Uncertainties in tropical-cyclone translation speed

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In the scientific literature there have been suggestions that anthropogenic climate change (ACC) may lead to slower movement of tropical cyclones, potentially resulting in more intense precipitation in their path. Motivated by this, a recent innovative study[1] suggested that over about the past 70 years there has been a considerable monotonic slowdown in translational speed in many regions of the world. Here I raise doubt as to the veracity of that finding, because the long-term changes appear to be due primarily to a few abrupt, step-like changes, both natural and artificial, in the early part of the record. This greatly reduces the likelihood that the apparent slowdown is driven primarily by anthropogenic causes.

Kossin[1] created a novel dataset of tropical-cyclone translation speed (TCS) based on the best available set of tropical cyclone tracks[2]. His careful analysis of linear trends of TCS by region led him to conclude that TCS has decreased since the mid-twentieth century. Although linear trend analysis is typically a reasonable manner in which to characterize long-term changes driven by gradually evolving phenomena such as ACC, it can yield misleading results when applied to phenomena whose time evolution includes large, abrupt changes. Much of the natural internal variability of the climate system is associated with regional modes that can exhibit regime-like behaviour, remaining in one phase for a decade or more, then transitioning rapidly to the opposite phase. Furthermore, artificial, abrupt transitions can be aliased into climate records by changes in measurement practices, such as the introduction of satellite remote sensing starting in the 1960s, which is known to affect tropical cyclone measurements[3].

Before delving into the specifics of the long-term changes in each region I first conduct an objective analysis to gauge the prospects for statistical models as alternatives to a linear trend, specifically those that incorporate step-like changes. The approach used here follows that used previously[4], with some minor modifications, along with some enhancements[5] (see Supplementary Methods). The strategy employs information-theoretic concepts to gauge the relative merits of three statistical models[4] fitted to each time series of TCS: a linear trend (TR), flat steps (FS) and sloped steps (SS). The latter two involve a series of segments whose boundaries are delineated by objectively determined change-points[6] (see Extended Data Table 1). Within each segment the variability is assumed to be characterized by either a constant mean (FS) or a linear trend (SS).

The method of evaluation of the competing statistical models is based on Schwarz's Bayesian Information Criterion[4] (BIC), which is a measure of relative goodness of fit. It consists of two components, one proportional to the mean square error and the other to the number of fitting parameters; the latter component serves as a penalty factor to guard against overfitting. Weights based on the BIC statistics[5] can be normalized, summing to one, so that they indicate the relative likelihood or strength of evidence that each of the three competing models provides the best fit.

Time series for the six basins used by Kossin[1] (NA, North Atlantic; EP, Eastern Pacific; WP, Western Pacific; NI, Northern Indian; SP, Southern Pacific; and SI, Southern Indian), constructed in a similar fashion (see Supplementary Methods) are given in Fig. 1, along with those for three aggregate regions (GL, Global; NH, Northern Hemisphere; SH, Southern Hemisphere). In addition, Fig. 1 displays the steps formed by the change-points and the relative likelihoods (see Extended Data Table 2).

Although the character of the TCS time series in Fig. 1 varies between regions, the results of the BIC analyses are consistent in that the FS model is selected as most likely in all cases except for in the WP in which the SS model is the pick. In two of the four basins that comprise the NH (NA and WP) the time series exhibit pronounced drops early in the record with no compelling long-term change after about 1970. This behaviour was responsible for the negative trends reported by Kossin[1]. The other two basins (EP and NI) have a different character, although the NI, the only basin reported to have a significant positive trend[1], interestingly has a dramatic step upwards at 1976–77, which coincides with a similar downward step in the WP. Not coincidentally, BIC analyses overwhelmingly reject the TR model in these two basins by ratios of 3:1 for WP and 9:1 for NI. The two basins that comprise the SH (SP and SI) share a common step downward in 1981[1] with no discernible downward trend before or after this time.

While the aggregate time series display some of the more outstanding features seen in their constituent basins, the BIC analyses yield generally more one-sided results in rejecting the trend model, with likelihood ratios of 4.5:1 for GL, 6:1 for NH and 2.5:1 for SH. The NH shows a very dramatic drop from the beginning to about 1970 whereas the SH is dominated by the drop in 1981, both of which are reflected in the GL.

Having demonstrated that the bulk of the outstanding reported trends[1] are better characterized as having arisen by step-like changes in the early part of the record than a monotonic trend, it is of interest to attempt to ascribe plausible causes. One potential explanation for step-like changes in TCS time series are regional climate modes representative of natural climate variability. Change-points determined[6] for available indices of a number of such well known modes (see Extended Data Table 3) were scrutinized for possible association with those from the TCS time series, yielding one obvious match. A widely reported regime shift in the Pacific Decadal Oscillation (PDO) in the mid-1970s corresponds well with change-points in the WP and NI TCS series, with a reversal of phase in the late 1990s. Qualitatively, the implied circulation changes associated with the PDO[7–9] are consistent with the step-like changes in TCS. Prior (subsequent) to 1977 the PDO low-level atmospheric circulation anomalies would seem to enhance (diminish) the strength of the flow, and presumably the steering speed of storms, in the North Pacific gyre in the WP, with opposite effects for the NI. Finally, in the SH the indices show no obvious relationship with the TCS series.

