RMK 25

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SMHI SWEDISH METEOROLOGICAL AND HYDROLOGICAL INSTITUTE

SMHI Reports
Meteorology and Climatology

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Final Report
IEA R&D WECS
Task I, Subtask B1

The Swedish prototype WECS constructed by Karlskronavarvet AB.
Rated power 3 MW.
Photo: The National Swedish Board for Energy Source Development.

SMHIs tryckeri, Norrköping 1981.

Issuing Agency
SMHI
Box 923
S-601 19 NORRKÖPING
SWEDEN

Report number
RMK 25

Report date
July 1981

Author (s)
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Title (and Subtitle)

Uncertainty in wind forecasting for wind power networks.

Abstract

Accurate wind forecasts will be essential in the utilization of wind energy conversion systems (WECS). In order to assess the reliability at present forecast methods for wind speed forecast data from the USA and Sweden have been verified. Data represent different methods, numerical/statistical and subjective, different locations, seasons and heights. However, the data sets are too small to allow any definite conclusions. The results point to that none of the tested forecast methods meet the requirements on forecast error put forward by utilities. The best forecasts were obtained by subjective methods based on numerical prediction for projection times less than +18h. Beyond that time objective, numerical/statistical methods showed to be better. National weather services are recommended to improve forecast methods for short-range forecasts, 0-12 hours ahead. To obtain sufficient forecast accuracy future WECS sites must also supply relevant observations of low level atmospheric structure.

Key words
Wind, forecasting, wind power, verification

Supplementary notes
Work funded by National Swedish Board for Energy Source Development under contract NE 5060601/Sweden

Number of pages
61

Language
English

ISSN and title

0347-2116 SMHI Reports Meteorology and Climatology

Report available from:

National Swedish Board for Energy Source Development
Box 1103
S-163 12 SPÅNGA, Sweden or

SMHI

SUMMARY

Accurate wind forecasts will be essential in the utilization of wind energy conversion system (WECS). Wind energy in a power grid enters a factor of uncertainty on the production side. The optimal integration of wind power is therefore highly dependent on wind forecasts. More accurate forecasts mean less investment in fast reserves and less dispatching of them.

Present forecast methods use numerical, statistical and manual techniques developed for general weather forecasting. However, in the USA, Sweden, Germany and New Zealand attempts have been made to adapt these methods to forecasting of wind speed at levels and sites relevant to wind energy production. In this study data from the USA and Sweden have been verified and forecast reliability presented as functions of projection time, time-of-year, geographical location, height and depending on different forecast methods. The limited data only allow some tentative conclusions. It seems clear, however, that no forecast method tested meets the very high demands put forward by utilities. Results also indicate that at the present time a human forecaster can contribute to the quality of a forecast for projection times up to 12-18 hours ahead. Beyond that time objective computer forecasts are better. National weather services are recommended to improve forecast methods for short-range wind forecasts (0-12 hours ahead).

SAMMANFATTNING

Noggranna vindprognoser kommer att bli mycket viktiga när det gäller det framtida utnyttjandet av vindenergin. När ett kraftnät tillförs vindkraft introduceras en osäkerhet på produktionssidan beroende på vindens relativt snabba variationer. Ett optimalt utnyttjande av vindkraft beror alltså i stor utsträckning på kvalitén på vindprognoser. Noggrannare vindprognoser betyder mindre investeringar i snabb reglerkapacitet.

Nuvarande prognosmetoder grundar sig huvudsakligen på numeriska och statistiska prognosmodeller samt de subjektiva metoder som utvecklats för den allmänna vädertjänsten. I USA, Sverige, Tyskland och New Zeeland har man dock gjort försök med vindprognoser för sådana höjder och platser som kan bli aktuella för vindenergiproduktionen. I denna rapport har vindprognoser från USA och Sverige verifierats och prognosnoggrannheten presenterats som funktion av prognosintervallet, årlig variation, olika platser, höjd och beroende på olika metoder. Det begränsade datamaterialet tillåter endast några preliminära slutsatser. Det står emellertid klart att ingen av de testade metoderna ger prognoser som motsvarar de krav kraftbolagen framfört. Resultaten visar också att den mänskliga prognostikern kan minska felet i objektiva prognoser fram till ca 18 timmars prognoslängd. De nationella vädertjänsterna rekommenderas att utveckla kraftigt förbättrade metoder för korta vindprognoser (0-12 timmar).

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1. INTRODUCTION

The implementing agreement of IEA* for a programme of research and development on wind energy conversion systems (WECS) was signed in Paris in October 1977. The R&D programme is detailed in four Annexes. Annex I deals with environmental and meteorological aspects of wind energy conversion systems, Annex II with evaluation of models for wind energy siting, Annex III with integration of wind power into national electricity supply systems and finally Annex IV deals with investigation of rotor stressing and smoothness of operation of large-scale WECS. Annex I contains 8 subtasks of which Sweden is responsible for five, Netherlands for two and Ireland for one. Six subtasks fall under the heading Environmental impact and operational safety of large-scale WECS (A1-A6), subtask B1 is the present project and subtask C1 deals with load case recommendations.

Annex I, Subtask B1, Investigation of Uncertainty in Wind Forecasting for Wind Power Networks was started in May 1979 with the following participating countries: Austria, Canada, Denmark, Germany, Ireland, Japan, Netherlands, New Zealand, Sweden and USA. Active countries, i e participating in expert meetings or submitting data for analyses have been: Austria, Germany, New Zealand, Sweden and USA. The National Swedish Board for Energy Source Development (NE) has been operating agent and Dr Svante Bodin, Swedish Meteorological and Hydrological Institute (SMHI), has been project manager.

Subtask B1 has the following objectives according to the implementing agreement:

'The objective of the work to be carried out in this area is to determine the level of uncertainty in wind forecasting for time periods extending from 1 hour up to 72 hours, appropriate for the planning of power extraction from a network of wind power plants. The objective includes the determination of the forecasting uncertainty for winds at different levels up to 100 m above the surface of the earth as a function of the forecast period, the roughness of the terrain, and the vertical stability of the air for different climatic regions and seasons of the year. It also includes uncertainty analysis of the predicted time duration of wind velocities which are of significant importance for the regulation of power extraction from wind power generators and other more conventional power plants.'

The implementing agreement also defines means for achieving these goals. However, the executive committee required all Annex I projects to be finished by the summer of 1980. This called for a revision of the original project definition.

* International Energy Agency

The revised means instead read:

a) Each participant will define criteria for an objective wind forecast verification scheme and for the determination of uncertainty levels of wind forecasts in terms of their relation to power generation efficiency.

b) The project manager will prepare and operationally test a computer programme for objective wind forecast verification at different wind levels and forecast periods. The computer programme will be made available to all participants in this subtask.

c) The project manager will test different wind forecast techniques for levels up to 100 m above the ground if possible for a period of one year by applying the computer code developed under b) above. Forecast and observational data are supposed to be supplied to the project manager by the participants. If time does not permit the testing of all supplied forecast techniques at least one such technique should be tested.

d) The project manager will compile the results of a) through to c) into a final report

There are several aspects of wind information that have to be considered. The wind itself is described by two numbers: a wind speed (m/s) and a wind direction (degrees). This project only concerns itself with wind speed. Wind direction might be of importance. The power output from a WECS array can vary as much as 5%, due to wind direction changes.

Wind speed is a constantly varying quantity when measurements are taken with a fast response anemometer. When decomposing the wind into an energy spectrum (fig. 1.1) it is clear that energy is distributed over the whole range of frequencies with two maxima around periods of 1 minute and 10 days. The first maxima is associated with energy input from shear and convective turbulence generation and the second one with large-scale baroclinic and barotropic instability as discussed by, for example, Fiedler & Panofsky (1970).

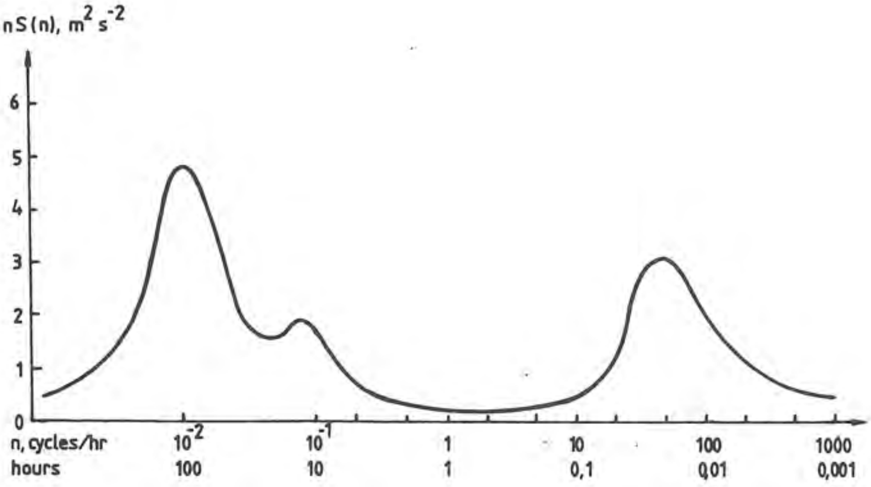


Figure 1.1 *Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).* S(n) *is the power spectral density.*

Turbulence characteristics of the wind are of great interest in WECS design but in trying to estimate a relation between wind speed and power output we would rather work with time averages of wind speed. The averaging time of wind speed, measured at synoptic observation stations, recommended by the World Meteorological Organization (WMO) is 10 minutes. But longer averaging times might also be used depending on various strategies employed by utilities in utilizing wind information. For integration purposes, however, turbulence properties, including gustiness, are unwarranted. The choice of averaging time also decides the lower limit for wind forecasting projection times.

Another property of interest is the time duration distribution, i.e. the frequency distribution of duration of certain wind speeds. The implementing agreement calls for an analysis of uncertainty of the predicted time durations of wind velocities. Such an undertaking has, however, not been possible. No such forecasts are being or have been, made at the present time.

Instead this report will concentrate on verification of fixed-time wind speed forecasts valid for different projection times, for different locations, heights and methods. The data that have been possible to collect during the short time available to the project are far from being conclusive, but have allowed some tentative conclusions and recommendations.

2. USE OF FORECASTS IN WIND ENERGY PRODUCTION

The degree of utilization of electric energy varies tremendously from country to country. It is, not surprisingly, high in the industrialized world, where Norway, Canada and Sweden have the highest per capita consumption of electricity. Looking at the absolute figures the USA produces roughly 2150 Twh per year followed by the Soviet Union 1110 Twh and Japan with 510 Twh (figures from 1976). The most important aspect of electricity production to wind energy integration is, however, the regional structure of the power grid. The distribution of production units and types of energy sources largely determines the necessary actions if wind energy is to be included in the grid at various penetration levels.

2.1 Structure of power grids in different countries

The structure of the power grid varies not only from country to country, but also within a country from utility to utility. In the USA electricity is produced by a large number of utilities ranging in size from small municipal utilities serving about 2000 people to large power pools serving 20 millions of people. In Sweden about 50% of the electricity is produced by the Swedish State Power Board while the rest is produced by private utilities or power pools.

Important aspects to consider when planning for wind power is to know where electricity is going to be produced and where consumption is greatest. In Sweden hydroelectric power is produced in the north and consumed in the south. Large transmission lines are needed to carry the power to the consumers.

Wind energy relies on the available wind, a highly variable resource in space and time. In order to reduce the effects of this variability it is an advantage to deploy WECS over large areas or in fairly widely separated clusters. In this way the probability of having enough strong winds somewhere increases. But this also means longer lines. Siting problems, arising from environmental or land use restrictions, will often make it impossible to freely optimize a wind energy system. But the structure of the existing power grid is also important in determining the ways in which wind energy can be integrated into the grid as discussed by Davitian (1978).

In this report results come primarily from the USA and Sweden. Therefore it seems relevant that the gross structures of the power grids in these two countries are discussed as examples of typical problems one has to consider when introducing wind energy.

2.1.1 Structure of US power grid

The annual production of electric energy amounted to 2123 Twh in 1976. Of this 77% come from conventional condense power and about 6% from nuclear power plants. Table 2.1, taken from Consodine (1977), shows a breakdown of percentage generation from different kinds of power sources in different regions of the USA. In most areas thermal condense power dominates.
Only along the west coast and in the Rocky Mountains area does hydroelectric power contribute significantly (more than 30%) to electricity production. These areas only produce about 16% of the nation's total supply.

Table 2.1

Regional power generation.

Region	Type of Generation (%)				Type of Fuels Used (%)			
	Hydro	Steam		Internal Combustion	Coal	Oil	Gas	Nuclear
		Conventional	Nuclear					
New England	7	68	25	*	8	64	1	26
Mid. Atlantic	13	79	8	*	49	39	2	9
E. North Central	1	90	8	*	83	5	4	8
W. North Central	11	80	8	2	61	2	28	9
South Atlantic	5	87	7	*	58	28	7	8
E. South Central	15	82	4	*	89	4	3	4
W. South Central	4	95	*	*	3	6	91	*
Mountain	30	69	*	*	68	8	25	*
Pacific	67	30	3	*	5	50	36	9
Alaska	17	74	*	9	19	12	68	*
Hawaii	*	97	*	3	*	100	*	*
Total United States	16	77	6	*	53	19	20	7

*<1%

Electricity is produced and delivered to the consumers by numerous large and small power companies. Utilities often join together into power pools in order to optimize the costs of generation units and dispatching of power. Excess power can also be sold to other utilities if the price is compatible with the cost of the utilities' own production units.

Where there is little or no hydropower fast reserves must be made up of rather expensive fuel consuming units like gas turbines or pumped hydroelectric power. The latter course has been taken for example in Germany, which lacks hydropower entirely.

2.1.2 Structure of Swedish power grid

For a long time the Swedish grid has been characterized by the large amount of hydroelectric power. Most of the investments have been made more than 20 years ago. Table 2.2 shows the electric energy balance for 1977 and the installed capacity. Still hydropower accounts for 60% of the electric energy produced in Sweden. The total is roughly 90 Twh. But Sweden also has the largest fraction of installed nuclear power per capita in the world which shows up as 22% or 19 Twh of annual energy production.

Almost all hydropower is produced in the north while consumption largely takes place in southern Sweden. Four 400 kV transmission lines carry most of the power to the south, an average distance of 600 km. Thermal power and industrial back pressure power are generated in the southern and middle parts of Sweden.

Table 2.2

Production of electric energy, 1978, in Sweden.

	Twh	%
Hydropower	52.7	60.0
Thermal power	34.7	40.0
- Condense conventional	7.6	8.7
- Condense nuclear	19.0	21.7
- Back pressure, industry	3.3	3.8
- " " , heating	4.7	5.4
- Gasturbine, diesel etc	0.1	0.1
	87.5	100.0

The Swedish State Power Board (Vattenfall) operates their 50% of the grid in close cooperation with private utilities or pools (which as a matter of fact are also owned by various communities like the city of Malmö etc). Electric power is also bought and sold within Scandinavia. Denmark is connected to the Swedish grid by means of a DC high voltage cable beneath Kattegat.

The referendum held in March 1980 decided that no more than 12 nuclear reactors will be permitted to be built in Sweden. When these reactors are worn down no replacements will be built. This means that Sweden already now has to take a serious look at alternative energy sources.

2.1.3 German power production

Germany is dependent to a large extent on fossil fuels for electricity generation. Table 2.3 shows the percentage contribution to the electricity production of different fuels in 1972. The total energy production in 1975 amounted to 302 Twh. The percentage of hydroelectric power is very small.

Coal, which is available at a cheap price throughout Germany, consequently plays an important rôle in the energy balance.

The figures are somewhat old and the present grid contains more nuclear power than in 1972. The main feature, however, the lack of appreciable hydropower resources, poses a problem in connection with the integration of wind power.

Table 2.3

Percentage of fuels used in Germany in 1972 for electricity production.

