ESTIMATES OF NET AIR-SEA FLUXES FOR THE TROPICAL AND SUBTROPICAL ATLANTIC BASED ON SATELLITE DATA

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ABSTRACT We estimate the net heat flux in the tropical and subtropical Atlantic Ocean using satellite data. These fluxes are related to changes in sea surface temperature (SST). This variable influences atmospheric circulations and is indicative of surface and subsurface oceanic circulations. We employ data from the geostationary METEOSAT-7 and 8 satellites and from the Special Sensor Microwave/Imager (SSM/I) for the shortwave and long-wave radiative fluxes, and for estimates of SST. For turbulent flux calculations, we use the bulk aerodynamic method with satellite estimates for wind speed and atmospheric humidity and temperature.

KEY WORDS: net air-sea fluxes, sea surface temperature, Atlantic Ocean, remote sensing of fluxes, METEOSAT

1. INTRODUCTION

Climate variability associated with phenomena such as frequency of tropical cyclones and precipitation over continents are associated with interactions between the atmosphere and oceans. From the atmosphere's perspective, this exchange is dependent on varying sea surface temperature, SSTs. The relevance of SST to climatic variability can be illustrated by considering the leading empirical mode of North Atlantic SST anomaly variability (Mestas-Nuñez and Enfield, 1999). This mode shows large amplitudes over the tropical and extra-tropical North Atlantic and is dominated by multi-decadal time scales. On these long time scales, the North Atlantic mode is associated with changes in tropical Atlantic hurricane activity (Goldenberg et al., 2001). On shorter interannual-to-decadal time scales, the relevant factor behind tropical Atlantic variability is the meridional gradient of SST. In the west, it affects the West African Monsoon (WAM); in the east, it influences atmospheric circulation causing a shift in the location of the Inter-Tropical Convergence Zone (ITCZ), thereby affecting precipitation in the Nordeste province of Brazil (Foltz et al, 2003, 2004). Since the key environmental variable for Atlantic climate is SST, understanding the surface heat fluxes which force the SST variability is the subject of this study.

The Atlantic Ocean provides a very good test region for attempting to sum all the flux terms and arrive at a net flux, because there are surface buoys in the tropical region, research vessels, and many volunteer observing ships to provide in situ data for anchoring the satellite estimates. The separate terms and the net can be tested independently by using the satellite-derived fluxes with an upper ocean reanalysis model (e.g., the Simple Ocean Data Assimilation (SODA) model (Carton et al., 2005) to compare with forcing provided by atmospheric reanalysis models. The satellite net flux estimates can be evaluated by comparison with the net gain or loss of heat by the ocean in certain regions to altimetric estimates of the sea surface height change over time.

2. BACKGROUND

We aim to evaluate accurately all the following terms in the air-sea energy exchange for the period 1992-2006.

$$H_{net} = \text{SW up} + \text{SW down} + \text{LW up} + \text{LW down} + \text{LHF} + \text{SHF} \tag{1}$$

where H_{net} is the net energy budget, with a positive value indicating loss from the ocean, i.e., vertical coordinate positive upwards; SW refers to solar radiation at the air-sea interface directed up or down; LW is the surface longwave radiation, 3-50 μm, directed up or down; LHF is latent heat flux due to evaporation; and SHF is sensible heat flux.

In section 3, we describe the methods and data used for the radiative transfer calculations and in section 4 we briefly describe the methods and data used for the turbulent fluxes of heat and water vapor. Section 5 presents the evaluation of the accuracy of the fluxes, section 6 presents examples of the fields, and section 7 gives a short summary and presents the plans for completing the collection of all the satellite flux estimates needed to force an ocean circulation.

3. METHODS FOR RADIATIVE FLUXES

A key role in the budget is played by the radiative fluxes. Under the International Satellite Cloud Climatology Project (ISCCP) (e.g., Rossow and Duenas, 2004), time series of cloud cover were produced, as well as surface radiative flux estimates at 2.5° resolution and 3-hourly time scale and are available for a period of about 20 years (e.g., Pinker et al., 2005). The temporal variability of clouds has a strong effect on the estimated surface fluxes, and the low spatial resolution of ISCCP, therefore, limits use of its data in smaller scale studies. The recent observations from METEOSAT-8 developed by the European Space Agency (ESA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) (Schmetz et al., 2002; Govaerts et al., 2005) are well suited to improve estimates of radiative fluxes. Our strategy to obtain long term information on radiative fluxes is: evaluation of SW radiative fluxes as available for longer time periods from geostationary platforms against the improved METEOSAT-8 observations during periods of overlap, so the inaccuracies in the longer time series can be estimated; development of an approach to derive long-wave fluxes; and development of capabilities to account for the radiative effects of aerosols. The SW radiative fluxes to be evaluated against METEOSAT-8 are based both on the ISCCP DX data gridded at 0.5° resolution and the high resolution METEOSAT-7.

