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RESEARCH ARTICLE

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Key Points:

- While global-storm resolving models generally capture large-scale characteristics of tropical convection, regional features vary greatly
- Most models reproduce observed seasonal shifts in the radiation balance in the Tropical Western Pacific but with differing cloud populations
- These models present a novel perspective on difficult-to-observe near-tropopause cirrus clouds

Supporting Information:

Supporting Information may be found in the online version of this article.

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Tropical Cirrus in Global-Storm Resolving Models: 3. Seasonal Changes and TTL Cirrus in the Tropical Western Pacific Using DYAMOND

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Abstract Recent advances in computer modeling have spurred the production of several global storm-resolving models (GSRMs), which explicitly represent atmospheric circulations from convective to global scales. As a result, GSRMs simulate the formation and evolution of tropical cirrus clouds more physically than typical global climate models/general circulation models (GCMs) which use parameterizations to represent deep convection. We analyze the output from nine GSRMs from the DYAMOND initiative, focusing on the second phase of DYAMOND that simulated a period in January–February 2020. This paper is the third in a series investigating tropical cirrus clouds in GSRMs using DYAMOND model output for an intercomparison. In the tropics, models capture the mean outgoing longwave radiation within -5 to 14 W m^{-2} of observed climatology, though most models have more convective precipitation over the 40-day simulation period than observed. While the models represent large-scale tropical convection with some fidelity, large regional differences in cloud properties and top-of-atmosphere radiation fluxes exist. We focus on a region within the Tropical Western Pacific to study the small-scale features available with the high spatiotemporal resolution of GSRMs. Most models that participated in both phases of DYAMOND capture the seasonal differences between the two phases, yet each model exhibits unique cloud populations that are persistent across seasons. GSRMs even simulate the notoriously difficult-to-observe tropical tropopause layer (TTL) cirrus, providing a novel perspective on TTL cirrus even though the models have different cloud characteristics over the short 40-days simulation.

Plain Language Summary As computer models improve and can run for longer at higher resolutions, it is important to evaluate the fidelity of these models to capture important atmospheric phenomena such as tropical convection and cirrus clouds. We analyze the output from nine Global Storm-Resolving Models (GSRMs), atmospheric models that resolve deep convection, or “storms”, and may simulate tropical cirrus clouds more physically than typical GCMs. The GSRMs simulate 40 days in both boreal winter and summer; while we primarily focus on results from the winter simulations, we also show comparisons across seasons. We evaluate the models’ ability to reproduce reasonable top-of-atmosphere radiation fluxes and cloud properties using available satellite data and reanalysis. We find that most models generally capture the characteristics of tropical convection but have great regional variation. Three models studied in detail each simulated thin cirrus clouds near the tropopause which are notoriously difficult to observe and simulate. Hence, these models can be a useful tool to study cirrus clouds, especially when used in an “ensemble”-like comparison since the models portray a wide range of behaviors overall.

1. Introduction

Cirrus clouds cover a substantial area of the tropics and are significant for several aspects of Earth's climate system. Cirrus are closely related to deep convection and may be formed directly from anvil outflow or indirectly from gravity waves (Gasparini et al., 2023; Sassen et al., 2009). Different formation mechanisms drive different cloud properties (Krämer et al., 2016; Weng et al., 2024) that impact the top-of-atmosphere radiative fluxes and the local heating within the clouds. The radiative fluxes are regulated by cirrus clouds due to the cold temperatures in the upper troposphere, where cirrus act to reduce the amount of outgoing longwave radiation (OLR) while having a small impact on shortwave (SW) radiation (e.g., Ackerman et al., 1988; Hartmann & Berry, 2017; Liou, 1986; Turbeville et al., 2022). Hence, the radiative balance is sensitive to cirrus clouds, which are themselves sensitive to ice microphysics, local heating, and convective-to large-scale circulations (e.g., Atlas

et al., 2024; Blossey et al., 2010; Dinh et al., 2014; Gettelman et al., 2012; Hartmann et al., 2001; Haslehner et al., 2024; Sokol & Hartmann, 2020). Large-scale circulations impact cirrus clouds, which may feedback on these circulations by strengthening the ascent and widening the descending branches of the Hadley cells (Albern et al., 2018; Su et al., 2017). Cirrus clouds impact the large scale environment and radiative fluxes while also being controlled by micro-scale to large-scale processes and complex feedbacks. Hence, modeling cirrus clouds is very challenging and contributes a large amount to uncertainty in climate predictions (Atlas et al., 2024; Hartmann & Berry, 2017; Sherwood et al., 2020; Sokol et al., 2024). While the high cloud altitude feedback is robustly positive, the uncertainty in the tropical anvil cloud area is broad and of uncertain sign with a range of -0.4 to 0 W/m²/K (Sherwood et al., 2020) broadened to include slightly positive values in more recent work (McKim et al., 2024; Sokol et al., 2024). Improving representation of cirrus clouds in models could reduce the overall uncertainty in cloud feedbacks in a warming climate.

In the tropics, cirrus clouds occur frequently in the tropical tropopause layer (TTL; 14–18 km), these are the coldest and highest cirrus on the planet and so have a stronger potential to reduce the OLR. The TTL is a transitional region from the upper troposphere to the lower stratosphere, having intermediate properties of both (Fueglistaler et al., 2009). Due to generally coarse horizontal and vertical resolution in the upper troposphere-lower stratosphere (UTLS; typically 12–20 km), global climate models/general circulation models (GCMs) cannot resolve the complex interactions of clouds, gravity waves, and water vapor occurring there. Clouds in the UTLS impact the top-of-atmosphere (TOA) radiation balance and radiatively heat the UTLS, which affects the circulation in the tropics along with the amount of stratospheric water vapor (E. J. Jensen et al., 1996; Haladay & Stephens, 2009; Solomon et al., 2010). Models that are able to resolve explicit convection may allow cirrus to form more naturally. However, even in models that do not parameterize deep convection, cirrus cloud properties and lifetimes in the tropics are highly sensitive to ice microphysical schemes (Atlas et al., 2024). Many ice microphysics schemes apply parameterizations of ice formation processes that were designed to simulate ice clouds at less extreme temperatures (i.e., at lower altitudes) than found in the TTL, which neglects important physical processes for and environmental drivers of cirrus cloud formation and evolution (Gasparini et al., 2023; Kärcher, 2022).

As computing resources increase, it has become feasible to run models with high enough resolution to represent deep convective storms explicitly at global scales. We must then diagnose model biases and areas for improvement to continue developing these global storm-resolving models (GSRMs). The DYAMOND (Dynamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) initiative collected output from several GSRMs that were initialized from reanalysis and run freely for 40 days (Stevens et al., 2019). The DYAMOND project provides an opportunity to analyze the current state of GSRMs, both individually and compared to other models of this type. We analyze the radiative budget, cirrus cloud properties, and TTL structure in these models. The improvements to horizontal and vertical resolution as well as explicit convection promise to improve the representation of cirrus clouds over traditional GCMs by simulating more thin cirrus (Stevens et al., 2020); however, cirrus in multiple models taking part in DYAMOND has been found to be highly sensitive to changes in ice microphysics (Atlas et al., 2024; Seiki et al., 2015; Sullivan & Voigt, 2021). Storm-resolving models generally reproduce vertical velocity variability, shifts in circulation, and the diurnal cycle of precipitation better than GCMs (Stevens et al., 2020), but they still need improvement in their portrayal of clouds from deep convection to cirrus clouds. Feng et al. (2023) show DYAMOND models capture some characteristics of mesoscale convective systems, such as the diurnal cycle, but overestimate convective precipitation and precipitation intensity from mesoscale convective systems. Some models have more isolated deep convective systems, especially over convectively active ocean regions (Feng et al., 2023).

This paper is third in a series on tropical cirrus in GSRMs using DYAMOND output. Using data from the first phase of the DYAMOND intercomparison (DYAMOND 1), Nugent et al. (2022) (Part 1) and Turbeville et al. (2022) (Part 2) found a large spread across models in the representation of tropical clouds, especially overshooting convection and cirrus. They showed that the variability of cloud properties comes from a combination of microphysical and dynamical differences in the model though it is impossible to quantify the contribution from each due to the format of the model comparison. This study expands on these previous results and focuses on the distribution and vertical structure of tropical cirrus clouds in DYAMOND, especially focusing on TTL cirrus in the Tropical Western Pacific (TWP) region. We analyze variables related to cirrus clouds such as convection, precipitation, and TOA radiation to build a conceptual picture of tropical clouds in these models.

