**Observations to Quantify Air-Sea Fluxes and Their Role in Global Variability and Predictability**

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# **ABSTRACT**

Flux products quantifying exchanges between ocean and atmosphere are needed for forcing models, understanding ocean dynamics, investigating the ocean’s role in climate, and assessing coupled models. Research experiments are essential to improve flux parameterizations, and longer research deployments are required to sample rare events. Needed technological improvements include longer buoy deployment life, more robust sensors and improvement of sensors for humidity, precipitation and direct gas and particle fluxes. A range of different flux products are needed, incorporating data from ships, satellites and models in different combinations and using different methods. Dataset validation requires high quality observations from ocean flux reference sites and from ships. The continued development of flux products from satellites provides much-needed sampling. Continual comparisons among products and with high quality observations are required to improve flux datasets and maintain calibration and the stability of satellite calibrations.

# **INTRODUCTION**

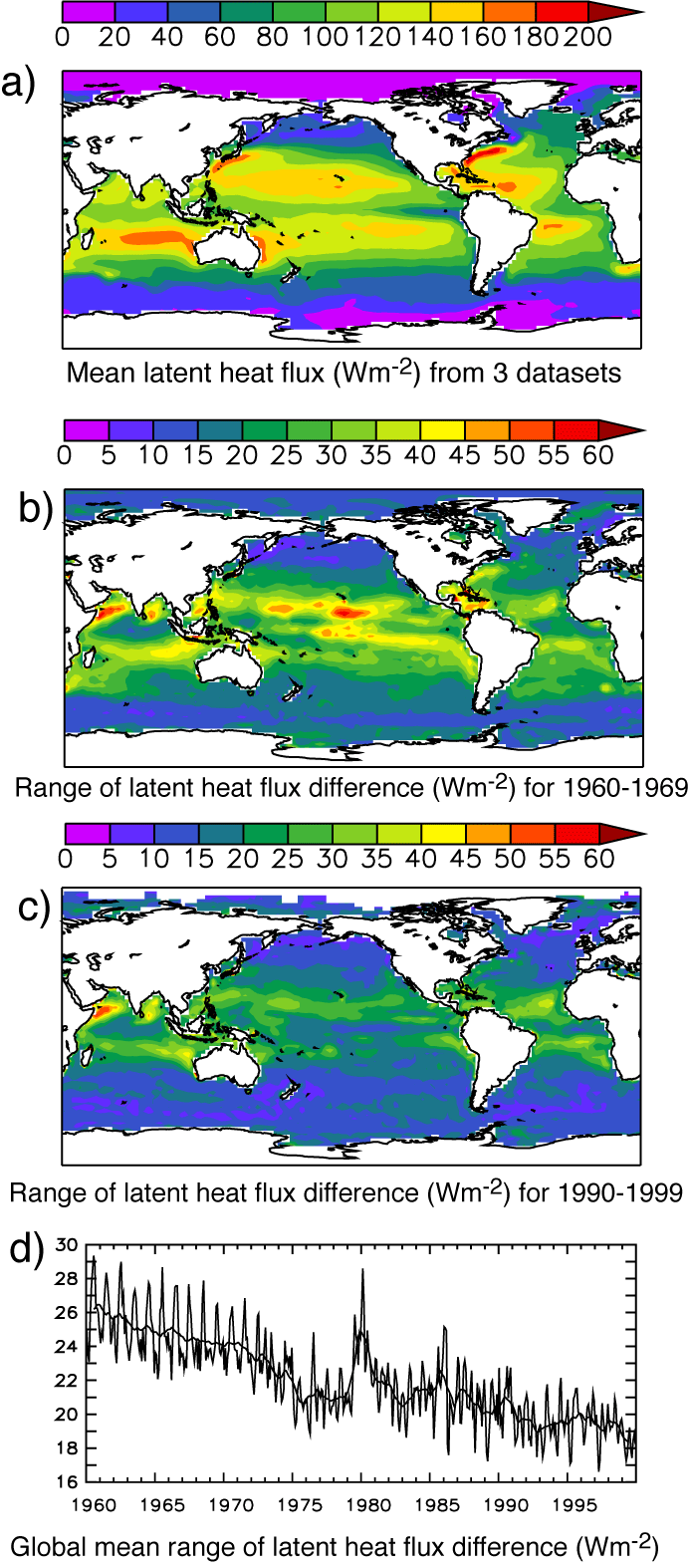
OceanObs99 envisaged an air-sea flux observing system comprised of sustained autonomous measurements and research campaigns to test and improve flux parameterizations used at the autonomous stations. Progress since OceanObs99 - reviewed at OceanObs09 [1] - includes the deployment of flux reference buoys, development of packages for routine direct measurements of turbulent fluxes, the use of *in situ* data to validate Numerical Weather Prediction (NWP) fluxes, the development of satellite-derived and blended flux products, and specialized validation activities.

