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L.C. Heijboer

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Koninklijk Nederlands Meteorologisch Instituut,
Meteorologisch Onderzoek,
Postbus 201,
3730 AE De Bilt,
Nederland.

U.D.C.: 551.509.322:
551.556.8

Some considerations about windpredictions over sea using a "limited area model" based on primitive equations

By L.C. Heijboer

1. Introduction

In the autumn of this year an extension of the current numerical system for the prediction of sea waves, swell and storm surges will become operational. The prognoses are based on wind forecasts computed with the aid of the formula of Hesselberg from pressure forecasts up to 24 hours ahead which are produced by a four level quasi-geostrophic model named BK4. The prognoses are produced four times a day. The grid distance of the numerical model is 187.5 km. Variable lateral boundary conditions are used provided by a hemispheric version of BK4 (grid distance 375 km) running twice a day till 36 hours ahead. This system is planned to be operational till about 1983.

After the operational introduction most of the research will be directed towards the development of a fine mesh limited area model based on primitive equations. It is hoped that such research ultimately will lead to better predictions of sea waves, swell and storm surges with forecast periods till about 24 hours ahead or even more.

Because the wave and set-up models use wind fields over sea as prime input the research will be mostly devoted to the prediction of better wind analyses and forecasts.

In this report some considerations are presented about probably important processes and the optimum use of the primitive equations with the hydrostatic assumption.

2. Atmospheric scales concerning the wind in the boundary layer.

Concerning the wind we firstly recognize that the atmosphere exhibits a very large variety of phenomena ranging from very short periods of about 1 second or less to periods of about several months or more, with wavelengths varying from less than 1 cm. to about 10.000 km.

Figure 1, which has been taken from the textbook of Dutton (1976), illustrates this.

For short range predictions the atmospheric turbulence, the meso-scale features and the weather systems are important. For the planetary waves it is sufficient that the forecasting model describes the quasi-stationary character of them. For filtered models this can be achieved by adding a so-called Cressman correction term to certain prognostic equations. Restricting ourselves to systems smaller than planetary scales the following table 1 gives an illustration of characteristic length and time scales and vertical velocities. U is a characteristic horizontal velocity (≈ 10 m/s).