Table 1

Models From DYAMOND Phase 2 Listed With Their Horizontal Resolution at the Equator (dx); Number of Vertical Levels (nlevs); Number of Vertical Levels in the Tropical Tropopause Layer (TTL) (nlevs TTL); Microphysics Scheme and References (mphys); Number of Moments in Microphysics Scheme (Mom); Which Types of Cumulus Parameterizations Are Used (D: Deep; S: Shallow; N: None); Whether the Atmosphere Model Is Coupled to an Ocean Model; and Further References for the Model

Model	dx (km)	nlevs	TTL nlevs	mphys	Mom	CP?	Coupled?	References
ARP	2.5	75 (60)	8	modified LAM model AROME	1	N	N	Voltaire et al. (2017)
GEOS	3	181	22	1 MOM 6 cat	1	D, S	N	Putman and Lin (2007); Putman and Suarez (2011)
ICON-NWP	2.5	77	8	Baldauf et al. (2011)	1	N	N	Klocke et al. (2017) Zängl et al. (2015)
IFS	4	137	15	ECMWF scheme	1	S	Y	ECMWF (2020a)
MPAS	3.75	55	N/A	Thompson WRF Single-Moment 6-Class	1.5	D, S	N	Skamarock et al. (2012)
SAM	4	61	8	SAM 1 MOM	1	N	N	Khairoutdinov et al. (2022)
SCREAM	3.3	128	18	P3	2	N	N	Caldwell et al. (2021)
SHIELD	3	79	8	GFDL MP v3 (Zhou et al., 2022)	1	S	N	Harris et al. (2021, 2023)
UM	4.5	55	7	Modified Wilson and Ballard (1999); Ice (Baran et al., 2016)	1	S	N	Walters et al. (2019)

The DYAMOND models simulate two seasons: Phase 1 from August to September 2016 and Phase 2 from January to February 2020. In Section 3.2, we compare the two phases of DYAMOND to climatology from Sassen et al. (2009) who found that cirrus are observed more frequently at night and in boreal winter. However, not all differences between phases of DYAMOND are from the change in season because many models had significant development, which changed the cloud characteristics. We highlight developments related to convection and cirrus clouds specifically.

In Section 2, we describe the data, model output, and domain. The results start with an overview of the cloud characteristics in the entire tropics from 30°N–30°S in Section 3.1. Then we dive deeper into the vertical structure of clouds and the environment in a subsection of the TWP (Section 3.2) and compare the seasonality between DYAMOND 1 and 2. Finally, Section 3.3 explores the differences in TTL cirrus in the models, and we conclude in Section 4.

2. Description of Model Output, Data, and Study Domain

One of our principal goals is to assess the quality of cirrus simulations. Data on clouds in the tropical upper troposphere and TTL is limited. Satellite data provides the most uniform coverage in the tropics and is our primary tool for comparison to model output.

2.1. DYAMOND Models

In previous studies, Nugent et al. (2022) and Turbeville et al. (2022) investigated the life cycle of tropical convection and cirrus in models that participated in the first phase of DYAMOND (hereafter DYAMOND 1; Stevens et al., 2019). This study incorporates results from the second phase of DYAMOND, which took place in boreal winter (hereafter DYAMOND 2). The DYAMOND 2 simulations were initialized on 20 January 2020 at 0 UTC from the European Center for Medium-Range Weather Forecast's (ECMWF) reanalysis and ran freely for 40 days (without nudging). The various models, identified in Table 1, were run at horizontal grid spacings of less than 5 km. This high horizontal resolution allows most models to turn off parameterizations for deep convection and shallow cumulus parameterizations; however, some models have a modified deep convective and shallow cumulus parameterization. See Table 1 for more information on the setup of the models. The models have different microphysics schemes, which vary greatly in their treatment of ice clouds such as cirrus. Seiki et al. (2022, Table 2) provides an excellent description of the cloud microphysics used in each of the DYAMOND models. Most models have a single moment bulk microphysics scheme except for SCREAM's double moment

Table 2

List of Models That Participated in Both Phases of DYAMOND and the Major Differences Between the Simulations That Are Known

Model	Differences
ARP	Microphysics tuned for high-resolution non-hydrostatic modeling
GEOS ^a	Poor version of microphysics in DYAMOND 1
FV3/SHiELD	Many significant changes
ICON	No significant changes
IFS	Small changes
MPAS	Coupled to 1D ocean model, updated cloud fraction in Thompson microphysics
NICAM ^a	Error in DYAMOND 2
SAM	Improved temperature profile used for precipitation-related coefficients
UM	None

Note. More details can be found in Text S1–S9 in Supporting Information S1. ^aRemoved from our analysis.

microphysics and MPAS's hybrid microphysics (predicts number concentration for rain and cloud ice only). Most models have 6 categories of hydrometeors (water vapor, cloud water, rain, cloud ice, snow, and graupel), but ARP, IFS, and UM have 5 categories (excludes graupel) and SCREAM model has 4 categories (the ice category accounts for different particle sizes and densities). We evaluate nine DYAMOND models against satellite data and reanalysis to see how well models represent the current climate.

2.1.1. Differences in Model Set-Up Between DYAMOND Phases

The models that participated in both phases of DYAMOND are ARP, GEOS, FV3/SHiELD, ICON, IFS, MPAS, NICAM, SAM, and UM. The notable model differences between the two phases of DYAMOND are listed in Table 2. More detailed information on the differences can be found in Text S1–S9 in Supporting Information S1.

Differences in model setups between DYAMOND 1 and 2 are small for IFS, ICON, and UM, which had few significant changes. In contrast, differences in models like SAM and FV3/SHiELD may be due to changes in the model itself. Although it is difficult to determine whether differences between DYAMOND 1 and 2 are due to model setup or seasonality, we will attempt to note which models had significant model development when comparing the radiative and cloud properties in each model.

2.2. Data

This study uses data from four satellite products with retrievals of cloud, precipitation, and radiative fluxes (details described below). Despite the models being initialized with ECMWF reanalysis on 20 January 2020, we do not expect the models to follow the same weather patterns as in the 2020 data beyond the first few days since the DYAMOND models are free running. For our comparisons, we use model output from days 10–40, which mean the models are simulating a climate similar to that of February 2020 but with differences as large as we might see in one season across multiple years so we default our comparisons to February or seasonal climatology.

The CERES-CloudSat-CALIPSO-MODIS (CCCM) product provides collocated cloud microphysics and TOA radiative fluxes with a horizontal footprint of roughly 30 km (Kato et al., 2010, 2011). We use three months of data over four years for comparison to DYAMOND, specifically July–September during the years 2007–2010 for DYAMOND 1 and January–March during 2008–2011 for DYAMOND 2 comparisons. The daytime values for TOA SW and longwave (LW) radiation as well as cloud top height (CTH) are used in this study. Additionally, we coarsened the model output to $0.3^\circ \times 0.3^\circ$ to match the footprint of CCCM for the radiation comparison but left the models at native resolution for the CTH analysis.

The LiDAR-raDAR (DARDAR) product (Deng et al., 2013) combines CloudSat, CALIPSO, and MODIS satellite measurements to derive microphysical properties of cirrus clouds over a broad range of optical thicknesses with a

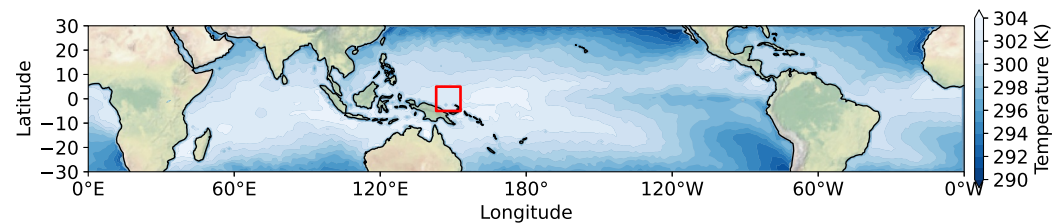


Figure 1. Study domain is plotted with sea surface temperature from 20 January 2020 00 UTC, the initial condition for DYAMOND 2. The $10^{\circ} \times 10^{\circ}$ Tropical Western Pacific (TWP) region (outlined in red) is used for an in-depth small-domain analysis.

fine horizontal spacing of ~ 1.1 km and a vertical resolution of 60 m (Deng et al., 2013; Sokol & Hartmann, 2020). DARDAR has a higher retrieval uncertainty for optically thin cirrus layers, which are detected only by the lidar (Cazenave et al., 2019). We use both daytime and nighttime values from the 2009 July to September DARDARv2 data set to compare to DYAMOND 1. For DYAMOND 2 comparisons, we have DARDARv2 data from February for eight years (2007–2017 with two years missing). The GSRM output is not coarsened for comparisons with DARDAR, which has a similar footprint to the model grid.

We use LW and SW radiative fluxes at TOA from the CERES SYN1deg product (Doelling et al., 2013, 2016), available from 2000 to 2019. The data has a $1^{\circ} \times 1^{\circ}$ horizontal resolution with an approximate uncertainty of 3 W m^{-2} (Kato et al., 2018). We seasonally subset this data to 1 August to 10 September of each year for DYAMOND boreal summer comparisons and 20 January to 28 February for DYAMOND boreal winter comparisons.

We use observations of precipitation from the Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERG) on a $0.1^{\circ} \times 0.1^{\circ}$ grid and 30-min output frequency (Huffman et al., 2015; Tan et al., 2019). The precipitation data matches the DYAMOND 2 simulation period from 20 January to 28 February 2020. While the IMERG product separates stratiform and convective precipitation automatically, the DYAMOND models do not have such a clear distinction; hence, we define stratiform precipitation uniformly across the data and model output as any precipitation occurring at a rate less than 1 mm hr^{-1} . This threshold is intentionally general, and our results are not sensitive to this threshold.

2.3. Study Domains

This study focuses on two main regions of climatic interest: the global tropics (GT; 30°N – 30°S) and the tropical western Pacific (TWP; 143°E – 153°E , 5°S – 5°N) as shown in Figure 1.

