AutoFlux: an autonomous system for the direct measurement of the air-sea fluxes of CO_2, heat and momentum

MJ Yelland PhD, RW Pascal HNC, PK Taylor PhD, BI Moat PhD, National Oceanography Centre, Southampton, UK

AutoFlux is an autonomous system for making direct measurements of the air-sea exchanges of CO_2, momentum and heat. Such measurements are usually restricted to short, dedicated air-sea interaction cruises on research ships which last only a few weeks. In contrast, AutoFlux was recently deployed continuously on the RRS *Discovery* for two years and is now currently part of a three year measurement programme on the Norwegian weather ship *Polarfront*. The instrumentation on *Polarfront* also includes two different wave measurement systems and digital cameras. The various systems are described and initial results presented.

AUTHORS' BIOGRAPHIES

Margaret J Yelland obtained a BSc in physics from Imperial College London in 1988, joined the Institute of Oceanographic Sciences, Wormley in 1989, followed the Institute to the National Oceanography Centre (NOC) Southampton in 1995, and gained a PhD in air-sea interaction from the University of Southampton in 1997. She is currently a Senior Scientific Officer in the Ocean Observing and Climate Division and is interested in the measurement and parameterisation of air-sea turbulent fluxes and wave breaking.

Robin W Pascal joined the Applied Physics Group at the Institute of Oceanographic Sciences, Wormley, in 1979, gained an HNC in electronic engineering in 1984 and followed the Institute to the NOC Southampton in 1995. He is currently a Senior Scientific Officer in the National Marine Facilities Division of NOCS. His interests include meteorology, air-sea interaction, wave measurement and the development of sensors and systems for the measurement of air-sea fluxes and waves.

Peter K Taylor obtained a BSc in physics from Imperial College London in 1969, a PhD in boundary-layer meteorology from the University of Southampton in 1973, joined the Institute of Oceanographic Sciences, Wormley in 1972 and followed the Institute to the NOC Southampton in 1995. Before his recent retirement he was head of the James Rennell Division for Ocean Circulation and Climate and in 2006 was awarded the American Meteorological Society Sverdrup Gold Medal for his research on air-sea interaction and global flux climatologies. He is now a visiting research fellow.

Bengamin I Moat obtained a BSc in Mathematics from De Montfort University Leicester in 1995 and joined the NOC Southampton. He gained a PhD from the University of Southampton in 2003. He is currently a Research Fellow in the Ocean Observing and Climate Division and is interested in wave breaking and the correction of air-sea flux measurements for the effects of air flow distortion.

INTRODUCTION

Science background

The atmosphere and ocean are physically linked by the turbulent air-sea fluxes, or exchanges, of sensible heat, latent heat and momentum. The two systems also exchange material in the form of aerosols and trace gases with the air-sea flux of CO_2 being of particular importance from a climate change perspective. The fluxes themselves are difficult to measure directly and are usually estimated from bulk formulae parameterisations. These empirical parameterisations relate the flux to mean meteorological variables, which are more easily measured, via a transfer coefficient (for the heat and momentum fluxes) or a transfer velocity (for the CO_2 flux). For example, the momentum flux τ is parameterised in terms of the drag coefficient CD which relates the flux to the mean wind speed U, and density of air ρ:

$$\tau = -\rho \text{ CD } U^2 \tag{1}$$

The flux of CO_2 is parameterised in terms of a transfer velocity, k

$$\text{Flux } CO_2 = k^* s^* \Delta pCO_2 \tag{2}$$

where ΔpCO_2 is the air-sea concentration difference of the gas and s is the solubility of CO_2 in sea water. The transfer coefficients and the gas transfer velocity are not constants, but may vary with wind speed, sea state etc.

