A Strategy for Marine Meteorological and Air-Sea Flux Observation

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1. INTRODUCTION

Traditionally, the bulk of surface marine observations have come from merchant ships. The primary purpose of these data has been for use in weather forecasting. However there have been numerous attempts use these observations to map the surface meteorological and air-sea flux fields. Now, with the desire to better understand the ocean's role in global climate, there is great need to make such maps, and to do so accurately. Unfortunately, the shipboard observations are mainly limited to major shipping routes and can exhibit significant errors associated with sensors, sensor placement, and air flow disturbance. Furthermore, few ships have been equipped to measure the shortwave and longwave radiative fluxes, which have instead to be estimated from rudimentary cloud descriptions. As a result, the uncertainties associated with ship-based climatolgies can be large.

An alternative method for obtaining surface meteorological and air-sea flux fields, attractive because of the availability of the data at regular time intervals and on a global grid, has been to make use of analyses and reanalyses produced using numerical weather prediction models. Unfortunately, recent field programs have found that large errors are also found in these products.

We propose a strategy for obtaining global marine meteorological and air-sea flux fields at the accuracies needed for climate research and as a component of a global climate observing system. High quality surface observations would be made from moorings at select locations to provide reference sites. Upgraded instrumentation would be placed on a subset of the Volunteer Observing Ships (VOS) and improved methodologies would be used in processing all VOS data. This strategy relies on recent progress in our ability to collect accurate, long time series of surface meteorology and air-sea fluxes from surface moorings and in improving VOS instrumentation and observing methods. The main use of the data from the reference sites and improved VOS would be to quantify the uncertainties in surface fields derived from models and remote sensing, as well as the standard VOS observations. Although the reference data could be assimilated in near-real time into models, this strategy assumes that in the future the models will increasingly rely on satellite data for initialization purposes.

2. RECENT PROGRESS IN MARINE METEOROLOGICAL MEASUREMENTS

2.1 The IMET System

Work has been underway to improve measurements from ships and also from surface buoys. Focused support by the National Science Foundation as part of the World Ocean Circulation Experiment (WOCE) led to extensive sensor testing and development, resulting in the Improved Meteorological System (IMET). IMET has been installed on a number of the U.S. *Research Vessels* and is now being placed on U. S. VOS. IMET has also been used on surface moorings in a number of research programs.

IMET uses sensors chosen based on laboratory and field studies for accuracy, reliability, low power consumption, and their ability to stay in calibration during unattended operation. Sensors are combined with front end and digital electronics to make a module that is digitally addressable (RS- 232 or RS-485), retains its calibration information, and provides either raw data or data in engineering units. On a buoy, a low power data logger is used to poll the modules, collecting and storing data. On a ship, a standard PC can be used for data acquisition and display. Each module can also be configured with its own battery and to internally record its data. The present set of IMET modules includes wind speed/direction, air temperature, sea surface temperature, relative humidity, precipitation, incoming shortwave radiation, incoming longwave radiation, and barometric pressure.

Laboratory calibrations and *in-situ* calibration studies and intercomparisons have been used to assess the accuracy of the IMET sensors as installed on buoys. Figure 1 summarizes the progress that has been achieved in reducing measurement error.

2.2 Recent Field Programs

Results from several recent programs illustrate the value of installing surface moorings as reference sites. The Subduction experiment, conducted in 1991-1993 in the northeast Atlantic, required accurate fields of buoyancy forcing to study the processes by which water in the upper ocean moves into the ocean's interior. A broadly spaced array of five surface moorings was deployed for two years to provide the means to develop accurate, gridded surface meteorology and air-sea flux fields (Moyer and Weller, 1997).

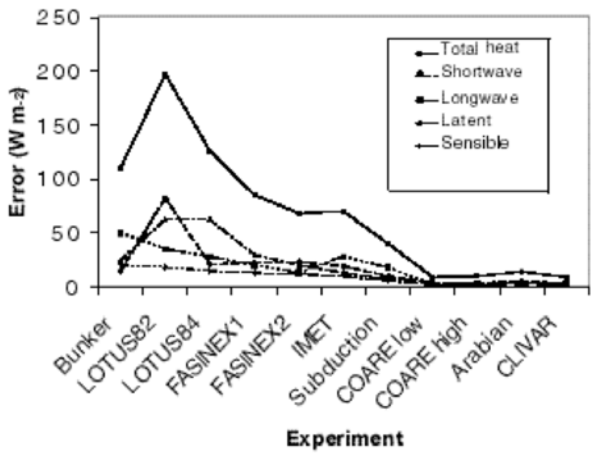

Figure 1. The reduction of measurement error in the components of the heat flux and net heat flux associated with surface mooring deployments since the early 1980s. The errors estimated in climatolgies of the early 1980s, such as Bunker's, are given as a starting point.

