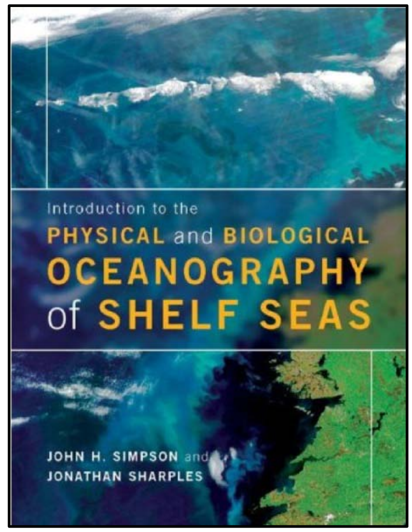
# Observational Data

# Turbulence and nutrient fluxes




**Data Source:**

This data was collected during a research cruise aboard the RV Prince Madog in summer 2006. The work was funded by the UK Natural Environment Research Council (grant numbers NER/D/S2002/00965 and NE/F014821/1).

**Data Acknowledgement:**

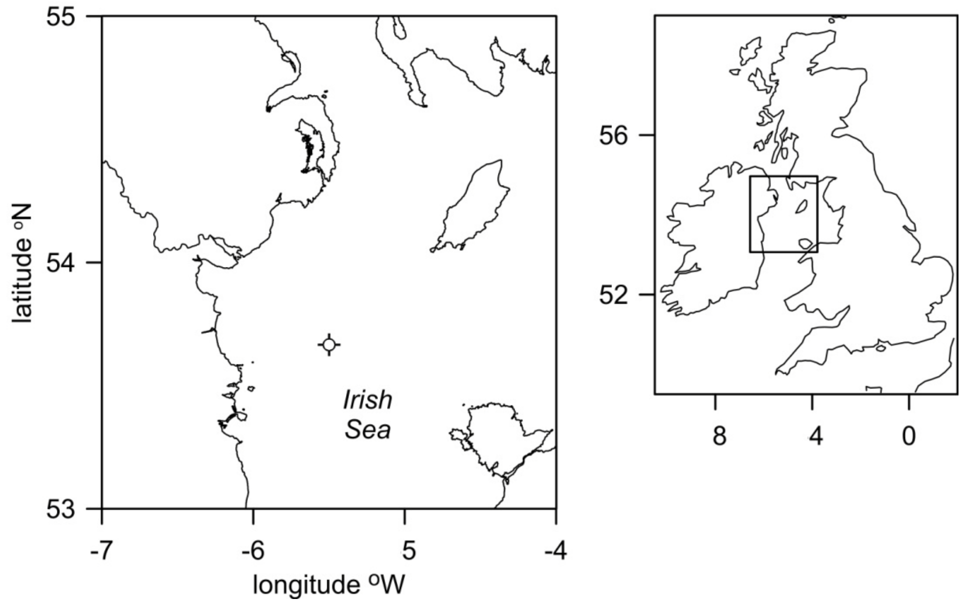
Data was supplied from Bangor University, UK, courtesy of Drs. Mattias Green and Tom Rippeth. Nitrate analyses courtesy of Stathys Papadimitriou.

**Summary of data uses:**

Tidal cycle variations in turbulent dissipation in stratified water; calculation of eddy diffusivities and gradient Richardson numbers; observations of interior mixing; estimation of nitrate and carbon fluxes at the base of the thermocline.

**Oceanographic Background and Useful Papers:**

The western Irish Sea is a seasonally-stratifying region on the NW European shelf. Thermal stratification in late spring through to early autumn arises due to the flux of heat into the water column overcoming the tidal and wind stirring (e.g. see Chapter 6 of the textbook).The stability of the thermocline is a fundamental limit on the supply of deep water nutrients upward to the photic zone. The stratification in the western Irish Sea sets up a mean, cyclonic (anti-clockwise) circulation plays a vital role in the survival of a population of *Nephrops* lobsters (see textbook Section 8.6.4).




Location map for the SWIS mooring site in the western Irish Sea (⌖).

The FLY turbulent dissipation profiler, flanked by Tom Rippeth (left) and Phil Wiles (right).

RV *Prince Madog* in the Irish Sea

*Useful papers:*

Rippeth, T. P., Wiles, P., Palmer, M. R., Sharples, J., and Tweddle, J. F., 2009. The diapcynal nutrient flux and shear-induced diapcynal mixing in the seasonally stratified western Irish Sea. *Continental Shelf Research*, 29, 1580-1587.

Sharples , J., Tweddle, J. F., Green, J. A. M., Palmer, M. R., Kim, Y-N, Hickman, A. E., Holligan, P. M., Moore, C. M., Rippeth, T. P., Simpson, J. H., and Krivtsov, V. 2007. Spring-neap modulation of internal tide mixing and vertical nitrate fluxes at a shelf edge in summer. *Limnology & Oceanography*, 52(5), 1735-1747.

