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A guide to the Nedwam wave model

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ABSTRACT

Nedwam is a numerical model for making North Sea wave forecasts. The Nedwam software is a KNMI product. The model physics of Nedwam is the same as that of the global wave model WAM. WAM has been developed by an international group of wave modellers, including people from the KNMI. Nedwam models the evolution of the two-dimensional wave-variance spectrum at each point of a stereographic grid which covers the North Sea and a large part of the Norwegian sea. The geographic grid contains 612 gridpoints. The grid spacing is approximately 75 km. The wave-variance spectrum is defined on a wave-vector grid of 25 frequencies by 12 directions.

The various terms in the central equation of wave physics have direct counterparts in the Nedwam model. Therefore, it will be relatively easy to change Nedwam if better representations for the various terms in this equation become available or if one wants to include data assimilation. As the total number of model variables is rather large, 612x25x12= 183600, the Nedwam model requires much more computer time and memory than previous KNMI wave models. On the other hand, it produces more detailed information, as in principle the full 2-D wave spectrum is available for all times and places. One can ask for *e.g.* the significant wave heights, the peak periods, the wave directions and the spectra at any grid point.

The first four chapters of this guide give a comprehensive description of the Nedwam wave model. The basic equation for the evolution of the wave spectrum is discussed and all the formulae which are used by the numerical model are given explicitly. The fifth chapter treats the Nedwam computer program and its implementation at the KNMI.

Contents

1 Introduction

In 1984, the SWAMP [1984] study revealed a number of basic shortcomings in all ocean wave models of that time. This has prompted a large international group of scientists, including G.J. Komen and P.A.E.M. Janssen from KNMI, to start to work on a better kind of model. They became known as the WAM (WAve Modelling) Group. The model which they have developed uses a radically new approach for ocean wave forecasting models. Every single wave component is a separate degree of freedom. Different wave components are coupled by a wave-wave interaction source function. Before 1985, algorithms to calculate good approximations to the wave-wave interaction for arbitrary wave spectra were too slow to be used in an operational forecast model. The breakthrough came from Hasselmann et al. [1985b] who proposed a very efficient method to approximate the wave-wave interactions. This opened the way to the development of the WAM model. Usually, models of the WAM type are called "third generation wave models". The WAM group has implemented and maintained a global wave model ("the" WAM model [WAMDI group, 1988]) at the ECMWF which runs on a day to day basis.

The wave model Nedwam ("*NEDerlands* WAve Model") is a North Sea version of this global WAM model. Nedwam uses the same grid as the KNMI wave model GONO. This is a stereographic grid which covers the North Sea and a part of the NE Atlantic up to 75^{0}N. The grid spacing at 60^{0}N is 75 km. The number of grid points is 612. The purpose of Nedwam is to give good wave forecasts for the North Sea. The Northern part of the grid is only included in order to handle properly cases where swell enters the North Sea from the North West. Of course, waves coming from the Atlantic into the Norwegian Sea can not be represented very well by Nedwam. In the Southern North Sea, a grid spacing of 75 km is rather large compared to the length scales of the coastline. In particular, the Nedwam Channel is far too wide. Therefore, if the winds come from the South or South-West, the Nedwam forecasts will be less reliable close to the Dutch coast, in particular for the longer waves (E_{10}).

Nedwam models the evolution of the wave-variance spectrum. The model calculates 300 components (12 directions times 25 frequencies) of the wave spectrum at each grid point. Nedwam uses a 30 minute time step for the propagation of wave-spectrum components and a 15 minute time step for the generation and decay of wave-spectrum components.

The first four chapters of this guide form a comprehensive description of the Nedwam model. References to the literature are given. The precise definition of the GONO grid, and some of its properties can be found in chapter 2. In chapter 3, the energy-balance equation which governs the evolution of the wave variance spectrum is given, and the various source terms which appear in this equation are discussed. The numerical model is based on a discretization of the energy balance equation. The discretization procedure is discussed in full detail in chapter 4, where all the formulae can be found which are used by the Nedwam model.

Chapter 5, the last chapter of this guide, is on the Nedwam computer program. The program is a realisation of the numerical model of the preceding chapter. The set-up, the I/O and the structure of the program are discussed here, as well as the implementation of the program in the operational environment of the KNMI.

2 The stereographic GONO grid

Nedwam uses the same stereographic grid as the KNMI wave forecasting model GONO. The precise definition of the GONO grid used by Nedwam is given in this section. Also some properties of stereographic projections are discussed, and it is discussed how close the metric of the GONO grid is to an Euclidean metric.

2.1 Stereographic projections

One of the ways to map part of the surface of a sphere to a part of the plane is to use a stereographic projection. The stereographic projection maps the sphere minus one point to the plane. In the following we shall always take this point to be the South Pole of the sphere.

The construction of a stereographic projection from the South Pole proceeds as follows. Take the plane tangent to the North Pole of the sphere, or any other plane parallel to the equator of the sphere. In the sequel, this plane will be called the stereographic plane. Then the image of a point on the sphere is the intersection of the straight line from the South Pole through the point on the sphere with the stereographic plane.

The stereographic projection has the following properties. The projection is angle preserving, that is the angle between two intersecting lines on the sphere is the same as the angle between the images of the intersecting lines on the stereographic plane. The South pole is mapped to infinity in the stereographic plane. Circles on the sphere which do not pass through the South Pole are mapped on circles in the stereographic plane and vice versa. However, the centre of a circle on the sphere is in general not mapped on the plane to the centre of the image of the circle. Straight lines on the stereographic plane correspond to circles which go through the South Pole on the sphere. In particular, meridians are mapped on straight lines on the stereographic plane. The equator on the sphere is a great circle. Any other great circle intersects the equator at two points which are located opposite each other. The images of great circles on the stereographic plane have the same property. The projection is not area conserving, that is the ratio between the length of a line element on the sphere and the length of its image varies with latitude. However, this ratio is independent of the direction of the line element. In the case that the stereographic plane is tangent to the North Pole, the ratio is given by

$$\frac{d\ell_{sphere}}{d\ell_{plane}} = \cos^2(\frac{\pi}{4} - \frac{\phi}{2}), \tag{1}$$

where ϕ denotes the latitude (positive for the Northern hemisphere, negative for the Southern). Note that the more southern one goes, the larger the area distortion becomes.

2.2 Definition and description of the GONO grid

The *GONO coordinates* x and y are defined as follows in terms of latitudes ϕ (positive for the Northern hemisphere, negative for the Southern) and longitudes ψ (positive for the Eastern hemisphere, negative for the Western) by the implicit equations:

$$\psi = \arctan\left(\frac{x + 1.45}{56.6 - y}\right) - \arctan\left(\frac{11.45}{56.6}\right) \tag{2}$$

$$\phi = \frac{\pi}{2} - 2\arctan\frac{\sqrt{(x + 1.45)^2 + (y - 56.6)^2}}{(1 + 1/2\sqrt{3})6370/75}\,. \tag{3}$$

Distances between GONO coordinates are expressed in grid units. The above definition of the GONO coordinates is the one used by the present version of Nedwam. Other definitions, with slightly different values of the parameters, have been used in the past, which may lead to differences of the order of tens of kilometers for positions in the North Sea.

The *proper GONO grid* is the area

$$1 \leq x \leq 17\,,\;\; 1 \leq y \leq 36\,. \tag{4}$$

Depending on the context, the term "GONO grid" refers either to the proper GONO grid, or to the infinite (x, y) plane.

GONO *gridpoints* are points with integer GONO coordinates (i, j). The GONO grid has $17 \times 36 = 612$ gridpoints. The GONO gridpoints of the GONO grid constitute the discrete space of Nedwam. Of course, Nedwam needs to know the difference between land and sea, so two kinds of gridpoints exist, *seapoints* and *landpoints*. Moreover, a depth has been assigned to every gridpoint. Because in deep water the value of the depth is irrelevant for waves, the depth has been set to $200m$ at all deep-water points. The depth of the landpoints is undefined.

A map of the GONO grid is given in *fig. 1.* The grid has been designed by J.W. Sanders

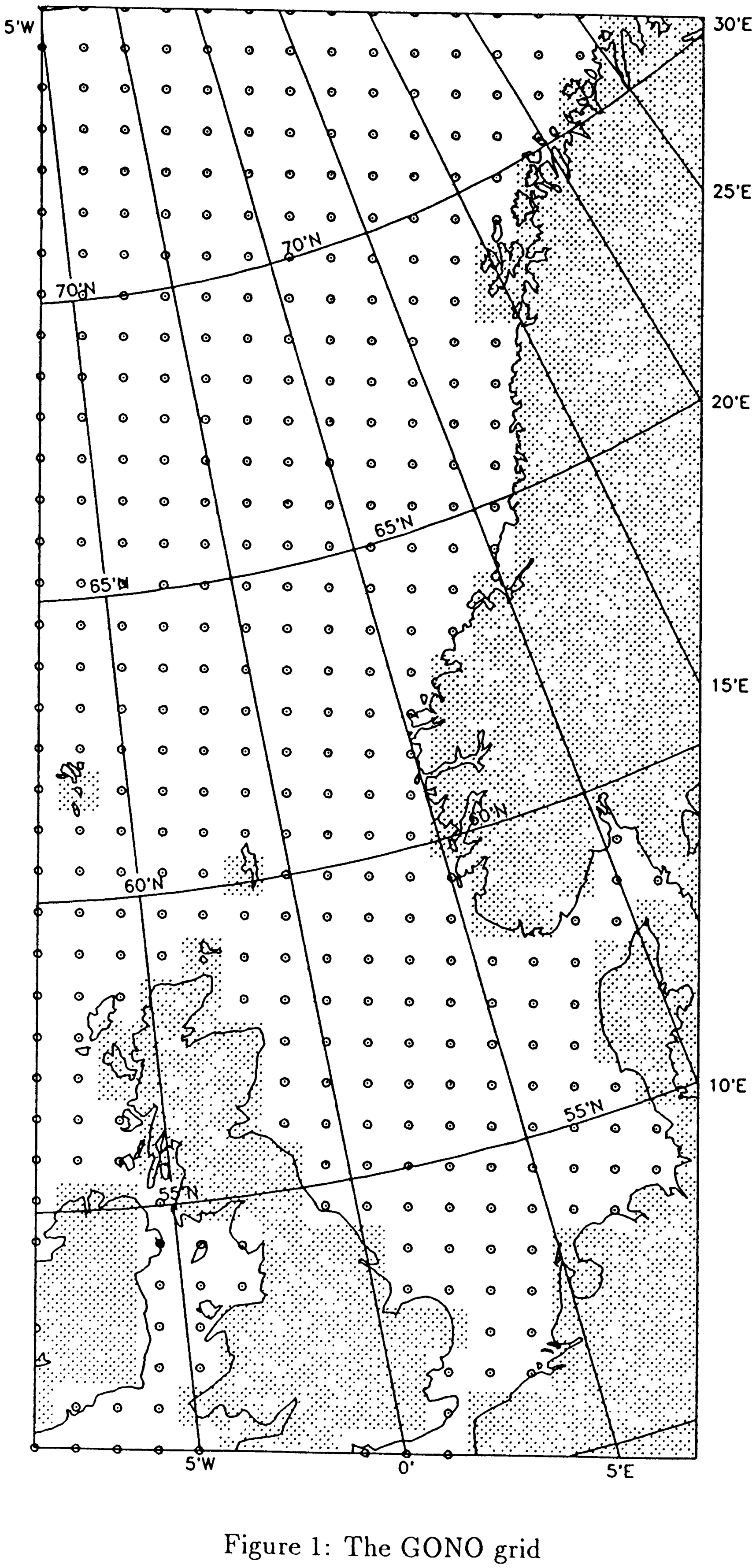


Figure 1: The GONO grid

[1976]. The area covered has been made large enough to make possible good wave forecasts for the central and southern North Sea. Swell can come into the North Sea from the North West, this is the reason why the area West of Norway is included in the GONO grid. Note that the grid resolution is too low to represent the geographic features of the Southern North Sea well. In particular, the Thames estuary and the Channel have been merged.

Formulae (2), (3) for the GONO coordinates correspond to a stereographic projection from a sphere with the following properties:

The coordinates of the North Pole are $(x, y) = (-1.45, 56.6)$.

The x-direction of the proper GONO grid goes roughly from West to East, the y-direction from South to North.

The point $(10, 1)$ has zero longitude, $\psi(10, 1) = 0$.

The meridian of 11.64^0 W runs parallel to the y-axis of the GONO grid.

The tilt angle δ, defined as the angle between the true North and the positive GONO y-axis, measured clockwise from the true North, depends on the position (x, y) and is given by

$$\delta = \arctan \frac{x + 1.45}{56.6 - y} . \tag{5}$$

The equator is $(1 + 1/2\sqrt{3})6370/75$ grid units from the North Pole. If one approximates the earth by a perfect sphere with a radius of 6370 km and takes the plane which cuts the earth at the 60^0N parallel as the stereographic plane, then a distance of 75 km on the earth corresponds to one grid unit on the stereographic plane.

If one approximates the earth by a perfect sphere of radius $R = 6370$km, then the scaling factor $s = d\ell_{earth}/d\ell_{GONO}$ between the length (in km) of a line element on the earth $d\ell_{earth}$ and the length (in grid units) of the corresponding line element on the GONO grid $d\ell_{GONO}$ is given by

$$s = \frac{2(1 + \frac{1}{2}\sqrt{3})(6370/75)^2}{(1 + \frac{1}{2}\sqrt{3})^2(6370/75)^2 + (x + 1.45)^2 + (56.6 - y)^2} \, 75\text{km/gridunit} . \tag{6}$$

The right hand side of the above equation reduces to 75 km/gridunit if $\phi(x, y) = 60^0$N.

Name	i	j	Latitude (degrees)	Longitude (degrees)	Depth (m)	Tilt angle (degrees)	Scaling factor (km/gridunit)
SW Corner	1	1	51.30	-9.11	100	2.52	71.56
SE Corner	17	1	49.43	6.72	0	18.36	70.72
NW Corner	1	36	75.09	-4.85	200	6.78	79.03
NE Corner	17	36	70.20	30.21	0	41.85	78.01
EURO	13	4	51.98	3.72	25	15.36	71.87
IJMUIDEN	13	5	52.60	4.01	25	15.64	72.14
K13	12	6	53.40	3.25	25	14.89	72.48
AUK	10	10	56.28	2.17	80	13.80	73.63
BRENT	8	17	61.16	1.79	200	13.42	75.41
MIKE	7	24	65.98	2.89	200	14.53	76.91

Table 1: Parameters of a few GONO grid points

The last properties are often referred to as " The GONO grid is a stereographic projection at 60^0N with a grid spacing of 75 km". The $1 + 1/2\sqrt{3}$ in the above formulae corresponds to the distance from the South Pole to the plane of the stereographic projection in earth radius units.

In Table 1 the latitudes and longitudes, the depths, the tilt angles and the scaling factors of some of the GONO grid points are listed. The mnemonic names, EURO,AUK,... given to some of the gridpoints, come from the names of observation stations close to them.

The gridpoints (i, j) with $i = 1, \ldots, 17$ and $j = 1, \ldots, 36$ have a consecutive numbering $ij = 1 \ldots, 612$ from the South West corner to the North East corner which is given by

$$ij = i + (j - 1) \times 17 \qquad (7)$$

Nedwam also uses an *extended grid* which covers the GONO grid plus a strip of one grid unit around it:

$$0 \leq x \leq 18, \quad 0 \leq y \leq 37 . \qquad (8)$$

The grid points in the extended grid are also numbered from the South West corner to the North Eeast corner, $\ell = 1 \ldots, 722$. The relation between the extended grid index ℓ and the GONO indices (i, j) of a gridpoint is

$$\ell = 1 + i + 19 \times j . \qquad (9)$$

2.3 The metric of the GONO grid

Free waves propagate along geodesics. Here "free" means the situation where are no sources, currents or depth variations to influence the waves. By definition, the shortest path between two points follows a geodesic. On the surface of the earth the geodesics are the great circles. The direction of the wave vector of the wave is constant in the sense that it stays parallel to the great circle, it is "parallel transported". Its direction with respect to the true North is not constant, of course. A narrow banded free wave train has a constant velocity and has a constant spatial extent. As mentioned in section 2.1, great circles are mapped on circles in the stereographic plane wich intersect the image of the equator at opposite positions. Let us call these circles in the stereographic plane again great circles.

Free waves travel along these great circles in the stereographic plane. The direction of the wave stays parallel to the circle. But the speed c' of a narrow banded wave train in grid units per time unit is not constant because of the scaling factor $s(\mathbf{x})$. It is the speed $c = s(\mathbf{x})c'$ on the surface of the earth which is constant. Moreover, the spatial extent of a narrow banded wave train in grid units is not constant, because the ratio $s(\mathbf{x})$ between the length of a line element on the earth and the length of the corresponding line element on the stereographic plane is not constant.

Nedwam corrects the wave speed in grid units for the space dependence of the scaling factor $s(\mathbf{x})$. So the mean position of a wave train is propagated correctly. But free waves in Nedwam propagate along straight lines in the grid instead of along great circles, and Nedwam also neglects the variation in the ratio of the lenghts of the line elements of the sphere and the plane due to the scaling factor.

The relative change in the spatial extent of a wave train is equal to minus the relative change in the scaling factor $s(\mathbf{x})$. The relative change in $s(\mathbf{x})$ is less than 0.5% per grid unit, as one can see from Table 1. This seems quite acceptable: as we shall see in Chapter 3, the relevant quantity is the wave variance spectrum F, and structures in the wave variance spectrum F, which propagate like wave trains, have usually a length of less than some 20 grid units, corresponding to a change of 10% per grid unit or more.

The great circle which goes through the point (x, y) in the direction θ with respect to the North has a radius, in grid units, of

$$R = \frac{1}{\cos(\pi/2-\theta)}\frac{1}{2}\left(\frac{r}{a}+\frac{a}{r}\right)r \tag{10}$$

with $r = (1+1/2\sqrt{3})6370/75 = 158.5$ the radius of the equator in grid units, and $a = \sqrt{(x+1.45)^2+(y-56.6)^2}$ the distance of the grid point from the North Pole in grid units. For a given point (x, y), the great circle with the smallest radius passes from East to West, while the great "circle" in the North South direction is a straight line towards the North Pole. For a given direction θ, the radius decreases going from the North Pole to the equator and increases again if one goes from the equator in the direction of the South Pole.

Let us now compare the difference between a line segment and a great circle arc with the same endpoints on the GONO grid. If the circle has a radius R and the length of the line segment is l, then the largest distance between the line segment and the circle arc is of the order of $1/8(\ell/R)\ell$ and the angle between the circle arc and the line segment at the endpoints is of the order of $1/2(\ell/R)$ radians. For the GONO grid, where $R > \approx 250$ gridunits, these effects are small. *E.g.*, for $\ell = 20$ and $R = 250$ one finds $1/8(\ell^2/R) \approx 0.2$ grid units and $1/2(\ell/R) \approx 2^0$.

So we have shown that geodesics in Nedwam can be very well approximated by straight lines and that one can neglect the variation in the conversion factor from lengths in grid units on the GONO grid to lengths on the surface of the earth. In this sense one can say the metric of the GONO grid is almost euclidean. On the other hand, in order to propagate correctly the mean position of structures in the wave variance spectrum, Nedwam corrects for the variation in the conversion factor from velocities in grid units per time unit on the GONO grid to velocities on the surface of the earth.

3 The evolution of the wave spectrum

Nedwam is a model of the wave spectrum. In this section it is explained what the wave spectrum is and which equations are used by Nedwam to describe its evolution.

3.1 The wave variance spectrum

The wave forecasting model gives a statistical description of the sea surface. It is not attempted to give a deterministic forecast for the position of the air-sea interface at all places and times. Anybody who has observed the irregular appearance of ocean waves will understand that this is not possible. On the other hand, it is often relatively easy to assess which wavelengths and directions dominate. This leads to the following statistical description of the sea surface.

