P4.7 HIGH WIND AIR-SEA EXCHANGES (HIWASE) – INITIAL TURBULENT FLUX RESULTS FROM STATION MIKE

John Prytherch[1], Margaret J. Yelland[1], Robin W. Pascal[1], Peter K. Taylor[1], Ben I. Moat[1], Ingunn Skjelvan[2], Craig Neill[2]

[1]National Oceanography Centre, Southampton, UK
[2] Bjerknes Center for Climate Research, Bergen, Norway

1. INTRODUCTION

HiWASE ("High Wind Air-Sea Exchanges") is a UK-SOLAS project which aims to improve the parameterisation of the turbulent air-sea fluxes of CO_2, momentum, sensible heat and latent heat, particularly under high wind speed conditions

In September 2006 scientists from the National Oceanography Centre (NOC) instrumented the Norwegian weather ship *Polarfront* (Fig. 1) with a range of sensors and systems including the air-sea flux system "AutoFlux" (Pascal and Yelland, 2004), a directional wave radar and two digital cameras. The *Polarfront* is owned and operated by Misje Rederi AS under contract to the Norwegian Meteorological Institute (DNMI). This ship and its predecessors have occupied Station Mike in the Norwegian Sea (66 N, 2 E) continuously for nearly 60 years, only coming in to port for 8 hours once every 4 weeks. As well as the DNMI's meteorological program, a hydrographic program is run by the Geophysical Institute of the University of Bergen. As part of the hydrographic program, colleagues from the Bjerknes Center for Climate Research (BCCR) obtain continuous measurements of the ΔpCO_2 from an automated system.

The AutoFlux system obtains direct measurements of the momentum and latent heat fluxes automatically using the inertial dissipation method. Fluxes calculated using the eddy correlation method are currently produced post-cruise. Near real-time (24 hours) summary results are transmitted to NOC from the ship via IRIDIUM and displayed on the project web page http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/index.php . The various systems on the ship all operate continuously, and will do so at least until the end of the project in late 2009. Continuous operation allows data to be obtained under a wide range of wind speeds and sea states: to date the maximum 10 minute mean wind speed is 28 m/s, with maximum significant wave heights (Hs) of 10 m.

Here we give an overview of the instrumentation and methods, present an initial assessment of the Licor-7500 gas analyser and show some preliminary flux results.

2. RATIONALE

For open ocean conditions the behavior of the momentum flux is reasonably well understood but there is still debate about the influence of sea state (e.g. Drennan et al., 2005). Similarly, there is a lack of direct measurements of this flux for winds over 28 m/s (Yelland et al. 1998), but it has been suggested that for winds over 25 m/s the drag coefficient may cease to increase linearly with increasing wind speed (Taylor and Yelland, 2001). The heat fluxes are less well known, with debate about any wind-speed dependence of the transfer coefficients. There have been few direct measurements of the heat fluxes above 15 m/s and none for winds of more than 20 m/s.

Figure 1. The *Polarfront* during a brief port call in Aalesund. The flux sensors are on the starboard side of the foremast platform.

In comparison to the other turbulent fluxes, the CO_2 flux is very poorly understood, with parameterizations of the gas transfer velocity differing significantly for winds of 7 m/s or more, and by 100% for winds of 15 m/s. The transfer velocity has a strong dependency on wind speed (parameterisations vary from roughly u^2 to u^3, e.g. Wanninkhof, 1992; Wanninkhof and McGillis, 1999) or the momentum flux, either directly or via a sea-state mechanism. The impact of high wind speed events is disproportionate to the frequency of their occurrence. For example, during winds of 21 m/s the flux of trace gases will be between 9 and 27 times that which occurs during winds of 7 m/s (the global average), depending on which parameterisation is used. To date there have been few direct measurements of the CO_2 flux and none above winds of 15 m/s.

In order to obtain improved parameterizations of the CO_2 and other fluxes it is necessary to obtain data

*Corresponding Author address: J Prytherch, Ocean Observing and Climate, National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK; email: jzp@noc.soton.ac.uk

across as wide a range of conditions as possible. The *Polarfront* operates in a region of the world's oceans which experiences extreme conditions in terms of wind speed and sea state. In addition, during the autumn months the ΔpCO_2 is still large and storms are frequent (Iden, 2003). By instrumenting the ship with automated systems which will operate continuously for three years, a comprehensive data set will be obtained. The data set includes: a) direct measurements of the fluxes of CO_2, momentum, sensible and latent heat; b) sea state information from a ship-borne wave recorder (SBWR) and from a wave radar system; c) whitecap fraction from digital cameras; d) mean meteorological data from both NOC and DNMI sensors; e) ΔpCO_2 from the BCCR system; f) navigation data from the ship's systems.

