Global and Regional Diurnal Variations of Organized Convection

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ABSTRACT
An automated objective classification procedure, the Convection Classification and Automated Tracking System (CCATS), is used to analyze the mean life cycles of organized convection in the global Tropics and midlatitudes (40°N–40°S). Five years (1989–93) of infrared satellite imagery are examined for the Pacific and Atlantic basins and one year (April 1988–March 1989) is studied for the Indian basin.

Two main classes of organized convection (lifetime of 6 h or more) are tracked: MCT and CCC. MCT represent a combined dataset of tropical cyclones and mesoscale convective complexes (MCC). Convective cloud clusters (CCC) meet the same cold cloud-top temperature, time, and size criteria used to distinguish MCC, but fail to sustain the same high degree of symmetry for at least 6 h. That is, CCC represent more elongated systems, such as squall lines. The frequency of CCC exceeds that of MCT by a factor of 30 over both land and sea.

MCT and CCC are each stratified into 12 continental and oceanic regions and the diurnal variation of system characteristics in each geographic region are studied, leading to composite life cycle descriptions for each region. Oceanic CCC formed overnight and the shorter-lived, land-based CCC formed in the afternoon; apart from this time offset, oceanic and land-based CCC were found to have very similar life cycle evolution patterns.

Continental MCT exhibit a rapid size expansion early; this is not part of the oceanic system life cycle. Apart from this growth spurt, the evolution of land and ocean MCT follows the same pattern of CCC with early symmetry, then size expansion until just before termination. Land-based MCT are longer lived and more symmetric than oceanic MCT.

1. Introduction
A significant amount of previous work on the characteristics of organized convection has been reported. Fritsch and collaborators have surveyed a variety of different geographic regions: Velasco and Fritsch (1987) investigated mesoscale convective complexes (MCC) over the Americas during 1981–83, while Miller and Fritsch (1991) investigated MCC in the western Pacific region during 1983–85; Laing and Fritsch (1993a,b) analyzed the Indian and African continents and ultimately compiled a global climatology of MCC (Laing and Fritsch 1997). Other recent works include Augustine and Howard’s (1991) documentation of the characteristics of MCC over the United States for the period 1985–87. Anderson and Arritt (1998) tabulated MCC and persistent elongated convective system (PECS) occurrences over the United States during 1992 and 1993. Mathon and Laurent (2001) explored the variation of long-lived cloud systems in west Africa for an 8-yr period.

It is well known that convective systems, such as tropical cyclones and MCC, can produce severe weather and copious rainfall in many cases (Maddox 1980; Fritsch et al. 1986; Fritsch and Forbes 2001). Evans and Jaskiewicz (2001), and Shemo and Evans (1996) investigated the contribution of organized convection to regional rainfall using both satellite-derived rainfall (Adler and Negri 1988) and rain gauge data. They found that convective systems with lifetimes of 6 h or more contributed in excess of 50% to the total regional rainfall in all regions studied, exceeding 80% in both the North Pacific and North Indian Ocean regions.

Documentation of the diurnal cycle of organized convection adds to the understanding of the global impact of these systems and their role in the climate system. Studies such as Lin et al. (2000) evaluate the efficacy of general circulation models in terms of their ability to replicate the diurnal and seasonal variations of the hydrological cycle (in their case, for the Amazon basin). Soman et al. (1995) examine the rainfall in Darwin, Australia, and aggregate area estimates of rainfall observations for comparison with satellites. They show that the Darwin rainfall exhibits an extreme diurnal variation, not in phase with oceanic precipitation. Dai (2001a,b) used present and past weath-
er reports to develop an observational analysis of precipitation variations globally. This research compliments the satellite-based analyses of the diurnal variations of organized convection over the global Tropics focused on here.

2. The automated objective classification system

An automated classification and tracking procedure (Evans and Shemo 1996) has been substantially improved (Tsakraklides 2000) and evolved into the Convection Classification and Automated Tracking System (CCATS) used in this study. Key steps of the CCATS analysis are briefly outlined here:

1) Digital infrared satellite images are scanned and areas of adjacent pixels representing cloud-top temperatures \(T_{CT}\) less than 219 K, the “cold” cloud area, are identified. When an area with \(T_{CT} < 219\) K is greater than 4000 km\(^2\) it becomes available to be classified as organized convection, otherwise it is immediately classified as disorganized short-lived convection (DSL). Classification as organized convection requires further testing on system lifetime.

