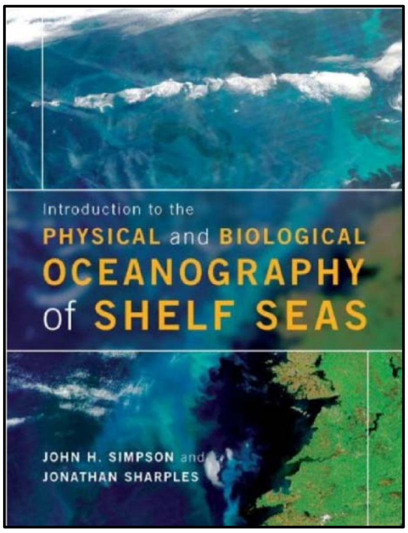
Projects using the Model S2P3



The following suggestions for laboratory or project work based on the S2P3 model are based either on published work using the model or on exercises that I have got students to work on. In each case the work could focus solely on either the physics or the biology of the problem, or make more detailed links between the physics and the primary production. I have also suggested two levels on which the projects can be tackled, a basic level suitable for single laboratory sessions (2 – 3 hours), and an advanced level suited to longer term project work.

All of these projects require the students to manipulate the data that is output to the model into ascii data files, so both student and lecturer/advisor need to read through the help on data output in the Guide to the S2P3 Model document. The data files can be read into typical analysis and graphics packages (I have used Matlab, Excel, Grapher and Surfer with students). Access to a good text editor is also useful (e.g. Microsoft Notepad provides basic viewing and searching; my own favourite is UltraEdit).

I have deliberately not provided detailed laboratory sheets for these projects. Lecturers will have their own ideas on what aspects of the work they would like students to focus on. Also, experience with using the model as a teaching tool has taught me that knowledge of the model's results gained while working through the model and developing your own route through a laboratory exercise is a vital part of developing a smooth laboratory session.

1. **The effect of storms on (i) turbulence at the thermocline and/or (ii) shelf sea primary production.**
   The default model run uses smoothly-varying seasonal meteorological forcing based on re-analysis meteorological model data provided by the UK Met Office. Altering this meteorological forcing allows an assessment of the effects that gales and storms might have on the physics of the summer thermocline, and on the primary production within the SCM.

   There are two ways of altering the meteorological data. First, every time the model runs using the default data, a file Celtic_met.dat is written that includes the daily values of meteorological information used in the default forcing. See the Guide to the S2P3 Model for information on the format of this file. Save this file to another filename, and then you can edit the wind speed in the new file. This is useful because you can, for instance, add a single wind event into the summer and so isolate its effects. A second way of investigating meteorological variability is to supply more realistic meteorological data. Several files of meteorological data from the UK Met Office model are provided along with the S2P3 model (see the Guide to the S2P3 Model). Alternatively you can supply your own data in a file with the required format. This more realistic data contains a range of wind events through the year, so providing the ability to assess inter-annual variability in summer thermocline physics and primary production.

In the model main menu, selecting the Meteorology option allows you to supply your own meteorological data file (see the Guide to the S2P3 Model, or select Help from the Meteorology menu).

<u>Basic Level:</u>
Physics:
Look at either the surface-bottom temperature difference or the potential energy anomaly, both available in the surface.dat output file. Using a file of the default data altered to include a wind event on one day in summer, the student can produce their own plot of how stratification or the potential energy anomaly are affected as a function of different strengths of wind (e.g. by incrementally increasing the wind speed on the day of the wind event). The form of this plot provides some insight into how stratification inhibits vertical mixing. This could be taken further by getting the students to compare the change in potential energy anomaly with the wind energy supplied, allowing calculation of a wind mixing efficiency (see Section 6.1.4 in the textbook).

Biology:
Wind events can alter the mixing of nutrients across the thermocline, and so have an effect on the primary production. Using the same approach of incrementally increasing the strength of winds during a one day mixing event in summer, get the students to look at time series of the integrated water column primary production over the wind event (data available in the surface.dat output file). Plotting these time series (for instance covering from 1 week before to 4 weeks after the wind event) on the same graph shows a couple of interesting results for discussion. (1) The wind speed appears to need increasing above some critical value before any effect on the primary production is seen. (2) The timing of the primary production response changes at higher wind speeds as the effect of the mixing on the light experienced by the phytoplankton becomes more important; the extreme effect is seen when the winds are strong enough to completely mix the water column, with subsequent re-stratification resulting in a surface bloom.

