Environment and the Lifetime of Tropical Deep Convection in a Cloud-Permitting Regional Model Simulation

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ABSTRACT

By applying a cloud-tracking algorithm to tropical convective systems in a regional high-resolution model simulation, this study documents the environmental conditions before and after convective systems are initiated over ocean and land by following them during their lifetime. The comparative roles of various mechanisms of convection–environment interaction on the longevity of convective systems are quantified. The statistics of lifetime, maximum area, and propagation speed of the simulated deep convection agree well with geostationary satellite observations.

Among the environmental variables considered, lifetime of convective systems is found to be most related to midtropospheric moisture before as well as after the initiation of convection. Over ocean, convective systems enhance surface fluxes through the associated cooling and drying of the boundary layer as well as increased wind gusts. This process appears to play a minor positive role in the longevity of systems. For systems of equal lifetime, those over land tend to be more intense than those over ocean especially during the early stages of their life cycle. Both over ocean and land, convection is found to transport momentum vertically to increase low-level shear and decrease upper-level shear, but no discernible effect of shear on the lifetime of the convective systems is found.

1. Introduction

Understanding the environmental processes that control the life cycle of tropical convective systems and their proper representation in global climate models has been a major challenge in climate modeling and prediction. It has long been known that the lifetime, vertical structure, and spatial coverage of convective systems determine their role in the global radiative budget and water cycle, which are responsible for some of the large uncertainties in climate change prediction. Processes related to the life cycle of convective systems are rarely explicitly represented in global climate model parameterizations (Del Genio et al. 2012), which assume a statistical quasi equilibrium to infer some aggregated characteristics of convective systems. The lack of adequate representation of cloud life cycle in GCMs is most often manifested as erroneous diurnal cycle and underestimation of stratiform precipitation (Dai 2006).

Better understanding the life cycle of convective systems, their interactions with the environment at scales smaller than those that can be resolved by current GCMs, and their accurate parameterization continues to be a critical issue.

The structure and temporal evolution of convective systems have been known to vary from region to region. This difference is most apparent between systems over oceanic and continental environments. Using geostationary satellite and spaceborne-radar observations, Futyan and Del Genio (2007) compared the life cycles of convective systems over Africa and the tropical Atlantic Ocean. They found that the systems over Africa start out as convective with frequent lightning and evolve to stratiform over time. Over the Atlantic, the convective fraction of the systems remains more or less unchanged into the dissipating stages, and lightning occurrence peaks late in their life cycle. The underlying mechanism for the difference between evolution and lifetime of convective systems over land and ocean may be related to the “convective sustainability” (Houze 2004) of the environment, that is, the ability of the environment to continuously trigger new convection that replaces the
aging parts of the system. The presence of deep warm and moist boundary layers has been proposed to be a sustainable environment (Kingsmill and Houze 1999). Over land, on the other hand, the lifetime of convective systems appears to depend on the initial vigor of the convection. Using infrared Geostationary Operational Environmental Satellite (GOES) images to objectively track convective systems, Machado and Laurent (2004) showed that the lifetime of convective systems over the Amazon is related to their initial areal expansion rate. Similarly over the continental United States, longer-lasting convection has been found to be related to higher rainfall rate and radar echo–top heights during convective initiation (Feng et al. 2012).

Lifetime of convective systems is also affected by wind shear. Using idealized two- and three-dimensional cloud-resolving model simulations, Rotunno et al. (1998) and Weisman and Rotunno (2004) show that low-level shear (0–3 km) contributes to the sustenance of mid-latitude squall lines by countering the vorticity associated with the downdraft of the primary convection and keeps the secondary updraft at the edge of the cold pool upright. Thus, in what is often referred to as Rotunno–Klemp–Weisman (RKW) theory, they propose that there exists an optimal shear that balances the storm-generated gust, where the updraft at the edge of the cold pool is the deepest. Weisman and Rotunno (2004) found that upper-level shear (above 5 km), however, resulted in weak and less organized systems, with no significant difference from the system obtained when wind shear is absent. The effect of shear on convection, however, is more complicated than these idealized simulations suggest, for one because convective systems are often a collection of several convective cells not necessarily organized to produce the optimal balance between vorticities with cold pool and wind shear required by the RKW theory. The interaction of convection with environmental wind involves acceleration and deceleration of winds by pressure gradients associated with the convection and vertical momentum transport (Yang and Houze 1996; Mechem et al. 2006; Moncrieff 2010), but despite their measurable effect on the winds, their impact on the lifetime of convective systems is not clear.

