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LETTER

Improved ice content, radiation, precipitation and low-level circulation over the tropical pacific from ECMWF ERA-interim to ERA5

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Abstract

This study evaluates changes in simulated Pacific climate between two ECMWF re-analyses; the ERA Interim (ERAI) and the newest ERA5. Changes in the Integrated Forecasting System (IFS) and possibly sea surface temperature result in greatly reduced discrepancies in ERA5’s ice water path (IWP), radiative fluxes and precipitation relative to satellite-based observational products. IWP shows the largest percentage change, increasing by over 300% from ERAI to ERA5, due to inclusion of falling ice (snow) that impacts radiative calculation. ERAI to ERA5 changes in high-cloud fraction are generally anticorrelated as expected with outgoing longwave radiation, with ERA5 having smaller longwave discrepancies versus CERES observations compared with ERAI. Reflected shortwave discrepancies are similarly reduced from ERAI to ERA5, which appears to be due to changes in both cloud fraction and optical depth. Finally, ERA5 also reduces a longstanding precipitation excess relative to the GPCP observational product in the southern trade winds region between the Southern Pacific and intertropical convergence zones. This appears to be related to cooler prescribed sea surface temperatures, thereby reducing local moisture supply via suppressing net latent heat flux and stronger surface trade-winds. Compared with GPCP and CERES, ERA5 shows similar geographic patterns of discrepancies to ERAI in terms of precipitation and top-of-atmosphere radiation, but their magnitudes are greatly reduced in ERA5.

1. Introduction

Recently, the European Centre for Medium-range Weather Forecasts (ECMWF) released its fifth generation of reanalysis or ERA5 (Hersbach and Dee 2016), following the previous generation—the ERA-Interim (ERAI). The ERA5 Integrated Forecasting System (IFS) and its data assimilation system have major modifications including higher spatial and temporal resolutions, a cloud microphysics scheme with multiple hydrometeor species, and an improved radiation scheme (Urraca et al 2018) with treatments of subgrid cloud heterogeneity and overlap, and allowing radiatively interactive falling ice (snow) (Forbes et al 2011, Copernicus Climate Change Service C3S (2017)).

This study considers ERA5’s representation of the Pacific climate from 60°S–60°N, which contains the Intertropical and Southern Pacific Convergence Zones (ITCZ, SPCZ), and the Indo-Pacific Warm Pool, which are regions of intense convective activity that efficiently transport heat to the free troposphere. These regions contribute to driving the Hadley and Walker Circulations, which are the mean meridional and zonal
overturning circulations, respectively. In the western Pacific, changes in tropospheric heating have been
weakened due to changes in atmospheric stability in the eastern Pacific, and therefore substantial changes in low-
level clouds, to an extent that may dominate short-term changes in global net TOA radiative fluxes (Gregory and
Andrews 2016, Mauritzen 2016, Zhou et al 2016).

Erai shows a consistent pattern of discrepancies in top-of-atmosphere (TOA) radiation relative to the
Clouds and Earth’s Radiant Energy System (CERES) satellite-based product, with too much outgoing TOA
longwave radiation in many Pacific convective regions, too much reflected shortwave radiation in the trade wind
regions, and too little in the coastal stratocumulus decks. This study investigates whether changes in Pacific
climate from ERAI to ERA5 reduce these discrepancies. It is partially motivated by the investigation of turning
on and off falling ice radiative effects (Fires) using offline runs of the ERA IFS in short-term forecasts in Li et al
(2014b) and the inclusion of radiatively interactive falling ice (snow) in ERA5.

The reanalysis assimilate large amounts of observational data, but with fewer direct surface-based or
radiosonde measurements over ocean than over land, as ocean surface and near-surface properties will be more
sensitive to changes in model physical parameterizations and their imperfections than those over land. Over
ocean they assimilate satellite-observed radiances and retrieved atmospheric wind vectors, but we restrict our
analysis to non-assimilated data to provide an independent test.

