ScienceBrief
keep up with science

# Climate change is probably increasing the intensity of tropical cyclones

**ScienceBrief Review** **March 2021**

Thomas R. Knutson[1], Maya V. Chung[2], Gabriel Vecchi[2,3,4], Jingru Sun[4], Tsung-Lin Hsieh[3] and Adam J. P. Smith[5].
1 National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ 08540 USA. 2 Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ 08540 USA. 3 High Meadows Environmental Institute, Princeton University, Princeton, NJ 08540 USA. 4 Department of Geosciences, Princeton University, Princeton, NJ 08540 USA. 5 School of Environmental Sciences and Tyndall Centre for Climate Change Research, University of East Anglia (UEA), Norwich NR4 7TJ, UK.

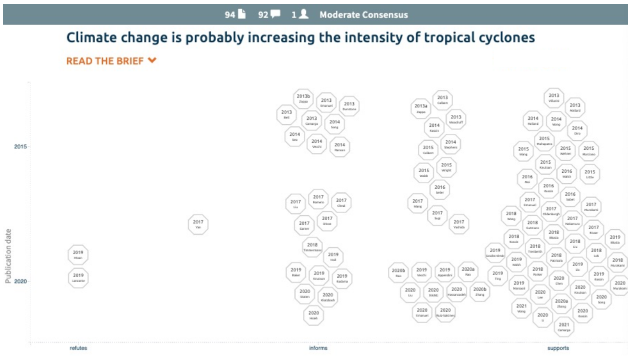
This ScienceBrief Review is part of a collection on Critical Issues in Climate Change Science, relevant to inform the COP26 climate conference to be held in Glasgow. Eds: Corinne Le Quéré, Peter Liss, Piers Forster. Time stamp: Published 26 March 2021. The evidence reviewed was published between 16 March 2013 to 12 February 2021. Search keywords used: "Climate Change" AND "Cyclone" (also "Hurricane" OR "Typhoon").

**Approach.** This ScienceBrief Review examines the link between climate change and tropical cyclones (TCs, including tropical storms, hurricanes, and typhoons). It synthesises findings from more than 90 peer−reviewed scientific articles gathered using ScienceBrief. The Brief and evidence can be viewed at: sciencebrief.org/topics/climate-change-science/cyclones

**Summary. Warming of the surface ocean from anthropogenic (human-induced) climate change is likely fuelling more powerful TCs. The destructive power of individual TCs through flooding is amplified by rising sea level, which very likely has a substantial contribution at the global scale from anthropogenic climate change. In addition, TC precipitation rates are projected to increase due to enhanced atmospheric moisture associated with anthropogenic global warming. The proportion of severe TCs (category 3 & 5) has increased, possibly due to anthropogenic climate change. This proportion of very intense TCs (category 4 & 5) is projected to increase, yet most climate model studies project the total number of TCs each year to decrease or remain approximately the same. Additional changes such as increasing rates of rapid intensification, the poleward migration of the latitude of maximum intensity, and a slowing of the forward motion of TCs have been observed in places, and these may be climate change signals emerging from natural variability. While there are challenges in attributing these past observed changes to anthropogenic forcing, models project that with global warming in coming decades some regions will experience increases in rapid intensification, a poleward migration of the latitude of maximum intensity or a slowing of the forward motion of TCs.**

## Key points.

It is extremely likely that human influence has been the dominant cause of the observed global warming since 1951, according to the IPCC Fifth Assessment Report (Bindoff et al., 2013). Further warming will likely lead to an increased proportion of TCs of higher severity (category 4 & 5) with more damaging wind speeds, higher storm inundation, and more extreme rainfall rates (Knutson et al., 2015; 2019; 2020; Walsh et al., 2016; 2019).




Snap shot of the Brief, showing moderate consensus among the scientific publications analysed. Click here to visit the Brief.

- **Observations since about 1980 show that, globally, the intensity and rate of intensification of TCs has increased slightly, with a stronger positive trend observed for the North Atlantic.** Modelling studies, supported by a theory of potential intensity of TCs, find that future mean intensities are projected to increase by about 5% for a +2°C global warming scenario.
- The global average proportion of intense TC occurrence (category 3 or higher; i.e., 1-minute maximum wind speeds of 50 m/s or higher) has increased since 1979, and **the proportion of category 4-5 storms** (winds 58 m/s or higher) **is projected to increase substantially under a warming climate**.
- The IPCC Fifth Assessment Report (Bindoff et al. 2013) conclude that an anthropogenic contribution to increased near-surface specific humidity has been identified with medium confidence in observations. They also conclude that it is very likely that there has been a substantial anthropogenic forcing contribution to observed global mean sea level rise since the 1970s. **Rising sea levels lead to higher average inundation levels from TCs, all else being equal, while enhanced atmospheric moisture probably leads to greater rainfall rates in TCs, based on theoretical expectations and TC simulations. These changes enhance the risk of flooding from individual TCs, and are projected to accelerate as warming continues**. Storm surge and flooding rainfall from TCs are extremely important for societal impacts of TCs as they have

been principal drivers of many of the large human loss-of-life disasters associated with TCs.

