Remote Sensing of Environment 201 (2017) 196–218

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Review and assessment of latent and sensible heat flux accuracy over the global oceans

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ARTICLE INFO

Keywords:
Ocean Heat Flux
Latent heat flux
Sensible heat flux
Ocean heat content
Scatterometer
Surface wind
Specfic air humidity
OceanSites
Remotely sensed data

ABSTRACT

For over a decade, several research groups have been developing air-sea heat flux information over the global ocean, including latent (LHF) and sensible (SHF) heat fluxes over the global ocean. This paper aims to provide new insight into the quality and error characteristics of turbulent heat flux estimates at various spatial and temporal scales (from daily upwards). The study is performed within the European Space Agency (ESA) Ocean Heat Flux (OHF) project. One of the main objectives of the OHF project is to meet the recommendations and requirements expressed by various international programs such as the World Research Climate Program (WCRP) and Climate and Ocean Variability, Predictability, and Change (CLIVAR), recognizing the need for better characterization of existing flux errors with respect to the input bulk variables (e.g. surface wind, air and sea surface temperatures, air and surface specific humidities), and to the atmospheric and oceanic conditions (e.g. wind conditions and sea state). The analysis is based on the use of daily averaged LHF and SHF and the associated bulk variables derived from major satellite-based and atmospheric reanalysis products. Inter-comparisons of heat flux products indicate that all of them exhibit similar space and time patterns. However, they also reveal significant differences in magnitude in some specific regions such as the western ocean boundaries during the Northern Hemisphere winter season, and the high southern latitudes. The differences tend to be closely related to large differences in surface wind speed and/or specific air humidity (for LHF) and to air and sea temperature differences (for SHF). Further quality investigations are performed through comprehensive comparisons with daily-averaged LHF and SHF estimated from moorings. The resulting statistics are used to assess the error of each OHF product. Consideration of error correlation between products and observations (e.g., by their assimilation) is also given. This reveals generally high noise variance in all products and a weak signal in common with in situ observations, with some products only slightly better than others. The OHF LHF and SHF products, and their associated error characteristics, are used to compute daily OHF multiproduct-ensemble (OHF/MPE) estimates of LHF and SHF over the ice-free global ocean on a $0.25^{\circ} \times 0.25^{\circ}$ grid. The accuracy of this heat multiproduct, determined from comparisons with mooring data, is greater than for any individual product. It is used as a reference for the anomaly characterization of each individual OHF product.

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http://dx.doi.org/10.1016/j.rse.2017.08.016
Received 1 November 2016; Received in revised form 21 July 2017; Accepted 13 August 2017
Available online 22 September 2017

1. Introduction

Accurate estimation of the ocean surface turbulent and radiative fluxes is of great interest for a variety of air-sea interaction and climate variability issues. Surface fluxes of heat, moisture, momentum, and gases play a key role in the coupling of the Earth's climate system and control many important feedbacks between the ocean and the atmosphere (Gulev et al., 2013). Furthermore, consistency studies of turbulent flux estimates and ocean heat storage estimates are also essential for constraining the Earth's energy budget in order to “track” the energy flows through the climate system, which in turn is critical for improving understanding of the relationships between climate forcings, the Earth system responses, climate variability and future climate change (Trenberth et al., 2009; von Schuckmann et al., 2016). The longest time series of surface fluxes going back to the mid-19th century can be derived from the Voluntary Observing Ship (VOS) data (Woodruff et al., 2011; Gulev et al., 2013). However, these data are characterized by insufficient and time-dependent sampling (Gulev et al., 2007a, 2007b), and by inaccuracies in state variables used for flux computation (e.g. Josey et al., 1999, 2014). In contrast, atmospheric re-analyses, as well as remotely sensed data, potentially provide much more homogeneous time series of atmospheric state variables for surface flux computation. However, remotely sensed data are limited in time to a few decades while reanalyses can be strongly influenced by variations in the type and amount of data assimilated, particularly across the transition to the satellite era in the early 1980s.

In addition, surface flux products from reanalyzes and remote sensing are also subject to biases and uncertainties and require further improvement for turbulent flux determination. These include; improvements in spatial and temporal resolution, the accuracy, and the characterization of the spatial and temporal distribution of errors of each flux component. It is one of the priorities of the World Climate Research Program (WCRP) to improve the accuracy of surface fluxes for climate studies to within “a few W/m^2” and $10\ W/m^2$ for individual flux components and the large scale net heat fluxes, respectively (e.g. WGASF, 2000; Bradley and Fairall, 2007). The Southern Ocean Observing System (SOOS) group recommends a better flux observation density for improving heat flux accuracies at regional scales (Gille et al., 2016). These requirements impose challenges including the development of new parameterizations, achievement of global and regional heat budget closure, reducing sampling uncertainties, and better scaling parameters for surface flux estimates.

