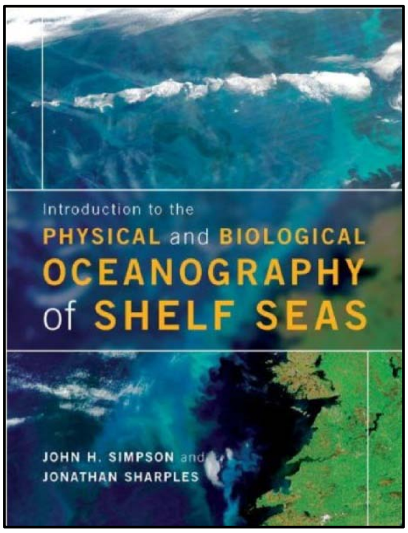
Guide to the S2P3 Model



1. Introduction
This 1-D (vertical) model is designed for use as an investigative (and educative) tool for problems concerning the link between the physical structure of the water column and primary biological production in coastal and shelf seas.

The physical model is forced by tidal currents, wind stress, and surface heat flux (solar radiation and surface heating/cooling). A turbulence closure sub-model provides the important link between vertical turbulent transfers and water stability. The biological component of the model is a simple cell quota model of carbon fixation, with one species of phytoplankton growing in response to light and dissolved inorganic nitrogen. The user has control over all model physical and biological driving parameters. Graphical screen output, suitable for basic visualisation and teaching purposes, is generated as the model operates. More detailed data is written to files for later analysis.

The physics equations used by the model are detailed in:
Sharples, J., et al., *Continental Shelf Research*, **26**, 733-751, 2006.

A full description of the biological model can be found in:
Sharples, J., *Journal of Plankton Research*, **30**, 193-197, 2008.

The model has been written in Fortran (complied using Lahey LF95 v7.2, www.lahey.com) and uses the *Winteracter* Fortran GUI toolset (Interactive Software Services Ltd., www.winteracter.com).

The model is supplied as an executable application that will only run under the Windows operating system.

This manual repeats the material available within the model Help, along with a section below providing basic instructions to get the model running. A separate document provides a more detailed tutorial on how to work with the model, and includes some suggested exercises of varying complexity that can be used for teaching.

2. Getting Started
Two files are required from the Cambridge University Press website (www.cambridge.org/oceanshelf):

S2P3.EXE	The model application
S2P3_HELP.HLP	Windows HLP file, called by the model help/instructions links

Note that the HLP file is a Windows Help file. However, Windows vista and Windows 7 do not contain the application required to view such a file. If that is the case for you, when you attempt to use the help file you will be offered a link to Microsoft that to download and install an application that will allow you to use the help file. The model will still run without the help file; instead you can refer to this document for advice on the model.

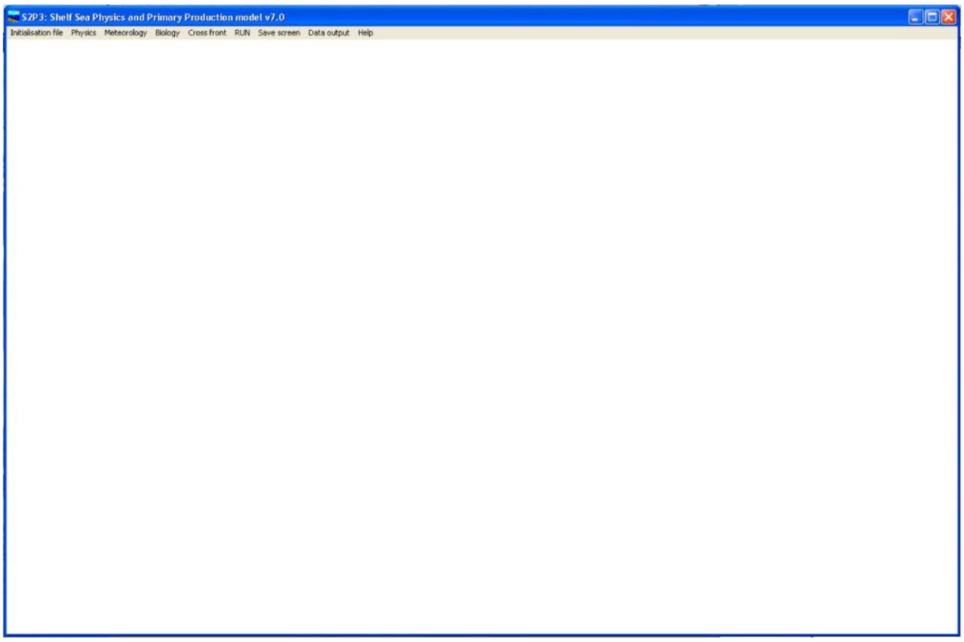
Additional files containing meteorological data, useful for some of the model exercises, are:

CelticSea_met2005.dat
CelticSea_met2006.dat
CelticSea_met2007.dat
CelticSea_met2008.dat
CelticSea_met2009.dat
CelticSea_met2010.dat

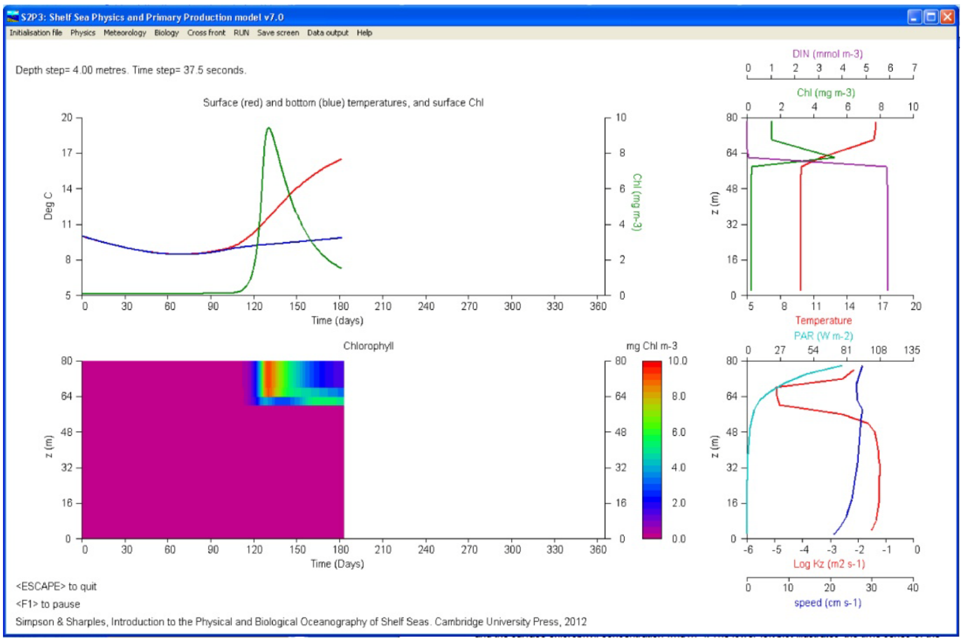
Create a directory on your computer's hard drive (e.g. c:\S2P3) and save all the above files into it.

