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Key Points:
- Current satellite estimates of surface shortwave and longwave radiative fluxes are compared to observations from a buoy under the marine stratus clouds during the buoy record of 2000–2012
- Satellite surface daily mean shortwave and longwave radiative fluxes agree well with buoy observations, and the agreement is better than that obtained from reanalyses
- The satellite products demonstrate stability; neither the buoy nor the satellite data showed considerable variability in surface radiation over the period that was studied

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Evaluating Surface Radiation Fluxes Observed From Satellites in the Southeastern Pacific Ocean

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Abstract This study is focused on evaluation of current satellite and reanalysis estimates of surface radiative fluxes in a climatically important region. It uses unique observations from the STRATUS Ocean Reference Station buoy in a region of persistent marine stratus clouds 1,500 km off northern Chile during 2000–2012. The study shows that current satellite estimates are in better agreement with buoy observations than model outputs at a daily time scale and that satellite data depict well the observed annual cycle in both shortwave and longwave surface radiative fluxes. Also, buoy and satellite estimates do not show any significant trend over the period of overlap or any interannual variability. This verifies the stability and reliability of the satellite data and should make them useful to examine El Niño–Southern Oscillation variability influences on surface radiative fluxes at the STRATUS site for longer periods for which satellite record is available.

Plain Language Summary The ability of satellites to provide accurate estimates of shortwave and longwave radiation reaching the surface of the ocean is investigated by comparing satellite estimates with observations from a surface buoy. The buoy was deployed since 2000 at a site 1,500 km off northern Chile, where persistent clouds complicate remote sensing of the ocean surface. Good agreement has been found between current satellite products and the buoy; the results are better than those found with surface radiation estimates based on reanalysis models. Since the satellite data capture well the annual cycle in radiative fluxes at the buoy, and there are no detectable trends in buoy and satellite shortwave and longwave radiation, the satellite data are seen to have good temporal stability. Neither satellite nor the buoy showed interannual variability in surface radiative fluxes at the site; using satellite data to map where El Niño–Southern Oscillation variability is seen shows that the STRATUS site is just south of the region where El Niño–Southern Oscillation variability is seen in surface radiative fluxes.

1. Introduction

1.1. Motivation

Oceans cover about two thirds of the globe and play an important role in the climate system. The oceans are a source of atmospheric moisture; they control air-sea exchange of heat and store it at various depths in the oceans. The need to improve estimates of ocean heat fluxes has been recognized and articulated in numerous workshops as described in Yu et al. (2013), WCRP (2012), and CLIVAR/ESA Scientific Consultation Workshop (WCRP, 2013). Indeed, many current efforts address issues related to different aspects of such fluxes (Bentamy et al., 2017; Josey et al., 2014; Valdivieso et al., 2017). Large-scale spatial observation of ocean-atmosphere interactions can be done from satellites. Quantification of the satellite estimates' accuracy requires evaluation against surface observations. In particular, it is important to have longer term in situ information so that the continuity and robustness of the satellite methods over time can be established. Moreover, since reanalyses are frequently used to force ocean models, it is also of interest to evaluate the quality of information from the models when compared that from satellites. One such record of surface meteorology and air-sea exchanges of heat, freshwater, and momentum is available from a long-term surface mooring located 1,500 km west of the coast of northern Chile (Colbo & Weller, 2007; Weller, 2015) known as the STRATUS Ocean Reference Station (ORS) or STRATUS. The unique observations made from this buoy are of particular interest since they meet the challenges for in situ validation facing the satellite and modeling communities in a data sparse region of persistent marine stratus clouds in the eastern boundary of the South Pacific. In this study, these high-quality observations are used for evaluating satellite estimates of surface shortwave (SW↓) and longwave (LW↓) radiative fluxes as well as reanalysis-based estimates of such fluxes.

Several studies (e.g., Jensen et al., 2008; Zhu et al., 2007) have identified tropical and subtropical low-level marine boundary layer clouds as an important component of the climate system, since they decrease the amount of solar radiation absorbed in the ocean's mixed layer but have minimal impact on the thermal radiation emitted to space. Klein et al. (1995) pointed to a negative correlation between sea surface temperature anomalies and low cloud amount in the northeast Pacific, while Xu et al. (2005) link subseasonal variability in the southeast Pacific stratus region to the regional lower atmospheric circulation.

