Evaluation of the Tropical TOA Flux Diurnal Cycle in MERRA and ERA-Interim Retrospective Analyses

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ABSTRACT

Reanalysis model output is extensively used in atmospheric research and must be rigorously and continuously evaluated to understand the strengths and weaknesses. This paper evaluates the tropical top-of-atmosphere (TOA) flux diurnal cycle in NASA’s Modern-Era Retrospective Analysis for Research and Applications (MERRA) and the ECMWF Interim Re-Analysis (ERA-Interim) against Clouds and the Earth’s Radiant Energy System (CERES) synoptic edition 3A (SYN Ed3A) TOA flux data. MERRA and ERA-Interim are able to reproduce large-scale features of the diurnal cycle, including land–ocean contrast. MERRA and ERA-Interim, however, fail to reproduce many regional features of the climatological annual diurnal cycle. The TOA flux diurnal cycle errors in regions dominated by convective diurnal cycles are 5–10 times larger than in nonconvective regions. These errors in the TOA radiative flux diurnal cycle are primarily attributed to errors in the cloud diurnal evolution and specifically the failure to reproduce diurnally forced propagating convection. The largest diurnal cycle errors are found in ocean convective regions (e.g., Indian and equatorial Pacific Oceans); the observed longwave cloud forcing (LWCF) diurnal evolution in several oceanic convective regions shows two peaks: an afternoon and a near midnight peak; however, the reanalysis models produce a single midnight peak. The outgoing longwave radiation (OLR) diurnal cycle over tropical land is 20%–30% too weak in both reanalyses. The small diurnal cycle errors in marine stratocumulus regions are a result of two common misrepresentations in MERRA and ERA-Interim: 1) the dissipation of marine stratocumulus clouds from morning to afternoon is too slow and 2) the cloud diurnal cycle is too weak. Overall, the intermodel differences in the representation of the TOA flux diurnal cycle are smaller than the differences between reanalysis models and observations.

1. Introduction

A comprehensive representation of the Earth system is required to understand the physical processes that drive climate variability and change. Retrospective analysis—referred to as reanalysis—is one technique for generating such a dataset. Reanalysis data products are generated using data assimilation techniques to constrain a forecast model solution against in situ, satellite, and other observations (e.g., Bosilovich et al. 2011). Reanalysis provides continuous and consistent information in space and time for many atmospheric variables, which is a significant advantage. Reanalysis products, however, contain biases that persist because of the necessary assumptions and simplifications in the host forecast model despite the observational constraints. Reanalysis output is used for many applications ranging from the analysis of synoptic-scale circulations (e.g., Catto et al. 2010) to climate studies (e.g., Trenberth et al. 2009; Deng et al. 2012). Since reanalysis products are ubiquitous in atmospheric research and are often considered to contain the best estimate of atmospheric state, deficiencies in these models must be documented for all aspects of atmospheric variability.

The diurnal cycle is a fundamental mode of earth system variability found in many geophysical quantities (Janowiak et al. 1994; Smith and Rutan 2003; Chung et al. 2009; Gray and Jacobson 1977; Minnis and Harrison 1984; Hartmann and Recker 1986; Harrison et al. 1988; Yang and Slingo 2001; Taylor 2012). The presence of a diurnal cycle, additionally, influences the evolution of geophysical processes important for climate; for example, cloud formation, surface turbulence, and surface evaporation rates.
The diurnal cycle structure significantly influences the top-of-atmosphere (TOA) and surface energy budgets (Rozendaal et al. 1995; Bergman and Salby 1997; Hall and Vonder Haar 1999; Loeb et al. 2009; Del Genio and Wu 2010; Taylor and Loeb 2013; Taylor 2014). Therefore, diurnal cycle behavior must be accurately represented in all numerical models, including reanalysis.

Numerical models of the atmosphere poorly represent the tropical diurnal cycle. A common flaw in global climate models (GCMs) is a generation of land convective precipitation and maximum cloudiness near local noon (e.g., Collier and Bowman 2004; Dai and Trenberth 2004; Dai 2006; Del Genio and Wu 2010). The errors in the precipitation timing and intensity unrealistically force the surface water and energy budget, leading to errors in surface runoff and evaporation (Del Genio and Wu 2010). Decker et al. (2012) found significant errors in the diurnal cycle of surface turbulent fluxes in reanalysis models as well. Slingo et al. (2003) evaluated the diurnal cycle of the Hadley Centre Coupled Model, version 3 (HadCM3) GCM over the tropics and found the largest differences between the GCM and observations occur over the Maritime Continent. The implications of this bias are suggested to affect other tropical and extratropical regions through atmospheric teleconnections (Slingo et al. 2003; Neale and Slingo 2003). Wonsick et al. (2009) examined hourly Meteosat-5 observations of diurnal variations in cloudiness over the Indian monsoon region and found complex diurnal and seasonal patterns of cloudiness. Although not the focus of the study, Wonsick et al. (2009) compared monthly mean cloud amount at 0600 UTC for the 2001 monsoon season using both observations and reanalyses and found large disparities in cloud amounts between the observed and modeled values. Few studies, however, have evaluated the tropical diurnal cycle of TOA fluxes in reanalyses.

This study fills a gap in the evaluation of reanalysis models: namely, documenting the fidelity of the TOA flux diurnal cycle in the tropics. The purpose of this study is to evaluate and document the diurnal cycle representation of the TOA radiative flux in two reanalysis models against Clouds and the Earth’s Radiant Energy System (CERES) synoptic edition 3A (SYN Ed3A) data described in section 2. The diurnal cycle representation of the reanalysis products is evaluated using a root-mean-square error metric explained in section 3. The results, summarized in section 4, utilize the root-mean-square errors (RMSE) to diagnose errors in the climatological reanalysis diurnal cycles and then apply several techniques to attribute the errors to specific diurnal cycle characteristics: namely, diurnal cycle magnitude and timing. A summary and conclusions are presented in section 5.