<u>Advanced Level:</u>
Physics:
With a single wind event as in the Basic Level above, output data files of hourly information on the vertical profiles of physical parameters (see the Guide to the S2P3 Model). This data could be used to investigate (i) inertial oscillations of the surface layer in response to a wind impulse, or (ii) the variations in vertical turbulent mixing at the thermocline as a result of the wind-induced shear. In (i) it should be noted that the results could be sensitive to the Background eddy viscosity used by the model. For (ii) there are some interesting published results that provide some thought-provoking background on the interaction between tidal and wind-driven shear (Itsweire et al., 1989, *J. Phys. Oceanogr*., 19, 302-320; Burchard & Rippeth, 2009, *J. Phys. Oceanogr*., 39, 969-985).

Biology:
Use daily and/or hourly profiles of physical and biological data (see the Guide to the S2P3 Model) over different wind events to investigate how the vertical DIN flux varies over a wind event (e.g. combine the profiles of eddy diffusivity in the physics with vertical gradients in DIN calculated from DIN profiles in the biology data). This could be extended to track the biological response through nutrient uptake, growth rate, and the appearance of new biomass.

2. Inter-annual changes in the timing of (i) the spring onset of stratification and/or (ii) the spring bloom.
The model has been used to investigate variability in the timing of stratification and the spring bloom in the northwestern North Sea (Sharples et al., 2006, *Cont. Shelf Res*., 26, 733-751). Variability can be driven either by inter-annual changes in the meteorology, or by changes in the phase of the spring-neap cycle. Focusing on the meteorology could either (i) use several files of annual meteorological information (e.g. such as those supplied with the S2P3 model) to assess typical variability in our current climate, or (ii) consider longer tem changes associated with a changing climate. For (ii) you can take advantage of a result from the North Sea work that showed that shelf sea winter sea temperatures were very strongly correlated with air temperature, and early spring air and sea temperatures play a large role in determining the net air-sea heat flux.

Basic Level:

Physics:

Add a spring-neap cycle to the default model run by introducing an S_2 tidal constituent via the **Physics** menu. For NW European shelf seas the S_2 current amplitude is typically 30% of the M_2 amplitude. Gradually alter the phase of the S_2 constituent, each time running the model and assessing the timing of the onset of *established* stratification (based on the temperatures in the surface.dat file) both as absolute day number and also in terms of the timing relative to the spring-neap cycle. Build up a plot similar to Fig. 8 in Sharples et al., 2006, and discuss why stratification tends to become established in the transition between spring and neap tides.

Alternatively, or in addition, assess the meteorologically-driven variability associated with inter-annual changes in the weather. The 6 annual meteorology data files provided with the S2P3 model provide the minimum amount of data necessary to address this issue.

In both of the above suggestions the student needs to think about what criteria to use to determine when the water column has become stratified. For instance, what surface-bottom temperature difference needs to be exceeded for the water to be classed as stratified? How long does stratification need to last for it to be viewed as established?

Biology:

Similar to the physics problems above but instead focus on the surface chlorophyll concentration as an indicator of the timing of the spring bloom. Again, the students need to set a consistent criterion for quantifying when the bloom has been triggered. They could think about a simple measure of surface chlorophyll, or perhaps some indicator of the surface phytoplankton growth rate (carbon fixation rate, or a rate of change of surface chlorophyll). There is no “correct” answer for what is the best criterion.

Advanced Level:

Physics:

It is instructive to have a look at the time series of the vertical profile of turbulent mixing as stratification is established. How does the turbulence closure scheme used by the model inhibit mixing as the surface layer warms? It is quite surprising how weak the vertical temperature gradient (or simply the surface-bottom temperature difference) is when turbulent mixing becomes limited to the “background” diffusivity. There is an important caveat here that is worth highlighting to the students. Many turbulence closure schemes operate almost as simple switches of the turbulent mixing. The transition between strong mixing in a vertically homogeneous water column, and mixing at the thermocline set by the background diffusivity, is very sharp. In other words, the closure scheme does not spend much time operating within the realm of $0.0<Ri<$critical Ri, and for much of the year in a stratified ocean the turbulent fluxes across the thermocline are controlled by the model’s parameterization of interior turbulence.

