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Chapter 6

Super Typhoon Bopha and the Mayo River Debris-Flow Disaster, Mindanao, Philippines, December 2012

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http://dx.doi.org/10.5772/intechopen.81669

Abstract

Category 5 (C5) Super Typhoon Bopha, the world's worst storm of 2012, formed abnormally close to the West Pacific Equator, and Bopha's Mindanao landfall has the record equatorial proximity for C5 storms. Bopha generated a debris flow that buried 500 ha of New Bataan municipality and killed 566 people. New Bataan, established in 1968, had never experienced super typhoons and debris flows. We describe the respective histories of New Bataan and Super Typhoon Bopha; debris flows; and how population growth and unwise settlement practices contribute to Philippine "natural" disasters. The historical record of Mindanao tropical cyclones yields clues regarding how climate change may be exacerbating near-equatorial vulnerability to typhoons. Existing models of future typhoon behavior do not apply well to Mindanao because they evaluate only the tropical cyclones that occur during the main June–October typhoon season, and most Mindanao tropical cyclones occur in the off season. The models also ignore tropical depressions, the most frequent—and commonly lethal—Mindanao cyclones. Including these in annual tallies of Mindanao cyclones up to early 2018 reveals a pronounced and accelerating increase since 1990. Mindanao is susceptible to other natural hazards, including other consequences of climate change and volcanic activity.

Keywords: Super Typhoon Bopha, Andap disaster, Mayo River, debris flows, climate change, ENSO, typhoon frequency

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1. Introduction

On 4 November, 2012, Super Typhoon Bopha generated a massive debris flow that devastated *barangay* (village) Andap in the Mindanao municipality of New Bataan and killed hundreds of people. In early 2013, we were designated as a field disaster-analysis team by Project NOAH (Nationwide Operational Assessment of Hazards), the disaster-assessment program of the University of the Philippines in Diliman, Quezon City.

Prior to our field work, we gathered high-resolution optical satellite imagery for mapping out the extent of the debris flow deposits and commissioned a Light Detection and Ranging (LiDAR) survey to generate detailed topographic maps of the area. In the field, we analyzed and plotted the new deposits on our new maps. They were clearly left by a debris flow, and we determined its velocity when it hit Andap from scarring on impacted trees. Old deposits were left in the area by debris flows that occurred long before New Bataan was established. Eyewitnesses recounted the Bopha event for us in detail, and long-time residents informed us that similar events had never happened before. We analyzed and reconstructed the event from all these gathered data.

An initial report we published in 2016 [1] described the Super Typhoon, the Mayo River debris flow, and the detailed geologic reasons for it. We also discussed how and reviewed how population growth and inadequate geological analysis of settlement sites contribute to Philippine "natural" disasters. Our report discussed how climate change may be bringing more frequent major typhoons and debris flows they trigger to Mindanao and to other vulnerable subequatorial areas. We did so by examining the sparse record of tropical cyclones that made landfall on Mindanao since 1945, associated records of the Pacific El Niño-Southern Oscillation (ENSO), and all western North Pacific tropical cyclones from 1945 to 2015.

Here, we update that evaluation with additional data from 2016 through February 2018. A positive outgrowth of this research is Project NOAH's new program that has identified more than a thousand Philippine alluvial fans and associated communities that might experience debris flows. This program already helped to mitigate debris flows on Luzon and Mindoro islands. We conclude by exploring possible protective measures for climate-related hazards that threaten Mindanao and other subequatorial areas.

2. Prolog to disaster: geomorphologic setting and history of New Bataan

Southeastern Mindanao is a rugged coastal range (**Figure 1**). About 35 km west of the coast, and 3 km upstream of Andap, the Mayo River drains a rugged, 36.5 km^2 watershed on the western slopes of the coastal range. In the Mayo watershed, many slopes are steeper than 35° and total relief is about 2320 m. Flowing northward, the Mayo River debouches through a narrow gorge to join the Kalyawan River, which flows northward along the Compostela Valley, as do other Agusan River southern tributaries.

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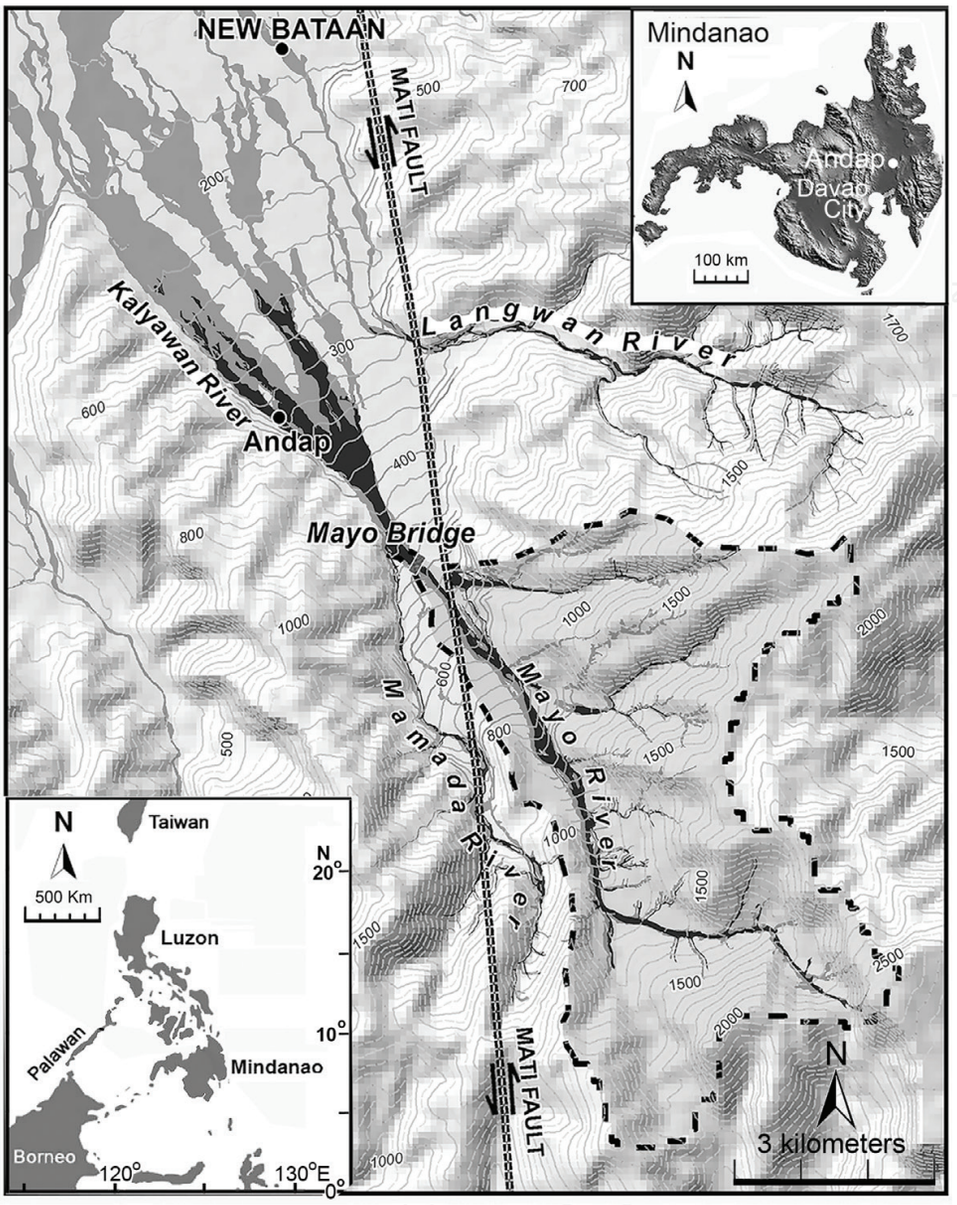