- Larger and more intense TCs tend to cause more damage than smaller, weaker storms, so shifts toward a greater proportion of intense storms are of concern. Historical normalized economic damage from TCs for the U.S. since 1900 is closely linked to storm minimum sea level pressures, which in turn are related to both storm intensity and size. **However, there is as yet no significant trend in U.S. landfalling major hurricane frequency since 1900, as measured by minimum sea level pressures** (Klotzbach et al., 2020), and this is the longest available record of intense (category 3 or higher) TC activity.
- **The observed global total number of TCs (including tropical storms and category 1−5 TCs) has not changed significantly in recent decades**. Total TC records include weaker TCs below major hurricane intensity, which statistically tend to be less damaging, yet these TC records also comprise some of the longest observational records of TCs for trend analysis. Century-scale records of landfalling hurricanes for the U.S., TCs for Japan, and severe TCs for northeast Australia all show significant decreases or little change (Knutson et al., 2019). Century-scale recorded increases in Atlantic basin-wide hurricane and tropical storm frequency are not considered reliable but are consistent with the impact of improved data quality. **While the number of TCs is projected to decrease globally in most studies, there is uncertainty, with increases or neutral trends predicted by some models. Regional TC frequency changes are of mixed sign in model projections and exhibit large spread**.
- **Quantitative contributions of anthropogenic climate change to the global TC intensification or increase in the proportion of intense tropical cyclones have not been confidently established,** in large part, because of sizable potential contributions from natural multi-decadal variability and non-greenhouse gas forcing since the 1970s, when hurricane data is of the highest quality. Trends in TC data can also be difficult to detect because the instrumentation used to measure TC characteristics is itself evolving in time.
- **Observations indicate that the latitude of maximum intensity of TC activity has migrated poleward, particularly in the northwest Pacific basin**. This change has been assessed as unusual compared with expected natural climate variability with low-to-medium confidence, raising the potential that TCs at high intensity may begin to impact locations further poleward than they have previously, potentially affecting areas that may be less well adapted.

## Observations and detection/attribution of changes

**The intensity of TCs has increased globally in recent decades, with the proportion of category 3-5 cyclone occurrence growing** by around 5% per decade since 1979, according to satellite-based intensity estimates (Kossin et al., 2020). Statistically significant increases were observed globally and in several basins, including the **North Atlantic** basin by Kossin et al. (2020). Observations since the 1980s indicate that globally, and to a greater degree in the North Atlantic, the likelihood of TC rapid intensification (RI, when TC intensity changes by more than 18 m/s in 24 hours) has increased (Bhatia et al., 2019). In terms of the longest available records of category 3-5 TCs, the frequency of landfalling major hurricanes for the U.S. exhibits no significant trend since 1900 (Klotzbach et al., 2020), nor does a U.S. landfalling TC power dissipation index indicate any significant trend since 1900 (Landsea, 2005).

- In the western **North Pacific**, tropical cyclones making landfall in eastern and south-eastern Asia have increased in intensity over 1977-2014 by +12 to +15% (Mei and Xie, 2016).
- In the **North Indian** basin, Mohapatra et al. (2015) find, based on observations over 1951-2010 (monsoon and post-monsoon seasons), that the probability of cyclonic disturbances intensifying into tropical cyclones has increased in the Arabian Sea in association with decreased vertical wind shear. They further report that the probability of tropical cyclones intensifying into severe tropical cyclones has increased over the Bay of Bengal in association with increased low-level cyclonic vorticity. For the Arabian Sea, model simulations suggest that recent increases in the occurrence of extremely severe tropical cyclones in the post-monsoon season are likely due in part to anthropogenic forcing (Murakami et al., 2017).
- In the **North Atlantic** basin, increasing intensity and intensification rate trends are interpreted as responding to some combination of changes in atmospheric aerosol concentration, human−caused changes in greenhouse gas concentrations, and natural variability (Bhatia et al., 2019). Past changes in aerosols have been suggested as important in driving changes in the intensity of North Atlantic hurricanes over recent decades (Villarini and Vecchi, 2013), with increases in aerosol emissions after World War II and decreases after the 1970s driving Atlantic hurricane intensity decreases and increases, respectively. Further research is required to better constrain the relative contributions of these different influencing factors to the observed changes (Walsh et al., 2019).