A major, international collaboration on improving the accuracy of surface flux fields over the western Pacific warm pool was carried out as part of the Coupled Ocean-Atmosphere

Response Experiment Experiment (COARE). The performance of sensors and bulk algorithms were closely scrutinized, and the in-situ meteorology and fluxes were compared to those from numerical weather prediction (NWP) models. (Weller and Anderson, 1996). Table 1 shows the agreement between the buoy and a nearby ship with attended sensors. Table 2 shows the differences found between the buoy and ECMWF fluxes for different conditions.

Table 1. 3-week averages of latent (Lat), sensible (Sen), net shortwave, net longwave, and net heat flux in W m-2 from *RV Moana Wave* and a nearby surface buoy in COARE.

Cruise	Leg 1		Leg 2		Leg 3	
	MW	Buoy	MW	Buoy	MW	Buoy
Lat	-90	-92	-118	-111	-138	-147
Sen	-6	-7	-8	-9	-9	-9
SWnet	225	225	162	162	164	173
LWnet	-63	-63	-52	-53	-54	-54.
Qnet	66	63	-17	-12	-37	-37

In 1994-1995, a surface buoy was deployed in the Arabian Sea for 12 months. Large differences were found between the buoy record of the air-sea fluxes and the fluxes from NWP models and many climatologies (Weller *et al*., 1998). Figure 2 compares the air temperature and the net heat flux from the buoy with that from the nearest grid point of the National Centers for Environmental Prediction (NCEP) NWP model. Note the negative bias in the NCEP air temperature in October through May andthe large negative bias in NCEP net heat flux throughout the year. During the Southwest Monsoon the model heat fluxes have the wrong sign in June and July.

Table 2. Comparison from COARE of average fluxes in W m- 2 from the buoy and from ECMWF (EC) during different conditions.

	Westerly Wind bursts		Low winds		Squalls	
	EC	Buoy	EC	Buoy	EC	Buoy
Lat	-208	-143	-86	-56	-158	-145
Sen	-12	-12	-8	-7	-10	-10
SWnet	213	157	196	202	250	162

LWnet	-55	-52	-53	-58	-57	-52
Qnet	-61	-49	49	81	24	-45

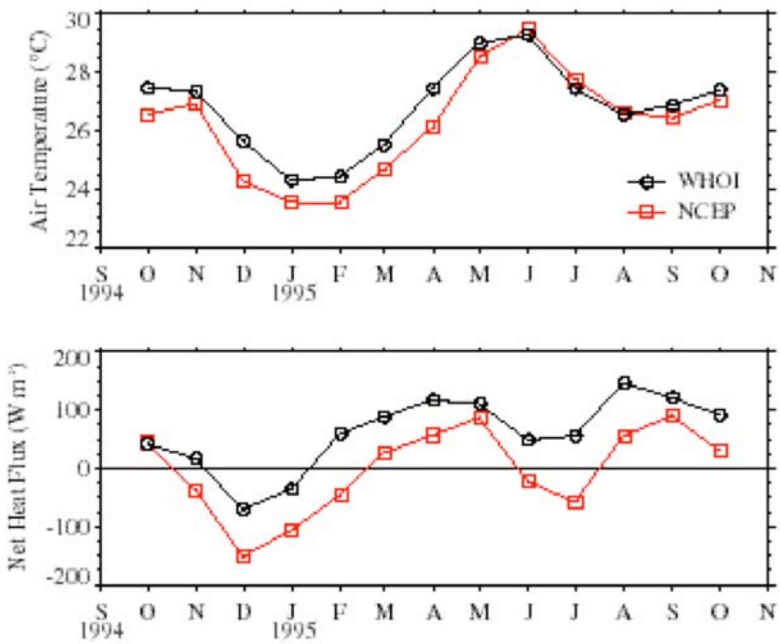

Figure 2. Comparison of monthly means of surface buoy (WHOI) and NCEP NWP surface air temperatures and net heat fluxes at 15.5°N, 61.5°E in the Arabian Sea.