Figure 1. Physical setting of the Andap disaster. Gray area enclosed by dashes is the Mayo River watershed. All steep slopes are contoured at 50-m intervals. Below 700-m elevations, the contour interval is 20 m to better define the gentler valley surfaces. New deposits of "true" debris flows are shown in solid black; associated hyperconcentrated-flow deposits are shaded in gray. Note that the topographic contour lines from the Mayo Bridge to Andap are convex northward, defining the surface of an alluvial fan just upstream from Andap. The trace of the Mati Fault is only generalized; it has numerous associated fractures in a broad zone along its length.

A site 8 km below the Mayo-Kalyawan junction in the eastern Compostela Valley called "Cabinuangan" because of its many huge Binuang (*Octomeles sumatrana*) trees began to be logged in the early 1950s [2]. As the loggers rapidly expanded their road networks, immigrant farmers from Luzon and the Visayan Islands followed closely behind, planting the cleared land mainly to coconuts, but also to rice, corn, bananas, coffee, cacao, abaca, and bamboo.

The Philippine government divided the public lands of Compostela Valley into formal municipal areas beginning in 1966. One covering 55,315 ha in Cabinuangan was named New

Bataan in 1968 because Luz Banzon-Magsaysay, a native of the Luzon province of Bataan and President Magsaysay's widow, had espoused its establishment. New Bataan was subdivided into 16 *barangays* (villages) comprising farm lots. A 154-ha area at the center of New Bataan was designated the town site and given the *barangay* name of "Cabinuangan." In 1970, 2 years after its founding, the population of New Bataan was 19,978 [3]; by 1 May, 2010, it had increased 238% to 47,470, including 10,390 in Cabinuangan and 7550 in Andap [4].

The town planners made a nice design for Cabinuangan, its streets fanning out geometrically from its central core of government and social buildings (**Figure 2A**). Unfortunately, the planners knew little about natural hazards. Even government authorities did not know that the Kalyawan River had been a conduit for ancient debris flows; as late as 2012, the official hazard map of New Bataan [5] evaluated only landslide and flood risks. This lack of geomorphologic knowledge was fatal during Bopha (**Figure 2B**).

Barangay Andap was established at the head of Compostela Valley on high ground 3 km upstream of Cabinuangan. That site was not recognized as an alluvial fan, a landform built up by successive debris flows. Our field work documented that the fan was built up by characteristically reverse-graded, matrix-supported debris-flow deposits of unknown but ancient age (**Figure 3**).

2.1. Debris flows

Among the world's most destructive natural phenomena, debris flows are fast-moving slurries of water and rock fragments, soil, and mud [6–9]. Many debris flows (**Table 1**) [10] are associated with volcanoes [11, 12]; many others are not, including the Mayo River event. All that is required to generate a debris flow is an abundance of loose rock debris and soil and a sudden large influx of water. They can be triggered by sudden downpours such as commonly delivered by tropical cyclones, by reservoir collapses [13], or by landslides dislodged by earthquakes into streams.

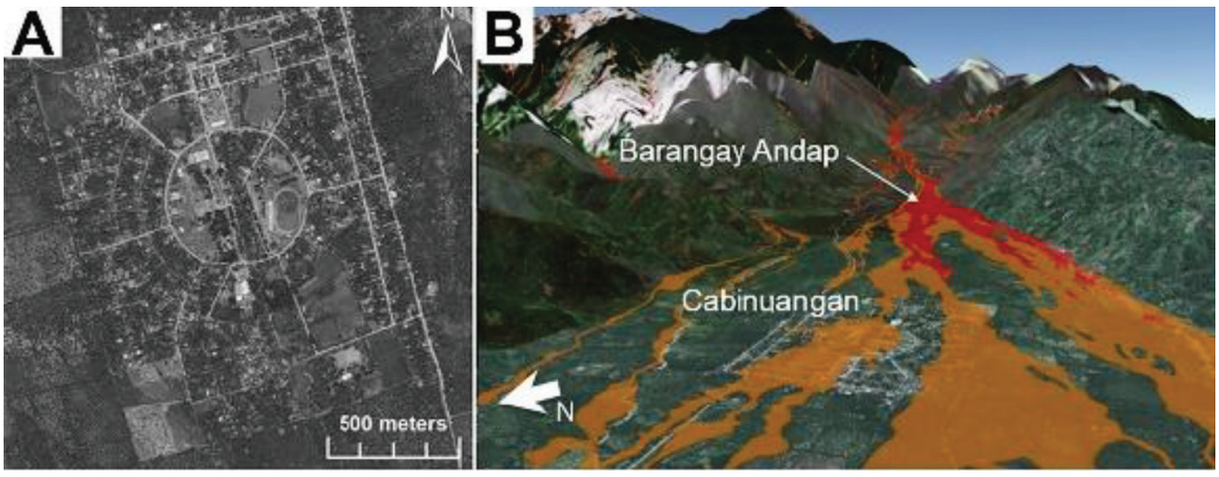


Figure 2. New Bataan. A= Andap, Google image of Cabinuangan (the central district of New Bataan) before the debris flow. B= Southward facing three-dimensional terrain diagram of Andap and Cabinuanga after the Mayo River disaster. Red areas are boulder-rich "true debris flow; orange areas are deposits of more dilute " hyperconcentrated" flows.