Assume that the elevation η of the sea surface at place $\mathbf{x}$ and time t can be expressed in terms of wave components as

$$\eta = \sum a_n \cos(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)\,, \tag{11}$$

where a_n is the amplitude, ω_n is the angular frequency and $\mathbf{k}_n$ the wave vector of the wave component. Let us further assume that the phases ϕ_n are statistically independent. The latter assumption can only be valid if the steepness of the waves is not too large. Furthermore, the other parameters, a_n, ω_n and $\mathbf{k}_n$, should vary sufficiently slow in space and time, *i.e.* have the almost the same value over many wave lengths and periods. Then η will have a gaussian distribution and all information we have about the surface is contained in its autocorrelation function:

$$C(\mathbf{r},\tau) = \overline{\eta(\,\mathbf{x},t)\eta(\mathbf{x}+\mathbf{r},t+\tau)}\,. \tag{12}$$

It is more convenient to work with the Fourier transform of this correlation function, which is called the wave variance spectrum:

$$F(\mathbf{k},\omega) = \frac{1}{(2\pi)^3}\int d\mathbf{r}\int d\tau\, C(\mathbf{r},\tau)\exp^{-i(\mathbf{k}\cdot\mathbf{r}+\omega\tau)}\;. \tag{13}$$

Integrating over the frequency ω one obtains:

$$F(\mathbf{k}) = \frac{1}{(2\pi)^2}\int d\mathbf{r}\, C(\mathbf{r},0)\exp^{-i\mathbf{k}\cdot\mathbf{r}}\;. \tag{14}$$

$F(\mathbf{k})$ is called the (2-dimensional) *wave (variance) spectrum* or the *wave energy spectrum.* Apart from defining F in the above intuitive way, there is another way, in terms of ensemble averages [Hasselmann 1968a], which is more suitable for rigorous theoretical manipulations.

In the absense of currents the frequency of a gravity surface wave is a function of the modulus of the wave vector $k = |\mathbf{k}|$ and the depth D, and the dependence of $F(\mathbf{k}, \omega)$ on ω becomes trivial: $F(\mathbf{k}, \omega) = \delta(\omega - \omega(k, D))F(\mathbf{k})$. Denoting with g the acceleration of gravity, one has

$$\omega^2 = gk \tanh kD \, . \tag{15}$$

In deep water this reduces simply to $\omega^2 = gk$. In Nedwam, instead of using the wave vector $\mathbf{k}$ as a basic variable, the frequency $f = 2\pi\omega$ and direction θ are used. The two forms of the spectrum are related by

$$F(f,\theta)d\theta df \;=\; F(\mathbf{k})d\mathbf{k} \, . \tag{16}$$

For deep water, when $\omega^2 = gk$, this gives

$$F(f,\theta) \;=\; \frac{4\pi}{\sqrt{g}} k^{3/2} F(\mathbf{k}) \, . \tag{17}$$

The relation between the amplitudes a_n at the beginning of this section and F is simply

$$F(f_n, \theta_n) \sim \frac{1}{2} a_n a_n \, . \tag{18}$$

The factor $1/2$ comes from averaging over the phase in eq. (1).

The integral of the wave variance spectrum is equal to $\overline{\eta(\mathbf{x},t)\eta(\mathbf{x},t)}$, the variance in the height of the sea surface, and is called the *wave variance* E:

$$E(\mathbf{x},t) \;=\; \int_0^\infty df \int_0^{2\pi} d\theta \, F(f,\theta;\mathbf{x},t) \, . \tag{19}$$

E has the dimension of a squared length and is directly related to the *significant wave height* H_s:

$$H_s = 4\sqrt{E} \, . \tag{20}$$

3.2 The energy balance equation

As we saw above, the wave spectrum $F(f,\theta)$ gives us the contribution to the wave variance of wave components with frequency f and direction θ, but gives no information on the value of random phases of the wave components. The definition of F is meaningful as long as its dependence on space and time is weak and the wave steepness is not too large. In such situations, one may consider the evolution in space and time of $F(f,\theta;\mathbf{x},t)$. As a matter of fact, for "adiabatic" changes (which in this context means about the same as "slow" changes), the *action* $A(\mathbf{k}) = F(\mathbf{k})/\omega$ turns out to be the more fundamental object [Witham 1974, Willebrand 1975], but the result may be expressed in terms of F again as follows.

The evolution of the wave variance spectrum is governed by the *energy balance equation.* In Nedwam current and refraction effects are neglected. Nedwam uses the plane of a stereographic projection for $\mathbf{x}$-space. The effect of the projection on the group velocity in the plane of the stereographic projection is taken into account by means of a scaling factor $s(\mathbf{x})$, but not the deviation of geodesics from straight lines and the $\mathbf{x}$-dependence of the relation between a surface element on the sphere and on the plane of the stereographic projection. Then the energy balance equation on the stereographic plane can be written as:

$$\frac{\partial F(f,\theta;\mathbf{x},t)}{\partial t} + \nabla \cdot \left(\frac{\mathbf{c}_g\,(f,\theta,D(\mathbf{x}))}{s(\mathbf{x})} F(f,\theta;\mathbf{x},t) \right) = S(f,\theta;\mathbf{x},t)\,. \tag{21}$$

The boundary condition for F at a land-sea boundary point $\mathbf{x}_b$ is, if the normal to the boundary is denoted by $\mathbf{n}(\mathbf{x}_b)$ and points towards the land,

$$\text{If } \mathbf{k}\cdot\mathbf{n}(\mathbf{x}_b) > 0, \quad F(f,\theta;\mathbf{x}_b,t) = 0\,. \tag{22}$$

If there is sea at the edge of the area under consideration, then the boundary condition at a point $\mathbf{x}_e$ on the edge is of the form

$$\text{If } \mathbf{k}\cdot\mathbf{n}(\mathbf{x}_e) > 0, \quad \frac{\partial F(f,\theta;\mathbf{x}_e,t)}{\partial x_n} = -\frac{1}{L}\lim_{\mathbf{x}\to\mathbf{x}_e} F(f,\theta;\mathbf{x},t)\,. \tag{23}$$

Here L is a length, and $\partial/\partial x_n$ denotes the derivative in the direction of the normal. If $1/L = 0$, one has an *open* boundary condition at the edge., if $1/L = \delta(x_n)$ (Dirac delta function) one gets the same *closed* boundary condition as for land-sea transitions. In Nedwam, $L \approx 750$km.

The advection of wave components is given by the left hand side of the energy balance equation. Each wave component propagates with its *group velocity*

$$\mathbf{c}_g = \frac{\partial \omega}{\partial \mathbf{k}} \tag{24}$$

over the surface of the earth. The group velocity depends on $\mathbf{x}$ through the depth D. But, as already mentioned above, depth refraction of waves has been neglected. The velocity in the plane of the stereographic projection is $\mathbf{c}_g/s$. The isotropic scaling factor $s(\mathbf{x})$ depends on the position $\mathbf{x}$ because the relation between distances on the spherical earth and distances in the plane of the stereographic projection varies a little with $\mathbf{x}$. In the absence of sources ($S = 0$), wave components travel in straight lines over the flat plane of the stereographic projection, and F is conserved in the sense that, apart from boundary effects, $\int F d\mathbf{x}_{plane} = constant$. These are approximations, because real waves travel in great circles over the surface of the earth which correspond to special circles in the stereographic plane, and because the conservation of F on the surface of the earth, $\int F d\mathbf{x}_{earth} = constant$, corresponds to $\int s^2(\mathbf{x}) F d\mathbf{x}_{plane} = const.$. As has been discussed in section 2.3, the above approximations are very good for the small portion of the earth covered by Nedwam. In a global model, of course, one cannot do this, and the advection equation which is used by the global WAM model takes all the curvature effects of the earth into account.

The creation and annihilation of wave components is given by the source term $S(f, \theta; \mathbf{x}, t)$ on the right hand side of the energy balance equation. The source is local in $\mathbf{x}$ and t, depends directly on f and θ and in addition is a functional of $F(f, \theta)$. In Nedwam S is split into four parts,

$$S = S_{in} + S_{dis} + S_{bot} + S_{nl} , \tag{25}$$

representing the wind input, the dissipation by whitecapping, the bottom dissipation and the non-linear wave-wave interactions, respectively. All source terms in Nedwam have the property that they vanish for zero F.

As we will see in sect. 4.4, there is also a “numerical source function”, suppressing too large instantaneous changes in individual spectral components.

Actually, eq. (21) is not used for all frequencies. The expressions which are used by Nedwam for the source terms would not account very well for the observed behaviour of high-frequency components of wave spectra. This in it self would not be so bad, as we are not very much interested in the precise shape of the high-frequency part of the spectrum anyway. But what is worse is the fact that a completely wrong high-frequency part will eventually also corrupt the medium and low-frequency parts of the spectrum. This is because the source terms for low and medium frequencies depend also on the high-frequency part of the spectrum, although not on its detailed structure. To avoid this, WAM and Nedwam use a parametrization for the part of the spectrum beyond a certain high-frequency limit. For frequencies below this limit, the time derivative is given by the energy balance equation. The spectrum is kept continuous at the limiting frequency. In Nedwam, for frequencies above this limit, the spectrum $F(\mathrm{k})$ is forced to have a $k^{-3.5}$ dependence, which is equivalent to that the spectrum $F(f,\theta)$ is forced to have a $k^{-2.5}c_g^{-1}$ dependence. In deep water, a $k^{-2.5}c_g^{-1}$ dependence is the same as the $1/f^4$ dependence which is used in the global WAM model.

The high-frequency limit itself depends on the spectrum: it is the maximum of two and a half times the mean frequency and 4.4 times the Pierson-Moscowitz frequency, provided this procedure yields a frequency below a certain absolute frequency limit of about $0.4Hz$, otherwise the frequency limit is set equal to this absolute frequency limit. The Pierson-Moscowitz frequency f_{PM} associated with the local wind friction velocity u_* is $f_{PM} = g/(2\pi 28 u_*)$.

3.3 The wind-input source term

In a classical paper, Miles [1957] has proposed a theoretical expression for the relation between the wind input and the wave variance spectrum. Snyder et al. [1981] fitted Miles theoretical curve to their experimental data, and proposed a simple formula to approximate the experimental result. The WAM model [WAMDI 1988] uses this formula except that WAM follows Janssen and Komen [1985] in eliminating the wind speed at a fixed height in favor of the friction velocity u_*. The wind input source term is given by

$$S_{in}(f,\theta) \;=\; \max\left\{0.25\frac{\rho_a}{\rho_w}\left(28\frac{u_*}{c_p}\cos(\theta-\phi)\;-\;1\right)\omega F(f,\theta)\;,\;0\right\} \tag{26}$$

where ϕ is the direction of the wind and $c_p = \omega/k$ the *phase* velocity of the wave component. ρ_a/ρ_w is the ratio of air to water density. In Nedwam, this ratio is put to a constant: $0.25\frac{\rho_a}{\rho_w} = 0.0003$.

Note that S_{in} is never negative, and that S is linear in F. If $28u_* < c_p$ then $S_{in} = 0$. So the wind cannot wave components make to grow which have a phase speed of more than $28u_*$. If $|\theta-\phi| \geq \frac{\pi}{2}$, then $S_{in} = 0$. So there is no effect of the wind on wave components which travel upwind.

In Nedwam, the friction velocity u_* is directly related to the wind speed at $10m$ height u_{10} by a simple draglaw [Janssen et al. 1987]:

$$u_* = \sqrt{c_D}u_{10}\,, \qquad c_D = \begin{cases} 1.2873\;10^{-3} & \text{if } u_{10} \leq 7.5m/s \\ 0.8\;10^{-3} + 0.65\;10^{-4}\,u_{10} & \text{if } u_{10} > 7.5m/s\,. \end{cases} \tag{27}$$

3.4 The dissipation source term

Relatively little is known about the surface-dissipation source term S_{dis}. White capping of waves seems to be the main source of dissipation of wave energy at the surface of the sea. The dissipation depends strongly on the wave steepness. Here, the wave steepness is roughly speaking the average waveheight over wavelength ratio. A first theoretical study is from Hasselmann [1974]. Komen et al. [1984] have attacked the problem of the study of the energy balance of a fully developed wind-sea spectrum. They looked for a dissipation source term which allowed for a reasonable equilibrium solution of the energy balance equation, and arrived at the following expression:

$$S_{dis}(f,\theta) \;=\; -3.33\,10^{-5}\left(\frac{\omega}{\langle\omega\rangle}\right)^2\left(\frac{\langle\alpha\rangle}{\langle\alpha\rangle_{PM}}\right)^2\langle\omega\rangle F(f,\theta)\,, \tag{28}$$

where $\langle\omega\rangle$ is the mean angular frequency originally defined as:

$$\langle\omega\rangle \;=\; \frac{1}{E}\int_0^\infty df\int_0^{2\pi} d\theta\,\omega F(f,\theta) \tag{29}$$

and $\langle\alpha\rangle$ is the integral squared wave steepness:

$$\langle\alpha\rangle = \frac{E\langle\omega\rangle^4}{g^2}\,. \tag{30}$$

$\langle\alpha\rangle_{PM} = 4.57\,10^{-3}$ is the empirically determined Pierson-Moskowitz value for the integral squared wave steepness of a fully developed wind sea spectrum. S_{dis} has a quasi-linear dependence on F, since the $\langle\omega\rangle$ dependence makes S a functional of F.

Later the WAM group has used an alternative definition of the mean frequency, which is less sensitive to details in the high-frequency tail, $\overline{\omega}$:

$$\overline{\omega} \;=\; \left[\frac{1}{E}\int_0^\infty df\int_0^{2\pi} d\theta\,\omega^{-1} F(f,\theta)\right]^{-1}\,. \tag{31}$$

Because the mean frequency is used in the definition of integral squared wave steepness, the definition of the latter quantity is also modified,

$$\overline{\alpha} = \frac{E\overline{\omega}^4}{g^2} \tag{32}$$

and the Pierson-Moskowitz value of this wave steepness is 0.66 times the numerical value of the original one. In addition, the overall constant in eq. (28) has been reduced to $-2.33\,10^{-5}$ [WAMDI 1988].

In shallow water the wave number is no longer a homogeneous function of the frequency. So in this case it makes a difference whether one expresses the dissipation source function in wave numbers or in wave frequencies. As the wave number formulation is the more fundamental one, it is natural to assume that the deep and shallow water expressions are identical in the wave-number formulation, and not in the wave-frequency formulation. This is what is done in the shallow water version of WAM and in Nedwam. Taking the second option for the mean frequency, and going back to S_{dis} in terms of wave numbers one arrives at:

$$S_{dis}(f,\theta) = -2.6\,\overline{\omega}\,\frac{k}{\overline{k}}\left(E\overline{k}^2\right)^2 F(f,\theta) \tag{33}$$

with the mean wave number $\overline{k}$ defined as:

$$\overline{k} = \left[\frac{1}{E}\int_0^\infty df \int_0^{2\pi} d\theta\, k^{-\frac{1}{2}} F(f,\theta)\right]^{-2} . \tag{34}$$

3.5 The bottom-dissipation source term

The water near the surface is set into motion by the surface waves. In case of a deep-water monochromatic wave, the water elements move in circles, which becomer smaller and smaller as one goes deeper below the surface. For shallow water, the water elements move in ellipses rather than in circles. The ellipses change from circles at the surface to horizontal straight lines at the bottom. The amplitude of the horizontal speed of the water elements is given by [Phillips 1977]

$$u = \frac{g k_n a_n}{\omega_n}\,\frac{\cosh\left(k_n\left(D-d\right)\right)}{\cosh\left(k_n D\right)} . \tag{35}$$

(The amplitude of the vertical speed is obtained from the above formula by replacing the cosh by a sinh.) Here a_n is the amplitude of the wave, D the depth of the sea and d is the depth below the surface of the water element. Near the bottom, the movement is damped by a factor $1/\cosh(kD)$, which amounts to 9% for a wavelength which equals twice the depth. The above formula for u applies till just above the bottom of the sea where a boundary layer starts where $u \downarrow 0$. The thickness of the boundary layer is much smaller than D, and the velocity at the top of the boundary layer, u_b, follows from the above formula (remember that $\omega^2 = gk \tanh kD$):

$$u_b = \frac{a_n \omega_n}{\sinh kD} . \tag{36}$$

If u_b is not negligible, there will be friction between the wave and the bottom causing the wave to lose energy to the boundary layer.

In the case of many waves, every wave will give a contribution like eq. (36) to u_b and the average of u_b squared will be halve the sum of the squares of these contributions. The factor one half arises because the phases of the various contributions are not correlated. Using the correspondence eq. (18) one can then express the average velocity squared at the top of the boundary layer in terms of the wave variance spectrum:

$$\overline{u_b^2} = \int_0^\infty df \int_0^{2\pi} d\theta \, \frac{\omega^2}{\sinh^2 kD} F(f,\theta) . \tag{37}$$

Looking for an empirical expression for the bottom friction, the first thing which springs to the mind is something like $-Cv^2$, with v a characteristic velocity. This is what JONSWAP [1973] has done, proposing the following expression for the bottom friction source term:

$$S_{bot} = -\frac{\Gamma}{g^2} \frac{\omega^2}{\sinh^2 kD} F(f,\theta) . \tag{38}$$

From the JONSWAP experiment data follows a mean value of $\Gamma = 0.038 m^2 s^{-3}$. Inside Nedwam, another, but equivalent, expression for the bottom friction is used:

$$S_{bot} = -\frac{(0.076 m^2 s^{-3})}{g} \frac{k}{\sinh 2kD} F(f,\theta) . \tag{39}$$

The above expression is no more than a crude approximation. Alternative formulations for the bottom friction exist [Hasselmann and Collins 1968b, Weber 1989], which are based on parametrizations of the turbulent bottom stress. But they have not yet been subjected to extensive tests. Test versions of Nedwam which use these alternative versions have been developed and are ready for use.

3.6 The wave-wave interaction source term

In linear wave theory, different wave components do not interact with each other. The wave spectrum formalism only works because the linear theory is a rather good approximation and the picture of a sea surface composed of stochastically independent wave components is a good one. However, the non-linear effects of resonant wave-wave interactions do not cancel in the course of time, but slowly but surely influence the evolution of the shape of the wave variance spectrum. The main effect is to redistribute energy from wave vectors where the wave variance spectrum has a high value to wave vectors where the wave variance spectrum has a low value, and to smooth the wave variance spectrum.

A general perturbation theory for wave-wave interactions was formulated by Klaus Hasselmann [1962;1963a,b].

One can envisage this in a picture where waves "collide" to produce other waves [Hasselmann 1985a]. The fundamental object turns out to be the wave action $\int d\mathbf{k}A(\mathbf{k}) = \int d\mathbf{k}\,(F(\mathbf{k})/\omega)$ rather than the wave variance. For gravity waves, the most "simple" collision involves four waves: two "initial-state" waves and two "final-state" waves. To calculate the probability of a collision, two ingredients enter. The first is a transition probability, a function of the four wave vectors and the four frequencies of the components which participate in the collision. This transition probability is fully symmetric under interchanges of its arguments (provided one changes sign if one interchanges an initial-state and a final-state component). This property is sometimes called detailed balance. The second ingredient is a triple product of action components $A(\mathbf{k}_{i_1})A(\mathbf{k}_{i_2})A(\mathbf{k}_f)$, with i_1 and i_2 denoting the initial-state components and f one of the final-state components. Replacing f by the other final-state component gives a second triplet associated with the same initial and final state. If a $A(\mathbf{k})$ occurs in the final state, the collision will contribute to the creation of this component, if $A(\mathbf{k})$ occurs in the initial state it will contribute to its annihilation. The net rate-of-change of component $A(\mathbf{k})$ is obtained by integrating, over all possible wave-vectors of the three collision partners, the transition probability times the sum of four triple action component products, two positive ones for its creation and two negative ones for its annihilation. Because of detailed balance, the net rate-of-change of the total action is zero, as the creation of one component is always balanced by the annihilation of another one.

The "collisions" satisfy conservation laws: the sum of the frequencies and the sum of the wave vectors of the ingoing wave components must be the same as the sum of the outgoing frequencies and the sum of the outgoing wave vectors. Together with detailed balance this implies the conservation by the wave-wave interactions of the action $\int d\mathbf{k}\,A(\mathbf{k})$, the wave variance (energy) $E = \int d\mathbf{k}\, F(\mathbf{k}) = \int d\mathbf{k}\, \omega A(\mathbf{k})$, and the wave momentum $\int d\mathbf{k}\, \mathbf{k} A(\mathbf{k})$.

The above picture is reminiscent of the Boltzmann picture of a gas of weakly interacting molecules as for instance exemplified in Ehrenfest' famous dog-flea model [Ehrenfest 1911].

