The Seasonal Cycle of the Radiation Budget and Cloud Radiative Effect in the Amazon Rain Forest of Brazil[Ⓔ]

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ABSTRACT

Changes in the climate system of the Amazon rain forest of Brazil can impact factors that influence the radiation budget such as clouds, atmospheric moisture, and the surface albedo. This study examines the relationships between clouds and radiation in this region using surface observations from the first year of the deployment of the Atmospheric Radiation Measurement (ARM) Program's Mobile Facility 1 (AMF1) in Manacapuru, Brazil, and satellite measurements from the Clouds and the Earth's Radiant Energy System (CERES). The seasonal cycles of the radiation budget and cloud radiative effects (CREs) are evaluated at the top of the atmosphere (TOA), at the surface, and within the atmospheric column using these observations and are placed into a regional context using the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). Water vapor and clouds are abundant throughout the year, even though slight decreases are observed in the dry season. The column water vapor load is large enough that the longwave radiative flux divergence is nearly constant throughout the year. Clouds produce a significant shortwave CRE at the surface and TOA, exceeding 200 W m^{-2} during the wet season. Discrepancies, especially in column shortwave radiative absorption, between the observations and MERRA-2 are demonstrated that warrant additional analysis of the microphysical and macrophysical cloud properties in MERRA-2. More trustworthy fields in the MERRA-2 product suggest that the expansive nearby river system impacts the regional radiation budget and thereby renders AMF1 observations potentially biased relative to regions farther removed from rivers within the Amazon rain forest.

1. Introduction

The Amazon rain forest is an important component of the global carbon and hydrologic cycles and is a region within the tropics with potential climate change sensitivities, especially with the recent trend of deforestation. Climate change is driven by alterations to regional and global radiation budgets, and uncertainties remain in the relationships between the biosphere, radiation, clouds,

and aerosols. It is therefore important to assemble a collection of observations from which models may be developed and evaluated and future observations may be compared to estimate the regional impacts of climate change in the Amazon rain forest. Observations presented in this study are particularly aimed at characterizing the radiation budget in the Amazon rain forest and especially the role of clouds upon it.

There have been past attempts to quantify radiation and energy budgets on regional and local scales in the tropics (Miller and Slingo 2007; McFarlane et al. 2008; Slingo et al. 2009; Parding et al. 2011; Miller et al. 2012; Collow et al. 2016a). These studies have produced either heating rate profiles or “bulk” measurements of the net radiative heating of the column, using the vertical cross-atmosphere radiative flux divergence (RFD). The RFD is presented in watts per meter squared and is defined so

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that net fluxes at the surface and the top of the atmosphere (TOA) are a positive quantity when there is net radiation transfer into the column. This sign designation means that a positive value of RFD (or the convergence of radiation into the column at its boundaries) implies bulk radiative heating within the column and a negative value implies radiative cooling. One of the first direct measurements of RFD is shown by [Miller and Slingo \(2007\)](#) using surface observations from radiometers and TOA radiative flux observations from a geostationary satellite for the column above Niamey, Niger, which lies in the West African Sahel region. Data from a single day with a resolution of 15 min demonstrated the impact of clouds on the downwelling shortwave (SW) radiation, and variability in the SW RFD resulting from changing cloud cover was easily detected through analyzing the SW radiation budget in combination with cloud radar data. [Slingo et al. \(2009\)](#) later expanded this study using the same dataset to provide a seasonal view over the West African Sahel and demonstrated that water vapor in the wet season prevented a portion of longwave (LW) radiation at the surface and within the lower troposphere from exiting at the TOA and that increased wet season clouds reflected, absorbed, and scattered incoming SW radiation, thereby preventing a portion from reaching the surface. An expanded study was presented by [Collow et al. \(2016a\)](#), which presented seasonal differences in the diurnal cycle of the RFD.

There is merit in computing the RFD and comparing it against simulated radiation budgets, but the RFD alone does not characterize the role of clouds in the column radiation budget. Combining vertical cross-atmosphere measurements of radiation with comprehensive knowledge of the clouds in the column provides a means of isolating, to a certain extent, the role of clouds in the bulk radiation transfer within the column. Two methods have been used in previous studies to make this calculation: the first uses a radiation transfer model in conjunction with measured thermodynamic and measured or estimated aerosol properties to compute the clear-sky flux and the second separates noncloudy and cloudy scenes in the observations and uses close-proximity noncloud scenes to estimate the clear-sky radiation budget. Each method has strengths and weaknesses.

[Miller et al. \(2012\)](#) presented a detailed analysis of the annual progression of RFD and cloud radiative effect (CRE) over the West African Sahel using the observation-separation method. The observed monthly RFD and CRE were compared to that projected in several general circulation models included in phase 3 of the Coupled Model Intercomparison Project. It was shown that clouds cause a slight net warming at the TOA

($\sim 20\text{--}40\text{ W m}^{-2}$) and more substantial net cooling at the surface ($\sim -30\text{--}100\text{ W m}^{-2}$) resulting in a net warming within the atmosphere as a result of an RFD between 30 and 70 W m^{-2} depending on the month. It was demonstrated that the regional radiation budgets over the Sahel portrayed in two commonly used GCMs contained improper partitioning of radiant energy between the surface and the atmosphere. It was also shown that some GCMs produce credible estimates of the net RFD and net CRE as a result of compensating errors.

[McFarlane et al. \(2008\)](#) used observations made on the islands of Nauru and Manus in the tropical western Pacific to investigate the impact of clouds on SW radiation. [McFarlane et al. \(2008\)](#) reported that low clouds tend to increase SW radiative absorption in the column compared to clear skies and that mid- and high-level clouds can either increase or decrease absorption depending on their location, particle size, and water vapor within the column. Their study suggested that averaging over the course of a day makes it difficult to detect variability in the absorption of radiation by clouds as the averaged data showed less than 5 W m^{-2} of absorption in many cases. [Parding et al. \(2011\)](#) also examined SW absorption in the tropical western Pacific within clouds using ground-based and satellite measurements. [Parding et al. \(2011\)](#) demonstrated that in order to reduce temporal and spatial mismatches in the data between the two boundaries in their study area, a 3-h average was required.

Previous studies have shown the radiation budget, and its controls in one tropical location may not be indicative of that in another. A lack of comprehensive knowledge of the tropical climate is a weakness in our understanding of the global energy budget, so more detailed studies, such as the current one, are desired. [Collow et al. \(2016a\)](#), [Miller et al. \(2012\)](#), [McFarlane et al. \(2008\)](#), and [Parding et al. \(2011\)](#) provide a solid framework from which to investigate the impact of clouds upon the radiation budget over the Amazon rain forest.

Numerous studies have analyzed the surface radiation budget in Amazonia, and many have focused upon the influence of biomass burning on solar insolation ([Eck et al. 1998](#); [Schafer et al. 2002](#); [Rosário et al. 2011](#)). Increased cloudiness during the wet season results in a decrease in the solar radiation reaching the surface with a reduction in insolation of 125 W m^{-2} at the diurnal maximum observed around local noon ([Hahmann and Dickinson 1997](#); [Culf et al. 1998](#); [Malhi et al. 2002](#)). Simulations of cloud radiative forcing suggest that almost triple the amount of SW radiation can reach the surface in the absence of clouds ([Culf et al. 1998](#)), although clouds are not the only feature within the atmosphere that can impact downwelling

SW radiation in this region. The aerosol single scattering albedo at both 440 and 870 nm can exceed 0.9 on average and the aerosol optical depth (AOD) at 440 nm can exceed unity when smoke is present (Schafer et al. 2002; Rosário et al. 2011), although the likelihood of smoke over this region of the Amazon rain forest is relatively small. With a surface albedo around 0.13 in the surrounding region, or smaller, because of dense vegetation, some of the downwelling solar radiation is reflected at the surface resulting in a daily maximum absolute value of the net surface SW radiative flux of about 625 W m^{-2} in the dry season and 500 W m^{-2} in the wet season (Giambelluca et al. 1997; Culf et al. 1998; Malhi et al. 2002).