Here we focus on requirements for measurements of ocean surface fluxes and flux-related variables necessary for observing and predicting the climate, biochemical, and eco systems. Uncertainty in the air-sea exchanges of heat, freshwater, carbon and other properties constrains our ability to understand and model changing climate. Flux products are required for forcing ocean models, understanding ocean dynamics, investigating the forcing of variability by the atmosphere and ocean, understanding the ocean’s role in climate variability and change, and assessing the realism of data-assimilative ocean models and coupled ocean-atmosphere models used for predictions from weather to climate time scales.

Direct flux measurements are scarce and cannot be used to generate global flux datasets. Rather the surface fluxes are parameterized in terms of bulk meteorological estimates of the surface atmospheric and oceanic states. These parameterizations, used to compute fluxes from observed variables as well as those used in NWP analyses and reanalyses, also require continuous improvement. An effective flux observing strategy must include comparisons of flux-related variables from different sources, ongoing improvements to the accuracy of parameterizations and development of flux products to satisfy the requirements of climate prediction. This paper follows from [1,2] and considers the observational strategy for physical fluxes: the turbulent fluxes of sensible and latent heat, long and shortwave radiation, evaporation, precipitation, and wind stress; and the fluxes of trace gases and aerosols.

# **ACCURACY AND RESOLUTION REQUIREMENTS FOR SURFACE FLUXES**

The benchmark for surface net heat flux accuracy is ±10 Wm-2 over monthly to seasonal time scales [3], implying determination of individual components of the net heat flux to a few Wm-2. Where fluxes are parameterized this limits the mean bias of the input observations of bulk meteorology [1]. Accuracy and resolution requirements are application dependent. The 10 Wm-2 benchmark is only possible on much longer scales. Accuracy requirements for net freshwater flux (E-P) are hard to estimate but uncertainty is dominated by precipitation. Biases in fluxes due to the parameterizations used in atmospheric reanalyses greater than 40 Wm-2 are common ([4] Fig. 1). For regional applications an accurate representation of synoptic and sub-synoptic wind stress variability is required. Available flux products produce insufficient ocean mixing due to poor representation of diurnal variations and small-scale variability such as at atmospheric fronts and SST gradients. Ocean wind-wave modeling requires highly accurate wind vectors with high space-time resolution.



*Figure 1: Monthly mean fluxes from NCEP, ERA-40, and OAFlux. a) latent heat flux averaged over 1960 to 1999; b) range across products in monthly-mean estimates from 1960 to 1969; c) as b) for 1990 to 1999.*

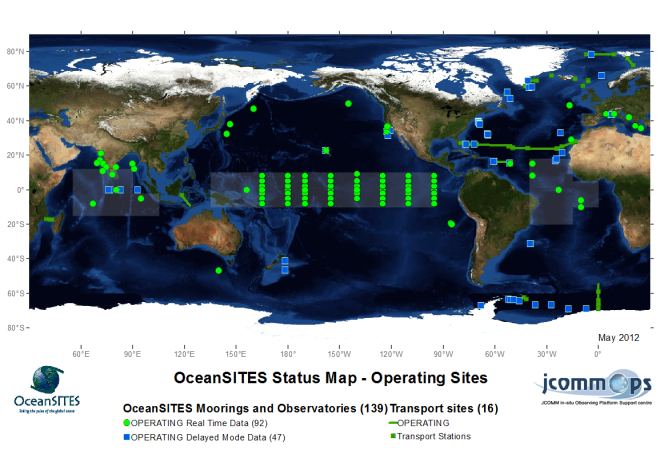
Climate scale integrations aggregate errors over large time and space scales and are particularly sensitive to systematic biases. There are currently no products that meet these accuracy requirements. Studies of climate change and decadal variability must resolve changes in the net heat flux of few Wm-2 per decade, well beyond the capabilities of current observing systems. These studies also require accurate estimation of ocean precipitation.

