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Vertical mixing in Lough Hyne during stratification

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Lough Hyne time series records showed a clear increase in vertical mixing associated with spring tides. Temperature records from the thermocline region were the most variable of the depths studied with differences of up to 0.7°C between readings taken 3 min apart.

Fjordic systems are typically stratified, leaving water at depth to be renewed at seasonal or longer time scales. Once isolated by stratification, deeper water may become anoxic and there is a build up of remineralized nutrients (e.g. Gillibrand et al., 1996). Vertical mixing is therefore an important process that can affect the cycling of nutrients and the availability of habitats to benthic species.

With a strong seasonal stratification, build up of nutrients below the pycnocline and deep-water anoxia, Lough Hyne (area 0.52 km^2, 51°30′N 9°18′W) has many typical fjordic features (Kitching, 1987; Johnson et al., 2000). The lough has been a site of scientific research for over 100 years (Minchin, 1991) and was declared a marine reserve in 1981. Tidal inflow is restricted to a narrow channel (The Rapids) with a sill depth of approximately 2 m. The main basin of the lough is 49 m deep and the pycnocline is usually steepest between 20 and 30 m depth.

Observations made in the lough during stratification show peaks in chlorophyll, phytoplankton cell counts and oxygen following spring tides (Johnson et al., 2000; Johnson & Costello, 2002). These were hypothesized to reflect an increased transfer of nutrients to surface waters due to the greater energy supply to the lough during spring tides. Although there were a number of lines of evidence for this enhanced mixing, high frequency observations of pycnocline activity were not available to evaluate the degree of vertical mixing. Results for a 14 day period containing a spring tide are presented in this note and provide a contrast to the longer (seasonal) timescales considered in Kitching et al. (1976).

Data collection

A series of four Minilog (Vemco Ltd, Canada) temperature loggers were tied to a mooring rope in the western trough of the lough in September 2002. The mooring rope had subsurface flotation to maintain the loggers in position regardless of tidal variation in absolute water depth. These loggers have a reported accuracy of 0.1°C, and laboratory checks were consistent with this. Temperature was logged every 3 min during the deployment. Two of the recorders had depth sensors and this confirmed the average depth of the loggers as 9, 18, 29 and 35 m. There were therefore two depths above the pycnocline, one in the pycnocline region and one in the isolated deep waters.

Time series records

The most striking element of the temperature time series is the convergence of temperatures at 9 and 29 m associated with the maximum tidal range during spring tides (Figure 1). This is consistent with increased vertical mixing causing an erosion of the pycnocline and a mixing of cooler waters into the overlying waters. Records from 18 m are not shown as they overlap with records from 9 m (average difference between 9 and 18 m 0.13°C, SE 0.001), indicating little stratification between these depths. There was very little change in temperature in the deepest waters and the variation recorded is towards the limits of datalogger resolution. A second feature of the time series is the relatively large variance of records from the 29 m logger. The thermocline region is fairly dynamic, consistent with tidal inflow currents as an important source of mixing energy. Spectral analysis of the detrended time series (using differencing) did not suggest any particular frequency peaks for the variability in the thermocline. Although there are likely to be internal waves associated with the variability in temperature at depth, a lack of clear wave frequencies is to be expected, as interactions between

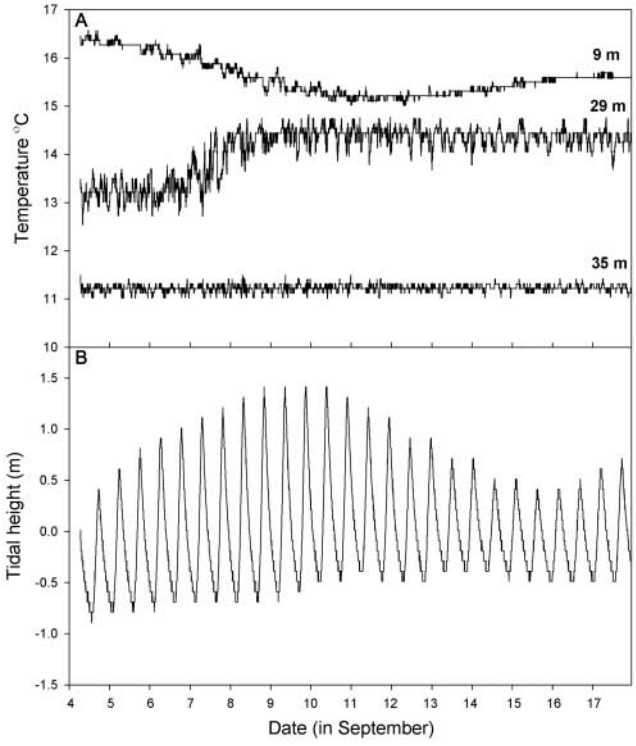

Figure 1. (A) Temporal variation in temperature at separate depths; and (B) tidally driven variation in water column level with respect to the mean level of the lough surface during the sampling period.

topography and currents tend to smooth out wave spectra (Saggio & Imberger, 1998).