Biology:

An observation noted in Sharples et al., *Cont. Shelf Res*., 2006, was that the winter shelf sea water temperature was largely controlled by the overlying air temperature. In a warming climate this means that the shelf sea will warm along with the rising air temperature, which will have an effect on the timing of spring stratification by influencing the net air-sea heat flux. By altering the meteorology supplied to the model it is possible to estimate how the timing of the spring bloom, and the length of time over which a shelf sea is thermally stratified during the year, may respond to a warming climate. Use the default meteorology data saved to Celtic_met.dat during a default run of the model in the present-day climate. For a model run in a warmer climate, simply add a fixed temperature increment to all the air temperatures in the meteorology file and then supply that file of meteorology data to the model (as a user-defined file under the **Meteorology** menu option) to yield a model simulation in a warmer climate. Note that a warmer climate will alter the heat content of the shelf sea, so you also need to change to initial winter sea temperature to achieve a heat cycle consistent with the warmer forcing. Add the same temperature increment that you applied to the meteorology to the initial winter temperature (under the **Physics** menu option). Remember to save the output data into new filenames (from the **Output data** menu option) for each run to avoid over-writing your results. Students could run a series of climate scenarios between, say, 1.0 and 5.0 ºC warming and plot the year day of the spring bloom against the warming. Discussion of the results could focus on a comparison between the model prediction of how bloom timing changes compared to what we currently know of the natural inter-annual variability (e.g. as predicted by the model in the basic level experiment on bloom timing, or as reported in the literature). In the context of the match-mismatch hypothesis (see Section 6.3.3 in the textbook), what are the possible consequences of the predicted change in bloom timing?

3. The role of the spring-neap cycle on (i) physical structure including thermocline turbulence and/or (ii) primary production in the SCM.

Basic Level:

Physics:

The default model set-up uses only the M_2 tidal constituent. Adding other tidal constituents (via the constituent buttons within the **Physics** menu) provides the students with a simple way of understanding how different constituents interact to yield more complex tidal current behaviour. $M_2 + S_2$ generates a simple spring-neap cycle, $M_2 + S_2 + N_2$ generates a spring-neap cycle modulated by the elliptical orbit of the moon. $M_2 + O_1$ or $M_2 + K_1$ illustrate the role of the diurnal constituents in producing diurnal inequality of the tides. The student would need to look at long (e.g. >1 month) time series of hourly data from the model, perhaps focusing on the surface currents or calculating depth-mean currents from the model output. This data could then be used as the basis for Fourier or harmonic analyses.

For the harmonic analysis problem the following is a simple Matlab function (harmonic.m) to fit data to one frequency, which could be adapted as required:

```
function S=harmonic(time,data,w1)

% S=harmonic(time,data) fits a single tidal constituent to a time
% series of data.
% "time" = array of times associated with data (N rows x 1 column)
% "data" = array of observational data to be fitted (N rows x 1 column)
% "w1" = frequency (radians per unit time) to be analysed for in "data"
%
% Data is fitted to:
%       predicted = S(1)+S(2)*cos(w1*time)+S(3)*sin(w1*time)
%
% A solution is found to the matrix problem
%                              A.S=C
% where A is an array of cos, sin, and cross terms, C is the array made
% up of combinations of the constituent terms and observations,
% and S is the array of estimated amplitudes for the tidal constituent.
%
%
N=length(data);                       % N is the number of data points
%
%
A1(1:N,1)=1;
A1(1:N,2)=cos(w1*time(1:N));
A1(1:N,3)=sin(w1*time(1:N));
%
A2=A1';        % A2 is the 3xN transpose of A1 (rows and columns
swapped).
%
A=A2*A1;       % A is the 3x3 array required for the analysis procedure.
%
C=A2*data;     % C is the 3x1 righthand array of the problem.
%
S=A\C          % S is the 3x1 answer, which can be used to calculate the
%              predicted tidal variability.
%
% end of function
```

The effect of the spring-neap cycle on the thermocline is evident if an S_2 constituent is added to the default model run. Initially use a *u*-component amplitude for S_2 of 0.13 m s^{-1} (30% of the default M_2 amplitude, which is what we see on the NW European shelf). The position of the thermocline can be viewed as representing a balance between the wind-driven and tidally-driven turbulence, which is nicely illustrated here with the spring-neap modulation of the position of the base of the thermocline. The process is evident while the model runs by watching the vertical profile of temperature (upper right plot) and the profile of daily-mean current speed (lower right plot. Altering the relative strength of the S_2 constituent changes the amplitude of the response of the thermocline. Outputting hourly data (see the **Output data** menu option) allows a more detailed view of this periodic erosion and re-establishment of the base of the thermocline.