2) For a system not yet classified as DSL, CCATS identifies the larger “warm” cloud area (cloud-top temperatures colder than 235 K) and matches it with the previously found cold cloud area. The centroid, the eccentricity, and various \(T_{CT}\) statistics are computed for the matched regions encompassed by each threshold temperature (219 and 235 K). Subsequently, the 219 and 235 K clusters are followed through time, and area-overlap criteria (based on Williams and Houze 1987) are used to track them. Track splits and mergers are dealt with based upon the direction of the two system tracks around the split/merger point (Tsakraklides 2000).

3) In the final stage of CCATS, each cluster is classified into one of four convective types:
   (i) tropical storms (CYC),
   (ii) mesoscale convective complexes (MCC),
   (iii) convective cloud clusters (CCC),
   (iv) disorganized short-lived convection (DSL).

   CYC are categorized by matching published, 6-hourly, “best-track” positions with identified clusters. MCC are categorized by meeting area (219 K > 50 000 km\(^2\)), eccentricity \(e > 0.7\), and time (>6 h or two consecutive satellite images) criteria. Any clusters that are tracked for 6 h but are not CYC or MCC are classified as CCC. Cold cloud clusters that do not meet the time criterion are stored as DSL. Due to the uncertainty in identifying CYC cloud clusters (Evans and Shemo 1996) and their far less frequent occurrence, CYC and MCC have been grouped together: this new group combining CYC and MCC is called MCT. Diagnostics of MCT and CCC are presented in section 4.

   Advances here on Evans and Shemo (1996) include calculation of the complete set of system characteristics for warm (235 K) cloud regions, as well as providing information on the growth in vertical, as well as horizontal, extent of the system.

3. Method

   a. Pretreatment of satellite data

   The infrared satellite imagery used in this study is a part of the International Satellite Cloud Climatology Project (ISCCP) B-3 dataset. Data covering the 5-yr period from 1 January 1989 to 31 December 1993 from GOES-7, GMS-4, and METEOSAT-4 imagery are analyzed. A 1-yr period of INSAT-1 data, from 4 April 1988 to 31 March 1989, is also analyzed. Thus, the CCATS analyses span the entire global Tropics and midlatitudes (40°N–40°S) for at least a year. The imagery for all four satellites consisted of full-disk images sampled to 30-km spatial and 3-h temporal resolution (Rossow et al. 1987). The longitudinal and latitudinal domain was cropped due to errors in the data obtained at a large zenith angle from the satellite subpoint: at large viewing angles the satellite records lower temperatures than reality. This is most likely due to the increase in optical thickness of cirrus clouds with larger zenith angles, resulting in less surface (warmer) contribution being received at the satellite sensor (Joyce et al. 2001). Thus only a subdomain of each full-disk image was used (Fig. 1).

   The cropped longitudinal areas are 220°–320°E (GOES-7), 130°–210°E (GMS-4), 320°–20°E (METEOSAT-4), and 30°–130°E (INSAT-1). In all cases, the cropped latitudinal area extends from 40°S to 40°N. Inter satellite calibrations allow for intercomparison across all regions (Janowiak et al. 2001).

   Following this initial image cropping, the systems were partitioned into land-based and oceanic systems. The criterion for this division was the location of the cold cloud centroid at the initial time of identification. This initial location of the cold cloud centroid further determined the system’s geographic region of occurrence (Table 1). Partitioning of the CCATS output resulted in the compilation of climatologies of organized convection over 12 different geographic regions (Table 1), of which four are continental and eight are oceanic (Fig. 1).

   b. System classification sensitivity to time criterion

   The time criterion of two consecutive satellite images differs from that used in some previous studies [e.g., Laun and Fritsch (1997) use three consecutive satellite images]. The two-image criterion satisfies the 6-h Maddox (1980) criterion if it is assumed that the satellite image snapshot represents the 3-h average (i.e., the system forms 1.5 h before the first image and terminates 1.5 h after the last image). Average lifetimes obtained from these analyses of 14 h (MCT) and 8 h (CCC) both
FIG. 1. Boundaries and relative sizes of the 12 different geographic regions (four continental and eight oceanic) for which these diurnal cycle climatologies were compiled. See Table 1 for latitudinal and longitudinal boundaries, as well as an intercomparison of the size of each region compared to the northwest Pacific. The regions are: 1) North America, 2) South America, 3) North Atlantic Ocean, 4) South Atlantic Ocean, 5) northeast Pacific Ocean, 6) southeast Pacific Ocean, 7) northwest Pacific Ocean, 8) southwest Pacific Ocean, 9) north Indian Ocean, 10) south Indian Ocean, 11) South Asia and northeast Africa, and 12) west Australia and southeast Africa.