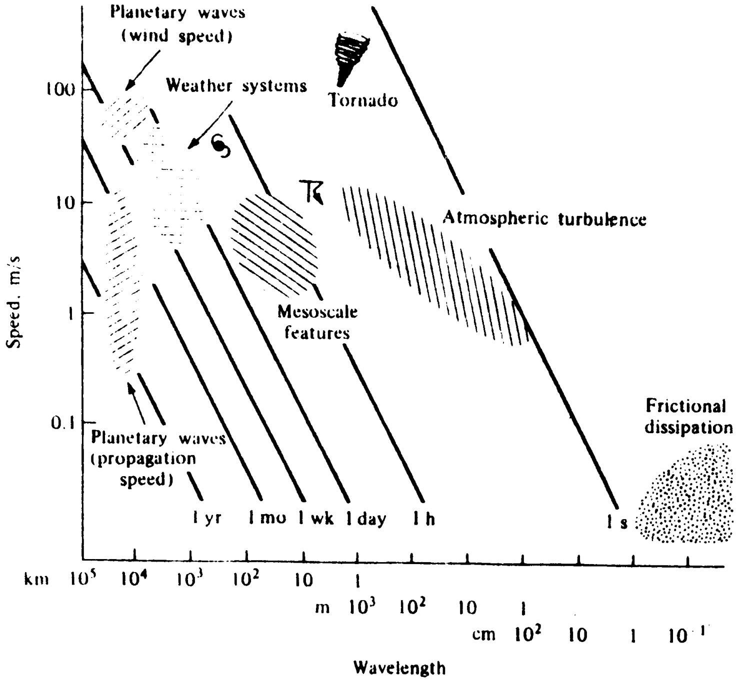
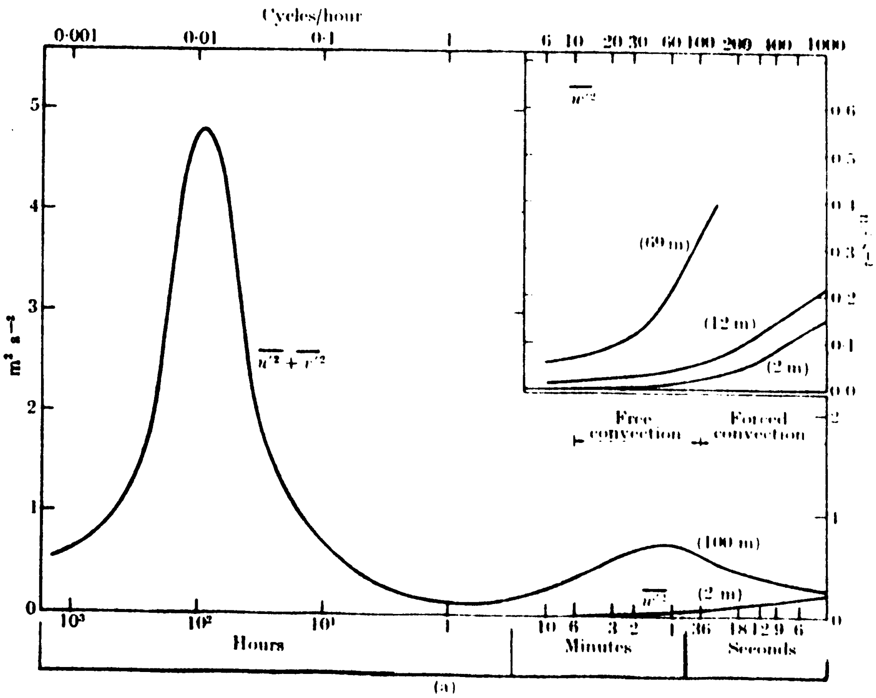


FIGURE 1.1
Scales of atmospheric phenomena. For many of these phenomena, it is possible to choose different length or speed scales, thus giving quite different time scales.

Fig. 1. (from Dutton "The ceaseless wind")



(a)

FIG. 2. (a) Smoothed power spectra of the horizontal wind speed at about 100 m height (following [27, 65, 110]) and of the vertical velocity at about 2 m, 12 m, and 69 m above the ground (following [11, 39]). The forced daily oscillation of the atmosphere has been omitted. The ordinates $\overline{u'^2} + \overline{v'^2}$ and $\overline{w'^2}$ represent respectively the variance of the horizontal wind (u, v) and of the vertical wind w as a function of period τ or frequency τ^{-1} (logarithmic scale).

Fig. 2. (from van Mieghem "Atmospheric Energetics")

system	time scale T	length scale L	vertical velocity W		
(I) large scale: baroclinic long waves	~1 day	~1000 km	~1 cm/s	$W \ll U$	hydro-static
baroclinic short frontal waves	~12 hours	~500 km	~10 cm/s	$W \ll U$	hydro-static
(II) intermediate scale: mesoscale features (fronts, squall lines etc.)	several hours	~10- ~100 km	~10- ~100 cm/s	$W < U$	hydro-static
(III) small scale: atmospheric turbulence	~ seconds- several minutes	~cm- ~1 km	$W \approx U$		non-hydro-static .

Table 1

In order to make reliable wind forecasts at sea level for the computations of sea waves, swell and storm surges, which gain their energy from the kinetic energy of the horizontal motion, it is important to know how the kinetic energy is distributed among the periods or scales. According to Van Mieghem (1973) a gap exists in the power spectrum for periods of roughly 1 hour and an eddy size of the order of 10 km. On both sides of this very flat minimum there exists a maximum occurring at a period of 1 minute and a maximum at a period of 4 days. The latter peak is mainly due to the transient synoptic weather systems and therefore depends largely upon baroclinic instability. See also figure 2 which has been taken from the textbook of Van Mieghem.

