Surface Fluxes and Surface Reference Sites

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<H1>: Abstract

Present methods and technology for obtaining surface fluxes over the global oceans are reviewed. Radiative, turbulent, and freshwater fluxes are considered, and the status of in situ and remotely sensed flux products assessed. Hence the required observing system to provide accurate gridded flux fields with good spatial and temporal resolution is described. The flux fields will be derived from satellite remote sensing and numerical models with calibration and verification against in situ data. Buoy reference sites and improved VOS will provide data to correct biases, develop regional tunings and formulations, and inject better temporal resolution. The system will require an ongoing partnership with NWP and climate modeling groups, remote sensing, and the in situ instrumentation teams.

Keywords: Air-sea flux, wind stress, reference sites, buoys, satellites, Voluntary Observing Ships

<H1>: Introduction

In this paper we will consider the role of surface flux data within a coordinated ocean observing system. We will argue that, for the foreseeable future, there will be a need for high quality measurements of the fluxes and/or the basic variables from which the fluxes can be calculated.

A major application of surface flux data is to force numerical ocean models of the ocean, and to verify and motivate improvements to numerical models of the coupled ocean-atmosphere system. Recent coupled ocean-atmosphere models (Barthelet et al., 1998; Boville and Gent, 1998; Gordon et al., 1998) can be run for many simulated years without adjustments to the modelled surface heat fluxes. Since the surface fluxes are internally determined by these models, we must ask why is it particularly important to verify the surface fluxes rather than other aspects of the simulated climate system?

Firstly, important energy transformations occur at or near the ocean surface. A major fraction of the radiative heat from the sun which enters the earth's atmosphere is absorbed in the upper ocean, much of the absorbed heat energy is transferred to the atmosphere as water vapour, and it is the release of this latent energy through condensation which then drives the large scale atmospheric circulation. On smaller scales the atmospheric motion is modified by the drag of the ocean surface, and the transfer of momentum gives rise to waves and currents as well as modulating the evaporation and the sensible heat transfer.

Secondly, the atmospheric boundary layer over the ocean is representative of the part of the troposphere in which we live. The historical archive of meteorological measurements almost entirely represents surface conditions. From a human viewpoint, understanding and simulating conditions in the lower atmosphere has many direct applications.

Thirdly, from a practical viewpoint, the ocean surface is a convenient, if sometimes inhospitable, interface on which to float instrumentation using buoys or ships. It is also the only part of the ocean amenable to direct satellite remote sensing.

Thus we need knowledge of the air-sea fluxes in order to quantify atmosphere-ocean coupling, to understand and attribute change observed in the ocean, and to determine the ocean’s role in weather and climate variability. The important question is to what extent our present knowledge of the fluxes is adequate for these purposes and to what extent an enhanced flux measurement programme is needed?

<H1>: Magnitudes and accuracy

<H2>: Which fluxes?

Which fluxes must we consider? The basic set of physical fluxes between the atmosphere and ocean are the transfers of shortwave radiation, Q_{sw}, longwave radiation, Q_{lw}, sensible heat, Q_{sen}, water vapour, E, precipitation, P, and momentum τ (wind stress). Given these, the various flux variables which couple the atmosphere and ocean can be determined. Thus for the latent heat flux Q_{lat}, net heat flux Q_{net}, and the freshwater flux, F_w, we have:

$$Q_{lat} \quad E \qquad\qquad Q_{net} = Q_{sw} + Q_{lw} + Q_{sen} + Q_{lat} \qquad F_w = E - P \qquad (1)$$

There are potential complications. For example, precipitation can transfer heat and momentum between atmosphere and ocean. However only in regions of intense precipitation (e.g. the Tropical west Pacific and Indian Oceans) are these fluxes likely to be significant.

The dynamic coupling depends both on the temporal and spatial variability of the fluxes. Water masses can form at the surface of the ocean in response to the buoyancy flux $F_\rho (Q_{sw}, Q_{lw}, Q_{sen}, E, P)$ and the mixing by the wind, and surface water is also carried into the interior of the ocean by Ekman pumping due to curl τ and by spatial differences in the ocean's response to the buoyancy forcing. The ocean currents that redistribute heat are driven both by the wind stress at the surface and in the interior by curl τ and the density gradients that result from the surface buoyancy flux.

<H2>: Magnitudes and variability

A problem in determining the fluxes is that, except on relatively short time scales, the mean net heat flux and its variability are small compared to the individual flux components. Figure 1 shows the distribution of the monthly mean, net surface heat flux for January and July and emphasises that the concept of equatorial heating and high latitude cooling is only true in terms of the annual mean flux. The ocean is heated throughout the year in the tropics; along the equator and in the northern Indian Ocean an annual mean value of several tens of W/m^2 results. But at middle and high latitudes the ocean is heated in summer and cooled in the winter. Over western boundary currents, such as the Gulf Stream and Kuroshio, the annual mean cooling reaches a maximum of 100 to 200W/m^2, however these areas of very large flux values are relatively small. Over most of the extra-tropical ocean, the annual mean flux is less than 30W/m^2 and, in many areas, the sign of this net flux is uncertain.