While the above review is not exhaustive, it shows that the lifetime of convective systems is likely related to various boundary layer (cold pools and surface fluxes) and tropospheric (moistening, updraft, and wind shear)

Table 1. Model setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Cumulus parameterization</td>
<td>None</td>
</tr>
<tr>
<td>Longwave radiation scheme</td>
<td>Rapid Radiative Transfer Model (Mlawer et al. 1997)</td>
</tr>
<tr>
<td>Shortwave radiation scheme</td>
<td>Dudhia (1989)</td>
</tr>
<tr>
<td>PBL scheme</td>
<td>Yonsei University scheme (Hong et al. 2006)</td>
</tr>
<tr>
<td>Land surface model</td>
<td>Noah (Mitchell et al. 2000)</td>
</tr>
<tr>
<td>Microphysics scheme</td>
<td>WRF single-moment 6-class scheme (Hong and Lim 2006)</td>
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processes at various stages of their life cycles. Using a cloud system–resolving regional model simulation and a cloud-tracking algorithm, this study aims to (i) document the evolution of these various environmental fields during the initiation and lifetime of convective systems over land and ocean and (ii) quantify their comparative relationships to the lifetime of the convective systems.

Application of the tracking algorithm, originally designed for satellite observations, onto the cloud systems simulated by a high-resolution regional model allows a thorough evaluation of the model’s ability to reproduce the cloud statistics observed by satellite and, more importantly, enables examination of the environmental processes before and during the lifetime of the convective system.

2. Methodology

a. Model and experiment description

The model used in this study is the Advanced Research Weather Research and Forecasting model, version 3.3 (ARW-WRF3.3; Skamarock 2008). The simulation has a grid spacing of 4 km and is run without any cumulus parameterization. The setup of the experiment and the physics schemes used are listed in Table 1. Initial, lateral, and surface boundary conditions are derived from the National Centers for Environmental Prediction (NCEP)’s Global Forecast System Final Analysis. The simulation runs from 20 November 2009 to 10 January 2010 freely (without reinitialization or interior nudging) with only the surface and lateral boundary conditions updated every 6 h. The simulation domain is shown in Fig. 1a. It includes the Indian Ocean, the Maritime Continent, parts of the western Pacific, and Australia.

b. Satellite observations

Satellite observations for the same period and domain are obtained from the Japanese Meteorological Agency’s Multifunctional Transport Satellite (MTSat). MTSat is a geostationary satellite that has been located at 145°E since 2006. The 10.8-μm narrowband brightness-temperature data with an hourly temporal and 5-km spatial resolution are used to identify and track the convective cloud systems.
c. Cloud tracking

The identification and tracking of observed and model-simulated convective systems is done in an identical manner. For comparison to the satellite data, the narrowband (10.2–12.2 μm) outgoing longwave flux from the model simulation is converted to an equivalent brightness temperature. First, the outgoing flux is converted to radiance at the middle of the wavelength band (11.1 μm) by assuming isotropic radiation, which is a reasonable assumption at these wavelengths, and dividing by the width of the band. Then, the radiance is converted to an equivalent brightness temperature using Planck’s function (Stephens 1994).