Prediction models based on primitive equations with the hydrostatic assumption cannot predict the time-evolution of the small scales. So these scales have to be ignored and their influence on the larger scales has to be parameterized in terms of those ones.

Neglect of the smallest scales introduces an error in the forecast wind. It is probably not known how the quality of the sea waves, swell and set up computations is influenced by that error.

So the use of the hydrostatic assumption forces us to restrict ourselves to the intermediate and large scales for making wind predictions. Therefore, the equations are averaged in time. According to Van Mieghem (see figure 2) and appropriate averaging period seems to be 10 minutes. Now the equation of horizontal motion near the surface can be written as:

$$\frac{d\vec{V}}{dt} + f\,\vec{k}\times\vec{V} = \vec{G} + \vec{F} \tag{1}$$

With $\vec{G} = -\alpha\nabla p$ the gradiënt force per unit mass,

$f\,\vec{k}\times\vec{V}$ = the Coriolis force per unit mass,

$f = 2\Omega \sin \varphi$,

Ω = the angular velocity of the earth,

φ = latitude,

α = specific volume of air,

$F = -\alpha \frac{\partial}{\partial z} \vec{\tau}_z$ the friction force per unit mass caused by the turbulent fluctuations of the small scales and

$\vec{\tau}_z$ = the horizontal component of the Reynolds stress.

$\vec{k}$ = unit vector in the vertical

It is difficult if not impossible to answer the question at what height above sea level equation (1) should be applied in order to yield reliable winds for sea wave growth and storm surges. To circumvent this question here we shall adopt the international agreement of taking 10 m height.

3. Difference between large scales and intermediate scales.

It can be shown that the instantaneous windfield, corresponding to atmospheric scales with Rossby number R_o<1, is entirely determined by the pressure and friction forces or by $\vec{G}$ alone if $\vec{F}$ is parameterized in terms of $\vec{G}$ and $\vec{V}$. For that purpose equation (1) is rewritten as:

$$\vec{V} = f^{-1}\,(\vec{G}+\vec{F}-\frac{d\vec{V}}{dt})\times\vec{k} \tag{2}$$

Substituting (1) after taking the time derivative for $\frac{d\vec{V}}{dt}$ into (2) gives:

$$\vec{V}=f^{-1}(\vec{G}+\vec{F})x\vec{k} + f^{-2}\frac{d}{dt}(\vec{G}+\vec{F}) - f^{-2}\frac{d^2}{dt^2}\vec{V} \quad (3)$$

From (2) follows after taking the n^{th} derivative:

$$\frac{d^n\vec{V}}{dt^n} = f^{-1}\left[\frac{d^n}{dt^n}(\vec{G}+\vec{F}) - f^{-1}\frac{d^{n+1}}{dt^{n+1}}\vec{V}\right]x\vec{k} \quad (4)$$

Repeating the process ultimately leads to the series:

$$\vec{V}=\vec{V}_{ls} - f^{-1}\frac{d\vec{V}_{ls}}{dt}x\vec{k} - f^{-2}\frac{d^2\vec{V}_{ls}}{dt^2} + f^{-3}\frac{d^3\vec{V}_{ls}}{dt^3}x\vec{k} + f^{-4}\frac{d^4\vec{V}_{ls}}{dt^4} \ldots\ldots \quad (5)$$

$$\ldots\ldots -(-1)^n f^{-(2n-2)}\frac{d^{2n-2}\vec{V}_{ls}}{dt^{2n-2}} + (-1)^n f^{-(2n-1)}\frac{d^{2n-1}\vec{V}_{ls}}{dt^{2n-1}}x\vec{k} + (-1)^n f^{-(2n)}\frac{d^{2n}\vec{V}}{dt^{2n}}$$