Although some of the step-like changes in the TCS series have an association with regional climate variability, much remains unexplained. Non-climatic factors may come into play, most notably the introduction of satellite remote sensing during the 1960s, before which ships, aircraft and island stations provided the only coverage over the oceans. During the 1960s the types of satellite observations evolved rapidly with the first research quality data in 1960, followed by the first operational weather satellite with once-per-day sampling in 1966, both polar orbiting[10]. Geostationary satellites were introduced in 1966[11] and full global satellite coverage began in approximately 1981 (refs 1,3). Additional inhomogeneities may have been introduced when new analysis techniques were introduced[2] and by the use of different data sources prior to and after 1963[10,12]. Given the various changes that have occurred, it is not surprising that tropical cyclones over the open Atlantic Ocean have been found to be considerably undercounted in the pre-satellite era[12,13].

There remains the outstanding question of how the introduction of satellite sensing could affect estimates of TCS. As posited by Kossin[1] "tropical-cyclone position should be comparatively insensitive to such changes". A plausible explanation would be that if satellites are able to sample portions of the domain that have climatologically slower cyclone movement, then introduction of satellite sensing would bolster the recorded number of slower cyclone tracks. Consistent with this hypothesis is the fact that in the Atlantic basin, in the pre-satellite era, ship track densities are greater in higher latitudes[13], where tropical cyclones move faster on average[14]. However, it is possible that such a bias also applies over land given a similar relation between population density and storm speed.

To further explore this question, Fig. 2 shows latitudinal profiles of the climatological average TCS (black) and the change in the relative number of observations of TCS going from the pre-satellite era to the satellite era (red) by basin. Positive (negative) values of the change indicate latitudes which are sampled more (less) frequently after the introduction of satellite remote sensing. During the satellite era increased (decreased) sampling of equatorward (poleward) latitudes having climatologically lower (higher) speeds is quite evident in three of the basins (WP, SP and SI) and reasonably evident in another (NA). For the remaining two basins (EP and NI) there is a lack of clarity in the relationship. It is noteworthy that the basins with the clearest implied satellite spatial sampling bias in Fig. 2 correspond to those with the most pronounced step-like drops in their time series in Fig. 1 at the time of satellite transition. Although this analysis, operating only in the latitudinal dimension, could be improved upon by a more sophisticated two-dimensional scheme[13], it does provide considerable evidence of a satellite sampling bias consistent with step-like drops in TCS in the early part of the record for some of the basins shown in Fig. 1.

Now, with some plausible explanations for the step-like changes in TCS series, it is worth trying to quantify the magnitude of their effects on trends. I approach this exercise adopting a minimalistic philosophy by selecting the fewest possible credible causes that explain the bulk of the behaviour. The first event chosen consists of the 1976 and 1997 change-points in the WP and NI associated with the PDO. Next chosen is a change-point associated with the introduction of satellite data in the NH; given the uncertainty in the timing, two dates—1960 (ref. 10) and 1965 (ref. 11)—are used to test the sensitivity of this choice. The last event is a SH change-point in 1981 associated with expansion to global satellite coverage[1,3].

To quantify the effects of the selected change-points, a trend analysis is conducted for a set of scenarios. In each scenario the TCS time series are adjusted to remove the effects of the change-points by equalizing the means of the segments on either side of each change-point. Each scenario includes an event either alone or in combination with other events. Extended Data Table 4 gives the specifications for nine scenarios with their associated trends in Extended Data Fig. 1 and further statistics in Extended Data Table 5. It can be seen that even a single event applied to one of the basins can greatly reduce the magnitude of the trend and render it non-significant. Used in combination the effect is even greater. Only for the GL, which is more heterogeneous, are multiple events required to render the trend non-significant. I note that except for NA, for all basins including the NH, the satellite change-point at 1965 is more effective than at 1960.

This work does not explicitly analyse land-only TCS, as was done previously[1]. The extended data tables 1 and 2 in Kossin[1] show that only for the NA and WP is there any evidence that land-only trends are more negative than those overall, and the veracity of the latter is weakened considerably based on more outlier-resistant trends[1]. As noted[1], land-only tracks constitute only about 10% of all tracks. Furthermore, in individual years the sample size can become quite small, and as seen in Kossin's Fig. 3, this results in large variance and some considerable outliers. For the NA it appears that three early-period outliers may be responsible for much of the trend. In a limited examination of the data for these outliers I found them to be the result of cyclone tracks truncated to include only the positions later in the storm life-cycle, transitioning to extratropical in character, as they moved poleward and became entrained into the faster mid-latitude westerlies.

Accordingly, I consider the land-only tracks to be unreliable indicators of the long-term behaviour of TCS.