Within Windows Explorer, go to your model directory and double-click the model icon:

The main model window then opens:



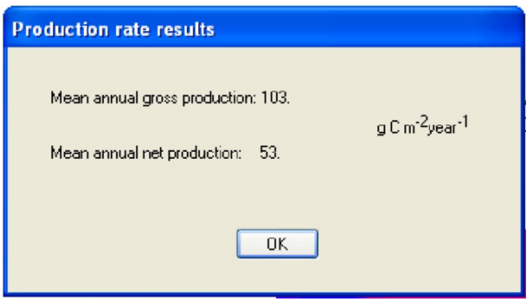
If you now click on the RUN option in the main menu, the model will run through one year of the default set-up. This is for conditions similar to the central Celtic Sea on the NW European shelf (51° N, 8° W), with seasonally-smoothed meteorological forcing (see Meteorology below). During the model operation the screen output looks like:



As the model runs data is output to the plots on the screen once per day, at noon. The plots to the left of the screen are time series, starting on January 1st and running through to December 31st. The upper plot on the left shows time series of the surface (red) and near-bed (blue) temperatures (°C) and the surface chlorophyll concentration (mg m^{-3}). The lower left plot illustrates the time series of the vertical structure of chlorophyll as coloured contours (mg m^{-3}). You can see in the above example how the default model run generates a seasonally-stratifying water column, with a spring phytoplankton bloom (see Chapter 6) and summer phytoplankton biomass located along the thermocline (see Chapter 7).

The plots to the right are vertical profiles of modelled parameters, refreshed at noon each day. Upper right plots show temperature (red, °C), chlorophyll concentration (green, mg m^{-3}), and dissolved inorganic nitrogen concentration (purple, mmol m^{-3}). The lower right plots show profiles of daily-mean current speed (dark blue, cm s^{-1}), the vertical distribution of daily-mean photosynthetically active radiation (light blue, W m^{-2}), and $\log_{10}$ of the daily-mean vertical diffusivity (red, m^2 s^{-1}).

While the model is running you can pause it by pressing the F1 key on the keyboard. Resume the run by selecting OK as prompted. The model can be stopped at any point by pressing the keyboard <escape> key. When the model ends, either at the end of a year's simulation or following <escape>, a summary of the annual primary production is reported:



Now that you have got the model running, the details of the menu options and how you can alter the physical and biological parameters that control the results are described below in detail.

3. Initialisation Parameters and Files

The model requires a set of initial parameters that describe the physical environment and the characteristics of the primary producers. There are also some output parameters that can be altered, both for the graphical display and for the data output by the model.

The initialisation parameters that are set up in the model menus can be saved into a text file, and later re-loaded to run the model again with the same parameters. You can have a look at the parameters in the initialisation file by running the model application and clicking on **Initialisation file** and **Save**. In the *Save initialisation parameters* dialog supply a file name (*.txt) and click Save.

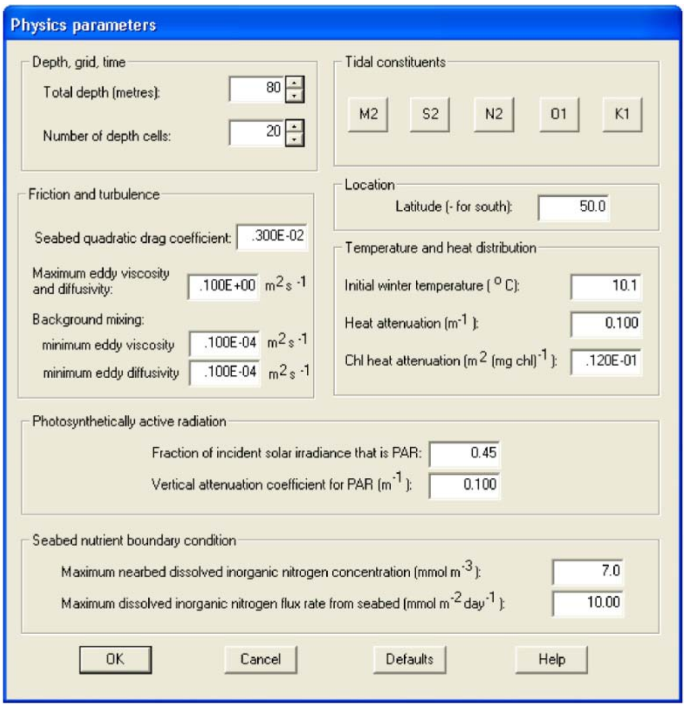
The file is written in standard ascii text which can be viewed using your favourite editor (e.g. Microsoft Notepad works well). Try to avoid viewing the initialisation file with anything that might upset the formatting. The model requires the initialisation file to have the correct format, otherwise you might re-load incorrect parameters or crash the model. If the model reports a FORTRAN error and crashes immediately after you have loaded an initialisation file, the most likely cause is that the file format is incorrect.

The model will attempt to run with any parameters that you supply, but obviously some will be more realistic than others. The following list is of the parameters in the initialisation file and suggested sensible ranges for those parameters. Don't feel too inhibited in drifting out of these suggested ranges, but do make sure you think carefully about the numbers you are supplying and whether or not they are physically or biogeochemically reasonable.

The following list describes all of the physics and biogeochemical parameters found in an initialisation file. The order is as they appear in the file, and they are grouped in terms of the dialogs called from the model main menu.

All parameter input dialogs have a “default” option. Selecting this restores the default values to all parameters within that dialog.

*3.1 Parameters set within the **Physics** dialog:*



Total depth (m): typically between 10 and 200 m for a shelf sea, though there is no reason not to try larger depths for modelling the slope or the open ocean.

Number of depth cells: this determines the model vertical resolution. Total depth divided by number of depth cells is the thickness of the individual depth cells used in the model grid. More depth cells provides better resolution, but the model will run much slower. The maximum number of depth cells allowed is 200.

Depth cell thickness (m): this is calculated by the model as (total depth / number of depth cells). It is provided as information in the initialisation file. Changing it in the initialisation file will not alter the model.

Time step (Δt , s): this is calculated by the model based on the depth cell thickness (Δz) and the maximum allowable turbulent viscosity and diffusivity (N_z^{max}) using a simple stability condition:

$$\Delta t < \frac{\Delta z^2}{2N_z^{max}}$$

Roughly speaking, this condition makes sure that the time step is small enough for the model to "see" something being mixed through a depth cell. If the condition were not met the model would become unstable. Note that the time step is proportional to the squared depth cell thickness, so if you double the number of depth cells (i.e. halve the cell thickness) you will reduce the time step by a factor of 4. Initially you might want to run the model with fairly coarse resolution (e.g. a depth cell thickness of 4 metres) to explore the results quickly. When you have decided what set of parameters you are particularly interested in, reduce the cell thickness to get better resolution in the model output. Altering the time step in the initialisation file will not alter the model.

Latitude (degrees): this is positive for the northern hemisphere, negative for the southern hemisphere (so a range of -90 deg to + 90 deg). Note that the latitude determines the seasonal and daily variation of clear sky radiation used by the model.

Bottom quadratic drag coefficient: this is the variable k_b in the book and controls the strength of bed friction. Typical values are 0.001 to 0.005.

Maximum diffusivity and viscosity (m^2 s^{-1}): this provides some further control on the time step used by the model (see "Time step" above). In regions of the water column where there is convective instability (e.g. the sea surface when there is surface cooling) the turbulence closure scheme can generate large values for the vertical eddy viscosity and diffusivity. It is possible for maximum values to reach above 0.5 m^2 s^{-1}. However, a value of 0.1 m^2 s^{-1} is often sufficient to remove convective instabilities quickly, and constraining the model to this maximum helps keep the time step from getting too small. Reducing this constraint to below 0.05 m^2 s^{-1} is not advisable. It is always worth checking that limiting the turbulent mixing in this way does not have a serious effect on the model results.

