Institution: 10007857 (Bangor University)

Unit of Assessment: 07 Earth Systems and Environmental Sciences

Title of case study:
Turbulence research improves ocean forecasting and marine energy infrastructure

1. Summary of the impact (indicative maximum 100 words)

New techniques for measuring, and novel measurements of, turbulence in continental shelf seas and estuaries, developed by Bangor University's Turbulence and Mixing Group, have revolutionised the representation of key vertical exchange processes within state-of-the-art numerical ocean models. These measurements have directly improved modelling accuracy of coastal sea mixing dynamics and the forecasts produced are directly applied in development of government policy, marine energy technology, and search and rescue activities in the UK (e.g. Met Office, Cefas) and Baltic Sea regions of Europe. This measurement of marine turbulence has also provided critical information in determining the effective siting of marine renewable energy plants.

2. Underpinning research (indicative maximum 500 words)

Seminal research by John Simpson (Bangor 1968-present) and colleagues during the 1970s and 1980s led to the recognition that correct parameterisation of key processes responsible for turbulence mixing are critical to the development of models which can correctly predict the transport of heat, freshwater and nutrients in shelf seas, key factors in determining their role in global climate and also the fate of river-borne pollutants in the sea.

In 1993, Simpson and Rippeth (Bangor 1989-present, NERC Fellow 1999-2007, currently Reader), subsequently joined by Wiles (PhD student then NERC Fellow 2002-9), Green (NERC Advanced Fellow then Senior Lecturer 2008-present), Lenn (NERC Fellow 2009-present), post-doctoral researcher Verspetch (2007-10) and several PhD students, began measurements of the rate of dissipation of turbulent kinetic energy (TKE): **the first data available for fundamental testing and validation of parameterisations of vertical mixing**. **For the first time in Europe, they used free-fall shear probes** in contrasting tidally energetic shelf-sea environments to generate extensive data sets of turbulent energy dissipation [ii, iii, vi]. These provided **important reference data sets for improved parameterisation of turbulence mixing models** [i, vi].

Since 1999, their NERC-funded research developed novel techniques for the measurement of turbulence parameters using relatively low cost acoustic doppler current profilers (ADCPs) from fixed moorings. The parameters include Reynolds stresses, shear production [iii, iv] and dissipation using a structure-function technique [vii]. They enable **long time-series measurements that were not previously possible** using shear probes on account of prohibitively high ship costs.

The group's measurements in seasonally stratified areas of the shelf **revealed that low levels of mixing in the thermocline exert a key control on primary production**, a large proportion of which occurs in the sub-surface chlorophyll maximum (SCM). The accurate simulation of primary production in the SCM, a key process in global biogeochemical cycles, is therefore dependent on the improved parameterisation of turbulent mixing within the thermocline.

The dispersion of freshwater from rivers exerts a strong influence on water column structure and circulation in adjacent coastal seas (termed ROFIs, Regions of Freshwater Influence). In collaboration with the National Oceanography Centre Liverpool and numerical modeller Prof. Burchard (Leibniz Institute for Baltic Sea Research), the **Bangor group has provided the crucial, first and still widely used data to test and elucidate the interaction between freshwater and stirring** in controlling stratification and flow in these regions [ii, v]. The ROFI regime is a particularly subtle and important component of the shelf seas where lateral gradients of salinity interact with the tidal flow, in the process of "tidal straining", which produces periodic stratification and intensifies density-driven circulation. Bangor's contribution in unravelling this process **has led**

to the designation of the principal controlling parameter as the "Simpson Number *Si*", after John Simpson. This designation is in recognition of both his fundamental work and subsequent contribution to model development. **This work established the need for the numerical models to resolve tidal timescales in these systems** [ii, v].

Our measurements, in parallel with elucidation of the forcing mechanisms, have provided the essential test bed for model developments [i, v, vi]. Prior to this work, there was no basis for testing and validation of numerical models of marine turbulent processes. Our novel ADCP measurement techniques allow for the first time reliable, long time-series measurements of turbulence in the marine environment [iii, iv, vii].

3. References to the research (indicative maximum of six references)
Bangor authors are in **bold**. Citation counts obtained through Google Scholar (October 2013).

