Supporting Information for "Pacific Decadal Oscillation Causes Fewer Near-Equatorial Cyclones in the North Indian Ocean"

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Supporting Information (SI)

SI Text

Note on quality of data of Tropical Cyclones over the north Indian Ocean basin

The technology and analysis protocols for tropical cyclone (TC) genesis and its intensity may have progressively evolved over time. Therefore, it is quite natural to expect some inconsistencies in the TC datasets. The published literature suggests that the decline in LLC frequency is real, even though there may be uncertainty in the magnitude of the decline. On the other hand, the increase in the intensity of the LLCs from epoch-1 (1951-1980) to epoch-2 (1981-2010), although consistent with other recent studies, may have larger uncertainties due to various reasons. These issues related to the frequency and intensity of the LLCs in the NIO are discussed below.

TC Frequency

1. The evolution of data collection and analysis protocols for TC genesis and intensity used by the India Meteorological Department (IMD) from 1877 to 2010 was highlighted by Mohapatra et al. (2012)[1]. During 1951-1960, there were 58 coastal surface observatories, 16 pilot balloon stations, and 6 Radiosonde stations (see Table 6 in Mohapatra et al (2012))[1]. A network of coastal stations near southern India, Andaman and Nicobar Islands, and Sri Lanka were established in 1952 (see Fig. 4 and Fig. 5 in Mohapatra et al (2010)[1]). The number of stations systematically increased after that. Based on the observational network, it was found that the genesis location, intensity, movement (track), and landfall can be best represented on the dataset from 1960 onwards. Therefore, if we define our epoch-1 as 1961-1980 and epoch-2 as 1981-2000, we still notice an epochal decline of LLCs from 38 to 18. Moreover, if we consider only the landfalling LLCs, the TC numbers have decreased from 26 to 14 during the same period. It is highly unlikely that the surface observational network will miss any of the landfalling storms from 1960 onwards. And even if some landfalling LLCs are missed, the chances of missing those LLCs are arguably larger in epoch-1 than in epoch-2. Therefore, the epochal decline in LLCs is also confirmed in the presence of better and denser observational networks from the 1960s.

2. The storm genesis positions before the satellite-era contain uncertainty, especially for the storm occurrence in the open oceans[2]. Veechi and Knutson (2011) suggested that an upward adjustment of hurricane counts may be needed during the pre-satellite era (before 1965) to account for likely "missed" TCs due to the sparse density of reporting ships in the North Atlantic. In the absence of any such study over the NIO, if we assume that this study would be qualitatively valid for NIO as well, then there would be "missed" TCs in the pre-satellite era in the NIO also. This means that the epochal decline in LLC frequency in our study may have been underestimated. The ship observations were quite high during the pre-satellite era, and many ships were registered under IVOF (Indian Voluntary Observing Fleet; (see Section 5.4 in Mohapatra et al (2012)[1]). In our study, TC genesis over a large area (5°N-11°N) over the NIO is defined as LLC. Therefore, it is highly likely that even in the presence of inaccuracy in the reported genesis locations, the epochal decline

in NIO LLC will persist. And lastly, the LLC tracks show that they generally move west-, north-, or northwest-ward (Fig. 1 of the paper). Therefore, the chance of an undetected LLC, later detected by an observational network north of 11°N, will not be classified as an LLC. This again shows that the number of LLCs in the pre-satellite era may have been underestimated. (On the other hand, the number of storms that form within 0°-5°N is negligible in the NIO. So an over count of LLCs due to storms formed south of 5°N and reaching 5°N and beyond is negligible).

3. There is often a question regarding whether the storms reported by the IMD suffered from a change in operational procedures that led to a change in classification. IMD added storm categories on the high wind side (Very Severe Cyclonic Storms and Super Cyclonic Storms) in 1974, and 1999 onwards based on the improvement in the observational network. The basic nomenclature remains the same, and there is no change in standard operating procedure for determining the location and intensity of TC. The IMD best track data takes into account the changes in the analysis protocols and has found that the data from 1961 is reliable[1]. Our conclusion regarding the decline in LLCs is also valid if we consider data from 1961.

4. Apart from the cyclone e-Atlas data, there are three more datasets available over the NIO during the analysis period. They are IBTrACS[3], IMD's Best Track data[1], and JTWC data[4]. The similar epochal decline is clearly evident in the IBTrACS, IBTrACS-IMD, and JTWC data as well, indicating the robustness of LLC decline in various datasets (see Table S2).

TC Intensity

Any trend analysis of TC intensities remains problematic due to a host of issues in the NIO. For example, Kossin et al. (2013)[5] mentioned that there was no satellite coverage for the entire Arabian Sea before 1998 as well as the Bay of Bengal before 1981. Therefore, the storm intensity might have been biased due to the oblique view offered by adjacent satellites or subjective analysis by experts. They showed a large spatial gap in data (their Fig. 1) based on Meteosat and GEOS satellites. However, they did not consider that polar-orbiting satellites were in operational use by the IMD from the 1960s, and any system with a lifespan of more than 12 h could not be missed[1]. Indian geostationary satellites, INSAT series, were operational since 1983 and were used for TC monitoring over the Bay of Bengal and the Arabian Sea. Moreover, coastal observatories were augmented in the 1940s and 1950s, followed by Indian satellites in the 1960s (See Section 5 in in Mohapatra et al (2010)[1]), which further helped in the detection of TCs and their intensity. Even with the above augmentation of observations, few studies[6] provided examples of a few NIO TCs that typically underestimated wind speeds and hence were treated as category-3 instead of category-4/5 TCs. Note that the number of LLCs in the Arabian Sea (AS) is very few (10 from 1951-2010). Hence the data uncertainty in the AS[5] will not change any of our conclusions.