Background viscosity (m^2 s^{-1}): This is a simple way of incorporating the mixing effects of interior processes such as internal waves or natural variability in the meteorological forcing (see, for instance, Sharples & Tett, *Journal of Marine Research*, **52**, 219-238, 1994). The model cannot simulate these interior processes (see Chapter 7 of the book), but not allowing for the mixing generated by them can have important consequences for the physics and the biogeochemistry. Typical values for the weak internal waves in the central Celtic Sea might be 1×10^{-5} to 5×10^{-5} m^2 s^{-1}, while approaching the stronger internal wave regime of the shelf edge could raise this by a factor of 10.

Background diffusivity (m^2 s^{-1}): See "background viscosity" above.

Initial water temperature (°C): The model starts the annual simulation on January 1st. In temperate northern hemisphere shelf seas the water column is usually well-mixed at this stage of winter, and this initial water temperature sets the modelled vertically-mixed water column temperature. Note that it is not the coldest temperature that the water column will reach; cooling could continue into early spring. If you are not sure what the initial water temperature in winter might be, estimate it and see what temperature the model predicts at the end of the year simulation. You can then use this prediction as your initial temperature - a few iterations of this might be necessary to get the initial temperature set correctly. For the southern hemisphere you need to assume that the first day of the annual simulation is 1st July and remember to configure any meteorological data to be consistent with this (see information on the **Meteorology** dialog below).

Heat vertical attenuation (m^{-1}): this is the attenuation coefficient that controls the exponential decay of heat down through the water column. A typical near-surface shelf sea value might be 0.1 m^{-1} in stratified regions, or as high as 0.4 m^{-1} in mixed regions where significant suspended material or CDOM limits heat transmission. The model applies a very simple approach to the wavelength dependence of radiation attenuation. The red end of the solar radiation spectrum is absorbed very rapidly, which is simulated by dumping 55% of the incident radiation into the top grid cell. The remaining 45% of the radiation is distributed exponentially.

Chl effect on heat attenuation (m^2 (mg Chl)$^{-1}$): this quantifies the effect of chlorophyll in the water raising the water opacity, and so affecting the attenuation of heat through the water. Note the units are equivalent to m^{-1} (mg Chl m^{-3})$^{-1}$, hence the impact is described in terms of a change in attenuation coefficient per unit of chlorophyll concentration. A typical value is 0.012 m^2 (mg Chl)$^{-1}$. See Kirk, J. T. O., *Light and Photosynthesis in Aquatic Ecosystems*, Cambridge University Press, 2010 for more details.

PAR attenuation coefficient (m^{-1}): similar to the heat vertical attenuation (see above), but here specific to the wavelengths of light that form PAR. A typical value in clear shelf waters is 0.1 m^{-1}, but increasing to 0.4 m^{-1} or higher in turbid regions.

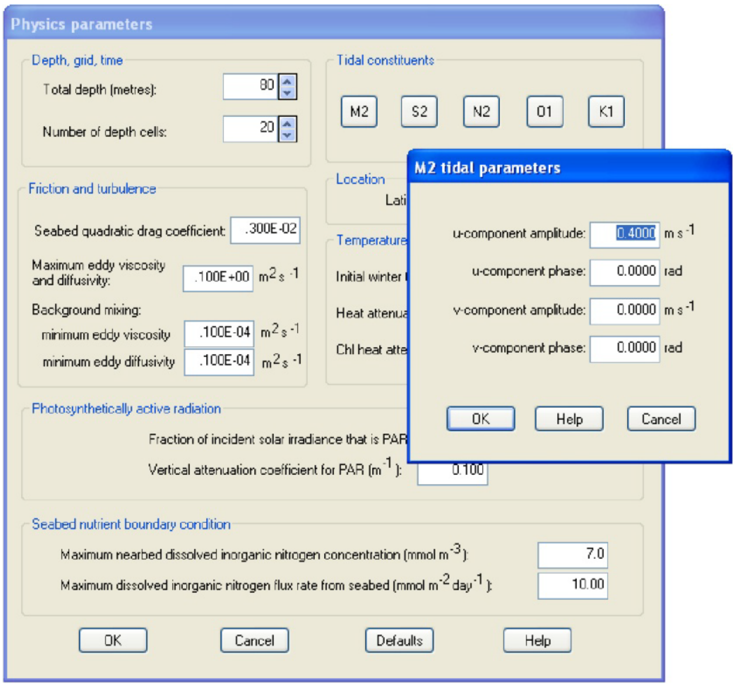
Fraction of surface radiation that is PAR: The model is forced by total radiation at the sea surface, supplied in the meteorological data or functions. Typically about 45% of that total radiation (i.e. a fraction 0.45) is within the range of wavelengths that make up PAR.

Maximum seabed dissolved inorganic N (mmol m^{-3}): the modelled water column is assumed to be well away from either freshwater sources or from the shelf edge, so that the dominant inorganic nitrogen (DIN) source is through regeneration of organic material in the seabed sediments. This maximum value is the concentration of DIN in the bottom of the water column that the model relaxes towards via a flux from the seabed dependent on the difference in DIN between the maximum value and the concentration in the bottom grid cell. Typically in the Celtic Sea we find the bottom DIN to be 7 - 9 mmol m^{-3}, increasing towards the shelf edge. You could also simulate a persistent mean upwelling of DIN over the shelf edge by setting the maximum to some mean value supplied across the shelf edge. The model cannot simulate inputs of DIN in surface water (e.g. in a plume from an estuary).

Maximum flux of inorganic N from the seabed (mmol m^{-2} d^{-1}): this controls the rate at which bottom water DIN can be replenished by the flux from the seabed (or from persistent upwelling). The model uses a default of 10 mmol m^{-2} d^{-1}. Values could be set by direct observations. In mixed water this flux can be used to tune a modelled vertically-uniform DIN concentration to be the same as that observed.

*3.2 Tidal parameters set by the constituent buttons in the **Physics** dialog:*
For more detailed information on how the tidal currents are set up within the model, see the description of **tidal forcing** below.

Tidal constituent information required by the model is input by selecting the constituent from the Physics dialog:

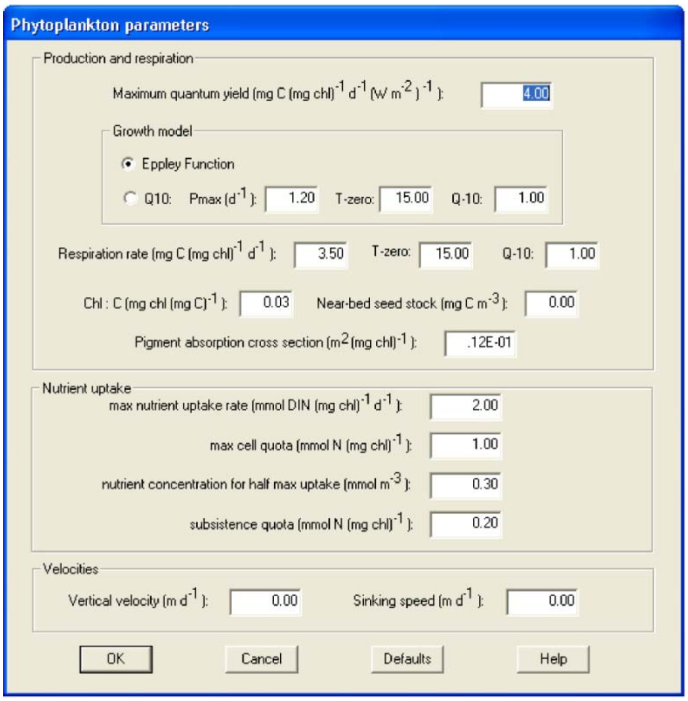


u amplitude (m s^{-1}): the amplitude of the tidal current along the x-axis (east-west) for each of the 5 tidal constituents M2, S2, N2, O1 and K1.
u phase (radians): the phase of the tidal currents along the x-axis for the 5 tidal constituents.
v amplitude (m s^{-1}): the amplitude of the tidal current along the y-axis (north-south) for each of the 5 tidal constituents.
v phase (radians): the phase of the tidal currents along the y-axis for the 5 tidal constituents.