Previous studies have not directly measured the surface upwelling and downwelling components of the LW radiative flux. As a result, these studies calculate the net LW radiative flux by subtracting the net SW radiative flux from the net all-wavelength flux (Culf et al. 1998; Malhi et al. 2002). Cloudiness and large values of water vapor prevent LW radiation from escaping to space, sending much radiation back to the surface, resulting in small values of net LW radiation at the surface. The net LW flux at the surface is relatively minuscule compared to the net SW flux, and through the course of the year the average monthly values of net LW flux leaving the surface never exceeds 35 W m^{-2} (Culf et al. 1998). Overnight the LW flux is slightly negative and only deviates from this value during the afternoon in the wet season and during sunlight hours in the dry season (Malhi et al. 2002). As a result of the small net LW flux, the net surface flux is positive during the day (the surface absorbs radiation) and minuscule at night (Malhi et al. 2002). To date, little work has been done incorporating radiative fluxes measured at the top of the atmosphere with those measured at the surface, therein creating a need for an understanding of the cross-atmosphere radiation budget over the Amazon.

Conspicuously absent from previous studies of regional radiation budgets is the issue of spatial variability over the land surface. This omission is largely due to the absence of data from which to potentially quantify this variability and prior to this study this is certainly true for the Amazon rain forest. Yet spatial variability when viewed through the lens of climate change may be the most important aspect of the current and future radiation budget in the region. It is addressed here using a combination of surface measurements and assimilated data and the analysis suggests that even in an area as broad as the Amazon rain forest far removed from significant biomass burning and with its assumed relatively homogeneous tree canopy, important regional differences in the radiation budget are implied.

The following section details the observations and data used in this study while results showing monthly averaged radiative fluxes and divergences, in addition to cloud radiative effect from observations and reanalysis in the Amazon rain forest of Brazil can be found in section 3.

2. Data and methods

a. AMF1

The Atmospheric Radiation Measurement (ARM) Program's Mobile Facility 1 (AMF1) was stationed in Manacapuru, Brazil ($3^{\circ}12'46.70''\text{S}$, $60^{\circ}35'53.0''\text{W}$, with 49-m altitude), throughout the year of 2014 as part of the Green Ocean Amazon (GOAmazon 2014/15) field campaign. This suite of instruments collected observations of meteorological, radiation, and aerosol conditions at the surface and within the troposphere above the site. Hemispheric pyranometers measured upwelling and downwelling SW radiative fluxes between 0.3 and $3 \mu\text{m}$, while hemispheric pyrgeometers measured long-wave radiative fluxes between 4 and $50 \mu\text{m}$ with uncertainties of 6% for SW and 2.5% for LW radiation (Stoffel 2004; Morris et al. 1996a,b). The radiometers were mounted 10 m above ground level in a well-maintained grass field and collected observations every minute. Clouds were analyzed using output from the Active Remote Sensing of Clouds (ARSCL) value-added product (Clothiaux et al. 2001), which combines data from a micropulse lidar (MPL), laser ceilometer, and vertically pointing 95-GHz cloud radar in addition to an MPL cloud mask value-added product based on Wang and Sassen (2001) at a temporal resolution of 30 s (Sivaraman and Riihimäki 1996). Cloud fraction was computed from the ARSCL dataset using the cloud mask as described by Kollias et al. (2007). ARSCL data are available beginning 28 April 2014, while the MPL cloud mask is available for the entire year of 2014. Liquid water path and integrated water vapor were measured by a line-of-sight microwave radiometer every 20 s, and these data have undergone extensive quality control (Cadeddu 1993). Aerosols are assessed using observations from a cloud condensation nuclei counter (Jefferson et al. 2010). Quality control through the ARM data stream protocol has been applied to all AMF1 observations. A true analysis of the energy budget must include the sensible and latent heat fluxes. Because of unexpected difficulties that arose throughout the campaign, the surface heat fluxes will not be included in this study. Additional information on the AMF1 and its instruments can be found in Miller and Slingo (2007) and Mather and Voyles (2013).

b. CERES

Measurements of the TOA radiative fluxes and cloud fraction were made by Clouds and the Earth's Radiant Energy System (CERES), which are on board the *Aqua* and *Terra* satellites (Wielicki et al. 1996). These satellites are on near-polar orbits and cross the equator at 1030 and 1330 local time. CERES contains a broadband radiometer that measures radiation between 0.2 and 100 μm , with the cutoff between the SW and LW radiation channels at 5 μm and a spatial resolution of 20 km (Wielicki et al. 1996). CERES-observed radiances are used in conjunction with Moderate Resolution Imaging Spectroradiometer (MODIS) and are converted to radiative fluxes using an angular dependence model (Loeb et al. 2005). The CERES synoptic 1° (SYN1Deg) product, which provides data every 3 h at a spatial resolution of 1°, is used in this study. The CERES and MODIS combination also observes cloud properties that are temporally interpolated using observations from geostationary satellites to provide cloud fraction data every 3 h in the CERES SYN1Deg data product (Doelling et al. 2013). The SYN1Deg data product also provides clear-sky radiative fluxes by removing cloudy pixels from the grid cell (Rutan et al. 2015).

c. MERRA-2

Developed by the National Aeronautics and Space Administration's Global Modeling and Assimilation Office, the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), provides a spatially and temporally consistent view of weather and climate around the globe by assimilating observations into a numerical model. Data from MERRA-2 are available beginning in January 1980 through the present at 0.5° latitude by 0.625° longitude spatial resolution and a minimum time step of 1 h. SW radiation is parameterized according to Chou and Suarez (1999), while LW radiation is parameterized according to Chou et al. (2001). Clouds are internally generated and their radiative properties are parameterized. MERRA-2 improves upon Modern-Era Retrospective Analysis for Research and Applications by assimilating additional observations, using updated parameterizations including forced precipitation seen by the land surface, and using global mass constraints that were heretofore neglected (Reichle and Liu 2014; Molod et al. 2015; Takacs et al. 2016). An additional improvement to MERRA-2 is the assimilation of aerosol optical depth from MODIS and the Aerosol Robotic Network (AERONET) through the Goddard chemistry, aerosol, radiation, and transport model to allow for a simulation of dust, sea salt, black carbon, organic

carbon, and sulfate (Buchard et al. 2015). The Multi-angle Imaging SpectroRadiometer (MISR) is also used to assimilate aerosol optical depth over bright surfaces.

d. Calculations and methods

RFD and cloud radiative effect were calculated using the following equations as described by Collow et al. (2016a):

$$\text{RFD}_{\text{SW}} = I_0 - \text{SW}\uparrow_{\text{TOA}} + \text{SW}\uparrow_{\text{surface}} - \text{SW}\downarrow_{\text{surface}}, \quad (1)$$

$$\text{RFD}_{\text{LW}} = \text{LW}\uparrow_{\text{surface}} - \text{LW}\downarrow_{\text{surface}} - \text{LW}\uparrow_{\text{TOA}}, \quad (2)$$

$$\text{RFD}_{\text{net}} = \text{RFD}_{\text{SW}} + \text{RFD}_{\text{LW}}, \quad (3)$$

$$\begin{aligned} \text{CRE}_{\text{TOA}} &= \text{LW}\uparrow_{\text{TOA,clear}} - \text{LW}\uparrow_{\text{TOA}} \\ &\quad + \text{SW}\uparrow_{\text{TOA,clear}} - \text{SW}\uparrow_{\text{TOA}}, \end{aligned} \quad (4)$$

$$\begin{aligned} \text{CRE}_{\text{surface}} &= \text{LW}\downarrow_{\text{surface}} - \text{LW}\downarrow_{\text{surface,clear}} \\ &\quad + \text{SW}\downarrow_{\text{surface}} - \text{SW}\downarrow_{\text{surface,clear}}, \end{aligned} \quad \text{and} \quad (5)$$

$$\begin{aligned} \text{CRE}_{\text{atmosphere}} &= \text{CRE}_{\text{TOA}} - \text{CRE}_{\text{surface}} + \text{SW}\uparrow_{\text{surface}} \\ &\quad - \text{SW}\uparrow_{\text{surface,clear}}. \end{aligned} \quad (6)$$