The validity of the lowest-order approximation for the wave-wave interactions is restricted to cases where the wave spectrum formalism is applicable, the joint probabilities for wave components should be given in good approximation by products of $A(\mathbf{k})$'s. Moreover, the wave spectrum should be sufficiently broad to counter effects of the inhomogeneity in the wave field [Alber 1978a,b; Janssen 1983]. Here "sufficient" means that the width over central value ratio's of the spectral peaks should be larger than the associated wave steepness.

The source term from the wave-wave interactions has the following form:

$$\frac{1}{\omega} S_{nl}(\mathbf{k}) = \int d\mathbf{k}_1 \int d\mathbf{k}_2 \int d\mathbf{k}_3\, \delta\left(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}\right) \delta\left(\omega(\mathbf{k}_1) + \omega(\mathbf{k}_2) - \omega(\mathbf{k}_3) - \omega(\mathbf{k})\right)$$
$$C\left(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}\right) \left(A(\mathbf{k}_1) A(\mathbf{k}_2) \left(A(\mathbf{k}_3) + A(\mathbf{k})\right) - A(\mathbf{k}_3) A(\mathbf{k}) \left(A(\mathbf{k}_1) + A(\mathbf{k}_2)\right)\right) \quad (40)$$

where C stands for the four-wave transition probability. The integral on the right hand side is often called the Boltzmann integral, because it has the same structure as its more celebrated namesake from statistical physics. For deep water, we here give the expression for C [Hasselmann 1962, van Vledder 1990].

$$C(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) = \frac{\pi g^4 M^2}{4 \omega_1 \omega_2 \omega_3 \omega_4} \quad (41)$$

with the transition amplitude M is given by:

$$M(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) = \left\{ \frac{2(\omega_1 + \omega_2)^2 (k_1 k_2 - \mathbf{k}_1 \cdot \mathbf{k}_2)(k_3 k_4 - \mathbf{k}_3 \cdot \mathbf{k}_4)}{\omega_{1+2}^2 - (\omega_1 + \omega_2)^2} \right.$$
$$+ \frac{1}{2} \mathbf{k}_1 \cdot \mathbf{k}_2 \mathbf{k}_3 \cdot \mathbf{k}_4 - \frac{1}{4} g^{-2} (\mathbf{k}_1 \cdot \mathbf{k}_2 + \mathbf{k}_3 \cdot \mathbf{k}_4)(\omega_1 + \omega_2)^4 + \frac{5}{6} k_1 k_2 k_3 k_4$$
$$\left. + \frac{1}{3} g^{-3} (\omega_1 + \omega_2)^2 (\omega_1 - \omega_3)^2 (\omega_1 - \omega_4)^2 (k_1 + k_2 + k_3 + k_4) \right\}$$
$$+ \left\{ \mathbf{k}_2 \leftrightarrow -\mathbf{k}_3\,,\ \omega_2 \leftrightarrow -\omega_3\,,\ \omega_{1+2} \leftrightarrow \omega_{1-3} \right\} + \left\{ \mathbf{k}_2 \leftrightarrow -\mathbf{k}_4\,,\ \omega_2 \leftrightarrow -\omega_4\,,\ \omega_{1+2} \leftrightarrow \omega_{1-4} \right\}, \quad (42)$$

with

$$\omega_i = \omega(\mathbf{k}_i)\,,$$
$$\omega_{i \pm j} = \omega(\mathbf{k}_i \pm \mathbf{k}_j)\,. \quad (43)$$

Because the dispersion relation $\omega^2 = gk$ has been used to keep the above expression reasonable compact, the above expression is only valid for deep water. In the simple case that all the wavevectors are equal, C reduces to $C(\mathbf{k},\mathbf{k},\mathbf{k},\mathbf{k}) = 4\pi g^2 k^6$, a result first obtained by Longuet-Higgins [1976].

The delta functions in the Boltzmann integral select frequency and total wave vector conserving sets of wave vectors, called resonating quadruplets, from the eight-dimensional space of sets of four wave vectors. These resonating quadruplets lie on a five-dimensional manifold, and one is still left with a three-dimensional integral for every component of $S_{nl}(\mathbf{k})$. The evaluation of $S_{nl}(\mathbf{k})$ by a direct numerical evaluation of these Boltzmann integral is too timeconsuming for present-day forecasting models. WAM and Nedwam rather use a discrete parametrization of the Boltzmann integral which will be discussed in section (4.9).

4 A numerical model of the wave spectrum

To model the evolution of the wave spectrum, Nedwam solves a finite difference version of the energy balance equation.

4.1 Discretization of space, time, frequency and direction

The wave variance spectrum F has five arguments, $\mathbf{x}=(x,y)$, t, f and θ. All of them need to be discretized. Space is represented by the 612 *GONO gridpoints* of the GONO grid of section 2. The grid spacing is approximately 75 km. The spectrum is evaluated every *propagation time step.* Nedwam has a propagation time step of 30 minutes. A propagation time step is subdivided in several *integration time steps.* The integration of the source term of the energy balance equation proceeds in integration time steps. The wind fields are kept constant during a *wind time step.* In Nedwam, the wind time step has been set to three hours. Nedwam uses the same *frequency direction grid* for f and θ as WAM. Wave direction is divided in twelve direction bins. The center of bin number one points in the direction of the positive y-axis of the GONO grid, the center of bin number four in the direction of the positive x-axis of the GONO grid and so on. Inside the model, the wave direction is defined to be the direction of $\mathbf{c}_g$, the direction the waves are going to (but for the output of the Nedwam program, this internal direction is always converted to the direction with respect to the true North the waves are coming from). The frequency grid contains 25 frequencies. The grid is logarithmic, every frequency is 10% higher than the previous one:

$$f_m = (1.1)^{m-1} f_1 \,, \quad m = 1, \ldots 25 \,. \tag{44}$$

The lowest frequency is given by

$$f_1 = 0.0418 Hz \,, \tag{45}$$

$(0.0418 = (1.1)^{15}/100)$, and the highest is

$$f_{25} = 0.4117 Hz \,. \tag{46}$$

4.2 The discrete energy balance equation

In section 3, the analytic form of the energy balance equation has been given, eq. (21),

$$\frac{\partial F}{\partial t} = -\nabla \cdot \left(\frac{\mathbf{c}_g}{s} F \right) + S \,. \tag{47}$$

In the numerical model, eq. (47) is replaced by a finite difference equation. Time is discretized in *propagation time steps.* In Nedwam, the propagation time step Δt_{prop} is 30 minutes. The discrete version of the energy balance equation expresses the spectrum F_{n+1} at time $t_{n+1} = t_n + \Delta t_{prop}$ in terms of F_n, the spectrum at time t_n. The contributions from the advection term (the $\nabla \cdot (\mathbf{c}_g F/s)$ term) and from the source term are calculated separately.

First, the increment due to advection in the absence of sources,

$$(F_{n+1} - F_n)_{prop} = \Delta_{prop}(F_n) \,, \tag{48}$$

is determined using the first order upwinding propagation scheme described in section 4.3. $\Delta_{prop}(F_n)/\Delta t_{prop}$ corresponds to the term $-\nabla \cdot (\mathbf{c}_g F/s)$ in the analytical form of the energy balance equation.

Next, the changes in F due to the source terms are integrated. The propagation time step is split into several *integration time steps.* In Nedwam, the propagation time step is split into two integration time steps of $\Delta t_{int} = 15$ minutes. Each integration time step, a source term increment is added to the spectrum,

$$F_{new} = F_{old} + \Delta_{int}(F_{old}) \,, \tag{49}$$

using the source term integration scheme of section 4.4 and the representations for the source terms as discussed in sections 4.6-4.9. $\Delta_{int}(F)/\Delta t_{int}$ corresponds to the term S in the analytical form of the energy balance equation. In this way, one obtains after the two source term time steps

$$\tilde{F}_n = F_n + \Delta_{int}(F_n) + \Delta_{int}(F_n + \Delta_{int}(F_n)) \,. \tag{50}$$

$\tilde{F} - F$ is the change due to the source terms in the spectrum in one propagation time step.

Finally, the advection increment is added to $\tilde{F}_n$ to get the spectrum at t_{n+1}. Summarizing, the finite difference equation for the energy balance looks like

$$F_{n+1} = F_n + \Delta_{int}(F_n) + \Delta_{int}(F_n + \Delta_{int}(F_n)) + \Delta_{prop}(F_n) \,. \tag{51}$$

Note we need an *initial wave spectrum* F_0 to calculate the series $F_0, F_1, F_2, \ldots$. In addition, to calculate the increment due to advection, boundary conditions are needed at land sea transitions and at the edges of the GONO grid. As mentioned in section 3.2, the Nedwam source term S vanishes for $F = 0$. This implies that if $F_0 = 0$, then $F_n = 0$ for all n, no matter how hard the wind is blowing. Of course, in nature, waves would be generated, even if $F_0 = 0$. But the model does not describe situations with extremely small F well. This is the reason one should always initialize the model with a non-zero spectrum F_0. One can either take for F_0 a spectrum calculated by a previous model run for time t_0 — such a spectrum is called a *restart spectrum* —, or a spectrum related to the windfield at t_0, e.g. a young windsea Jonswap spectrum [JONSWAP 1973]. The energy balance equation is rather robust in the sense that F_n hardly depends on the choice of F_0 if t_n is of the order of two days or more.

4.3 The propagation scheme

The advection part of the energy balance equation, eq. (21), is given by:

$$\left(\frac{\partial F}{\partial t}\right)_{prop} = -\nabla \cdot \left(\frac{\mathbf{c}_g(f,\theta;\mathbf{x})}{s(\mathbf{x})} F(f,\theta;\mathbf{x},t)\right) . \tag{52}$$

Nedwam uses a first order, upwinding (FU) scheme to discretize this equation. Let us denote by $F_n(i,j;m,k)$ the spectral component with frequency f_m and direction θ_k at time t_n and at gridpoint $\mathbf{x} = (i,j)$ on the GONO grid. Similarly, $c_g(i,j;m)$ stands for the magnitude of the group velocity $\mathbf{c}_g$ at gridpoint (i,j) for frequency f_m, and $s(i,j)$ for the scaling factor s at (i,j). In the Nedwam GONO grid, the x-index i ranges from 1 to 17, and the y-index j ranges from 1 to 36. The discrete counterpart of eq. (52) in the FU scheme is given by

$$F_{n+1}(i,j;m,k) - F_n(i,j;m,k) = \Delta_{prop}(F_n(i,j;m,k)) , \tag{53}$$

$$\begin{aligned} \Delta_{prop}(F_n(i,j;m,k)) = & \\ -\frac{\Delta t_{prop}}{\Delta x}|\cos\theta_k| & \left(\frac{c_g(i,j;m)}{s(i,j)}F_n(i,j;m,k) - \frac{c_g(i-\sigma_i,j;m)}{s(i-\sigma_i,j)}F_n(i-\sigma_i,j;m,k)\right) \\ -\frac{\Delta t_{prop}}{\Delta y}|\sin\theta_k| & \left(\frac{c_g(i,j;m)}{s(i,j)}F_n(i,j;m,k) - \frac{c_g(i,j-\sigma_j;m)}{s(i,j-\sigma_j)}F_n(i,j-\sigma_j;m,k)\right) \end{aligned} \tag{54}$$

with

$$\sigma_i = \cos\phi/|\cos\phi| \, , \sigma_j = \sin\phi/|\sin\phi| \, . \tag{55}$$

The time increment is $\Delta t_{prop} = 30$ minutes and the gridpoint distance is $s(i,j)\Delta x = s(i,j)\Delta y \approx 75$km in Nedwam.

The sea in Nedwam has two types of boundaries: on the one hand transitions between land and sea, and on the other hand the edges of the GONO grid. Equation (53) applies to GONO seapoints (i,j), and boundary conditions are needed if the point $(i',j') = (i - \sigma_i, j)$ or the point $(i',j') = (i, j - \sigma_j)$ happens to be a landpoint or happens to lie outside the GONO grid. The boundary conditions are implicitly given by assigning a spectrum F to all points in the extended grid. The extended grid consists of the GONO grid plus a strip of a width of one gridpoint around it. At GONO landpoints (i',j') one defines, for all times:

$$\text{For landpoints } (i',j'): \quad F(i',j') = 0 \; . \tag{56}$$

This boundary condition is the counterpart of eq. (22). In the global WAM model, landpoints are treated in the same way. However, the global WAM model has no edges which contain seapoints, and the following boundary condition is specific for Nedwam. For points (i',j') at the edge of the extended grid one defines:

$$\text{For points } (i',j') \text{ on the edge of the extended grid: } F(i',j') = 0.9F(i,j) \; . \tag{57}$$

Here (i,j) is the GONO gridpoint closest to (i',j'). The value of 0.9 roughly corresponds to a value of $L = 75\text{km}/(1-0.9) \approx 750\text{km}$ in the analytical boundary condition, eq. (23). At the corners of the extended grid 0.9^2 is taken instead of 0.9. The value of 0.9, a compromise between the 1.0 of an open boundary and the 0.0 of a closed boundary, was found after a little tuning [Sanders 1976, Karssen 1987]. This boundary condition does not always have the desired effect. If strong winds blow into the grid, the waves near the sea edges of the grid tend to be overestimated. In particular, this often happens near the North Western corner of the grid. Taking boundary fields from the global WAM model would solve this problem.

The boundary condition $F = 0$ at landpoints tacitly implies that, at the first seapoint, the component of the fetch perpendicular to the shore is given by the distance between the last landpoint and the first seapoint, and that the boundary between land and sea goes through the *last landpoint,* not through the first seapoint.

The FU scheme is called forward because it calculates forward in time (an obvious requirement for a forecast model), and upwinding because it determines the space derivative by looking in the direction where the wave component is coming from. One is not free in choosing between the upwinding and downwinding alternatives because a forward downwinding scheme is not stable. The relative sizes of the time step, the effective space step

$s(i,j)\Delta x$ and the lowest frequency are chosen in such a way that the following inequality, called the *Courant criterion,* is always satisfied:

$$\frac{c_g(i,j,m)\Delta t_{prop}}{s(i,j)\Delta x} \leq \frac{1}{2}\sqrt{2}\,. \tag{58}$$

The scheme would have been unstable if this inequality would have been violated.

A nice property of the FU scheme is that a positive definite spectrum F stays for ever positive definite. The main disadvantage of the FU scheme is that small scale structures are smoothed too much [Dijkhuis]. This numerical dispersion effect goes with the square root of time or distance. On the other hand, most numerical propagation schemes break up structures which are both small in frequency direction space and $\mathbf{x}$-space into separate parts, instead of stretching them. This "garden sprinkler effect" arises because the velocities of the wave components can only have certain discrete values, determined by the frequency direction grid. In the FU scheme the two effects, smoothing and garden sprinkler, compensate somewhat. For fixed Δx the FU performs in general better if one takes the largest Δt_{prop} allowed by the Courant criterion. This is the reason why in Nedwam one has a larger propagation time step than integration time step.

4.4 The source term integration scheme

The source part of the energy balance equation, eq. (21), is given by:

$$\left(\frac{\partial F(f,\theta;\mathbf{x},t)}{\partial t}\right)_{int} = S\left(f,\theta;\mathbf{x},t;F(\mathbf{x},t;f',\theta')\right)\,. \tag{59}$$

The primes have been added to f' and θ' to indicate that the source depends on the values of F at all frequencies and all directions. On the other hand, S is local in $\mathbf{x}$, that is $S(\mathbf{x})$ depends only on $F(\mathbf{x})$ at the same position $\mathbf{x}$.

Given the spectrum at time t, the source term integration scheme calculates the spectrum at time $t' = t + \Delta t_{int}$, as it would be if there were no change due to advection:

$$F_{t'}(i,j;m,k) = F_t(i,j;m,k) + S_t(i,j;m,k)\Delta t_{int}\,, \tag{60}$$

where, like in the preceding subsection, i and j are the coordinates in the GONO grid, m stands for the frequency f_m and k for a the direction θ_k. In principle, a very straightforward scheme is used to calculate $S_t \Delta t_{int}$, but there are a few delicate points one should know about.

The first delicate point is that eq. (60) is only used up to a high-frequency limit. This limit is given by

$$f_{hf} = \min(f_{25}, \max(2.5\overline{f}, 4.4 f_{PM})) , \tag{61}$$

where $\overline{f}$ denotes the mean frequency of the spectrum at time t and position (i,j), and $f_{PM} = g/(2\pi 28 u_*)$ is the Pierson-Moskowitz frequency associated with the wind friction velocity u_* at time t and position (i,j). f_{25} is the highest frequency of the frequency grid. For the calculation of the mean frequency, see section 4.5. Note that f_{hf} depends both on the time t and the position (i,j). Let n_{hf} be the index in the frequency grid of the highest frequency below f_{hf}

$$f_{n_{hf}} \leq f_{hf} < f_{n_{hf}+1} \, . \tag{62}$$

Eq. (60) is used to calculate the change in components F with $m = 1, \ldots, n_{hf}$. The frequencies $f_1, f_2, \ldots, f_{n_{hf}}$ are called *prognostic frequencies.* For frequencies above $f_{n_{hf}}$, which are called *diagnostic frequencies,* the spectrum is supposed to have a diagnostic tail, proportional to $1/(c_g k^{2.5})$:

$$F(i,j;m,k,) = \frac{c_g(i,j;n_{hf})k(i,j;n_{hf})^{2.5}}{c_g(i,j;m)k(i,j;m)^{2.5}} F(i,j;n_{hf},k) \, , \tag{63}$$

with $k(i,j;n)$ the wave number and $c_g(i,j;n)$ the group velocity which correspond to frequency f_n and the depth of the gridpoint (i,j). Actually, Nedwam uses a rather indirect way to do this. First the mean frequency of the spectrum at time t is calculated. Next f_{hf} is determined and the diagnosticy tail is calculated. Then all mean parameters which are needed for the calculation of the source function are recalculated, and finally eq. (60) is used to calculate the change in the prognostic components.

As discussed in section 3.2, the source term has contributions from the wind-input, the dissipation due to white capping, the bottom dissipation and the wave-wave interactions,

$$S = S_{in} + S_{diss} + S_{bot} + S_{nl} \tag{64}$$

The numerical representations of the source terms will be discussed in sections 4.6-4.9. The calculation of the average quantities is discussed in section 4.5. Apart from the discrete wave-wave interaction source term, which has no direct analytical counterpart, the expressions for the numerical source terms and averages are very similar to those for the analytical ones.

Now comes the next delicate point. The effective total source term is limited to a certain frequency dependent value:

$$S_{eff}(i,j;m,k) = \text{sign}(S(i,j;m,k)) \min\left(|S_(i,j;m,k)|\Delta t_{int}, C_{max}\right) , \qquad (65)$$

with

$$C_{max} = (0.62\,10^{-4}\,m^2 s^{-4})\,f^{-5} . \qquad (66)$$

C_{max} limits the absolute change in a wave component, especially for the high-frequency ones, and has been introduced for stability reasons. Nedwam uses the same C_{max} as WAM. Note that C_{max} does *not* depend on Δt_{int}. For a very small integration time step Δt_{int}, of the order of two minutes or less, one has simply $S_{eff} = S$. But for the 20 minute time step of WAM or the 15 minute time step of Nedwam, the difference $S_{eff} - S$ is not zero. Incidentally, the model wind-sea growth curves obtained with 15 and 20 minute time steps are closer to observed wind-sea growth curves than the model wind-sea growth curves obtained with very small timesteps. The reason why WAM and Nedwam use the high-frequency tail and the limitation on the change of a prognostic component is that the source terms are too simple to account for the high-frequency part of the spectrum. Discretizing the energy balance equation makes the problem worse, as the time scales of the high-frequency components are much shorter than for the low-frequency components. Of course, one would like to have a static cutoff $f_{hf} = f_{25}$ instead of the dynamic one eq. (61), and to have no limitation on the change of wave spectrum component. Maybe, in the future, the source functions — in particular S_{diss} — will be improved in such a way that one can do this, but for the time being WAM and Nedwam have resort to these tricks in order not to run into problems with the high-frequency part of the wave spectrum.

In the global WAM model a semi-implicit integration scheme [WAMDI] is used instead of the explicit integration scheme $F(t') = F(t) + S(t)\Delta t$. Using the explicit scheme and a time step of 15 minutes, some unphysical oscillations of the wave spectrum state can appear if the individual contributions almost cancel in the total source term. For a forecast model, however, this is not a great disadvantage, as in real-world situations such cancellations occur only rarely, and, moreover, the amplitude of the oscillations is limited and small compared to the error which arises from the uncertainty in the driving wind field.