i) Burchard, H., Peterson, O. and **Rippeth, T.P.** (1998). Comparing the performance of the Mellor-Yamada and the κ-ε two-equation turbulence model. *Journal of Geophysical Research*, **103**, 10543-10554. DOI: 10.1029/98JC00261. Published in a peer-reviewed journal, 146 citations

ii) **Rippeth, T.P., Fisher, N.R.** and **Simpson, J.H.** (2001). The cycle of turbulent dissipation in the presence of tidal straining. *Journal of Physical Oceanography*, **31**, 2458–2471. DOI: 10.1175/1520-0485(2001)031<2458:TCOTDI>2.0.CO;2. Published in a peer-reviewed journal, 94 citations

iii) **Rippeth, T.P., Williams, E.** and **Simpson, J.H.** (2002). Reynolds stress and turbulent energy production in a tidal channel. *Journal of Physical Oceanography*, **32**, 1242-1251. DOI: 10.1175/1520-0485(2002)032<1242:RSATEP>2.0.CO;2. Published in a peer-reviewed journal, 86 citations

iv) **Rippeth, T.P., Simpson, J.H., Williams, E.** and Inall, M.E. (2003). Measurement of the rates of production and dissipation of turbulent kinetic energy in an energetic tidal flow: Red Wharf Bay revisited. *Journal of Physical Oceanography*, **33,** 1889-1901. DOI: 10.1175/1520-0485(2003)033<1889:MOTROP>2.0.CO;2. Published in a peer-reviewed journal, 60 citations, submitted to RAE 2008

v) **Simpson J.H.,** Burchard, H., **Fisher, N.R.** and **Rippeth, T.P.** (2002). The semi-diurnal cycle of dissipation in a ROFI: model-measurement comparisons. *Continental Shelf Research*, **22**, 1615-1628. DOI: 10.1016/S0278-4343(02)00025-0. Published in a peer-reviewed journal, 56 citations, submitted to RAE 2008

vi) **Simpson, J.H.,** Crawford, W.R., **Rippeth, T.P., Campbell, A.R.** and **Cheok**, **J.V.S.** (1996). The vertical structure of turbulent dissipation in shelf seas. *Journal of Physical Oceanography*, **26**, 1580-1590. DOI: 10.1175/1520-0485(1996)026<1579:TVSOTD>2.0.CO;2. Published in a peer-reviewed journal, 168 citations, Submitted to RAE 2001.

vii) **Wiles, P.J., Rippeth, T.P., Simpson, J.H.** and Hendricks, P.J. (2006). A novel technique for measuring the rate of turbulent dissipation in the marine environment. *Geophysical Research Letters*, **33,** L21608. DOI: 10.1029/2006GL027050. Published in a peer-reviewed journal, 38 citations, submitted to RAE 2008

4. Details of the impact (indicative maximum 750 words)

The Bangor marine turbulence research allowed a fundamental validation and improved representation of vertical exchange processes in numerical models of shelf seas. Through close collaboration with numerical modellers Burchard and Bolding, the results were incorporated into the General Ocean Turbulence Model (GOTM), *the* vertical exchange scheme used within the main UK and international-community oceanographic models including GETM (General Estuarine Transport Model), POLCOMS (Proudman Oceanography Lab Community Ocean Model), FVCOM (Finite Volume Coastal Ocean Model), SHYFEM (Shallow Water Hydrodynamic Finite Element Model) and NEMO (Nucleus for European Modelling of the Ocean). By providing the essential test bed for model validation, the Bangor research allowed for the first time accurate representation of mixing processes in shelf-sea models, resulting in significant improvements to their capacity to provide predictions for specific policy and ocean management decisions [1].

Through the numerous applications of these models, and the ADCP turbulence measurement techniques, this research has had direct impacts on policy formulation, European law enforcement, off-shore renewable energy development and the sustainable exploitation of shelf sea environments, as evidenced by the examples provided below.

1. Economic impacts of novel Acoustic Doppler Current Profiler applications in marine renewables industry developments

The application of ADCPs to measure turbulence, as pioneered by Rippeth et al., has been applied widely in marine infrastructure programmes and in particular the **development of tidal energy projects**, including the world's largest tidal array (2011) currently being built in Scotland (**total cost £40M**). The turbulence data collected using the Bangor method fed directly into the Environmental Impact Assessment on the effect of the current turbines on the environment – crucial in the authorisation of the project [9]. The techniques are further applied by environmental survey companies to select the optimum position for tidal energy devices for maximised power output and minimised risk [3, 4], providing direct economic benefits to these companies whilst **helping reduce costs** for the tidal energy industry. For example the technique reported in (vii) directly facilitates commercial surveys by Titan Environmental Surveys Ltd, contributing significantly to its £3M turnover and employment of 37 FTE members of staff [3]. Additionally, the research (ii, iv) directly enables Partrac, one of the largest UK marine survey companies, commissioned by (amongst others) Scottish Power Renewables, to regularly collect water column turbulence data for commercial projects of £150-350k in value [4]. Additionally, the techniques were deployed for understanding the distribution of matter in the ocean for *Charting Progress 2; the improved UK framework for advances towards clean, healthy, safe, productive and biologically diverse oceans and seas* [8], which "provides a solid foundation for policy-makers to make the strategic and far reaching decisions needed to meet our legislative obligations and to protect our marine resources". The report highlights how this work facilitated a "major advance" and "has provided previously unavailable information on how SPM (suspended particulate matter) responds to physical processes and new data on the reasons for variations in turbidity in UK shelf waters" [8].