The same sign convention has been used so any flux that is entering the atmospheric column, such as reflected surface SW radiation, is positive and any flux that is leaving the column, such as LW radiation emitted at the TOA, is negative. Similarly, a positive RFD means there is a net gain of radiation to the column so that the column is warming radiatively, while there is a net loss of radiation from the column if the RFD is cooling. Clear-sky SW and LW TOA and surface radiative fluxes were computed on a monthly basis using a technique similar to Ramanathan et al. (1989), Cess et al. (1995), Miller et al. (2012), and Collow et al. (2016a), and a detailed description of this methodology can be found in the appendix of Miller et al. (2012). The calculation of the clear-sky SW radiative fluxes relies on a linear relationship between the observed SW fluxes and the cosine of the solar zenith angle. Clear-sky LW radiative fluxes are determined based on the maximum outgoing TOA LW flux and minimum surface downwelling LW flux. As in other observational studies of cloud radiative effect, our results may be influenced by the method we used to calculate the clear-sky radiative fluxes. Relying primarily on observations has its drawbacks, and those used in this study to represent the clear-sky radiative fluxes when computing the CRE are those that represented the clearest conditions that were observed. We defend our choice philosophically by noting that truly clear skies in this region are extremely rare whereupon calculations of the clear-sky fluxes using a radiation

FIG. 1. Monthly averaged (a) observed liquid water path and MERRA-2 cloud water path (g m^{-2}), (b) integrated water vapor (cm), and (c) cloud coverage in Manacapuru, Brazil, during 2014 from observations (black) and MERRA-2 (red). Error bars represent the standard deviation of the daily averages.

transfer model will produce values of CRE that may exceed those that actually occur over the Amazon rain forest.

Solar insolation entering at the TOA from MERRA-2 is used for all calculations, including the observations of RFD. Following the calculations, all quantities were averaged over the course of a month based on daily averages and the standard deviation of the daily averages was calculated. Observations from AMF1 and CERES were compared to MERRA-2 as a validation exercise and to determine how well the observations at a station within the Amazon rain forest represent the regional climate. All radiative quantities are only presented for the CERES SYN1Deg 3-h time period while CERES is overhead, giving one time step during the day and one at night.

3. Results

a. Moisture, clouds, and aerosols

Meteorological contrasts between the wet and dry seasons, as shown by Collow et al. (2016b), can be linked to seasonal variations in the radiation budget at the TOA, at the surface, and within the atmospheric column. Figures 5 and 10 from Collow et al. (2016b) have been expanded upon to include a comparison to MERRA-2 and can be seen in Fig. 1. A seasonal cycle is present in the observations of atmospheric moisture, with maxima in the wet season of January through

March and minima in the dry season, which includes July, August, and September. Since MERRA-2 has difficulty distinguishing between liquid and ice water path through a temperature-only criterion, liquid and ice water path in MERRA-2 are combined and presented as cloud water path. Therefore, a direct comparison between the observations and MERRA-2 cannot be made, as observations of ice water path are not available. The line of sight microwave radiometer is not reliable during rainfall events, and therefore the number of available data points during the wet season is reduced, likely skewing the mean liquid water path to be slightly lower than reality. The observations have gone through extensive quality control measures based on rainfall and brightness temperatures giving confidence in the values presented. There is some overestimation of cloud water path in MERRA-2 for half of the year, between April and August, with the largest deviations around 100 g m^{-2} in April and August (Fig. 1a). Some of this overestimation could be related to ice in MERRA-2 that is not observed by the microwave radiometer. Despite the overestimation in the monthly means, the error bars, representing plus or minus one standard deviation of daily means within each month, overlap throughout the year. The day-to-day variability in cloud water path is underestimated in MERRA-2 during the wet season, which could be attributed to the comparison of a point observation to a grid box with 0.5° spatial resolution. Another possibility is that MERRA-2 could be missing deep convective events with high values of liquid water path during the wet season that would increase both the average and the standard deviation.

MERRA-2 is rather accurate in its assessment of the integrated water vapor, with MERRA-2 and the observations never deviating more than 0.15% of one another (Fig. 1b). MERRA-2 performs well for most months for cloud coverage as well. Cloud coverage is lower in the months of June and July in MERRA-2, with values that are more similar to CERES observations compared to observations from the micropulse lidar. This is not surprising considering both MERRA-2 and CERES SYN1Deg are gridded products that incorporate the Goddard Earth Observing System Data Assimilation System (Doelling et al. 2013; Molod et al. 2015).

While MERRA-2 performs well in comparisons with observations of vertically integrated thermodynamic fields, there are shortcomings when it is compared to vertical profiles of the monthly average cloud fraction as seen in Fig. 2. Since the cloud radar was not fully operational at the onset of the AMF1 deployment, observations of the vertical profile of cloud fraction are presented beginning in May. As discussed by

FIG. 2. Monthly average vertical profile of cloud fraction for the year 2014 in Manacapuru, Brazil, from observations (black) and MERRA-2 (red).

Collow et al. (2016b), deep convection occurs in the wet and transition seasons with clouds spanning the troposphere. The drying of the midtroposphere during the dry season results in a bimodal vertical profile of cloud fraction with maxima near the surface and in the cirrus layer (Figs. 2f–h). Regardless of the season, MERRA-2 lacks low-level cloudiness and exaggerates the cloud fraction above 10 km. Low-level clouds are an important determinant of SW absorption in the tropics as shown by McFarlane et al. (2008), and this is likely to impact the SW radiation budget and heating rate profile. Clouds are also displaced to higher altitudes in MERRA-2 relative to the observations in every month, which can play a role in the outgoing LW radiation (OLR).

One reason for the interest in the Amazon rain forest within the climate science community is the varying aerosol conditions. Air in the wet season is often considered pristine with aerosols limited to biogenic sources (Williams et al. 2002). Biomass burning becomes more common in the dry season, increasing the concentration of aerosols and therefore cloud condensation nuclei (CCN). CCN concentrations gradually increase through the transition season with an abrupt increase in August at both 0.4 and 1.1 supersaturation (Fig. 3). Daytime CCN concentrations peak in August while nighttime concentrations peak in September. The annual maximum daytime CCN concentration at 0.4 supersaturation is rather large, exceeding 1000 cm^{-3} , indicating that

aerosols may have an impact on the absorption of SW radiation within the column as well as the reflectivity of clouds. Aerosol absorption coefficients from the particle soot absorption photometer were also analyzed but are

FIG. 3. Monthly averaged daytime and nighttime CCN concentration at (a) 0.4 and (b) 1.1 supersaturation during the day (blue) and night (red) in Manacapuru, Brazil, during 2014. Error bars represent the standard deviation of the daily averages.

FIG. 4. Monthly averaged (a) daytime SW outgoing, (b) daytime LW outgoing, and (c) nighttime LW outgoing radiative flux at the TOA (W m^{-2}) in Manacapuru, Brazil, during 2014 from CERES observations (black) and MERRA-2. Error bars represent the standard deviation of the daily averages.

not shown since the results are nearly identical to the CCN concentrations. Aerosols are represented in MERRA-2; however, CCN data are not available. Total aerosol optical depth is assimilated and the model includes an algorithm to separate this into aerosol optical depths of black carbon, organic carbon, sea salt, dust, and sulfates that can impact the radiation budget. Aerosol optical depth is difficult to observe in regions that are often cloudy, such as the Amazon, and in this case daily aerosol optical depth data is available for less than half of the year. As a result, aerosol optical depth is not discussed.

b. Radiative fluxes and divergences

The radiative fluxes leaving at the TOA as measured by CERES and calculated by MERRA-2 can be seen in Fig. 4. Absolute and percent differences between the observations and MERRA-2 in the TOA radiative fluxes, as well as for all other radiative quantities, can be found in the supplemental material. The SW and LW radiative fluxes plotted are the monthly averages of the afternoon and overnight observations made by CERES and the corresponding data points from MERRA-2. The TOA SW flux overnight is zero so only the afternoon observation is shown. The observed annual maximum reflection of SW radiation occurs in February, which coincides with the annual maximum in cloud fraction as observed by CERES and the MPL and the annual maximum in solar radiation (Figs. 1c and 4a). A general correlation can be seen between reflected SW radiation

and cloud fraction with the annual minimum occurring in September.