2.3.1. Global Tropics (GT)

This analysis uses data to evaluate model output from the global tropics (GT; 30°N – 30°S). The model output and satellite data for TOA radiation and precipitation are compared on a common 1×1 degree grid, with the model output and precipitation coarsened to this resolution. To calculate the thin cirrus fraction (defined as columns with ice water path (IWP) between 0.1 and 100 g m^{-2}), we use the native grid data IWP to identify such columns and compute the cloud fraction over 1° squares for plotting and comparison.

2.3.2. Tropical Western Pacific (TWP)

We do an in-depth analysis of the small-scale and local features of GSRMs by using a small $10^{\circ} \times 10^{\circ}$ region in the convectively active TWP region (143°E – 153°E , 5°N – 5°S), which is outlined by the red box in Figure 1. This domain matches the TWP analysis from Turbeville et al. (2022), which used DYAMOND 1 model output. The TWP is convectively active year-round and has the key feature that the SW cloud radiative effects (CRE) from convection are approximately balanced by LW CRE from cirrus clouds (Hartmann & Berry, 2017; Hartmann et al., 2018). We analyze tropical clouds and TTL cirrus in DYAMOND 2 and compare it to available output from DYAMOND 1 (Section 3.2).

3. Results

Results are broken into three distinct parts: (a) statistics of global tropical convection and cirrus clouds in DYAMOND 2, (b) a regional study in the TWP of seasonal variations between DYAMOND 1 and 2, and (c) an analysis of modeled TTL cirrus and its relationship to the thermodynamic state of the TTL in DYAMOND 2. When comparing results between DYAMOND 1 and 2, we note major model developments that may impact those comparisons.

3.1. Global Tropics

In order to determine how well the DYAMOND models simulate large-scale convective features, we compare OLR, precipitation, and cirrus cloud fraction statistics in the tropical band from 30°N to 30°S. The differences in radiation fluxes at the top of atmosphere can expose the differences in microphysics through its impact on cloud radiative forcing (Atlas et al., 2024; Seiki et al., 2022).

The climatological distribution of OLR at TOA in the tropics has three local minima: the Maritime continent/western Pacific Ocean, continental Amazon, and south-central Africa. Most models underestimate the convection over land in the Amazon or African regions (Figure 2); ARP closely matches climatology over land. Half of the models also underestimate convection in the South Pacific Convergence Zone (SPCZ). (Note that model abbreviations, such as ARP, are listed in Table 1.) Aside from SCREAM, most models have a shift in the location of convection in the Indian Ocean and the TWP region, which could be a remnant of the model initialization using the 2020 reanalysis which had a lower than average OLR in the SPCZ or a consequence of the high variability in the western Pacific region (see the 2020 OLR data and interannual standard deviation in Figure S4 in Supporting Information S1). Like the year-to-year variability in OLR, the models also show a large variability in mean values and spatial distribution of OLR.

The standard deviation of 13 years of CERES data for January–March (JFM) is around 20 W/m² in the Maritime Continent and TWP regions with a maximum east of the TWP box at 30 W/m² (not shown). Thus, it is not surprising to see ± 20 W/m² model differences (grayed out in Figure 2) due to the free-running behavior of the models. However, the model differences from observations in some regions exceed 100 W/m² in magnitude. The spatiotemporal mean values of OLR in the GT range from 250.8 W/m² in MPAS to 272.1 W/m² in SAM. While the climatological mean falls within the model spread at 258 W/m², the majority of the models (all but MPAS and ARP) simulate a mean OLR larger than CERES (Figure 3a).

The models's biases in OLR suggest that they do have some individual large-scale and local differences from climatology: SAM and IFS have too little convection across the tropics; SCREAM has too little anvil and convective clouds in convectively active regions; GEOS has an intertropical convergence zone that is too narrow and an SPCZ that is too weak; MPAS has extremely low OLR in the west-central Pacific which is only partially counteracted by weak convection over land; the other models (ICON, UM, SHIELD, and ARP) match the tropical mean OLR within 8 W/m² with larger regional differences.

Despite convection occurring in slightly different locations in each model, the cumulative tropical precipitation is between 107 and 127 mm by the end of the simulations, excluding MPAS which has anomalously low precipitation (Figure 3a). All the models other than MPAS overestimate accumulated precipitation compared to the IMERG observations, which measured 99 mm of precipitation accumulated from 30 January to 28 February 2020.

The energy budget in the tropics roughly balances precipitation with radiative cooling. As a saturated air parcel rises, it will condense to form cloud particles in the liquid or ice phases which may then sediment out and contribute to surface precipitation (Figure 3a) if it reaches the ground before sublimating or evaporating. Precipitation rates are affected by both moisture and cloud sources/sinks where differences in cloud ice may be significant (Gao et al., 2005). Since the models have similar moisture profiles in the tropics, differences arise mainly from the cloud ice microphysics in the model. Models with higher rain rates have comparatively larger OLR (Figures 3a and 3b). For example, MPAS accumulates very little precipitation meaning that less cloud condensate sediments as precipitation and falls to the surface than in other models; in the absence of a strong cloud sink from precipitation, more cloud ice reaches the upper troposphere and spreads into anvil clouds contributing to the low mean OLR. MPAS is an extreme example of this in the tropics. Most other models have a higher OLR and a higher precipitation, suggesting that they precipitate more effectively so less cloud condensate reaches the upper troposphere.

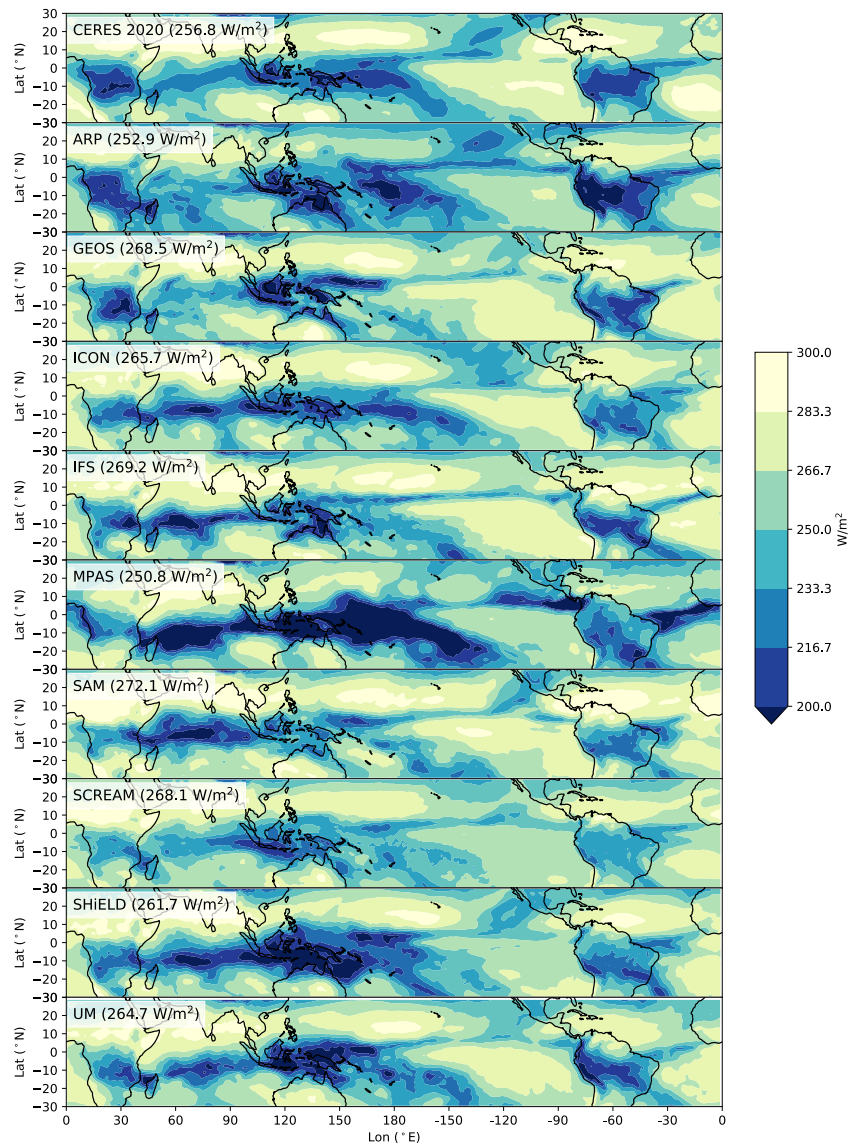


Figure 2. Observed mean outgoing longwave radiation (OLR) from CERES from the months of January, February, and March during each year from 2001 to 2013 is shown in the top panel. Model output coarsened to 1° and averaged over the last 30 days of the simulation period is plotted as the difference from observations in panels below. The model name and spatiotemporal mean of OLR are noted in the upper left corner of each panel. The warmer colors indicate that the models have a higher mean OLR than the data at that location over the 30 days, and vice versa for cooler colors.

