npj | climate and atmospheric science

www.nature.com/npjclimatsci

ARTICLE OPEN

Check for updates

Quantifying the cooling effect of tropical cyclone clouds on the climate system

Liang Hu[1], Elizabeth A. Ritchie[2,3]✉ and J. Scott Tyo[1]

The net effect on the upwelling radiation caused by tropical cyclone clouds is calculated over a 20-year global data set, and the corresponding contribution to the earth energy balance is analyzed. Tropical cyclone clouds are shown on average to increase the upwelling radiation at the top of the atmosphere compared with the background non-tropical-cyclone-cloud climatology. This increase in upwelling radiation provides an overall cooling effect on the climate system because the increased reflected shortwave radiation (cooling) outweighs the decreased emitted longwave radiation (warming). While the effect neglects the (likely considerable) contribution due to tropical cyclone drying, the amount of cooling by clouds alone represents a considerable fraction of the excess warming energy in the climate system. Thus, any future change in tropical cyclone activity has the potential to impact the overall energy balance if it substantially alters this total. The seasonal and geographic distribution of warming and cooling effects, and the diurnal dynamics that impact whether any particular cyclone is net cooling or net warming are discussed in this study.

npj Climate and Atmospheric Science (2023)6:99 ; https://doi.org/10.1038/s41612-023-00433-z

INTRODUCTION

The primary driver of the Earth's climate system is the distribution of net downward radiation at the top of the atmosphere (TOA) owing principally to the Sun–Earth geometry. We refer to the TOA as a fictitious boundary at some distance above the surface where the downwelling flux is due only to incoming solar radiation and not due to complicated effects at different layers of the atmosphere. Clouds are an essential component of the re-distribution of this solar energy in the climate system through their effect on shortwave (SW) and longwave (LW) radiative fluxes, as well as their contribution to energy re-distribution through phase changes of water. Thus, they are an important component of the radiation budget and earth energy balance.

The interactions among clouds and other components of the Earth climate system are quite complex, and they are an area of active investigation[1–3]. A large amount of the incoming solar energy is reflected by clouds, and this effect dominates in the SW radiation regime (wavelengths less than 3 μm). In the LW regime (wavelengths longer than 3 μm), thermal processes dominate. Since clouds generally reduce LW penetration[4], their presence limits the amount of LW radiation released from the surface of the earth[5–7] that can escape into space. The cloud then re-emits at a colder apparent temperature that depends on cloud height, reducing the net upwelling LW radiative flux. Of the two mechanisms, SW reflectance increases the total upwelling radiation and acts as a cooling effect on the earth energy balance, while LW attenuation reduces the upwelling radiation and acts as a warming effect when compared with the clear sky condition. Note that throughout this paper we use the convention that upwelling radiation is positive. Thus, an increase in upwelling radiation represents a cooling effect.

The overall contribution of clouds to the radiation budget is complicated and depends on the specifics of the Earth-ocean-atmosphere system. With a globally averaged cloud-radiative effect of 20 W m^{-2}, clouds act to strongly cool the planet[8]. However, as the climate warms, the effect of clouds generally and their radiative effects are expected to increase[9,10]. The latest studies conclude that the net effect of changes in clouds in response to global warming is to amplify human-induced warming, that is, the net cloud feedback is positive with high confidence[11].

In recent decades, a great deal has been learned about clouds and their radiation contribution to the earth energy balance[12,13]. Satellite observations show that on average over the tropical belt, when deep convection is more aggregated, the free troposphere is drier, the deep convective cloud coverage is less extensive, and the emission of heat to space is increased. An enhanced aggregation of deep convection is thus associated with a radiative cooling of the tropics[14,15]. However, the specific impact of clouds due to tropical cyclones on the earth energy balance is relatively unknown. Most tropical cyclone studies examine intensity, track, and precipitation, but little is known about their radiation contribution to the earth energy balance. There are three reasons for the lack of research in this area. First, compared with tropical cyclone characteristics such as intensity and precipitation, their radiation does not cause direct major damage and is not of immediate concern. Second, as tropical cyclones are surrounded by other cloud systems with which they have complicated interactions, it is difficult to decide the boundary between the tropical cyclone and non-tropical cyclone regions. This is exacerbated because tropical cyclones affect the cloud and humidity distribution in the surrounding environment. Third, a large number of tropical cyclones needs to be analyzed over a long period of time in order to draw robust conclusions about their radiation impact on the earth energy balance.

Satellite remote sensing technology has been used extensively to assess tropical cyclone intensity[16–20], tropical cyclone genesis[21], tropical cyclone location and tracking[22], wind structure[23–25], and precipitation[26–28]. In addition, there have been some attempts to isolate the tropical cyclone clouds in satellite images using

[1]Department of Electrical and Computer Systems Engineering, Monash University, Clayton, VIC 3800, Australia. [2]School of Earth, Atmosphere & Environment, Monash University, Clayton, VIC 3800, Australia. [3]Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia. ✉email: liz.ritchie-tyo@monash.edu

segmentation algorithms mostly for tracking purposes[23,29]. To our knowledge, no other groups have calculated the net radiation of tropical cyclone clouds directly, as previous studies on tropical cyclone radiation are mainly about the radiation effect of the tropical cyclone cold wake area[30], outgoing LW radiation over western North Pacific[31], tropopause layer cooling over tropical cyclones[32], or the role of cloud radiative interactions in tropical cyclone development[33].

We recently presented a semi-automated remote sensing framework that segments tropical cyclone clouds in satellite images[34] and used the segmented images to compute the global contribution of tropical cyclone clouds to the upwelling radiation during 2016, We found that tropical cyclone clouds were responsible for a net increase in upwelling radiation compared to the clear-sky condition that is significant compared with the surplus energy in the earth energy balance[35]. Although the overall impact of tropical cyclone clouds in this single year of data is net-cooling, there is a distribution of results for individual storms that range from slightly warming to significantly cooling[34]. To date, there is no understanding of what drives this distribution. In addition, we considered the net contribution by tropical cyclone clouds relative to the clear sky condition, and it is not clear that this is the correct comparison. It seems more plausible that under the hypothetical situation that we removed a tropical cyclone from its position in the tropics that what would naturally replace it would not be clear sky, but instead would be some other type of convective system under the existing large-scale conditions. Thus, we believe that the correct comparison to calculate the net radiation due to tropical cyclone clouds is that of other tropical clouds. Finally, while we demonstrated that tropical cyclone clouds may produce an increase in upwelling radiation that is large enough to have an impact on the global earth energy balance, the original study did not consider a long enough data set to robustly quantify the result, consider whether there are regional differences, or consider how changes in tropical cyclone activity might affect the earth energy balance.

In this paper, we expand the data set to include all tropical cyclones in all basins from 2001 to 2020 to verify the conclusions in[34] over a longer-term period. In addition, we replace the clear sky condition in[34] with an hourly 20-year-mean non-tropical-cyclone-cloud radiation climatology as our background climatology to characterize radiative conditions more accurately in the absence of tropical cyclones. We explore the interannual, regional, and diurnal variation of the signature to understand how tropical cyclone cloud activity impacts the earth energy balance. Finally, we develop an understanding of the tropical cyclone physical characteristics, seasonality and locations that result in net positive (cooling) or negative (warming) totals to the earth energy balance and discuss the implications of these findings. Our results demonstrate that the increase in upwelling radiation due to tropical cyclone clouds is robust over the two-decade dataset.

