# Project Severe Weather Archive of the Philippines (SWAP). Part 1: Establishing a Baseline Climatology for Severe Weather across the Philippine Archipelago

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Friday 6$^{\text{th}}$ September, 2024

**Abstract**

Because of the rudimentary reporting methods and general lack of documentation, the creation of a severe weather database within the Philippines has been difficult yet relevant target for climatology purposes and historical interest. Previous online severe weather documentation i.e. of tornadoes, waterspouts, and hail events, has also often been few, inconsistent, or is now defunct. Many individual countries or continents maintain severe weather information through either government-sponsored or independent organizations. In this case, Project SWAP is intended to be a collaborative exercise, with clear data attribution and open avenues for augmentation, and the creation of a common data model to store the severe weather event information will assist in maintaining and updating the database in the Philippines. For this work, we document the methods necessary for creating the SWAP database, provide broader climatological analysis of spatio–temporal patterns in severe weather occurrence within the Philippine context, and outline potential use cases for the data. We also highlight its key limitations, and emphasize the need for further standardization of such documentation.

## 1 Introduction

Convective storms such as thunderstorms are capable of producing large hail (*yelo*), extreme rainfall (*Labis na pag-ulan*), and tornadoes/waterspouts (*buhawi/ipo-ipo*). It can be destructive to man-made structures and can lead to loss of life, especially in urban areas with high population, building density, and variable quality. This is an important challenge for meteorologist as such forecasts require knowledge of the environment of the storms, which can be obtained from radiosonde measurements or numerical weather prediction models. However, tallying the impacts of each severe weather events (SWEs) that occurred poses yet another challenge due to the problems associated with non-meteorological effects in data collection [1], which is why the approach to data acquisition needs to be standardized to reduce potential error sources [2, 3].

Archives of SWEs, mostly on tornadoes, occurrence are currently spread among individual countries and regional research groups, with varying quality, standards, and temporal coverage. Thus, it is difficult to draw conclusions about the worldwide spatial or temporal distribution of tornado frequency or strength. Efforts to estimate a global climatology have been made, notably by Fujita [4] and Goliger & Milford [5], but relied on fragmented and sometimes contradictory sources. The more recent European Severe Weather Database (ESWD), published by the European Severe Storms Laboratory [ESSL; 6], has been used to estimate tornado climatologies for Europe [7]. This dataset is now integrated well to the global archives by Maas et al. [8] and their Tornado Archive (TA) with over 100,000 tornadoes tallied.

The production of an official, organized database of extreme weather reports is essential to identify the nature of these phenomena [9]. An inventory of events is the first step to identify threats, and it is valuable information for planning and insurance matters [9]. For this reason, several countries and regions in the world have generated severe weather and tornado databases, including China [10], Italy [11], Portugal [12], the Czech Republic [13], the British Isles [14], and the USA [15], among others. These databases are mainly supported and maintained by their national agencies, such as national meteorological services [e.g. 16–18] and, in some other cases, as part of academic projects [e.g. 19, 20].

Similarly, extensive climatologies have been conducted on the incidence of waterspouts in Europe and North America [21]. In Catalonia, Spain, the information obtained from social networks was essential to improve the climatology of tornadoes and waterspouts. It led to a better understanding of the frequency and distribution of waterspouts and severe weather [22]. The relatively high incidence of waterspouts around the Florida Peninsula led to an attempt to predict these events by applying a statistical model that considers a significant number of variables [23]. The regional predictions of the model on the probability of waterspout incidence were better than some of the applied indices. In summary, research on waterspouts has become relevant in the last decade.

Furthermore, due to the significant importance of hail climatology research, in situ measurement at weather stations, rawinsonde measurements, and several kinds of remote sensing data, such as radar and satellite, have been used to analyze the temporal and spatial distributions of hails across different continentals and countries of the world [24]. There are also several studies about the climatology of hail day [25], hail frequency and size [26], large hail [27], and the potentially influential factors of hailstorms [28] in China in recent decades collected and provided by the National Meteorological Information Center.

Besides these professional observation datasets, social databases had also been used to demonstrate the characteristics of hail distributions, such as news reports, disaster addresses from insurance companies, records of the agriculture and housing industry, and statistical yearbooks. Tuovinen et al. [29] investigated the severe hails in Finland by collecting newspaper, storm spotter, and eyewitness reports in 70 years. The ESWD which is a database of SWEs reported from crowdsources in 2002 [6]. The Tornado and Storm Research Organization (TORRO) holds a website to let voluntary persons upload severe weather reports such as tornadoes, lightning and damaging hailstorm on the island of Britain [30]. However, damage quantification and characterization are more problematic due to the meteorological context in which each case occurs, e.g. events occurring during a severe storm. Such issues need to be considered to establish the limitations of baseline climatology within the country based only on documentary evidence.

This paper establishes the first, simple database for SWEs and a baseline climatology that include tornadoes, waterspouts, and hailstorms based on data compiled from hemerographic sources and personal communications, which contributes to the knowledge of climate types in the Philippines through Project Severe Weather Archive of the Philippines (SWAP). Now in its 2nd Data Release (labelled as SWAP DR2), we utilized the compiled data to investigate the distribution of severe weather occurrence and record-keeping, as well as the interdependence between the two. We present the compiled database as-is, acknowledging known biases existing therein. As the true severe weather climatology is fundamentally intertwined with the historical context surrounding its observation, we analyze trends in our database with both in mind.

# 2 Methodology

## 2.1 Data Sources: Tornado, Hail, and Waterspout database

The documentary information was collected from official and non-official sources. The first type of data contains reports from the Department of Science and Technology-Philippine Atmospheric, Geophysical, Astronomical Services Administration (DOST-PAGASA)[1], National Disaster Risk Reduction and Management Council (NDRRMC)[2], Department of Social Welfare and Development and their Disaster Response Operations Management, Information and Communication sector (DSWD-DROMIC)[3], and local civil protection units distributed throughout the country. These are the official sources that were also included in the archive.

Information not included in any major available dataset was obtained from other reliable sources as indicated in De Coning and Adam (2000), which were used both to add new tornadoes and fill in missing data for existing ones. Doing so is quite time-consuming, as a vast number of different sources are involved, and the effort to find and parse them is continuing. The non-official sources include eyewitness reports, media news/newspapers[4], and information from social media platforms (e.g. Twitter, Facebook, and YouTube). Such documentary data were exhaustively evaluated to identify fake events. The updated database includes, as far as possible, information about the type of event, date, hour, location (latitude-longitude coordinates), tags e.g. tornadoes, hails, elevated, high-based etc., photographs and videos through the documentation column, and other relevant information. To regulate the process, every tornado in the database was given a mandatory "Source" attribute which either referred to one of our major datasets or another source (usually a web link). We

[1] Available: https://www.pagasa.dost.gov.ph/
[2] Available: https://ndrrmc.gov.ph/
[3] Available: https://dromic.dswd.gov.ph/
[4] Most of these newspapers are available at the National Library of the Philippines (NLP) upon request. Same goes to other official sources such as those from DOST-PAGASA whose documents are very difficult to find in the internet.

designate these sources whether they are still functioning (Active), preserved somewhere else like a library (Preserved), or no longer accessible or maintained (Inactive).

The official record on damage to public and residential infrastructure is limited to only a few tornadoes e.g. the Manila City and Bacolor, Pampanga Tornado events. Despite the scarcity of information about the damage caused by each tornado or waterspout in the database, a classification using, for instance, the Enhanced Fujita Scale (EF) was carefully considered, but should be updated upon further review. Although there are inconsistencies to the details provided by eyewitnesses and media news, in addition to the lack of instrumentation for immediate forecasting, the structural differences in the buildings in Philippines compared to those considered in the EF scale, the limited capacity to conduct field investigations, and the nonexistence of a meteorological observer network, we intend to provide initial ratings to these events by examining texts and the damages it caused through photographic/videographic evidences.

## 2.2 Spatial Analysis and Smoothing

Although Project SWAP, as it currently stands, includes more than half a thousand SWEs, our database is necessarily incomplete, and likely unrepresentative despite covering from 1969-Present due to the lack of other tallied SWEs within the project. A spatial smoother was employed to account for shortcomings in our samplings, and to provide a preliminary climatological estimate of severe event. A non-parametric multivariate kernel density estimation (KDE) was employed to identify and examine hazard patterns/hotspots on a 11 km x 11 km horizontal grid using a kernel function [31]. The general equation for a multivariate KDE with $\geq$ 2-dimensions given multivariate data set is expressed as;

$$\hat{f}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K\{\frac{1}{h}(x - x_i)\} \tag{1}$$

Where $K$ is the kernel function, in this study, a symmetrical Gaussian kernel was chosen shown by;

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-t^2/2} \tag{2}$$

Meanwhile, a cross validation was utilized to identify the most optimal bandwidth $(h)$[5], the other variable in Equation 1, by exhaustively considering parameter conditions, assuming with fixed metric and kernel function i.e. Euclidean points and Gaussian. This is conducted through $k$-fold cross validation with 100 iterations for each 10000 candidates to each of our array of data. Though, a very large grid can be time-consuming to search through. Typically, the GridSearchCV (GSCV) offers such capability having 3 compulsory parameters; the estimator, grid of parameters, and number of cross validation ($k$), and is widely used on machine learning for hyperparameter optimization. However, another way to consider on identifying $h$ is to utilize an adaptive bandwidth with different $h$ values based on the local density of the observations under consideration [32, 33].