3. INSTRUMENTATION AND METHODS

3.1 Sea state

In 1978 DNMI equipped the *Polarfront* with a ship-borne wave recorder (SBWR): the system was upgraded in 1996 and again in 2006. The SBWR uses two pairs of accelerometers and pressure sensors, mounted amidships 2 m below the water line on either side of the ship. The SBWR is a well-tested system, which provides reliable wave height data (e.g. Holliday et al., 2006) but does not provide any directional information. The lack of directional information means that it can be difficult to separate wind sea from swell, and impossible to know the orientation of the swell to the wind sea. For this reason NOC installed the commercial directional wave radar system "WAVEX". This uses data from a dedicated x-band marine radar to obtain 2-dimensional wave spectra. However, the WAVEX system does not measure surface elevation directly, but uses a (commercially confidential) algorithm to infer wave heights. It is believed that this is the first time the two systems have been deployed together for more than brief periods. The data from the two systems are complementary: the combination of reliable wave heights from the SBWR and the directional wave spectra from the WAVEX will provide a very comprehensive sea-state data set. Raw data is saved from both the SBWR (a 30 minutes sample period every 45 minutes) and the WAVEX (raw data twice per hour, spectra and derived parameters once every 5 minutes).

NOC also installed two digital cameras in the port/forwards corner of the bridge. These take images of the sea surface every 10 minutes which are analysed at NOC to produce an estimate of whitecap fraction. "Sea spikes" in the raw wave radar images will be related to wave breaking. These estimates of wave breaking and whitecap coverage will be related to wind and sea-state conditions and ultimately used in the CO_2 flux parameterisation.

3.2 Mean meteorology

DNMI has a range of sensors on the ship. These record, amongst other things, wind speed and direction, air temperature and humidity, atmospheric pressure and sea surface temperature. NOC installed additional mean meteorological sensors for downwelling long- and short-wave radiation, IR sea surface temperature, wet- and dry-bulb air temperature. The fast response flux sensors are detailed below.

3.3 ΔpCO_2

In the spring of 2005, colleagues from BCCR installed an IR based system for measurements of the surface water and atmospheric CO_2 partial pressure. The CO_2 system is patterned after and operates under principles similar to those described in Wanninkhof and Thoning (1993) and Feely et al. (1998). The system is calibrated hourly with three reference standards obtained from NOAA/Climate Monitoring and Diagnostics Laboratory (CMDL). The instrument outputs data for the surface ocean CO_2 partial pressure every 5 minutes. Data for the atmospheric CO_2 concentration are reported every hour. Surface salinity (for CO_2 solubility) is obtained from a Seabird microTSG sensor (provided by NOC as part of HiWASE) as well as daily Nansen bottle samples (Fig. 2).

Figure 2. One of the *Polarfront* crew preparing the Nansen bottle.

3.4 Flux sensors

The flux sensors are mounted on the starboard/forward corner of the ship's foremast platform (Fig. 1). The sensors are a Solent R3A sonic anemometer, a Systron Donner MotionPak and two Licor-7500 open-path gas analysers. The R3A anemometer is mounted about 15 m above the ship's waterline. The MotionPak is mounted 1.3 m below the head of the R3A. The two Licors are also mounted about 1.3 m below the R3A, with one projecting about

80 cm forwards and the other 80 cm to starboard. The R3A and the Licors both output data at 20 Hz.

The MotionPak uses three orthogonally mounted solid-state quartz angular rate sensors (resolution < 0.004 °/sec), and three linear servo accelerometers (resolution < 10 μg) and has been successfully used for ship motion corrections to EC flux measurements for a number of years (e.g. Edson et al., 1998). The 100 Hz data output from the MotionPak are logged via the analogue input channels to the anemometer. An electronic synchronization signal is input to the analogue channels of the Licors and sonic anemometer so that the data streams can be accurately aligned during post-processing.

