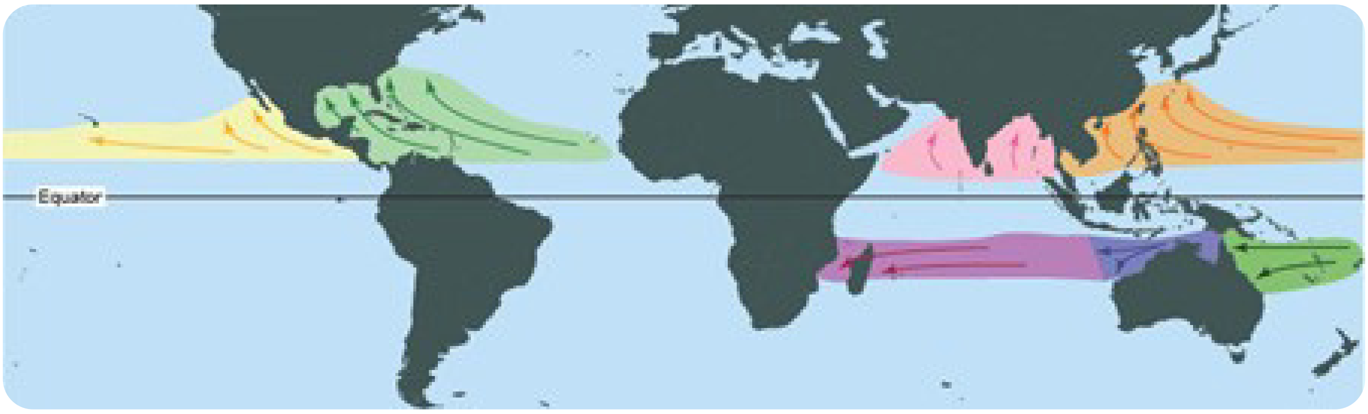
NOTE 2c

Tropical Cyclone Risk Modeling

Windstorms are often characterized as one of three types: tropical cyclones (e.g., hurricanes, typhoons), extratropical storms (e.g., European winter storms, blizzards), and severe convective storms (e.g., tornados). This note focuses on tropical cyclones.

Tropical cyclones are intense, rapidly rotating storms that originate over tropical oceans (Figure 1) and are typically characterized by strong winds.[1] They occur in the Pacific, Indian, and North Atlantic Oceans. While they can occur all year long, their peak of activity is generally between late May and early December in the Northern Hemisphere, and between late October and early May in the Southern Hemisphere. In addition to wind hazards, tropical cyclones can trigger cascading hazards such as storm surge (coastal inundation), rainfall-induced flooding, and rainfall-induced landslides. These storms can cause impacts to people, assets, and governments; and climate and disaster risk financing (CDRF) mechanisms may be needed to build financial resilience to risks that cannot be cost-effectively mitigated or avoided.

Figure 1: Tropical cyclone formation areas (colored zones with arrows)



Source: National Oceanic and Atmospheric Administration, "Tropical Cyclone Introduction," February 24, 2025, https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction.

Tropical Cyclone Modeling Approach

Like risk models for other natural hazards, tropical cyclone risk models combine modules on hazard, exposure, vulnerability, and loss (see Note 2 on catastrophe risk modeling for more details).

[1] See National Oceanic and Atmospheric Administration, "Tropical Cyclone Introduction," February 24, 2025, https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction. Please note that tropical cyclones cannot form within approximately 5 degrees latitude from the equator. This is due to the underlying physics of tropical cyclone formation; the Coriolis force that causes cyclones to spin is not strong enough within the latitudes closest to the equator.

The hazard module includes:

a) A model of tropical cyclone occurrence (i.e., tropical cyclone tracks). Tropical cyclone models make it possible to stochastically simulate cyclone tracks over thousands of years. Traditional hazard models tend to use historical track records (parent tracks) as the basis for the stochastic simulation.[2] These parent tracks (based on historical events) are then used to derive potential stochastic events using statistical and physics-based principles.

b) Functions to estimate the severity of wind speed at any given location based on these tracks. Wind fields are estimated at any location using windstorm characteristics, but also taking into account land use and local topography (e.g., by using high-resolution satellite data and digital elevation models). Attention to land use and topography is particularly important in urban areas, as high concentrations of buildings can have an impact on wind variability.

