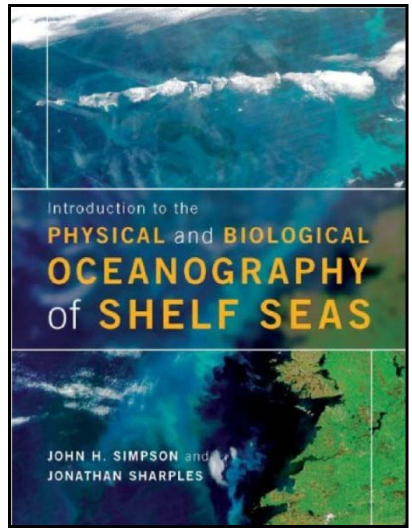
First Tutorial on the Model S2P3



1. Introduction.
This tutorial complements the Guide to the S2P3 Model. The Guide provides a detailed set of instructions on how the model is operated. This tutorial will lead you through the basic physics and biology simulated by the model and provide some initial guidance on running the model and interpreting the output. The tutorial includes a set of questions that can be answered as you work through the material. These questions are designed to get you familiar with how the model works and the output data available. More detail on the physical and biological processes that can be investigated using this model can be found in the textbook, Chapters 6, 7 and 8.

2. The physics and biology of a shelf sea water column.
2.1 Seasonal heating/cooling [See the textbook, Section 2.2].
Temperate shelf seas experience a seasonal cycle of surface heating and cooling. In winter, the weak solar irradiance (heat into the sea surface) is less than the heat output from the sea surface (a combination of heat loss by infra-red radiation, conduction and evaporation), and so the *net heat flux* is back into the atmosphere. Thus the sea surface cools, becomes denser than the water below it, and convectively overturns. The water column remains vertically mixed.

At about the time of the spring equinox, the solar irradiance increases enough to dominate the heat balance (i.e. it becomes greater than the surface heat loss), and the water column begins to warm up. This net heat input is distributed exponentially through the water column. In the absence of any turbulence (mixing), this distribution causes the upper water to warm up (and so become less dense), thus generating *stratification* and a thermocline. Surface temperature rises rapidly through summer. Bottom temperature creeps up very slowly as little radiation reaches it directly and the thermocline inhibits mixing of surface heat downward.

As surface temperature rises, the infrared heat output from the sea surface increases very rapidly (longwave heat output is dependent on surface temperature raised to a power of 4). Sometime in midsummer the surface heat loss exceeds the solar irradiation, so that the upper layer begins to cool. This drives convective mixing, which gradually deepens the thermocline until, in autumn, the water column returns to a completely mixed state.

2.2 Tidal mixing [see the textbook, Section 6.1].
Tidal currents are slowed by friction against the seabed. This generates a vertical gradient in current speed (i.e. current shear). Anywhere that has current shear is a site of turbulence generation. Turbulence can act against any stratification, and either weaken it or completely remove it by redistributing the density structure of the water column. The tidally-averaged power of tidal energy dissipation is given by:

$$P_T = \frac{4}{3\pi} k_b \rho_0 \hat{u}_{M2}^3 \qquad \text{[W m}^{-2}\text{]}$$

with k_b the bottom drag coefficient (approximately 0.003), ρ_0 (kg m^{-3}) the density of seawater, and $\hat{u}_{M2}$ (m s^{-1}) the depth-averaged amplitude of the M_2 tidal current. A similar equation could be written for other tidal constituents, but for now we will use only the M_2 constituent as it is often dominant. Most of this turbulence simply cascades down to smaller and smaller eddies, and is ultimately disspiated as heat. A small fraction of it (typically 0.3%) is available to mix the stratification. Note that the mixing power is proportional to the cube of the tidal current. So, a small change in current amplitude leads to a large change in mixing. An analogous analysis can be carried out for the effect of surface winds, injecting turbulence and mixing into the sea surface.

2.3 Partitioning of shelf seas [see the textbook, Sections 6.1 and 6.2].

Whether or not a shelf sea water column becomes stratified in spring and summer depends on the relative contributions of surface heating and tidal (plus wind) mixing. If tidal mixing is weak, or the water column is deep, then the mixing will not be enough to prevent stratification by heating. Such areas of shelf seas stratify in summer, with a warm surface layer separated from a cold bottom layer by a thermocline. If, however, the tides are very strong, or the water is shallow, then the power available from the tides to mix the water column will always be capable of preventing stratification. Such areas of shelf seas remain vertically mixed all year, with a cool temperature. Thus, shelf seas are partitioned into seasonally-stratifying and permanently-mixed regions, as a function of the speed of the tidal currents and the depth of the water. In many shelf regions, where the tides dominate the input of turbulent mixing, the controlling parameter is $SH = \log_{10}(h/u^3)$, with h the water depth and u an appropriate measure of the strength of the tidal currents. High values of *SH* occur in regions that stratify, and low values in regions that remain mixed. The heating and mixing inputs balance at a critical value of *SH*, marking the tidal mixing fronts (see the textbook, Chapter 8).