Schumacher and Houze (2003) found that the stratiform to convective precipitation ratio in the tropics (20°N – 20°S) is about 24% using observations from Tropical Rainfall Measuring Mission. To ease the consistent comparison between models and observations in this study, we define stratiform precipitation as all precipitation weaker than 1 mm/hr. Using that definition, data from IMERG from 30°N – 30°S during the DYAMOND 2 period shows that about 14% of precipitation is from stratiform clouds, as shown in Figure 3b. While IMERG has been shown to overestimate precipitation overall and underestimate light precipitation (Bolvin et al., 2021; Pradhan et al., 2022), some models (in particular, SAM, SCREAM, and ICON) agree well with IMERG. However, many models underestimate the fraction of overall precipitation that is stratiform, consistent with results from Feng et al. (2023). Note that our results are not sensitive to small changes in the choice of threshold, which was chosen to identify differences between light rain and heavy precipitation associated with deep convection.

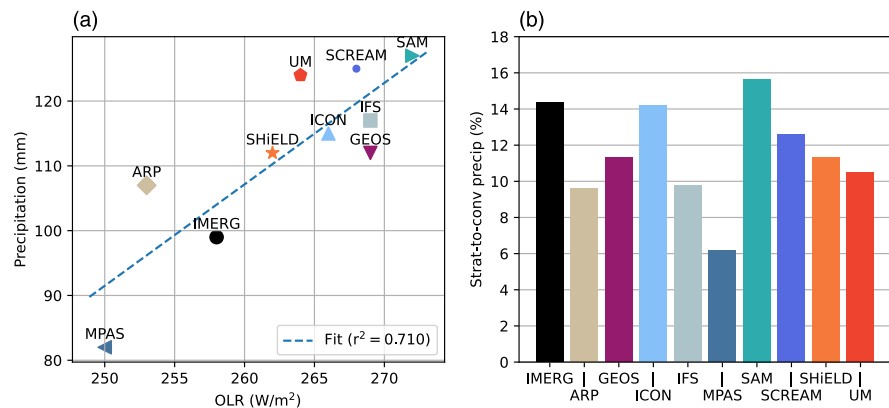


Figure 3. (a) Accumulated precipitation and mean outgoing longwave radiation (OLR) over the tropical band from 30°N to 30°S from day 10–40. The first ten days are ignored as spin-up. The data is from January 30 to 28 February 2020 from Integrated Multi-Satellite Retrievals for GPM precipitation. (b) The stratiform to convective precipitation ratio is plotted as a percent with the models listed from highest to lowest accumulated precipitation from left to right.

The model biases in OLR are consistent with the frequency distribution of IWP in the tropics as seen in Figure 4. Notably, IFS has very little ice greater than 1 kg/m², contributing to its warm bias in OLR. While SCREAM has fewer anvils (intermediary values of IWP around 1e–2 kg/m²), it has more 1° × 1° boxes with large IWP (likely associated with convection). Most models produce a large number of grid columns with small IWP ($\leq 1e-4$ kg/m²), which are not included in DARDAR retrievals. The prediction of greater amounts of thinner cirrus than retrieved by DARDAR may have some support in recent balloon-borne lidar observations in the tropics, which find a population of very thin cirrus that are not detected by the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) instrument on which the DARDAR retrievals rely (Lesigne et al., 2024).

Now that we have established the general convective characteristics of the DYAMOND 2 models, we compare the properties of ice clouds by using IWP as a proxy for ice cloud type. Thin cirrus clouds are defined as $1e-4$ kg/m² $\leq$ IWP < 0.1 kg/m², following Sokol and Hartmann (2020) and Turbeville et al. (2022). This threshold is used to compute cloud fraction on the native grid, which is then averaged to 1° squared boxes. Note that these fractions

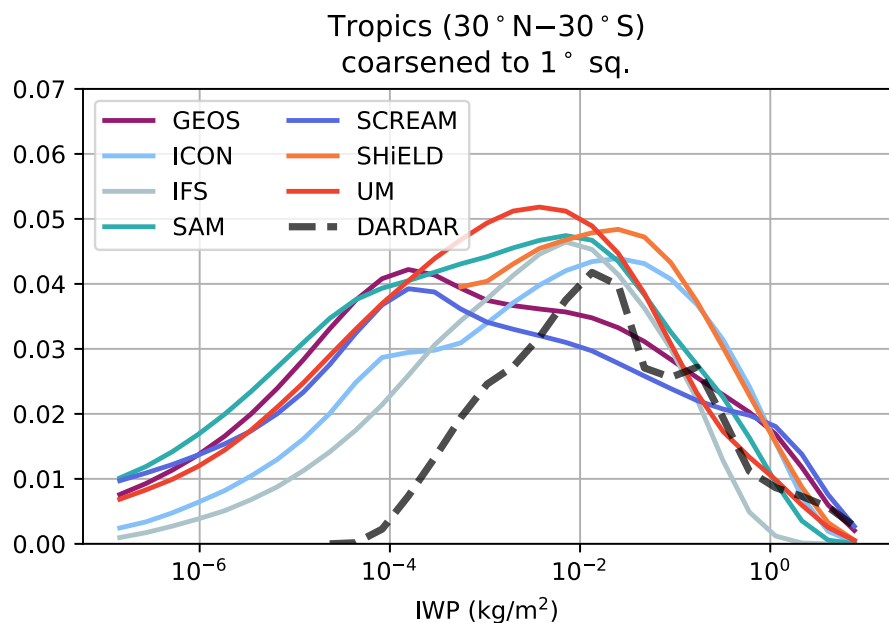


Figure 4. Normalized histograms of ice water path (IWP) in the tropics after the model output was coarsened to 1° squared. SHIELD (orange) is inaccurate below 10⁻³ kg/m² and thus not included here. DARDAR here includes IWP from 30°N–30°S from nine Februarys and is not coarsened here.

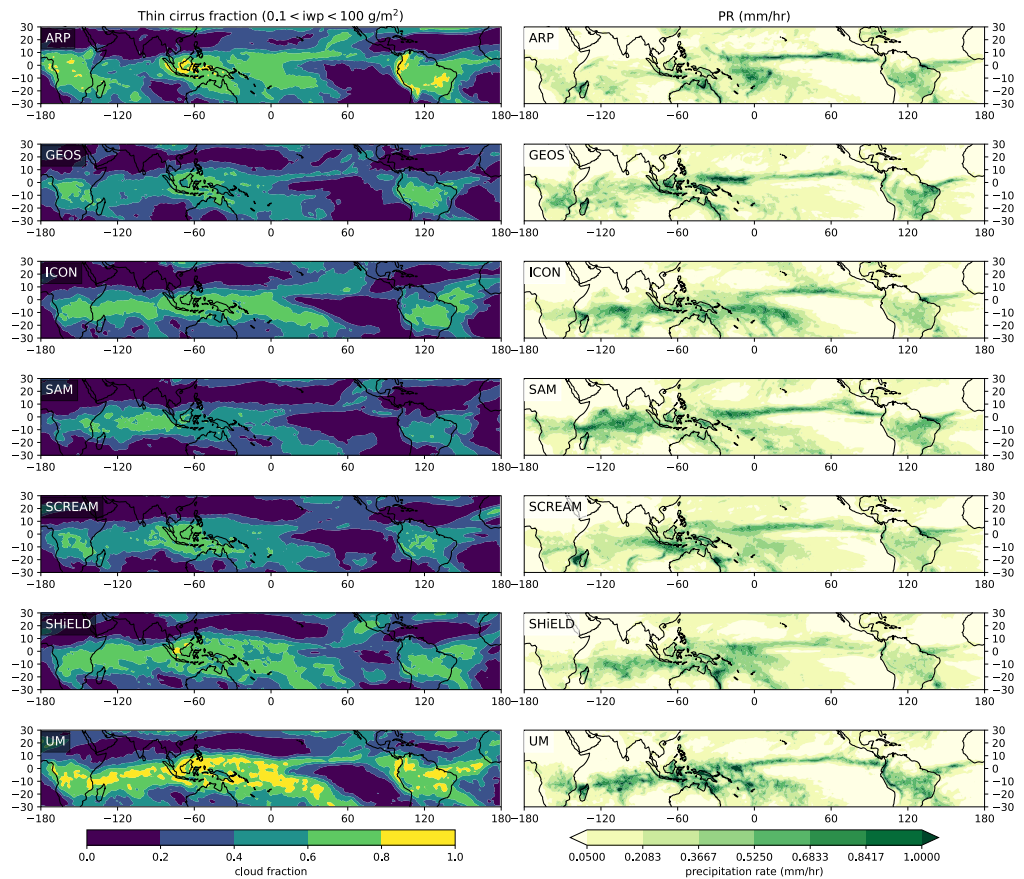


Figure 5. Thin cirrus cloud fraction ($1e-4 \text{ kg/m}^2 \leq \text{IWP} < 0.1 \text{ kg/m}^2$) is plotted on the left for each model (label in top left of each panel). The mean precipitation rate is plotted on the right for comparison to regions of frequent deep convection.

have a small sensitivity to the choice used for the upper bound but a larger sensitivity for the lower bound (our definition of clear sky) since most models produce prolific amounts of small IWPs. The observed maximum of thin cirrus cloud fraction from Sassen et al. (2009, Figure 1) occurs over the tropical ocean from the eastern Indian Ocean to the western Pacific with local maxima over continental Amazon and Africa. Sassen et al. (2009) found that thin cirrus are strongly correlated with deep convective cloud fraction and cover broader regions around convective areas. We show similar results in Figure 5, which shows side-by-side plots of thin cirrus cloud fraction and mean precipitation rates (a proxy for convection).