It is a great challenge to disentangle the factors that cause changes between the IFSs used in the ERAI and
ERA5 reanalyses (Hersbach et al 2020). Initial evaluation studies have noted that ERA5 shows a more consistent
Lagrangian transport over the Asian monsoon regions (Legras and Bucci 2020), better conservation of potential
temperature at high altitudes (Hoffmann et al 2019) and small biases over the tropical tropopause (Tegtmeier
et al 2020) where there was an increase in the number of IFS levels. Satellite and ground-based radiometers also
show lower magnitudes of radiative flux bias (Urraca et al 2018), and when a land surface model was evaluated
with ERA5 and ERAI inputs, discrepancies were reduced relative to eight observed surface properties (Alberge,
et al 2018).

This analysis considers changes in ice water path, radiation, precipitation, cloud fraction and near-surface
properties over the tropical Pacific Ocean from ERAI to ERA5. We are particularly interested in whether changes
from ERAI to ERA5 over the Pacific are consistent with the reported changes due to falling ice radiative effects
(Fires) by (Li et al 2014b, 2015, 2016). The ERAI IFS and approximately half of the Coupled Model
Intercomparison Project phase 6 (CMIP6) models (Li et al 2020a) do not include falling ice (i.e. snow) mass in their
radiative transfer calculations (Li et al 2012, 2013, 2014a, 2014b, Waliser et al 2009, 2011). It was found that
adding Fires to the ERAI IFS significantly reduced discrepancies in TOA radiation relative to the CERES
satellite-based products (Li et al 2014b) and similar mean-state changes were seen in controlled simulations with
the CESM1-CAM5 and MIROC6 fully-coupled GCMs (Li et al 2015, 2016, Chen et al 2018, Michibata et al
2019).

Our analysis is limited to 2007–2010 when all satellite products are available, but we find that substantial
reductions in the magnitude of discrepancies relative to satellite-based products for ice water path (IWP),
radiation and precipitation do not depend upon the length of the analysis period. Ultimately, while the changes
in IWP follow those expected due to the inclusion of radiatively active snow, comparison of ERAI–ERA5
differences in cloud fractions and near-surface properties provide better candidates to explain other changes in
TOA and surface radiation and precipitation. It is likely that the implementation of Fires in ERA5 either did not
lead to some of the changes and improvements that may have been expected given the previous results of Li et al
(2014b), Li et al (2015), Chen et al (2018) and Michibata et al (2019) or the impacts of Fires that were
outweighed by other changes from ERAI to ERA5. The potential reasoning for this result will be discussed.

2. The ECMWF IFS in ERA-interim and ERA5

The ECMWF IFS global model provides operational weather forecasts, and is also used for monthly and seasonal
predictions. Erai used a 2006 IFS release (Cye31r2: Dee et al 2011) and a 4-dimensional variational data
assimilation system with a 12-hour analysis window. ERA5 uses a newer IFS release (Cye41r2) operationalized in
2016 (Hersbach et al 2020).

Relative to the ERAI IFS, the ERA5 IFS improved model physics, the dynamical core, data assimilation and
model resolution. The changes in convection, cloud microphysics and radiative transfer calculations are relevant
to this study; thus they are briefly described below.

The IFS convection parameterization follows Tiedke (1989). Modifications from ERAI to ERA5 include a
variable convective available potential energy (CAPE) adjustment time-scale and reformulating the organized
entrainment from a moisture-convergent-dependent formulation to one dependent on environmental
humidity (Bechtold et al 2008, Hirons et al 2013, Bechtold et al 2014). The latter is responsible for an increase in
the occurrence of congestus clouds, realistic transition from shallow to deep convection and a more realistic precipitation distribution. The former improves the diurnal cycle of convection.