2.4 The thermocline.

In areas that stratify, the thermocline is a critical feature in the physics and biogeochemistry of the water column. Thermoclines are effective barriers to vertical mixing, separating the water column into two distinct mixed layers (the bottom layer mixed by the tides, the surface layer mixed by the wind).

One way of quantifying the ability of a thermocline to resist mixing, or the stability of the thermocline, is by using the *Gradient Richardson Number* (*Ri*, see textbook Section 4.4.1 for a complete derivation):

$$Ri = -\frac{\dfrac{g}{\rho_0}\dfrac{\Delta\rho}{\Delta z}}{\left(\dfrac{\Delta U}{\Delta z}\right)^2}$$

with g=9.8 m s^{-2}, ρ_0 (kg m^{-3}) the water density, $\Delta\rho/\Delta z$ the vertical density gradient across the thermocline, and $\Delta U/\Delta z$ the vertical velocity gradient across the thermocline. The negative sign is because we define the vertical axis as positive upwards, so that a stable density gradient is calculated as negative and the resulting *Ri* is positive. *Ri* is a ratio between the strength of the stratification and the generation of turbulence. A neutrally stable water column has *Ri*=0. As stratification increases, *Ri* increases above 0 and mixing is gradually weakened (physically, more energy is required from the turbulence to do work against the density gradient). Above a critical *Ri* all mixing is prevented. There are various estimates of what this critical *Ri* is. It is often taken to be somewhere between 0.25 and 1.

2.5 The response of the primary producers [see textbook Sections 5.1, 6.3 and 6.4].
Phytoplankton require both sufficient light and sufficient nutrients to grow. If either of those resources is missing, then the phytoplankton respire (i.e. they can only survive by utilising their internal stores of energy, and will eventually die).

In temperate shelf seas in winter there is normally plenty of dissolved inorganic nutrient available, but the vertically-mixed state of the water means that the phytoplankton are being continuously transported between the weakly-lit surface water and the dark deeper water. They cannot achieve net growth because the average light that they receive while being mixed through the water column is not sufficient for photosynthesis.

If the tides are weak, and stratification starts in spring, then the developing thermocline acts as a barrier preventing the transfer of water properties (heat, nutrients, phytoplankton) between the upper and lower layers. The phytoplankton in the surface layer suddenly find themselves in trapped an environment where there are sufficient nutrients and light, leading to rapid growth and the spring bloom in the surface layer. In the bottom layer, life is not so good. The phytoplankton are trapped in a layer with even less light than they were experiencing before stratification, and so they respire. Meanwhile, in the surface layer, the stability of the thermocline that held the phytoplankton nearer to the light starts to have a negative impact on growth as it prevents the replenishment of the nutrients from the bottom layer. The bloom decays as the phytoplankton become nutrient-limited, leaving a low chlorophyll, low nutrient surface layer above a low chlorophyll, high nutrient bottom layer. The only place in the water column where phytoplankton are able to grow is inside the thermocline, where the light is just sufficient and there is a weak flux of nutrients from the bottom layer driven by internal wave mixing [see the textbook, Section 7.3].

The spring bloom does not occur in a water column that stays vertically mixed all year. You will be investigating this with the model.

3. Getting familiar with the model.

The model is 1-dimensional (vertical), with the water column split into a series of evenly-spaced grid cells. The basic forcing parameters are tidal currents, air-sea heat flux, and wind stress. The air-sea heat flux can act to stratify the water column during spring/summer, while the tidal currents and surface wind stress, along with net heat loss in the winter, act to mix the water. The ability of the turbulence to mix the thermal (density) gradients is controlled by a turbulence scheme that provides the link between the gradient Richardson number and the turbulent *viscosity* and *diffusivity*. This turbulence mixes the physics (momentum, heat), and also the biology (phytoplankton, inorganic nutrients).

Phytoplankton are modeled as a single species that fixes carbon in response to light and nutrients. Sufficient quantities of both resources are required for net growth. A cell quota approach is used: the phytoplankton cells contain carbon and nutrients, with the internal concentration of nutrients determining the growth rate. The internal nutrients are taken up from dissolved inorganic nitrogen in the surrounding water.