2. Data

a. Radiative flux observations

The CERES SYN Ed3A Terra + Aqua dataset contains all-sky outgoing longwave radiation (OLR) and reflected shortwave (RSW) fluxes and clear-sky OLR (OLRCls) and RSW (RSWCls) fluxes extending from July 2002 through October 2012 with 1° × 1° spatial and 3-hourly temporal resolution (Loeb et al. 2009; Doelling et al. 2013). The 3-hourly resolution is obtained by merging CERES observations aboard the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites with radiances observed from five geostationary (GEO) satellites. The merging process involves several steps: 1) calibration of each GEO instrument against Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data, 2) a narrowband to broadband radiance conversion, 3) GEO broadband radiance to irradiance integration, and 4) normalization of GEO derived flux to CERES. Before step 1, Terra and Aqua MODIS are cross calibrated and placed on the same radiometric scale. Doelling et al. (2013) indicates that uncertainties in the CERES SYN Ed3 data are generally independent of local time. The largest errors in the merging process occur over desert regions, leading to a 10% overestimate in morning TOA fluxes. Using GEO radiances in the merging process reduces OLR and RSW flux uncertainties in the monthly mean values by 20% over assumptions of constant meteorology. Daily mean OLR and RSW uncertainties are reduced by 50% and 20%, respectively. Doelling et al. (2013) provides a detailed description and validation of CERES SYN data product.

CERES data are used to characterize the TOA radiative flux diurnal cycles across the tropics—defined as 30°N–30°S—and the relative contributions from clear- and cloudy-sky fluxes. For the remaining discussion a diurnal cycle composite of a given variable is denoted with the subscript DC (e.g., OLRDC). The radiative effect of clouds within the CERES SYN Ed3 dataset are quantified using longwave cloud forcing (LWCF) and shortwave cloud forcing (SWCF): LWCF = OLRCLS − OLR and SWCF = RSWCLS − RSW. All-sky albedo (aDC), clear-sky albedo (aclsDC), and cloudy-sky albedo (aclsDC = aDC − aclDC) terms are also used to analyze the SW diurnal cycle. The aDC and aclsDC are defined conventionally: aDC = RSWDC/ISRDC and aclDC = RSWCLS/ISRDC, where ISRDC represents the diurnal cycle of incoming solar radiation. Albedo variables are only defined when the 3-hourly mean solar insolation values exceed 100 W m−2.
b. Reanalysis models

1) MERRA

The Modern-Era Retrospective Analysis for Research and Applications (MERRA; Bosilovich et al. 2008) is a reanalysis from NASA extending from 1979 to the present. TOA flux output from July 2002–October 2012 is used in this study to match the range of the CERES SYN Ed3A data. MERRA variable fields are derived from the Goddard Earth Observing System (GEOS) version 5 data assimilation system, which uses three-dimensional variational data assimilation (3DVar), which is referred to as the National Centers for Environmental Prediction (NCEP) unified gridpoint statistical interpolation scheme (Rienecker et al. 2011; Decker et al. 2012). MERRA TOA flux output with native spatial resolution and temporal resolution of \( \frac{1}{2}^\circ \times \frac{1}{2}^\circ \) and 1 hourly (obtained from ftp://goldsmr2.sci.gsfc.nasa.gov/data/) are regridded to \( 1^\circ \times 1^\circ \) and averaged to 3-hourly resolution for comparison with CERES data.

2) ERA-INTERIM

The European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) product (Berrisford et al. 2011; Dee et al. 2011) is the most recent reanalysis from ECMWF covering the period 1979–present. ERA-Interim uses cycle 31r2 of the ECMWF Integrated Forecast System at spatial resolution of T213 (~80 km) for surface and many other gridpoint fields; basic dynamical fields have a higher spatial resolution with a T255 spherical harmonic representation (Berrisford et al. 2011; Dee et al. 2011). ERA-Interim uses variational bias correction for satellite data and incorporates full four-dimensional variational data assimilation (4DVar). 4DVar is a temporal extension of 3DVar enabled by the coexistence of a reanalysis and forecast system. ERA-Interim produces four analyses (0000, 0600, 1200, and 1800 UTC) and two 10-day forecasts per day (initialized at 0000 and 1200 UTC). Forecast model level data are archived at \( \frac{1}{2}^\circ \times \frac{1}{2}^\circ \) and \( 1^\circ \times 1^\circ \) and averaged to \( 1^\circ \times 1^\circ \) by the ECMWF servers (http://data-portal.ecmwf.int/data/d/interim_mnth/).

3. Methodology

a. Diurnal cycle evaluation

RMSE is used to quantitatively evaluate the climatological annual and climatological seasonal mean TOA flux diurnal cycles in the MERRA and ERA-Interim against CERES. The climatological annual mean diurnal cycle is defined as the composite diurnal cycle from July 2002 to October 2012. The climatological seasonal mean diurnal cycle is defined as the composite for each conventionally defined 3-month season: March–May (MAM), June–August (JJA), September–November (SON), and December–February (DJF). The diurnal cycle RMSE metric is defined as

\[
\text{RMSE}_{\text{Var, model}} = \sqrt{\frac{1}{N} \sum_{h=1}^{N} [\text{Var}_{\text{model}}(h) - \text{Var}_{\text{CERES}}(h)]^2}. \tag{1}
\]

In (1), \( \text{Var} \) represents any TOA flux variable (OLR, OLR\textsubscript{CLR}, LWCF, RSW, RSW\textsubscript{CLR}, or SWCF); “model” refers to either MERRA or ERA-Interim; \( h \) represents the 3-hourly interval; and \( N \) represents the total number of intervals \( (N = 8) \). Here, \( \text{Var}_{\text{model}}(h) \) and \( \text{Var}_{\text{CERES}}(h) \) represent the climatological annual or climatological seasonal diurnal cycle for any variable after removing the diurnally averaged flux. As a result, the RMSE metric in (1) only includes contributions from errors in the diurnal cycle representation and not differences in the climatological state.