It is known (Yelland and Pascal, 2004) that the output from the Licor sensors is sensitive to the angle of the head to the vertical. Turning the head by 90° causes a change in the mean measured value of about 1%. This is caused by the sensor head deforming slightly in response to any force applied across it, and may vary from one sensor to another. Installing two Licors on the *Polarfront* allows us to shroud one Licor while leaving the other open. The shroud is made so that the sensing volume is covered without touching or supporting the sensor head in any way. Data from the sensors while shrouded are used to derive a correction for head deformation, using ship motion data from the MotionPak. It should be noted that this correction method will also correct for other mechanically-induced errors, e.g. gyroscopic effects on the chopper motors etc. At every port call the crew remove the shroud from one sensor and place it over the other. This will allow us to monitor the effect of head deformation and determine whether the problem worsens over time.

3.5 AutoFlux logging system

In the AutoFlux system, all data are acquired to, and processed on, one UNIX workstation. The workstation system clock is automatically checked against the GPS time signal and corrected to ensure that all data are correctly time-stamped. The whole system is powered through an un-interruptible power supply which ensures a clean shutdown if the power failure is lengthy. On return of power all systems are automatically re-started and all acquisition and processing programs are launched. These programs all run on an hourly sampling cycle and are "overseen" by program monitoring software which re-launches any program which has crashed or hung. Data loss of more than one hour is therefore rare. Summary flux results, basic information from all data streams (including the wave and ΔpCO_2 systems), and workstation housekeeping information are sent automatically via IRIDIUM once per day. Data from these messages are displayed under the project web pages at http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/OBS/data_intro.php . This allows the status of the systems to be monitored remotely. The 2-way IRIDIUM link also allows fault-finding and solving to be performed remotely.

3.6 Flux calculation methods

There are two main methods for calculating the turbulent fluxes. The inertial dissipation (ID) method relies on good sensor response at frequencies up to at least 10 Hz. The ID method has the advantage that a) the flux results are insensitive to the motion of the ship and b) they can be corrected for the effects of the ship distorting the air flow to the sensors using numerical models of the flow around the ship. Yelland et al. (1998) showed that biases of up to 60% are possible in momentum flux measurements made via the ID method from well-exposed instruments on research ships, and that the biases can be removed using the results from the numerical models. Momentum and latent heat flux measurements have been successfully made using the ID method for a number of years. In contrast, sensible heat and CO_2 flux measurements are made more difficult by the lack of sensors with the required high frequency response.

The eddy correlation (EC), or covariance, method is the most direct and requires good sensor response up to only about 2 Hz, but is a) very sensitive to ship motion which has to be removed from the measured wind speed fluctuations and b) the fluxes can not be directly corrected for the effect of air flow distortion. It has been shown that the EC method is more sensitive to flow distortion than the ID method (e.g. Oost, 1994) which suggests that biases in EC-derived fluxes could be large. Biases in the EC fluxes can be estimated by comparison with the (corrected) ID fluxes, where available.

The AutoFlux automated processing calculates the momentum and latent heat fluxes using the inertial dissipation method. At present, EC calculations of all the turbulent fluxes are performed at NOC using the method described in Edson et al. (1998).

4. PRELIMINARY RESULTS

4.1 Flow distortion

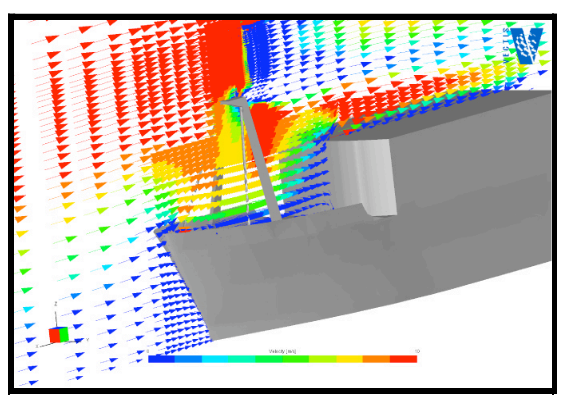

Figure 3. Bow-on flow over a simplified model of the *Polarfront*.

A detailed 3-D numerical simulation of the air flow over the *Polarfront* has not yet been performed so the results shown below have not been corrected for flow distortion biases unless otherwise stated. However, a preliminary study of a very simplified ship geometry (Fig. 3) suggests that flow distortion at the foremast platform will be relatively small: for bow-on flows the vertical displacement of the flow is estimated at about 1 m, and mean wind speed biases at about 1%. These biases will increase as the wind moves off the bow.

