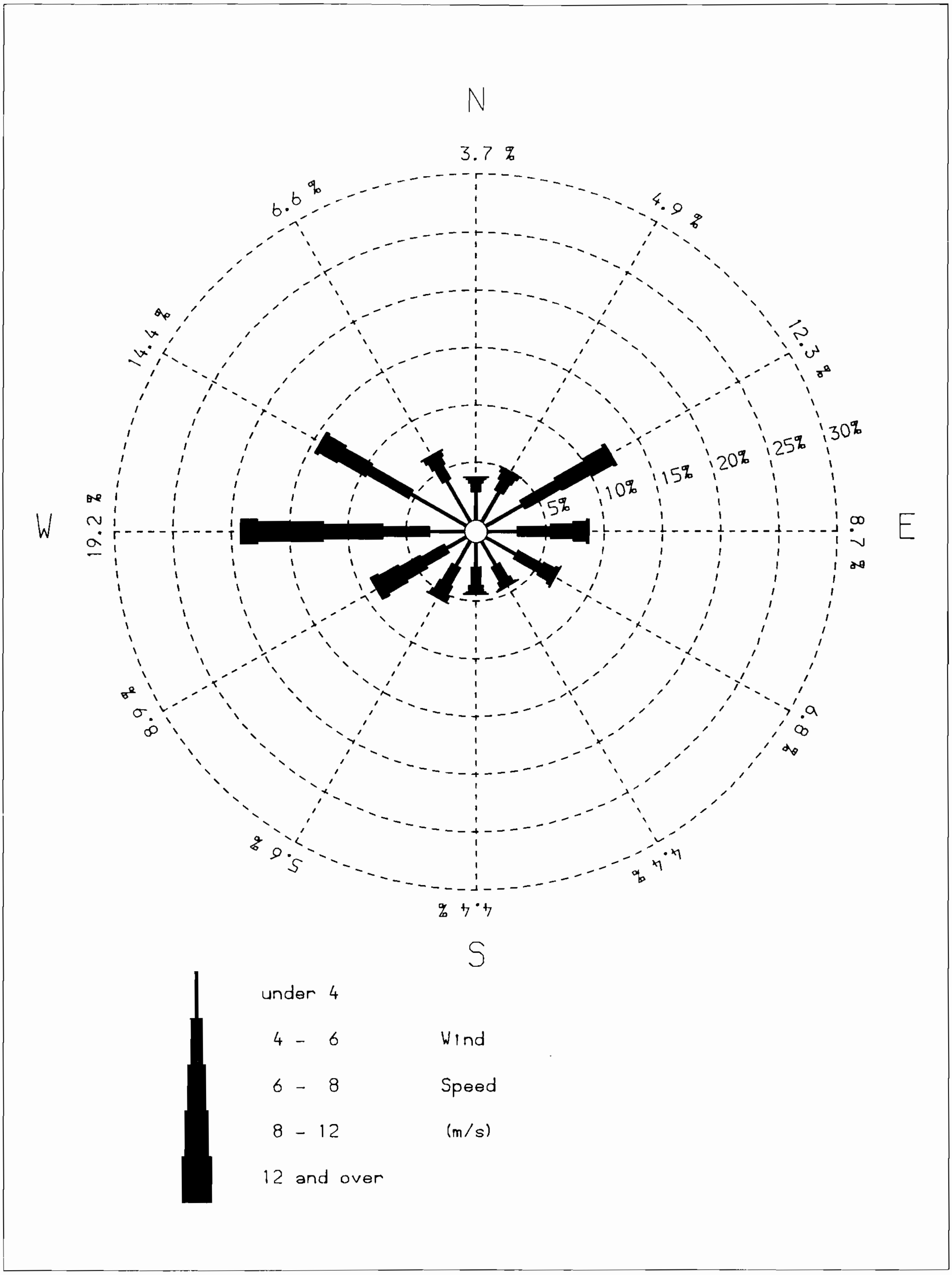
The next step was to determine how the wind speeds were to be altered to obtain the "target" distribution of wind speed in each direction sector. The wind speeds in each wind speed/direction box were multiplied by a factor. This factor was greatest for the lower wind speeds and as the wind speeds increased the factor reduced. The average speed factor for each direction sector is given below.