The RMSE values in (1) are normalized by the magnitude of the climatological OLR\textsubscript{CERES} and RSW\textsubscript{CERES} diurnal cycle to provide a relative measure of the error magnitude. The diurnal cycle magnitude \( (\sigma_{\text{Var,DC}}) \) is defined as the standard deviation over the observed climatological diurnal cycle,

\[
\sigma_{\text{Var,DC}} = \sqrt{\frac{1}{N} \sum_{h=1}^{N} [\text{Var}_{\text{CERES}}(h)]^2}. \tag{2}
\]

Normalization by \( \sigma_{\text{Var,DC}} \) characterizes the diurnal cycle error relative to the magnitude of the climatological annual or climatological seasonal diurnal cycle; this normalized quantity is referred to as NRMSE\textsubscript{Var}. All longwave and shortwave flux quantities are normalized by \( \sigma_{\text{OLR,DC}} \) and \( \sigma_{\text{RSW,DC}} \) (shown in Figs. 1 and 2, respectively) to retain the relative contributions of clear-sky flux and cloud forcing terms to the all-sky NRMSE.

b. Error attribution

The second part of this paper attributes reanalysis diurnal cycle errors to specific diurnal cycle characteristics: namely, diurnal cycle magnitude and timing. Several techniques are applied to characterize the reanalysis diurnal cycle errors: Fourier decomposition, diurnal range and local time of maximum and minimum value metrics, and diurnal evolution histograms.
A Fourier first harmonic fit is used to characterize the diurnal cycle magnitude and timing. Fourier decomposition is used extensively to characterize diurnal cycle characteristics (e.g., Hartmann and Recker 1986; Yang and Slingo 2001; Yang et al. 2008; Taylor 2012). Fourier first harmonic decomposition fits a cosine function to each climatological and seasonal diurnal composite. The result is a two-term (amplitude and phase) characterization of the diurnal cycle. The amplitude of the diurnal cycle represents the magnitude, whereas the phase represents the timing. For clarity, the diurnal phase is discussed in terms of local solar time (LST) of diurnal cycle maximum instead of radians or degrees. The terms $A_{\text{variable}}$ and $P_{\text{variable}}$ refer to the first diurnal harmonic amplitude and phase of the subscripted variable, respectively.

The Fisher statistical significance test ($F$-test) is used to determine the statistical significance (Minnis and Harrison 1984; Taylor 2012) of the Fourier first harmonic fit. The $F$-test compares the variance of the diurnal cycle in the data to the variance of the first harmonic cosine fit to test for statistical significance. Areas where the first harmonic fit is not statistically significant at the 90% confidence level are shaded in white in all contour figures.

The first harmonic decomposition appropriately characterizes the OLR and LWCF diurnal cycles but poorly represents the SW diurnal cycle terms: RSW, RSWCLR, and SWCF and the associated albedo quantities (Taylor 2014). Therefore, the diurnal cycle strength and timing in SW flux terms are determined using magnitude and local time of maximum and minimum value metrics of $a_{\text{DC}}$, $a_{\text{clr,DC}}$, and $a_{\text{cld,DC}}$. The local time of maximum and minimum column albedo tracks the 3-hourly interval in which the diurnal cycle is maximum and minimum.

Finally, diurnal evolution histograms are created to further attribute errors in the reanalysis diurnal cycle. Diurnal evolution histograms are useful tools for studying the diurnal cycle because they demonstrate the complete diurnal evolution. Diurnal evolution histograms describe the likelihood of a variable to occur at a given time interval relative to the daily probability distribution function (PDF; Morcrette 1991; Yang and Slingo 2001; Taylor 2012). A diurnal evolution histogram is created by taking the difference between the PDF...
within each 3-hourly interval and the 24-h (daily) PDF. Positive (negative) frequency anomalies indicate higher (lower) probabilities of a particular value to occur at a specific time.

4. Results

a. Climatological annual diurnal cycle evaluation

The climatological annual diurnal cycle representation in the reanalysis models is quantified using NRMSE, which is described in section 3. NRMSE for a given reanalysis model and variable is referred to as NRMSE\textsubscript{model,Var} and NRMSE\textsubscript{Var} refers to the error for both models.

1) LONGWAVE (LW) FLUXES

(i) Common features

Reanalysis diurnal cycle errors in OLR\textsubscript{DC}, OLR\textsubscript{CLR,DC}, and LWCF\textsubscript{DC} indicated by NRMSE are shown in Fig. 1: MERRA (left) and ERA-Interim (right). NRMSE\textsubscript{OLR} (Figs. 1a,b) shows large regional variability in the diurnal cycle representation in MERRA and ERA-Interim. The largest NRMSE\textsubscript{OLR} errors are found in oceanic convective regions, a feature common to both reanalyses. NRMSE\textsubscript{OLR} values range between 40% and 400% over convective oceans, with the largest values occurring over the ITCZ, the western Pacific, and central Indian Ocean. The magnitude and structure of these maximum errors is similar in ERA-Interim and MERRA. The absolute RMSE\textsubscript{OLR} (not shown), however, is larger over land than ocean regions: 4–24 W m\textsuperscript{-2} over land and 0–8 W m\textsuperscript{-2} over ocean. Percent errors are larger over ocean because \( \sigma_{OLR,DC} \) is smaller.