[5]Also known as the smoothing parameter. The resultant probability density function (PDF) is sensitive to the chosen bandwidth. One can also either use Scott's and Silvermann's estimation methods.

# 3 Data Discussion

## 3.1 Limitation of Project SWAP

**a. Number of SWEs.** Many SWEs go unreported or unrecorded, especially in areas or time periods with less infrastructure or lower population density [34, 35]. This is reflected, for example, prior to 2010s including the years 2010 and 2016, were only 2 and 8 cases were tallied to the archive, respectively. We are not sure why it is difficult to look for SWEs way back on Year 2010, but the lack of cases in Year 2016 was likely due to the August 14 Manila Tornado that occurred on the Metro, making it a standout signature, while the rest of the SWEs were concealed by the alias.

The more general increase throughout the time period is due to a combination of better access to more recent tornado records and population expansion that allowed more tornadoes to be observed. Similar patterns are present in most other datasets e.g. ESWD [6], but they are unlikely to be physical trends, and instead reflect societal growth over time. Under-reporting of the total tornado number can also occur when tornado families are judged to be individual tornadoes [36].

In historical reconstructions of tornado, hail, and waterspout events, where the best available sources are newspaper reports written by journalists rather than meteorologists, severe wind events such as microbursts can be misidentified as tornadoes. Reports of tornadic activity are also sometimes sensationalized [37]. Still, the under-reporting effects previously discussed are generally of much larger magnitude, meaning that any observed tornado count for a given region, especially in the pre-modern era, is very likely an underestimate.

**b. Tornado and Waterspout Intensity, and Hailstone Sizes.** Most of the waterspout events within Project SWAP have occurred on open waters without any damage to property. Thus, was straightforwardly rated as EF0. A tiny fraction of the waterspout events were rated as EF1 which impacted several homes made of light construction materials and shanties.

The difficult part is initially rating more than 300 tornadoes included Project SWAP. Around a half of total tornadoes were initially rated by this project as EF1, given that most of the infrastructures around the country fall under *One- or two-family residences*, *Low-rise (1-4 story) bldg.*, and both *Hard and Softwood Trees* damage indicators. A more comprehensive survey and assessment to update these initial ratings are needed in rectifying

Following the TA's guidelines [8], tornadoes for which an intensity rating is unassigned are given EFU (EF-Unknown), which the other half of the tornado reports in this project were recorded. This occurs when a tornado is confirmed (e.g., visually), but no damage is found [38]. In other cases, tornadoes may be rated EFU because there were no damage assessment conducted by professional surveyors, and in some databases e.g. León-Cruz et al. [39] and National Institute of Water and Atmospheric Research [40], the tornadoes in this category are the majority. While NCEI/SPC until 2016 rate tornadoes that did not cause observable damage as EF0.

Table 1: Distribution of documented SWEs based on the damage and diameter scale adopted.

| EF Scale | No. of Tornadoes | No. of Waterspouts | Hail Scale | No. of Hail events |
|---|---|---|---|---|
| EFU | 152 | 0 | Undefined | 27 |
| EF0 | 12 | 132 | Small $\geq 1$ cm | 74 |
| EF1 | 156 | 6 | Severe $\geq 2$ cm | 18 |
| EF2 | 11* | 0 | Large $\geq 3$ cm | 13 |
| EF3 | 0 | 0 | Sig. Hail $\geq 5$ cm | 3 |
| EF4 | 0 | 0 | | |
| EF5 | 0 | 0 | | |

*Note: EF2 cases are subject to further and extensive re-evaluation, thus can be downgraded in the archive. However, we consider that some of these events are applicable to have such initial rating (e.g. 1991 Lantapan, Bukidnon Tornado that led to the signing of Proclamation No. 769).

Other avenues to provide damage estimates for tornadoes are either by adopting the International Fujita (IF) Scale developed by the ESSL [41] or developing a damage scale based on the structures suited in the Philippines. Recently, the use of the IF scale (preliminary ver.) was demonstrated and evaluated by Pucik et al. [42] by applying it to a violent tornado case in Czechia on 24 June 2021. The feedback from the surveyors has been used to improve the IF scale providing a more coherent, global framework for rating tornado and convective wind damage. Either this will be adopted by our country's national weather bureau or develop a new system depending on factors such as the unique structural characteristics found in the Philippines, the availability of data for calibration, and the practical applicability of the scale in local contexts is another subject area that is required to touch and ponder on.

Hail sizes were also estimated based on photographic and videographic evidences presented and included for this project. Most authors have indicated that stones of severe sizes have diameters greater than 2 cm [26, 43] or 2.5 cm [44]. While other authors have established the threshold at which hail becomes "large" at 3 cm [45]. A new category called "significant hail" was also introduced for cases in which the severity has been catastrophic for and in which the the diameter has reached at least 5 cm [46, 47].

Therefore, with current support from recent researches and findings, Project SWAP creates a simple hail scale that considers the initial diameter to classify the hail type as;

Small hail: $\geq 1$ cm

Severe hail: $\geq 2$ cm

Large hail: $\geq 3$ cm

Significant hail (Sig. Hail): $\geq 5$ cm

If a hail event was reported but without any traceable photographic and/or videographic evidences, then we will consider and label it as 'Undefined'. Table 1 depicts the counts of SWEs that includes tornadoes, waterspouts, and hail reports with respect to the scaling utilized on this project.

**c. Location and Coordinates.** Path widths are difficult to measure and rather unreliable at high degrees of precision—for example, exhibiting unnatural, unexplained shifts over time. Pathlength is more easily measured, but in older and even new records can suffer from underestimates, through incomplete surveying of the entire track, or overestimates, through judgment of tornado families as individual tornadoes [36] The only available and thorough tornado track being generated in the country was conducted on the August 14, 2016 EF1 Manila Tornado by stitching videographic evidences [48].

Some databases recorded all tornado paths as single point coordinates (e.g., Mexico, Argentina, China), while others included paths of two or more points (e.g., Europe, Canada, Japan). Most of these archives had a mix of both, with the proportions of each depending on the quality of observations. Furthermore, a few datasets, such as those for Argentina and South Africa, record only the town in which a tornado occurred, meaning that the coordinates listed are simply those of the town center.

That being said, we adopted a single point coordinate for this archive, resulting in some level of bias. For documented cases, e.g. Manila Tornado, the coordinates were placed on a well-known infrastructure it impacted such as hospitals, convenience stores, or schools etc. within the area of interest. However, difficult cases were tallied only on the town-level in which a tornado occurred and seen. With no single objective procedure for resolving these biases, we present the database as-is and recommend careful consideration of individual data collection methodologies in future analysis using it. We hope that tornado paths/swaths in most, if not all of the tornado cases, will be included in a future data releases and version of this archive.

**d. Sounding Profiles.** In the context of a tornado, hail, and waterspout database, these sounding profiles (Skew-T Hodograph) provide critical insights into the environmental conditions leading up to and during SWEs.

By analyzing the vertical structure of the atmosphere at various layers, sounding profiles help identify key factors such as instability, wind shear, moisture content, and temperature gradients, which are essential for understanding the potential for severe weather development. Inclusion of these profiles in the archive allows researchers and meteorologists to understand atmospheric conditions with the occurrence of tornadoes, hail, and waterspouts, enhancing predictive capabilities and stimulate this research area.

These sounding profiles were queried and analyzed through SounderPy of Gillet [49], either from observational standpoint or reanalysis analogs mainly from ERA5, or in both. Files will have the standard *csv* and a special *cm1* input formats for Cloud Model 1 simulations which will be available alongside the SWAP DR2.

## 3.2 Temporal Distribution of Severe Weather Activity

In this research, 596 reports were collected as of the SWAP DR2 increasing the documented activity considerably. Thus, the current climatology considers a total of 326 tornadoes, 133 hail events, and 137 waterspouts distributed over 500 severe weather days. SWAP DR2 currently runs from

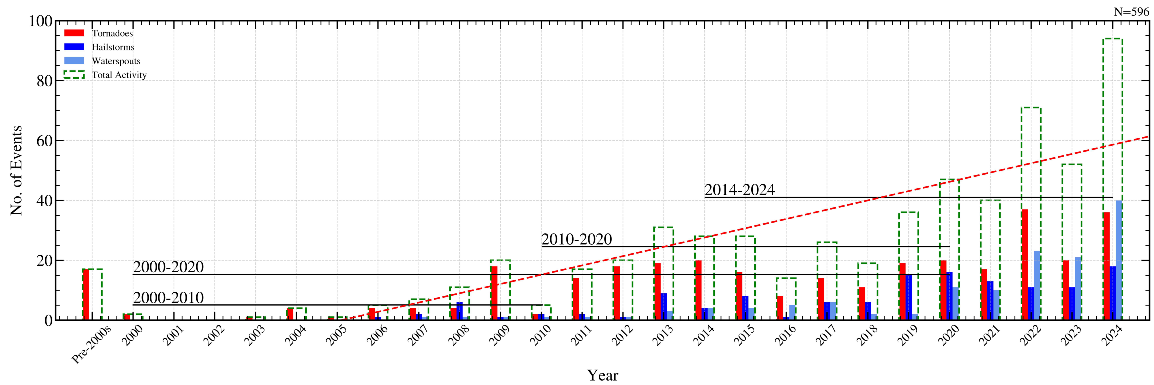


Figure 1: Annual distribution of documented tornadoes, hail, waterspouts, and total activity in Philippines for the period 1969-2024. The black solid lines indicate annual averaged activity for different periods. The red dashed line corresponds the linear $R^2$ trend from 2004-2024 period.

