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REPLY

Reply to Comment on 'Roles of interbasin frequency changes in the poleward shifts of maximum intensity location of tropical cyclones'

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Abstract

Recently a pronounced global poleward shift in the latitude at which the maximum intensities of tropical cyclones (TC) occur has been identified. Moon *et al* (2015 *Environ. Res. Lett.* **10** 104004) reported that the poleward migration is significantly influenced by changes in interbasin frequency. These frequency changes are a larger contributor to the poleward shift than the intrabasin migration component. The strong role of interbasin frequency changes in the poleward migration also suggest that the poleward trend could be changed to an opposite equatorward trend in the future due to multi-decadal variability that significantly impacts Northern Hemisphere TC frequency. In the accompanying comment, Kossin *et al* (2016 *Environ. Res. Lett.* **11** 068001) questioned the novelty and robustness of our results by raising issues associated with subsampling, contributions from some basins to poleward migration, and data dependency. Here, we explain the originality and importance of our main findings, which are different from those of Kossin *et al* (2014 *Nature* **509** 349–52) and reaffirm that our conclusions are maintained regardless of the issues that were raised.

In our original article (Moon *et al* 2015), we showed that a poleward migration in the average latitude at which tropical cyclones (TCs) achieved their lifetime-maximum intensities (LMI), reported by Kossin *et al* (2014, hereafter KEV2014), is greatly influenced by basin-to-basin changes in TC frequency associated with multi-decadal variability, particularly for the Northern Hemisphere (NH). We concluded that an opposite trend in the frequency variations over the past 30 years between the North Atlantic (NA) and the eastern North Pacific (EP) where climatological mean latitudes of LMI are high (26.1 °N) and low (16.5 °N), respectively, played a key role in driving the interbasin frequency contribution to the poleward shift of LMI location.

Kossin *et al* (2016, hereafter KEV2016) argued that introducing the role of the interbasin frequency changes as something new is misrepresentative. It is true that KEV2014 explored the possibility that changes in the relative annual frequency of storms from each basin could contribute to the global trends in the latitude of LMI. However, although KEV2014 examined the issue we focused on, their final conclusions were clearly different from those in our original paper, particularly on the issue of which factor was the main contributor to the global migration trends of LMI latitudes. KEV2014 found that the intrabasin poleward migration dominated the global trends, but we concluded that the interbasin frequency component was the larger contributor to the trends (see figures 3(c) and (d)). A quantitative analysis in our original paper investigated the relative importance of both factors. The different views between the two papers for the dominant factor also resulted in differences in explaining the main mechanism driving the global trend in the migration; KEV2014 asserted that the migration trend is linked to tropical expansion and anthropogenic contributions, while we claimed that it is more likely connected to natural variability associated with the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation. These results support that the methods and conclusions in our original paper are novel.

KEV2016 also raised a concern that subsetting of a large data sample (i.e., global) into subsamples (i.e., hemisphere) can often reduce statistical significance which diminishes the global result. We do not discount the concern of subsampling, but we emphasize that the subsampled number of TCs for the NH (total 1873 TCs) is large enough to avoid statistical uncertainty. In addition, the segregated analysis into hemispheres was meaningful since the main findings in our original paper, that is, the major causes of the poleward migration in both hemispheres were different (see discussion section in our original paper), was only discovered by the segregated analysis. It also should be noted that a robust relationship should not necessarily become statistically insignificant when subsampled.

KEV2016 stated that there are large and statistically significant poleward migration rates in the western North Pacific (WPAC), South Pacific (SPAC), and South Indian Ocean (SIO) basins, which contribute substantially to the global poleward migration rate. We agree that these basins contribute to the poleward migration, but we question that the contributions of these components are large enough to dominate the global migration trend. Figures 3(c) and (d) clearly reveals that all intrabasin contributions, including the three basins that KEV2016 stated have significant poleward migration components, could not produce the globally significant poleward trend. In fact, the trend analysis for individual basin reveals that only the SIO among all basins has a significant poleward migration rate in best track data (see table 1 of KEV2014 and our original paper) based on the 95% confidence bounds. Furthermore, the poleward migration component rate in the SIO no longer is significant for ADT-HURSAT data (see table 1 of KEV2014). These results are different from KEV2016's claims in which the WPAC, SPAC, and SIO all have statistically significant poleward migration rates. It also should be noted that the intrabasin migration trend in the WPAC turns out to be mainly influenced by a long-term frequency change of TC groups with low or high climatological mean latitudes of LMI, rather than a systematic poleward migration of TCs moving along similar tracks in a basin. This finding is similar to the frequency changes of EP and NA TCs with very low and high climatological mean latitudes of LMI playing a significant role in the global migration. This supports that the TC frequency changes that the original paper focused on play a crucial role in global as well as intrabasin migration of LMI latitudes.

As a final note, KEV2016 emphasized the robustness of the migration rates in the homogenized data (i.e., ADT-HURSAT, Kossin *et al* 2013) with limited availability for the NH in addition to the historical best track data. Their results for the homogenized data support the importance of intrabasin migration in the NH, but interestingly, the homogenized data yield an insignificant poleward migration rate for the SH, which is very different from the significant result found in the best track data (table 1 in KEV2014). These results suggest that there is a clear data dependency to the migration rates. In our original paper (supplementary information), the issues related to data as well as TC threshold utilized have been extensively discussed. For instance, KEV2014 limits their study to only TCs with intensities of at least hurricane or typhoon strength (Kossin *et al* 2013), i.e., the maximum wind speed (MWS) is more than 33 m s^{-1}, for the homogenized data. However, they include tropical depressions with MWS of less than 17 m s^{-1}, which are notoriously difficult to try to assess intensities (Kossin *et al* 2013), for best track data analysis. Both results from KEV2014 and our original paper showed that the global, hemispheric, and interbasin poleward trends vary by the data source and TC intensity threshold utilized (see our supplementary information and table 1 of KEV2014). Compared to the intrabasin migration trends, the estimation of interbasin frequency contributions in our original paper should not be significantly influenced by the data source or threshold utilized because we used only climatological LMI latitude (by assuming that there is no poleward migration for all basins) as well as interbasin frequency change rates for the calculation (see our equation (1)). Both of these values are generally not sensitive to the data selection over the analysis period (Landsea *et al* 2010). This implies that our main conclusions do not significantly depend on the choice of data.

In conclusion, our original paper pointed out the importance of the interbasin frequency changes to the poleward migration noted in KEV2014 and concluded that the observed poleward migration for the NH, which accounts for the majority of global TC frequency, is mostly controlled by the interbasin changes in TC frequency while the migration for the SH is influenced by the intrabasin migration component for each basin. In a global sense, although both factors contribute to the poleward migration trends, KEV2014 found that intrabasin migration was the dominant factor, while our original paper found that interbasin frequency changes were the dominant factor. The basis of these conflicting results is connected with subsampling and data sensitivity issues. As KEV2016 indicated, the intrabasin migration rates are sensitive to subsampling and data selection issues, which hamper a consensus in determining the dominant factor. However, our main conclusions related to the interbasin frequency contribution remain robust since the estimation of TC frequency is not very sensitive to those issues, at least for the present analysis period (1982–2012). In particular, we emphasize again that a statistically significant global poleward trend can be identified in the data simply from the frequency changes in each basin regardless of the magnitude of the intrabasin migration rates.

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