On average, MERRA-2 overestimates the amount of SW radiation leaving at the TOA, although an exception to this can be seen during June and July. June and July experience the annual minima in solar insolation, and although there is an overestimation in cloud water path, there is some uncertainty in the observations of cloud fraction, possibly related to low-level fog not detected by CERES. As a result it is difficult to say whether the accuracy during these months is related to the annual minimum in solar insolation or cloud properties. The annual maximum solar insolation occurs in February, which experiences the smallest difference in TOA SW radiation between the observations and MERRA-2, aside from June and July. The largest overestimation in reflected SW radiation at the TOA occurs in April and August, corresponding to the two months with the largest overestimation of the average cloud water path. Cloud fraction in MERRA-2 agrees quite well with the observations from the micropulse lidar, indicating clouds are likely too reflective in MERRA-2 during these months. The overestimation in reflected SW radiation in the transition to the wet season during September, October, and November is the reverse with too-frequent cloudiness.

The amplitude of the seasonal cycle in LW radiation emitted at the TOA is smaller than that for SW radiation, encompassing a spread of around 50 W m^{-2} (Figs. 4b,c). The influence of atmospheric moisture and clouds can easily be seen with a maximum of OLR in the dry season and a minimum in the wet season. Even with year-round cloudiness, the annual average TOA LW radiative flux is very similar to the global annual mean of 239 W m^{-2} (Trenberth et al. 2009). MERRA-2 captures both the magnitude and variability of the OLR however a small underestimation, below 30 W m^{-2} , can be seen throughout the year during the day and at night (Figs. S3b,c in the supplemental material). This underestimation is consistent with the vertical profile of cloud fraction seen in MERRA-2 and the observations, as cooler cloud-top temperatures reduce OLR.

The influence of clouds and moisture throughout the year can also be detected in the annual cycle of the surface radiative fluxes and is most obvious through an increase in the downwelling component of the surface SW radiative flux during the dry season (Fig. 5). Aerosols likely have little impact on the annual cycle of downwelling SW radiation at the surface. The wet season is rather pristine as has been noted in previous studies and MERRA-2 estimates monthly mean aerosol radiative effects below 10 W m^{-2} , peaking in September (not shown). The annual maximum in the downwelling

FIG. 5. Monthly averaged surface (a) downwelling SW, (b) upwelling SW, (c) net SW, (d) downwelling LW, (e) upwelling LW, and (f) net LW radiative flux (W m^{-2}) in Manacapuru, Brazil, during 2014 from observations (black) and MERRA-2 (red). Monthly averaged daytime (solid) and nighttime (dashed) LW fluxes are shown. Error bars represent the standard deviation of the daily averages.

component of the surface SW radiative flux occurs at the same time as the maximum cooling resulting from aerosols in MERRA-2. The largest discrepancies between MERRA-2 and the observations, exceeding 100 W m^{-2} , occur in June and July, which is when MERRA-2 is the most accurate in representing the SW flux leaving at the TOA (Fig. S5a in the supplemental material). Accuracies in SW radiation at the TOA are not in phase with those at the surface hinting that MERRA-2 may be correct at the surface or TOA for a given month but potentially for the wrong reasons. MERRA-2 also tends to have a smaller standard deviation in the surface SW radiative fluxes, lacking some of the day-to-day variability seen in the observations.

The upwelling component of the surface SW radiative flux is always lower in MERRA-2 and has a slightly lower-amplitude seasonal cycle (Fig. 5b). The annual average albedo while CERES is overhead is 0.093 in MERRA-2 compared to 0.1873, which was observed at the AMF1 site, making it likely that MERRA-2 has an albedo that is more representative of the Amazon rain forest than the observation site. The radiometers are located in a grass field, while the surrounding area comprises a mature forest. The albedo of a grass field tends to be a bit higher than the albedo in a rain forest (Giambelluca et al. 1997). The biggest difference in albedo occurs in August with roughly 70 W m^{-2} of

SW radiation not being reflected by the surface in MERRA-2 (Fig. S5b). This is somewhat contradictory to the SW TOA radiative flux considering MERRA-2 sees an excess amount of SW radiation leaving at the TOA. The differences in the upwelling component of the surface SW flux between MERRA-2 and the observations are also present in the net surface SW flux (Fig. 5c).

An interesting feature of the radiation budget is the ratio of the upwelling and downwelling LW radiative fluxes (Figs. 5d and 5e). A very large percentage of the LW radiation emitted by the surface is absorbed by the atmosphere and emitted toward the surface as indicated by the net LW flux at the surface, although these observations show a slightly larger net LW flux than what was reported in Manaus by Culf et al. (1998) (Fig. 5e). Clouds and moisture prevent a large fraction of LW radiation from reaching the TOA, thereby warming the troposphere and surface. The correlation coefficient between the daily average surface downwelling LW flux, normalized by the Stefan–Boltzmann constant multiplied by 2-m temperature to the power of 4, and integrated water vapor is 0.62, which indicates a strong relationship between the two. The variability within the components of the surface LW flux is minimal, especially when compared to the variability with each month of the downwelling surface SW radiative

FIG. 6. Monthly averaged (a) daytime SW, (b) daytime and nighttime LW, and (c) daytime net RFD (W m^{-2}) in Manacapuru, Brazil, during 2014 from observations (black) and MERRA-2 (red). Monthly averaged daytime (solid) and nighttime (dashed) RFDs are shown. Error bars represent the standard deviation of the daily averages.

flux. However, the diurnal cycle of the surface LW fluxes are muted in MERRA-2 as the daytime and nighttime upwelling and downwelling LW radiative fluxes lie in between the observed daytime and nighttime fluxes.

Heating (or cooling) of the column gases and particles can be quantified with the vertical cross-atmosphere RFD and is shown in Fig. 6. The annual progression of the daytime SW RFD is a function of both clouds and solar insolation with more SW radiation absorbed within the column when clouds are more frequent and solar insolation is maximized (Fig. 6a). SW RFD spans roughly 50 W m^{-2} throughout the year, which is smaller than the annual range in the TOA SW radiative flux and the downwelling SW radiative flux. THE SW RFD increases between May and September at the same time solar insolation increases and cloudiness decreases. Deep convective wet season clouds are more reflective than upper-level dry season clouds sending more SW radiation to space that is therefore not available to heat the column. MERRA-2 drastically underestimates the amount of SW radiation absorbed within the column with differences in monthly mean ranging between 120 and 170 W m^{-2} (Fig. S7a in the supplemental material). This underestimation is consistent with the fact that MERRA-2 has too much SW radiation leaving at the TOA and too much net SW radiation absorbed at the surface. The largest difference in SW RFD between the observations and MERRA-2 occurs in June and July despite the fact that MERRA-2 is accurate at the TOA during those months.

MERRA-2 fails to capture the observed day-to-day variability in the observations of SW RFD, and, although the magnitude in SW RFD does not change much throughout the year, there are subtle differences between MERRA-2 and the observations in the limited seasonal cycle. The seasonal cycle in MERRA-2 appears to be more closely tied to the annual progression in solar insolation, as opposed to cloudiness as seen in the observations, with the annual minimum in SW RFD coinciding with the annual minimum in solar insolation. However, the range between the annual minimum and maximum SW RFD is rather accurate in MERRA-2, less than 2 W m^{-2} away from the observations. Clouds in MERRA-2 are likely not absorbing a consistent amount of radiation throughout the year and are instead reflecting it to space.