4.2 Momentum flux

The Solent sonic anemometers have been used for measuring the momentum flux for nearly 20 years. The mean relationship between the drag coefficient (CD_{10N}) and the 10m neutral wind speed U_{10N} is shown in Fig. 4. An estimate of the vertical displacement of the flow of 1 m has been used, but no correction to the mean wind has been applied yet. However, it can be seen that these ID results are very similar to previous open-ocean data(e.g. Smith, 1980; Yelland et al., 1998).

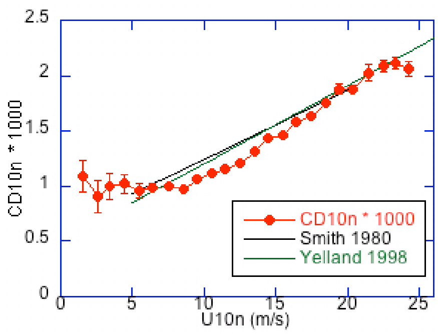

Figure 4. The mean CD_{10N} to U_{10N} relationship.

Data from the ship's navigation system has not yet been synchronised with the fast-response sensor data. This will be done by comparing the data from the MotionPak rate sensor with rate-of-change of heading from the ship's gyro. EC momentum fluxes will be produced once this is done.

4.3 Latent heat flux

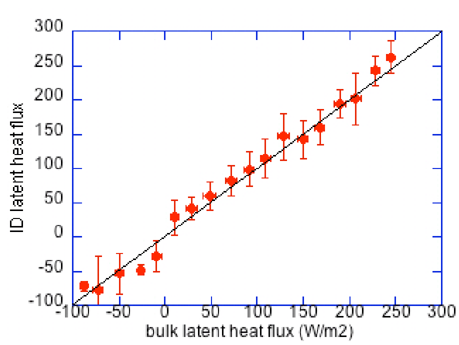

Figure 5. Latent heat fluxes (W/m^2) calculated from the ID method against those estimated from the bulk formula of Smith (1988). A 1:1 line is shown.

The Licor has good high frequency response ($f^{-5/3}$) to H_2O fluctuations which means that these data can be used to calculate the latent heat flux using the ID method. Figure 5 compares latent heat fluxes from the ID method with those from a bulk formula. When the Licor was shrouded, the latent heat fluxes went to within a few W/m^2 of zero (Section 4.4). Future comparison of ID and EC latent heat fluxes will allow us to estimate the flow-distortion bias in the EC estimates of *all* the scalar fluxes, including the CO_2 flux.

4.4 Licor head deformation

Data from a 5 day period were used to make a preliminary investigation of the relationship between the data output from a shrouded Licor and the platform accelerations as measured by the MotionPak. Multiple linear regression was used to calculate a simple correction for head deformation. Latent heat and CO_2 "fluxes" were calculated using the EC method from the same (shrouded) data, both before and after correction. Ten minute averaged U_{10N} varied from 5 to 19 m/s during this 5 day period, with a mean value of 12 m/s.

Figure 6 shows a histogram of the latent heat "fluxes" from the shrouded Licor. Before correction the mean latent heat flux was +2.5 W/m^2 with a standard deviation (s.d.) of 5.3 W/m^2. After correcting for head deformation this is reduced to a mean of 0.03 (s.d. 1.46) W/m^2. Similarly, the CO_2 "flux" for uncorrected data

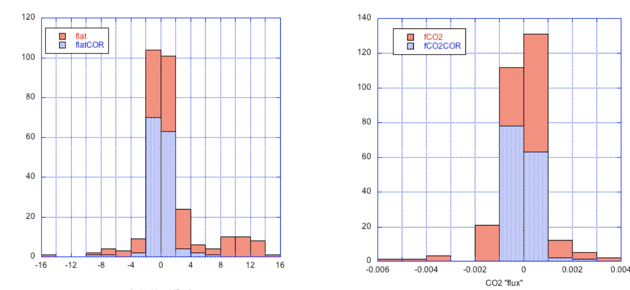

Figure 6. The effect of correcting for head deformation on the latent heat (left) and CO_2 (right) "fluxes" from the shrouded Licor.

was -0.10 (s.d. 1.17) μmol/m^{2}s. After correction this reduced to a mean of 0.05 (s.d. 0.39).

