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Reply

Reply to "Comments on 'Spatial and Temporal Trends in the Location of the Lifetime Maximum Intensity of Tropical Cyclones'"

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We appreciate the comments of [1] (hereafter K18) on [2] (hereafter TE17). The inspiration for TE17 came from the findings of [3] (hereafter KEV14), which showed that the latitude where tropical cyclones are reaching their lifetime maximum intensity (LMI) is moving poleward on average, but the rate differs between ocean basins. In TE17, we further assessed the latitude where tropical cyclones reached their LMI in the western North Pacific and North Atlantic oceans with three main objectives: (1) to assess spatiotemporal patterns in the latitude of LMI; (2) to determine if the migration of LMI latitude is dependent upon the tropical cyclone's LMI; and (3) to assess whether tropical cyclones are achieving their LMI closer to or farther from their eventual landfall location. Here we discuss these three objectives of TE17 in the context of the commentary by K18 and considerations for future research.

For Objective 1 of TE17, K18 notes the potential for errors resulting from using a relatively short time frame for the analyses. Based on the methods of KEV14, we limited our data set to a short period (1977–2015) to analyze patterns in LMI latitude, choosing data accuracy over length of time and sample size. It is well documented that because of inherent issues in the hurricane database, especially earlier in the record, researchers must be cautious when selecting a period of study. KEV14 and [4] (hereafter KEC16) argue that LMI location is less sensitive to data inconsistencies than other tropical cyclone characteristics, allowing for a longer period of study; however, in TE17 we used intensity information in addition to LMI location, meriting a shorter period focused on the time after the introduction of geostationary weather satellites. At the time we originally downloaded the data for TE17 from the International Best Track Archive for Climate Stewardship, nulls were listed for the year of 1976. Thus, we started the study in 1977. We are uncertain why those data were not available at that time.

Indeed a longer data set, or one with different start and end points, may have changed the interpretation of the results for Objective 1 in TE17, just as the small extension of the period of study from KEV14 (1982–2012) to TE17 caused a change in the trends seen in the migration of LMI latitude. This is discussed in depth by K18 and summarized in Table 1. Please note that these summaries are focused on the decadal trends in the migration of LMI locations, and each respective publication contains extensive additional analyses. The discrepancies in the results and explanations shown in Table 1 highlight a major challenge in hurricane climatology: selecting an appropriate period of study that allows not only for reliable data but for an accurate representation of the multi-decadal cycles known to affect hurricane frequency, intensity, and spatial patterns. Additionally, the combined results add to the literature demonstrating that tropical cyclones in each ocean basin are not responding similarly to anthropogenic forcing.

Table 1. A summary of the results from the referenced studies on migration of LMI latitude. Shown are the years of data used for the analysis, the minimum intensity of tropical cyclones included, the linear trend for the North Atlantic (NATL) and western North Pacific (WPAC) Oceans (given in linear rate of change per decade), and the explanation given for those trends, if any, as presented in the publications. The 95% confidence bounds or p-values are included when given. KEV14 used two data sets and both trends are listed. The linear trend in the WPAC listed in KEC16 and the second WPAC trend listed in K18 is the trend of the residuals after accounting for the Pacific Decadal Oscillation and El Niño Southern Oscillation. The second NATL trend listed for K18 is the residual trend after accounting for the Atlantic Multidecadal Oscillation.

	KEV14	**KEC16**	**TE17**	**K18**
Years	1982–2012	1945–2013	1977–2015	1945–2016
Intensity min.	n/a	35 kt	35 kt	35 kt
WPAC linear decadal trend	37 ± 55 km N, 105 ± 71 km N	$0.21 \pm 0.13°$ N	$0.2°$ N, $p = 0.32$	$0.16°$ N, $p = 0.05$ $0.19 \pm 0.125°$ N ***
Explanation *	tropical expansion (anthropogenic forcing)	tropical expansion (anthropogenic forcing)—mostly independent of natural variability	appears to have cyclical cause **	tropical expansion (anthropogenic forcing)
NATL linear decadal trend	7 ± 98 km N, 12 ± 126 km S	n/a	$1.2°$ S, $p < 0.01$	$0.09 \pm 0.28°$ S
Explanation *	tropical expansion (explanation given for global mean change, not NATL specifically)	n/a	changes in genesis location resulting from spatial changes in favorable genesis environments [5]	Atlantic Multi-decadal Oscillation

* These are simplified explanations that are explained thoroughly in the respective publications; ** TE17 was largely based on [6] (completed May 2016). KEC16, which was published online soon after (July 2016), was unintentionally overlooked during the revision process for TE17; otherwise, TE17 may have interpreted the results differently in the WPAC; *** Does not include the year 2016 in analysis.

For Objective 2, TE17 assessed how intensity influenced the migration rate of LMI latitude. An immediate influence of intensity appears when tropical depressions were removed for analyses (KEC16 and TE17 only used tropical cyclones that reached tropical storm strength or greater), which affected the rate of migration. This result may be an artifact from issues with the record of weaker tropical cyclones or an indication that the weaker cyclones are being affected differently. After separating the tropical cyclones into quartiles of LMI, results indicated that the latitudes where the strongest tropical cyclones in the North Atlantic reached their LMI migrated south at a greater rate than their weaker counterparts. This could be related to an overall spatial shift in the strongest storms or a result of the strong influence from the Atlantic Multi-decadal Oscillation highlighted by K18. Because of sample size issues it is challenging to study the most extreme events but they warrant additional consideration, especially in the North Atlantic where they have recently shown pronounced changes [7] that have been attributed to climate change. One potential method for further analyses when historical data may be unreliable or lacking in sample size is to use synthetic tropical cyclones, such as those described by [8], which were used by KE16 and in our own laboratory [9]. These synthetic events are an opportunity to study rare events or model tropical cyclones in a different environment and could provide additional insight on intensity-based migration.

The third objective of TE17—to assess changes in distance from LMI location to landfall—was important to us because we share a common goal with KEC16 in understanding the potential influence of spatial changes in hurricane activity on the public. KEC16 used synthetic events to estimate future changes in hurricane exposure in the western North Pacific as a result of a continued migration of LMI locations. We encourage more studies in this area, especially those that may combine how spatial changes in future tropical cyclone exposure (KEC16) may be combined with projected changes in the populations they are affecting [10].

We appreciate the clarifications and alternate perspective provided in K18. It is our hope that this comment and reply provide additional insight into LMI migration specifically, and more generally the opportunities for future research on the changes in tropical cyclone behavior and their potential human impacts.

Conflicts of Interest: The authors declare no conflict of interest.

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