An automated convective system tracking algorithm, which is similar to that described by Williams and Houze (1987) and Futyan and Del Genio (2007) is applied to both the satellite data and the model output. A cloud system is defined as a contiguous region of $T_b$, 235 K for both, and each system is identified and given a cloud identification number. Figures 1c and 1d show those systems and the identification numbers assigned for the purpose of tracking them through their lifetime.

d. Evaluation

Once the simulated convective systems are defined and tracked in the same manner as those from the MTSat observations, the model’s ability to reproduce various statistics of the observed convective systems is assessed. Figure 2 shows a brief summary of the results of this evaluation. Overall, the simulated statistics of the lifetime of convective system are comparable to those observed by MTSat (Fig. 2a). In both cases, less than 1% of the systems last more than 13 h and more than 90% of them last less than 5 h. In general, the simulated systems have a shorter lifetime than those observed. The statistics...
of the model and observed maximum system size during their life cycles are also compared (Fig. 2b). The simulated systems tend to be slightly smaller than the observed systems, as seen in the mode (largest number) equivalent radius. The smaller convective system size simulated using the WRF single-moment 6-class microphysics scheme (WSM6) is consistent with previous studies (e.g., Van Weverberg et al. 2013). The most significant difference between the observed and simulated systems is found in their minimum brightness temperature (averaged within each convective system, Fig. 2c). The simulated convective systems are colder than those from MTSat by about 12 K (i.e., the simulated systems have much higher cloud tops than observed), suggesting that the convective updraft speed in the model is too high and/or that the model underpredicts stratiform cloud area, which can have lower cloud-top height (i.e., higher brightness temperature). The propagation characteristics of the observed and simulated convective systems, on the other hand, are fairly close (Fig. 2d).

The temporal evolution of the model precipitation pattern was compared with Tropical Rainfall Measuring Mission (TRMM-3B42; Huffman et al. 2001) 3-hourly precipitation observation (Fig. 3). The Hovmöller diagrams show precipitation averaged between 5°S and 5°N. The time period of the simulation corresponds to the winter of 2009/10, during which two episodes of Madden–Julian oscillation were observed, one during late November and early December (eastern side of the domain), followed by another one during late December and early January (western end of the domain). The model captures the precipitation patterns associated with these two episodes, including their weakening during their passage through the Maritime Continent, fairly well. However, the model fails to reproduce the westward-propagating signals. This limitation is related to the regional model’s tendency to concentrate precipitation at the edges of the regional domain. Systems that are too close to the boundary that touch the boundary at any point during their lifetime are excluded from the analysis.

The above characteristics of the convective systems are found to be most sensitive to the choice of microphysics scheme used and to a lesser degree to horizontal grid spacing. Some of the microphysics schemes available in the WRF modeling system were tested at various horizontal grid spacings. Simulations with horizontal
resolution of 1 km were conducted, and fall velocity of graupel and snow were reduced to try reducing the bias in the simulated brightness temperature and cloud size. The sensitivity results suggest that these properties are more sensitive to the choice of microphysics scheme than to horizontal resolution and ice fall velocity. Considering limitations of computational resources and the need to track propagation of convective systems over a large domain, a 4-km grid spacing with WSM6 was deemed optimal for the purpose of the study.

e. Compositing strategy

Convective systems are composed of distinct regions depending on the microphysical process of rain formation. These are the convective core, characterized by strong updrafts throughout the troposphere, characteristic of new convective cells, and broad stratiform region, with weak updrafts in the upper troposphere and downdrafts and divergence at low levels as these cells age (Houze 1997). This study documents the evolution of environmental conditions in both regions of the convective systems. The convective core and stratiform regions of a system are identified in this study using their vertical velocity profiles. For every pixel in the convective system, if there is a vertical velocity minimum above the lowest model level and below the level of maximum vertical velocity, and the minimum vertical velocity is negative (downward), then that pixel is defined to be in the stratiform region of the system. Otherwise, it is in the convective region. As an example, Fig. 4a shows a cross section of the vertical velocity of an arbitrary convective system on which the above definition is used to identify the two regions. At low levels, strong updrafts dominate within the convective cores and relatively weak downdrafts dominate over stratiform regions. The probability distributions of the 800-hPa vertical velocity averaged over the two regions for all the convective systems considered in this study are shown in Fig. 4b. While convective updrafts can reach up to 2 m s$^{-1}$, downdrafts over stratiform regions are rarely larger than −0.5 m s$^{-1}$ in the model.