Such experiments have both confirmed the accuracy possible with the unattended surface buoys and increased the awareness of the large uncertainties in air-sea fluxes from climatologies and NWP models.

3. USE AND LIMITATIONS OF THE STANDARD VOS OBSERVATIONS

3.1 Detecting and correcting errors

Systematic errors in the standard VOS observations were identified during the VOS Special Observing Programme - North Atlantic, VSOP-NA, (Kent et al. 1993a). For example air temperature data from ships' screens were found to be biased high in sunny weather (Kent *et al.* 1993b) although humidity data was unaffected (Kent & Taylor, 1996). Adjusting wind speed data for anemometer height and using the "Beaufort Scale" of Lindau (1995) for visual winds reduced the random errors in the observations by 10 to 15% (Kent *et al.*, 1998). To correct for these various effects requires information on the observation techniques. For the VOS the main source of this is the List of Selected Ships ("WMO47", WMO,1998).

3.2 The SOC flux climatology

In preparing the new SOC climatology of surface fluxes, Josey *et al.* (1998), merged the WMO47 metadata onto the Comprehensive Ocean Atmosphere Data Set, COADS (Woodruff et al. 1993), using the ships' call signs. They attempted correct for all known observing errors and chose their flux algorithms on the basis of recent research (Josey *et al.* 1997, Yelland *et al.* 1998). Nevertheless the global mean surface heat flux into the ocean calculated from the SOC climatology was about 30 W m-2, too large a value to be physically plausible. Previous investigators (e.g. DaSilva *et al*. 1974) had corrected similar imbalances by global adjustment of the fluxes. However the good agreement between the unadjusted SOC fluxes and IMET buoy data (Figure 3) indicates that global adjustment is not valid. Heat flux values derived from hydrographic data suggest that the SOC fluxes may be in error in particular areas; for example, the Gulf Stream and Kuroshio regions and the very poorly sampled southern oceans

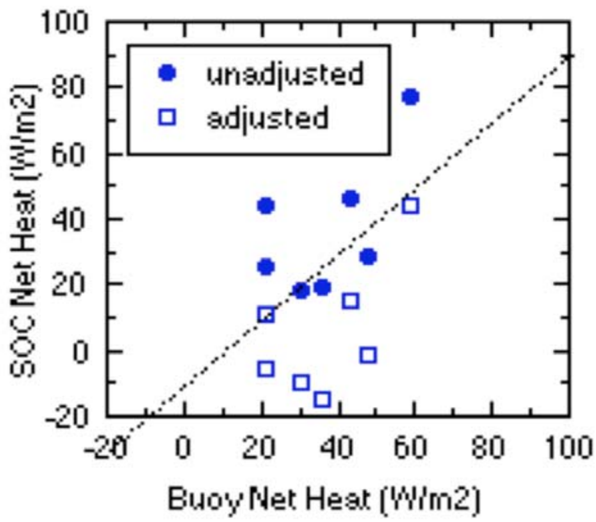

Figure 3. Comparison of the net heat flux calculated from the SOC climatology and from IMET buoy data. The open symbols show the effect of globally adjusting the SOC fluxes to balance the heat budget.

4. THE EVOLUTION OF BUOY AND SHIPBOARD OBSERVATIONS

4.1 Concerns about buoy observations

Large *et al.* (1995) have suggested that, above some threshold wind speed, buoy wind data may be significantly biased low due to the sheltering effect of the waves. For an anemometer at 5m height errors of 20% were predicted at 20m s-1 wind speed. Figure 4 shows comparisons between ship data and a sonic anemometer mounted at 5.5m on a Nomad buoy during the Storm Wave Study 2 (SWS-2) experiment. While some data agree with the Large *et al.* curve other points show significantly less error. Comparison of the wind speed to wind stress relationships derived from the buoy and ship data sets suggested an even smaller wind speed error, about 2%.