Note that the constituent phase angles are relative to 0000 hrs January 1st on the year of the model simulation. In addition to the forcing information for the tidal currents, the initialisation file also provides information on the characteristics of the tidal current ellipse for each of the 5 tidal constituents. This information is not taken from the initialisation file and utilised by the model, but is calculated each time the physics parameters are set.

tidal ellipse orientation (radians): the angle between the x-axis (eastward) and the major axis of the tidal current ellipse, positive anti-clockwise from the x-axis.
tidal ellipse polarisation: a value between -1 and +1 describing the ellipticity of the tidal current ellipse (i.e. how squashed it is) and the direction of rotation of the tidal current vector. A value of +/-1 represents a circle, and 0 is a degenerate ellipse (rectilinear tidal flow). Negative polarisation is for a vector progressing clockwise (anti-cyclonic), positive polarisation for a vector progressing anti-clockwise (cyclonic).
tidal ellipse semi-major axis (m s^{-1}): the total amplitude of the tidal currents resolved along the major axis of the tidal current ellipse.

*3.3 Parameters set in the **Biology** - **Phytoplankton Growth** dialog:*



Growth model (1=Eppley, 2=Q_{10}): this sets which formulation for phytoplankton growth to use. Setting the growth model to 1, or selecting the Eppley Function option in the dialog, tells the model to use the Eppley relation between maximum phytoplankton growth rate and temperature (see: Eppley, R. W., Temperature and phytoplankton growth in the sea. *Fishery Bulletin*, **70**, 1063-1085, 1972):

$$P^b_{\max} = 0.59e^{0.0633T} \text{ [d}^{-1}\text{]}$$

Note that $P^b_{\max}$ is the maximum growth rate (e.g. g C m^{-3} d^{-1} or g Chl m^{-3} d^{-1}) normalised by biomass concentration in the same units (e.g. g C m^{-3} or g Chl m^{-3}). This growth rate, the associated biomass, and the temperature, T , are those at the grid cell in the model at which growth rate is being calculated.

Setting the growth model to 2, or selecting the Q10 option in the dialog, tells the model to use a Q_{10} description of phytoplankton growth as a function of temperature. The Q_{10} description (see for instance Valiela, I., *Marine Ecological Processes*, Springer, 2010) describes the temperature dependence of some biological rate, *r*, as:

$$Q_{10} = \left(\frac{r_1}{r_2}\right)^{10/(T_1 - T_2)}$$

with rate r_1 measured at temperature T_1 and r_2 at T_2. Most biological rates have Q_{10} between 2 and 3. The rate, r , at some temperature T is then:

$$r = r_2 Q_{10}^{\,(T - T_2)/10}$$

This parameterisation of growth (or respiration) rate requires 3 parameters to be specified:

Reference maximum growth rate (d^{-1}): this is a biomass normalised growth rate, e.g. r_2 (d^{-1}) in the equation above, and will be the maximum that the phytoplankton can achieve (i.e. neither light nor nutrients limiting) at the reference temperature, T_2, of the Q_{10} formulation. It is a time scale for doubling phytoplankton biomass. A typical value might be about 1 d^{-1}, with a sensible range between about 0.25 and 2 d^{-1}.

Reference temperature (°C): the reference temperature, T_2, at which the maximum growth rate is that above. The Q_{10} formulation will raise growth rate when the temperature is above the reference temperature and reduce growth rate below the reference temperature.

Q_{10} exponent for growth: this controls the sensitivity of the growth rate temperature dependence, with higher exponents leading to greater changes to growth with temperature. A typical value for phytoplankton is 2. If the exponent is set to 1 (the default value) then there is no temperature dependence and the maximum growth rate is always the reference maximum growth rate.

Note that the above 3 parameters only appear in an initialisation file if the growth model has been set to 2.

Max light utilisation coefficient (mg C (mg Chl)$^{-1}$ d^{-1} (W m^{-2})$^{-1}$): this is the parameter α_q in the PAR-growth curve (see Chapter 5). It controls the initial slope of the curve as light increases from zero. The model default is 4.0 mg C (mg Chl) d^{-1} (W m^{-2})$^{-1}$. A useful range is between about 1 and 10 mg C (mg Chl) d^{-1} (W m^{-2})$^{-1}$.

Reference respiration rate (mg C (mg Chl)$^{-1}$ d^{-1}): phytoplankton respiration is described using a Q_{10} formulation (see the above description of the growth model). The reference respiration rate is that measured at some reference temperature (see below). The model default is 3.5 mg C (mg Chl)$^{-1}$ d^{-1}. A suitable range is difficult to define, and measurements are harder to find than those of growth rate. The sensitivity of the critical depth to respiration rate does allow some assessment of whether or not a suitable rate has been used if you have access to biomass data from a vertically-mixed region; i.e. too low a respiration rate will result in high biomass concentrations.

Reference temperature for respiration rate (°C): the temperature at which the reference respiration rate (above) was measured.

Q_{10} exponent for respiration: this controls the sensitivity of the respiration rate temperature dependence, with higher exponents leading to greater changes to respiration with temperature. Typical values for phytoplankton are between 2 and 3. If the exponent is set to 1 (the default value) then there is no temperature dependence and the respiration rate is always the reference rate.

Chl:carbon (mg Chl (mg C)$^{-1}$): the amount of chlorophyll in the phytoplankton per unit of carbon. Typically we expect this value to change, both between species in a community and within one species as the light it receives varies. The use of a single, fixed value is an important assumption made by the model. Typical values have been measured at 0.01 - 0.05 (Holligan et al., *Marine Ecology Progress Series*, **14**, 111-127, 1984), with higher values generally associated with phytoplankton at the thermocline.

Near-bed seed stock of phytoplankton (mg C m^{-3}): this can be used to prevent a phytoplankton species from completely disappearing, or perhaps to simulate the over-wintering of phytoplankton cysts. The model prevents the bottom depth cell phytoplankton concentration from dropping below this seed value. The default value is 0 mg C m^{-3} (i.e. seed stock not used).

Pigment absorption cross-section (m^2 (mg Chl)$^{-1}$): the effect of phytoplankton biomass on the absorption of light (PAR) through the water column. Default value is 0.012 m^2 (mg Chl)$^{-1}$. See Kirk, J. T. O., *Light and Photosynthesis in Aquatic Ecosystems*, Cambridge University Press, 2010 for more details.

Maximum nitrate uptake rate (mmol (mg Chl)$^{-1}$ d^{-1}): the maximum rate at which phytoplankton can assimilate nitrate from the surrounding pool of inorganic nitrogen. It is the value that the Michaelis-

Menton uptake curve approaches at high ambient inorganic nitrogen (see Chapter 5). The default value is 2 mmol (mg Chl)$^{-1}$ d^{-1}. Model results are not overly sensitive to this value, unless it is changed by a factor of 10, as nitrate assimilation is strongly inhibited by the phytoplankton reaching the maximum cell nutrient quota (see below).

Maximum cell nutrient quota (mmol N (mg Chl)$^{-1}$): the maximum amount of nitrate that the phytoplankton can contain per unit chlorophyll. The default value is 1 mmol (mg Chl)$^{-1}$. Nitrate assimilation decreases as this maximum quota is reached, and is zero at the maximum quota.