Zoltan Tasi– Unsplash.com

**The modelled effect of human−induced climate change on TC intensities is qualitatively consistent with the observed increases, but it is not clear whether an anthropogenic influence on TC intensity or proportion of intense TCs is distinguishable from natural variability at present** (see review in Knutson et al., 2019). In one study, Bhatia et al. (2019) demonstrate that observed increases in TC rapid intensification in the Atlantic in recent decades are highly unusual (though not unprecedented) compared to one model's simulation of natural internal variability, an example of using modelled climate variability to test for how unusual an observed trend is estimated to be compared to natural variability.

**The latitude of maximum tropical cyclone intensity has migrated polewards in both hemispheres**, coinciding with the poleward expansion of tropical boundaries observed in some regions (Kossin et al., 2016; Walsh et al., 2019; Staten et al., 2020). During the past 30 years, peak cyclone intensity has migrated on the order of 50-60 km per decade in each hemisphere (Kossin et al., 2014). However, while Kossin et al. (2016) show that the observed poleward migration of the latitude of maximum TC intensity in the western North Pacific is robust to statistical removal of Pacific Decadal Oscillation and El Niño/Southern Oscillation signals, there remains uncertainty regarding the extent to which the TC changes result from human−caused greenhouse warming; Knutson et al. (2019) concluded that there is low-to-medium confidence that the changes are highly unusual compared to natural variability.

- Northward migration of the latitude of maximum tropical cyclone intensity has been especially pronounced in the **northwest Pacific** (Kossin et al., 2016)
- In recent decades, cyclone exposure in the **western North Pacific** has decreased in the Philippines and the South China Sea while increasing in the East China Sea, Japan, and the Korean Peninsula (Colbert et al., 2015; Kossin et al., 2016; Xiang et al., 2020).

  In the **North Indian** basin, northward migration of the mean latitude of cyclone formation has been observed since the mid 20th century (Mohapatra et al., 2015).
- A statistically significant movement of TCs toward land regions has been observed globally and in the **northwest Pacific** basin during 1982-2018 (Wang and Toumi, 2021), although the relative contributions of natural variability and anthropogenic forcing to this observed trend have not been established.

**The forward motion (translation speed) of tropical cyclones may have slowed over the continental U.S. since 1901** (Kossin, 2019), although the causes of this decline are uncertain. It is possible that this change represents a climate change trend emerging from the background of natural variability. In contrast, while a slowing was observed globally since the mid-20th century (Kossin, 2018; 2019), the majority of this decline was during 1949−1981, with a weak or no trend in later observations (Zhang et al., 2020). It has also been suggested that the global decline could instead be due to systematic data biases (Moon et al., 2019) or natural variability, possibly combined with changes in measurement technology after the introduction of satellite-based remote sensing of tropical cyclones in the 1960s (Lanzante, 2019). Slower forward propagation speed can be important for tropical cyclone impacts, including an increase in rainfall and flooding, due to the longer duration a tropical cyclone is within the same area (Kossin, 2018).

**Concerning extreme TC precipitation events**, **formal detection and attribution studies of individual events** (Van Oldenborgh et al., 2017) **suggest possible human contributions to observed extreme precipitation events from all sources, including TCs and other influences**. The IPCC Fifth Assessment Report (Bindoff et al. 2013) conclude that there is medium confidence that anthropogenic forcing has contributed to intensified heavy precipitation in general at the global scale since the mid-20th century. They did not separately assess TC-related precipitation extremes. Theoretical and model-based research suggest a warming-induced increase in extreme TC-related rainfall rates (Knutson et al. 2020; Liu et al. 2020). However, an anthropogenic influence on observed TC-related rainfall that is outside the range of estimated natural variability has not yet been demonstrated in existing studies.

- One extreme precipitation event was driven by **Hurricane Harvey**, which made landfall over Texas in August 2017, with very slow forward motion (translation speed) leading to extremely high multi-day rainfall totals over the Houston area. Observed 3−day total precipitation exceeded 750 mm over a large area (van Oldenborgh et al., 2017). In the early northern summer of 2017, the ocean heat content and sea surface temperature of the Gulf of Mexico were at (then) record high levels, providing the energy for intense evaporation, moistening the atmosphere (Trenberth et al., 2018). Trenberth et al. (2018) assert that the intensity of rainfall during Hurricane Harvey could not have occurred without human−caused climate change. Event attribution studies estimated that climate change was responsible for approximately +15% to +38% increased rainfall intensity and a +3 to +3.5−fold increase in the likelihood of extreme multi-day precipitation events, such as the one associated with Hurricane Harvey (van Oldenborgh et al., 2017; Risser & Wehner, 2017). It was also found that urbanisation exacerbated the rainfall and flooding in Houston from Hurricane Harvey (Zhang et al. 2018).