1969-Present, with period between 1969-1999 were called as 'Pre-2000s' due to the lack of available data (total of 17 tornadoes were documented and indexed).

The annual distribution of severe weather activity in Philippines is shown in Fig. 1. The documented events vary from 5, 15, 25, and 41 events yr-1, on average, for the periods 2000-2010, 2000-2020, 2010-2020, and 2014-2024, respectively. Reports of tornadoes have increased by 2009, so as waterspouts by 2019. The highest tornadic activity was reported in 2022, with a total of events (37 tornadoes and 23 waterspouts) while the highest total activity is on the current year 2024 (36 tornadoes, 18 hail reports, 38 waterspouts). The low number of events reported in 2010 and 2016 is attributed to the initially applied methods used in the updated database and the low density of reliable information sources. The entire tornado and waterspout dataset shows a maximum of 3 tornadoes on the same day.

In recent years there has been an incremental trend in tornado activity records in US and European databases [50, 51]. This apparent increase in the activity could be associated with the addition of more official databases and the higher public interest in events with high social impacts [3]. The same goes for the Philippines, it is inferred that such behavior is associated with enhanced social attention to these natural phenomena, the extensive use of social media networks, and increased access to internet services.

The highest severe weather activity is recorded in the warm spring and summer period, which starts between March-April with break-even counts at first, then severe weather season underway (Fig. 2a). The prolonged severe weather season, which includes tornadoes, hail events, and waterspouts, extends from May to August (Fig. 2a) winding down by September. During summer (June, July, and August, JJA), the number of documented tornadoes oscillates around 50 mo-1 (Fig. 2a), while hail events decline throughout the said period. In this season, the arrival of tropical waves and onset of southwesterly winds to Philippines [52, 53] favors the moisture transport from oceans to the continental areas. The quality of low-level moisture leading to instability and ambient wind profile i.e. wind shear are the primary ingredients for robust convective storms to initiate capable of producing severe weather hazards at such period [54–61].

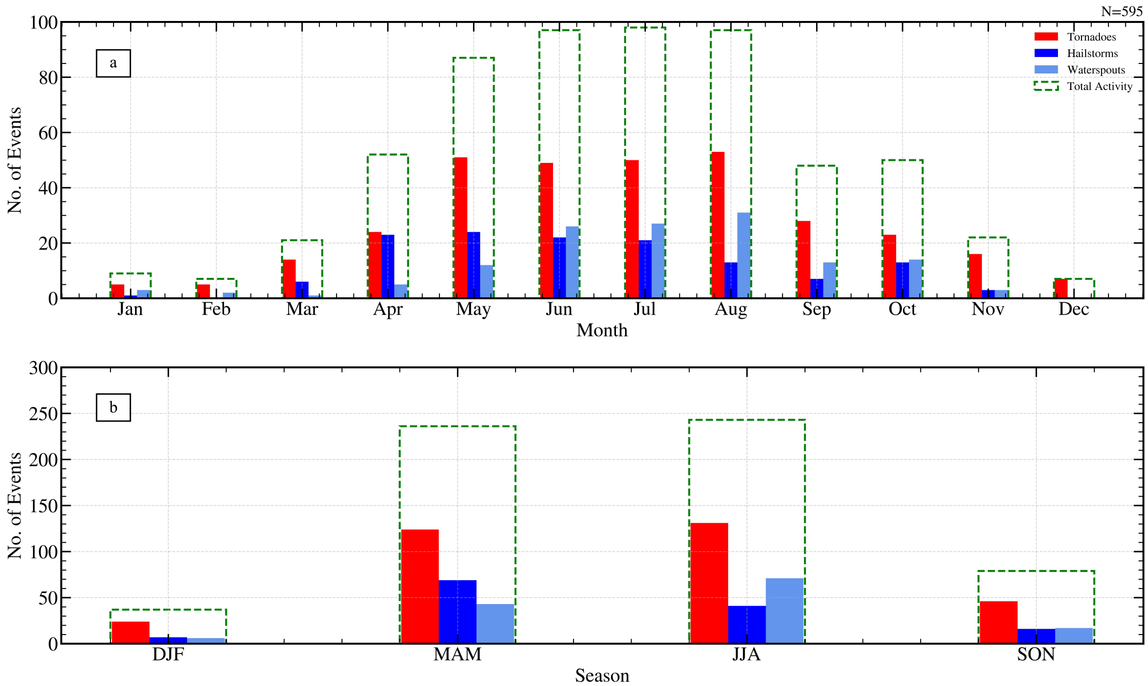


Figure 2: (a) Monthly and (b) seasonal distribution of documented tornadoes, hail, waterspouts, and total severe weather activity in Philippines.

Furthermore, the maximum registers of waterspouts are also on JJA period with August being at the highest (Fig. 2a). A lag period is evident when comparing the occurrence of the typical tornadoes and waterspouts. Interestingly, the active season of waterspouts coincides with the seasonal occurrence of tropical cyclones [39, 62]. In this sense, a relationship can be established between the tropical cyclone and the waterspout seasons. Although such an association is known in other parts of the world [63], it has not previously been recognized in the Philippine context. Further research is needed to understand in-depth the implications of tropical cyclone activity and waterspouts in the country and generally, the timing of these SWEs to other pre-existing weather systems.

Some tornadoes and waterspouts were documented in the cold winter period of December, January, and February (DJF) and in autumn (September, October, and November, SON). These events have been classified as cold tornadoes [64] and could be associated with a different dynamic than the conditions of the warm tornado season. Seasonally, the number of documented SWEs between November and February is reduces (an average of 11 SWEs yr-1) with average of 8 tornadoes yr-1, 4 hail events yr-1, and 2 waterspout yr-1 on that time span and can be related to stability conditions derived from the cold air masses from Northeast monsoon and reduced moisture fluxes into the continent.

In summary, the severe weather season kicks off in spring (March, April, and May, MAM), reaches its peak in summer (JJA) along with reported hail decreasing, accompanied by the winding down of SWEs in autumn (SON), and finishes in winter (DJF) (Fig. 2b). There is an evident difference between tornadoes, commonly reported in spring and summer, and waterspouts, which have their

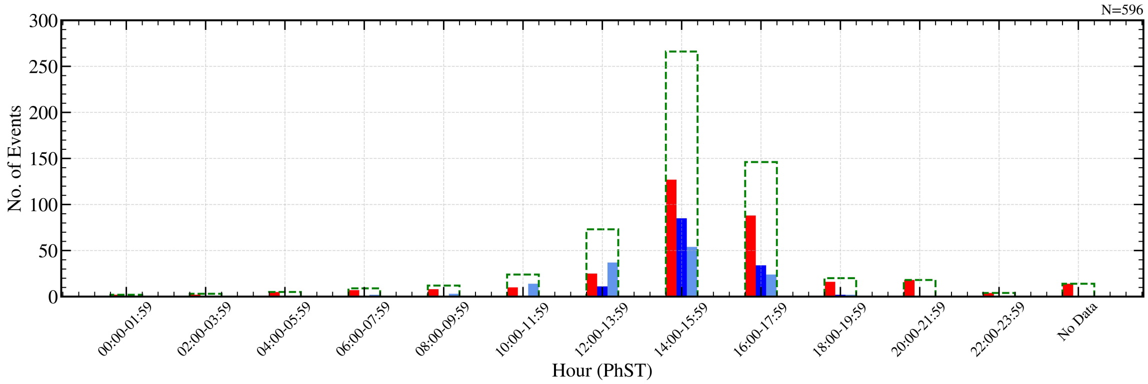


Figure 3: Diurnal distribution (local time) of documented tornadoes, hail, waterspouts, and total severe weather activity in Philippines.

active period between summer and autumn. It is inferred that waterspouts are notably influenced by tropical cyclone activity, principally along the coast of the Pacific Ocean. On the other hand, tornadoes are more related to instability conditions derived from the pass of easterly waves, moisture advection, favorable wind profile, and the late cold front activity.

The diurnal distribution (Fig. 3) shows that these phenomena are usually reported between 14:00 and 15:59 h local time (06:00-07:59 h UTC), followed by 16:00-17:59 h local time (08:00-09:59 h UTC). This behavior is associated with daytime heating and the development of air-mass thunderstorms [65], necessary for convection to persist, hailstone to develop along the updrafts, and tornadogenesis. The diurnal distribution of severe weather activity reported in Philippines matches the findings in several climatologies [10, 11, 51] and rainfall climatologies by Banares et al. [66].

## 3.3 Spatial Distribution of Severe Weather Activity

The spatial distribution of SWEs is a crucial aspect of risk management associated with this phenomenon. Geographical characteristics and meteorological conditions are features to be considered in every baseline climatology for SWEs.

Figure 4a shows the geographic distribution of all documented SWEs across the archipelago. The highest tornadic and hail activity is registered in Greater Metro Manila (GMM) area encompassing Southern Luzon, National Capital Region (NCR), and Region III (Central Luzon). While scattered area of waterspout events were seen in along the coast of Southern Luzon and even at Laguna Lake, notably with the quadruple spouts back in May 2020 at height of pandemic. On the other hand, a large swath of waterspout events coinciding with few tornadic events was recorded in the Regions VI and VII (Western and Central Visayas). Lastly, another area where significant number of tornadoes were recorded was evident along BARMM (Bangsamoro Autonomous Region in Muslim Mindanao) and Region XII (SOCKSARGEN) with North and South Cotabato, Sultan Kudarat, and Maguindanao as its favored corridor for severe weather activity, making it 2nd on the highest tornadic activity. Notably, a regional tornado outbreak occurred in South Cotabato at the afternoon of September 30, 2009 impacting several municipalities, including Koronadal City.