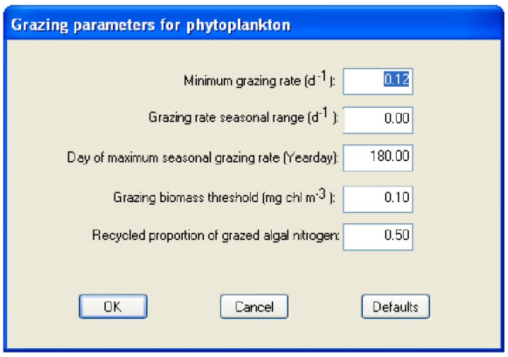
Subsistence cell nutrient quota (mmol N (mg Chl)$^{-1}$): the internal nitrate concentration, normalised by biomass, required before there can be phytoplankton growth. It is used in the model to modify the rate of photosynthesis. If the cell nitrate quota drops below the subsistence quota, biomass begins to be lost. The default value is 0.2 mmol (mg Chl)$^{-1}$. It should be greater than zero and less than the maximum cell nutrient quota.

Nitrate uptake half-saturation concentration (mmol m^{-3}): the ambient concentration of dissolved inorganic nitrogen at which a nitrate-starved phytoplankton achieves half of the maximum nitrate uptake rate. The default value is 0.3 mmol m^{-3}. The value sets the steepness of the initial slope of the Michaelis-Menton uptake curve.

Swimming speed (m d^{-1}): vertical swimming speed for the phytoplankton. The model only applies this speed during daylight, with swimming speed set to zero when it is dark. Positive speed is upward. Typical values might range between 1 and 10 m d^{-1}. Note that in the Eulerian framework of this type of model the application of a swimming (or sinking) speed is to the whole phytoplankton population. This framework is not well suited to swimming strategies that might depend on resource needs of phytoplankton cells; a Lagrangian modelling approach is then far preferable (e.g. Ross & Sharples, *Journal of Marine Systems*, **70**, 248-262, 2008).

Sinking speed (m d^{-1}): vertical sinking speed for the phytoplankton. The model applies this speed all the time. Set the speed to be negative for sinking.

*3.4 Parameters set in the **Biology** - **Grazing** dialog:*
Grazing of the phytoplankton is forced as a fraction of phytoplankton biomass removed each time step. It can be given a simple seasonal sinusoidal variability. The model default is a fixed value applied all year.



Minimum grazing rate (d^{-1}): the lowest grazing impact of the year. If a zero grazing rate range is set (see below), then this minimum grazing rate is the fixed grazing rate applied all year.

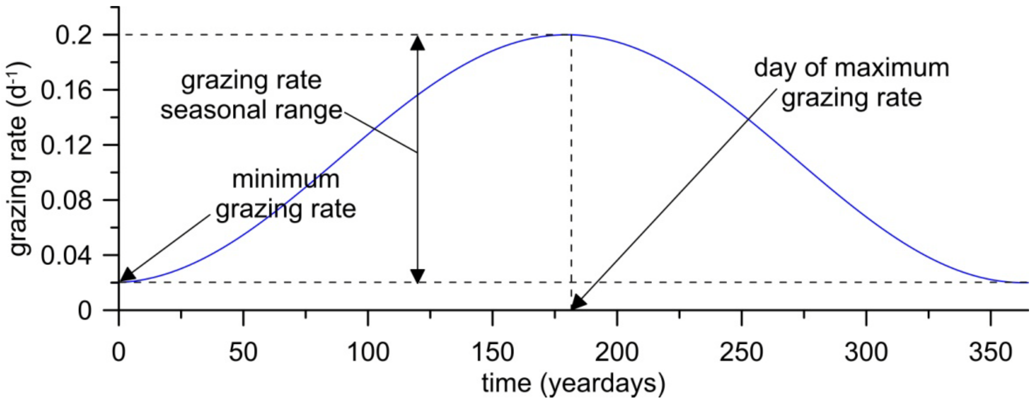
Grazing rate seasonal range (d^{-1}): the highest grazing rate of the year. This controls the seasonal variability of grazing applied through the year. Set it to zero (the default) for a fixed grazing rate (controlled by the minimum grazing rate, above).

Year day on which maximum grazing rate is reached: the day of the year (year day) on which the maximum grazing impact is reached. This parameter thus controls the phase of any seasonal variation in grazing impact.

The model calculates a grazing rate, g (d^{-1}), for each day of the year, t, from:

$$g(t) = g_{min} + \frac{g_{range}}{2}\left[1 + \cos\left(\omega_a\left(t - t_{max}\right)\right)\right]$$

With g_{min} the minimum grazing rate, g_{range} the grazing rate seasonal range, ω_a (d^{-1}) the annual frequency and t_{max} the year day of maximum grazing. The following plot illustrates how these parameters control the seasonality of grazing:



Biomass threshold for grazing (mg Chl m^{-3}): threshold of chlorophyll concentration below which grazing is not applied. This allows simulation of grazers not feeding in low-biomass regions. It can be an important parameter in allowing phytoplankton to over-winter without needing to include some seed stock.

Proportion of grazed organic N recycled to ambient DIN (0.0-1.0): the proportion of the grazed phytoplankton organic nitrogen (cellular nitrogen) that is immediately recycled back into the pool of ambient dissolved inorganic nitrogen by bacteria. This is an important parameter that controls the amount of regenerated production possible. Typically the value might be 0.5, though values approaching 1 are seen in surface layers dominated by small phytoplankton in an efficient recycling community.

4. Tidal Forcing in the Model

The barotropic tidal flow in the model is generated by a sea surface slope (or horizontal pressure gradient) that oscillates at the tidal frequency. The model can include forcing from 5 tidal constituents:

M2 (principal lunar tide)	period = 12.42 hours
S2 (principal solar tide)	period = 12.00 hours
N2 (principal lunar elliptic)	period = 12.66 hours
O1 (principal declinational)	period = 25.82 hours
K1 (declinational)	period = 23.93 hours

Typically you may have tidal constituent information based on *u* (east-west) and *v* (north-south) currents measured by a current meter. The data required by the model assumes that you have performed a harmonic analysis separately on the *u* and *v* current data recorded close to the sea surface, fitting the data to a tidal equation of the form:

u(tidal) = *A*cos((*freq* x *time*) - *phase*) where *freq* is the frequency of the tidal constituent. Make sure that the units of *freq* and *time* are consistent, and if you want to attempt to get the phasing of the tide close to your observations make sure that the time axis of your current data has *time*=0 at midnight on January 1st (i.e. the same as the model). *A* (m s^{-1}) is the amplitude of the tidal constituent and *phase* is the phase angle (radians) that sets the timing of the tidal currents. For each tidal constituent the model requires 2 values for *A* (one for the *u*-component and one of the *v*-component) and 2 values of *phase*.

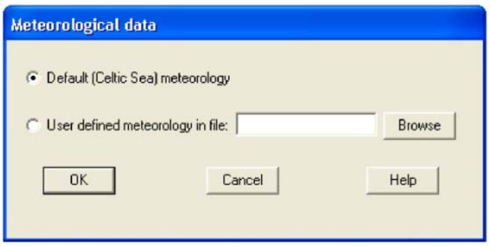
The model uses this tidal constituent information and the Coriolis parameter, *f*, calculated from the latitude to calculate the pressure gradient amplitudes needed to generate a tidal current ellipse similar to the one which has characteristics resulting from your harmonic analysis. Using your tidal information the model calculates the length of the semi-major axis of the tidal current ellipse (*S*), the polarisation of the ellipse (*P*), and the orientation of the major axis measured anti-clockwise from the x-axis. The pressure gradient amplitudes along the major and minor axes of the ellipse (PG_{major} and PG_{minor}) for a tidal constituent are then given by:

$PG_{major}=(freq+Pf) \times S$
$PG_{minor}=(f+Pfreq) \times S$

The orientation of the tidal current ellipse is used to transform the pressure gradient into *x* and *y* components.