'target sector'	Average speed ratio
345-15	0.98
15-45	1.03
45-75	0.93
75-105	0.96
105-135	1.08
135-165	1.13
165-195	1.12
195-225	1.09
225-255	1.00
255-285	0.95
285-315	0.98
315-345	0.96

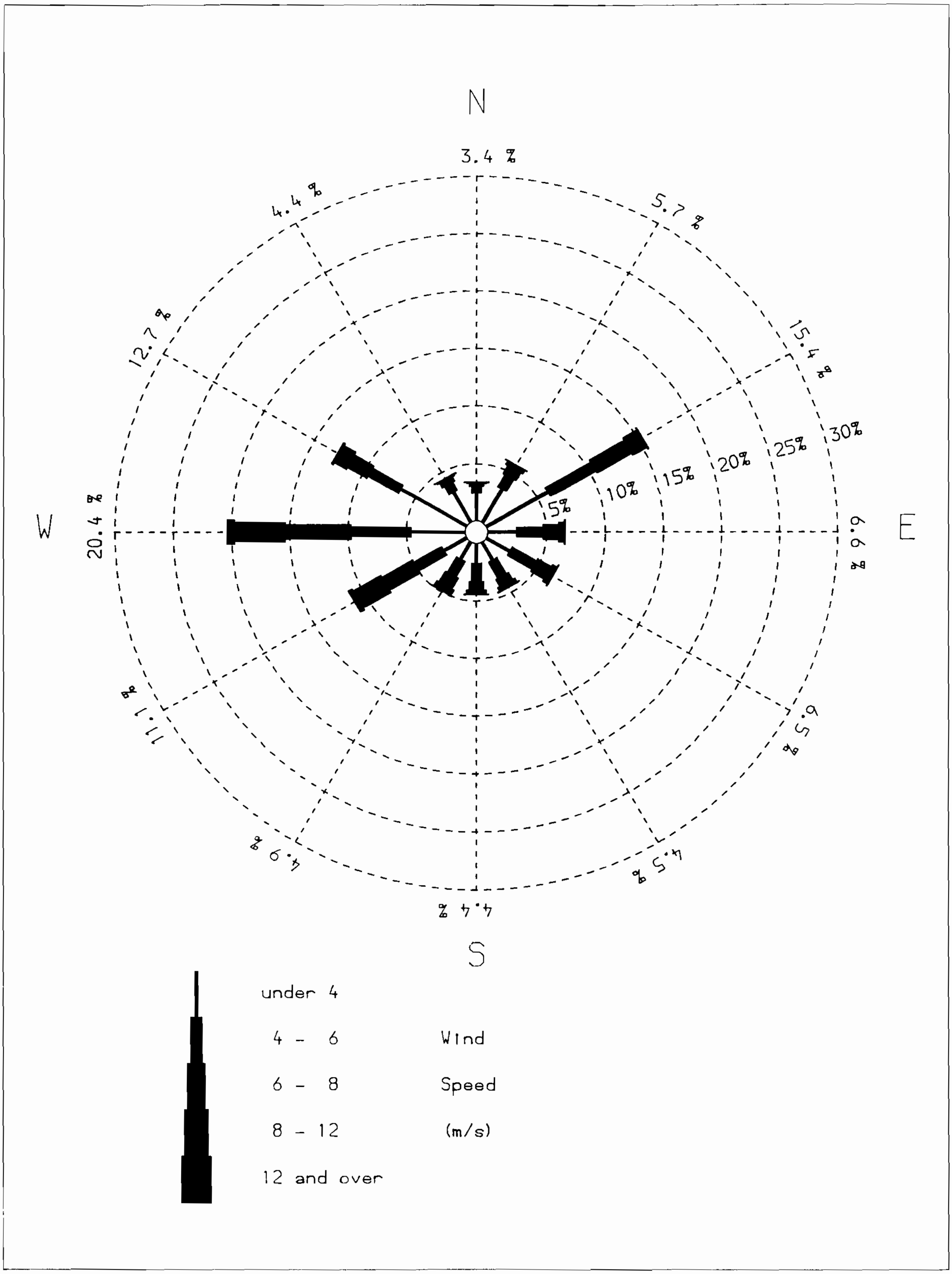
The wind rose obtained from analysing the time series modified from the 'real' 1960-69 time series was identical to the wind rose for the 'real' 1970-79 wind data.