exceed the 6-h criterion of Maddox (1980) for MCC lifetime. If the three-image criterion is applied, approximately 25% of the systems classified as organized convection (MCT and CCC) using the two-image criterion remain. Importantly, the diurnal lifecycle evolution diagnosed is the same whether the two- or three-image criterion is used.

c. Diurnal system characteristics

Convective systems are intercompared according to the following diurnal characteristics: (i) frequency, (ii) genesis time, (iii) termination time, (iv) eccentricity $\varepsilon$, (v) size $S$, (vi) average cloud-top temperature $T_{CT}$, (vii) temperature standard deviation $\sigma_{CT}$, and (viii) area ratio ($235 \text{ K}/219 \text{ K}$).

Systems in each of the 12 regions are identified according to local standard time (LST, converted from UTC using longitude). The longitudinal distribution of systems results in an hourly scale being resolved in the analysis, even though the satellite data are at 3-h intervals; thus, after conversion to local time, a 3-h running smoother of the time series for each variable is applied.

The formulas used to calculate each of the system variables are summarized in Table 2 and their interpretation is reviewed here. The frequency of systems is simply a count of the number of systems observed at each time. Genesis refers to the time that the classification program first identifies a system; termination refers to the last time the system is identified. The eccentricity, $\varepsilon$, of a system is a measure of the shape of a system and the size, $S$, is the area of a system in km$^2$. The average cloud-top temperature, $T_{CT}$, includes all pixels inside the below 219 K cloud-top temperature boundary of the system. Lower average cloud-top temperatures correspond to higher cloud-top heights. The temperature standard deviation, $\sigma_{CT}$, measures the spatial variability of the cloud-top temperatures observed in a system: a high standard deviation indicates that embedded towers are present for that system time; increasing $\sigma_{CT}$ with time implies vertical growth of towers within the cloud cluster; a low temperature standard deviation is indicative of stable $T_{CT}$ values, indicating that stratus or cirrus clouds are likely being detected. The area ratio of a system ranges from zero to one and is a calculation of the ratio between the 219-K threshold.
area and the 235-K threshold area; a high area ratio indicates that the total cloud shield of a system consists mostly of cold clouds. Combination of the average temperature and area ratio of a system with the standard deviation gives further insight on the system’s vertical growth. The information contained in all three variables must be used concurrently to do this. For example, a period of overall vertical growth for a MCT would be one that exhibits a decreasing system average cloud-top temperature, an increasing standard deviation, and an increasing area ratio in time. Evolving deep convective towers are dominating. When $\sigma_{ct}$ begins to decrease, then a cirrus shield is likely in place. These statistics are not available for the region covered by the INSAT data—that is, regions 9–12 in Table 1.

4. Intercomparison of diurnal cycles around the globe

Climatologies of MCT and CCC over the 12 regions have been compiled from 1989 to 1993 for regions 1–8 in Table 1 (40°N–40°S, 130°–30°E) and from 1987 to 1988 for regions 9–12 (40°N–40°S, 30°–130°E). Diurnal composites for both MCT and CCC have been created for each region. The mean temporal evolution of each system type in each region is constructed by examining the diurnal evolution of each system characteristic. For example, the mean genesis (termination) time period is the period of highest frequency of genesis (termination) throughout the day; the times of maximum area, eccentricity, and vertical growth help complete the diurnal lifecycle study. Schematic summaries of the detailed objective diagnostics are used to succinctly describe the diurnal lifecycle evolution in each case; the process of constructing these diurnal CCC and MCT cycles is described in section 4a. Composite diurnal lifecycles for oceanic (section 4b) and continental (section 4c) systems are reviewed in turn for representative regions. Finally, these diurnal evolutions of oceanic and continental systems are compared and contrasted (section 4d).