The question of how tropical cyclones may change in a warmer climate has been discussed broadly. A theoretical study based on a simple Carnot cycle model showed that a significant increase in tropical cyclone intensity could occur in a warming climate[36]. Another study examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over a 35-year period using best-track archives in an environment of increasing sea surface temperature[37]. They found that there has been a large increase in the number and proportion of hurricanes reaching categories 4 and 5, while the overall number of cyclones and cyclone days has decreased. However, their study was limited by inconsistencies in the global tropical cyclone best track archives that underpin their study. Studies using a homogeneous dataset based on satellite imagery extending back to the 1980s also suggest a global increase in the intensity of the most intense tropical cyclones although regional differences exist[38,39]. Furthermore, global model studies have documented the potential effects of climate change on tropical cyclones[40–44]. While there is wide variation in the results of these studies, the consensus is for a tendency toward decreasing frequency, increasing proportion of intense, and increasing precipitation of tropical cyclones as the climate warms[44–46]. However, there is currently little information on how the structure, size, convective activity, or seasonal activity of tropical cyclones will change. Furthermore, although there has been a significant number of research studies on the variation of tropical cyclone intensity due to climate change, there are few studies about the impact of a warming climate on tropical cyclone cloud net radiation or on the feedback that tropical cyclone cloud net radiation provides to the climate system. Our results will help understand the feedback between future tropical cyclone activity as impacted by a warming climate and the total radiation budget. We show that factors such as location, time during season, and size of storm are all important. Depending on how future tropical cyclone activity changes, our results show that the feedback on the climate system may be positive or negative.

RESULTS

Global annual upwelling radiation from tropical cyclone clouds

The annual net cloud radiation and frequency distributions of the 2038 global tropical cyclones that occurred between 2001 and 2020 are shown in Fig. 1. Unlike our previous work that used the clear sky condition as the baseline, the present work uses an hourly non-tropical cyclone-cloud climatology as the reference (see Section 4, hereafter referred to as the background climatology). The annual tropical cyclone cloud net radiation is positive throughout the 20-year period, amounting to an annualized average increase in upwelling radiation of 26 TW (Fig. 1a, blue bars). This tropical cyclone cloud net contribution represents a cooling effect on the climate system. It is calculated relative to all other non-tropical cyclone clouds and clearly indicates that tropical cyclone clouds provide a distinctive contribution to the radiation budget. L'Ecuyer[35] estimates that globally averaged over a year there is an excess 300 TW in the climate system. While this represents a fraction of a percent of the total incoming solar flux, it is this extra 300 TW that drives climate warming. When compared with the estimated 300 TW annualized average of total excess energy in the climate system that drives climate warming[35], the tropical cyclone cloud upwelling contribution represents an important cooling effect on the climate system that amounts to 8% of the total excess energy. Note that throughout this paper, we present the radiative contribution to the EEB in units of annualized TW. While written as a power unit, it is actually an energy unit since the time in all computations is one year.

The tropical cyclone cloud net radiation varies annually over the 20-year period. It is highly correlated with the number of tropical cyclone days ($r = 0.66$) and less so with the number of tropical cyclones ($r = 0.35$) that form each year. There is a strong seasonal pattern that follows the tropical cyclone seasonal cycle with a maximum in tropical cyclone cloud-related net radiation in August (northern hemisphere) and January (southern hemisphere) (Fig. 1b). Minimum tropical cyclone cloud-related net radiation occurs in November and April, which are the transition months between tropical cyclone seasons in the northern and southern hemispheres. In both hemispheres, 107% (larger than 100% as tropical cyclone clouds produce more negative net radiation after the autumn equinox) of the net tropical cyclone cloud radiation is contributed between the spring and autumn equinoxes (Fig. 1b, c), which is also consistent with the relatively higher (70%) tropical cyclone activity during that period. The sign of the average tropical cyclone cloud radiation contribution becomes negative in the eighth month after the vernal equinox, indicating that late-season storms have a markedly different contribution than early-

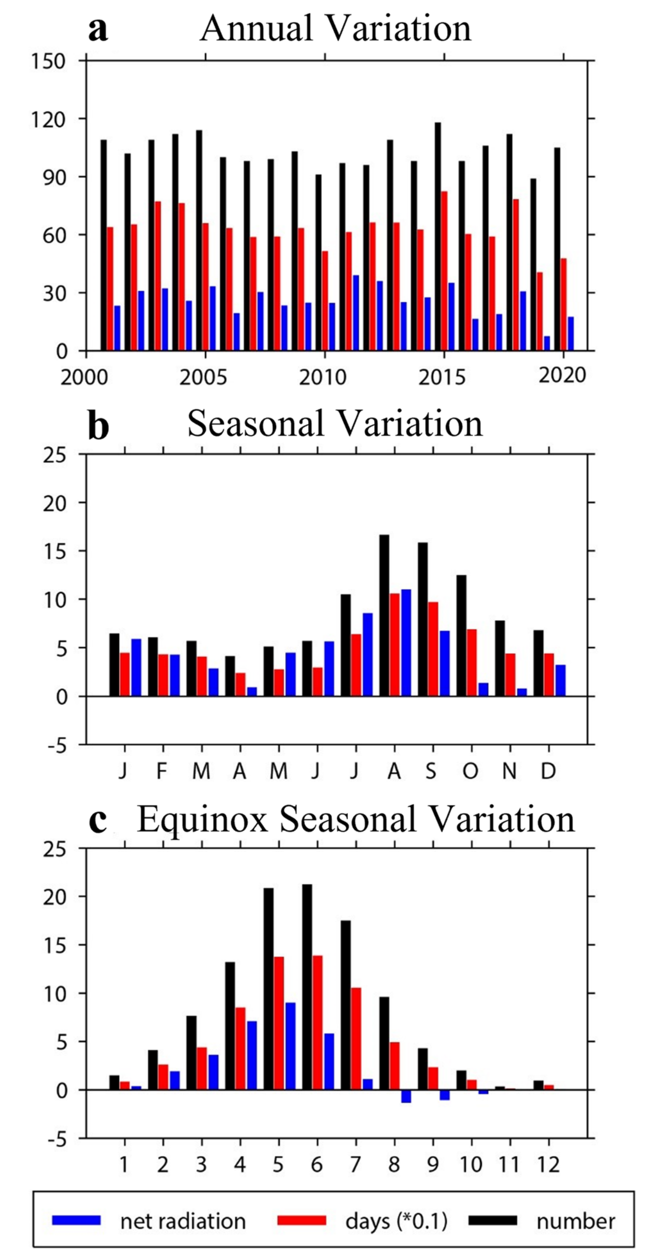

Fig. 1 Annual and seasonal variation of tropical cyclone activity. Tropical cyclone cloud net radiation (TW) (blue), number of tropical cyclones (black), and the number of tropical cyclone days (×0.1) (red) depicting the (**a**) annual, (**b**) seasonal variation, and (**c**) seasonal variation relative to the local vernal equinox.

and mid-season cyclones. The annual and seasonal variation suggests that the tropical cyclone cloud net radiation contributes more to the earth energy balance in some years, and it plays a larger role during the northern hemisphere peak tropical cyclone season.

The annual proportion of tropical cyclones, tropical cyclone days and net radiation due to tropical cyclone clouds by basin for the Western North Pacific (WP), Eastern North Pacific (EP), North Atlantic (NA), North (NI) and South (SI) Indian, and South Pacific (SP) Oceans is shown in Fig. 2. The WP produces the highest annual average net radiation contribution to the earth energy balance (Fig. 2a). This coincides with it having by far the largest annual average tropical cyclone numbers (Fig. 2b) and tropical cyclone days (Fig. 2c) of the six global tropical cyclone basins. The proportion of net radiation produced in the WP basin is higher relative to the proportion of tropical cyclone activity (measured by number of tropical cyclone days or total number of tropical cyclones) in that basin (Fig. 2). This is also true for the SP basin. The NI basin produces the lowest annual average tropical cyclone cloud net radiation contribution, and that contribution is opposite in sign to all other basins (warming). The magnitude of the net radiation produced by tropical cyclone clouds in the NI, NA, and EP basin is proportionally lower than the corresponding tropical cyclone activity (Fig. 2).