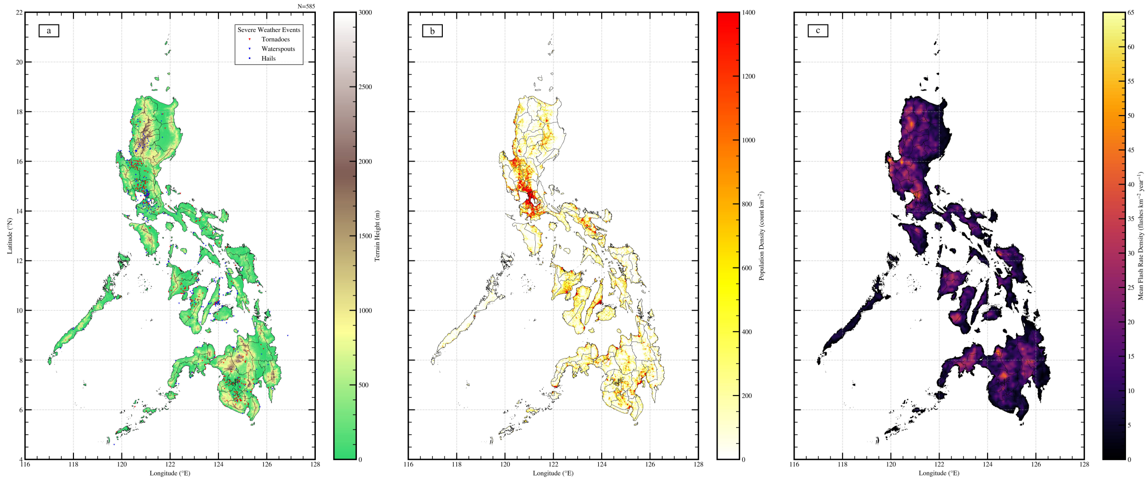


Figure 4: Geographical distribution of (a) documented tornadoes (red triangles), hail events (blue circles) and waterspouts (blue triangles) in the Philippines from SWAP DR2, (b) Philippine population density from 2020 [67], and (c) climatological mean flash rate density from LIS-TRMM [1998-2014; 68, 69]

There is a clear association between population density and documented tornadoes (Fig. 4a,b). More than 50% of the Philippine population are located where the SWEs are recorded. The Region IV-A, NCR, and Region III takes up 30%[6] of it providing a hint to the number of the documented SWEs (48%) were located in the Luzon landmass (Fig. 5). The population density effect on tornado detection is well known [35]. In addition to the population factor, the improvement in internet coverage and smartphone devices explains the increase in the number of reported tornadoes in recent years. This situation implies that the actual number of cases has been underestimated. Even though the aforementioned regions along Visayas down to Mindanao may have present topography and environmental characteristics similar to those observed throughout the GMM, the number of tornadoes, hails, and waterspouts documented is lower as seen in Figures 5.

Fig. 4c shows the climatological mean flash rate density observed by the Lightning Imaging Sensor (LIS) aboard Tropical Rainfall Measurement Mission satellite [TRRM; 68, 69]. Some studies have documented relationships among large hail, thunderstorms, and tornadoes, all of them associated with severe convective storms [e.g. 70]. The flash rate climatology presents a pattern most similar to SWE distribution across the GMM, but not for the SMOr and the SMOc. The convective processes are intensified over those regions, influenced by the upscale growth forming mesoscale convective systems [MCS; 71][7] and Southwest Monsoon [52]. These spatial variations could result from the differences in data sources. While the tornado and waterspout information comes from reports by inhabitants, the flash data come from satellite-mounted lighting sensors.

Fig. 6a,b,c displays a kernel density estimation made from `sci-kit learn` Python package with a 11 km search radius and 121 km of spatial resolution. A clear and well-defined hotspot for

[6] Based on 2020 Census of Population and Housing by the Philippine Statistics Authority.

[7] However, MCS were also reported along Mindanao's favorable area for tornadic storms to consummate. See Lagare et al. [72].

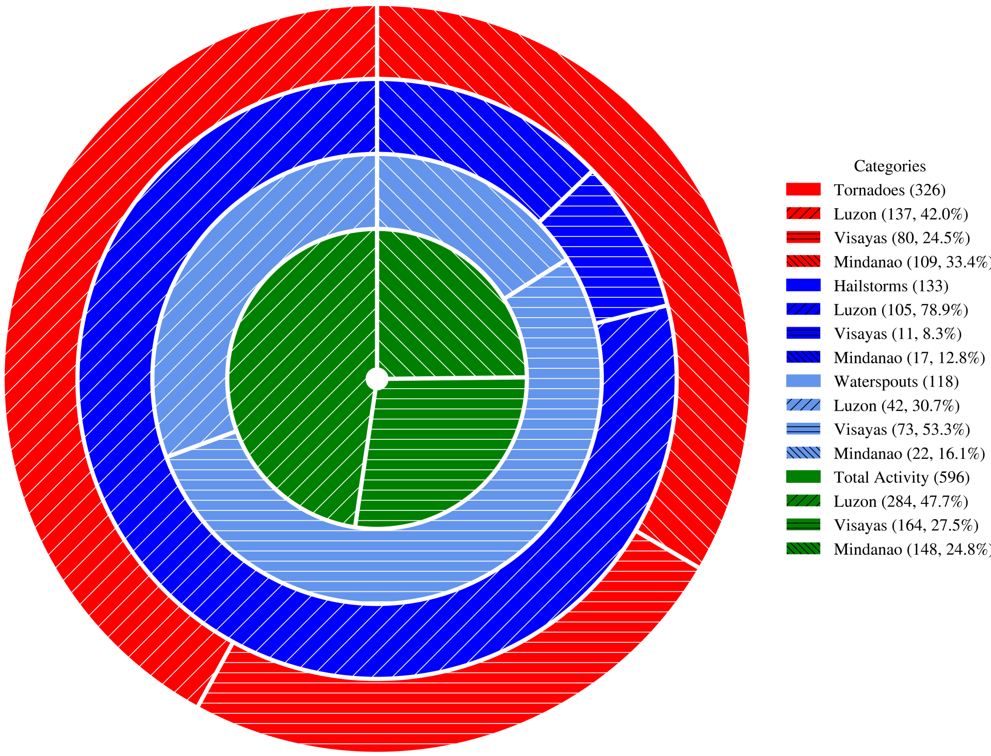


Figure 5: Percentage distribution of documented tornadoes (red), hail events (blue) and waterspouts (light blue), and total severe weather activity (green) across Luzon (//), Visayas (=), and Mindanao (\\) from SWAP DR2.

all hazards threat with bimodal distribution was latched in the GMM and greatest likelihood for severe weather at the upper-portion of Metro Manila-Pampanga area and another at Pangasinan, while another hail hotspot was denoted along Benguet region (Fig. 6a,b). A total of 137 tornado and 105 hail reports have been documented over this area i.e. ≥40% and ≥70%, respectively of the total within SWAP DR2. Some of the notable events include the first recorded tornado in the Philippines back on June 1968 by Grazulis [73], a potential EF2 tornado that tore parts of Bulakan, Bulacan on August 1998, the well-documented EF1 Manila Tornado on August 2016, the quadruplet waterspouts in Laguna Lake on May 2020, a significant 8 cm hail in Norzagaray, Bulacan on August 2021, and yet another Pampanga Tornadoes that impacted towns of Magalang and Arayat back on June 2023 and May of this year, respectively.

This specific hotspot in Luzon is surrounded by complex terrain features. In particular, to the west is form Zambales Mountain Range (ZMR) and to its east is the Sierra Madre Mountain Range (SMMR). Previous researches show that for landfalling tropical cyclones (LFTC), the complex terrain is crucial for magnifying rainfall across Luzon through orographic effects [74, 75]. Although these were applied to TCs instead, such geographic features may also be conducive for building instability favorable for occurrence of severe weather in the area both on TC and non-TC days.[8]

[8]This is most likely the case during SWM periods, as southwesterly (veering) winds blow over the ZMR. Due

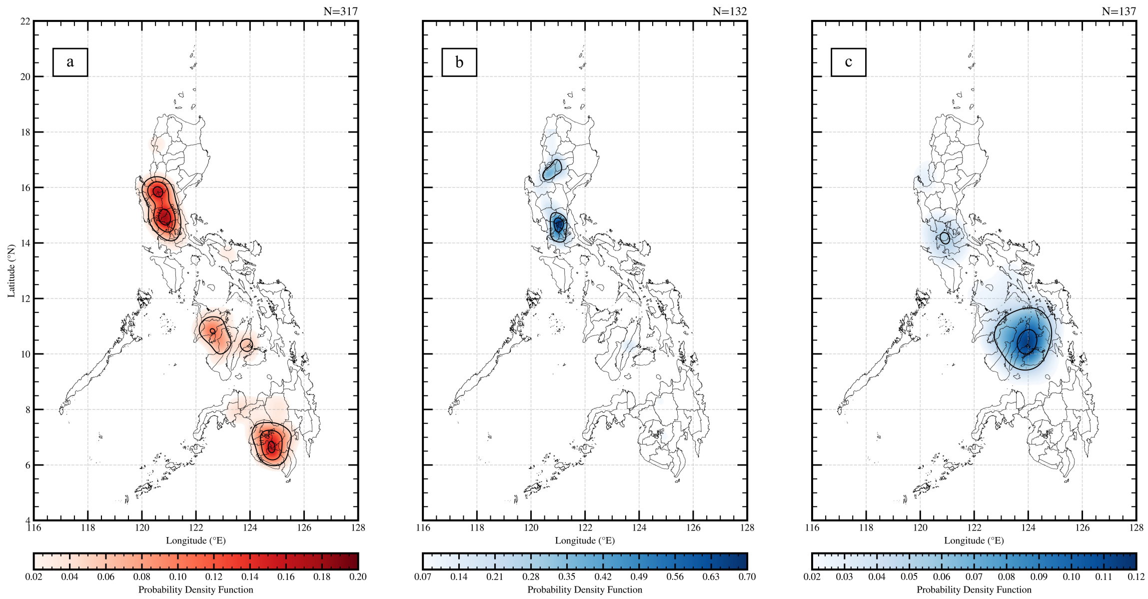


Figure 6: Kernel density estimate on a 11 km x 11 km grid of (a) tornado events, (b) hailstorm events, and (c) waterspout events from SWAP DR2. Labeled contour isoline are included at each panel. Heavier colors represents a higher SWE estimate.