Coal	37%
Brown coal	24
Oil	19
Gas	8
Uranium	3
Water	5
Miscellaneous	4
	100%

Total production in 1975: 302 Twh

2.2 Integration of wind power in the power grid

Wind power is characterized by its variability in time and space. Normally a utility has good control over its production units even if accidents can happen. The problem usually is to predict the load, the variance of which to a high degree is explained by regular annual, weekly and diurnal variations. In addition to these variations one finds variations due to changing weather conditions which also affect the load, such as cold spells (increased heating), warm spells (air conditioning), windy weather (higher ventilation) etc. Although not as predictable as the more regular variations weather can still be predicted with good accuracy for shorter ranges (1-2 days ahead), but there is a need for more accurate long-range forecasts (2-30 days ahead).

Wind energy is bound to the variations of the wind, which is normally more variable than the general weather conditions. The wind, through its cubic relationship with wind power, affects the

- operations - daily unit scheduling and hourly dispatching
- planning strategy, and
- economics

of a utility when wind energy is introduced in the grid.

The wind shows variations from place to place and in time due to changing large-scale weather patterns as well as local influences.

These variations take place with various frequencies, from turbulent fluctuations with periods of the order of seconds to minutes, meso-scale meteorological variations with periods about 1-3 hours and large-scale, synoptic variations with periods of 3 hours-10 days.

Each of these intervals has to be coped with in order to integrate wind energy in the grid. The turbulent fluctuations generally enter as a construction problem which generally can be solved. Some exposed locations, such as the edge of sharp bluffs or steep knolls, might create turbulence patterns and resonance phenomena which inhibit WECS use. However, a relation between wind speed and power output must generally be based on some representative averaging time, long enough to smooth out turbulence variations but short enough to allow for turbine dependent adjustments. In Sweden power-wind speed relations are established for 10 minute averages of wind speed and power output. Fig 3.1 shows the power-wind curves for the first Swedish experimental WECS with a rated power of approximately 60 kW.

Even with as short an averaging time as 10 minutes there is an obvious scatter in actual measurements of wind speed - power output relations. However, wind speed measurements do give fairly accurate power output information for a single WECS. The problem becomes more complicated when WECS clusters or groups are considered. Several effects tend to blur the wind speed - power output relation. Among them we find successive wake interference, different for different boundary layer stabilities, wind direction dependency due to local topography, varying number of WECS operating and topographically induced stationary wind patterns. When several WECS groups are considered geographical variations of wind speed patterns, i e weather system scale variations, must be taken into account in order to compute the final expected wind power resource at any particular time. According to Kahn (1978) and others a dispersion of WECS arrays is beneficial to wind energy production.

Wind energy enters uncertainty on the production side in the operations of a utility. In the first simple economic feasibility analysis of wind energy integration into existing power grids wind energy has been treated as a 'negative load' which has to be predicted together with the other load factors. Computer models can then be used for simple economic studies assuming different degrees of penetration of wind energy and other parameter values. Davitian (1978) provides a basic discussion of the utilization of wind energy and some of its economic aspects. This report will not dwell extensively upon these problems.

It has, however, become evident that in order to more realistically simulate the impact of wind energy on utility operations more relevant wind data are needed. This means wind data for the heights 50-150 m at several different locations to see the effect of dispersed wind power contributions due to spatial wind variation. So far studies have only been based on low-level wind measurements extrapolated to WECS hub heights.

Once the properties of the wind energy contribution to a power grid are known, it is possible to reoptimize the system. However, some simple effects of wind energy can be seen radily. The short term variation of wind power output of the order of 10 minutes to 1 hour must be met with the operating reserve capacity or fast reserve. In Sweden the fast reserve is 10 minutes and usually made up of hydroelectric power.

As seen in 2.1 hydroelectric power is not available as an operating reserve in many utilities. Instead expensive gas turbines or pump stations must be used.

Also larger time variations of the order of 1/2-3 hours must be balanced by regulative power like thermal power stations and/or hydropower. This is in the dispatching range where selling and buying also become alternatives. Decisions concerning start-up or close-down of thermal power units become important.

The steadier wind power as a source becomes or the more accurately it can be predicted the less has to be invested in reserve capacity, especially the fast reserve. The actual investments depend of course on penetration level of wind energy, wind climate and deployment of WECS groups, structure of the grid and pooling possibilities.

Some studies, based on rather incomplete data and pessimistic assumptions regarding wind forecasts, have given some preliminary results. Larsson (1978) sees no problems for South Sweden Power Company to accomodate up to 20% wind energy in the grid. This is because of the large amount of hydropower available. Sørensen (1978) discusses the integration of wind power in a (hypothetical) Danish grid with its exclusive use of conventionally fuelled thermal power plants without energy storage facilities. Only using persistence wind forecast he comes up with an optimum level of wind energy of about 25%. This level corresponds to the level at which an appreciable fraction of wind energy has to be dumped and the increased costs for start-up and peak unit management become substantial.

The properties of wind energy also affect daily operations in a utility planned for WECS integration. Even if wind forecast uncertainty is important in assessing the optimum configuration of generating units of a particular utility it is still essential to design forecasts in such a way that they can readily be used by the dispatcher on duty.

2.3 Relevance of forecast uncertainty to wind energy production

Wind forecasts are of great value to wind energy production. Basically they affect costs by reducing the operating reserve and making it possible to adapt profitable running strategies. For a given penetration level of wind energy and a given configuration of generating units and grid structure there probably exists an uncertainty level which must not be surmounted. A study by Goldenblatt (1979) concerns the integration of wind power into the grid of one particular utility, the New England Gas and Electric Association (NEGEA). Goldenblatt's analysis of operating reserve requirements is based on a standard deviation of forecast error of 2 m/s. The analysis shows that if the wind speed forecast error could be cut to half, i e 1 m/s, it would mean a reduction of operating reserve costs by two thirds, which, for a large power company, would mean a substantial saving. This figure is roughly constant for penetration levels between 5-40%. Wind energy is not used operationally on an appreciable scale anywhere in the world to-day. Requirements for wind forecasts are difficult to assess. In some countries preliminary discussions have taken place revealing some basic aspects. Wendell et al (1978) report from an introductory meeting between forecasters, researchers, dispatchers and utility people. Preceding the meeting telephone interviews had been made with dispatchers. Results identified three cases for which wind forecasts are of great importance.

1. Weekly planning of maintenance of WECS units.
2. Daily scheduling of the unit commitment mix.
3. Hourly dispatching and as a guide in decisions concerning selling and buying of excess or deficit power.

A preference for a probabilistic forecast was expressed by some dispatchers. However, it was regarded as important to study more carefully the response of load-scheduling models to assumptions regarding wind forecast error.

Some specific requirements have emerged which were discussed at the first meeting of experts of this project. The three cases above have been identified as suitable classes for forecast specification. In Wendell (1978) there was also expressed a requirement for forecast uncertainty of the total load. Utilities wanted forecasts to be accurate enough to enable load forecasts to be within ±5% of the expected power level to meet the 5-7% power reserve requirement. This was based on assumed penetration level of 10%. This means typical RMS errors of the order of 1.5 m/s for a WECS penetration level of 10%.

Errors of such a small magnitude can definitely not be obtained today. Discussions with dispatchers and planners of the Swedish State Power Board (Vattenfall), have revealed similar opinions as in the USA.

The wind forecast error affects the planning of wind power integration in the grid. The level of uncertainty influences the localization of reserve power in the country and the planning of new transmission lines. Pump stations for storing wind energy from windy to calm days are being considered.

In the verification of wind forecasts, some utility people in Sweden have stated that they are not really interested in verification of power output but only wind speed. Too many factors contribute to the final power output from WECS to make such a verification meaningful. However, the closeness to cut-out power is judged as an important piece of information.

'Vattenfall' (The Swedish State Power Board) puts the stress on short-range forecasts, the most important interval for operations being projection times between 2-6 hours. All wind forecasts should refer to fixed time 10-minutes averages.

For the 0-6 hour forecasts updating is wanted every hour decreasing to once a day for the +2 day forecast.

The following table shows the requirements of resolution, i.e., which fixed projection times for the forecasts are wanted for.

Range	Forecasts for
0-6h	Every half hour (i.e. +0.5, +1, +1.5, ..+6)
6-12h	" hour
12-24h	" third hour
24-48h	" sixth "

Assuming a figure of 10% penetration of wind power in the grid the utility people suggest the following permissible RMSE:

RMSE	Forecast length
±1 m/s	<4 hours
±1.5 m/s	4-10 hours
±2 m/s	<10 hours

One must keep in mind that Sweden has plenty of fast reserves, during normal operating conditions, in hydropower.

'Vattenfall' is mostly interested in verification of wind speed in terms of standard deviation of wind speed error but also contingency verification of forecasting the operational classes of no wind/wind energy production.

German utilities have conveyed requirements for wind forecasts according to the following table

Forecast length	Forecast
+24 hours	Three hourly averages of wind power
+8-+24 hours	Hourly averages of wind power
+2-+8 hours	15-minute averages of wind power
+1-+2 hours	10-minute averages of wind power
+1 hour	All wind power drops from present level

German utilities have not been able to specify any guidelines for required accuracy of wind forecasts. However, it is quite clear that the accuracy of wind power forecasts requires far better wind forecasts than are available to-day.

The magnitude of wind forecast errors has immediate effects on the planning and operations of utilities integrating wind energy in the grid. The more wind power the more important wind forecasts become. Economics is an important aspect of wind power. Cutting the error to half means reserve savings with a factor of the order of 3 for utilities with little hydropower. Realistic wind forecast errors of forecasts issued for other purposes end up in the neighbourhood of 2-3 m/s which is far too much as compared to the requirements put forward by utilities. In this report verification is carried out on forecasts specifically aimed at heights and times relevant to wind energy production. But one must keep in mind that these forecasts are made with the methods operationally available to-day applied to scanty and limited data. No development of new, improved methods has been done.

3. VERIFICATION METHODS

3.1 Verification procedures and wind forecast for WECS

The power that can be extracted from the wind is theoretically proportional to the cube of the wind speed. Due to the design of the WECS it is not possible to convert all of this energy into electricity. The WECS is in general designed in such a way that it starts at some minimum wind speed (V_{cut-in}) and stops at some other maximum speed ($V_{cut-out}$), when the stress on the WECS gets too large. From V_{cut-in} the energy converted into electricity will increase when the wind increases until rated power (V_R) is reached. When the wind speed is between V_R AND $V_{cut-out}$ the produced energy is constant and independent of wind speed. Fig. 3.1 shows an example of a wind speed - power relation for the first Swedish prototype WECS.

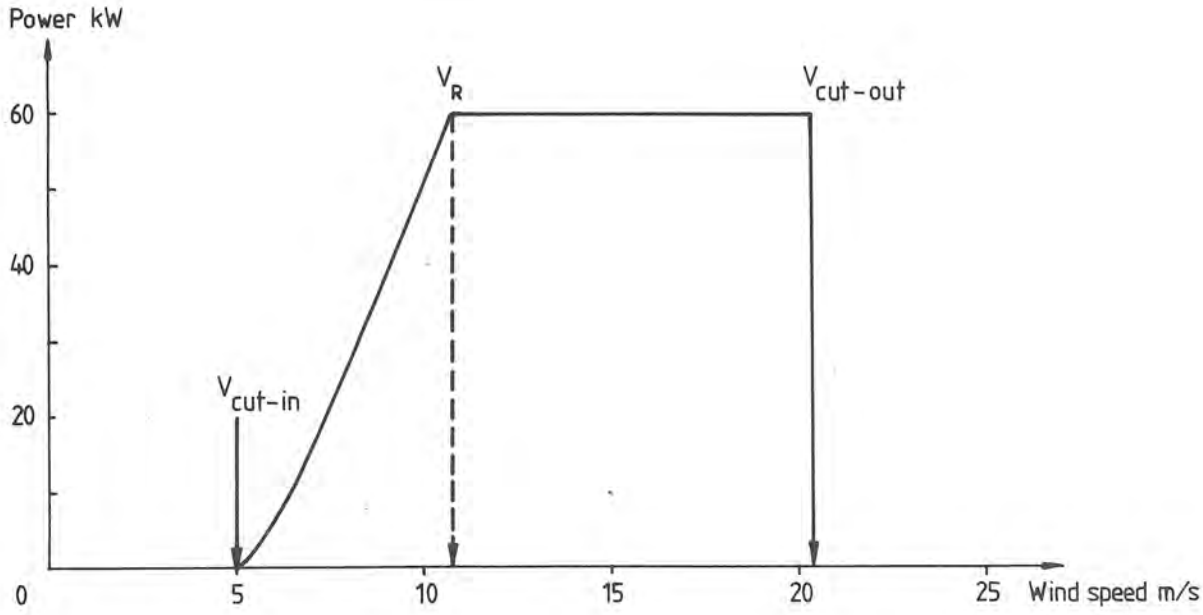


Figure 3.1 Characteristics of the Swedish experimental WECS with horizontal axis and 18m diameter. $V_{cut-in} \simeq 5$ m/s, V_R (rated power) $\simeq 11$ m/s and $V_{cut-out} \simeq 21$ m/s. Rated power $\simeq 60$ kW.

A power company is of course interested in knowing not only if the WECS will work or not but also how much power it will produce. The intervals of the wind speed that have been chosen for the verification of the wind speed forecasts, are because of that: $0-V_{cut-in}$, $V_{cut-in} - V_R$, $V_R - V_{cut-out}$, $V_{cut-out} - V_{\infty}$. It is only in the interval $V_{cut-in} - V_R$ that the produced power varies. In the others it is either zero or constant.

The wind speed forecasts, however, are given as continuous figures in m/s.

V_{cut-in}, V_{Rated} and $V_{cut-out}$ are characteristics of different WECS and vary with design. In this study, however, we have chosen to fix these values in order to make verifications comparable. The actual figures used in this report are: $V_{cut-in} = 5.6$ m/s, $V_{Rated} = 12$ m/s and $V_{cut-out} = 21$ m/s. These values are averages for the German, Swedish and American prototypes.

3.2 Description of statistical scores

With the intervals mentioned above a so-called contingency table can be constructed with four classes. Figure 3.2 shows an example.

FORECAST		OBSERVED				
		$0 \leq V < V_{cut-in}$	$\leq V <$	$V_R \leq V < V_{cut-out}$	$\leq V$	
	Class	1	2	3	4	Sum
$0 \leq V < V_{cut-in}$	1	148	113	2	0	263
$V_{cut-in} \leq V < V_R$	2	60	252	31	0	343
$V_R \leq V < V_{cut-out}$	3	0	18	19	2	39
$V_{cut-out} \leq V$	4	0	0	0	0	0
	Sum	208	383	52	2	645

Figure 3.2 Contingency table for Block Island in USA with forecast method back-up and forecast length +9h.

From this table 7 different scores can be constructed. These are called in the following, column 1, column 2, hit percent, threat score, skill score, bias and correlation, and are used to give a comprehensive picture of forecast reliability. Many of the scores only refer to the two situations: the WECS is either operating or not. This means that a simplified contingency table can be set up with the two classes: 1&4 (not operating) and 2&3 (operating). This is shown in fig. 3.3.

Column 1 simply refers to the first column of the table printed by the verification code. It defines the probability of being correct when forecasting either class 2 or 3, i e wind energy production. It is expressed as a percentage.

Forecast class	Observed class		
	2&3	1&4	Total
2&3	A	B	C
1&4	D	E	F
Total	G	H	I

Figure 3.3 Simplified contingency table.

With the symbols used in figure 3.3 this score for the classes 2&3 will be (A/C)x100.

Column 2 tells the probability of being incorrect when forecasting no wind energy production, i e wind speeds in class 1 or 4. Using the notation in figure 3.3 it is defined as (D/F)x100.

Hit percent is the number of hits divided with the total number of forecasts. With the notation in figure 3.3 the hit percent is defined as 100x(A+E)/I. From the four class contingency table in figure 3.2 different hit percents can be constructed, e g from the classes 2&3. In that case the other two classes are excluded.