For every hour in the lifetime of each convective system tracked, the environmental conditions during the 12 h before and 12 h after that hour are documented. This allows for examination of the changes of the
environmental conditions leading to the triggering of the deep convection, during the lifetime of the convection, and after convection dissipates. The convective systems are binned by their lifetime (Fig. 4c). Of the total of 17,789 distinct (after excluding those merging or splitting or that last less than 2 h) convective systems tracked, 14,862 are found to have started over ocean and 2,934 over land. Among these systems, 6,703 and 1,537 have lifetimes between 4 and 12 h for ocean- and land-triggered deep convection, respectively. The 12-h lifetime bin contains 146 (52) systems for ocean (land)-triggered systems. Systems with lifetimes longer than 12 h are excluded from the study because of limited sample size.

Documentation of the evolution of various fields is divided into three periods: (i) the 12 h leading to the first appearance of the system \( T_b < 235 \text{ K} \) at the fixed location where it first appeared, (ii) the time between its beginning and its end moving along its path, and (iii) the 12 h after its ending at the fixed location where deep convection was last detected. Figure 4d demonstrates this composite analysis using broadband outgoing longwave radiation (OLR). The horizontal axis shows the lifetime bins, while the vertical axis gives the time since detection of the system. The average OLR for all systems of a given lifetime, at the given time since detection, are shown. The first 12 h in the vertical axis \((-12 \text{ to } 0)\) correspond to the time before the triggering of convection. The region of low OLR (blue colors) corresponds to the period between the beginning and end of the convective cores (their lifetime). Hence the blue region is larger for longer-lived systems. The time afterward corresponds to the 12 h after the end of the convective core but at the location where the convective core ends. The various fields that are subsequently analyzed will also be plotted in this framework to depict their evolution during the lifetime of convective systems.

3. Evolution of the environment

a. Free troposphere

The evolution of various tropospheric fields before the triggering and following the convective systems is examined using the framework presented in the last section. Figure 5 shows the evolution of lower-tropospheric

FIG. 6. Evolution of 500-hPa water vapor mixing ratio \((\text{g kg}^{-1})\) averaged over the core and stratiform regions of convective systems initiated over land and ocean.
As noted in the definition of convective core (Figs. 4a, b), the vertical velocity at 800 hPa is positive (upward). In general, for the same lifetime, the initial updraft (time = 0 h) in convective cores over land is stronger than that over ocean, but it declines more rapidly with time. Over stratiform regions, the vertical velocity at time = 0 h is also positive before it becomes negative at time = 0 h, marking the transition from convective core to stratiform region. The average vertical velocity in the stratiform region is about 20% of that over the convective cores. The average vertical velocity over stratiform regions also decreases more rapidly over land than over ocean as is the case with the convective core. This supports the “convective sustenance hypothesis” that lifetime of convection over land depends mainly on the initial intensity, while over ocean there are sustenance mechanisms that may affect its lifetime even if the initial intensity is not strong.

The triggering of deep convection at time = 0 h is marked by rapid moistening of the middle troposphere. Figure 6 shows the evolution of water vapor mixing ratio at 500-hPa level over the convective core and stratiform regions of ocean and land convective systems. Both over land and ocean, longer-lasting convective cores seem to have larger midtropospheric moisture (Figs. 6a, b). A relationship between moisture and lifetime is not as apparent over stratiform regions (Figs. 6c, d). For the same lifetime, the midtroposphere over land is generally drier than that over ocean by about 25% before the initiation of convection and by about 15% afterward.