SI References

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SI Tables

Table S1. The number of TCs in the BoB (83°-95°E) basin based on IMD eAtlas dataset[7] in the post-monsoon season during epoch-1 (1951-1980) and epoch-2 (1981-2010).

Epochs	Number of LLC	TCs north of 11°N	Total Number
Epoch-1	46	20	66
Epoch-2	26	21	47

Table S2. The number of LLCs (83°-95°E, 5°-11°N) during the pre-monsoon season (April-May) over the BoB during epoch-1 (1951-1980) and epoch-2 (1981-2010) from IMD eAtlas (IBTrACS) dataset.

Epochs	Number of LLC
Epoch-1	9 (10)
Epoch-2	7 (7)

Table S3. The number of TCs in the NIO basin based on IMD eAtlas/IBTrACS/JTWC datasets during the post-monsoon season[3,4,7] indicating the robustness of LLC decline in various datasets. The difference in LLC numbers is caused by the estimation of maximum sustained wind speeds (MSW) and TC categorization by various agencies. IBTracks-IMD represents counts of LLCs categorized as per the IMD criteria[7]. Note that IBTrACS does not provide wind speed information for the entire analysis period (1951-2010). Wind speed information from three agencies were substituted to check whether the IBTrACS matches IMD e-Atlas. DS824 winds were used for the period 1981-1990, USA agencies winds for 1981-1990 and RSMC (New Delhi) winds for 1990-2010 respectively. JTWC's intensity estimates are 5-10 Knots higher than IMD[8] leading to a much higher number of LLCs. For example, weak storms whose peak MSW speeds were just above the IMD cyclone threshold (34 Knots) for one or two 6-hourly periods, were reported by JTWC, but not by the IMD. Besides, JTWC data from 1945-1970 have not been reviewed or updated over the NIO.

Epochs	IMD e-Atlas	IBTrACS	IBTrACS-IMD	JTWC
Epoch-1	46	45	33	55
Epoch-2	26	27	19	26

SI Figures

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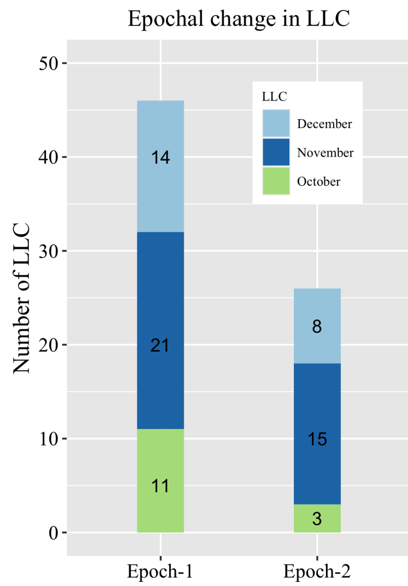

Figure S1. The number of LLC over the Bay of Bengal (83°-95°E, 5°-11°N). during epoch-1 and epoch-2

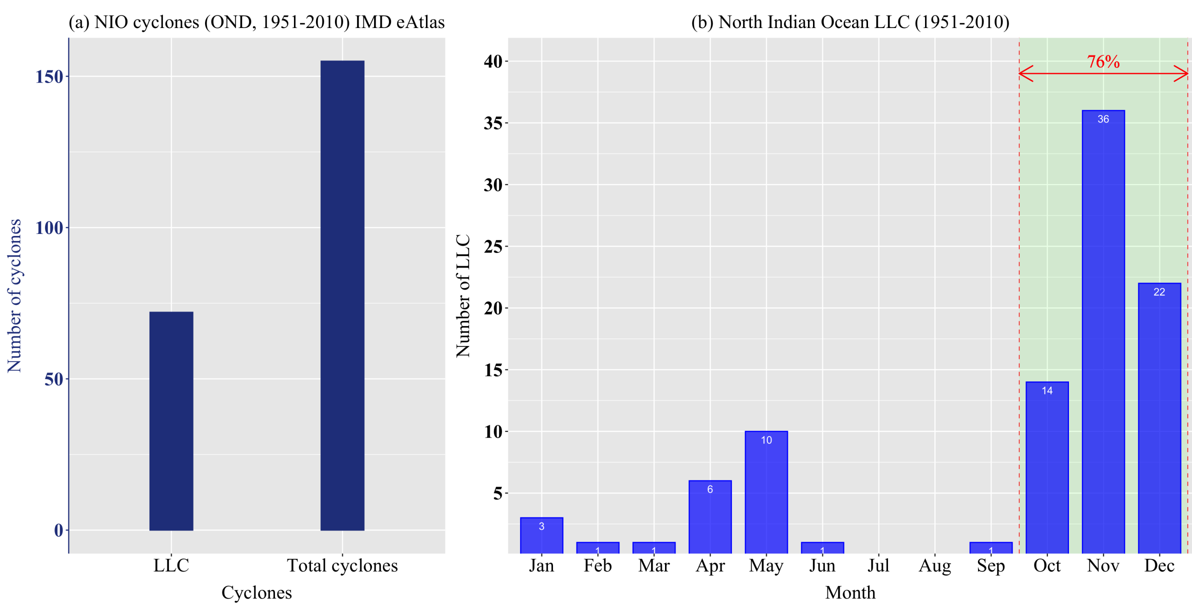

Figure S2. (a) Total number of cyclones during post-monsoon (OND) season and (b) the monthly frequency of LLC in the Bay of Bengal (83°-95°E, 5°-11°N).