In the original version of the University of Maryland Surface Radiation Budget (UMD/SRB) algorithm (Pinker et al., 2005), cloud information is derived from the relevant visible channel and used to infer surface SW fluxes. A modified version of this algorithm allows for the use of independent information on clouds and aerosols. Such a version (Pinker et al., 2003) was used to derive SW fluxes from METEOSAT-8. Comparison between simultaneous estimates of shortwave flux from Meteosat 7 and 8 exhibit significant differences (not shown here).

Observations from METEOSAT-8 can serve as a calibrator of longer time series. Only recently is large scale information on aerosol properties becoming available (e.g., Mishchenko et al., 2002) Over oceans, aerosol information is available from several sources, e.g., the Goddard Institute for Space Studies (GISS), the Moderate Resolution Imaging Spectroradiometer (MODIS), from chemical transport models (COGART), and from amalgamation of satellite products, chemical transport models, and observations (e.g., AERONET). We have improved our surface radiative flux retrieval methodology by incorporating a representation of aerosol optical properties (Liu et al., 2005).

Errors in satellite SST have been identified as major contributors to errors in the flux fields. Algorithms to estimate SST from Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) observations have been developed (Sun and Pinker, 2006), implemented, and partially evaluated. An example of SST over the Atlantic as derived from the SEVIRI four channel algorithm is shown in Figure 1. Several methods have been implemented to derive down-welling LW. We used the approach of (Schlüssel et al., 1995) with the brightness temperatures of SSM/I microwave channels (see the lower panel of Fig. 2)

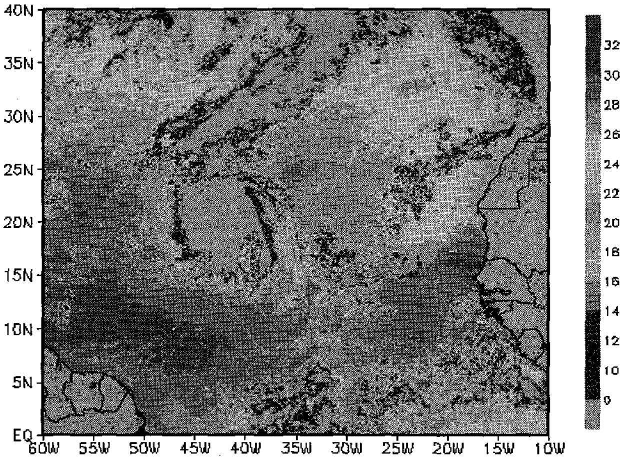

Figure 1. SST from the SEVIRI-4 channel algorithm for September 27, 2004 .

4. METHODS AND DATA USED FOR TURBULENT FLUXES

The two energy budget terms, LHF and SHF, are obtained from the bulk aerodynamic formulas of [23]:

$$LHF = -\rho \bullet L \bullet C_E(U_a - U_0)\,(q_a - q_s) \qquad (2)$$

where U_a is the mean wind speed at 10 m height and U_0 is the current speed at the sea surface, usually set to zero; q_s is the saturation vapor pressure at the sea surface, corrected for salt effects, and simply a function of SST; q_a is the atmospheric humidity at the reference height, 10 m; C_E is the exchange coefficient for water vapor, the Dalton number; and L is latent heat of evaporation.

SHF has a similar equation:

$$SHF = -\rho C_p C_H\,(U_a - U_0)\,(T_a - T_s) \qquad (3)$$

where T_s is SST; T_a is the air temperature at 10 m height; C_p is the specific heat at constant pressure; ρ is air density; and C_H is the exchange coefficient for sensible heat, the Stanton number. C_H is set equal to C_E. The most recent summary of work on C_E in the past 25 years is provided by Drennan et al. (2006).

Estimates of the surface wind are a product of merged data of vector winds from scatterometers including those on European Remote Sensing satellites 1 and 2 (ERS 1 and 2), the NASA scatterometers (NSCAT) and Quikscat with wind speed estimates from microwave radiometers. Estimates of the humidity difference between the air-sea interface and the atmosphere are made using SSTs to obtain q_s. The term q_a is proportional to the column-integrated water vapor, obtained from the SSM/I in the U.S. Defense Meteorological Satellite Program (e.g., Liu and Niiler, 1984; Schulz et al., 1997). The protocol for the flux calculations is the one developed by the satellite group at the Institut Francais de Recherche pour l'Exploitation de la Mer (IFREMER), Bentamy et al. (2003).