In conclusion, as in other fjordic systems, tidal energy appears to drive vertical mixing during stratification in Lough Hyne (Stigebrandt & Aure, 1989). The greater currents and volume of water at spring tides (Bell & Barnes, 2002) cause erosion of the thermocline and provide an explanation for the periodic pulses of phytoplankton abundance observed by Johnson et al. (2000). Lough Hyne is sheltered by surrounding hills and waves rarely exceed 1 m height, so there is little influence of wind on the mixing of deeper waters. At larger time scales, the relative density of the inflow will affect the depth at which it interleaves with lough water, with implications for renewal of the bottom waters (Allen & Simpson, 2002).

Single temperature profiles tend to give a static view of thermoclines. The results presented here show how dynamic the water column is at depth, with differences of up to 0.7°C between successive readings at 29 m. This high frequency variability may have implications for sampling programmes that use discrete samples to characterize the plankton at different depths (e.g. Rawlinson et al., 2004). Benthic communities are clearly structured by the seasonal stratification in the lough: deeper sediments are composed of successional species that die off as bottom waters become anoxic (Kitching et al., 1976). Spring–neap fluctuation of the thermocline may provide opportunities for mobile predators to scavenge on benthic organisms killed or incapacitated by anoxic waters (e.g. *Asterias rubens*, Thrush, 1988). The high frequency variability in temperature at 29 m implies that the water column is not as static as suggested by current meter measurements (Bell & Barnes, 2002). This turbulence has implications for the supply of particulates to suspension feeders such as sponges, which are at their most diverse at depths close to the thermocline (Bell & Barnes, 2000). The relative ease of sampling at the lough, should facilitate future investigations of the effects of water column mixing on the associated benthic and pelagic communities.

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REFERENCES

Allen, G.L. & Simpson, J.H., 2002. The response of a strongly stratified fjord to energetic tidal forcing. *Estuarine, Coastal and Shelf Science*, **55**, 629–644.

Bell, J.J. & Barnes, D.K.A., 2000. A sponge diversity centre within a marine 'island'. *Hydrobiologia*, **440**, 55–64.

Bell, J.J. & Barnes, D.K.A., 2002. The relationship between sedimentation, flow rates, depth and time at Lough Hyne Marine Nature Reserve. *Irish Naturalists' Journal*, **27**, 106–116.

Gillibrand, P.A., Turrell, W.R., Moore, D.C. & Adams, R.D., 1996. Bottom water stagnation and oxygen depletion in a Scottish sea loch. *Estuarine, Coastal and Shelf Science*, **43**, 217–235.

Johnson, M.P. & Costello, M.J., 2002. Local and external components of the summertime plankton community in Lough Hyne, a stratified marine inlet. *Journal of Plankton Research*, **24**, 1305–1315.

Johnson, M.P., Costello, M.J. & O'Donnell, D., 2000. Techniques for the objective detection of pattern in chlorophyll samples at different temporal scales: an example using data from Lough Hyne, a seasonally stratified inlet. *Hydrobiologia*, **421**, 103–113.

Kitching, J.A., 1987. Ecological studies at Lough Hyne. *Advances in Ecological Research*, **17**, 115–186.

Kitching, J.A., Ebling, F.J., Gamble, J.C., Hoare, R., McLeod, A.A.Q.R. & Norton, T.A., 1976. The ecology of Lough Hyne. XIX. Seasonal changes in the western trough. *Journal of Animal Ecology*, **45**, 731–758.

Minchin, D., 1991. An historical summary of scientific activities. In *The ecology of Lough Hyne* (ed. A.A. Myers et al.), pp. 25–29. Dublin: Royal Irish Academy.

Rawlinson, K.A., Davenport, J. & Barnes, D.K.A., 2004. Vertical migration strategies with respect to advection and stratification in a semi-enclosed lough: a comparison of mero- and holozooplankton. *Marine Biology*, **144**, 935–946.

Saggio, A. & Imberger, J., 1998. Internal wave weather in a stratified lake. *Limnology and Oceanography*, **43**, 1780–1795.

Stigebrandt, A. & Aure, J., 1989. Vertical mixing in basin waters of fjords. *Journal of Physical Oceanography*, **19**, 917–926.

Thrush, S.F., 1988. Behavioural observations on sublittoral populations of starfish in Lough Hyne. *Irish Naturalists' Journal*, **22**, 430–436.

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