GEOS and SCREAM simulate three local maxima in cirrus cloud fraction in the same three regions as observed; however, the maximum over the tropical ocean is subdued in both. Most models generate a large swath of cirrus clouds extending from continental Africa in the west to the south-central Pacific Ocean along the SPCZ, not distinguishing the three different regions of cirrus related to convection. However, there is a strong correlation between cirrus clouds and convection as noted by Sassen et al. (2009). The DYAMOND models also have a higher cirrus cloud fraction at the edges of convective areas, especially in UM from a combination of too much anvil cirrus spread and too few grid boxes with small IWPs; UM tends to favor thicker anvil with more substantial IWPs. Perhaps the higher fraction of cirrus at the edge of convection is related to the phenomena of increased deep convection at the edge of convecting regions as described in Windmiller and Hohenegger (2019).

3.2. DYAMOND 1 Versus DYAMOND 2

Most models participated in both DYAMOND 1 and 2 by submitting 40-day free-running simulations. DYAMOND 1 simulates 01 August to 10 September 2016; DYAMOND 2 simulates 20 January to 28 February 2020. There are two contributors to the differences between models in the two phases of DYAMOND: (a) the season via the initial conditions and prescribed sea surface temperatures, and (b) significant model development that

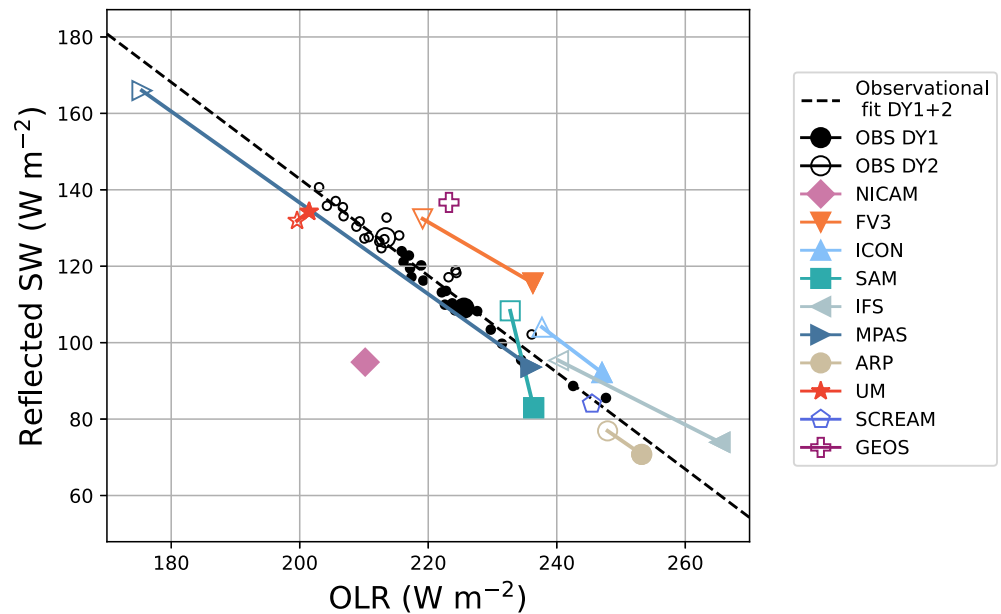


Figure 6. Mean OLR (upward longwave (LW)) is plotted against mean reflected shortwave (SW) radiation (upward SW) at TOA for the TWP region. The models are shown in the colors indicated in the legend with the solid and open symbols for DYAMOND 1 and 2 respectively. The observations from CERES are plotted year by year for both July–August and January–March seasons to match the seasons from DYAMOND boreal summer and winter, respectively. The multiyear mean is plotted as the large solid and open circles for DYAMOND 1 and 2 respectively.

impacted tropical high clouds. Some models made negligible changes to the model setup, dynamics, or microphysics; however, others had significant model development in the 3 years between DYAMOND 1 and 2 submissions. The developments most important for tropical cirrus clouds are listed in Table 2. The analysis in the following section uses a regional subset from the tropical Western Pacific (TWP, 143°E–153°E, 5°N–5°S); the impact of this domain choice is discussed below.

Aside from SAM and MPAS, the models are qualitatively similar in the TWP between DYAMOND 1 and 2 as shown in Figure 6 (i.e., those with a relatively high mean OLR in DYAMOND 1 like ARP, ICON, and IFS also have a high mean OLR in DYAMOND 2). Hence, we are making a decent comparison between DYAMOND 1 and 2 using the TWP region. The impact of choosing a small domain like the TWP can increase the variance among the models. For example, MPAS and UM have lower mean OLR in the TWP while the other models (in order of mean OLR: SHIELD, GEOS, SAM, ICON, SCREAM, ARP, and IFS) have a slightly high mean OLR compared to climatology. CERES has a standard deviation of ± 20 W/m² in the TWP; we can expect the models to vary by around 20 W/m² due to differences in weather patterns from year to year. Models like UM, SHIELD, SAM, and ICON are within this range of observed OLR in the TWP, but models like SCREAM, ARP, and IFS tend to produce higher mean OLR in the TWP than we would expect from their relative GT mean; on the other hand, MPAS has a large negative local difference in OLR in the TWP. The mean values of OLR for the GT, TWP, and local differences between the two regions are listed in Table S1 in Supporting Information S1. Furthermore, we note a slightly positive Madden-Julian Oscillation and El Niño during February 2020 compared to the climatology used in our results. In the CERES data from February 2020, there is a slight eastward shift of convection in the west Pacific compared to climatology, which only a couple of models capture (Figure 2).

3.2.1. Radiative Fluxes in the TWP

The long-term net cloud radiative effect in the TWP is near zero due to the infrequent but strong SW impacts of deep convection balanced by the long-lasting but weak impacts of cirrus clouds (e.g., Gasparini et al., 2019; Hartmann & Berry, 2017; Wall & Hartmann, 2018). The dashed line in Figure 6 fits 20 years of observational data from CERES across seasons and approximates the balance of LW and SW CRE, which approximately cancel in this region (Hartmann & Berry, 2017). There is a clear shift in the observed OLR and reflected SW radiation between seasons; the boreal winter (Figure 6 open black circles) has a generally lower OLR and higher reflected

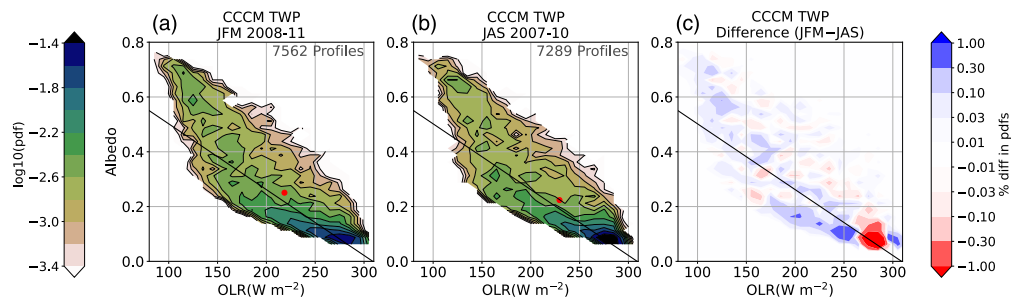


Figure 7. The joint albedo-OLR histogram is plotted for observations using CCCM for (a) boreal winter (January–March for comparison with DYAMOND 2), (b) boreal summer (July–September for comparison with DYAMOND 1), and (c) the seasonal difference (a)–(b). The black line denotes the observed balance between LW and SW at TOA in the TWP region from the boreal summer data; this line is replicated on (b), and (c) for visual comparison. The red dot denotes the mean albedo and OLR for the data.

SW radiation at TOA compared to the boreal summer (Figure 6 closed black circles) over 20 years of observations. Most models qualitatively capture the seasonal shift in TOA radiation, having a similar slope to the observational best fit. SAM, which had major model developments between DYAMOND 1 and 2, is an outlier in terms of slope.

While some models fall within the observed range of either reflected SW or OLR, they do not capture the observed balance between SW and LW radiative fluxes (e.g., FV3/SHIELD, GEOS, NICAM). Other models such as ARP, IFS, and ICON are on the limits of what is observed for reflected SW and OLR. This lack of balance is likely due to a combination of a short simulation period, a small analysis domain, and a lack of tuning to achieve global radiative balance. Despite these issues, the models are reasonably close to the data. The seasonal shifts in FV3/SHIELD, ICON, IFS, and ARP are nearly parallel to the dashed line. FV3 had major model development to become SHIELD but that does not seem to change the characteristic model behavior in the convectively active TWP region from DYAMOND 1 to 2.