In Visayas regions, two small tornado hotspots was discovered overlayed by a strong signal of waterspout events across parts of Region VI and VII shown in Figure 6a,c (as also depicted and discussed earlier). In particular, the Panay Islands, Negros Provinces, and much of Central Visayas shows a notable signature of SWEs focused along waterspouts. Two potential EF2 tornadoes were recorded in this area, both occurred in Cebu back on 2013 – one in Minglanilla and the other at Lapu-Lapu City. Meanwhile, more than 100 cases of waterspout events were documented in this area as well, which were mostly rated with confidence as EF0s. A significant portion of the waterspout reports correspond to short duration (maximum 20 min). However, with an extraordinary number of documented waterspout events in these aforementioned area of Visayas, compared to other severe weather hotspots in the archipelago, an extensive analysis is required to understand the environment surrounded by mostly bodies of water suitable for tornadogenesis and non-tornadogenesis.[9]

In Mindanao, the data on tornado hotspots highlight a significant area of increased tornadic activity ($\geq$100 tornadoes), particularly in South Cotabato extending towards North Cotabato, with a weaker influence noted in Northern Mindanao. This region stands out due to its frequent occurrence of tornadic storms, contributing to its classification as a tornado hotspot. Interestingly, this increased tornado activity is situated between two major mountain ranges: the Pantaron Mountain Range to

to conservation of potential vorticity, a lee-side cyclogenesis and its associated meso-low occurs at the backside of ZMR and seems to be the 'spark' for the Manila Tornado case as studied by Capuli [48] and so as to other SWM period/JJA/warm summer season tornadoes along the hotspot zone in Luzon. On the other hand, prevailing easterly winds conditions during MAM season and monsoon breaks that can potentially lead to severe convective storms remains understudied.

[9]Most of these visayas-located waterspouts are rotating anti-cyclonically while few cases rotate cyclonically, based on documented videos linked in SWAP DR2.

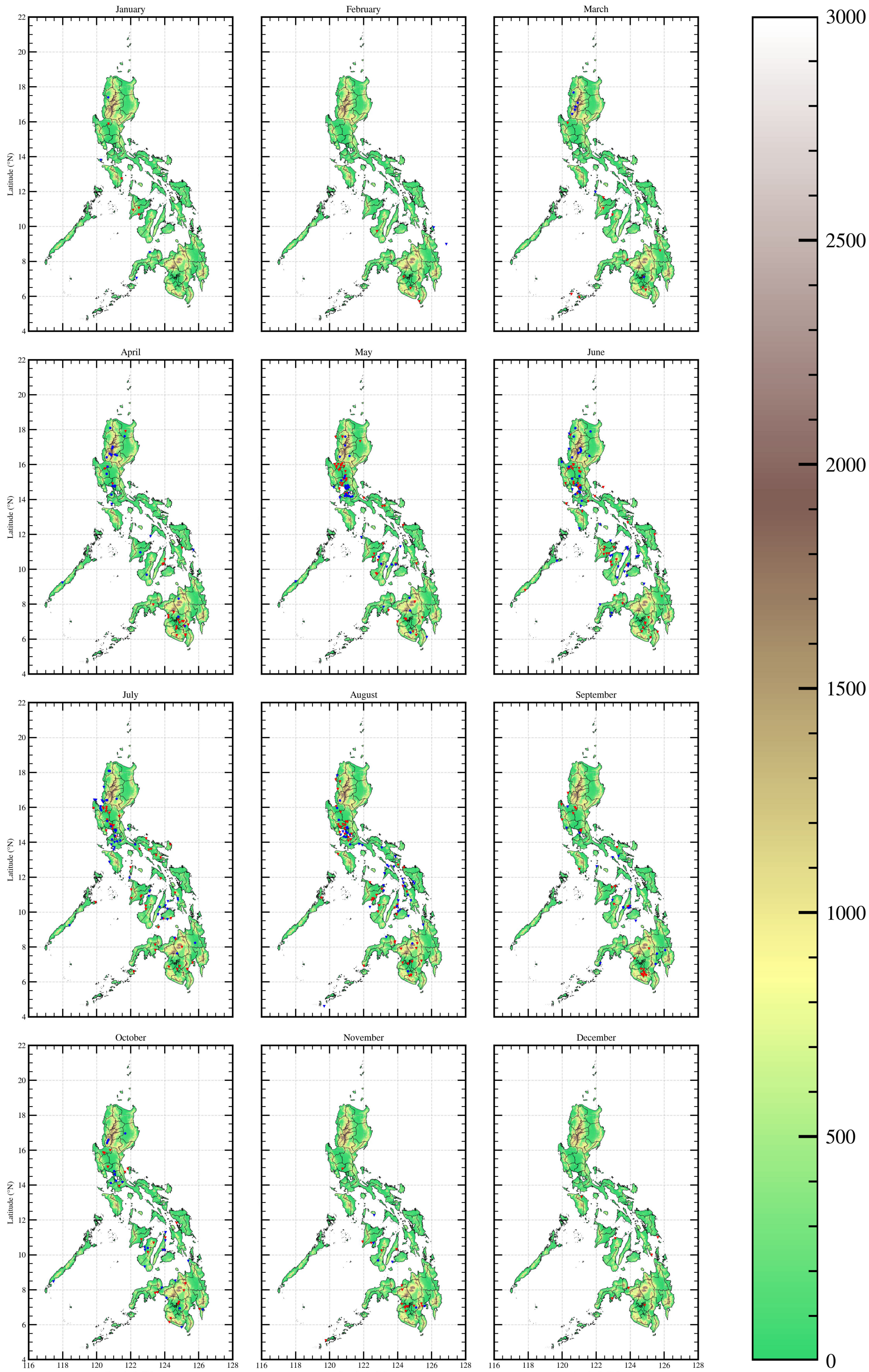


Figure 7: Monthly geographical distribution of documented tornadoes (red triangles), hail events (blue circles) and waterspouts (blue triangles) in the Philippines from SWAP DR2.

the east and the Highlands of Tiruray to the west. This geographical positioning may play a critical role in the development and intensification of tornadic storms in the area. The mountains could influence local wind patterns, moisture distribution, and the stability of the atmosphere, creating favorable conditions for tornado formation. This interplay between topography and weather patterns may partially explain why this region experiences higher-than-average tornadic activity compared to other areas in Mindanao.

Additionally, the region has a historical record of significant tornado events, including three potential EF2 tornadoes. Notably, a killer tornado struck Zamboanga del Sur in June 1990, resulting in the deaths of up to 30 people in Manukan, despite being outside the main hotspot zone. Other destructive tornadoes were recorded in Lantapan, Bukidnon in July 1991, a regional tornado outbreak in South Cotabato back on September 2009, and in Pikit, North Cotabato in August 2015. The severity and impact of these tornadoes further underscore the vulnerability of the region to SWEs, especially within the identified hotspot zone. However further studies could explore the precise meteorological mechanisms at play, enhancing the understanding of tornadogenesis in this complex terrain.[10]

Figure 7 shows the monthly spatial distribution of all tornadoes, hails, and waterspouts across the archipelago within SWAP DR2. The winter period (DJF) shows few and scattered cases of tornadoes across the entire archipelago. At the beginning of the active season in March, the number of cases increases with hail activity picking up in the Northern Luzon, and tornado activities within Panay Islands, Maguindanao, and South Cotabato. By April, a dominant hail event pattern is observed across the Luzon Landmass, while tornado season had a head-start in the Mindanao influence zone. In May, there are relatively high concentrations of tornadoes and hail events along the bimodal hotspots in Luzon, mixed batch of severe weather along Regions VI and VII, and scattered severe weather activity within Mindanao as well.

At the initial peak on June, severe weather activity is already spread out across the country, with tornado and hail reports centered in Pangasinan and across GMM area. Also, waterspout and tornado season is underway in Western and Central Visayas region, so as in Mindanao. This pattern is maintained throughout July and August across the country, with increased waterspout activity along the Visayas regions. At September, severe weather season in Luzon is about to end with decrease of severe weather activity (decrease in tornado cases) and shifts down south, with notable clusters around Visayas and Mindanao hotspots. October registered some hailstorm activity across NCR and Baguio due to monsoon breaks shifting the wind pattern to easterlies and the initial arrival of Northeast Monsoon. Meanwhile, Visayas and Mindanao severe weather season is still on going along Negros Provinces and Cebu, and along the Mindanao tornado hotspot as depicted earlier. By November, severe weather activity caps off in Luzon as Northeast Monsoon starts to advance and effect the landmass, so is about to end for Visayas with fewer registered SWEs, however Mindanao tornado activity remains quite active, surprisingly. By December, the severe weather activity flattens across the archipelago with few documented cases within the aforementioned month.

