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Seasonal and interannual variability of the mixed layer heat budget in the Caribbean Sea

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ABSTRACT

The long-term mean annual cycle and interannual variability of the mixed layer heat budget in the Caribbean Sea are quantified by using high resolution oceanic and atmospheric reanalysis products (the GLobal Ocean ReanalYsis and Simulations, GLORYS2V4, and ERA-Interim) for the period spanning from January 1993 to December 2015. In this region the mixed layer depth (MLD) is relatively shallow, oscillating spatially from 10 to 90 m, with maximum values observed during the dry season (December to March), and minimum values during the main rainy season (September to November). The highest MLD values are found in the northwestern part of the basin and the lowest in the Central and northern South American coastal region. The strength and location of greater MLD oscillations over the Caribbean Sea depend on the intensity of the zonal winds and the location of the Caribbean-Low Level Jet (CLLJ). At interannual timescales, reanalysis data shows that the MLD anomalies are associated with extreme phases of the El Niño Southern Oscillation (ENSO); however, low statistical correlation suggests that other factors, such as a Quasi-Biennial Oscillation (QBO), or a weak ENSO cycle with a 2-year periodicity, could influence this region, and induce changes in the depth of the mixed layer and in the heat budget within it. The seasonal ocean heat balance within the mixed layer ranges between -315 and 393 W m^{-2} in the Caribbean region (monthly means around $\pm$ 60 W m^{-2} averaged over the entire domain). The net air-sea heat flux varies seasonally around $\pm$ 60 W m^{-2}. Analysis of this term shows that during the dry season (rainy season), when the MLD is deep (shallow) the region loses (gains) heat, with net short wave radiation being the main gain, and the latent heat the main loss at seasonal and interannual timescales. The advection term is an order of magnitude less (monthly means from -2 to 7.5 W m^{-2}) but has the highest values during the dry season in the northwest Caribbean Sea, when the winds and surface currents are intense. This term tends to provide small interannual heat variability (up to $\pm$ 2 W m^{-2}). The entrainment is almost negligible in its contribution to the budget. At interannual timescales this flux reduces the stored heat by up to $\pm$ 1 W m^{-2}. It is noted that although the MLD is not so clearly related with ENSO, the heat stored in this layer is significantly modulated by El Niño/La Niña remote forcing, especially during the period spanning from 1992 to 2001 when intense ENSO events occurred and affected the air-sea fluxes, and the advection. The CLLJ influences both the MLD and the heat budget in the Caribbean Sea. This jet is being modulated by ENSO and other long-term oscillations.

1. Introduction

The Caribbean Sea is characterized by strong air-sea interaction processes, which are important for the global climate system, given that this region is the major pathway of heat and salt fluxes from the tropics to the mid-latitudes, where atmospheric and oceanic coupling is the main controlling mechanism of the North Atlantic climate (Gallegos, 1996), and is the main conduit of the upper part of the northward flowing meridional overturning circulation (Schmitz and Richardson, 1991; Schmitz and McCartney, 1993; Kirchner et al., 2008). Therefore, understanding the dynamics that govern oceanic heat budget changes within the upper mixed layer in the Caribbean Sea is required to improve numerical models aimed at forecasting future climate change by means of a quantitative diagnostics of the coupling between the atmosphere and the ocean.

Due to the significance of this subject, several studies have focused

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on the heat budget and air-sea interactions in the Caribbean Sea (Jacobs, 1951; Budyko, 1955, 1963; Colón, 1963; Hastenrath, 1968, 1976; Bunker, 1976; Hastenrath and Lamb, 1978). Such studies have determined the important role of the annual cycle of latent heat and advection terms. Such investigations have used climatic atlas data and available routine ship observations and thus only the seasonal variations of the major heat budget components have been quantified. Furthermore, the divergence of the heat transport and storage terms in those investigations were usually calculated as residuals and the seasonal march of the heat budget components were averaged over the entire Caribbean Sea; resulting in an inadequate smoothing of some spatial features that prevail in the region.

Later on, Etter et al. (1987) reviewed previous studies and provided a more detailed analysis of average monthly and multi-annual rates of oceanic heat storage, coupling their results with the surface heat exchange data from other investigators. Their estimates were computed directly from monthly mean climatic summaries of vertical temperature data from the National Oceanographic Data Center (NODC) for the decade 1967–1976. The monthly mean oceanic heat transport divergences were derived as residuals in the heat budget equation (by subtracting the oceanic heat storage from the net oceanic heat gain) and compared to the water transports determined from thermal structure data.

Etter et al. (1987) analysis further improved estimation of the heat budget of the Central American Seas but due to the limited spatial resolution (5° lat/lon grid) of their estimations results still need further revision. These authors divided the Caribbean Sea area into southern and northern provinces relative to 15°N, given the dichotomous behavior of the heat storage, and found the importance of Ekman pumping and heat advection due to currents in the southern province. Also, the heat transport divergence in this region was found to be related to upwelling in all seasons but autumn, with the largest magnitudes in winter.