The daily cycle of radiation due to various components including total tropical cyclone cloud radiation, net tropical cyclone cloud radiation, the non-tropical-cyclone cloud radiation, which is used as the background climatology to calculate the net radiation due to tropical cyclone clouds (described in the methodology section), and the clear sky radiation are shown in Fig. 3 along with the uncertainty in the calculation of the net radiation due to tropical cyclone clouds.

There is a diurnal cycle in the net radiation exhibited by each component in Fig. 3 although the daily cycle of radiation averaged over all tropical cyclone clouds globally (dot dash line) clearly exhibits a much stronger diurnal cycle than the background climatology (dash line). The net radiation due to tropical cyclone clouds (solid black line and red/blue shading) exhibits a tendency for positive net radiation during the day when direct reflection of the incoming SW radiation is maximized and negative net radiation at night when only LW emission contributes to the net upwelling radiation. In addition, the tropical cyclone cloud net radiation during the day varies with the solar SW intensity, but it tends to be relatively constant at night. Overall, the magnitude of the positive net integrated radiation in the daytime is larger than that of the negative net integrated radiation at night, due in part to the fact that tropical cyclones primarily occur before the local autumnal equinox (Fig. 1c) when incoming SW solar radiation is maximized. The uncertainty is considerably lower in magnitude than the net radiation itself indicating the reliability of the calculation. The average net radiation due to tropical cyclone clouds over one 24-hour period is approximately $+0.042$ TW (annualized average), which is an overall daily cooling effect on the earth due to tropical cyclone clouds relative to the background climatology.

Individual tropical cyclone contribution and distribution

While the overall contribution of tropical cyclone clouds to the earth energy budget is an increase in upwelling radiation, some tropical cyclones produce increased upwelling while others produce decreased upwelling radiation over their lifetime. In this paper we define cooling tropical cyclones as those that increase upwelling radiation and warming tropical cyclones as those that decrease upwelling radiation through their cloud contribution. Figure 4 shows the frequency distribution of lifetime net radiation for all 2038 tropical cyclones. Most tropical cyclones contribute net upwelling radiation between -1 and 1 TW over their lifetime (Fig. 4). Just over seven percent (7.2%) of tropical cyclones increase upwelling radiation by more than 1 TW, and only a very small fraction (0.3%) decrease upwelling radiation by more than 1 TW. Cooling tropical cyclones exist for, on average, 1.3 days longer than warming tropical cyclones, which also contributes to their larger overall net radiation contribution (Fig. 4, Supplementary Fig. 1). Overall, the majority of tropical cyclones (74%) are cooling, while approximately 26% of the tropical cyclones are warming (Table 1). With the exception of the NI basin, the distribution of cooling and warming tropical cyclones and percentage of cooling tropical cyclones are remarkably similar across basins (Supplementary Fig. 2), ranging from 71% in the SI to 87% in the EP (Table 1). The NI basin is a special case that contributes no net upwelling radiation to the EEB (Fig. 2, Supplementary Figs. 1 and 2). As discussed below, this is due to the relatively higher activity of late

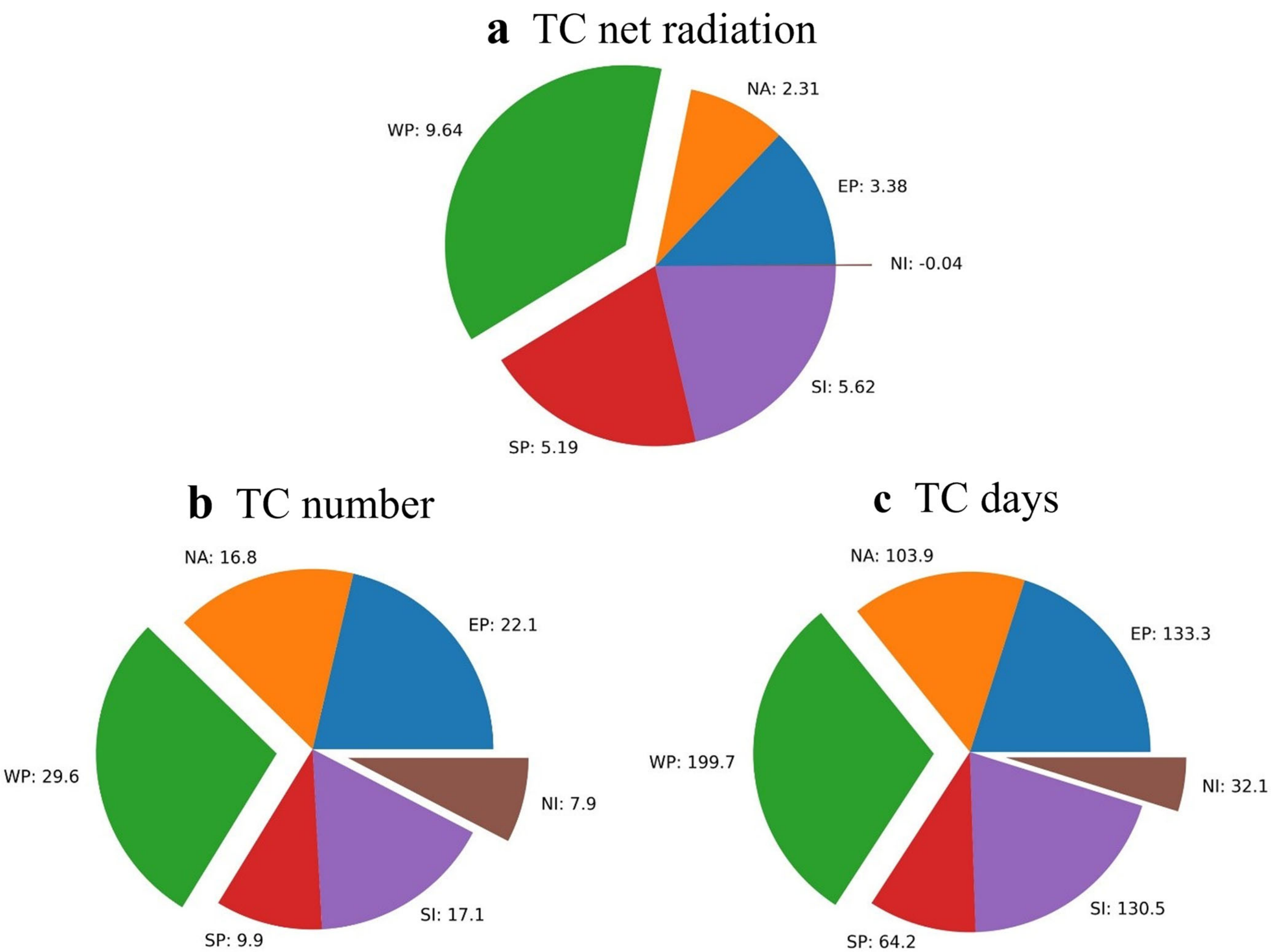

Fig. 2 Annual average tropical cyclone activity by basin. Annual average (**a**) tropical cyclone cloud net radiation (Units: TW), (**b**) tropical cyclone number, and (**c**) number of tropical cyclone days for all six basins.