# **OBSERVING SYSTEMS FOR SURFACE FLUXES AND RELATED PARAMETERS**

The surface flux observing system uses instruments mounted on moorings, ships and satellites. Radiative and precipitation fluxes are usually measured directly. Precipitation is difficult to sample because of its patchiness, only remote sensing methods (surface-based radars and/or satellites) offer any spatial coverage at short time scales. With some exceptions, turbulent fluxes are computed from meteorological variables using bulk flux algorithms with roughly double the uncertainty of directly-measured fluxes. Instruments and accuracies for various methods are described in [1]. The components of the observing system are:

**OceanSITES:** A centralized database of high-quality surface moorings including Ocean Reference Stations [http://www.oceansites.org/].

**Operational Buoys:** International cooperation now maintains tropical moorings (TAO/TRITON, RAMA, PIRATA, [5]). All surface moorings carry basic meteorological sensors to support determination of the turbulent air-sea fluxes of heat, freshwater, and momentum via the bulk formulae methods; many also carry barometric pressure, rain, and solar flux sensors.

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*Figure 2: Global map of flux reference sites.*

**Voluntary Observing Ships (VOS):** The multi-decadal record from VOS contains parameters from which all components of the heat budget and precipitation can be estimated [6].

**Research Vessels (RVs):** Following OceanObs99 routine underway data collection efforts from RVs have begun with the establishment of the SAMOS initiative [http://samos.coaps.fsu.edu/html/] provide a versatile platform for flux measurement including gases and particles [7].

**Remotely sensed data:**

Turbulent fluxes are estimated from remotely sensed atmospheric parameters using bulk parameterizations [8]. The most mature satellite algorithms are for SST and vector and scalar wind speeds and stress. New methods of estimation of near-surface humidity and temperature show important improvements [8]. Satellite based estimates of surface radiative fluxes use measurements of top-of-the-atmosphere radiation and cloud measurements with radiative transfer models from a variety of polar-orbiting and geostationary satellites.

# **FLUX PRODUCTS**

# **Gridded *In situ* Datasets**

Multi-decadal flux datasets have been based on VOS observations in the International Comprehensive Ocean-Atmosphere Dataset (ICOADS, [6]).

# **Satellite Data Products**

Satellites provide good quality estimates of surface stress and radiation for recent decades. However sampling is irregular in space and time, resulting in spatially and temporally varying error characteristics [9,10,11] and irregular representation of fine synoptic scale variability. Gridded surface sensible and latent heat flux products from several sources were compared with *in situ* direct flux measurements by the SeaFlux project [4]; uncertainties are on the order of 20 Wm-2.

The International Satellite Cloud Climatology Project (ISCCP) and the NASA/GEWEX Surface Radiation Budget (SRB) provide solar and IR radiative surface fluxes for the period 1983 to 2007 and beyond from GOES satellites. Quality declines at high latitudes and there appears to be artifacts in time series due to changes to satellite platforms, indicating calibration problems. *In situ* measurements of surface radiative properties can be used to evaluate these issues, but are limited to lower latitudes. Evaluations of downward shortwave radiation at the available buoy sites are encouraging [12] but suggest major departures in the tropical oceans (Fig. 3). It is clear from this figure that sampling is inadequate; IR flux has about half this number of buoys.