<<Figure 1 near here>>

Zonal averages of monthly mean flux components (Figure 2) show that over most of the globe the dominant components are the shortwave heating and the latent heat loss to the atmosphere. The shortwave heating, peaking around 1000W/m^2 on a sunny day, is in the mean around 200 W/m^2 in the summer hemisphere whereas the mean wintertime latent heat loss is around 100W/m^2 The upward and downward longwave fluxes are each a few 100W/m^2 whereas the net longwave is typically 40 to 80 W/m^2. The sensible heat flux is generally small except in high latitudes in the wintertime. Taking for examples the North Atlantic and North Pacific the typical ocean heating in

July is between 100 to 150 W/m^2 into the ocean whereas the cooling in January is typically 50 to 200 W/m^2.

<<Figure 2 near here>>

The interannual variability of the monthly mean net heat flux is illustrated in figure 3. Typical monthly mean variability is relatively small, about 20 to 30 W/m^2 in summer and 30 to 50 W/m^2 in winter, and is dominated by the variations in latent heat flux. On shorter time scales much larger variations can occur. The typical synoptic variability in mid-latitudes is around 3 to 5 days with very rapid flux changes associated with the frontal systems in extra-tropical cyclones. In tropical regions variability occurs on a variety of scales associated with convective organisation.

<<Figure 3 near here>>

<H2>: Accuracy required

A flux of 10 W/m^2 over one year would, if stored in the top 500m of the ocean, heat that entire layer by about 0.15C. Temperature changes on a decadal timescale are at most a few tenths of a degree (e.g. Parilla et al., 1994) so the global mean budget must balance to better than a few W/m^2. Thus we must attempt to measure fluxes, which are order 100's W/m^2 and which vary on many time and space scales, to an accuracy of a few W/m^2.

<H1>: Flux data sources

The main sources of flux estimates are in situ measurements from buoys and ships, remotely sensed data from satellites, and the output from numerical forecasting models, all have their advantages and limitations.

<H2>: Ship observations

Our present understanding of the climate over the global ocean (e.g. Ebensen and Kushnir, 1981; Oberhuber, 1988; da Silva et al., 1994; Josey et al., 1999a,b) is based on the meteorological reports from the Voluntary Observing Ships (VOS) of the World Weather Watch. Traditionally these data have been gathered primarily in support of weather forecasting. Modern numerical weather prediction (NWP) models show nearly as much skill in the poorly sampled southern hemisphere as in the well sampled northern hemisphere (White & da Silva, 1999) and, with the increasing availability of satellite data, the argument for maintaining and improving the VOS system purely for initialising our present weather prediction models is becoming less convincing. However the VOS data are also used for other purposes, for example for regional forecasting and nowcasting, loss adjustment in the insurance industry, and search and rescue. Most importantly, estimates of climate change over the ocean (Folland and Parker, 1995; Jones et al., 1988) are also based on VOS data, providing a strong argument that these data should continue to be collected.

Inevitably the characteristics of these data (biases, precision etc.) have changed with time and will continue to do so. There have been changes in instrumentation, for example, sea surface temperature buckets have varied in efficiency (Folland and Parker, 1995) and increasingly been replaced by engine room intake readings which are of dubious quality (Kent et al., 1993a). The increasing use of anemometers to estimate the wind results in errors due to airflow disturbance and errors in calculating the true wind velocity (Taylor et al., 1999a). However the major change has been in the size and type of the ships with modern ships typically larger, faster, and travelling on different routes compared to past decades. The wheelhouse region of a large modern container ship does not represent an ideal site for meteorological measurements. In recent years our understanding of the resulting errors has increased significantly (Kent and Taylor, 1995; 1996; 1997; Kent et al., 1993b; 1998; Taylor et al. 1995; 1999a) allowing the possibility both of correction schemes and improved observational methods.

Because there are about 7000 VOS, with ships continually leaving the system and new ships being recruited, the instrumentation provided has generally been basic and inexpensive. For some time there have been suggestions that improved instrumentation might be placed on a subset of the VOS e.g. (Taylor, 1984). An example is the Improved Meteorological System, IMET (Hosom et al., 1995) developed at Woods Hole Oceanographic Institution (WHOI) which has been installed on a number of the U.S. Research Vessels and is now being placed on U. S. VOS. IMET uses sensors chosen on the basis of 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, 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. A standard PC can be used for data acquisition and display. 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.

The sampling limitations of ship data have been well illustrated by comparison with fluxes from the NWP reanalysis projects (White and da Silva, 1999). Figure 4 shows the correlation between the VOS based climatology (da Silva et al. 1994) and NCEP reanalysis evaporation estimates for the Indian Ocean and western Pacific for individual monthly means. The correlaton is clearly higher in the shipping lanes across the Indian Ocean and in the well sampled waters near Japan than it is in other regions. Since it is highly unlikely that the model performance would vary on such small spatial scales, this indicates that the sampling by the ships is not sufficient to define the fluxes on a month by month, interannual basis in these regions. Only by taking a climatological monthly mean over a period of several years can the correlations be improved in the sparsely sampled regions.

<<Figure 4 near here>>

<H2>: Buoy data

Many countries now operate coastal buoy arrays, for example the NDBC (Gilhousen et al., 1990) and AES (Axys, 1996) buoys off North America, and the ODBS buoys off Japan. Taking as an example the NDBC buoys, these range in type from the very large 12m and 10m discus designs, through the 6m Nomad buoy to the 3m Discus buoy. Over 20 buoy locations have been maintained in both the Atlantic and Pacific with most time series dating from the mid 1970's, or early 1980's, to the present. In addition to standard surface meteorological data, spectral wave data and current profiles are available from some locations. Although primarily established for weather forecasting and now-casting purposes, these buoys have also been used for calibration of remotely sensed data from satellites; examples include sea surface temperature (Reynolds & Marisco; 1993), altimeter wind speeds and wave heights (Cotton and Carter, 1994; Ebuchi and Kawamura, 1994; Gower, 1996), scatterometer wind data (Quilfen and Bentamy, 1994; Graber et al., 1996; Geshelin and Dobson, 1997) and passive microwave winds (Halpern et al., 1994).