To meet these community requirements, the European Space Agency (ESA) launched a project called Ocean Heat Flux (OHF (http://www.oceanheatflux.org/) aiming at development, validation, and evaluation of satellite-based estimates of surface turbulent fluxes and their documentation, particularly those derived from ESA satellite/mission earth observation (EO) data, as well as all bulk parameters needed for turbulent flux calculations over the global ocean. OHF involves a number of objectives and studies. The main OHF objectives include (but are not limited to); establishing a reference surface flux dataset (to maximize the use of remotely sensed data including ESA products), development and accuracy assessment of an ensemble of ocean heat turbulent flux products available over decadal or longer timescales (in order to foster the use and validation of ESA mission data).

For these purposes, OHF uses in-situ, satellite-based, blended or synthetic, and reanalysis-derived surface fluxes over the global ocean, with synoptic and sub-synoptic spatial resolution for the period 1999–2009. The project makes use of the most modern global satellite surface flux data sets such as those from IFREMER (Institut Français pour la Recherche et l'Exploitation de la MER; France), HOAPS (the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite; Germany), SEAFLUX (Woods Hole Oceanographic Institution, Woods Hole (WHOI); USA), and J-OFURO (Japanese Ocean Flux Data sets with Use of Remote Sensing Observations; Japan). These are used along with surface turbulent fluxes from three modern reanalyzes: ERA-Interim (Dee et al., 2011), NCEP-CFSR (Saha et al., 2010) and NASA MERRA (Rienecker et al., 2011), as well as the synthetic OAFLUX product (Yu et al., 2008) and the VOS based NOCS2 surface flux climatology (Berry and Kent, 2009). Because these flux products were derived using different approaches and data sources, they all have their strengths and weaknesses. Wide use of these products for different climate applications such as (among others) forcing ocean models (e.g., Ayina et al., 2006), analyzing ENSO dynamics (Mestas-Nuñez et al., 2006, 2013), and/or evaluating the intra-seasonal variability (Grodsky et al., 2009) requires a detailed quantitative assessment of each product's limitation and of and inter-product differences.

This study presents pilot results from the OHF project that describe uncertainties of the different flux products. Such intercomparison is supplemented by the validation of individual surface flux components against estimates based on in-situ buoy and ship data, especially buoy data included in the Flux reference OceanSites network (http://www.oceansites.org/). Consideration is also given to a new approach to using observations that are themselves incorporated into the flux products that are being validated.

The datasets used in this study are described in Section 2, while OHF products, all available at the same space and time resolution, are described in Section 3. Section 4 demonstrates the impact of recalibration on each OHF product. Regional product inter-comparisons are introduced in Section 5. The accuracy and quality of each OHF flux product, and the ensemble mean flux product, is discussed in Sections 6 and 7.

2. Flux products

2.1. IFREMER

In this study, we use the new IFREMER turbulent fluxes (version 4) available daily over the global ocean on a 0.25° regular grid. It is an updated version of (Bentamy et al., 2013). The bulk variables such as surface wind speed (U_{10}) and specific air humidity (q_a) at 10 m height are estimated from remotely sensed observations. U_{10} is mainly obtained from scatterometers onboard ERS-1 (1992–1996), ERS-2 (1996–2001), and QuikSCAT (1999–2009) satellites. More specifically, the main change with respect to IFREMER version 3 described in Bentamy et al. (2013) is the use of new ERS-1 and ERS-2 wind retrievals (Bentamy et al., 2013, 2016). To enhance the sampling of surface winds, version 7 of wind speed from Special Sensor Microwave Imager (SSM/I) onboard Defense Meteorological Satellite Program (DMSP) F10, F11, F13, F14, and F15 satellites (Wentz, 2013)is used as ancillary data.

Specific air humidity is derived, over special sensor microwave imager (SSM/I) radiometer swaths, based on the use of the model relaying brightness temperature measurements (Tb) and q_a (Bentamy et al., 2013). For this study, a new reprocessing of q_a is performed with respect to the use of the recently reprocessed fundamental climate data record (FCDR) brightness temperatures (Sapiano et al., 2012).

2.2. HOAPS

Data used in this project are from HOAPS-3 (Andersson et al., 2010, 2011), which utilizes passive microwave data from SSM/I to retrieve bulk variables. HOAPS-3 latent heat flux is based on the bulk COARE3 algorithm (Fairall et al., 2003) This algorithm requires atmospheric specific humidity (implemented after Bentamy et al., 2003), sea surface saturation specific humidity (q_s), as well as near surface wind speed (U_{10}). Sea surface temperature (*SST*) for q_s estimation is taken from the NODC/RSMAS Pathfinder SST (Casey et al., 2010), which uses AVHRR observations adjusted to drifting buoy data. This is, therefore, a ‘bulk’ *SST*, whereas ideally q_s should be estimated from a skin temperature, which can differ by a few tenths of degree Kelvin. HOAPS 3 near surface