1.2. Extended Value of Buoy Observations

Two general locations, just southwest and northwest of 20°S, 85°W, have been selected for anchoring the STRATUS ORS surface mooring. More than one site is used so that successive mooring deployments, which are each typically 1 year in length, can be overlapped to support intercomparison of observations. The maximum distance between the mooring sites of the time series used here was 80 km.

Satellite wind and blended surface meteorological products and shipboard observations taken during the mooring cruises over the years (De Szoeke et al., 2010) have shown general homogeneity in the region within 100 km of 20°S, 85°W when looking at the surface meteorology and air-sea fluxes on time scales longer than daily. The data used here are from 10 deployments, merged into one time series characteristic of the region. The observations span the period of 2000 to 2012, including 9 full calendar years of unbroken time series from 2000 to 2010 and a continuation in 2011 after a gap; this allows description of the mean annual cycle and interannual variability as well as examination of trends. Weller (2015) found that annual variability in the air-sea heat flux is dominated by the annual cycle in the net shortwave radiation and that during the austral summer, the ocean is heated. The 9 year mean annual air-sea heat flux was 38 Wm^{-2}, with the positive sign indicating ocean heat gain. Greater ocean cooling was seen in 2006–2008, during La Niña events. Over the 9 year record from 2000 to 2010 significant increases from the 9 year means in wind speed, wind stress, and latent heat flux were seen (0.8 ms^{-1}, 0.022 Nm^{-2}, and 20 Wm^{-2} or 13%, 29%, and 20%, respectively). For the same period, the decrease in the annual mean net heat flux was 39 Wm^{-2} or 104% of the mean.

In this study, we have used the observations of radiative fluxes (SW↓ and LW↓) at this site for evaluating the utility of satellite methods to derive such fluxes. Good agreement between the two would indicate that the use of satellite estimates could be expanded in space and time to cover areas of the oceans where buoy observations are not available. Methodology will be described in section 2, satellite data used in this study will be described in section 3, results will be presented in section 4, and a summary will be presented in section 5.

2. Methodology

The methodologies for deriving SW↓ (0.3–4.0 μm) and LW↓ (4.0–100.0 μm) radiative fluxes from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations as used in this study are described in Nussbaumer et al. (2012) and Wang and Pinker (2009). Briefly, the SW↓ inference scheme denoted here as UMD_MODIS_SW is based on the delta-Eddington approximation to solve the radiative transfer equations (Joseph et al., 1976). The model calculates SW↓ radiative fluxes for a plane-parallel, vertically inhomogeneous, scattering, and absorbing atmosphere in seven spectral intervals (0.2–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–1.19, 1.19–2.38, and 2.38–4.0 μm) at specified pressure levels. The radiative transfer model accounts for absorption by ozone and water vapor, multiple scattering by molecules, multiple scattering and absorption by aerosols and cloud droplets, and multiple reflection between the atmosphere and surface. The atmosphere is divided into more than 30 layers, depending on the aerosol profiles and on the presence of clouds and cloud layers. The vertical profiles of ozone and water vapor densities, temperature, and pressure are those of the standard atmospheres (Kneizys et al., 1980). The parameterizations used in the new inference scheme for ozone, water vapor Rayleigh Scattering, water clouds, ice clouds, and aerosols are described in detail in Appendix A of Wang and Pinker (2009). The implementation of the model is detailed in section 3.1.

The LW↓ inference scheme used here is denoted as UMD_MODIS_LW and is driven with a synthesis of the latest 1° resolution MODIS level-3 cloud parameters and information from the European Centre for Medium-Range Weather Forecasts ERA-Interim (ERA-I) model-analysis. The clear-sky contribution in the model is based on the Rapid Radiative Transfer Model (Mlawer et al., 1997), while a statistical cloud structure model and parameterization determines the cloud contribution to LW↓. European Centre for Medium-Range Weather Forecasts ERA Interim Reanalysis model (Dee et al., 2011) parameters of vertical structure of temperature and humidity were used.