MERRA and ERA-Interim both reproduce OLR\textsubscript{DC} well in land (e.g., northern Africa, central Australia) and oceanic nonconvective regions (Peruvian and Californian marine stratocumulus). The NRMSE\textsubscript{OLR} values in land convective regions range from 0% to 80% (Figs. 1a,b). In ocean nonconvective regions, NRMSE\textsubscript{OLR} values are slightly higher than over land but do not exceed 120%. The term NRMSE\textsubscript{OLR,CLR} indicates that diurnal cycle errors in land nonconvective regions are due to the representation of OLR\textsubscript{CLR,DC}. However, the NRMSE\textsubscript{OLR} values are slightly higher than over land but do not exceed 120%.
in ocean nonconvective regions is attributed to errors in the climatological annual LWCFDC.

Regional variability is found in the contributions of OLRCLR,DC and LWCFDC errors to NRMSEOLR. The NRMSELWCF (Figs. 1e,f) resembles NRMSEOLR over most ocean regions, suggesting that diurnal cloud evolution errors are the primary cause of NRMSEOLR. The NRMSEOLRCLR reaches 100% in several oceanic convective regions; however, in absolute terms RMSELWCF is between 3 and 5 times larger than RMSEOLRCLR. The NRMSELWCF is also the dominant contributor to NRMSEOLR in land convective regions (e.g., central South America and Central Africa). The largest NRMSEOLR and NRMSELWCF values occur over areas (identified by Yang and Slingo 2001) where propagating convection dominates the diurnal cycle (e.g., Indian Ocean, Central Africa, and the South Pacific convergence zone). The results demonstrate that the reanalysis models have the most difficulty reproducing the climatological annual OLRDC in convective regions because of errors in the cloud diurnal evolution: specifically, regions of propagating convection.

(ii) Reanalysis model differences

Intermodel NRMSEOLR differences are most pronounced in convective regions from differences in the diurnal cloud evolution. The NRMSEERA,OLR ranges from 80% to 160% over the Amazon region and NRMSEMERRA,OLR is much lower with only a small region of errors greater than 80% in the northeastern corner of the region. The NRMSEMERRA,OLR ranges between 20% and 100% over Central Africa and the Maritime Continent, whereas NRMSEERA,OLR ranges from 60% to 120% in the same regions. Intermodel differences in oceanic convective regions are most pronounced in the Pacific and Atlantic ITCZ, where NRMSEERA,OLR and NRMSEMERRA,OLR reaches 100%; NRMSEMERRA,OLR and NRMSEMERRA,LWCF do not reach these values.

Intermodel differences in NRMSEOLRCLR are small. The largest difference in clear-sky OLR errors between the reanalysis models exists over Central Africa, along the southern Andes, and in certain ocean nonconvective regions. The NRMSEMERRA,OLRCLR is significantly higher than NRMSEERA,OLRCLR. The NRMSEMERRA,OLR is also slightly higher than NRMSEERA,OLR over the African Sahel region, over parts of eastern Asia, and over northern Australia.

2) SHORTWAVE (SW) FLUXES

(i) Common features

Reanalysis diurnal cycle errors in RSWDC, RSWCLR,DC, and SWCFDC indicated by NRSME are shown in Figs. 2a–f: MERRA (left) and ERA-Interim (right). NRMSESW values are smaller than in the LW because σRSW,DC is larger. The largest NRMSESW values are found over equatorial oceans where NRMSESW,merra reaches 75% (Figs. 2a,b). Both models exhibit 20%-50% NRMSESW values along coastal regions of climatological marine stratocumulus. This feature common to MERRA and ERA-Interim is attributed to diurnal cloud evolution errors, as in the LW. The NRMSESW values are smaller for both reanalyses over land and generally do not exceed 25%. As indicated by the significant similarity between NRMSESW and NRMSESWCF, the majority of RSWDC errors are due to reanalysis errors in SWCFDC.

NRMSESWCLR values are small over the land and ocean. In absolute terms, RMSESWCLR does not exceed 5 W m−2, except over a few localized areas: that is, the Himalayas and Atacama Desert (not shown). One noteworthy region is the Atlantic and coastal northern African region where background aerosol concentrations are known to be high because of the large-scale transport of Saharan dust (e.g., Prospero and Carlson 1972). Both reanalysis models produce larger NRMSESWCLR values in this region likely because of errors in the aerosol optical depths. The NRMSESWCLR values, however, occur without a comparable error in the RSWDC. Figures 2e,f show that NRMSESWCF values of 15%–25% compensate for the RSWCLR,DC errors. This indicates that the reanalysis models have compensating some errors in the cloud and aerosol diurnal cycles over the Atlantic and coastal North African region. The CERES RSWCLR,DC, however, is influenced by the reliability of the cloudy-sky versus clear-sky determination, which is difficult over the northern Africa coast because of the presence of large aerosol optical depths (Minnis et al. 2008). Some of the NRMSESWCLR differences between CERES and reanalysis result from uncertainty in the cloud mask.

(ii) Reanalysis model differences

ERA-Interim reproduces the climatological annual RSWDC better than MERRA in most ocean regions. NRMSESW,ERA values are lower than NRMSESW,MERRA by as much as 50% over the equatorial central Pacific Ocean and equatorial Atlantic Ocean (Figs. 2a,b). The NRMSEERA,RSW is also significantly smaller than NRMSEMERRA,RSW in the Pacific Ocean between 10° and 20°N and for much of the Indian Ocean. The NRMSEMERRA,RSW values are slightly lower than ERA-Interim in marine stratocumulus regions.