The three wind time series were converted to simulated wave climates using the HINDWAVE model set-up for Barry. The three resulting distributions of wave height and direction are shown at the end of this section, derived from 'real' wind data for 1960-69 and for 1970-79, and simulated wind data for 1970-79.

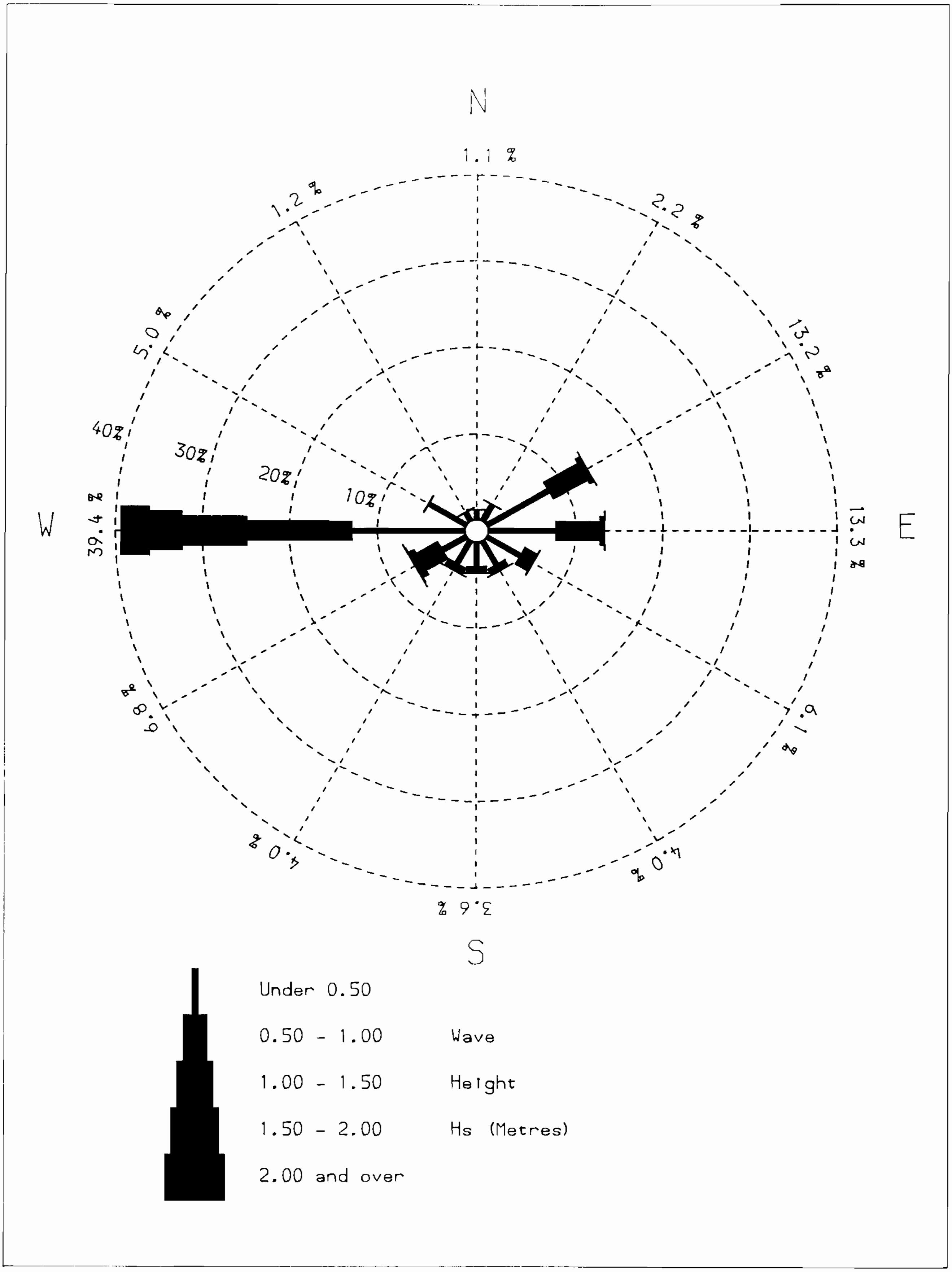
In general, the comparison of the wave roses derived from the real and simulated wind data for 1970-79 is good. In some cases the waves have changed too much (in height and direction) while in others the waves have not changed enough. However, this is mainly due to the rather coarse resolution of the values in the wave menu file used by HINDWAVE, and does not imply an error in the WINDSEQ model.