a. Construction of the composite diurnal life cycle for North Atlantic CCC

Evolution of the diurnal variation of system characteristics for North Atlantic CCC is described here in terms of the diurnal cycle of all system characteristics (size, $e$, etc.). The individual system characteristics are recorded in Fig. 2 and the timings of the extremes for each characteristic (e.g., maximum size or symmetry) are recorded. As noted in section 3c, all times given are approximate local standard time (LST) from midnight through 2300 LST. In each panel of Fig. 2 the diurnal time evolution of a frequency is plotted: the diurnal evolution of the number of systems whose genesis time occurs in each time window is plotted in Fig. 2a; Fig. 2b records the frequency of systems reaching their largest cold cloud area; the number of systems reaching their maximum eccentricity at each time is plotted in Fig. 2c; Fig. 2d displays the number of systems designated as terminating at each hour; the frequency of systems recording their minimum averaged cloud-top temperature each hour is plotted in Fig. 2e.
Fig. 2. North Atlantic CCC diurnal variation of (a) genesis time; (b) size, $S$; (c) eccentricity, $e$; (d) termination time; (e) minimum cloud-top temperature, $T_{CT}$; and (f) standard deviation of $T_{CT}(s)$. In all plots, time is on the abscissa; the ordinate in each plot represents the number of systems achieving the stated criterion in each 3-h period (e.g., approximately 1100 CCC are undergoing vertical growth at 0600 LST). A schematic diurnal lifecycle derived from these analyses is pictured in Fig. 3a.
FIG. 3. Schematic composite diurnal lifecycles for (a) CCC and (b) MCT in the North Atlantic. The axis is local time (h) and the average lifetime (expressed as the number of 3-hourly spaced images) of the system is indicated at the top of the image. The range of times corresponding to substantial frequency of each measure are identified using horizontal bars. Genesis time is marked using the thunderstorm symbol; large rates of vertical growth by the ascending arrow; size growth by the cloud, high eccentricity ($\varepsilon > 0.5$) by $\varepsilon$; and termination of the system by the heavy cross $\times$.

Based on the data plotted in Fig. 2, composite diurnal lifecycles are constructed; the examples of North Atlantic CCC and MCT are illustrated schematically in Fig. 3. The average lifetime (expressed as the number of 3-hourly spaced images) of the system is indicated at the top of the image. This system lifetime statistic is derived by considering the mean number of consecutive images recorded for each North Atlantic CCC in the raw analyses. Comparison of this diagnostic with the mean elapsed time between composite genesis and termination provides confirmation of the choice of these time ranges. The range of times corresponding to the substantial frequency (time period of near-maximum frequency) of each system characteristic are identified using horizontal bars. Genesis time is symbolized by the lightning cloud; large rates of vertical growth (determined from the $T_{CT}$ diagnostics) by the tall cloud; size growth by the low horizontal cloud; high eccentricity (most symmetric) by $\varepsilon$; and termination by the heavy cross $\times$.

b. Oceanic systems

Composite diurnal lifecycles were constructed for all 12 regions by considering the evolution of each system characteristic for the 24 h after genesis. The diurnal evolution of CCC [section 4b(1)] and MCT [section 4b(2)] is described here for the eight oceanic regions (Fig. 1, Table 1).

1) OCEANIC CCC

A schematic diurnal cycle for North Atlantic CCC is presented in Fig. 3a to illustrate the typical diurnal cycle for oceanic CCC. Genesis most often occurs between 0200 and 0400 LST and systems terminate between 1300 and 1500 LST, with average lifetime of 8.4 h. Systems quickly attain their highest degree of symmetry shortly after genesis ($\varepsilon > 0.5$) and remain uniformly symmetric over most of their lifecycle. Oceanic CCC begin their vertical growth phase shortly after local sunrise. Subsequently, these systems rapidly increase in areal extent, peaking in size just prior to termination. Since system termination is defined to occur when the area of cloud colder than 219 K is subcritical, the horizontal expansion of the system must also correspond to a collapse in the coldest cloud tops.