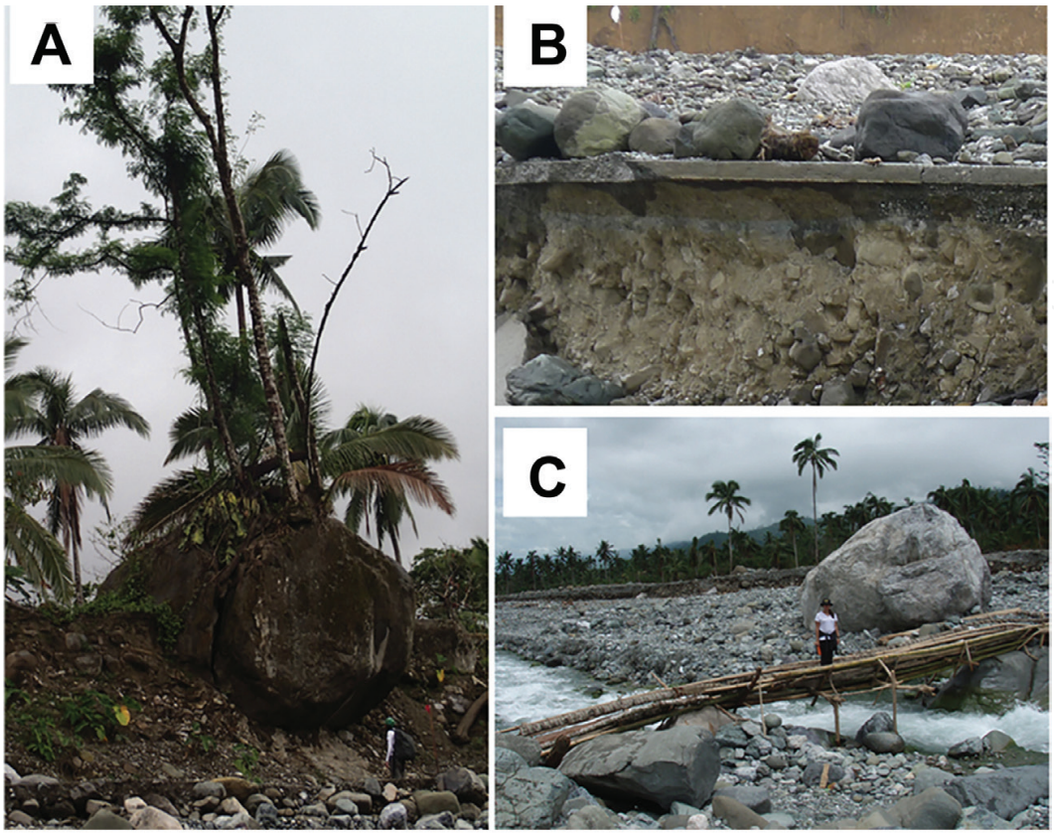


Figure 3. Debris-flow deposits in the New Bataan area. (A) Boulder in ancient reverse-graded debris-flow deposit. Well-established trees indicate an age of some decades prior to the settlement of the town. (B) Old debris-flow deposits underlying New Bataan—Andap high-way. Boulders and cobbles are separated from each other by a matrix of finer-grained sediment, as they were while still flowing. For scale, the concrete is 15-cm thick. The coarse sediments atop the highway are new debris-flow deposits from Typhoon Bopha. (C) Boulder-rich deposits of debris flows that destroyed much of the barangay, at the site of the destroyed Mayo River bridge.

The lethality and capacity for damage of a debris flow is not determined by its size alone. If its path is sparsely populated, such as at Mount St. Helens, or if the people in harm's way are familiar with the hazard, such as at Pinatubo Volcano, even large debris flows may not inflict casualties.

Rain on mountain slopes that falls strongly and lasts long enough will dislodge soil and loose rock into landslides. These may coalesce into debris flows, which are slurries of sediment and water that look and behave like concrete pouring out of a delivery truck. By weight, the water rarely exceeds 25%; only 10% may be enough to provide mobility. Gravel and boulders constitute more than half of the solids, and sand typically makes up about 40%. Silt and clay normally constitute less than 10% and remain suspended in the water [21, 22]. Students of debris flows frequently say "In stream floods, the water carries the sediment; in debris flows, the sediment carries the water."

While a debris flow is contained in a mountain channel, it carries large boulders with remarkable ease. In part, this is because of the high buoyancy of the dense slurry. Additionally, boulders in the flow repeatedly bounce away from the channel floor and sides up into the "central plug" of the flow near the surface, where friction with the channel is minimal and the

Location	Date	Trigger	Volume, 10^6 m^3	Deaths
Rios Barrancas and Colorado, Argentina [14]	1914	Failure of ancient landslide dam	2000 estimated	?
Bucao River, Pinatubo Volcano, Philippines [13]	10 July, 2002	Caldera lake breach	<<160	0
Bucao River, Pinatubo Volcano, Philippines [15]	5–6 Oct, 1993	Typhoon Flo (Kadiang) rains	110	0
Kolka Glacier, North Ossetia, Russia [16]	2002	Large glacial detachment	~100	125
Nevados Huarascan, Peru [17]	1970	Pyroclastic flows melted snow and ice	100 (flow volume)	18,000
Nevado del Ruiz, Colombia [14]	13 Nov, 1985	Pyroclastic flows melted snow and ice	40	23,000
Mayo River, Mindanao, Philippines [1]	4 Dec, 2012	Typhoon Bopha (Pablo) rainfall	25–30	566
Cordillera de la Costa, Vargas, Valenzuela [18]	Dec 1999	Heavy rain	19	30,000
Mayon Volcano, Philippines [19]	30 Nov, 2006	Typhoon Durian (Reming) rains	19	1226
Pine Creek—Muddy River, Mount St. Helens, Washington, USA [20]	18 May, 1980	Pyroclastic surge melted snow & ice	14	0

Table 1. The global record of the 10 largest debris flows, ranked by decreasing volume. Modified and updated from [10].

flow is fastest, enabling them to migrate quickly to the front of the flow. There, they become part of a moving dam of boulders, logs, and tree debris being pushed along by the flowing mass contained behind it.

The moving frontal dam ponds the main flow body, which is richer in sand, silt, and clay and progressively becomes more dilute toward the rear, undergoing transitions into what are called *hyperconcentrated* flows, somewhat confusingly because they carry much more sediment than do normal streams. In hyperconcentrated flows, sand, silt, and clay typically comprise up to 75% by weight. Such flows look like normal, turbid flood waters, but their velocities are much greater, typically 2–3 m/s [23]. They are too dilute to transport boulders and can transport gravel only by pushing and rolling it on the channel floor. To the rear, hyperconcentrated flows are succeeded by even more dilute, turbid flood water. In the literature, somewhat confusingly, "debris flow" sometimes refers to only a true debris-flow phase. Sometimes, however, the term means an entire hydrologic event consisting of debris-flow, hyperconcentrated, and normal stream-flow phases, as we do here in reference to the Mayo River debris flow.

When a debris flow emerges from the mountains, it spreads out, and the increased basal friction slows it down. Some of its sediment load drops out and adds volume to an *alluvial fan*, a cone-shaped feature that topographic maps show as contour lines that are convex in the downstream direction, as seen in **Figure 1**. Even after the debris flow spreads out, large boulders (**Figure 3**) continue to be transported by combined flotation, push, drag, and rolling. The hyperconcentrated and normal-flood phases may extend many kilometers beyond the

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alluvial fan. Debris flows vary in volume by many orders of magnitude (**Table 1**), the most frequent ones being only a 1000–100,000 m^3 and the largest more than a 100,000,000 m^3 [10].