The following analyses were performed: evaluation of the UMD_MODIS satellite estimates against the surface observations from the STRATUS buoy; evaluation of independent satellite estimates and reanalysis products against the same buoy observations; evaluation of the capability of the satellite estimates to represent the observed annual cycle in both the SW↓ and LW↓ fluxes; and comparison of "trends" in the SW↓ and LW↓ fluxes in the satellite estimates against those based on buoy observations.

To facilitate the comparisons, the satellite data were centered at 20.0°S, 85.0°W. The matching is done both in time and space. Cases for which both satellite and ground observations are available at daily time scale were selected for those periods that all data compared had information. The spatial matching is based on the buoy location and the selection of the satellite grid box that covers that location. Subsequently, we evaluate the satellite value at the buoy location using weights that are function of latitude and longitude. Since most in situ observations of radiative fluxes over the oceans are of shorter duration or intermittent, the unique data set obtained at the STRATUS site provides an opportunity for evaluating the performance of the satellite data over a longer period of time.

3. Data

3.1. Satellite Products of Radiative Fluxes

3.1.1. University of Maryland

Radiative fluxes, SW↓ and LW↓, are available for the period July 2002 to December 2012 and were derived with the University of Maryland (UMD) inference schemes of Wang and Pinker (2009) for SW↓ and Nussbaumer et al. (2012) for LW↓. Both methods were implemented globally with products from the MODIS sensor both on Aqua and Terra (King et al., 1992) at 1° spatial resolution at a daily time scale. Evaluation of these products against the Pilot Research Moored Array in the Tropical Atlantic moorings in the tropical Atlantic (Bourlés et al., 2008), the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network moorings in the tropical Pacific Ocean (McPhaden et al., 1998), and against buoys of opportunity were reported on in Grodsky et al. (2009), Pinker et al. (2009), Niu et al. (2010), Ma and Pinker (2012), and Pinker et al. (2014).

3.1.2. Clouds With the Earth's Radiant Energy System

Used are the global surface flux data for total sky condition of Clouds with the Earth's Radiant Energy System SYN1deg-day which are described as "The Synoptic Radiative Fluxes and Clouds (SYN1deg-Day)" products that contain a day of space and time averaged Clouds with the Earth's Radiant Energy System geostationary enhanced temporally interpolated data (Kato et al., 2015). The 1° regional fluxes are daily averages from the Synoptic Radiative Fluxes and Clouds (SYN1deg-1Hour) product.

3.1.3. Global Energy and Water Exchanges/Surface Radiation Budget

The Global Energy and Water Exchanges/Surface Radiation Budget data are the daily averages (UTC time) of global surface fluxes for all sky condition at 1° spatial resolution (SRB Science Team, 2016; Hinkelman et al., 2009).

3.2. Reanalysis Data

3.2.1. ERA-Interim

These data (Berrisford et al., 2009; Dee et al., 2011) are downloaded from http://rda.ucar.edu. Used here are monthly mean forecast field (2 per day) of forecasts of 12-hr accumulation Gaussian grid nLat * nLon = 256 * 512; units are W m^{-2} s. Daily data are also from the forecast field forecast hours with 12 hr sampling, time reference: 00UTC and 12UT, 2 records per day of 12 hr forecast accumulation Gaussian grid nLat * nLon = 256 * 512, in W m^{-2} s.

3.2.2. The Climate Forecast System Reanalysis

The data come from the National Center for Environmental Prediction (Saha et al., 2010) as downloaded from http://rda.ucar.edu/. Monthly mean forecast field (4 per day) of 6 hr average resolution 0.5° units: W m^{-2}; daily data forecast field-forecast hours = 6 hr time reference: 00UTC, 06UTC, 12UTC, and 18UTC-4 records per day of 6 hr forecast average resolution 0.38°; units are W m^{-2}.