The LW RFD is roughly constant between January and April, indicating that water vapor is playing a larger role on the absorption of LW radiation with the column than clouds as liquid water decreases in the column in April while the LW RFD does not change (Fig. 6b). Furthermore, a comparison with the clear-sky fluxes shows the amount of LW radiation absorbed within the column due to clouds during this time period is not consistent (Fig. 7h, discussed later). The annual minimum LW RFD occurs in June and July even though the minima in clouds and moisture occur in August and September. This could be related to the annual maximum surface temperature occurring during August and September or the large increase in CCN concentrations seen during those two months. Overall, MERRA-2 is more accurate in the LW RFD than the SW RFD, especially during the day. At night there is roughly 20 W m^{-2} more LW radiation absorbed by the column in the observations (Fig. S7b).

Through the course of the year, the positive daytime net cross atmosphere RFD indicates that the column is warming radiatively midday (Fig. 6c). Since the LW cross-atmosphere RFD has a smaller annual amplitude, the SW cross-atmosphere RFD takes an active role in determining how the net cross atmosphere RFD will change. The underestimation of the SW RFD is evident in the net RFD with the differences between MERRA-2 and the observations linked to the SW RFD given that the LW RFD is rather accurate during the day. A small cancellation of errors occurs when MERRA-2 absorbs too much LW radiation (e.g., in May); however, this is minimal and is only on the order of $5\text{--}10 \text{ W m}^{-2}$.

c. Cloud radiative effect

The impact of clouds on the radiation budget in Manacapuru, Brazil, can be seen in the CRE as presented in Fig. 7. Maximum SW radiative cooling at the

FIG. 7. Midday and nighttime monthly averaged (a) SW, (b) LW, and (c) net surface CRE (W m^{-2}); (d) SW, (e) LW, and (f) net TOA CRE (W m^{-2}); and (g) SW, (h) LW, and (i) net atmospheric CRE (W m^{-2}) in Manacapuru, Brazil, during 2014 from observations (black) and MERRA-2 (red). Error bars in (i) represent the standard deviation of the daily averages.

surface at midday due to clouds occurs in the wet season and minimum cooling occurs in the dry season, with the annual cycle tied to the annual cycle in cloud fraction (Fig. 7a). MERRA-2 always underestimates SW cooling at the surface because of clouds with the biggest difference, about 175 W m^{-2} , in July (Fig. S9a in the supplemental material). This is not too surprising considering MERRA-2 underestimates cloudiness and the largest deviation in SW RFD occurs during this month. Interestingly, the surface SW CRE is most accurate in MERRA-2 only one month later in August. It is likely that the surface SW CRE is only 12 W m^{-2} different between MERRA-2 and the observations during this month for incorrect reasons. Absorption of SW radiation is greatly underestimated in August, and this is also the same month that sees the largest deviation between MERRA-2 and observations in the TOA SW radiative flux and cloud water path. LW radiative warming at the surface due to clouds is nearly constant and almost negligible through the year with little difference between day and night (Fig. 7b). MERRA-2 produces a slightly smaller surface LW CRE throughout the year during the day and at night, but this difference remains below 25 W m^{-2} (Fig. S9b). This minimal impact in LW radiation results in a net cooling at the surface because of clouds that is dominated by the surface SW CRE (Fig. 7c).

Cooling of the earth-atmosphere system also occurs at the TOA (Fig. 7d). The largest TOA SW CRE occurs in

February in the observations and March in MERRA-2, coinciding with the annual maximum cloud fraction (Figs. 1c and 7d). Clouds impose a smaller cooling at the TOA as the transition season progresses. MERRA-2 overestimates the SW radiative cooling at the TOA, which is in line with a bright bias seen in global validation efforts (Bosilovich et al. 2015). Unlike at the surface, the TOA LW CRE is not stable throughout the year and plays a role in the radiation budget. While still smaller than the impact of clouds on SW radiation, the LW TOA CRE is roughly constant through the wet season but then decreases into the transition season (Fig. 7e). The lack of deviation during the wet season indicates that water vapor dominates the LW TOA CRE rather than clouds. There is a net cooling because of clouds at the TOA, and, although the SW and LW TOA CRE mirror one another, the seasonal cycle of clouds and moisture is evident in the annual progression (Fig. 7f).

Although clouds are extensively cooling the earth-atmosphere system in SW radiation at the surface and TOA, they provide a warming in the column heat budget with an annual average of roughly 100 W m^{-2} but only 65 W m^{-2} in MERRA-2 (Fig. 7g). Clouds reflect more SW radiation than is absorbed, leading to large changes at the boundaries but small changes within the column itself. Most of the underestimation in SW CRE in MERRA-2 occurs in the dry and transition seasons, which are when the largest deviation in SW RFD occurs. The difference in SW RFD between the observations

and MERRA-2 is larger than the deviation in SW CRE, indicating there is something other than clouds within the column that is not absorbing enough SW radiation, especially during the wet season when there is over 100 W m^{-2} of SW radiation that is not absorbed. It is also possible that the wet season has a similar SW CRE in the observations and MERRA-2 since the technique used to define the clear-sky SW radiative fluxes results in the clearest observed fluxes as opposed to the completely clear-sky fluxes seen in MERRA-2. This is likely to be a larger issue during the wet season when it is cloudy over three-quarters of the time, giving differing results between the two seasons.

Radiation absorption when the atmosphere is cloudy also occurs in the LW radiation part of the spectrum (Fig. 7h). Clouds tend to either warm the column or be somewhat negligible (during the dry season) in LW radiation according to the observations. MERRA-2 overestimates the atmospheric LW CRE, always warming the column because of clouds, with the largest overestimation, nearly 50 W m^{-2} , occurring in August (Fig. S9h). The observations of net atmospheric CRE do not appear to have much of a seasonal cycle because the SW and LW CREs counteract one another. In contrast, the underestimation of SW CRE in MERRA-2 during the dry season is evident in the net atmospheric CRE, with a minimum in the warming as a result of clouds within the column in July. This coincides with MERRA-2's annual minimum in cloud fraction.

d. Regional radiation budget

Land surface changes such as deforestation, along with the presence of the Amazon River and its tributaries, create a nonuniform landscape within the Amazon rain forest. The surface albedo varies based on whether the area is a mature forest, grass field, or body of water, which can therefore impact the regional radiation budget. In addition, the Amazon River can act as a moisture source and induce clouds. To determine how well the observations from the AMF1 represent the region, a regional view of the radiation budget and cloud radiative effect in MERRA-2 (e.g., months of the wet and dry seasons) is presented. February is chosen to represent the wet season while August is used for the dry season. The black dot in Figs. 8 through 13 represents the location of the AMF1, while the gray lines are the centers of the Amazon River and its tributaries. The Rio Negro is located north and west of the AMF1 in Manacapuru, Brazil, and the Rio Solimões is south and west. These two rivers merge to form the Amazon River to the east of the AMF1 near Manaus, Brazil. The Rio Negro and Amazon River are resolved in MERRA-2; however, the rivers to the south are not.

The regional LW, SW, and net radiative fluxes at the TOA can be seen in Fig. 8. There are seasonal differences in the magnitude and spatial pattern of LW radiation lost at the TOA. Smaller spatial variations within the region arise during the wet season compared to the dry season, likely because the column is inundated with so much moisture that the LW radiation window region between 8 and $12 \mu\text{m}$ is effectively closed. Higher surface temperatures to the south and east of the region (Fig. S11b in the supplemental material) create a strong gradient of LW radiation lost at the TOA during the dry season. The spatial patterns of total precipitable water vapor and high clouds also exhibit this gradient (Fig. S12b in the supplemental material), with fewer clouds and less vapor to the south and east to absorb LW radiation before it is lost at the TOA.