The sensible heat flux calculation using Eq. 3 requires that one obtain the atmospheric air temperature T_a at a reference height of 10 m. As proposed by Kubota and Shikauchi (1995), T_a can be estimated using the Bowen ratio, which is defined by:

$$\beta = \frac{C_p C_h (T_s - T_a)}{L C_e (q_s - q_a)} \qquad (4)$$

where β is the Bowen ratio. The method assumes a constant value for the Bowen ratio which is an approximation that is good in the tropics, where the value is close to 0.1. Eventually, some other method may be found for SHF, or atmospheric numerical models at high resolution and with data assimilation may increase in accuracy beyond what this method offers. (See work by Yu et al., 2004, who attempt this idea.)

We focus on weekly averages and 0.5-1.0° resolution in the gridded flux fields. We expect this to be an adequate time resolution for the ongoing ocean modeling work. At the minimum, it will provide the required check for biases in flux products of the atmospheric reanalysis.

5. EVALUATION OF THE SURFACE FLUXES

The net surface energy budget will be evaluated in three ways:

(1) through estimation of the local storage and horizontal advection of heat based on simultaneous reanalysis of ocean temperature and currents,

(2) through comparison with the heat budget at fixed mooring sites in the tropics, which can be used to check on our integrated net flux.

(3) through comparison with changes in steric sea level estimates from satellite altimetry as a further check on net heat loss or gain

6. SOME RESULTS

One example of three individual terms in Eq. 1. is illustrated in Figure 2, which shows three-month averages over the months of January, February, and March in 1996 of latent heat flux, short wave downward radiation, and net longwave heat flux. We note the effects of the cloudiness associated with the ITCZ just north of the equator in the SW radiation and the maximum solar heating south of the equator at this time of year. The net longwave flux is close to zero in the deep tropics due to the humid atmosphere and cloudiness causing large values of downward longwave radiation. To the north and south, there are relatively large net longwave losses in the clearer, drier atmosphere of the subtropical high pressure regions. Latent heat flux is very small from the cold upwelling waters off Africa, both north and south of the equator. The role of the tradewinds in enhancing the evaporation is clearly seen with very large values just north of South America and along the Gulf Stream.

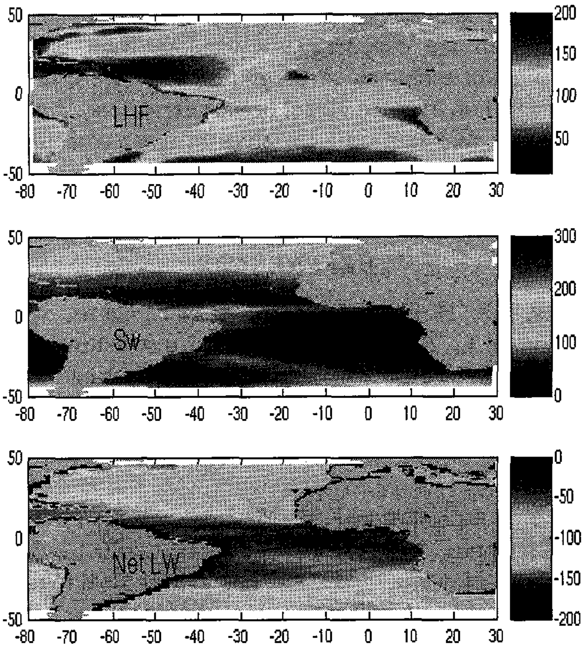

Figure 2. Averages of three flux terms over the first three months of 1996. Scales are in W m^{-2}.

7. SUMMARY AND PLANS

Methods and data are available to obtain all the terms in Eq. 1 using satellite techniques. We will analyze the net heat flux for the integrated values over months and years and study the relationship to known advection in the ocean, SST changes and climate signals. We will then test whether these fluxes produce more realistic oceanic circulations when forcing the ocean reanalysis models (compared with atmospheric model fluxes).

Future satellite systems will improve the coverage and accuracy of all the sensors employed today. However, in order to develop a long time series worthy of a climate record, we also must use the existing time series as soon as possible. This requires that we continuously test and refine our methods, as presented here, and work towards better measurements and increased sampling of the relevant variables. Similar research with satellite flux estimates can be carried out for the East Asian region.

To force the ocean model, we need in addition to the heat flux, the momentum flux and the net mass flux. The momentum flux is available from the satellite wind fields mentioned above. For the net mass flux, we need in addition to the evaporative water loss from the sea, precipitation estimates. A program to produce estimates of precipitation over the global oceans exists (e.g., Adler et al., 2000). We can avail ourselves of those data for the oceanographic model runs.

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Acknowledgments. We appreciation the international collaboration of the METEOSAT Second Generation Research and Applications Program with its free and open access to the data from METEOSAT 8. These data make it possible to carry out the project described here. Financial support has been provided by several governmental agencies over many years in France and the U.S.A. We hereby voice our sincere appreciation without mentioning each individual grant.