Simpson, J.H., Green, J.A.M., Rippeth, T.P., Osborn, T.R., and Nimmo-Smith, W.A.M., 2009. The structure of dissipation in the Western Irish Sea front. *Journal of Marine Systems,* 77, 428–440.

Green, J. A. M., Simpson, J. H., Thorpe, S. A., and Rippeth, T. P., 2010. Observations of internal tidal waves in the isolated seasonally stratified region of the western Irish Sea. *Continental Shelf Research*, 30, 214–225.

**Data:**

1. ADCP data over 10 days, including the time of the turbulence station.
2. Vertical profiles of turbulent dissipation, diffusivity, temperature, salinity and density collected over 49.5 hours using the FLY free-fall turbulence profiler.
3. Nitrate analyses from bottle samples collected close to the time of the turbulence station.

**Data Files:**

<u>ADCP data:</u>

An upward-looking 300 kHz ADCP was moored at position 53º 40.0’ N, 5º 30.0’W for a period of 9 days. Vertical profiles of currents were recorded, with a vertical bin size of 2 metres and a sampling time of 2 minutes. The data is in the Matlab file `SWIS_ADCP`, with the following variables:

| | |
|---|---|
| velN | 6480 vertical profiles of northward current, m $s^{-1}$, positive towards the north. |
| velE | 6480 vertical profiles of eastward current, m $s^{-1}$, positive towards the east. |
| dd | array containing the times (decimal days) for each vertical profile. |
| hab | an array of the heights above the seabed (metres) for each ADCP depth bin in the vertical profiles. |

Turbulence data:

A Matlab MAT file `SWIS_turbulence` contains the following variables:

| | |
|---|---|
| Dens | 259 vertical profiles of water density (kg $m^{-3}$) |
| Kz_1 | 259 vertical profiles of vertical eddy diffusity ($m^2$ $s^{-1}$) calculated using the dissipation data from shear probe 1 on the FLY turbulence profiler. |
| Kz_2 | 259 vertical profiles of vertical eddy diffusity ($m^2$ $s^{-1}$) calculated using the dissipation data from shear probe 2 on the FLY turbulence profiler. |
| Nsq | 259 vertical profiles of the squared buoyancy frequency (s-2), calculated from the density profiles. |
| Sal | 259 vertical profiles of salinity (PSS) from the FLY profiler. |
| Temp | 259 vertical profiles of temperature (ºC) from the FLY profiler. |
| dd | array containing the times (decimal days) for each vertical profile. |
| eps_1 | 259 vertical profiles of turbulent dissipation ($m^2$ $s^{-3}$) from shear probe 1 on the FLY turbulence profiler. |
| eps_2 | 259 vertical profiles of turbulent dissipation ($m^2$ $s^{-3}$) from shear probe 2 on the FLY turbulence profiler. |
| hab | an array of the heights above the seabed (metres) for each measurement in the vertical profiles. |

Nutrient data:

The spreadsheet `SWIS_nutrients.xlsx` contains the results of chemical analyses for nitrate+nitrite (mmol $m^{-3}$) carried out on bottle samples collected during CTD profiles around the time of the turbulence work. Data columns in the spreadsheet are:

| | |
|---|---|
| depth | depth at which water samples were taken (metres). |
| NO3+NO2 | nitrate+nitrite (mmol $m^{-3}$) in water samples. |
| temp | CTD temperature recorded at the time water samples were taken. |

Chlorophyll data:

The spreadsheet `SWIS_chlorophyll.xlsx` contains the results of chemical analyses for chlorophyll concentration (mg $m^{-3}$) carried out on bottle samples collected during all CTD profiles during the cruise. Data columns in the spreadsheet are:

| | |
|---|---|
| chl a [filter] | chlorophyll concentration from a filtered water sample (mg $m^{-3}$). |
| voltage 4 (fluorometer) | voltage from the CTD fluorometer recorded when the Chl sample was taken. |

<u>CTD data:</u>

Files of data for the CTD profiles used to collect the nutrient data. There are 3 profiles, `cast021.dat, cast022.dat` and `cast023.dat`. The data columns are:

| | |
|---|---|
| depth | depth (metres) of the centre of a depth bin, with data averaged into 1 metre bins. |
| temp | temperature (°C), averaged within each depth bin. |
| sal | salinity (PSS), averaged within each depth bin. |
| fluor | fluorometer voltage, averaged within each depth bin. |
| density | density (kg $m^{-3}$) averaged within each depth bin. |

**Possible Analyses:**

1. *Relating dissipation and current time series. [Textbook Section 7.2].*
   Simply contouring the turbulent dissipation profiles are juxtaposing with a contour plot of the profiles of current speed illustrates the quarter-diurnal signal in turbulent dissipation and how the timing of turbulent dissipation varies away from the seabed. Maximum near-bed dissipation occurs at the time of maximum near-bed flow, but then the dissipation maximum is gradually lagged higher in the water column. Dissipation follows current shear rather than current speed (i.e. shear generates turbulence), so further calculating profiles of current shear from the ADCP data and comparing with the turbulent dissipation is also instructive. When calculating shear it is worth investigating what might be a suitable time window over which to average the shear data. For instance, it is worth perhaps averaging over 20 minutes or so (e.g. the typical internal wave period) instead of using the shear based on individual 2-minute ADCP profiles.