The bulk formulae parameterisations are used to estimate fluxes from mean parameters when producing global climatologies of the CO_2 flux, for example. However, the parameterisations themselves have uncertainties. The momentum flux is the best understood. Over the open ocean the drag coefficient shows a roughly linear increase with wind speed and its magnitude is known to within about 10% for wind speeds up to about 30m/s (the limit to which direct measurements of the fluxes have been made[1,2,3]). At higher winds the uncertainty is much greater since there are no direct flux measurements, but there is some evidence suggesting the drag coefficient becomes constant. In addition, the influence of sea state on the momentum flux is still hotly debated and is thought to be particularly large in coastal regions.[4,5,6] The heat fluxes are reasonably well understood but uncertainties of about 20% exist in their parameterisations in terms of mean variables. In addition, the variation of the heat transfer coefficients with wind speed is still subject to debate. Some authors suggest that the transfer coefficient for latent heat increases with wind speed whereas others suggest it is a constant. The transfer coefficient for sensible heat is even less well understood than that for the latent heat. There are few direct measurements of the heat flux for winds over 15m/s and none over 20m/s: high wind speed measurements would allow the dependency on wind speed to be determined more accurately.

Parameterisations of the CO_2 transfer velocity differ by about 50% for winds of 7m/s, which is the average wind speed over the world's oceans, and by 100% at 15m/s. Fig 1 illustrates the strong dependency of the transfer velocity on wind speed, and the wide range of suggested parameterisations.[7,8,9,10] It should be noted that to date there have been few direct measurements of the CO_2 flux and none obtained at mean wind speeds of more than 15m/s. As well as wind speed, it is also thought that the transfer velocity depends on sea state, wave breaking, whitecapping, and the presence or otherwise of surfactants and rain. Determining the relative importance of the various forcing parameters requires a large dataset.

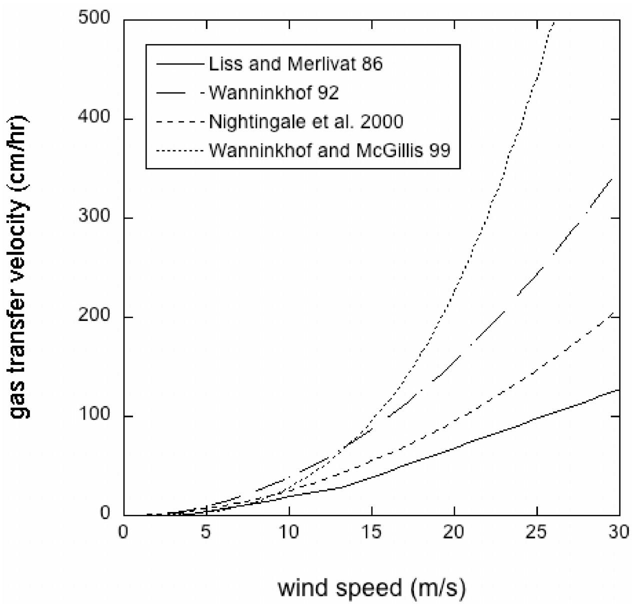

Fig 1: Parameterisations[7,8,9,10] of the gas transfer velocity, *k*, in terms of the mean wind speed from various studies as given in the key. Note that no direct measurements of *k* have been made for winds over 15m/s

Knowledge of the behaviour of the heat and momentum fluxes at high winds is necessary to improve our understanding of the generation and development of storms and hurricanes. Improved understanding of the CO_2 transfer velocity will directly impact climate change studies. In order to improve the flux parameterisation it is necessary to obtain direct measurements of the fluxes, along with measurements of all the relevant mean meteorological and sea state parameters. Such air-sea interaction experiments are usually restricted to short (six weeks or less) dedicated research cruises, where the range of conditions encountered are limited. To obtain a comprehensive dataset, continuous measurements need to be made for many months to ensure sufficient data are collected over as wide a range of conditions as possible.

AutoFlux and the weather ship 'Polarfront'

AutoFlux is an autonomous system for making continuous direct measurements of the air-sea fluxes of CO_2, momentum, sensible heat and latent heat as well as various mean meteorological parameters. As part of the UK-SOLAS (Surface Ocean – Lower Atmosphere Studies) project HiWASE (High Wind Air Sea Exchanges) AutoFlux was deployed on the Norwegian weather ship *Polarfront* in September 2006 and will operate continuously for two or three years. *Polar-*

front 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 eight hours once every four weeks. While on station the ship drifts beam-on to the wind, only turning bow-on to the wind when steaming slowly back to position or when hove-to in winds over 15 to 20m/s. As well as the DNMI's meteorological programme, a hydrographic programme is run by the Geophysical Institute of the University of Bergen. As part of the hydrographic programme, colleagues from the Bjerknes Center for Climate Research (BCCR) obtain continuous measurements of the ΔpCO_2 from an automated system. The various systems on the ship all operate continuously and this 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 26m/s, with maximum significant wave heights (Hs) of 12m.