This calculation of the pressure gradients is based on the assumption that the surface currents that provided the tidal constituent information are largely free of frictional effects from the bottom boundary layer. In many cases this will be an approximation, so the resulting modelled tidal currents may differ from your observations. The differences occur mainly in the phasing of the currents. Ideally, if detailed knowledge of the modelled currents compared to your observations is required, you should use the option of hourly data output (see Data Output below) to generate some current data on which you can then perform a harmonic analysis and check the modelled currents against your observations.

5. Meteorological Data



The **Meteorology** dialog offers two choices for the meteorological data to be used by the model.

5.1 Default (Celtic Sea) meteorology.
This is a set of meteorology data based on a seasonal analysis of information from North Atlantic model of the UK Met Office. The 3-hourly data, from the meteorological model grid cell located at 50 deg N 7 deg W (central Celtic Sea), was averaged to daily values and then fitted to a sinusoidal curve with period 1 year. This yielded smooth functions describing the meteorological forcing parameters as a function of the annual cycle (yearly angular frequency ω_a) and time, *t*. The functions used are:

$$\text{wind speed} = \sqrt{\left(62.9 + 26.8\cos(\omega_a t) + 7.9\sin(\omega_a t)\right)} \quad [\text{m s}^{-1}]$$
$$\text{air temperature} = 12.5 - 3.3\cos(\omega_a t) - 2.5\sin(\omega_a t) \quad [°\text{C}]$$
$$\text{air pressure} = 1016.0 \quad [\text{mbar}]$$
$$\text{relative humidity} = 81.4 - 2.3\cos(\omega_a t) + 0.8\sin(\omega_a t) \quad [\%]$$
$$\text{cloud cover} = 66.5 + 5.1\cos(\omega_a t) - 4.1\sin(\omega_a t) \quad [\%]$$

Each time the model is run with these default functions, a file "Celtic_met.dat" is written containing the daily meteorological data in the format:

Julian Day, wind speed (m s^{-1}), wind direction (deg clockwise from north), cloud cover (%), air temperature (°C), air pressure (mbar), relative humidity (%)

There are 4 points to note about these meteorological functions.

(i) Only air temperature and wind speed have significant variability on the annual time scale. For an example see Sharples, *Journal of Plankton Research*, **30**, 183-197, 2008. For air pressure the fitted annual variability is so weak that the model simply uses an average value.
(ii) Wind speed is based on fitting the squared wind speed to the annual cycle, as ideally we want to use the seasonally-varying wind *stress* (proportional to wind speed squared).
(iii) Cloud cover from the meteorological model is available as "low level", "medium level" and "high level". When using such modelled cloud data it is the "low level" cloud that probably has the most relevance to the air-sea heat fluxes in the S2P3 model.
(iv) There is no consistent annual cycle to wind direction in the Celtic Sea, so the model rotates the wind vector by 72 deg clockwise each day.

5.2a User defined meteorology.
You can supply your own meteorological forcing by setting up an ascii text file with daily meteorological data in the format:

Julian Day,wind speed (m s^{-1}), wind direction (deg clockwise from north), cloud cover (%), air temperature (deg C), air pressure (mbar), relative humidity (%)

For an example of the required file format, see the file "Celtic_met.dat" generated by the model when run with the default Celtic Sea annual cycles.

Use the Browse button in the **Meteorology** dialog to select the file containing your meteorological data. The model will report back if it finds that it cannot read the format of the file.

Note that wind direction is that of the wind vector; i.e. a direction of 90 degrees is an eastward wind (or a westerly in meteorology parlance).

5.2b Meteorological data from the UK Met Ofifce.
Courtesy of the UK Met Office, files of meteorological data for the central Celtic Sea between the years 2005 and 2010 are also provided. Data was extracted from the Met Office North Atlantic model, with the 3-hourly data used to produce time series of daily mean meteorological parameters. The filenames of this data are:

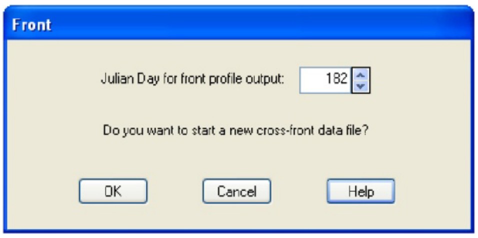
CelticSea_met2005.dat
CelticSea_met2006.dat
CelticSea_met2007.dat
CelticSea_met2008.dat
CelticSea_met2009.dat
CelticSea_met2010.dat

These files are useful for assessing the effects of day-to-day variability in meteorological forcing, along with an indication of inter-annual variability. The files can be used to drive the model by following the instructions for "User defined meteorology" above. The file format is as described under "User defined meteorology". An extra column of data in these files indicates the number of 3-hourly data used to produce the daily mean. A value of "0" indicates a data gap in the North Atlantic model output, and the daily mean parameters on that day take their average values on that day across 2005-2010.

Please note the following copyright associated with the data from the UK Met Office:

requires a separate licence from the Met Office. Please contact the Met Office directly with any licensing questions: http://www.metoffice.gov.uk/about-us/contact.

6. Cross front



The model can be used to synthesise a 2-D section through a shelf sea front, by running it several times with different tidal and/or depth parameters. The same approach has been used in:

> Sharples, J. and J.H.Simpson. 1996. The influence of the springs-neaps cycle on the position of shelf sea fronts. In: *Buoyancy Effects on Coastal Dynamics*, D.G.Aubrey & C.T.Friedrichs (Eds). Coastal and Estuarine Studies Volume 53, AGU, 71-82.
>
> Sharples, J. 2008. Potential impacts of the spring-neap tidal cycle on shelf sea primary production. *Journal of Plankton Research*, **30(2)**, 183-197.

The success of the approach arises from the dominance of the vertical heating-mixing competition in setting the vertical structure of the NW European shelf seas. It may not be appropriate everywhere.

At the day specified in the **front** dialog the model outputs vertical profiles at noon into an ASCII data file front_data.dat with the following columns:

SH: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter; u^3 here is the long-term average of the depth-averaged cubed current speed.

height: height above the seabed (metres). These heights mark the centres of the model grid cells, where the scalars and velocity are located.

temp: temperature at **height**, noon value.

chl: noon concentration of chlorophyll (mg m^{-3}) at **height**.

cellN: noon concentration of cellular nitrogen (mmol m^{-3}) at **height**.

uptake: amount of dissolved inorganic nitrogen (mmol m^{-3}) taken up at **height** in the previous 24 hours.

netPP: net primary production (mg C m^{-3}), or net carbon fixed, at **height** over the previous 24 hours.

grossPP: gross primary production (mg C m^{-3}), or gross carbon fixed, at **height** over the previous 24 hours.

DIN: noon concentration of dissolved inorganic nitrogen (mmol m^{-3}) in the water at **height**.