An important distinguishing characteristic of true debris-flow deposits is "reverse grading": boulders tend to be smaller at the base and increase in size upwards. Large boulders commonly jut out at the top of a deposit, as observed at New Bataan (**Figure 3A**). In addition to the buoyancy they experience from the dense slurry, the best mechanism advanced to explain reverse grading is *kinetic sieving* [7, 11, 24–26]. While flowing, shear at the base of a debris flow continuously causes temporary void spaces of different sizes to open, and particles of equivalent sizes migrate into them. Smaller voids form and are filled by smaller solid particles more frequently, and so larger boulders migrate up toward the top of the flow. Another characteristic of debris-flow deposits that distinguish them from the deposits left by normal streams, in which particles grade upward from coarse to fine, is "matrix support" (**Figure 3B**). A mixture of the finer sediment that constituted the bulk of the flow separates the larger rock fragments from each other. A useful guide for distinguishing the effects of debris flows from those of floods was published by Pierson [27].

3. Super Typhoon Bopha

On 23 November, 2012, a large area of convection began forming at 0.6°N latitude, 158°E longitude [28] (**Figure 4A**). Two days later, while still unusually close to the equator at 03.6°N, 157°E, it was categorized as a tropical depression. It was upgraded to Tropical Storm Bopha three days later on 26 November, while at 04.4°N, 155.8°E, a latitude where the Coriolis effect was too weak to quickly cause it to rotate. Only four days later, on 30 November, while Bopha was still at 3.8°N, 145.2°E, it did grow into a Category 1 typhoon.

Bopha then rapidly gained in intensity. On 1 December, while at 5.8°N, 138.8°E, it had intensified into a C4 Super Typhoon. On 2 December, wind speeds were 259 km/h, those of a C5 Super Typhoon. Notably, this happened while Bopha was at 7.4°N, 128.9°E, closer to the equator than any Category 5 tropical cyclone ever had before. On 3 December, as Bopha interacted with Palau Island, it weakened temporarily into a C3 typhoon before reintensifying back to C5. On 2 December, Bopha entered the Philippine area of responsibility at 8 a.m. local time and was assigned the local name of Pablo.

Bopha crossed the eastern Mindanao coast at about 7.7°N on 4 December at 0445H, the global record proximity to the equator for all C5 tropical cyclones (**Figure 4B**). Average wind speeds and gusts were 185 and 210 km/h, respectively. Many fisher folk at sea were lost, and many coastal dwellers were drowned.

Once onshore, Bopha weakened rapidly as it expended much of its energy in wreaking great havoc. Numerous deaths and severe injuries were attributed to flying trees and debris [29]; however, by far, the greatest cause of death and destruction was the Mayo River debris flow that the typhoon rains generated (**Figure 4C**).

Bopha passed through Mindanao, entered the Sulu Sea, and crossed Palawan Island to enter the West Philippine Sea. There, it reversed course and approached northern Luzon but dissipated before reaching it.

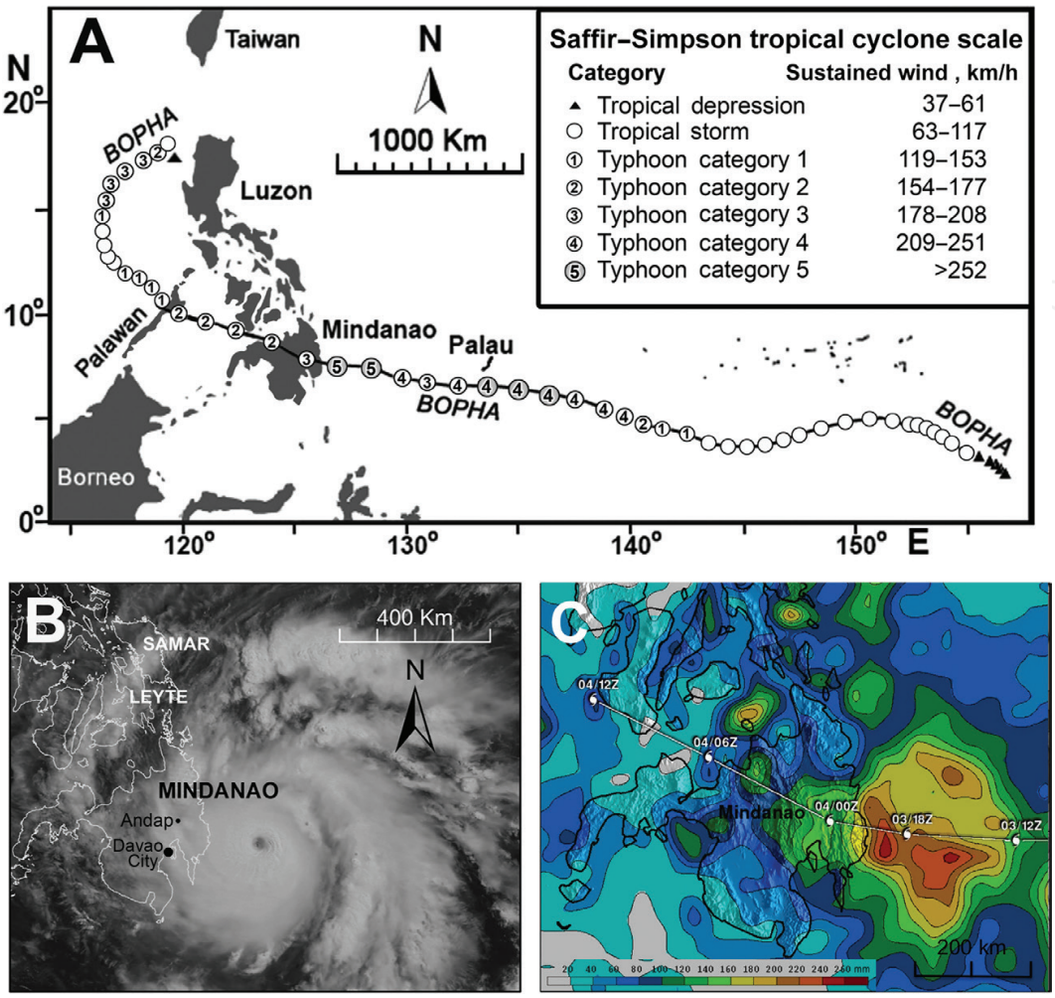


Figure 4. Typhoon Bopha (Pablo). (A) Track and development of the Super Typhoon. New Bataan, Andap, and the Maragusan rain gauge lie beneath the Category 3 icon following the Mindanao landfall. (B) Bopha nearing landfall (modified from [28]). (C) Tropical Rainfall Measurement Mission (TRMM) image from which NASA [28] estimated that Bopha delivered over 240 mm of rainfall near the coast.

The United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) [30] reported that 1146 Filipinos were killed by Bopha; 834 were still missing, and 925,412 were rendered homeless. It totally or partially destroyed more than 233,000 and caused 1.04 billion U.S. dollars of damage to buildings, crops, and infrastructure. Bopha was the most costly typhoon in Philippine history up to that time—only to be superseded less than a year later in November 2013 when Super Typhoon Haiyan generated the storm-surge that destroyed Tacloban City and devastated widespread areas in the central Philippines.

4. The Mayo River debris flow

The available rain gauge data for Bopha were gathered at Maragusan municipality, 17 km south of Andap (**Figure 5**). Even at that distance, given the Bopha's huge size, these data are good proxies for the rainfall that caused the debris flow. They show that the Mayo River

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watershed received 120 mm of rain from midnight on 4 December until the flow occurred at 6:30 that morning. It fell as intensely as 43 mm/h, and 4.4 million m^3 were accumulated. These values greatly exceeded the debris-flow initiation thresholds at the Philippine volcanoes Mayon and Pinatubo [31, 32] and Taiwan [33, 34].