Threat score. By means of figure 3.3 the definition of the threat score for classes 1&4 will be E/(F+H-E). It is obvious that it varies from 1, when all forecasts are right, to 0 when E is equal to zero.

Skill score is computed from $\frac{(A+E-J)}{(I-J)} \times 100$ where J, the number of forecasts expected to be correct by $J = \frac{(C \times G)+(F \times H)}{I}$. This score is a total score, i e takes account of all classes. It shows the improvement over chance (=0). The higher the skill score is the better the forecast.

Bias of e g classes 1&4 is given by $\frac{F}{H}$. Bias tells how much a class is overpredicted or underpredicted.

Correlation. This correlation is constructed in such a way that, if all forecasts are correct, it takes on a value of 1 and all wrong gives -1. With the notation in figure 3.3 the correlation becomes

$$\frac{A \cdot E - B \cdot D}{\sqrt{C \cdot F \cdot G \cdot H}}.$$

The scores described above are derived from the contingency table. In the verifications we also use some statistical measures which are computed directly from the forecast and observed values. These are: median, mean standard deviation, skewness, RMS-error and correlation. The statistics are generated both for observations and forecasts. When data permit, a persistence forecast is generated and the statistics computed.

This reference forecast is the simplest possible and uses only observations. If, for example, a wind speed of 6 m/s is observed at 00z this value is taken as the forecast of all subsequent times, e g +3, +6, +9, ... hours. RMSE of persistence is a measure of the autocorrelation of the wind at a particular location.

3.3 Problems with power output verification

In Sweden wind reports are mostly given as 10-minute averages. A station reporting wind speed on the hour is in practice giving the average wind speed during the preceeding 10 minutes. This means that although there is a direct connection between wind speed and generated power (through figure 3.1) the generated power for a longer period is not the same as the energy computed from the wind observation. This is so because we do not know the wind speed between the observation times. For example, a day when the wind is very gusty, the wind may be much higher at the observing time than in the mean time. On the other hand if a mean value is given for a whole hour this value will perhaps lie below V_{cut-in} and no power would be expected from the WECS. In reality the wind may be larger than V_{cut-in}, at some times and the WECS will actually contribute power. This means that when the wind varies considerably more frequent wind observations are needed to adequately assess wind power output. In terms of wind forecasts this means optimizing averaging time or/and also predicting the wind variance. The averaging time, given a specific wind-power relation, is based on the characteristics of the WECS, its inertia and control system - lining it up along the wind and pitching the blades. In Sweden this relation turns out to be based on 10-minute averages of wind speed and 10-minute integrated power output. This happens to be the same averaging time used by synoptic observation stations. Most WECS power wind relations are established for similar averaging times. From the dispatcher's point of view it would be more convenient to be able to handle hourly power production in decisions concerning unit commitment and let the fast reserve take care of variation on a shorter scale. However, as pointed out above, the relation between wind speed and power output of a WECS will deteriorate when using longer averaging times. The final averaging time used will be a compromise between these two aspects.

Different averaging times will affect forecast reliability. Longer averaging time will smooth out higher frequency variations of wind speed. It would in that case become easier to forecast hourly averages than 10-minute averages. In the following, Swedish verifications refer to 10-minute averages while the US forecasts and observations refer to 1-hour averages.

4. WIND DATA

4.1 Data sets used in wind forecast verification

Four countries have submitted wind forecasts along with verifying observations to the project manager. In these data sets no time period is more than eleven months. The US data cover the longest period, from December 1977 through October 1978. Sweden has data from September 1978 until May 1979 and Germany and New Zealand only for 3 months. However, all data sets have been verified and all the scores have been computed. The data sets from Germany and New Zealand are unfortunately very small. These data are too incomplete to allow any comparison with the other data sets and have consequently been excluded from the results below. Only American and Swedish results will be shown here. Table 4.1 summarizes all the data received by the project manager. In the Appendix a description of all the sites can be found.

4.2 Forecast methods

Only the Swedish and American methods will be described here.

Swedish forecast methods

Three different forecast methods have been employed. The first one will be referred to as numerical/statistical and involves steps 1 and 2 below. The other two, type A and type B, also involve manual interpretation and synoptic judgement. The three main steps are as detailed in Granfall (1980).

1. Surface pressure forecasts produced by SMHI's 6-layer quasi-geostrophic numerical weather prediction model. The model is run 4 times a day with a grid distance of 150 km. In this study forecasts are only generated from 00z and 12z data. See Moen (1975).

2. The output from the numerical prediction model is then interpreted statistically to wind speed and direction by a method that will be described below.

3. Finally a meteorologist can modify this objective forecast by means of later observations, general synoptic back-ground material and personal experience.

The computer-produced wind predictions are in general ready three hours after the main observation times 00z and 12z. At this time a new local weather observation is available. Experience has shown that an objective forecast is improved if a later incoming observation is weighted into the forecast. It has also been shown that meteorologists can improve the objective forecast by subjective modifications, at least out to +24 hours ahead.

Country	Location	Period J F M	A M J	J A S	O N D	Height (m)	Method	Forecast length (h)
Sweden	Forsmark	79			78	50,100	Num/stat	+6,+12,+18,+24,+30
"	"	79		78		"	Sub A	+3,+6,+9,+15,+21
"	"	79		78		"	" B	+3,+6,+9
New Zealand	Wellington airport				79	10,600	Subjective	+6
USA	1 Block Island		78		77	46	2 Num/stat	+9,+12,+15,+18,+21,+24, +30
"	2 Boone		78		77	"	"	"
"	3 Holyoke		78		77	"	"	"
"	4 Huron		78		77	"	"	"
"	5 Kingsley Dam		78		77	"	"	"
"	6 Montauk		78		77	"	"	"
"	7 Point Arena		78		77	"	"	"
"	8 Russell		78		77	"	"	"
"	9 San Gorgonio		78		77	"	"	"
Germany	Cuxhaven			79		10,50	Num/stat	+24
"	Tating			79		10,50	"	"
"	Bredstedt			79		50	"	"

Table 4.1

Summary of data used for verification of wind forecasts for WECS.

The computer-made forecasts mentioned under 1, only deal with phenomena on the synoptic or planetary scale (1000-10000 km). Because of this the numerical model is unable to forecast local weather on a scale smaller than twice the grid distance. This is overcome by establishing statistical relations between the numerical predictions and the local wind.

From wind measurements in a tower at Forsmark in middle Sweden (see site description) during the period 1976-04-23--1978-03-31 regression equations have been derived between the geostrophic wind and the measured wind at different heights. Such a regression equation is derived for each combination of level (100 and 50m), season of the year (summer and winter), time of initial data (00 and 12z) and wind direction making a total of 17 regression equations.

Three different forecast methods have been tested, the numerical/statistical and the two subjective, A and B:

1) The numerical/statistical method is completely objective and used the numerical forecasts under A and with the interpretation of geostrophic wind described above.

2) In the subjective forecast, type A, a wind observation at the site three hours after the initial data time is weighted into a new forecast value. This forecast is used as guidance to a meteorologist subjectively producing the final forecast.

3) The subjective forecast, type B, is made in the same way but instead of the +3 hour wind observation the +9 hour wind observation is weighted into the forecasts.

Figure 4.1 shows how the +3 and +9 hour wind observations are incorporated into the forecast.

The numerical/statistical forecasts utilize observations up to 00z and 12z respectively. For example, a +24h forecast is defined as one which is valid for a time 24 hours after the time of the latest observations used to prepare the forecast. However, the subjective A and B forecasts use observations 3 hours and 9 hours after midnight and noon GMT used by the basic numerical/statistical method. Because of this a forecast valid 24 hours after midnight and noon GMT is actually referred to as a +21h and a +15h forecast, since it is not theoretically possible to use the forecast before 03z (15z) and 09z (21z) respectively. All other projection times have been transformed correspondingly for the subjective A and subjective B methods. The effective projection times are indicated at the bottom of fig 4.1.

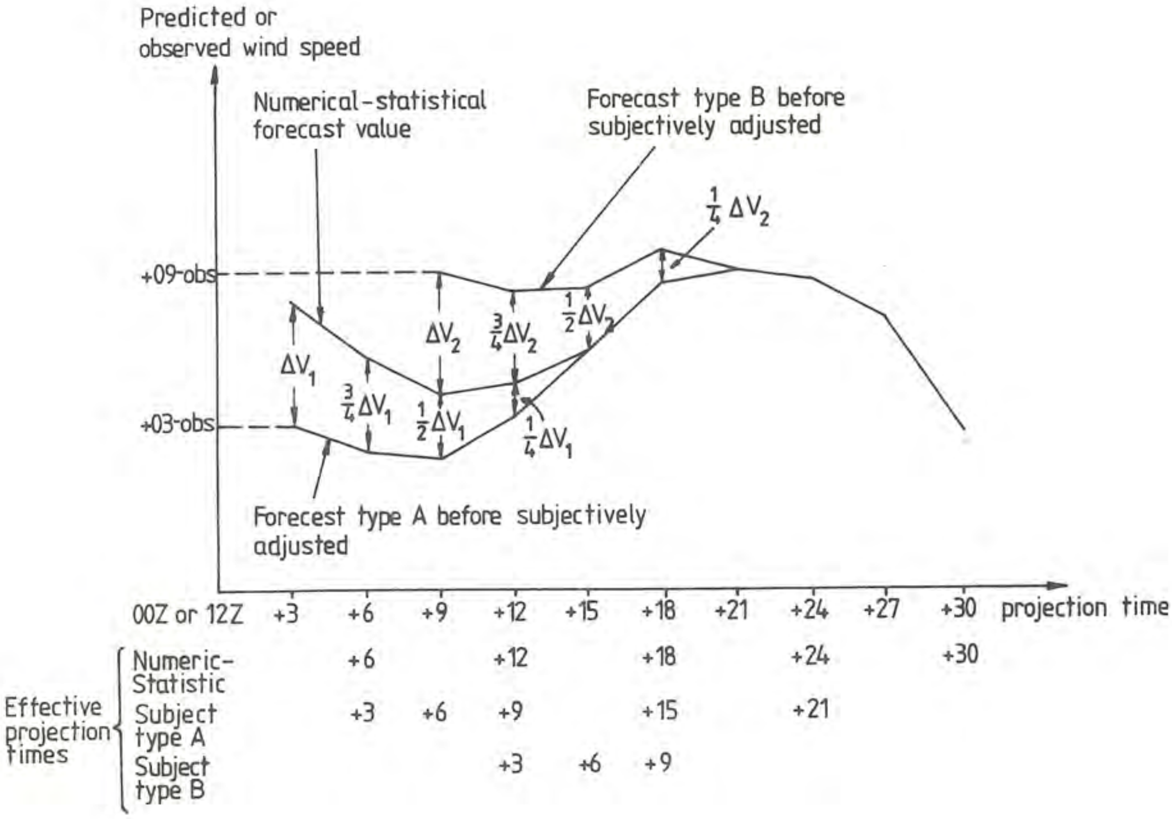


Figure 4.1 Schematic description of how the +3 and +9 wind observations are weighted into the type A and B forecast respectively.

The US forecast method

The MOS-technique, Model Output Statistics, developed at Techniques Development Laboratory of the NWS* has been adapted for WECS forecasting of wind speed. In this application two schemes have been used: back-up and primary.

A primary forecast is one developed using onsite observations as predictors. Back-up forecasts were developed using only model output as predictors; it was assumed that onsite data were not available at forecast time.

The forecasts were intended for use twice daily to serve as 0600z-0600z and 1800z-1800z 24h forecasts. The forecasts are for hourly average winds and the forecast frequency is three-hour intervals, except for the final projection time which is a six-hour interval.

The forecasts were produced by the MOS-technique described in the meteorological literature. In this case, the predictors for the linear regression equations were selected from the LFM (Limited-area Fine Mesh) model.

* National Weather Service

For a general background see Glahn (1970) and Carter & Gilhousen (1979).

The automated forecasts are based on linear regression equations that were derived by relating wind observations (predictand data) to output from a numerical prediction model (predictor data). Separate equations were developed to forecast U- and V-components and the wind speed.

The screening regression technique selects the predictor which yields the highest reduction of variance for any one of the predictands when combined with the other terms in a multiple linear regression equation. The same procedure is followed until either 10 predictors have been chosen or the additional reduction of variance is less than 0.5%. The equations for the U- and V-components are also derived simultaneously. The forecast wind direction is computed from forecasts of the U- and V-components. A serious problem of this approach has been under-forecasting the speed. A separate regression equation was derived for the speed to overcome just such a problem. Despite this, MOS-forecasts have still under-forecast high wind speeds. Therefore, the regression estimates of wind speed are enhanced by the use of the so-called 'inflation' transformation.

The amount of data available was divided roughly in half to form a dependent (developmental) data sample and an independent data sample. The developmental sample consisted of all dates from December 1, 1976, through November 30, 1977. Separate equations were developed for each site, each forecast cycle (00z and 12z) and each forecast projection.

The development sample was not stratified according to season because of the small sample size (about 300 cases per equation). Because of this small sample, some of the high wind speed categories were rarely observed. If any category had less than 10 cases, the regression equation to forecast the probability of that category was not derived.

Table 4.2 shows the list of potential predictors available to forecast the tower winds. Not all the predictors are output from a numerical model. The first six predictors listed are observed wind conditions at the tower and several climatic terms. This tower wind, the hourly-averaged wind observed at 3 hours after model run time (00 or 12 GMT), can be a useful predictor for short-range forecasts when persistence is important. Since it was wanted to determine the effect of these observed winds as predictors, equations with and without them were developed. When the observed winds were included in the regression run as potential predictors, the resulting equations were labeled 'primary'.

As for the Swedish subjective A and B forecasts the effective projection times for the 'primary' forecasts have been changed. A forecast valid 9 hours after 00z and 12z is regarded as a +6h forecast. Corresponding changes have been made for the other projection times. The longest primary forecast is effectively a +27h forecast instead of a +30h forecast. This makes it possible to compare quantitatively different methods fairly.

When the observed wind was not in the predictor list, the resulting equations were labeled 'back-up'. The harmonics of the day of the year are the climatic terms which are included to help account for daily variation in the mean wind at the sites.

The remaining predictors are forecast fields from the Limited-area Fine Mesh (LFM) model (Gerrity, 1977) that have been interpolated to the WECS sites. This model has been producing forecasts from 0000 and 1200 GMT data daily since 1971.

Forecast fields from 6-30 hours were available as possible predictors. In addition to forecast wind fields, stability indices, vorticity at several levels, and mean relative humidity were also potential predictors. Certain fields have been averaged by five points to eliminate small-scale noise. Besides being offered as continuous predictors (in their original form), some variables were also offered in binary form.

Table 4.2

Surface observations, climatic terms and LFM output used as potential predictors for 18h wind speed forecasts.

Field	Smoothing (points)	Time (hours)
Observed U, V wind components	-	3
Observed wind speed (S)	-	3
Sine day of year	-	-
Cosine day of year	-	-
Sine 2*day of year	-	-
Cosine 2*day of year	-	-
Boundary layer U, V, S wind	5	6,12,18,24,30
850mb U, V, S wind	1,5	6,12,18,24,30
700mb U, V, S wind	1,5	6,12,18,24,30
1000mb geostrophic U, V, S wind	5	12,18,24,30
Boundary layer relative vorticity	5	12,18,24,30
850mb relative vorticity	5	12,24
K index	5	12,24
Total totals index	5	12,24
(1000mb temp) - (850mb temp)	1	12,24
Mean relative humidity	1,5	6,12,18,24,30
850mb height	5	6,12,18,24,30

5. VERIFICATION RESULTS

5.1 Applicability of wind data

The periods during which forecasts and wind observations have been available to this verification task have been short and can of course not be taken as climatologically representative for the different sites. Table 5.1 shows how the average wind speed varied during the Swedish test period and how it compares with an eleven year climatology. All figures in table 5.1 have been taken from the meteorological station Grundkallen, which is situated on a small island about five kilometers from Forsmark.