Further details on the physics employed by the model can be found in:
Sharples et al., 2006, *Continental Shelf Research*, **26**, 733-751.

The biological component is described in:
Sharples, 2008, *Journal of Plankton Research*, **30**, 183-197.

3.1 Getting the model ready and a first run.
Two files are required:

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

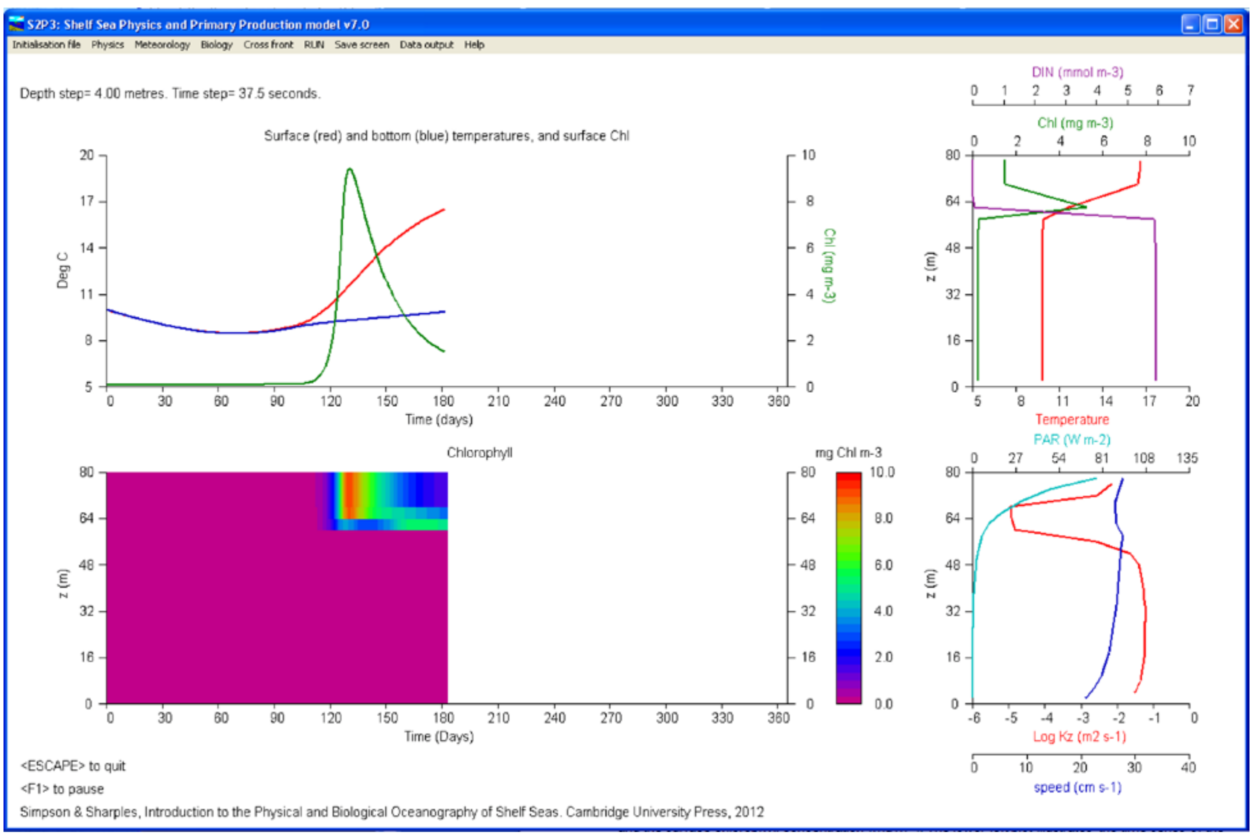
Create a directory on your computer's hard drive (e.g. c:\S2P3) and save all the above files into it. There are also several files of meteorological data available. For now we will ignore those and use the default data within the model.

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

This sets the model application running, opening up the main model window. Note the **Help** menu option. Selecting this, followed by Instructions, provides you with details on the parameters used by the model and the data that can be output.

The model is all set to run with default parameters, so you can click on **RUN** in the main menu and watch the simulation for one year in a stratifying northern-hemisphere shelf sea appear.

The screen output will look like this:



The plots on the screen are:
Upper left: time series plot of surface (red) and bottom (blue) temperature, and surface chlorophyll (green).
Lower left: time series contour plot of the depth-time distribution of chlorophyll.
Upper right: vertical profiles of temperature (red), dissolved inorganic nitrogen (purple), and chlorophyll concentration (green).
Lower right: vertical profiles of daily-mean noon irradiance (light blue), current speed (dark blue) and $\log_{10}$ eddy diffusivity (red).