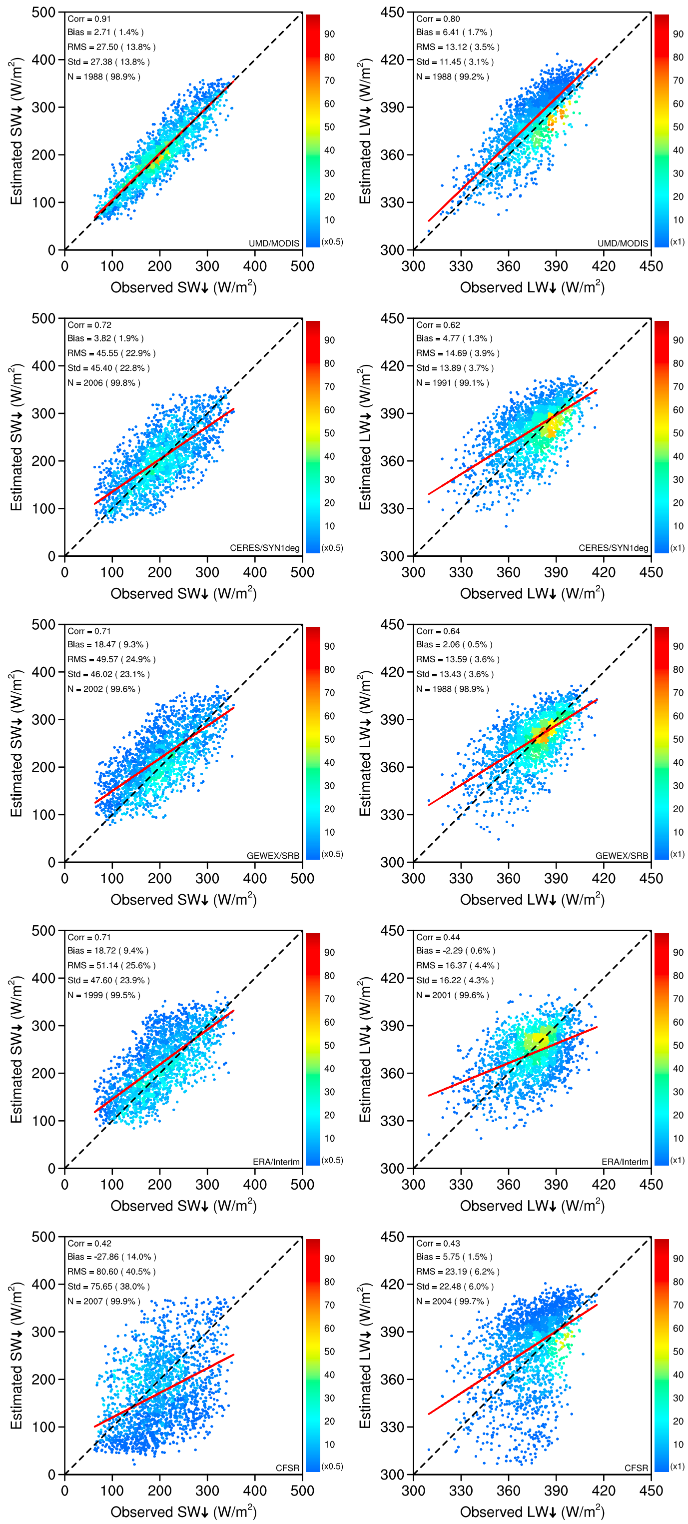

Figure 1. (left) Evaluation of satellite estimates of SW↓ radiative fluxes against the Ocean Reference Station STRATUS buoy at daily time scale during 1 July 2002 to 31 December 2007; (right) same as for SW↓ but for LW↓. Row 1: UMD_MODIS_SW for SW↓ and UMD_MODIS_LW for LW↓; row 2: same as above for CERES/Syn1deg; row 3: same as above for Global Energy and Water Exchanges/Surface Radiation Budget; row 4: same as above for Era-I; row 5: same as above for Climate Forecast System Reanalysis. The color bar denotes the number of elements that fall in each bin of the grid via bivariate probability density distribution method. The boundary is [50,400], and the bins are [35,35] for shortwave flux. The boundary of longwave flux is [300,450], and the bins are [30,30].