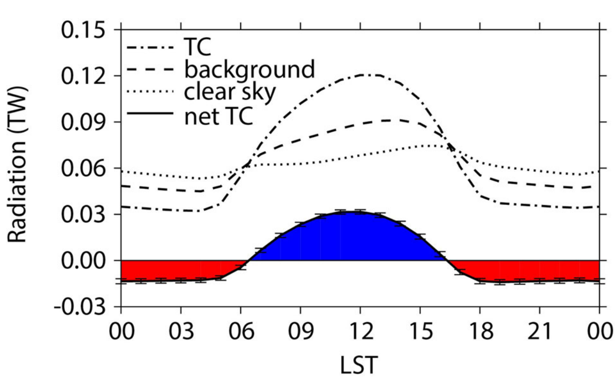

Fig. 3 Average diurnal cycle of radiation. The average diurnal cycle of various components of radiation (TW) over the 20-year period including the total tropical cyclone cloud contribution (dot dash line: +1.58 TW), contribution by non-tropical-cyclone clouds (background - dash line: +1.54 TW), contribution by clear sky (dotted line: +1.50 TW), and the net tropical cyclone cloud contribution (tropical cyclone clouds minus background climatology - solid line: +0.042 TW). Blue shading indicates positive net radiation (cooling) and red shading indicates negative net radiation (warming). The error bars indicate the uncertainty in the tropical cyclone cloud net radiation.

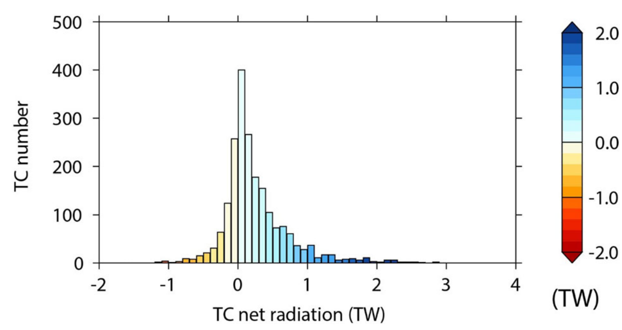

Fig. 4 Frequency distribution of tropical cyclone cloud net radiation. Frequency distribution of net radiation due to tropical cyclone clouds calculated over the lifetime of each tropical cyclone for the period 2001–2020.

season storms in that basin. Other contributing factors to the difference between the NI and other basins are currently under investigation.

The average diurnal cycle of the cloud net radiation signal for cooling and warming tropical cyclones are compared in Fig. 5. Figure 5a indicates that both cooling and warming tropical

Table 1. The total number[a] of cooling and warming tropical cyclones globally and by ocean basin.

	WP	EP	NA	NI	SP	SI	Total
Cooling tropical cyclones	441 (75%)	311 (71%)	243 (73%)	76 (48%)	171 (87%)	271 (79%)	1514 (74%)
Warming tropical cyclones	146 (25%)	126 (29%)	88 (27%)	82 (52%)	25 (13%)	70 (21%)	539 (26%)

[a]Percent of basin total is provided in brackets.

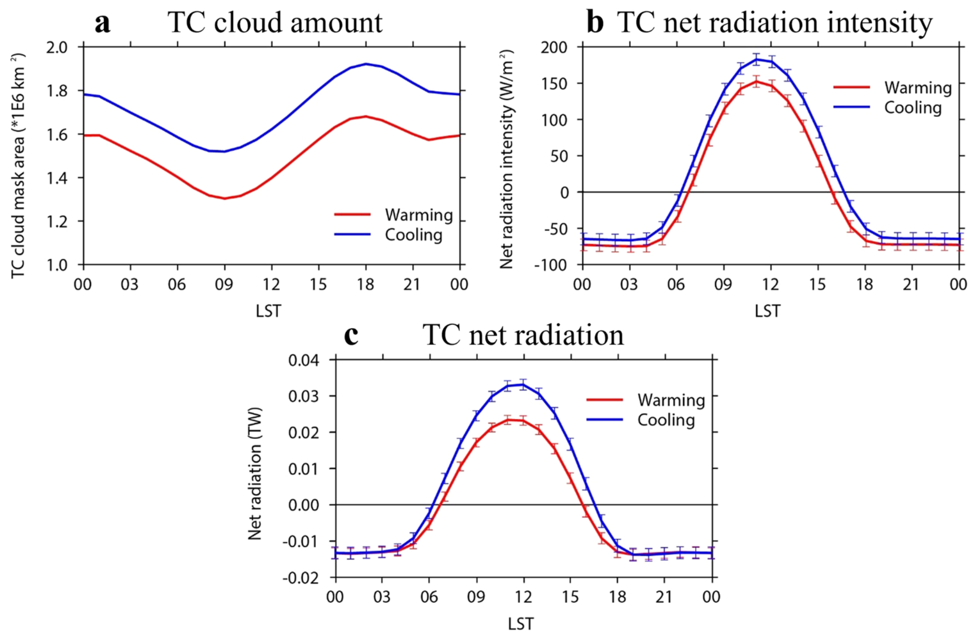

Fig. 5 20-year average diurnal cycle of tropical cyclone cloud properties. The average daily diurnal cycle of net radiation due to tropical cyclone clouds over the 20-year period (TW) separated out by cooling (blue) and warming (red) tropical cyclones for: (**a**) tropical cyclone cloud area; (**b**) tropical cyclone cloud net radiation intensity per pixel; and (**c**) the tropical cyclone cloud net radiation. The error bars give the uncertainty as described in the text.

cyclones have more clouds at night (1800–0600 LST) than during the daytime (0600–1800 LST). In addition, the net radiation intensity and overall net radiation due to tropical cyclone clouds is net upwelling for all tropical cyclones, and it is of similar magnitude at night regardless of whether the tropical cyclone is cooling or warming (Fig. 5b, c), indicating that the cloud top temperatures associated with the two types of tropical cyclones are similar and produce similar LW upwelling radiation. Thus, it is the daytime cloud differences that determine whether the tropical cyclone is cooling or warming. We note a point for future study that for areas over land, such as over the Australian continent and western North America, it is the nighttime cloud activity that determines whether a particular case is cooling or warming. The relative frequency of tropical cyclone days over land is small, and this point is not explored further in this paper.

During the day, the main factors that affect the radiation are the cloud fraction, the sun elevation, and the length of day. Cooling tropical cyclones have more clouds during the day than warming tropical cyclones (Fig. 5a), which in turn produces more reflected SW radiation (Fig. 5c). In addition, the net radiation intensity is higher for cooling compared with warming tropical cyclone clouds during the day, and cooling tropical cyclones produce positive net radiation intensity for a longer period because of the longer day (Fig. 5b). This is because in both the northern and southern hemispheres, the majority of cooling tropical cyclones occur during the summer, whereas the peak frequency of warming tropical cyclones lags by 2–3 months and occurs predominantly after the autumnal equinox (Fig. 6). Thus, the solar elevation angle and length of day is higher for cooling tropical cyclones compared with warming tropical cyclones, resulting in a higher SW reflectance and positive net radiation for cooling tropical cyclones. The only exception to this is in the NI basin where there is a double peak in tropical cyclone activity, one in May and a larger peak in October/November, with a lull in the summer during the peak of the monsoon. In this basin there is a higher percentage of warming tropical cyclones compared with the other basins (Fig. 6, Table 1) because of the much higher proportion of late season tropical cyclones that form when the sun angle is relatively low.