**For tropical cyclone frequency (including tropical storms and category 1-5 TCs), the observed total global annual number has not changed significantly in recent decades**. While total TC frequency includes weaker TCs below category 3 intensity, which statistically tend to be less damaging, long TC frequency records also comprise some of the longest observational records of TCs for trend analysis. Therefore, they can be useful for climate change detection/attribution studies, which are looking for evidence of emerging greenhouse gas-induced trends.

**Century-scale records of landfalling tropical cyclones for the U.S., Japan, and northeast Australia show significant decreases or little change** (Knutson et al., 2019). Century-scale recorded increases in Atlantic basin-wide hurricane and tropical storm frequency are consistent with the impact of improved monitoring, which suggests that these recorded increases should not be interpreted strictly as climate change signals (Vecchi and Knutson, 2011; Landsea et al., 2010). In a unique study comparing patterns of past observed TC frequency trends and model simulations, Murakami et al. (2020) show that two high-resolution coupled climate models, when forced with observed historical forcings, reproduce the global spatial pattern (a mixture of increases and decreases) over 1980-2018. These simulations suggest that the observed regional increase in TC frequency in the Atlantic basin since 1980 is due, in part, to a recovery from a preceding suppressed period of Atlantic TC frequency, due to increased aerosol forcing. Aerosol forcing increased in the mid-20th century and decreased following the 1980s.

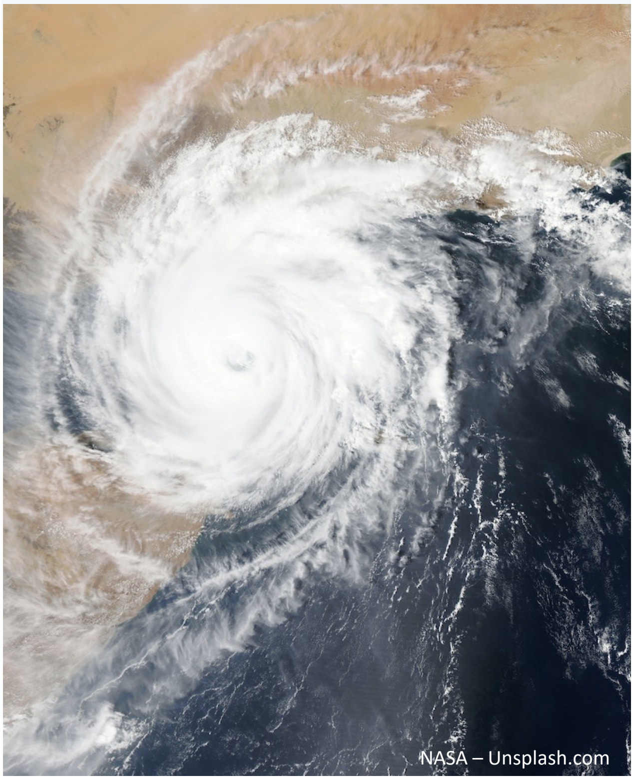
Murakami et al. (2020) also projects a decrease in tropical storm frequency globally and over the Atlantic over the coming century as greenhouse gas influences increasingly dominate over projected aerosol influences. Their finding is notable since their models are the only ones thus far that have demonstrated the capability to simulate the observed pattern of TC frequency change globally since 1980 fairly realistically. Villarini & Vecchi (2012) and Dunstone et al. (2013) also indicate that aerosol forcing was an important, if not dominant, driver of multi-decadal Atlantic hurricane variability, driving a reduction between the 1950s and the 1980s and an increase since the 1990s. These studies imply that trends in tropical cyclone frequency since 1980 cannot be extrapolated to generate predictions of what changes to expect over the coming century due to increasing greenhouse gases.