Operational buoy arrays may now be deployed in the open ocean. Foremost of these was the TOGA TAO array (McPhaden et al., 1998). A major responsibility for the western part of the array is now to be assumed by the TRITON programme (Kuroda et al., 1999) and a similar array (PIRATA) is being implemented in the Tropical Atlantic (Servain et al., 1998). However it seems unlikely that the extension of moored buoy arrays to cover the global ocean would be feasible given the resources required. For example maintenance of the TAO array, some 70 moorings between 10°S to 10°N across the Pacific Ocean, requires nearly one year of ship time per year (McPhaden et al., 1998).

The TAO and PIRATA arrays use the relatively simple and inexpensive Autonomous Temperature Line Acquisition System (ATLAS) buoys which measure a basic set of meteorological variables. "Flux buoys" which measure all the variables required to estimate the heat, momentum and radiative fluxes have been developed, principally by a group at WHOI as part of the IMET programme. They have been used in the Subduction experiment in the North Atlantic (Moyer and Weller, 1997), in the west Pacific during the TOGA COARE experiment (Weller and Anderson, 1996), and in the Arabian Sea (Weller et al., 1998). Such buoys are more expensive and require more predeployment preparation and post-deployment calibration than the ATLAS buoys. However the value of these buoy data in verifying model fluxes will be illustrated below (Sections 3.3 and 5.2.1) and it will be argued (Section 5) that deployment of a limited number of these buoys would form a valuable part of a GOOS.

<H2>: Model derived data

There are many potential advantages in using a numerical model to determine the air-sea fluxes. Flux values are obtained on a regular grid based on the assimilation of a wide range of data types into the dynamic framework provided by the model. However present NWP models are not optimised to produce fluxes, hence the achieved space/time resolution is not optimal and often the parametrisation formulae used are inadequate. Siefridt et al. (1999) show how the quality of NWP flux estimates may variously improve or worsen with time as attempts are made to improve the model's forecasting ability. As an example of the recent performance of two models, Figure 5a shows a comparison with net heat fluxes measured by a buoy deployed in the Arabian Sea for a 12 month period during 1994 - 1995 (Weller et al., 1998). Whereas the buoy and ship derived flux estimates were in good agreement, in this region the NCEP and ECMWF models exhibited less solar heating and more latent cooling. Taking the mean over the deployment period, the buoy and ship data indicated about 60 W/m^2 heat into the ocean, while the ECMWF model only showed 10 W/m^2 heating and the NCEP model had 5 W/m^2 cooling.

<<Figure 5 near here>>

The advantage of having the ship data as well as the buoy data is illustrated in Figure 5b. The flux values from the SOC climatology (Josey et al. 1999a), an average over the period 1980 to 1993, are in good agreement with the data from the buoy deployment period showing that the conditions measured were typical. Thus we would expect a climate model also to simulate the observed fluxes. However a version of the Hadley Centre climate model showed heat fluxes which were too large and a net cooling of about 50 W/m^2 - more than 100W/m^2 different from the buoy values. While the Arabian Sea is probably not typical of model performance over the global ocean, these results do demonstrate that recent NWP and climate models can have significant flux errors in some geographical regions.

The recent reanalysis projects have aimed to provide temporally consistent analyses of the atmospheric conditions including the surface fluxes. However being based on NWP models the models used for reanalysis were not optimised for flux estimation. A particular weakness is in the simulation of boundary layer cloud. Stratocumulus topped boundary layers are frequent over the world ocean and have a structure which is determined by the balance between the surface fluxes, cloud top processes, and the large scale environment (e.g. Albrecht et al., 1995). The vertical resolution of present NWP models does not reproduce this structure and, as a result, stratocumulus topped boundary layers are poorly simulated. Thus Figure 6 shows estimates for net shortwave radiation for the ocean surface over the tropical Pacific for July 1983 - 1990. The satellite based estimate (Darnell et al. 1992) suggests that the ship based estimate (da Silva et al. 1994) is reasonably accurate despite the latter's primitive parametrisation formula (which depends on the cloud amount estimated by the ships' officers). In contrast the ECMWF reanalysis uses a sophisticated radiative transfer model but does not predict the clouds correctly and hence shows an incorrect distribution of net shortwave. Admittedly the NCEP reanalysis (not shown) performed better with regard to low level stratocumulus clouds compared to ECMWF which suggests that simulating cloud layers may not be beyond the ability of present-day NWP systems. However elsewhere over the Pacific the net shortwave flux was under estimated. There is still room for improvement.

<<Figure 6 near here>>

Finally, we noted in the Introduction that coupled ocean-atmosphere models can be run without flux correction. This implies that the net surface air-sea heat and water fluxes calculated by the model are consistent with the simulated ocean heat and fresh water transports. However the individual flux components must also be quantitatively correct if the surface properties and the formation of water masses are to be realistically simulated. Thus, for example, the Gordon et al. (1998) model simulates SST fields which change little with time but which are different from observed SST values by 1 to 4 C over large regions of the ocean. The atmospheric part of that model, HADAM3, is similar to that which was shown to over-predict evaporation in the Arabian Sea (Figure 5b); its performance will be examined further in Section 5.3.