2. Economic and policy impacts through applications of the General Ocean Turbulence Model and General Estuarine Transport Model to public services

Models incorporating the GOTM vertical exchange scheme have been used for a variety of applications across Europe. These include environmental impact assessments for power plants, predictions for the sustainable management of shelf seas and short-term forecast and warning systems.

In the UK, GETM is used, for example, by the **UK Nuclear Inspectorate** for modelling thermal plumes in shallow water and has contributed to a decision on permissions to build new marine infrastructure with a value of £10Bn [5]. Within the Defra centre, Cefas, GETM is central to the coupled physical-biogeochemical model used to estimate carbon and nutrient flows in shelf seas [5]. This has been instrumental in tracking the distribution of plankton as part of the Marine Ecosystems Connections programme, which provides essential indicators of healthy, productive and biologically-diverse European shelf seas for compliance with international targets for reducing rate of biodiversity loss in ecosystems susceptible to change. Moreover GETM predictions have been used to define ecohydrodynamic regions in UK shelf seas that underpin the application of the **UK Government Marine Strategy Framework Directive** [5]. POLCOMS has, for example, been used to **develop short-term storm flood warning systems** as part of the 2008-2011 EU Program Mi-Core.

The Danish Defence Centre for Operational Oceanography (DCOO) applies GETM for its ocean forecasts around Denmark which, for example, play a crucial role in search and rescue activities, daily sailing forecasts and ice forecast warnings [7]. In Germany, GETM has, for example, been used to **assess the impact of cooling plumes from new coal-fired power stations**. GETM predictions were used by German government regulatory authorities to require alterations in cooling water discharge plans and to estimate the potential nature and fisheries compensations. Many other examples of applications of GETM, including direct referencing to research by Simpson et al. at Bangor, can be found on the GETM website [6].

3. Impact on second generation ocean model applications
The vertical exchange algorithms originally tested and implemented into GOTM (i), have now been applied to the development of new models. Although the new models are superior in computing architecture and power, the turbulence parameterisations underpinned by the Bangor measurements remain central to them. In NEMO, GOTM was superseded by a generic length scale model (GLS) in 2010, and it is used by the UK Met Office for their short-range ocean and climate forecasting and to provide the daily coastal seas and ecosystem forecasts. According to the Lead Scientist in the Ocean Modelling group at the Met Office, GOTM is regarded as "the absolute gold standard in turbulence modelling" [2].

5. Sources to corroborate the impact (indicative maximum of 10 references)

Formal statements:

1. A formal statement from the Sektionsleiter and main developer of GOTM at the Leibniz Institute for Baltic Sea Research Warnemuende confirms all claims of the importance of Bangor research for the development of GOTM and its applications.
2. A formal statement from the Lead Scientist, Ocean Modelling Group, UK Met Office confirms all claims of the impact of the Bangor work on model development and integration of the science into second-generation models.
3. A formal statement from the Principal Oceanographer, Titan Environmental Surveys Ltd confirms claims of the relevance of the Bangor research for their commercial activities.
4. A formal statement from the Director, Partrac Ltd confirms claims of the relevance of the Bangor research for their commercial activities.
5. Defra Centre for Environment, Fisheries and Aquaculture Science (Cefas). Their answer to our Freedom of Information request is available on request. The Cefas modelling capacity, including GOTM and GETM applications, is further described at: http://www.nerc.ac.uk/research/programmes/shelfsea/documents/cefas-report.pdf

Applications of GOTM and referencing in documents in the public domain:
Copies of these documents with the relevant sections highlighted are available on request

6. GETM website with examples of projects and applications: http://getm.eu/index.php?option=com_content&task=blogsection&id=4&Itemid=42
7. A document summarising the operational applications of the hydrodynamic forecasts of the Danish Centre for Operational Oceanography is available on request. Related up-to-date forecast maps are available at: available at: http://ifm.fcoo.dk/?lang=en.
8. The UK Marine Monitoring and Assessment Strategy (UKMMAS) community. July 2010. Charting Progress 2. The State of UK Seas. Feeder Report: Ocean Processes Section 3.7.3.1 Available at: http://chartingprogress.defra.gov.uk.
9. DP Marine Energy Ltd Environmental Impact Assessment Scoping Report. May 2009. http://www.scotland.gov.uk/Resource/0041/00413717.pdf and the SeaGen Environmental Monitoring Programme Final Report. January 2011 http://seagenwales.co.uk/files/SeaGen-Environmental-Monitoring-Programe-Final-Report.pdf provide examples of applications of the ADCP techniques to the development of tidal energy arrays.