[10]as also noted the same for the severe weather hotspot in Luzon.

## 4 Conclusion and Recommendation

This paper has presented the first baseline climatology of SWEs encompassing tornadoes, hails, and waterspouts in the Philippines. Project SWAP and its DR2 consists of previous literature and recent documentary datasets, with a temporal coverage of 56 yr (1968-2024). The archive has many potential uses: its global reach allows for worldwide estimates of severe weather climatology, including intercomparisons of severe weather observation and documentation methodologies. We hope that the digitized dataset will open possibilities for more broad climatological studies. More importantly, this project and paper itself can serve as a foundational piece for aspiring filipino researchers trying to get a grasp and would like to study meteorology, and SWEs such as tornadoes in the Philippine context in the future. Still, any analyses using this archive will require careful consideration of biases therein, many of which we have discussed.

On the analysis side, the increase in the number of documented SWEs is attributed to the rise in public awareness of these natural phenomena, the growth in the use of social networks (e.g. Facebook, Twitter, and YouTube), and improvements in information technologies (e.g. internet access). Such an apparent increase in tornadic, hail, and waterspout activity in Philippines could be associated with natural variability as well. For example, previous studies have been showing the influence of the El Niño-Southern Oscillation (ENSO) and the Madden-Julian Oscillation (MJO) in convection processes and precipitation [76–78]. However, it is not yet possible to determine the influence of such oscillations on tornado formation in Philippines, as there is insufficient evidence and a relatively short data series on tornadoes.

The monthly distribution shows that the beginning of the most active phase of the severe weather season is in April. This first activity fits with the most active tornado phase in the USA [70]. In May, SWEs have been previously documented across the country, in particular at lower Region I and Region III encompassing GMM area and Southern Luzon, with early termination between September-October. This may be indicating that this portion of the country may be related to similar atmospheric processes that lead to supercell formation and tornadogenesis, especially during Southwest Monsoon periods and the start of TC season in the western Pacific. However, easterly wind setups during months of April and May may also provide the same hazardous meteorological condition. Several studies documented the characteristics and role of tropical activity in rainfall in Philippines. However, the impact of TCs on tornadogenesis and severe weather initiation remains understudied in the Philippine context.

Meanwhile, down south towards the Western and Central Visayas, waterspouts, along some tornadoes in the Panay Islands, are the main show with severe weather activity. The start of increased waterspout and tornado activity is in May followed by scattered and clumps of activity across the island groups of Visayas until it slowly winds down by November. On the other hand, Mindanao, particularly BARRM and Region XII, had a head start in terms of severe weather; mostly tornadic events, from April to November with severe weather season capping off by December across the country. The environments in these locations were generally comprised in accordance to the Philippine Climate Types developed by Coronas [79] and Kintanar [80], but the convective and kinematic setup of these remains to be studied.

Project SWAP and its DR2 shows that nearly 50% of cases are documented in the Pangasinan-GMM influence area. This fact may involve 2 critical issues: first, there is a clear relationship with population density. Demographic effects on tornado documentation have been previously reported [19, 35, 51], and Philippines is no exception. Second, this spatial pattern could also be related to topographic features. Much of these hotspots, pertaining to the Luzon and even Mindanao hotspots, were located in between two mountainous areas. Topographic effects were also reported along Luzon [74, 75], but seldom, if not none, along Mindanao hotspot zone. However, a previous study on an MCS [72] may give an insight to the role of complex terrain along the said hotspot and for the increased tornadic activity in the area of interest. A complete, thorough mesoscale analysis of convective and wind profile setting of these severe weather hotspots we identified in the Philippine context has been proposed.

What is more striking is that the locations of these severe weather hotspots are well-placed to the climate types, specifically along Climate Type 1 and 3. As a quick discussion, Climate Type 1, so as Type 3 at one point, was characterized by pronounced wet season influenced by the southwesterlies from May to October and the dry season from November to April caused by the prevailing winds in form of north Pacific easterlies, with maximum rainfall during June to September [81, 82]. However, the timing of the wet season can vary depending on the onset of the southwesterly wind that flows at the country, tied to the Asian summer monsoon. Still, aiding on the initiation convective activity over the western coast of the Philippines during monsoon period [83].

Now, this begs the question; what are the convective and kinematic mechanisms within these climate types, not based on rainfall and temperature, making it favorable environment for severe weather? *What makes the clock tick* capable of producing these SWEs? As proposed and a Part 2 of this project, we will explore and establish another baseline climatology, this time centered around hazardous convective weather setups across the archipelago.


## Acknowledgments

We are very grateful to the Philippine population for reporting the occurrence of tornadoes in their communities. We also appreciate the valuable comments of the three anonymous reviewers and editor, which helped to improve this manuscript. This work received no funding. However, it was made possible through extensive and exhaustive effort, whose dedication and commitment to advancing our understanding of severe weather phenomena were indispensable. We would also like to extend our appreciation to the government agencies, acting as the primary source, for providing essential data that contributed significantly to this work. Finally, we are thankful to our families and loved one for their unwavering support throughout the project.


### Author Contributions

G. H. Capuli is the project leader of Project SWAP. Thus, conceptualized and leads the initiative, and designed-conducted the experiments/analysis. So as to the writing of the manuscript.

## Conflicts of Interest

The author declares that they have no competing interests.

## Data Availability

Project SWAP and its SWAP DR2 is available and distributed on Zenodo. Sounding profiles will be available soon on the aforementioned Zenodo page. The Digital Elevation Model (DEM) is from SRTM15Plus distributed and available on OpenTopography. The population density is available through World Population Hub. Finally, the lightning data from the TRMM is accessible through NASA Earth Data. All of these data is distributed under Creative Commons CC-BY 4.0. Proper attribution is required for these datasets.

This paper has made of use of the following Python packages: `sci-kit learn`, `Matplotlib`, `GeoPandas`, `Pandas`, `Rasterio`, `rioxarray`, `NumPy`, `Regionmask`

# References


[1] H. E. Brooks, G. W. Carbin, and P. T. Marsh, "Increased variability of tornado occurrence in the United States," *Science*, vol. 346, no. 6207, pp. 349–352, 2014. DOI: 10.1126/science.1257460.

[2] P. Concannon, H. Brooks, and C. Doswell III, "Climatological risk of strong and violent tornadoes in the United States," *Preprints, 2nd Conference on Environmental Applications*, pp. 212–219, 2000.

[3] B. Antonescu, D. M. Schultz, A. Holzer, and P. Groenemeijer, "Tornadoes in Europe: An Underestimated Threat," *Bulletin of the American Meteorological Society*, vol. 98, no. 4, pp. 713–728, 2017. DOI: 10.1175/BAMS-D-16-0171.1.

[4] T. T. Fujita, "Tornadoes around the World," *Weatherwise*, vol. 26, no. 2, pp. 56–83, 1973. DOI: 10.1080/00431672.1973.9931633.

[5] A. Goliger and R. Milford, "A review of worldwide occurrence of tornadoes," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 74-76, pp. 111–121, 1998, ISSN: 0167-6105. DOI: 10.1016/S0167-6105(98)00009-9.

[6] N. Dotzek, P. Groenemeijer, B. Feuerstein, and A. M. Holzer, "Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD," *Atmospheric Research*, vol. 93, no. 1, pp. 575–586, 2009, 4th European Conference on Severe Storms, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2008.10.020.

[7] J. Grieser and P. Haines, "Tornado Risk Climatology in Europe," *Atmosphere*, vol. 11, no. 7, 2020, ISSN: 2073-4433. DOI: 10.3390/atmos11070768.

[8] M. Maas, T. Supinie, A. Berrington, S. Emmerson, A. Aidala, and M. Gavan, "The Tornado Archive: Compiling and Visualizing a Worldwide, Digitized Tornado Database," *Bulletin of the American Meteorological Society*, vol. 105, no. 7, E1137–E1152, 2024. DOI: 10.1175/BAMS-D-23-0123.1.

[9] H. Brooks and C. A. Doswell, "Some aspects of the international climatology of tornadoes by damage classification," *Atmospheric Research*, vol. 56, no. 1, pp. 191–201, 2001, Conference on European Tornadoes and Severe Storms, ISSN: 0169-8095. DOI: 10.1016/S0169-8095(00)00098-3.

[10] J. Chen *et al.*, "Tornado climatology of China," *International Journal of Climatology*, vol. 38, no. 5, pp. 2478–2489, 2018. DOI: 10.1002/joc.5369.

[11] M. M. Miglietta and I. T. Matsangouras, "An updated "climatology" of tornadoes and waterspouts in Italy," *International Journal of Climatology*, vol. 38, no. 9, pp. 3667–3683, 2018. DOI: 10.1002/joc.5526.

[12] P. Leitão and P. Pinto, "Tornadoes in Portugal: An Overview," *Atmosphere*, vol. 11, no. 7, 2020, ISSN: 2073-4433. DOI: 10.3390/atmos11070679.

[13] R. Brázdil *et al.*, "Spatiotemporal variability of tornadoes in the Czech Lands, 1801–2017," *Theoretical and Applied Climatology*, vol. 136, no. 3, pp. 1233–1248, 2019, ISSN: 1434-4483. DOI: 10.1007/s00704-018-2553-y.