This paper describes the AutoFlux system and flux measurement methods, the various instrumentation on the *Polarfront*, and presents a preliminary analysis of the data. AutoFlux also monitors the performance of the other systems on board *Polarfront,* such as the ship's existing ship-borne wave recorder and the directional wave radar system WAVEX which was installed as part of HiWASE. The two wave systems will also be described and a brief comparison of the data will be presented.

INSTRUMENTATION AND METHODS

The various systems installed on *Polarfront* will allow an extensive, comprehensive air-sea interaction dataset to be obtained. The dataset 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 NOCS and DNMI sensors;
e) ΔpCO_2 from the BCCR system;
f) navigation data from the ship's systems.

The AutoFlux system monitors all these systems, except the cameras, and transmits near real-time (24h) summary results and housekeeping information to NOCS via the IRIDIUM satellite communications system. These summary data are displayed on the project web page [see Conclusions section]. This section presents a brief description of the various systems and then a more detailed description of the AutoFlux system.

Sea state and whitecap fraction

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 sensors consist of two pairs of accelerometers and pressure sensors mounted port and starboard on the ship's hull 1.5m below the waterline, close to the pitch axis of the ship. Data from the port and starboard instrument pairs are combined to eliminate the effects of ship roll both in accelerations and pressure, and the accelerometer signal is double-integrated with respect to time to generate ship heave. The pressure sensors provide a wave height signal additional to the heave and the two are combined to calculate *in situ* sea surface height variability (ie, the wave height).[11] The SBWR is a well-tested system which provides reliable wave height data. It was used extensively for offshore wave measurement on light-vessels and weather ships.[12,13]

Today the SBWR is in continued routine use on a number of research ships world-wide, one of which recently measured a number of peak-to-trough wave heights of nearly 30m.[14] However, 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 NOCS 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 complete description of the sea-state. Both operate continuously. Raw data is saved from both the SBWR (a 30min sample period every 45min) and the WAVEX (raw data twice per hour, spectra and derived parameters once every 5min).

NOCS also installed two digital cameras in the port/forwards corner of the bridge. These take images of the sea surface every 10min which are analysed at NOCS 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.

Mean meteorology and navigation

DNMI has a range of sensors on the ship which record, amongst other things, wind speed and direction, air temperature and humidity, atmospheric pressure and sea surface temperature. NOCS 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 sensors used for flux measurement are detailed below. The mean meteorological data are sampled at 10Hz (NOCS) or output as a 1min average (DNMI). Data from the ship's navigation systems are also sampled at 1Hz.

ΔpCO_2 system

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.[15,16] 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 5min. 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 NOCS as part of HiWASE) as well as daily Nansen bottle samples.

Flux sensors

The flux sensors are mounted on the starboard/forward corner of the ship's foremast platform (Fig 2). A Solent R3A sonic anemometer (Gill Instrument Ltd, UK) provides 3-axes wind velocity and sonic air temperature which are used to calculate the momentum and sensible heat fluxes. Two Licor-7500 open-path gas analysers provide water vapour and CO_2 concentrations which are used to calculate the latent heat and CO_2 fluxes. The open-path Licor is relatively low-powered and does not require frequent complex calibrations, and is thus suitable for long-term deployments. A Systron Donner MotionPak provides measurements of the platform motion. The R3A anemometer is mounted about 15m above the ship's waterline. The MotionPak is mounted 1.3m below the head of the R3A. The two Licors are also mounted about 1.3m below the R3A, with one projecting about 80cm forwards and the other 80cm to starboard. The R3A and the Licors both output data at 20Hz.