<H2>: Remotely sensed data

<H3>: Introduction

Flux related variables obtained by satellite remote sensing include SST, wind, surface shortwave radiation, precipitation, and latent heat flux. Most satellite derived variables require good in situ verification or calibration, this is not always available. Depending on the derived parameter different problems arise, for example SST estimates derived from AVHRR are affected by instrument biases and atmospheric transmission effects, whereas for microwave instruments like the

SSM/I there can be a problem with calibration differences between radiometers on successive platforms. In additional, some products suffer from delays in availability.

Although satellites would appear to have the potential to provide consistent observations over the global ocean in many cases the sampling achieved in satellite-derived datasets has significant limitations. Wide swath (~ 1400 km) sensors mounted on two polar orbiting satellites are the minimum required to give monthly mean fluxes (e.g. see Taylor, 1984). However, although three similar microwave radiometers with a wide swath (for SSM/I ~ 1400 km) are presently in polar orbits, with a further radiometer in a precessing orbit over the tropics (TRMM), most of the derived datasets make no use of all available data. This has serious consequences for the achieved sampling especially if processes have a marked diurnal cycle, e.g. tropical precipitation. For some instruments, such as the ATSR, the swath is limited due to the principles of the instrument design. For other instruments, for example the AMI on the ERS satellites, the sampling is limited due to multiple operation modes. SST estimation using IR radiometers is strongly limited by clouds.

<H3>: Winds and wind stress

The ERS AMI and NSCAT scatterometers have demonstrated the ability to determine surface winds from satellites. The microwave scatterometer is less affected by variations in atmospheric transmission compared to passive instruments. Perhaps the major limitation is that the physics of the backscatter is not fully understood and the calibration depends on empirical comparisons. However as more scatterometer data becomes available the inversion models are becoming better defined (Freilich and Dunbar, 1999). The instruments have an inherent ambiguity for wind direction but this does not appear to be a problem for winds over about 6 m/s (Gonzales and Long, 1999). The instruments are normally calibrated to give the 10m neutral wind velocity which on average can be reasonably accurately converted to wind stress; however knowledge of the atmospheric stability is required to determine the actual wind. Since the scatterometer signal depends on the roughness of the sea surface a calibration in terms of wind stress would avoid this problem and might well be more accurate.

Wind speed estimates, for heat flux determination, may be obtained from passive microwave radiometers such as the SSM/I. Algorithms include the neural network approach of Krasnopolsky et al. (1995), or the more physically based algorithm of Wentz (1997) and Wentz and Spencer (1998). The latter estimates a bias of less than 0.5 m/s and rms error of under 1 m/s which is similar to scatterometer data and significantly better then VOS wind data. Compared to the scatterometer the SSM/I has a wider swath giving better sampling; however data from both instruments are degraded by rain.

<H3>: Radiative flux determination

Shortwave: Surface shortwave radiative flux products obtained from satellite radiance data are considered significantly superior to the SW fluxes calculated in the reanalysis projects or NWP models (Glecker et al. 1994). Nevertheless surface SW insolation obtained from satellite based programs and radiative transfer theory generally exceed measured values Thus the estimated global and monthly averaged GEWEX SRB (Whitlock et al., 1995) insolation is too large by about 15 Wm^{-2}. The estimated rms error for monthly mean GEWEX SRB insolation in a 280 by 280 km grid box is 20-25 Wm^{-2}; the errors being smaller for midlatitudes, larger in the tropics, and largest in regions with extensive biomass burning. Whether the errors in surface insolation are larger (or smaller) over sea is not known.

Longwave: The major problem for determining the surface LW radiation from satellite are the clouds. The downwelling flux depends on the cloud base height and the emissivity. Although algorithms exist these remain at the experimental stage (Gupta et al. 1992); more work is needed before reliable estimates of the longwave can be obtained from satellites (WCRP/GEWEX, 1996).

<H3>: Turbulent flux determination

Sea surface temperature: Knowledge of the sea surface temperature is required for almost all methods of determining the turbulent fluxes by satellite. The accuracy of SST determination was recently addressed by an OOPC Workshop (Arkin, 1998). Although remotely sensed sea surface temperature data from infra-red radiometers have been available for some 20 years the error budget is still dominated by the instrument calibration accuracy and atmospheric transmission effects. Continual calibration against in situ data is required to remove measurement biases. Satellite data improves the coverage compared to in situ data but regions of persistent cloudiness exist which are poorly sampled by the satellites. Despite being a wide swath instrument flown on a pair of satellites the AVHRR provides under 50% global coverage daily. Improved operational instruments such as the AATSR and the SEVIRI (which will be flown on a geostationery satellite) may improve SST sampling but there will be a need for calibration or verification against in situ data for the foreseeable future.

Near surface Air temperature: No satellite based technique is available for determining air temperature in the near surface layer and hence the sensible heat flux. Methods which have been suggested include using the sea surface temperature and near surface humidity and assuming a surface relative humidity (Liu, 1988), using a Bowen ratio approach, or determining the air-sea temperature difference from the observed cloud types (Curry et al. 1999). Jones et al. (1999)

suggest using total atmospheric water vapour and SST in a neural network approach. Independent data from a wide range of climatic conditions is needed to test these various indirect techniques.