Biology:
Using the default model run, add an S_2 tidal constituent of *u*-component amplitude 0.13 m s^{-1} (i.e. 30% of the M_2 amplitude, which is what we see on the NW European shelf) via the **S2** constituent button in the **Physics** menu. The model will then simulate spring-neap periodicity in phytoplankton biomass in the SCM and erosion of biomass from the SCM into the bottom water. See Sharples, 2008, *J. Plankt. Res*., **30**, 183-197). This will be evident in the model real-time plots, both in the contoured time series of the chlorophyll (lower left), and by watching the vertical chlorophyll profile in the upper right plot. Altering the strength of the S_2 constituent will strengthen or reduce these spring-neap signals. Further analysis of the data (e.g. contouring biomass over 1 month) requires data to be output hourly (see the **Output data** option in the model menu).

<u>Advanced Level:</u>
Physics:
Students could use the hourly and/or daily physical data (see **Output data**) to assess how the vertical eddy diffusivity responds to a spring-neap cycle, both throughout the entire water column and by focusing on the diffusivity at the base of the thermocline. Initially use the default model set-up along with a *u*-component amplitude for the S_2 constituent of 0.13 m s^{-1}. Then have a look at what happens when the relative strength of the S_2 amplitude changes, altering the spring-neap contrasts. As the amplitude of the S_2 constituent changes relative to the M_2 amplitude, how does the vertical eddy diffusivity change? For instance, over a spring-neap cycle, how does the relative strength of the near-bed or lower thermocline eddy diffusivity change? The effects could be assessed on both fortnightly and semi-diurnal time scales.

Biology:
The information provided in the daily profiles of physics and biology can be used to calculate and plot profiles of vertical turbulent mixing of nitrogen, phytoplankton uptake of nitrogen, phytoplankton growth rate and phytoplankton biomass over 1 month. Use the default model set-up along with a *u*-component amplitude for the S_2 constituent of 0.13 m s^{-1}. This provides a useful understanding of the response time scales of the biology to a periodic physical forcing. A similar analysis was carried out in Sharples, 2008, *J. Plankt. Res*., **30**, 183-197, and also illustrated in the textbook in Fig. 7.10.

4. Tidal mixing fronts: position, spring-neap adjustment, and biological response.
The model has been used to address the problem of frontal position, spring-neap adjustment of frontal position, and the biological response in Sharples & Simpson, 1996, *Buoyancy Effects on Coastal Dynamics*, D.G.Aubrey & C.T.Friedrichs (Eds), Coastal and Estuarine Studies Volume 53, AGU, 71-82, and in Sharples, 2008, *J. Plankt. Res*., **30**, 183-197.

<u>Basic Level:</u>
Physics:
The default model is set up to simulate a seasonal cycle in a stratifying temperate shelf sea. By gradually reducing the amplitude of the M_2 tidal currents (via the M2 button in the **Physics** menu) students can make a simple, visual estimate of the strength of the tidal currents that is just able to prevent summer stratification (for a depth of 80 metres and the default meteorology, the critical current speed amplitude is about 0.725 m s^{-1}). In doing this they have found the tidal mixing front (e.g. see the textbook, Chapter 8). A better estimate of the critical current amplitude can be made by getting the students to produce a plot of surface-bottom temperature difference (e.g. on day 200, as read from the file surface.dat) versus the M_2 tidal current amplitude. By setting some stratification criterion that defines the position of the front (e.g. a surface-bottom temperature

difference of 0.25 or 0.5 ºC), the current amplitude at the front can be interpolated from the plot. If there are sufficient students in the class you could split them into groups, each using a different total water column depth (say between 60 and 100 metres). Each group can then report on the value of the M_2 tidal current amplitude that they found for the front, and on the value for $SH = \log_{10}(h/u^3)$, with *h* the depth and *u* the current amplitude. The value for *SH* will be close to 2.3, but will decrease slightly at higher *h*. This is a boundary layer effect and is detailed in Simpson & Sharples, 1994, *J. Geophys. Res*. 99, 3315-3319.

Biology:
Set the model ready with the default parameters, and then get the students to run the model several times holding the depth constant but gradually changing the M_2 current amplitude (via the M2 button in the **Physics** menu) from 0.9 m s^{-1} to 0.4 m s^{-1}. For each run, make a note of the surface temperature and surface chlorophyll concentration on day 200 by looking in the surface.dat output file. Plot the temperature and chlorophyll concentration as a function of current amplitude. Initially the students might use a velocity increment of 0.1 m s^{-1} (e.g. model runs at current amplitudes of 0.9, 0.8, 0.7 etc. m s^{-1}). It will be clear from the sudden change in surface temperature where the front is, so they can carry out more model runs with finer changes in the current amplitude near the front. The final plot will show the transition from warm surface water and low surface chlorophyll, through the front with elevated chlorophyll, and into the mixed water with lower surface temperature and moderate concentrations of surface chlorophyll. The plot is similar to the surface data likely to be seen as a ship crosses a tidal mixing front.