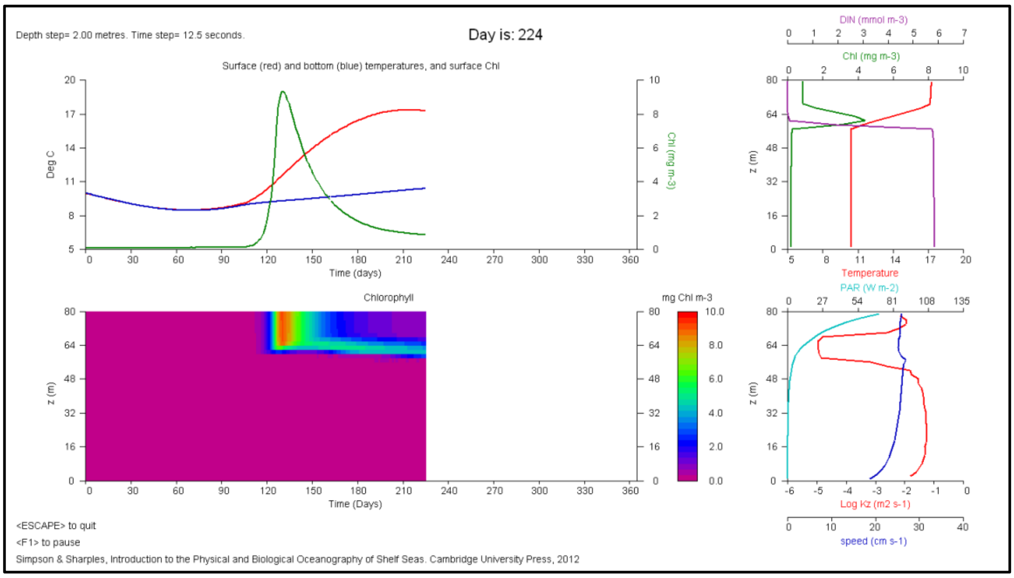
hKz: height above the seabed (metres). These heights mark the boundaries between grid cells, where K_z (vertical eddy diffusivity) is located.

logKz: $\log_{10}$ of the vertical eddy diffusivity ($m^2\ s^{-1}$) at height **hKz**. The output value is a noon to noon average of 24 hourly values.

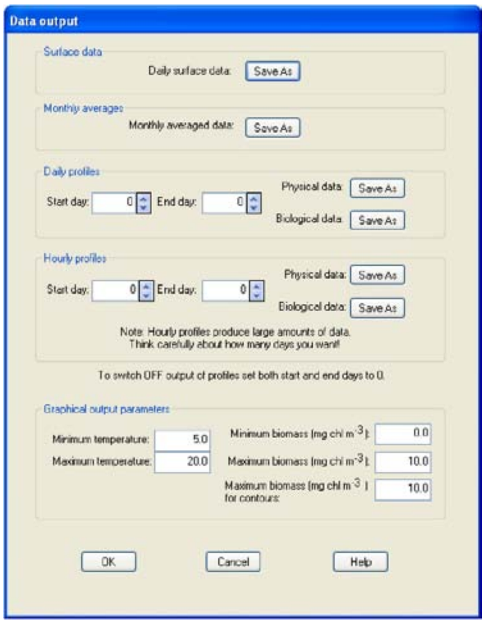
As long as the **Cross front** main menu option is not chosen again, or the model is not closed and re-started, the profile data at the specified day is appended to the end of the front data file for each new run. So, for instance, if you keep the total depth fixed but run the model several times each with a different tidal current amplitude, the front data file is filled with data in much the same way as a transect of CTD stations across a tidal mixing front might look. If **Cross front** is selected, or the model is shut down and then re-started, then the front data file will be over-written. So, remember to re-name the front data file if you wish to keep it.

7. Save screen

The model graphical output can be saved as a bitmap image file, either at the end of a model run or after pressing <escape> partway through a run. Select **Save screen** from the main menu and provide a filename for the bitmap as prompted.



8. Data output



The model outputs several data files during operation. Each file has a default filename and is over-written on each model run unless a user-defined filename has been specified. A user-defined filename is only used for the model run immediately following the selection of the filename. Any additional run will revert to the default filenames and will not over-write a user-defined file.

8.1 Daily surface data:
This data output is always switched on, with data going to either the default file "surface.dat" or to a file that you choose under "Save As". Data is output at each model noon, as an ASCII text file with the following columns:

JD: Julian Day

time: time (year days); data is output at noon on each day

SH: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter; u^3 here is the long-term average of the depth-averaged cubed current speed.

Ts: sea surface temperature (°C)

Tb: near-bed sea temperature (°C)

Ts-Tb: surface-bottom temperature difference (°C)

PHI: potential energy anomaly (J m^{-3})

spd: daily-mean, depth-averaged current speed (m s^{-1})

stress: daily-mean surface wind stress (N m^{-2})

Qs: surface solar radiation (W m^{-2})

Qflux: net surface heat flux, positive is heat into the sea surface (W m^{-2})

CHLs: surface chlorophyll concentration (mg m^{-3})

CHLt: depth-integrated chlorophyll (mg m^{-2})

DINs: surface concentration of dissolved inorganic nitrogen (mmol m^{-3})

netp: net daily water column primary production (g C m^{-2} d^{-1})

grossp: gross daily water column primary production (g C m^{-2} d^{-1})

Note that the net primary production is calculated at each model time step as the gross primary production minus respiration.

8.2 Monthly averaged data:
This data output is always switched on, with data going to either the default file "monthly.dat" or to a file that you choose under "Save As". Note that the months are set up for the case of the northern hemisphere (model run starts on January 1st), so the timing of the months will not be correct for the southern hemisphere (in that case either treat this output as an estimate or use the information in the surface data file to calculate a better result).

Data is output at the end of each month, as an ASCII text file with the following columns:

month: January = 1, December = 12. Days in each month are based on a non-leap year. This is only applicable to the northern hemisphere.

SH: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter; u^3 here is the long-term average of the depth-averaged cubed current speed

Ts: monthly mean sea surface temperature (deg C)

Tb: monthly mean near-bed water temperature (deg C)

delta-T: monthly mean surface-bottom temperature difference (deg C)

Wstress: monthly mean wind stress (N m^{-2})

Chlt: monthly mean water column integrated chlorophyll (mg Chl m^{-2})

Ct: monthly mean water column integrated organic carbon (g C m^{-2})

Cgross: total gross carbon fixed in the month (g C m^{-2})

Cnet: total net carbon fixed in the month (g C m^{-2})

accumC: net carbon fixed since January 1st (g C m^{-2})

8.3 Daily profiles:
This data is only output if End day > Start day in the *daily profiles* section of the **Data output** dialog. If End day = Start day = 0 no daily data files are opened. Vertical profiles of physical and biological data are output at noon, into ASCII files with the following columns:

Physics profiles:
time: decimal days with time=0.0 at 0000 hrs January 1st.

hu3: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter, with h the water depth and u^3 the long-term depth-average of the cubed current speed.

height: height above the seabed (metres). These heights mark the centres of the model grid cells, where the scalars and velocity are located.

temp: temperature at **height**, noon value.

sigmat: density-1000 kg m^{-3} at **height**, noon value.

u: east-west current velocity component at **height**, averaged over 24 hours (noon to noon). Positive values to the east.

v: north-south current velocity component at **height**, averaged over 24 hours (noon to noon). Positive values to the north.

h_turb: height above the seabed (metres). These heights mark the boundaries between grid cells, where the turbulence parameters are located.

Ri: gradient Richardson number at height **h_turb**. Ri is constrained to lie between -1.0 and 10.0; i.e. if Ri > 10.0, Ri is output at 10.0. The output value is a noon to noon average of 24 hourly values.

logKz: $\log_{10}$ of the vertical eddy diffusivity (m^2 s^{-1}) at height **h_turb**. The output value is a noon to noon average of 24 hourly values.

logdiss: $\log_{10}$ of the turbulent dissipation (m^2 s^{-3}) at height **h_turb**. The output value is a noon to noon average of 24 hourly values.

logtke: $\log_{10}$ of the turbulent kinetic energy (m^2 s^{-2}) at height **h_turb**. The output value is a noon to noon average of 24 hourly values.