4.2 Future evolution

Traditional methods of flux estimation from buoy data are based on the "bulk formulae" for which the required "transfer coefficients" are not well known for all conditions. The buoy used in the SWS-2 experiment was an operational Nomad weather buoy equipped with a sonic anemometer sampling at 20Hz and a data logger capable of calculating the turbulence spectrum and hence making wind stress

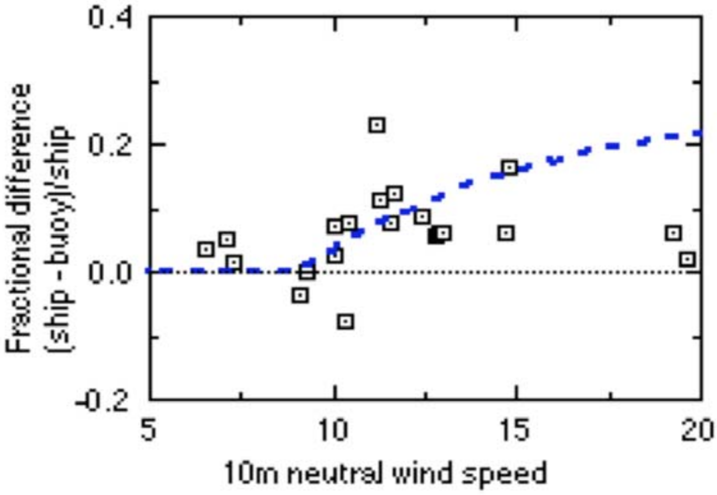

Figure 4. The fractional difference between 10m neutral wind speeds measured using sonic anemometers mounted on a ship and on a buoy less than 10km away. The broken line shows the Large *et al*. (1995) prediction.

estimates using the inertial dissipation (ID) technique (Edson *et al.*, 1991). The ID method of flux estimation does not use transfer coefficients, nor requires accurate measurement of, and compensation for, the buoy motion (as does the eddy correlation, EC, method). Yelland *et al.* (1998) found that ID derived wind stress data showed, for a given wind speed, negligible effects of sea state on the wind stress. This has resulted in the reliability of the ID estimates to be questioned (Donelan *et al.*, 1997), however during SWS-2 consistent stress values were obtained from both buoy and ship. These questions must be fully resolved before the ID method is implemented operationally.

4.3 Concerns about ship observations

A major source of error in the VOS observations is the calculation of the true wind velocity. Firstly the anemometer reading may be wrong because the ship significantly disturbs the airflow or because of the difficulty in reading a fluctuating instrument dial. Secondly, mistakes occur in the conversion to true wind (Kent *et al.*, 1993a). Errors in the wind estimation effect all the turbulent flux estimates. There are also concerns with regard to the accuracy of sea surface temperature (particularly from bucket or engine intake readings) and dew point data (particularly from thermometers in screens).

4.4 Future evolution of VOS measurements

Improved sensors (e.g. of the IMET type) would improve the accuracy of sea surface temperature and humidity data. Steps are in hand to improve the accuracy and detail of the WMO47 information on observing methods; this should be a major contribution to improving the standard VOS data set.

For wind velocity, it would be better if the VOS reported the velocity relative to the ship and also the ships' velocity. Failing this an automatic true wind calculation system should be provided, possibly as part of the ships' navigation system. However the problem of flow distortion by the ship remains. An attempt is being made to determine the average error for different classes of ship using Computational Fluid Dynamics modeling (Moat *et al.*, 1997). A better approach might be the implementation on a subset of the ships of the ID flux estimation method. This technique does not require estimation of the true wind speed and is less prone to flow distortion or ship motion effects than the EC method. Fairall *et al.* (1997) describe an instrumentation package capable of both ID and EC flux estimation for use on research ships. The AutoFlux project (AutoFlux group, 1998) aims to develop a prototype ID flux estimation package for use on VOS. This will feature a new fast response sonic- thermometer and an IR absorption hygrometer.

5. THE STRATEGY

We recommend establishment of surface moorings as high quality reference sites at select locations around the world. This would be done as part of the Global Eulerian Observatories (GEO) to be established under GOOS. In parallel, there would be upgrades to the VOS hardware and improvements to VOS observing system documentation. Analyses of the data would see increased emphasis on regional validation and on comparison with flux fields derived from NWP models and remote sensing data, hence motivating improvements to the models and algorithms.

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