with $n > 1$ and $\vec{V}_{ls} \equiv f^{-1}(\vec{G}+\vec{F})x\vec{k}$. To keep the mathematics simple the total time derivative of f and $\vec{k}$ have been neglected. It can be shown with scale analysis that it does not significantly alter the results. ls represents the abbreviation of large scale.
$\vec{V}_{ls}$ is the wind caused by gradient and friction forces alone.
Using scale analysis the absolute magnitudes of the terms of the series (5) are estimated. Therefore we introduce a characteristic windspeed U, time T and length-scale L with

$$U\equiv|\vec{V}_{ls}| \quad \text{and} \quad L\equiv U.T \quad (6)$$

Assuming that

$$\left|\frac{d^n\vec{V}_{ls}}{dt^n}\right| \approx \frac{U}{T^n} = \frac{U^{n+1}}{L^n} \quad \text{and} \quad \left|\frac{d^n\vec{V}}{dt^n}\right| \approx \frac{V}{T^n} = \frac{V\,.U^n}{L^n} \quad (7)$$

The series converges for

$$Ro\equiv \frac{U}{f.L} < 1 \quad (8)$$

Taking U=10 m/s and $f=10^{-4}s^{-1}$
then $L=U/f \approx 10^5$m or 100 km (wavelength ∿4L=400 km) and
$T=L/U \approx 10^4$s or 3 hours (period ∿4T=12 hours).
This result was already obtained in a different way by Hesselberg (1915).
It follows immediately from figure 1 that a wavelength of 400 km and a period of 12 hours separate the weather systems from the mesoscale features. Obviously that division occurs for a Rossby number ≈1.

Let us restrict ourselves to the large scale systems for the moment and look at the magnitudes of the first four terms of the series (5) which are given in table 2.

system	length scale L	1st term	2nd term	3rd term	4th term
short frontal waves	∿500 km	∿10 m/s	∿2 m/s	∿0.4 m/s	∿0.08 m/s
long baroclinic waves	∿1000 km	∿10 m/s	∿1 m/s	∿0.1 m/s	∿0.01 m/s
planetary waves	∿10000 km	∿10 m/s	∿0.1 m/s	∿0.01 m/s	∿0.001 m/s

Table 2

Retaining the first term only, the resulting errors are presented in table 3.

	1st term (retained) wind determined by gradient and frictional forces	2nd term (retained) isallobaric and curvature terms
short frontal waves	∿20%	∿5%
long baroclinic waves	∿10%	∿1%
planetary waves	∿ 1%	∿0.1%

Table 3

Resulting errors % for large scale systems omitting higher order terms of series (5).

The foregoing analysis indicates that it is permitted to split the horizontal wind $\vec{V}$ into two parts namely

$$\vec{V}=\vec{V}_{synoptic}+\vec{V}_{mesoscale} \qquad (9)$$

where $\vec{V}_{synoptic}$ is the part due to the large scale systems which can be computed with the convergent series (5) and the rest $\vec{V}_{mesoscale}$ is ascribed to the mesoscale features such as fronts, squall lines etc. Scale analysis suggests that $\vec{V}_{synoptic}$ can be approximated with sufficient accuracy by the first two terms of the series.

4. Mesoscale features

It is clear that prediction models based on filtered equations where the wind field is entirely determined by the pressure field cannot really predict the evolution of the mesoscale features. Regarding the frontogenesis for instance a filtered model such as BK4, which is a quasi-geostrophic four level model, can concentrate a small preexisting temperature gradient in case of a confluent flow as far as the horizontal scale is larger than 100 km. See also Holton (1972, page 204). Advection of the gross features of fronts is also possible. A fully developed front however cannot be predicted. Prediction models based on the primitive equations with the hydrostatic assumption are capable of describing the time behaviour of fronts in more detail except for the small scale features having scales <10 km which are non-hydrostatic. To achieve that the following conditions have to be fulfilled:

1. The horizontal grid distance of the model must be <100 km.
2. High vertical resolution (10 levels or more?).
3. The mesoscale features (fronts) which have to be predicted must be present already in the initial analysis. With respect to the windfield this means that the initial windfield must consists of real windanalyses in stead of balanced winds determined from the pressure field.