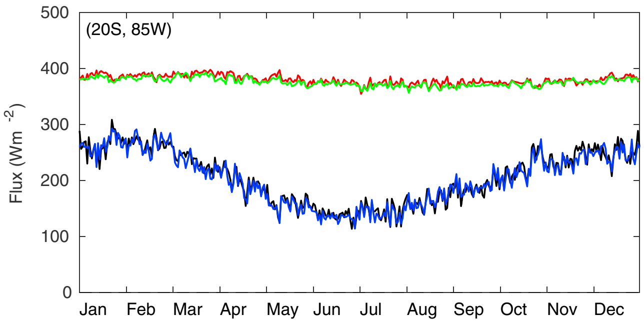

Figure 2. The annual cycle of SW↓ and LW↓ radiative fluxes averaged for the period of 2001–2012 as observed from the Ocean Reference Station STRATUS buoy and satellite. Black: SW↓ satellite; blue: SW↓ as observed by the buoy; red: LW↓ from satellite; green: LW↓ as observed by the buoy.

3.3. Buoy Observations of Radiative Fluxes

The radiative flux measurements at STRATUS are part of a comprehensive set of observations made from a surface buoy using two independent and improved instrument packages (Hosom et al., 1995) recording wind speed and direction, air temperature and humidity, sea surface temperature and salinity, incoming shortwave radiation, incoming longwave radiation, barometric pressure, and rain rate. In this study, we use only the radiation measurements. The radiometers were mounted at about 2.8 m above the sea surface; the raw measurements for each parameter are made once a second and then averaged, the averages are recorded once per minute, and hourly averages are transmitted. Every year a fresh mooring and surface buoy are deployed, and their exact location is provided in Weller (2015). Detailed discussions of the instrumentation and sensors are given by Colbo and Weller (2009), Weller et al. (2012), and Bigorre et al. (2013). Overlapping deployments of successive surface buoys and deployment on the ship on an independent set of meteorological and air-sea flux sensors are done to support quantification of the uncertainties in the buoy measurements (typically fielded by Dr. Chris Fairall of the NOAA Earth System Research Laboratory, Boulder, CO). In addition, as each buoy has two redundant meteorological systems, analysis of the data from the pairs of sensors further supports identifying any drift. Longwave radiometers are calibrated using a blackbody in a water bath, and shortwave radiometers are calibrated against reference radiometers in the open. Calibrations have been done before and after deployment to examine effects of exposure on the buoy. Accuracies of buoy meteorological sensors based on laboratory and field calibrations and intercomparisons for monthly and longer time scales are incoming shortwave 4 Wm^{-2}, incoming longwave 5 Wm^{-2}, net longwave 2 Wm^{-2}, and net shortwave 3 Wm^{-2} (Weller, 2015).

4. Results

4.1. Evaluation Against Buoy Observations at Daily Time Scale

Evaluations of the satellite estimates of SW↓ and LW↓ radiative fluxes against the buoy at daily time scale were conducted for the period when the buoy observations and all the independent products were available. Namely, 1 July 2002 to 31 December 2007 (Figure 1). The best agreement with the buoy was found for the UMD/MODIS products, where linear fits (red) were closest to the 1 to 1 black dashed line. The correlation coefficient for both cases is high (above 0.80), the biases were 2.71 and 6.41 Wm^{-2} (which are about 1.4% and 1.7% of the mean), and the root-mean-square were 27.50 and 13.12 Wm^{-2} (which are about 13.8% and 13.12 of the mean), respectively. The UMD/MODIS, Global Energy and Water Exchanges/Surface Radiation Budget, ERA/Interim data used here are at 1° resolution (the original resolution of ERA-I data is 0.703125°; for the calculations presented here we have downloaded the 1° data as provided at the ERA-I official website). The Climate Forecast System Reanalysis data are 0.5° resolution and were upscaled to 1°. Among the reanalyses products, Climate Forecast System Reanalysis-buoy comparisons had the largest root-mean-square differences.