The evolution of zonal wind shear during the lifetime of the convective systems is examined in order to understand the interactions of the latter with horizontal momentum. In this study, low-level wind shear is defined as the absolute value of the difference between zonal wind at 800 hPa and the lowest model level (about 1000 hPa; Fig. 7); similarly, the upper-level wind shear is defined as the absolute value of the difference between zonal wind at 200 and 800 hPa (Fig. 8). Figure 7 shows the evolution of low-level wind shear averaged over the convective core and stratiform regions over ocean and land. In all four cases, the initiation of convection is accompanied by
enhanced low-level wind shear, particularly over the stratiform regions. This interaction of convection with zonal momentum appears to be stronger over land where the downdrafts are particularly strong (Fig. 5d). This result is consistent with the convective momentum transport theory forwarded by Moncrieff (1992) and the results of numerical simulations by Moncrieff and Klinker (1997) that show momentum transport by propagating convective systems accelerates the lower-tropospheric environmental wind in the direction of the system propagation and increases the low-level shear, while it decreases upper-level shear. For the closer look at the effect of vertical momentum on the low-level winds, the probability distribution of acceleration of winds by the vertical momentum transport 2 h before and 2 h after the initiation of convection are calculated. Acceleration by vertical momentum transport as $-\left( \left( w_{700hPa} - w_{900hPa} \right) / \left( z_{700hPa} - z_{900hPa} \right) \right)$ averaged over the convective core or stratiform area. The absolute values introduced because the main area of interest is the vertical transport of the absolute value of momentum not its horizontal direction, which would vary from system to system. Figure 9 shows the PDFs of the acceleration 2 h before and after the initiation of convection, averaged over convective and stratiform regions for both systems over ocean and land. Momentum transport can both accelerate and decelerate low-level winds with comparable frequency. Before the initiation of convection, momentum transport accelerates low-level winds for 53% of the systems over ocean and 48% of those over land. At 2 h into the life of the systems, the numbers are 56% and 60% and 65% for the stratiform regions. Thus acceleration of the low-level winds can at least partly be explained by downward momentum transport especially by the subsidence in the stratiform regions as argued by Moncrieff (1992) and Moncrieff and Klinker (1997). The comparable likelihood of acceleration/deceleration of low-level winds by vertical momentum transport before the initiation of convection suggests that the acceleration of the winds just before the initiation of the convective system is not necessarily forced by this mechanism. The role of vertical momentum transport and the associated shear in the lifetime of convective...
systems will be further assessed in comparison to other processes in the next section.

b. The boundary layer

In the last subsection, the free-tropospheric processes that take place during the lifetime of convective systems were examined. Here, the analysis is extended to the boundary layer. Figure 10 shows the evolution of sensible heat fluxes associated with convective systems triggered over ocean and land. The sharp contrast of the heat flux between oceanic and continental convection is apparent. Over ocean, an increase in sensible heat fluxes takes place following the triggering of deep convection and the anomaly lasts about as long as the convection itself. Over land on the other hand, sensible heat fluxes peak 3–5 h prior to the triggering of deep convection. Upon the triggering of deep convection the fluxes are shut off as the surface is cooled because of the cloud cover. The gradual recovery of sensible heat fluxes at time = 18–20 h shows their diurnal nature over land (Figs. 10b,d). Similar behavior is observed in the evolution of latent heating fluxes (Fig. 11). Once again, the increase in surface fluxes over ocean is primarily a response to convection while over land it occurs before the convection and is presumably part of the diurnal forcing. The above characteristics of surface heating fluxes are true for both the core and stratiform regions of the convective systems, but the surface fluxes under stratiform regions of oceanic systems are generally stronger than those under the convective cores (Figs. 10a,c and 11a,c).