As well as the graphical output to the screen, the model also has the ability to write data files of all the physical and biological variables. Select **Help** and **Instructions**, and choose **Data Output** for further information. The output files are standard ASCII format, and so can be read by and text editor (e.g. notepad).

Things to notice:

- The model begins at the start of the year, with a cool, vertically mixed water column.
- The water continues to cool as a result of heat losses from the sea surface to the atmosphere being larger than the weak irradiance received from the winter sun.
- In the middle of March the water begins to warm up as the solar irradiance finally becomes larger than the heat loss. The increase in irradiance is evident in the plot of the light profile.
- Shortly after the equinox the rate at which the water is being heated by the solar irradiance becomes greater than the ability of the tidal mixing to maintain vertical homogeneity. The water begins to stratify (surface temperature increases far more rapidly than the bottom temperature) from about day 105.
- As the stratification starts, so does the spring bloom. The diffusivity profile illustrates how the mixing drops significantly at the thermocline, separating the upper and lower layers.
- As the bloom continues, notice the rapid decrease in nutrients in the surface layer. Nutrients in the bottom water remain high, but they are not mixed into the surface layer because of the low mixing in the thermocline.
- In the contour plot, notice that the bloom was confined to the upper few metres of the water column.
- During the summer, with stratification well-established, the surface layer remains devoid of nutrients and chlorophyll. Growth does carry on in the sub-surface chlorophyll maximum (SCM) in the thermocline. This is caused by a weak flux of nutrients through the thermocline driven by, for instance, internal waves (see the textbook, Chapter 7).
- In the middle of summer the surface temperature begins to decrease as a result of the longwave back radiation (this heat loss is proportional to T_s^4, and so increases dramatically as the surface temperature increases). At the surface cools, the very top of the water becomes convectively unstable, mixing down through the surface layer. Notice the themocline deepening through late summer.
- In late autumn the water becomes completely mixed again, and nutrients are replenished throughout.

Question 1:

Looking at the output from the default model run, answer the following:

(a) What was the maximum chlorophyll concentration reached in the surface water during the spring bloom? What day did this occur on? [Look in the output file surface.dat].

(b) What was the depth-integrated chlorophyll concentration (mg chl m^{-2}) at the time of the maximum of the spring bloom? [Look in the output file surface.dat].

(c) What was the gross annual production rate reported at the end of the model run? [This is reported by the model at the end of the annual run].

3.2 Changing model parameters.

You have control over all the physical and biological parameters that the model requires to run. To change any physics parameters, select **Physics** to get to the physical parameter menu. To change biological parameters, select **Biology** and **Phytoplankton growth** (for parameters that control growth) or **Grazing** (for parameters that control the loss of phytoplankton to grazers). The details of the different parameters under each of these menus can be found by selecting the **Help - Instructions** button, or by selecting Help from within the Physics or Biology parameter menus.

When you change parameters, you can save the new initialisation data by selecting **Initialisation file** and **Save** from the main menu. Selecting **Initialisation file** and **Load** allows you to read in a file of previously-saved initialization data. When you start to address more complex questions with the model it is important that you keep a clear record of what you do, and be methodical. Spend some time planning what you want to do. Remember, each time you change a parameter you are conducting an experiment with the model.

The model run with the default parameters resulted in a water column that stratified during summer. We can prevent stratification by either increasing the tidal currents, or by decreasing the depth. Select **Physics** and the tidal constituent **M2**. The default tidal current amplitude is 0.4 m s^{-1}. Replace this with 1.0 m s^{-1} and run the model again. Notice now that the water column remains completely mixed all year.

Question 2:

You have just run the model with a water column that remained well-mixed throughout the year.

(a) What was the maximum surface chlorophyll concentration reached? What day did this occur on?
(b) At the time of the maximum surface chlorophyll concentration, what was the depth-integrated chlorophyll concentration (mg m^{-2})?
(c) What was the gross annual production rate reported at the end of the model run?

We will now consider the interaction between the water depth and the growth of the phytoplankton in vertically mixed conditions. Make sure the model is set up with the default initialisation parameters. You can do this by selecting the Default option in each of the parameter windows. Alternatively (and more quickly) simply close the model application and re-start it. In the **physics** parameter menu change the **M2** tidal current amplitude to 2.0 m s^{-1} (i.e. this will keep the water well-mixed all year even in moderately deep water). Run the model (note that the default depth is 80 metres) and write down the maximum surface chlorophyll concentration and the annual net production rate. Now change the depth of the model (in the physics parameter menu) to 60 metres. Note that you should try to keep the vertical resolution the same as the previous run (about 4 metres), so as well as changing the depth, also change the number of grid cells (i.e. 60/4 = 15 grid cells for a resolution of 4 metres). Again note the maximum chlorophyll concentration and the annual net production rate. Repeat this process for depths of 100, 120, 140 and 160 metres.