Significant intermodel differences in the RSWDC representation are also found over land regions. As in OLR, MERRA captures the land convective RSWDC better, with the exception of the Ivory Coast region. Over the Amazon basin, NRMSESW,MERRA values
range from 5% to 25%, whereas NRMSE\textsubscript{RSW,ERA} values range from 15% to 30%. Similar differences are found over the Central African convective region and over the Maritime Continent.

Both reanalysis models exhibit smaller NRMSE\textsubscript{RSW} over land nonconvective regions; however, NRMSE\textsubscript{RSW,ERA} values over the Sahara and Western Australia are a factor of 2 higher than NRMSE\textsubscript{RSW,MERRA}. The maximum NRMSE\textsubscript{ERA,RSW CLR} values (Fig. 2f) occur over land nonconvective regions: namely, the Atacama Desert in South America, the southern Himalayas, and western Australia, reaching ~50% in localized areas, significantly higher than NRMSE\textsubscript{MERRA,RSW CLR} (Fig. 2c). The RSW\textsubscript{DC} intermodel differences in the land nonconvective regions are caused by errors in RSW\textsubscript{CLR,DC} due to an error in the climatological annual diurnal evolution of clear-sky albedo (not shown).

b. Attribution of climatological diurnal cycle errors

The previous section outlined errors in the TOA flux diurnal cycle representation within MERRA and ERA-Interim. This section attributes the NRMSE values to specific diurnal cycle characteristics—magnitude and timing—using Fourier first harmonic analysis, the diurnal maximum of column albedo, and diurnal evolution histograms. Figures 3–7 summarize the climatological annual Fourier first harmonic results for $A_{\text{OLR,clim}}$, $A_{\text{OLR CLR,clim}}$, $A_{\text{LWCF,clim}}$, $P_{\text{OLR,clim}}$, and $P_{\text{LWCF,clim}}$, respectively. The climatological annual mean OLR, OLR\textsubscript{CLR}, and LWCF first harmonic diurnal cycle amplitude and phase is computed as in Taylor (2012) and is shown as a reference. The first harmonic phase of the clear-sky OLR diurnal cycle is not shown, because the regional variability is very low and the reanalysis model errors are small. Figure 8 shows the $\alpha_{\text{cd,DC}}$ diurnal maximum $A_{\text{albedo,clim}}$ representing $\alpha_{\text{cd}}$ diurnal cycle magnitude.

The tropical diurnal cycle is traditionally separated into four regimes: land convective, land nonconvective, ocean convective, and ocean nonconvective (Bergman and Salby 1996). Different clouds types dominate each regime; each cloud type possesses different diurnal cycle characteristics. For this reason, the following discussion is organized by these regimes.

1) LAND NONCONVETIVE

Errors in the reanalysis model TOA flux diurnal cycle representation in land nonconvective regions are the second smallest of any climatological diurnal cycle regime. The NRMSE\textsubscript{OLR} in this regime results from a 20%–30% underestimate of the OLR\textsubscript{CLR,DC} amplitude. Figures 3 and 4 illustrate that both MERRA and ERA-Interim produce $A_{\text{OLR,clim}}$ and $A_{\text{OLR CLR,clim}}$ values that are too weak over the Sahara Desert, Saudi Arabia, and central Australia (Figs. 3b,c and 4b,c). ERA-Interim $A_{\text{OLR,clim}}$ and $A_{\text{OLR CLR,clim}}$ values, however, more closely resemble observations over the Sahara and other land nonconvective regions (Figs. 3c and 4c). Both MERRA and ERA-Interim capture $P_{\text{OLR,clim}}$ (Figs. 6b,c) and
$P_{\text{OLR,clim}}$ (not shown) accurately over land non-
convective regions; the differences found are less than
1 h. The lower NRMSE$_{\text{ERA,OLR}}$ values compared with
NRMSE$_{\text{MERRA,OLR}}$ in land nonconvective regions re-
sults from better simulation of $A_{\text{OLR,clim}}$.

In terms of shortwave fluxes, NRSMW$_{\text{RSW}}$ and
NRMSE$_{\text{RSW,CLR}}$ values are much larger in ERA-Interim
than MERRA over several land nonconvective regions
(Figs. 2a,b). The larger NRMSE$_{\text{RSW,ERA}}$ is attributed to
larger RSW$_{\text{CLR,DC}}$ errors. The NRMSE$_{\text{RSWCLR,ERA}}$ values

FIG. 4. Differences between the CERES observed and reanalysis model climatological
annual $A_{\text{OLR,clim}}$: (a) CERES $A_{\text{OLR,clim}}$, (b) MERRA $A_{\text{OLR,clim}}$ minus CERES
$A_{\text{OLR,clim}}$ and (c) ERA-Interim $A_{\text{OLR,clim}}$ minus CERES $A_{\text{OLR,clim}}$.

FIG. 5. Differences between the CERES observed and reanalysis model climatological an-
nual $A_{\text{LWCF}}$: (a) CERES $A_{\text{LWCF,clim}}$, (b) MERRA $A_{\text{LWCF,clim}}$ minus CERES $A_{\text{LWCF,clim}}$
and (c) ERA-Interim $A_{\text{LWCF,clim}}$ minus CERES $A_{\text{LWCF,clim}}$. 
are attributed to an underestimation of the $\alpha_{\text{olr,DC}}$ diurnal range, especially over northern Africa (not shown). From a climatological perspective, MERRA captures the RSW$_{\text{DC}}$ better than ERA-Interim over land nonconvective regions.