Near Surface Humidity: Satellite methods of determining the atmospheric surface humidity near the surface and hence the latent heat flux include monthly mean correlation with the total water vapour (Liu & Niiler, 1984), correlation with the water content of the lower atmosphere (Schulz et al. 1993, Schluessel et al., 1995), EOF analysis of the total water content and the lower atmosphere water content (Chou et al. 1995, 1997) and a neural network approach (Jones et al. 1999). As for near surface air temperature these are all indirect approaches which need independent verification.

<H3>: Precipitation:

Particularly in the tropics, precipitation can be both intense and sporadic providing a major measurement and sampling problem for in situ instruments. Thus the major problem facing satellite estimates of precipitation is the lack of verification data. Early attempts at validation were restricted to comparisons with climatologies obtained from present weather reports from VOS which also suffer from large uncertainties (Jaeger, 1976; Legates and Willmott, 1990, Legates, 1995). However recently three Algorithm Intercomparison Projects (AIP) have been sponsored by the Global Precipitation Climatology Project (GPCP, Huffman et al. 1997). In addition, the NASA WetNet project has sponsored three Precipitation Intercomparison Projects (PIP).

The GPCP has provided data on a 2.5˚ x 2.5˚ latitude-longitude grid for the period July 1987 to March 1998 from satellite and terrestrial observations. Global climatological fields of monthly mean precipitation over both ocean and land were derived from a combination of satellite and terrestrial observations. The satellite values are a combination of infrared cloud top temperatures, for tropical and sub-tropical deep convective rainfall, and passive microwave estimates. While the latter are better correlated with surface rainfall, adequate resolution is only obtained by mounting the sensors on polar orbiting satellites, implying a relatively poor sampling rate.

The CPC Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997) consists of a 17 year period (1979 - 1995) of 2.5˚ x 2.5˚ latitude-longitude gridded global (ocean and land) monthly precipitation fields. A variety of satellite measurements, gauge observations, and NCEP-NCAR reanalysis were used. Sharing several common data sources, differences between CMAP and GPCP are small over tropical and subtropical oceans. Over extra-tropical oceans the additional use of MSU data (see Spencer, 1993) and the outgoing longwave radiation (OLR) based Precipitation Index (OPI, see Xie and Arkin, 1998) resulted in significant differences.

Passive microwave algorithms (e.g. Ferraro et al. 1994 and Bauer and Schlüssel 1993) have been used to derive SSM/I based precipitation fields. Although these data are presented with a higher spatial and temporal resolution (typical 1° x 1° in latitude and longitude and one to five days) the sampling error is likely to be dominant, particularly where only one of the SSM/I sensors has been used.

The goal of the Algorithm Intercomparison Projects (AIP) was to verify different satellite algorithms against ground "truth" from gauges and radar estimates. The AIP's have been focussed on regional areas with different atmospheric conditions. AIP-1 was conducted over Japan and surrounding waters (Lee et al. 1991; Arkin and Xie 1994), AIP-2 was located over the British Isles and surrounding waters (Allam et al. 1993; Liberti 1995), and AIP-3 over the radar covered area of the TOGA COARE experiment (Ebert and Manton 1998). The Precipitation Intercomparison Projects (PIP) rejected the idea that ground data are accurate enough to serve as a final calibration standard (Smith et al., 1998). They aimed to establish a passive microwave algorithm that incorporated the best features of all existing algorithms.

Among results from the AIP's it was found that NWP models show similar biases and rms errors as the satellite algorithms but exhibited much lower correlations since they can’t resolve the raining and non raining areas. Indeed both AIP's and PIP's stressed the need for any algorithm to successfully distinguish between raining and non-raining areas. In PIP-3 the reanalyses did well over the extratropical oceans compared to the satellite estimates. In the tropics they were not as good as the better satellite estimates. Differences between GPCP and Xie-Arkin (CMAP) are greater than 1 mm./day over large areas of the west tropical Pacific. Overall it is still difficult to say which climatological dataset might be the best estimate. All strategies to build long term datasets can be defended on scientific grounds. However, the user must be careful when making a choice; for example, it might be not meaningful to use a dataset which contain reanalyses data to validate the reanalyses. A further conclusion is that not only must the quality of satellite estimates be improved but also the status of routinely gained surface based measurements. This is important because the development of a calibration model as demanded by PIP-2 is not easy and will be a long-term project. A first step in this direction is the attempt to archive high quality ground radar data for comparison with measurements of the Tropical Rainfall Measurement Mission (TRMM) sensors.

<H2>: The Residual method

In the residual method (Trenberth and Solomon 1994; Keith 1995) the top of the atmosphere radiation budget and the divergence of the atmospheric energy transport is used to infer the net surface heat flux. Used with the atmospheric moisture budget the net freshwater flux can also be obtained (Trenberth and Guillemot 1998), although the accuracy is crucially dependent on the calculated wind and moisture divergence. With confidence in the atmospheric analyses increasing, results from the residual method are very plausible (Trenberth 1998). The main limitations with this method are the lack of estimates of the individual fluxes and the reliance on atmospheric model data, thus precluding use for model verification.