The ERAI stratiform cloud parameterization was based on Tiedtke (1993), which prognostically models cloud condensate mixing ratio and cloud fractional area with representations of cloud formation and dissipation processes. Cloud condensate is split into cloud water and cloud ice according to the ambient temperature while rain and snow are diagnosed. In contrast, ERA5 prognostically models cloud water, ice, rain and snow mixing ratios with single-moment bulk cloud microphysics (Forbes et al 2011), although it retains the prognostic cloud fractional area approach of Tiedtke (1993). The snow generation rate depends on temperature and a critical ice water content at which the conversion from ice to snow becomes efficient. The ERA5 cloud microphysics scheme differs from that of Morrison and Gettelman (Gettelman et al 2010, 2015, Gettelman and Morrison 2015) (MG2) used in prior research on FIREs, and a key difference is that combined cloud ice and snow contents with a single particle size distribution are used to calculate ice-cloud radiative properties, rather than separate cloud ice and snow contents with different size distributions. Models using versions of the ERA5 IFS scheme in CMIP6 did not show the same improvements relative to non-FIREs models (i.e. those without falling ice radiative effects) that was seen in the models that used MG2 (Li et al 2020b).

The radiation schemes are similar between ERAI and ERA5, with ERA5’s being described in Morcrette et al (2008). It uses the Rapid Radiation Transfer Model [RRTM] from Mlawer et al (1997) and Iacono et al (2008). ERAI only includes liquid and ice cloud water content, but not precipitating hydrometeors whereas ERA5’s radiation scheme adds prognostic stratiform snow to the total ice water. However, radiative effects of stratiform rain and convective condensate or precipitation are not yet included (Forbes et al 2011). The total ice water content is used to calculate ice-cloud radiative properties with a single effective diameter. In (Li et al 2014b, 2015, 2016), ice-cloud radiative properties allowed different effective diameters for suspended and falling particles, unlike ERA5. Particle size differences between floating ice and snow may affect the vertical heating rate profiles. Additionally, ERA5 uses the Monte Carlo independent column approximation (Raisanen et al 2004) to represent subgrid cloud heterogeneity and overlap.

Here we take the forecast fields of cloud ice, radiation, surface latent and sensible heat flux, and precipitation on a $1^\circ \times 1^\circ$ latitude-longitude grid. Monthly averages are taken from daily forecast accumulations at steps of 12–24 and 24–36 h, for all time steps within the given month. The wind fields are monthly means of daily means and we use 2007–2010 inclusive for the reanalyses and all data products. The same fields are used from both ERAI and ERA5, except for ERA5 where the prognostic snow water content is added. ERAI’s spatial resolution is approximately 79 km (TL255) on 60 vertical levels from the surface up to 0.1 hPa, while for ERA5 it is about 31 km (TL639) on 137 vertical levels from the surface up to 0.01 hPa. We regrid ERAI and ERA5 at the same horizontal resolution as that in the CERES radiation fields.

3. Observations

All satellite datasets are regridded onto a $1^\circ \times 1^\circ$ latitude-longitude grid. For ice water path (IWP) we use the CloudSat-CALIPSO radar-lidar based 2C-ICE cloud product (Deng et al 2010, 2013). A flag-based partitioning method (Waliser et al 2009, Li et al 2012) separates IWP into larger particle mass, which is considered to be precipitating stratiform and convective ice, as well as smaller particle mass, which is considered to be quasi-suspended cloud ice.

Top of atmosphere (TOA) and surface radiation fields are from Clouds and the Earth’s Radiant Energy System–Energy Balanced and Filled (CERES-EBAF, Loeb et al 2009, 2012, Kato et al 2011, 2012a, 2012b) Edition 4. Precipitation is from Global Precipitation Climatology Project (GPCP) Version 2.3 (Adler et al 2003, 2018), which uses satellite data over ocean.

The data used is limited to 2007–2010 as these are the only complete years of data available for all products. The limiting dataset is 2C-ICE, which lost nighttime data following a CloudSat battery anomaly in 2011.