For a closer look at the evolution of the boundary layer, the environment surrounding a composite of convective cores that last 9 h is considered. Figure 12 shows the Hovmöller diagrams of sensible and latent heat fluxes as well as surface wind convergence for convective cores. The black slanted line marks the location of minimum OLR. The negative and positive positions indicate the previous and future location of the convective core, respectively. The horizontal axis represents the location of the convective systems in the 12 h before and after the given instant. Since, on average, these systems propagate at about 12 km h⁻¹, the axes are provided in units of distance to provide the reader with spatial perspective. Thus ~100 km represents the location of the convection about 8 h ago and likewise 100 km represents where it will be after about 8 h. During the early stages of oceanic convection, peak surface fluxes are at or slightly behind the location of the convective core. But as the convection ages, the surface fluxes peak ahead of the convective core (Figs. 12a,b, left panels). Over land, the surface fluxes are near zero in the area surrounding the convective core (Figs. 12a,b, right panels) because of cloud cover. But farther away, strong surface fluxes evolve gradually with the diurnal cycle. Near surface winds peak ahead of the convective core and their lead increases while their magnitudes decline as the convective systems grow and age. The peak surface winds associated with the systems over ocean are about twice as strong as those over land. Near-surface processes under stratiform regions of convective systems also evolve in a similar manner as those under convective cores (Fig. 13). The fact that the peak surface fluxes are behind, while the surface wind peaks are at or ahead of the minimum OLR, suggests that the during the early stages of the lifetime of the systems fluxes are primarily modulated by boundary layer cooling and
drying not by the wind gusts. But later as the systems age, the peak fluxes and peak wind speeds are more or less collocated.

4. Relationship between lifetime of convection and the environmental variables

As discussed in the previous section and elsewhere in the literature, processes such as vertical transport of moisture and horizontal momentum as well as variations in surface fluxes are integral parts of the lifetime of convective systems. In this section, a comparative assessment of the relationship of these processes to the lifetime of the convective systems is provided. We start out with a hypothesis that the lifetime of convective systems is related to the six variables discussed in the last section: (i) intensity of updraft/downdraft (800-hPa vertical velocity), (ii) midtropospheric moisture, (iii) upper- and lower-tropospheric zonal wind shear, and (iv) surface sensible and latent heating fluxes.

The analysis involved the following steps.

(i) Areal averages of each of the above listed variables over both the convective core and stratiform regions of each system are calculated.
(ii) Then the elements of the sample are sorted by increasing magnitude and are partitioned into six bins of equal sample size. Each bin contains 983 systems.
(iii) For each bin, the mean and standard deviation of lifetime of the convective systems is calculated.
(iv) To address the issue of causality, the environmental conditions 2 h before and 2 h after the initiation of convection are considered.

The resulting relationships between environmental variables and the mean lifetime of the convective systems before and after their initiation are shown in Figs. 14 and 15 for ocean and land regions, respectively. The error bars indicate one standard deviation ($\pm 1\sigma$). For all the environmental variables, before as well as after the initiation of convection, the sensitivity of lifetime of convection (the variations in the mean) to any of the individual variables...
is small in comparison to the respective standard deviations. Thus, taken individually, the environmental conditions, at least the ones considered in this study, have little value as predictors of lifetime the convective systems. Nevertheless, comparison of the trends in the lifetime provides some insight into the role of certain variable or interaction mechanism in comparison to others.

The lifetime of convective systems both over land and ocean is found to have comparatively clear relationship with the midtropospheric moisture (Figs. 14d and 15d). Convective systems initiated in an environment where midtropospheric moisture 2 h before is higher tend to last longer on average. This is also true for higher midtropospheric moisture 2 h after the initiation, presumably by the vertical transport of moisture by the convection itself. The relationship between midtropospheric moisture and longer-lasting convective systems is consistent with previous study over the continental United States (Feng et al. 2012).

The lifetime of convection also shows some weak trend with respect to surface sensible heat fluxes. For all the other variables, there is no clear trend in the lifetime of convection with the increasing values of the individual variables. This does not necessarily mean that lifetime of convection is not affected by these variables; one can imagine a situation where the relationship is not monotonic. For example, as discussed in the introduction, there may be an optimal amount of shear that is favorable for a long-lasting convection.