The posed conditions imply an observational network at sea level as well as for the upper air which is sufficiently dense to describe frontal characteristics with scales ranging from ∿10-∿100 km. It is probably possible that over sea the current observational network is not dense enough for that purpose.

Further investigations can possibly give a further insight in that difficult problem.

5. Synoptic weather systems and the formula of Hesselberg

It follows from figure 2 that most of the wind energy is concentrated in the weather systems. The maximum occurs at a period of about 4 days. For such systems the instantaneous windfield is entirely determined by the pressure field. Their behaviour in time can be described both by the filtered equations and the primitive equations.

Before discussing the windpredictions let us see how well analysed winds compare with winds computed with the formula of Hesselberg. At the Royal Netherlands Meteorological Institute such wind computations are made using three hourly pressure analyses at sea level. They are used as input for sea wave, swell and water set-up computations. The formula of Hesselberg written out in detail reads:

$$\vec{V}=f^{-1}(\vec{G}+\vec{F})x\vec{k} + f^{-2}\left[\frac{\partial}{\partial t}(\vec{G}+\vec{F})+(V.\nabla)(\vec{G}+\vec{F})\right] \tag{10}$$

According to Hesselberg the friction force $\vec{F}$ has been parameterized as

$|\vec{F}| = b|\vec{V}|$ where $\vec{F}$ and $-\vec{V}$ deviate an angle β from each other. See figure 3. The angle β stems from the fact that in general the wind veers with height so that the direction of $\vec{F}=-\alpha \frac{\partial \vec{\tau}_z}{\partial z}$ is different from that of $\vec{\tau}_z$.

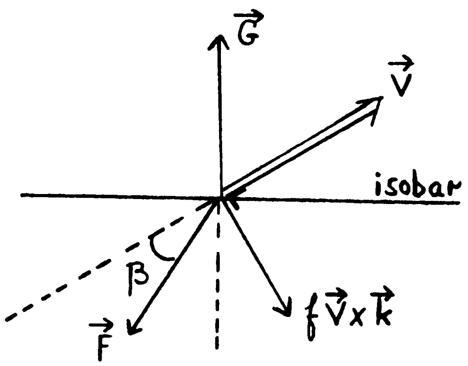


Fig.3

According to Bijvoet (1957) it appears that over sea the angle β is nearly constant and that the proportionality factor b in principal depends on the difference between the air temperature and the sea surface temperature. That difference largely determines the stability of the air. The more stable the air the more b increases.

The wind $\vec{V}$ is computed from (10) by using pressure analyses which are represented by an incomplete Fourier series. The analysis programme has been developed by Kuipers (to be published). Using the formula of Hesselberg the following sources of errors must be taken into account.

1. The approximation of the formula itself with respect to (5). We have already seen in table 3 that the error is greatest for the short frontal waves and amounts to ∿5%.

2. Truncation errors made in the computations of the first and second order derivatives of the pressure. Due to the fact that the analyses are given by an analytical expression they are zero for the spatial derivatives. The time derivatives are estimated by taking three hourly differences between two subsequent analyses. We have seen that for the weather systems the time scales are >3 hours. So three hourly differences seem suitable for taking smaller time intervals the pressure fluctuations caused by the mesoscale features will probably spoil the results. If it turns out that nevertheless the use of three hourly differences gives too large truncation errors then a possible way is to use pressure tendencies which are computed from filtered models for instance BK4 or from PE-models after removing the mesoscale fluctuations.

3. The parameterization of the friction $\vec{F}$. This is a rather crude procedure. Perhaps taking a quadratic dependence of $\vec{F}$ on $\vec{V}$ would be more suitable. A further investigation into the parametrization of $\vec{F}$ especially concerning the problems near the coast is perhaps necessary.