4. Results

4.1. Evaluation of ice water path (IWP)

Figures 1 (a), (b) and (c) show the 2007–2010 2C-ICE mean total (TIWP), cloud (CIWP), and precipitating (i.e., snow) water path (SWP). The ERAI (figures 1 (d) and (e)) and ERA5 (figures 1 (f), (g) and (h)) minus 2C-ICE maps are also shown. Note that in ERAI, TIWP is identical to CIWP. From figure 1 (e) and (g), reanalysis CIWP agrees to within ±20 g m$^{-2}$ against each other, except near 60 °S/N where ERA5 regularly produces 20–40 g m$^{-2}$ less CIWP, bringing high-latitude ERA5 CIWP into better agreement with 2C-ICE.

CIWP is underestimated by >50% in both ERAI and ERA5, mainly over the ITCZ, SPCZ, and Tropical Warm Pool (TWP), which might be due partly to their exclusion of CIWP inside convective core updrafts.
The ERA5 SWP is the main factor for reducing the Pacific mean TIWP bias from 114 g m$^{-2}$ to 65 g m$^{-2}$, and once again, the biases are larger in convective areas, meaning that the missing ice mass in convection scheme may be important (figures 1(f) and (h)). Overall, SWP accounts for approximately 80% of TIWP in the 2C-ICE data and 58% in ERA5. The more realistic representation of TIWP in ERA5, due primarily to SWP, would be expected to reduce radiation discrepancies between ERA5 and CERES.

### 4.2. Changes in radiation budget components

Figure 2 shows pairwise differences in radiation budget components between ERAI and ERA5, between ERAI and CERES, and between ERA5 and CERES over 2007–2010. In general, ERA5 has substantially reduced biases in all terms: typically reduced by $\sim 5$ W m$^{-2}$ for TOA upward longwave (RLUT: Radiation Longwave Upward at TOA) and 5–15 W m$^{-2}$ for TOA upward shortwave (RSUT) and shortwave downward at surface (RSDS). For domain average, the mean bias (M) in RLUT is reduced 3.5 W m$^{-2}$ in ERAI to 2.1 W m$^{-2}$ in ERA5 and root-mean-square-error (RMSE) from 4.3 W m$^{-2}$ in ERAI to 2.8 W m$^{-2}$ in ERA5. The mean bias in RSUT (RSDS) is reduced from 4.7 (−2.2) W m$^{-2}$ in ERAI to −0.4 (−0.7) W m$^{-2}$ in ERA5 while the RMSE in RSUT (RSDS) is reduced from 10.0 (9.8) W m$^{-2}$ in ERAI to 6.7 (7.7) W m$^{-2}$ in ERA5.

Clouds are the most likely candidates to explain large changes in TOA radiative fluxes, and their effects can also be understood following the framework of Zelinka et al (2016) in which cloud-driven changes in TOA radiation can be decomposed into contributions from optical depth, altitude, and cloud fraction. TOA longwave fluxes are generally more sensitive to changes in cloud height and fraction, while shortwave changes are more sensitive to cloud optical depth and height.

The additional high-altitude ice mass seen by the radiative transfer code on the implementation of FIREs should contribute to a greater high-altitude cloud mass, generally reducing outgoing longwave radiation and increasing reflected shortwave radiation. Figure 2(a)’s changes in RLUT are consistent with this expectation in the SPCZ and ITCZ, but not around and to the north of the maritime continent (MC). The most striking changes from ERAI to ERA5 are in shortwave radiation, with far less TOA reflectance in the convective western...
Paciﬁc and around the trade-wind cumulus transition regions of the Californian and Peruvian stratocumulus decks. Opposite changes in shortwave radiance occur at the coastal edges of the stratocumulus decks and in the Eastern Paciﬁc cold tongue. Comparing ﬁgures 2(b), (e) and (h), (f) and (i), there is a widespread reduction in the magnitude of discrepancies relative to CERES for each term, when going from ERAI to ERA5.

Changes in the spatial pattern of radiation often reﬂect changes in circulation and thermodynamic heat transfer as parts of energy and hydrological balances.