## Detection/attribution of climate change signal

**In terms of assessment of the above findings, some observed changes in tropical cyclone metrics, including increased intensities and an increased fraction of storms reaching major hurricane strength, are qualitatively consistent with expectations from models with climate warming. A number of the observed TC changes may be early indicators of emerging anthropogenic influence, particularly if one is attempting to avoid overlooking or understating anthropogenic influence on observed change (i.e., "Type II error avoidance", following Knutson et al., 2019). However, using assessment criteria that require more robust evidence to conclude that observed changes are unusual compared to natural variability (i.e., "Type I error avoidance"), it is not clear whether the influence of anthropogenic climate change on the observed changes in these tropical cyclone metrics is distinguishable from natural variability at present (Knutson et al., 2019).**

**These distinctions are important because if climate change trend signals are present that are highly unusual compared to estimated natural variability and are well-reproduced by climate models that include anthropogenic forcings, this can greatly increase confidence in future model projections driven by greenhouse gas increases; such is the case for observed global mean temperature increases since 1900, for example.**

**The observed TC timeseries with currently the strongest cases that the changes are highly unusual compared with expected natural variability include: i) the poleward migration of latitude of maximum TC intensity in the northwest Pacific since the 1940s (low-to-medium confidence of detection compared to natural variability); ii) the slowing of TC propagation speed over the continental U.S. since 1901; and iii) increase in rapid intensification of Atlantic TCs in recent decades. (Cases (ii) and (iii) were published after the Knutson et al. 2019 assessment and thus have not yet been assessed but may have similar confidence levels to case (i), i.e., low-to-medium confidence of detection compared to natural variability). The observed pattern of increases and decreases in tropical storm frequency since 1980 across the tropics can be simulated reasonably well by two climate models forced by historical forcings; this same model pair projects future decreases in tropical cyclone frequency globally and over most tropical regions.**


NASA – Unsplash.com

## Future projections

**Confidence in future projections depends on the capability of models for simulating the observed climatology of TC behaviour and any observed trend or variability. Confidence also increases when scientific understanding of physical mechanisms for changes is well developed, and if**

**there is a detectable and attributable trend in the TC metric already present in observations.**

**The proportion of tropical cyclones reaching category 4 & 5 intensity is projected to increase in a warming climate**, **with a corresponding reduction in the proportion of low-intensity cyclones** (Wehner et al., 2015; Bhatia et al., 2018; Vecchi et al., 2019; Knutson et al., 2020). In one study, the annual number of days in which category 4 & 5 storms are projected to occur increases 35% globally by the late 21st century under a medium emissions future scenario (RCP4.5), while the number of category 4 & 5 storms is projected to increase 24% (Knutson et al. 2015), also implying an increase in duration per storm of category 4-5 conditions. Higher-resolution models are better suited for attempting to realistically simulate category 4 & 5 storms (Davis, 2018). Although models used in existing climate change studies are not optimal in that regard, a survey of studies using relatively higher resolution (< 28 km grid spacing) models suggests a +10 to +15% increase in the global proportion of these severe cyclones in a +2$^{o}$C warming scenario (Knutson et al., 2020). For comparison purposes, the Knutson et al. (2020) assessment re-scaled the TC projections from many separate studies, which had assumed a mix of future emission scenarios, into a single group of estimates under an assumed +2$^{o}$C global warming scenario.

Although the Knutson et al. (2020) assessment concluded that with medium-to-high confidence the proportion of category 4 & 5 storms relative to all storms would increase with global warming, there was low confidence in how the frequency of category 4 & 5 storms is expected to change, owing to the diversity of projections across available modelling studies. A survey of future projections of category 4 & 5 storm frequency at the basin scale further highlights the uncertainty in the expected sign of change (Knutson et al., 2020).

- The **eastern North Pacific** shows the largest increase in category 4 & 5 storm frequency among individual basin projections (Knutson et al., 2020).
- In the **North Atlantic**, category 4 & 5 storms are projected to increase in frequency by a factor of 1.5 to 2.0, depending on emissions scenario, according to one modelling study (Murakami et al., 2018), while a multi-study assessment reported uncertainty in the sign of change projected by different modelling studies (Knutson et al. 2020).
- For the **southwest Pacific**, most models project a decrease in the frequency of Category 4 & 5 cyclones (Knutson et al., 2020).

**For tropical cyclone intensity, a +2$^{o}$C warming scenario is projected to yield a +5% (+1 to +10%) increase in maximum wind speed** (Knutson et al., 2020), **resulting in greater potential damage per storm**. This estimate is consistent with thermodynamic predictions using the potential intensity (PI) theory, which estimates the theoretical maximum intensity of a cyclone within a specific local environment (Emanuel, 1987; Sobel et al., 2016). The presence of only a weak increasing trend in global historical tropical cyclone intensity since 1980 is possibly due to the opposing effect of aerosol cooling (Sobel et al., 2016) on the effect of greenhouse gas-induced warming. However, future greenhouse warming is anticipated to exceed the effects of aerosol cooling on TC intensity, increasing the likelihood of more intense tropical cyclones and rendering the changes more detectable compared to natural variability (Villarini and Vecchi, 2013; Sobel et al., 2016).