For CO_2, application of the corrections for head deformation results in a significant reduction in both the mean bias and the scatter. However, the residual values are still significant compared to typical "real" flux values. The corrections will be refined using a much larger data set obtained from the shrouded Licors.

The residual effect of head deformation on the EC latent heat flux is small. Figure 7 shows 10 days of latent heat flux data from the Licor with no shroud on (Yelland et al., 2007). Results were calculated using the EC method and include the correction for head deformation. Ten minute averaged U_{10N} values ranged from 5 to 16 m/s, with a mean of 10 m/s. There is good agreement in the mean between the EC data and estimates of the latent heat flux from the bulk formula of Smith (1988). The large scatter may be due to the wide range of relative wind direction used in this sample (±100° of bow-on).

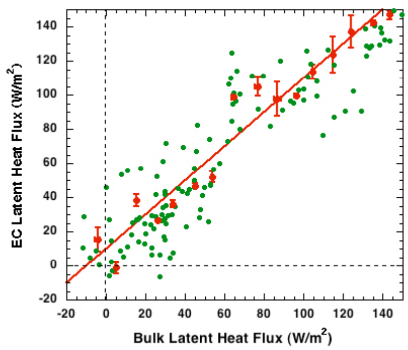

Figure 7. EC latent heat fluxes against bulk formula estimates. Green points are individual 1 hour samples, red points show average results per 10 W/m^2 (error bars are ± 1 s.d.) and the red line shows the linear regression of the averaged results.

4.5 Licor lens salt contamination

CO_2 fluxes, when calculated using the EC method from measurements made in open ocean conditions using open path sensors have always given higher than expected values of the CO_2 transfer velocity. The transfer velocity calculated from open path measurements can be as much as an order of magnitude greater than values obtained from established 'indirect' techniques such as radiocarbon inventories, dual tracer release and flux measurements obtained from closed path sensors. However, the open path sensors are the standard against which other methods of flux measurement are compared when making measurements on land as they directly measure the flux of interest and remove potential sources of error such as sampling tubes.

It has been proposed that the apparent error in the magnitude of CO_2 fluxes as measured by open path sensors is due to a cross sensitivity of the sensor's CO_2 absorption band to water vapour caused by a build up of salt on the sensor lens (Kohsiek, 2000).

The effect of salt on the performance of the Licor instruments has been examined in laboratory conditions. Sprays of either fresh water or seawater were directed onto the sensor lens and the response of the CO_2 and H_2O channels recorded. Immediately following both types of spray, both the H_20 and CO_2 signals fluctuate significantly. The CO_2 signal recovers to a 'realistic' value in both the fresh and salt-water case within approximately 2 hours. The H_20 signal recovers following the fresh water spray within approximately 2 hours. The H_2O signal following saltwater spray tends to a value significantly different from the value prior to spraying. This effect may allow the condition of the sensor lens to be determined and 'clean' or 'dirty' periods of CO_2 data selected.

An automated lens cleaning system has been installed on the *Polarfront* in September 2008. The system directs a spray of fresh water onto both sensor lenses with a predetermined time interval. The initial results from this system are currently being analyzed.

6. SUMMARY

The HiWASE project is in the process of obtaining a comprehensive and extensive data set of air-sea fluxes and the associated forcing parameters. Initial results are very encouraging and have shown that;

a) the Licor has the high frequency response required to calculate the latent heat flux via both the inertial dissipation (ID) and eddy correlation (ED) methods. Once the ID results are corrected for flow distortion, a comparison of the ID and EC latent heat fluxes will allow us to correct all the EC scalar fluxes (sensible heat and CO_2) for the effects of flow distortion.

b) the *Polarfront* is an excellent platform from which to make air-sea flux measurements since preliminary model studies suggest that the effects of flow distortion are small compared to other ships.

c) for H_2O, the mechanical problems with the Licor sensor can be removed by developing a correction factor which is a function of platform motion.

d) A correction is required to remove the effect of sensor lens salt contamination from the CO_2 signal. This is being developed and initial results are encouraging. Application of an automated cleaning system and schemes to identify 'clean' periods of data will allow the correction procedure to be validated.