Although some models simulate the shift between seasons with the correct direction and slope, there are still inherent model biases. The mean OLR and reflected SW radiation are similar for DYAMOND 1 and 2 for each model except SAM and MPAS. In other words, the differences between seasons in a single model is smaller than the differences across models in a single season; this is similar to our earlier findings that the regional differences in tropical cloud populations in a single model are small compared to differences across models (Turbeville et al., 2022). Some models, like ARP, IFS, and ICON, consistently do not simulate enough thick convective or anvil clouds (low reflected SW and high mean OLR). On the other hand, some models (e.g., UM, GEOS) have excessive anvil cloud decks that greatly reduce the mean OLR or thick congestus clouds that increase the amount of reflected SW radiation. FV3/SHIELD nicely aligns with the seasonal shift but does not capture the LW–SW balance since it has too much reflected SW per the mean OLR (i.e., clouds are too bright). Once again, SAM and, probably, MPAS had major differences in model setup between the two runs so interpreting their changes is difficult.

The differences in cloud populations present in each model and season are clear when we look at the seasonal shift in the joint albedo-OLR histograms in Figure 7. This introduces some nuance to the mean values presented in Figure 6 by including the distribution of SW and LW radiative fluxes since albedo is the ratio of reflected to incoming solar radiation. High albedo and low OLR signify deep convection while high OLR and low albedo signify clear sky. The CCCM histogram has a banana-like shape stretching from the deep convective region in the top left to the clear sky region in the lower right. Values with intermediary albedo and OLR range from thick anvil clouds extending from deep convection to thin cirrus which can have albedo-OLR values near clear sky. Turbeville et al. (2022) used this joint albedo-OLR histogram to describe differences in cloud populations in DYAMOND 1, which they summarized in a schematic in their Figure 4f.

In the observations, both boreal summer and winter joint albedo-OLR histograms have two local maxima at clear sky and deep convective cloud values. The summer and winter histograms look qualitatively similar but when we take the difference between them (Figure 7c), some features appear. Red colors show where albedo-OLR pairings are more prevalent in boreal summer and blue colors where they are more prevalent in the winter. The

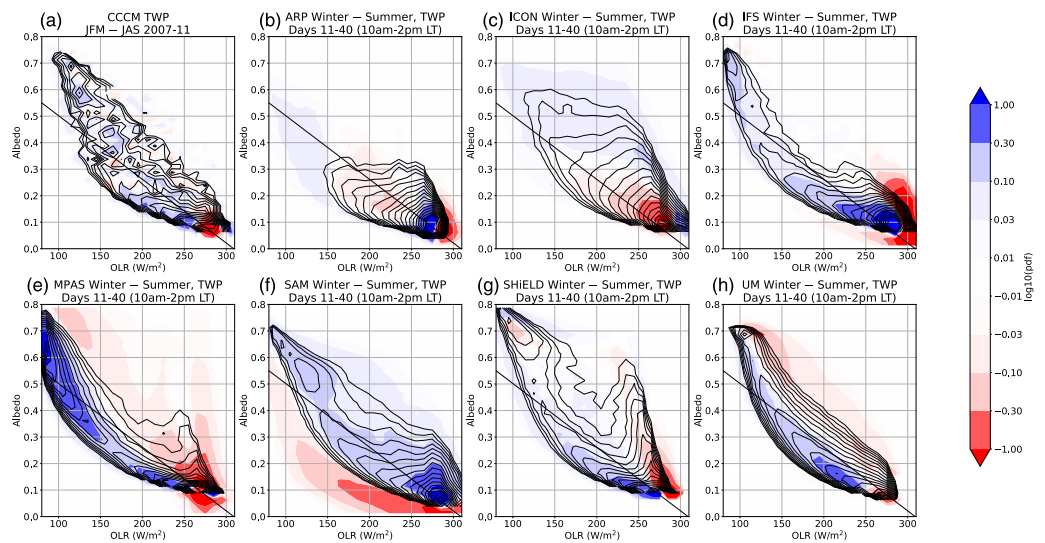


Figure 8. The joint albedo-OLR histogram for the boreal winter in the TWP region is shown in the black contours (same contour levels as Figure 7a) with the difference between boreal winter (blue colors) and summer (red colors) for (a) observations from CCCM (reproduced from Figure 7c), and (b)–(h) models (the difference between DYAMOND 1 from DYAMOND 2). Note that the models have been coarsened to $0.3^\circ \times 0.3^\circ$ for comparison to CCCM observations. The black line denotes the observed balance between longwave and SW at TOA in the TWP region; this line is replicated on the model plots for visual comparison. Recall, that SAM and, likely, MPAS had major differences in model setup between DYAMOND 1 and 2.

observations have two key differences: (a) the boreal winter data has more convective and anvil clouds (with medium to high albedo and low to medium OLR), (b) the boreal summer data has more concentrated clear-sky values around 275 W/m^2 and 0.1 albedo. There are consistent seasonal shifts of CERES TOA fluxes seen in Figure 6 towards lower OLR and higher albedo. The CCCM boreal winter data has a wider distribution around the clear sky end of the diagram, perhaps indicating the presence of more thin cirrus in the winter. This is consistent with observations using MISR CTH that shows boreal winter tends to have higher cloud tops (more thin cirrus with albedo < 0.3) (Chae & Sherwood, 2010). Chae and Sherwood (2010) also found there were fewer thick clouds (albedo > 0.3) in boreal winter, which differs from the CCCM results here.

Figure 8 reproduces the difference plot from Figure 7c and compares with models that participated in both DYAMOND 1 and 2. The black contours are the joint histograms for boreal winter, showing that the models have a large variance in the shape of their underlying joint albedo-OLR histogram. Aside from SAM, the models have similar characteristics between the seasons (See Figures S2 and S3 in Supporting Information S1 for the joint albedo-OLR histogram of the winter and summer simulations separately).

In Figure 8, four models (IFS, FV3/SHIELD, MPAS, and UM) show a shift towards more anvil clouds in the boreal winter, similar to the observations. The models also simulate seasonal shifts and cloud populations that are not apparent in the observations. For example, MPAS and UM also show a shift in the deep convection towards lower OLR and lower albedo in boreal winter. In UM, this shift is likely from higher CTHs in the winter with less optically thick deep convective clouds. ARP and ICON show strong yet opposite dipoles in the difference between seasons; ARP has slightly more anvil cirrus in the winter while ICON has less. ARP and ICON both have a joint histogram that is restricted to the lower right corner, rarely simulating $0.3^\circ \times 0.3^\circ$ averaged boxes that reach albedo-OLR values of deep convection (black contours in Figures 8b and 8c).

3.2.2. Vertical Structure of Clouds

Differences in TOA radiation result from variations in cloud amount and vertical structure across the simulations. The mean vertical profiles of modeled cloud fraction (Figures 9a and 9c) and condensate (Figures 9b and 9d) in the models are shown in Figure 9. The differences in the TTL ice water content (IWC) are around an order of magnitude, highlighted by the log scale in Figures 9b and 9d.

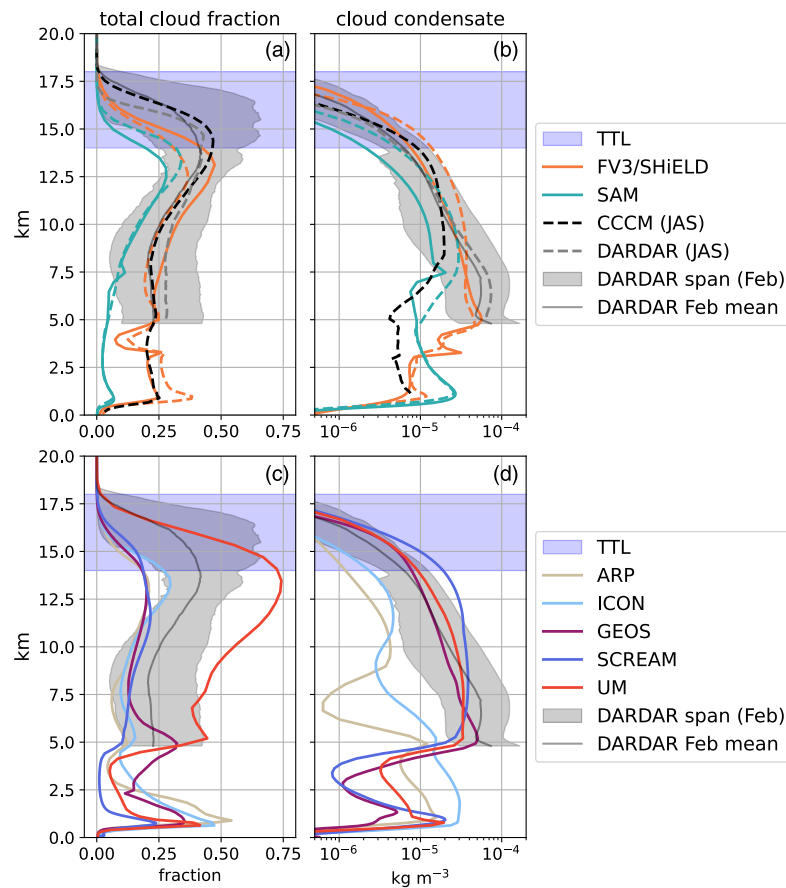


Figure 9. The top row compares observations and models from both DYAMOND 1 and 2 for (a) cloud fraction defined as ice water content (IWC) $> 5 \times 10^{-7} \text{ kg m}^{-3}$ and (b) mean IWC. The CCCM (black dashed line) and DARDAR observations (gray dashed line) coincide with the DYAMOND 1 season. The gray shading shows the range of observed ice cloud condensate using DARDAR from each February for 9 years with the solid gray line showing the interannual February mean. The bottom row compares observations (February across 9 years using DARDAR) to models that were only in DYAMOND 2 for (c) cloud fraction and (d) mean cloud condensate from the last 30 days of the simulations.