For an informative addition to the above, once the position of the front has been found get the students to set the M_2 tidal current amplitude to that at the front and to add an S_2 tidal constituent (via the S2 button in the **Physics** menu) of about 30% of the M_2 amplitude. Running the model will show the effect of spring-neap frontal adjustment in driving fortnightly pulses in surface chlorophyll (e.g. see the textbook, Section 8.6.1).

Advanced Level:
Vertical slices of the physical and biological properties across the front can be synthesized by using the data stored in the file front_data.dat. Each time the model is run data is written to the file on the day specified in the **Cross front** menu (see the Guide to the S2P3 Model for more information on how this works). If the students carry out a series of runs, holding the depth constant and gradually changing the M_2 tidal current amplitude, then the file front_data.dat will eventually hold data suitable for contouring into frontal sections of physical and biological properties.

Physics:
A basic front section can be contoured using the temperature profiles in front_data.dat. The physics underlying this temperature structure can be emphasized by contouring a slice of the vertical turbulent diffusivity, which shows the strong gradient in mixing between the mixed and stratified regions.

The adjustment of the front over the spring-neap cycle can also be analysed. Set the default model ready and set the M_2 *u*-component amplitude at 0.9 m s^{-1}. Add an S_2 tidal constituent with an amplitude of 30% of the M_2 constituent. Run the model, and look in the surface.dat file to identify the year days of adjacent neap and spring tides in mid summer (i.e. somewhere between days 180 and 200). Remember that the frontal adjustment lags the spring-neap cycle of tidal mixing by about 2 days. Next, select the **Cross front** menu option and set the year days to that of the neap tides plus 2 days. Run the model to synthesise a frontal section; i.e. change the M_2 amplitude incrementally between, say, 0.9 and 0.3 m s^{-1}, always setting the S_2 amplitude to be 30% of the M_2 amplitude. Once this has been completed, *rename the front_data.dat file* so that it does not get over-written. This file now contains a post-neaps section through the front. Go into the **Cross front** menu option and set the year days to that of the spring tide plus 2 days. Run the model to produce another frontal section, and again rename the front_data.dat file. This second file contains a post-springs section through the front. The student now has sufficient data to analyse the changes in physical structure across the front arising from the spring-neap modulation of mixing and subsequent frontal adjustment.

Biology:

After running the model across a front with just an M_2 tidal current, the resulting front_data.dat file contains information with which to analyse the biogeochemical structure of the front. Basic properties such as chlorophyll, dissolved inorganic nitrogen and temperature can be contoured to illustrate typical cross-frontal observations. Further analysis could combine the information on nitrogen (both dissolved and within the phytoplankton) and the vertical eddy diffusivity to investigate the turbulent mixing of nutrients towards the sea surface at a front, so addressing the role of horizontal gradients in vertical turbulent mixing in driving enhanced frontal primary production.

5. Notes.

- *Vertical resolution.*
  The default vertical resolution used by the model is 4 metres. For most computers likely to be used by students, this results in model run times that are a practical balance between resolution and the time available in a laboratory session to generate the data. Halving the depth cell thickness to 2 metres will result in the model time step decreasing by a factor of 4; thus increasing model resolution has a big effect on the amount of time the model takes to run. A useful approach is to use the default resolution while trying out ideas, and then increasing the resolution when the final output data is required (being careful to check that there are no significant differences between model results with the same parameter set but with different vertical resolution).

- *Calculation of turbulent fluxes.*
  Turbulent fluxes of scalar properties can be calculated from the daily and hourly profiles output by the model. With this model data a mean flux will be calculated using a mean diffusivity (either hourly- or daily-mean) and a measure of the vertical gradient of the scalar. Strictly a mean turbulent flux should be calculated as the average of (diffusivity x scalar gradient), not as average diffusivity x average gradient. In our own work at sea we tend to find that turbulence varies far more than the scalar gradients, so the simplification involved in calculating fluxes from the model output is not serious.

- *Errors and bugs.*
  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.

- Finally, if you develop your own ideas on laboratory or project work using the model, and would like to let others know about them, please let me know and we can add them to the CUP website associated with the textbook.

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