Biological profiles.
time: decimal days with time=0.0 at 0000 hrs January 1st.

hu3: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter, with *h* the water depth and u^3 the long-term depth-average of the cubed current speed.

height: height above the seabed (metres). These heights mark the centres of the model grid cells, where the scalars and velocity are located.

PAR: mean PAR (W m^{-2}) received within the model grid cell centred at **height**, noon to noon.

chl: noon concentration of chlorophyll (mg m^{-3}) at **height**.

cellN: noon concentration of cellular nitrogen (mmol m^{-3}) at **height**.

netPP: net primary production (mg C m^{-3}), or net carbon fixed, at **height** over the previous 24 hours.

grossPP: gross primary production (mg C m^{-3}), or gross carbon fixed, at **height** over the previous 24 hours.

uptake: amount of dissolved inorganic nitrogen (mmol m^{-3}) taken up at **height** in the previous 24 hours.

DIN: noon concentration of dissolved inorganic nitrogen (mmol m^{-3}) in the water at **height**.

Note that the net primary production is calculated at each model time step as the gross primary production minus respiration.

Default data filenames for the daily profiles are "physday.dat" and "biolday.dat" for the physics and biology data respectively.

8.4 Hourly profiles:
This data is only output if End day > Start day. If End day = Start day = 0 no daily data files are opened. Vertical profiles of physical and biological data are output at the start of each hour, into ASCII files with the following columns:

Physics profiles.
time: decimal days with time=0.0 at 0000 hrs January 1st.

hu3: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter, with *h* the water depth and u^3 the long-term depth-average of the cubed current speed.

height: height above the seabed (metres). These heights mark the centres of the model grid cells, where the scalars and velocity are located.

temp: temperature at **height**, instantaneous value.

sigmat: density-1000 kg m^{-3} at **height**, instantaneous value.

u: east-west current velocity component at **height**, instantaneous value. Positive values to the east.

v: north-south current velocity component at **height**, instantaneous value. Positive values to the north.

h_turb: height above the seabed (metres). These heights mark the boundaries between grid cells, where the turbulence parameters are located.

Ri: gradient Richardson number at height **h_turb**. Ri is constrained to lie between -1.0 and 10.0; i.e. if Ri > 10.0, Ri is output at 10.0. The output value is an average over the previous hour.

logKz: $\log_{10}$ of the vertical eddy diffusivity (m^2 s^{-1}) at height **h_turb**.The output value is an average over the previous hour.

logdiss: $\log_{10}$ of the turbulent dissipation (m^2 s^{-3}) at height **h_turb**. The output value is an average over the previous hour.

logtke: $\log_{10}$ of the turbulent kinetic energy (m^2 s^{-2}) at height **h_turb**. The output value is an average over the previous hour.

Biological profiles.
time: decimal days with time=0.0 at 0000 hrs January 1st.

hu3: $\log_{10}(h/u^3)$, the Simpson-Hunter stratification parameter, with h the water depth and u^3 the long-term depth-average of the cubed current speed.

height: height above the seabed (metres). These heights mark the centres of the model grid cells, where the scalars and velocity are located.

PAR: PAR (W m^{-2}) received within the model grid cell centred at **height**, instantaneous value.

chl: instantaneous concentration of chlorophyll (mg m^{-3}) at **height**.

cellN: instantaneous concentration of cellular nitrogen (mmol m^{-3}) at **height**.

netPP: net primary production (mg C m^{-3}), or net carbon fixed, at **height** over the previous hour.

grossPP: gross primary production (mg C m^{-3}), or gross carbon fixed, at **height** over the previous hour.

uptake: amount of dissolved inorganic nitrogen (mmol m^{-3}) taken up at **height** in the previous hour.

DIN: instantaneous concentration of dissolved inorganic nitrogen (mmol m^{-3}) in the water at **height**.

Note that the net primary production is calculated at each model time step as the gross primary production minus respiration.

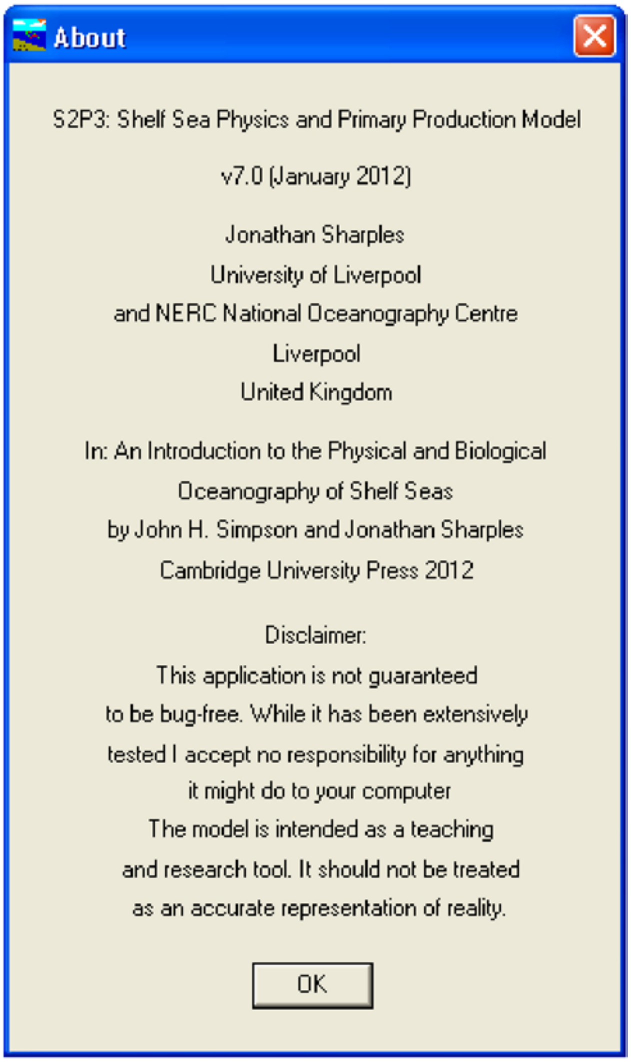
Default data filenames for the daily profiles are "physhour.dat" and "biolhour.dat" for the physics and biology data respectively.

8.5 Graphical output parameters:
These parameters control some of the aspects of the screen output that cannot be pre-determined by the model input parameters.

The minimum and maximum temperature and biomass set the axes limits for the temperature and chlorophyll time series and for the noon temperature and chlorophyll profile plots. The maximum biomass for contours sets the upper chlorophyll concentration in the time series of contoured chlorophyll. Separate control of the contour plot allows the detail of low-chlorophyll regions (e.g. the sub-surface chlorophyll maximum) to be seen if required.

9. Help

The **Help** option in the main menu provides you with almost all of the information in this guide, via the **Instructions** option. Note also the **About** option, which includes the model version number and an all-important disclaimer.



10. Notification of bugs and errors.
While I have shirked responsibility for any bugs or errors existing in the model in the disclaimer, I am keen that new errors are found and fixed. If you find an error, or if you have any suggestions for improvements or additions to the model (e.g. to the types of data output for instance), then I will be happy to hear about them. I will endeavour to fix any errors found. I will make other alterations/ additions depending on demand and time constraints. Modified version of the model will be posted on the CUP website, along with notes on the changes that have been made.

Jonathan Sharples
jons@liverpool.ac.uk
4th January 2012