*Figure 3: Comparison of mean downward solar radiation satellite products with buoy observations for the last 20 years as a function of latitude: upper panel, mean difference; lower panel, number of buoy sites.*

Composite satellite-based precipitation products include CMAP, GPCP and CMORPH. There are differences between these products [13]; reported accuracies are within 50%

# **Fluxes from NWP reanalyses and operational analyses**

Numerical models provide fluxes and meteorological parameters on a regular global grid. NWP models still have poor representation of some physical processes near the surface and do not adequately use available observational data. High quality *in situ* flux data are required for validation: the WCRP SURFA initiative [http://www.ncdc.noaa.gov/oa/rsad/air-sea/index.html] provides an infrastructure for comparisons. Atmospheric reanalyses provided long-term flux datasets based on consistent model formulations including assimilation of atmospheric data. Although not high accuracy [9], reanalysis fluxes have been used in a wide range of research applications.

# **Blended and hybrid turbulent heat flux products**

Global flux products using multiple input data sources [14] are being developed. These include hybrid products, which select variables from different sources including NWP, satellite, and *in situ* variables. Bias adjustments based on product differences, energy constraints or fits to satellite or *in situ* data can be applied [9]. Blended datasets, where multiple data sources are combined for each variable using an objective analysis, can be in good agreement with climate quality *in situ* data. Blended products are likely to produce the best quality flux datasets for many applications including for forcing ocean models and analysis of interannual variability.

# **THE NEED FOR NEW OBSERVATIONS**

Research campaigns and expansion of the sustained high quality *in situ* observations of flux-related variables are especially needed at high latitudes and coastal regions, where variability is high. The turbulent transport coefficients in existing bulk flux algorithms vary with wind speed and atmospheric stability. Much less well understood is the influence of wave characteristics such as steepness, age, breaking, white-capping, direction of propagation relative to the wind and the presence/absence of swell.

New sustained observation programs using direct flux observing technologies on more continuously operating platforms (buoys, weather ships, and research vessels) are needed to supplement research campaigns. Measurements of whitecaps will aid development of algorithms for remote sensing for use in new gas and aerosol flux parameterizations. Direct covariance flux packages should be added to buoy networks to improve accuracy and parameterizations.

Direct measurements of gas and aerosol fluxes are still exploratory and parameterizations are very uncertain [15, 16]. Recent aerosol flux formulations converge to only about a factor of five, and more measurements are required in a variety of different conditions. Many more measurements of ocean and atmospheric pCO2 are needed [16, 17] along with improved data management to facilitate the development of both new parameterizations and of high spatial resolution global CO2 air-sea flux products with realistic variability. Information on ocean biology and aerosols from satellites provides important information for gas exchange [17].

Validation of open ocean satellite precipitation measurements uses comparisons with precipitation radars at coastal and island-based sites which are in turn calibrated against *in situ* rain gauges and disdrometers. However, as algorithm retrieval errors have a strong dependence on meteorological regime, ships equipped with credible precipitation instruments could provide important validation particularly with the Global Precipitation Measurement (GPM) constellation of satellites. A renewed effort to develop and deploy improved accuracy shipboard and/or buoy rain gauges is required.

# **TECHNOLOGY DEVELOPMENT AND IMPROVED OBSERVATIONS**

*In situ* sensors for the fluxes of energy, heat, water and salt were recently reviewed [18]. There is a continuing need to investigate the performance of existing sensors, for example calibration and comparability of radiometers remains a challenge, gas flux sensors are of marginal accuracy and reliability in open ocean conditions, and aerosol flux measurements are in their infancy. The development and introduction of new sensors, for example for CO2, ozone, SO2, and DMS concentration is a priority.

Increasing power availability on buoys will allow long-term deployments in harsher environments. Increased buoy power will also support routine deployments of optical gas analyzers (for CO2 and H2O). The coincident measurement of aerosol fluxes and chemical and physical fluxes is needed for coupling ocean biology and climate [17]. The development of small-volume gas and aerosol flux sensors will allow deployment on moorings and drifters. Low-power, self-contained flux sensor packages suitable for deployment on coastal weather and navigational buoys should be developed.

Accurate measurements of precipitation at sea are vital. Optical disdrometers are expensive. Well-calibrated and properly installed funnel rain gauges can be effective but need developing to sample blown rain and should ideally be deployed alongside optical rain gauges. Cost-effective rain radar technology for use on ships should be developed. Underwater acoustic sensors have shown some promise.