4.5 The calculation of mean quantities

Various mean quantities, which are functionals of the wave spectrum, are needed for the source term integration scheme and the calculation of the dissipation source term. Moreover, the model also routinely calculates from the spectrum some other mean quantities, which are of interest for the users of the model, like the mean wave direction and the E_{10}. For completeness, the way the mean quantities are calculated will be given in this section.

In general, integrals over the wave spectrum are calculated by the model as follows. The frequency range is divided in two pieces. The integral over the first piece, from f_1 until f_{25}, is approximated by applying the trapezium rule:

$$\int_{f_0}^{f_{25}} df \int_0^{2\pi} d\theta A(f,\theta) \approx \sum_{m=1}^{24} (f_{m+1} - f_m) \sum_{k=1}^{12} \frac{2\pi}{12}\frac{1}{2} \left(A(m+1,k) - A(m,k)\right) . \qquad (67)$$

The integral over the second piece, for frequencies f_{25} and higher, where the spectrum F is always related by a power law to the spectrum at $f = f_{25}$, is approximated by ad-hoc methods.

Let us introduce some notation. Frequencies beyond f_{25} will be defined like the first 25 ones;

$$f_m = (1.1)^{m-1} f_1 , \quad m \geq 1 . \qquad (68)$$

Beyond f_{25}, the spectrum F will be defined by the power law

$$\text{For } m \geq 25\text{:} \; F(i,j;m,k) = \frac{c_g(i,j;25)(k(i,j;25)^{2.5}}{c_g(i,j;m)(k(i,j;m)^{2.5}} F(i,j;25,k) . \qquad (69)$$

A shorthand notation for the sum over the the directions and the frequencies from f_ℓ until f_u of a quantity A will be

$$\sum_\ell^u (A) = \sum_{m=\ell}^{u-1} (f_{m+1} - f_m) \sum_{k=1}^{12} \frac{2\pi}{12}\frac{1}{2} \left(A(i,j;m+1,k) - A(i,j;m,k)\right) . \qquad (70)$$

The *wave variance* E at position (i,j) is given by

$$E = \sum_1^{25}(F) + \sum_{25}^{54}(F) . \qquad (71)$$

In this case, the tail has been integrated numerically.

The *mean frequency* $\overline{\omega}$ at position (i,j) is given by

$$\langle 1/\omega \rangle = \frac{1}{E} \left(\sum_1^{25} (F/\omega) + \frac{1}{4}\frac{2\pi}{12} \sum_{k=1}^{12} F(i,j;25,k) \right) , \qquad (72)$$

$$\overline{\omega} = \langle 1/\omega \rangle^{-1} . \tag{73}$$

In the above formula, it has been assumed that the tail is proportional to $1/f^4$, which is a good approximation because the difference between $\sim f^{-4}$ and $\sim 1/(c_g k^{2.5})$ is not important if the depth is smaller than the wavelength. As f_{25} corresponds to a wavelength of the order of $10m$ and the lowest depth in Nedwam is $15m$, this is always the case. The $1/f^4$ tail is integrated analytically.

The *mean wave number* $\overline{k}$ at position (i,j) is given by

$$\langle 1/\sqrt{k} \rangle = \frac{1}{E}\left(\sum_{1}^{25} (F/\sqrt{k}) + \frac{\sqrt{g}}{2\pi}\frac{1}{4}\frac{2\pi}{12}\sum_{k=1}^{12} F(i,j;25,k) \right) , \tag{74}$$

$$\overline{k} = \langle 1/\sqrt{k} \rangle^{-2} . \tag{75}$$

Here, again, the tail of the spectrum has been approximated by a $1/f^4$ function. Also, for the high frequencies the approximation $\sqrt{k} = \omega/\sqrt{g}$ has been made. With these approximations, the tail can be integrated easily.

The E_{10} is defined as the contribution to E from wave components with periods of more than $10s$. Let $f_{m_{10}}$ and $f_{m_{10}+1}$ be the frequencies around $0.1Hz$ in the frequency grid:

$$f_{m_{10}} \leq 0.1Hz < f_{m_{10}+1} . \tag{76}$$

Then the E_{10} at position (i,j) is given by

$$E = \sum_{1}^{m_{10}} (F) + \frac{2\pi}{12} \sum_{k=1}^{12} (0.1Hz - f_{m_{10}}) \Big\{ F(i,j;m_{10},k) + \frac{1}{2}\frac{0.1Hz - f_{m_{10}}}{f_{m_{10}+1} - f_{m_{10}}} (F(i,j;m_{10}+1,k) - F(i,j;m_{10},k)) \Big\} . \tag{77}$$

The last term represents the contribution from frequencies between $f_{m_{10}}$ and $0.1Hz$, integrated with the trapezium rule.

Next we come to the *mean wave direction.* It is defined in terms of the mean sine and cosine of the wave components,

$$\langle \sin \rangle = \frac{1}{E'} \sum_{1}^{25} (F \sin\theta) \tag{78}$$

and

$$\langle \cos \rangle = \frac{1}{E'} \sum_{1}^{25} (F \cos\theta) , \tag{79}$$

with $\theta = (2\pi(k-1)/12)$ and $E' = \sum_1^{25}(F)$. In the above formulae the high-frequency tail has been neglected altogether. The directions of the wave spectrum components are defined as going to, with respect to the GONO grid y-axis, but the mean wave direction in Nedwam is defined like a wind direction as coming from, with respect to the true North. Thus the tilt angle $\delta(i,j)$ of eq. (5) between the GONO grid y-axis and the true North appears in the formula for the mean wave direction θ_{wave} at position (i,j):

$$\theta_{wave} = \arctan\frac{\langle\sin\rangle}{\langle\cos\rangle} + \ell\pi + \delta(i,j)\,, \tag{80}$$

where ℓ is chosen such that θ_{wave} is the direction the waves are coming from *i.e.*, $\ell = 1$ if $\langle\cos\rangle \geq 0$ and $\ell = 0$ if $\langle\cos\rangle < 0$. The *mean wave direction variance* is connected to the value of $\langle\sin\rangle^2 + \langle\cos\rangle^2$. The definition of the mean wave direction variance $\sigma_{\theta_{wave}}$ is

$$\sigma_{\theta_{wave}} = \sqrt{2\,(1 - \langle\sin\rangle^2 - \langle\cos\rangle^2)} \tag{81}$$

Note that $0 \leq \sigma_{\theta_{wave}} \leq \sqrt{2}$ (in radians). If $E' = 0$ the above formulae for $\langle\sin\rangle$ and $\langle\cos\rangle$ are ill defined and cannot be used. Then the model puts $\langle\sin\rangle = 0$ and $\sigma_{\theta_{wave}} = \sqrt{2}$. In the output of the model, θ_{wave} and $\sigma_{\theta_{wave}}$ are converted from radians to degrees.

The *mean direction of the* E_{10} at position (i,j) is defined completey analoguously the definition of the mean wave direction. The only difference is that the mean sine and cosine of the E_{10} are given by

$$\langle\sin_{10}\rangle = \frac{1}{E'}\sum_1^{25}(F\sin\theta) + \frac{1}{E'}\frac{2\pi}{12}\sum_{k=1}^{12}(0.1Hz - f_{m_{10}})\sin\frac{2\pi(k-1)}{12}\Bigg\{F(i,j;m_{10},k) + \frac{1}{2}\frac{0.1Hz - f_{m_{10}}}{f_{m_{10}+1} - f_{m_{10}}}(F(i,j;m_{10}{+}1,k) - F(i,j;m_{10},k))\Bigg\} \tag{82}$$

and

$$\langle\cos_{10}\rangle = \frac{1}{E'}\sum_1^{25}(F\cos\theta) + \frac{1}{E'}\frac{2\pi}{12}\sum_{k=1}^{12}(0.1Hz - f_{m_{10}})\cos\frac{2\pi(k-1)}{12}\Bigg\{F(i,j;m_{10},k) + \frac{1}{2}\frac{0.1Hz - f_{m_{10}}}{f_{m_{10}+1} - f_{m_{10}}}(F(i,j;m_{10}{+}1,k) - F(i,j;m_{10},k))\Bigg\}\,. \tag{83}$$

The *one-dimensional frequency spectrum* can also be considered as a mean quantity. It is obtained as follows:

$$F_1(i,j;m) = \frac{2\pi}{12}\sum_{k=1}^{12}F(i,j;m,k)\,. \tag{84}$$

The *peak frequency* at a particular gridpoint (i,j) properly speaking is not a mean quantity. It is found as follows. First m_{max} is determined for which F_1 is maximal. A parabola is fitted through $F_1(i,j;m_{max}-1)$, $F_1(i,j;m_{max})$ and $F_1(i,j;m_{max}+1)$. Then the peak frequency $f_p(i,j)$ is given by the position of the maximum of the parabola.

4.6 The wind-input source term

The wind-input source term of the model is a direct transcription from the analytical one which is discussed in section 3.3. Remember that the indices i and j label the position in the GONO grid, the index m labels the frequency and the index k labels the direction of the wave component. The numerical wind-input source term is given by

$$S_{in}(i,j;m,k) = \max\left\{0.0003\,\omega(m)\left(28u_*(i,j)\frac{k(i,j;m)}{\omega(m)}\cos\left(\frac{2\pi(k-1)}{12}-\phi(i,j)\right)-1\right)F(i,j;m,k)\,,0\right\}, \tag{85}$$

where $u_*(i,j)$ and $\phi(i,j)$ are the magnitude and the direction of the friction velocity at position (i,j) and $\omega(m)/k(i,j;m)$ is the phase velocity c_p of the wave component $F(i,j;m,k)$. ϕ is defined as the direction where the wind is blowing to, with respect to the y-axis of the GONO grid. $2\pi(k-1)/12$ is the direction of the wave vector of wave component $F(i,j;m,k)$, also with respect to the y-axis of the GONO grid. The factor 0.0003 stands for $0.25\rho_a/\rho_w$, one quarter of the ratio of the density of air to the density of water.

In Nedwam, the friction velocity u_* is directly related to u_{10}, the wind speed at $10m$ height, by a simple draglaw:

$$u_* = \sqrt{c_D}u_{10}\,, \quad c_D = \begin{cases} 1.2873\,10^{-3} & \text{if } u_{10} \le 7.5m/s \\ 0.8\,10^{-3} + 0.65\,10^{-4}u_{10} & \text{if } u_{10} > 7.5m/s \end{cases} . \tag{86}$$

4.7 The dissipation source term

The dissipation source term of the model is a direct transcription from the analytical one which is discussed in section 3.4. Remember that the indices i and j label the position in the GONO grid, the index m labels the frequency and the index k lables the direction of the wave component. The numerical dissipation source term is given by

$$S_{dis}(i,j;m,k) = -2.6\,(2\pi)\overline{f}(i,j)\,E(i,j)^2\,\overline{k}(i,j)^3\,k(i,j;m)\,F(i,j;m,k)\,, \tag{87}$$

where $k(i,j;m)$ is the wave number of wave component $F(i,j;m,k)$, $\overline{f}(i,j)$ is the mean frequency of the spectrum $F(i,j)$ at position (i,j), $E(i,j)$ the wave variance at position (i,j) and $\overline{k}(i,j)$ is the mean wave number of the spectrum at position (i,j). The mean quantities $\overline{f}$, E and $\overline{k}$ are functionals of the spectrum $F(i,j)$. They are defined in section 4.5.

4.8 The bottom-dissipation source term

The bottom-dissipation source term of the model is a direct transcription from the analytical one which is discussed in section 3.5. Remember that the indices i and j label the position in the GONO grid, the index m labels the frequency and the index k lables the direction of the wave component. The numerical bottom-dissipation source term is given by

$$S_{bot}(i,j;m,k) = -\frac{(0.076m^2s^{-3})}{g}\frac{k(i,j;m)}{\sinh(2k(i,j;m)D(i,j))}F(i,j;m,k)\,, \tag{88}$$

where $g = 9.806ms^{-2}$ denotes the gravitational acceleration, $k(i,j;m)$ is the wave number of wave component $F(i,j;m,k)$ and $D(i,j)$ is the depth of the GONO grid at position (i,j).

4.9 The wave-wave interaction source term

The wave-wave interaction source term of the numerical model does not correspond directly to the analytic wave-wave interaction source term, eqs. (40)-(43), of section 3.6.

In section 3.6, the wave-wave interaction source term is expressed in terms of an integral over resonating wave-vector *quadruplets* (eq. (40)). A set of four wave vectors forms a resonating quadruplet if the wave vectors and frequencies satisfy the resonance conditions

$$\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4 = 0 \tag{89}$$

$$\omega_1 + \omega_2 - \omega_3 - \omega_4 = 0\,. \tag{90}$$

If one would like to obtain the wave-wave interaction source term S_{nl} from eq. (40), one should discretize the five-dimensional space of resonating quadruplets, and calculate for each quadruplet $(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$ the contributions to $S_{nl}(\mathbf{k}_1)$, $S_{nl}(\mathbf{k}_2)$, $S_{nl}(\mathbf{k}_3)$ and $S_{nl}(\mathbf{k}_4)$. This is what is done in *e.g.* the one gridpoint research wave model EXACT-NL [Hasselmann 1981]. But EXACT-NL uses as many as 600000 interacting quadruplets, and this method is too slow to use for the 612 gridpoint model Nedwam.

Of course, one of the approaches to simplify the EXACT-NL procedure is to use less interacting quadruplets. Hasselmann et al. [1985b] have carried this approach to the extreme: they proposed to represent the five-dimensional space of resonating quadruplets by a very simple two-dimensional space whith only one type of quadruplet. The surprising and good thing is that this turns out to work rather well. The above approximation is called the *discrete interaction approximation.*

Of each quadruplet, two of the wave vectors are the same, $\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}$, and the other two have frequencies which are $\omega_+ = (1+\lambda)\omega$ and $\omega_- = 1-\lambda)\omega$, with $\lambda = 0.25$. Clearly the resonance condition eq. (90) is satisfied. In [Hasselmann 1985a] it was found that quadruplets with $\lambda \approx 0.25$ give particularly large contributions to the wave-wave interactions. The precise value of λ has been chosen with some care. The angles of the third and the fourth wave follow from the condition eq. (89), $2\mathbf{k} = \mathbf{k}_+ + \mathbf{k}_-$. Given $\mathbf{k}$ and λ, there are two solutions, one is obtained from the other one by a reflection in $\mathbf{k}$. In deep water, the wave vector $\mathbf{k}_+$ makes an angle of $\mp 11.48^0$ with $\mathbf{k}$ and the wave vector $\mathbf{k}_-$ makes an angle of $\pm 33.56^0$ with $\mathbf{k}$ (note the signs). For shallow water the dispersion relation $\omega = \omega(k)$ is depth dependent, and if one would wish to retain $2\mathbf{k} = \mathbf{k}^+ + \mathbf{k}^-$, the angles of $\mathbf{k}^+$ and $\mathbf{k}^-$ with respect to $\mathbf{k}$ should be depth dependent. However, in WAM and Nedwam ones gives up this relation for shallow water, and one always takes the deep water quadruplets.

To similate the shallow water effect, an effective shallow water factor is introduced [Herterich 1980, WAMDI 1990],

$$S_{nl}(i,j;m,k) = R\big(0.75\overline{k}(i,j)D(i,j)\big)S_{nl,deep}(i,j;m,k)\,, \tag{91}$$

with

$$R(x) = 1 + \frac{5.5}{x}(1 - 0.883x)\exp^{-1.25x}\,, \tag{92}$$

where $\overline{k}(i,j)$ is mean wave number (see section 4.5) and $D(i,j)$ the depth at GONO gridpoint (i,j).

In WAM and Nedwam, one has two quadruplets, which are mirror images, for every (f,θ) in the frequency direction grid. So in total, there are only $2 \times 25 \times 12 = 600$ resonating quadruplets instead of the 600000 of EXACT-NL. In *fig. 2* a mirror-image pair of resonating quadruplets is drawn on the frequency direction grid.

$\mathbf{k}$ corresponds to a gridpoint of the frequency direction grid, but $\mathbf{k}_+$ and $\mathbf{k}_-$ do not.

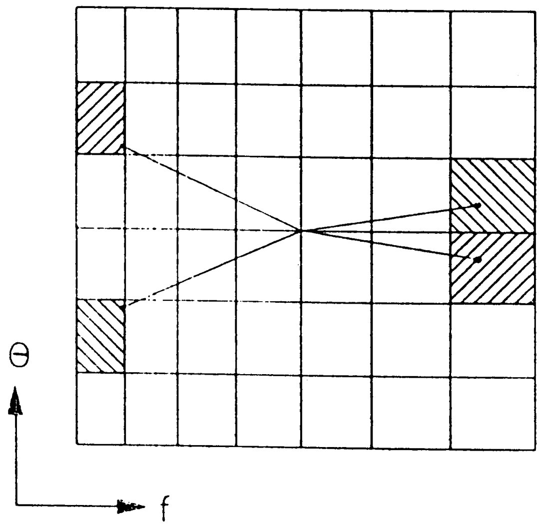


Figure 2: (After van Vledder [1990]) One of the mirror image pairs of resonating quadruplets which are used by WAM in the frequency direction grid. The hatched areas indicate which gridpoints are involved in the bilinear interpolation to (f_+, θ_+) and (f_-, θ_-).