4. Uncertainty in the pressure analyses themselves. That kind of error largely depends on the density of surface observations of pressure and wind. In the analysis programme the winds over sea are incorporated geostrophically with a friction reduction. Over land they are not taken into account. That means that over sea at a point of observation the pressure gradient is largely geostrophically approximated by the real wind. So according to table 3 for the short frontal waves an error of ∿20% can be possible.

In tables 4 and 5 which are contingency tables the computed wind speeds from (10) are compared with real wind observations averaged over 10 minutes intervals at 10 m heights. Table 4 is valid for a position at the North Sea near Texel (Platform K13, 53.2°N and 3.2°E) and table 5 for weathership M (66.0°N and 2.0°E). Indeed the tables show that the errors are larger than the formula of Hesselberg suggests. Apart from the sources of error already mentioned another source is the observational error and the fact that the use of mean values over 10 minutes allows mesoscale features in the wind data. It has been shown by Timmerman (1977) that near the island of Texel the observational errors and the differences between the computed wind with the formula of Hesselberg and the average over 10 minutes of the real wind are of the same order of magnitude with a standard deviation of about 4 kts. Table 4 shows that the differences between computed and observed winds are of comparable magnitude. So observational errors and mesoscale features are probably the greatest sources of error at the North Sea near Texel. However this does not hold for weathership M.

The fact that the computed winds at K13 are more accurate than those at weathership M can be attributed to a greater accuracy of the pressure analyses at platform K13. The same features as for the computed winds are shown by the contingency tables of the computed significant wave heights compared with the real wave observations. These wave heights have been computed with the operational wave program named "GONO" which has been developed by Sanders (1976 and 1979). It is shown by tables 6 and 7 that the relatively large deviations in the calculated winds are also revealed in the computed significant sea wave heights. The deviations at M are also larger than at K13.

The foregoing considerations suggest that for the Norwegian Sea and for the Northern part of the North Sea the wind computations can be improved by analysing the pressure field more accurately. For the Southern part of the North Sea this does not hold and further improvement can only be expected by analysing the windfield itself. That opens the possibility to take fully into account the measured wind at the observation point.

The problem is to construct good guess fields over sea. Two approaches would be possible:

1. Updating with the wind prognoses of the primitive equation model itself. This has the advantage of taking into account properly predicted mesoscale features in the guess field in data sparse areas.

(kts) → Comp. / ↓Obs.	0-6	7-16	17-21	22-27	28-33	34-40	41-47	
0-6	18	24						42
7-16	19	110	23	7				159
17-21		14	33	31	2			80
22-27			8	25	20	6		59
28-33				1	1	4	6	12
34-40						1	2	3
41-47							1	1
	37	148	64	64	23	11	9	356

Table 4
Platform 53.2°N-3.2°E (North Sea)
Dec'77, Jan'78, Febr'78
Computed windspeed(kts) with the formula of Hesselberg compared with real observations.

(kts) → Comp. / ↓Obs.	0-6	7-16	17-21	22-27	28-33	34-40	41-47	48-55	56-63	
0-6	4	11	2	1						18
7-16	5	56	19	11	3					94
17-21	2	33	23	14	5	2	1			80
22-27		10	19	21	8	1	1		1	61
28-33		6	17	13	10	13	6	1		66
34-40		2	2	3	8	5	2			22
41-47			1	1	1	1	1	1		6
	11	118	83	64	35	22	11	2	1	347

Table 5 as for table 4 except for:
Weathership M (Norwegean Sea)
66.0°N-2.0°E

H_s(m) → Comp. / ↓Obs. H_s (m) ↓	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	
0-1	30	1								31
1-2	80	83	16	1						180
2-3	3	41	46	7	4					101
3-4		1	10	19	6	1				37
4-5				5	2					7
5-6					2	1				3
6-7						1				1
7-8										
	113	126	72	32	14	3				360

Table 6
Computed significant sea wave heights with "GONO" compared with observations for Platform 53.2°N-3.2°E (North Sea) Dec'77, Jan'78, Febr'78.