The influence of the Rio Negro, and to a lesser extent the Amazon River, can be detected in the spatial pattern of the wet season TOA SW radiative flux (Fig. 8c). While the cloud coverage is not increased in the immediate area around the rivers, the cloud optical thickness is larger, particularly for high clouds (not shown). The high clouds tend to allow some SW radiation to be transmitted, but the larger optical thickness during the wet season likely increases reflection and reduces transmission. During the wet season, the cloud coverage is quite substantial and rather stable. In contrast, cloud coverage, rather than cloud optical depth, plays a larger role in the TOA SW flux in August, and no influence from the rivers can be seen.

There is little spatial deviation in the net surface LW radiative flux, especially in the wet season, but the influence of the Rio Negro and Amazon River is still present (Figs. 9a and 9b). The net LW surface flux is slightly higher over these rivers. As discussed in section 3b, the LW radiative fluxes do not change much throughout the year because of the high loading of water vapor. Even though spatial variability is present in total precipitable water vapor, the IR window is essentially closed throughout the region regardless. It is therefore fitting that the surface LW radiative flux also exhibits minimal spatial variability. There is little spatial variation in 2-m temperature within the majority of the Amazon region south of the equator; however, differences in the surface LW radiative flux arise in the vicinity of the rivers because these areas tend to be warmer and moister than the surrounding areas. More variability in the net surface LW flux is present in August (Fig. 9b) because of the presence of a larger temperature and moisture gradient (not shown), even though the spatial pattern during the dry season net LW flux is dominated by the 2-m temperature. While the AMF1 is located in a grass field, the Rio Negro and Rio

FIG. 8. Regional (a),(b) LW, (c),(d) SW, and (e),(f) net TOA radiative flux (W m^{-2}) in (left) February and (right) August 2014 in the Amazon rain forest in MERRA-2. Gray lines indicate the center of rivers in the region, and the black dot indicates the location of AMF1.

Solimões are nearby. It is possible that the observations of the surface LW flux are influenced by the warm, moist air near the rivers, making our observations of the net surface LW radiation roughly 10 W m^{-2} larger than areas in the Amazon a distance away from the rivers.

Minimal spatial variability and change in the net LW radiative flux at the surface enables the net surface radiative flux to be dominated by the SW component (Fig. 9). The net surface SW radiative flux is nearly the inverse of the net TOA SW radiative flux. Areas with a decreased net TOA SW radiative flux, such as over the Rio Negro during the wet season, also see a less

negative net surface SW radiative flux. Those regions experience more reflection of SW radiation by clouds, thereby reducing the amount of SW radiation reaching the surface. The surface albedo is also a contributing factor to the surface SW budget and the albedo is lower over the rivers than the surrounding rain forest. But, this difference in albedo seems to be compensated by changes in cloud coverage, especially during the dry season.

Absorption of SW radiation shows little spatial variability across the Amazon rain forest as inferred from the similar spatial patterns found in the net surface and

FIG. 9. As in Fig. 8, but for the surface radiative flux.

TOA SW radiative fluxes. This can be seen in the unvarying regional SW RFD (Figs. 10c,d). However, given the underestimation of SW radiation absorbed within the column above the AMF1 in MERRA-2, there is uncertainty in whether SW RFD in the region is really as consistent as portrayed in MERRA-2. With consistent SW absorption within the region, the spatial pattern of the net RFD is dominated by the LW RFD (Fig. 10). Increased moisture and cloudiness absorb LW radiation along the Rio Negro and Amazon River in both February and August. The resulting LW RFD, and therefore net RFD, is less negative over the rivers as the column is losing less energy at the boundaries.

The spatially consistent SW RFD in the Amazon can be confirmed by investigating the CRE at the TOA, at the surface, and within the atmospheric column (Figs. 11–13). Like the observations made by the AMF1, clouds have a significant impact on the SW radiation at the TOA and surface. Along the Rio Negro, clouds produce an average SW radiative cooling of 130 W m^{-2} at the TOA and surface in February (Figs. 11c and 12c). This value is consistent with that reported by Culf et al. (1998) for Manaus. Dry season (August) spatial patterns of the TOA and surface SW CRE reflect the spatial pattern in cloud fraction; owing to reductions in cloud coverage and optical depth, the surface and TOA SW CREs are decreased. Yet the TOA and surface CREs

FIG. 10. As in Fig. 8, but for the RFD.

still larger than those observed during the wet season CREs in other continental tropical regions (Collow et al. 2016a). Clouds are not only prevalent but evidently they are highly reflective whereupon large CRE's are observed at the boundaries. Their impact on the column itself is, however, much less; the SW atmospheric CRE that is only a fraction of the TOA and surface CRE (Figs. 13c and 13d). It is also worth noting that MERRA-2 underestimates SW absorption as a result of clouds in August compared to the observation at the AMF1, and this could be true for the region as a whole.

As expected, the impacts of clouds in the LW radiation part of the spectrum at the TOA and surface are not as extreme as in the SW, with less spatial variation, but

nonetheless are still important in the net radiation budget (Figs. 11a,b and 12a,b). Little influence is seen from the rivers, as the entire region is abundant with water vapor. Colder cloud-top temperatures in the western part of the region and along 2°S in the wet season (not shown) decrease the LW radiation that is released to space at the TOA and result in a slightly larger TOA LW CRE. A similar feature is present in August, although the spatial pattern is different. When compared to cloud radar data at the AMF1, MERRA-2 tends to have higher, and therefore cooler, cloud tops. Without radar data from other locations within the region, it is difficult to state whether the spatial pattern in cloud-top temperature is accurate in MERRA-2. Together, the cloud-top

FIG. 11. As in Fig. 8, but for the TOA CRE.

temperature, cloud fraction, and column precipitable water vapor produce the spatial pattern of TOA LW CRE in the dry season. In the event that the spatial pattern of cloud-top temperature is not correct, the spatial pattern of TOA LW CRE will contain errors as well.

The column itself is warming radiatively as a result of clouds in LW, SW, and net radiation (Fig. 13). As discussed earlier, there is spatial homogeneity in the amount of SW radiation that is absorbed, and the amount of SW radiation is smaller than that absorbed in LW radiation. Thus, over the Amazon rain forest, the LW atmospheric CRE is the controlling factor for the spatial pattern of net atmospheric CRE. This result supports the observations presented in section 3b, and

in this respect, the observations from the AMF1 are representative of the region. However, spatial variations within components of the radiation budget exist in the Amazon rain forest as a result of deviations in surface and cloud properties. Influences from the Rio Negro and Amazon River are present, particularly during the wet season; however, this is not seen with the rivers located to the south as they are not fully resolved in MERRA-2.

4. Conclusions

The Amazon rain forest is in the midst of changes as a result of deforestation and the impacts of greenhouse

FIG. 12. As in Fig. 8, but for the surface CRE.

gas accumulation. A central question is the radiation budget in the region and how it might be altered by these changes. This study is based upon observations from the first year of a two-year deployment of the AMF1 near Manacapuru, Brazil, in the heart of the rain forest and in support of the GOAmazon 2014/15 field campaign, with the primary goal of documenting the interaction between clouds, aerosols, and the radiation budget in this important region. Measurements collected by the AMF1 are supplemented by measurements of the radiative fluxes and cloud fraction at TOA from CERES thereby enabling the CRE and other radiative quantities to be computed for the column above the AMF1 instrumentation. These point measurements are examined

in a regional context using MERRA-2, which is an assimilated product combining numerous satellite and in situ observations with a numerical model.