Bilinear interpolation is used to connect $\mathbf{k}_+$ and $\mathbf{k}_-$ to gridpoints on the frequency direction grid. The components F^+ and F^- which correspond to $\mathbf{k}^+$ and $\mathbf{k}^-$ are obtained from the four frequency direction gridpoints around (f^+, θ^+) and (f^-, θ^-):

$$F^+ = \sum_{\ell=1}^{4} w^+(\ell) F(i,j; m_\ell^+, k_\ell^+) \tag{93}$$

$$F^- = \sum_{\ell=1}^{4} w^-(\ell) F(i,j; m_\ell^-, k_\ell^-) \ . \tag{94}$$

If k corresponds to frequency f_m and direction θ_k, and if the orientation of the multiplet is denoted by σ, then the indices m_ℓ and k_ℓ and the weight factors w_ℓ are given by:

$$\begin{array}{lll}
m_1^+ = m + 2 & k_1^+ = k \bmod 12 & w_1^+ = 0.669 \times 0.617 \\
m_2^+ = m + 2 & k_2^+ = k - \sigma \bmod 12 & w_2^+ = 0.669 \times 0.383 \\
m_3^+ = m + 3 & k_3^+ = k \bmod 12 & w_3^+ = 0.331 \times 0.617 \\
m_4^+ = m + 3 & k_4^+ = k - \sigma \bmod 12 & w_4^+ = 0.331 \times 0.383 \\
m_1^- = m - 4 & k_1^- = k + \sigma \bmod 12 & w_1^- = 0.019 \times 0.881 \\
m_2^- = m - 4 & k_2^- = k + 2\sigma \bmod 12 & w_2^- = 0.019 \times 0.119
\end{array}$$

$$m_3^- = m - 3 \quad k_3^- = k + \sigma \bmod 12 \quad w_3^- = 0.981 \times 0.881$$

$$m_4^- = m - 3 \quad k_4^- = k + 2\sigma \bmod 12 \quad w_4^- = 0.981 \times 0.119\,, \tag{95}$$

except for that if $m = 1, 2, 3, 4$, then $m_\ell = 1$ and $w_\ell = 0$. The signs σ in the expressions for the k_ℓ correspond to the two possible configurations of the quadruplet. If necessary, a $1/f^4$ tail, which corresponds to the deep-water limit of eq. (69), is added to the spectrum for frequencies beyond f_{25}. Except for the lowest frequencies, one has

$$\sum_\ell w_\ell^+ = 1$$

$$\sum_\ell w_\ell^- = 1 \tag{96}$$

and

$$\sum_\ell w_\ell^+ f_{m_\ell^+} = f^+$$

$$\sum_\ell w_\ell^- f_{m_\ell^-} = f^- \tag{97}$$

and

$$\sum_\ell w_\ell^+ \theta_{k_\ell^+} = \theta^+$$

$$\sum_\ell w_\ell^- \theta_{k_\ell^-} = \theta^- \,. \tag{98}$$

To stay as close as possible to the integral expression eq. (40), the contribution from a quadruplet to the wave-wave interaction source function S_{nl} should be proportional to

$$C(\mathbf{k}, \mathbf{k}, \mathbf{k}^+, \mathbf{k}^-)\big(A(\mathbf{k})A(\mathbf{k})(A(\mathbf{k}^+) + A(\mathbf{k}^-)) - 2A(\mathbf{k}^+)A(\mathbf{k}^-)A(\mathbf{k})\big)\,.$$

Since the frequencies and directions within the multiplet have a fixed relationship, C can be written as

$$C(\mathbf{k}, \mathbf{k}, \mathbf{k}^+, \mathbf{k}^-) = g^{-4}\omega^{12}C'$$

with C' a dimensionless constant. For shallow water, C' would have been depth dependent, $C' = C'(kD)$. Substituting $A(\mathbf{k}) = F(\mathbf{k})/\omega$, and switching from $\mathbf{k}$ to f and θ as variables, one finds, using $F(\mathbf{k}) = (g^2/\omega^3)F(f, \theta)$ (see eq. 17),

$$\big(A(\mathbf{k})A(\mathbf{k})(A(\mathbf{k}^+) + A(\mathbf{k}^-)) - 2A(\mathbf{k}^+)A(\mathbf{k}^-)A(\mathbf{k})\big) \sim$$

$$g^6\omega^{12}\left\{\frac{F^2F^+}{(1+\lambda)^4}+\frac{F^2F^-}{(1-\lambda)^4}-2\frac{FF^+F^-}{(1-\lambda^2)^4}\right\}.$$

Some more factors g and ω come from the phase space and the δ-functions of eq. (40) and the change from $S(\mathbf{k})$ to $S(f,\theta)$. Combining the above results, the contribution from one quadruplet to the wave-wave interaction source term is found to be:

$$\delta S^Q = Cg^{-4}\omega^{11}\left\{\frac{F^2F^+}{(1+\lambda)^4}+\frac{F^2F^-}{(1-\lambda)^4}-2\frac{FF^+F^-}{(1-\lambda^2)^4}\right\}. \tag{99}$$

C is a dimensionless constant, which does not follow directly from eq. (40), but has to be tuned in such a way that the restricted set of quadruplets reproduces as far as possible the full integral, eq. (40). In WAM and Nedwam one uses

$$g^{-4}C = 3000m^{-4}s^8 . \tag{100}$$

From eq. (40) it follows that the rates of change of the action densities which come from the quadruplet $(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$ are related by

$$\delta A(\mathbf{k}_1)d\mathbf{k}_1 = \delta A(\mathbf{k}_2)d\mathbf{k}_2 = -\delta A(\mathbf{k}_3)d\mathbf{k}_3 = -\delta A(\mathbf{k}_4)d\mathbf{k}_4 .$$

In the discrete case, and changing to f and θ as variables, this becomes

$$\frac{1}{2}\frac{\delta S(f,\theta)}{\omega}\Delta\theta\Delta f = -\frac{\delta S(f^+,\theta^+)}{\omega^+}\Delta\theta^+\Delta f^+ = -\frac{\delta S(f^-,\theta^-)}{\omega^-}\Delta\theta^-\Delta f^- , \tag{101}$$

where the factor 1/2 arises because in our case $\mathbf{k}_1 = \mathbf{k}_2$. In WAM and Nedwam, $\Delta\theta_k = \Delta\theta = \pi/6$, and $\Delta f_i \sim f_i$ (see eqs. (44) and (67) which imply $\Delta f_i = (f_{i+1} - f_{i-1})/2 = (1.1 - 1/1.1)f_i/2)$. Thus eq. (101) simplifies to

$$\frac{1}{2}\delta S(f,\theta) = -\delta S(f^+,\theta^+) = -\delta S(f^-,\theta^-) .$$

After bilinear interpolation to the frequencies and directions around (f^+, θ^+) and (f^-, θ^-), one arrives at

$$\begin{aligned}
\delta S^{0,\sigma}(i,j;m,k) &= -2\delta S^{Q,eff}(i,j;m,k;\sigma) \\
\delta S^{+,\sigma,\ell}(i,j;m_\ell^+,k_\ell^+) &= w_\ell^+\delta S^{Q,eff}(i,j;m,k;\sigma) \\
\delta S^{-,\sigma,\ell}(i,j;m_\ell^-,k_\ell^-) &= w_\ell^-\delta S^{Q,eff}(i,j;m,k;\sigma) ,
\end{aligned} \tag{102}$$

where $S_{Q,eff}$ is obtained from S^Q by multiplication with shallow water correction factor R from eq. (91):

$$S^{Q,eff} = R\Big(0.75\bar{k}D\Big)S^Q(i,j;m,k;\sigma)\,. \tag{103}$$

Finally, the components of the discrete wave-wave interaction source term $S_{nl}(i,j;m,k)$ are obtained by adding the various contributions:

$$\begin{aligned} S_{nl}(i,j;m,k) \;=\; & \sum_{\sigma=\pm1} \delta S^{0,\sigma}(i,j;m,k) + \\ & \sum_{\sigma=\pm1}\sum_{\ell=1}^{4} \delta S^{+,\sigma,\ell}(i,j;m,k) + \\ & \sum_{\sigma=\pm1}\sum_{\ell=1}^{4} \delta S^{-,\sigma,\ell}(i,j;m,k)\,. \end{aligned} \tag{104}$$

In the above sums, only the contributions from multiplets with central frequencies which are below the high-frequency cut-off are considered ($m \le n_{hf}$). Generally, a component $S_{nl}(i,j;m,k)$ receives 18 contributions δS from 15 different points of the frequency direction grid (see *fig. 2*).

After the bilinear interpolation, the net contribution of δS^Q to the rate of change of the action still vanishes, because

$$\begin{aligned} & \frac{1}{2}\frac{\delta S^{0,\sigma}(i,j;m,k)}{\omega_m}\Delta f_m \Delta\theta + \sum_{\ell=1}^{4} \frac{\delta S^{+,\sigma,\ell}(i,j;m_\ell^+,k_\ell^+)}{\omega_{m_\ell^+}}\Delta f_{m_\ell^+}\Delta\theta \\ & = \frac{1}{2}\frac{\delta S^{0,\sigma}(i,j;m,k)}{\omega_m}\Delta f_m \Delta\theta \left\{1 - \sum_{\ell=1}^{4} w_\ell^+\right\} \;=\; 0 \end{aligned}$$

and similarly for the m_ℓ^-. The last step holds by virtue of eq. (96). Near the low edge of the grid, *i.e.* $m \le 4$, eq. (96) does not hold, and there the action is not conserved. If $m \ge 4$, the net contribution of δS^Q, to the net rate of change of the wave variance, which is given by

$$\begin{aligned} & \delta S^{0,\sigma}(i,j;m,k)\Delta f_m\Delta\theta + \sum_{\ell=1}^{4}\delta S^{+,\sigma,\ell}(i,j;m_\ell^+,k_\ell^+)\Delta f_{m_\ell^+}\Delta\theta \\ & \qquad + \sum_{\ell=1}^{4}\delta S^{-,\sigma,\ell}(i,j;m_\ell^-,k_\ell^-)\Delta f_{m_\ell^-}\Delta\theta \;=\; \\ & \delta S^{0,\sigma}(i,j;m,k)\Delta f_m\Delta\theta (f_m)^{-1}\left\{2f_m - \sum_{\ell=1}^{4} w_\ell^+ f_{m_\ell^+} - \sum_{\ell=1}^{4} w_\ell^+ f_{m_\ell^-}\right\} \;=\; 0 \end{aligned}$$

also vanishes. In the last step, both eq. (97) and the resonance condition eq. (90) have been used. On the other hand, the net contribution of δS^Q to the net rate of change of the wave momemtum (defined as $\sum(F/\omega)\mathbf{k}\Delta f\Delta\theta$) in general is not zero. This is because of two reasons. First, because the angles of $\mathbf{k}^+$ and $\mathbf{k}^-$ are kept fixed, the resonance condition eq. (89) is satisfied for deep water only, and, second, even for deep water one has

$$\left\{2\mathbf{k}_m - \sum_{\ell=1}^{4} w_\ell^+ \mathbf{k}_{m_\ell^+} - \sum_{\ell=1}^{4} w_\ell^+ \mathbf{k}_{m_\ell^-}\right\} \neq 0 \; .$$

because bilinear interpolation in frequency direction space is not the same as bilinear interpolation in k-space.

The most important properties of the discrete wave-wave interaction are the same as those of the analytic wave-wave interaction: the total wave variance is conserved, the main effect is to smooth the shape of the spectrum, and for windsea wave variance is transferred from a region at or near the peak to higher and lower frequencies.

5 The Nedwam computer program

At the KNMI, the Nedwam computer model is used to make wave forecasts for the North Sea. A 30 hour forecast is issued four times a day.

5.1 The computational task of the Nedwam program

The task of Nedwam is to calculate a series of wave-spectra fields from a series of wind fields. The calculation is done over a finite area, the GONO grid, and over a finite time-span. The GONO grid is shown in *fig. 1* on page 7. As shown in *fig. 3*, the main input of Nedwam consists of wind fields.

A Nedwam *run* is labelled by its *analysis date-time group* (analysis dtg or, for short, *dtg*). In the operational situation, the analysis dtg corresponds to the latest synoptical time before the execution of the run. The purpose of the Nedwam run is to produce wave forecasts for some period after the analysis dtg. This period is called the *forecast period.* Normally, the forecast period of Nedwam is 30 hours. The forecast period ends at the *end date-time group* (end dtg) of the run. Clearly, Nedwam needs forecasted wind fields over the forecast period.

The method to obtain the wave state at the analyis dtg differs from the method used by most types of meteorological models to obtain an initial state. In meteorological models, the initial state is obtained by merging the forecast from the previous run with the observations which have been made since the previous run was executed. But Nedwam does not use wave observations. Instead an improved wave state at the analysis dtg is obtained by using analysed instead of forecasted wind fields to recalculate the wave evolution over the period before the analysis dtg of the run. The latter period is called the *analysis period.* The start

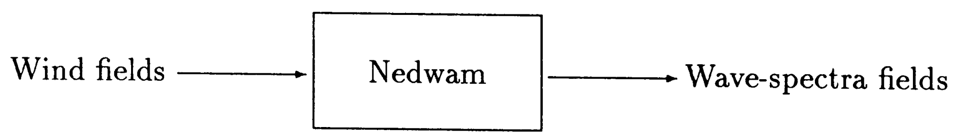


Figure 3: The computational task of Nedwam

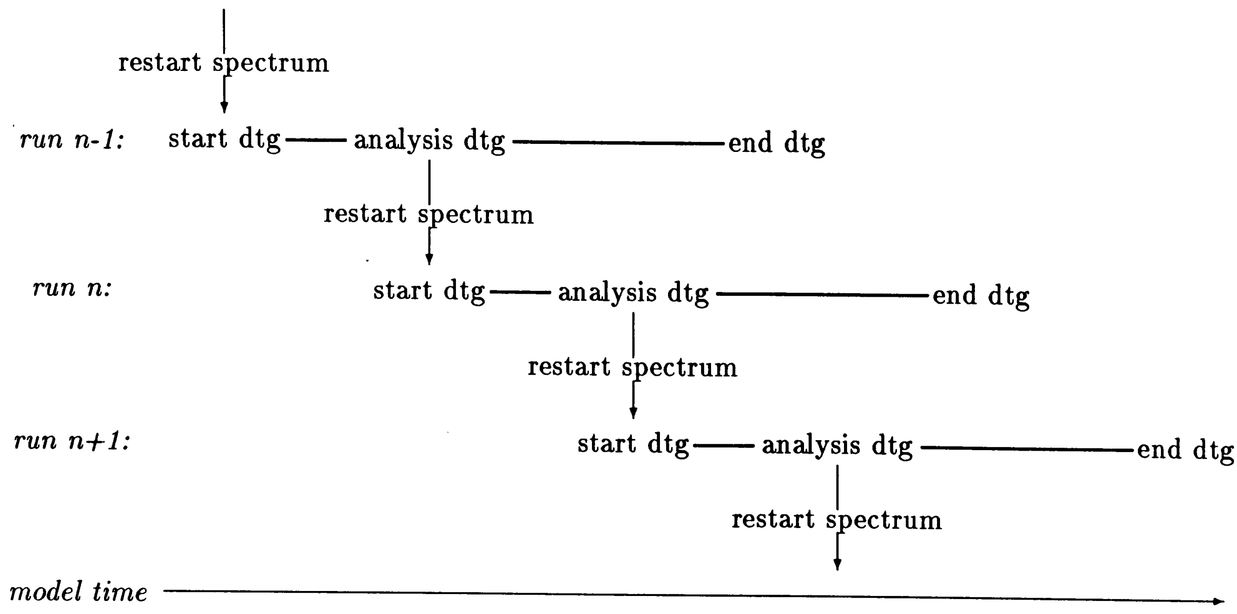


Figure 4: Subsequent Nedwam runs

of the analysis period is called the *starting date-time group* (start dtg) of the run.

In the previous run, forecasted wind fields were used to calculate the wave state at the present analysis dtg. The analysed wind fields which are used by present run to recalculate the evolution over the analysis period generally will be better than the forecasted wind fields, resulting in an improved wave state at the analysis dtg.

Normally, the start dtg of the present run equals the analysis dtg of the previous run. So, if Nedwam is run four times a day, then the analysis period is six hours. The initial-state wave-spectrum field at the start dtg comes from the output of the previous run.

In an uninterrupted series of runs, the analysis periods are neatly joined to give a series of analysed wave states. The relation between subsequent runs is illustrated in *fig. 4*.

In case one or more runs have not been executed for some reason, it is not always feasible to connect the present run to the previous run, as the calculation of the evolution of the wave spectrum over a very long analysis period might be too time consuming, or as some of the wind fields of the analysis period might be missing. The analysis period is not allowed to be larger than a certain maximum. In the present version, this maximum is 12 hours. If a restart spectrum exists from a previous run for the the start dtg, it is always used.

In case there is no restart spectrum, the wave spectrum at the start dtg is set equal to a JONSWAP [1973] spectrum. The parameters of the JONSWAP spectrum depend on the the local windspeed and direction. It has been found that after at most two days one cannot distinguish anymore a series of runs starting from a restart spectrum from a series of runs starting from a JONSWAP spectrum.

The output of Nedwam consists of wave data over the forecast period, including the analysis dtg. More information on the Nedwam output can be found in section 5.5 and in Appendices D and E.

5.2 Nedwam and the KNMI environment

Nedwam is a part of the Automatic Production Line (APL) of the KNMI. The APL is a set of numerical weather prediction models. Some of the models have been developed at the KNMI, other ones are adaptations of existing models to the specific needs of the KNMI. The model results are written into a common data base. All output fields are written in the international meteorological FM 92 GRIB code of the World Meteorological Organisation [WMO 1988]. And, in the near future, all output timeseries will be written in the FM 94 BUFR code [WMO 1988].

The central APL model is the Fine Mesh Limited Area atmospheric circulation Model (LAM). The boundary condition fields for the LAM are taken from the global ECMWF model. Nedwam uses the $10m$ wind fields of the LAM for input. LAM 30 hour forecasts are made four times a day, and Nedwam makes four times a day a 30 hour forecast too.

The LAM grid is different from the GONO grid used by Nedwam. Hence, the wind fields must be interpolated from the LAM grid to the GONO grid. Special care is taken to treat the interpolation near land-sea transitions well. For a GONO seapoint, only the neighbouring LAM seapoints are taken into account in the interpolation, but the neighbouring LAM landpoints are ignored. For a GONO landpoint, it is just the other way round. So the interpolation program for the winds must have access to the land/sea character of the LAM and the GONO grid points. In the present version of the Nedwam program package, this information is stored inside the directory of the interpolation program. If the LAM grid or the GONO grid ever changes in the future, one has to update this information.

As a back-up for LAM winds, British Meteorological Office fine-mesh (UKMO) wind fields can be used. UKMO forecasts are made twice daily. If UKMO forecasts are used, Nedwam makes twice a day a 36h forecast. In the interpolation of the wind fields from the UKMO grid to the GONO grid, the land-sea transitions are not taken into account.

5.3 The NEWA system

The Nedwam part of the APL is called the NEWA system. (Note that, the term "Nedwam" is rather ambiguous: it can refer to the NEWA system, to the Nedwam Fortran computer program, or to the Nedwam numerical wave model.)

The NEWA system is implemented on a CONVEX C1 superminicomputer which has a UNIX operating system.

One NEWA run, 6h analysis + 30h forecast, takes about a quarter of an hour of computer time. The internal memory requirement of the Nedwam program is about 7 Mb, that of the Bimwam program (see next section) is about 18 Mb. The on-disk memory requirement is about 15 Mb, mainly for storing model output data.

The NEWA system consists of several modules. Each module is executed by a separate shell *script*. The scripts are written in Unix C-shell. A script may call other scripts or Fortran programs. The central modules are the wind-field interpolation module *make_Wamwinds.sc* and the Nedwam wave-model module *run_Nedwam.sc.*

The modules are started in the appropriate order by the the *NEWA.ISF* intermediate supervisor script. This "intermediate" supervisor in turn is started by the supervisor of the APL. *NEWA.ISF* has three main internal control variables: the wind-field type *runid*, the analysis date-time group *dtg* and the forecast period *fp*. The wind-field type is a character variable which indicates whether LAM winds from the KNMI ('L') or UKMO winds from the British Meteorogical Office ('B') should be used. The analysis dtg is given in *yymmddhh* format, *e.g.* 92041206 stands for April 12, 6Z00, 1992. The forecast period refers to the forecast period in hours of the Nedwam run. Two of these parameters, *runid* and *dtg* can be specified as arguments of *NEWA.ISF.* If not specified, *runid* is initially set to 'L'. If a run which uses LAM winds is not possible, *e.g.* because the LAM forecast fields are not available, *runid* is reset to 'B' and a run which uses UKMO winds is started. Special care is taken that, if necessary, runs with UKMO winds can alternate runs with LAM winds. The analysis·dtg can only be specified in combination with the wind-field type. If *dtg* is not specified, then the analysis dtg is determined according to the actual real-world date and time.

If there are LAM or UKMO wind-field files available, and no run for the analysis dtg has been completed successfully yet, *NEWA.ISF* starts the first module.

The modules which are started by *NEWA.ISF* are relatively loosely connected. Therefore, there is some redundancy in the checks made by the various modules. Each module can be started independently, if necessary.

The first module which is started by *NEWA.ISF* is the wave-data observation module *run_GTSwam.sc.* This module collects wind and wave-height observations from the operational KNMI date base of GTS observations over a 12 hour period before the analyis dtg. The observations are stored for verification purposes. Also, observations might be needed for wave-data assimilation in future versions of the Nedwam model. *run_GTSwam.sc* has only one argument, *dtg.*

The next module which is started by *NEWA.ISF* is the wind-field interpolation module *make_Wamwinds.sc.* The purpose is to interpolate wind fields on the wind-model grid to wind fields on the wave-model grid. This is done using standard APL programs. Land-sea transitions are taken into account in the interpolation from the LAM grid to the GONO grid, but not in the interpolation from the UKMO to the GONO grid. The script has three argument, *dtg, fp* and *runid.* The wind-field interpolation module is called several times by *NEWA.ISF* with different values of its arguments. *NEWA.ISF* always tries to make wind-field files of the same wind-field type which cover all of the forecast period and an analysis period which extends 12 hours back into the past. *NEWA.ISF* will not attempt to make a wave-model run if *make_Wamwinds.sc* fails to make a file with interpolated winds over the forecast period.

After successful execution of the wind-field interpolation module, *NEWA.ISF* starts the Nedwam wave-model module *run_ Nedwam.sc.* This is the script which calls the Fortran program Nedwam. The executable of Nedwam is called *nedwam.exe.* The program Nedwam is an implementation of the numerical Nedwam model of chapter 3. The wave model script has two arguments, *dtg* and *runid.* In addition to the two arguments, the script has three more control parameters: the forecast period *fp*, the analysis period *ana*, and the restart parameter *isitrs. isitrs* = 'YES'/'NO' indicates whether a restart wave spectrum from a previous run is to be used or not. *fp*, *ana* and *isitrs* depend on the parameters of the previous run and on which wind-field files and restart files are available. After a successful run, the five control parameters are stored in a file *Last_nedwam.sc_run*. Some permanent information, like the depth of the sea and the group velocities for all frequencies for all gridpoints, should be present in a rather large binary file WAMGEO. If necessary, the WAMGEO file will be regenerated automatically by the Fortram program Prewam.