5. Summary and discussion

This study applies a brightness temperature–based cloud-tracking algorithm to high-resolution regional model–simulated cloud systems to (i) document the evolution of environmental conditions during the lifetime of convective systems and (ii) quantify the relationship of lifetime of convection with various mechanisms of interaction of convection with the environment. As discussed in several other studies, convective systems over ocean and land start with strong low-level convergence
and updraft followed by a broad stratiform region of low-level divergence and downdraft (Figs. 5 and 12). During its lifetime, convection is accompanied by a moist midtroposphere (Fig. 6) and vertical mixing of momentum (Figs. 7 and 8). Over ocean, the rise in surface fluxes follows the propagating convective systems and is generally located slightly behind the center of the convection early in the lifetime of convection and slightly ahead of it later (Figs. 12 and 13, left panels). Over land, on the other hand, the initiation of convection follows the diurnal rise in surface fluxes by 3 h after the peak surface fluxes (Figs. 10 and 11, right panels). Unlike over ocean, where the cold pools and wind gusts associated with convection enhance surface fluxes, the cooling of the surface by cloudiness suppresses surface fluxes over land even though convective downdraft and associated outflow are stronger (Figs. 5 and 12c, right panels).

The role of the various mechanisms of interactions between convection and the environment in the lifetime of convection is examined using the statistical

FIG. 12. Composite spatial structure and temporal evolution of (a) sensible and (b) latent heat fluxes (W m$^{-2}$) and (c) surface wind speed (m s$^{-1}$) under convective cores of systems that last 9 h. The solid line marks the location of minimum OLR and the composite system is propagating to the right at 12 km h$^{-1}$. 
relationship between the area-integrated value of various variables 2 h before and 2 h after the initiation of convection. For both systems over ocean and land, longevity of convective systems is found to be related to relatively moist midtroposphere before as well as after their initiation. To a lesser extent, larger surface sensible heating fluxes and upper-level wind shear before as well as after their initiation also seem to play a positive role in the lifetime of the systems over ocean. While convection accelerates low-level winds by transporting momentum from the upper to the lower troposphere, this interaction does not appear to be an important factor in the longevity of convective systems.

Many of the results summarized above are in agreement with results from previous observational studies. Shipborne measurements by Saxen and Rutledge (1998) during Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) show similar results. According to their analysis, long-lasting convective systems produced stronger
modulations of surface fluxes than the short-lived ones
and peak sensible, and latent heat fluxes of about 60 and
250 W m\(^{-2}\), respectively, were observed for the long-
lasting systems. These numbers are comparable to our
modeling results for the composite of systems lasting 9 h
(Figs. 11 and 12, left panels). More recently Chuda et al.
(2008) analyzed shipborne measurements over the
tropical western Pacific. Using the radar reflectivity and
in situ precipitation observation, they estimated that
convective systems enhance total sensible and latent
heat fluxes by 41% and 10%, respectively. Thus in terms
of fractional variation, sensible heat fluxes are more
sensitive to convective activity than latent heating fluxes.
This might explain the slightly stronger relationship of
the former with the mean lifetime of the convection that
we found in this study. Our statistical analysis suggests
low-level shear does not have a monotonic relationship
with longevity of convective systems over both ocean and
land in contrast to the results of Weisman and Rotunno
(2004), both low and high low-level shear appear to favor
longevity over ocean. The study provides some support
to the “convective sustenance” hypothesis discussed in

![Graphs showing the relationship of the mean lifetime of convective systems over ocean to area average of the various environmental fields 2 h before and after their initiation. The error bars indicate one standard deviation from the mean.](https://journals.ametsoc.org/doi/abs/10.1175/JAS-D-12-0260.1)
the introduction. Whether it is through surface fluxes or convective transport of momentum, convective systems over ocean are more likely to interact with the environment in a manner that enables them to last longer. Over land, convective systems decay throughout most of their lifetime, which is related to their initial intensity as indicated by Machado and Laurent (2004) and Feng et al. (2012). Environmental conditions after their initiation (such as reduced surface fluxes because of cloud cover) are generally unfavorable for the initiation of new convective cells (Futyan and Del Genio 2007).

As noted in the introduction, many of the processes discussed in this study take place within an area smaller than a size of a typical GCM grid. Efforts at improving the representation of lifetime of convective systems and their role on the water and energy budget through improved representation of these processes are ongoing. By assessing the comparative importance of different mechanisms of convection–environment interactions,
this study provides some guidance for improving representations of convection in models.

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