Table 5.1

Monthly averages of wind speed from the observations at 06, 12 and 18z at Grundkallen.

	Sep 78 - May 79	1965-75	
September	10.0	9.8	m/s
October	10.6	10.6	
November	12.5	11.0	
December	8.0	11.4	
January	7.3	10.0	
February	6.4	9.9	
March	9.6	9.3	
April	6.4	8.5	
May	7.9	8.3	
Mean value	8.7	9.9	

From the table it is clear that the wind speed during the test period was lower than normal. During December through February it was considerably lower than normal.

5.2 Forecast reliability

5.2.1 Diurnal variations

In USA one has already found from previous wind forecasting investigations that the two mountain sites Boone and San Gorgonio have an extraordinary diurnal variation in wind speed. To be able to see how this affects the forecasts, we have separated forecasts made from 00z and 12z data. In addition to Boone and San Gorgonio, Forsmark in Sweden will also be examined.

Figure 5.1 shows the diurnal variation of the wind speed at the surface at Boone and San Gorgonio. This figure shows that a wind maximum in Boone develops in the early morning and in San Gorgonio in the evening instead of, what would be expected, in the middle of the day when the temperature and vertical mixing are highest.

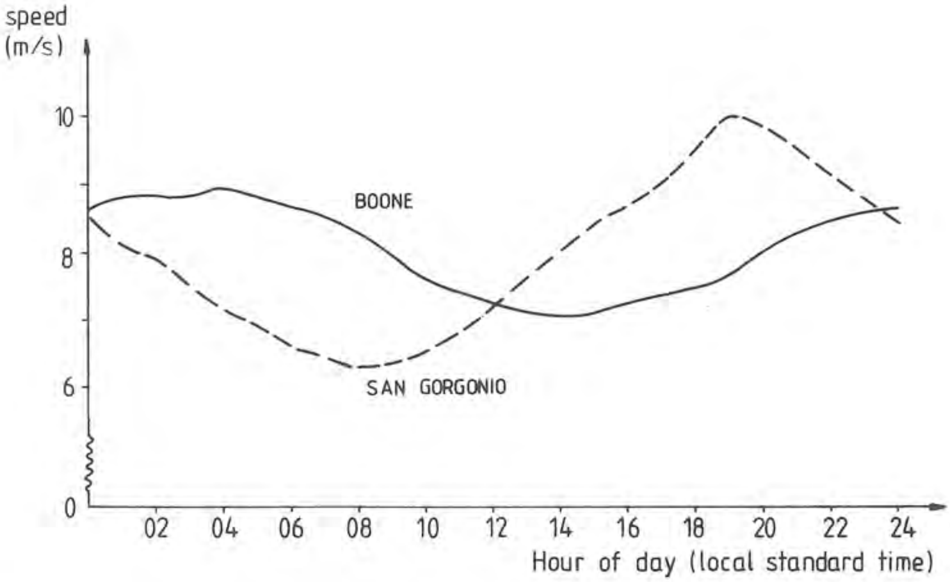


Figure 5.1 Mean annual diurnal variation of wind speed at San Gorgonio and Boone.

Compared with other North American sites the wind speed variation during the day was also large at these two sites.

In figures 5.2 and 5.3 the variation in the RMSE is shown during the day separated into forecasts made from 00z and 12z. It is obvious that in Boone the largest error is between 4 and 7 o'clock in the morning, i e at the time when wind speed normally decreases.

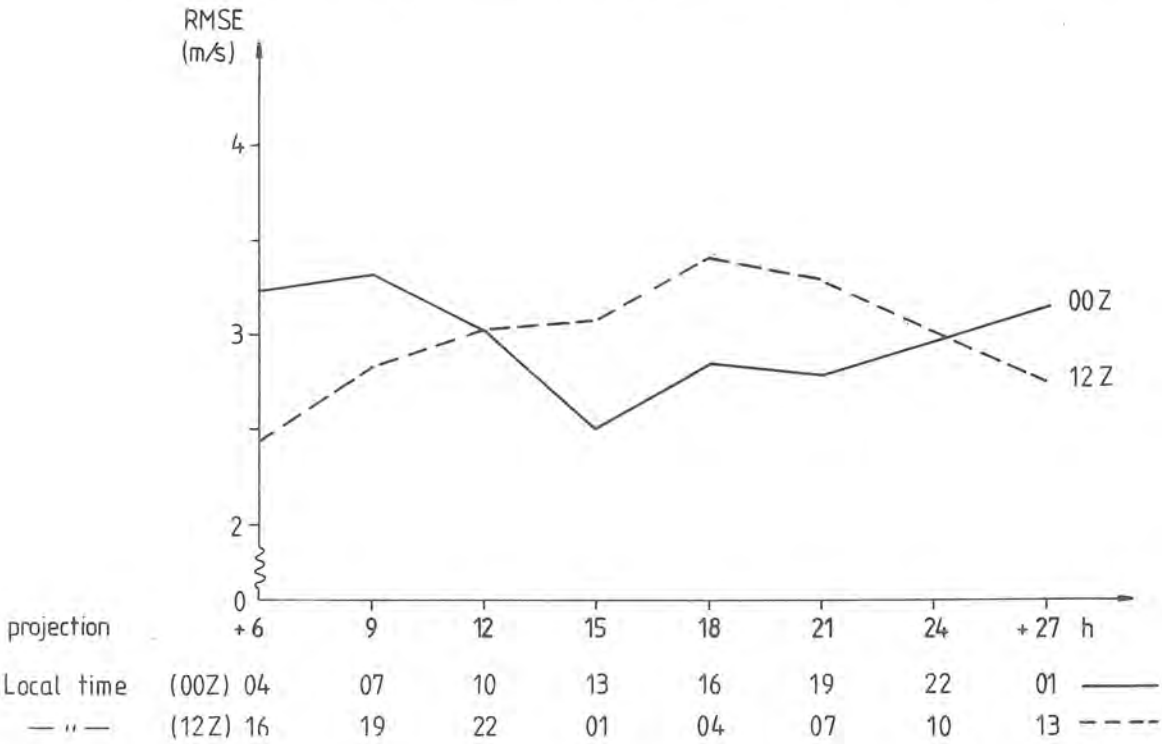


Figure 5.2 Diurnal variation of wind speed forecast error for Boone. Method: MOS-primary.

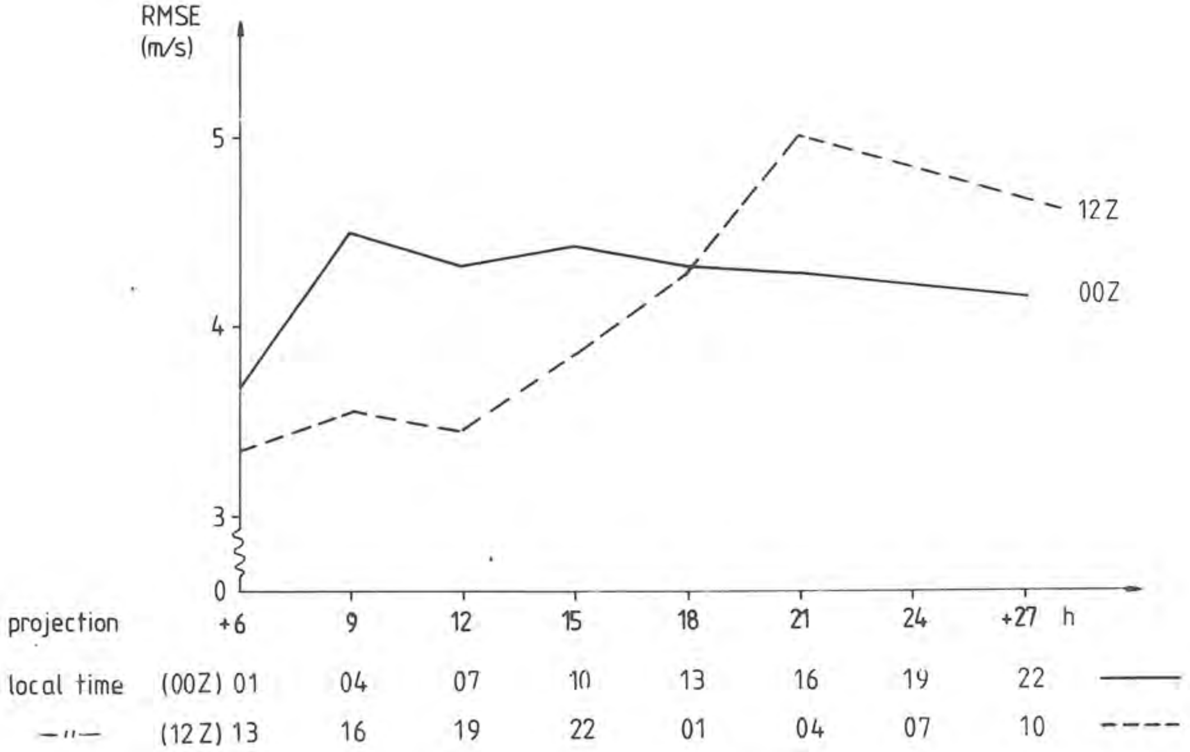


Figure 5.3 Diurnal variation of wind speed forecast error for San Gorgonio. Method: MOS-primary.

Also in San Gorgonio the largest error occurs when the wind speed decreases and in this case the largest error appears at 4 o'clock in the morning.

At Forsmark there are no significant differences between forecasts made from midnight or noon data using the subjective method during spring and summer (not shown here). Fig 5.4 (b) shows Type A and B forecast error (RMSE) as a function of projection time separated into forecasts made from 00z and 12z data. Type A forecasts show that the error for 12z forecasts grows faster than for 00z forecasts for the longer projection times, i e that night time forecasts are better than day time forecasts. The numerical/statistical forecasts behave differently according to fig 5.4 (a). Both 00z and 12z forecasts show a relative decrease in forecast error during the day. For 00z forecast this occurs for +12 - +18h projection times while for 12z forecasts it occurs for +24 - +30h forecasts.

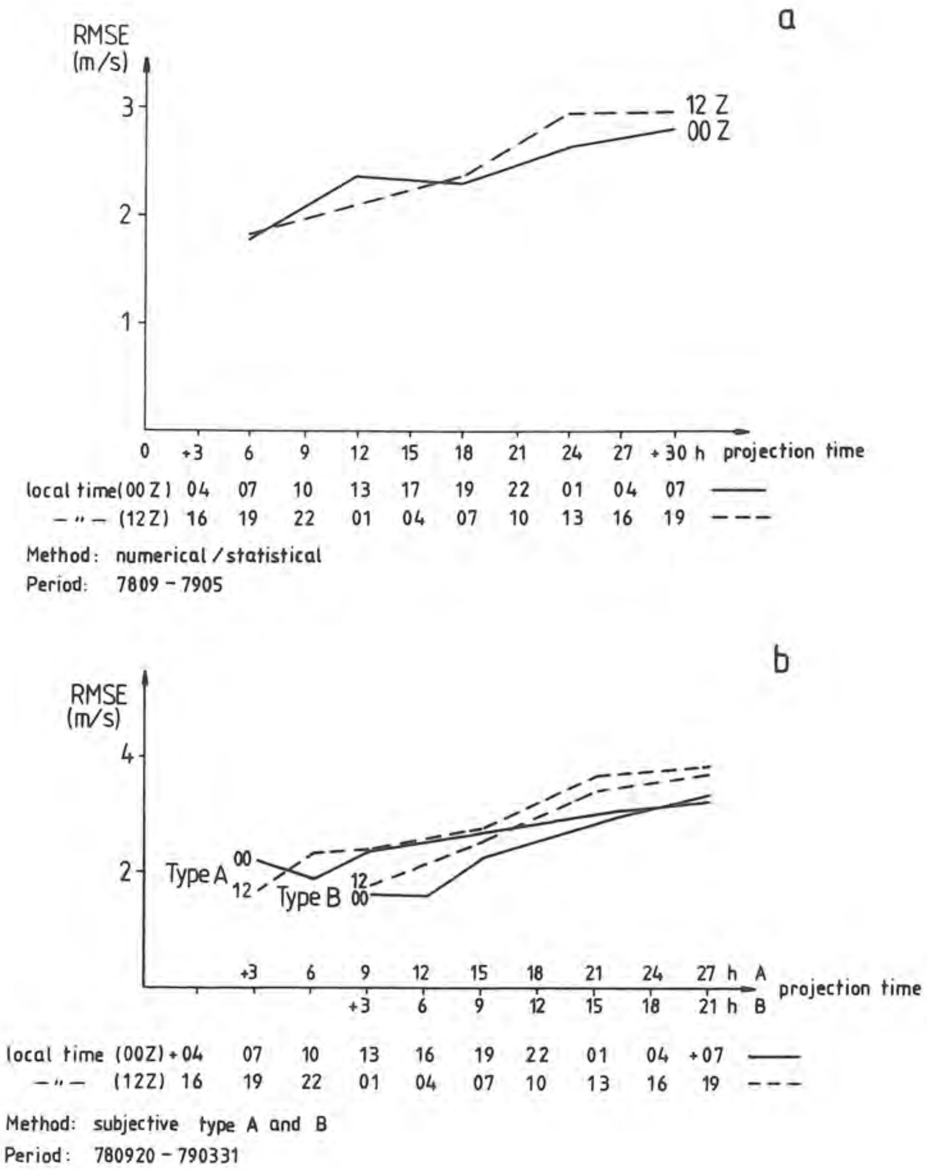


Figure 5.4 Diurnal variation of wind speed forecast error at Forsmark.

The general monotonic increase besides this diurnal variation is similar in the two cases.

Granfall (1980) found that during spring and summer the winds at midnight (GMT) at the levels 50 m and 100 m were only weakly correlated with the (large-scale) geostrophic wind. If the geostrophic wind was weaker than 6 m/s wind speeds anywhere between 1 and 11 m/s could occur. After having studied the temperature and wind profiles at these times (a typical case from 14 July, 1976, is shown in figure 5.5) it was concluded that these super- or sub-geostrophic winds could be explained by means of a nocturnal jet oscillation.