Some hazard models also integrate a component to account for cascading hazards such as storm surge and rainfall-induced floods. Most storm surge models simulate the wave height at the coastline as a function of windstorm intensity. More sophisticated models also simulate inland inundation. Rainfall-induced flooding is typically based on hydrological models (runoff models) and estimated streamflow (also called discharge) from meteorological data (mainly precipitation and temperature) and catchment characteristics (see Note 2a for more information on flood modeling).

The ***exposure*** module uses detailed inventories of built assets and population. It consists of a detailed inventory of assets, including location details (e.g., latitude and longitude, street address), replacement cost, and characteristics such as construction type, year built, number of stories, roof type, basement, etc.

Finally, the ***vulnerability*** module uses available knowledge of the damage to various types of buildings zand infrastructure exposed to different wind speeds and durations. It includes functions estimating potential physical damage both for wind- and water-based sub-perils. Vulnerability functions associated with wind damage are generally based on wind speed or wind gust, while vulnerability functions associated with water damage can be estimated using wave height (in the case of storm surge), water depth (for both storm surge and rainfall-induced flood), or even water flow (although the latter is less commonly considered).

The combination of these modules enables the probabilistic estimation of total (ground-up) losses, which can be translated into government or insured losses when financial conditions are applied (e.g., limits, deductibles).

[2] An example of public domain historical tracks can be found in the International Best Track Archive for Climate Stewardship (IBTrACS); see the National Centers for Environmental Information website at https://www.ncei.noaa.gov/products/international-best-track-archive.

Novel Modeling Approaches

Traditionally, stochastic tropical cyclone catalogs simulate probable losses based primarily on historical records (e.g., events occurring in the past century). However, to account for the effects of climate change, novel methods using a forward-looking approach have recently been developed. Leveraging both physics-based simulation of atmospheric properties and machine learning, these models simulate possible future windstorm tracks and incorporate climate trends to estimate cyclone frequency and severity over the medium to long term (next 10 to 50 years).

Similarly, the increasing use of real-time Earth observations and physics-based global precipitation models (GPMs) enables a more accurate estimation of probable precipitation under present and future climatic conditions.

Implications for Disaster Risk Financing and Insurance

The modeling of possible tropical cyclone scenarios using the approach above enables the development of a loss curve (risk profile) estimating likely losses as a function of annual probability—either for individual assets or for a whole portfolio (e.g., buildings, people, crops, etc.). Such modeling is crucial to inform the development of a disaster risk financing strategy (see Note 4).

Tropical cyclone risk modeling is crucial to select appropriate DRFI instruments for tropical cyclone risks. For example, risk modeling is used to design tropical cyclone insurance policies and their associated pricing. Tropical cyclone modeling may also be used to design parametric triggers; see Box 1 for the application of modeling to parametric insurance in the Pacific.

Since it is possible to forecast tropical cyclones a few days in advance, associated risk models can also be used for anticipatory action (impact-based forecasting) and for designing early action triggers to provide rapid payouts.

Box 1.
Tropical Cyclone Risk modeling and application for parametric insurance in the Pacific region

Many Pacific island countries are highly vulnerable to tropical cyclone, including (but not limited to) Fiji, Niue, Tonga, Samoa, the Cook Islands, and Vanuatu. To better understand tropical cyclone risk in the region and inform risk financing decisions, the World Bank funded the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI). This initiative collected exposure data, created inventories of built assets and population, and compiled country-specific information on hazards and risks (within the Pacific Risk Information System [PACRIS]).

In 2011, the initiative developed a stochastic risk model using the traditional approach discussed above. In 2024, the World Bank worked with the Pacific Catastrophe Risk Insurance Company (PCRIC)—the regional risk pool—and private sector experts to develop risk profiles of people impacted, using updated hazard and risk information and the novel physics-based approach discussed above.