2) LAND CONVECTIVE

The large NRMSE$_{\text{OLR}}$ values over land convective regions result from errors in both diurnal cycle amplitude and phase for LWCF$_{\text{DC}}$ and OLR$_{\text{DC}}$. Both reanalysis
models simulate \( P_{\text{OLR,clim}} \) (Figs. 6b,c) and \( P_{\text{LWCF,clim}} \) (Figs. 7b,c) values too early in the day. ERA-Interim \( P_{\text{OLR,clim}} \) over the Amazon convective region, Central Africa, and the Maritime Continent occurs 2–8 h too early (Fig. 6c). MERRA \( P_{\text{OLR,clim}} \) agrees better with observations over land convective regions, showing only 2–4-h differences in \( P_{\text{OLR,clim}} \) (Fig. 6b). Fewer 1° × 1° regions exhibit a statistically significant first harmonic fit for ERA-Interim in land convective regions than for MERRA and observations, indicated by the white shading in Figs. 3 and 6.

Reanalysis models also underestimate \( A_{\text{OLR,clim}} \) and \( A_{\text{LWCF,clim}} \) over land convective regions by 20%–30% contributing to NRMSE\( P_{\text{OLR}} \). ERA-Interim underestimates \( A_{\text{OLR,clim}} \) most significantly over the Amazon convective region and the Maritime Continent (Fig. 3c). MERRA also underestimates \( A_{\text{OLR,clim}} \) in these same regions (Fig. 3b) but less than ERA-Interim. The reanalysis model representation of \( A_{\text{LWCF,clim}} \) is regionally dependent. Over central South America, ERA-Interim captures the complex features near the Brazilian coastline better than MERRA (Figs. 5b,c). MERRA performs significantly better over the Maritime Continent as ERA-Interim \( A_{\text{LWCF,clim}} \) is much too low (Fig. 5c). Over Central Africa, MERRA and ERA-Interim both show \( \sim 10 \text{ W m}^{-2} \) underestimates of \( A_{\text{LWCF,clim}} \). Neither model captures \( A_{\text{LWCF,clim}} \) well; percent errors exceed 50% these regions.

Diurnal cycle histograms further illustrate the inter-model differences in the land convective diurnal cycle. The diurnal evolution histogram analysis over central South America (0°–15°S, 50°–70°W) illustrates that MERRA produces a better \( \text{LWCF}_{\text{DC}} \) diurnal cycle structure (Fig. 9). The CERES climatological annual \( \text{LWCF}_{\text{DC}} \) evolution histogram (Fig. 9a) shows maximum and minimum \( \text{LWCF} \) values that occur near 1700 and 0900 LST, respectively. The maximum \( \text{LWCF}_{\text{DC}} \) timing produced by MERRA (Fig. 9b) matches observations well; however, the amplitude of diurnal \( \text{LWCF} \) variability is too low. ERA-Interim produces peak cloudiness near the time of the minimum \( \text{LWCF}_{\text{DC}} \) in observations (Fig. 9a), 4–6 h too early. MERRA, therefore, produces a more realistic \( \text{OLR}_{\text{DC}} \) simulation in central South America because of a better simulation of the \( \text{LWCF}_{\text{DC}} \) timing.

The \( \text{RSW}_{\text{DC}} \) in land convective regions is reasonably well produced by the reanalysis models. Figure 8 shows the diurnal maximum of \( \alpha_{\text{cld,DC}} \). MERRA \( A_{\text{albedo,clim}} \) values are higher than observations over the northern Amazon region, the Ivory Coast region, and portions of the Maritime Continent (Fig. 8a). ERA-Interim \( A_{\text{albedo,clim}} \) values are closer to observations than MERRA over the northern Amazon but are also too large over Central Africa and the Maritime Continent (Fig. 8b). The errors in \( A_{\text{albedo,clim}} \), however, are generally less than 20%. In land convective regions, ERA-Interim simulates a better
RSWDC because the diurnal maximum of cloudy-sky albedo is better simulated than MERRA. Several arc-like and linear structures over Western Africa, Eastern Africa, central South America, eastern India, and parts of the Atlantic and Indian Oceans are evident in Fig. 8. These structures are GEO satellite artifacts in the SW that occur at large satellite view angles. These artifacts are most evident in the differences plots; however, the presence of GEO artifacts does not change the overall conclusions.

3) OCEAN CONVECTIVE

Ocean convective regions show the largest NRMSE_{OLR} (Figs. 1a,b) and NRMSE_{RSW} (Figs. 2a,b) values. Large NRMSE_{OLR} values in oceanic convective regions are attributed to the misrepresentation of the climatological annual LWCF_{DC} timing. CERES P_{LWCF,clim} (Fig. 7a) occurs between 2000 and 0400 LST and P_{OLR,clim} (Fig. 6a) occurs between 0400 and 1000 LST for most of the statistically significant oceanic convective regions (Taylor 2012). In these regions, the observation–reanalysis differences in P_{LWCF,clim} range from ±2 to ±12 h.

The largest errors in P_{OLR,clim} and P_{LWCF,clim} in oceanic convective regions are in the regions dominated by propagating convective features. Observations show complex features in the timing of peak cloudiness particularly over the Indian Ocean (Fig. 7a), where P_{OLR,clim} ranges from midafternoon to early morning. The existence of propagating convective features is inferred from the parallel P_{OLR,clim} or P_{LWCF,clim} contours (Fig. 7a) that emanate from land convective regions during the day producing P_{LWCF,clim} values over certain tropical oceans at night (Yang and Slingo 2001; Neale and Slingo 2003; Taylor 2012). Reanalysis models, however, do not capture these features (Figs. 7b,c).