4.2. Evaluation of the Satellite-Based Annual Cycle Against Observations

Noting the strong annual cycle in SW↓ reported by Weller (2015), a comparison was made between the buoy and satellite surface radiation time series. The annual cycle of SW↓ and LW↓ radiative fluxes averaged for the period of 2002–2012 as observed from the buoy and the (UMD/MODIS) satellite radiative flux components over the annual cycle are plotted in Figure 2 and show that the satellite SW↓ annual cycle closely matches the observed annual cycle, while both the observed and satellite LW↓ show no significant annual cycle.

4.3. Evaluating Trends and Interannual Variability in the Satellite Radiative Fluxes

Weller (2015) reported significant trends in wind speed, wind stress, and latent heat flux during 2000–2009; there were also two periods of persistent negative air-sea heat flux associated with cool, fresh surface waters in 2006 and in 2007–2008, roughly aligned with La Niña events. During these events, though no correlated

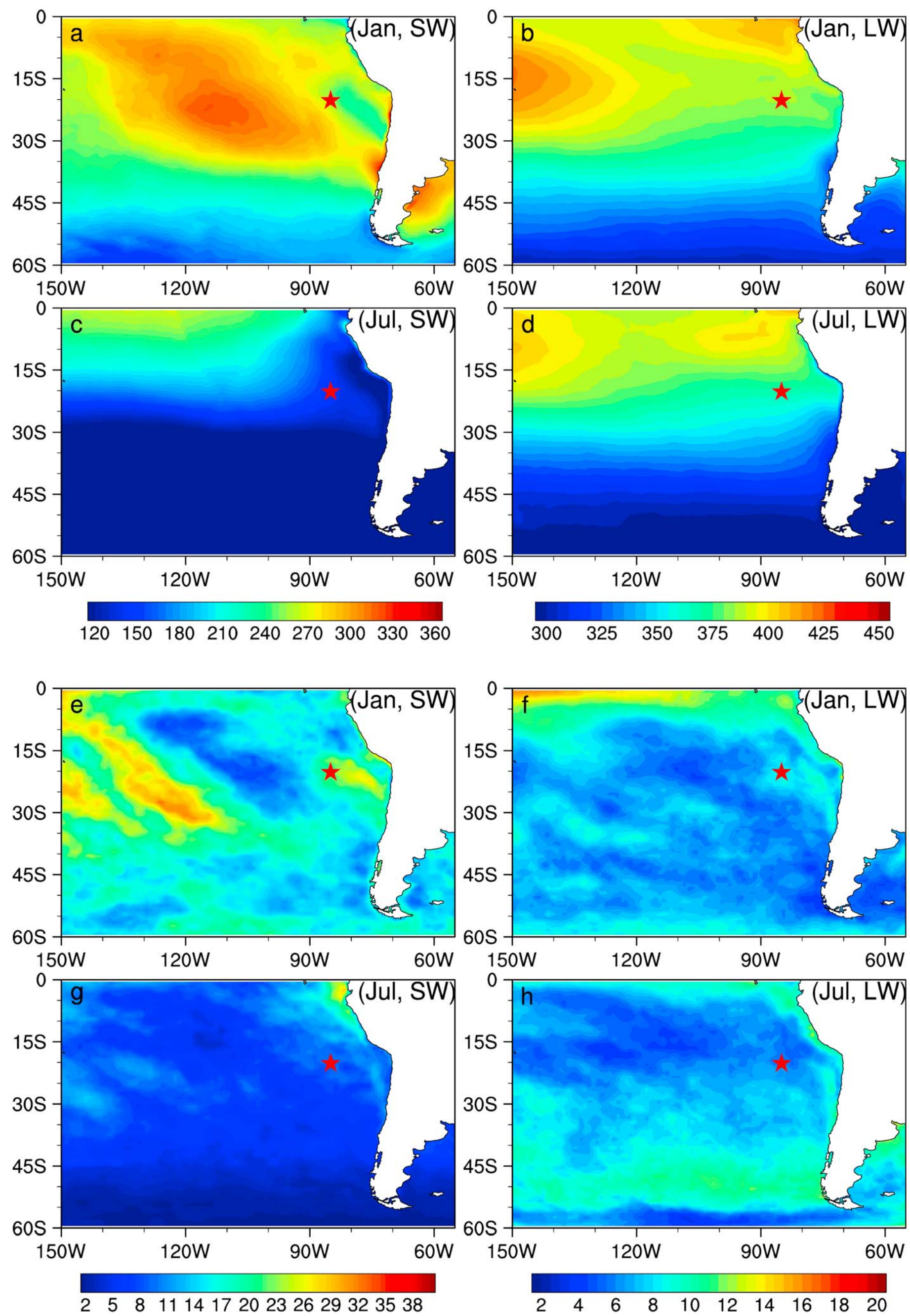

Figure 3. (top) Monthly average fields of radiative fluxes (University of Maryland/Moderate Resolution Imaging Spectroradiometer) for the STRATUS extended region during the period of 1 July 2002 to 7 July 2010. (left) SW↓ for January and