Persistent cloud cover and high moisture loads are a characteristic of the atmosphere in the Amazon rain forest and are controlling factors of the regional radiation budget. Radiation is absorbed within the column in the SW and the LW by clouds and water vapor, although the SW absorption (RFD) and the SW CRE are approximately double in magnitude relative to their LW radiation counterparts at midday. Shielding of the surface by copious clouds during the wet season produces a strong surface midday SW CRE, which at times exceeds -400 W m^{-2} , and a pronounced TOA SW CRE,

FIG. 13. As in Fig. 8, but for the atmospheric CRE.

which reaches as much as -300 W m^{-2} . The seasonal SW CRE sensitivity is clearly evident in that dry season values are at least half of those observed during the wet season. To the extent that MERRA-2 is able to accurately characterize the regional variability in SW CRE, the region would be best characterized as having a nearly constant spatial variability.

On average the atmosphere is cooling in the Amazon rain forest because of LW radiation emitted to space, but observed positive values of the atmospheric LW CRE indicate that clouds have a net warming effect on the column, as expected. That said, magnitudes of the LW CRE at the surface, at TOA, and net are in the neighborhood of 50 W m^{-2} or less. Considerably larger

observed magnitudes of the LW RFD ($\sim -200 \text{ W m}^{-2}$) confirms the expectation that water vapor loading is the primary modulator in the LW cross-atmosphere radiation budget. Unlike the SW RFD and CRE, which are indicated by MERRA-2 to be relatively constant across the region, the LW RFD and CRE show regional variability that correlates with surface structure and large-scale gradients. Warming in the LW is enhanced over the Rio Negro and Amazon River where the additional moisture can enhance LW absorption of radiation and higher cloud tops can reduce the amount of LW radiation lost at the TOA.

The performance of MERRA-2 is worth comment. MERRA-2 underestimates the atmospheric SW CRE in

the dry season, which contributes to the underestimation of SW absorption within the column. And the underestimation of SW RFD in the wet season suggests there are other components of the atmospheric column, potentially aerosols, which are not absorbing the correct amount of SW radiation. There is circumstantial evidence in these data that cloud optical thickness modulates the SW RFD and CRE during the wet season given the preponderance of clouds and that cloud fraction may be the dominant modulator during the dry season. Obtaining a statistically significant observation of aerosol optical depth is complex because of the large cloud fraction in the region and was not attempted in this study. Perhaps it can be examined in a future study. One undeniable finding of this study is that the clouds produced by the parameterizations used in MERRA-2 are unrealistic in this region. There are too many high clouds, a complete absence of shallow convective clouds, and suggested issues with cloud optical thickness. A serious limitation is that clouds simulated in MERRA-2 seem too reflective and not absorbing enough, which could be a result of the cloud overlap scheme that is used (Chou and Suarez 1999). Scaling of the cloud optical depth within a cloud layer tends to favor reflective properties when there are multiple cloud layers present in the column. Such issues with the representation of cloud properties are pervasive in many models, and MERRA-2 is no exception; for this reason we suggest caution when using SW radiation fields over the Amazon basin in MERRA-2. Partitioning of SW radiation between that lost at the TOA, absorbed by the surface, and absorbed within the column is not correct. Even if one of these three is correct, it is likely not for the right reasons given that the other two components are incorrect. Fixing this shortcoming would likely remedy a number of the issues that are found in the MERRA-2 SW and LW radiation budgets as compared to observations.

Correctly characterizing the surface albedo is difficult in the best of situations and using a single observation site in a grass field that is surrounded by a mature rain forest is clearly suspect. We therefore recommend the use of land surface models that might be able to reconcile this shortcoming or placing radiometers above the canopy of the rain forest to get measurements of the upwelling SW radiative flux at the surface that are more representative of the nearby forest and region.

The extraordinarily large midday SW CRE observed in this study appears to be a strong lever in the Amazon rain forest as deforestation continues and greenhouse gases accumulate. If deforestation modifies the regional daytime cloud cover, water vapor loading, or both, a strong response in the radiation budget would likely be

modulated by the SW CRE. Similarly, any change in the regional atmospheric circulation forced by anthropogenic greenhouse forcing that impacts daytime clouds in this region could invoke a strong radiative feedback via the SW CRE.

GOAmazon 2014/15 has already provided a wealth of new information from which to vet some of the more difficult process-related issues related to atmosphere-biosphere exchanges. An intriguing issue for future research is the extent to which the atmosphere and biosphere communicate through the radiation budget. And as the campaign continues it will be interesting to see how much year-to-year variability exists within the radiation budget in the Amazon rain forest. Intensive aircraft campaigns within GOAmazon 2014/15 will also enable future studies to analyze scattering and absorbing characteristics of clouds and the relationship between biogenic and anthropogenic aerosols, clouds, and the radiation budget within the region.

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REFERENCES

- Bosilovich, M. G., and Coauthors, 2015: MERRA-2: Initial evaluation of the climate. NASA Tech. Rep. NASA/TM-104606, 139 pp. [Available online at <https://gmao.gsfc.nasa.gov/pubs/tm/docs/Bosilovich803.pdf>.]
- Buchard, V., and Coauthors, 2015: Using the OMI aerosol index and absorption aerosol optical depth to evaluate the NASA MERRA aerosol reanalysis. *Atmos. Chem. Phys.*, **15**, 5743–5760, doi:10.5194/acp-15-5743-2015.
- Cadeddu, M., 1993: Microwave radiometer (MWRLOS). Subset used: 2014-01-09 to 2014-12-31, 3.21297 S 60.5981 W: ARM Mobile Facility (MAO) Manacapuru, Amazonas, Brazil; AMF1 (M1). ARM Climate Research Facility Data Archive, accessed 6 January 2015, doi:10.5439/1046211.
- Cess, R. D., and Coauthors, 1995: Absorption of solar radiation by clouds: Observation versus models. *Science*, **267**, 496–499, doi:10.1126/science.267.5197.496.