The inability to capture the propagating convective features in the Indian Ocean leads to significant errors in the LWCF_{DC} diurnal structure. Figure 10 shows the diurnal evolution histogram over the Indian Ocean region (55.0°–95.0°E, 0.0°–15.0°S). The observed LWCF diurnal evolution histogram (Fig. 10a) indicates a single diurnal cycle peak with maximum and minimum values around 1700 and 0000 LST, respectively. MERRA and ERA-Interim reproduce the single peak in LWCF_{DC}; however, both the maximum and minimum values are shifted 3–5 h too late.

This inability of the reanalysis models to capture diurnally forcing propagating convective features from the Maritime Continent to the Indian Ocean is of particular interest because of the regional colocation with the Madden–Julian oscillation (MJO; Neale and Slingo 2003; Matthews 2008; Ling et al. 2013). Neale and Slingo (2003) show that a better simulation of the diurnal cycle around the Maritime Continent improves the simulation of clouds and precipitation over the Indian Ocean, which can directly impact the simulation of the MJO and can further have global impacts through teleconnections (Neale and Slingo 2003; Slingo...
et al. 2003). Missing propagating convection additionally removes the observed land–ocean interactions that are critical to the energy budget in this region. The unrealistic characterization of the convection, furthermore, changes the distribution of convective heating of the atmosphere over the Maritime Continent and the Indian Ocean. It is speculated that the poor simulation of diurnally forced propagating convection represents a failure of the convective parameterization to organize convection.

Figure 11 shows the diurnal evolution histogram in the equatorial western Pacific (160.0°E–180.0°E, 10.0°N–10.0°S). CERES observations (Fig. 11a) show a bimodal structure in LWCFDC with maximum values around 1300 and 0000 LST. The reanalysis models, however, simulate a single maximum occurring around 0000 LST (Figs. 11b,c). Johnson et al. (1999) describe that the oceanic convective diurnal cycle in terms of three cloud types: 1) morning shallow, nonprecipitating convection; 2) afternoon scattered, precipitation cumulus congestus; and 3) nocturnal organized convection. These results suggest that the both reanalysis models are unable to capture the afternoon peak in the LWCFDC because of a lack of afternoon cumulus congestus. Additionally, Figs. 10 and 11 demonstrate—especially over ocean convective regions—that the intermodel diurnal cycle differences are less than the model–observational differences.

The largest NRMSE$_{RSW}$ values in oceanic convective regions are attributed to errors in both diurnal cycle amplitude and timing. The $A_{\text{albedo,clim}}$ in the equatorial, central Pacific and Atlantic Oceans ranges from 0.0 and 0.10 (Fig. 8). The reanalysis models both produce $A_{\text{albedo,clim}}$ values that are too large, >100%. Diurnal evolution histograms indicate that the reanalysis models produce too much morning $\alpha_{\text{albedo,clim}}$, causing >100% $A_{\text{albedo,clim}}$ differences with observations. The overproduction of morning cloudiness in the equatorial, central Pacific and Atlantic Ocean regions is a much larger problem in MERRA than ERA-Interim, resulting in larger values of NRMSE$_{RSW}$.

4) OCEAN NONCONVECTIVE

The climatological annual NRMSE$_{OLR}$ (Figs. 1a,b) and NRMSE$_{RSW}$ (Figs. 2a,b) are smallest in ocean non-convective regions. The small errors in this region are primarily caused by reanalysis models simulating a weaker than observed cloud diurnal cycle. Figures 3 and 5b,c illustrate that $A_{\text{OLR,clim}}$ and $A_{\text{LWCF,clim}}$ are too small in marine stratocumulus (MSc) regions in both reanalysis models by 10%–20%. The diurnal cycle evolution histograms (not shown) indicate that the reanalysis models take too long to dissipate morning cloudiness in MSc regions, reducing the cloud diurnal cycle amplitude. There is good agreement between the reanalysis models and observations for $p_{\text{LWCF,clim}}$ (Fig. 7).
shows larger errors in \( P_{L,WCF,c_{l_{i}m_{i}z}} \) (Fig. 7c), where LWCF_{DC} peaks later in the day farther off the coast from MSc regions. This is a consistent feature in all Southern Hemisphere MSc regions in ERA-Interim.

The small errors in RSW_{DC}—as in OLR_{DC}—are caused by producing an \( \alpha_{c_{l_{i}d_{i},D_{C}}} \) that is too weak. Figure 8 demonstrates the weaker \( A_{a_{l_{i}l_{i}b_{o}},c_{l_{i}l_{i}m_{i}}} \) in reanalysis models over MSc regions. MERRA \( A_{a_{l_{i}l_{i}b_{o}},c_{l_{i}l_{i}m_{i}}} \) values in most cases (e.g., over the Peru and Namibian MSc regions) are closer to observations than ERA-Interim. ERA-Interim \( A_{a_{l_{i}l_{i}b_{o}},c_{l_{i}l_{i}m_{i}}} \) values are closer to observations in a few places (e.g., Californian and Australian MSc regions). In summary, diurnal cycle errors in ocean nonconvective regions are small and result from a reanalysis model cloud diurnal cycle that is too weak.

c. Seasonal TOA flux diurnal cycle characteristics

The most significant seasonal differences in TOA flux diurnal cycle characteristics can be summarized in two points: 1) Reanalysis model errors in the large-scale features of the climatological annual TOA flux diurnal cycles persist regardless of the season. 2) However, the magnitude of the diurnal cycle errors exhibits a dependence on seasonal solar insolation.