CCC are relatively infrequent in the South Atlantic (frequency about 30% of North Atlantic) and their genesis times do not show such a clear diurnal preference (Fig. 4). Comparison of the mean statistics between the hemispheres reveal that, on average, South Atlantic CCC are larger, less symmetric and occur more than 10°E further poleward than the Northern Hemisphere systems at these longitudes; more midlatitude systems are influencing the characteristics used to describe South Atlantic CCC compared to North Atlantic CCC. Even still, their basic lifecycle (immediate vertical growth and rapid symmetry, accompanied by horizontal growth and peak size just prior to termination) is qualitatively similar and their afternoon termination is consistent with North Atlantic systems.

2) OCEANIC MCT

A mean diurnal lifecycle for oceanic MCT (Fig. 3b) is described here, once again using the North Atlantic
systems as a representative sample. Genesis of oceanic MCT occurs in the late night and early morning hours (0500–0600 LST); systems grow quickly in the vertical (0500–0800 LST), reaching their peak symmetry (0700–0900 LST) prior to attaining their largest size (1100–1600 LST). System termination occurs in the evening (1700–2200 LST).

MCT are marginal systems (fewer than one system in existence per hour on average) in the eastern South Pacific and South Atlantic. Although these Southern Hemisphere basins have few MCT systems, their diurnal cycles are similar to the mean oceanic MCT just described for the North Atlantic.

Intercomparison of the basins reveals special concerns for the North Indian Ocean: here, MCT patterns are more akin to land-based CCC [cf. Fig. 5 with Figs. 6a and 7a; section 4c(1)]. North Indian Ocean MCT form in the morning (0800–1100 LST), peak in symmetry midafternoon (1400–1600 LST) and size around termination (between 2000 and 2300 LST; Fig. 5). It is likely that these systems are dominated by the landmass to the north, since this is the most geographically confined of the ocean basins. This hypothesis is consistent with Dai (2001b), who found that the diurnal cycle of offshore near-coastal rainfall was similar to that of land-based systems rather than oceanic systems. Inspection of the genesis locations for these systems (Fig. 8) confirms a maxima just east of the Indian subcontinent and north of Malaysia.

c. Land-based systems

Four continental regions are surveyed (Fig. 1, Table 1). Due to the small areas captured for Southern Africa and Western Australia, these locations rimming the South Indian Ocean are grouped as one region.

1) CONTINENTAL CCC

The diurnal cycle of North American CCC (a) genesis frequency, (b) maximum cold cloud area, (c) maximum eccentricity, (d) termination frequency, (e) minimum mean cloud-top temperature, and (f) maximum cloud-top temperature variance are plotted in Fig. 9. As with Figs. 2 and 3, these system characteristics are once again used to construct a schematic figure of the composite lifecycle (Fig. 7). Schematic composite diurnal lifecycles illustrate that CCC are generally daytime systems in North and South America (Figs. 6a and 7a) and South Asia (not shown), although onset and termination times vary somewhat across locations. Genesis typically occurs between 1400 and 1700 LST (1300–1500 LST) in North (South) America and earlier (1000–1300 LST) in South Asia (not shown). South Asian systems typically
FIG. 8. Geographic distribution of the diurnal cycle for genesis locations of all CCC observed from the INSAT satellite. Note the local maximum in genesis locations just to the east of the Indian subcontinent, as discussed in the text. Oceanic systems in this region have a mean diurnal cycle similar to land-based systems in other regions.
have shorter lifetimes, generally terminating between 1500 and 1600 LST compared to 1900 and 2100 LST for systems in the Americas.

While onset and termination of the systems vary in their timing, CCC across different regions have largely similar evolutionary structures: the systems attain their highest degree of symmetry within 1–2 h of genesis; their deep vertical growth phase begins once the storm is relatively symmetric and may continue as the areal extent begins to increase (especially in the Americas). The greatest areal extent of the system is reached as the storm becomes less symmetric, within 1–2 h of termination (Figs. 6a, 7a).

Southern Africa and west Australian CCC have similar lifecycles to other continental systems, but are nocturnal and have the shortest mean lifetimes of all regions and classes. These CCC are symmetric early, becoming less symmetric as they increase in horizontal area. As noted in the discussion of methodology, information on the vertical growth of these systems is not available.