Fig 2: The weather ship *Polarfront*. The arrow indicates the position of the fast response flux sensors

The MotionPak uses three orthogonally mounted solid-state quartz angular rate sensors and three linear servo accelerometers and has been successfully used for ship motion corrections to flux measurements for a number of years.[17] The 100Hz data output from the MotionPak are low pass filtered (30Hz cutoff) before being sampled by the R3A anemometer's analogue input A/D. The data are then averaged and output at 20Hz.

An electronic synchronisation 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. The 20Hz data from all the fast response sensors are transmitted wirelessly from the foremast to an aerial on top of the bridge, and hence to the AutoFlux acquisition system.

It was found that the output from the Licor sensors is sensitive to the angle of the head to the vertical.[18] 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 one Licor to be shrouded while the other is left uncovered. 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. A separate correction will be developed for each sensor. It should be noted that this correction method will also correct for other motion-induced errors, eg, gyroscopic effects on the chopper motors etc. At every port call one of the ship's crew removes the shroud from one sensor and places it over the other. This will allow us to monitor the effect of head deformation and determine whether the problem worsens over time.

Flux calculation methods

There are two main methods for calculating the turbulent fluxes. The inertial dissipation (ID) method[19] relies on good sensor response at frequencies up to at least 10Hz. 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 air flow around the ship.[20] Biases of up to 60% are possible in momentum flux measurements made via the ID method from well-exposed instruments on research ships,[1] but these 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 2Hz, 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[21] 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, real-time processing calculates the momentum and latent heat fluxes using the inertial dissipation method. At present, EC calculations[17] of all the turbulent fluxes are performed during post-processing at NOCS.

AutoFlux logging system

In the AutoFlux system, all data are logged to, and processed on, one UNIX workstation (a SUN Fire V210 server). 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 via 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. Each data stream (mean meteorology, navigation, sonic anemometer, 2xLicor, ΔpCO_2, SBWR and WAVEX) has a separate acquisition program and a separate analysis program. The results from each analysis program are then used to calculate hourly fluxes.

This modular approach means it is straightforward to add an extra data stream to the system if required. All programs 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 to NOCS 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. Once every three months NOCS staff visit the *Polarfront* while it is in port to retrieve all raw data, clear disk space and perform sensor maintenance or repair as necessary.

There is redundancy in most data streams, eg, there are four air temperature sensors (NOCS and DNMI) which means instrument failure is not catastrophic. The main exception is the single sonic anemometer which is crucial to all of the flux measurements, but this is an extremely reliable sensor. In the first 12 months of deployment the only significant data loss occurred when water ingress to a junction box on the foremast caused a loss of power to the fast response sensors. This was rectified 18 days later during the subsequent port call.

PRELIMINARY FLUX RESULTS

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 1m, and mean wind speed biases at about 1%. These biases will increase as the wind moves off the bow.

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 1m 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.[1,22]

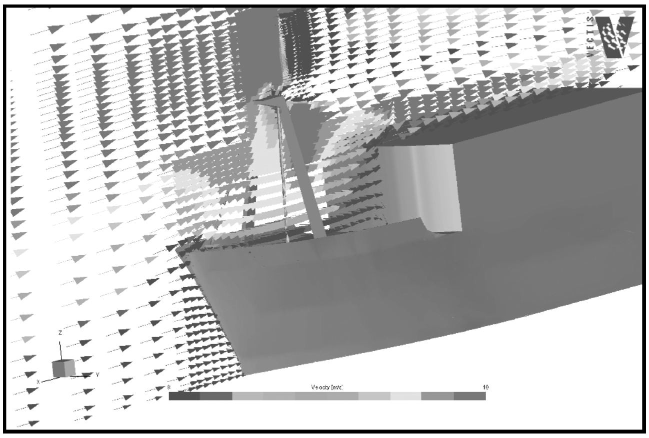

Fig 3: A slice of data from a 3-D computational fluid dynamics simulation of the air flow over a very simplified representation of the *Polarfront*