- Chou, M.-D., and M. Suarez, 1999: A solar radiation parameterization for atmospheric studies. NASA Tech. Rep. NASA/TM-1999-104606, 51 pp. [Available online at http://www2.mmm.ucar.edu/wrf/users/phys_refs/SW_LW/New_Goddard.pdf.]
- , X.-Z. Liang, and M. M.-H. Yan, 2001: A thermal infrared radiation parameterization for atmospheric studies. NASA Tech. Rep. NASA/TM-2001-104606, 68 pp. [Available online at http://www2.mmm.ucar.edu/wrf/users/phys_refs/SW_LW/Goddard_part2.pdf.]
- Clothiaux, E. E., and Coauthors, 2001: The ARM millimeter wave cloud radars (MMCRs) and the active remote sensing of clouds (ARSCL) value added product (VAP). DOE Tech. Memo. ARM VAP-002.1, 56 pp. [Available online at https://www.arm.gov/publications/tech_reports/arm-vap-002-1.pdf.]
- Collow, A. B., V. P. Ghatge, M. A. Miller, and L. Trabachino, 2016a: A one-year study of the diurnal cycle of meteorology, clouds, and radiation in the West African Sahel region. *Quart. J. Roy. Meteor. Soc.*, **142**, 16–29, doi:10.1002/qj.2623.
- , M. A. Miller, and L. Trabachino, 2016b: Cloudiness over the Amazon Rainforest: Meteorology and thermodynamics. *J. Geophys. Res. Atmos.*, **121**, 7990–8005, doi:10.1002/2016JD024848.
- Culf, A. D., G. Fisch, J. Lean, and J. Polcher, 1998: A comparison of Amazonian climate data with general circulation model simulations. *J. Climate*, **11**, 2764–2773, doi:10.1175/1520-0442(1998)011<2764:ACCOACD>2.0.CO;2.
- Doelling, D. R., and Coauthors, 2013: Geostationary enhanced temporal interpolation for CERES flux products. *J. Atmos. Oceanic Technol.*, **30**, 1072–1090, doi:10.1175/JTECH-D-12-00136.1.
- Eck, T. F., B. N. Holben, I. Slutsker, and A. Setzer, 1998: Measurements of irradiance attenuation and estimation of aerosol single scattering albedo for biomass burning aerosols in Amazonia. *J. Geophys. Res.*, **103**, 31 865–31 878, doi:10.1029/98JD00399.
- Giambelluca, T. W., and Coauthors, 1997: Observations of albedo and radiation balance over postforest land surfaces in the eastern Amazon basin. *J. Climate*, **10**, 919–928, doi:10.1175/1520-0442(1997)010<0919:OOAARB>2.0.CO;2.
- Hahmann, A. N., and R. E. Dickinson, 1997: RCCM2–BATS model over tropical South America: Applications to tropical deforestation. *J. Climate*, **10**, 1944–1964, doi:10.1175/1520-0442(1997)010<1944:RBMOTS>2.0.CO;2.
- Jefferson, A., and Coauthors, 2010: Cloud condensation nuclei particle counter (AOSCCN100). Subset used: 2014-01-01 to 2014-12-31, 3.21297 S 60.5981 W: ARM Mobile Facility (MAO) Manacapuru, Amazonas, Brazil; AMF1 (M1). ARM Climate Research Facility Data Archive, accessed 7 February 2015, doi:10.5439/1025150.
- Kollias, P., M. A. Miller, E. P. Luke, K. L. Johnson, E. E. Clothiaux, K. P. Moran, K. B. Widener, and B. A. Albrecht, 2007: The Atmospheric Radiation Measurement program cloud profiling radars: Second-generation sampling strategies, processing, and cloud data products. *J. Atmos. Oceanic Technol.*, **24**, 1199–1214, doi:10.1175/JTECH2033.1.
- Loeb, N. G., S. Kato, K. Loukachine, and N. Manalo-Smith, 2005: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the *Terra* satellite. Part I: Methodology. *J. Atmos. Oceanic Technol.*, **22**, 338–351, doi:10.1175/JTECH1712.1.
- Malhi, Y., E. Pegoraro, A. D. Nobre, M. G. P. Pereira, J. Grace, A. D. Culf, and R. Clement, 2002: Energy and water dynamics of a central Amazonian rain forest. *J. Geophys. Res.*, **107**, 8061, doi:10.1029/2001JD000623.
- Mather, J. H., and J. W. Voyles, 2013: The ARM climate research facility: A review of structure and capabilities. *Bull. Amer. Meteor. Soc.*, **94**, 377–392, doi:10.1175/BAMS-D-11-00218.1.
- McFarlane, S. A., J. H. Mather, T. P. Ackerman, and Z. Liu, 2008: Effect of clouds on the calculated vertical distribution of shortwave absorption in the tropics. *J. Geophys. Res.*, **113**, D18203, doi:10.1029/2008JD009791.
- Miller, M. A., and A. Slingo, 2007: The ARM Mobile Facility and its first international deployment: Measuring radiative flux divergence in West Africa. *Bull. Amer. Meteor. Soc.*, **88**, 1229–1244, doi:10.1175/BAMS-88-8-1229.
- , V. P. Ghatge, and R. K. Zahn, 2012: The radiation budget of the West African Sahel and its controls: A perspective from observations and global climate models. *J. Climate*, **25**, 5976–5996, doi:10.1175/JCLI-D-11-00072.1.
- Molod, A., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: Evolution from MERRA to MERRA2. *Geosci. Model Dev.*, **8**, 1339–1356, doi:10.5194/gmd-8-1339-2015.
- Morris, V., and Coauthors, 1996a: Ground radiometers on stand for upwelling radiation (GNDRAD60S). Subset used: 2014-01-01 to 2014-12-31, 3.21297 S 60.5981 W: ARM Mobile Facility (MAO) Manacapuru, Amazonas, Brazil; AMF1 (M1). ARM Climate Research Facility Data Archive, accessed 5 January 2015, doi:10.5439/1025192.
- , and Coauthors, 1996b: Sky radiometers on stand for downwelling radiation (SKYRAD60S). Subset used: 2014-01-01 to 2014-12-31, 3.21297 S 60.5981 W: ARM Mobile Facility (MAO) Manacapuru, Amazonas, Brazil; AMF1 (M1). ARM Climate Research Facility Data Archive, accessed 5 January 2015, doi:10.5439/1025281.
- Parding, K., L. M. Hinkelman, T. P. Ackerman, and S. A. McFarlane, 2011: Shortwave absorptance in a tropical cloudy atmosphere: Reconciling calculations and observations. *J. Geophys. Res.*, **116**, D19202, doi:10.1029/2011JD015639.
- Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, and B. R. Barkstrom, 1989: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. *Science*, **243**, 57–63, doi:10.1126/science.243.4887.57.
- Reichle, R. H., and Q. Liu, 2014: Observation-corrected precipitation estimates in GEOS-5. NASA Tech. Rep. NASA/TM-2014-104606, Vol. 35, 24 pp. [Available online at <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150000725.pdf>.]
- Rosário, N. E., M. A. Yamasoe, H. Brindley, T. F. Eck, J. Schafer, 2011: Downwelling solar irradiance in the biomass burning region of the southern Amazon: Dependence on aerosol intensive optical properties and role of water vapor. *J. Geophys. Res.*, **116**, D18304, doi:10.1029/2011JD015956.
- Rutan, D. A., and Coauthors, 2015: CERES synoptic product: Methodology and validation of surface radiant flux. *J. Atmos. Oceanic Technol.*, **32**, 1121–1143, doi:10.1175/JTECH-D-14-00165.1.
- Schafer, J. S., B. N. Holben, T. F. Eck, M. A. Yamasoe, and P. Artaxo, 2002: Atmospheric effects on insolation in the Brazilian Amazon: Observed modification of solar radiation by clouds and smoke and derived single scattering albedo of fire aerosols. *J. Geophys. Res.*, **107**, 8074, doi:10.1029/2001JD000428.
- Sivaraman, C., and L. Riihimäki, 1996: Cloud mask from micro-pulse lidar (30SMPLCMASK1ZWANG). Subset used: 2014-01-01 to 2014-12-31, 3.21297 S 60.5981 W: ARM Mobile Facility (MAO) Manacapuru, Amazonas, Brazil; AMF1 (M1). ARM Climate Research Facility Data Archive, accessed 6 January 2015, doi:10.5439/1027736.

- Slingo, A., H. E. White, N. A. Bharmal, and G. J. Robinson, 2009: Overview of observations from the RADAGAST experiment in Niamey, Niger: 2. Radiative fluxes divergences. *J. Geophys. Res.*, **114**, D00E04, doi:[10.1029/2008JD010497](https://doi.org/10.1029/2008JD010497).
- Stoffel, T., 2004: Ground radiation (GNDRAD) handbook. ARM Climate Research Facility Rep. ARM TR-027, 13 pp.
- Takacs, L. L., M. J. Suárez, and R. Todling, 2016: Maintaining atmospheric mass and water balance in reanalyses. *Quart. J. Roy. Meteor. Soc.*, **142**, 1565–1573, doi:[10.1002/qj.2763](https://doi.org/10.1002/qj.2763).
- Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. *Bull. Amer. Meteor. Soc.*, **90**, 311–323, doi:[10.1175/2008BAMS2634.1](https://doi.org/10.1175/2008BAMS2634.1).
- Wang, Z., and K. Sassen, 2001: Cloud type and macrophysical property retrieval using multiple remote sensors. *J. Appl. Meteor.*, **40**, 1665–1682, doi:[10.1175/1520-0450\(2001\)040<1665:CTAMPR>2.0.CO;2](https://doi.org/10.1175/1520-0450(2001)040<1665:CTAMPR>2.0.CO;2).
- Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth observing system experiment. *Bull. Amer. Meteor. Soc.*, **77**, 853–868, doi:[10.1175/1520-0477\(1996\)077<0853:CATERE>2.0.CO;2](https://doi.org/10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2).
- Williams, E., and Coauthors, 2002: Contrasting convective regimes over the Amazon: Implications for cloud electrification. *J. Geophys. Res.*, **107**, 8082, doi:[10.1029/2001JD000380](https://doi.org/10.1029/2001JD000380).