July; (right) LW↓ for January and July; (bottom) spatial variability of the standard deviation (std) of monthly mean values at each point based on averages for the period (July 1983 to December 2012). The std values at the red star locations (20°S, 85°W) are January, SW~20.31; July, SW~8.78; January, LW~8.76; and July, LW~5.97.

variability was seen in buoy SW↓ and LW↓, air temperature was cooler and surface air was drier. Of interest was whether or not the satellite surface radiation time series were also as stable (lacking significant trends) and whether or not there was any interannual variability in the satellite time series, perhaps stemming from impacts of atmospheric variability associated with the La Niña events. Time series of daily anomalies (daily values minus the longer term daily annual cycle) of SW↓ and LW↓ fluxes were produced and statistics of the time series as well as the temporal variability of various low-pass filtered versions

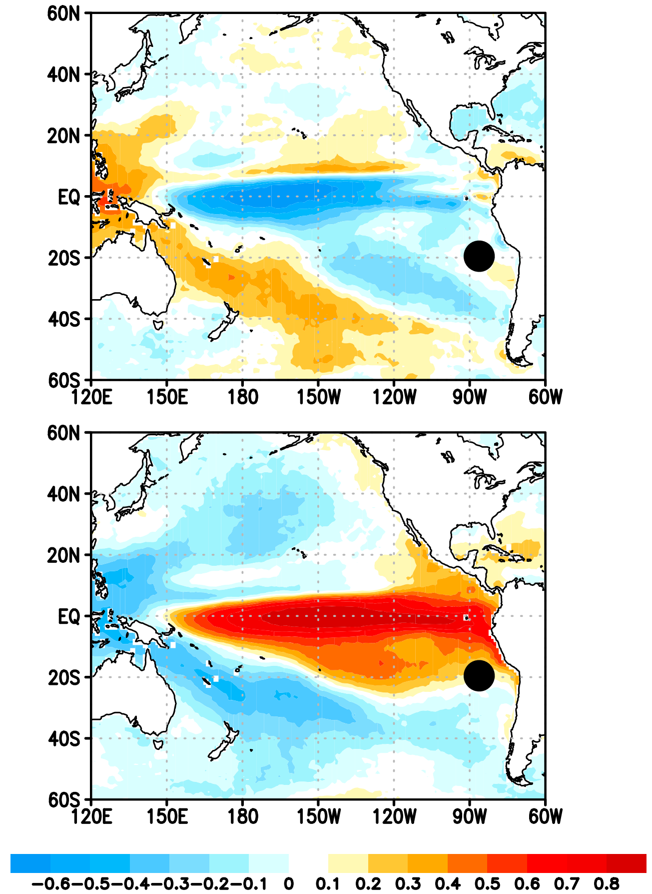

Figure 4. Correlations between Nino3 and (top) UMD_MODIS_SW (SW↓) and (bottom) UMD_MODIS_LW (LW↓) fluxes. Period: July 1983 to December 2012 (these longer time series are described in Pinker, Bentamy, et al. (2017) and Pinker, Grodsky, et al. (2017)). Location of STRATUS buoy is also shown as a black dot.