This work has demonstrated that previously reported decreases in TCS[1] are likely to be due to a combination of natural internal climate variability and abrupt changes early in the record owing to changes in measurement practices, particularly the introduction of satellite remote sensing capabilities during the 1960s (around 1980) in the Northern (Southern) Hemisphere, rather than indicative of a change in the climate system. The fact that changes are step-like, and especially since most of the long-term change in TCS originates in the early part of the record, argues strongly against a dominant ACC effect. However, a more subtle effect due to ACC cannot be ruled out entirely, and would require more detailed analysis to reveal.

Data availability

The tropical-cyclone data analysed in this study were taken from the International Best Track Archive for Climate Stewardship (IBTrACS; https://www.ncdc.noaa.gov/ibtracs/, file ftp://eclipse.ncdc.noaa.gov/pub/ibtracs/v03r10/all/csv/Allstorms.ibtracs_all.v03r10.csv). Indices of a variety of the most commonly cited regional climate modes of variability were obtained from several sources: the Earth System Research Laboratory (ESRL; https://www.esrl.noaa.gov/psd/data/climateindices/), the National Centers for Environmental Information (NCEI; https://www.ncdc.noaa.gov/teleconnections/), the National Center for Atmospheric Research (NCAR; https://climatedataguide.ucar.edu/climate-data/), the University of East Anglia (UEA; https://crudata.uea.ac.uk/cru/data/nao/) and the British Antarctic Survey (BAS; http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.1957.2007.seas.txt).

Code availability

The FORTRAN code used to perform the change-point analyses[6] is available from the author on request.

Online content Any Methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available in the online version of the paper at https://doi.org/10.1038/s41586-019-1223-2.

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Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41586-019-1223-2

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Fig. 1 | Time series of annually averaged TCS with model fits by region. Time series of annually averaged TCS (km h-1) from 1949 to 2016 (thin black curve), with the fits for the FS model (thick black lines) and the SS model (thick red lines). The colour bar at the top depicts the relative weights from the BIC analysis corresponding to models FS (black), TR (cyan) and SS (red). Each panel corresponds to a different region: GL (**a**), NH (**b**), SH (**c**), NA (**d**), EP (**e**), WP (**f**), NI (**g**), SP (**h**) and SI (**i**).

Fig. 2 | Latitudinal profiles of TCS and change in sampling due to satellites. Climatological average TCS (km h-1; black lines) from 1949 to 2016 and relative percentage change in number of TCS observations (solid red lines) as a function of latitude. Changes represent the difference, the satellite era's observations minus those from the pre-satellite era, where 1966 begins the satellite era for NA, EP, WP and NI and 1982 begins the satellite era for SP and SI. Zero change in observations is given by the dashed red line. Each panel corresponds to a different region: NA (**a**), EP (**b**), WP (**c**), NI (**d**), SP (**e**) and SI (**f**).

Extended Data Table 1 | Change-point analysis results for the basin TCS time series plotted in Fig. 1
For each basin the year of each change-point is given in the order in which they were selected, along with the *Z*-statistic, probability associated with the *Z*-statistic and the change-point signal-to-noise ratio (SNR)[6]. The SNR is computed by extending a maximum of 20 values from each change-point[6]. The SNR quantifies the magnitude of the discontinuity and is defined as the ratio of the variance associated with a change in mean between two segments to the variance within the segments.

Extended Data Table 2 | Relative weights based on the Bayesian information criterion
Weights are given by region (columns) and statistical model (rows). For a given region the weights sum to one and can be interpreted as the likelihood, relative to the other two models, that the given model is the most appropriate one. The odds ratio for a given model(s) is its weight(s) divided by the sum of the weights for the remaining models.

Extended Data Table 3 | Change-point analysis results for regional mode index time series
As for Extended Data Table 1 except for time series of indices of regional climate modes. The first part of the index name is an abbreviation of the index, while the second part indicates the source (see the 'Data availability' section), since some were based on different definitions.

Extended Data Table 4 | Scenarios for the trend analyses in Extended Data Fig. 1
The columns give the scenario number, a description of the scenario, the year of the change-points and basins to which they are applied, and the colour of the bar plotted in Extended Data Fig. 1.

Extended Data Table 5 | Statistics for trend analysis
Trend (km h^{-1} yr^{-1}) (top), Spearman correlation (middle) and probability (two-tailed Student's *t*-test) by scenario (columns, see Extended Data Table 4). Significances utilize actual sample size (68) except when the lag-1 autocorrelation is greater than 0, which is the case for WP, in which case the effective sample size (64) is used in the computation of the *t*-statistic[4].

Extended Data Fig. 1 | Trends and significances by scenario and region. Each bar represents the trend (km h^{-1} yr^{-1}) corresponding to one of the nine scenarios given in Extended Data Table 4. Since some scenarios are redundant for a given basin, only the first occurrence is plotted. Stippling indicates significance at the 5% level based on a two-tailed Student's *t*-test. Each panel corresponds to a different region: GL (**a**), NH (**b**), SH (**c**), NA (**d**), EP (**e**), WP (**f**), NI (**g**), SP (**h**) and SI (**i**).