After the debris flow began, it was sustained by another 24 mm of torrential rain that fell until 7 a.m., delivering an additional 900,000 m^3 of water. The rainstorm peak in intensity, 52 mm/h, happened at 6:45 a.m. A half-kilometer downstream of the Mayo Bridge (**Figure 1**), the Mamada River discharges into the Kalyawan River; the storm runoff from its 17.7 km^2 watershed, along with the discharge from other Kalyawan tributaries, diluted the debris flow into hyperconcentrated flows that extended 2 km beyond Cabinuangan (**Figure 2B**).

Several geological factors contributed to make the debris flow possible. The Mati Fault in **Figure 1** is a major splay of the Philippine Fault zone, so the rocks of the Mayo watershed have undergone extensive fracturing, making abundant rock debris and facilitating its weathering into soils. Mining and logging has denuded the watershed slopes, facilitating landslides. Bopha's winds uprooted trees on the slopes, exposing soils to storm runoff. Soils are rich in clay, which increases the debris-flow mobility and runout distance [35]. Furthermore, the 2012 debris flow swelled as it easily incorporated the old debris-flow deposits that lay abundantly along its path (**Figure 3B**).

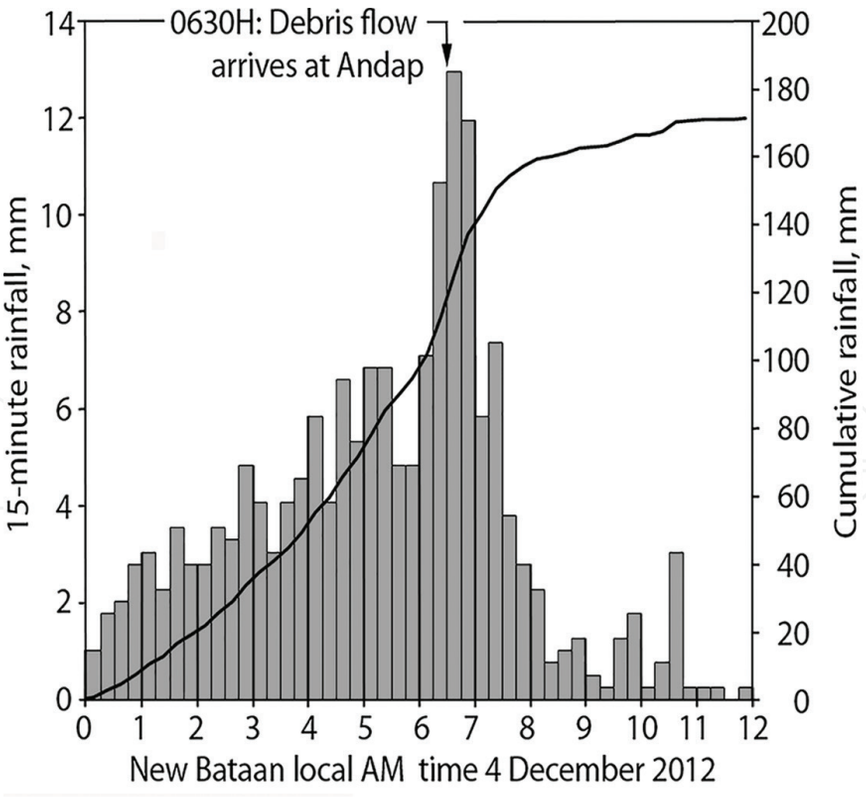


Figure 5. The rainfall that triggered and sustained the Mayo debris flow. Histogram measures the rain that fell during successive 15-minute intervals; 120 mm had accumulated by the time the debris flow hit Andap. Another 24 mm of peak rainfall sustained the flow until 0700H before the storm began to wane.

At about 6:30 a.m., Andap resident Eva Penserga watched in horror as a sturdy concrete bridge 1.5 km upstream of Andap was obliterated by the 16-m high front of a full-fledged debris flow emerging from the Mayo River gorge. A truck on the bridge carrying 30 construction workers was carried away. Several minutes later, surviving Andap residents watched for 5–10 minutes as the debris flow passed through the village.

Tragically, alerts radioed by the government before the catastrophe had urged people to avoid floods at the Andap community center because it stood on high ground. About 200 of them joined the local inhabitants there; 566 people were swept away, 7.5% of the population counted in Andap by the 2010 census.

We calculated a maximum debris-flow velocity of 60 km/h from amateur videos and the length of the debris-flow deposit. Nothing could withstand the main flow, but along its eastern edge, 70 m upstream from the obliterated Andap community center, slower velocities are documented by damage to trees that still survived (**Figure 6**). When a flow of water or debris encounters and rides up an obstruction, the height to which it rises is a measure of its velocity [36]. If all of the kinetic energy of the flow was converted to potential energy as it rose up against the trees, the 1.8 m run-up height h recorded by the highest damage indicates a velocity v of 5.8 m/s, or 21 km/h, from $v = (2gh)^{1/2}$. This is only a minimal value, because the formula takes neither channel roughness nor internal friction into account.

Our satellite imagery, the maps of Bopha after the disaster that we made with LiDAR data, and our field measurements yield a volume of the Andap debris-flow deposit of 25–30 million



Figure 6. Data used to reconstruct the velocity of the debris flow that destroyed Andap. The woman is pointing at the flow level before run-up. Remnants of Andap are in the background; the yellow sign commemorates all the victims by name.

m^3. This ranks it seventh among the largest debris flows of the world (**Table 1**). The width of the deposit is 0.2–1 km wide. The deposits with the greatest thickness of 9 m, in the 500 ha Andap area, includes boulders 16 m in size (**Figure 3C**). Thicknesses decrease downstream to about 0.25 m, and the sediments diminish in size into pebbly, laminated hyperconcentrated-flow sands that cover a 2000 ha area which extends 8 km north of Cabinuangan. In this area, abundant tree trunks and other forest debris (**Figure 7**) that contained many cadavers accumulated in creeks. To impart a sense of the maximal damage, the debris flow wreaked upstream of Cabinuangan, and **Figure 8** presents before and after aerial coverage of the Mayo Bridge and Andap areas.



Figure 7. Hyperconcentrated flows left large tangles of lumber and tree debris with many cadavers at numerous Cabinuangan (central New Bataan) sites.