More recently, Jouanno and Sheinbaum (2013) investigated the mixed layer heat budget of the Caribbean upwelling system during the onset of the Atlantic warm pool (June–September) using high-resolution observations of sea surface temperature (SST) and a high-resolution (1/12°) regional model. They determined that vertical mixing is the major contributor to the cooling of the mixed layer heat budget in the nearshore and offshore Colombian Basin. Furthermore, they found that intense mesoscale eddies have an important effect on the shape of the turbulent cooling, contradicting the conventional view that the offshore cold water signature in the region is due to the direct effect of surface layer Ekman transport away from the coast.

All the aforementioned studies contributed towards current understanding of the main terms associated with the variability of the Caribbean Sea heat budget. From such studies, it was concluded that although the surface heat exchange is an important term, the oceanic heat storage rates are related primarily to horizontal heat transport. In the southern Caribbean, where upwelling processes occur, this budget has been associated with Ekman pumping, vertical mixing, and advection due to ocean currents and mesoscale eddies. However, the year-to-year changes of the heat budget terms and the possible forcing mechanisms have not yet been determined.

Despite previous results providing further insight towards understanding the annual cycle of the oceanic heat budget in this region, inadequate data resolution means that several uncertainties remain unaddressed. These could be solved using data and products currently available.

The purpose of this study is to quantify the surface layer heat budget in the Caribbean Sea using high resolution atmospheric and oceanic reanalysis products. Unlike previous studies, this investigation not only focuses on the annual cycle but also offers important insights on the variability of the terms contributing to the oceanic heat balance at interannual timescales.

2. Background

The seasonal climate of the Caribbean Sea is determined by the space-time dynamics of diverse synoptic features, the most dominant being the subtropical high of the North Atlantic and the associated strength of the easterly trade winds (Taylor and Alfaro, 2005). The annual march of atmospheric events is marked by the alternation of rainy and dry seasons coincident with the dynamics of the Caribbean-Low Level Jet (CLLJ) (Cook and Vizy, 2010). During the boreal winter, strong winds, cold SSTs, and reduced atmospheric humidity characterize the driest season of the year and are concomitant with the southernmost position of the Intertropical Convergence Zone (ITCZ). During the summer, when the North Atlantic high is displaced northwards and the convergence band is located over the Caribbean Sea, the ocean warms and atmospheric moisture increases in association with the rainy season (Hastenrath, 1984).

However, the dry winter/wet summer regime only partially defines the seasonal climatology of this region. Other synoptic features influencing the Caribbean Sea climate are: polar front intrusions of mid-latitude origin, locally known as "*Nortes*" in Spanish (Magaña et al., 1999; Poveda et al., 2006) which modify the dry winter and early summer climates of the northern Caribbean, producing strong winds and rain events (Amador et al., 2006); westward propagating tropical disturbances, easterly waves, tropical storms and hurricanes during summer, which are associated with heavy rainfall (Taylor and Alfaro, 2005); and the occurrence of the Mid-Summer Drought (MSD) or "*Veranillo*" in Spanish, which is a minimum in convective activity and precipitation during the summer season that causes a bimodal rain distribution in the region, with maxima in June and September–-October and a relative minimum during July–August (Magaña et al., 1999). Also, the topography (continental territories, island chains and mountain ranges) interacts with the regional circulation and produces local changes in the climate system.

Responses of the oceanic upper layer to seasonal changes in climate are well documented by previous investigations. These studies show that this region exhibits a strong dynamic coupling between atmosphere and ocean. For instance, the divergence (upwelling) from the South American coast and convergence (downwelling) towards the Greater Antilles and related seasonal sea level and SST variability have been linked to the CLLJ wind stress curl dipole pattern (Gordon, 1967; Andrade and Barton, 2005; Ruiz-Ochoa et al., 2012; Torres and Tsimplis, 2012).

Also, the dominant surface currents flowing west-northwestward, the cyclonic circulation of the Panama-Colombia gyre and the eastward flow along the Central and South American Caribbean coast are associated with intense air-sea interactions through wind stress and surface heat flux forcing (Wüst, 1963, 1964; Mooers and Maul, 1998; Andrade et al., 2003).

The location of the mixed layer depth (MLD) results from the interaction of surface heating and cooling, wind and convective mixing, molecular diffusion and horizontal advection (Muller-Karger et al., 2015). There are few studies relating MLD variations to such interactions in the region, albeit none of them provide a detailed description of the dynamics inducing spatial changes at seasonal timescales.

Air-sea coupling and related upper ocean layer variability, in the Caribbean Sea is also affected by important large-scale climatic processes, such as the El Niño Southern Oscillation (ENSO). Hastenrath (1984) observed that anomalously dry summers, accompanied by lower sea level pressure (SLP) and higher SST in the equatorial Pacific are related to higher SLP and lower SST in the tropical Atlantic, indicating an anomalously strong North Atlantic High associated with El Niño. Previous studies detected changes in precipitation patterns during the warm and cold phases of ENSO (Ropelewski and Halpert, 1987, 1996; Kiladis and Diaz, 1989; Enfield and Mayer, 1997; Enfield and Alfaro, 1999; Poveda and Mesa, 1999; Giannini et al., 2000, among others). A mechanism that links Caribbean climate and precipitation in the Pacific