Question 3:

You should have noticed that the maximum chlorophyll concentration and the annual net production rate both decreased quickly as the depth of the water column was increased.

(a) Why?
(b) For the deeper water, what limits summer primary production?
(c) For the shallower water, what was limiting production in summer?

In the physics and biology parameter menus you can change several other parameters. With any complex model it is strongly advisable to change only one parameter at a time, and make sure you fully understand how it changes the model results.

Spend some time now investigating how the following parameters affect (or do not affect) the model results in stratifying and permanently mixed water columns. To make easy comparisons you may wish to save the output screen (select **Save screen**) for different runs. You could assign each parameter investigation to different groups in the class, and each group report back their findings and interpretation to the rest of the class.

(1) The vertical attenuation coefficient for PAR (investigate values between 0.10 and 0.15 m^{-1}).
(2) The maximum near bed dissolved inorganic nitrogen concentration (investigate values between 3 and 10 mmol m^{-3}).
(3) Add a spring-neap cycle to the tides. Do this by setting the S2 current via the Physics parameter menu. Typically the S2 amplitude is about 30% of the M2 amplitude in NW European shelf seas.
(4) The phytoplankton respiration rate (investigate values between 1.0 and 5.0 mg C (mg chl)$^{-1}$ d^{-1}).
(5) The phytoplankton maximum quantum yield (investigate values between 2 and 10 mg C (mg chl)$^{-1}$ d^{-1}(W m^{-2})$^{-1}$).

Answers to the Questions:

Question 1:

(a) What was the maximum chlorophyll concentration reached in the surface water during the spring bloom? What day did this occur on? [Look in the output file surface.dat].

Looking in the file surface.dat, the peak of the spring bloom reached a concentration of 9.4 mg Chl m^{-3} and occurred on day 131 (based on finding the maximum surface chlorophyll concentration in the CHLs column of the file).

(b) What was the depth-integrated chlorophyll concentration (mg chl m^{-2}) at the time of the maximum of the spring bloom? [Look in the output file surface.dat].

On day 131, the depth-integrated chlorophyll was 176 mg Chl m^{-2} (the CHLt column in the file).

(c) What was the gross annual production rate reported at the end of the model run? [This is reported by the model at the end of the annual run].

100 g C m^{-2} $year^{-1}$

Question 2:

(a) What was the maximum surface chlorophyll concentration reached? What day did this occur on?

2.18 mg Chl m^{-3} on day 223.

(b) At the time of the maximum surface chlorophyll concentration, what was the depth-integrated chlorophyll concentration (mg m^{-2})?

On day 223, the depth-integrated chlorophyll was 155 mg Chl m^{-2}.

(c) What was the gross annual production rate reported at the end of the model run?

106 g C m^{-2} $year^{-1}$

Discussion notes:
Compared to the stratifying case in Question 1, the mixed water does not experience a spring bloom. Instead it sees a broader but less concentrated peak in chlorophyll. However, while concentrations are lower, the mixed water means that they are held throughout the entire depth. The effect is to end with annual primary production very similar to the stratifying case.

In a real, mixed shelf sea water column it is likely that the attenuation of light will be higher.

Question 3:

You should have noticed that the maximum chlorophyll concentration and the annual net production rate both decreased quickly as the depth of the water column was increased.

(a) Why?

Deepening the total depth leads to an increase in the time that phytoplankton spend in regions where growth is light limited. As the net primary production tends towards zero, the depth of the water column in summer approaches the critical depth for growth (see the textbook, Section 5.1.5).

(b) For the deeper water, what limits summer primary production?

The phytoplankton are light-limited.

(c) For the shallower water, what was limiting production in summer?

The growth is nutrient limited. You can see this by watching what happens to the DIN profile (top left plot) during the simulation. Also, if you increase the nitrate supply rate (by altering the nutrient boundary condition in the **Physics** menu), the annual production rate changes.

Notes:
The net production and water depth information can be plotted independently (load into Matlab, Excel or other analysis/graphics package). This makes it easier to visualize how the water depth approaches the critical depth, and introduces the idea of post-analysis of model results. The critical depth concept can be explored further by altering the phytoplankton respiration rate or the attenuation of light.