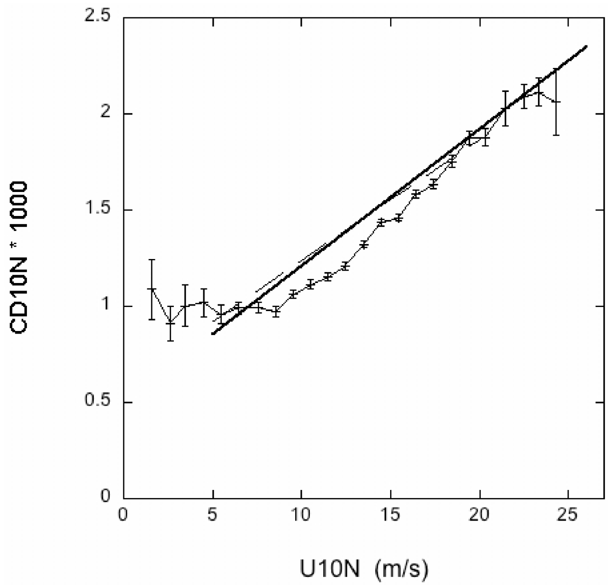

Fig 4: The mean drag coefficient to wind speed relationship from the *Polarfront* dataset. Error bars show the standard deviation of the mean for each 1m/s bin. The thick solid line is the relationship found by Yelland *et al*[1] and the thin dashed line is that from Smith[22]

Data from the ship's navigation system has not yet been synchronised with the fast-response sensor data. This requires comparison of the data from the MotionPak rate sensor with rate-of-change of heading from the ship's gyro. EC momentum fluxes can then be calculated.

Latent heat flux

The Licor has good high frequency (2-10Hz) response to H_2O fluctuations which means that these data can be used to calculate the latent heat flux using the ID method. Fig 5 compares latent heat fluxes from the ID method with those from a bulk formula.[23] When the Licor was shrouded, the latent heat 'fluxes' were within a few W/m^2 of zero. Detailed comparisons 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.

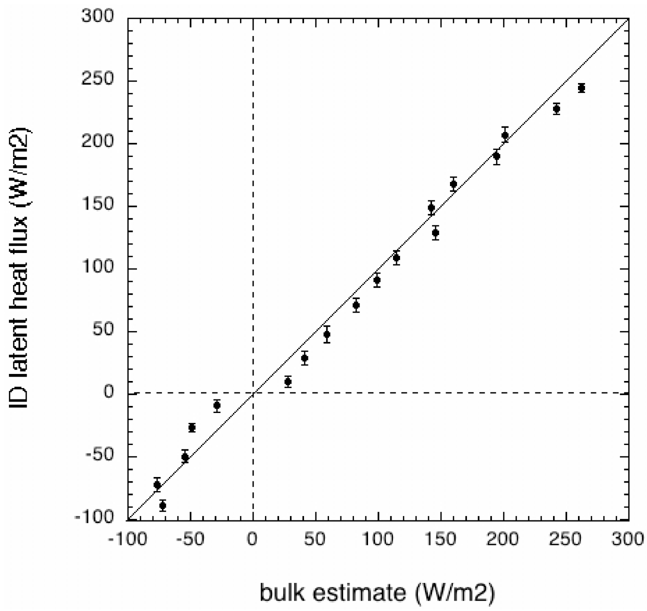

Fig 5: Latent heat fluxes (W/m^2) calculated from the ID method against those estimated from a bulk formula.[23] A 1:1 line is shown

Licor head deformation

Data from a five-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 wind speeds varied from 5 to 19m/s during this five day period, with a mean value of 12m/s. Fig 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 (sd) of 5.3 W/m^2. After correcting for head deformation this is reduced to a mean of 0.03 (sd 1.46) W/m^2. Similarly, the CO_2 'flux' for uncorrected data was -0.10 (sd 1.17) μmol/m^{2}s. After correction this reduced to a mean of 0.05 (sd 0.39).

For the CO_2 flux, 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 dataset obtained from the shrouded Licors. The residual effect of head deformation on the EC latent heat flux is small. Fig 7 shows 10 days of latent heat flux data from the Licor while un-shrouded. Results were calculated using the EC method and include the correction for head deformation. Ten minute averaged U_{10N} values ranged from 5 to 16m/s, with a mean of 10m/s. There is good agreement in the mean between the EC data and estimates of the latent heat flux from a bulk formula.[23] The large scatter may be due to the wide range of relative wind direction used in this sample (±100° of bow-on).