Work is needed to extend capabilities to extreme wind conditions. Here, the priority should be placed on the design of sensors capable of performance in environments with heavy spray loads.

Also important is the adoption of best practices for deploying sensors on ships and buoys [1]. High quality flux systems can be installed on vessels to understand the performance of the ship’s existing sensors and guide improvements. Careful location of sensors, minimizing shadows, flow disturbance, and heat island effects remains essential.

# **DATA MANAGEMENT, STEWARDSHIP AND DISSEMINATION**

Surface flux and related datasets are obtained from a variety of platforms and methods and require data homogenization, documentation, and scientific data stewardship. The flux measurement handbook [ftp://ftp1.esrl.noaa.gov/users/cfairall/wcrp\_wgsf/flux\_handbook/] and the “Ten Climate Monitoring Principles” [19] guide flux data collection, documentation and management. International co-ordination is required to make flux data and products from a variety of methods and in various data formats easily available to a wide range of users. Free and open data access and centralized data availability and cataloging are needed to provide wider access for applications including dataset evaluations and comparisons, and climate variability and predictability studies. The WCRP SURFA, SAMOS, and OceanSITES are examples of well-structured and open data management systems.

# **RECOMMENDATIONS**

**1) Expand surface flux reference network under OceanSITES:** Current priorities for expansion are for sub-polar and high-latitude regions, where the sampling is sparse and variability is high, and also in regions with severe weather conditions. When technology allows, observation capability should be extended to direct turbulent fluxes including gas and particle fluxes.

**2) Increase the number of ships making high quality routine flux-related measurements:** Research vessels should routinely make high quality measurements of mean meteorology, radiative fluxes and precipitation and subsurface data. A subset should also measure direct fluxes, currents, directional wave spectra and other sea state information with a focus on regions of high variability and gaps in the OceanSITES network.

**3) Enhance/Maintain VOS:** The ability to maintain long-term *in situ* flux datasets requires the reinvigoration of the VOS scheme including an emphasis on providing the full ship report including visual observations of cloud, waves and weather, complete observation metadata and an increased number of regularly-reporting ships.

**4) Enhance satellite flux observing system:** Priorities for satellite observations include improved retrievals of precipitation, near-surface air temperature and humidity and whitecap characteristics. Improved sampling is needed for vector winds, especially during high wind speed and rainy conditions, and also improved temporal coverage and higher spatial resolution for both passive and active microwave sensors especially in coastal regions.

**5) Improve flux observing system technologies:**

Priorities for technology improvement include: Increased power and bandwidth on moorings; More robust and capable platforms with greater survivability for deployment in harsh environments; Improved gas and aerosol flux sensors including accurate and low-power sensors for CO2, ozone, SO2 and DMS; Accurate and low-cost precipitation sensors;

**6) Advance flux parameterizations:** More direct flux measurements are needed to improve flux parameterizations, particularly under high and low wind conditions and for gases and particles under all conditions. Wave characteristics, including wave breaking, should be incorporated into parameterizations of turbulent fluxes of momentum, heat, water, gases and particles, and potentially sea surface albedo. Improved parameterizations of near-surface variations of ocean temperature with depth are needed.

**7) A range of independent and well-characterized flux products is needed:**

A wide range of flux products is needed including from NWP/Reanalysis, satellite, *in situ*, and blended, each characterized by realistic estimates of uncertainty and error covariance. Flux products including variables such as gas transfer velocity, air-sea biogeochemical and particle fluxes, and whitecap fraction should be developed. The validation and comparison of flux products is a priority.

**9) Improve validation and parameterizations for NWP and reanalysis model fluxes:** Observationalists, dataset developers and modelers should collaborate to validate and characterize fluxes from NWP and reanalysis using high quality flux data in a variety of regions, facilitated by the SURFA flux comparison project.

**10) Improve data stewardship and dissemination:** Flux data and products should be made more easily available to both the research and operational communities and the benefits of aggregation of high quality flux data should be promoted. Improved metadata, including on dataset characteristics and suitability for particular applications should be produced, both by dataset producers and providers.

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