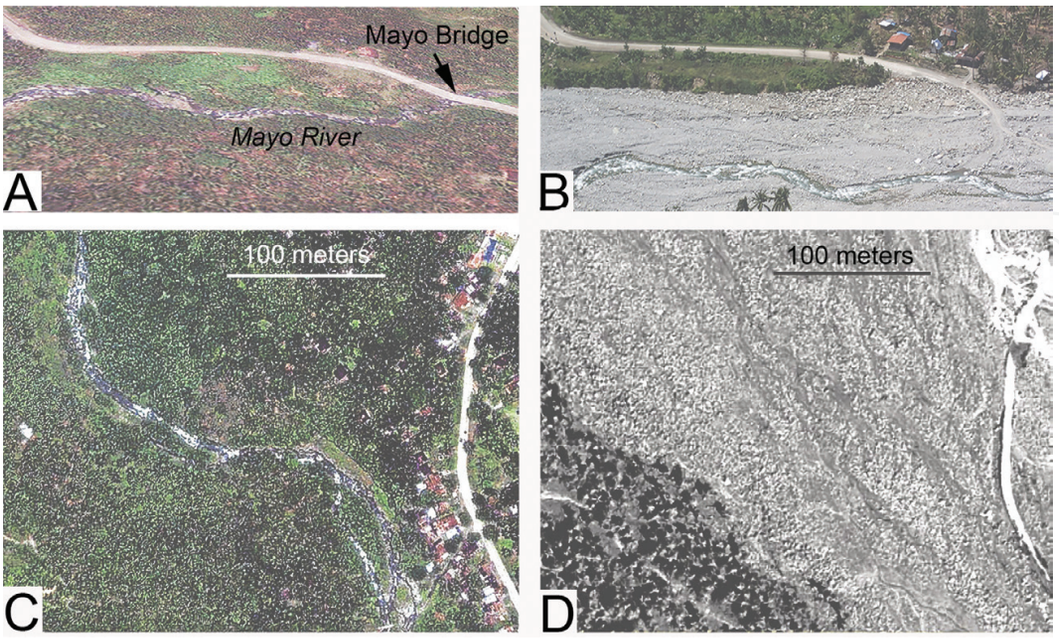


Figure 8. Upstream impacts of the debris flow. (A) Google image of the Mayo River and Mayo Bridge before the debris flow. (B) Post-Bopha air photo of the same area. The large boulder in **Figure 3C** is where the temporary road crosses the stream. (C) Air photo of Andap before Bopha. (D) Same area after the debris flow.

5. The role of Philippine population growth

The global increase in death and damage from natural calamities can be ascribed in part to anthropogenic climate change, but another important reason is the expansion of growing populations into high-risk areas [37]. Landslide disasters are also increasing in developed European and North American nations [35–39], but the trend is especially pronounced in places visited by tropical cyclones [40, 41]. Nowhere is this better exemplified than in Mindanao and by the Andap catastrophe.

The founding of the newer Mindanao settlements including New Bataan was largely driven by rapid population growth [42]. In 1950, the average Filipino farmer cultivated one hectare; this was cut in half by the early 1980s. When New Bataan was settled in 1968, the Philippine population was 36.4 million and was growing 2.98% a year. By July 2018, it had almost tripled, to 106.6 million [43]. A congressional bill filed in 2003 was meant to provide contraception to the poor. The Philippines is predominantly Roman Catholic, and only after strenuous clerical opposition was the bill finally passed in December 2012—coincidentally, the month that Bopha arrived. It must be said that, for all his failings, Rodrigo Duterte is the first Philippine President to take population growth seriously, beginning with his providing contraception to the poor of Davao City when he was its Mayor. Still, the annual growth rate has dropped to 1.72%, but that equates to two million more Filipinos annually. Virtually no areas free of hazards are available to house them.

The Philippine coastal areas, which provide housing and sustenance for two-thirds of the population, are fully developed and increasingly crowded. Metro Manila, the most populated and fastest-growing area, is extracting so much that it is subsiding several centimeters to more than a decimeter annually, losing area to the sea and becoming ever less able to accommodate more people because of worsening floods and tidal incursions [44]. Other rapidly growing Philippine coastal cities including Davao City southwest of Andap (**Figure 4B**) are probably experiencing the same problems.

Real-estate interests are taking advantage of the urgent need for living space by seeking to reclaim 38,272 ha of Philippine coastal areas, including 26,234 ha that comprise virtually the entire near-shore zone of Manila Bay [45]. This, even though rapid subsidence increasingly subjects coastal Metro Manila to storm surges, and the metropolis is overdue for a major earthquake, enhanced ground shaking and liquefaction that would disproportionately damage reclaimed land. Inexorably, other people are seeking living space inland, where natural hazards abound, especially landslides and debris flows. Davao City is a 100-km southwest of Andap (**Figure 4B**). Before leaving to assume the Presidency, Mayor Rodrigo Duterte approved a 200-ha reclamation project for the city [46]. No geological feasibility studies were conducted. The city shares a similar geographic setting with Tacloban City, at the head of a bay. In 2013, a huge storm surge generated by Typhoon Haiyan was funneled up the bay to obliterate much of Tacloban. Davao City is close to segments of the Philippine Fault; offshore earthquakes could similarly funnel tsunamis up to Davao.

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6. Will climate change bring more frequent typhoons to Mindanao?

6.1. The historical record of tropical cyclone landfalls in Mindanao

The alluvial fan on which Andap was built, and the ancient debris-flow deposits under New Bataan testify that such flows occurred many times before Super Typhoon Bopha. The youngest of these left the deposits underlying the highway in **Figure 3B**; the sizes of some trees rooted in old deposits (**Figure 3A**) indicate that one event occurred decades or even a century before New Bataan was settled in 1968.

Do these old debris-flow deposits and the Andap disaster merely represent the most recent rare and essentially random Super Typhoons, or will Mindanao and other low-latitude regions suffer from such catastrophes more frequently as the climate changes? Most climatologists [47–52] equate climate change with fewer but more intense tropical cyclones due to rising sea-surface temperatures and atmospheric water vapor. But this says nothing about whether typhoons will hit Mindanao more frequently in the future, even though their history since 1945 suggests as much (**Figure 9A**).