<H1>: Types of flux algorithm

<H2>: Introduction

Details of the different algorithms used for the fluxes are available from many publications. In particular the Joint JSC/SCOR Working Group on Air-Sea Fluxes is preparing a Report which will summarise many of the algorithms in common use. In this paper we will simply classify the different algorithms in terms of whether they represent a direct measurement, a physically based parametrisation, or a statistically derived parametrisation.

<H2>: Direct measurement

Clearly the ideal way of determining the fluxes would be by direct measurement. Direct measurement of the turbulent fluxes on research ships has become an established technique (e.g. Fairall et al., 1997; Hare et al., 1999). Sensors include sonic anemometer/thermometers, and microwave refractometers or differential absorption IR sensors for humidity. With electronic motion measurement packages now available, the main problems in implementing the eddy correlation technique are the degradation of the sensors in the marine environment and the likelihood of turbulence distortion by the ship.

Recent studies (Philipona et al. 1995; Fairall et al. 1998) have improved techniques for estimating downwelling longwave radiation using a pyrgeometer. Instruments need to be individually calibrated; one method is the use of a radiative transfer model with on-site atmospheric soundings. With care accuracies of 5 W/m^2 or better are possible however there are many potential sources of error; on many ships finding a suitable instrument site with a clear sky view is not easy.

The shortwave insolation has both direct and diffuse components and Baseline Surface Radiation Network (BSRN, DOE, 1996) standards for climate monitoring require separate measurements of each. Suitable radiation sensors for shipboard use have been successfully demonstrated (Reynolds, 1998). However at present most marine measurements of shortwave insolation have been obtained using pyranometers only. Experience during TOGA COARE suggested that a well calibrated and maintained instrument should provide a measurement accuracy equivalent to better than 10 W/m^2 in a daily mean, although errors at solar noon would be significantly higher. Although not attaining the BSRN standard, more extensive pyranometer data would be easily capable of quantifying the biases in surface SW estimates in many present NWP models (Figure 6).

<H2>: Physically based formulae

For determining the turbulent fluxes the main physically based algorithms are the inertial dissipation method (IDM) and the bulk formulae. The IDM (Edson et al., 1991) has been routinely used for wind stress determination on research ships (e.g. Fairall et al., 1990, 1997; Yelland et al., 1994; Yelland and Taylor, 1996) and has been successfully used on an operational meteorological buoy (Dobson et al., 1999; Taylor et al., 1999b). Although correction for any disturbance to the mean wind flow is required (Yelland et al., 1998) IDM flux estimates are less affected by distortion of the turbulent field and therefore might be most valuable when used in conjunction with eddy correlation estimates.

Although often described as "empirical" the bulk formulae can be derived through Monin-Obukhov similarity theory (e.g. Geernaert, 1990). These formulae provide the basis for air-sea flux climatologies of the turbulent fluxes and of the turbulent flux equations in numerical models of the atmosphere. They are empirical only to the extent that our knowledge of the transfer coefficients is based on measurement campaigns. The drag coefficient may or may not depend on "wave age" (Komen et al., 1998; Taylor and Yelland, 1999) and methods of determining it from wave spectra have been proposed (Janssen, 1989; Makin et al., 1995). In contrast, although more measurements of the transfer coefficients for heat and water vapour are becoming available (e.g. DeCosmo et al., 1996; Dupuis et al., 1999), Fairall et al. (1996) still found it preferable to base their TOGA COARE algorithm on the Liu et al. (1979) surface renewal model rather than on empirical data.

The satellite based methods for surface flux retrieval using radiative transfer models, and many passive microwave algorithms, also represent physically based models. Wave retrievals from altimeter data may also be placed in this category.

<H2>: Statistical formulae

We define statistically based formulae to be those which are based on statistical correlations because either the set of observed variables, or the physical understanding, is not sufficient to directly derive a formulae. Examples include obtaining downwelling SW and LW radiation from ships' cloud observations, and satellite estimates of : SST (because of the tropospheric correction problem), surface wind, near surface humidity and precipitation (estimated from cloud top temperatures). We also include in this category neural network based algorithms. A problem with statistical techniques is that they are tuned to the population of samples used in their derivation. If that population is not representative (due to a change in region, climate, or instrument response) biases can occur. A particular danger is the use of high quality measurements from air-sea interaction investigations to develop an algorithm. Such experiments are few in number and may be held in regions which are climatologically important but which are not typical of much of the global ocean, for example the TOGA COARE experiment.

We suggest that, where a quantity is obtained through a statistical algorithm, enough direct or physically based estimates must be obtained on a continuing basis to ensure that the retrieval algorithm remains valid.

<H1>: Proposed strategy

<H2>: Introduction

In the previous sections we have noted that the problem of surface flux determination is that we require the magnitude and variability of a small net flux which is the residual of much larger flux components. We have described the data sources for flux determination, generally drawing attention to the errors and limitations of each, and we have noted that many of the available flux algorithms have a weak, or even no, basis in physics. Our aim has been to discourage the view that surface fluxes can, or will be, adequately determined by a single section of the GOOS whether by using in situ measurements, satellite data, or numerical models. A combined strategy is required.

We note that there is an increasing requirement for flux data with a coverage and resolution which conventional in situ data sources cannot supply. We also note that many of the satellite flux products are obtained using statistical algorithms. Thus while satellite data may make important contributions to the determination of surface wind, surface SW radiation, and precipitation, we suggest that these data be best used by assimilation into a numerical model of the ocean-atmosphere system. In some cases assimilation of the measured brightness temperatures may well be preferable. The full suite of surface fluxes would then be obtained from the model. However the fluxes must be verified and for that we propose a set of surface reference sites and platforms. These would consist of complementary measurements from moored buoys and upgraded VOS systems.