examined. A trend of 0.26 W m^{-2} yr^{-1}, which was not statistically significant, was found in the buoy SW↓ with the mean annual signal removed; the corresponding UMD/MODIS SW↓ had a nonsignificant trend of 0.15 W m^{-2} yr^{-1}. The buoy anomalous LW↓ had a trend of 0.00 Wm^{-2} yr^{-1}, while the UMD/MODIS anomalous LW↓ had a nonsignificant trend of 0.03 Wm^{-2} yr^{-1} (figures for the satellite trend comparison are not shown). By applying a 5 day running mean and other low-pass filters, it was anticipated that there might be apparent anomalies in satellite surface radiation in 2006 and again in 2007 to 2008. However, the appearance and alignment of such interannual variability in satellite surface radiation with 2006 and 2007–2008 were not found, matching the same lack of such a signal on the buoy SW↓ and LW↓. The lack of significant trends and interannual variability in both the satellite and STRATUS surface radiation suggests that the satellite radiative fluxes have both a temporal stability and lack of sensitivity to variability in the lower atmosphere.

4.4. Climatology of Regional Radiative Fluxes

Given the good agreement between UMD/MODIS and STRATUS SW↓ and LW↓, satellite radiative fluxes were used to examine further the characteristics of the larger domain in which the buoy is embedded. In particular, finding that surface air and sea temperatures at STRATUS showed variability coincident with La Niña events, while surface radiative fluxes there did not show interannual variability motivated an examination of where STRATUS was located with respect to where ENSO variability in surface radiative fluxes was found. The 9 year climatology of SW↓ and LW↓ fluxes from the UMD satellite product for January and July in the domain bounded by 55°W to 155°W and 60°S to 20°S is shown in Figure 3. This domain was selected to match the one selected in Weller (2015) where the mean sea level pressure and mean 10 m wind vectors for September 2001 as obtained from the National Center for Environmental Prediction-Department of Energy Reanalysis-2 (Kanamitsu et al., 2002) are illustrated. In this domain, the SW↓ flux maximum location moves from about 25°S, 100°W in January to the northwest in July. For LW↓ the move is not as dramatic as for the SW↓. We have also further investigated the relationship between radiative fluxes at the STRATUS buoy site and the Nino3 Index but found low correlations. The explanation for this finding can be found in Figure 4 that shows the correlation between the radiative fluxes and Nino3 over large portion of the Tropical Pacific. As seen, the location of the buoy is at the fringes of such an influence.

5. Summary

Observational studies have identified open cells embedded in the uniform stratocumulus decks which complicate their representation in models (Stevens et al., 2005). Difficulties were also reported in comparisons with satellite observations. For instance, Ghate et al. (2009) found that low cloud fraction derived from the International Satellite Cloud Climatology Project (Rossow & Schiffer, 1999) compared poorly with low cloud fraction derived from the STRATUS ORS. Thus, it is important to establish to what extent *more recent* satellite observations of clouds that are used for retrieval of surface radiative fluxes (which as yet, do not account for the complex structure of such boundary layer clouds) can reproduce the observations from STRATUS ORS. Such insights could provide valued information for studies that deal with coupling between the ocean and atmosphere in the eastern tropical South Pacific. Confidence in satellite-based information is gained by evaluation against ground observation of high quality. Information over oceans, especially, for longer time periods, is not readily available. The STRATUS ORS has been operational for over 10 years and is located in the stratus deck regions of the Eastern Pacific, which is scientifically challenging (Zheng et al., 2011). The observations from ORS meet challenges facing the satellite community. In this study, we found excellent agreement between MODIS-based satellites and buoy observations of SW↓ and LW↓ fluxes and in their representation of the annual cycles. We have also compared trends in these variables as available from the two independent sources. Both the buoy and collocated satellite SW↓ and LW↓ lacked significant trends or interannual variability. Given this validation the satellite fluxes were used to map where ENSO variability occurs, and the fluxes at STRATUS have very low correlation to Nino3. The confirmation of the quality of the UMD/MODIS fluxes is encouraging, since satellite observations are now available at longer time scales and could be used to study trends in this region as well as representing large-scale variability of the radiative fluxes in the region.

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