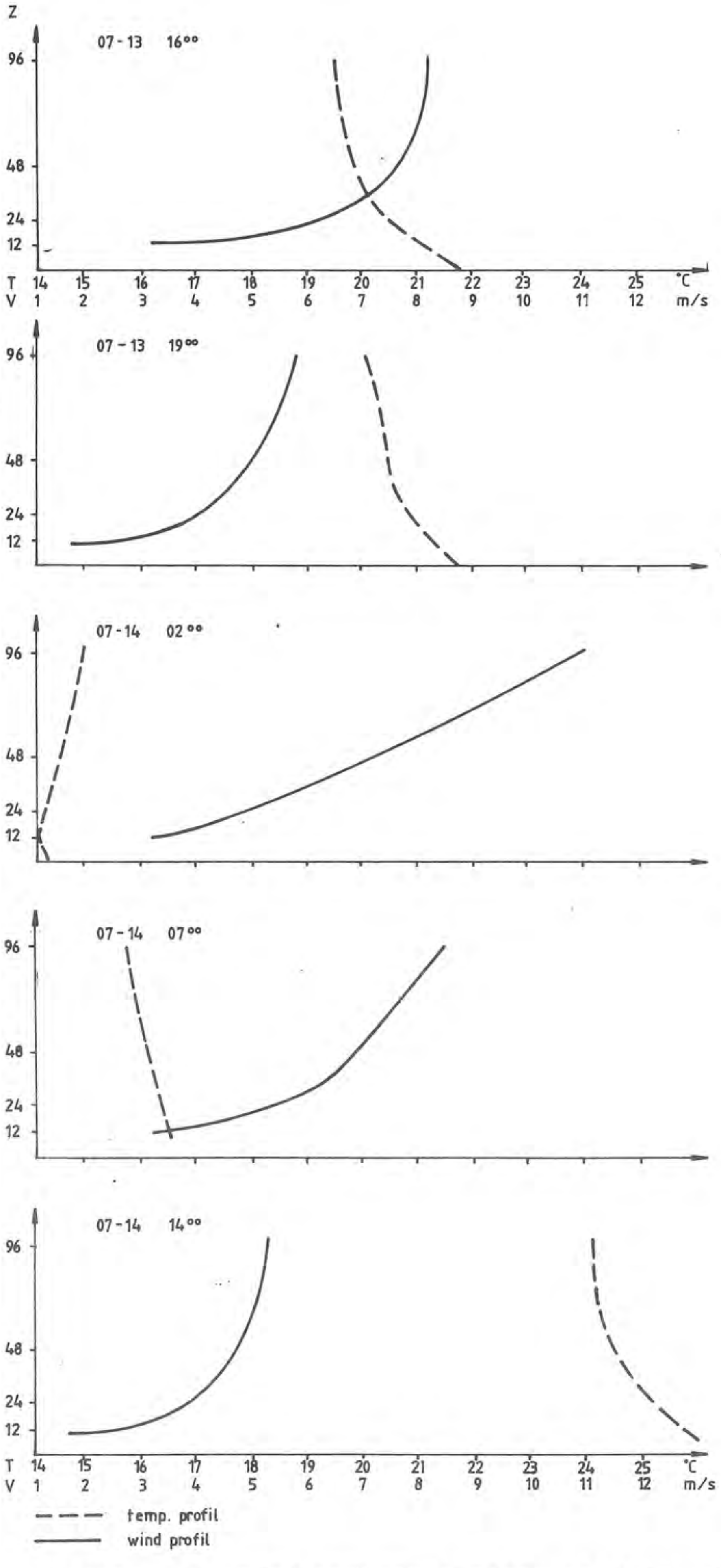


Figure 5.5 Wind and temperature profiles during an occasion with a nocturnal jet oscillation.

5.2.2 Seasonal variations

The American data comprise the major part of a full year - 11 months, the Swedish data only 8 months. The US forecasts have been examined to evaluate seasonal variations in forecast error. In order to see if different areas respond differently to seasonal changes the data have further been separated into coastal and inland sites. The west coast sites, however, are usually in more exposed, mountainous regions and have been treated as a third group.

Figures 5.6, 5.7 and 5.8 show how RMSE and correlation vary during the year. All sites have been normalized by their own total average, in order to enhance the annual variation. From the figures it can be seen that the errors are smallest during June through September.

To examine if the errors depend on the variation of monthly mean wind speed the RMSE has been divided by the average wind speed ($\overline{v}$) and the standard deviation of the observed wind (σ_{OBS}) respectively. The results are shown in figures 5.9, 5.10 and 5.11, where Block Island and Montauk Point represent east coast conditions and Huron the inland sites.

From the figures it can be seen that if RMSE is divided by the standard deviation (σ_{OBS}) the error will be largest during the summer months. There is no big difference between inland sites and coastal ones. The differences between different coastal sites are larger than the difference between inland and coastal sites. If the RMSE is normalized by the mean wind ($\overline{v}$) the variation of the coastal sites during the year is small. For the inland site there are very few data during January through February. However, for the rest of the year errors during summer are different when normalized by V and σ respectively.

Even after normalizing by $\overline{v}$ and σ_{OBS} respectively there is a seasonal variation. The gap in the data does not allow any clear conclusions but the figures hint that it is more difficult to make forecasts during the winter and autumn than during the summer as would be expected.

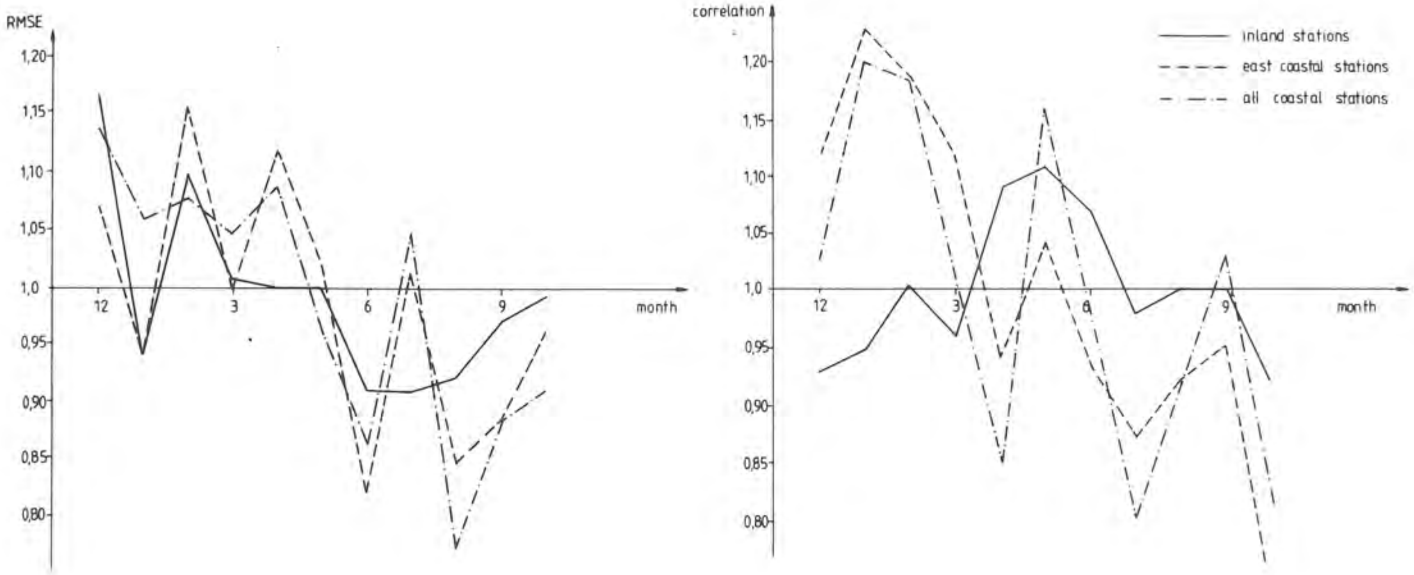


Figure 5.6 Annual variation of forecast error. Monthly averages of RMSE and correlation normalized by total average. Method: MOS-back-up Projection time +9h.

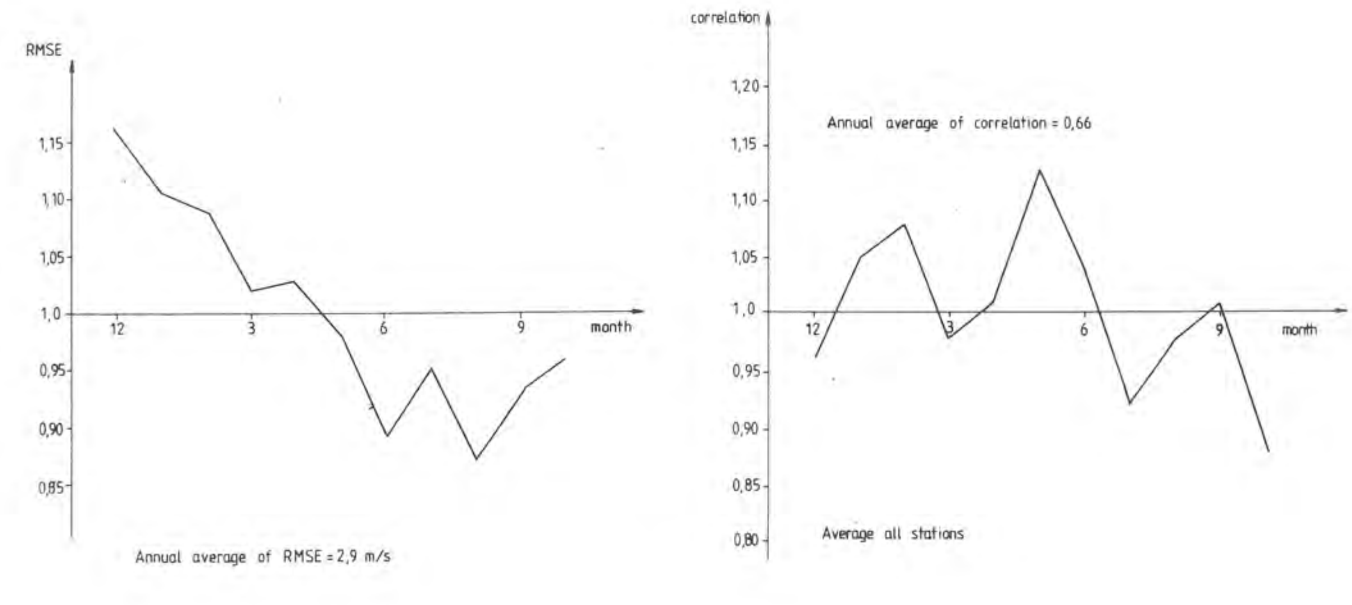


Figure 5.7 Annual variation of forecast error. Monthly averages for all US locations normalized by total average. Method: MOS-back-up Projection time +9h.

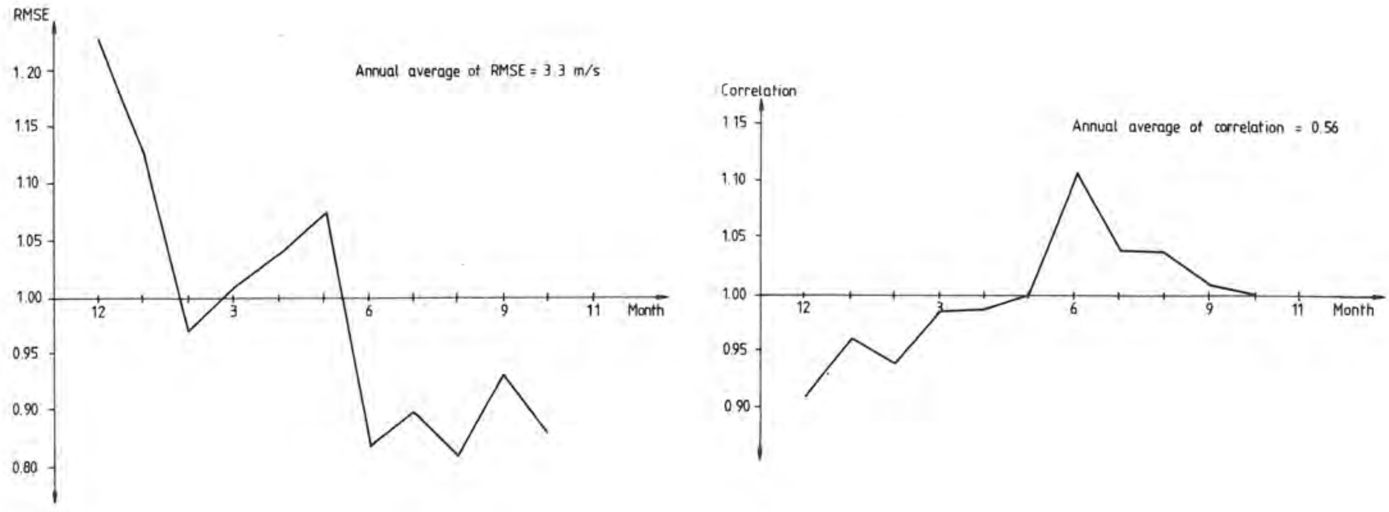


Figure 5.8 Annual variation of forecast error. Monthly averages for all US locations normalized by total annual average. Method: MOS-primary Projection time +27h.

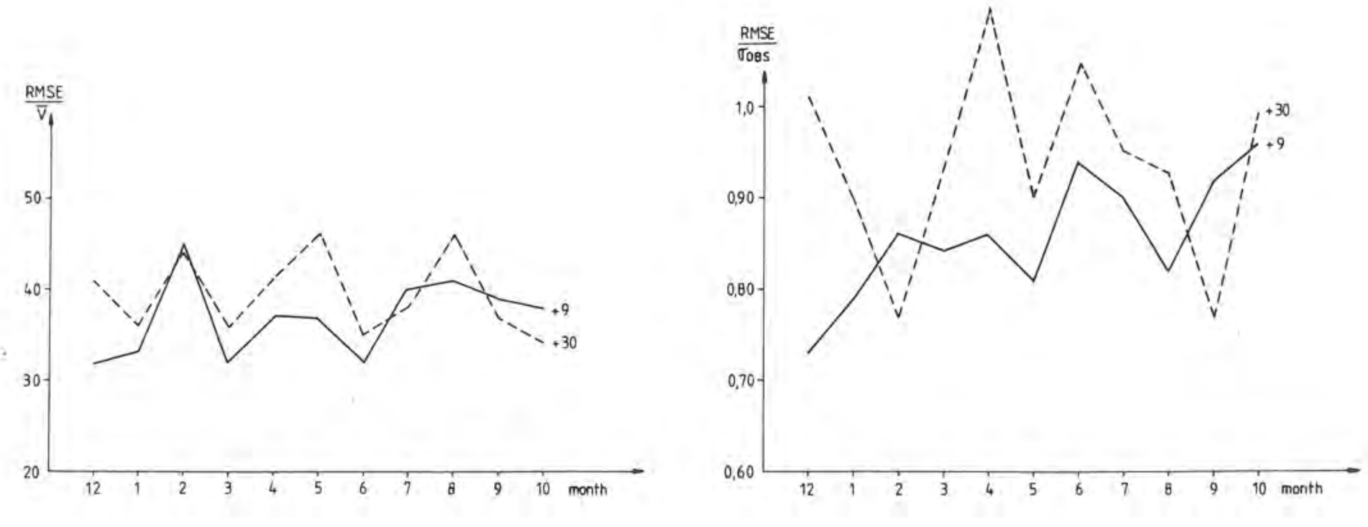


Figure 5.9 Annual variation of forecast error. Monthly averages of RMSE normalized by average wind speed and standard deviation for Block Island. Method: MOS-back-up Projection time +9h and +30h.

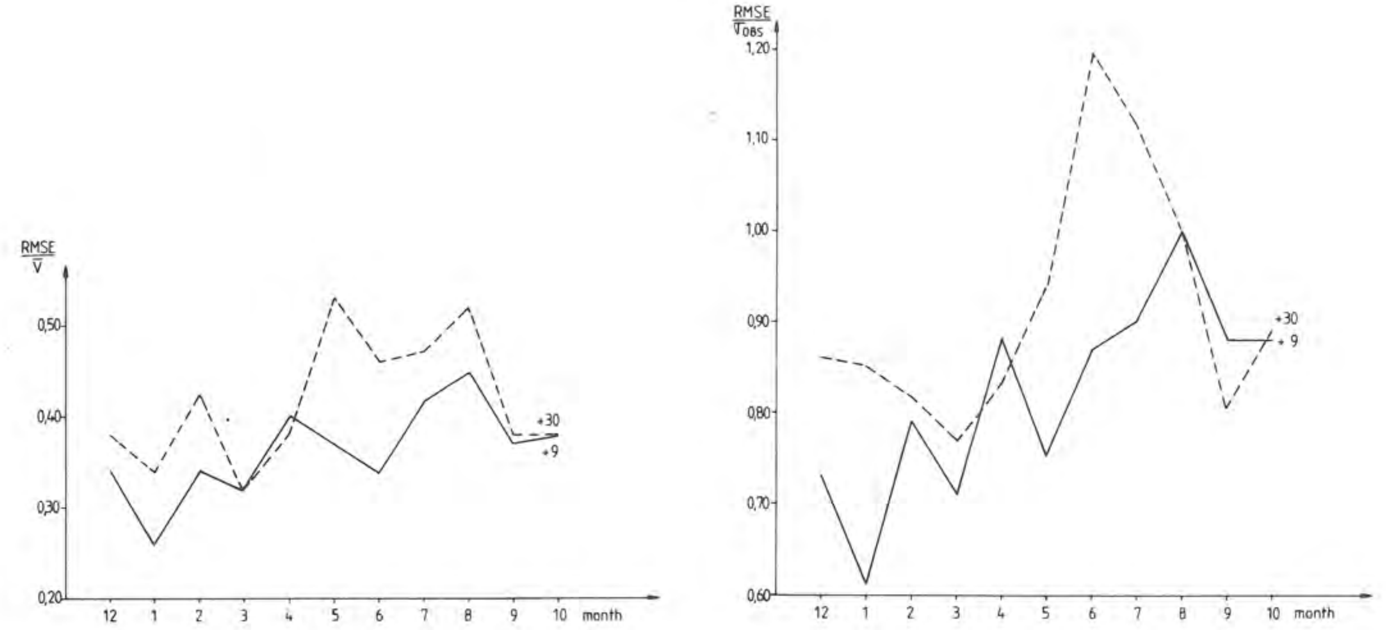


Figure 5.10 Annual variation of forecast error. Monthly averages of RMSE normalized by average wind speed and standard deviation for Montauk Point. Method: MOS-back-up Projection time +9h and +30h.