[14] K. J. Mulder and D. M. Schultz, "Climatology, Storm Morphologies, and Environments of Tornadoes in the British Isles: 1980–2012," *Monthly Weather Review*, vol. 143, no. 6, pp. 2224–2240, 2015. DOI: 10.1175/MWR-D-14-00299.1.

[15] L. Guo, K. Wang, and H. B. Bluestein, "Variability of tornado occurrence over the continental United States since 1950," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 12, pp. 6943–6953, 2016. DOI: 10.1002/2015JD024465.

[16] ECCC (Environment and Climate Change Canada), *Canadian National Tornado Database: Verified Tracks (1980-2009)*, Dec. 2015. [Online]. Available: https://open.canada.ca/data/en/dataset/65658050-7a80-4da3-9a09-da137c203a34.

[17] J. Riesco Martín, F. Polvorinos Pascual, J. Á. Núnez Mora, J. de Dios Soriano Romero, and C. Jiménez Alonso, "Climatología de tornados en España Peninsular y Baleares," *Agencia Estatal de Meteorología Madrid*, 2015. DOI: 10.31978/281-15-005-8.

[18] NCEI (National Centers for Environmental Information), *Storm Events Database*, 2024. [Online]. Available: https://www.ncdc.noaa.gov/stormevents/.

[19] M. A. F. S. Dias, "An Increase in the Number of Tornado Reports in Brazil," *Weather, Climate, and Society*, vol. 3, no. 3, pp. 209–217, 2011. DOI: 10.1175/2011WCAS1095.1.

[20] M. V. Sioutas, "A tornado and waterspout climatology for Greece," *Atmospheric Research*, vol. 100, no. 4, pp. 344–356, 2011, 5th European Conference on Severe Storms, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2010.08.011.

[21] M. Sioutas, W. Szilagyi, and A. Keul, "Waterspout outbreaks over areas of Europe and North America: Environment and predictability," *Atmospheric Research*, vol. 123, pp. 167–179, 2013, 6th European Conference on Severe Storms 2011. Palma de Mallorca, Spain, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2012.09.013.

[22] O. Rodríguez, J. Bech, J. Arús, S. Castán, F. Figuerola, and T. Rigo, "An overview of tornado and waterspout events in Catalonia (2000–2019)," *Atmospheric Research*, vol. 250, p. 105 415, 2021, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2020.105415.

[23] A. Devanas and L. Stefanova, "Statistical Prediction of Waterspout Probability for the Florida Keys," *Weather and Forecasting*, vol. 33, no. 2, pp. 389–410, 2018. DOI: 10.1175/WAF-D-17-0100.1.

[24] J. T. Allen *et al.*, "Understanding Hail in the Earth System," *Reviews of Geophysics*, vol. 58, no. 1, e2019RG000665, 2020. DOI: 10.1029/2019RG000665.

[25] M. Li, Q. Zhang, and F. Zhang, "Hail Day Frequency Trends and Associated Atmospheric Circulation Patterns over China during 1960–2012," *Journal of Climate*, vol. 29, no. 19, pp. 7027–7044, 2016. DOI: 10.1175/JCLI-D-15-0500.1.

[26] X. Li, Q. Zhang, T. Zou, J. Lin, H. Kong, and Z. Ren, "Climatology of Hail Frequency and Size in China, 1980–2015," *Journal of Applied Meteorology and Climatology*, vol. 57, no. 4, pp. 875–887, 2018. DOI: 10.1175/JAMC-D-17-0208.1.

[27] X. Ni, A. Muehlbauer, J. T. Allen, Q. Zhang, and J. Fan, "A Climatology and Extreme Value Analysis of Large Hail in China," *Monthly Weather Review*, vol. 148, no. 4, pp. 1431–1447, 2020. DOI: 10.1175/MWR-D-19-0276.1.

[28] W. Zhao *et al.*, "Declining hailstorm frequency in China during 1961–2015 and its potential influential factors," *International Journal of Climatology*, vol. 38, no. 11, pp. 4116–4126, 2018. DOI: https://doi.org/10.1002/joc.5556.

[29] J.-P. Tuovinen, A.-J. Punkka, J. Rauhala, H. Hohti, and D. M. Schultz, "Climatology of Severe Hail in Finland: 1930–2006," *Monthly Weather Review*, vol. 137, no. 7, pp. 2238–2249, 2009. DOI: 10.1175/2008MWR2707.1.

[30] J. Webb, D. Elsom, and G. Meaden, "Severe hailstorms in Britain and Ireland, a climatological survey and hazard assessment," *Atmospheric Research*, vol. 93, no. 1, pp. 587–606, 2009, 4th European Conference on Severe Storms, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2008.10.034.

[31] B. W. Silverman, *Density Estimation for Statistics and Data Analysis*. Chapman & Hall - Monographs on Statistics and Applied Probability, 1986, p. 186, ISBN: 9780412246203. DOI: 10.1201/9781315140919.

[32] L. Breiman, W. Meisel, and E. Purcell, "Variable Kernel Estimates of Multivariate Densities," *Technometrics*, vol. 19, no. 2, pp. 135–144, 1977, ISSN: 00401706. DOI: 10.2307/1268623.

[33] I. S. Abramson, "On Bandwidth Variation in Kernel Estimates-A Square Root Law," *The Annals of Statistics*, vol. 10, no. 4, pp. 1217–1223, 1982. DOI: 10.1214/aos/1176345986.

[34] B. E. Aguirre, R. Saenz, J. Edmiston, N. Yang, D. Stuart, and E. Agramonte, "Population and the Detection of Weak Tornadoes," *International Journal of Mass Emergencies & Disasters*, vol. 12, no. 3, pp. 261–277, 1994. DOI: 10.1177/028072709401200301.

[35] C. J. Anderson, C. K. Wikle, Q. Zhou, and J. A. Royle, "Population Influences on Tornado Reports in the United States," *Weather and Forecasting*, vol. 22, no. 3, pp. 571–579, 2007. DOI: 10.1175/WAF997.1.

[36] C. A. Doswell and D. W. Burgess, "On Some Issues of United States Tornado Climatology," *Monthly Weather Review*, vol. 116, no. 2, pp. 495–501, 1988. DOI: 10.1175/1520-0493(1988)116<0495:OSIOUS>2.0.CO;2.

[37] M. Bradford, "Historical Roots of Modern Tornado Forecasts and Warnings," *Weather and Forecasting*, vol. 14, no. 4, pp. 484–491, 1999. DOI: 10.1175/1520-0434(1999)014<0484:HROMTF>2.0.CO;2.

[38] NOAA (National Oceanic and Atmospheric Administration), *Storm Data Preparation*, Jul. 2021. [Online]. Available: https://www.weather.gov/media/directives/010_pdfs/pd01016005curr.pdf.

[39] J. F. León-Cruz, L. F. Pineda-Martínez, and N. Carbajal, "Tornado climatology and potentially severe convective environments in Mexico," *Climate Research*, vol. 87, pp. 147–165, 2022. DOI: 10.3354/cr01692.

[40] NIWA (National Institute of Water and Atmospheric), *New Zealand Historic Weather Events Catalogue*, 2021. [Online]. Available: https://hwe.niwa.co.nz/.

[41] P. Groenemeijer, A. Holzer, T. Kühne, and T. Púčik, "The International Fujita Scale and its implementation," *European Severe Storms Laboratory*, p. 151, 2023, 11th European Conference on Severe Storms. DOI: 10.5194/ecss2023-151.

[42] T. Púčik *et al.*, "The Violent Tornado on 24 June 2021 in Czechia: Damage Survey, Societal Impacts, and Lessons Learned," *Weather, Climate, and Society*, vol. 16, no. 3, pp. 411–429, 2024. DOI: 10.1175/WCAS-D-23-0080.1.

[43] J. L. Cintineo, T. M. Smith, V. Lakshmanan, H. E. Brooks, and K. L. Ortega, "An Objective High-Resolution Hail Climatology of the Contiguous United States," *Weather and Forecasting*, vol. 27, no. 5, pp. 1235–1248, 2012. DOI: 10.1175/WAF-D-11-00151.1.

[44] K. A. Bowden, P. L. Heinselman, D. M. Kingfield, and R. P. Thomas, "Impacts of Phased-Array Radar Data on Forecaster Performance during Severe Hail and Wind Events," *Weather and Forecasting*, vol. 30, no. 2, pp. 389–404, 2015. DOI: 10.1175/WAF-D-14-00101.1.

[45] N. M. Taylor, "Climatology of sounding parameters identifying the potential for convective storm development over central Alberta," Master's Thesis, University of Alberta, 1999. DOI: 10.7939/R3RX93M73.

[46] R. Stull, *Practical Meteorology: An Algebra-Based Survey of Atmospheric Science. Version 1.02.* University of British Columbia, 2017, p. 940, ISBN: 9780888652836.

[47] J.-P. Tuovinen, J. Rauhala, and D. M. Schultz, "Significant-Hail-Producing Storms in Finland: Convective-Storm Environment and Mode," *Weather and Forecasting*, vol. 30, no. 4, pp. 1064–1076, 2015. DOI: 10.1175/WAF-D-14-00159.1.

[48] G. H. Capuli, "Severe Weather Analysis of Tornado (SWAT): Synoptic and Convective Setting of EF1 Manila Tornado (14 August 2016)over Philippines," Undergraduate Thesis, Rizal Technological University, Jan. 2024. DOI: 10.13140/RG.2.2.18973.12005.