The next script started by *NEWA.ISF* after a successful Nedwam wave-model module run is the *run_Bimwam.sc* script which starts the Fortran program Bimwam. A legacy from the past, the Bimwam program has a double purpose: to write some of the output of the Nedwam model in TSF format [Hafkenscheid 1988]. and to run the Sectormodel or "Bim" wave model. The Sectormodel is discussed in [van der Tol 1988]. For the Sectormodel, the input comes from *PREPOC* module of the VAKA system. The VAKA system contains the Sectormodel for waves and the Sectormodel for storm surges of the APL. For the time being, the VAKA modules are started by the intermediate supervisor of the WAQUA system. The WAQUA [de Vries] system is the North Sea storm-surge part of the APL. So the Sectormodel part of Bimwam can only run if the WAQUA system is on. The Bimwam module script has two arguments, *dtg* and *runid*. Priority is given to the first task of Bimwam, to write part of the Nedwam model output in TSF format. Bimwam will only be executed after a successful Nedwam run. On the contrary, if the Sectormodel input is missing, this is no reason not to run the Bimwam module. The arguments of the last successful *run_Bimwam.sc* run are stored in the file *Last_bimwam.sc_run*, toghether with *fp*.

Finally, after a successful *run_Nedwam.sc* run two more scripts are started by *NEWA.ISF*. *Postwam.sc* does some post processing of results in Nedwam files. *Cleanwam.sc* removes most data files which are older than 24 h. Both scripts have one argument, *dtg*.

The above description of the script reflects the status of summer 1990. It is quite likely that there will be some changes as the KNMI gains more experience with the APL. More and more up-to-date information on how to use the scripts, can be found in the on line documentation (*.documentation*) files.

5.4 The data structures of the NEWA system

A list of data-file names used by Nedwam and the NEWA system can be found in Appendix C. The data structures of Nedwam will be discussed in the next section. The principal data flow of the NEWA system is as follows. First wind fields from LAM or UKMO field files are interpolated to the GONO grid, resulting in NEWA wind field files. Next the Nedwam wave model calculates the evolution of the wave-spectrum field from the NEWA wind fields. Various types of output files are produced: logfiles, data files to be used by subsequent runs, and data files on the forecasted evolution of the waves. The results are presented in the Nedwam field file, in the Nedwam timeseries file and in the Nedwam spectra file. Additional spectra and timeseries at gridpoints specified by the user can be produced too.

The NEWA system is run after each forecast run of the LAM model.

First the observation module searches the GTS data base of the APL for observations. Waveheight and windspeed observations in the GONO grid area for the analysis date-time group *dtg* are put in a wave-data observation file. Similar files are made for the dtg's of 3 hour, 6 hour, 9 hour and 12 hour before *dtg*. The name of the wave-data observation file of date-time group *yymmddhh* is NEWA_GTS_*yymmddhh*.

Next, the wind-field interpolation module makes NEWA wind-field files from the LAM or UKMO field files. The name of each data file is labelled by its analysis date-time group in *yymmddhh* format. The LAM field files have names LAMF_FMT_*yymmddhh*00_00000_AB, the UKMO field files UKMO_ARG_*yymmddhh*00_00000_AB. The NEWA wind-field files are called NEWL_INP_*yymmddhh*00_00000_AB if they are calculated from LAM fields (NEWL wind fields) and NEWB_INP_*yymmddhh*00_00000_AB if they are calculated from UKMO field (UKMO wind fields). The NEWL and NEWB wind fields are stored in the form of wind-field components with respect to the GONO grid. All fields are coded in the standard FM 92 GRIB code of the World Meteorological Organization [WMO 1988]. The GRIB code keys are given in appendix D. The LAM and UKMO files are much larger than the NEWA wind-field files, because they contain apart from the $10m$ wind fields many other types of fields.

The wind-field interpolation module will use modified interpolation weights if a "modified weight file" NEWr_weights_m exists (r = 'L' or 'B'). The quality of the interpolated wind fields is improved by using modified interpolation weights in the vicinity of land-sea transitions. For the LAM grid, this file exists, but for the UKMO grid no modified weight file has been made so far. To regenerate the modified weight file, land-sea mask files which contain the land/sea character of the LAM gridpoints and the GONO gridpoints are needed. The latter can be made by programs of the wind-field interpolation module, but the LAM land-sea mask file should be supplied externally. If the LAM or the GONO grid ever will be changed in the future, the modified weight file should be changed accordingly.

Four times a day, at 00Z, 06Z, 12Z and 18Z, the LAM produces a forecast file which contains the analysed fields of that time and 3 hourly forecasted fields up to +30 hours. At the intermediate times of 03Z, 09Z, 15Z and 21Z an analysis file is produced with analysed fields only. UKMO +36 hour forecasts are produced twice a day, at 00Z and 12Z, and UKMO analyses are produced at 06Z and 18Zs. The NEWA wind-field files match the LAM/UKMO field files. Every NEWA run, a NEWL forecast wind-field file is made from the last LAM forecast, and an analysis wind-field file is made from the preceding LAM analysis file. If there are no LAM forecasts available for all of the forecast period, it is tried to make NEWB wind-field files from UKMO field files.

In this way, the forecast period of the run is covered by one file containing the wind fields of the analysis for em dtg, the +3 forecast for *dtg*+3 hours, and so on till the +30 forecast for *dtg*+30 hours. The wind fields of the analysis period are in a separate files. In the usual LAM case, the analysis of *dtg*-3 hours is in the NEWL analysis file of *dtg*-3 hours, and the analysis of *dtg*-6 hours is in the NEWL forecast file of the previous NEWA run. If necessary, *e.g* in the case of missing previous wind-model forecast runs or alternating LAM and UKMO runs, additional NEWA wind-field files are made to cover the 12 hours preceding the analysis dtg.

The NEWA wind-field files are input files for the wave-model module which runs the Nedwam program. The data structures of the Nedwam program are discussed in the next section.

As mentioned in section 5.3, the first task of the Bimwam module is to change the temporary Nedwam timeseries file NEWA_TMP_*yymmddhh* into the final timeseries file NEWA_TMS_*yymmddhh*00_0*fp*000_TW. A second task of the Bimwam module is to estimate confidence levels for the wave height and E_{10} by means of the simple Sectormodel and to add these quantities to the timeseries. The input for the Sectormodel is taken from the VAKA_INP_0000000000_00000_VB file from the VAKA system. Information on the status of the VAKA/WAQUA system is read from the WAQG_DTM_0000000000_00000_LC file.

NEWA.ISF writes diagnostic messages concerning the status of each executed module to a summary logfile, *NEWA.shortlog*. The meaning of the exit status codes of the shell scripts is given in Appendix G. The various programs and scripts write more detailed diagnostic messages to the standard output device. The Unix operating system allows for redirecting this information to a comprehensive logfile, *NEWA.longlog*.

5.5 The data structures of the Nedwam program

A list of the input and output files of the Nedwam program can be found in Appendix C, and a list of the common block variables in Appendix F. The minimal input of Nedwam consists of control parameters, I/O file directory names, a permanent data-base file and a proper forecast wind-field file which covers the forecast period of the run. Normally, additional wind-field files will be used to cover the analysis period of the run, and the wave spectrum at the start dtg of the run will be read from a restart spectrum file. Moreover, there may be an user supplied input file containing a list of grid points where additional timeseries and/or spectra are required.

The Nedwam wave-model module script has two arguments, the analysis date-time group *dtg*, and the wind-field type *runid*. Three more control parameters are the forecast period *fp*, the analysis period *ana* and the restart parameter *isitrs* (*isitrs*='YES'('NO') if a restart spectrum is (is not) to be used). *fp*, *ana* and *isitrs* depend on the parameters of the previous run, read from the file Last_nedwam.sc_run, and on which wind-field files and restart files are available. Normally, *runid*='L' (LAM winds), *fp*=30 hours, *ana*=6 hours and *isitrs*='YES'.

The five control parameters of the Nedwam wave-model module script correspond directly to the five control parameters of the Fortran program Nedwam. They are read from the standard input device. Also the names of the directories of the input files and output files are read from the standard input device. The standard input device is redirected to a namelist in the run_nedwam.sc script.

Nedwam needs to know the properties of the GONO grid, in particular the depth at all the gridpoints. This information is put in a permanent data-base file WAMGEO, together with various other constants used by the program. If, for some reason, WAMGEO is missing at the start of the Nedwam module script run, it will be regenerated by the execution of the

Fortran program Prewam.

The NEWA wind-field files have names NEW*r*_INP_*yymmddhh*00_00000_AB with *r* the *runid* of the run. In these GRIB-coded [WMO 1988] files, the wind fields are stored in the form of components with respect to the GONO grid. The GRIB code keys are given in Appendix D. Nedwam can only run successfully if a proper forecast wind-field file for *yymmddhh=dtg* exists. Normally the analysis wind-field file for *yymmddhh=dtg*-3h and a forecast or analysis wind-field file for *yymmddhh=dtg*-6h are used to cover the analysis period of the run.

If possible, the wave spectrum at the starting date-time group of the run is read from the restart file NEWA_RST_*yymmddhh*, with *yymmddhh* corresponding to the starting dtg of the run. The restart file are binary files. They are quite large, almost 1Mb.

Internally, the Nedwam program calculates the evolution of the wave spectrum in time steps of 30 minutes. So for a run over a period of length of 36 hours, 72 wave spectra are calculated, each spectrum represented by $612 \times 300 = 183600$ numbers. Not all this information is stored, neither internally, nor externally. Internally, only the current spectrum and spectral increment are stored. Also, only the current wind field is stored. Externally, at regular time intervals, part or all of the spectral information is written to various output files. Internal communication goes mainly through common blocks. The parameters and common blocks are listed in Appendix F. In Nedwam, the current wave spectrum is represented by an array F1(L,M,K) where L labels the gridpoints on the extended grid (eq. (9)), M labels the frequencies (eqs. (44-46)) and K labels the directions (see sect. 4.1). A similar array, F2(L,M,K), contains the increment due to advection, eq. (54). The source-term increment of eq. (60) is contained in the array SL(IJ,M,K). The current wind speed, direction and friction velocity are in the arrays U10(IJ), THW(IJ) and USTAR(IJ), respectively. IJ labels the gridpoints on the GONO grid (eq. (7)). The wind direction THW is defined as going to, with respect to the positive y-axis of the GONO grid. Although the code of Nedwam is very similar to the code of the global WAM model, there a some differences which one should be aware of if one wants to adapt a WAM subroutine for use in Nedwam. *E.g.*, in the global WAM model the wave spectrum is represented by F(L,K,M): the order of the direction and frequency indices is reversed.

Restart files, NEWA_RST_*yyhhmmdd* are dumped every 6 hours, starting at the analyisis dtg of the run. So a normal Nedwam run with *fp*=30 hours produces seven restart files (in the present configuration of the NEWA system, the ones with *yymmddhh*≥*dtg*+24h are removed by the Nedwam module script to save memory). The binary restart files are intended only for use by later Nedwam runs and not for presentation purposes.

Nedwam fields on the GONO grid at *dtg*, *dtg*+6h, *dtg*+12h, ... *dtg*+*fp*h, are written to the Nedwam output field file. The fields in question are wind speed, wind direction, significant waveheight, mean wave direction, variation in the mean wave direction, mean period, peak frequency, E_{10}. The definition of the various mean quantities has been given in section 4.5. The name of the output field file is NEW*r*_MAP_*yymmddhh*00_00000_AB (*yymmddhh*=*dtg*, *r*=*runid*). The field file is GRIB coded, the GRIB keys are given in appendix D.

Listed in Appendix B are 20 special gridpoints, the GONO swellpoints. Timeseries of eleven quantities over the forecast period at the GONO swellpoints are written to a temporary Nedwam timeseries file. The timestep of the timeseries is one hour. In addition to the quantities written to the output field file, also the mean E_{10} direction and the variance in the mean E_{10} direction are written to the timeseries file. The name of the temporary timeseries file is NEWA_TMP_*yymmddhh*. It is an intermediate file: the Bimwam module adds a few more quantities from the Sectormodel and writes all information to the (final) Nedwam timeseries file called NEWA_TMS_*yymmddhh*00_0*fp*000_TW, with the forecast period *fp* a two-digit number. This final timeseries file is TSF coded [Hafkenscheid 1988]. The TSF keys are given in appendix E.

Timeseries of the full wavespectra over the forecast period at the 20 GONO swell points mentioned above are written, with a timestep of three hours, to the Nedwam spectra file, NEWA_TSS_*yymmddhh*00_0*fp*000_TW. Also this file is TSF coded.

It is possible for the user to get timeseries and/or spectra at points which are different from the 20 GONO swell points. In the present version of Nedwam this works as follows. The user should supply a file NEWA_REQUEST containing a list of points for which the timeseries and/or the spectra are requested. Then the timeseries for these points are written to the NEWA_RQT_*yymmddhh*_*fp* file and histograms of the spectra to the NEWA_RQS_*yymmddhh*_*fp* file. The timestep is three hours. Both these files are formatted.

After a successful Nedwam run, the control parameters are written to a file WAMSTATUS. This file is not used by the NEWA system, because the Nedwam module script writes equivalent control parameters to the file Last_nedwam.sc_run.

5.6 The organization of the Nedwam program

The Nedwam numerical model of chapter 4 is implemented as the Nedwam program. The main program reads like a flow chart, see *fig. 5.* The hierarchy of the Nedwam subroutines is given in *fig. 6.*

The program has three general service routines. All business relating opening and closing files is directed through the routine WFILE. Diagnostic messages are sent by the message subroutine WRMSG. The program uses character variables to represent date-time groups which indicate the current time, the times when the next wind fields should be read, when the next output of a restart field should be done, etc. The routine INCDATE which adds an integer number of seconds to a date-time group in *yymmddhhmmss* format is used to change time indicator variables.

The program begins with an initialization part.

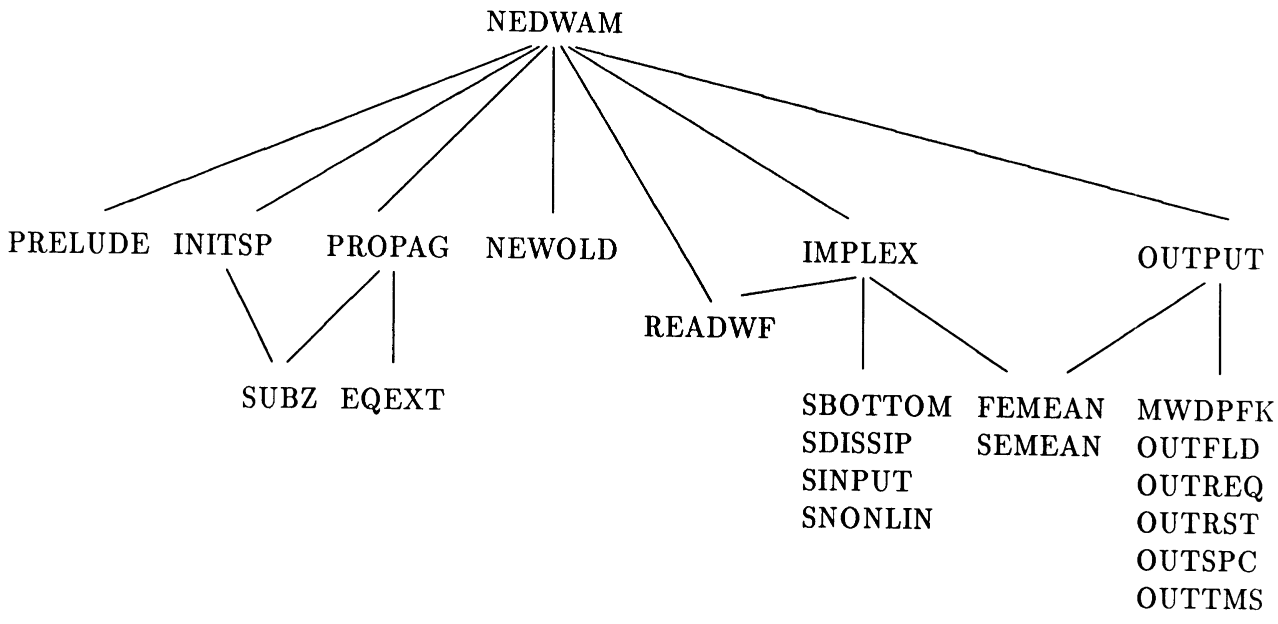
The first subroutine called by the main program is the initialization subroutine PRELUDE. This routine starts by reading the control parameters of the run and the names of the directories of the input and the output files. Next some files are opened, and the time indicator variables are initialized. Finally the permanent data-base file WAMGEO is read.

The next subroutine called by the main program is the routine READWF, which reads for a given date-time group the wind fields from a Nedwam wind-field file. To read the GRIB-coded wind fields, the KNMI library programs GETFLD and DECOGC are used. READWF tries to find the best possible wind field: first it looks for an analysis for the requested dtg, if this analysis is not found it then looks for a +3h forecast, then for a +6h forecast, and so on. Having read the wind fields, the wind-time indicators are reset. One is the dtg of the next wind field to be read, and the other one is at which value of the current program time this field should be read. This is done in such a way that the wind field of time *dtgw* is used from one and a half hour before *dtgw* to one and a half hour after *dtgw.* Also the conversion from wind speed to wind friction velocity is done by this routine. At the initialization stage, the wind fields at the start dtg of the run are read.

Next the INITSP routine sets the wave spectrum at the start dtg of the run. If possible, it is read from a restart file. If there is no restart file, a JONSWAP spectrum is used for

```
      PROGRAM NEDWAM
(Declarations)
      CALL PRELUDE
      CALL READWF
      CALL INITSP
      CALL OUTPUT
2000  CONTINUE
      CALL PROPAG
      DO 2001 ISCE=1,NPROOS
            CALL IMPLEX
            CALL INCDATE(CDT,IDLSCE)
2001  CONTINUE
      CALL NEWOLD
      CALL OUTPUT
      IF (CDT .LT. CENDDT) GOTO 2000
      CALL WRMSG(3)
      END
```

Figure 5: The main program of Nedwam



Nedwam service routines: INCDATE WFILE WRMSG

Figure 6: The hierarchy of the Nedwam subroutines

the wave spectrum. Because the parameters of the JONSWAP [1973] spectrum depend on the wind field, the wind fields at the start dtg of the run had to be read first. The auxiliary routine SUBZ is used to set the spectrum for landpoints equal to zero.

The last call of the initialization part is a call to the OUTPUT routine. At the start dtg this call has little effect since in the operational version of the program no output is produced for the analysis period. The only thing OUTPUT does at this stage is to call OUTREQ which then reads a list of points for which additional timeseries and/or spectra are requested. OUTPUT will be discussed in more detail below.

After the initialization part, the body of the program is started.

The evolution of the wave spectrum is calculated using the discrete energy balance equation. This is done in a double loop structure, corresponding to the scheme of section 4.2. The outer loop is over propagation time steps. The inner one over integration time steps. Each propagation time step is divided in NPROOS = 2 integration time steps.

The propagation loop starts with a call to the propagation routine PROPAG which calculates the increment of the spectrum due to advection using the algorithm of section 4.3. The routine EQEXT is called to evaluate the spectra at the boundaries of the extended grid (see section 4.3). The spectra at the land points are set equal to zero by the routine SUBZ.

Next the effect of the source terms is calculated in the integration loop. Each integration time step the source term integration routine IMPLEX is called. This routines reads new wind fields when this is necessary according to the wind-field time indicators and calculates the source term of the energy balance equation with the source term integration scheme of section 4.4.

IMPLEX calls many subroutines. The READWF routine to read the wind fields has been decribed above. The FEMEAN and SEMEAN routines calculate mean quantities which occur in the expressions for the source functions. The definitions of the mean quantities have been given in section 4.5. The wind-input source function of section 4.6 is calculated in SINPUT, the dissipation source term of section 4.7 in SDISSIP, the bottom-dissipation source term of section 4.8 in SBOTTOM and the wave-wave interaction source term of section 4.9 in SNONLIN.