Next, ﬁgure 3 compares reanalyses’ precipitation with GPCP, and ERAI-ERA5 changes in precipitation and its distribution between convective (ConPCP) and large scale (LSP) precipitation are also shown alongside cloud fraction by level. ERA5 shows less total precipitation than ERAI in most areas, except for a small band in the eastern ITCZ (ﬁgure 3(a)). Discrepancies versus GPCP are reduced in most areas from ERAI to ERA5, although a small V-shaped region between the ITCZ and SPCZ sees an underestimate in ERA5 (ﬁgure 3(b) and (c)).

By considering the radiation, precipitation and cloud fraction changes together, we note ERAI to ERA5 changes in three particular regions:

(i) The ITCZ and SPCZ exhibit generally increased high-cloud cover (HCC) (ﬁgure 3(f)) that coincides with reduced outgoing longwave radiation (ﬁgure 2(a)). There is a shift from convective to large-scale precipitation (ﬁgures 3(d) and (g)) while decreased shortwave reﬂection (ﬁgure 2(d)) in concert with minor changes in total cloud cover (ﬁgure 3(e)) implies decreased cloud optical depth and possibly also cloud overlap.

(ii) In the Indo-Paciﬁc Warm Pool near the MC, there is a reduction in HCC (ﬁgure 3(f)), which is offset by mid-cloud cover (MCC) changes (ﬁgure 3(h)), resulting in a small reduction in total cloud cover (ﬁgure 3(e)). The reduction in cloud-top altitude increases outgoing longwave (ﬁgure 2(a)). The decrease in convective precipitation is not offset by increased large-scale precipitation (ﬁgures 3(d) and (g)).

(iii) In the nonconvective V-shaped region between the ITCZ and SPCZ, there are minor cloud and radiation changes, but a decrease in convective precipitation (ﬁgure 3(d)).
Understanding the physical causes responsible for changes in the convective regions (i) and (ii) in ERA5 would require a more intensive investigation. Potential candidates include IFS resolution changes that especially results in stronger but narrower convective anvils or from cloud-overlap assumptions (Hoffmann et al. 2019). For shortwave changes, using the radiative kernels first calculated in Zelinka et al. (2016) (https://github.com/mzelinka/cloud-radiative-kernels), we estimate that RSUT changes by approximately $\sim 2$ W m$^{-2}$%$^{-1}$ in response to TCC over tropical ocean. Across much of the warm pool, where ERAI to ERA5 decreases in RSUT widely exceed 10 W m$^{-2}$, TCC changes vary from 0%–4%. Therefore cloud cover changes alone are insufficient to fully explain the RSUT differences (figure 2(d)), leaving a substantial role for changes in cloud optical depth and possibly cloud overlap.

Changes in cloud overlap from ERAI to ERA5 clearly have an effect in the western tropical Pacific, where large increases in the sum of cloud cover at different levels driven primarily by more MCC, which do not result in a corresponding increase in TCC (figure 3(e)). The precipitation change is also suggestive of changes in cloud structure; while large-scale (stratiform) precipitation does not increase but convective precipitation is strongly reduced from ERAI to ERA5 (figures 3(d) and (g)). This may be due to modifications in convection parameterization (Bechtold et al. 2008, Hirons et al. 2013, Bechtold et al. 2014), in particular, the modification of the dynamic entrainment rate that suppresses deep convection and allows more realistic transition from shallow to deep convection.

Overall, all radiative fluxes are brought closer to CERES-EBAF for ERA5 (figures 2(c), (f) and (i)) in ERA5 relative to ERAI (figures 2(b), (e) and (h)), although regional biases remain in ERA5 with generally too little shortwave reflectance over a small region in the western Pacific, and too much over the southeast and northeast Pacific where convective activity is not significant. These remaining biases may be related to boundary-layer cloud parameterization.