**Rapid intensification is projected to become more probable over the 21st century** (Emanuel 2017; Bhatia et al. 2018), **although relatively few studies have examined this metric to date**.

**Most studies project a decrease in the global frequency of tropical cyclones** (tropical storms plus categories 1−5 combined) **with warming, albeit with large uncertainty that includes the potential for global increases**. The vast majority of climate model studies predict a decrease in the frequency of tropical cyclone activity, or no change (e.g., Mallard et al., 2013; Walsh et al., 2019; Knutson et al., 2015; Murakami et al. 2020), averaging around −14% for +2$^{o}$C of warming in a multi-study assessment (Knutson et al., 2020). There are some exceptions, with two modelling systems predicting increases in overall cyclone frequency (Emanuel, 2013; Bhatia et al., 2018; Vecchi et al., 2019), which reflects differences in the type and detailed formulation of models used. Theoretical explanations of the physical mechanisms to cause a change in cyclone frequency have been a challenging topic (e.g., Vecchi et al., 2019; Hsieh et al., 2020), compounding uncertainty around the model projections (Walsh et al., 2016; Knutson et al., 2020).

- Projections of TC frequency within individual basins are more uncertain, particularly for the **central and eastern North Pacific** (Walsh et al., 2019). The majority of models project a small decrease but some project increases (Knutson et al., 2020).
- Projections for the **southern Indian** and **southwest Pacific** basins show strong agreement among most modelling studies for a reduction in cyclone frequency (Walsh et al., 2016; Knutson et al., 2020). Large natural variability in these regions suggests the projected reductions in at least some models are not statistically significant (Walsh, 2015).
- Reductions are also projected for the **North Indian** (Mohapatra et al., 2015), **tropical Atlantic**, and coastal **East Pacific** basins (Diro et al., 2014).

**Some models project changes in locations of storm activity, such as a poleward migration of the latitude of maximum tropical cyclone intensity** in the western North Pacific.

- In the **western North Pacific**, a poleward migration has been observed since the late 1940s. A poleward migration is projected to occur under future warming scenarios in some models (Kossin et al., 2016), further altering the regional tropical cyclone risk. By the late 21st century, under a high future emissions scenario (RCP8.5), the average latitude of storm formation is also projected to have migrated further northwards. According to a modelling study by Lok et al. (2018), the number of tropical cyclones making landfall in south China is projected to decrease, but the average intensity of those that do make landfall is projected to increase.

- In the **North Atlantic**, future warming under a medium future emissions scenario (CMIP3 SRES-A1B) is projected to result in a reduction of straight moving tropical cyclones, with storm tracks curving to stay over the open ocean instead, according to Colbert et al. (2013). This results in a reduction of −1 to −1.5 cyclones per decade making landfall in the southern Gulf of Mexico, Caribbean, and central America. A similar-sized increase was projected for cyclone landfall over the U.S. mid−Atlantic region (Liu et al., 2017; 2018; Wright et al., 2015).

**Future projections of the forward motion (translation speed) of tropical cyclones is uncertain**, with different studies projecting both increases and decreases. Future research is required to reach consensus on the impact of human−caused warming on translation speed (Knutson et al., 2020).

- In the **Gulf of Mexico**, one study projects an increase in summer northward winds and a 10% increase in translation speed, as well as an increase in the rate of tropical cyclone landfall over Texas (Hassanzadeh et al., 2020).
- In the **North Atlantic**, a high-resolution regional model under a high future emissions scenario (RCP8.5) projected a reduction of translation speed by the late 21st century, compared to recent climate (Gutmann et al., 2018). Another study projected decreasing TC translation speed, but this was projected mainly in Northern Hemisphere midlatitudes, for example, off the east coast of North America, where TCs are typically recurving and accelerating in the westerlies (Zhang et al., 2020).

**The rainfall−rate of tropical cyclones is projected to increase with human−caused global warming, and this is expected to exacerbate tropical cyclone flood risk** (Wright et al., 2015; Kossin, 2018; Knutson et al., 2015; Liu et al., 2019). In a multi-model assessment of tropical cyclones, under a +2°C warming scenario, near-storm rainfall rates are projected to increase globally by an average of +14% (+6 to +22%), with the rainfall rate in many individual basins projected to incur similar increases (Knutson et al., 2020). There is general consistency among models in the sign of this projection, globally and at the basin scale. Projected increases in tropical cyclone rainfall rates match, or slightly exceed, thermodynamic expectations of about 7% per degree Celsius of climate warming (Kodama et al., 2019; Knutson et al., 2015; 2020; Liu et al., 2019). This expectation is based on the Clausius−Clapeyron relation, which implies that a tropical atmospheric column will typically hold about 7% more water vapor per degree Celsius increase of surface temperature. Projected rainfall rate increases in excess of purely thermodynamic expectations may be connected to the projected increase in storm intensity associated with warming (Liu et al. 2019).