Spatial distribution of net radiation due to tropical cyclone clouds

The spatial distribution of annualized tropical cyclone frequency and tropical cyclone cloud net radiation are shown in Fig. 7. The general pattern of tropical cyclone cloud net radiation (Fig. 7d) unsurprisingly matches the spatial distribution of tropical cyclone cloud frequency (Fig. 7a). The majority of the tropical cyclone affected areas have a cooling effect (blue shading) both for tropical cyclones (Fig. 7d) and for all of the clouds (Fig. 7e) over the year. There are three maxima (>0.016 TW per pixel annualized), one over the northwest Pacific, one over the northeast Pacific, and another over the northern Australia, which correspond to peaks in the tropical cyclone frequency density. There are some regions of net warming due to tropical cyclone cloud radiation near the equator in the SI, SP, and WP, as well as in the Arabian Sea and the mid-Atlantic (brown shading); these regions are not studied in this paper since they have relatively low tropical

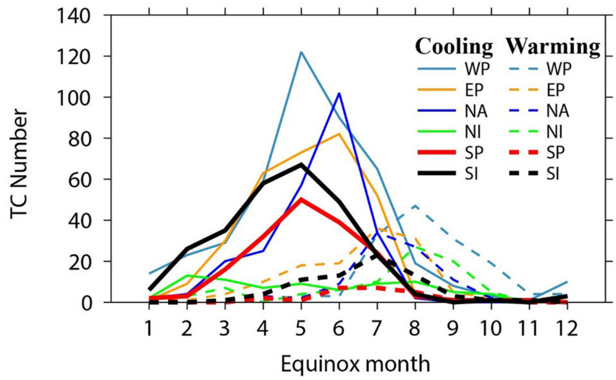

Fig. 6 Seasonal variation of tropical cyclone activity by basin. The seasonal variation of tropical cyclone number relative to the solstice/equinox for cooling and warming tropical cyclones by ocean basin.

cyclone cloud frequency. Over the arid and semi-arid Australian continent, Indian subcontinent, and the southwest portion of North America, both the tropical cyclone cloud and all cloud contributions to the net radiation are warming. In these regions the relative humidity in the daytime is much lower than that during the night-time, thus more tropical cyclone clouds form at night over these regions. These are also regions where tropical cyclones are dissipating after making landfall and their clouds are relatively warmer, although still colder than the ground. Overall, the magnitude of the LW radiation contribution for tropical cyclone clouds in these semi-arid land regions is greater than that of the SW radiation, contributing to an overall warming effect.

The tropical cyclone cloud net radiation contribution (Fig. 7f) to the net radiation from all clouds shows that tropical cyclones account for a large proportion of the "all cloud" radiation. There are small regions in the WP main development region, off the Northwest Shelf of Australia, the Arabian Sea and portions of the Bay of Bengal where the contribution due to tropical cyclone clouds is opposite in sign to the "all cloud" contribution. However, the net radiation contribution over the WP, EP and northern Australia is more than 20% of the "all cloud" contribution, and this is much higher than the tropical cyclone cloud frequency contribution (Fig. 7c, f). This indicates that the tropical cyclone cloud net radiation can have significant impact on the regional contribution to the earth energy balance[47,48]. Notably, these are in open-ocean regions that, in the absence of cloud, would be responsible for significant absorption of downwelling solar flux.

DISCUSSION

The cloud net radiation for 2038 tropical cyclones from 2001 to 2020 is calculated using a semi-automated cloud segmentation algorithm. In general, tropical cyclone clouds provide a net positive contribution to the upwelling radiation and therefore are a net cooling effect on the earth energy balance. This has important implications because:

1. The contribution by tropical cyclone clouds to the earth energy balance over the past 20 years is a significant fraction of, and opposite sign to, the excess energy in the climate system. That is, tropical cyclone clouds are a large contributing factor to offsetting the current energy imbalance. Changes in this net contribution due to future tropical cyclone changes will be important.
2. Current projection consensus is for a decrease in tropical cyclone numbers but increase in frequency of the higher intensity tropical cyclones. As more intense tropical cyclones are longer lived and tend to occur during the peak season, a higher proportion of more intense tropical cyclones may lead to a higher cooling (upwelling) contribution.
3. The net radiation contribution by tropical cyclone clouds is more dependent on the number of tropical cyclones days rather than the number of tropical cyclones. Current projections do not provide information about the future number of tropical cyclone days.
4. The net radiation contribution by tropical cyclone clouds is dependent on when they form in the season, and late-season tropical cyclones are more likely to be warming. Thus, changes in the time of occurrence of tropical cyclones, that is a shift to earlier or later season activity, would impact the contribution to upwelling due to tropical cyclone clouds.

The data presented above allow us to draw several conclusions about the mechanisms for the significant net cooling contribution that tropical cyclone clouds make to the earth energy balance. Most importantly, the net radiation of any particular storm is closely linked to the diurnal balance between daytime reflected radiation and the 24-hour emitted infrared radiation. During the day, the large cloud cover produced by tropical cyclones creates a significant increase in the upwelling radiation due to reflected SW radiation at the top of the atmosphere. At night there is no downwelling radiation to reflect, so the upwelling radiation is all LW emitted radiation. Since tropical cyclone clouds are generally much colder than the surface, this leads to a decrease in upwelling radiation at night. Whether a specific tropical cyclone is cooling or warming depends on this balance. However, since both warming and cooling tropical cyclones emit similar amounts of radiation at night, it is differences in the daytime radiation due to their clouds that lead to a tropical cyclone being cooling or warming. The primary differences between cooling and warming tropical cyclones are that during the day, cooling tropical cyclones have a higher cloud amount, they produce higher peak net radiation intensity, and produce net positive radiation for a longer period compared with warming tropical cyclones. A large part of the reason why the cooling tropical cyclone signal is dominated by the SW effect is that they tend to occur between the local vernal and autumnal equinoxes so that the longer day and higher sun angle results in higher SW reflectance. Because the majority of tropical cyclones occur during these months the majority of tropical cyclones globally (~74%) are cooling.

Second, cooling tropical cyclones tend to occur earlier in the season with a peak in cooling activity occurring 2–3 months ahead of the peak in warming tropical cyclones in all basins except the NI. This is when sea-surface temperatures are warmest, and the environment is most supportive of tropical cyclones.

Third, the geographic distribution of radiation attributable to tropical cyclone clouds closely follows the distribution of tropical cyclone frequency. However, what may be more important is how much of the radiation in each region is due to tropical cyclone clouds and the regional differences that give rise to a higher proportion of warming versus cooling tropical cyclones in some basins. In the NI basin, tropical cyclones form either very early in the season before the summer solstice, or late in the season (peak activity) well after the autumnal equinox and thus produce a higher percentage of warming tropical cyclones resulting in overall a mixture of weak net negative and positive upwelling radiation. In the EP, WP and Northern Australia regions, tropical cyclone clouds account for a very large percentage (>20%) of the total net radiation from all clouds, which is much higher than the actual tropical cyclone cloud contribution, and these regions (with the exception of the EP) are all low-cloud-frequency areas. This latter point suggests that tropical cyclone clouds are responsible for generating a significant portion of the cloud cover over what would otherwise be very low albedo open ocean. Furthermore, the net radiation contribution due to tropical cyclone clouds is measured against the background climatology, and this also has a