Most models simulate a trimodal peak in tropical cloud fraction as observed (e.g., Johnson et al., 1999; M. P. Jensen & Genio, 2006; Kubar & Hartmann, 2008). The DARDAR observations show the range of monthly mean ice cloud condensate across 9 years of February data (gray shading) with the interannual mean shown as the solid gray line in Figure 9b; the DARDAR data matching the DYAMOND 2 (solid gray line) is similar to the data matching DYAMOND 1 (dashed gray line) but has slightly higher cloud tops in the boreal winter. The observations show a wide range in the cloud fractions from year-to-year that is larger than the difference between the seasonal shift of the mean profiles. Observations show a consistent anvil cloud fraction peak in the TTL. The models slightly underestimate the altitude peak in the cloud fraction (below the base of the TTL) and disagree on its magnitude (from 0.2–0.75). The bottom row of Figure 9 shows cloud fraction and cloud condensate profiles for the DYAMOND 2 models only (except SAM and SHIELD which are in the top row) and the DARDAR observations match the DYAMOND 2 season using data from February 2007–2017. The models vary more in the upper troposphere than the observational spread of nine years of data. Some of the models (e.g., ARP and ICON) underestimate both the cloud fraction and cloud condensate (Figure 9) relative to observations. On the other hand, UM greatly overestimates the cloud fraction especially the ice cloud fraction (Figure 9c) but falls within the range of observed ice cloud condensate from 9 years of DARDAR (Figure 9d).

There is less observed variation in the cloud condensate year-to-year, but the models vary by over an order of magnitude at the anvil cloud fraction peak around 14 km. There is also a large spread in the models near the melting layer from near 0 cloud fraction in SAM to 0.4 in UM and nearly two orders of magnitude in cloud water content (a mixture of ice and supercooled liquid above the freezing point and melting snow and liquid below the

freezing point). In the TTL (shaded blue in Figure 9), the simulated cloud fraction and the IWC vary by factors of about 4 and 10 across models, respectively. While TTL cirrus may not have a strong impact on TOA radiation, they can influence stratospheric water vapor and TTL temperature (e.g., Fueglistaler et al., 2009; Haladay & Stephens, 2009). The variation of TTL cirrus properties in the models is discussed in more detail in the next section.

The top row in Figure 9 compares DYAMOND 1 and two output in the TWP region for two models: SAM and FV3/SHIELD. Both models produce a similar anvil cloud peak across seasons in the cloud fraction (Figure 9a) just below the TTL. While some of the differences between DYAMOND 1 and two output may be due to a slight seasonal shift in the model, the observed values are consistent across seasons, so there is little seasonal shift in clouds in the TWP region. Thus, some of the difference between DYAMOND 1 and 2 may be from changes to the models themselves. We examine SAM and FV3/SHIELD as a case study.

In DYAMOND 1, SAM underestimated both the cloud fraction and mean condensate, but, in DYAMOND 2, SAM falls within the observations. This may be due to the improved temperature profile used for precipitation coefficients and in the tropics, which impacts the cloud structure; the clouds reach higher and are optically thicker. For more details on the changes between DYAMOND 1 and two in SAM, see Text S8 in Supporting Information S1.

The differences between FV3 (DYAMOND 1) and SHIELD (DYAMOND 2) are subtle despite major model development. SHIELD has a higher anvil cloud fraction but less cloud condensate signifying a thinning of the upper level clouds compared to FV3. For example, this could be explained by changes to the microphysics: the transport of heat from sedimentation was added in DYAMOND 2; the terminal velocity of ice, critical cloud droplet radius for autoconversion, and cloud ice to snow accretion efficiency were all decreased. All of these are small changes may cause small ice to remain aloft longer, partially explaining the differences between DYAMOND 1 and 2 for FV3/SHIELD.

Other models differences between DYAMOND 1 and 2 are listed in the Text S1–S9 in Supporting Information S1, but due to the setup of this study, it is impossible to quantify the impact of the different model setups and microphysics on cirrus clouds. Atlas et al. (2024) performed a single model study to show the impact of changing microphysics scheme in SAM and how that impacts the global distribution of clouds and cirrus. Others studies also show large sensitivity to microphysics (e.g., Baran et al., 2016; Chen et al., 2016; Lamraoui et al., 2023; Milbrandt & McTaggart-Cowan, 2010; Morrison et al., 2020; Seiki et al., 2015; Sullivan & Voigt, 2021).

3.3. TTL Cirrus in the Models

Some of the discrepancies in the model output in the UTLS may be related to the relatively short duration (40 days) of these simulations, which may not allow the spin up of the large-scale circulations, such as the Brewer-Dobson Circulation and stratospheric processes (Blossey et al., 2010; Fueglistaler et al., 2009). Figures 10a and 10b show the temperature from the last 5 days of the simulations and the temperature drift from the first to last 5 days after the model spin up. The temperature varies most strongly above the cold point, signifying that the stratosphere is not in equilibrium by the end of the 40-day simulation. However, the temperature drifts differ by as much as ± 4 K across the models within the TTL, where convective overshoots and thin cirrus influence temperatures (Kuang & Bretherton, 2004; Yang et al., 2010). Nonetheless, these results are encouraging for simulations of TTL cirrus clouds; in the subset of DYAMOND 2 models that we looked at here, thin TTL cirrus clouds occur frequently in the simulation period below the cold point tropopause (Figure 11d). The frequency of clouds reaching the TTL is largest in SCREAM and UM, which also have the highest relative humidity. ICON, ARP, and GEOS have fewer clouds with tops in the TTL and a lower relative humidity.

Figure 11 shows the joint histogram of CTH versus OLR (a proxy for the opacity of clouds at colder temperatures). The top row shows the roughly linear relationship between OLR and CTH that we expect for thick clouds; here we use an ice cloud mixing ratio threshold of $1\text{e}-5 \text{ kg/m}^3$ to identify the cloud top. However, when we reduce the threshold by one and then two orders of magnitude (middle and bottom row, respectively), the amount of thinner cirrus (high CTH coupled with higher OLR values) increases. A cloud threshold of $1\text{e}-7 \text{ kg/m}^3$ (bottom row) shows a significant amount of thin TTL cirrus that is largely missing from the other two rows.

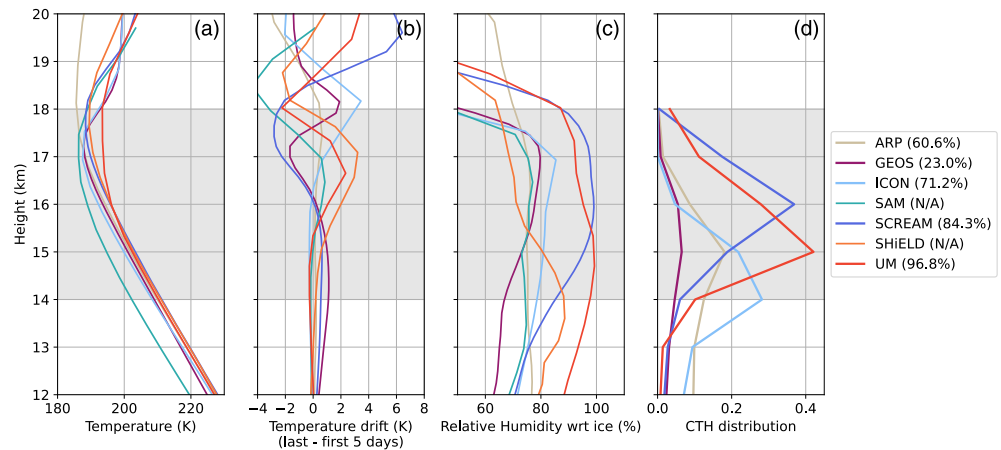


Figure 10. (a) The mean profiles of temperature are plotted for each model; (b) the temperature drift is plotted as the difference between the first (days 10–15) and last 5 days (days 35–40) of the simulation after the ten day spin up period; (c) the mean profile of relative humidity with respect to ice, which depends on both temperature and water vapor; and (d) the histogram of cloud top height (CTH) with bins every kilometer in altitude and a cloud threshold of $1\text{e-}7\text{ kg/m}^3$ (the cloud cover for clouds with a CTH above 12 km is noted in the legend). SAM is excluded from CTH profile.

The observations of CTH from CALIPSO may be most comparable to the lowest cloud threshold (bottom row of Figure 11), which includes more thin cirrus. Where the models have a nearly constant CTH across OLR values in the bottom row, the observations have a dip in CTH at intermediary values of OLR using co-located CERES data. Note that the footprint of the CCCM data set ($\sim 25\text{ km}$) is somewhat coarser than the model grid spacing ($\sim 5\text{ km}$), which could lead to some differences in the relationships shown in Figure 11.