Figure 12 shows the 3-month season of maximum NRMSE_{OLR} for MERRA and ERA-Interim. A general feature common to MERRA and ERA-Interim is the occurrence of maximum NRMSE_{OLR} during the 3-month season with the highest values of solar insolation (JJA for north of the equator and DJF for south of the equator). Higher insolation values lead to larger diurnal cycle amplitudes, and from the climatological analysis above, the reanalysis models tend to underestimate diurnal cycle amplitudes, leading to higher errors.

Figure 13 shows the seasonal dependence of NRMSE_{LWCF} in central South America. Both reanalysis models show the smallest errors in the winter months (JJA) and the largest errors in spring and summer months (SON and DJF, respectively); this result also indicates that seasons with higher insolation have the larger errors. Figure 13 shows that MERRA produces smaller errors in all seasons compared to ERA-Interim, especially in DJF, when convection is most intense. This result suggests that MERRA is able to simulate more intense convection than ERA-Interim in the Amazon region.

5. Summary and conclusions

The fidelity of the mean state and variability in reanalysis fields must be rigorously and continuously evaluated to understand strengths and weaknesses. The focus of this paper was to evaluate the representation of the tropical TOA flux diurnal cycle in MERRA and ERA-Interim against CERES SYN Ed3A 3-hourly TOA flux data.
The MERRA and ERA-Interim reanalysis models are able to reproduce the large-scale patterns of the TOA flux diurnal cycle climatology. Land–ocean contrasts in diurnal cycle amplitude are captured well by ERA-Interim and MERRA. Further, the diurnal cycle timing is simulated well in many regions (e.g., land and ocean nonconvective). Discrepancies between reanalysis models and observations become large at regional scales and in convective regions.

The results show a significant regional variability in reanalysis diurnal cycle errors. The smallest errors occur in land and ocean nonconvective regions for OLR and RSW. The OLR and RSW diurnal cycle errors in land and ocean nonconvective regions are 5–10 times smaller than in land and ocean convective regions. A portion of the large error in convective regions is attributed to reanalysis models producing a diurnal cycle that is too weak over all land regions. The majority of error in convective diurnal cycle regions, however, is attributed to the inability of both reanalysis models to capture the diurnal cycle of propagating convection. This error is most pronounced in the Indian Ocean and around the Maritime Continent but also impacts the OLR and RSW diurnal cycle representations in central South America and Central Africa. Overall, the significant regional errors in the TOA flux diurnal cycle occur during the season with the largest solar insolation. Model errors are generally lowest in local winter and highest in local summer, especially for land regions. However, along the equator, in several MSc regions the seasonality of errors is dependent on local effects.

Each reanalysis model has its strengths and weaknesses. Overall, MERRA simulates the tropical TOA congestus; therefore, the result suggests that reanalysis models fail to produce enough afternoon cumulus congestus clouds. Additionally, the errors in the cloud diurnal cycle evolution can influence the net cloud radiative forcing in the reanalysis by redistributing convective clouds through the day and altering the SWCF. Observations suggest that the LWCF and SWCF of deep convective clouds tend to offset. However, the errors in the diurnal cycle of convective clouds in reanalysis produce maximum cloudiness at night likely altering balance between LWCF and SWCF of deep convective clouds.

From a seasonal perspective, the largest errors in the TOA flux diurnal cycle occur during the season with the largest solar insolation. Model errors are generally lowest in local winter and highest in local summer, especially for land regions. However, along the equator, in several MSc regions the seasonality of errors is dependent on local effects.

The largest diurnal cycle errors are found in ocean convective regions (e.g., equatorial Pacific Ocean). The results indicate that this is due to a complete misrepresentation of the cloud diurnal evolution. The observed LWCF diurnal evolution in the western Pacific indicates two peaks, one in the afternoon and one after midnight; however, the reanalysis models produce a single midnight peak in LWCF. The dominant cloud type in the afternoon over tropical oceans is cumulus congestus; therefore, the result suggests that reanalysis models fail to produce enough afternoon cumulus congestus clouds. Additionally, the errors in the cloud diurnal cycle evolution can influence the net cloud radiative forcing in the reanalysis by redistributing convective clouds through the day and altering the SWCF. Observations suggest that the LWCF and SWCF of deep convective clouds tend to offset. However, the errors in the diurnal cycle of convective clouds in reanalysis produce maximum cloudiness at night likely altering balance between LWCF and SWCF of deep convective clouds.

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flux diurnal cycle better than ERA-Interim. Specifically, MERRA produces smaller errors by representing the diurnal cycle amplitude and phase in land convective regions better than ERA-Interim. ERA-Interim, however, produces smaller errors than MERRA over many land nonconvective regions by producing larger OLR diurnal cycle amplitudes. For ocean convective regions, neither model performs particularly well because of the common misrepresentation of diurnally forced propagating convection. Both models perform well over ocean nonconvective regions, exhibiting small errors in the OLR and RSW diurnal cycle representation because of a diurnal cycle that is too weak in MSc regions. It is speculated that the higher native spatial resolution of MERRA contributes to the better comparison with CERES observations over land convective regions because smaller-scale features are resolved and stronger horizontal gradients can be produced. However, the overall intermodel differences in the TOA flux diurnal cycle are smaller than the differences with observations.

Future work is needed to fully explain and attribute the errors found in this study to specific model physical parameterization. The physical mechanisms contributing to the tropical diurnal cycle must be better understood to improve the diurnal cycle representation in reanalysis models. Because of the widespread usage of reanalysis models in climate research and the lack of previous work done on the evaluation of their diurnal cycle representations, these results will benefit the scientific community through a better understanding of the strength and weaknesses of ERA-Interim and MERRA reanalyses.

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