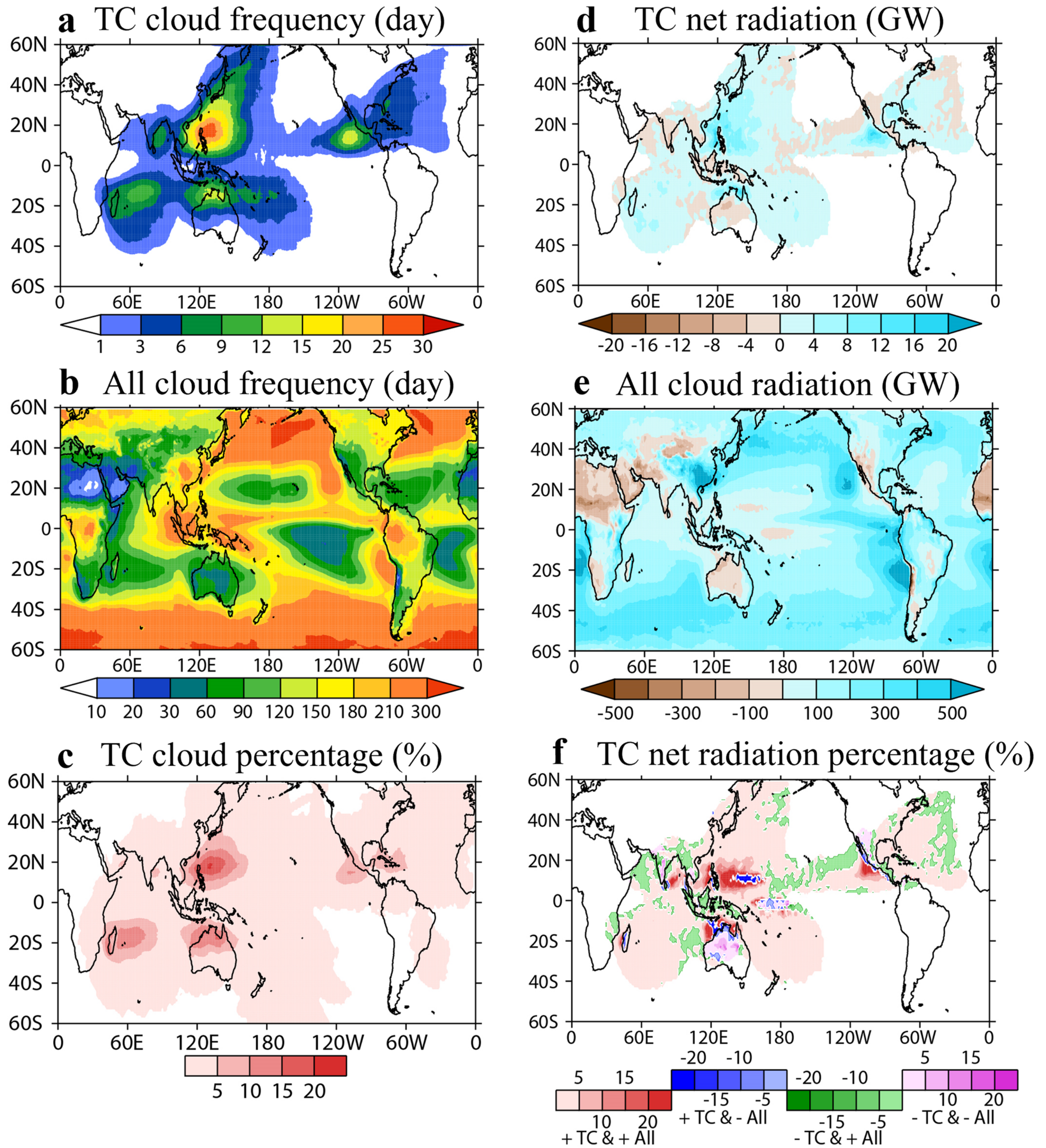

Fig. 7 Annual average spatial distribution of clouds. The 20-year annual average spatial distribution of: (**a**) tropical cyclone cloud frequency (days); (**b**) all cloud frequency (days); (**c**) the relative frequency of clouds due to tropical cyclones (%); (**d**) tropical cyclone net radiation relative to the background climatology (GW); (**e**) all cloud net radiation (tropical cyclone clouds + non-tropical-cyclone clouds) relative to clear sky (GW); (**f**) the contribution of tropical cyclone net radiation to all cloud net radiation (%). In **f**, the red shading indicates regions where both the tropical cyclone and all cloud net radiation is positive (cooling), blue shading is positive tropical cyclone (cooling) and negative all cloud (warming) net radiation, green shading is negative tropical cyclone (warming) and positive all cloud (cooling) net radiation, and pink is both tropical cyclone and all cloud negative (warming) net radiation. The negative percentage indicates that the sign of the net radiation due to tropical cyclones is opposite that of the "all cloud" net radiation.

seasonal (not shown) and spatial dependency (Fig. 7e). In fact, in some regions it was noted that the sign of the tropical cyclone net radiation contribution was, on average, opposite to that of the background climatology. Further examination of the spatial and seasonal changes in the background climatology may well help understand this signal and further elucidate how tropical cyclone clouds impact the EEB.

There are a few regions of the Earth where the total radiation contribution from tropical cyclone clouds is net warming. These include the Australian continent, southwest deserts of north America, and the Arabian Peninsula, which are arid generally high-albedo land regions. Landfalling tropical cyclones bring more disorganized, warmer cloud cover that does not increase the reflected SW over these regions as much as over ocean regions but causes a significant reduction in emitted LW. This results in a net warming radiation contribution by tropical cyclones in these regions. There are also two anomalous regions in the mid-Pacific Ocean straddling the equator and one in the South Indian Ocean that have net warming contribution. The causes of these anomalies are under investigation.

There are two caveats to the results presented in this study. First, the cloud pixel mask only considers specific pixels identified as cold tropical cyclone clouds and excludes many clear and very low-level cloud pixels within the tropical cyclone circulation. In addition to influencing the region within the tropical cyclone circulation, a tropical cyclone also influences regional weather and even the global climate[14,15]. Thus, the cloud pixel mask likely underestimates the total radiation contribution due to tropical cyclones whose dynamic structure is different to other tropical mesoscale convective systems. We are currently studying other mask identification methods that will allow better labeling of cyclone vs non-cyclone areas regardless of cloud temperature. Second, the time series of each tropical cyclone in the dataset is truncated as described in the methods section to ensure the tropical cyclone net radiation is calculated in consistent 24-hour periods reflecting equal parts daytime and night-time periods. This results in an average reduction in the considered lifetime of 13–14% across all tropical cyclones and reduces the net radiation attributed to tropical cyclones.

METHODS

Data

To quantify the upwelling radiation due to tropical cyclone clouds, three sources of data from the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) are used (Supplementary Table 1). The NOAA International Best Track Archive for Climate Stewardship (IBTrACS) tropical cyclone best-track dataset[49] provides all tropical cyclone locations over all tropical cyclone basins. The NCEP/CPC Global Merged IR Brightness Temperature Dataset (GPM_MERGIR) at 30-minute temporal and 4-km spatial resolution[50] is used to segment the tropical cyclone clouds, and the observed TOA fluxes and cloud area fraction products from the Clouds and Earth's Radiant Energy System (CERES) Synoptic (SYN) 1-hour and 1-degree resolution dataset[51] are used to calculate the radiation contribution by tropical cyclones. The period of study is 2001–2020.

Tropical cyclone cloud labeling

The hourly tropical cyclone center positions from the best-track data are linearly interpolated to match the half-hourly temporal resolution of the brightness temperature data, enabling the segmentation algorithm to be performed at high frequency. Full details of the segmentation algorithm can be found in ref. [34]. The tropical cyclone cloud segmentation task is accomplished by a semi-automated algorithm which takes a time series of brightness temperature images of tropical cyclones and uses image processing techniques to segment each image and label all tropical cyclone cloud pixels. An example of labels determined by the segmentation algorithm is shown in Supplementary Fig. 3 for Tropical Storm Conson in August 2016 in the WP basin, showing results at 4 instances through the tropical cyclone life. This result illustrates the ability of the algorithm to successfully segment the cloud coverage of Tropical Storm Conson and capture changes in the tropical cyclone shape across instances. Full results for all tropical cyclones globally in 2001–2020 are available in the Monash Bridge Repository (https://doi.org/10.26180/21436017).

Calculation of net radiation

An hourly 1×1 degree SW/LW TOA non-tropical-cyclone-cloud radiation climatology is used as the background climatology to calculate the net radiation due to tropical cyclone clouds. The climatology is calculated hourly across the entire year (as a 20-year mean) and includes all non-tropical-cyclone-cloud pixels including deep organized convection, deep un-organized convection, shallow clouds, and clear sky. The background climatology is calculated as the mean 2001–2020 CERES radiation data in every hour and 1×1 degree grid box in which no tropical cyclone cloud was present. The maximum possible datapoints used to calculate the mean in any grid point is 20 (because it is an hourly 20-year climatology). However, because tropical cyclone clouds are sometimes present in some grid boxes, the number of data points used to calculate the mean may sometimes be less than this. Supplementary Fig. 4 shows the sample size over three high tropical cyclone frequency regions, the WP, EP and northern Australia, and demonstrates that for the majority of the time more than half of the 20-years of radiation data are used to calculate the background climatology even in these high tropical cyclone frequency regions.