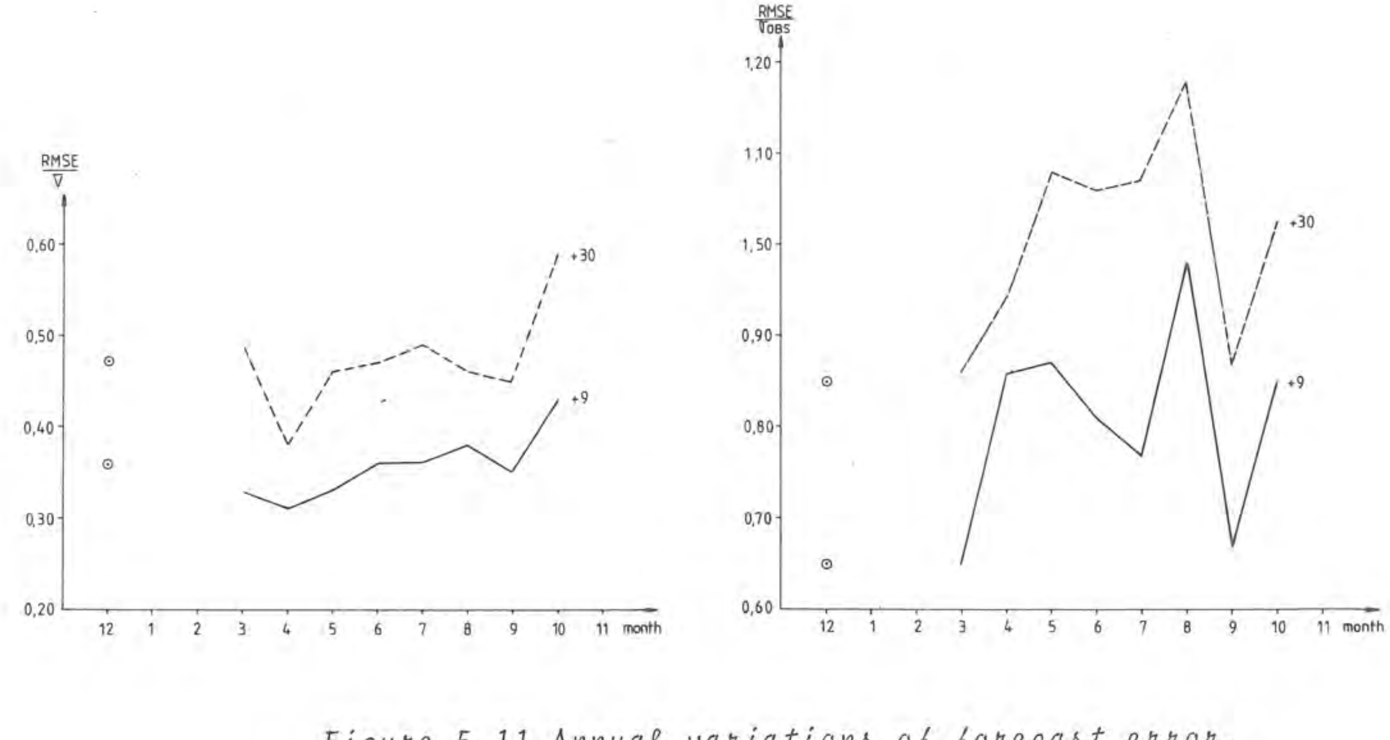


Figure 5.11 Annual variations of forecast error. Monthly averages of RMSE normalized by average wind speed and standard deviation for Huron. Method: MOS-back-up Projection time +9h and +30h.

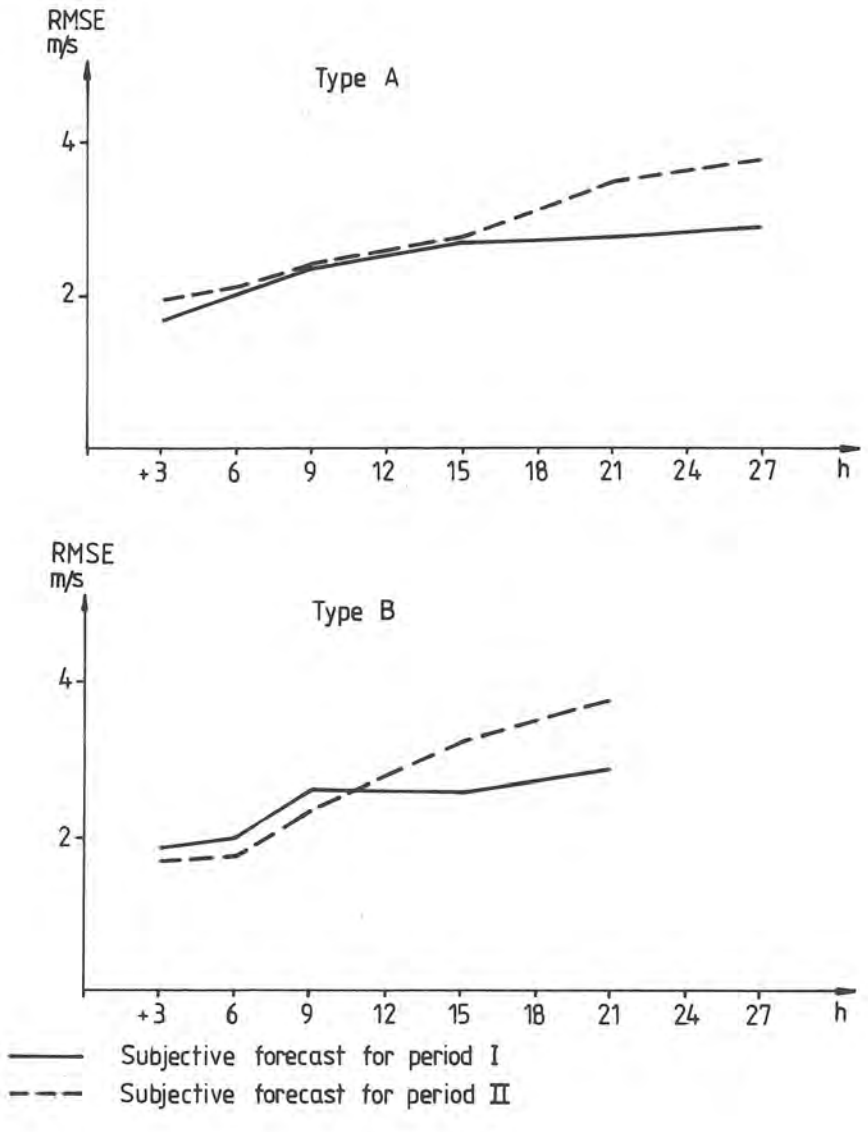


Figure 5.12 RMSE for subjective forecasts in Forsmark split up in spring and autumn (period I: 20 Sep 1978 - 12 Oct 1978 and 1 Apr 1979 - 28 May 1979) and winter (period II. 1 Jan 1979 - 31 Mar 1979).

The Swedish forecasts have been made only for a short time. However, comparing spring -autumn and winter (period I, 20 Sept 1978 - 12 Oct 1978 and 1 April 1979 - 28 May 1979, period II, 1 January 1979 - 31 March 1979) yields the result that forecast errors were about equal during both periods for A-type forecasts +12h and for B-type +6h. The longer forecasts (see fig 5.12) during period I obtained considerably lower RMSE-values than period II forecasts. The material is too small to allow any definite conclusions. Tables 5.4 and 5.5 also contain some information concerning seasonal variations of forecast error. Subjective B forecasts from Forsmark here show some improvement during winter while numerical forecasts actually show a deterioration at both levels for +6h forecasts. Different forecast methods seem to react differently in different weather situations and during different seasons.

5.2.3 Geographical variations

In this section the forecast quality for different geographical regions is examined. This can only be done for the US data. The nine American sites have been grouped into flat land sites, coastal sites and mountain sites. The coastal sites are: Block Island, Montauk Point on the east coast and Point Arena on the west coast. The flat land sites are: Huron, Kingsley Dam and Russell. The mountain sites are: Boone and San Gorgonio. Holyoke is treated separately.

Table 5.2

Averages of 3 flat land sites (P), 3 coastal sites (C) only the 2 east coast sites (CE) and 2 mountain sites (M) in the US. Period: December through October. Method: MOS-primary.

	+6 hours				+27 hours			
	P	C	CE	M	P	C	ME	M
Column 1, 2&3	83	85	85	78	78	82	85	80
Column 2, 2&3	41	33	36	29	47	43	45	34
Hit percent 2&3	74	78	77	76	68	71	72	74
Skill score	37	48	47	42	24	33	34	38
Correlation	70	77	78	78	52	61	65	72

	RMSE			
Projection time	Mountain	Flat land	E coast	W coast
+ 6h	3.19	2.60	2.29	2.46
+15h	3.48	3.02	2.76	3.26
+21h	3.85	2.98	2.92	3.52
+27h	3.68	3.33	2.98	3.57

Table 5.2 shows a summary of verification scores for different regions of the USA for the period Dec 1977 - Oct 1978.

Looking at RMSE first mountain areas have the largest RMSE-values for all projection times, followed by the inland stations. The east coast locations perform the best for all projection times. The upper part of the table, showing some other scores for +6h and +27h forecasts, does not show the same consistency. Coastal sites seem to have a lead for +6h forecasts but for +27h mountain stations come out the best.

The figures are changed only slightly when treating east coast locations separately.

Earlier verifications of MOS-forecasts indicate similar results. The MOS-technique seems to work best in the eastern USA, along the Gulf Coast and in southern California. The poorest forecasts were obtained in the interior regions of the USA especially in the southwest.

These variations might be due to different weather conditions and MOS' capacity relating to different kinds of climates. Increased absolute errors might not necessarily correspond to an increase in relative error, i e RMSE normalized by σ. The material, however, is too scarce to allow any conclusion.

5.2.4 Variation with height

The variation of forecast error with height can only be studied from the Swedish data, for which forecasts have been made for 50 m and 100 m heights. Table 5.3 shows various verification scores for the two methods described above: Subjective, Type B and numerical/statistical. From the table it is obvious that the forecasts for 100 m are at least as good as those for 50 m height in terms of correlations and hit percent. In terms of unnormalized RMSE, however, the error increases somewhat with height while normalized values show similar skill.

Tables 5.4 and 5.5 show +6h forecast verifications during different seasons for 50 m and 100 m heights at Forsmark. In both cases, i e for Subjective B and numerical/statistical, RMS-error increases with height while the normalized values decrease with height for subjective forecasts, showing that increased variance accounts for the increase in RMSE. This is also reflected in the correlation figures for Subjective B forecasts but not for numerical/statistical ones. However, the differences are small for the latter cases. The weak seasonal variation does not change these characteristics.

In general the wind at 50 m and 100 m should have similar couplings to the geostrophic wind with a tendency for more degrees of freedom at 100 m than at 50 m. However, forecasts are as good or better at 100 m than 50 m. This could be due to special circumstances at Forsmark, such as topographic influences or influences from the power plant buildings which would be expected to decrease with height.

The material, however, is far too small to say anything certain about this issue.

Table 5.3

Forecast verification scores for different heights for Forsmark, Sweden. Projection time +6h.

Subjective with numerical guidance, type B
Sept - Dec 1978 and Jan - May 1979

	50 m	100 m
RMSE (RMSE/σ_o)	1.72 (0.7)	1.89 (0.62) m/s
Correlation	0.75	0.80
Column 1, 2&3	71	85
Column 2, 2&3	16	16
Hit percent, 2&3	75	84
Skill score	54	63
Total hit percent	77	81

Numerical/statistical
Sept 1978 - May 1979

	50 m	100 m
RMSE (RMSE/σ_o)	1.84 (0.7)	2.28 (0.7) m/s
Correlation	0.73	0.73
Column 1, 2&3	72	82
Column 2, 2&3	15	25
Hit percent, 2&3	79	80
Skill score	55	52
Total hit percent	78	74

Table 5.4

Forecast error for different heights: Seasonal variation.

Forsmark, Sweden +6h   Seasons: Autumn (SO)
Winter (JF)
Spring (MAM)

Subjective, with numerical guidance, type B

RMSE m/s parenthesis, normalized by σ

	50 m	100 m
Autumn	1.98 (-)	2.36 (-)
Winter	1.61 (0.60)	1.77 (0.50)
Spring	1.76 (0.76)	1.89 (0.73)
Total	1.72 (0.70)	1.89 (0.62)

Correlation

	50 m	100 m
Autumn	-	-
Winter	0.83	0.86
Spring	0.69	0.74
Total	0.75	0.80

Table 5.5

Same as above but seasons are: SON, DJF and MAM.

Numerical/statistical

RMSE m/s parenthesis, normalized by σ_o

	50 m	100 m
Autumn	1.64 (0.75)	2.2 (0.81)
Winter	2.03 (0.71)	2.5 (0.74)
Spring	1.87 (0.75)	2.2 (0.76)
Total	1.84 (0.70)	2.3 (0.71)

Correlation

	50 m	100 m
Autumn	0.74	0.72
Winter	0.71	0.70
Spring	0.68	0.69
Total	0.73	0.73

5.2.5 Variation with projection time

It is of considerable interest to study the decay of forecast skill with projection time to judge the usefulness of different forecasts. Figs 5.13-5.16 show various plots of forecast errors as a function of projection time. It should then be remembered that MOS-primary uses an observation 3 hours after the main observing times (12z and 00z). This is also true for the subjective, Type A Swedish forecast. They are comparable in this report.

Fig 5.13 shows a comparison of MOS-primary and MOS-back-up (note that the two time scales start at +6h and +9h respectively!). The 9 locations are divided into coastal stations (C), mountain sites (M) and low land stations (P). Holyoke is treated separately. The total average is denoted by A. The values for the whole period are used. Both methods show similar skill. On the average RMSE starts with approximately 2.8 m/s and increases to about 3.3 m/s for +27h forecast projection. Holyoke is the best station in both cases and MOS performs the worst for the mountain locations with an error between 3.5 and 4 m/s.

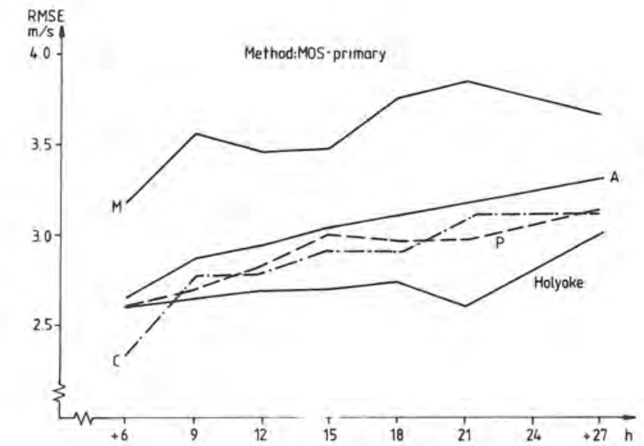
Fig 5.14 shows results from the same period and locations,but verification score is hit percent. Average values start at about 74% for MOS-primary and MOS-back-up and drop to about 57% after +27h. San Gorgonio is quite good while Kingsley Dam emerges as the worst. Mountain sites perform well while flat land stations rapidly drop below 70%. The spread, however, is small.