COMPARISON OF WAVE SYSTEMS

As briefly described above, the two wave systems on *Polarfront* have very different measurement principles, with the SBWR providing direct measurements of the wave heights but no directional information, whereas WAVEX provides excellent wave period and direction information but infers wave height statistics indirectly. Both systems store raw data as well as processed parameters and also output commonly used statistical wave parameters such as significant wave

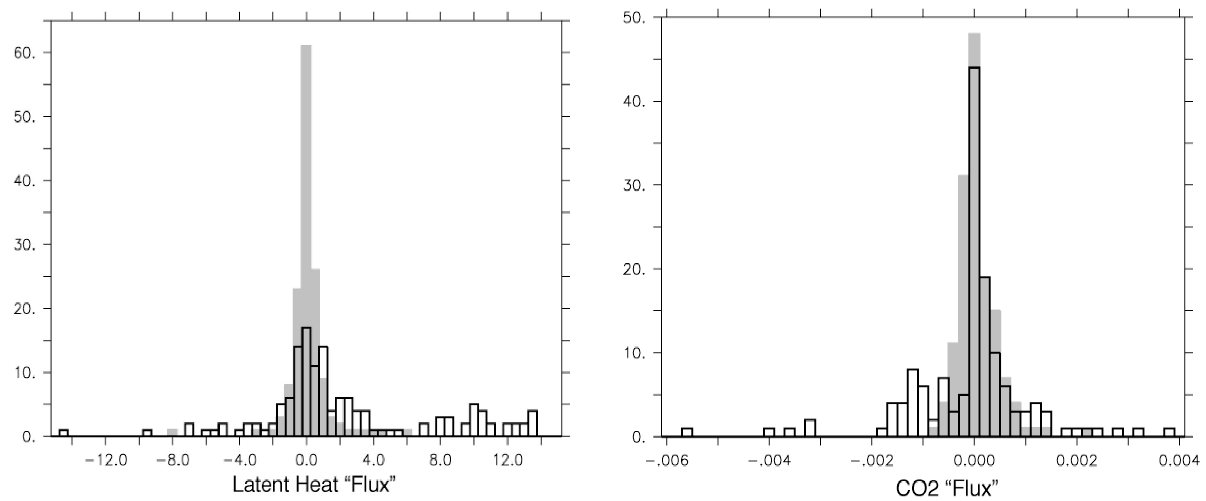

Fig 6: Latent heat (left, W/m^2) and CO_2 (right, mmol/m^{2}s) 'fluxes' from the shrouded Licor before (white) and after (grey) correcting for the deformation of the sensing head

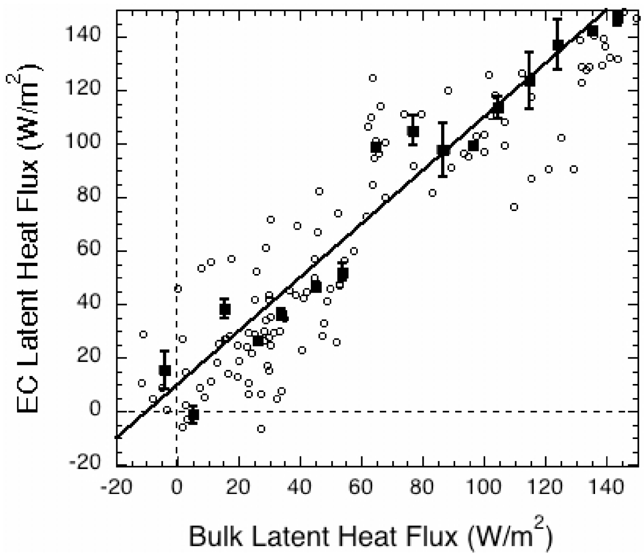

Fig 7: EC latent heat fluxes against bulk formula[23] estimates. Individual 1h samples (o) and average (■) results per 10 W/m^2 bin (error bars are ± 1 sd) are shown. The solid line shows the linear regression of the averaged results

height, Hs, and zero up-crossing period, Tz, which are defined as;

$$Hs = 4^{*}m0^{1/2} \quad (3)$$

$$Tz = (m0/m2)^{1/2} \quad (4)$$

where m0 and m2 are the zeroth- and second-order spectral moments. It should be noted that the spectral moments are dependent on the 'automatic calibration' of the wave spectra which is carried out to infer wave heights.[24]