H_s(m) → Comp. / ↓Obs. H_s (m) ↓	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	
0-1	18	1								19
1-2	16	18	5	1	1					41
2-3	18	41	28	7	3	1				98
3-4	6	25	37	21	9	4		1	1	104
4-5	1	10	12	20	8	5	6	2		64
6-7			2	1	7	1	3	1	1	16
7-8				1	2	1		2		6
8-9			2							2
	59	95	86	51	30	12	9	6	2	350

Table 7 as for table 6 except for:
Weathership M (Norwegean Sea)
66.0°N-2.0°E

A disadvantage is that false predicted mesoscale features are also possible.

2. Computing the winds from the guess field with the formula of Hesselberg using the analysed pressure field of which the guess field can be delivered by either a primitive equation model or a filtered model. This second possibility has the advantage of removing erroneously predicted mesoscale features by the primitive equations if used for updating.

Concerning the time interval of updating it follows from the time scales of the mesoscale systems (<3 hours) that hourly updating could be necessary in stead of the currently used 3 hourly updating.

6. Wind prognoses for synoptic weather systems.

For primitive equations models wind prognoses can be achieved as follows:

1. Computing the wind from the predicted pressure fields with the formula of Hesselberg.
2. Taking the predicted wind itself which is directly computed by the model with equation (1).

For filtered models only the first possibility remains. This method is presently used at the Royal Netherlands Meteorological Institute to make wind predictions 24 hours in advance with the aid of a four level quasi-geostrophic model named BK4. These forecasts are made every six hours and they are used as input for sea wave, swell and storm surge predictions.

To investigate the capability of the filtered model BK4 and of models based on primitive equations concerning wind predictions with the aid of the formula of Hesselberg the direction and strength of the forecast pressure gradients for periods up to 24 hours ahead were verified for the period 1 december 1976 till 30 november 1978. These verifications were carried out for the BK4-model, for the prognoses of the 10-layer model received from Bracknell and for the 24 hours surface pressure prognoses from Washington. During the same period two versions of the wave prediction model GONO ran parallel, namely one version based on BK4-predictions and another one based on the 10-layer model predictions from Bracknell. It turned out that for forecasting periods till 12 hours ahead for both systems there were no significant differences between forecasts of the pressure gradients as well as forecasts of the significant wave heights. For forecasting periods 24 hours ahead the pressure gradients from the American model as well as those from the 10 layer model were better. However, the differences between the filtered model and the two models based on primitive equations did not lead to large differences in the predicted wave heights. Only in the winter season the latter were slightly better.

The above mentioned results indicate that using a coarse resolution and the formula of Hesselberg for the windcomputations the full capability of a primitive equation model will not be utilized as far as short range forecasts till 24 hours ahead are considered. For forecasts going further in advance e.g. till 48 hours with the same resolution PE models will give better results over filtered models because they are physically more complete.

7. Initialisation.

Using filtered models there are no initialisation problems. For primitive equation models the initialisation problem consists of removing the components of erroneous gravity waves of which the time behaviour can be described by the model. Two possibilities exist, namely to balance the wind field with the pressure field or to filter out the unwanted gravity waves from the windanalyses using the so called "normal mode initialisation".

For the description of the time behaviour of mesoscale features only the latter possibility remains because using the balancing method these features are removed.

8. General conclusions.

For short range forecasts till 24 hours ahead better windpredictions could be achieved if the primitive equations were optimally used. Therefore the following conditions are probably necessary:

1. horizontal grid distance has to be <100 km.
2. high vertical resolution.
3. the use of real wind analyses as initial conditions.
4. the use of "normal mode" initialization.
5. hourly updating of the analyses in stead of three hourly time intervals to describe the behaviour of mesoscale ystems (fronts).

6. the use of all available surface and upper-air observations especially wind observations.
7. careful parametrization of atmospheric turbulence especially in the boundary layer with regard to the friction.

For forecast periods more than 24 hours ahead, with the same resolution, predictions based on primitive equations will be more accurate than those based on filtered equations.

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