The radiation contribution of each pixel within the cloud mask is calculated by combining the segmentation results with the CERES radiation dataset via a coordinate-matching scheme that is necessary due to the difference in spatial resolution of the two datasets[34]. Finally, the tropical cyclone cloud net radiation is calculated by subtracting the background climatology from the total upwelling radiation (Supplementary Figs. 5 and 6). When the net upwelling radiation with the tropical cyclone present is higher than the background climatology, the pixel has a positive upwelling contribution that is net cooling. Likewise, when the net upwelling radiation is negative, that pixel has a net warming effect on the earth energy balance.

The uncertainty of CERES radiation data is also important to quantify. As the results shown in this study are based on the 20-year-mean LW and SW data, and the net radiation is defined as the difference between the tropical cyclone cloud radiation and background climatology, the monthly uncertainty of the LW and SW products are used when we discuss the 20-year-mean result. The uncertainty is calculated as simple averages. Therefore, the uncertainty of the net radiation is:

$$MU_{LW(TC\ clouds)} + MU_{LW(climatology)} + MU_{SW(TC\ clouds)} + MU_{SW(climatology)} \quad (1)$$

where MU is the measurement uncertainty for each of the quantities in Eq. (1). As the tropical cyclone and non-tropical cyclone LW and SW products are all-sky observations, the monthly CERES uncertainties for the all-sky product for LW (SW) of 0.53 (3.5) W m^{-2} are used[52]. The resulting monthly uncertainty of the net radiation is therefore $[3.5\ W\ m^{-2} + 3.5\ W\ m^{-2}] + [0.53\ W\ m^{-2} + 0.53\ W\ m^{-2}] = 8.06\ W\ m^{-2}$. For the case study in Supplementary Fig. 6, the hourly uncertainty of the CERES LW (SW) product is 3.1 (16.7) W m^{-2} for all sky[52]. Therefore, the uncertainty of the hourly net radiation is $[16.7\ W\ m^{-2} + 16.7\ W\ m^{-2}] + [3.1\ W\ m^{-2} + 3.1\ W\ m^{-2}] = 39.6\ W\ m^{-2}$.

Consistent period for radiation calculation

Tropical cyclone net radiation depends on the difference between SW radiation and LW radiation, and since SW reflectance occurs only during the daytime, the balance of the tropical cyclone cloud distribution during the day and night is important. However, the lifetime of a tropical cyclone as defined in the IBTrACS best track database is almost never an integer number of 24-hour periods. Furthermore, as the tropical cyclone traverses the basin, local solar time (LST) is more important than 24-hour periods in describing the impact of the tropical cyclone on the earth energy balance because of its effect on the SW reflectance. Thus, the time of genesis and end-of-life in LST has an impact on tropical cyclone energy statistics. Supplementary Table 2 quantifies this effect by examining the average contribution of the extra fraction of a day removed to round the tropical cyclone lifetime down to a full integer day. Cooling tropical cyclones lose on average 1.0 days, mostly during in the daytime, which is 13.6% of the time record, but 16.3% in net radiation to the entire tropical cyclone. Warming tropical cyclones lose on average 0.9 days at night, which is 14.5% in time but 23.6% in net negative radiation, which is lost to the entire tropical cyclone life span. However, Supplementary Table 2 demonstrates that cooling tropical cyclones are, on average, net positive both for the integer number of full-days and the extra time, while warming tropical cyclones are, on average, net negative for both intervals. Thus, although both types of tropical cyclones lose contributions to their total radiation through the truncation to whole day periods, the loss is of the same sign as the overall net contribution by that tropical cyclone.

Even though Supplementary Table 2 shows that truncating each tropical cyclone time series to integer LST days results in a loss of time and net radiation for both warming and cooling tropical cyclones, the integer LST days [integer × (00–24 LST)] are used in calculating the tropical cyclone cloud net radiation in this study. This avoids the effects of using the different beginning and end times of each tropical cyclone in IBTrACS, which causes daytime/night time biases in the net radiation calculation and are not consistently applied across regions and over time. Testing demonstrated that there is no change to the overall conclusion of this study if the entire tropical cyclone lifespan data are used. Furthermore, Supplementary Fig. 6 highlights that the contribution by the tropical cyclone clouds in an individual tropical cyclone increases as the tropical cyclone matures and then decreases as it weakens and dissipates. The relative contribution at the start and end of each tropical cyclone lifetime is relatively small in almost all cases, and truncation effects do not affect the overall net radiation to a large degree.

DATA AVAILABILITY

The cloud mask data that support the study are published in the Monash Bridge Repository: https://doi.org/10.26180/21436017.v1.

Received: 26 October 2022; Accepted: 18 July 2023;
Published online: 24 July 2023