Verification in terms of skill does not change this situation. Holyoke is the best and Kingsley Dam the worst. The avergage is the same for both methods. This can be seen from fig 5.15.

In fig 5.16 RMSE and hit percent (class 2&3) are compared for three different methods: The US MOS-primary, Swedish subjective, Type A and numerical/statistical. Forecasts refer to 50 m height and data from the whole periods are used.

The Swédish methods start from about 1.8 m/s RMSE for +6h after which errors increase monotonically up to 2.9 m/s for +30h forecasts. Around +18h the numerical/statistical method beats the subjective, Type A, i e the meteorologist actually deteriorates the statistical method! However, the differences are small. The US forecasts for 3 coastal locations show much larger RMSEs, values starting at 2.3 m/s and ending up at 3.1 m/s for +21h forecasts.

Comparing hit percents gives similar results for the two Swedish methods. However, the hit percent of MOS is higher than the Swedish despite the fact that RMSE is much larger for MOS. This reflects a much higher variance of wind speed at the US locations.



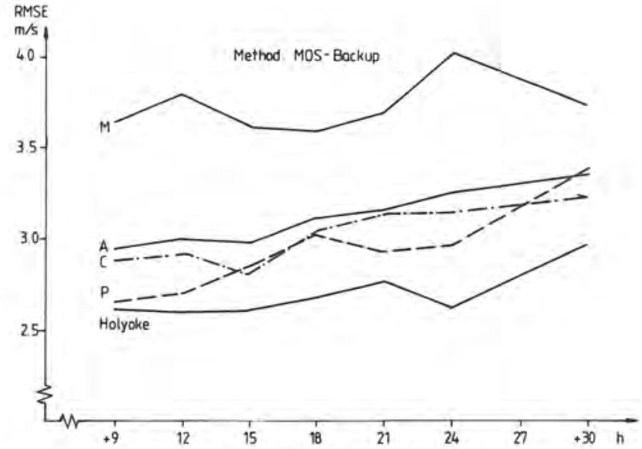
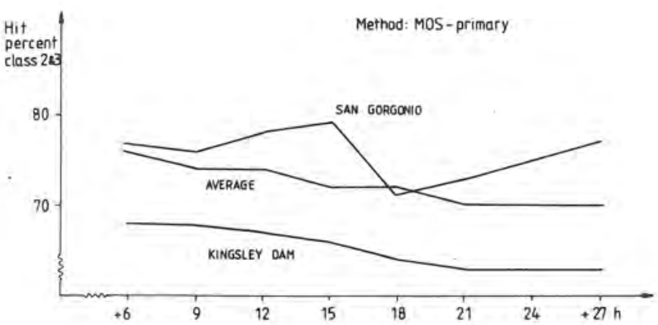
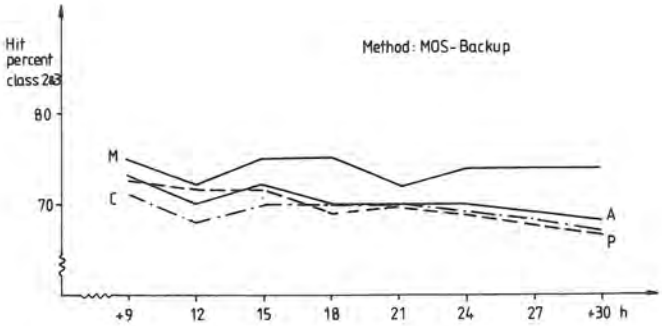


Figure 5.13 Variation of forecast error with forecast time.

RMSE for 9 US locations grouped into coastal stations (C), mountain stations (M) and low land stations (P). Holyoke is treated separately. Total average is denoted A.





A = Average score
M = Mountain stations
C = Coastal stations
P = Stations on flat land

Figure 5.14 Variation of forecast error with forecast length.

Hit percent for 9 US locations. For MOS-primary only averages for all stations and best and worst stations are shown.

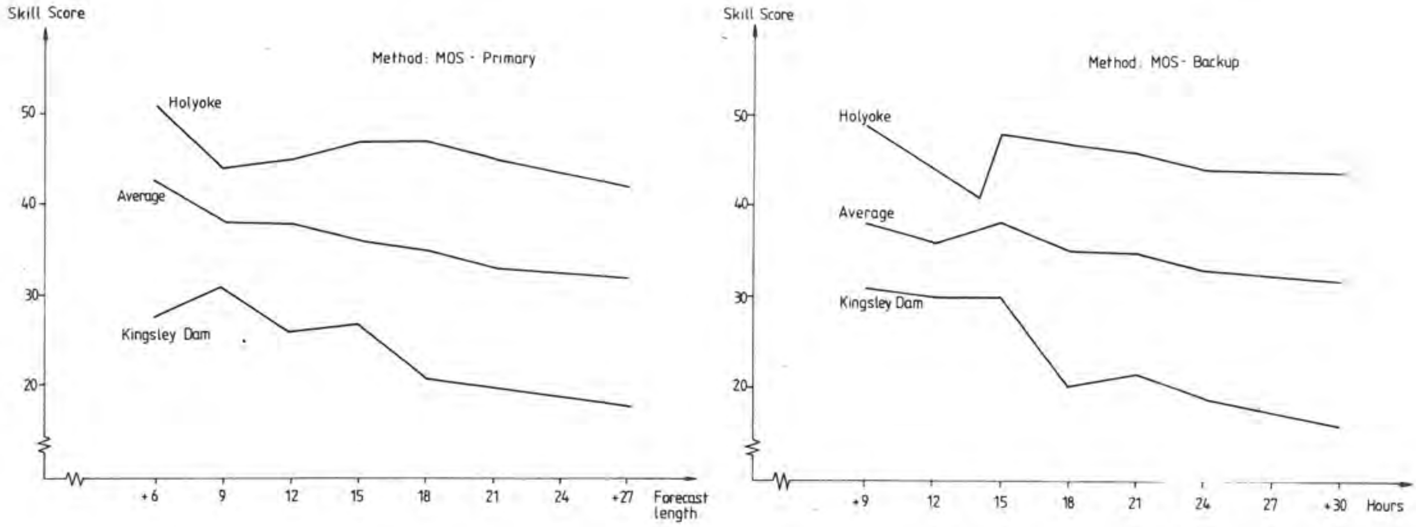


Figure 5.15 Variation of forecast error with forecast length.
Scill score for 9 US locations. Only averages for whole period of all stations and best and worst stations are shown.

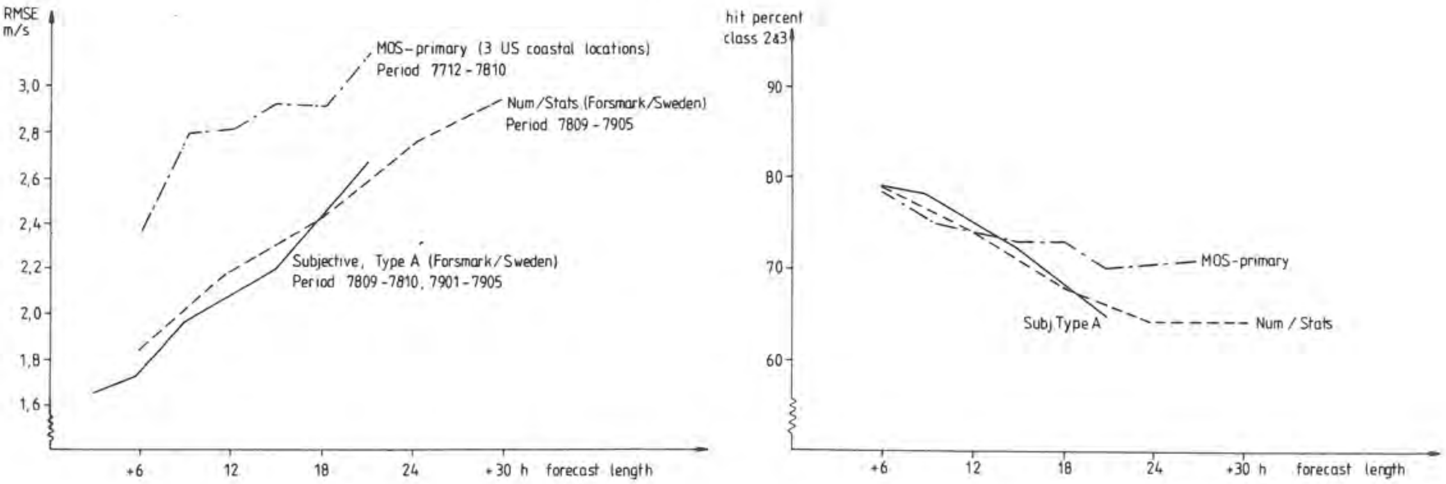


Figure 5.16 Forecast error and its variation with forecast length.
Comparison between 3 forecast methods for 50m level. Averages over whole periods.

5.3 Comparison of different forecast methods

Some attempts have been made to try to compare different forecast methods. Such a comparison should in fact be made for the same place, same data but with the different methods under consideration. This has only been possible for some few cases.

The Swedish data from Forsmark have been subjected to three different methods, one of them numerical/statistical, the other two variations of a mixed numerical/subjective method. +6h forecasts are available for 50 m and 100 m and allow some comparisons. Tables 5.6 and 5.7 show different scores for the three methods above. In addition a persistence forecast has also been verified and serves as a reference. Both 50 m and 100 m heights have been verified for the whole period September through October and January through March. For 50 m all three methods show similar scores but with slightly better results for subjective A. All methods also improve over persistence. RMSE is about 1.7 - 1.8 m/s, while persistence is 2.3 m/s. All methods, including persistence are equally good in forecasting classes 2&3. Going up to 100 m makes subjective B slightly better than the others. RMSE has risen but also correlations and hit percent. Normalizing with respect to the observed standard deviation actually gives lower RMSE.

These results seem to indicate that subjective judgement can improve the simple numerical/statistical scheme. However, the differences are small for both heights. There is an almost 1/4 reduction of RMSE over persistence.

Table 5.8 shows an attempt to compare the US data with the Swedish Forsmark data. Of the US locations Montauk Point has been chosen because of its resemblence to Forsmark, situated at an east coast. It is possible to find one coinciding data period, from Dec through May for +12h forecast and height 50 m. Four different methods are compared: MOS-primary, MOS-back-up, Persistence (based on MOS-data and Forsmark-data separately) and the numerical/statistical Swedish scheme.

The RMSE is considerably higher for Montauk Point than for Forsmark. Comparing with persistence and normalizing with the standard deviation gives comparable figures. Actually US forecasts are slightly better than the Swedish ones. This is especially true if hit percent, class 2&3, and correlations are compared. However, it must be kept in mind that US forecast refer to 1 hour averaging times while the Swedish forecasts are for 10-minute averages. As discussed in 3.3 this means that part of this difference in forecast skill can be explained by this difference in averaging time. The conclusion that the MOS-system produces better forecast than the simplier Swedish model is not surprising. It is actually worthwhile to emphasize at this point that better numerical prediction models and statistical methods do give better forecasts.

Fig 5.16 in section 5.2 gives some supplementary information. In these figures forecast error, RMSE, has been plotted as a function of forecast times. Even if data are not directly comparable, these figures indicate that the subjective methods exhibit smaller errors initially than both of the numerical methods. However, the error grows more rapidly with projection time for the subjective method than for the numerical/statistical ones. Comparing the Swedish data the numerical method becomes better for forecasts longer than +18 hours. The MOS-method shows somewhat irregular behaviour. The same tendency is also evident in the hit percent of classes 2&3 where MOS is significantly better for all times. Actually MOS never goes below 70%.

Root-mean-square errors vary between 1.6 m/s for +3h forecasts for Forsmark to almost 5 m/s for some US locations. The error varies between different places indicating that some places are more difficult to forecast for than others. The lower figure of 1.6 m/s for +3h barely meets the requirements put forward by the Swedish State Power Board. The skill in predicting the occurrence of wind power/no wind power is really not too bad but forecasts are still too poor in the critical range between cut-in and rated power wind speed. For the remainder of forecast lengths, methods and places forecast quality seems to be clearly unsatisfactory.

The large uncertainty partly indicates that forecasting the wind accurately is difficult. This can be seen, for example, by comparing the present results with Kruse & Strüning (1977). The meteorological expertise has not been directed towards meeting such stringent demands, as those put forward by the utilities, in the past. Other applications have been satisfied with less accurate wind forecasts, e g where warnings have been issued for much longer periods and where short-range variations have been less important. This is reflected in the fact that the wind forecasts studied in this report have been produced by available methods even if they have been adapted for this specific application.

It is possible to reduce forecast error in the future. The great economic value of good wind forecasts would definitely motivate increased research to develop new forecast methods for wind energy forecasting. Some directions can be indicated here

1. - improving the basic numerical forecast models used by most weather services by increasing numerical resolution and introducing sophisticated boundary layer parameterizations. This can be accomplished by upgrading available computer capacity.

2. - Developing improved statistical techniques involving predictors more relevant to boundary layer winds.

3. - Developing and implementing numerical boundary layer models in 1-3 dimensions. This is probably the most effective way of obtaining better forecasts. It depends, however, on point 1.

In order to get improved forecasts for the whole range of 1 hour to 10 days all three ways have to be taken. Other ways of improving the forecasts can be found in the observational data. All prediction methods require initial data. Mast measurements of wind, temperature and humidity at different heights up to 150 m are needed at every large WECS site. Boundary layer height is an important parameter which can be obtained by remote sensing techniques. Sufficiently long series of data are needed to develop stable statistical regression equations as in the MOS-technique.

The general synoptic network is insufficient when forecasting for time scales shorter than +6 hours. To achieve real reduction in forecast error weather services would have to supplement the synoptic network with a denser network of, for example, automatic stations with sensors for pressure, wind speed and direction, temperature and humidity. These data are needed to initialize various models for short-range weather forecasting or together with satellite and radar information form the basis for very short-range subjective forecasts.

In summary we can say:

- A better forecast model and a better statistical scheme also give better forecasts.

- Subjective methods are better for short-range forecast, <18h, but deteriorate faster than numerical/statistical methods which become better than subjective after >18h.

- The overall quality of the wind forecasts examined does not appear to be adequate for producing reliable wind power forecasts for a single WECS. Only for +3h the Swedish requirements are almost met.

- From a meteorological point of view the forecasts treated here represent what is currently possible.

- Wind speed forecasts can be improved by means of research and development together with increased number of and increased quality of observations.

Table 5.6

Comparison between different methods at Forsmark.

Height: 50 m Forecast length: +6h

Period: September - October, January - May

Methods: Subjective A, Subjective B
Numerical/statistical
Persistence

	Subj A	Subj B	Num/stat	Pers
Column 1, 2&3	74	71	68	74
Column 2, 2&3	18	16	14	25
Hit percent 2&3	79	79	79	75
Hit percent 1-4	77	77	78	74
Skill score	53	54	55	47
Correlation	77	75	73	61
RMSE	1.73	1.72	1.80	2.27
RMSE/σ_{obs}	0.66	0.70	0.70	0.89

Table 5.7

Comparisons between different methods at Forsmark.

Height: 100 m Forecast length: +6h

Period: September - October, January - May

Methods: Subjective A, Subjective B
Numerical/statistical
Persistence

	Subj A	Subj B	Num/stat	Pers
Colummn 1, 2&3	84	85	80	80
Column 2, 2&3	23	16	22	29
Hit percent 2&3	81	84	79	76
Hit percent 1-4	77	81	76	69
Skill score	56	63	54	42
Correlation	77	80	73	64
RMSE	2.05	1.89	2.23	2.65
RMSE/σ_{obs}	0.64	0.62	0.71	1.00

Table 5.8

Comparison between different methods.