<H2>: Surface reference sites and platforms

<H3>: Moored buoys

Moored Flux buoys will provide the primary flux reference sites. The accuracy achievable with buoy sensors has improved significantly (Figure 7) so we can be confident in the accuracy of the basic meteorological variables which are measured. Provided we are confident in the flux parametrisations we can also be confident in the fluxes. Thus deployment of flux buoys at a limited number of sites will provide invaluable data for the development and verification of model and remote sensed surface fluxes.

<<Figure 7 near here>>

The flux buoys must provide accurate measurements of the basic meteorological variables and the downwelling SW and LW radiation. Future developments may include the addition of instrumentation to measure the direct and diffuse solar radiation (e.g. Reynolds, 1998) and to provide turbulent flux estimates using eddy correlation and or inertial dissipation. Power availability and maintenance intervals are likely to be the main constraints.

The initial list of stations (Table 1) has been designed to address the scientific objectives of the GEO project. This list is very preliminary; further input is needed from those involved in considering the role of the ocean in climate, from the remote-sensing and modeling communities, and from those willing to make the commitment to deploy and maintain ocean observatories.

<<Table 1 near here>>

<H3>: Upgraded VOS measurements

Firstly the present VOS system (along with other data streams used for NWP initialisation) needs to be continued for the foreseeable future to maintain continuity in our climate record. Indeed a general rule must be that new observing systems should be operated in parallel with the old systems until biases and errors characteristics have been carefully compared; this may take a decade or more. In addition we will show (Section 5.3) that VOS data also have a valuable role for model verification.

However there is a problem with present VOS data in that, although new climatologies attempted to correct biases in the ship observations before calculating the fluxes, the mean global ocean surface heat budget showed a flux of 30 W/m^2 into the ocean. This is much greater than could be explained by ocean heat storage, indicating that biases still remain in the data set either due to observational errors or inadequate sampling. da Silva et al. (1994) used inverse analysis to calculate flux adjustments; the shortwave flux was reduced by about 8% and the latent flux increased by 13%. However Josey et al. (1999a) showed that agreement between their flux climatology and the IMET buoy deployments would be degraded by applying such corrections. The implication is that the heat budget imbalance must vary geographically, depending on sampling density and possibly the regional climate. We need to understand and quantify this varying flux bias and this requires a source of better qualtity measurements. Furthermore, in future we expect the model fluxes to improve and, in parallel, we shall need better estimates of the basic variables and hence the fluxes.

Both to improve the quality of the VOS data set and to identify the source of data biases we propose a subset of the VOS be equipped with improved sensors. The IMET system (Hosom et al. 1995) or the VSOS system which incorporates high quality radiation sensors (Reynolds, 1998) are examples of the type of system which should be implemented. For economy of maintenance and for efficient liaison with the shipping companies it is desirable that ships chosen should, where possible, also be those recruited to perform ocean observations and that the different instrument systems be maintained by the same "Port Meteorological/Oceanographic Officers". Section 5.4 gives approximate costing for an improved system.

<H3>: Flux measurements from ships

However good the determination of the basic variables there is still a need for flux data to improve our knowledge of the transfer coefficients. Flux measurement packages such as that of Fairall et al. (1997) should be routinely mounted on research ships (see Section 5.4 for costs). The large size of most VOS, and the need for autonomous operation without maintenance, present major difficulties for flux measurement from VOS. However the AutoFlux project (AutoFlux-Group, 1997) aims to develop a prototype instrumentation package capable of flux measurement, centred on using the inertial dissipation method, which would be suitable for deployment on merchant ships.

It might be argued that the need for direct flux measurements will decrease as our confidence in the flux formula increases. However direct measurement of the fluxes obviates some problems associated with determining the basic variables. With continuing improvements in electronics and sensor technology it is possible that in the not too distant future the observing system will include directly measured fluxes obtained from autonomous merchant ships plying the oceans unmanned!

<H2>: Example of combined use of ship and model data

In section 3.3 and Figure 5 we showed an example where flux buoy data were used to detect biases in NWP fluxes for the Arabian Sea. Ship data, verified against the buoy, were used to provide climatological context for the buoy data and hence to verify fluxes from a climate model. Here we shall extend that example. Figure 8a shows a comparison between monthly mean buoy data and fluxes from a model, the HADAM3 model which forms the atmospheric component of the Hadley Centre coupled model (Gordon et al., 1998). It is clear that the model is also over estimating the latent fluxes at other sites as well as the Arabian Sea. The importance of ship data is to extend the verification beyond the limited number of sites and periods for which we have buoy data (Figure 8b). The results are very similar to those obtained by the buoy comparison, thus giving confidence in the use of ship data for this purpose.

<<Figure 8 near here>>

The frequent data available from the buoy can be used to examine whether the model simulates the observed variability on shorter time scales than is possible using monthly mean ship data. Indeed, for the example shown, the model's over-estimate in the Arabian sea appears to have been due to several factors: a larger air-sea humidity deficit, higher monsoon winds, larger transfer coefficients, and different correlations between the basic variables. The availability of the buoy data allowed these different factors to be examined.