2. *Calculating profiles of eddy diffusivity and gradient Richardson number. [Textbook Sections 4.4.1, 7.2].*
   If the students are provided with profiles of dissipation and density from the `SWIS_turbulence` file, they can then calculate profiles of $N^2$ and so profiles of the vertical eddy diffusivity $K_z$ (see equation 7.11 in the textbook). By assuming that the density profiles from the Fly profiler were roughly co-located with the ADCP data, vertical

profiles of the gradient Richardson number (equation 4.56 in the textbook) can be calculated by combining the Fly and ADCP data. Students can then see the link between mixing and stability, and look at the large gradients in turbulent diffusivity across pycnoclines. The interior dissipation and diffusivity can be compared to typical model outputs (e.g. Fig. 7.5 in the textbook).

Note that there needs to be some thought applied to the shear time-averaging window and the timing of the data from the turbulence profiler. The turbulence profiles were collected in groups of 4 – 6, typically taking about 30 minutes for each group. Averaging the turbulence profiles within each of these groups, and comparing with shear averaged over the time of the group, is a reasonable approach.

3. *Calculation of the vertical nitrate and carbon flux. [Textbook Sections 7.3.1, 7.3.2].* This is a challenging task, perhaps more suited to a longer piece of project work. The goal is to estimate the flux of nitrate into the base of the thermocline, and/or the flux of phytoplankton carbon from the thermocline into the bottom tidally-mixed layer. The flux of a substance with concentration [*S*] is:

$$-K_z \frac{\Delta[S]}{\Delta z}$$

with $K_z$ ($m^2\ s^{-1}$) the vertical eddy diffusivity and $\Delta[S]/\Delta z$ the vertical gradient of the substance. The diffusivities can either be calculated through the analyses suggested in 2 above, or can be taken from the `SWIS_turbulence` file.

The nitrate gradient (or nitrate+nitrite gradient, but we are assuming this is predominantly nitrate) can be estimated from the nitrate data in the `SWIS_nutrients` spreadsheet. However, a better estimate of the gradient co-located with the turbulence measurements is to generate a temperature-nitrate relationship within the base of the thermocline, using the information in the `SWIS_nutrients` spreadsheet, and then to use the temperature gradient provided by the Fly temperature profiles to produce nitrate gradients. The relationship within the base of the thermocline is approximately linear. See Sharples et al., 2007, for an example of using this type of approach. Then the time series of diffusivity and nitrate gradient in the base of the thermocline can be calculated, and a daily-mean flux estimated. If we assume that new primary production utilizing this nitrate source is operating at Redfield C:N=6.6 (mol C (mol N)$^{-1}$), we can then estimate the potential for nitrate-fuelled primary production in the thermocline.

The phytoplankton carbon gradient is a little trickier. The data in the `SWIS_chlorophyll` spreadsheet can be used to generate a calibration equation linking CTD fluorometer voltage to chlorophyll concentration. Plot voltage (y-axis, the dependent variable) against Chl (x-axis) and perform a linear regression of voltage as a function of Chl. Then invert the equation to get Chl as a function of voltage. You can get the students to use the scatter about the regression line as a measure of the error in the calibration. This calibration equation can then be used to calculate Chl from the fluorometer voltage profiles in the CTD data. To get to phytoplankton carbon we need to assume a value for the phytoplankton C:Chl ratio. This was not measured during the cruise, but a useful estimate for a shelf sea thermocline phytoplankton population is 25 g C (g Chl)$^{-1}$ (Holligan et al., 1984, *Marine Ecology Progress Series*, 14, 111-127).

It is not usually possible to relate chlorophyll or carbon concentration to temperature through the base of the thermocline. The temperature-nitrate regression is relatively robust because the endpoints of the nitrate (i.e. the surface and bottom layer concentrations) are approximately horizontally uniform on the scale of a few tidal excursions. The chlorophyll, or carbon, gradient is set by the peak chlorophyll concentration within the sub-surface chlorophyll maximum. This is likely to be very patchy horizontally, so will display little or no link to temperature through the thermocline. Instead we can calculate a mean C gradient within the base of the thermocline from the 3 CTD profiles. This will introduce some additional error in the flux measurement, but should be acceptable as we tend to find that variability in fluxes is dominated by the variability in the turbulence rather than changes in the gradient of nitrate or chlorophyll.

The endpoint of the flux calculations above can be an estimate of (1) the potential rate of nitrate-fuelled primary production in the sub-surface chlorophyll maximum (in, say, g C m$^{-2}$ d$^{-1}$), and (2) the rate at which phytoplankton carbon is being eroded from the thermocline into the bottom mixed layer (also g C m$^{-2}$ d$^{-1}$). Get the students to think about the implications of these two numbers.