2) CONTINENTAL MCT

Continental MCT are found to be nocturnal, in agreement with previous studies (e.g., Laing and Fritsch 1997; Fritsch and Forbes 2001; Mathon and Laurent 2001). Genesis typically occurs between 1500 and 1800 LST and systems terminate between 0400 and 0700 LST on the following morning; the average lifetime of these systems is 13.2 h (4.4 images). The peak MCT genesis period is included within the broader CCC genesis win-
d. Comparison of oceanic and land-based diurnal life cycles

1) OCEANIC VERSUS CONTINENTAL CCC

Composite lifecycles show nighttime initiation of oceanic CCC (between 0200 and 0400 LST) with termination between 1300 and 1500 LST (average lifetime 8.4 h); in contrast, continental CCC are generally afternoon systems, generating between 1300 and 1700 LST and terminating between 1500 and 2000 LST. Land-based systems in the Americas form earlier and decay later than those over South Asia.

In spite of the time shift in genesis and termination between oceanic and land-based CCC, their mean evolution patterns are very similar. Systems reach their peak symmetry early, then grow quickly (both vertically and horizontally), losing symmetry as they reach their maximum size just prior to termination.

2) COMPARING OCEANIC AND CONTINENTAL MCT

As with CCC, diurnal timing of oceanic and land-based MCT is offset: early morning genesis of oceanic MCT (0500–0600 LST), compared to afternoon (1300–1700 LST) for land-based systems; termination of oceanic MCT occurs in the early afternoon (1100–1500 LST), compared to morning (0400–0700 LST) termination over land.

Diurnal evolution of land- and ocean-based MCT differs. Oceanic MCT quickly peak in symmetry, remaining symmetric for the majority of their lifecycle; size increases between 1100 and 1600 LST and continues until system termination. Continental MCT rapidly increase in areal extent, becoming increasingly symmetric and taller overnight; further areal growth and decreasing symmetry in the early morning lead up to termination.

5. Discussion and conclusions

A mean diurnal lifecycle for long-lived (lifetime >6h) convective systems has been compiled using an objective technique, CCATS. Data were analyzed for all systems in the latitude range 40°N and 40°S; 5 yr of International Satellite Cloud Climatology Project (ISCCP) analyses of Geostationary Operational Environmental Satellite (GOES), Geostationary Meteorological Satellite (GMS), and Meteosat data were used for most regions; only 1 yr of raw INSAT satellite data was available for this diurnal cycle composite.

Oceanic and land-based CCC were found to have very similar lifecycle evolution patterns, although oceanic CCC formed overnight and the shorter-lived, land-based CCC formed in the afternoon. The frequency of CCC exceeded that of MCT by a factor of 30 over both land and oceans.

Land-based and oceanic MCT lifecycles differ somewhat: the rapid, early growth in size evident in continental MCT is not part of the oceanic system lifecycle. Apart from this growth spurt, the evolution of land and ocean MCT follows the same pattern of CCC with early symmetry, then size expansion until just before termination. Land-based MCC are longer lived and more symmetric than oceanic MCT and form in the late afternoon (1300–1700 LST) compared to oceanic system genesis in the early morning (0500–0600 LST).

While the timings of genesis and termination determined here correspond to those identified in other work (e.g., Laing and Fritsch 2000; Dai 2001b), oceanic systems have been identified as comprising the majority of both MCT and CCC in these analyses. This result differs from earlier work. To check the sensitivity of the time criterion used here (two images for MCC versus three images in Laing and Fritsch 2000), the three-image subsample was studied. The relative frequency of land and oceanic CCC and MCT in this group (~25% of the total dataset) is preserved. Hence, the increase in oceanic systems is not merely an artifact of the system lifetime threshold used here. Another possible source for this discrepancy is interannual variability. The 5-yr period (1989–93) studied here differs from those reported in Laing and Fritsch (2000). The 1989–93 period includes an extended El Niño phase, so some shift toward more oceanic systems should be expected 1) in the western and central North Pacific (from South Asia; Chan 1985), 2) in the western South Pacific (compared to Australia), as well as 3) shifts in centers of convection in the Indian Ocean (Evans and Allan 1992). An ongoing study of interannual variability aims to determine what fraction of this difference might be accounted for by this El Niño tendency.

There was a suggestion of semidiurnal variation in CCC in some regions, but the signal was very weak compared to the diurnal signal. Analyses of rainfall observations (Dai 2001b) suggest that the semidiurnal cycle (where present) is much stronger in the local summer. Thus, the data presented here are being further analyzed to include seasonal variability; these results will be reported on in the future.
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