- In the **North Atlantic**, an +8 to +17% increase in rainfall rate was projected for U.S. landfalling tropical cyclones under a medium future emissions scenario (SRES−A1B & RCP4.5) (Wright et al., 2015) and a +24% increase using a high future emissions scenario (RCP8.5) with a high-resolution convection−permitting regional model (Guttman et al., 2018).
- In the **western North Pacific**, studies have projected a +5 to +7% increase in rainfall rates of typhoons occurring in a warmer climate (Wang et al., 2014; 2015).

**Tropical cyclone size changes with climate warming could also be important for future impacts because TC size is an important factor in storm destructiveness**. However, model projections of future changes in TC size changes vary across existing studies, leading to low confidence at present in these projections (Knutson et al., 2020).

John Middelkoop – Unsplash.com

## Storm Surge Impacts

**Continued sea level rise will result in more severe storm surge inundation and flooding, all else being equal. Flood risk will likely be further exacerbated by higher tropical cyclone intensities and increased tropical cyclone rainfall rates, while uncertain changes in future tropical cyclone frequency and storm tracks could reduce or further exacerbate these risks.** In coastal regions, higher storm inundation levels will be among the greatest potential impacts of future tropical cyclones under climate change, where the combination of likely increased storm intensity and rainfall rates and continued sea level rise will act to increase inundation risk of low−lying, unprotected regions (Walsh et al., 2019; Woodruff et al., 2013; Marsooli et al., 2019; Knutson et al., 2020). However, the net influence of storm frequency change and storm track changes on coastal surge risk is unclear: fewer tropical cyclones may occur, as simulated in the majority of studies, including a possible decrease even in category 4-5 tropical cyclones, as simulated in some studies (Knutson et al., 2020). If such changes materialised, they would act to reduce surge risk, offsetting to some degree the increased risk due to sea level rise and the likely increases in storm intensities and precipitation rates.

- In the **North Indian Ocean**, one modelling study suggests a possible +20% or +30% increase in storm surge height along the Indian coast, depending on future warming scenario (Rao et al., 2020a; 2020b).
- In the **western North Pacific**, storm surge levels in the Pearl River Delta region are projected to

increase by +8.5% by the late 21st century (2075−2099) under a high future emissions scenario (RCP8.5) (Chen et al., 2020). When combined with sea level rise and local geologic displacement, storm inundation levels may increase by approximately 1m.

- In the **North Atlantic**, Marsooli et al. (2019) project that the combined effects of sea level rise and tropical cyclone storm surge by the late 21st century (2070−2095), under a high emissions scenario (RCP8.5), will result in the historical 100−year flood level occurring every 1−30 years in the Gulf of Mexico and southeast Atlantic coast, and every year in the mid−Atlantic coast. Little et al. (2015) found that climate models that projected the greatest 21st-century increase in sea level in the North Atlantic also projected the greatest increase in Atlantic hurricane activity, leading to a further increased probability of extreme storm surge outcomes over the 21st century.
- In the **New York City** region, the downscaling model of Garner et al. (2017) projected that climate change impacts on hurricanes, apart from sea level rise, has little net influence on storm surge risk in the region by 2300, as tropical cyclone tracks shifted away from landfall in the region under climate change, which offset the effect of storm strengthening. Sea level rise acted to increase storm inundation risk, all other factors equal.

## Concluding Remarks

**This ScienceBrief Review is consistent with findings of the IPCC** described in the Special Report on the Oceans and Cryosphere in a Changing Climate (Pörtner et al., 2019). Their findings relating to tropical cyclones are summarised as follows:

- "*Anthropogenic climate change has increased observed precipitation (medium confidence), winds (low confidence), and extreme sea level events (high confidence) associated with some tropical cyclones, which has increased intensity of multiple extreme events and associated cascading impacts (high confidence).*"
- "*There is emerging evidence for an increase in annual global proportion of Category 4 or 5 tropical cyclones in recent decades (low confidence).*"
- "*Increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal hazards (high confidence).*"

**In addition, this review is also consistent with the findings of the WMO Task Team on Tropical Cyclones and Climate Change**, as described in two assessment reports, focusing on detection and attribution of past tropical cyclone activity (Knutson et al. 2019) and projections of TC changes with future global warming (Knutson et al., 2020).