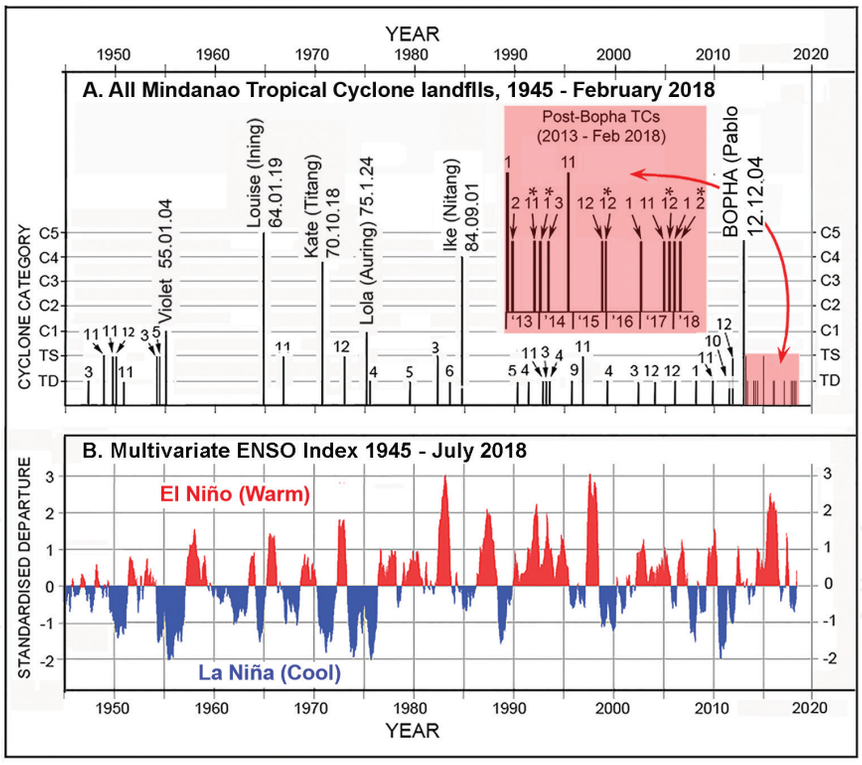


Figure 9. Historical record of Mindanao typhoons. (A) The record from 1945 to February 2018. Cyclone categories: TD = tropical depression; TS = tropical storm; C1–C5 are categories increasing in strength; their respective sustained wind speeds are given in **Figure 4A**. Each typhoon is dated as YY.MM.DD. Number over each TD and TS is the month of occurrence, from 1 January to 12 December. In the insert, asterisked TDs caused fatalities. (B) The record of all El Niño and La Niña events since 1945. From [58, 59].

The literature regarding the frequency of West Pacific typhoons yields little insight pertinent to Mindanao. Two reports [53, 54] exemplify the problem; the significant multi-year fluctuations they reported are not manifested in Mindanao. Neither study included tropical depressions among their data because these are harder to define and are more ephemeral, and thus they ignored most of the Mindanao occurrences. Landfalls are easy to locate; however, tropical depressions can be lethal on Mindanao. For example, 5 of the 13 that came after Bopha (**Figure 9A** insert) caused fatalities. In addition to ignoring tropical depressions, the data set utilized by reference [54], which is entitled "Inactive Period of Western North Pacific Tropical Cyclone Activity in 1998 –2011," was limited to tropical cyclones of the June -October main typhoon season. Of the 45 that made landfall on Mindanao since 1945, only 5 came in that season: Typhoons Kate in October 1970 and Ike in September 1984, and 3 of the 11 tropical depressions. For Mindanao, unlike for the northwest Pacific as a whole, 1998–2011 was not at all a slack cyclone period.

Until 1990, tropical cyclones rarely and sporadically made landfall on Mindanao because it was in the ephemeral southern fringe of the northwest Pacific typhoon track. Since the U.S. Navy Joint Typhoon Warning System began to archive northwest Pacific tropical cyclones in 1945, only 34 visited Mindanao by February 2012 [55]. After Bopha, another 13 had arrived by February 2018 (**Figure 9A**). These 47 landfalls are incontrovertible, and our search for what the future might hold begins with them.

During 30 of the 45 years from 1945 to 1990, including the 8 years from 1956 to 1963, not one tropical depression visited Mindanao. Most of the rare Mindanao tropical cyclones were weak: six tropical depressions and eight tropical storms. Since 1955, five typhoons did make landfall on Mindanao before Bopha, although Louise and Ike barely crossed northernmost Mindanao. In 1970, C4 Kate passed 45 km south of New Bataan, which experienced heavy rain and floods but not much wind. Only five tropical cyclones of all categories arrived during the northwest Pacific peak typhoon season of June through October, although these included Kate in October 1970 and Ike in September 1984. A total of 36 came during the off season: 18 in March through June and 18 during November through January.

In the period from 1945 to 1989, Mindanao tropical cyclones occurred only every 2.5 years on average. Then, from 1990 to 2017, they began arriving roughly once a year. It is also troublesome that Mindanao has recently begun to suffer lethal cyclones in consecutive years. In December 2011, a year before Bopha, Tropical Storm Washi killed 1268 people in Cagayan de Oro City, on the northern Mindanao coast 180 kilometers from New Bataan [56, 57]. Two months earlier, a tropical depression arrived in Mindanao, making 2011 only the fifth year since 1945 for the island to receive two tropical cyclones. In 2014, Mindanao experienced Tropical Depression Lingling and Tropical Storm Jangmi. Last, in the 5 years since Bopha, 2 tropical storms and 11 tropical depressions have visited Mindanao—so frequently that they had to be plotted as an insert in **Figure 9A**.

The increasing frequency of Mindanao storms since 1990, although alarming, cannot be ascribed simply to the climate change from global warming. We must consider whether these

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changes are tied to multi-annual and multi-decadal fluctuations in western North Pacific sea-surface temperatures.

6.2. El Niño-Southern Oscillation (ENSO) and typhoon frequency

ENSO is the complex result of ocean-atmosphere interactions that are best expressed by fluctuating sea-surface temperatures in the central and eastern equatorial Pacific (**Figure 9B**), from warmer during El Niño to cooler during La Niña periods [58, 59]. During an El Niño, atmospheric pressures are high over the western Pacific and low in the eastern Pacific, and the situation reverses during a La Niña. Both phases occur every 3–5 years; typically, El Niño episodes last 9 months to a year and La Niñas as long as 3 years [60].

Tropical cyclones tend to form farther east, are more widely dispersed, and curve northward during El Niño episodes, thus are rarer in the Philippines. During La Niñas, their tendency is to start farther west, remain below 23°N, and take more westward courses, and so they make more frequent Philippine landfalls, most during a main September–November season [48, 51, 61–63]. Except for their tendency to arrive later than November, all the typhoons before Bopha that made Mindanao landfalls since 1945 fit that pattern by occurring during La Niñas (**Figure 9**). Bopha came either during a weak La Niña [64] or a weak El Niño [65]. From 1945 to 2018, the weaker storms and depressions that visited Mindanao showed no marked preference between El Niño and La Niña episodes, although they tended to occur during La Niñas from 1945 to 1975 and 1996 to 2012 and during El Niños from 1979 to 1995 and 2013 to 2018.

A major analysis [66] has predicted that global warming will increase the historical average frequency of extreme La Niñas from one every 23 years to one every 13 years. Three effects of global warming are blamed: first, the western North Pacific region of insular seas and islands that includes the Philippines is expected to warm more quickly than the central Pacific; second, the temperature gradients in the surface waters of the tropics will increase; and last, extreme El Niños, which will occur more frequently, are usually followed by extreme Niñas [67]. Given the tendency of typhoons to make landfalls on the Philippines more frequently during La Niñas, the country including Mindanao should expect greater future storminess.

Another cycle of sea-surface temperature, the Pacific Decadal Oscillation (PDO), is so-called because its periods last for two or three decades [68, 69]. This cyclicity is most distinctly expressed in the northern Pacific but is not clearly manifested in the tropics, although one study [70] attributes an interdecadal variation in May-June rainfall over southern China to a complex interplay between the PDO and the ENSO. The PDO does not correlate with Mindanao landfalls, or even with the frequency of all northwest Pacific typhoons.