Height: 50 m Forecast length: +12h

Period: December - May

Methods: MOS-primary (Montauk Point)
MOS-backup (" ")
Numerical/statistical (Forsmark)
Persistence (Montauk Point & Forsmark)

	MOS-P	MOS-B	Pers/MOS	Num/stat	Pers/NS
Column 1, 2&3	84	86	72	70	63
Column 2, 2&3	36	47	53	27	34
Hit percent, 2&3	79	75	64	72	65
Hit percent, (total)	64	59	52	71	64
Skill score	38	32	19	41	29
Correlation	71	71	43	61	36
RMSE	2.93	3.08	3.92	2.27	2.88
RMSE σ_{obs}	0.73	0.77	1.05	0.83	1.11

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The integration of wind energy into electrical power grids is an important problem when discussing the future of wind energy. No practical experience of penetration levels of the order of 10% or more exists. This also affects the possibilities of evaluating the uncertainty of wind speed forecasts for wind energy production. In this study a survey of existing forecasts for WECS has been undertaken. Some existing data sets have been used. However, the data show clear limitations as discussed in section 4.1. Some of the data only cover a couple of months time. In general, data that cover most of the year still only represent one particular year. Seasonal variations must be judged against this background. The smallness of the data sets must also be kept in mind when discussing other results.

The data are furthermore scattered around the world, valid for different forecast length and different local times. They apply to different heights and are produced by different methods. An important task is to try to compare different methods and to arrive at some conclusions regarding the best method in terms of development potential. From the data provided, it has only been possible to find a few periods with similar conditions concerning projection time, height and comparable geographical locations, as discussed in 5.3. No direct comparisons have been possible. Only some general features have been possible to identify and point out. It is clear, however, that better models do produce better forecasts for all time-scales.

Because of the limitations of the available data many of the results are inherently uncertain and some of the questions concerning forecast reliability have only been partly answered. This is particularly true for the verification of power output from WECS or an array of WECS. This has not even been attempted. It is the opinion of the participating representatives that this is not feasible at this time because firm relationships between the power output and the forecast wind speed have not been established for all of the averaging times used by participants. In addition Swedish State Power Board representatives have not shown any interest in power output verification as discussed in section 2.3. This job should be carried out at a national level in close cooperation with utilities.

The shortest forecasts verified in this study are for +3 hour forecasts produced for Forsmark, Sweden, based on a combination of numerical/statistical methods. The US MOS-primary is really a +6h forecast because of the use of a local observation 3 hours after basic data collection time. Most utilities put most of the stress on the very short-range forecasts, 3-6 hours ahead.

For example, the Swedish State Power Board has put up requirements of RMSE of the order of ±1 m/s for +3h forecasts and ±1.5 m/s for +6 hours ahead. This is not too bad for +6 hours according to figure 5.16 (RMSE as a function of time) where subjective, type A has a RMSE of ±1.7 m/s. For +3h on the other hand RMSE is a little more than ±1.6 m/s compared to required ±1 m/s. For shorter forecasts we cannot predict what will happen with forecast error. It may level off, or continue to decrease. It also seems that for longer forecasts reliability drops faster than error tolerances. This means that the range utilities give the largest emphasis to, i e ~ 3 hours ahead, shows unsatisfactory forecast reliability. This forecast range is unfortunate because most forecast methods are designed for synoptic scale forecasts from +6h to +48h. It must therefore be pointed out that at present relevant methods have not been developed or applied to the problem of forecasting wind speed for this very short time scale. If research is initiated it should be directed primarily towards developing methods and systems for 0-+6h forecasts of wind speed.

Even if some methods verified in this study are up to current standard of operational meteorology the results presented here from a meteorological point of view do not represent what is scientifically possible. This becomes evident when comparing in a relative sense the wind forecasting results with other types of meteorological forecasts of other parameters, fields in which development has been going on for a long time and where results show a higher level of certainty.

6.2 Recommendations

The limitations of the present report concerning the basic data used for forecast verification and the conclusions drawn warrant some recommendations for future work. Based on the conclusions above and in section 5.3 these recommendations can be summarized as follow.

- Forecast reliability has to be considerably improved. Exact figures of required RMSE and correlations are difficult to quantify at the present time. They are expected to vary from country to country and between utilities depending on the power grid structure and the amount of wind energy introduced.

- There is a definite need for developing forecast methods for very short-range forecasts, i e 0-6 hours ahead.

- It is strongly recommended that national weather services improve their basic subjective and objective (i e numerical and statistical models) guidance, especially for the range +3-+12 hours.

- It is recommended to investigate to what extent other weather or weather-related factors such as turbulence, gustiness, precipitation (hail, sleet, snow, freezing rain or drizzle) and thunderstorms affect wind power production and the need for predicting these elements.

- Verification of wind forecasts should also be carried out in terms of power output after utilities have defined operational wind - power relations for WECS or clusters of WECS. Wind forecasts should also, alternatively, be expressed as probability forecasts.

- Future studies of forecast reliability and development of forecast methods should be performed in close cooperation with utilities.

Acknowledgements

The authors of this report wish to sincerely thank the members of the group of technical representatives for their kind assistance in this work and for their readiness to make data available to the project. In particular we would like to express our appreciation and gratefulness to Mr Harry Wegley and Dr Gerd Tetzlaff for their many contributions to the work. The typing of the report by Mrs Kerstin Fabiansen and drawing of the figures by Mrs Anita Bergstrand and Mrs Gunbritt Rosén are also gratefully acknowledged.

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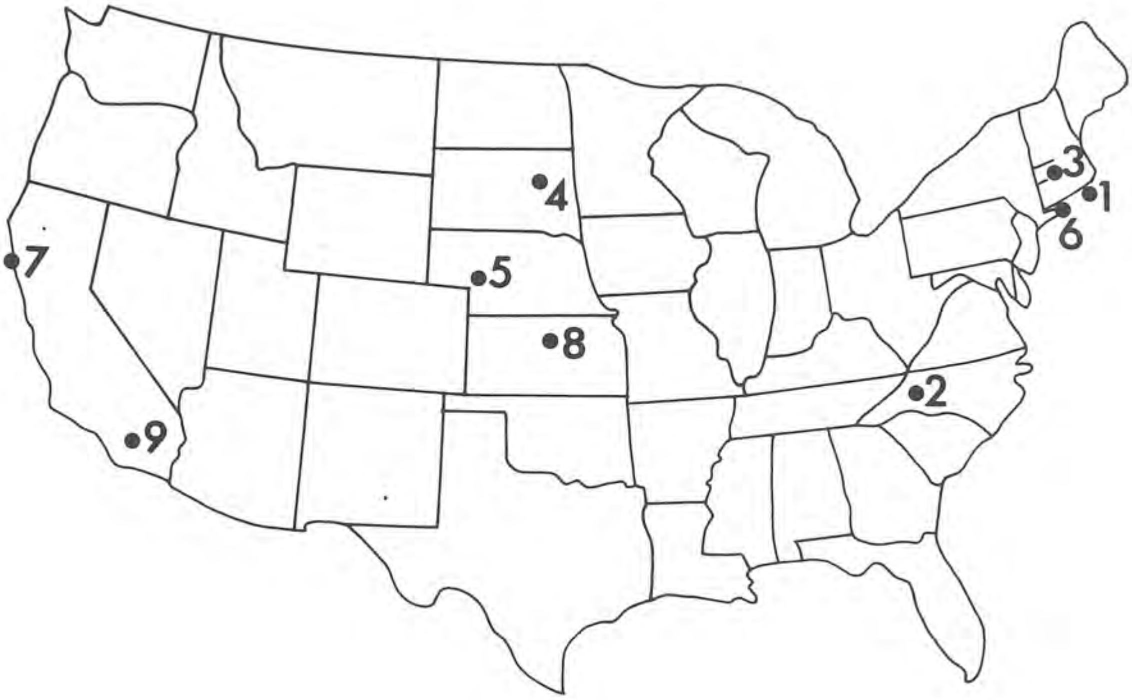
APPENDIX

Site descriptions

1. US sites.

2. Swedish site Forsmark.

1. US sites



1. Block Island

1. General location:

Block Island is located about 20 km off the eastern tip of Long Island and about 15 km south of the Rhode Island coast. There was a US weather station about 300 meters north of the site. That station was open from 1903-1950.

2. Specific location

41° 10'N 71° 34'W

3. Description of surrounding topography:

The island is about 10 km N-S by 6.5 km E-W. Its vegetation is primarily maritime shrubs with a few domestic trees in the populated areas. There are numerous fresh water ponds and swamps. The land slopes gradually upward to the south, terminating in cliffs of about 50 m on the southern shore.

4. Elevation

The elevation of the proposed site is 9 m MSL.

2. Boone, NC

1. General location

Boone is located in the Blue Ridge Mountains of North Carolina between Knoxville, TN and Wildesboro, NC in the corner of North Carolina. Some weather data have been collected at a station on Grandfather Mountain about 18 km southwest of the proposed site.

2. Specific location

36° 15'N 81° 40'W

3. Description of surrounding topography

The site is on top of a hill called Howard's Knob. It is free of any man-made obstacles. The nearest higher terrain is Rich Mountain approximately 2.7 km to the northwest which is about 110 m higher.

Vegetation consists of general hardwood forests. Howard's Knob slopes downward in all directions from the site.

4. Sea level Elevation

1348 m MSL

3. Holyoke, MA

1. General location

Located in west central Massachusetts approximately 11 km NW of Westover, AFB., which has an active weather station from which climatology is available.

2. Specific location

42° 15' 01"N 72° 38' 45"W

3. Description of surrounding topography

This site is situated on top of a hill in an approximately NS ridge line. There is a steep cliff to the west which drops off about 250 m to the valley floor within 0.4 km. The slope is more gradual to the east taking about 2 kilometers to get down to the 60 m level. The ridge is thickly forested with oak and scrub oak with the tallest trees being about 10 m high.

3. Sea level elevation of site

323 m MSL

4. Huron, SD

1. General location

The site is located about 8 km northeast of the city of Huron, SD on the banks of the James River. Weather data is available from Howes Municipal Airport in Huron.

2. Specific location

44° 24' 35"N 98° 08' 28"W

3. Description of surrounding topography

Located in a relatively flat area with a drop of about 18 m in 400 m to the river on the northwest. The vegetation is mostly grazing land with some hay fields in the area. Trees along the river banks are below the elevation of the site.

4. Site elevation

403 m MSL

5. Kingsley Dam, NB

1. General location.

Located in the southwest part of the state, 72 km west of North Platte and 16 km north of Ogallala. The nearest NWS weather station is at North Platte.

2. Specific location

41° 10' 45"N 101° 39' 30"W

3. Description of surrounding topography

The site is located just south of the Kingsley Dam with the reservoir extending to the northwest. The country side is grass covered rolling hills with no trees in the general vicinity.

4. Site elevation

1033 m MSL

6. Montauk, Long Island, NY

1. General location

Montauk, Long Island is on a NNW facing bay on Long Island Sound very near the eastern most end of the island. Meteorological data (winds) prior to 1972 are available but may be influenced by proximity to buildings.

2. Specific location

41° 03'N 71° 57'W

3. Description of surrounding topography

The area of the site is essentially a flat grass covered area a hundred meters wide and long. The northern perimeter is bounded by open water (Fort Pond Bay) while the land surrounding the rest of the site is generally flat to gently rolling with no more than 10 meters of relief within 800 m.

4. The elevation of the proposed site is approximately 3 m MSL.

7. Point Arena, CA

1. General location

This site is approximately 160 km north of San Fransisco on the Pacific sea coast. The nearest NWS station is at San Fransisco. There is also a NWS station at Eureka. Wind data are also available for the Point Arena Coast Guard station.

2. Specific location

38° 56' 40"N 123° 43' 00"W

3. Description of surrounding topography

This site is on a gently sloping (seaward) relatively flat area. The sea cliff is at least 275 m from the site. Vegetation is composed of grass with no trees within 300 m of the site.

4. Elevation of site

23 m MSL

8. Russell, KN

1. General location

Russell is in central Kansas which has a FAA weather station about 5 km NE of the site.

2. Specific location

38° 50' 50"N 98° 51' 25"W

3. Description of topography

The site is flat open farm land with no hills, gullies or prominences in the vicinity. Vegetation consists of wheat fields and grassland.

4. Sea level elevation

567 m MSL

9. San Gorgonio, CA

1. General location

This site is located approximately 65 km east of Riverside, just north of Interstate 10. The nearest NWS station is at Los Angeles. There is, however, data available from March AFB., at Riverside.

2. Specific location

33° 56' 10"N 116° 34' 33"W

3. The land in the immediate vicinity of this site is relatively flat sloping gently to the southeast. The site is on a horizontally widening plain about 10 km 'downwind' from San Gorgonio Pass and 455 m lower in elevation. The pass separates the San Jacinto Mountains to the south from the San Bernardino Mountains on the north. In both ranges there are mountain peaks exceeding 3000 m MSL and average 1500 to 2500 m on the ridge. The vegetation is native grass and salt brush, with no trees in the area.

4. Elevation of site

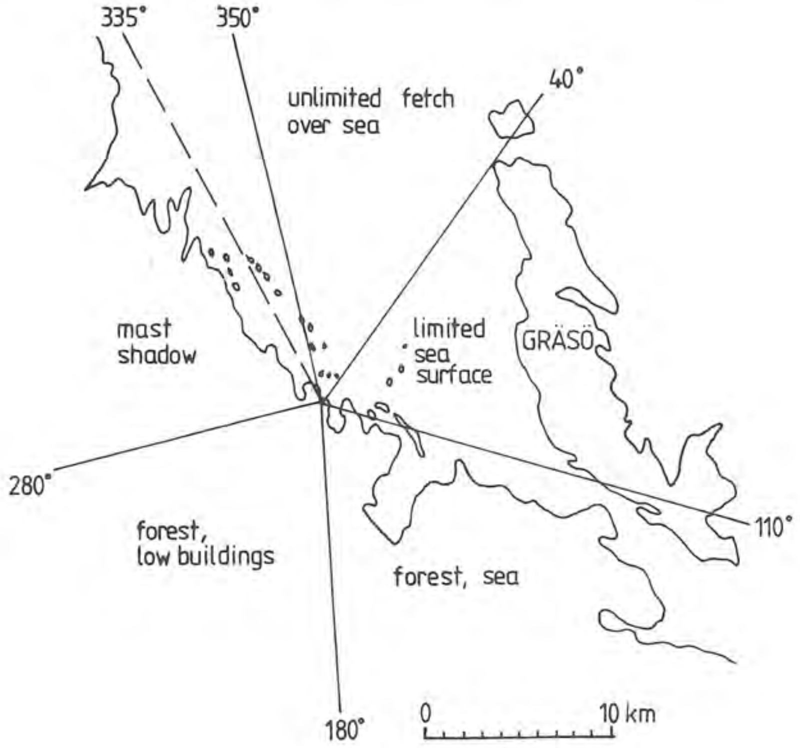
336 m MSL

2. Forsmark Nuclear Power Plant, Sweden

This location is situated at 62°N and 18°E on the Swedish east coast where the Gulf of Bothnia changes into the narrow Åland Sea. The map below shows the location of the mast in comparison to the surrounding terrain features.

The mast is situated about 75m from the shore in an opening in the forest. The lowest anemometer of 12m is located at the average tree top level. In order to make height truly comparable with other flat sites, height should be reduced by 15m to allow for zero-plane displacement.

Anemometers are only mounted on one side of the mast. In the sector 280°-350° the mast partly or completely shadows the anemometer with a corresponding reduction in the usefulness of the data in this sector.



Wind sectors around Forsmark.

Figure Mast location and Forsmark Nuclear Power Plant.

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ISSN 0347-2116