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<H2>: System Cost estimates

<H3>: Upgraded VOS costs

The cost of an upgraded VOS system depends on the implementation strategy adopted. Traditionally VOS instrumentation has been inexpensive being, in effect, semi-disposable. An upgraded system could be assembled relatively inexpensively by linking standard sensors through commercially available interface units to a standard PC system running custom software. Similar installations are successfully used on research ships where the instrumentation is calibrated, installed, and actively maintained for individual research cruises. However the maintenance of order 100's of such systems on VOS would be very difficult and very costly, being highly labour intensive. Experience shows that it is all too easy to under estimate the management problems of, for example, ensuring that a correct, current calibration is used with each sensor, and there is a danger that the resulting data would be of disappointing quality. Hence we are proposing a more sophisticated approach such as that embodied in the IMET system (Hosom et al., 1995). Such a system features custom instrument modules that store the calibration, allow flexible sampling, have low drift/high accuracy amplifiers, and sufficient bits of resolution to provide the required accuracy over wide environmental ranges. Maintenance is simplified because the whole module is swapped to go for calibration, and through the construction design with virtually maintenance free titanium housings, underwater grade exterior connectors, etc. This approach trades a higher capital cost against cheaper maintenance costs and is much more likely to provide the quality of data required.

Here we will estimate the installation costs for the present prototype systems as built in small numbers (lots of 10s) at research institutions. The capital cost is aportioned roughly equally between sensor cost, electronics, and labour. However all of these would be reduced by volume production, and the last two significantly given redesign to allow easy mass manufacture. To equip 100's or more VOS with hardware manufactured commercially, the reduction in cost is estimated to be between 30 and 50%. To achieve such cost reductions would require collaboration between Meteorological Agencies in selecting a particular design and manufacturer, and hence ensuring volume production. The costs (in $US) are estimated for three levels of installation as follows:

Level 1: equip the ship completely, but with no real time display and no real time delivery of data; use stand alone, self recording instrument modules; this is the least desirable option: $59K + $2.5K calibration costs.

Level 2: display all the data in real time aboard the ship for use by ship's crew; link all the sensor modules to a central logger using acoustic and RF modems or wires as appropriate; instrument modules have digital front ends only. A SST sensor inside the hull near the bow passes data via an acoustic modem through the steel of the ship to a central logger at the base of the bow mast. The central logger is linked to the bridge via RF modem. The basis is a Level 1 system but minus $800 per module for logger and logger housings: $79.5K + $2.5K calibration costs.

Level 3: make data available in real time to the external world. There are many alternative methods. The least expensive for NOAA ships would be to insert the meteorological data into the SEAS/Inmarsat communication system. This uses Inmarsat C status messages as a no-cost path to pass low volumes of data. It would require a $4K multiple port expander on the computer. Alternatives would be Argos, Orbcomm etc at greater cost: $83.5K + $2.5K calibration costs.

<H3>: IMET "flux buoy" costs

In this section we give cost estimates for a "flux reference site" buoy. For comparison a typical cost for a standard meteorological buoy with duplicated sensors is about $170K

Cost of preparing buoy and mooring: First we estimate the costs for a basic, meteorological (surface fux reference site) buoy for deployment in 5,000 m of water for 1 year. It is assumed that all permanent equipment exists, only expendables are bought new. No data telemetry is included; there is Argos PTT for position on hull, one further PTT underwater on bridle in case the buoy turns turtle. The mooring has acoustic release at bottom, but no in line ocean measurements with 2 glass balls to keep the release upright. The mooring line is plastic jacketed wire rope in upper 1500m, then synthetic. Hence expendables costs for a basic flux buoy built and delivered to shipping dock: $100K

Miscellaneous flux buoy costs: Cost of buoy hull and tower assembly: $35K. Sensor preparation (includes burn-in, cold-room and field test sensors against standards, check for RF interference, read and verify data): $15K. Sensor calibration before and after deployment: $20K. For data telemetry 6 Argos platforms are used to get hourly averaged met data through from both IMET systems: $5K each. Argos costs plus 1.25 man month programmer to work on data, quality control it, and forward for use: $40K.

IMET system cost: The buoy is equipped with two complete IMET systems, internally recording (wind speed and direction, SW, LW, relative humidity, air temperature, sea temperature, precipitation, air pressure); cost of about $55K each. Again, the same cost reduction could be achieved as for VOS if these were produced commercially.

<H3>: Research ship direct flux system

Here we estimate the cost of a system for direct flux measurement for use on a research ship; the system would be autonomous although the availability of technical support is assumed. There would also be a substantial software development cost, but this would be spread over the number of units built. Cost of one system: $60K + $60K for complete set of spares); Mounts, cables etc.: $25K. A complete system would also include SST, bulk air temperature/RH, rain rate, and downward IR and solar fluxes. These would add about $30K or would be obtained from an IMET system.

<H1>: Summary

In this paper we have reviewed current methods and technology for obtaining surface fluxes over the global oceans. Radiative, turbulent, and freshwater fluxes have been considered, and the status of in situ and remotely sensed flux products reviewed. We have then described a system which will provide accurate gridded fields with good spatial and temporal resolution. These fields will be derived from satellite remote sensing and numerical models with calibration and verification against in situ data. Buoy reference sites and improved VOS will provide data to correct biases, develop regional tunings and formulations, and inject better temporal resolution. The system will require an ongoing partnership with NWP and climate modeling groups, remote sensing, and the in situ instrumentation teams.

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