PCRIC used this updated risk information to design parametric insurance products for tropical cyclone that would provide rapid payouts to sovereign governments in the aftermath of disasters and thus support relief efforts. For all products, PCRIC used the modeled risk profiles to estimate average annual losses and to price the products. The modeled losses were compared with historical losses to minimize basis risk (i.e., the risk that payouts are inadequate and are not triggered when countries experience damage).

Several parametric tropical cyclone products have been developed. The first product includes an event occurrence–based trigger called "modeled loss" and uses the PCRAFI model. Following an event, the reported cyclone track and wind speed intensities are matched with the closest hazard event in the model database. The hazard event is then superposed on the building exposure data, and damage is assessed as a function of hazard intensity (e.g., wind speed) and building characteristics (e.g., construction type, year built, number of stories). A payout is provided if the resulting damage exceeds a threshold pre-agreed with the government.

Such a modeled loss can be calculated rapidly (within a few days) and is generally associated with relatively low basis risk (i.e., payouts tend to be provided when actual damage has occurred). However, it is highly reliant on the quality and robustness of the model.

PCRIC developed a second parametric product in 2024 using more recent risk profiles. This new product uses a parametric index of people impacted, since these metrics are more closely connected to emergency losses than building damage. This index is based on wind field and the number of people located in each impacted area. To account for disproportionate effects, it is weighted depending on the remoteness of the impacted island and the cyclone category. A payout is provided if the index exceeds a pre-agreed threshold.

Finally, PCRIC designed a third and simpler type of product, called a "Cat in a Box." This product triggers based solely on the track and category of the tropical cyclone. It does not consider damage. A payout is provided if the event exceeds Category 3 within a pre-agreed geographic area (e.g., buffer zone around the island). This type of trigger is more transparent than others, and simpler to communicate to stakeholders. However, it is associated with relatively high basis risk, since the trigger is not connected with reported or estimated damage. For example, a Category 2 event may cause damage but will not trigger a payout since it does not reach the pre-agreed (Category 3) threshold.

FAQs

What are the key limitations of windstorm risk models?

Damage information remains scarce and sporadic for a number of assets, in particular for critical infrastructure networks. In many countries, such damage information is insufficient to calibrate and validate models appropriately. Therefore, vulnerability assessments are generally associated with large uncertainties, and these should be taken into account by decision-makers.

In addition, many existing tropical cyclone risk models estimate the likelihood and severity of events based on recorded historical tracks. This situation is slowly changing with the development of novel approaches that use machine learning to simulate possible future scenarios.

Finally, windstorms have cascading effects and generally trigger other hazards such as storm surge, rainfall floods, and rainfall-induced landslides. Although model adjustments might be applied to account for these cascading perils, research analyzing the compound impact of cascading hazards is still in its infancy.

How do I know if I can trust a tropical cyclone risk model?

While tropical cyclone risk models have high degrees of potential bias and uncertainty due to the complexity of the peril being modeled, they are still representations of the physical world and can therefore be tested at various levels to ensure they provide trustworthy risk metrics. The approach to such testing is similar to that for other perils in that the model needs to be calibrated and validated against historical data. This process can be particularly complicated in emerging market and developing economies (EMDEs), where historical data are often limited.

Where data are available, the model needs to be validated both at an individual-component level (for example, by comparing modeled and historical data for wind speed, etc.) and at the output level (for example, by comparing population affected in historical events to population estimated by the model).

Reading List

Grossi, P., and H. Kunreuther, eds. 2005. Catastrophe Modeling: A New Approach to Managing Risk. Springer.

National Oceanic and Atmospheric Administration. 2025. “Tropical Cyclone Introduction.” February 24, 2025. https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction#:~:text=A%20tropical%20cyclone%20is%20a,a%20tropical%20cyclone%20can%20form.

Willis Towers Watson. 2024. “Safeguarding Your Organisation: Effective Strategies for Windstorm Risk Management.” July 4, 2024. https://www.wtwco.com/en-us/insights/2024/07/safeguarding-your-organization-effective-strategies-for-windstorm-risk-management.