After the call to IMPLEX, the INCDATE routine increases the current time of the program, CDT, by the integration time step IDLSCE = $900s$.

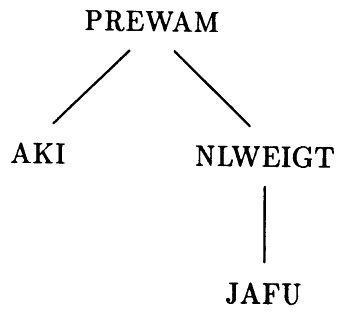


Figure 7: The hierarchy of the Prewam subroutines

After the integration loop, the results of advection and integration are combined by the NEWOLD routine.

Next the OUTPUT routine is called. First, the FEMEAN, the MWDFPK and the SEMEAN routines are called to calculate all mean quantities of section 4.5. Time indicator variables are used to indicate what kind of output should be produced. *E.g.* output of fields is only done every six hours, that is once in every twelve propagation steps. OUTPUT calls for each output data type a separate subroutine. OUTRST is used for the output of restart fields. The ouput of (temporary) timeseries is done by OUTTMS, of the spectra by OUTSPC and of the fields by OUTFLD. The timeseries and spectra in the grid points which have been supplied by the user are produced by OUTREQ. OUTFLD uses the KNMI library routines CODEGC and PUTFLD to write fields to the GRIB-coded Nedwam field file. The TSF library routine CPDTSF is used by OUTSPC to write to the TSF-coded Nedwam spectra file.

Finally it is checked whether the running date-time group of the run has already reached the end dtg of the run. If this is the case, the program stops.

The WAMGEO file can be regenerated by the separate program Prewam. It contains all kinds of permanent information, like the depth at the gridpoints, the group velocities and wave numbers for all frequencies at all gridpoints, and the weights of eqs. (93) and (94) used by the non-linear wave-wave interaction source term routine SNONLIN. As shown in *fig. 7*, Prewam has three subroutines: the function AKI to calculate the wavenumber k as a function of the frequency f and the depth D, the routine NLWEIGT to calculate the weights for the non-linear wave-wave interactions, and the auxiliary routine JAFU.

A Acronyms and symbols

Acronym/symbol	Meaning
A	Wave action density (F/ω).
APL	The Automatic Production Line of KNMI models.
BIMWAM	A module of the NEWA system, see section 5.3.
BUFR	A WMO code for meteorological timeseries [WMO 1988].
$\mathbf{c}_g$	Wave group velocity.
$\mathbf{c}_p$	Wave phase velocity.
c_D	Drag coefficient.
dtg	Date-time group.
dtg	Analysis date-time group, see chapter 5.
D	Depth.
E	Wave variance.
E_{10}	Variance of waves with periods of more than $10s$.
f	Frequency.
fp	Forecast period, see chapter 5.
F	Wave variance spectrum.
g	Gravity.
ECMWF	The European Centre for Medium-Range Weather Forecasts.
GRIB	A WMO code for meteorological fields [WMO 1988].
GONO	*GOlven NOordzee*, a KNMI North Sea wave model.
GONO grid	The stereographic grid used by Nedwam, see chapter 2.
GTS	The Global Telecommunications System for meteorological data.
H_s	Significant waveheight ($4\sqrt{E}$).
JONSWAP	A Joint North Sea WAve Project of the early seventies.
i,j	Labels of GONO grid x,y coordinates.
ij	Label of gridpoint on the GONO grid (see chapter 2).
k	(1) Wave number (modulus of $\mathbf{k}$). (2) Direction label.
$\mathbf{k}$	Wave vector.
KNMI	*Koninklijk Nederlands Meteorologisch Instituut*, Royal Netherlands Meteorological Institute.
l	Label of gridpoint on the extended grid (see chapter 2).

(continued on next page)

(continued from page 56)

Acronym/symbol	Meaning
LAM	The Limited Area Model of the APL.
m	Frequency label.
NEDWAM	*NEDerlands* WAve Model.
NEWA	The Nedwam part of the APL, see section 5.3.
runid	Wind-field type, see chapter 5.
s	Scaling factor between distances on the GONO grid and distances on the earth, see chapter 2.
S	Source term of the energy-balance equation.
S_{bot}	The bottom-dissipation source term.
S_{dis}	Dissipation source term.
S_{in}	Wind-input source term.
S_{nl}	Wave-wave interaction source term.
TSF	Time Series Format, a KNMI code for meteorological time-series.
u_{10}	Wind speed at a height of $10m$.
u_*	Wind friction velocity.
UKMO	The United Kingdom Meteorological Office.
VAKA	The wave and storm-surge Sectormodels of the APL.
WAM	A WAve Model [WAMDI 1988].
WMO	The World Meteorological Organisation.
WAQUA	The storm-surge model of the APL.
Δt_{prop}	Propagation time step.
Δt_{int}	Source term integration time step.
Δx	Grid spacing.
δ	Tilt angle of the GONO y-axis with respect to the North.
η	Sea-surface elevation.
θ	Direction of a wave-spectrum component.
θ_w	Mean wave direction.
ϕ	(1) Wind direction. (2) Latitude.
ψ	Longitude.
ω	Angular frequency.

Table 2: Acronyms and symbols.

B The 20 GONO swell points

Name	i	j	Latitude (degrees)	Longitude (degrees)	Depth (m)
MIKE	7	24	66.01	2.89	200
BRENT	8	17	61.19	1.79	200
UTSIRA	11	15	59.36	5.02	200
CLAYMORE	7	13	58.69	-0.67	120
BRAE	9	13	58.41	1.84	120
JUTLAND	14	12	56.83	7.47	30
TURBOT BK.	8	11	57.25	0.07	80
AUK	10	10	56.31	2.17	80
EKOPUMP	8	9	55.95	-0.41	70
GORM	13	9	55.15	5.25	40
GERMAN B.	15	8	54.11	7.06	30
DOGGER BK.	11	7	54.23	2.45	30
AMELAND	14	7	53.70	5.66	25
L7	13	6	53.26	4.30	30
K13	12	6	53.44	3.25	25
HEWETT	11	5	52.97	1.93	25
IJMUIDEN	13	5	52.64	4.01	25
EURO	13	4	52.01	3.72	25
TWIN	12	3	51.55	2.45	35
VARNE	11	2	51.08	1.21	30

Table 3: The 20 GONO swell points. i and j are the GONO grid coordinates of the swell points. Eastern longitudes are positive, western negative. The depths indicated are the ones used by Nedwam rather than the actual depths at the given positions.

C Nedwam directory and file names

The directory names of the NEWA system are not fixed, but can be changed easily in the various script files. In *Fig. 8* the situation as of Summer 1990 is shown. The top directory

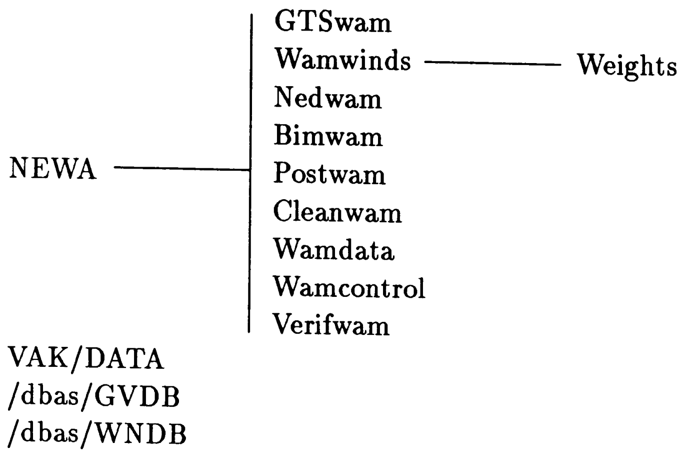


Figure 8: The directory configuration of the NEWA system.

of the NEWA system is the NEWA directory, which contains the *NEWA.ISF* script. To each module of the NEWA system corresponds a separate subdirectory of NEWA: GTSwam for the collection of GTS observations, Wamwinds for the interpolation of wind fields, Nedwam for the wave model, Bimwam for the Bimwam module, Postwam for the postprocssing and Cleanwam for the script which deletes obsolete date files. Wamwinds has a subdirectory Weights. This subdirectory contains the weights file which is used for the interpolation of wind fields from the LAM grid to the GONO grid and the necessary programs to regenerate this weight file.

Apart from these module subdirectories, NEWA has a Wamdata subdirectory for operational data which are not fields, a Wamcontrol subdirectory for the permanent database file and run-status files, and a Verifwam subdirectory where selected data for verification purpose are collected and processed.

The Bimwam module gets some input data from the VAK/DATA subdirectory of the

Suffix	File type
.a	Object library file
.documentation	Documentation file
.exe	Executable
.f	Fortran source
.ISF	Unix C-shell script file which is one of the APL intermediate supervisors.
.mk	Unix make file
.o	Object file
.sc	Unix C-shell script file

Table 4: The file suffix convention of the APL.

VAKA system.

In principle, all data for the NEWA system and the other APL systems are to be read from and written to common KNMI data bases. Two of these data bases have been implemented already and are used by the NEWA system: the GTS observation data base and the GRIB field data base. The GTS observation data files are written to the directory /dbas/WNDB and the GRIB fields to /dbas/GVDB.

The file names follow the APL standard. For program files, the suffix indicates the file type. The suffices are listed in *Table 4*.

The names of the the data files which are used by the Nedwam Fortran program are listed in *Table 5*. *U* is the Fortran the unit number. In the table, *yymmddhh* is an 8-digit date-time group, *r* is a letter which specifies wind-field type: *r*='L' in case of LAM winds and *r*='B' in case of UKMO winds, and *fp* is a 2-digit number which equals the forecast period in hours.

Various other data files which are used by programs of the NEWA system, but not by the Nedwam Fortran program, are listed in *Table 6*.

U	Name	Description
1	WAMGEO	Input permanent data base. Unformatted.
2	WAMSTATUS	Output control parameters of a succesful run.
3	NEW*r*_INP_*yymmddhh*00_00000_AB	Input interpolated wind-field file. GRIB coded.
4	NEWA_RST _*yymmddhh*	Input restart wave-spectrum file. Unformatted.
5	(standard input)	Input control parameters and directory names.
6	(standard output)	Output logfile.
10	NEW*r*_MAP_*yymmddhh*00_00000_AB	Output fields. GRIB coded.
12	NEWA_TSS_*yymmddhh*00_0*fp*00_TW	Output wave spectra in 20 fixed gridpoints. TSF coded.
13	NEWA_TMP_*yymmddhh*	Output timeseries in 20 fixed gridpoints. Unformatted.
16	NEWA_RST _*yymmddhh*	Output restart wave-spectrum file. Unformatted.
17	NEWA_REQUEST	Input of special gridpoints. Formatted.
18	NEWA_RQS_*yymmddhh_fp*	Output of wave spectra at special gridpoints.
19	NEWA_RQT_*yymmddhh_fp*	Output of timeseries at special gridpoints.

Table 5: Names of data files of the Nedwam Fortran program.

Name	Description
LAMF_FMT_*yymmddhh*00_00000_AB	Input LAM field file for *make_Wamwinds.sc.* GRIB coded.
UKMO_ARG_*yymmddhh*00_00000_AB	Input UKMO field file for *make_Wamwinds.sc.* GRIB coded.
VAKA_INP_0000000000_00000_VB	Input wind-field file for *run_Bimwam.sc.*
SHIPS*yymmddhh*00.DAT	Input file with GTS SHIP bulletins for *run_GTSwam.sc.*
NEWA_GTS_*yymmddhh*	Output file with GTS 10*m* wind observations and wave observataions. Formatted.
NEWA_TMS_*yymmddhh*00_0*fp*00_TW	Output combined Nedwam and Bimwam timeseries in 20 fixed gridpoints. TSF coded.
Last_nedwam.sc_run	Control parameters of the last completed *run_Nedwam.sc* run.
Last_bimwam.sc_run	Control parameters of the last completed *run_Bimwam.sc* run.
WAQG_DTM_0000000000_00000_LC	Control parameters of the last completed or current VAKA system run.

Table 6: Names of various data files used by the NEWA system.

D The contents and keys of the GRIB field files

The fields files of the NEWA system are FM 92 GRIB coded (see [WMO 1988]).

The input wind-field file NEWr_INP_*yymmddhh*00_00000_AB contains the $10m$-wind field analysis and forecasts up to +30 h (+36 h in the case of UKMO winds) at 3 hourly intervals. The parameters which specify the wind fields are listed in *Table 7*.

The output field file NEWr_MAP_*yymmddhh*00_00000_AB contains the analysis and forecasts of the output fields up to +30 h (+36 h in the case of UKMO winds) at 6 hourly intervals. The eight types of output fields have been list in *Table 8*. Note that the wind fields in the input file and in the output files are represented in different ways.

The codes in the tables refer to the value of octet no. 9 in section 1 of the GRIB key. The assignment of codes to the various wave parameters in *Table 8* is particular to KNMI.

Code	Field parameter.	Unit
123	u-component of the wind, along the x-axis of the GONO grid.	m/s
124	v-component of the wind, along the y-axis of the GONO grid.	m/s

Table 7: Contents and parameter codes of the NEWr_INP_*yymmddhh*00_00000_AB input wind-field file.

Code	Field parameter	Unit
20	Wind direction, coming from, with respect to the true North.	10^0
21	Wind speed.	m/s
64	Significant waveheight.	$0.5m$
245	Wave direction variance.	degrees
246	Mean wave direction, coming from, with respect to the true North.	degrees
247	Peak frequency of the wave spectrum.	s^{-1}
248	Mean wave period.	s
249	E_{10}.	m^2

Table 8: Contents and parameter codes of the NEWr_MAP_*yymmddhh*00_00000_AB output field file. The definition of the mean quantities can be found in section 4.5.

Octet no.	NEWA value(s)	Meaning
1	32	Length of section 1.
2-5	0	
6	2	Grid type: stereographic.
7	17	Number of points along the x-axis.
8	0	
9	36	Number of points along the y-axis.
10	0	
11	-41700	y'-coordinate of the origin of the grid ($100m$).
12-13	0	
14	1840	x'-coordinate of the origin of the grid ($100m$).
15-16	0	
17	0	Direction increments: given.
18	-15450	y'-coordinate of the extreme point of the grid ($100m$).
19-20	0	
21	13840	x'-coordinate of the extreme point of the grid ($100m$).
22-23	0	
24	750	Direction increment along the x-direction ($100m$).
25	0	
26	750	Direction increment along the y-direction ($100m$).
27	0	
28	64	Scanning mode: W to E consecutive, S to N.
29	60	Latitude at which octets 24-27 are specified.
30	0	
31	-1164	Meridian which is parallel to the y-axis
32	0	of the grid (0.01^0).

Table 9: Codes for section 2 of the GRIB key.

The values of the other octets of the GRIB key are given in *Table 9 and 10.* The (x', y') coordinate system mentioned in the Table 9 has its origin at the North Pole and has the same orientation as the stereographic grid. Note that the specification of the stereographic grid differs from the specification of the polar stereographic grid in [WMO 1988]. The value of octet 10 of section 1 (see Table 10) of the Nedwam field file is always 102 (mean sea level), although the wind fields are actually for $10m$ above the mean sea level.

Octet no.	NEWA value(s)	Meaning
1	24 or 27	Length of section 1.
2-4	0	
5	KNMI: 96	Identification of centre.
	British Met: 74	
6	LAM winds: 61	Model identification.
	UKMO winds: 62	
7	Nedwam: 255	Grid definition.
8	128	Section 2 present, section 3 not present.
9	*see Table 8*	Indicator of parameter.
10	NEWr_INP: 105	Indicator of level type:
		105: to be specified in m in octet 11,12;
	NEWr_MAP: 102	102: mean sea level
11	10	Level height: $10m$.
12	0	
13	yy	Analysis year.
14	mm	Analysis month.
15	dd	Analysis day.
16	hh	Analysis hour.
17	mm	Analysis minute.
18	1	Indicator of unit of time range: hour.
19	fp	Forecast time in units of octet 18 (hours).

Table 10: Codes for section 1 of the GRIB key.

E The contents and keys of the TSF coded files

The timeseries and spectra files are TSF coded. The TSF code [Hafkenscheid 1988] of the KNMI is very similar to the binary FM 94 BUFR code of the WMO [1988]. It is foreseen that in the future the timeseries and spectra files will be BUFR coded.

The output spectra file NEWA_TSS_*yymmddhh*00_0*fp*00_TW contains spectra of the analysis and forecasts up to +*fp* h at twenty special gridpoints, the GONO swellpoints. The timestep of the spectra file is 3 hours. The GONO swellpoints are listed in Appendix B. In the TSF system, each type of parameter has been assigned a certain code. In the case of the spectrum, this is done in terms of parameters defined at multiple levels, every level corresponding to a particular frequency. The first spectral parameter contains the values of the frequencies of the levels, each one of the other twelve contains the wave spectrum for a fixed direction. The TSF codes of the spectral parameters are listed in *Table 11.*

The output timeseries file NEWA_TMS_*yymmddhh*00_0*fp*00_TW contains timeseries of the analysis and forecasts up to +*fp* h for 14 types of parameters at the 20 GONO swellpoints. The timestep of the timeseries file is 1 hour. The 14 types of parameters are listed in *Table 12.* In contrast to the more complicated case of the TSF key codes for the spectral parameters, the timeseries parameters are defined at a single level.

The assignment of codes to the various wave parameters is particular to KNMI.

The values of the other TSF keys are listed in in *Table 13.* The number of timelevels (KRTL) of the spectra file is 11 (13) for a +30h (+36h) forecast run, the number of timelevels of the timeseries file is 31 (37).

Code	Spectral parameter	Unit
54009	The frequencies of the levels.	s^{-1}
54010 - 54021	1-D Wave spectra at direction 1-12, at frequencies specified by parameter 54009.	m^2s,

Table 11: Parameter codes of the NEWA_TSS_*yymmddhh*00_0*fp*00_TW spectra file.

Code	Field parameter	Unit
20	Wind direction at 10m height, coming from, with respect to the true North.	10^0
21	Wind speed at 10m height.	m/s
54022	Significant waveheight.	m
54023	E_{10}.	m^2
54024	Mean wave direction, coming from, with respect to the true North.	degrees
54025	Wave direction variance.	degrees
54026	Mean E_{10} direction, coming from, with respect to the true North.	degrees
54027	E_{10} direction variance.	degrees
54028	Mean wave period.	s
54029	Upper bound for H_s from Bimwam.	m
54030	Lower bound for H_s from Bimwam.	m
54031	Upper bound for E_{10} from Bimwam.	m^2
54032	Lower bound for E_{10} from Bimwam.	m^2
54033	Peak frequency of the wave spectrum.	s^{-1}

Table 12: Contents and parameter codes of the NEWA_TMS_*yymmddhh*00_0*fp*00_AB time-series file. The definition of the mean quantities can be found in section 4.5.

Generic name	Value	Meaning
KTYP	1	File organisation type: unformatted.
KMDI	'7FFFFFFF'x	Missing data indicator.
KDRT	0	Data representation type: words.
KIYY	*yy*	Analysis year.
KIMM	*mm*	Analysis month.
KIDD	*dd*	Analysis day.
KIHH	*hh*	Analysis hour.
KIMM	*mm*	Analysis minute.
KISS	*ss*	Analysis second.
KPDIL	15	Length of KPDI.
KPDI(1)	26	Length of BUFR indent section 1 in octets.
KPDI(2)	1	BUFR edition number.
KPDI(3)	255	Originating centre.
KPDI(4)	0	Update sequence number.
KPDI(5)	0	Integer value of flag bits.
KPDI(6)	255	BUFR message type.
KPDI(7)	1	BUFR message sub type: TSF.
KPDI(8)	0	Local table version number: standard.
KPDI(9)	KIYY	Year, most typical for the message contents.
KPDI(10)	KIMM	Idem, month.
KPDI(11)	KIDD	Idem, day.
KPDI(12)	KIDD	Idem, hour.
KPDI(13)	KIMM	Idem, minute.
KPDI(14)	255	Model identification.
KPDI(15)	255	Product definition number.
KTIN	TSS: 3 TMS: 1	Time step in units indicated by KTUN.
KTUN	14	Time unit of KTIN: hours.
KRTL	*see text*	Number of timelevels.
KRDP	20	Number of data points.
KRML	TSS: 25	Number of multiple levels.
KACC	2	Accuracy of horizontal coordinates: 0.01^0.
KIAF	0	Indicator additional field: none.
KWAF	0	Data with additional fields: none.
KRSE	TSS: 0 TMS: 14	Number of single element parameters.
KSLE	TMS: *see Table 12*	Array containing the single element parameter codes.
KRME	TSS: 13 (= 1 + 12) TMS: 0	Number of multiple element parameters.
KMLE	TSS: *see Table 11*	Array containing the multiple element parameter codes.