In the models, it is not uncommon for TTL cirrus clouds to occur above thicker clouds, given the relatively low values of OLR that occur with high CTH. For example, comparing the rows for a given OLR, the CTH increases as the cloud threshold decreases (from top to bottom rows in Figure 11). This high frequency of TTL cirrus above thicker clouds has been observed in the tropical Pacific in observations from the Central Equatorial Pacific

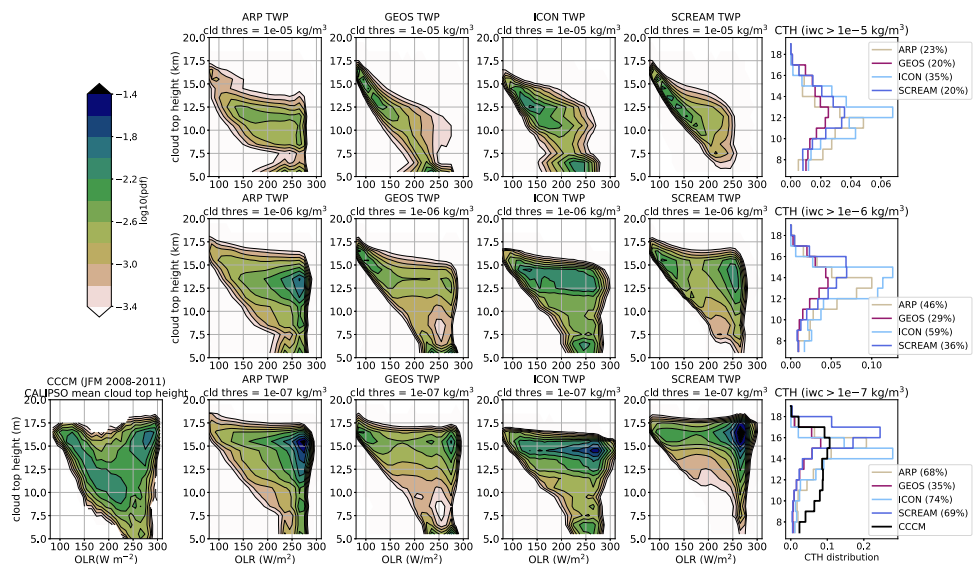


Figure 11. This is a joint histogram of OLR and CTH using IWC thresholds of $1 \times 10^{-5}\text{ kg/m}^3$ (top), $1 \times 10^{-6}\text{ kg/m}^3$ (middle), and $1 \times 10^{-7}\text{ kg/m}^3$ (bottom). We focus on clouds above the melting layer around 5 km. The bottom left shows observations from CCCM output of mean CTH over a 20 km swath using the lidar from CALIPSO (January–March 2008–2011), which is likely closest to our lowest cloud threshold. The next four columns show ARP, GEOS, ICON, and SCREAM. The far right column shows the CTH distribution for each row. Note the x-axis changes on each. The cloud cover for clouds above 5 km are noted in the legend.

Experiment (CEPEX; McFarquhar et al., 2000). The peak in the distribution in Figure 11 (top row) mostly occurs at deep convective values (high CTH and low OLR), but as the cloud threshold decreases the peak in the distribution shifts to the right towards TTL cirrus values (near 15 km altitude and high OLR; Figure 11 bottom row). There is some variance among the models in how they are simulating TTL cirrus. This may be partly related to the fact that SCREAM and GEOS have a higher vertical resolution than ICON and ARP, especially in the TTL region which could contribute to the different distribution of CTH with OLR. SCREAM simulates the TTL cirrus at higher altitudes but at a similar frequency to ARP and ICON. SCREAM also has a higher cold point and relative humidity than the other models included here (Figures 10a and 10c), contributing to its more abundant TTL cirrus.

Further, we verified that the models are truly simulating thin TTL cirrus by confirming that cloud base heights were mostly above 12.5 km (not shown). In the intermediary stages (middle row in Figure 11), these thick cirrus are most likely related to convection whereas the thin TTL cirrus (bottom row in Figure 11) seem more detached from the convective cores (especially in SCREAM and GEOS where the local maxima in frequency of occurrences is restricted to the upper right corner). These GSRMs, and likely other cloud-resolving models, are simulating thin cirrus that seem to lack a direct connection to convection. There may, however, be a more subtle connection because the outflow from convection produces high humidity layers in the TTL that are then more easily stimulated by gravity waves to form cirrus. The relationship in SCREAM between a higher relative humidity and higher CTH for thin cirrus is promising. There is some debate whether TTL cirrus are formed mostly in situ or extruded from deep convection (E. J. Jensen et al., 1996; Garrett et al., 2006; Immler, 2008; Nugent et al., 2022; Schoeberl et al., 2018; Virts et al., 2010). Hence, the DYAMOND models provide an excellent basis for showing that models with different dynamics and microphysics simulate TTL cirrus, but they provide few answers regarding the dominant formation mechanisms. Future work using a single cloud-resolving model from DYAMOND that includes tracers to identify the origin of a cloud parcel may provide a path to quantifying the fraction of TTL cirrus that originate directly from convection or form in situ.

4. Conclusions

Output from nine GSRMs that participated in the DYAMOND project was compared to climatology to understand the ability of an individual model to represent the current climate with fidelity. Generally, the models, with only one exception, underestimate convection over land in the Amazon or African regions. Half the models underestimate convection in the SPCZ and the shift in location of convection in the Indian and western Pacific ocean regions. All models except one overestimate tropical mean accumulated precipitation compared to the IMERG observations over the 40 days. Most models have too much intense precipitation from convection and under-represent light or stratiform precipitation outside convective clouds.

In agreement with observations, there is a strong correlation between cirrus and convection. Some DYAMOND models have a higher cirrus cloud fraction at the edges of convective areas. Some models like GEOS and SCREAM produce a local peak in cirrus over the Amazon, Maritime Continent/west Pacific, and Africa. Other models that produce more convection over the Indian Ocean also have a higher cirrus cloud fraction there.

We also compared seven models that participated in both phases of DYAMOND in the TWP region. Four models capture the seasonal shifts in LW and SW TOA radiation (namely, ARP, FV3/SHIELD, ICON, IFS, and MPAS) though they differ in the magnitude of this shift. Other models had major developments that changed the characteristics of the clouds in those models (e.g., SAM). While model biases are dominant, the seasonal shift is robust among the models towards more anvil clouds in boreal winter.

Some models such as ARP, IFS, and UM have large local differences in the TWP compared to the tropical average, so the TWP may not accurately represent the global tropical behavior. However, one advantage to using high-resolution modeling is the detail provided at regional scales. In a region as convectively active as the TWP, these models do simulate the characteristics of tropical convection with some fidelity. However, the unique characteristics and biases of cloud properties in each model are persistent, which needs to be recognized in single model studies when attempting to generalize results. Treating the models as an ensemble provides results more like climatology and represents a range of variability. Thus, there is some hope for using these models for predictions for future climates, as in Merlis et al. (2024).

Unlike typical GCMs, GSRMs can represent fine-scale features due to their higher horizontal, vertical, and temporal resolution. One fine-scale feature that we discussed in Section 3.3 is the ability to represent thin TTL

cirrus clouds. While there is much diversity among the models in the mean thermodynamic structure of the UTLS especially considering temperature, moisture, and clouds, the models all simulate some thin TTL cirrus clouds.

We have shown that the models represent a diverse array of tropical clouds, convection, precipitation, and radiative balance. There are strong model biases both across the tropics and in a smaller subset of the TWP. A single model study must keep these biases in mind; however, as an ensemble, these models represent the current climate with some fidelity and provide a diverse set of realizations. An obvious question is: What is responsible for the large model spread in cloud properties in these DYAMOND models? Is it mainly from dynamical responses driven by vertical velocity fields, mesoscale to large-scale circulations, and clear-sky cooling rates? Or is it from ice microphysical processes such as nucleation, ice sedimentation, etc.? An important next step is to quantify the sensitivity from cirrus clouds to climate across global or regional storm-resolving models, as done for single models in Satoh et al. (2018) and Bolot et al. (2023). Sullivan and Voigt (2021) and Atlas et al. (2024) found that ice microphysics in a single model changed the TOA radiative fluxes greatly. More work can be done to distinguish the internal spread of the multi-model ensemble from the spread due to true parameter uncertainties (the range of vapor deposition rates, the different behaviors of ice due to ice habit, etc.) that will help constrain the contribution of cirrus clouds to our climate sensitivity.

Data Availability Statement

Model output from DYAMOND is available at <https://easy.gems.dkrz.de/DYAMOND/>. The combined radar-lidar (DARDAR) product was obtained from the ICARE Data and Services Center <http://www.icare.univ-lille1.fr/projects/dardar>. Global Precipitation Measurement IMERG data with 30-min output frequency was obtained from <https://gpm.nasa.gov/data/IMERG>. The data from the A-Train Integrated CALIPSO, CloudSat, CERES, and MODIS Merged Product Release B1 (CCCM) were obtained from <https://search.earthdata.nasa.gov>. The radiation data is from the CERES SYN1deg satellite product and can be obtained at <https://ceres.larc.nasa.gov/data/#syn1deg-level-3>. ERA5 temperature reanalysis from the Atmospheric Model on model levels (Hersbach et al., 2023) was downloaded using the CDS API from the Copernicus Climate Change Service. All code used for this analysis is available on Zenodo (Turbeville, 2024).

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