A direct comparison of Hs and Tz from the two systems is shown for 12 months of data in Fig 8. The SBWR does not correct the data for ship steaming through the waves so data have been restricted to periods when the ship was drifting by selecting data when ship speed over the ground was less than 1.5m/s. The WAVEX shows a persistent tendency to overestimate Hs compared to the SBWR, and the overestimate is often large (a factor of 2) when the wave heights are small (3m or less as measured by the SBWR). The mean agreement in Tz is reasonably good, if scattered, for the longer period waves. For shorter period waves, the WAVEX Tz tends to be larger than that from the SBWR: this is the opposite of what may be expected if the ship is drifting in the same directions as the waves since the SBWR does not account for ship motion over the ground and would therefore be expected to overestimate Tz to some extent. Tz and Hs are both derived from the spectral moments which suggest that these are being overestimated by the 'automatic calibration' of the wave spectra. Time series of Hs showed that the WAVEX data agreed more closely with those from the SBWR during storms when the dominant waves were wind-driven. Periods where the WAVEX persistently over-estimated Hs occurred when the seas were swell-dominated, usually during light winds. This is demonstrated in Fig 9 where the mean ratio (WAVEX Hs /SBWR Hs) is shown.

The WAVEX system identifies primary and secondary waves, with different periods and directions associated with each. It is thought that the over-estimate of Hs by the WAVEX may be caused by swell waves being identified as the primary waves, but treated as wind waves for the purpose of calculating the spectral moments. This is currently being investigated.

CONCLUSIONS

AutoFlux is the only autonomous system capable of obtaining continuous, direct measurements of the turbulent air-sea fluxes of momentum, sensible heat, latent heat and CO_2. It has proved capable of long-term operation, requiring visits to the ship for routine maintenance only once every three months. The main purpose of the system is to collect data from the fast response sensors along with mean meteorolo-

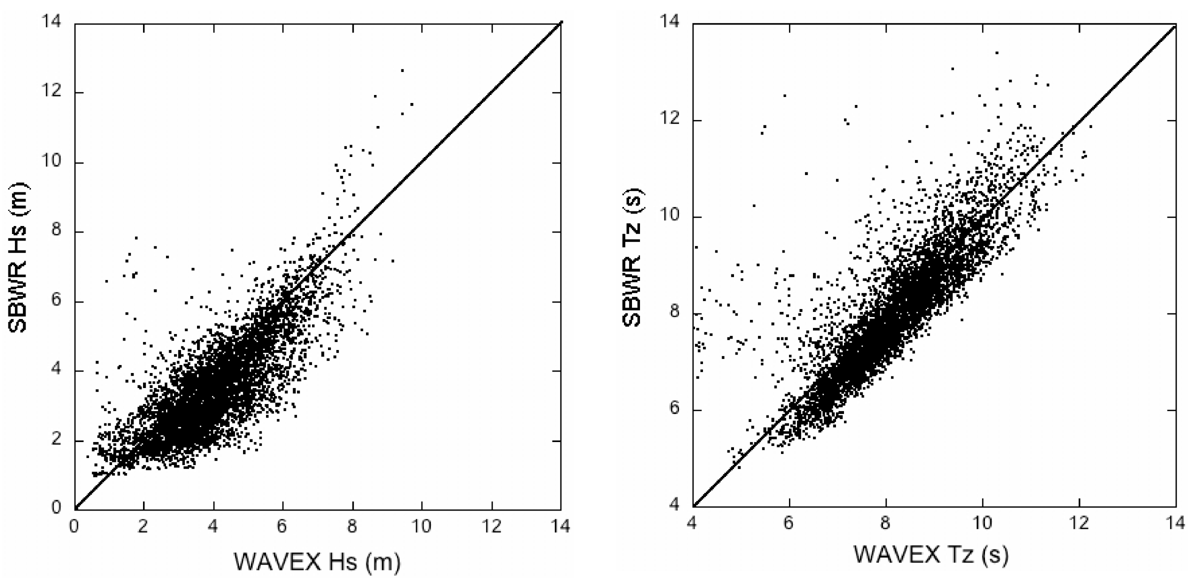

Fig 8: Hs (left) and Tz (right) from the two wave systems. The solid line indicates a 1:1 relationship