REFERENCES

1. Arking, A. The radiative effects of clouds and their impact on climate. *Bull. Am. Meteorol. Soc.* **72**, 795–814 (1991).
2. Hobbs, P. V., Ed. *Aerosol-cloud-climate Interactions* 1st edn, (*Academic Press*, San Diego, California, 1993).
3. Stephens, G. L. Cloud feedbacks in the climate system: a critical review. *J. Clim.* **18**, 237–273 (2005).
4. Kiehl, J. T. & Trenberth, K. E. Earth's annual global mean energy budget. *Bull. Am. Meteorol. Soc.* **78**, 197–208 (1997).
5. Ge, X., Ma, Y., Zhou, S. & Li, T. Impacts of the diurnal cycle of radiation on tropical cyclone intensification and structure. *Adv. Atmos. Sci.* **31**, 1377–1385 (2014).
6. Michael, B., Bell, M. T. & Brown, B. R. Impacts of radiation and upper-tropospheric temperatures on tropical cyclone structure and intensity. *J. Atmos. Sci.* **76**, 135–153 (2019).
7. Ruppert, J. H., Wing, A. A., Tang, X. & Duran, E. L. The critical role of cloud-infrared radiation feedback in tropical cyclone development. *Proc. Natl Acad. Sci. USA* **117**, 27884–27892 (2020).
8. Boucher, O., & Randall, D. *"Clouds and aerosols" in Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013).
9. Soden, J. et al. Quantifying climate feedbacks using radiative kernels. *J. Clim.* **21**, 3504–3520 (2008).
10. Vial, J., Dufresne, J. L. & Bony, S. On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates. *Clim. Dyn.* **41**, 3339–3362 (2013).
11. Forster, P., et al. *"The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity." Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021).
12. Dessler, E. Cloud variations and the Earth's energy budget. *Geophys. Res. Lett.* **38**, L19701 (2011).
13. Otto, F. et al. Energy budget constraints on climate response. *Nat. Geosci.* **6**, 415–416 (2013).
14. Tobin, I. et al. Does convective aggregation need to be represented in cumulus parameterizations? *J. Adv. Modeling Earth Syst.* **5**, 692–703 (2013).
15. Bony, S. et al. Observed modulation of the tropical radiation budget by deep convective organization and lower-tropospheric stability. *AGU Adv.* **1**, e2019AV000155 (2020).
16. Dvorak, V. F. Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Weather Rev.* **103**, 420–430 (1975).
17. Velden, C. S., Olander, T. L. & Zehr, R. M. Development of an objective scheme to estimate tropical cyclone intensity from digital geostationary satellite infrared imagery. *Weather Forecast.* **13**, 172–186 (1998).
18. Piñeros, M. F., Ritchie, E. A. & Tyo, J. S. Objective measures of tropical cyclone structure and intensity change from remotely sensed infrared image data. *IEEE Trans. Geosci. Remote Sens.* **46**, 3574–3580 (2008). 11.
19. Olander, T. L. & Velden, C. S. The advanced Dvorak technique: Continued development of an objective scheme to estimate tropical cyclone intensity using geostationary infrared satellite imagery. *Weather Forecast.* **22**, 287–298 (2007).
20. Hu, L., Ritchie, E. A. & Tyo, J. S. Short-term tropical cyclone intensity forecasting from satellite imagery based on the deviation angle variance technique. *Weather Forecast.* **35**, 285–298 (2020).
21. Piñeros, M. F., Ritchie, E. A. & Tyo, J. S. Detecting tropical cyclone genesis from remotely sensed infrared image data. *IEEE Trans. Geosci. Remote Sens. Lett.* **7**, 826–830 (2010).
22. Rodríguez-Herrera, O. G. et al. Automatic tracking of pregenesis tropical disturbances within the deviation angle variance system. *IEEE Trans. Geosci. Remote Sens. Lett.* **12**, 254–258 (2014).
23. Zhang, C., Wang, X. & Duanmu, C. Tropical cyclone cloud image segmentation by the B-spline histogram with multi-scale transforms. *Acta Meteorol. Sin.* **24**, 78–94 (2010).
24. Knaff, J., Slocum, C. J., Musgrave, K. D., Sampson, C. R. & Strahl, B. R. Using routinely available information to estimate tropical cyclone wind structure. *Mon. Weather Rev.* **144**, 1233–1247 (2016).
25. Dolling, K., Ritchie, E. A. & Tyo, J. S. The use of the deviation angle variance technique on geostationary satellite imagery to estimate tropical cyclone size parameters. *Weather Forecast.* **31**, 1625–1642 (2016).
26. Kummerow, C., Barnes, W., Kozu, T., Shiue, J. & Simpson, J. The tropical rainfall measuring mission (TRMM) sensor package. *J. Atmos. Ocean. Technol.* **15**, 809–817 (1998).
27. Hou, Y. et al. The global precipitation measurement mission. *Bull. Am. Meteorol. Soc.* **95**, 701–722 (2014).
28. Guzman, O. & Jiang, H. Global increase in tropical cyclone rain rate. *Nat. Commun.* **12**, 1–8 (2021).
29. Fiolleau, T. & Roca, R. An algorithm for the detection and tracking of tropical mesoscale convective systems using infrared images from geostationary satellite. *IEEE Trans. Geosci. Remote Sens.* **51**, 4302–4315 (2013).
30. Zhang, J., Lin, Y. & Ma, Z. Footprint of tropical cyclone cold wakes on top-of-atmosphere radiation. *Geophys. Res. Lett.* **48**, e2021GL094705 (2021).
31. Sobel, H. & Camargo, S. J. Influence of western North Pacific tropical cyclones on their large-scale environment. *J. Atmos. Sci.* **62**, 3396–3407 (2005).
32. Rivoire, L., Birner, T., Knaff, J. A. & Tourville, N. Quantifying the radiative impacts of clouds on tropopause layer cooling in tropical cyclones. *J. Clim.* **33**, 6361–6376 (2020).

33. Wu, S. N., Soden, B. J. & Nolan, D. S. Examining the role of cloud radiative interactions in tropical cyclone development using satellite measurements and WRF simulations. *Geophys. Res. Lett.* **48**, e2021GL093259 (2021).
34. Nguyen, K. T., Hu, L., Alenin, A. S., Ritchie, E. A. & Tyo, J. S. A satellite-based remote-sensing framework to quantify the upwelling radiation due to tropical cyclones. *IEEE J. Sel. Top. Appl. Earth Observations Remote Sens.* **14**, 5488–5500 (2021).
35. L'Ecuyer, T. S. *"Earth's energy balance" in International Encyclopedia of Geography: People, the Earth, Environment and Technology*. 1st edn, (John Wiley & Sons, Ltd., 2017).
36. Emanuel, K. A. The dependence of hurricane intensity on climate. *Nature* **326**, 483–485 (1987).
37. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H. R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309**, 1844–1846 (2005).
38. Kossin, J. P., Olander, T. L. & Knapp, K. R. Trend analysis with a new global record of tropical cyclone intensity. *J. Clim.* **26**, 9960–9976 (2013).
39. Kossin, J. P., Knapp, K. R., Olander, T. L. & Velden, C. S. Global increase in major tropical cyclone exceedance probability over the past four decades. *Proc. Natl Acad. Sci. USA* **117**, 11975–11980 (2020).
40. Bengtsson, L., Botzet, M. & Esch, M. Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus A* **48**, 57–73 (1996).
41. Sugi, M., Noda, A. & Sato, N. Influence of the global warming on tropical cyclone climatology: an experiment with the JMA global model. *J. Meteor. Soc. Jpn. Ser. II* **80**, 249–272 (2002).
42. Oouchi, K. et al. Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses. *J. Meteor. Soc. Jpn. Ser. II* **84**, 259–276 (2006).
43. Yoshimura, J., Sugi, M. & Noda, A. Influence of greenhouse warming on tropical cyclone frequency. *J. Meteor. Soc. Jpn. Ser. II* **84**, 405–428 (2006).
44. Bengtsson, L., Botzet, M. & Esch, M. Hurricane-type vortices in a general circulation model. *Tellus A* **47**, 175–196 (1995).
45. Christensen, J. H., & Kanikicharla, K. K. *"Climate phenomena and their relevance for future regional climate change" in Climate change 2013: the physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, United Kingdom and New York, NY, 2013).
46. Seneviratne, S. I., et al. *"Weather and climate extreme events in a changing climate" in Climate change 2021: the physical science basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, (*Cambridge University Press, Cambridge, United Kingdom and New York, NY*, 2021).
47. Trabing, C., Bell, M. M. & Brown, B. R. Impacts of radiation and upper-tropospheric temperatures on tropical cyclone structure and intensity. *J. Atmos. Sci.* **76**, 135–153 (2019).
48. James, H. R., Wing, A. A., Tang, X. & Duran, E. L. The critical role of cloud–infrared radiation feedback in tropical cyclone development. *Proc. Natl Acad. Sci. USA* **117**, 27884–27892 (2020).
49. Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J. & Neumann, C. J. The International Best Track Archive for Climate Stewardship (IBTrACS): unifying tropical cyclone best track data. *Bull. Am. Meteorol. Soc.* **91**, 363–376 (2010).
50. Janowiak, J., Joyce, B., & Xie., P. *NCEP/CPC L3 Half Hourly 4km Global (60S - 60N) Merged IR V1, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC)* (NASA, 2017).
51. Doelling, D. R. *CERES Level 3 SYN1deg-1h Terra-Aqua-MODIS HDF4 file–Edition 4A, Data set* (NASA Langley Atmospheric Science Data Center DAAC, 2017).
52. Doelling, D. R. et al. Geostationary enhanced temporal interpolation for CERES flux products. *J. Atmos. Ocean. Technol.* **30**, 1072–1090 (2013).

ACKNOWLEDGEMENTS

Some of the early stages of this research were performed while all authors were employed at the University of New South Wales, Canberra. This research was undertaken with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government. This research is supported by an Australian Research Council Discovery Project grant DP210103203.

AUTHOR CONTRIBUTIONS

L.H. performed the research, contributed to analyzing the results, and wrote the first draft of the manuscript. E.A.R contributed to conceptualizing the science problem, designing the methodology, analyzing results, providing supervision to L.H., and revising the manuscript. J.S.T. contributed to conceptualizing the science problem, designing the methodology, analyzing results, providing supervision to L.H., and revising the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41612-023-00433-z.

Correspondence and requests for materials should be addressed to Elizabeth A. Ritchie.