ACKNOWLEDGEMENTS

Many thanks to: the crew of the *Polarfront* who are unfailingly helpful; Knut Bjorheim, Head of the Observations Department at DNMI for granting us permission to use the ship; Lasse Stenberg and Jon Halvard Berntsen of DNMI for their help with the ship's systems; Jeff Hare (University of East Anglia) for getting us started with his motion-correction algorithms. HiWASE is a UK-SOLAS project (grant number NE/C001826/1) funded by the UK Natural Environment Research Council.

REFERENCES

Drennan, W. M., P. K. Taylor and M. J. Yelland, 2005: On parameterising the sea surface roughness. *J. Phys. Oceanog.* 35(5) 835-848.

Edson, J. B. A. A. Hinton, K. E. Prada, J. E. Hare, and C. W. Fairall 1998: Direct covariance flux estimates from mobile platforms at sea. *J. Atmos. Oceanic, Technol.*, **15**, 547-562.

Feely, R. A., R. Wanninkhof, H. B. Milburn, C. E Cosca, M. P. Stapp, P. Murphy, 1998: A new automated underway system for making high precision pCO~2 measurements onboard research ships. *Analytica Chimica Acta.,* **377**(2-3): 185-191

Holliday, N. P., M. J. Yelland, R. W. Pascal, V/ R. Swail, P. K. Taylor, C. R. Griffiths, E. C. Kent, 2006: Were extreme waves in the Rockall Trough the largest ever recorded? *Geophysical Research Letters* VOL. 33, L05613, doi:10.1029/2005GL025238

Iden, K. A., 2003: Analysis of meteorological observations from Station Mike 1949-2002, *Proceedings of Climar II. Second JCOMM Workshop on Advances in Marine Climatology,* Brussels, Belgium, November 2003

Kohsiek, W., 2000: Water Vapor Cross-Sensitivity of Open Path H2O/CO2 Sensors. Journal of Atmospheric and Oceanic Technology, 17, 299-311.

Oost, W. A., C. W. Fairall, J. B. Edson, S. D. Smith, R. J. Anderson, J. A. B. Wills, K. B. Katsaros and J. DeCosmo, 1994: Flow distortion calculations and their application in HEXMAX. *J. Atmos. & Oceanic Tech.*, **11**(2), 366 - 386.

Pascal, R W and M J Yelland 2004: AutoFlux: a system for the autonomous measurement of the turbulent air-sea fluxes of momentum, heat and CO_2. *Proc. NERC Technology Forum,* Southampton Oceanography Centre, 2004.**

Smith, S. D., 1980: Wind Stress and Heat Flux over the Ocean in Gale Force Winds. *J. Phys. Oceanogr.*, **10**, 709-726.

Smith, S. D., 1988: Coefficients for Sea Surface Wind Stress, Heat Flux and Wind Profiles as a Function of Wind Speed and Temperature. *J. Geophys. Res.*, **93**, 15467-15474.

Taylor, P. K. and M. J. Yelland, 2001: The dependence of sea surface roughness on the height and steepness of the waves. *J. Phys. Ocean, 31, (2), 572 – 590*

Wanninkhof, R, 1992: Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.*, **97** 7373-7382.

Wanninkhof, R. and K. Thoning, 1993: Measurement of fugacity of CO~2 in surface water using continuous and discrete sampling methods. *Mar. Chem.* **44** (2-4):189-205.

Wanninkhof, R., and W. R. McGillis, 1999. A cubic relationship between air-sea CO2 exchange and windspeed. *Geophys. Res. Let.*, **26** (13), 1889-1892

Webb, E K., G I Pearman and R. Leuning, 1980: Correction of flux measurements for density effects due to heat and water vapour transport. *Q. J. R. Meteorol. Soc.* **106** 85-100

Yelland, M. J., B. I. Moat, P. K. Taylor, R. W. Pascal, J. Hutchings, V. C. Cornell, 1998: Wind stress measurements from the open ocean corrected for flow distortion by the ship. *J. Phys. Ocean.* **28** (7), 1511-1526

Yelland M. J. and R. W. Pascal, 2004: Direct measurement of the air-sea turbulent fluxes of momentum, heat and CO_2. *Presented at the SOLAS Science Conference* 13th-16th October 2004, Halifax, Nova Scotia **

Yelland M J, R W Pascal, P K Taylor, B I Moat, I Skjelvan, C Neil, 2007: Continuous air-sea flux measurements at Station Mike. *Geophys Res Lett. in prep*.

** Available from www.noc.soton.ac.uk/ooc/mjy