4.3. Changes in low-level thermodynamics and precipitation

Finally, we consider the possible causes of the reduced precipitation in the V-shaped region between the ITCZ and SPCZ. In prior research on FIREs, Li et al. (2014b) found that including the radiative effects of snow stabilized the atmosphere in convective regions, causing less vigorous convection and weaker low-level outflows.
This results in stronger trade winds, which may stir the ocean surface and cool SSTs, and also increase net advection of moisture into the convective regions. Together, these factors reduce precipitation in the V-shaped region. However, ERAI and ERA5 assimilate QuikSCAT observations, and show only small changes in low-level winds in this region (Figures not shown), breaking the coupling inherent in that process.

Furthermore, the reanalyses use prescribed SSTs, although measured SST refers to temperatures obtained at depths typically within a few metres rather than the skin temperature. As proposed in Hirahara et al. (2016), during 2007–2010 ERA5 uses the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) (see Donlon et al. (2012)), while during 2007–2009 ERAI used the NCEP Real-Time Global sea surface temperature (NCEP RTG; Thiébaux et al. (2003)).

Figure 4(e) shows that ERA5’s ocean skin temperatures are cooler across large areas of the Pacific during 2007–2010. The IFS responds with cooler near-surface air temperatures in the western Pacific (figure 4(d)). If it is assumed that the near-skin layer is at the saturated vapour pressure, then the cooler SSTs in ERA5 coincide with a reduced near-surface vapour pressure gradient in the western Pacific V-shaped region (figures 4(a), (b) and (c)). The IFS does indeed respond to this, with a reduction of $>5 \text{ W m}^{-2}$ in latent heat flux in a substantial strip of the V-shaped region (figure 4(g)). With $1 \text{ W m}^{-2}$, corresponding to 0.26 mm day$^{-1}$ of evaporation, this factor can explain the majority of the reduced precipitation in the V-shaped trade-wind region in figure 3(a): ultimately, there is a reduced local evaporation due to the cooler ocean skin temperatures.

5. Summary and discussion

Altogether, the net effect of changes in ERA5 relative to ERAI results in smaller discrepancies relative to the best available observations of the radiation budget, circulation and precipitation. The IFS used in the newest ERA5 includes many improvements to its cloud, convective and radiation schemes from that used in ERAI (Hersbach et al. 2020). This study presented relevant differences over the Pacific between these two reanalyses and compared them to observation-based products that are not assimilated (except for surface wind). Overall, ERA5 shows reduced biases in total ice water path (TIWP) versus CloudSat-CALIPSO, in radiation budget components versus CERES and in precipitation versus GPCP. The mean precipitation is lower in ERA5 than ERAI, representing an improvement versus GPCP. This improvement is driven by relatively large decreases in
convective precipitation that are not compensated by increases in large-scale (stratiform) precipitation over the western Pacific and trade-wind regions. We then examined the ERA5-ERAI differences in near-surface variables and turbulent heat fluxes which are not observed. Noting that in the V-shaped region between the ITCZ and SPCZ, there are implied changes to the near-surface vapor pressure deficit which reduce evaporation to an extent that is sufficient to explain the reduced precipitation in ERA5.

This work was motivated by a specific hypothesis related to the inclusion of radiatively interactive falling ice in the new ERA5 IFS. From prior controlled simulations with FIREs on and off in coupled models and offline runs with the ERAI version of the IFS (Li et al 2014b), it is expected that radiatively-interactive falling ice (snow) reduces outgoing longwave in deep convective regions, stabilizes the atmosphere there and changes low-level circulation in a way that results in nonlocal temperature and precipitation changes. In the case of the ERAI to ERA5 transition, the improved Pacific climate representation relative to independent satellite datasets cannot be linked to these FIREs hypothesis. Rather, the changes in radiation in most areas are qualitatively consistent with changes in cloud fraction, with a contribution from optical depth in the western tropical Pacific. There is also a clear evidence of difference in cloud overlap between ERAI and ERA5 in the western tropical Pacific, and precipitation changes are consistent with changes in convection that may be driven by the updated IFS’ convection scheme and changes in model resolution that likely impact the partitioning between convective and large-scale precipitation except for the Indo-Pacific Warm Pool region.