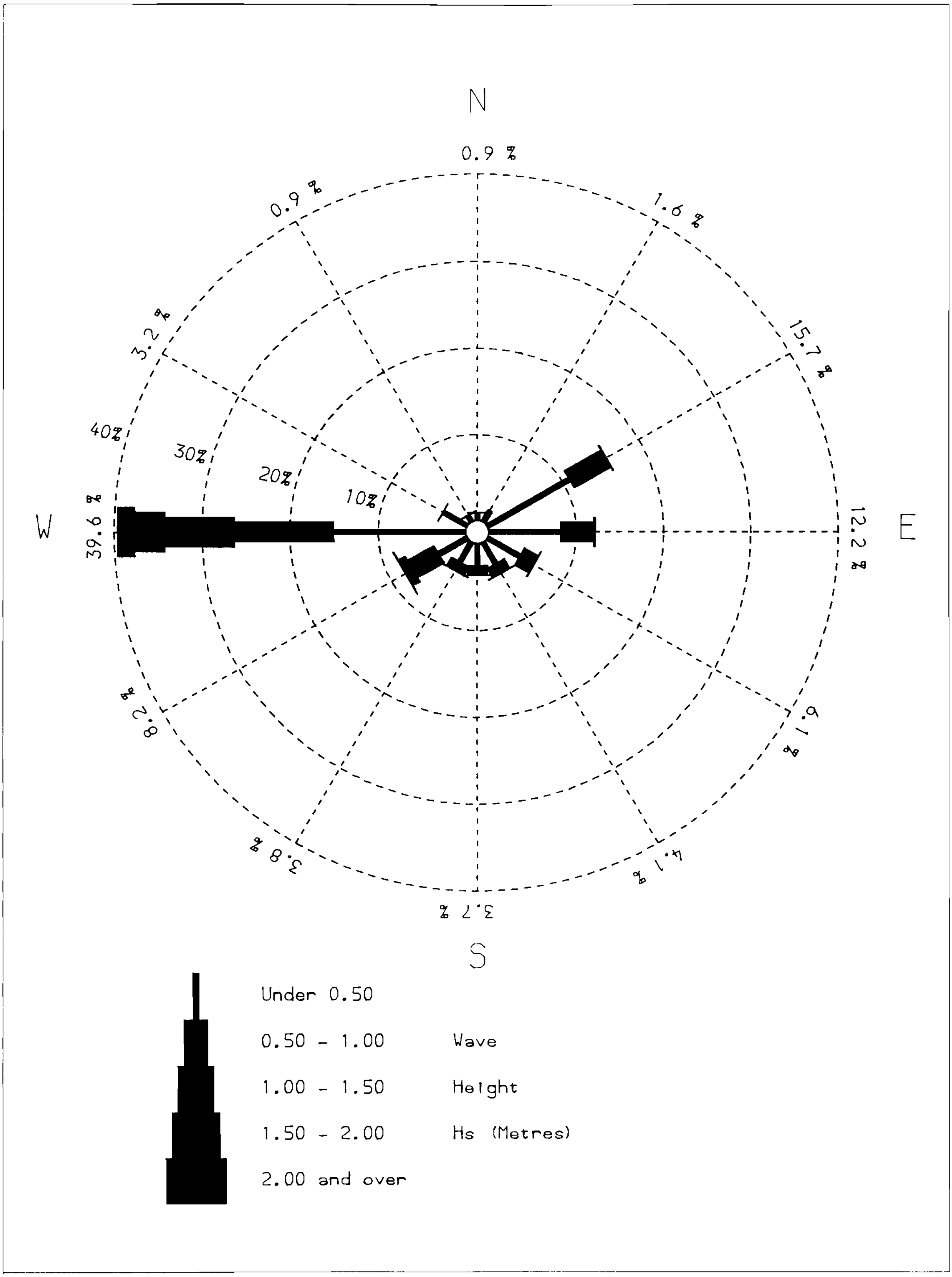
Wind rose for Rhoose 1960-1969



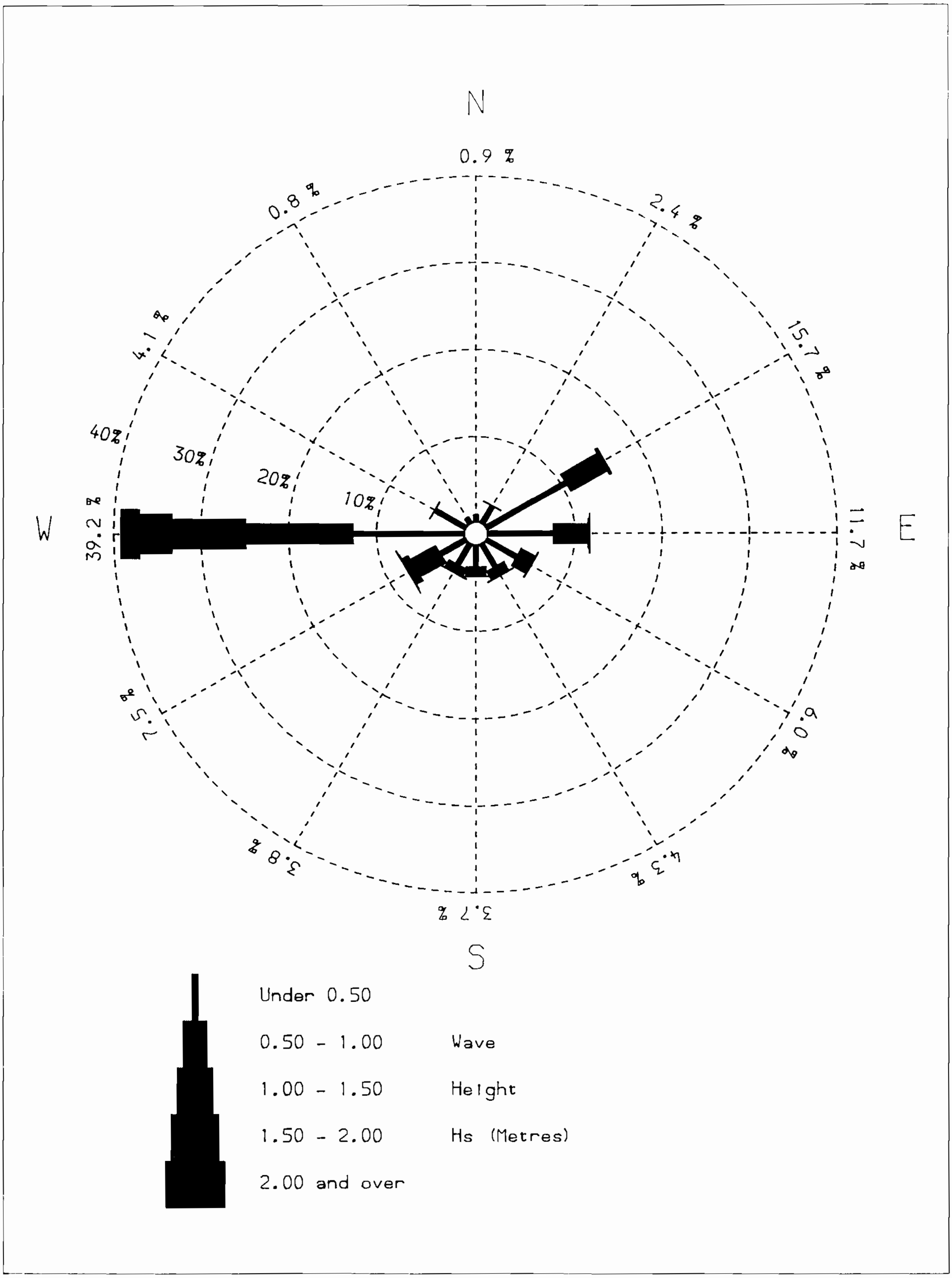
Wind rose for Rhoose 1970-1979



Wave rose for Barry - 1960-1969



Wave rose for Barry - 1970-1979



Wave rose for Barry - 1970-1979 based on wind data for 1960-69