Table 13: TSF key codes

F The COMMONS of the Nedwam program

Parameter	Value	Meaning
NX	17	Number of gridpoints in the x-direction of the GONO grid.
NY	36	Number of gridpoints in the y-direction of the GONO grid.
IOTOT	612	=NX*NY, total number of gridpoints of the GONO grid.
IL	19	=NX+2, number of gridpoints in the x-direction of the extended grid.
JL	38	=NY+2, number of gridpoints in the y-direction of the extende grid.
JL1	37	=JL-1
ITOT	722	=IL*JL, total number of gridpoints of the extended grid.
KL	12	Number of wave directions.
ML	26	=ML1+1
ML1	25	Number of wave frequencies.
ML54	54	Number of frequencies, including a f^{-4} tail (eqs. (70), (71)).
NSEG	5	Maximum number of land/sea segments for a fixed GONO j-coordinate.
NSWP	20	Number of GONO swellpoints, see sect 5.5.

Table 14: The Fortran parameters of the Nedwam program.

Name	Description
COMMON/DATES/	Date-time groups.
COMMON/GRIDPA/	Relation extended grid versus GONO grid. SCH.
COMMON/INDNL/	Indices and weights for the wave-wave interactions.
COMMON/LOGSEA/	Land/sea indicator.
COMMON/MEANPA/	Frequency grid and miscellaneous.
COMMON/RUNRST/	Wind-model identification, restart flag.
COMMON/SHALLO/	Wave numbers, group velocities and depths.
COMMON/SOURCE/	Source function (SL) and related variables.
COMMON/SPECTR/	Spectrum (F1) and increment from advection (F2).
COMMON/SWLPTS/	Swell (special output) points.
COMMON/TBVAPL/	E_{10} parameters. TSF buffer array.
COMMON/TIMEPA/	Time steps.
COMMON/UBUF/	Organization of GONO grid in "segments".
COMMON/WINDPA/	Wind field at 10m and wind-stress field.

Table 15: The Fortran COMMON blocks of the Nedwam program. The contents of the COMMONS are listed on the following pages.

COMMON /**DATES**/ - Variables used for storing date-time groups.

Variable	Type	Meaning
CBGNDT	CHARACTER*12	Start date-time group (dtg) of the run in *yymmddhhmmss* format.
CDT	CHARACTER*12	Current dtg.
CENDDT	CHARACTER*12	End dtg of the run.
CWNDDT	CHARACTER*12	Dtg of the next windfield to be read.
CRNWDT	CHARACTER*12	If CDT=CRNWDT, the next windfields are read.
CSHIFT	CHARACTER*12	Analysis dtg of the run.
COUFLD	CHARACTER*12	If CDT=COUFLD, output of fields is done.
COURST	CHARACTER*12	If CDT=COURST, output of a restart file is done.
COUSPC	CHARACTER*12	If CDT=COUSPC, output of spectra is done.
COUTMS	CHARACTER*12	If CDT=COUTMS, output of timeseries is done.

COMMON /**GRIDPA**/ - Relation between the extended grid and the GONO grid. SCH.

Variable(dimension)	Type	Meaning
ICE(IOTOT)	INTEGER	ICE(IJ) is the extended grid index of GONO grid-point IJ. ICE(IJ) corresponds to the quantity $\ell(ij)$ of section 2.2, eqs. (7) and (9).
SCH(ITOT)	REAL	Scaling factor relating distances on the earth to those on the stereographic plane SCH(IJ)= $d\ell_{earth}/d\ell_{GONO}$, in *km/gridunit* (!). See section 2.1.

COMMON /**INDNL**/ - Indices and weights used in the computation of the non-linear wave-wave interactions, see section 4.9. Used by subroutine SNONLIN.

Variable(dimension)	Type	Meaning
ACL1	REAL	=ABS(CL1).
ACL2	REAL	=ABS(CL2).
AFM(ML1)	REAL	Weight which is set to zero if the lowest frequency of a quadruplet is below the the lowest frequency of the frequency grid.
AFP(ML1)	REAL	AFP(M)=1.

AL11	REAL	$(1+\lambda)^4$
AL12	REAL	$(1-\lambda)^4$
AL13	REAL	=AL11*AL12.
CL1	REAL	=−0.383: minus weight in angular grid, '$1+\lambda$' wave.
CL2	REAL	= 0.119: weight in angular grid, '$1-\lambda$' wave.
CL11	REAL	=1−ACL1.
CL21	REAL	=1−ACL2.
CON	REAL	=3000, $g^{-4}C$ of eq. (100), the coupling strength (in $m^{-4}s^8$) of the wave-wave interaction in the discrete interaction approximation.
F11(ML1)	REAL	F11(M)= $(f_M)^{11}$.
FKLAM(ML1)	REAL	FKLAM(M) = 0, M=1,4 and FKLAM(M) = 0.981, M=5,25: weight in frequency grid, '$1-\lambda$' wave.
FKLAM1(ML1)	REAL	FKLAM1(M) = 0, M=1,4 and FKLAM1(M) = 1.-FKLAM(M), M=5,25 weight in frequency grid, '$1-\lambda$' wave.
FKLAP(ML1)	REAL	FKLAP(M) = 0.331, M=1,25: weight in frequency grid, '$1+\lambda$' wave.
FKLAP1(ML1)	REAL	FKLAP1(M) = 1-FKLAP(M), weight in frequency grid, '$1+\lambda$' wave.
IKM(ML1)	INTEGER	Frequency index array, '$1-\lambda$' wave, $m_1^- = m_2^-$ of eq. (95).
IKM1(ML1)	INTEGER	=IKM+1, $m_3^- = m_4^-$ of eq. (95).
IKP(ML1)	INTEGER	Frequency index array, '$1+\lambda$' wave, $m_1^+ = m_2^+$ of eq. (95).
IKP1(ML1)	INTEGER	=IKP+1, $m_3^+ = m_4^+$ of eq. (95).
JA1(2,KL)	INTEGER	Angular index array, wave, related to $k_{1,3}^-$ and $k_{1,3}^+$ of eq. (95).
JA2(2,KL)	INTEGER	Angular index array, wave,, related to $k_{2,4}^-$ and $k_{2,4}^+$ of eq. (95).

COMMON /**LOGSEA**/ - Land/sea indicator.

Variable(dimension)	Type	Meaning
SEA(IOTOT)	LOGICAL	SEA(IJ)= .TRUE. for sea points, .FALSE. for land points.

COMMON /**MEANPA**/ - Frequency grid parameters. Variables used for computing wave energy, mean frequency and mean wave direction. Miscellaneous.

Variable(dimension)	Type	Meaning
C(ML1)	REAL	C(M)=28/(2πFR(M)).
DELTH	REAL	= 2π/KL: angular increment in radians.
DELTHA	REAL	=DELTH 180/π: angular increment in degrees.
DELTH2	REAL	=DELTH/2.
DFIM(ML1)	REAL	DFIM(M)=(DFR(M)-DFR(M-1))/FR(M) for M=2,...ML1-1; DFIM(1)=DFR(1)/FR(1); DFIM(ML1)=DFR(ML1-1)/FR(ML1).
DFR(60)	REAL	DFR(M)=(FR(M+1)-FR(M))*DELTH2 =0.1*FR(M)*DELTH2, for M=1,59. DFR(60)=0.1*FR(60)*DELTH2.
EMEAN(IOTOT)	REAL	EMEAN(IJ) is the wave variance E in m^2 at GONO gridpoint IJ. See section 4.5.
FMEAN(IOTOT)	REAL	FMEAN(IJ) is the mean frequency in Hz at GONO gridpoint IJ. See section 4.5.
FOM(ML1)	REAL	FOM(M) = (0.0003)(2π)FR(M).
FPEAK(IOTOT)	REAL	FPEAK(IJ) is the peak frequency in Hz at GONO gridpoint IJ. See section 4.5.
FR(60)	REAL	FR(M)=$f_1(1.1)^{M-1}$, $f_1 = 0.0418$, frequencies in Hz.
G	REAL	= $g = 9.806$, gravity in m/s^2.
GZPI28	REAL	= $g/(2\pi 28)$.
IE10(IOTOT)	INTEGER	IE10(IJ) is the E_{10} at GONO gridpoint IJ in cm^2 (!). See section 4.5.
KLP1	INTEGER	=KL+1=13.
MWD(IOTOT)	INTEGER	MWD(IJ) is the mean wave direction at GONO gridpoint IJ in degrees, coming from, with respect to the true N. See section 4.5.
PI	REAL	π.
PIH	REAL	= $\pi/2$.
ZPI	REAL	= 2π.
PIG18	REAL	= $\pi/180$.
SCHAR(IOTOT)	REAL	SCHAR(IJ)= $\delta(ij)$, the tilt angle of the positive GONO y-axis in radians, measured clockwise from the true North. See section 2.2.

COMMON /**RUNRST**/ - Wind-model identification flag, restart flag.

Variable	Type	Meaning
ISITRS	INTEGER	ISITRS = 1 if a restart wave spectrum from a previous run is to be used for the wave spectrum at the start dtg of the run, ISITRS=0 if a JONSWAP spectrum is to be used for the wave spectrum at the start dtg of the run.
IRUNID	INTEGER	Number which indicates the *runid* of the run. IRUNID = 61 if LAM wind fields are to be used, IRUNID = 62 if UKMO wind fields are to be used.

COMMON /**SHALLO**/ - Wave numbers, group velocities and depths.

Variable(dimension)	Type	Meaning
AKMEAN(IOTOT)	REAL	Mean wave number, see sect 4.5.
CGOND(ITOT,ML1)	REAL	CGOND(L,M) is the group velocity c_g at gridpoint L of the extended grid for frequency M.
FAK(IOTOT,ML54)	REAL	FAK(IJ,M) is the wavenumber k at gridpoint IJ of the GONO grid for frequency M.
FRK(IOTOT,ML54)	REAL	FRK(IJ,M) = $1/(c_g(ij,m)k(ij,m)^{2.5})$, the high-frequency tail parametrization factor at gridpoint IJ of the GONO grid for frequency M. See sect. 4.4.
IDPTH(IOTOT)	INTEGER	Depth in m of the GONO grid.

COMMON /**SOURCE**/ - Source function and related variables.

Variable(dimension)	Type	Meaning
FCONST(IOTOT,ML1)	REAL	=1 for prognostic frequencies and is =0 for diagnostic (high) frequencies (see sect. 4.4).
FRH(30)	REAL	Tail factors, [FR(ML1)/FR(ML1+M-1)]**4, used in subroutine SNONLIN.
SDS(IOTOT)	REAL	Frequency independent part of the dissipation source function.
SL(IOTOT,ML,KL)	REAL	Total source function in m^2s^{-1}.

COMMON /**SPECTR**/ - Spectrum and increment from advection.

Variable(dimension)	Type	Meaning
F1(ITOT,ML,KL)	REAL	Wave variance spectrum in m^2.
F2(ITOT,ML,KL)	REAL	Spectral increment due to advection in m^2.

COMMON /**SWLPTS**/ - GONO swell points, special grid points. Output of the regular timeseries and spectra is done at the swell points only. See Appendix B.

Variable(dimension)	Type	Meaning
SWELLP(NSWP)	CHARACTER*4	GONO coordinates of the swellpoints in the GONO grid in $iijj$ format.

COMMON /**TBVAPL**/ - E_{10} parameters. TSF buffer array.

Variable(dimension)	Type	Meaning
IE10DV(IOTOT)	INTEGER	E_{10} in cm^2 (!), integral of the wave spectrum over frequencies lower than $0.1Hz$. See section 4.5.
ME10D(IOTOT)	REAL	Mean direction of the E_{10} in degrees, going to, clockwise, with respect to the true North.
MWDVR(IOTOT)	REAL	Variance in the E_{10} mean direction in degrees.
PBUF(125000)	REAL	Buffer array for the TSF spectra output file.

COMMON /**TIMEPA**/ - Time steps.

Variable(dimension)	Type	Meaning
DELT5	REAL	=IDLSCE/2. Normal value: 450.
IANAL	INTEGER	Analysis period in hours.
IFP	INTEGER	Forecast period in hours.
IDLFLD	INTEGER	Output timestep fields in hours. Normal value: 6.
IDLPRO	INTEGER	Propagation time step in seconds. Normal value:1800.

IDLRST	INTEGER	Output timestep restart files in hours. Normal value: 6.
IDLSCE	INTEGER	Integration time step in seconds. Normal value: 900.
IDLSPC	INTEGER	Output timestep spectra in hours. Normal value: 3.
IDLTMS	INTEGER	Output timestep timeseries in hours. Normal value: 1.
IDLWND	INTEGER	Wind time step in seconds. Normal value: 10800.
NPROOS	INTEGER	= IDLPRO/IDLSCE, the number of integration time steps in one propagation time step. Normal value: 2.

COMMON /**UBUF**/ - Organization of GONO grid-points in horizontal "segments". Used by subroutines INITSP and PROPAG to distinguish land points from sea points.

Variable(dimension)	Type	Meaning
LLAND(NSEG,NY)	INTEGER	LLAND(K,J) indicates whether segment K at latitude J consists of land (2) or sea (1). There are NPAWE(J) segments (see below). For K > NPAWE, LLAND(K,J) = LLAND(NPAWE,J)
LP(NSEG,NY)	INTEGER	LP(K,J) is the number of points in segment K at latitude J. Undefined if K is larger than NPAWE(J), the number of segments at latitude J.
LPM(NY)	INTEGER	The index in the extended grid of the point below the first seapoint of latitude J. Undefined if there are no seapoints at latitude J.
LPP(NY)	INTEGER	The index in the extended grid of the point above the first seapoint of latitude J. Undefined if there are no seapoints at latitude J.
LPT(NY)	INTEGER	LPT(J) is the total number of points in all the segments at latitude J. Undefined if there are no seapoints at latitude J.

LZ(2,NY)	INTEGER	LZ(1,J) is the number of landpoints before the first segment of latitude J. LZ(2,J) is the number of landpoints after the last segment of latitude J. NX=LZ(1,J)+LPT(J)+LZ(2,J) for all J. If latitude J does not contain any seapoint, then LZ(1,J)=NX, LZ(2,J)=0, LPT(J)=undefined.
NPAWE	INTEGER	NPAWE(J) is the number of segments at latitude J. NPAWE(J)=0 if latitude J does not contain any seapoint.

COMMON /**WINDPA**/ - Wind field at $10m$ and wind-stress field.

Variable(dimension)	Type	Meaning
THW(IOTOT)	REAL	Wind direction in radians, going to (!), clockwise, relative to the positive y-axis of the GONO grid.
USTAR(IOTOT)	REAL	Friction velocity in m/s.
U10(IOTOT)	REAL	Wind speed at $10m$ in m/s.

Table 16: The contents of the Fortran COMMON blocks of the Nedwam program.

G Status codes of the NEWA system shell scripts

The diagnostic messages of the Nedwam and Bimwam Fortran programs are meant to be self-explanatory.

They are sent to the standard output device. Also the diagnostic messages of the various script files, except for those of the intermediate supervisor script *NEWA.ISF*, are sent to the standard output device. In the usual set-up of the NEWA system, these diagnostic messages are redirected to a comprehensive logfile. The name of the comprehensive logfile is *NEWA.longlog.*

The diagnostic messages of the intermediate supervisor script are sent to a summary logfile. The name of the summary logfile is *NEWA.shortlog.*

Each script file returns an exit or status code after execution. The default value of the status code is zero. Different values indicate abnormal situations. The status codes returnded by the various scripts are written into the summary logfile.

Listed below are the explanations of the status codes of the *NEWA.ISF* control script of the NEWA system, the *run_GTSwam.sc* script which collects wave observations, the *make_Wamwinds.sc* script which takes care of the interpolation of wind fields from the atmospheric model grid to the GONO grid, the *run_Nedwam.sc* script which runs the Nedwam wave model program, and the *run_Bimwam.sc* script which runs the Bimwam program.

STATUS		Meaning
0		OK
1	WARNING:	Failure of the *run_GTSwam.sc* run which collects wave observations for verification purposes.
2	ERROR:	Failure of the *make_Wamwinds.sc* run which interpolates the forecasted input wind fields from the atmospheric-model grid to the GONO wave model grid. No Nedwam run possible.
20	WARNING:	Failure of a *make_Wamwinds.sc* run which interpolates input wind fields of the analysis period from the atmospheric-model grid to the GONO wave model grid. The quality of the results of the Nedwam run may be affected.
3	ERROR:	Failure of the *run_Nedwam.sc* run of the Nedwam wave model.
4	ERROR:	Failure of *run_Bimwam.sc* which runs the simple "Bim" wave model (Sectormodel) and makes a combined Nedwam/Bim timeseries file.
40	WARNING:	Failure of that part of *run_Bimwam.sc* which runs the simple "Bim" wave model (Sectormodel). The Nedwam timeseries file is made in the proper way.
5	ERROR:	Failure of the *run_Postwam.sc* run which post-processes Nedwam and Bimwam results.
6	ERROR:	Failure of the *run_Cleanwam.sc* run which removes obsolete data files.
7	ERROR:	NEWA directory not found.
70	WARNING:	No date-time group of a previous succesful run found.
71	ERROR:	*run_GTSwam.sc* script not found.
72	ERROR:	*make_Wamwinds.sc* script not found.
73	ERROR:	*run_Nedwam.sc* script not found.
74	ERROR:	*run_Bimwam.sc* script not found.
75	ERROR:	*run_Postwam.sc* script not found.
76	ERROR:	*run_Cleanwam.sc* script not found.
77	ERROR:	GRIB fields data-base directory not found.

Table 17: The status codes of the intermediate supervisor script *NEWA.ISF* which controls the NEWA system.

STATUS		Meaning
0		OK
1	WARNING:	No KNMI observational data-base file found for the requested date-time group.
3	ERROR:	Running *GTSwam.exe* failed.
5	ERROR:	Making *GTSwam.exe* failed.
7	ERROR:	Directory not found.
8	WARNING:	Failure in removing obsolete NEWA_GTS files.
9	ERROR:	Argument of *run_GTSwam.sc* is missing.

Table 18: The status codes of the *run_GTSwam.sc* script which collects wave observations.

STATUS		Meaning
0		OK
1	WARNING:	The NEWA_INP wind-input file exists already, and is not replaced by a new one.
3	ERROR:	The KNMI tool *copyGVDB2TMP_00* failed.
4	ERROR:	The KNMI tool *horint.exe* failed.
7	ERROR:	Directory not found.
9	ERROR:	Illegal *runid*, only *L* and *B* are allowed.

Table 19: The status codes of the *make_Wamwinds.sc* script which interpolates input wind fields from the atmospheric model grid to the GONO wave model grid.

STATUS		Meaning
0		OK
1	ERROR:	Missing wind-input files.
3	ERROR:	Running *nedwam.exe* failed.
4	ERROR:	Running *prewam.exe* failed, missing WAMGEO file.
5	ERROR:	Making *nedwam.exe* failed.
6	ERROR:	Making *prewam.exe* failed, missing WAMGEO file.
7	ERROR:	Directory not found.
9	ERROR:	Illegal *runid*, only *L* and *B* are allowed.

Table 20: The status codes of the *run_Nedwam.sc* script which runs the Nedwam wave model.

STATUS		Meaning
0		OK
1	ERROR:	Missing NEWA_TMP input file with temporary Nedwam timeseries.
2	WARNING:	The "Bim" (Sectormodel) part of the *Bimwam.exe* run failed, but the Nedwam timeseries are written to the NEWA_TMS file in the proper way.
3	ERROR:	Running *bimwam.exe* failed.
5	ERROR:	Making *bimwam.exe* failed.
7	ERROR:	Directory not found.
9	ERROR:	Illegal *runid*, only L and B are allowed.

Table 21: The status codes of the *run_Bimwam.sc* script which runs the simple "Bim" wave model (Sectormodel) and makes a combined Nedwam/Bim timeseries file.

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