These processes are considered stronger candidates than falling ice radiative effects to explain most of the large-scale radiation and precipitation changes from ERAI to ERA5. We argue that this does not invalidate previously documented results from short-term IFS forecasts, off-line radiative properties experiments using CloudSat-CALIPSO and changes in CESM1-CAM5 climate sensitivity simulations, in which adding FIREs substantially changes the simulation of Pacific climate. Rather, the ERA5 implementation of FIREs has had a smaller relative effect on simulated Pacific climate than other changes to the IFS. To best justify the effect of the falling ice radiative effects (FIREs) on the improvement of ERA5 fields is to turn off FIREs with the same configuration as in the standard ERA5 and rerun a whole assimilation system and compare with standard ERA5 fields. However, it is out of the scope of the present study.

It is unambiguous that including radiatively active snow results in a substantial reduction in the discrepancy of Pacific TIWP from ERAI to ERA5, but we note that despite the 300% increase, it remains underestimated relative to CloudSat 2C-ICE. ERA5 therefore probably underestimates the impact of FIREs on the present climate. Furthermore, it implements a different scheme for representing falling ice than that used in the study of Li et al (2020b), which include a large-particle-size mode. CMIP6 models with this less-realistic implementation did not show the same strong pattern of radiative flux, circulation and precipitation changes relative to non-FIREs models that occurs in models with the more-realistic scheme by including falling ice radiative effects.

In conclusion, ERA5 includes numerous improvements (Hersbach et al 2020) that reduce discrepancies versus observation-based products across the Pacific, when compared with ERAI. This includes substantial improvements in atmospheric ice content, radiative fluxes, circulation, thermodynamics and precipitation, which occur over all four seasons, not just the annual mean (see appendix figures A1–A4).

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The availability of vertically-resolved cloud hydrometeor profiles 2C-ICE (Deng et al 2010, 2013) is derived from CloudSat-CALIPSO (Stephens et al 2008, Austin et al 2009; http://www.cloudsat.cira.colostate.edu/). The CERES Energy Balanced and Filled [CERES-ERA] data provide radiation at TOA and corresponding surface flux radiation products constrained by TOA CERES-ERA adjustments [https://ceres.larc.nasa.gov/order_data.php].

The GPCP Version 2.3 combined monthly precipitation data set is obtained from https://www.esrl.noaa.gov/psd/. The QuikSCAT sea-surface wind data under all weather and cloud conditions are available at http://podaac-www.jpl.nasa.gov for the obs4MIPS project.

ERAI and ERA5 data are obtained from https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/ and https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset.

Data availability statement

No new data were created or analysed in this study.
Appendix Figures

Figure A1. Seasonal cycle of (a) outgoing longwave radiation at TOA (RLUT) for ERAI (red), ERA5 (green) and CERES (black) averaged over the Pacific basin (120°E–300°E, 60°S–60°N). (b) Same as (a) but for reflected shortwave at TOA (RSUT). (c) Same as (a) but for downward shortwave radiation at surface (RSDS).

Figure A2. Same as figure A1 but for the Tropical Western Pacific region (120°E–180°, 10°S–10°N).
Figure A3. (a) December–January–February (DJF) time-averaged differences of ERA5–ERAI in radiative fluxes (W m$^{-2}$) for upward longwave radiative flux at the top of atmosphere (RLUT) with M represents mean difference and R is for root-mean-square between ERA5 and ERAI, (b) bias of RLUT for ERAI against CERES, with 'M' represents mean bias and 'R' is for root-mean-square error relative to CERES, (c) same as (b) but for ERA5, (d)–(f) same as in (a)–(c) but for reflected radiative shortwave flux (RSUT) at the top of atmosphere, (g)–(l) same as in (a)–(c) but for downward radiative shortwave flux at surface (RSDS). The annual average is over 2001–2017.

Figure A4. Same as figure A1 but for June–July–August (JJA).
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