[49] Gillett, K., "SounderPy: Vertical profile data retrieval & analysis tool for Python," *Zenodo*, 2024. DOI: 10.5281/zenodo.10011851.

[50] S. M. Verbout, H. E. Brooks, L. M. Leslie, and D. M. Schultz, "Evolution of the U.S. Tornado Database: 1954–2003," *Weather and Forecasting*, vol. 21, no. 1, pp. 86–93, 2006. DOI: 10.1175/WAF910.1.

[51] P. Groenemeijer and T. Kühne, "A Climatology of Tornadoes in Europe: Results from the European Severe Weather Database," *Monthly Weather Review*, vol. 142, no. 12, pp. 4775–4790, 2014. DOI: 10.1175/MWR-D-14-00107.1.

[52] F. Cruz, G. Narisma, M. Villafuerte, K. Cheng Chua, and L. Olaguera, "A climatological analysis of the southwest monsoon rainfall in the Philippines," *Atmospheric Research*, vol. 122, pp. 609–616, 2013, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2012.06.010.

[53] C. Dominguez, J. M. Done, and C. L. Bruyère, "Future Changes in Tropical Cyclone and Easterly Wave Characteristics over Tropical North America," *Oceans*, vol. 2, no. 2, pp. 429–447, 2021, ISSN: 2673-1924. DOI: 10.3390/oceans2020024.

[54] E. N. Rasmussen and D. O. Blanchard, "A Baseline Climatology of Sounding-Derived Supercell andTornado Forecast Parameters," *Weather and Forecasting*, vol. 13, no. 4, pp. 1148–1164, 1998. DOI: 10.1175/1520-0434(1998)013<1148:ABCOSD>2.0.CO;2.

[55] R. L. Thompson, R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, "Close Proximity Soundings within Supercell Environments Obtained from the Rapid Update Cycle," *Weather and Forecasting*, vol. 18, no. 6, pp. 1243–1261, 2003. DOI: 10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2.

[56] H. E. Brooks, J. W. Lee, and J. P. Craven, "The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data," *Atmospheric Research*, vol. 67-68, pp. 73–94, 2003, European Conference on Severe Storms 2002, ISSN: 0169-8095. DOI: 10.1016/S0169-8095(03)00045-0.

[57] H. E. Brooks, "Proximity soundings for severe convection for Europe and the United States from reanalysis data," *Atmospheric Research*, vol. 93, no. 1, pp. 546–553, 2009, 4th European Conference on Severe Storms, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2008.10.005.

[58] R. Davies-Jones, "A review of supercell and tornado dynamics," *Atmospheric Research*, vol. 158-159, pp. 274–291, 2015, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2014.04.007.

[59] A. F. Prein and G. J. Holland, "Global estimates of damaging hail hazard," *Weather and Climate Extremes*, vol. 22, pp. 10–23, 2018, ISSN: 2212-0947. DOI: 10.1016/j.wace.2018.10.004.

[60] B. H. Tang, V. A. Gensini, and C. R. Homeyer, "Trends in United States large hail environments and observations," *npj Climate and Atmospheric Science*, vol. 2, no. 1, p. 45, 2019, ISSN: 2397-3722. DOI: 10.1038/s41612-019-0103-7.

[61] C. J. Nixon, J. T. Allen, and M. Taszarek, "Hodographs and Skew Ts of Hail-Producing Storms," *Weather and Forecasting*, vol. 38, no. 11, pp. 2217–2236, 2023. DOI: 10.1175/WAF-D-23-0031.1.

[62] H.-F. Teng, J. M. Done, and Y.-H. Kuo, "Landfalling tropical cyclone characteristics and their multi-timescale variability connected to monsoon and easterly formation environments over the western north pacific," *Quarterly Journal of the Royal Meteorological Society*, vol. 147, no. 738, pp. 2953–2977, 2021. DOI: 10.1002/qj.4108.

[63] S. J. Weiss, "Some climatological aspects of forecasting tornadoes associated with tropical cyclones," *Preprints 17th Conf. on Hurricanes and Tropical Meteorology*, pp. 160–163, 1987.

[64] M. Taszarek and L. Kolendowicz, "Sounding-derived parameters associated with tornado occurrence in poland and universal tornadic index," *Atmospheric Research*, vol. 134, pp. 186–197, 2013, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2013.07.016.

[65] A. Dai, "Global Precipitation and Thunderstorm Frequencies. Part II: Diurnal Variations," *Journal of Climate*, vol. 14, no. 6, pp. 1112–1128, 2001. DOI: 10.1175/1520-0442(2001)014<1112:GPATFP>2.0.CO;2.

[66] E. N. Bañares *et al.*, "Seasonal and diurnal variations of observed convective rain events in metro manila, philippines," *Atmospheric Research*, vol. 258, p. 105 646, 2021, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2021.105646.

[67] CIESIN (Center for International Earth Science Information Network), "The spatial distribution of population density in 2020, Philippines," *WorldPop*, 2020. DOI: 10.5258/SOTON/WP00674.

[68] C. Kummerow, W. Barnes, T. Kozu, J. Shiue, and J. Simpson, "The Tropical Rainfall Measuring Mission (TRMM) Sensor Package," *Journal of Atmospheric and Oceanic Technology*, vol. 15, no. 3, pp. 809–817, 1998. DOI: 10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2.

[69] D. J. Cecil, D. E. Buechler, and R. J. Blakeslee, "Gridded lightning climatology from TRMM-LIS and OTD: Dataset description," *Atmospheric Research*, vol. 135-136, pp. 404–414, 2014, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2012.06.028.

[70] M. Taszarek *et al.*, "Severe Convective Storms across Europe and the United States. Part I: Climatology of Lightning, Large Hail, Severe Wind, and Tornadoes," *Journal of Climate*, vol. 33, no. 23, pp. 10 239–10 261, 2020. DOI: 10.1175/JCLI-D-20-0345.1.

[71] C. Lagare, T. Yamazaki, and J. Ito, "Characteristics of Mesoscale Convective Systems in the Philippines," in *EGU General Assembly Conference Abstracts*, ser. EGU General Assembly Conference Abstracts, May 2023, EGU-10920, EGU–10 920. DOI: 10.5194/egusphere-egu23-10920.

[72] C. Lagare, T. Yamazaki, and J. Ito, "Numerical simulation of a heavy rainfall event over Mindanao, Philippines, on 03 May 2017: mesoscale convective systems under weak large-scale forcing," *Geoscience Letters*, vol. 10, no. 1, p. 23, 2023, ISSN: 2196-4092. DOI: 10.1186/s40562-023-00277-8.

[73] T. P. Grazulis, *The Tornado – Nature's Ultimate Windstorm*. University of Oklahoma Press, 2001, p. 348, ISBN: 9780806135380.

[74] A. M. F. Lagmay, G. Bagtasa, I. A. Crisologo, B. A. B. Racoma, and C. P. C. David, "Volcanoes magnify Metro Manila's southwest monsoon rains and lethal floods," *Frontiers in Earth Science*, vol. 2, 2015, ISSN: 2296-6463. DOI: 10.3389/feart.2014.00036.

[75] B. A. Racoma, C. David, I. Crisologo, and G. Bagtasa, "The Change in Rainfall from Tropical Cyclones Due to Orographic Effect of the Sierra Madre Mountain Range in Luzon, Philippines," *Philippine Journal of Science*, vol. 145, pp. 313–326, Dec. 2016.

[76] S.-K. Lee, A. T. Wittenberg, D. B. Enfield, S. J. Weaver, C. Wang, and R. Atlas, "US regional tornado outbreaks and their links to spring ENSO phases and North Atlantic SST variability," *Environmental Research Letters*, vol. 11, no. 4, p. 044 008, Apr. 2016. DOI: 10.1088/1748-9326/11/4/044008.

[77] M. J. Molina, J. T. Allen, and V. A. Gensini, "The Gulf of Mexico and ENSO Influence on Subseasonal and Seasonal CONUS Winter Tornado Variability," *Journal of Applied Meteorology and Climatology*, vol. 57, no. 10, pp. 2439–2463, 2018. DOI: 10.1175/JAMC-D-18-0046.1.

[78] M. K. Tippett, "Robustness of Relations between the MJO and U.S. Tornado Occurrence," *Monthly Weather Review*, vol. 146, no. 11, pp. 3873–3884, 2018. DOI: 10.1175/MWR-D-18-0207.1.

[79] J. Coronas, *The Climate and Weather of the Philippines, 1903 – 1918*. Pranava Books, 1920, p. 195.

[80] R. Kintanar, "Climate of the Philippines," *Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)*, p. 38, 1984.

[81] J. C. A. C. Peralta, G. T. T. Narisma, and F. A. T. Cruz, "Validation of High-Resolution Gridded Rainfall Datasets for Climate Applications in the Philippines," *Journal of Hydrometeorology*, vol. 21, no. 7, pp. 1571–1587, 2020. DOI: 10.1175/JHM-D-19-0276.1.

[82] C. Jamandre and G. Narisma, "Spatio-temporal validation of satellite-based rainfall estimates in the Philippines," *Atmospheric Research*, vol. 122, pp. 599–608, 2013, ISSN: 0169-8095. DOI: 10.1016/j.atmosres.2012.06.024.

[83] I. Akasaka, "Interannual variations in seasonal march of rainfall in the philippines," *International Journal of Climatology*, vol. 30, no. 9, pp. 1301–1314, 2010. DOI: 10.1002/joc.1975.