6.3. Other expected behaviors of future typhoons

Seven prominent climate scientists who reviewed [52] the great body of research on how climate change might be affecting tropical-cyclone activity explain that its many conflicting results arise from great variations in cyclone frequencies and intensities, as well as serious

lacks in the quantity and quality of the records. The authors are not sure that the observed changes exceed the variability due to natural causes, but predict that by 2100 the averaged *frequencies* of all tropical cyclones will decrease 6–34%, They also believe, however, that *intensities* will increase 2–11% by century's end because, although the frequency of all tropical cyclones is expected to decrease, the most intense ones will become more frequent. Importantly, the review predicts a 20% increase of rainfall within 100 kilometers of storm centers, which would generate larger debris flows. This increase is ascribed [71] to anthropogenic warming, which weakens the summertime winds that carry the tropical cyclones along. Already, their translation speeds decreased globally by 10% from 1949 to 2016. This slowing enhances the amount of time they have to take up water vapor from the ocean and deliver rain when their centers reach land.

In short, the record of increasingly frequent landfalls on Mindanao may or may not indicate that more frequent typhoon disasters will happen there in the future, although recent reports [66, 67] strongly imply as much. Low-latitude areas, however, are given short shrift by most meteorological and climatologic analyses. We urgently need to understand how anthropogenic global warming is changing tropical-cyclone behavior in subequatorial regions because so many people live in them.

7. A new Philippine catalog of alluvial fans and their associated debris-flow hazards

Following our study of the Andap disaster, Project NOAH used high-resolution digital terrain models to identify and catalog all Philippine alluvial fans, by analyzing geomorphic features, slopes, gradients, and stream networks nationwide. The catalog is accessible online for free in the NOAH portal [72].

More than 1200 alluvial fans were identified, and communities that might be affected by their debris flows are being educated about the hazard. In October 2015, Typhoon Koppu (Lando) generated devastating debris flows on alluvial fans in Nueva Ecija province, but the vulnerable communities were warned and evacuated, and so no one was killed [73]. Later that year, Typhoon Melor (Nona) also triggering massive debris flows in Mindoro Island, burying or sweeping away houses and infrastructure in several communities situated on alluvial fans. Again, timely warnings and evacuations prevented the loss of life [74].

8. Other climate-related hazards in the Philippines and Mindanao

Future fluctuations between extreme El Niños and La Niñas pose other threats. Philippine rainfall is modulated by ENSO; El Niños bring droughts, and La Niñas cause excessive rainfall [75, 76]. Rock debris accumulates on slopes during a protracted El Niño drought; the

http://dx.doi.org/10.5772/intechopen.81669

succeeding La Niña episode brings heavy downpours that mobilize the accumulated material into landslides and debris flows. Another serious hazard associates with ENSO is forest fires: rainy La Niña episodes promote strong vegetation growth that a succeeding El Niño drought dries out and renders inflammable.

Mindanao has 21 active and potentially active volcanoes [77]. They are tourist attractions, producing geothermal energy, some are actively mined, and many support large agricultural populations. These volcanoes still lack thorough study and monitoring instrumentation, and similar to the situation at Pinatubo Volcano on Luzon Island before its catastrophic 1991 eruption, their populations are unfamiliar with eruptions and lahars. Any major eruption will eventually be followed by a large typhoon and lahars. The larger Mindanao volcanoes, being structurally and mechanically weak [78], do not need to erupt to undergo debris flows. All that is needed to trigger them would be exceptionally strong rainstorms in their vicinities.

9. Conclusions

Bopha formed, became Category 5 Super Typhoon, and made landfall closer to the equator than any C5 tropical cyclone ever had before. More than 120 mm of rain fell on the Mayo River watershed in only 7 hours. A catastrophic debris flow it generated devastated *Barangy* Andap and killed 566 of its inhabitants. We measured its deposit as a dry volume of 30 million m^3, making it the seventh largest globally.

Debris flows are remarkably poorly understood in the Philippines. This is especially true in Mindanao because it is located in the southern fringe of the typhoon track of the northwest Pacific and has rarely experienced typhoons and the debris flows they generate. This lack of experience is a main cause of the loss of life in Andap.

New Bataan and Andap were established in 1968 by people who did not understand the nature of the ancient debris-flow deposits on which they were building and the hazard that produced them. This was still the case when Bopha approached: government authorities broadcast the fatal advice for people to avoid flooding on the high ground at Andap, which was sitting on the Mayo River alluvial fan. The lack of understanding about debris flows persisted after the disaster; government scientists assigned to explain the tragedy and select relocation sites for the displaced people called it a "flash flood" [78].

New Bataan and Andap were settled in the late 1960s because of rapid population growth. The population continues to explode and has to occupy areas vulnerable to natural hazards. The lesson of Andap and numerous other recent disasters is that new settlements must not be established before the hazards that threaten them have been properly evaluated. But this is a daunting requirement, because few, if any, safe sites remain unoccupied.

Whether or not Mindanao will experience more frequent typhoons and debris flows is an urgent question that is very difficult to answer. In 1945, Western North Pacific tropical

cyclones began to be archived accurately; by 1990, the frequency of Mindanao landfalls had doubled. Learning whether this is caused by anthropogenic global warming is complicated by deficiencies in the quantity and quality of the archived data and by the irregularities in the ENSO climatic rhythms. For Mindanao, the problem is especially difficult because most of its tropical cyclones do not arrive in the main typhoon season of July through October, and most are only tropical depressions, which most climatologists and meteorologists do not include as data for their models.

Philippine typhoons occur most frequently during La Niña episodes, and from July to October, in Mindanao, however, they arrive during the off season from November to June. Extreme El Niños and La Niñas are expected to succeed each other more frequently. This is an excellent example of how Earth systems, which are kept in balance by numerous interacting phenomena, oscillate vigorously when they are disturbed. Global warming is a continuing and accelerating disturbance that prevents returns to equilibria. Mindanao and the entire Philippine nation urgently need to prepare their populations for more frequent hazards, including floods, storm surges, landslides, debris flows, and forest fires.

A developing country like the Philippines has limited resources for hazard-mitigation measures. Philippine society is intensely focused on the family, and so the best and least expensive governmental approach is to provide every family with good, easily-accessible information, so it can develop its own emergency plans.

Project NOAH's mandate tasks are to evaluate the nation's numerous natural hazards, to educate each community about the hazards that threaten it, and to advise them how to respond when a threat materializes. Our study of the Mayo debris flow motivated us to identify more than 1200 Philippine alluvial fans and to prepare the communities that its debris flows may affect. This work has already helped to save lives from major debris flows in 2015.

Acknowledgements

This work was funded by the Philippine Department of Science and Technology (DOST) and the Volcano Tectonics laboratory of the National Institute of Geological Sciences at the University of the Philippines (U.P.). LiDAR data covering the New Bataan area were provided by the U.P. Training Center for Applied Geodesy and Photogrammetry. DOST's Advanced Science and Technology Institute and the Philippine Atmospheric, Geophysical and Astronomical Services Administration provided rainfall data. We thank Congresswoman M. C. Zamora for logistical support and Thomas Pierson for the information about debris-flow mechanics.

Conflict of interest

We have no conflict of interest to declare.

http://dx.doi.org/10.5772/intechopen.81669

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