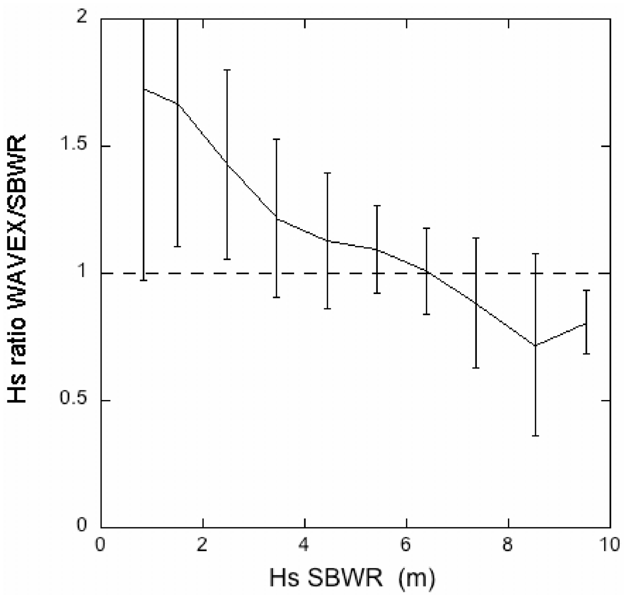

Fig 9: Averaged WAVEX:SBWR ratio for significant wave height (Hs). The dashed line indicates 1:1 agreement

gical and navigation data required for flux calculations. However, the modular arrangement of the system means it is flexible: data from additional sensors can be logged and processed, and summary data from other complex systems can also be logged.

As configured on the *Polarfront*, AutoFlux logs data from the WAVEX marine wave radar system, the ship borne wave recorder and BCCR's underway pCO_2 system. Inclusion of data from these systems in the daily IRIDIUM message means that they can also be monitored remotely via the project web site at http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/index.php. Two-way communications via IRIDIUM means that all systems can be monitored remotely which keeps data loss to a minimum. By the end of the three-year deployment a unique, comprehensive air-sea interaction dataset will have been obtained. This will allow the physical forcing of the air-sea fluxes to be better understood and improved parameterisations will be produced.

The good high frequency response of the Licor-7500 to moisture fluctuations means that the latent heat flux can be calculated by both the ID and EC methods. The ID latent heat fluxes will be corrected for the effects of air flow distortion using numerical models of the air flow around the ship. Comparison of the corrected ID fluxes with those from the EC method will allow us to obtain a correction for flow distortion which can be applied to all the EC scalar fluxes, ie, the EC sensible heat and CO_2 fluxes as well as the EC latent heat flux. Corrections to the data for deformation of the sensor head have proved effective in removing the small mean bias in the shrouded 'flux' data and also greatly reducing the scatter.

Initial comparisons of the sea state data from the WAVEX and SBWR wave systems has shown that the WAVEX tends to significantly overestimate the wave heights, particularly under swell dominated or low wind speed conditions. The reasons for this are currently being investigated. However, the combination of data from the two systems provides a comprehensive, directional description of the sea state.

ACKNOWLEDGEMENTS

AutoFlux was initially developed at the National Oceanography Centre (NOCS) under MAST-3 funding and subsequently under the NOCS Technology Innovation Fund. The deployment on the *Polarfront* is part of the 'HiWASE' (High Wind Air-Sea Exchanges) project, supported by NERC grant NE/C001826/1. The work is also supported by NOCS funding through the Oceans 2025 programme. We are grateful to Knut Bjorheim of the Norwegian Meteorological Institute for use of the *Polarfront*, and the ship's crew for their help and enthusiasm.

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