## 2020 in a climate change context:

**The 2020 North Atlantic hurricane season was active, with the largest number of named storms on record (30) and an above-average number of intense hurricanes (six Category 3-5, five Category 4-5 hurricanes). The extreme number of named storms, reaching Iota, included many that were of relatively short duration; eight storms lasted as a tropical storm or stronger for only two days or less. Short-duration storms have likely had a spurious increase due to enhanced monitoring and reporting (Landsea et al., 2010, Villarini et al., 2011); however, 22 long-duration storms is still more than any year since 1878, as reported in Landsea et al. (2010). Thus, even when focusing on longer-duration storms, 2020 appears to be the year with the most named tropical storms since the late 19th century. 2020 had many major hurricanes (six), but this is not unprecedented. 2005 had seven major hurricanes, and other years with six major hurricanes include 2017, 2004, 1996, 1950, 1933, and 1926.**

**Observing more intense hurricanes is qualitatively consistent with the expected impact of greenhouse gas-induced warming on intense tropical cyclones (e.g., Bhatia et al., 2018; Murakami et al., 2020; Knutson et al. 2020) and continues a recent multi-decadal increase in intense and rapidly intensifying hurricane activity (e.g., Bhatia et al., 2019; Kossin et al., 2020). However, this enhanced activity is also consistent with a number of other coincident climate drivers, including a contribution from the ongoing La Niña event of 2020, internal decadal climate variability (e.g., Yan et al., 2017), and the impact of reductions in aerosols over the tropical Atlantic in recent decades (e.g., Dunstone et al., 2013; Villarini and Vecchi, 2013; Murakami et al., 2020). A quantitative partitioning between the various climate factors impacting the number of major hurricanes and rapidly intensifying hurricanes in the Atlantic during 2020 remains to be done, and with multiple plausible contributors to an active hurricane season, the enhanced hurricane activity of 2020 cannot be attributed to anthropogenic climate change at this stage.**

**The full Brief and references since 2013 can be explored on** [sciencebrief.org/topics/climate-change-science/cyclones](sciencebrief.org/topics/climate-change-science/cyclones).

### References prior to 2013


- Bindoff, N.L. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis*. WG I, Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter10_FINAL.pdf

- Emanuel, K. A., 1987: The dependence of hurricane intensity on climate. *Nature*, 326, 483–485, https://doi.org/10.1038/326483a0
- Landsea, C., 2005: Hurricanes and global warming. *Nature* 438, E11–E12, https://doi.org/10.1038/nature04477
- Landsea, C. et al. 2010: Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts, *Journal of Climate*, 23 (10), 2508–2519, https://doi.org/10.1175/2009JCLI3034.1
- Pörtner, H.-O. et al. (eds), 2019: IPCC Special Report on the ocean and cryosphere in a changing climate, https://www.ipcc.ch/srocc/
- Vecchi, G. A., & Knutson, T. R., 2011: Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878–1965) using ship track density. *Journal of Climate*, 24 (6), 1736-1746, https://doi.org/10.1175/2010JCLI3810.1
- Villarini, G., & Vecchi, G. A., 2012: Twenty-first-century projections of North Atlantic tropical storms from CMIP5 models. *Nature Climate Change*, 2 (8), 604-607, https://doi.org/10.1038/nclimate1530



**Suggested citation.**

Knutson, T. R., Chung, M. V., Vecchi, G., Sun, J., Hsieh, T-L. and Smith, A. J. P., 2021: ScienceBrief Review: Climate change is probably increasing the intensity of tropical cyclones. In: Critical Issues in Climate Change Science, edited by: Corinne Le Quéré, Peter Liss & Piers Forster.

https://doi.org/10.5281/zenodo.4570334



**Acknowledgements.**

ScienceBrief Reviews are supported by the European Commission via projects CRESCENDO, 4C, and VERIFY(grants no. 641816, 776810, 821003).

This review was supported in part by NOAA/OCO (award NA18OAR4310418), the Cooperative Institute for Modeling the Earth System (CIMES; NOAA award NA18OAR4320123) at Princeton University, NASA (award 80NSSC19K0482), and the Carbon Mitigation Initiative (CMI) at Princeton University's High Meadows Environmental Institute.

The authors thank K. Emanuel, B. Reichl and Y. Sun for comments on an earlier version of this Review.


**About ScienceBrief.**

ScienceBrief is a web platform that helps make sense of peer-reviewed publications and keep up with science. It is written by scientists. ScienceBrief Reviews support transparent, continuous, and rapid reviews of current knowledge.

ScienceBrief is supported by the University of East Anglia (UEA). The platform was initiated with funding from the UK NERC International Opportunities Fund (NE/N013891/1). The ScienceBrief platform is developed by Anthony Jude De-Gol.

sciencebrief.org

news.sciencebrief.org